



New Diagnostic Tools for Probing Collapsing Voids Driven by Hypersonic Impact

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Declaration

I hereby certify that the material of this thesis, which I now submit for the award of Doctor of Philosophy of Imperial College London, is entirely my own work unless otherwise cited or acknowledged within the body of the text.

George Rowland

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Abstract

First Light Fusion (FLF) are attempting to harness fusion energy through hypersonic impact of targets containing voids filled with fusion fuel. They wish to diagnose the conditions within these voids. Development of novel methods to achieve this goal was the motivation for this PhD project. Possible probes identified were particle beams and X-rays generated by high power lasers such as the Cerberus laser at Imperial College and X-pinch produced X-rays. To predict the time of impact and synchronise a diagnostic probe by creating and sending a trigger in advance, a sensor known as a Faraday gate was used, which detects projectiles using electromagnetic induction. Experimental work on Faraday gates showed a linear relation between projectile velocity and output voltage and that gates were sensitive to projectiles with velocities ranging between a few ms^{-1} and several kms^{-1} . Preliminary work commenced on a theoretical model to predict projectile velocity from the voltage induced within a Faraday gate. Tests on the validity of the model initially showed good agreement.

Source sizes from Cerberus-generated X-rays were measured to be between 10 and 100 μm for foil targets. Source sizes from 5 μm diameter carbon fibre were found to be $<5 \mu\text{m}$ but results were limited by low flux. X-pinch source sizes were found to be between 10 and 50 μm and by manipulating the detector, smaller sources $<10 \mu\text{m}$ were measured. The average lower sizes and variability found for X-pinch sources means they are the preferable X-ray source for imaging FLF experiments. Source sizes for Cerberus-generated proton beams were measured to be between 5 and 40 μm and varied over the beam profile. The peak beam energy of 10 MeV limits penetration beyond a mm of FLF target, sufficient penetration would require protons with energy $>40 \text{ MeV}$ and a PW laser system, compared with Cerberus which is currently TW.

An experiment was devised to laser launch a foil flyer, to emulate an FLF projectile, which was then probed using Cerberus. A Q-switched Nd:YAG laser system was installed to launch flyers. Initial results showed that the drive laser caused flyers to respond in a time similar to the YAG laser pulse duration of 20 ns. Optical imaging with light from Cerberus showed flyer velocities up to 1.2 kms^{-1} and laser energy conversion efficiencies up to $\sim 30\%$. Results for varying probe times showed an almost linear relationship between flyer displacement and time, concurring with previous experiments. A Cerberus-generated proton beam was used to image a flyer and investigate any electromagnetic fields. A shot taken with the proton beam arriving $1.6 \mu\text{s}$ after flyer launch showed no observable deflection behind the flyer. An upper limit on the fields was determined to be an electric field of $\sim 9 \times 10^5 \text{ Vm}^{-1}$ or a magnetic field of 38 mT.

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Outputs of the Thesis Research

Several presentations of the work from this PhD project have been produced, all presented by the author:

- “Physics of the Collapse of Voids in Shock Compressed Targets” — Institute of Shock Physics Seminar, Imperial College, 2017
- “Investigating the Electromagnetic Induction in a Faraday-Type Sensor by Accelerated Projectiles” — First Light Fusion Seminar, 2017
- “Synchronising high-velocity gas guns to short-pulse lasers using electromagnetic induction Faraday sensors.” — Plasma Physics Group Seminar, Imperial College, 2017
- “Developments in the Characterisation of X-ray Sources for Probing Shock-Induced Cavity Collapses” — Postgraduate Symposium, Imperial College, 2019
- “Developments in the Characterisation of X-ray Sources for Probing Shock-Induced Cavity Collapses” — Plasma Group Seminar, Imperial College, 2019
- “Proton and X-ray Radiography for Future FLF Experiments — Should you Invest in Lasers or X-pinch?” — First Light Fusion PhD Day Conference, 2021

In addition, data from the Dry-Pinch X-pinch which is shown in Chapter 5 was taken as part of a shot campaign from which the paper “A portable X-pinch for X-ray diagnostics of warm dense matter” [51] has been published. The author of this thesis was a secondary author for this paper and provided assistance with X-ray source size measurement.

Papers derived from the work in Chapter 8 are currently in the early stages of writing which will continue after submission of this thesis.

Role of the Author

Of the experimental work shown in Chapter 4 all data was taken solely by the author, aside from the work carried out on the gas gun at First Light Fusion where there was additional assistance provided by Tim Ringrose, Peta Foster and Hugo Doyle.

Data from shots with X-pinch presented in Chapter 5 were taken using two X-pinch: Nene and Dry Pinch. Results from the former were initially taken with assistance from Simon Bland and then solely by the author once the firing procedure had been learnt. Results from

the latter were from shots fired by Jergus Strucka, where the author assisted in shot preparation and operation of diagnostics.

Data from X-ray emission on Cerberus in Chapter 5 was taken using diagnostics set up and developed by the author in the target area where all shot preparation was also carried out by the author. For the earliest shots, the laser was operated by Samuel Eardley and later by James Fullalove. Similarly with data for proton beams generated by Cerberus in Chapter 6, diagnostics were set up, developed and maintained solely by the author and the laser was operated by James Fullalove.

Development on the new beamline for work in Chapter 8 was carried out by the author with help from James Fullalove and Nick Stuart until the introduction of the Nd:YAG system for which there was initially a lot of assistance by Roland Smith in installation and operation, till the author was capable to operate independently. The author was responsible for running and maintaining the target area and diagnostics used for taking data presented. The Cerberus laser was operated by James Fullalove for any shots using Cerberus.

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Chapter 1

Introduction

1.1 Modern Life and Our Effect on the Planet

To claim that we are heading toward and directly causing an ecological disaster is not dramatic exaggeration but grim reality. Even over the course of this PhD, the repercussions of climate change have become increasingly apparent. Take the seemingly annual, evermore devastating wildfires in California and Australia [1–7], Texas freezing over in early 2021 [8, 9] or the hottest ever temperatures recorded in the UK in 2019 [10] to name but a few examples. While some effort is being made to counter climate change and more minds are gradually being made aware of our responsibility to the planet, severe damage to the environment is a continual and real problem. This is driven by an understandable need to support economies and an ever increasing population but we find ourself in an unsustainable position.

Our enormous appetite for energy has led to the release of greenhouse gases (GHG) such as carbon dioxide and methane, through the combustion of fossil fuels, at an unprecedented rate since the advent of the industrial revolution more than 100 years ago. In fact, at our current rate of use of nonrenewables such as coal and oil, our stores at present will not last us more than another 100 years and our need for energy is only going to increase [11]. For context, it is estimated that, by the end of the 21st century, we will consume as much energy within 20 years as we have since the beginning of civilisation [12]. Our literal appetite and requirement to feed and sustain an increasing population has led to the widespread destruction of precious ecosystems, meaning less of the crucial carbon uptake by forests and causing the extinction of wildlife in our wake. These forests are often replaced by agriculture which not only produces even more GHGs but also more food than we have means to store or distribute to those who need it, leading to wastage. All these factors are acting together and if our ways are not

changed we will experience an increase in inhabitability through rising sea levels, desolation of existing landmass through other disasters like wildfires and a mass extinction event as wildlife struggles to compete with a rapidly changing environment.

Clearly, something has to fundamentally change. On a social level, our attitude toward food, water and plastic as resources has to adapt as there is an enormous amount of wastage into landfills and the oceans. On a larger scale we have to shed our dependence on GHG producing, non-renewable energy sources as they are just that, non-renewable, finite. Realistically, these goals are rooted in education, scientific effort and hinge on the responsible actions of everybody on the planet. Despite this doom and gloom, there is always hope. The rise in usage of renewable sources of energy such as solar and wind as our technology improves will go a long way toward saving the planet. However, there also exists the current “holy grail” of renewable energy which is a driving force for this PhD and the subject we shall next discuss — fusion energy.

1.2 Harnessing the Stars

Nuclear fusion is the process by which two smaller nuclei join to become a third larger particle; this union is typically accompanied by the release of a large amount of energy as the fusion reactants create a more stable particle. Often, a secondary particle such as a neutron or alpha is produced and the released energy is shared amongst all the fusion products. The reason fusion is so attractive is that, per unit mass of fuel, more energy is released than the combustion of fossil fuel and even nuclear fission by at least an order of magnitude [13]. Another, more fantastical way to look at nuclear fusion is the modern day realisation of the work alchemists of old were trying to complete. While it is not the transformation of lead to gold, it is still a form of nuclear transmutation. The difference between then and the present day is that we now understand how such processes occur in nature: the alchemists did not know fusion was occurring above their very heads in the Sun and other stars [12]. In a more macabre form, fusion can also be used for destruction with nuclear weapons; however, this project is not interested in this utilisation but in the harnessing of fusion for the production of a clean source of energy. In the stars, fusion occurs from the lowest mass element, hydrogen, all the way up to elements such as cobalt, nickel and iron [12]. Up to this point energy is released by fusion but energy is required to create heavier elements. On Earth, the most important fusion reactions for potential energy generation schemes occur between hydrogen or more specifically two of its isotopes, deuterium and tritium [13] which we shall now consider in more detail.

In order to make fusion take place, two positively charged nuclei must overcome their coulomb repulsion to get close enough for the strong force to take effect. This can be achieved by heating the nuclei to a high enough energy to cause a thermonuclear reaction [13]. This temperature requirement necessitates that the reactants are in the plasma phase, a state where the nuclei of atoms become dissociated from their electrons and create a quasi-neutral mix of ions and electrons. This poses two problems: achieving these extreme conditions and then confining the plasma for long enough to create significant fusion and extract the energy [13]. Equation (1.1) shows a fusion reaction we are interested in,



This reaction is important since, at relatively low energies, it has a higher cross section than other fusion reactions which involve deuterium alone. This means we can initiate the reaction on a larger scale at lower temperatures than for other reactants [13]. We can obtain deuterium as it is naturally occurring in water and relatively abundant, at roughly 1 part in 6500 in the form of heavy water, D_2O ; tritium is radioactive with a ~ 22 year half-life and not naturally abundant though it can be produced in other fusion reactions [13]. Tritium production is a critical condition for a reactor along with the aforementioned plasma creation and confinement, all of which we shall discuss shortly.

Prior to that we shall compare fusion as an energy source to its contemporaries. Firstly there is the combustion of fossil fuels which harnesses the chemical energy stored in molecules. This releases a moderate amount of energy but more than a few eV per molecule is rarely produced for such an exothermic reaction. As can be seen in Equation (1.1), a quantity of energy more than 6 orders of magnitude greater is released in the fusion of two nuclei [13]. There are fission reactions, where large unstable nuclei are split into 2 or more fragments, which release more energy than a single fusion reaction [13]. However, this is typically shared by more daughter product particles and a significant proportion is given as the momentum of the massive fission fragments which is essentially “lost” as residual heat in radioactive waste. As such, fusion is still a more theoretically efficient source for energy generation. The vast difference between the energy liberated in nuclear reactions and chemical reactions is due to a fundamental difference in the nature of each. Chemical reactions concern the destruction and subsequent formation of more stable molecular bonds through the movement of electrons and typically liberate energy of the order eV. Whereas in nuclear reactions, energy is liberated directly from the rest mass energy of nucleons as they are moved into more stable configurations. This energy is of the

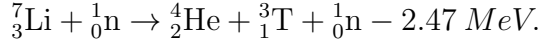
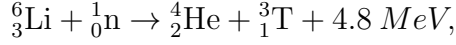
order MeV. Another advantage of fusion energy over fission is that a reactor is by its nature a lot safer. There is no chance of a meltdown or uncontrolled chain reaction leading to an explosion as if there is not a constant injection of fusion fuel to the system the reaction will die and the amount of fuel present typically never exceeds more than a single gram at any one time [12]. Moreover, the primary “waste” product in Equation (1.1) is helium, an inert and useful gas which is much safer than the frequently long-lived radioactive and unstable daughter nuclei produced in fission [11].

As some context for how much energy is in fact produced in nuclear fusion, if we could react the naturally occurring deuterium from the water in a kettle of volume 1.7 litres with equal parts of tritium, the energy released would be enough to boil that same volume of water in the kettle from room temperature $\sim 100,000$ times over. The equivalent amount of coal needed to be combusted to release this much energy would be around 2 tons. Thus we can see that, if fusion energy were to become commercialised, our energy needs will be sated for many years to come. On the other hand, fusion is not without its drawbacks, for example the tritium fuel is radioactive and if it combines with oxygen as T_2O and enters the body it can cause harm [11]. Another consideration is the activation of the walls of a reactor as a result of neutron capture, this is an inevitability for a nuclear plant of any kind. However, it is less of an issue for a fusion plant which does not have to deal with intrinsic fission fragments whose lives are much greater than an initially stable wall material which has been activated. Due to this, a fusion plant will only have to be shielded for roughly 100 years before it can be demolished [12].

A current obstacle to be overcome to make a commercialised reactor is reaching ignition, this where a reactor is self-sustaining: enough fusion energy is generated and enough tritium can be bred in situ to keep further fusion reactions going. To overcome the D-T coulomb repulsion and start fusion, the temperature must be $T \sim 10^8$ K (or energy of ~ 10 KeV) [13]. A further stipulation is that a condition known as the Lawson criterion must be satisfied. This states that for a plasma to undergo fusion, the product of the plasma density, n and the time for which the plasma is confined, τ_c is greater than or equal to a function of the temperature of the plasma [13],

$$n\tau_c \geq f(T). \tag{1.2}$$

The Lawson criterion dictates the confinement of the plasma which will become apparent when we discuss the different approaches to fusion below. A reactor must also be able to create more tritium fuel as it operates, two possible mechanisms for this are as follows,



These reactions show that the presence of lithium in the reactor is required from which tritium can be bred. As such it is clear that lithium and deuterium are the primary resources we require for fusion [11]. As the required temperature for fusion is so high, any material which directly contacts the plasma will be significantly damaged. For this reason, ways of effectively confining the plasma have to be devised. The first method of interest is magnetic confinement fusion (MCF) which uses strong magnetic fields to contain a torus of plasma, examples of devices which utilise this technique are the Tokamak and the Stellarator [11]. This type of fusion can be carried out at relatively low pressure and density but require, as a result of Equation (1.2), a confinement time of the order a few seconds. This poses a problem as a second is an age for this temperature and density plasma to exist [12]. The second common approach to fusion is inertial confinement fusion (ICF); this is commonly attempted by focusing high power laser pulses onto the surface of a mm scale capsule of fusion fuel. This ablates the surface of the fuel capsule and drives an implosion, raising the pressure and density enough to enable fusion [11]. As a consequence, Equation (1.2) only requires a confinement time of less than a nanosecond [12]; the difficulty in this approach arises from instabilities which inhibit a symmetrical implosion and cause a mix between hot and cold material.

More recently a new approach has been devised by First Light Fusion (FLF), Oxford, the body who funds this project. Their approach is a type of inertially confined fusion but rather than high power lasers, shock drivers such as light gas guns and pulse power machines are used to impact and implode a fuel-filled cavity. This method aspires to use a shock wave to create the conditions required to achieve fusion. While this approach is still in its infancy, it potentially avoids a few of the difficulties encountered by the “classic” spherical fusion techniques. Firstly, by sacrificing the symmetric geometry of traditional ICF, the Rayleigh-Taylor instability is no longer of critical concern; neither are large confinement times needed as high instantaneous densities are reached as the shock drives the asymmetric cavity implosion. In other words, shock driven fusion presents a middle ground between traditional MCF and ICF. We shall now discuss the goals of FLF in more detail, the problems which they need to overcome and how this PhD fits in with their objectives.

1.3 First Light Fusion and the Aims of this Project

An experimental FLF target consists of a millimetre scale cavity, containing fusion fuel, which is embedded within a polymer block (polymethyl methacrylate — PMMA). This structure is impacted by a hypervelocity (velocity $>3 \text{ kms}^{-1}$) projectile, driving a shock wave travelling at several kms^{-1} through the whole target. Everything this shock wave passes will be raised to a higher, instantaneous state of pressure, temperature and density. Knowledge and understanding of these conditions within the cavity is clearly fundamental to the goal of FLF as that is a direct indication of whether fusion relevant conditions have been achieved. Moreover, establishing the states within any material undergoing extreme loading is crucially important to high energy density physics (HEDP) and equation of state (EoS) studies; the results feed directly into mathematical models and hydrodynamic simulations. Tied together, this work allows us to better design materials and targets to operate optimally under extreme conditions and allows us to better predict their response in subsequent scenarios [14].

From the nature of a FLF experiment, there are three main considerations. Firstly, if we wish to image a shock front travelling at 10 kms^{-1} through a mm scale cavity at a spatial resolution of $10 \mu\text{m}$, we require a method of probing with duration no longer than 1 ns to avoid excessive motion blur. This is quicker than any camera shutter and so we need to generate a probe which has this kind of duration i.e. a laser or pulsed-power driven source of radiation or particles. Secondly, in order to image this shock front at a chosen location within a target we must know exactly how fast, and when, the target is impacted to trigger the probe to arrive at the moment we desire. In other words, we need a method for precise synchronisation of the probe and impact systems. Finally, a hypervelocity impact induces a density sufficient to cause an initially transparent polymer block to become opaque to optical light. In all, this means we desire either a probe of penetrating radiation such as X-rays or energetic particles such as protons, with at most $\sim\text{ns}$ pulse duration and a method of synchronising the probe with the arrival of the shock in the target.

A visual representation of the main goals of this PhD in the context of a FLF experiment is shown in Fig. 1.1. Here we have a PMMA target containing a spherical cavity being impacted from the left by a projectile, launching a shock into the PMMA target. Parameters such as temperature, density and pressure of the PMMA in its shocked and unshocked states are denoted by “1” and “0” subscripts respectively. The unshocked state should be quantifiable prior to conducting the experiment, while the instantaneous shocked state will be measured using a probe synchronised to the passage of the shock (the probe in Fig. 1.1 is clearly not

synchronised to the shock as it has arrived too early — this is a design choice in the image for ease of viewing). Steps 1 and 2 form the “synchronisation” aspects of the PhD which will be to establish a method for detecting a projectile and predicting impact in order to trigger a diagnostic probe as described in the previous paragraph. Steps 3 and 4 form the “characterisation” aspects of the PhD which will be to measure parameters of each probe including energy and pulse length such that we can evaluate the suitability of the probe for a potential FLF experiment. The final step of this project will be in the execution of an experiment as shown in Fig. 1.1.

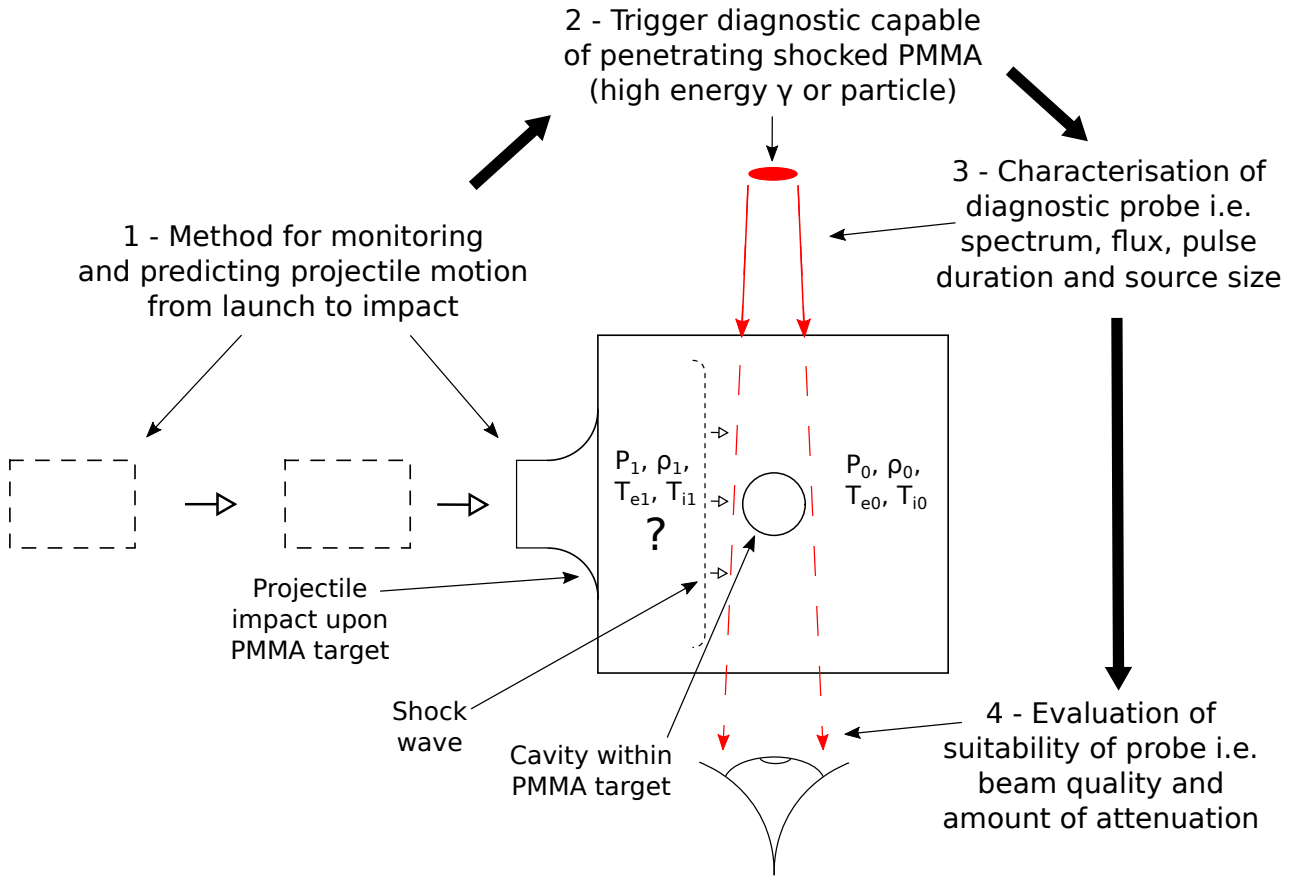


Figure 1.1: Diagram showing an example FLF experiment. A PMMA block, containing a spherical cavity, is impacted from the left by a projectile. A shock wave is launched into the PMMA block. Conditions in the PMMA before and after passage of the shock are annotated and denoted by “0” and “1” subscripts respectively. Main objectives of this PhD are shown by steps 1 through 4.

It is worth briefly mentioning here that a prime candidate for a probe generator which satisfies the above requirements is a short pulse (duration < 1 ps) laser. The interaction of a laser pulse with a suitable target will generate a pulse of X-rays, proton and electrons with durations comparable to the laser pulse. A second consideration is an X-pinch, a pulse power machine which can generate X-ray pulses of $\sim$ ns duration. For the rest of this thesis we shall

first explore the fundamental shock wave physics briefly mentioned in the previous paragraphs. We will then discuss the function and specifics of the pieces of equipment, used as impact drivers and probe generators, in this project. This will include gas guns, X-pinches and short pulse lasers. Next, we will consider methods for synchronisation of probe and impact driver. Then we will compare X-ray production characteristics of a short pulse laser and X-pinch. In addition, we will discuss the characteristics of proton pulses generated by short pulse lasers and finally the synchronisation of a short pulse laser with an analogue to a gas gun launch. For further context, a visual representation of the structure of this thesis is shown in Fig. 1.2.

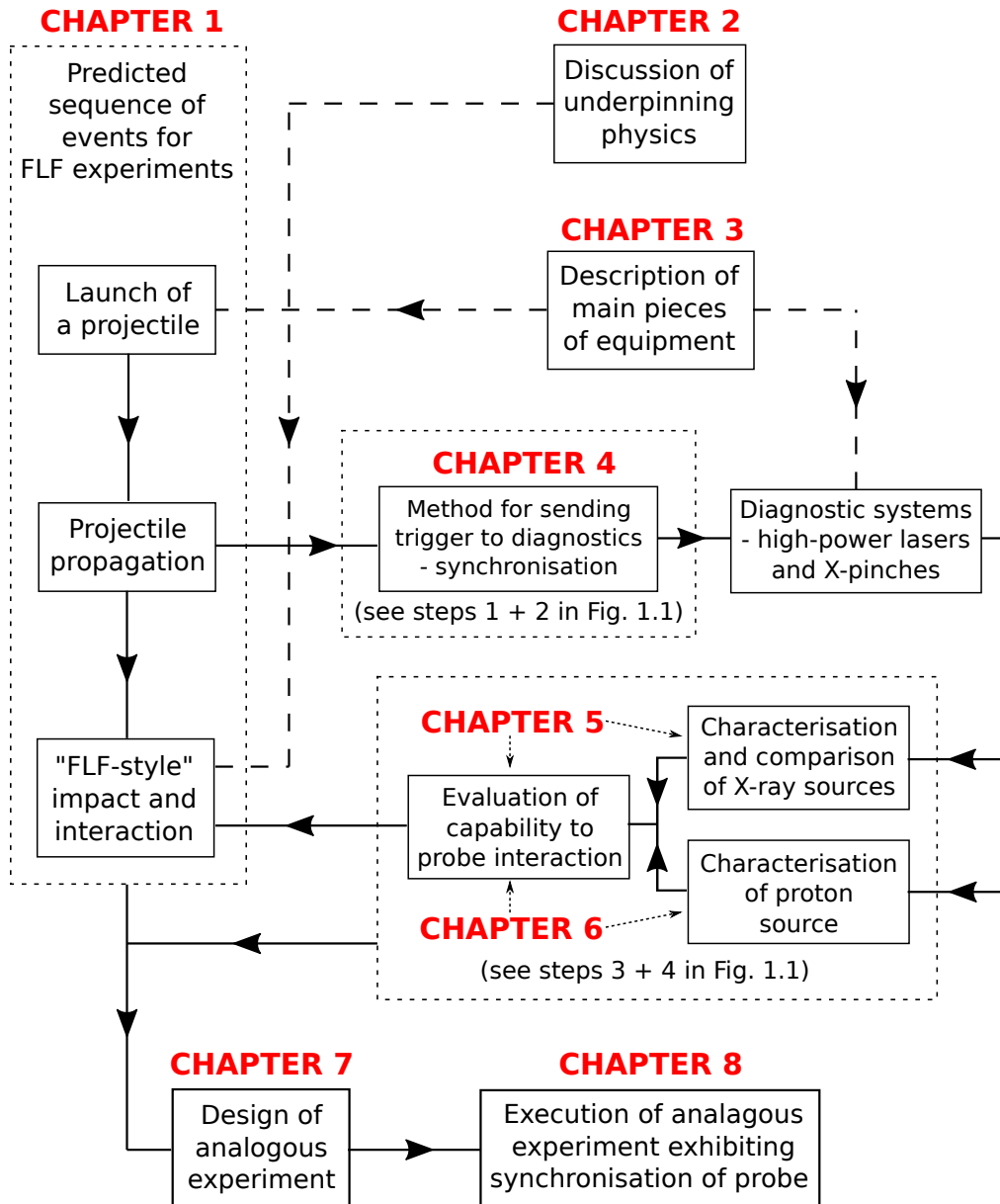


Figure 1.2: Schematic showing a visual representation of the content and structure of the chapters in this thesis. The schematic provides context for the relevance of each chapter to aspects of a FLF-style experiment. The large dashed lines with arrows indicate thesis inputs originating from existing work and literature i.e chapters 2 and 3.

Chapter 2

Relevant Underpinning Physics

2.1 Shock Wave Physics

This chapter will outline the physics of shock waves and introduce a framework for finding the conditions induced by a shock wave. This will be developed in the context of a First Light Fusion (FLF) impact experiment. Fundamental shock wave physics is well covered in several text books; the description here is inspired by some such works, specifically [14–16].

2.1.1 Defining a Shock

A shock wave is defined as a wave front, travelling faster than the sound speed of the medium it is propagating through. Across the wave front, there is a discontinuous and adiabatic transition in state variables [14,15]. A state variable can refer to any of the following: pressure, density, specific internal energy, and temperature. Note that density is interchangeable with the inverse of the specific volume, with “specific” being a synonym for “per unit mass”. An equation relating these variables is known as an equation of state (EoS). As was mentioned in the introduction, the EoS can be derived for different materials through application of the extreme loading provided by shock waves and measurement of the state variables before and after the shock.

Other crucial parameters in shock physics are the velocity of the shock wave, and the particle velocity in the medium driven by the shock. We can illustrate all of these variables in a theoretical FLF impact, see Fig. 2.1. We begin with a projectile which collides with a stationary target at the impact velocity U_I . The projectile decelerates, remains connected to the target, and drives a shock wave of velocity U_S . The projectile, along with target material swept behind the shock front, moves with the particle velocity u_P . Initially the target is

unshocked and takes ambient values of pressure, density and specific internal energy given by P_0 , ρ_0 and E_0 respectively. Behind the shock, these values are raised to their shocked values denoted by the subscript 1 shown in Fig. 2.1. Methods for measurement of these velocities and the state variables above form the basis for this PhD.

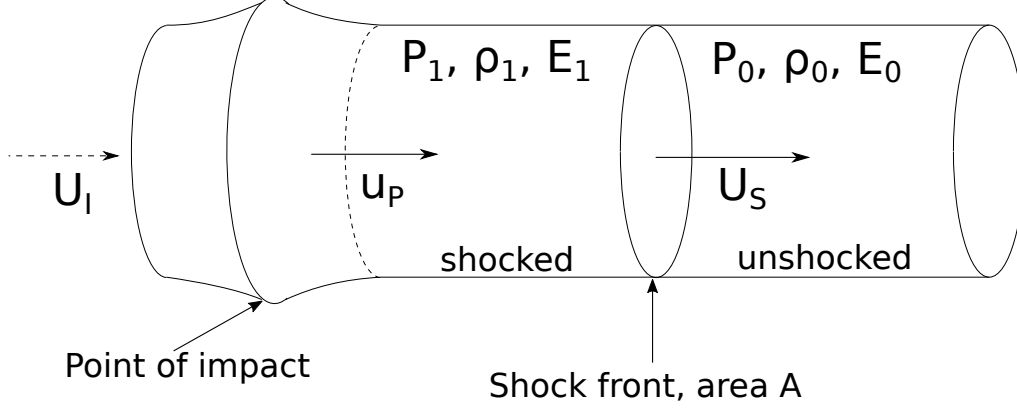


Figure 2.1: Diagram showing a simplified FLF impact event. A projectile moving at a velocity U_I , impacts a target, is decelerated to the particle velocity u_P , and becomes connected to a stationary target (dotted arrow over U_I denotes the projectile is not moving with the impact velocity at the time of the image). The projectile drives a shockwave of velocity U_S and cross sectional area A into the target and material swept behind the shock begins to move at the particle velocity u_P . Values for the pressure P , density ρ and specific internal energy E in the shocked and unshocked material are denoted by subscripts 1 and 0 respectively.

2.1.2 Shock Wave Evolution

A shock wave discontinuity can develop from a pressure pulse in a process known as “shocking up” [14]. This process is illustrated in part (a) of Fig. 2.2. Consider a continuous pressure pulse, this can be approximated into a series of incremental steps in pressure over time. The first step in pressure increases the density of the material through which it passes. A successive step increases the pressure again and travels through material at slightly higher density than the previous. As such it will travel faster than the last “step” since it is generally found that sound speed is higher in more dense material and for higher pressures [14, 15]. These effects lead to the trailing parts of the wave catching the front and the pressure pulse becoming steeper until a shock discontinuity forms. This visualisation becomes more useful when considering release waves.

A release, or rarefaction, wave is a continuous wave which follows a shock wave upon cessation of its driving force. It is a negative gradient pressure pulse through which a shocked material relaxes, lowering its density to an ambient state. Unlike the action of a shock wave, this process is gradual and not adiabatic [14]. The development of a release wave is exactly

the reverse of the development of a shock wave, see part (b) of Fig. 2.2. Successive parts of a release wave lower the pressure in the material, experience a lower density and hence move at a lower velocity. Thus a release wave disperses as it propagates [14]. The velocity of a release wave behind a shock is given by the sum of bulk sound speed in the pressurised material and the particle velocity of the material through which it moves. This means a release wave will necessarily catch up with and overtake a shock front [14]. At which point the shock wave becomes subsonic and in particular, incapable of driving conditions we desire for fusion in this project. Hence, perhaps obviously, shock waves require sufficient driving force to keep them supersonic. This consideration will become fundamentally important when considering potential shock drivers in later sections.

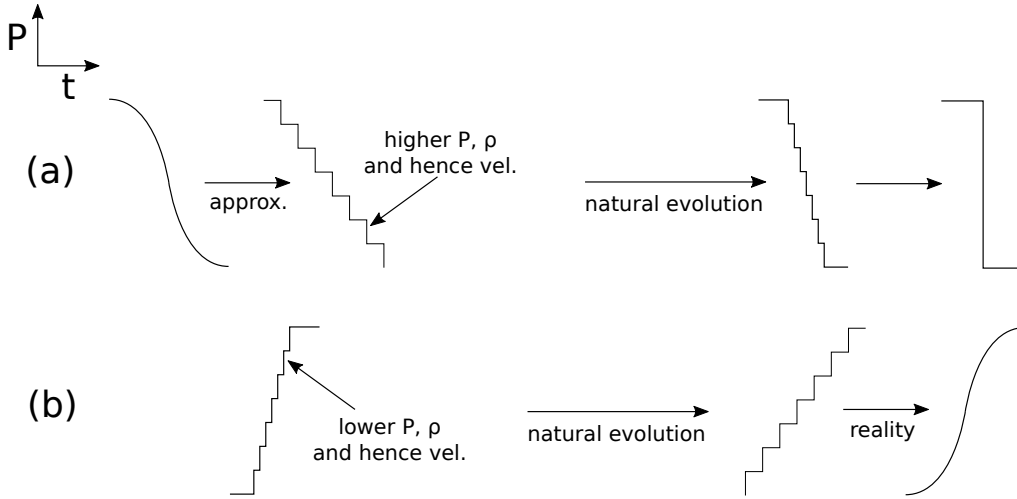


Figure 2.2: Diagram illustrating (a): the emergence of a shock discontinuity from an initially continuous pressure pulse and (b): the natural dispersion of a release or rarefaction wave as it propagates.

2.1.3 Conservation Laws Across a Shock

In order to develop an analytical framework with which to derive shocked material states in a FLF experiment, it is necessary to note a few crucial points and assumptions. Firstly, we shall assume all impacts are at hypervelocity (velocity $>3 \text{ kms}^{-1}$). This means that, upon impact, a target will behave like a fluid, or hydrodynamically [14], as the force of the projectile is large enough to overcome the strength of the intermolecular bonds of the material. In simple terms, the forces and stress within the material are only considered to be due to pressure induced by the impact and prior to impact, initial pressure in the target is negligible since $P_0 \ll P_1$. We also assume that the target is initially stationary and that body forces, such as gravity, are negligible [14]. Finally, the target and impactor are assumed to be impedance matched. If

two materials are impedance matched, they are at the same pressure state and have the same particle velocity. This implies they must then remain in contact as described in Fig. 2.1. If the impactor and target are not impedance matched, energy must transfer between the two in order to reach the same pressure and particle velocity otherwise they shall separate [14].

Now we shall define the laws of conservation across a shock discontinuity. Until now we have not considered the implications of a discontinuous, i.e. instantaneous, jump in conditions for the laws of conservation. A discontinuity suggests a transfer of energy in an infinitely small time, which in reality, is unphysical. Thus a shock front is not technically discontinuous but actually a rapid change in the state variables. As such, the laws of physics must be obeyed across the shock wave and there exists three main equations which describe conservation across a shock. These are the so called Rankine-Hugoniot conservation relations,

$$\rho_0 U_S = \rho_1 (U_S - u_P) \quad (2.1)$$

$$P_1 = \rho_0 U_S u_P \quad (2.2)$$

$$E_1 - E_0 = \frac{1}{2} P_1 (V_0 - V_1) \quad (2.3)$$

where $V = 1/\rho$ is the specific volume, and all other symbols are as defined in Section 2.1.1 and illustrated in Fig. 2.1. Equation (2.1), Equation (2.2) and Equation (2.3) describe conservation of mass, momentum and energy respectively [14].

2.1.4 A Framework for Describing Shocked Material States

With Equations (2.1) to (2.3) we have three relations and five variables, U_S , u_P , P_1 , ρ_1 and E_1 . We assume E_0 and ρ_0 are known for an ambient material and that P_0 is negligible as discussed in the previous section. In order to find these variables at any time, we require at least one more equation. One option is to assume that fluids have a thermodynamic equation of state relating internal energy to pressure and volume [14, 16], of the form,

$$E = E(P, V). \quad (2.4)$$

Alternatively there is also a relation between shock and particle speed for a material which is inferred by measuring each speed simultaneously during an experiment. This equation holds provided the material does not change phase and takes the form,

$$U_S = c_0 + Su_p, \quad (2.5)$$

where c_0 is related to the bulk sound speed of the material and S is a positive constant since shock speed can not be below particle speed. These must be determined in experiment [14]. This is however not the complete picture. Equation (2.5) takes this form for metals, but for polymers — as we have in the case of PMMA — we require a more complex form. Armed with the Rankine-Hugoniot conservation laws and either one of Equation (2.4) or a form of Equation (2.5) it will in principle be possible to find all five variables, U_S , u_P , P_1 , ρ_1 and E_1 , for a single shock state of a material provided one variable is measured on shot. Hopefully, this fact impresses upon the reader the importance of quantitative measurement of just one of these variables in an impact. This process can be repeated for a range of different impact parameters to populate a fuller description of the behaviour of a material under different loading conditions.

The final tool that is useful to introduce is a means of graphically representing all the attainable states of a material. Typically variables are represented in P - V , P - u_P and U_S - u_P space on a so called Hugoniot curve, an example of which is shown in Fig. 2.3. Two crucial points are as follows. Firstly, a Hugoniot curve does not represent a thermodynamic loading path for the material but simply a locus of states attainable by a material undergoing shock compression [14]. Secondly, a Hugoniot curve is said to be centred upon an arbitrary set of initial conditions [16]; the principal Hugoniot is one which is centred upon standard conditions i.e. room temperature and pressure [14]. As such, a material experiencing shock compression is represented as a straight line linking the initial state of the material and the final state. This is shown in Fig. 2.3 by the red line between initial state (V_0, P_0) to final state (V_1, P_1) and is also known as the Rayleigh line, the equation for which is [14],

$$P_1 - P_0 = \rho_0^2 U_S^2 (V_1 - V_0). \quad (2.6)$$

Note that the gradient of the Rayleigh line is also the square of the dynamic shock impedance, $Z = \rho_0 U_S$ [14] and presents a method for direct measurement of the shock velocity in an impact if the initial and final states are measured for a material with a known Hugoniot. Furthermore, the area under the Rayleigh line gives the change in specific internal energy, $E_1 - E_0$ [14] as can be seen from Equation (2.3).

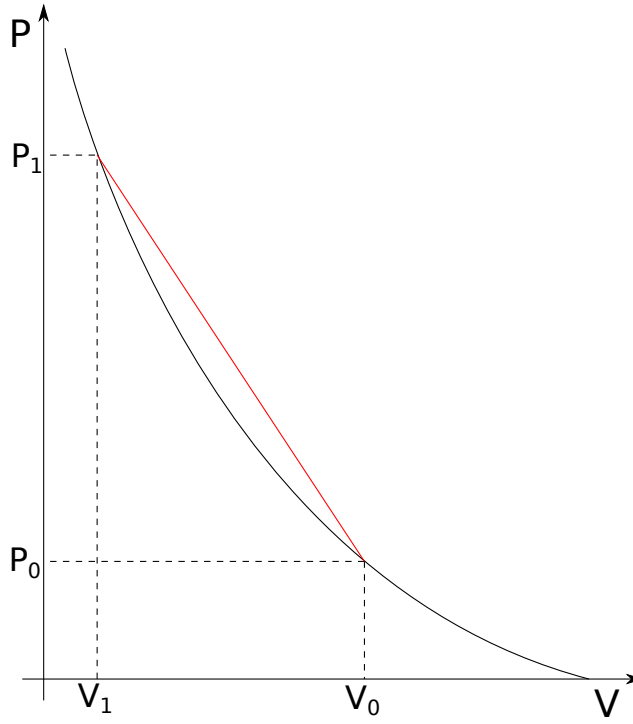


Figure 2.3: Plot showing an idealised example Hugoniot curve in P - V space (black line). The initial and final states of the medium before and after shock compression are (V_0, P_0) and (V_1, P_1) respectively. Also shown is the Rayleigh line (red line) which is the thermodynamic loading path between the two states [14].

The final technique we will describe here ties in the Hugoniot curve with concepts from Section 2.1.3 and a parameter we have not yet discussed in any detail but will become significant to the rest of this project, impact velocity U_I . This technique is known as impedance matching. As will shortly become clear, it is convenient to deal with Hugoniots in P - u_P space for impact studies. Firstly, we can express the Hugoniot in P - u_P space by substituting Equation (2.5) into Equation (2.2),

$$P_1 = \rho_0(c_0 + Su_P)u_P. \quad (2.7)$$

Now consider the situation where we have an impactor and target of the same material with a known Hugoniot. The target will have its Hugoniot in P - u_P space centred upon $(0,0)$ as shown by the black line in Fig. 2.4. The impactor will have the same Hugoniot but reflected in the P axis (since the shock travels in the opposing direction in the impactor) and centred upon the impact velocity $(U_I, 0)$, as shown by the red line in Fig. 2.4. Upon impact, the pressure in the target and impactor rises and they remain connected i.e. they are impedance matched. We now recall from Section 2.1.3 that two impedance matched materials must reach the same P - u_P state. This state is the point at which the Hugoniot curves cross, point (u_{P1}, P_1) in Fig. 2.4. Therefore, provided we know the Hugoniot of a material and impactor we can calculate the

final P - u_P state with knowledge of the impact velocity alone. A further point we can make from the symmetry of the red and black lines in Fig. 2.4 is that when the target and impactor are the same material, the final particle velocity is exactly half the impact velocity [14],

$$U_I = 2u_P. \quad (2.8)$$

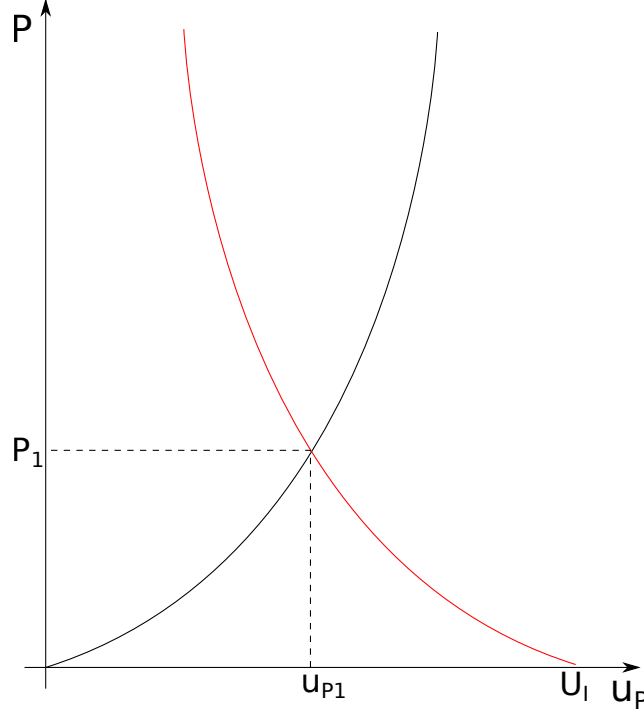


Figure 2.4: Plot demonstrating the method of impedance matching in P - u_P space. The black line is the Hugoniot curve for a target initially at rest, the red line is the Hugoniot curve for a projectile of the same material which impacts, and remains connected to, the target at velocity U_I . The shocked state reached after impact is the cross point, (u_{P1}, P_1) .

Conversely, this technique can also be used to construct the Hugoniot of an unknown target if a method for u_P measurement is used and the Hugoniot of the impactor is known. This concludes the section on an analytical framework for determining shocked states of materials, in experiments relevant to this project. The next step is in the treatment of a collapsing cavity within a target being driven by a shock.

2.2 Shock-Induced Cavity Collapse

The study of cavity collapse began with the investigation of propeller damage due to cavitation bubbles in water. It was Lord Rayleigh who developed the first complete mathematical description of a single bubble undergoing symmetric collapse in 1917 [17]. It was shown that extreme instantaneous pressure and temperature is created during collapse which caused the propeller damage. A further development came in 1933, as light emission was shown to be produced by ultrasonically driving cavity collapse in a liquid. This manifested as darkening on a submerged photographic plate [18]. This light emission is known as sonoluminescence (SL) and has since become an independent field of research [19–21]. In addition to researching SL and damage mitigation in propellers, the energy concentration in cavity collapse has also been harnessed for initiation of explosives [22–25, 30] and in the treatment of kidney stones through shock wave lithotripsy [26, 27].

This project is specifically interested in asymmetric cavity collapse. This type of collapse can be achieved by driving a cavity next to a solid boundary which inhibits symmetric collapse [28, 29] or alternatively, an asymmetric collapse can be induced using an initially planar shock from projectile impact upon a cavity embedded within a target. The latter is the method we shall consider for this project. Asymmetric cavity collapse dynamics have been studied in multiple works [24, 25, 30–35] and its description in this section is inspired by that body of research. For the purposes of this project, we define a cavity as a void containing either air or fusion fuel. In practice the cavity is formed from two pieces of poly-methyl methacrylate (PMMA) each with a hemispherical void which, when glued together, form a spherical cavity which can be filled using small fill tubes drilled into the PMMA. Crucially, we also assume that the shock driven into the target is sufficient to cause the PMMA to behave hydrodynamically.

A cavity subjected to the above shock conditions undergoes a characteristic collapse, which is illustrated in Fig. 2.5. This figure shows experimental data of an asymmetric cavity collapse from Escauriza et al., taken at the European Synchrotron Radiation Facility (ESRF) [35]. The beamline used by Escauriza at ESRF provides the capability to take images over a whole collapse using X-ray pulses with 100 ps length and a minimum inter-pulse time of 176 ns [34]. Fig. 2.5a shows a cavity before and immediately after arrival of the shock wave, driven by the impact of a gas gun projectile. Note that both the interface between the two pieces of PMMA forming the cavity and the shock front can be observed in these X-ray images. Furthermore after the shock passes the increased density of the PMMA manifests as a darkening in the radiograph.

The first two frames in Fig. 2.5b show the first important characteristic of asymmetric cavity collapse: after passage of the shock front, the upstream side of the cavity begins to invert and form a jet. This jet forms when a shock is strong enough to cause hydrodynamic behaviour of the cavity interface. Escauriza determined this to occur in PMMA for shock pressures greater than 8.49 GPa [34]. The jet then strikes the opposing side of the cavity, with the initial impact occurring between frames 2 and 3 of Fig. 2.5b. This action induces a hotspot of higher pressure and temperature than the shock alone, and can create a flash of light. Additionally the impact of the jet forms a secondary water-hammer shock wave [32] which can be seen in frame 3 of Fig. 2.5b. After the jet impact, the remnants of the cavity form a pressurised toroid which continues to implode. A secondary hotspot and another shock wave is then formed as this toroid totally collapses (between frames 3 and 4 of Fig. 2.5b) and a second flash of light can be observed. Note that the flashes of light from these two hotspots are not visible in the collapse shown in Fig. 2.5 but evidence for both flashes is provided by several works [24,36,37]. These two hotspots would be the most likely candidates for points at which we could achieve fusion in a cavity containing fusion fuel. As such, knowledge of the conditions at these points is the ultimate motivation for this PhD.

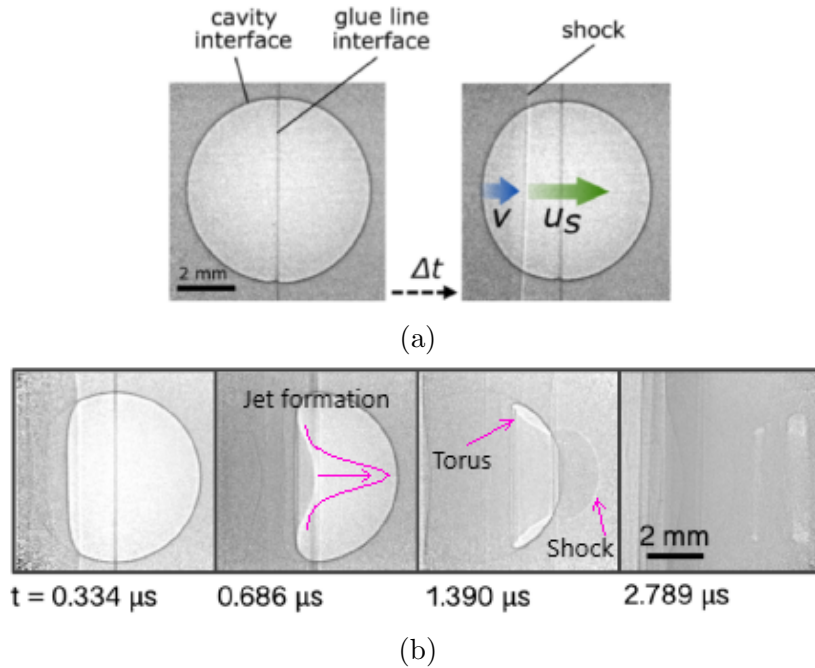


Figure 2.5: X-ray radiographs of a cavity undergoing asymmetric collapse taken from Escauriza et al. [35]. Fig. 2.5a shows a cavity prior to, and just after, arrival of a shock wave. The cavity interface, shock wave and glue line between the two PMMA pieces forming the cavity are all visible. Fig. 2.5b shows the complete collapse of a different cavity. This exhibits the formation of a jet, the water hammer shock after the jet impacts the other side of the cavity and the subsequent formation and collapse of a torus. The times of the frames are relative to the arrival of the shock at the cavity interface.

Previously, the flashes of light produced in asymmetric cavity collapse have been measured to determine the temperature of the hotspots [24, 25, 30]. In one case the temperature was estimated as 20,000 K by measuring amplitudes of emission for three separate wavelengths of light emission and comparing to a blackbody spectrum [32]. Furthermore, measurement of the jet velocity can yield useful information for calculating the expected pressure at the point of jet impact. Analysis by Escauriza [35] determined that the final velocity of the jet u_{jet} (in kms^{-1}) in PMMA relates to the particle velocity as,

$$u_{jet} = 3.99u_P - 0.59. \quad (2.9)$$

According to Bourne [30], the pressure at the point of jet impact P_{jet} can be found from u_{jet} with,

$$P_{jet} = \rho_0 c u_{jet} \quad (2.10)$$

where c would be the shock velocity in PMMA. We can further specify that the pressure caused by the jet must be at least half the value given by Equation (2.10) (i.e. $P_{jet} = \rho_0 c u_{jet}/2$) since the impact is symmetric, see explanation for Equation (2.8). We can also specify that the maximum pressure will be that given by the water hammer pressure caused by hydrodynamic PMMA impacting solid PMMA. Thus, by measuring the particle velocity behind a shock it should be possible to estimate the pressure at the jet impact in an asymmetric collapse using Equation (2.9) and Equation (2.10). This ties in with the framework derived in Section 2.1 to give a potential method for finding the conditions created in shock-induced cavity collapse.

2.2.1 Summary of the Challenges of Probing Shock-Induced Cavity Collapse

The problems described herein form the crux of the issues faced by this PhD project. Fig. 2.5b shows the timescale of the collapse where $t = 0$ is the arrival time of the shock at the cavity interface; timescales of a few μs are typical for a cavity collapse. Within this time-frame, there are two sub- μs events of interest, which create points of high energy density: jet impact and toroid collapse. Prior to the shock arriving at the cavity, there is a time associated with the propagation of the shock through the target, as well as a time associated with the launch of a projectile into the target. This emphasizes the requirement for precise synchronisation of a probe to the projectile impact in order to isolate an event such as the torus implosion.

This is compounded by the need for a probe which can penetrate the increased densities caused by a shock wave. We have already seen that synchrotron X-ray radiation makes an excellent candidate for catching the whole collapse as the train of 100 ps pulses at ESRF acts like a “shotgun” with a large temporal spread. However, synchrotrons are not ubiquitous and access requires a long timescale bid process, which may be inconvenient for a fast moving industrial project. Also, what if we wish to precisely “snipe” and isolate a particular event with higher temporal resolution? A high-power laser generated probe could fulfil this purpose as the probe pulse length can be on the order of the laser pulse length, gaining almost 3 orders of magnitude better temporal resolution than ESRF in the case of a few hundred fs pulse. Moreover, by tailoring a target and using a laser of sufficient intensity it is possible to generate energetic particle probes which are sensitive to electromagnetic fields as well as X-ray probes.

The problem here is that synchronising a short-pulse probe to a relatively long, $\sim\mu\text{s}$ process like a cavity collapse requires more precision than for a synchrotron. Clearly, there are advantages for both synchrotrons and high-power laser-generated probes and the exploration of the capabilities of high-power lasers and other short-pulse energetic probe generators for probing cavity collapse will form the bulk of this thesis, along with methods for synchronisation.

Prior to that, it is necessary to include some reference information on the capabilities of different shock drivers as there is the additional requirement on pressure to induce hydrodynamic behaviour in a cavity collapse ($P > 8.49 \text{ GPa}$). Along with a brief description of the largest pieces of scientific equipment (such as gas guns and high-power lasers) which are used in this project.

2.3 Comparison of Potential Shock Drivers

Here we shall briefly discuss the suitability of different shock drivers to the goals of this project. Table 2.1 lists a variety of pressure environments given by Bourne [14]. The first stipulation on pressure is that it must be greater than 8.49 GPa to cause hydrodynamic behaviour of the cavity interface in PMMA, ruling out a mechanical press. Note here that the pressures listed in Table 2.1 are not a definite value for performance since for the same driver, shock pressure is higher in a target of higher density. This is reflected in Equation (2.2) and the fact that shock/sound velocity is generally higher in more dense materials. Another consideration is the strain rate of the environment. In the context of this project, the strain rate essentially describes the speed at which a target is decreasing in length as it undergoes compression. A higher strain rate leads to a more rapid compression which is reflected by the higher strain

rates given by gas guns, lasers and pulsed-power (Z Machine) when compared with mechanical presses and diamond anvil cells.

Next, we require the loading time of the shock driver to be long enough to complete the cavity collapse before the release wave catches the shock as discussed in Section 2.1.2. Cavity collapse is a several- μs process, as such this means laser and pulsed-power driven shocks will likely be too short-lived for this purpose. Moreover, a short-lived shock will be able to propagate less far into a target leading to a smaller region in which to probe. This is a further issue for laser driven shocks, since a cavity collapse target is a few mm in size. Conversely, loading time must be short enough to cause a step increase in pressure, density and drive a shock, meaning mechanisms which cause a quasi-static increase in pressure such as mechanical presses and diamond anvil cells are unsuitable.

Therefore, the most promising candidates for providing a shock for cavity collapse, with a sufficiently large, step increase in pressure and density and a long enough loading time are currently single-stage and two-stage light-gas guns. We shall discuss the function of these types of gas guns in the next chapter. It is also worth mentioning here that FLF are making use of both gas guns and pulse power to magnetically launch projectiles but the use of the latter is outside the scope of this thesis.

Loading Environment	P [GPa]	Loading time [μs]	Target scale [mm]	Impulse [GPa μs]	Strain rate [s^{-1}]
Mechanical Press	0.01	Quasi-static	50	∞	$10^{-5} - 10^{-1}$
Diamond Anvil Cell	300	Quasi-static	1	∞	
Single-Stage Light-Gas Gun	150	10	100	1500	$10^4 - 10^8$
Two-Stage Light-Gas Gun	300	3	50	900	
Z Machine	500	0.1	10	50	
Large Lasers	1000	0.001	1	1	
Earth Core	~ 360	N/A	N/A	N/A	N/A

Table 2.1: Table listing important parameters for various pressure environments, all information provided by Bourne [14] apart from the strain rates which were provided by Melkote et al. [38]. Note that the values given here are not absolute limits but provide an appreciation of typical values for parameters accessible by each loading mechanism. Also included is the pressure at the centre of the Earth for comparison.

Chapter 3

Instrumentation

The experimental work in this thesis was conducted using several pieces of complex scientific equipment. In this chapter, a brief description of each system is provided along with its function. Where appropriate, any auxilliary diagnostics used in measuring the performance of the piece is also described in this chapter. The information given by these diagnostics is typically not the main focus of the work in this thesis but is pertinent to multiple subsequent chapters, hence their description here.

3.1 Two-Stage Light-Gas Guns

As discussed in Section 2.3 two promising shock drivers for producing shock-induced cavity collapse are two-stage and single-stage light-gas guns. Since their advent, the high pressure, density and temperature induced in targets (compression factors as high as 3.5, pressures up to 500 GPa and an increase in temperature of several thousands K [39]) by light-gas guns has been harnessed for many applications. For instance, equation of state (EoS) studies [39–43] by measuring state variables as covered in Section 2.1. In addition to EoS, shock induced phase change and dynamic fracture can be studied [43], and crucially to this project, the study of asymmetric cavity collapse (Section 2.2) [31, 32, 34]. To this end, we wish to maximise the pressure driven into a target by a shock driver. Therefore, this project focuses on the use of two-stage light-gas guns which are generally capable of providing the highest pressure of the two (see Table 2.1).

Despite the length, the name “two-stage light-gas gun” actually describes this piece of equipment quite succinctly, in that it is a gun with a barrel made of two distinct sections, or stages, which accelerates a projectile using a light-gas (as in helium or hydrogen, the hyphen-

ation here is critical — the author will attest that these are anything but light mechanical systems, after having to lift several barrels). A generalised schematic of a two-stage light-gas gun, referred to as TSLGG from now on, is shown in Fig. 3.1. With reference to Fig. 3.1, a TSLGG begins with a breech, (a), inside which sits a piston, (b). The breech uses either a reservoir of compressed light-gas (then termed a gas-gas TSLGG) or a gunpowder charge (then termed a powder-gas TSLGG) which is released or ignited respectively. This action rapidly supplies kinetic energy to the piston, launching it into the pump tube, (c). The pump tube is filled with a light-gas which is compressed by the piston to high instantaneous pressures up to ~ 1 GPa. There is a tapered transition section after the pump tube, (d). The design of this section is such that, upon impact, the piston behaves hydrodynamically and flows into the taper allowing the light-gas to reach pressures as high as 1 GPa. This forms the first stage of the TSLGG.

Once the gas ahead of the piston reaches the desired pressure, a burst valve, (e), situated at the end of a tapered transition section, ruptures and releases the compressed light-gas into the launch tube, (g), inside which is positioned the main projectile, (f). The compressed light-gas transfers its energy to the projectile, which is accelerated down the launch tube and into a target chamber which are both evacuated prior to firing. This forms the second stage of the TSLGG. The use of light-gases has not been addressed yet but they are used simply because gases such as hydrogen or helium fundamentally have a higher sound speed than air (sound speed being inversely proportional to the square root of density) which results in a higher velocity in the final projectile [42]. Hydrogen offers the highest sound speed and hence performance. It is however, rather explosive when mixed with oxygen and thus a significant safety risk if ignited. Since sources of ignition are generally the most certain occurrence in life behind taxation and death, helium is commonly chosen as a light-gas as it is safer to handle.

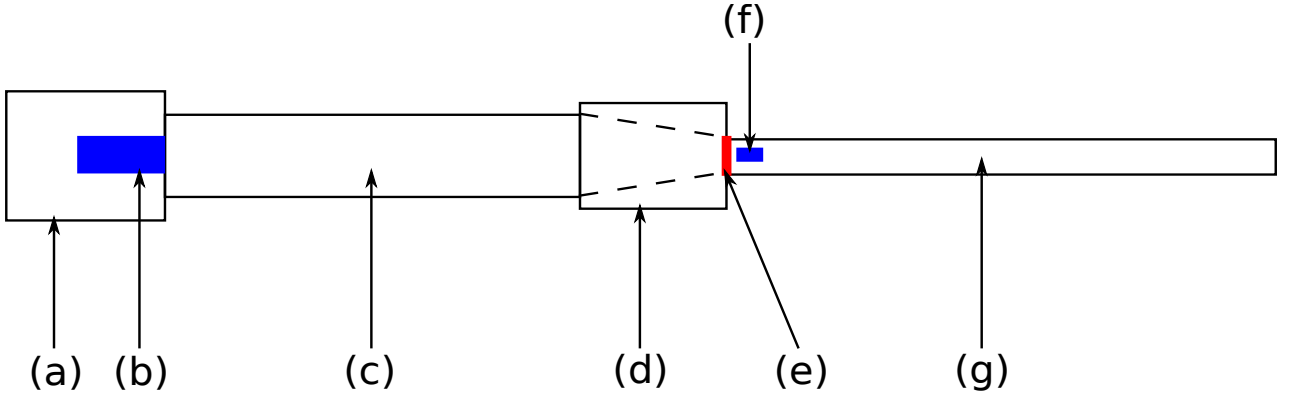


Figure 3.1: Schematic showing the construction of a general two-stage light-gas gun. Prior to firing this consists of (a) a powder or gas breech, (b) a piston situated within the breech, (c) a pump tube filled with a light-gas, (d) a tapered coupling section sealed on one end with a petal valve or burst disk (e), the operation of which introduces jitter into the system. Just behind the burst disk sits the projectile (f) within an evacuated launch tube (g). The launch tube terminates into a target chamber which has been omitted.

To conclude this section, the specifications of the main guns available for this project are described. Firstly there is the gun located at First Light Fusion, Oxford. This is an immobile, powder-gas TSLGG of total length 7.5 m. Using a 42 mm diameter piston and hydrogen as the light-gas, it is capable of launching a primary projectile of diameter 12.7 mm at up to $\sim 8 \text{ kms}^{-1}$ once every 45 minutes [42]. The second gun is a more compact and mobile, gas-gas TSLGG. This gun was built at Imperial College London and moved to Oxford over the course of this PhD. It has a total length of 4.1 m, uses a 50 mm diameter piston and helium as the light-gas to launch a 10 mm diameter primary projectile at up to $\sim 5 \text{ kms}^{-1}$ once every ~ 60 minutes [34].

3.2 X-Pinches

In simplest terms the X-pinch is a pulse-power machine which can produce X-ray pulses with excellent temporal (sub-ns) and spatial ($< 10 \text{ } \mu\text{m}$) resolution for imaging small-scale, rapid evolving processes. Considerable research on the X-pinch has focused on characterising the X-ray source [44–51]. Further to this, the X-pinch has specifically been used as a radiographic backlighter source for imaging other X-pinches, Z-pinches and wire arrays [46–48, 52, 53]. Its application to microlithography [44] and X-ray diffraction studies has also been explored [49]. The following description of the X-pinch was inspired by this body of research.

To understand the operation of the X-pinch, first consider a single current-carrying wire. Supplying a large current will resistively heat the wire to the point at which it will become

a dense plasma and explode outward due to plasma pressure. The current simultaneously generates a strong inward magnetic pressure due to the $J \times B$ force. These two pressures form an unstable equilibrium; any small fluctuation in the equilibrium can cause an instability to grow in the plasma. Specifically, the $m = 0$ or “sausage” instability, named for its appearance. This instability leads to hotspots at random points along the wire where the magnetic pressure overcomes the plasma pressure, imploding the plasma to extreme density. This is the broad underpinning physics behind a Z-pinch. The X-pinch takes this a step further to confine the randomly occurring hotspots to a single point. An X-pinch is created by taking two or more fine wires and crossing them in an “X” formation between two electrodes. When supplying current through these wires, the current is divided equally across them, apart from at the cross point, through which the sum current passes and is hence the location of the strongest magnetic field. This reliably localises the hotspot formation, as described above, to the cross point. With a sufficiently large current of $\sim$ few 10s to 100s kA delivered at a rate typically $\gtrsim 1$ kA/ns [50] the hotspot implodes to high enough temperature and density to be capable of radiating as an X-ray source (despite this, some work has shown X-ray emission from an X-pinch with a current rate a factor ~ 2 below this limit [51]). The unique characteristics of this source is described in detail in Section 5.2.2, for organisational purposes, alongside other the X-ray sources used in this thesis.

This project made use of two different portable X-pinchs, “Nene” and “Dry Pinch I”, both currently based at Imperial College London and both are used for experimental work presented in Chapter 5. While fundamentally similar, they differ in subtle ways which will now be described.

3.2.1 Nene

A schematic with the main components of Nene is shown in Fig. 3.2. In order to drive an X-pinch load on Nene, charge is first stored in its Marx bank, an oil filled reservoir containing 4 capacitors [50]. In operation, these were charged in parallel to 45 kV and discharged in series to a water-filled dielectric pulse-forming line. This raises the voltage to a peak value up to ~ 250 kV. When close to peak voltage, breakdown occurs across a SF₆ filled spark gap, delivering approximately 50 kA in ~ 60 ns to the X-pinch load [50]. The X-pinch load for Nene on all shots presented in this thesis was $4 \times 5 \mu\text{m}$ tungsten wires. Pre-shot these wires were placed into the removable anode plate and then connected to the lower cathode by placing the anode into a holding plate which completed a circuit back to the Marx bank. The anode

plate is rotationally free allowing precise twisting of the wires so they cross and form the X-pinch. The electrodes sit within a multi-port vacuum chamber which allows the attachment of diagnostics with direct line of sight of the X-pinch centre. The vacuum chamber was evacuated to $\sim 1 \times 10^{-4}$ mbar using a turbo pump before a shot. This Marx bank design represents a traditional method for creating an X-pinch.

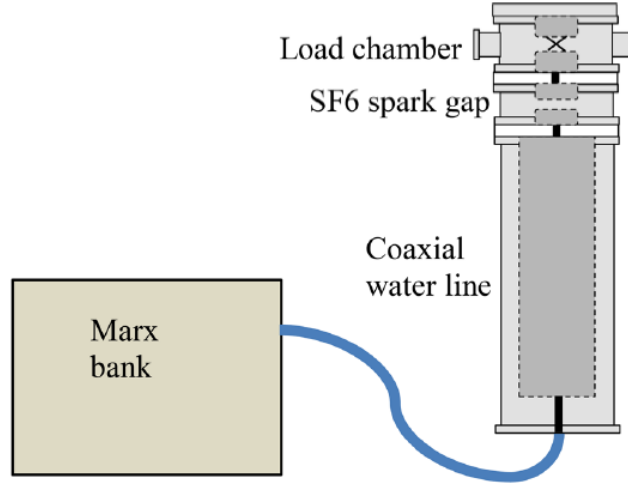


Figure 3.2: Diagram showing the structure of the Nene X-pinch, based at Imperial College. Schematic sourced from Shelkovenko et al. [50]

3.2.2 Dry Pinch I

Dry Pinch I is a newer X-pinch than Nene and is constructed slightly differently. As with Nene we begin with capacitors to store charge, though Dry Pinch I forgoes the Marx bank design for a more compact, oil-free capacitor arrangement. Dry Pinch I also does not contain a water line or SF₆ spark gap as Nene does. Instead, the capacitors are charged to 85 kV and discharged through a dry air switch, into the X-pinch load, delivering on average 127 kA in ~ 348 ns [51]. The result of this is that Dry Pinch I contains no water hence the naming and is also oil and SF₆ free, the latter of which is a dense, environmentally hazardous and colourless, odourless asphyxiant. This design makes Dry Pinch I both more compact and portable than Nene. Also note that Dry Pinch I delivers a higher current but operates at a lower voltage than Nene. The X-pinch load for all shots on Dry Pinch I presented in this thesis was 4×30 μm silver wires. The loading procedure and general design of the vacuum chamber was the same as for Nene.

3.3 The Cerberus Laser System

The Cerberus laser system is a hybrid Nd:Glass OPCPA laser based at Imperial College London. Its description in this section will be a brief summary pertaining to the two main beamlines that are used in the experimental work in this thesis. The important components in the front-end of the laser are shown in Fig. 3.3. The main short-pulse beam starts as a 5 nJ, 250 fs “seed” pulse produced by a diode-pumped Nd:Glass oscillator (Time Bandwidth Products GLX), which defines the central wavelength of the laser at 1054 nm (overlapping with the gain profile of Nd:YLF and Nd:Phosphate glass). This pulse then undergoes temporal stretching and amplification through a total of four optical parametric amplifiers (OPAs), using a specialised technique called optical parametric chirped-pulse amplification (OPCPA), to achieve a pulse of ~ 10 mJ with duration 1.8 ns. OPCPA in Cerberus works by taking the aforementioned seed and stretching the pulse in time such that higher frequencies in the pulse are delayed compared to the lower frequencies, giving the pulse a “chirp”. Stretching the pulse and applying a chirp effectively lowers the intensity without compromising much energy. This allows the pulse to be amplified to greater energies without damaging the amplifier gain medium. Independently this is known as chirped pulse amplification (CPA). In order to amplify the stretched seed within an OPA an additional energy source is needed. This comes from a “pump” pulse which, when temporally, spatially and phase matched with the seed, will preferentially transfer energy to the seed if the frequency of the pump is higher than the seed. This forms the basis of OPCPA.

The pump pulse follows a separate beamline which is separated from the seed pulse immediately after the oscillator by means of a Pockels cell operated at 10 Hz. The pump pulse is first stretched before amplification in a diode-pumped, Nd:YLF regenerative amplifier which applies a gain of $\sim 6 \times 10^6$ to the pump by passing the Nd:YLF amplifier rod a total of ~ 45 times. Next a double-passed, flashlamp-pumped, 7 mm Nd:YLF rod amplifier takes the pulse to 30 mJ. A portion of this pulse ($E \sim 10$ mJ) is split off to pump the first two OPA stages after being temporally compressed to 6 ps and frequency doubled to 527 nm through second harmonic generation. The remaining portion of the pump is stretched once more to 1.4 ns and then amplified using two more flashlamp-pumped Nd:YLF amplifiers which can be configured to produce a pulse of up to ~ 180 mJ. Any amount of this pulse can be divided between pumping the final two OPAs and a second beamline (although it should be said running the maximum available energy down the latter beamline is ill-advised, as shall be seen later). This second beamline can be split once again between a diagnostic beamline for the MAGPIE pulsed-power generator in an external lab and a direct beamline into the Cerberus main target area lab. The

latter of these beam paths is used in Chapter 8 of this thesis and the beam will be referred to as the Cerberus “long”-pulse from now, noting the important characteristics of 1.4 ns pulse length and tunable energy.

The Cerberus short pulse is referred to in Chapters 5 to 8. So far we have discussed its amplification to a ~ 10 mJ, 1.8 ns pulse after the four OPA stages. After this, the pulse passes a pre-pulser created by Samuel Eardley for a previous PhD project [54], which can be used to add an arbitrary controlled (time-delay and energy) pre-pulse to the beam. The pulse then passes through a series of flashlamp-pumped Nd:Glass amplifiers to get to ~ 0.5 J. A small portion of the beam can be picked off at this point and is compressed to ~ 500 fs before being sent to the Cerberus main target area for use in optical diagnostics. The rest of the pulse propagates to the Cerberus main target area before a final amplification and compressor taking the beam to up to 5 J (limited by B-integral in air and the target chamber window) and ensuring a pulse length of typically ~ 700 fs. The exact diagnosis of the characteristics of this particular pulse is crucial to experiments in Chapters 5 to 8 and shall now be discussed.

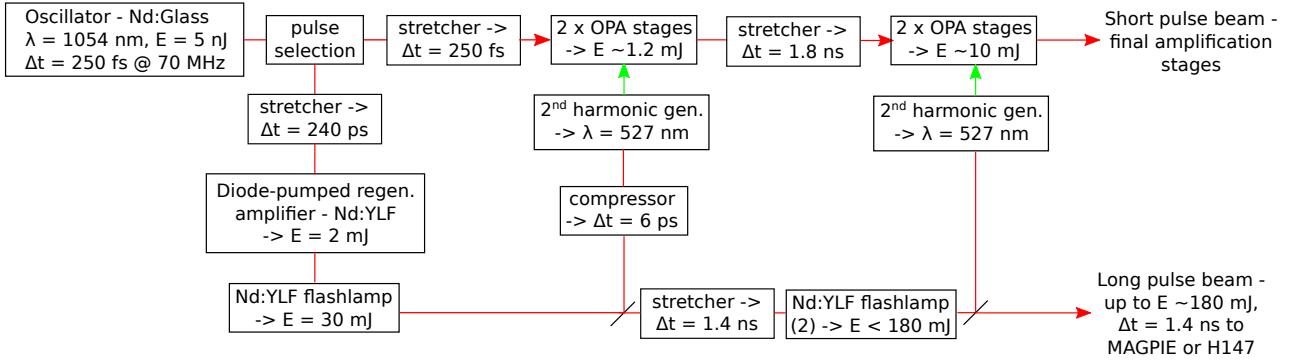


Figure 3.3: Diagram showing a considerably simplified view of the main components of the front end of Cerberus laser system, based at Imperial College.

3.3.1 Cerberus Short-Pulse Diagnostics

Energy Measurement The energy of the Cerberus short pulse was calculated on-shot using a fast (1 ns) rise-time photodiode (PD) which observed a rejected portion of the beam from the compressor grating zero order before the Cerberus target chamber. Since the PD produces a voltage and not an energy, a test shot was taken before every main shot where the responses of the PD, PD_{test} and an energy meter, E_{test} were measured. The energy meter received the whole beam and was placed at the target chamber entrance. The on-shot energy of the short pulse, $E_{on-shot,sp}$ was then inferred from the ratio of the PD responses on the test and main shots multiplied by the energy meter reading, i.e.,

$$E_{on-shot,sp} = \frac{PD_{on-shot}}{PD_{test}} \times E_{test}. \quad (3.1)$$

The data set from all the test shots is shown in Fig. 3.4 and was accumulated over the course of the work shown in this thesis and the thesis of Samuel Eardley [54]. In the case where only an on-shot PD reading was available, the on-shot energy was found using the linear relation retrieved from Fig. 3.4,

$$E_{on-shot,sp} = 0.019PD_{on-shot} + 0.482. \quad (3.2)$$

Note that the spread of data is large due to drifting of the laser alignment over a time-scale of several months as was first described and experimentally confirmed by Eardley [54]. In the cases where Equation (3.2) was used to find on-shot energy, the errors in the on-shot energy measurement were much larger to reflect large spread.

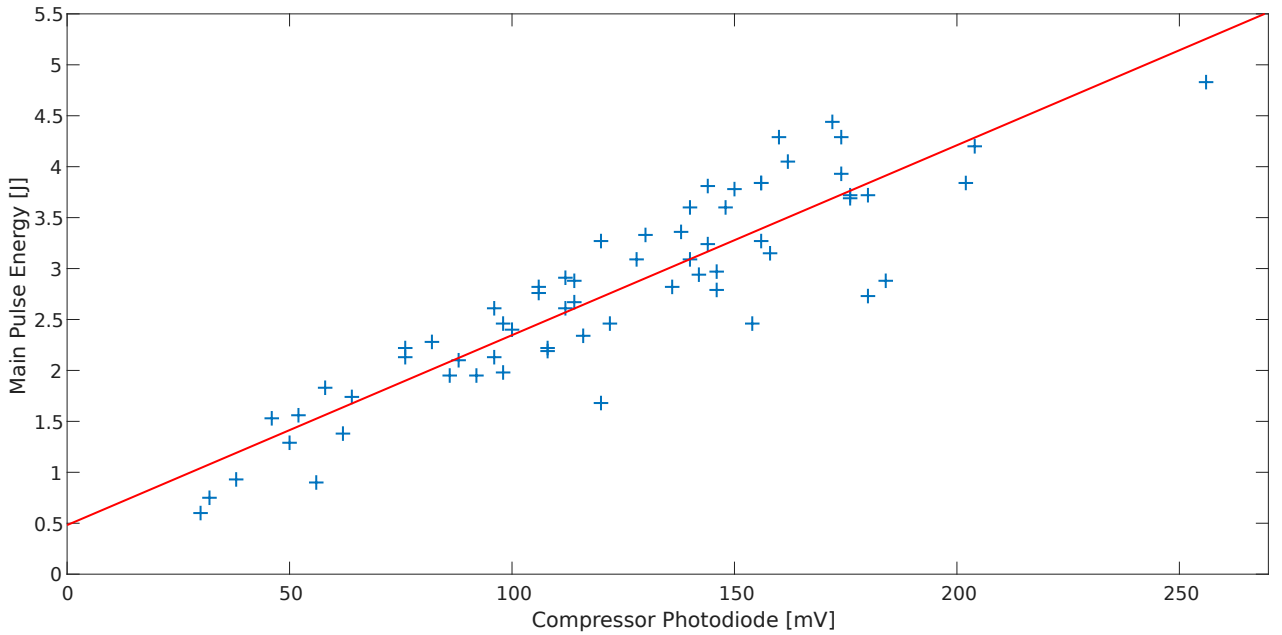


Figure 3.4: Graph showing the long-timescale (multiple months) relation between a photodiode and energy meter, both viewing the Cerberus short pulse, close to the target chamber. Each data point is from a test shot where the photodiode and energy meter were run simultaneously. The on-shot short pulse energy was found from the photodiode response and the linear relation from this graph.

Pulse Length Measurement The sub-ps pulse length of the Cerberus short pulse was measured on-shot using a single shot 2nd order autocorrelator viewing a ghost beam from the mirror placed immediately before the target chamber entrance. An example trace from the autocorrelator is shown in Fig. 3.5. Since the Cerberus pulse here is Gaussian in time, the full-width half-max (FWHM) of the autocorrelator trace is directly related to laser pulse length, Δt according to $\Delta t = FWHM/\sqrt{2}$ [55].

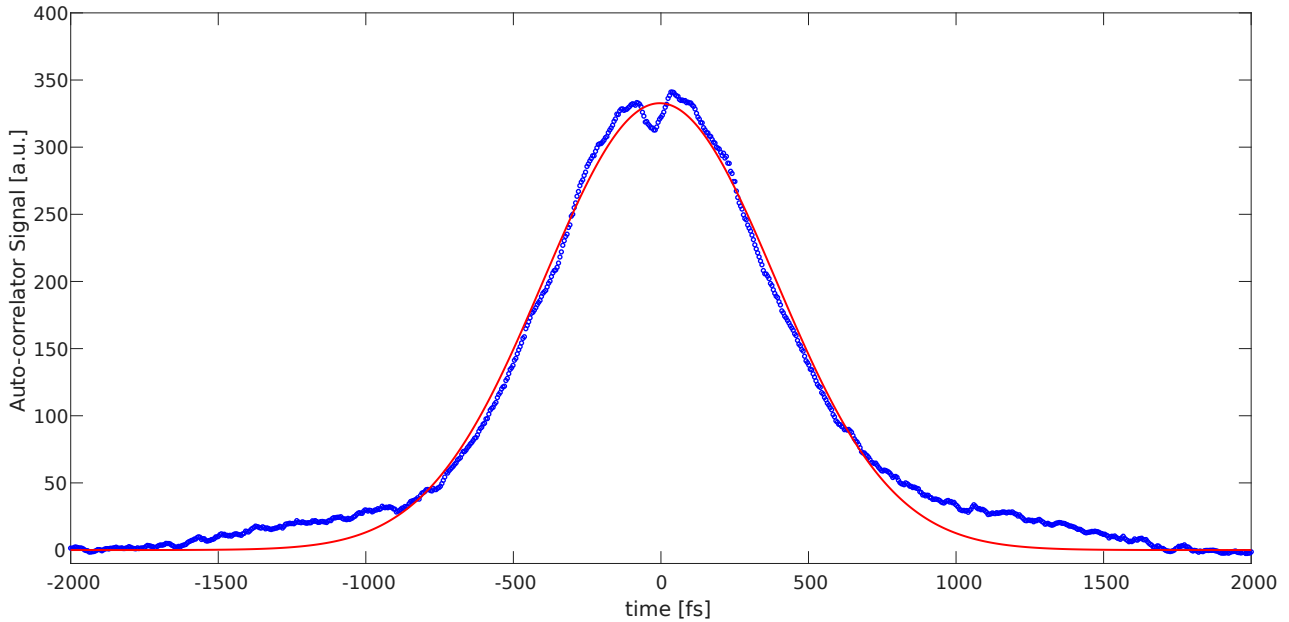


Figure 3.5: Graph showing an example autocorrelator trace from a Cerberus shot with a Gaussian profile (solid, red line) fitted to the real data (blue points). The FWHM of this trace is 1021 ± 19 fs, which yields a laser pulse duration of 722 ± 13 fs. The error in the FWHM measurement and hence the laser pulse duration originates from the discrepancy in the fit of the Gaussian profile.

Focal Spot Size Measurement of the exact Cerberus short pulse focal spot on-shot was impossible, as such, measurements were taken pre-shot and used as an estimate. The focal spot of the Cerberus laser pulse was created by focusing the beam down using a F/3 gold off-axis parabolic mirror (OAP) [56]. The spot was optimised and measured at low power by finely adjusting the OAP position and angle and viewed using a camera and microscope objective placed at the target chamber centre (TCC) just before full power shots were taken. This camera was also used to define TCC. An example focal spot is shown in Fig. 3.6. The area of the focal spot was calculated using a code created by Eardley [54] which measures the spot size by first subtracting any background noise then summing the area of pixels with an intensity greater than $1/e^2$ multiplied by the peak pixel intensity. In addition to this, an extra feature was added to measure the full vertical and horizontal size or extent of each spot as they

were rarely circular and occasionally had extra, bright lobes in the case of poor optimisation. The focal spot shown in Fig. 3.6 was found to have a horizontal and vertical size of $7.7\ \mu\text{m}$ and $8.4\ \mu\text{m}$ respectively. This was the optimum size achieved in the work in this thesis and is a factor ~ 2 larger than the spot size expected from the OAP.

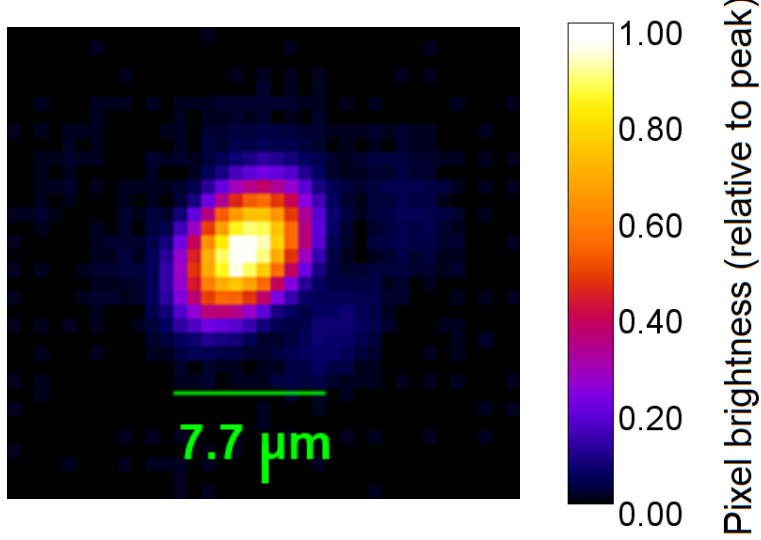


Figure 3.6: Image of the Cerberus short pulse focal spot. The area of this spot was found to be $5.1 \times 10^{-7}\ \text{cm}^{-2}$ and had a vertical and horizontal size of $8.4\ \mu\text{m}$ and $7.7\ \mu\text{m}$ respectively.

3.4 Other Laser Systems

For this project there was also a second laser system which was employed for the experimental work shown in Chapter 8. This was an Nd:YAG, Q-switched laser (Quanta-ray GCR 270 [57]) operated at $1064\ \text{nm}$. Characterising the pulse of this laser was much simpler than for Cerberus by virtue of its longer pulse length and the nature in which it was operated which shall now be described. Firstly, the energy of the laser was able to be precisely controlled using the laser control pad and then rejecting a portion of the beam using an external waveplate-polariser combination (the exact layout of the external optics used in the experiment is covered in Chapter 8). The output was then observed on an energy meter which remained stable to within $3\ \text{mJ}$ for a $50\ \text{mJ}$ pulse when operated in single-shot mode. As such, on-shot energy could be determined by tuning before a shot and firing immediately to reduce uncertainty in its value due to beam drift for example.

The pulse duration of the laser was known to be of several 10s of ns hence the duration was able to be measured using a $1\ \text{ns}$ rise-time PD. In this set up, a ghost beam leaking from a mirror on the beamline was observed on-shot by the PD giving a measure of the pulse duration and relative arrival time for each shot. An example of a pulse measured by the PD is shown

in Fig. 3.7. The FWHM of each trace was used as an estimate for the pulse duration. Finally, the laser spatial profile was reliably known on every shot as the final part of the beamline involved injecting the beam into (and slightly overfilling) a 1 mm diameter core, multi-mode fibre. This design choice was deliberate in order to achieve a reliable laser profile size amongst other reasons. All of which are elaborated on in detail in Chapter 8.

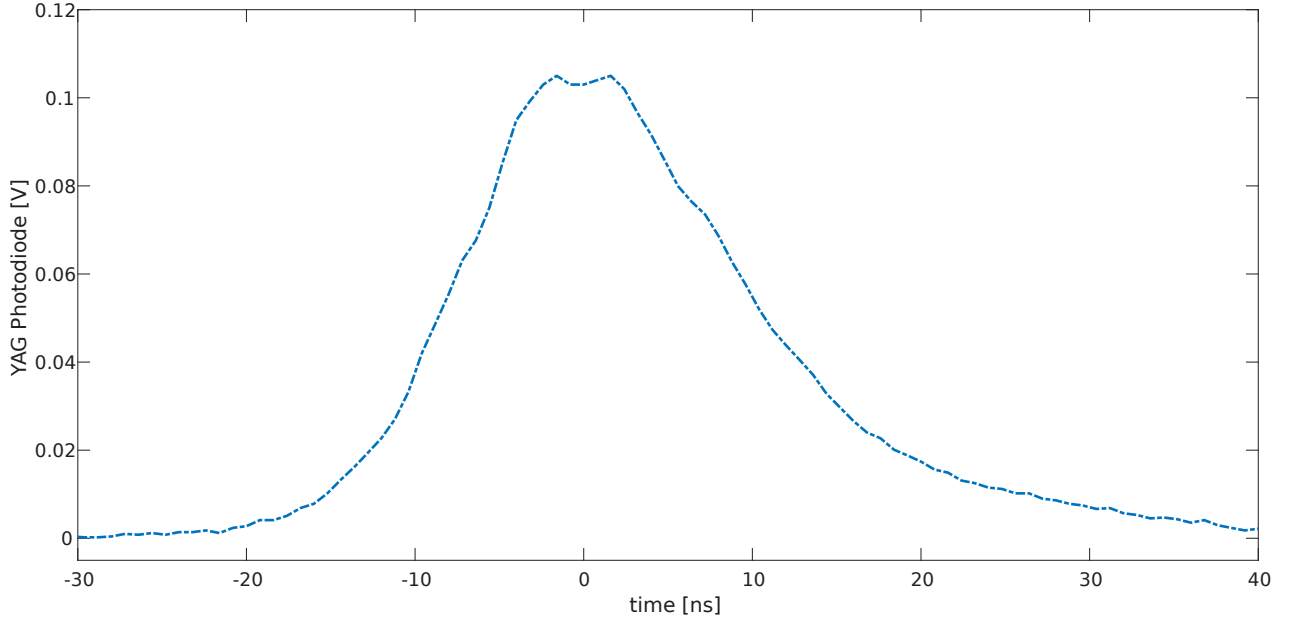


Figure 3.7: Graph showing the signal from a 1 ns rise-time photodiode observing a ghost beam leaking from a mirror on the Quanta-ray GCR 270, Nd:YAG laser beamline used in this project. These traces were acquired on-shot for the laser and the FWHM of the signal was used as an estimate for the pulse duration. The FWHM of this pulse was found to be 18.4 ns.

Chapter 4

Methods for Synchronising Diagnostic Probes to Two-Stage Light-Gas Guns

4.1 The Challenges in Synchronising a Long Trigger-Time Probe to a Two-Stage Light-Gas Gun

To begin this chapter we will give an overview of the objective of this entire PhD project, in the form of an idealised experiment. In order to help visualise this, see Fig. 4.1 for a pictorial summary of the sequence of events involved in a shock-induced cavity collapse, driven by a two-stage light-gas gun (TSLGG), and the proposed synchronisation of a diagnostic probe. The events labelled 1 through 5 were introduced when describing the function of a TSLGG in Section 3.1. We will now consider those steps in the context of an experiment specific to this project. Firstly, we trigger the launch of a TSLGG (event 1. in Fig. 4.1) and the piston begins to move from the breech, into the pump tube (event 2. in Fig. 4.1). This occurs with an inherent jitter. Jitter is a term used here to describe variation in the time of occurrence of an event caused by uncontrollable, and often random, factors. Jitter is a fundamental problem in this project. Launch jitter can however be quantified and potentially mitigated against by detecting the piston as it begins to accelerate through the pump tube, when compared to the launch trigger signal (see step 3. in Fig. 4.1). At some point, the pressure of the light-gas situated ahead of the piston in the pump tube is high enough to rupture the petal valve in the transition section of the TSLGG (event 4. in Fig. 4.1). This releases highly pressurised gas into the launch tube which begins to accelerate the main projectile sat in the launch tube (event 5. in Fig. 4.1). The rupture of the petal valve also has an associated jitter which can be quantified by observing the progression of the piston in the pump tube and the subsequent movement

of the main projectile in the launch tube. The main projectile accelerates through the launch tube and eventually impacts the target beyond the end of the gun barrel. Immediately after the barrel and prior to the impact, there will be diagnostics to witness the projectile (event 6. in Fig. 4.1). Methods for detecting the piston and projectile progression through the TSLGG and pre-impact diagnostics form a fundamental part of this chapter and will be discussed in the next section.

The projectile then impacts, and launches a shock into, the target which eventually causes a cavity implosion (event 8. of Fig. 4.1). We wish to probe this implosion. As such, we must trigger a diagnostic at some point before the implosion for a probe pulse to arrive during an interesting and well defined point in time, such as jet formation. How early in time we must trigger a probe is entirely dependent on how long it takes from trigger to arrival of the probe. Firing a probe with a short trigger time, i.e. ~ 1 ns, is a relatively simple problem; in the case of a complex laser system such as Cerberus which delivers a pulse to target ~ 100 ms after triggering, this becomes significantly more complicated.

To trigger a probe to arrive during a precise moment within a cavity collapse we must predict the projectile impact time and the velocity at which this occurs. Along with the material properties of the target and projectile, we can then predict the shock progression and cavity collapse in the target using the physics described in Chapter 2. Due to the jitter inherent in the launch of a TSLGG, it follows that we must use diagnostics to monitor the progression of each shot within the optically opaque barrel, to quickly predict impact parameters as early as possible, and use this to trigger a probe. This need for active prediction and real time calculation rules out diagnostics which need to be analysed post-shot, to yield projectile velocity for example. A proposed synchronisation method for this project begins with piston/projectile sensors at fixed positions along the TSLGG. Realistically, the earliest position for a sensor is immediately after the piston begins to move into the pump tube. As soon as a second sensor responds, an average velocity can be obtained. Increasing the number of these sensors along the full length of the TSLGG will allow further measurement of velocity, and by extension, determination of the acceleration of the piston and projectile. In theory, combining these sensors with pre-impact diagnostics immediately before the target should allow accurate prediction of impact time and velocity.

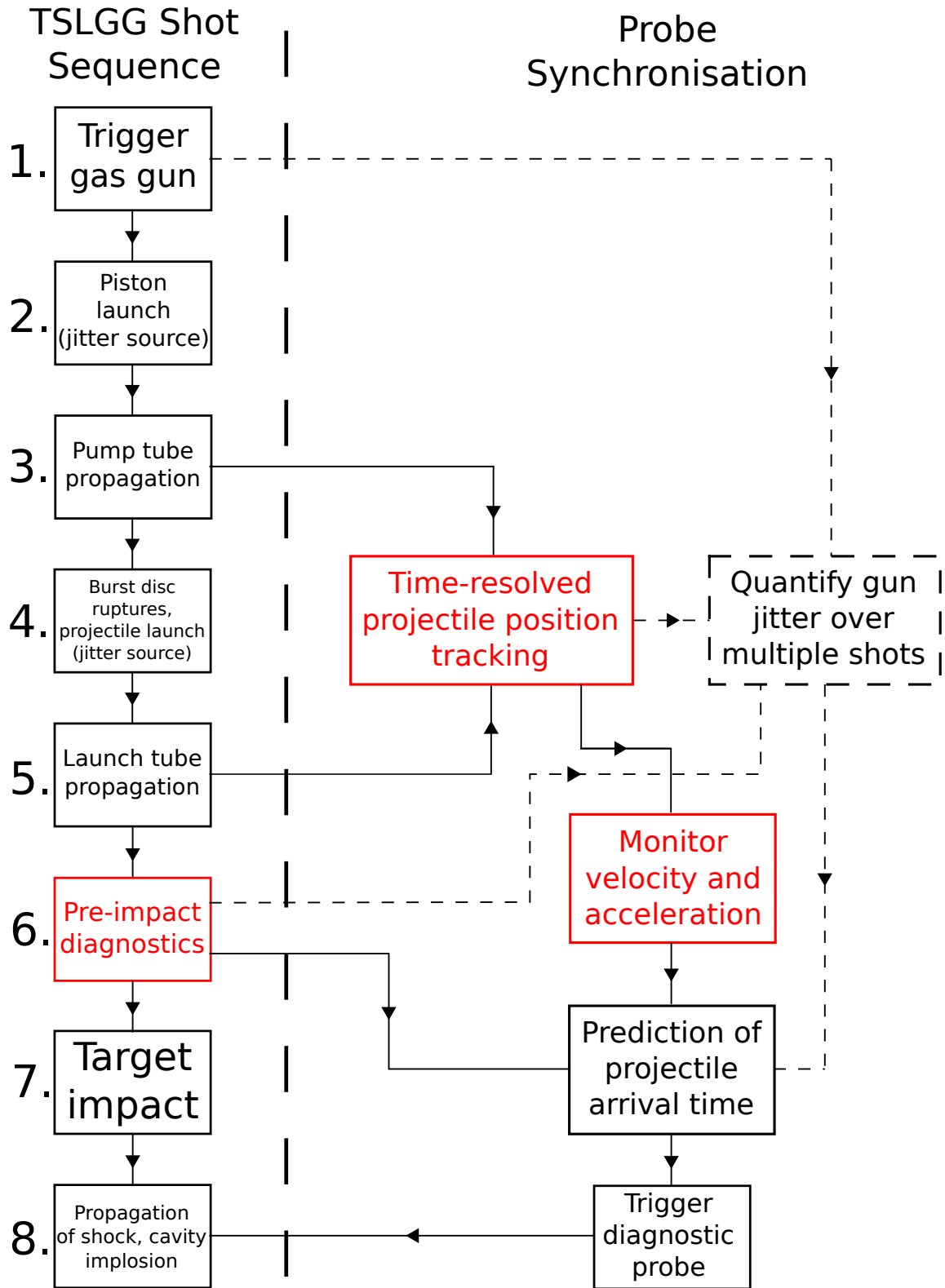


Figure 4.1: Simplified schematic showing the sequence of events in a shock-induced cavity collapse experiment, driven by a two-stage light-gas gun (TSLGG). Also shown is the notional sequence of events used to synchronise a separate diagnostic probe to the experiment. The solid lines show the “real-time” steps involved in synchronising a probe on a given shot. The smaller dashed lines indicate the use of results from a series of shots as feedback to aid in synchronisation, in theory accuracy in synchronisation will be progressively improved by quantifying system jitter for a particular gas gun. Red squares indicate sections which will be discussed in this particular chapter.

An advantage of using position sensors which straddle the locations of the largest sources of jitter on the TSLGG (such as rupture of a burst disc) is that over a series of shots, the jitter can be quantified for a single TSLGG. Combining this data with the time at which the gun is triggered and the pre-impact diagnostics could be used to develop an algorithm, perhaps making the prediction of target impact time and velocity even more accurate over time. A further advancement could be made if velocity is obtained during a shot from a single position sensor.

4.2 Review of Projectile Detection Diagnostics

In this section we will review several methods for detecting the position of a piston/projectile, pertinent to a TSLGG launch as described in Section 4.1. For each method, we shall evaluate its capabilities for position detection, its extension to velocity measurement (velocimetry) and whether it can be used for early time triggering. “Early” here is defined by the ability to sense a projectile or piston travelling within the barrel of the gun; “late” being defined by position detection beyond the end of the barrel, i.e. pre-impact diagnostics shown in Fig. 4.1.

4.2.1 Contact Methods

The first method to consider typically uses pins or contacts which, when physically impacted by a projectile or shock, complete a circuit. This is marked by a sharp increase in voltage which can be recorded by an oscilloscope for example. These can be placed along the inside of the barrel of a TSLGG at defined points, providing a measure of average projectile velocity by using the time between observation of signals from adjacent pins [42]. This would be a viable option for early triggering. It is however, not possible to measure velocity from a single pin. These pins or contacts can also be placed on the surface of, or embedded within, a target [58]. The former will allow measurement of the exact moment of target impact. The latter form will be triggered when driven by a shock wave in the target. Thus by using multiple pins, shock velocity can be measured. Both cases would however give very little time to trigger a diagnostic since they are in direct contact with the target.

This method does have some downfalls. They are single use, meaning they must be replaced after every shot. This will increase the cost and complexity per shot. Furthermore, pins located along the inside of a gun barrel are intrusive and require electronic connections through the barrel. This is possible for a small number of pins but if we use many along the full length of the

gun, as would be desired for this project, the integrity of the barrel could become compromised. They could also be mis-triggered by material or compressed gas blown ahead of a piston or projectile, leading to an uncertainty in position detection.

4.2.2 “Light-Break” Methods

The sensors described in this method are also known as light gates. They operate similarly to the previously discussed contact methods, but have no solid parts which are broken or connected through physical contact with the projectile or piston, and as such hold the advantage that they are not single use as mechanical pins are. A single light gate consists of an emitter/receiver pair which gives a continual voltage-high output when the receiver senses the emitted beam. When the beam between an emitter/receiver pair is blocked, the light gate output voltage drops. As with contact pins, two gates used in series can give the average velocity between the gates. Velocity can not be obtained from a single gate due to debris, e.g. from the burst disc, behind the projectile keeping the gate from returning to its high voltage state immediately after passage of the main projectile. Typically multiple light gates are used as pre-impact diagnostics immediately after the gun barrel, providing a measure of impact velocity and a late trigger for diagnostics [42]. It would also be possible to use them along the barrel of the TSLGG for an earlier trigger but as with pins, they are intrusive and hence cause the same problem of compromising the barrel integrity as two pressure-resistant, transparent windows would need to be installed for each gate.

Despite being reusable — and hence cheaper and easier to characterise long-term when compared to pins — light gates are still susceptible to problems from debris behind and blown ahead of a projectile or piston as well as muzzle flash [59]. This again leads to uncertainty in position detection. Light gates commonly use optical light in their beams however it is possible to avoid interruption from muzzle flash and low density debris ahead of a projectile/piston by using X-rays. An X-ray emission source combined with a scintillator and photo-multiplier tube makes an effective substitute as shown by Mashimo [58]. This does however necessitate making the projectile/piston at least partly opaque to the X-ray source.

4.2.3 Electromagnetic Induction Methods

The position sensors described here harness electromagnetic induction to detect a projectile through the solid body of a gun barrel. This allows early detection in the pump tube, without intruding into or compromising the barrel in any way. Moreover they are insensitive to

muzzle flash and debris/gas blow-by, presenting several advantages over the methods described previously. Firstly there is the magnetoflyer method [59], which uses a coil around the gun barrel for early signal detection; a signal is induced in these coils when a projectile or piston containing a magnet (a so called “magnetoflyer”) passes through, as described by the Faraday law of induction [60]. As with all other discrete detector methods, using two or more of these allows average velocity to be determined between adjacent coils. This method is relatively inexpensive and effective but the projectile is limited to one which contains a magnet. A pure copper or polymer projectile would not induce a voltage in a sensor coil of this type.

This method can be improved upon by removing the magnet from the magnetoflyer and placing a static magnet or array of magnets around the coil located on the gun barrel. In principle this method can be used to detect almost any kind of projectile or piston and does not sacrifice any of the other advantages given by the magnetoflyer method. This particular improved sensor was first demonstrated by Saito [61] and from here, will be referred to as the Faraday gate. For both of these electromagnetic induction related sensors it should also be possible to determine velocity from the response of a single gate, this will be addressed in the context of the Faraday gate along with a more detailed description of what has been mentioned here in the next section as it became a focus for part of this PhD. Finally, it is important to note here that early detection using either of these induction methods is entirely dependent on the magnetic fields involved being able to penetrate the barrels of the gun.

4.3 The Faraday Gate

As introduced in the previous section, the Faraday gate is a diagnostic which uses electromagnetic induction to detect a projectile. It is relatively cheap since the same unit can be used on many shots unlike a pin detector. It is unaffected by debris and muzzle flash unlike a light gate and can detect a moving projectile within a gun barrel without breaching the barrel walls. As such it is ideal for projectile/piston detection, velocity measurement and early triggering.

A basic Faraday gate consists of a coil of wire with a connection to observe induced voltage, situated in the inner radius of a permanent annular magnet. For context, Fig. 4.2 shows a photo of the coil inside of one of the first Faraday gates made in this project and a schematic of the cross section of that Faraday gate as it would look in operation. In this project, all Faraday gates were produced by 3D printing a protective plastic outer casing, inside which a coil of enamel-coated copper wire was hand wound. The copper wire has a nominal resistance of $0.3482 \Omega\text{m}^{-1}$ [62]. The inner diameter of the gate depended on the outer diameter of the

barrel on which it was placed. As such, the size of the permanent annular magnet which sat around the copper coil and within the plastic casing was selected accordingly. The particular gate shown in Fig. 4.2 had a coil of 80 turns and was built to fit onto the 31 mm outer diameter launch tube of the portable gas-gas TSLGG as detailed in Section 3.1. The chosen magnet was a 60 mm outer diameter, 40 mm inner diameter strong neodymium ring magnet [63]. Using a Hall probe with a transverse attachment, the magnetic flux density at the centre of this magnet was determined to be ~ 50 mT.

The process of induction in the Faraday gate coil can be explained thus. As a conductive projectile approaches the gate along the central axis of the magnet, an electromotive force is induced within the projectile which creates eddy currents. These currents arise from the changing magnetic flux observed by the projectile as it passes the annular magnet which in turn generate a secondary magnetic field around the projectile. This secondary field opposes the field of the permanent magnet. The induced magnetic field around the projectile causes a changing flux in the coil of the Faraday gate and hence induces a small electromotive force [61]. This can be detected if the ends of the coil are connected via BNC cables (to minimise noise pickup in the lab environment) to an oscilloscope, for example.

In principle, the Faraday gate can be used to detect any object moving through its centre which is electrically conductive, and thus able to support eddy currents. In addition, the response of a Faraday gate will depend on the relative magnetic permeability of the projectile material. For two electrically conductive projectiles moving at identical velocities, the magnitude of the induced voltage in a Faraday gate coil is larger for the material with a relative permeability further from unity. Table 4.1 shows a selection of different materials and their associated relative permeabilities, from this we can see that the strongest responses in the Faraday gate will come from steels and ferrous materials. Despite this, as we will see later in this chapter, detectable signals can still be achieved using small (< 2.5 g) masses of copper.

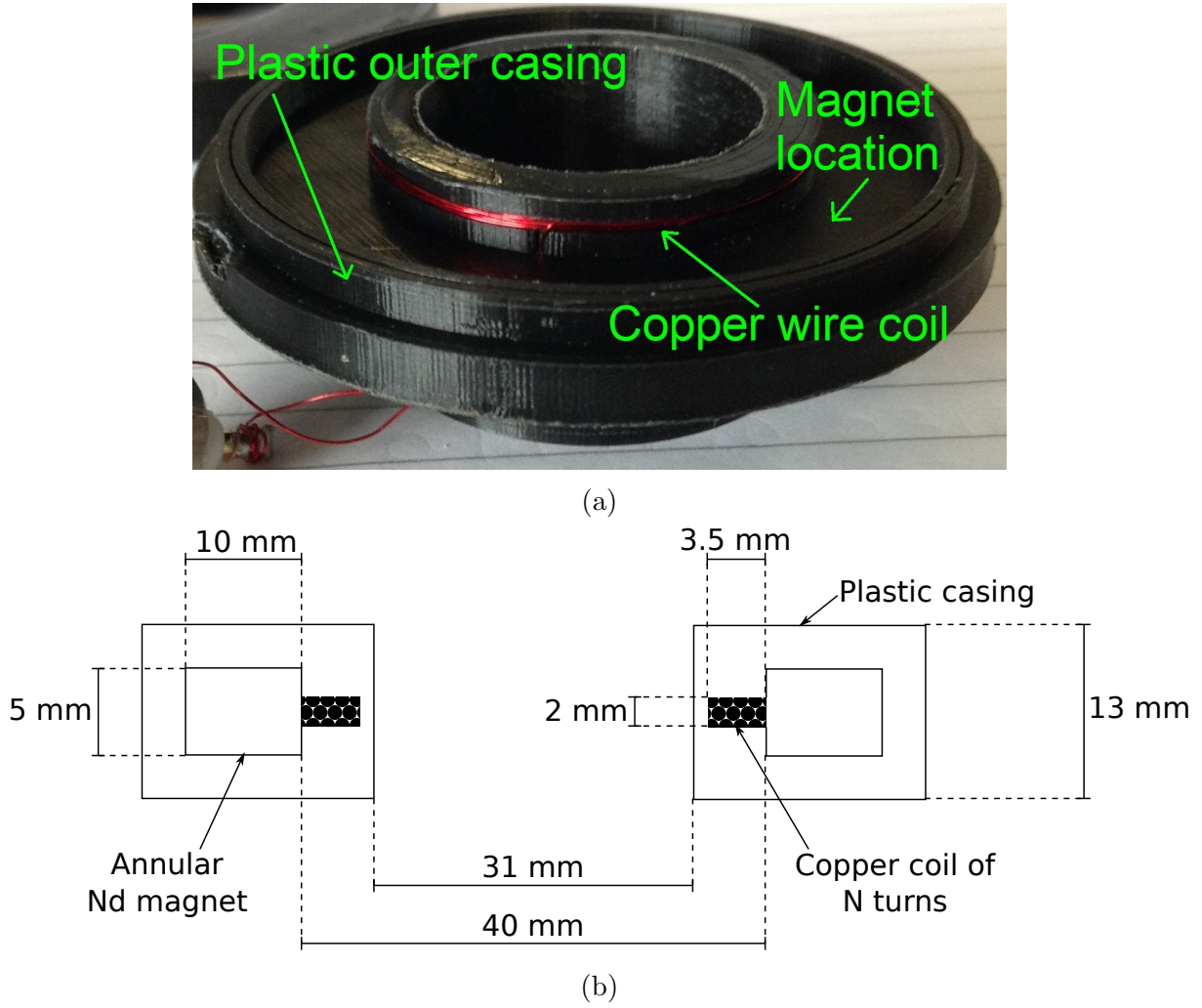


Figure 4.2: Photo showing the coil inside one of the first Faraday gates produced for this project (a) and schematic diagram showing the central cross-section of that Faraday gate as it would look in operation (b). The photo also shows the empty space where a permanent annular magnet would sit and one half of the protective casing of the Faraday gate. The inner diameter, 31 mm, was chosen such that it would fit onto the launch tube of the portable gas-gas TSLGG as described in Section 3.1. Not clearly visible in the bottom-left of (a) and omitted from (b) is the connection of the internal coil to a BNC adapter which allows the voltage induced in the coil to be read by an oscilloscope or trigger system for example.

It should also be possible to determine the velocity of a projectile from the time variation of the voltage it induces within a single Faraday gate. According to the Faraday-Lenz law the electromotive force in the coil ϵ_{coil} , is given by,

$$\epsilon_{coil} = -N \frac{d\Phi}{dt} \quad (4.1)$$

where N is the number of turns in the coil and Φ is the magnetic flux through the coil. Magnetic flux can be substituted by $\Phi = \vec{B} \cdot \vec{A} = B_z A$, where $\vec{B}$ is the magnetic flux density in the coil, $\vec{A} = A \hat{n}$ is the area of the coil A multiplied by the unit vector normal to the coil area $\hat{n}$ and B_z is the component of magnetic flux density parallel to $\hat{n}$. The direction of velocity of

a projectile through the Faraday gate coil is also parallel to $\hat{n}$ which is defined here as the z -direction. Combining this all together yields an expression for the electromotive force,

$$\epsilon_{coil} = -NA \frac{dB_z}{dt} \quad (4.2)$$

which can be manipulated to give,

$$\epsilon_{coil} = -NA \frac{dB_z}{dz} \frac{dz}{dt} \quad (4.3)$$

and $dz/dt = v_{proj}$ is just the velocity of the projectile causing the change in flux through the coil. Therefore, we finally have,

$$\epsilon_{coil} = -NA v_{proj} \frac{dB_z}{dz}. \quad (4.4)$$

From this we can see that, with knowledge of how the magnetic flux density through the coil varies with projectile position (and the area and number of turns of the coil), we can determine the velocity of a projectile from the induced voltage. This is however quite a complicated problem as will be fully discussed later. For now we shall move on to discuss experimental findings taken with Faraday gates before returning to consider the problem of velocity determination from a single gate in more detail.

Material	Rel. Permeability, μ_r
Vacuum	1
Air	1.00000037
Wood	1.00000043
Water	0.999992
Copper	0.999994
Aluminium	1.000022
Nickel	100 - 600
Iron (99.8% pure)	5000
Ferrite (NiZn)	16 - 640
Ferrite (used in Section 4.4.1)	125
Ferrite (MnZn)	≥ 640
Austenitic stainless steel	1.003 - 7
Martensitic stainless steel (hardened)	40 - 95
Carbon steel	100
Martensitic stainless steel (annealed)	750 - 950
Ferritic stainless steel	1000 - 1800

Table 4.1: Table showing the relative magnetic permability of various materials. Included are some common elements, various steels and ferrites and non-metallics for comparative purposes.

4.4 Experiments Using the Faraday Gate Technique

4.4.1 Drop Experiments

The purpose of the first experiments were to observe the behaviour of the test Faraday gate systems at low velocities ($<6 \text{ ms}^{-1}$). For example, finding how the output voltage of the Faraday gate depends on the velocity of a projectile passing through it would yield useful information, such as whether the signal would be large enough to damage an oscilloscope when scaled to high velocities and larger projectiles on a gun driven experiment. A vertical set-up was devised where low velocities would be achieved by the projectile being accelerated by gravity over a $\sim 1 \text{ m}$ distance, a diagram for this experiment is shown in Fig. 4.3. In this experiment, a projectile approaches a first light gate via a PVC guiding tube and upon breaking the light gate beam, a drop in voltage is observed which is restored after the projectile passes. The light gate beams were apertured to 3 mm using holes drilled into the tube, any smaller than this did not yield enough light to activate the receiver. The projectile then passes through a Faraday gate, inducing a voltage in the coil of the Faraday gate. Finally, the projectile passes through a second light gate which behaves as the first does. The light gates are used to find the projectile's average velocity as it passes through the Faraday gate position in order to relate this to the signal produced by the Faraday gate.

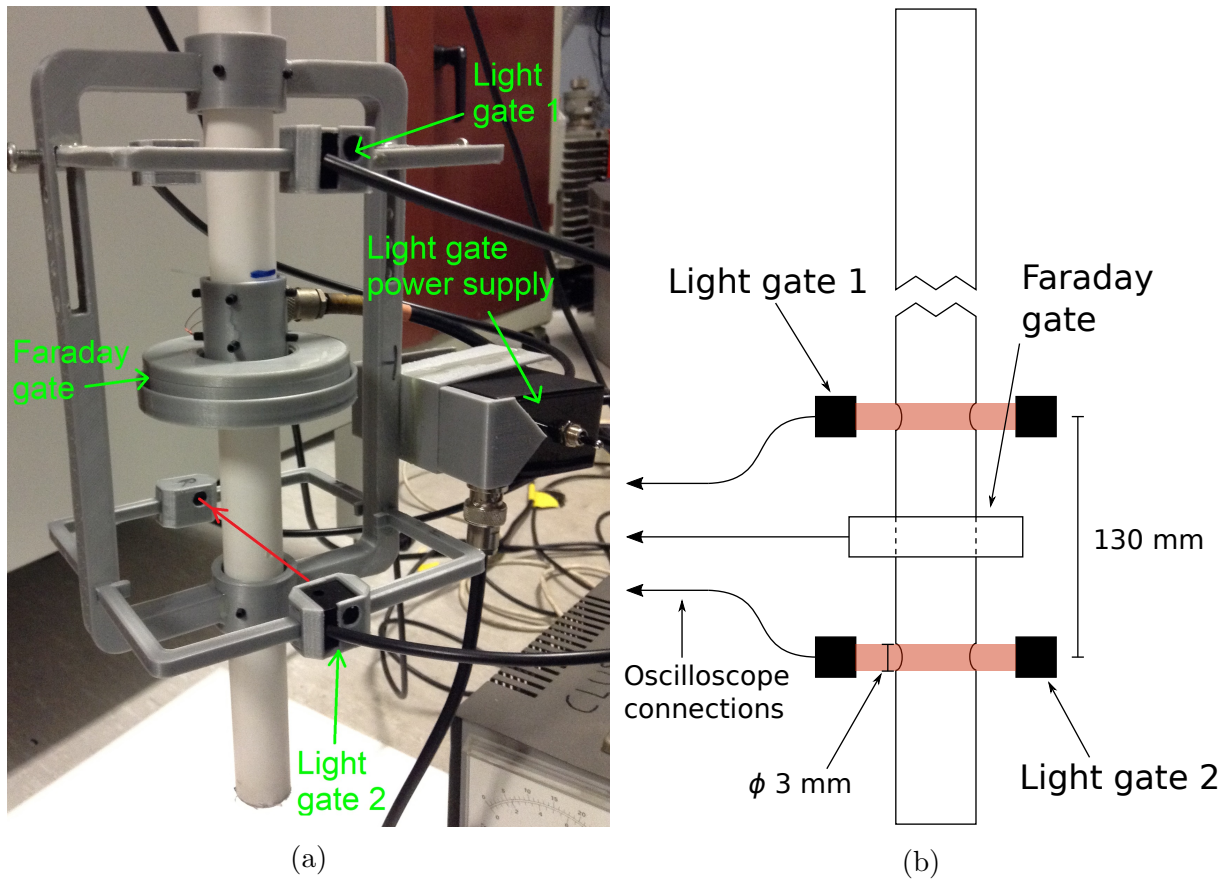


Figure 4.3: Diagram displaying a photo (a) and schematic (b) of the set-up for the low velocity tests on the Faraday gate. Two light gates are held in a 3D printed assembly that attaches to a PVC pipe. The pipe is used as a gun barrel analogue, to guide projectiles through the centre of the light gates. The light gates consist of an infra-red emitter/reciever pair whose beam penetrates the PVC pipe through a hole of diameter 3 mm. These light gates are separated by a distance of 130 mm and are placed either side of a Faraday gate which is also attached to the pipe. These components are all connected to the same oscilloscope at 50 Ω impedance, via BNC connections. Note the PVC pipe extends above the upper light gate by ~ 1.5 m.

Faraday Gate Output Versus Projectile Velocity

Dropping a material from ~ 1.5 m, would achieve maximum velocities in the region 5 - 6 ms^{-1} and for this reason it was initially decided to try ferromagnetic materials as these would produce the strongest signals in the Faraday gate. The projectiles used for this experiment are shown in Fig. 4.4. Firstly, a ferrite rod was chosen as it would likely create a strong and distinct signal in the Faraday gate coil thanks to its high magnetic permeability, see Table 4.1. A thin ring of steel made from a staple was also used to see whether a signal could be produced by something of much smaller mass at the speeds accesible by this set-up. An example oscilloscope trace for a ring drop is shown in Fig. 4.5, showing the Faraday gate is sensitive to small mass (< 0.5 g) ferromagnetic projectiles moving at low velocities. This graph shows two different ways of measuring the difference in time between either interrupting (light gate signal drops)

or restoring (light gate signal rises) the light gate beams, Δt . These time measurements each correspond to an average velocity of the projectile between the light gates. For consistency, the difference between interruption of the light gates was used throughout.

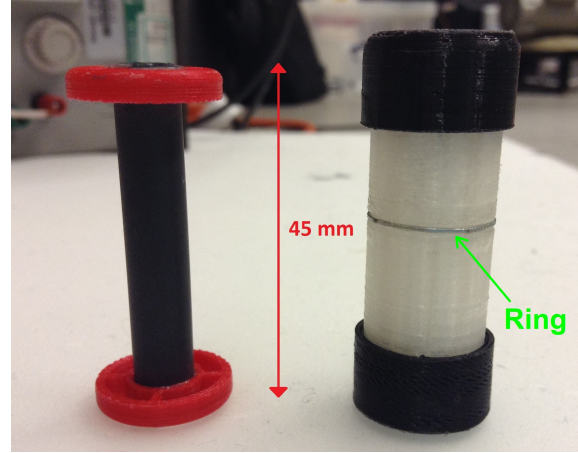


Figure 4.4: Projectiles used for the first drop experiments. On the left is a ferrite rod and on the right is a ring of steel made by joining two ends of a staple. Both of these were mounted using 3D printed parts (with low permittivity) which allowed them to fall down the PVC pipe centrally without significant tumbling.

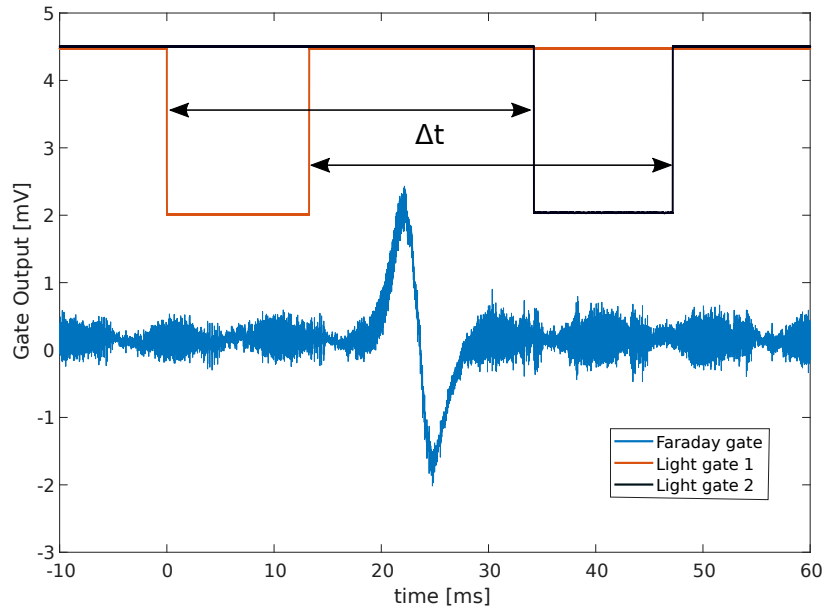


Figure 4.5: Plot showing the voltage output of the three diagnostic components used in a drop using the ring projectile. The red and yellow lines are the voltage signals produced by the first and second light gates respectively and the blue line is the output of the Faraday gate. The light gate signals have been scaled by a factor of $1/2000$ and shifted up by 2.5 mV for ease of viewing all signals on the same axes. Also annotated are time differences between the light gate signals either being interrupted or restored due to the projectile motion.

Using both projectiles shown in Fig. 4.4, multiple drops were taken and the heights from which each was dropped were varied slightly in order to vary velocity through the Faraday gate. The peak Faraday gate voltage was recorded and the average velocity through the Faraday gate was calculated. These parameters were plotted against each other. Error bars and a line of best fit were added and the resulting graphs for the ferrite rod and steel ring are shown in Fig. 4.6a and Fig. 4.6b respectively. Note that the output of the Faraday gate is two orders of magnitude lower for the ring than the rod, this may be due to the difference in volume and shape of the projectiles. The increased length of the rod, and the fact that it is a solid cylinder rather than a ring means the rod should be able to support a larger induced current than the ring, leading to a larger Faraday gate response. A further influence on the difference could be due to a larger magnetic permeability of the rod. This could not be confirmed, however, as the magnetic permeability of the staple forming the ring is unknown.

For this experiment, the error on the Faraday gate output was taken as the noise level on the oscilloscope trace which was a much larger factor for the ring as the signal was close to the noise level, the noise can be seen in Fig. 4.5. The error on the average velocity was computed from the response time of the light gates and the error on the measurement of the light gate separation. For both of the projectiles, we have found there is a linear relationship between projectile velocity and Faraday gate output in the low velocity range we have looked at, as we might have expected from Equation (4.4). Assuming this relationship holds at higher velocities, we can see that if the ferrite rod was moving at $\sim \text{kms}^{-1}$ velocities, the output would be as high as 100 V meaning that significant attenuation of the signal would be required before it could be safely recorded by an oscilloscope. This result is useful, as for any projectile material, a low velocity shot can be taken in order to assess the output of the Faraday gate at high velocity as a protective measure against damaging an oscilloscope.

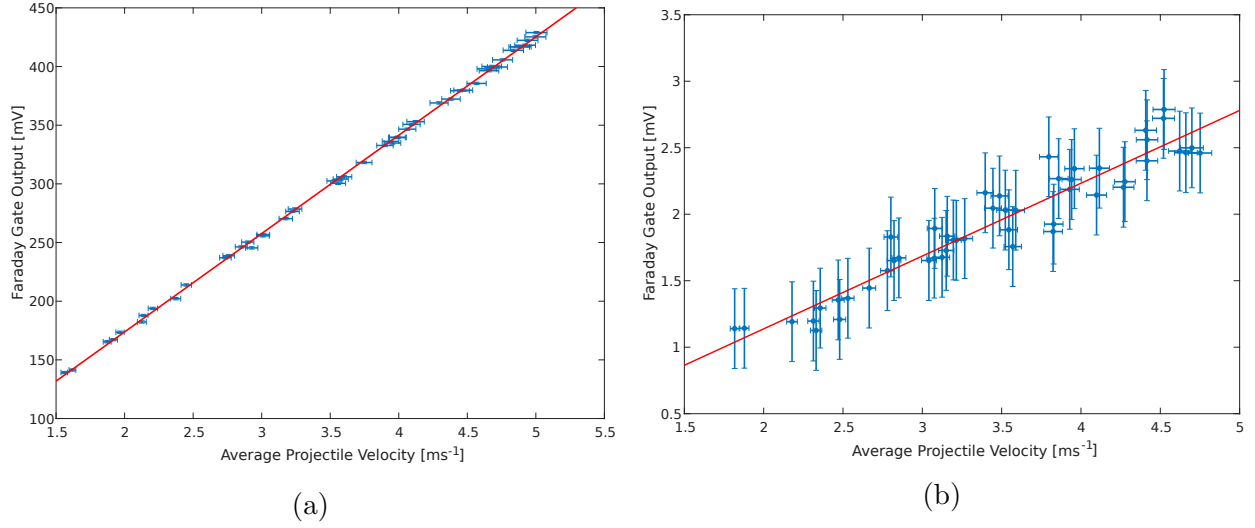


Figure 4.6: Plots showing the peak Faraday gate output voltage versus average projectile velocity for the ferrite rod (a) and the steel ring (b), each point on the graph represents a single drop.

Non-Ferromagnetic Projectiles and the Effect of Projectile Shape

For the next experiment it was decided to observe the effect of using materials with lower magnetic permeabilities. As such, two cylindrical copper projectiles were produced, one identical in dimensions to the ferrite rod from the previous experiment and one with twice the diameter (15 mm compared with 7.5 mm) and of slightly longer length (65 mm compared with 45 mm). The copper projectile of the same dimensions as the ferrite cylinder was dropped down the drop set-up shown in Fig. 4.3, however no signal was seen at low velocity ($<6 \text{ ms}^{-1}$). The larger cylindrical copper projectile was then dropped and a signal was seen, shown by the blue line in Fig. 4.7. A slot was sawn along the 65 mm length of the larger projectile increasing the perimeter of the circular cross section of the cylinder by 40%. The projectile was then dropped again and the resulting signal is shown by the red line in Fig. 4.7. These signals are interesting as they both show two distinct sinusoid-like signals from the Faraday gate, with the second being approximately a mirror image of the first. By looking at the separation of these signals it is clear that they both happen at essentially the same time and are separated by $\sim 13 \text{ ms}$. The projectiles in both case were moving at $\sim 5 \text{ ms}^{-1}$ which suggests the projectile moved 65 mm in the time between the two signals, the length of the projectile.

This could suggest that the first signal begins to rise as the leading face of the projectile experiences a change in magnetic flux as it approaches the Faraday gate magnet generating increasing eddy currents. This creates a changing, secondary field around the projectile which causes a change in flux in the coil of the Faraday gate, generating the positive voltage we

initially see. As this face leaves the other side of the gate we have exactly the same change in fluxes through the projectile and coil but in reverse, leading to the negative voltage in the coil that we see. To give further credence to this hypothesis, the widths of the “sinusoids” shown by the unslotted projectile (blue line) are ~ 8 ms. At a velocity of 5 ms^{-1} , the projectile would have moved 40 mm. As will be shown later, this correlates with the region of strongest magnetic field around the Faraday gate magnet. After this point, as one section of the projectile is entering the magnetic field of the Faraday gate magnet another is leaving. The currents generated in each of these regions would generate opposing magnetic fields and cancel each other, i.e. creating no change in flux in the Faraday gate coil causing a “null” region after the first “sinusoid”. As the trailing face of the projectile approaches the magnetic field we would create the reverse changes in flux as seen when the projectile first approaches the field. Thus creating the second signal which approximately mirrors the first.

The lower voltage exhibited by the sawn projectile suggests that the change disrupts the formation of eddy currents in the projectile. In order to determine whether the currents are generated on the surface of the projectile or internally, it may be useful to test a hollowed-out cylinder of the same material and compare the Faraday gate signal, however this was not conducted in these experiments.

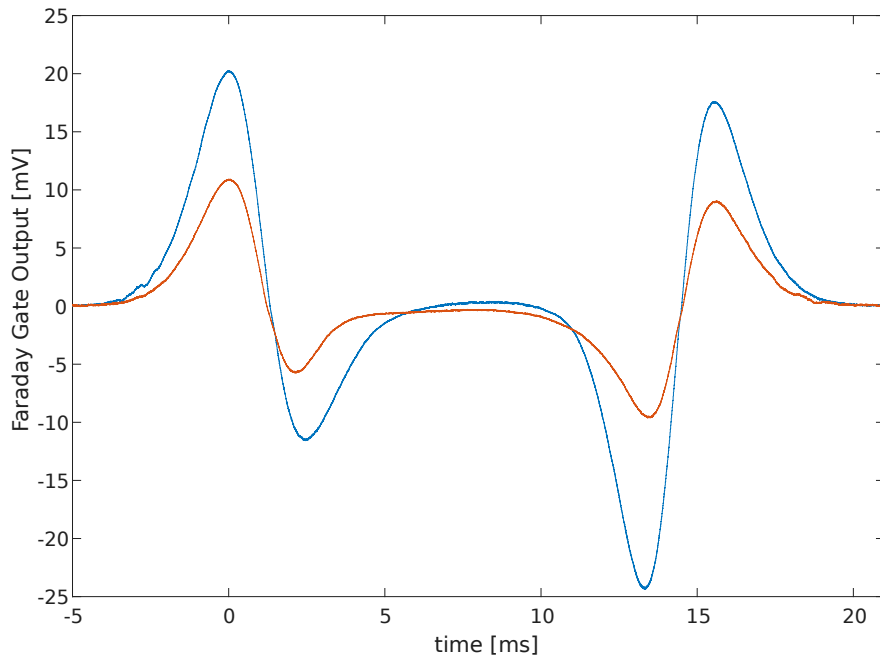


Figure 4.7: Plot showing the Faraday gate output for a copper projectile with no slot (blue line) and for the same projectile with a slot sawn into it along the axis (red line). In each drop the projectile was moving at $\sim 5 \text{ ms}^{-1}$. The data was slightly smoothed for clarity.

4.4.2 Two-Stage Light-Gas Gun Tests

Portable Two-Stage Light-Gas Gun Experiments

The next experiment fielded several Faraday gates upon the launch tube of the portable gas-gas TSLGG detailed in Section 3.1. This was the barrel they were initially designed for. We began by accelerating the projectiles with a compressed air jet to propel them to velocities of maximum $\sim 60 \text{ ms}^{-1}$. The main purpose of this experiment was to find whether shielding of the magnetic field from the Faraday gate would occur in a metallic barrel and if acceleration can be determined with an array of gates. If we can determine the acceleration of a projectile, prediction of when it will impact a target downstream of the barrel can be found more accurately. The experiment was set up as shown in Fig. 4.8. Four Faraday gates were attached to the barrel in order to detect a projectile passing through; a pair of light gates were placed 10.5 cm beyond the final Faraday gate to determine the projectile velocity at this point and all signals were recorded on two synchronised oscilloscopes. Compressed air at pressures between 4 and 6 bar was used to propel a projectile of mass 2.10 g, the projectile consisted of a cylinder of copper (9 mm diameter by 0.5 mm thickness) attached to a cylindrical polycarbonate sabot which sealed the projectile in the launch tube (10 mm diameter by 20 mm thickness).

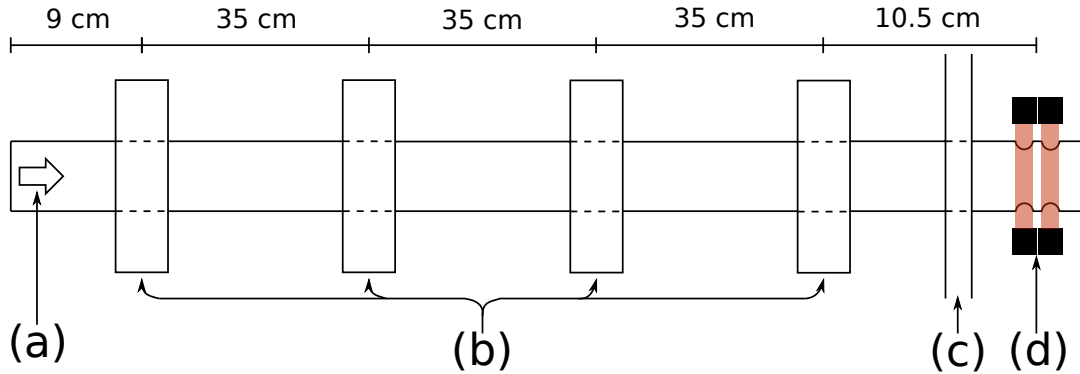


Figure 4.8: Diagram showing the set-up of the experiment fielding Faraday gates on the launch tube of the portable TSLGG. Here we have (a), the position at which compressed air was released to launch a projectile, (b), four Faraday gates placed at intervals shown by the diagram along the launch tube, (c), target chamber wall and (d), a barrel extension containing two light gates separated by 12 mm.

Multiple shots were taken with this set-up and an example of the output of the array of the Faraday gates is shown in Fig. 4.9. Already we can see that the shielding from the barrel has not caused us to be unable to detect the moving projectile. Also note that the shape of the Faraday gate output pulses is unlike anything seen in the previous drop tests using extended copper projectiles, its cause has not been reconciled yet but potentially could be visualised by

partly overlapping the two separate sinusoid-like signals shown by the blue line in Fig. 4.7 with the positive voltage parts adding together to form the central spikes. From these traces we can extract the time at which the maxima of each Faraday gate trace occurs. Assuming that each maximum occurs when the projectile passes through the centre of the Faraday gate, we can plot the position of the projectile along the launch tube against the time at which each Faraday gate is reached. This was carried out for three shots which had different light gate velocities and the resulting graph is shown in Fig. 4.10, each data set was well fitted by a quadratic suggesting there is approximately constant acceleration of the projectile. The fitting for each shot was used to derive an equation of motion of the form $x = at^2 + bt + c$, which provides the position x (in m) of a projectile at a time t (in s) after launch. Coefficients a , b and c were calculated by the fitting software. With reference to the colours of each data set in Fig. 4.10 the equation of motion for each shot is given by,

$$\text{Black} : x = 1070t^2 + (8.77 \times 10^{-2}) \quad (4.5)$$

$$\text{Blue} : x = 743t^2 - (4.91 \times 10^{-2}) \quad (4.6)$$

$$\text{Red} : x = 420t^2 + (9.26 \times 10^{-4}). \quad (4.7)$$

In every shot, the coefficient b was found to be negligible (at least 10 orders of magnitude smaller than c), as such b has been set to 0. These equations were used to derive the time at which each projectile passed the light gate position by substituting $x = 1.25$ m and solving for t . By differentiating each equation in x with respect to t , we find a formula for velocity v (in ms^{-1}) after a time t for each projectile,

$$\text{Black} : v = 2140t \quad (4.8)$$

$$\text{Blue} : v = 1490t \quad (4.9)$$

$$\text{Red} : v = 840t. \quad (4.10)$$

Substituting the derived time at which each projectile passed the light gate allows us to then infer a velocity for each projectile as it passed the light gate. In each shot, the derived values of velocity were found to be slightly higher than the velocity given directly by the light gates by $\sim 3 \text{ ms}^{-1}$ (or a 5% error).

The reason for this discrepancy is not known for certain however a suspected source is uncertainty in the start point of the launch as the projectile was roughly placed in the barrel and the initiation of acceleration was created crudely by turning the valve on a compressed gas

pipe by hand. A further source of systematic error in this experiment arises from the accurate and precise measurement of the Faraday gate positions. The coil has a finite width and the gate itself sits over the barrel, so getting the gates exactly above the points shown in Fig. 4.8 is difficult. The main source of statistical error in this experiment is due to noise on the Faraday gate signal. Noise fluctuation in the voltage at each peak will lead to uncertainty in the time at which each peak occurs. This affects the earlier gates more which had lower, broader peaks. These error sources have been incorporated into the data in Fig. 4.10.

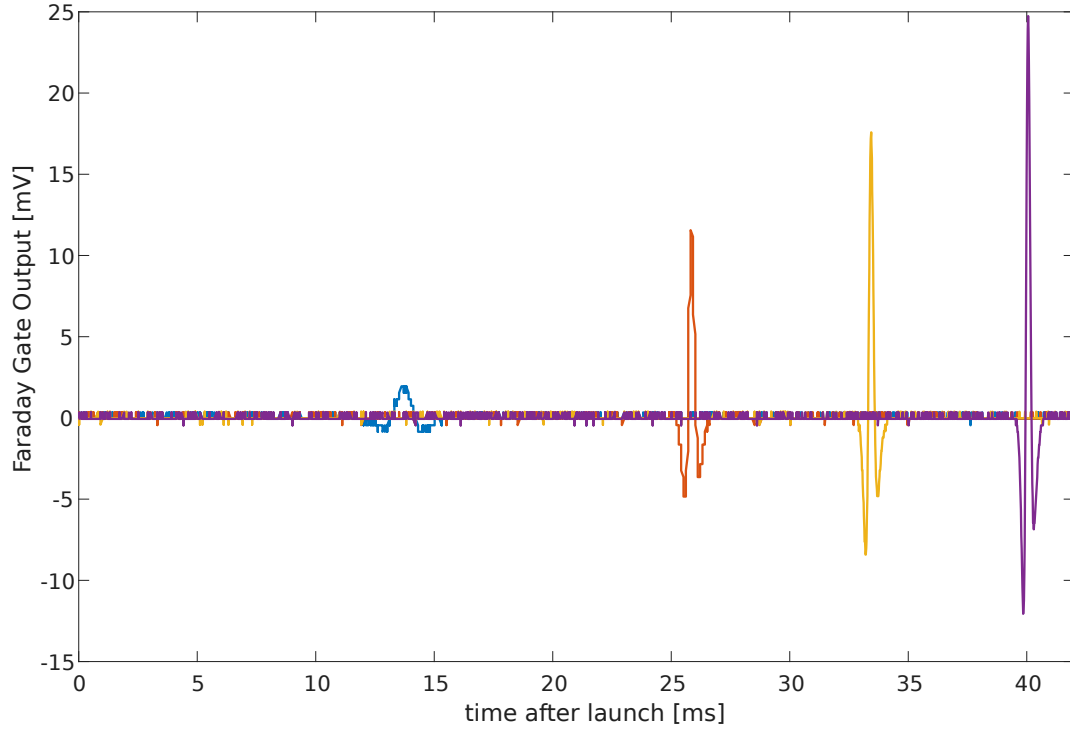


Figure 4.9: Graph showing the output of four Faraday gates after a projectile was launched through the launch tube of the portable TSLGG. The blue line represents the first Faraday gate containing 90 turns of wire, the red represents the second with 70 turns, the yellow represents the third also with 70 turns and finally the purple line is the fourth gate with 80 turns. The light gate pair gave a maximum velocity of 58 ms^{-1} for this shot.

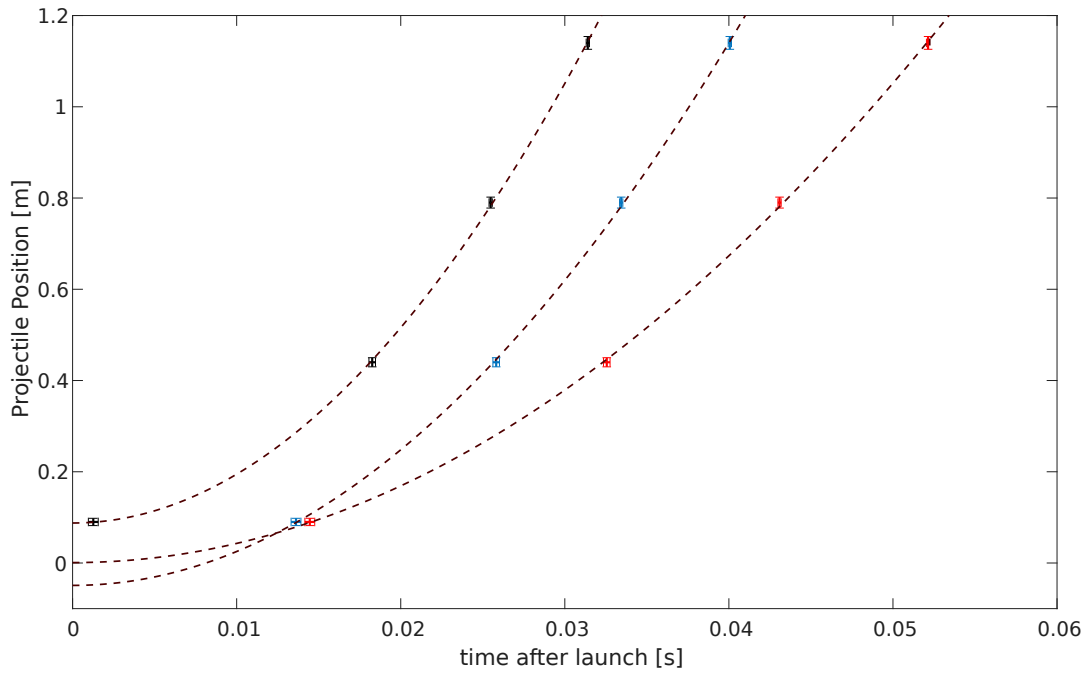


Figure 4.10: Graph showing the variation of the position of three projectiles along the launch tube of the portable TSLGG with time after launch. The black data points are for a shot at 67 ms^{-1} at the light gate position, the blue data points are for a shot reaching 58 ms^{-1} and the red points are for a shot reaching 41 ms^{-1} .

Deceleration of Projectiles by a Faraday Gate

By the laws of energy conservation, in order to induce a signal in the Faraday gate coil, the projectile must couple some energy into the gate. This will manifest as a reduction in the velocity of the projectile and in this section we shall consider the magnitude of the deceleration caused by each gate for a single shot. Starting from the output traces for each Faraday gate such as those shown in Fig. 4.9, we can find the total energy E extracted over a time t using,

$$E = \frac{V^2}{R}t, \quad (4.11)$$

where R is the total resistance of the Faraday gate coil and V is the voltage output of the gate. As such, by squaring the voltage trace, numerically integrating the squared trace over time and then dividing by the total resistance of the coil of wire in a gate, we can find the energy extracted by each gate. The total resistance of a coil was calculated by measuring the length of wire in each gate and multiplying by $0.3482 \text{ } \Omega\text{m}^{-1}$ [62]. For a single shot, the energy reduction by all four gates was found to be of the order 10^{-8} J which equates to a change in velocity of the order 10^{-3} ms^{-1} . For a projectile moving at 10s of ms^{-1} this is a negligible change.

By using Equations (4.5) to (4.10) to find projectile velocities and hence kinetic energy at each gate position, it was also found that the energy extracted by a gate is proportional to the kinetic energy of the flyer as it passes that gate.

FLF Two-Stage Light-Gas Gun Experiments

In order to field a Faraday gate upon the smallest diameter barrel of the First Light Fusion TSLGG (see Section 3.1), the previous design would have to be adapted to increase the inner diameter of the gate from 31 mm to 77 mm. This meant using a larger toroidal magnet, the only magnet that could be found to fit this purpose was a 190 mm outer diameter, 85 mm inner diameter ferrite magnet [64]. Coils of 70 turns were wound for these Faraday gates and the resulting gate was overall much heavier and less compact when compared with the previous version. Despite this, initial dropped-projectile tests carried out with the new gates showed no significant decrease in sensitivity. Fig. 4.11 shows a photo of the new gates on the launch tube of the FLF TSLGG. In addition to the Faraday gates, there was a single light gate positioned at the end of the launch tube and within the target chamber. This light gate was used as a trigger for the oscilloscopes which observed all Faraday gate signals in these shots.

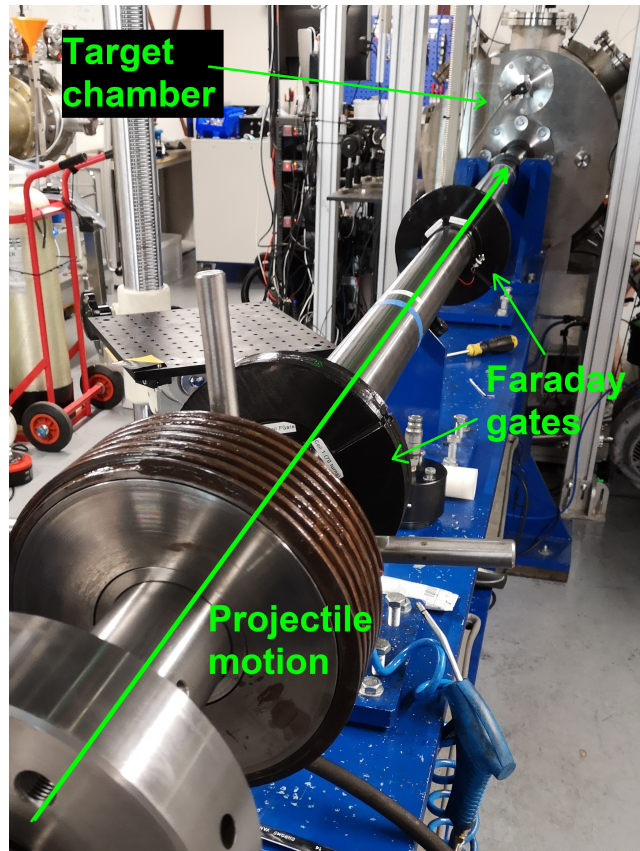


Figure 4.11: Photo showing the set-up of the Faraday gates upon the launch tube of the FLF TSLGG. For context the launch tube is ~ 3 m long and the Faraday gates are 20 cm in diameter.

The projectiles used in the FLF TSLGG were 10 mm diameter polycarbonate sabots, each tipped with a 10 mm diameter, 1 mm thick cylindrical copper flyer. The total projectile was 2.43 g in mass and 13.1 mm long. The first shots taken used compressed air much like the gas gun experiment on the portable TSLGG which yielded a maximum velocity of $\sim 60 \text{ ms}^{-1}$. On all shots taken, no signals were seen on any the Faraday gates. After this it was decided to conduct a full-power launch with the set-up unchanged. This would accelerate the projectile up to several kms^{-1} . Two full-power shots also yielded no response from the Faraday gates. This initially suggested that the barrel of the gun was shielding the magnetic field of the ferrite magnets but perhaps the gates were also unable to detect the small copper flyer. In order to check whether the Faraday gates were insensitive to the projectiles, the next shot had a rearranged set-up where a gate was placed within the target chamber, off the barrel and ahead of the light gate. Fig. 4.12 shows the arrangement of Faraday gates, the light gate and the distances between them for this set-up.

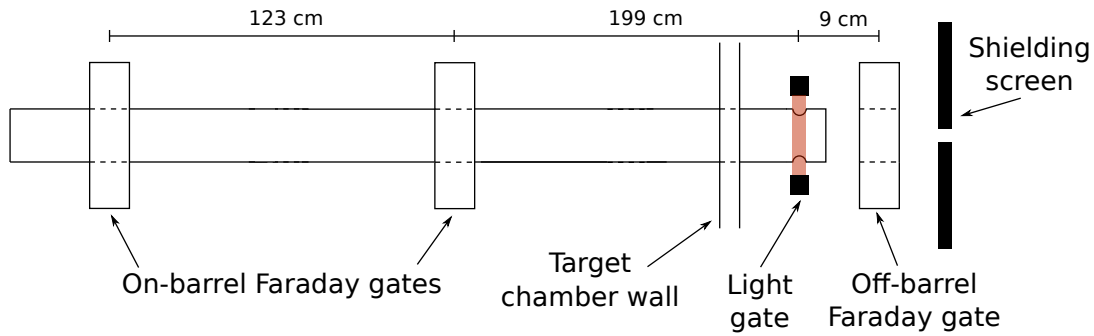


Figure 4.12: Diagram showing the set-up of an experiment fielding Faraday gates on the launch tube of the FLF TSLGG. There are two Faraday gates mounted upon the launch tube. A light gate is situated within the target chamber upon a barrel extension. The light gate is used as a trigger for the oscilloscope which all Faraday gates are connected to. A final Faraday gate was placed off the barrel and beyond the light gate. Finally a piece of shielding was added in an attempt to protect the Faraday gate.

A full-power shot with this set-up yielded no response from the on-barrel gates as before, however a signal was seen by the gate inside the chamber. The passage of the projectile is shown by the sharp spike in voltage at roughly 0.026 ms in Fig. 4.13. Since $t = 0$ was set by the light gate, this is the first shot where a velocity could be estimated thanks to the Faraday gate response. The velocity was estimated from these two time points to be at least 4 kms^{-1} . It was difficult to measure the exact distance between the light gate and Faraday gate coil in-situ hence 9 cm was a low estimate. By looking at the time width of the spike shown in Fig. 4.13 and applying the velocity estimate, we can determine that the projectile travelled $\sim$ few cm while the signal was produced, which correlates with the region of strongest magnetic field through

the centre of the Faraday gate that the projectile would pass through. Note also the longer timescale fluctuation after the initial spike. If this were to be caused by the projectile moving through the gate, taking the centre of the fluctuation as the moment the projectile passes the Faraday gate, the projectile would have been moving at 750 ms^{-1} which is far too slow for a launch with this gun. The source of this signal is not known for certain but a potential cause became apparent after examining the chamber post-shot. Fig. 4.14 shows photos of the gate within the target chamber, before and after a shot. As can be seen, the events of the shot ripped out and destroyed the coil from the inside of the gate. The force of the expanding gas behind the projectile likely tore the coil from the Faraday gate. Before the circuit was severed it is possible that the motion of the coil within the magnets field could have induced the longer timescale voltage fluctuation we see in Fig. 4.13.

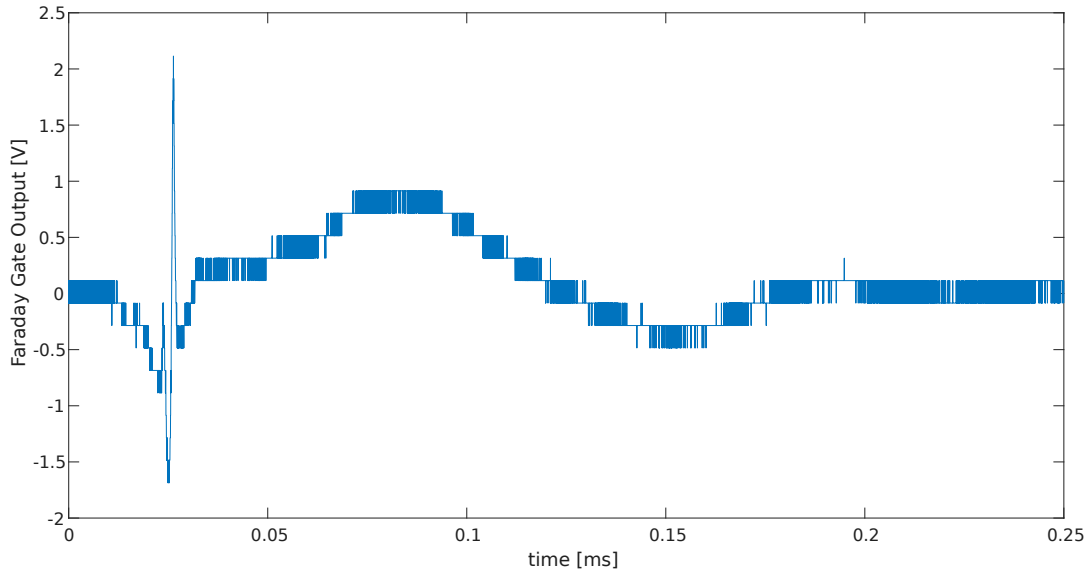


Figure 4.13: Plot showing the response of a Faraday gate on a FLF TSLGG shot using a 10 mm diameter, copper tipped poly carbonate projectile. This Faraday gate was placed off the barrel of the gun and within the target chamber of the tube. The zero-time here corresponds to the time at which the projectile passed the light gate immediately before the Faraday gate.

From the shots with the FLF TSLGG we can determine that the barrel of the gun is most likely the reason for the Faraday gates being unable to detect projectiles. The steel from the FLF TSLGG barrel is not demagnetised which could act to shield the projectile from the field produced by the magnet in the Faraday gate or the gate coil from the induced field around the projectile. This can be reconciled with the results from the portable TSLGG which crucially did have a demagnetised barrel. Thus, the magnetic field could reach the projectiles within its barrel and the induced field around the projectile could reach the gate coil. It is also possible that the larger thickness of barrel may have caused the issue however this was unable to be

tested. A quick (but likely expensive) way to definitively test this would be to replace the launch tube of the FLF TSLGG with a demagnetised version of the same thickness.

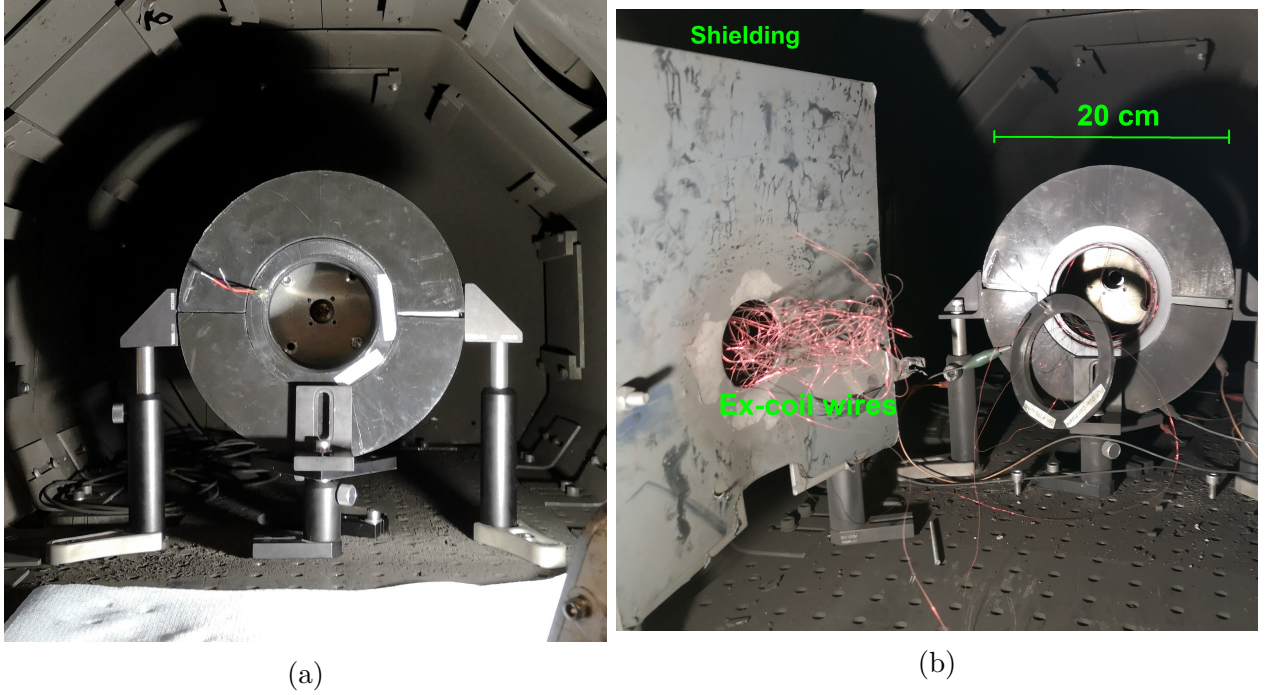


Figure 4.14: Photos showing a Faraday gate before (a) and after (b) a shot with the FLF TSLGG. The Faraday gate was placed within the target chamber of the gun, hence the destruction of the gate. Note also that the coil from the inside of the gate is lodged inside the shielding which was used in an attempt to protect the gate.

A possible explanation for the inability of the Faraday gate to sense a projectile through the FLF TSLGG barrel arises from the skin effect. In the context of this project, the skin effect gives rise to a characteristic length, known as the skin depth, over which the changing magnetic field generated around a projectile is exponentially attenuated by the material of a gun barrel. The magnetic field from the projectile induces currents in the barrel which in turn generate an opposing magnetic field and cancels the field from the projectile, effectively shielding the Faraday gate from the projectile. The skin depth for a barrel can be calculated using,

$$\delta = \sqrt{\frac{2}{\mu\omega\sigma}}, \quad (4.12)$$

where μ is the permeability of the barrel ($\mu = \mu_r\mu_0$, the product of the relative permeability and the permeability of free space), σ is the conductivity of the barrel material and ω is the angular frequency of the magnetic field generated around the projectile [60]. We can estimate the frequency of the magnetic field around the projectile from the period of the oscillatory outputs from Faraday gates, as shown in Fig. 4.9 and Fig. 4.13.

For the portable TSLGG, the four Faraday gates were all able to detect the projectile. In each case we expect the skin depth to be larger than the barrel thickness — 10.5 mm. From Equation (4.12), we can infer that the smallest skin depth will be seen at the Faraday gate where the projectile is moving fastest (the purple trace in Fig. 4.9) since the frequency of the oscillating magnetic field will be largest. For the FLF TSLGG, Faraday gates upon the barrel could not detect the projectile, hence we expect the skin depth to be smaller than the barrel thickness — 32.2 mm. We can use the frequency of the off-barrel Faraday gate response, shown in Fig. 4.13, to estimate the skin depth we would expect within the barrel. The main problem with measuring the skin depths is that the exact conductivity and permeability of each barrel is not known, we can however estimate values.

The barrels are formed of two different types of steel, one demagnetised (portable) and one magnetic (FLF). Depending on exact composition, some steels can have conductivities (at room temperature) varying between $1.45 \times 10^6 \text{ Sm}^{-1}$ and $7 \times 10^6 \text{ Sm}^{-1}$. Since the portable TSLGG barrel is demagnetised we would expect the relative permeability to be close to that of a non-magnetic material i.e. ~ 1 . Austenitic steel is a form of steel which is commonly non-magnetic, from Table 4.1 we see that the relative permeability of this steel can be 1.003, which we can use as an initial approximation. Using different steels shown in Table 4.1 as a start point to estimate the relative permeability of the FLF TSLGG barrel, the value could potentially be between 40 and 1800. The largest possible skin depth will be achieved using the smallest permeability in this range.

Table 4.2 shows the results of this investigation. The first column specifies the Faraday gate trace under inspection with reference to the figure it originates from. The second column, T , is the period of the oscillation extracted from each trace and the third column, ω , is the angular frequency derived from the period, T , i.e $\omega = 2\pi/T$. The fourth and fifth columns give estimated values for the relative permeability, μ_r and conductivity, σ respectively. The sixth column is the calculated skin depth and the seventh column is the thickness of each barrel for comparison to the skin depth.

If we first consider the Faraday gate used on the FLF TSLGG, the largest estimate for the skin depth — 0.1 mm — is found for the smallest estimates for relative permeability and conductivity, $\mu_r = 40$ and $\sigma = 1.45 \times 10^6 \text{ Sm}^{-1}$. This skin depth is much smaller than the barrel thickness of 32.2 mm i.e. the magnetic field from the projectile will not penetrate the barrel which is concurrent with evidence from the experiment. For the Faraday gates used on the portable TSLGG the results are less conclusive, using low estimates for relative permeability

and conductivity of 1.003 and $1.45 \times 10^6 \text{ Sm}^{-1}$ respectively, the gate at which the projectile is moving slowest (gate 1) yields a skin depth of 17.7 mm — larger than the barrel thickness. This means the field will penetrate the barrel, which is concurrent with the experiment. For the next three gates, using the same values for relative permeability and conductivity, we find that the skin depth is less than the barrel thickness. This means that the field should not be able to penetrate the barrel, contrary to experimental findings. For the latter three portable TSLGG gates, the difference between the values of skin depth and barrel thickness is relatively small (between 3% and 17%) when compared with the FLF TSLGG gate difference (99.7%), it is possible that the discrepancy for the portable TSLGG gates could arise from over-estimating the conductivity of the portable TSLGG barrel. As mentioned above, the conductivity is unfortunately unknown. Using a relative permeability closer to 1 does not increase the skin depth to values greater than the barrel thickness.

From this investigation we can conclude that the skin effect may be the cause for the inability for some Faraday gates being unable to detect projectiles. This is under the caveat that the conductivity of the portable TSLGG barrel has been over-estimated. It would therefore be prudent to find the conductivity and relative permeability of each barrel in order to more precisely constrain the results of this investigation. We can also suggest that, in order to detect projectiles through the FLF TSLGG barrel, the barrel should preferably be made from a demagnetised steel with similar thickness to the portable TSLGG barrel. An alternative solution would be to produce gun barrels from a material which is not electrical conductive and otherwise has the same or better strength properties compared to steel.

Faraday Gate	T [s]	ω [rads ⁻¹]	μ_r	σ [Sm ⁻¹]	Skin depth [mm]	Barrel thickness [mm]
FLF TSLGG Fig. 4.13	3.4×10^{-6}	1.9×10^6	40	1.45×10^6	0.1	32.2
			40	7×10^6	0.06	
			1800	1.45×10^6	0.02	
			1800	7×10^6	0.01	
port. TSLGG, gate 1 (blue trace) Fig. 4.9	1.8×10^{-3}	3.5×10^3	1.003	1.45×10^6	17.7	10.5
			1.003	7×10^6	8.1	
port. TSLGG, gate 2 (red trace) Fig. 4.9	6×10^{-4}	1.1×10^4	1.003	1.45×10^6	10.2	
			1.003	7×10^6	4.6	
port. TSLGG, gate 3 (yellow trace) Fig. 4.9	5.1×10^{-4}	1.2×10^4	1.003	1.45×10^6	9.4	
			1.003	7×10^6	4.3	
port. TSLGG, gate 4 (purple trace) Fig. 4.9	4.3×10^{-4}	1.5×10^4	1.003	1.45×10^6	8.7	
			1.003	7×10^6	3.9	

Table 4.2: Compilation of results from the investigation into whether the skin effect is the cause of the inability of Faraday gates to detect projectiles through the FLF TSLGG barrel.

4.5 Measurement of Velocity from a Single Faraday Gate

We are now at a point where we can be confident that a Faraday gate would make an appropriate diagnostic for early detection of a projectile in the barrel of a TSLGG. This is provided that the barrel is made of a material which does not shield the projectile from the magnetic field of the gate. We could use a series of gates, spanning the whole gun, combined with target impact sensors to monitor the progression of a projectile throughout a shot. Using this set-up, sources of jitter for a gun could be characterised and measurements of projectile velocity and acceleration could be taken. Then, through taking many shots, it should be possible to build up an understanding of the behaviour of a particular gun. In theory, this can be used as feedback to better predict projectile impact time, based on its early progression, and thus trigger a diagnostic to arrive at a desired time after impact. A more advanced capability of a Faraday gate which could aid in the goal of impact prediction was hinted at earlier in this chapter — the challenge of measuring projectile velocity using a single gate.

A logical start point for this goal is to attempt to create and test a numerical a model for a gate which incorporates the characteristics of the gate coil and magnetic field, along with the projectile composition and velocity. From this, experimental data can be compared against the model to ascertain the accuracy of the model. From the theory outlined in Section 4.3, we can deconstruct the process of induction in a Faraday gate into discrete steps which can ideally be tested separately to aid in development of the model. Firstly, we define a cylindrical projectile in a cylindrical coordinate system, moving at v_{proj} in the z direction through the centre of a magnet which creates a field with cylindrical symmetry, i.e. depending only on radial position (r) and distance from the magnet (z), $\vec{B}_0(r, z)$. Fig. 4.15 shows a visual representation for context. We recall that a projectile experiences a changing magnetic flux as it approaches a Faraday gate. This changing flux induces an electromotive force (EMF) within the projectile. If we assume that this induction causes several current loops to form in the projectile, we can break the projectile into several discrete loops ϵ_{loop} . Then the EMF in any loop is given by the change in flux through the area enclosed by the loop (grey area shown in Fig. 4.15) as it moves through the magnetic field. At any given moment, the EMF induced in a loop will depend on its (r, z) coordinate within the magnetic field and the velocity of the projectile.

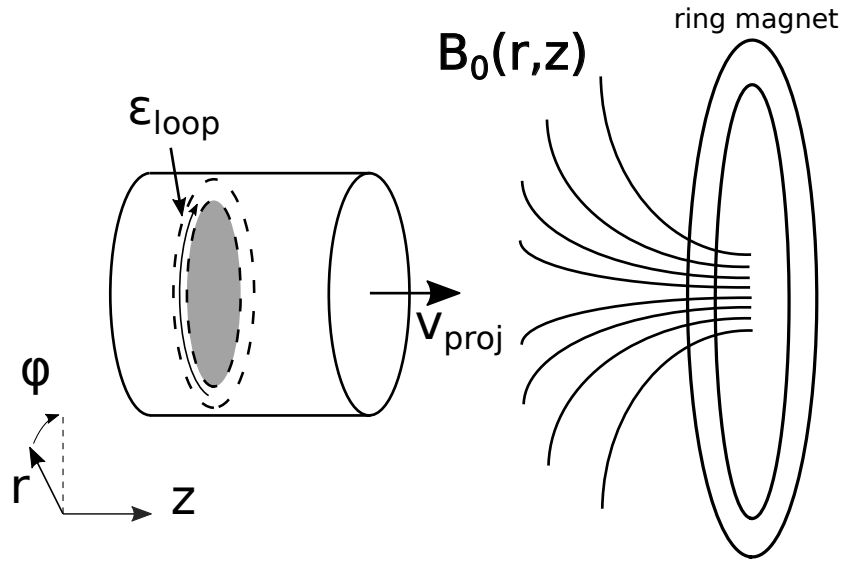


Figure 4.15: Diagram visualising the induction of an EMF ϵ_{loop} within a projectile moving at velocity v_{proj} through the centre of a magnetic field around a static ring magnet $\vec{B}_0(r, z)$.

From the Faraday-Lenz law, the EMF induced in a given loop at position (r_{loop}, z) must be,

$$\epsilon_{loop}(r_{loop}, z) = -\frac{d\phi_{B_0}}{dt} \quad (4.13)$$

where ϕ_{B_0} is the magnetic flux through the circular area with radius r_{loop} , enclosed by ϵ_{loop} .

We can make the substitution $d\phi_{B_0} = \vec{B}_0(r, z) \cdot d\vec{A}$, where $A = \vec{A}/\hat{z}$ is the area enclosed by ϵ_{loop} . We can further simplify by removing the dot product by dealing with the component of magnetic field parallel to $d\vec{A}$ and in the z direction i.e. $d\phi_{B_0} = B_{0,z}(r, z)dA$. Then we replace the circular area element $dA = 2\pi r dr$. Thus we can find the magnetic flux through a circular area with radius r_{loop} ,

$$\phi_{B_0} = \int_0^{r_{loop}} B_{0,z}(r, z) 2\pi r dr. \quad (4.14)$$

Substituting Equation (4.14) into Equation (4.13) we now have,

$$\epsilon_{loop}(r_{loop}, z) = -2\pi \frac{d}{dt} \int_0^{r_{loop}} B_{0,z}(r, z) r dr \quad (4.15)$$

$$= -2\pi \frac{dz}{dt} \frac{d}{dz} \int_0^{r_{loop}} B_{0,z}(r, z) r dr \quad (4.16)$$

$$= -2\pi v_{proj} \frac{d}{dz} \int_0^{r_{loop}} B_{0,z}(r, z) r dr. \quad (4.17)$$

This is part 1 of the process. For the next step, we see that the EMF in each loop within the projectile will result in a current loop which will then change after every time-step in the projectile motion through the magnetic field. Each loop of changing current will in turn generate a changing magnetic field through the Faraday gate coil. The total magnetic flux contributed by of each of these current loops, through the area enclosed by the coil, must therefore be evaluated after each time-step in the projectile motion. This is a non-trivial issue which the author is yet to find an analytical solution for. Initially, it was thought that the Biot-Savart law could be used to find the magnetic field from a current loop at an arbitrary location but it quickly became apparent that this would not work as the Bio-Savart law is only appropriate for steady state currents. If this magnetic flux can be quantified however, calculating the EMF in the Faraday gate coil ϵ_{coil} should be analagous to Equation (4.17), multiplied by a factor N for the number of turns in the coil.

Despite the difficulty in realising how to model the latter parts of this process, Equation (4.17) is still relatively simple to implement numerically. To that end a short experiment was devised to test the theory. The first objective, however, was to quantify the z component of the magnetic field around one of the static ring magnets. The method for which will now be described.

4.5.1 Determination of the Magnetic Field of a Permanent Annular Magnet

The magnet used here is the 60 mm outer diameter, 40 mm inner diameter, 5 mm thick neodymium magnet referred to earlier in this chapter [63] which was built into a Faraday gate. In order to measure the z component of the magnetic field around this magnet, the transverse attachment of a Hall probe was used as shown in Fig. 4.16. The magnetic field was measured in the region that a projectile would pass through: between $r = \pm 10$ mm and $z = \pm 40$ mm where $z = r = 0$ is at the centre of the magnet.

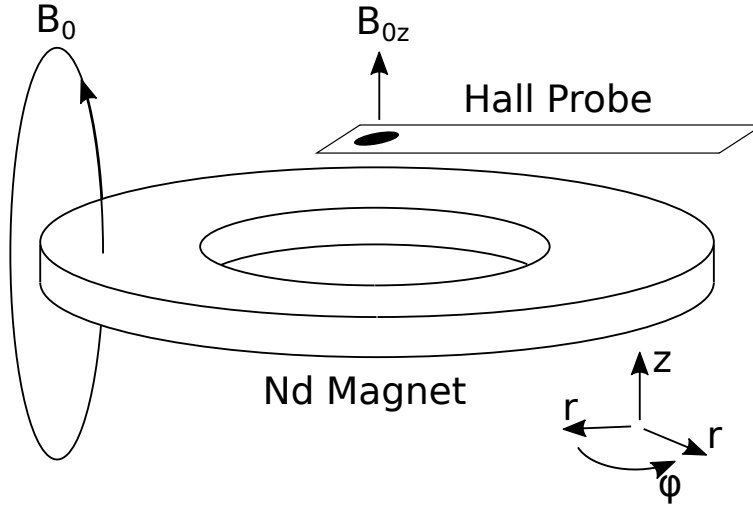


Figure 4.16: Diagram demonstrating the method for measurement of the z component of the magnetic field surrounding a permanent annular magnet.

To find an analytical form for the magnetic field, the variation of the field in the z and r directions were measured and a numerical fit made to a dataset of discrete field values. Fig. 4.17a shows an example of the variation of the field in the z axis for $r = 0$, 20 more graphs were then produced for each value of r between ± 10 mm. Using Origin as a data fitting software, it was found that these graphs were well fitted by an equation of the form,

$$B_{0,z}(z) = \left[\beta(r) + \frac{A(r)}{w(r)\sqrt{\pi/2}} \exp \left(- \frac{2[z - z_c(r)]^2}{[w(r)]^2} \right) \right] [1 + F(r)z^2 + G(r)z^4], \quad (4.18)$$

where each fitting parameter: β , A , w , z_c , F and G varies according to r position. This process was repeated to examine the variation of the field in the r direction, Fig. 4.17b shows an example of the variation of the field over r for $z = 2.5$ mm. 19 more graphs were produced for values of z between ± 40 mm which were all found to be fit by an equation of the form,

$$B_{0,z}(r) = c(z) + b(z)r + a(z)r^2. \quad (4.19)$$

where each fitting parameter: c , b and a varies according to z position.

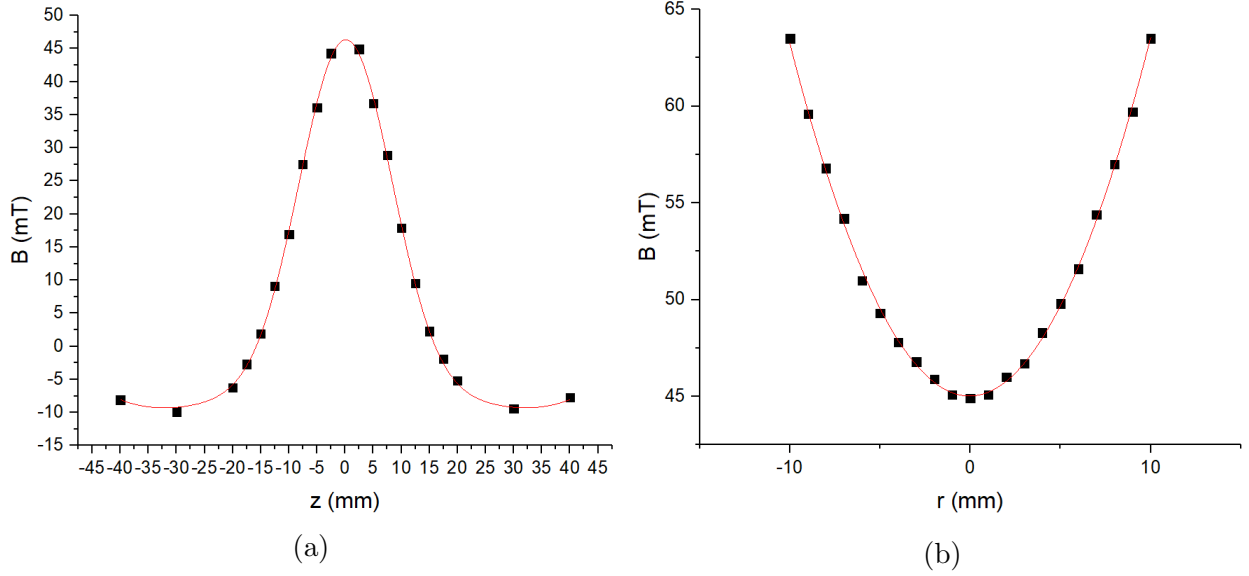


Figure 4.17: Plots showing (a), the shape of the z component of the magnetic field in the z direction through the central axis of the annular magnet and (b), the shape of the z component of the magnetic field in the r direction at the surface plane of the annular magnet. Data is shown by the black points and the fit in red.

Using Equations (4.18) and (4.19) and assuming that the magnetic field is cylindrically symmetrical we can express the field at any position within the limits measured using,

$$B_{0,z}(z, r) = \left[\beta(r) + \frac{A(r)}{w(r)\sqrt{\pi/2}} \exp \left(- \frac{2[z - z_c(r)]^2}{[w(r)]^2} \right) \right] [1 + F(r)z^2 + G(r)z^4] \times [1 + v(z)r + u(z)r^2], \quad (4.20)$$

where $v = b/c$ and $u = a/c$. The next step was to find analytical expressions for all of the coefficients in Equation (4.20) β , A , w , z_c , F , G , v and u . This was achieved by extracting values for the coefficients from every graph of the types shown in Fig. 4.17 and plotting against z position (for u and v) or r position (for β , A , w , z_c , F and G). The coefficients were then fitted to, providing functions dependent on only r or z . For context, Fig. 4.18 shows the variation of the coefficient w with radial position r .

The expressions for each coefficient were fed back into Equation (4.20) to give a full expression which describes the z component of the magnetic field explicitly in z and r . The fit of the expression to the raw measurements of $B_{0,z}$ is shown in Fig. 4.19.

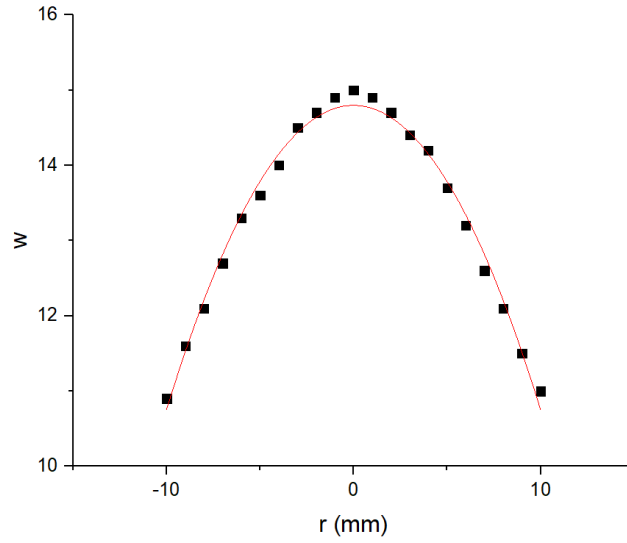


Figure 4.18: Plot showing the variation of the coefficient w with radial position r about the field surrounding the annular magnet. Values of w were extracted from graphs of the type shown in Fig. 4.17a. Data is shown by the black points and the fit in red.

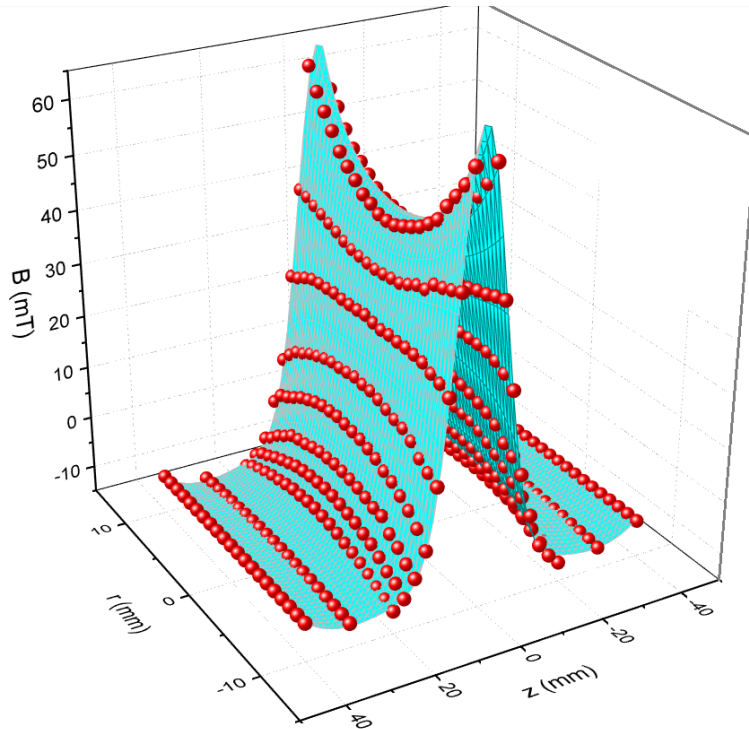


Figure 4.19: Plot showing the fitting of a 3D surface (blue) to discrete measured magnetic field data (red points) which describes the z component of the magnetic field surrounding a permanent annular magnet. The 3D surface represents an equation in r and z which gives the value of the field at a point in space between $r = \pm 10$ mm and $z = \pm 40$ mm.

4.5.2 Experimental Validation of the Model

Using the expression for $B_{0,z}$ derived in the previous section and Equation (4.17), a code was created which takes the velocity of a projectile along with a radial position for a loop within a projectile as inputs and returns the calculated EMF induced at that radial position. This can then be iterated over z positions to give the total EMF as the loop passes through the entire magnetic field. In order to test this code, an experiment was devised in which the EMF in a projectile could be physically measured. This would require the connection of the projectile to an oscilloscope to monitor the EMF. This made movement of the projectile impractical. As such, the “projectile” was mounted upon a vertically oriented tube and instead the magnet was made into the projectile by dropping it with the tube passing through its centre. The simplest way to test this model was to attach a single loop of copper wire to the tube, electrical contacts could be attached to the ends of the loop and to an oscilloscope. A light gate was used to measure the velocity of the magnet just prior to the copper loop. Fig. 4.20 shows a schematic of the experimental setup.

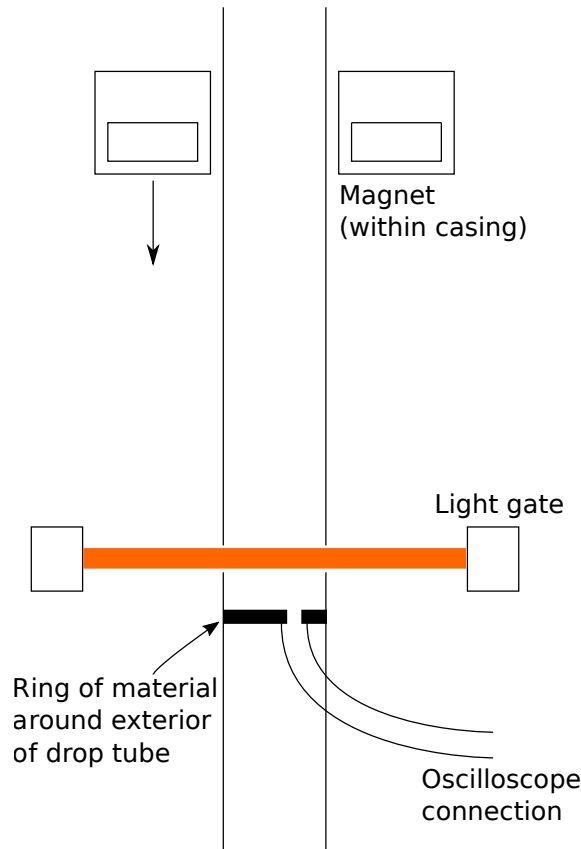


Figure 4.20: Diagram showing the experimental setup which quantified the EMF induced in a “projectile” in the form of a stationary loop of copper mounted upon the surface of a vertical drop tube. The loop had a small break which was connected at each end to an oscilloscope. The magnet was dropped past the loop inducing an EMF detected on the oscilloscope. A light gate was used to measure the velocity of the magnet just before it passed the loop.

The ring of copper wire sat at a radius of 10.9 ± 0.2 mm around the centre of the drop tube. The velocity of the magnet in one drop was found, from the light gate, to be 4.3 ± 0.2 ms⁻¹. The radius and velocity were input to the code and Fig. 4.21 shows the comparison of the real data to simulated data. As can be seen, the data and simulation match to within ~ 1 mV (10% minimum/maximum voltage) which is an encouraging result. It is possible that the small ~ 1 mV discrepancy in the simulation arises from uncertainty in the magnet velocity as it passes the loop and uncertainty in measuring the radial position of the loop. Extending this to the EMF in a larger projectile, i.e. extended in z and r , should be simple but it assumes all induction in the projectile takes the form of circular loops. It would be useful to conduct a similar experiment with electrodes attached to other parts of a cylindrical projectile with a radial slot cut along its z axis in order to observe behaviour in the radial axis. Despite this, the results shown here are actually of great use to the magnetoflyer method for projectile detection outlined in Section 4.2.3 which is essentially a replication of this experiment but with a magnetic field moving through the centre of the loop in a barrel and not around the exterior. The magnetic field used in the simulation would be destroyed on each shot as it is incorporated into the projectile but if several similar magnets are used it would not be unreasonable to assume they have similar fields provided characterisation of an appropriate sample prior to shots.

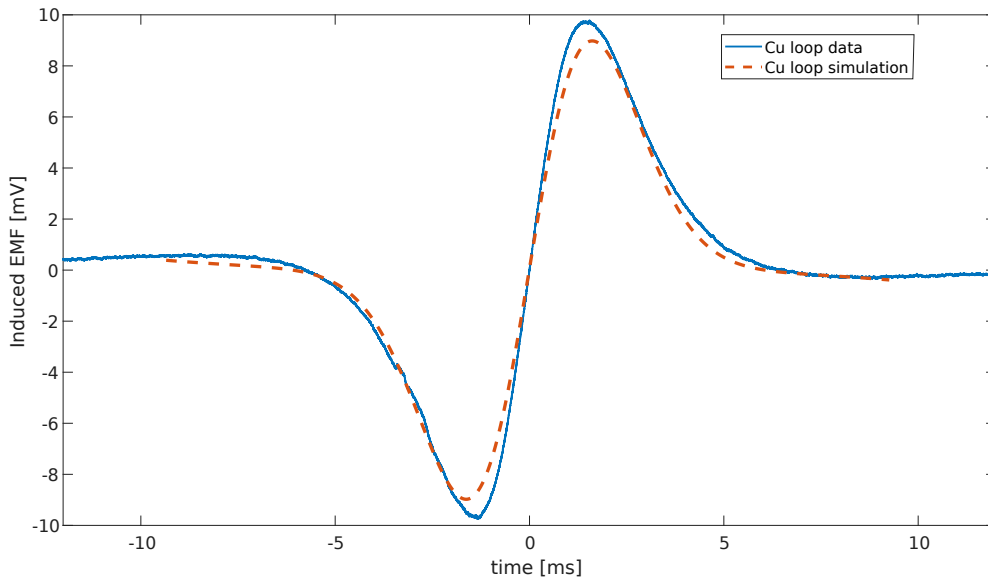


Figure 4.21: Graph showing the induced EMF observed in a ring of copper wire (blue data) due to its movement relative to a permanent annular magnet. Also shown is simulated data (red dashed line) for comparison.

4.6 Chapter Summary

We began this chapter by considering the problem of synchronising a long-trigger time diagnostic such as a high-power laser to a two-stage light-gas gun, a system with many inherent sources of temporal jitter. A method was proposed, through the detection of a projectile within the gun early in its flight and prediction of the impact of the projectile upon a target. Several projectile detectors were then discussed, including the applicability of each to the goal of early detection and extension to impact prediction. A promising candidate was selected for use in this project, a sensor which harnesses electromagnetic induction to detect a projectile, without contact, through an unbroken gun barrel. This was referred to as a Faraday gate, of which several test systems were produced by the author for this project. These detectors consist of a coil of wire sat within the magnetic field of a static annular magnet and sit around the outside of the barrel of a gun.

Experimental work began on the Faraday gates in order to characterise their behaviour. Projectile velocity and output voltage were found to be linearly related for identical projectiles and gates were found to work for projectiles with velocities ranging between a few ms^{-1} and several kms^{-1} . They were fielded upon two different gas guns, the results from which indicate that an experiment which intends to use a Faraday gate is dependent upon the material the gun barrel is made from. Faraday gates were found to work with a barrel of 10.5 mm thickness, demagnetised steel but not with a magnetic, 32.2 mm thickness steel barrel. An investigation into the skin effect suggests that the issue could arise from the latter barrel being impermeable to the oscillating magnetic field produced around a projectile when passing a Faraday gate. Potential solutions to this problem include reducing the thickness of the barrel and using a demagnetised or non-electrically conductive material for the barrel.

Work began on a theoretical model to simulate the voltage induced within a Faraday gate. The goal of this was to predict the velocity of a known projectile given the voltage produced by a single gate during flight. Finding the velocity through this method would aim to further constrain impact prediction for a projectile. The process was broken down into several steps which need to be modelled over a projectile flight: induction within the projectile, generation of a magnetic field around the projectile due to currents in the projectile caused by the aforementioned induction, resultant change in magnetic flux experienced through the coil within the Faraday gate, induction within the Faraday gate coil due to the changing flux. Progress was made toward simulating the first of these steps and a simple experiment was devised to test the validity of the model which initially showed good agreement to within 10%.

Chapter 5

Comparison of X-ray Sources for Probing Cavity Collapse

5.1 Using X-ray Sources for Probing Cavity Collapse

A primary reason for using X-ray radiation for probing cavity collapse is its ability to penetrate high density materials undergoing dynamic shock compression. The increase in density caused by passage of a shock can lead to a target becoming opaque to visible light but not to higher energy radiation such as X-rays. Furthermore, the fraction of X-ray radiation which is absorbed by a material is set by parameters including density, allowing determination of conditions inside a target. Since there is a jump in density immediately behind a shock wave, it is possible to track the movement of a shock by taking multiple radiographs in sequence. Precise knowledge of the time between radiographs would then allow a measurement of shock velocity for example, satisfying a goal of this project. Fig. 2.5 from Section 2.2 shows an example of imaging a shock front in PMMA using ESRF X-ray radiation.

The above imaging technique harnesses the attenuation of X-rays in matter, to probe interfaces between regions of different densities in a material, at a μm scale. It is possible to probe materials with X-rays at even smaller scales using more specialised techniques. Among these techniques are X-ray diffraction [65] which probes atomic structures by virtue of their similar size (sub-nm) to X-ray wavelengths. Also X-ray spectroscopy [65–67], which harnesses the energy of X-rays being of the order of the binding energy of core electrons to infer electronic and atomic structures. The precise function of these techniques is beyond the scope of the experimental work in this thesis, which is focused on the characterisation of specific X-ray sources for radiographic imaging of mm scale targets which we shall now discuss.

Arguably, there are three crucial aspects defining the characteristics of an X-ray probe. These are: spectral brightness, pulse duration and source size. The spectrum of an X-ray pulse will determine its penetrative capabilities; too soft and the radiation will not pass through a target, too hard and all regions of the target may become transparent regardless of density or composition. The spectral character can however be tailored using spectral isolation techniques provided a broadband X-ray source. Now, consider a probe with sufficiently hard photons to penetrate a target, if there is a low number of photons per unit time per unit area, or flux, incident upon the target, a radiograph may still be of poor quality if the signal is of similar magnitude to noise on the detector. The source brightness then incorporates the flux per unit solid angle. Brightness is a useful characteristic for comparing sources, since brightness has no dependence on distance of a target from a source, unlike flux. We can further relate the spectral character and brightness of a source using spectral brightness. This aspect specifies the source brightness divided over a specific spectral bandwidth. Characterising the spectral brightness of several sources over many bandwidths represents an attractive way to compare sources but relies on having effective, narrow-bandwidth spectral isolation methods and being able to carry out simultaneous brightness measurements which may not always be easily achieved or practical for a source.

The duration of an X-ray pulse becomes fundamentally important when imaging rapid processes which evolve on the timescale of the X-ray pulse. Consider a shock wave moving at 4 kms^{-1} through a 4 mm diameter cavity. If we wish to probe the structure of the cavity undergoing collapse at $10 \text{ }\mu\text{m}$ resolution, we require a probe of duration no longer than 2.5 ns otherwise the image quality will be compromised by motion blur.

Finally, the size of an X-ray source will define the minimum spatial resolution of an ideal imaging system, this is particularly crucial for beam-like sources such as synchrotron radiation which cannot be easily magnified. Point-like sources can avoid this limit to some degree by using an imaging system with large magnification however insufficient flux may then become an issue for a detector far from the source.

The exact dependence of spatial resolution on source size in ideal point-projection imaging is defined below. Following that, we shall consider the physics of X-ray generation by sources relevant to this project including high-power lasers and X-pinchs, with specific emphasis on the four parameters described above. The focus of the chapter will then move on to methods for measurement of source size and the development of source size measuring diagnostics on X-pinchs and high-power lasers.

5.1.1 Minimum Spatial Resolution in Point-Projection Imaging due to Finite Source Size

The fundamental reason we need to know the dimensions of any imaging light source is because the spatial resolution of an image taken with that source is directly affected by the source size. The consequences of this are detailed here. Consider a perfect point source S' , projecting an image of an object of size δ as shown in Fig. 5.1. Due to the point-like nature of the source, the image will be perfectly sharp with no blurring and the size of the image is given by,

$$\delta' = \frac{p+q}{p}\delta \quad (5.1)$$

$$\equiv M\delta. \quad (5.2)$$

where p and q are defined in Fig. 5.1. This figure also shows a projection of the same object by a finite source S , which inherently causes blurring at the edges of the image by an amount, R_P given by,

$$R_P = \frac{q}{p}S \quad (5.3)$$

$$= (M-1)S. \quad (5.4)$$

As we reduce the object size δ , the image size will tend to the size of the blurring R_P (i.e. $M \times \delta = \delta' \rightarrow R_P$) at which point we will lose all definition of the original object in our image. This tells us that the limit on the smallest object we can resolve will be when $\delta' = R_P$. Hence, combining Equation (5.2) and Equation (5.4) we find,

$$\delta_{min} = \frac{M-1}{M}S. \quad (5.5)$$

This tells us the smallest observable detail we can theoretically resolve in a point-projection image is dependent on the magnification of the imaging system and the source size but is more strongly affected by source size. This, however, only considers a simplified view of spatial resolution due to finite source size. Other effects on spatial resolution include diffraction, object penetration and finite detector resolution.

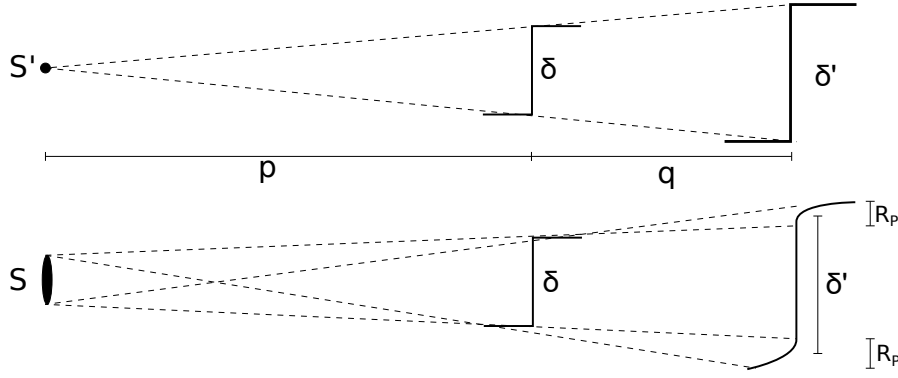


Figure 5.1: Diagram showing the projection of an object of size δ by two different sources S' and S . S' shows an infinitely small point source which creates an image of size δ' with no geometric edge blurring whereas S shows a finite source which leads to an image with edges blurred by an amount R_P . This is also referred to as a penumbra.

5.2 Methods for X-ray Generation

5.2.1 High-Power Lasers

The qualities of X-rays, generated by high-power lasers are influenced by the intensity and pulse duration of the laser. In this section we discuss X-ray generation mechanisms relevant to the Cerberus laser system. The peak intensity of Cerberus is $\sim 10^{19} \text{ Wcm}^{-2}$ and the pulse duration is $\sim 700 \text{ fs}$, placing it in the short pulse laser category (long pulse defined here as $t > 10 \text{ ps}$ [68]). Due to the high intensity, the electric field of a Cerberus laser pulse will ionise the surface of a solid density target within a few laser periods [69] (1 laser cycle = 3.5 fs), long before the peak of the pulse arrives. The mechanisms by which this occurs are mainly tunnel ionisation and over-the-barrier ionisation, which become the dominant processes for lasers with intensity $> 1.4 \times 10^{14} \text{ Wcm}^{-2}$ [69]. These mechanisms occur when the laser electric field is sufficient to warp the Coulomb potential binding an electron to an ion. As the potential is suppressed, it is more likely that an electron can quantum-tunnel through the barrier and escape (tunnel ionisation [69]). Suppression of the barrier below the rest energy of the bound electron will cause the electron to spontaneously escape (over-the-barrier ionisation [69]).

This ionisation initially causes the formation of a surface plasma on a target, with a steep gradient in electron density. The direction of the gradient is parallel to target normal. The pulse length of Cerberus defines the next steps in the interaction with the target. Essentially, the ions in this plasma move on a timescale greater than the laser pulse and so can be considered static. The applied electromagnetic field causes electrons in the plasma to oscillate with a frequency characteristic of the plasma electron density, the plasma frequency ω_P ,

$$\omega_P^2 = \frac{n_e e^2}{m_e \epsilon_0}, \quad (5.6)$$

where n_e , m_e and e are electron density, electron rest mass and electronic charge respectively and ϵ_0 is the permittivity of free space. At some value of electron density, the plasma frequency will equal the frequency of the laser field. This value of electron density is known as the critical density and corresponds to the point to which a laser pulse will penetrate into the target surface plasma, also known as the critical surface.

Having ionized a surface layer of plasma and penetrated to the critical surface of said plasma, the energy of the pulse is coupled into the target through absorption mechanisms which are defined by the pulse intensity. The dominant mechanism for a Cerberus pulse is vacuum (or Brunel) heating [69–71]. In vacuum heating, an obliquely incident laser pulse has a component of electric field which causes electrons at the critical surface to oscillate parallel to the direction of the electron density gradient. This happens to be a component of P-polarised light, which is why the Cerberus laser pulse is P-polarised and never incident normal to a target surface (as well as to minimise reflection back through the system, which might cause optical damage). This electric field component pulls electrons from the surface plasma, out into the vacuum in front of the target. As the laser electric field reverses, it then accelerates them back into the surface plasma. Returning to the critical surface, the electron will still be accelerating due to the electric field but the field cannot penetrate beyond this point. This essentially means electrons are freely launched into the target at relativistic speeds, creating a divergent beam of so called hot electrons directed normal to the target surface.

These hot electrons directly form the roots of the X-ray generation in Cerberus produced plasmas used as X-ray sources for imaging (and also have important consequences for ion acceleration, see Chapter 6). They cause an avalanche of further ionisation through collisions and emit X-rays through three main mechanisms or transitions: free-free, free-bound and bound-bound. Free-free transitions occur when an electron undergoes deceleration in the electric field of an ion and emits a Bremsstrahlung (braking radiation) X-ray photon, free-bound transitions are also known as recombinations, where an ion captures a free electron and in doing so releases an X-ray photon. Both of these mechanisms contribute to an X-ray pulse with a continuum spectrum stretching over several keV [71]. The final, bound-bound transitions occur when an electron moves from an outer level of an ion to a low-energy, inner level and emits a characteristic X-ray photon which contributes discrete peaks or line emissions to the continuum spectrum.

The brightness from these laser driven X-ray pulses can be as high as $10^{17} \text{ Wcm}^{-2} \text{ sterad}^{-1}$ [71]. The temporal profile of an X-ray pulse generated as above is tough to determine directly since it is on the scale of the laser pulse [71] and current X-ray detectors are not capable of accurate measurement at the required time resolution. Despite this, we can set an upper bound of less than 1 ns which is smaller than the timescales of dynamics in a cavity collapse.

Measurement of the spatial profile of a general laser generated X-ray source and how it originates has however been the focus of many works, e.g. [72–74]. Some limiting factors in the X-ray source size are the size of the laser focal spot and the angle of divergence of the subsequently generated hot electron beam. It has been shown that higher laser intensities increase the divergence of the electron beam and hence X-ray source size, see Fig. 5.2. Due to the divergence, target thickness is intrinsically linked to X-ray source size since a thicker target provides more length in which the electron beam can diverge and scatter. From Fig. 5.2, applying a divergence of 30 degrees for a Cerberus laser pulse of intensity $\sim 10^{19} \text{ Wcm}^{-2}$ and laser focus of $10 \mu\text{m}$ diameter onto $15 \mu\text{m}$ thick aluminium yields an estimate for X-ray source size of few 10s μm . Other factors which increase source size include the presence of a pre-plasma generated by a laser pre-pulse [72], which effectively increases the laser focal diameter by extending out from the front of a target into the laser beamline.

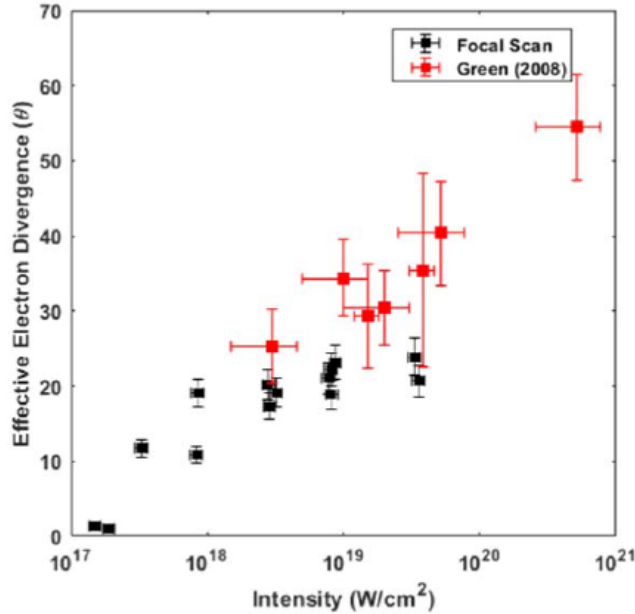


Figure 5.2: Graph showing the relation between electron divergence and laser intensity onto a target, produced by Armstrong et al. [72]. Data for this graph was taken by Armstrong et al. (black) and Green et al. [75] (red).

5.2.2 X-Pinches

X-pinch functionality is detailed in Section 3.2. In summary, an X-pinch drives a current through thin, crossed wires located between two electrodes at its centre. The current resistively heats the wire (so plasma is ablated from its surface) and generates an opposing implosive force from the $J \times B$ component of the Lorentz force. This implosion is localised at the cross point of the wires where current flow and hence $J \times B$ is greatest. When a current of several 10s to 100s kA is delivered at a rate of $\gtrsim 1$ kA/ns, the implosion, which is driven by $m = 0$ “sausage” instabilities, compresses the wire plasma to sufficient density and temperature that an X-ray source is produced. This process is represented in parts (a-c) of Fig. 5.3.

The evolution of this source consists of three major events, of interest to this project. The first event is the creation of the source described above. This source is a “thermal” burst of relatively soft ($E < 5$ keV) X-rays which has been measured to exist for less than 1 ns and be under $10\ \mu\text{m}$ in size [49–51]. This fact, combined with a large flux of the order 10^{15} - 10^{16} Wcm^{-2} [50] makes this source an attractive tool for point-projection radiography, and crucially, of particular interest for imaging cavity collapse.

The second event is caused by the continued collapse of the plasma at the X-pinch cross point. Eventually, the $m = 0$ instability leads to the plasma breaking apart at the cross point and an extremely high potential difference develops between the two halves of the now separated plasma, effectively forming a miniature pair of electrodes. The potential difference becomes large enough for electron beams to stream across the gap and collide with the anode plasma, see part (d) of Fig. 5.3. This creates a harder ($E > 10$ keV) X-ray source, occurring a few ns after the soft source. Despite being more penetrative than the soft source, the hard source is not necessarily as desirable as the soft source as it has been measured to have result in temporal and spatial resolutions up to $\sim 100\ \mu\text{m}$ in size and existing for more than 1 ns [49–51].

The third interesting event is not present in every X-pinch shot which will be made evident and discussed in the results in this chapter. Essentially, electrons which collide with the anode, as described in the previous paragraph, can penetrate and continue passing through the anode wire plasma and encounter a colder, denser region of plasma away from the X-pinch cross point. This decelerates the electrons and they begin to emit radiation over an extended (from several hundreds of μm to a mm in size) region. This source is not particularly useful for imaging due to its relatively large size but does have important consequences for results presented in this thesis. This effect was noticed by Shelkovenko et al. [50] but is not well reported in any other literature, likely due to the conditions required for its occurrence which shall be addressed later.

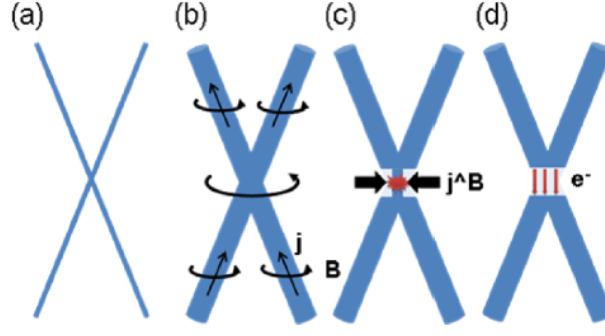


Figure 5.3: Diagram illustrating the formation and development of an X-pinch source. Part (a) shows the X-pinch wires pre-shot. Part (b) shows the current flow through the wires, ablation of the wires and the magnetic field due to the current flow. Part (c) shows the plasma implosion and formation of the small soft X-ray source caused by the $J \times B$ force concentrated at the cross point. Part (d) shows the secondary, harder source formed by electrons streaming across the gap which develops after the plasma breaks apart following the primary source shown in part (c). Diagram taken from Zucchini et al. [49].

5.3 X-ray Source Size Characterisation

In this section we move on to concentrate specifically on the measurement of X-ray source sizes.

5.3.1 Principles of Source Size Measurement

Two methods for X-ray source size measurement were used in the experimental work presented in this chapter. The first involves the use of a small pin-hole aperture and the second uses the shadow cast by a large obscuring object which is traditionally, but not always limited to, a knife-edge. These methods are elaborated upon here. The function of a pin-hole for source size measurement is determined by the relative size of the source and the pin-hole, hence there are two modes of operation for when the source size is either smaller or larger when compared to the pin-hole.

Pin-Hole Method 1 (Diameter > X-ray Source) When a source of light is much smaller than an ideal pin-hole aperture, the source will project an image of the pin-hole. For context, this is shown in Fig. 5.4. To visualise the projection of the pin-hole, consider an ideal point source at the centre of the extended source. Tracing lines (dotted lines in Fig. 5.4) from this point source to a detector position and touching the pin-hole edges show the ideal pin-hole image of size $I = M \times A$ where M is the magnification of the system and A is the pin-hole diameter. In this case the magnification is given by $M = (p + q)/p$ where p is the distance from

source to pin-hole and q is the distance from pin-hole to detector. Taking this a step further, we consider a real, finite source. Drawing rays (dashed lines in Fig. 5.4) from the edges of the source to the detector and touching the pin-hole edges shows regions where only a portion of the light from the source will arrive, creating a zone in the image plane referred to as a penumbra. The penumbra essentially causes blurring of the edges of the pin-hole image and is equivalent in size to the resolution of the image. The size of the penumbra R_p is directly related to the source size S according to $R_p = (M - 1)S$.

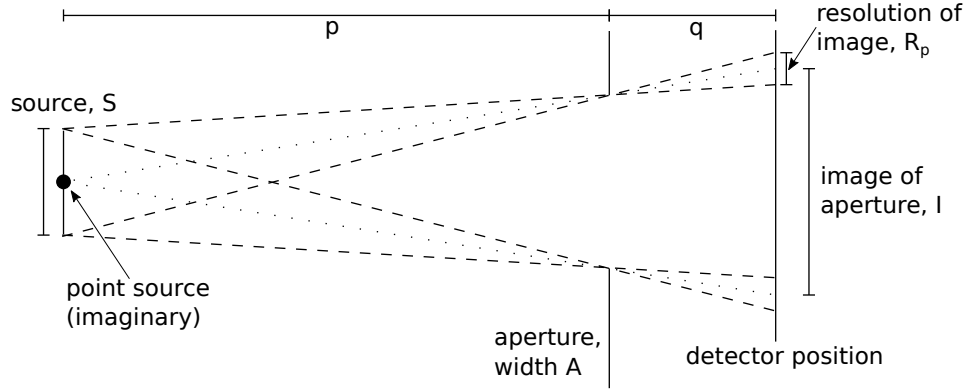


Figure 5.4: Diagram showing I , the projection of an image of a pin-hole aperture (dotted lines) of size A by a light source of size S where $S < A$. The distance from the source to the pin-hole is p and the distance from the pin-hole to detector position is q . The finite size of the source leads to a penumbral blurring (dashed lines) of the edges of the pin-hole image of size R_p which is directly related to S .

Pin-Hole Method 2 (Diameter < X-ray Source) When a source of light is much larger than a pin-hole aperture, an inverted image of that source is projected by the pin-hole. This is illustrated in Fig. 5.5. The image of the source formed at a detector position has size R_p , which is directly related to the source size by $R_p = M \times S$ and the magnification in this case is given by q/p .

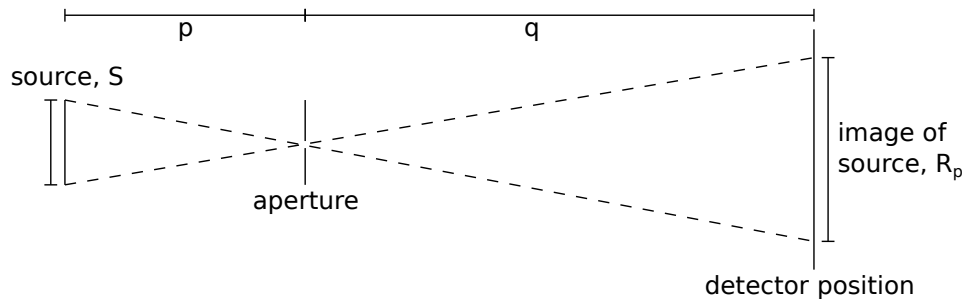


Figure 5.5: Diagram showing the idealised projection of a light source by a pin-hole aperture where the source is much larger than the pin-hole. The distance from the source to the pin-hole is p and the distance from the pin-hole to detector position is q . The finite size of the source S is imaged by the pin-hole, creating an inverted projection of the source of size R_p which is directly related to the source size and system magnification.

The “Knife”-Edge Method In the literature this method is often referred to as penumbral imaging however it could be argued that this is not specific enough as the first pin-hole method listed above is also a form of penumbral imaging. As such it will be referred to as the “knife”-edge method in this thesis. Knife edges have historically been used to obscure light sources as they have little-to-no edge defects and form sharp lines when used to cast shadows. However, any flat edge can be used in principle. In fact, for X-ray imaging it is often more useful to use thick (couple of mm) edges of high Z metals with curved edges as traditional thin, steel razor blades are more easily penetrated by X-ray radiation, leading to uncertainty as to whether the transition region from light to dark in an image is a true penumbra. As shall be seen, this project presents a technically simple to implement but novel development of this technique, discussed in Section 5.4.1.

Fig. 5.6 shows the effect of a sharp “knife”-edge which obstructs some of the light from a source, projecting regions of light, and shadow (umbra), onto a detector separated by a transition region caused by the finite size of the source: a penumbra. In Fig. 5.6, the size of the penumbra R_p is related to the source size S' according to $R_p = M \times S'$ and the magnification is $M = q/p$ much like the second pin-hole method. It is worth noting here that, for a source which is not spherically symmetric i.e. a wire or foil plasma ionised by a high-power laser, measurement of the source size will be sensitive to the geometry of the emitting region and the elevation of the detector away from the axis in which the source extends. The true source size S , elevated by an angle θ relative to a detector is then given by, $S = S'/\cos(\theta)$. This case is also illustrated in Fig. 5.6.

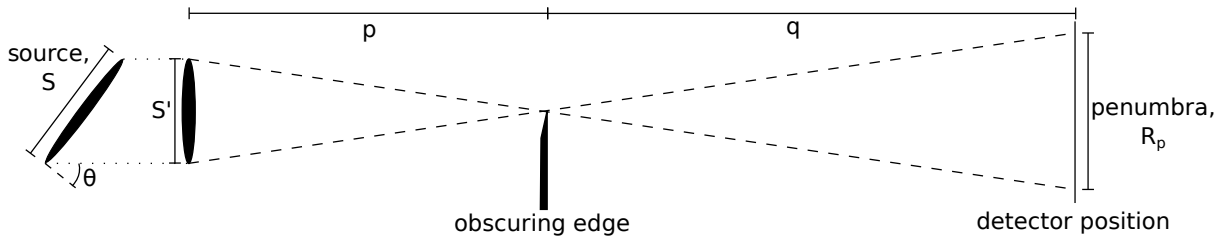


Figure 5.6: Diagram showing the projection of a shadow from an obscuring edge by an extended and tilted light source. The distance from the source to the edge is p and the distance from the edge to detector position is q . The finite source size S' leads to a penumbra between the light and dark regions of the projection of size R_p which is directly related to S' . The detector may be elevated at an angle θ from the dimension in which the true source S extends. In this case the detector views a component of the true source.

5.3.2 Physical Limits on Source Size Measurement

In this section we will discuss the major sources of error which will limit the minimum source size that can be measured by the diagnostic systems described above. In the last section we considered the measured size of an image or blurring, R_p to be only a function of the finite source size and system magnification. This is however an idealised situation and there are three other main effects which will also contribute to our measurement of R_p . These arise from finite detector resolution R_{det} , diffraction R_{diff} and penetration of light through a “knife”-edge or pin-hole, R_{pen} . We modify our expression for R_p to include all these sources as,

$$R_p^2 = R_{SS}^2 + R_{det}^2 + R_{diff}^2 + R_{pen}^2, \quad (5.7)$$

where R_{SS} is now the true size of the image or geometric blur created by the finite source size in a diagnostic system as described in Section 5.3.1 [76].

R_{det} is determined by the physical limitations of a detector, i.e., the grain size in a film sets the size of the smallest measurable feature in an image. R_{pen} is only a consideration for penetrative radiation and can be estimated with knowledge of the material composition and thickness of an edge or pin-hole along with the system magnification. R_{diff} depends on whether we are in the near-field or far-field diffraction limit. The boundary between the far- and near-field diffraction regions is given by the Fraunhofer distance,

$$p + q = \phi^2 / \lambda \quad (5.8)$$

where $p+q$ is the source-detector distance, λ is the wavelength of a photon and ϕ is the limiting aperture in the system, either the source size or the pin-hole, whichever is smallest [77]. In the case where $p + q \geq \phi^2 / \lambda$, we are in the far-field (Fraunhofer) diffraction resolution limit. The size of the blurring due to diffraction is then given by [77],

$$R_{diff} = 1.22(p + q) \frac{\lambda}{\phi}. \quad (5.9)$$

If $p + q < \phi^2 / \lambda$ then the size of the blurring due to diffraction is given by the near-field (Fresnel) diffraction resolution limit [78],

$$R_{diff} = \frac{0.515}{M} \sqrt{\frac{\lambda q}{2}}. \quad (5.10)$$

These sources of error will be evaluated during the discussion of results later in this chapter.

5.3.3 X-ray Detectors

Two types of 2D X-ray detector were used in this project, image plate and Kodak DEF, a type of photographic film. The details of both are discussed in this section.

Image Plate An image plate (IP) is a type of reusable 2D image detector which is sensitive to ionising radiation including X-ray and gamma rays as well as particles such as electrons, protons and neutrons. The mechanism by which they detect ionising radiation and particles is a well understood process [79–83]. The active part of the IP is a phosphor layer containing $\text{BaF}(\text{Br},\text{I}):\text{Eu}^{2+}$ grains. An incident ionising photon or particle can oxidise Eu^{2+} ions to Eu^{3+} in the phosphor by liberating a photo-electron. This electron is then captured in a lattice defect within the conduction band of the phosphor layer called an F centre. This forms a latent image stored in a metastable state. The latent image stored on the IP after each shot was read using a Fuji FLA5000 IP reader. This works by illumination of the plate by a well-focused red laser (typically HeNe) which excites the trapped photo-electrons from the lattice and causes recombination back to Eu^{2+} along with the release of a blue, ~ 400 nm wavelength photon which is captured by a photo-multiplier tube (PMT) in the reader. This process is known as photo-stimulated luminescence (PSL). The plate can then be reused after being wiped by exposure to visible light. The reader records the signal from the IP, by default, on a logarithmic scale, known as quantum level (QL). This is converted to PSL using,

$$PSL = \left(\frac{R}{100}\right)^2 \left(\frac{4000}{S}\right) 10^L [(Q^{L/2^B} - 1)^{-1/2}] \quad (5.11)$$

where R is the pixel size setting of the image plate reader in micrometres and S , L and B are the sensitivity, latitude and bit depth settings of the image plate reader respectively [82]. The (R, S, L, B) settings used for all IP scans in this thesis were (50, 5000, 5, 16).

The metastable state in which images are stored on IP can be degraded over time through exposure to white light or by fade due to thermally stimulated recombination of the Eu^{2+} ions [80, 82]. There are three main types of IP available: Fuji BAS-SR, Fuji BAS-MS and Fuji BAS-TR. Both SR and TR incorporate a blue dye which reduces scatter of red photons from the readout laser and as such improves resolution by reducing PSL from adjacent phosphor grains however this means they are more susceptible to fade due to improved absorption of infrared radiation [79, 80]. MS and SR both have a protective upper layer of Mylar which improves humidity resistance but sacrifices some level of sensitivity below ~ 5 keV. The sensitivity of each of these IP types on two different FLA IP readers is shown in Fig. 5.7. As can be

seen, MS is the most sensitive of the three in this energy range, for this reason and its lower susceptibility to fade, it was chosen for use in the shots shown in this chapter.

According to Maddox et al. [82] the natural fade of MS is most rapid in the first ~ 20 minutes after exposure. The fade continues at a slower rate before reaching a plateau after ~ 2000 minutes (or about 1.5 days). Due to the let-up time of the Cerberus vacuum chamber and proximity to the scanner, it was convenient to scan all IP data taken in this chapter as close as possible to 30 minutes after exposure. This time was chosen for consistency and allowed for fast feedback for monitoring the experiment, for example, it was obvious from the IP scans if the X-ray diagnostic had become misaligned. By scanning after each shot, such issues could then be addressed immediately rather than waiting several hours and potentially wasting subsequent shots. The IP was also transported in a light-tight case away from any heat sources to minimise further image fade.

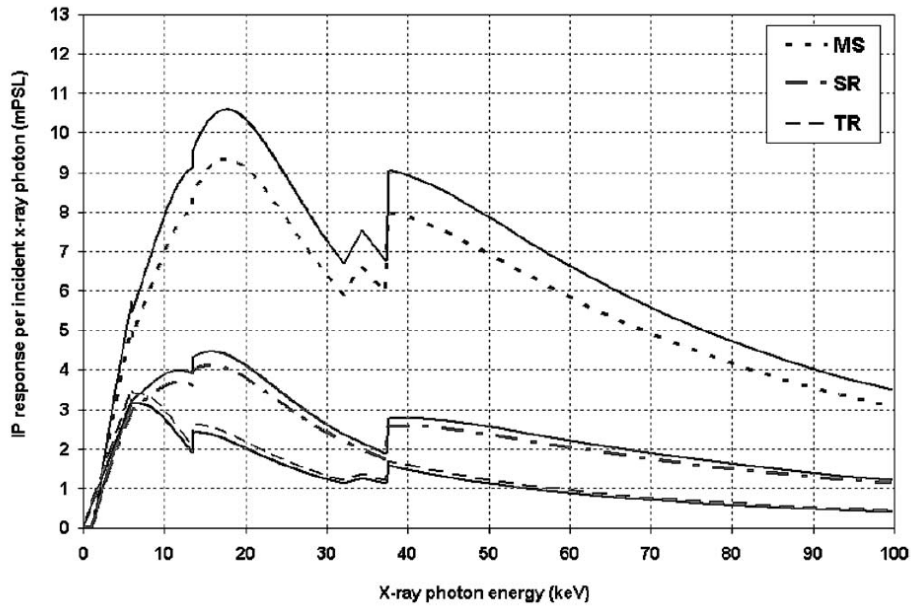


Figure 5.7: Graph showing X-ray sensitivities of Fuji BAS-SR, Fuji BAS-TR and Fuji BAS-MS type IPs, for photon energies between 0 and 100 keV. The dashed lines show sensitivities as read by a FLA7000 reader and the solid lines show sensitivities as read by a FLA3000 reader. Graph taken from Meadowcroft et al. [80].

Kodak DEF Film Kodak direct exposure film (DEF) is a photographic film which has been widely used for X-ray radiographic imaging. This is due in particular to its sensitivity to photons in the energy band 1-10 keV. The problem with using DEF now is that it has been discontinued and as such, is a rare commodity. It is formed from a $185 \mu\text{m}$ polyester substrate with a $13 \mu\text{m}$ layer of emulsion on either side [84]; the emulsion contains grains of silver bromide which capture X-ray photons and release photo-electrons. These photo-electrons

are simultaneously stored by the grains. Upon exposure to a developer solution, the grains in the emulsion layer become opaque and an image can be viewed [85]. Due to the attenuation of signal by the substrate, the second layer of emulsion will contribute significant optical density at X-ray photon energies of greater than 4 keV [84]. This is demonstrated in Fig. 5.8 as well as the sensitivity of the whole film between 1 and 10 keV. Beyond these bounds, DEF is less sensitive to photons making it particularly useful for imaging the X-pinch soft X-ray source, as discussed in Section 5.2.2, which emits X-rays below 5 keV.

DEF boasts a significantly higher spatial resolution than IP owing to an average grain size of $\sim 2 \mu\text{m}$ [84, 86] compared to the $\sim 50 \mu\text{m}$ per pixel measured in this experiment for IP. However, DEF is not as sensitive as IP at energies above 10 keV and the lower spatial capability of IP can be overcome by increasing the magnification of an imaging system, for example. DEF is also not reusable and the development process must be repeated exactly in each shot in order to quantitatively compare separate films. Taking the factors listed in this section into account, IP was chosen as the standard X-ray detector for this project, with DEF used for “targeted” shots to harness its 1-10 keV sensitivity.

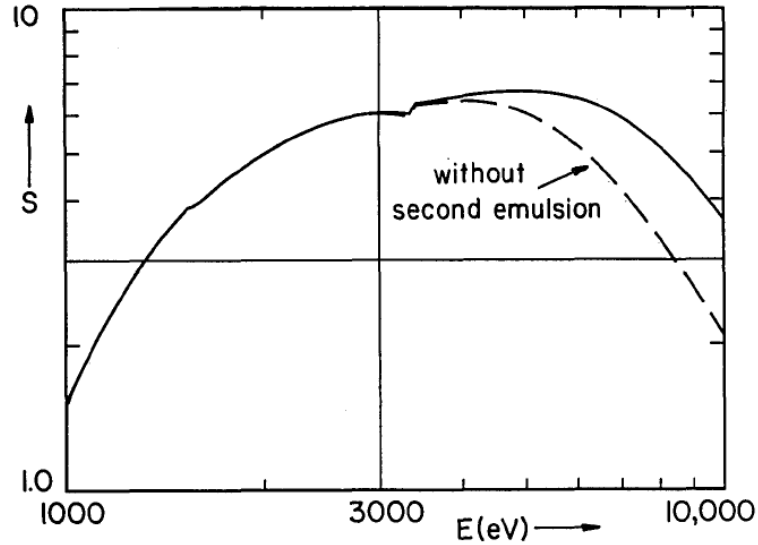


Figure 5.8: Plot showing the sensitivity of Kodak DEF to photons between 1 and 10 keV, measured by Henke et al. [84]. Also shown is the sensitivity of DEF with the second emulsion removed which shows a reduction in sensitivity for photons above ~ 4 keV.

5.4 X-ray Source Size Measurement on Cerberus

5.4.1 Development of X-ray Source Size Diagnostic on Cerberus

X-ray source size measurement on Cerberus was conducted using the “knife”-edge method as described in Section 5.3.1. Due to spatial limitations from other diagnostics in the chamber, the source size line-of-sight of target normal was elevated vertically and horizontally above the mid-plane of the target chamber by 45 ± 1 degrees and 55 ± 3 degrees respectively. The difficulty in measuring the horizontal elevation is represented in the larger error. Fuji BAS-MS image plate (IP), see Section 5.3.3, was used as the detector and was initially situated in a KF50 extension pipe protruding from the target chamber, to extend the source-detector distance to allow for higher magnification. The image plate was positioned 74.2 ± 0.5 cm from target chamber centre (TCC) to maximise potential system magnification. To achieve reliable image plate positioning on shots, a 3D printed mount with magnetic fixtures to hold it to a KF50 termination flange was created, see Fig. 5.9. Initially a steel razor blade was used as the edge. This was mounted statically with optics posts but due to difficulty in alignment a translation stage was introduced after a few unsuccessful shots. The next consideration was that the thin steel edge would transmit some radiation leading to a larger error in source size measurement due to transmission, see R_{pen} in Section 5.3.2. As such, this was replaced by a higher Z material, a few mm thick tantalum foil with a slightly curved or rolled edge. As well as the higher Z of tantalum increasing X-ray absorption, the rolled-edge gives a cross-sectional profile which increases in thickness more rapidly than for a knife-edge. The tantalum edge was placed 14.4 cm from the source giving a magnification ~ 4.2 and oriented to measure vertical source size. This arrangement is shown in Fig. 5.10.

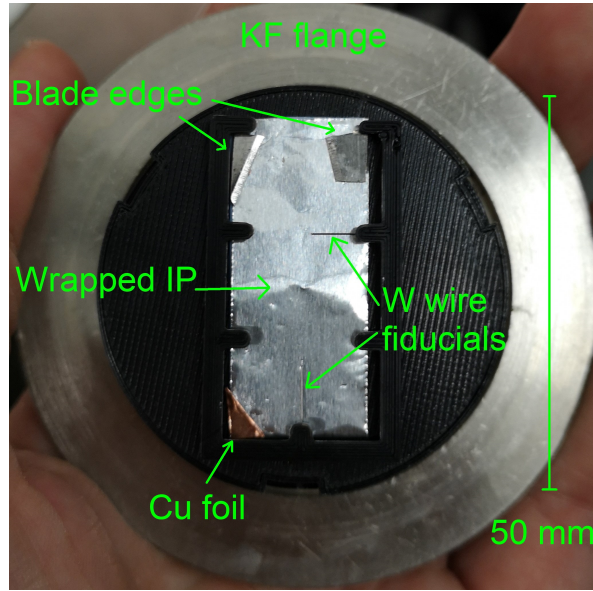


Figure 5.9: Photo of the first IP mount for Cerberus X-ray source size measurement. The black plastic mount was used to hold IP (wrapped in $15\ \mu\text{m}$ thick Al foil) and magnetically attached to a KF50 termination flange. The $200\ \mu\text{m}$ tungsten wire fiducials are a permanent fixture on the mount, allowing for comparison of film position and image features between shots. There are a number of blade edges attached to the Al foil which were present on the shot after this picture was taken. The fiducials and blades were used for measuring the detector spatial resolution.

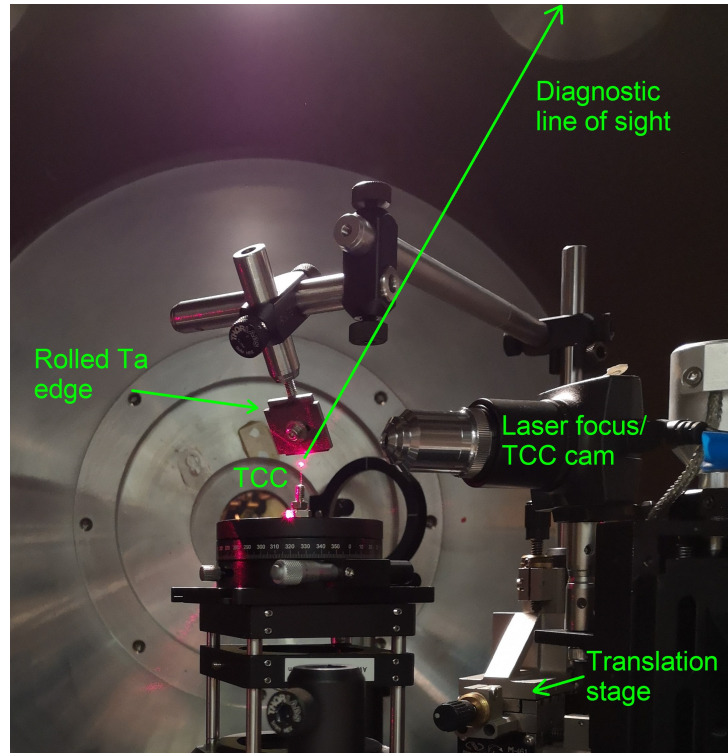


Figure 5.10: Photo showing an early iteration of the Cerberus X-ray source size diagnostic layout. Situated at TCC is a wire illuminated by a red laser beam used for aligning the diagnostic. The edge used here is a rolled-edge tantalum foil, held in position with optics posts and aligned using a translation stage which is partly obscured by the TCC camera used for viewing the Cerberus short pulse at focus (not pertinent to this diagnostic). Just out of shot is the extension pipe in which the IP detector is located but the line of sight is detailed.

An example penumbra taken with this arrangement is presented in Fig. 5.11a. This shot used the Cerberus main beam ($E \sim 1.2$ J, $I \sim 8 \times 10^{17}$ Wcm $^{-2}$) focused onto a 15 μm Al foil. Note that the IP was wrapped with the 15 μm foil for protection from visible light, low energy particles and target debris. A lineout was taken over the penumbra, shown by the black box, producing the plot in Fig. 5.11b. The width of this lineout and lineouts from all other similar shots were generally made as large as possible in order to average out effects from scratched regions of IP, for example, whilst still avoiding fiducials and IP edges. Measuring the width of the transition in this lineout, R_{SS} , gives the source size S according to $R_{SS} = M \times S$ where M is the magnification, see Section 5.3 for the theory. As such, R_{SS} was found by first estimating the maximum and minimum PSL values either side of the penumbra. Then finding the width of the transition in pixels between 10 and 90 percent of the difference between these PSL levels. This process is illustrated by the black annotations on Fig. 5.11b. To convert from pixels to actual distance it was necessary to find a calibration of $\mu\text{m}/\text{pixel}$. This was done by placing objects of known size upon the IP and taking 1:1 magnification images. This is shown by the fiducials and blades on Fig. 5.9 as well as the fiducial shadow on Fig. 5.11a. This also doubles as a measure of the finite detector resolution R_{det} . The calibration was found to be 50 $\mu\text{m}/\text{pixel}$, in line with the expected pixel size from the image plate reader. Converting R_{SS} to a distance in μm , dividing by M and compensating for elevation yielded a vertical source size of 372 ± 120 μm . The main source of error here arose from the difficulty in measuring the penumbra width. This source size is much larger than should be expected from a laser focus of ~ 10 μm .

A further error source worth mentioning here arises from the rotation of the IP/penumbra prior to measuring the penumbra width. Effort was made to align the knife-edge and image plate in the chamber such that the IP could be scanned with the penumbra aligned parallel to the pixels in the scan. Despite this, scans from shots such as the one shown in Fig. 5.11a typically had to be rotated 1-2 degrees in order to take a lineout over the edge (having the penumbra orthogonal to the lineout direction is a requirement of the analysis software, ImageJ). Since the pixels are square, this rotation will introduce an error in the measurement of the pixel width of a penumbra. Due to the small rotation, this error source was estimated to be less significant than the error in penumbra width caused by factors which are discussed in the following paragraph.

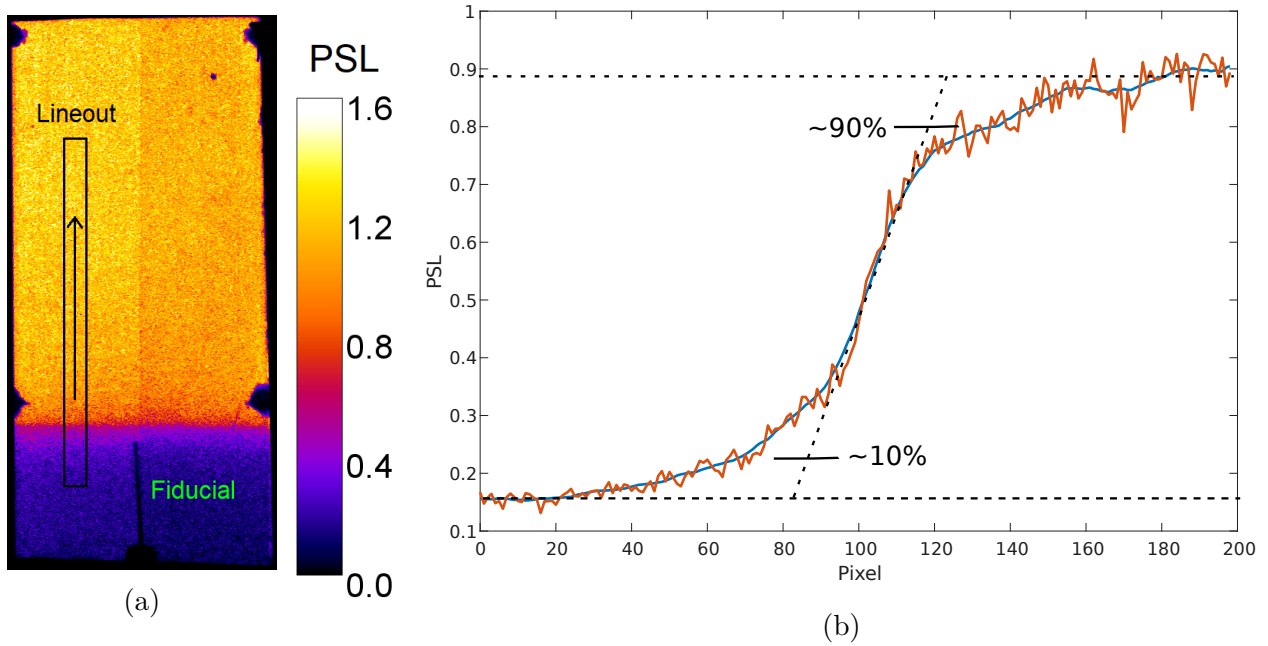


Figure 5.11: Image plate scan showing a penumbral shadow cast by a tantalum edge after a Cerberus shot upon $15\ \mu\text{m}$ Al (a). The shadow from a $200\ \mu\text{m}$ tungsten wire fiducial can also be seen. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows the real data (red line) along with a smoothed profile (blue line) which assisted in measuring the transition width. The black annotations are purely for illustrating the process of measuring the transition and not fully accurate. The real width was estimated to be 21.9 ± 7 pixels, yielding a source of $372 \pm 120\ \mu\text{m}$. The errors were large due to difficulty in determining the pixel width.

Some thought was put into the diagnostic to deduce the reason for the apparent large source size compared to the drive laser focal spot. It was realised that the production of charged particles (CPs) had been overlooked in the first iteration of the diagnostic and so the logical step was to employ static magnets to deflect ions and electrons ahead of the IP. A pair of strong neodymium ring magnets were mounted inside the chamber, producing a field between the two of $\sim 45\ \text{mT}$. Despite the addition of a translation stage to align the tantalum edge, achieving satisfactory alignment was still awkward due to the degrees of freedom of the square edge, positioned at such horizontal and vertical elevation. This motivated the development of a novel technique for penumbral imaging — using a ball-bearing. Due to being spherical, the ball-bearing is much simpler to align as tilting does not matter. This had the added bonus of avoiding some of the error in pixel measurement caused by needing to rotate an IP scan as discussed in the previous paragraph. The material chosen for the ball-bearings was tungsten carbide. For reference, the characteristics of these ball-bearings are discussed below, in Section 5.4.2.

Returning to the source size diagnostic, we now have the addition of magnets for CP deflection and a new “knife”-edge in the form a tungsten carbide ball-bearing (WCBB). The WCBB was oriented vertically to, and placed 4.6 cm from the source, giving a larger magnification of 14.8. An image of this layout is shown in Fig. 5.12. An example penumbral shadow image taken with this arrangement is shown in Fig. 5.13a. This shot was the Cerberus short pulse ($E \sim 1.6$ J, $I \sim 4.7 \times 10^{17}$ Wcm $^{-2}$) on a $5\mu\text{m}$ diameter carbon fibre. As before, a lineout was taken from the IP scan, see Fig. 5.13b. Note here the smaller PSL by a factor of 1000 compared with Fig. 5.11b. This is due to a lower X-ray flux from carbon fibre compared to aluminium foil and the reduction in signal from the removal of CPs. Following the same process as before, a vertical source size was measured from Fig. 5.13b and found to be $76 \pm 14 \mu\text{m}$. This is still relatively large compared to an expected source size of order the laser focus but a significant improvement on the previous result. The larger source is likely influenced by the difficulty in measuring the width of the penumbra due to low flux and resultant effect of noise, and the potential for hot electron transport along the length of the fibre.

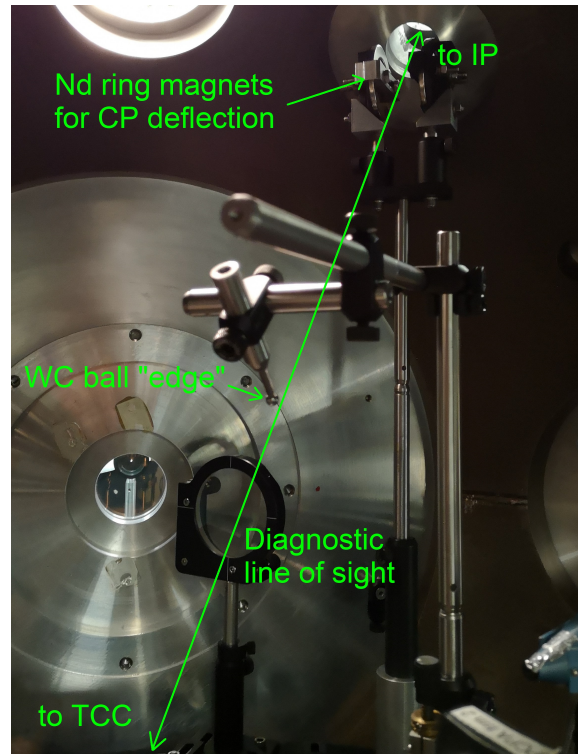


Figure 5.12: Photo showing first major developments on the Cerberus X-ray source size diagnostic layout. In place of a tantalum rolled-edge is now a tungsten carbide ball-bearing. In addition magnets have been added to deflect charged particles. TCC is just out of shot in this picture however the entrance to the KF50 pipe containing the IP is visible at the top.

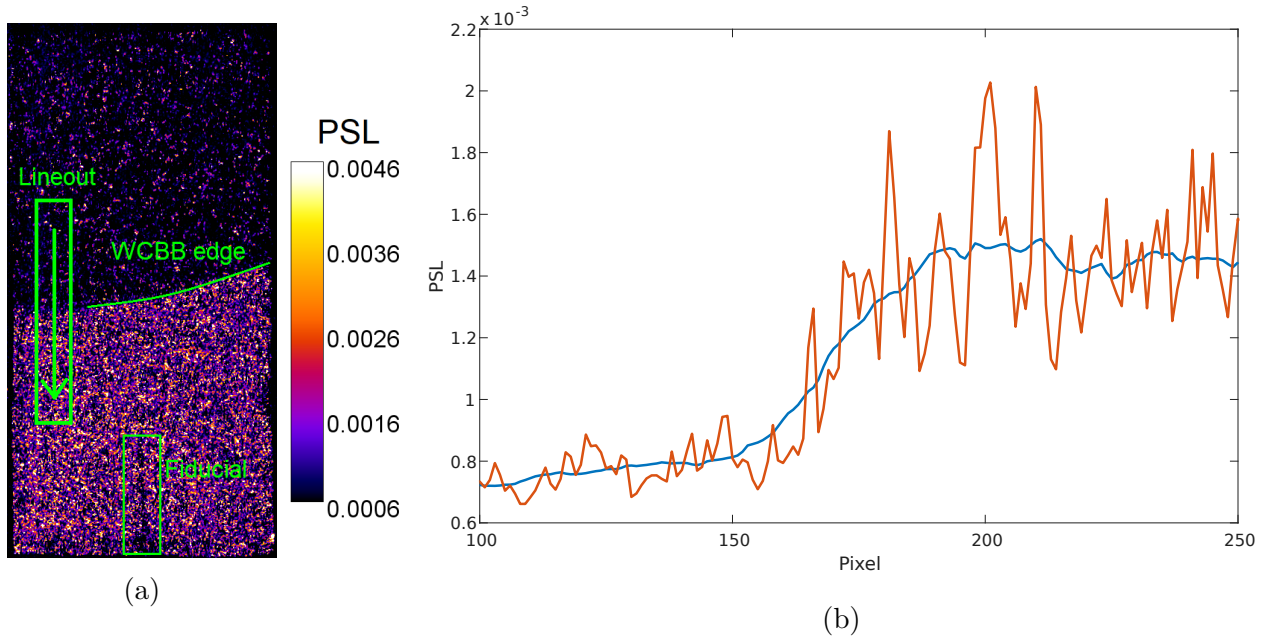


Figure 5.13: Image plate scan showing a penumbral shadow cast by a tungsten carbide ball-bearing after a Cerberus shot on a $5\text{ }\mu\text{m}$ carbon fibre (a). The shadow from a $200\text{ }\mu\text{m}$ tungsten wire fiducial can also be seen. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows the real data (red line) along with a smoothed profile (blue line) which assisted in measuring the transition width. The penumbra width was estimated to be 16 ± 3 pixels, yielding a source of $76\pm 14\text{ }\mu\text{m}$. Note that the low PSL and large relative noise made measurement of the pixel width difficult which is reflected in the error.

After several more shots, it became clear there was a need to increase the flux onto the IP. Low flux became a problem on shots where the relative sizes of the penumbral transition and noise on the IP were similar. Making source size measurement difficult and increasing errors. The simplest solution to this was to bring the detector closer to the source due to the inverse square law. Closer to the source, a detector will however, be more susceptible to secondary sources of contamination such as stray CPs and X-rays produced by high energy CP collisions elsewhere in the chamber. Therefore, it was necessary to implement a more sophisticated mount for the IP. Fig. 5.14a and Fig. 5.14b respectively show a photo and cross-sectional schematic of the improved IP mount. The holder was designed with the objective of enclosing the IP in as much lead as possible. A sturdy base for the mount was formed by taking four optic post holders and screwing them to a 21.5 cm diameter target chamber flange, see Fig. 5.14a, which replaced the previous flange with the KF pipe extension. Four optics posts were fixed into these holders and two 3D printed plastic plates were fixed to the posts, separated by about 5 cm . Crucially these plates had a hole in their centres which fit a fifth optic post. A 3 mm thick lead cage was wrapped around, and glued to, these plastic plates. An additional layer of Mylar was placed within the lead cage in order to absorb scattered low energy X-rays. The

lead cage extended beyond the top plate by several cm. A third 3D printed plate was produced to be the IP mount. This had another 3 mm layer of lead upon the plastic and incorporated small magnets on top of the lead which were used to hold the IP in place by virtue of the magnetic strip on the rear of an IP. This mount was bolted to a fifth post which could slide freely through the first two plates. To prevent the mount falling out a collar was attached to the other end of the post once fully inserted. This mount was designed to be retractable for ease of loading IP and then pulling the mount back to be seated within the lead cage providing good protection from CPs and scattered X-rays. For shots, the mount was held in place in its retracted state using more magnets attached to the mount and upper fixed plate.

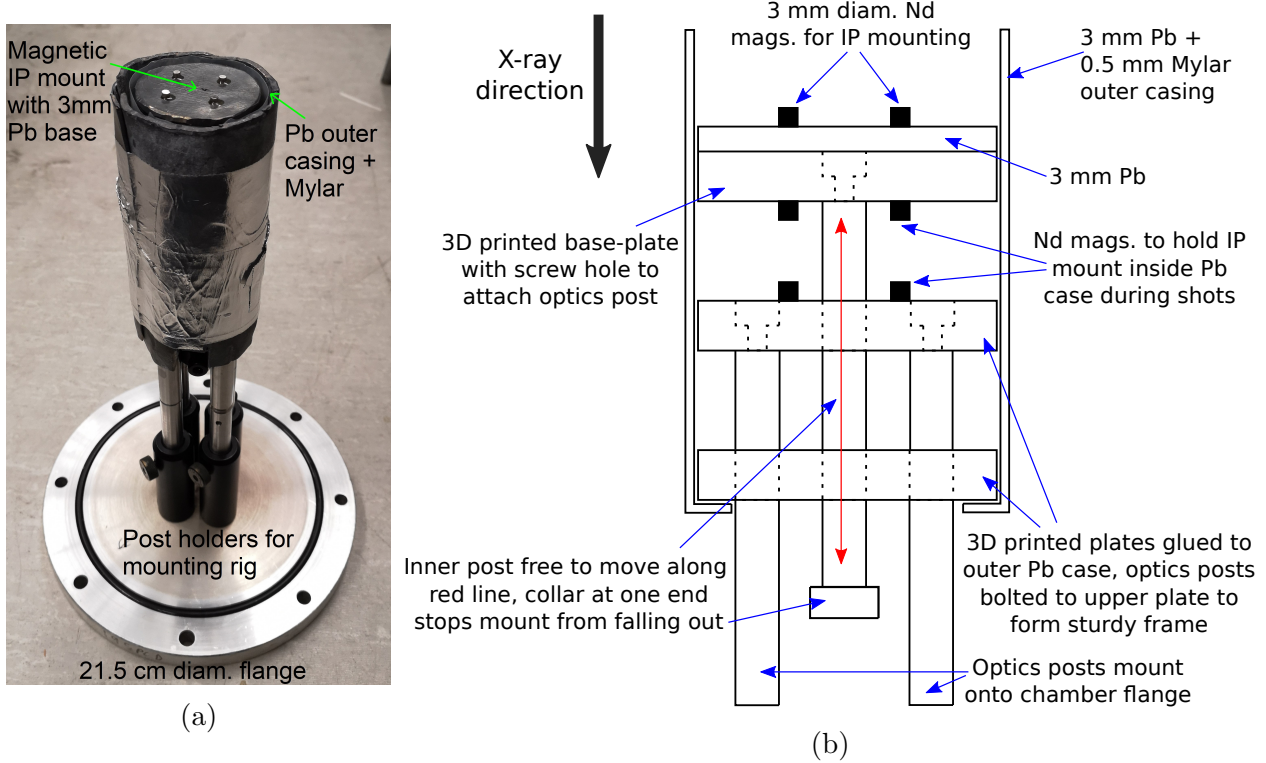


Figure 5.14: Photo (a) and cross-sectional schematic (b) for an improved IP holder which added additional high-Z shielding to reduce noise, and was implemented within the Cerberus target chamber. The mounting point was designed using magnets to be retractable in order to provide ease of loading, reliable IP positioning and good shielding from stray CPs and scattered X-rays.

The decrease in source-detector distance would not only increase X-ray flux incident on the IP but also undesired CP flux. As such, improvements to the CP deflection magnets were implemented by using two pairs of neodymium plate magnets ahead of the IP. Providing a larger area for deflection along the diagnostic line of sight, by a factor >2 over the previous magnets. In addition to this, a second WCBB was introduced, oriented orthogonally to the first, for measuring horizontal source sizes. Larger area, circular IP was used which made

imaging the shadows slightly easier. These changes are all shown in Fig. 5.15. The source-detector distance was decreased by a factor ~ 2 to 32.6 cm, notionally increasing flux by factor 4. The vertically-aligned WCBB was placed 1.4 cm from TCC, giving a magnification of 23.3 and the horizontally-aligned WCBB was placed 0.6 cm from TCC, giving a magnification of 55.7. An example IP scan from a shot taken with this arrangement is shown in Fig. 5.16a. The shot used the Cerberus short pulse focused onto $15\text{ }\mu\text{m}$ aluminium ($E \sim 3.85\text{ J}$, $I \sim 1 \times 10^{19}\text{ Wcm}^{-2}$). A number of interesting features are present on Fig. 5.16a, firstly the penumbral shadows cast by the two orthogonal ball-bearings are clearly visible, a shadow from the edge of the CP deflection magnets is also visible. Two smear-like features are present on the IP which were deduced to be from CPs by repeating the shot with no magnets. Clearly it is challenging to fully mitigate the charged particle noise background, but the data here was still analysable regardless of the streaks as they were far enough away from the WCBB edges. Both horizontal and vertical lineouts were taken to measure each corresponding source size. The lineout shown in Fig. 5.16b is from the vertical WCBB and shows a higher PSL and a smoother trace free of the noise issues seen in the previous lineout, as desired. Following the same process as before, the vertical and horizontal source sizes were found to be $34.9 \pm 4.8\text{ }\mu\text{m}$ and $39.8 \pm 5.5\text{ }\mu\text{m}$ respectively. A realistic value for the source size.

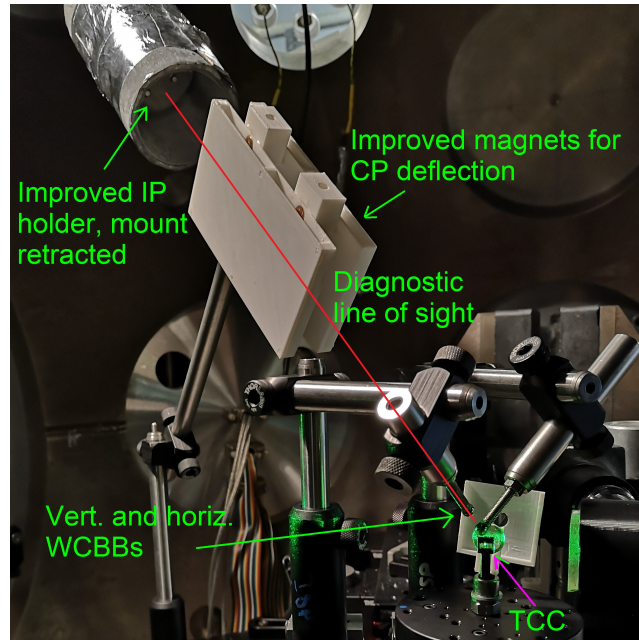


Figure 5.15: Photo showing the final refinements of the Cerberus X-ray source size diagnostic layout. The main difference being the new IP mount which brought the IP closer to TCC by a factor ~ 2 to improve X-ray flux. A second tungsten carbide ball-bearing was added to allow simultaneous vertical and horizontal source size measurement. The CP deflection magnets were improved by adding more pairs along the diagnostic line of sight. Note that the IP mount in its retracted state is visible here.

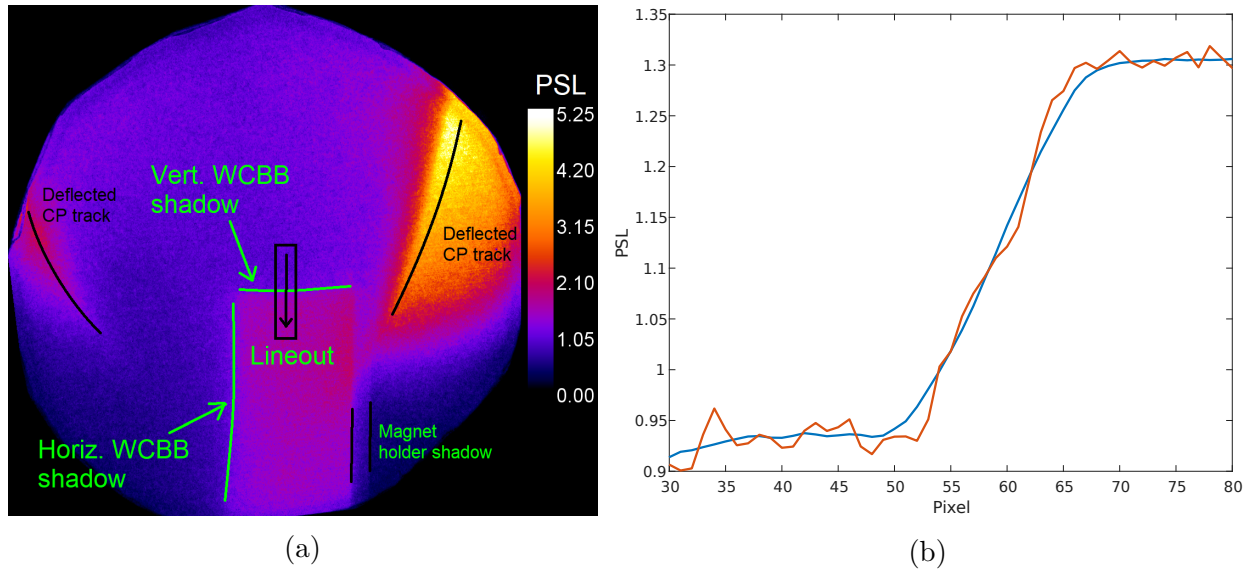


Figure 5.16: Image plate scan showing the penumbral shadows cast by two, orthogonally oriented tungsten carbide ball-bearing after a Cerberus shot upon $15\text{ }\mu\text{m}$ thick aluminium (a). Streaks can be seen upon the IP caused by deflected CPs. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows the real data (red line) along with a smoothed profile (blue line) which assisted in measuring the transition width. The penumbra width in (b) was estimated to be 11.5 ± 1.5 pixels, yielding a measured source size of $34.9 \pm 4.8\text{ }\mu\text{m}$.

Beyond this point, the Cerberus X-ray source size diagnostic did not undergo any more major changes, apart from minor tweaks to magnification. The full results and discussion of source size measurements from this diagnostic are covered in the next section.

5.4.2 Tungsten Carbide Ball-Bearing Characteristics

The ball-bearings used in these experiments are 5 mm diameter, grade 10, tungsten carbide ball-bearings (WCBB). A photo is shown in Fig. 5.17. Grade 10 denotes that the maximum surface roughness of the ball is $0.025\text{ }\mu\text{m}$ or the average deviation of the surface profile from the nominal diameter of 5 mm is $0.025\text{ }\mu\text{m}$. The smaller the grade, the smoother the ball-bearing. As such these balls have very few surface defects and their high degree of smoothness make them excellent edges for penumbral imaging. One advantage over the razor edge is that these balls are much harder than steel blades and hence are less susceptible to damage to the surface smoothness.

As with the rolled-edge, the line-integrated cross-sectional thickness increases far more rapidly than for a razor blade which combines with the attenuating power of tungsten carbide compared to steel or iron, minimising errors in source size measurement due to X-ray transmission. Fig. 5.18 shows the transmission of X-rays of varying energy for 15 μm thick iron versus 15 μm thick tungsten carbide alongside 15 μm thick aluminium which is present as a protective IP cover on all Cerberus shots. The data for these transmission curves is provided by the CXRO database.



Figure 5.17: Photo of the 5 mm diameter, grade 10, tungsten carbide ball-bearings used as a novel “knife”-edge for penumbral imaging in this project.

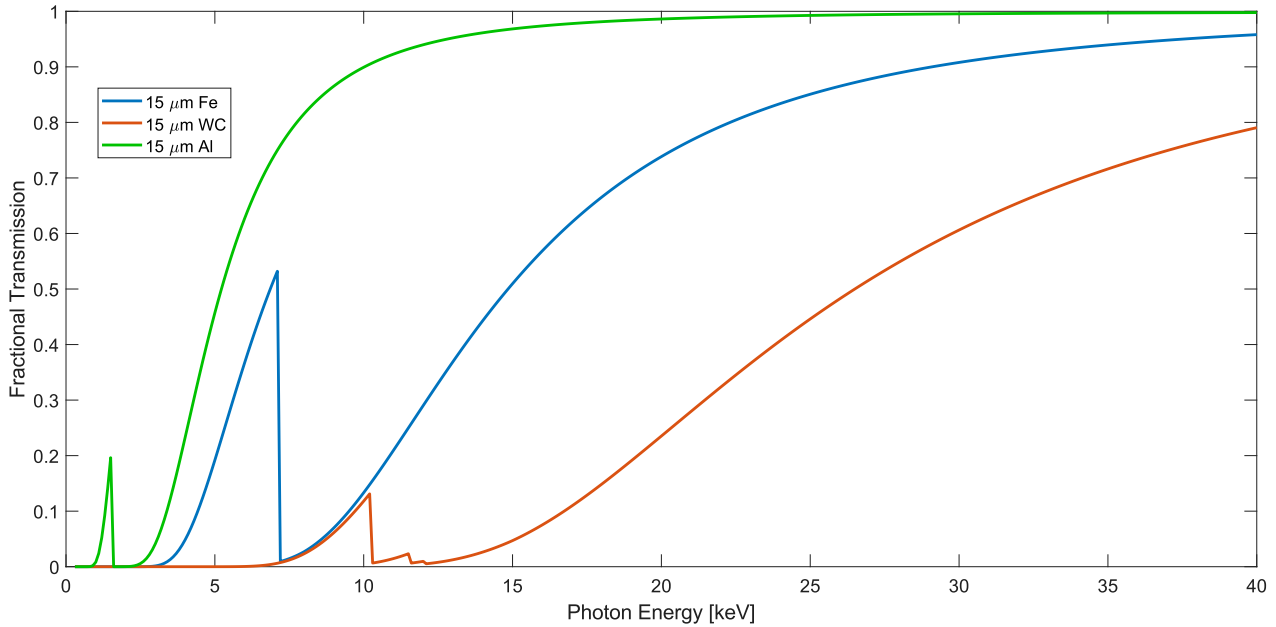


Figure 5.18: Plot showing the calculated transmission of X-ray energies between 0 and 40 keV through 15 μm thick tungsten carbide, 15 μm thick iron and 15 μm thick aluminium. The aluminium attenuation provides context for filtration present on all shots.

5.4.3 Results and Discussion

For X-ray source size measurements on Cerberus there were a total of four different targets used. These were two foils, aluminium of thickness $5\text{ }\mu\text{m}$ and $15\text{ }\mu\text{m}$, and two “wire” targets, $5\text{ }\mu\text{m}$ diameter carbon fibre and $200\text{ }\mu\text{m}$ diameter tungsten wire. The results provided here were taken using the source size measurement rig as shown in Fig. 5.15, after it had been optimised for incident flux and charge particle deflection. We shall now deal with the wire and foil shots separately.

Foil Targets

These shots formed the bulk of the results in this section. Generally, relative to the size of laser focal spot, the foils used here can be considered as semi-infinite slabs of aluminium. As such, the difference between results would be expected to be due to a factor 3 difference in target thickness. The thicker foil should provide more material for the electron beam in which to diverge. Recall that the production of the electron beam and its role in the generation of X-rays is outlined in Section 5.2.1. We expect there to be a small difference between measurements of vertical and horizontal source size for a circular laser focal spot on an extended foil target. The exact difference between the vertical and horizontal sizes should be due to the angle of incidence of the laser upon the foil. The laser is incident at an angle of 15 degrees to target normal, hence we would expect the horizontal X-ray source size to be $\sim 97\%$ of the size of the vertical X-ray source size. Another variable was also introduced into the experiment through inclusion of a tailored prepulse, timed to be incident on target 50 ps ahead of the main pulse.

Firstly, we shall consider the effect on source size from varying target thickness. Fig. 5.19 shows these results. For each shot, there was generally a separate measurement for the vertical and horizontal source size unless one axis had become misaligned. One shot in the $5\text{ }\mu\text{m}$ foil data yielded only a horizontal source size measurement due to misalignment of the vertical axis. This is shown by a single point labelled “H”. In many cases, the horizontal and vertical measurements were close (within $2\text{--}3\text{ }\mu\text{m}$ of each other) or the error bars on each measurement were greater than the difference between them. Under these circumstances, the two values were averaged and are shown by points labelled “ave” on Fig. 5.19. For shots where the vertical and horizontal source sizes were different, the measurements were left separate. There are five such occurrences in the $15\text{ }\mu\text{m}$ data in Fig. 5.19 which are identifiable by two points labelled “V” and “H” and with identical intensity since they came from the same shot. In all of these it is noteworthy that the vertical source size was always larger than the horizontal but the

discrepancy exceeds the expected difference due to the angle of incidence of the laser. This could be a systematic error from measurement, however the variation between vertical and horizontal source is not comparable for each shot. It is possible that a smaller than expected horizontal source size could be achieved if the laser is incident upon the side edge of a target. This was sometimes done as the edge provided a clear point to focus to for the purpose of getting the target reliably to TCC. Unfortunately, the realisation that this technique would potentially cause a difference in source size only came during the analysis of these shots and it was erroneously not noted when the edge of a foil was shot.

Overall, a relationship between laser intensity and source size can not be constrained due to the large errors present on each data point and the large variation in source size over a relatively small intensity range (less than one order of magnitude). It is also not possible to see a trend in the $5\text{ }\mu\text{m}$ data due to limited statistics. The data that is present does however indicate a smaller source size for the thinner foil as expected, but not by a factor three. To improve this data set it is clear that more measurements of $5\text{ }\mu\text{m}$ foil shots need to be conducted. There would also be a benefit from conducting the experiment over a larger intensity range for both foils.

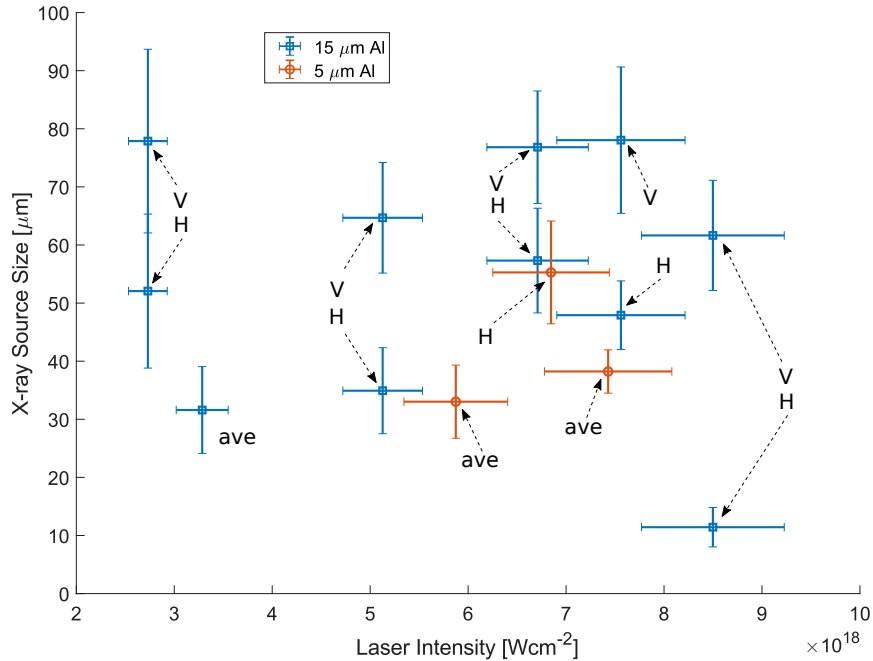


Figure 5.19: Graph showing the results of X-ray source size measurements for the Cerberus laser pulse onto $15\text{ }\mu\text{m}$ (blue points), and $5\text{ }\mu\text{m}$ (red points) thick aluminium.

For the addition of a prepulse, the data for $15\text{ }\mu\text{m}$ aluminium and $5\text{ }\mu\text{m}$ aluminium will be handled separately. For clarity, the prepulse capability for Cerberus described here was produced as a part of the PhD project of Samuel Eardley [54] and used as an interesting

secondary variable to supplement the results in this project. For each prepulse shot, the energy of the prepulse was determined by comparing the peak brightness of the main beam focal spot and the prepulse beam focal spot, which were separately isolated, using the focal spot camera. This was conducted at low power and made use of ND filters to prevent damage to the focal spot camera. With this method, the prepulse was selected to be 5 orders of magnitude lower in intensity than the main beam (chosen such that it would be a factor 10 more intense than the laser pulse pedestal). The results for 15 μm aluminium with and without prepulse are shown in Fig. 5.20. All points have been labelled “V”, “H” or “ave” to denote a vertical, horizontal or averaged source size respectively. From this, we can see that the presence of a prepulse seems to result in a smaller source size, at least over the intensity range presented in these results. This effect agrees with the results and explanation given by Eardley [54]. In their results they suggest that the prepulse is sufficient to produce a preplasma which causes a self-focusing effect on the main laser pulse, effectively reducing the size of the electron beam which directly influences the X-ray source size.

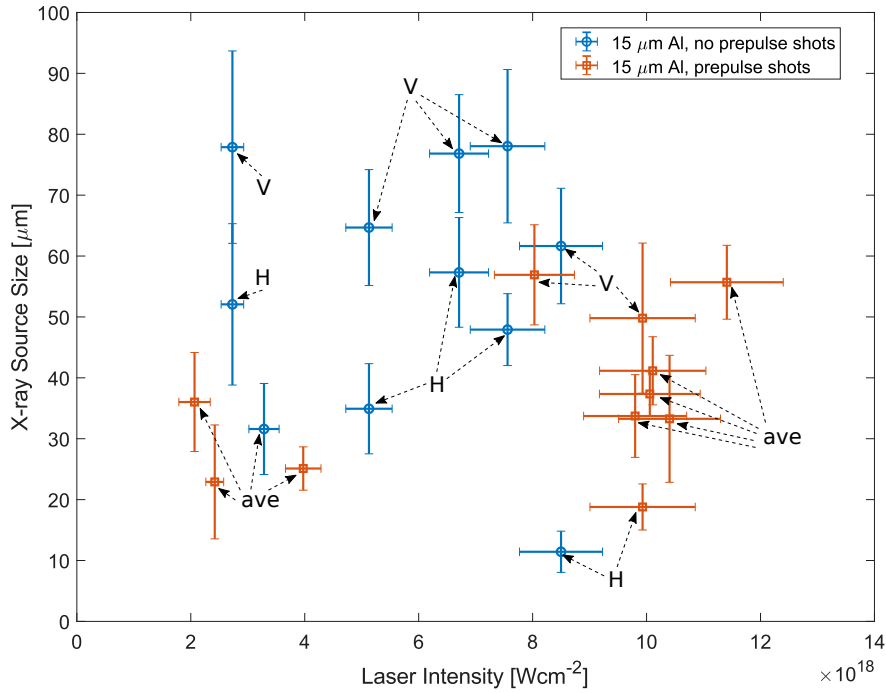


Figure 5.20: Graph showing the results of X-ray source size measurements for the Cerberus laser pulse onto 15 μm thick aluminium, without a prepulse (blue points) and with a prepulse (redpoints). The prepulse was less intense than the main beam by a factor 10^5 and arrived 50 ps before the main beam.

The final set of foil shots were the prepulse shots upon 5 μm aluminium. Much like the 5 μm aluminium shots without prepulse, there were only a few results over a small intensity range, hence it is not possible to draw a definite relation between laser intensity and source size.

Despite this, the results are presented visually in Fig. 5.21. All points have been labelled “V”, “H” or “ave” to denote a vertical, horizontal or averaged source size respectively. In addition to the 50 ps early prepulse shots, there was also one interesting shot upon 5 μm which used the same intensity prepulse but with an arrival time 2 ns before the main beam. In theory the long time difference should allow the formation of a preplasma which can expand from the surface of the target and cool. This should cause the main beam to form a larger focal spot upon the blown-off material which extends back down the laser propagation direction. Overall we would expect this to result in a larger X-ray source size. The result of this shot showed a vertical source size of $99.7 \pm 5.3 \mu\text{m}$ and a horizontal source size of $51.0 \pm 7.6 \mu\text{m}$. The vertical size is larger than any other measurement shown in Fig. 5.21 by a factor ~ 2 while the horizontal size is on par with the largest measurements shown in Fig. 5.21.

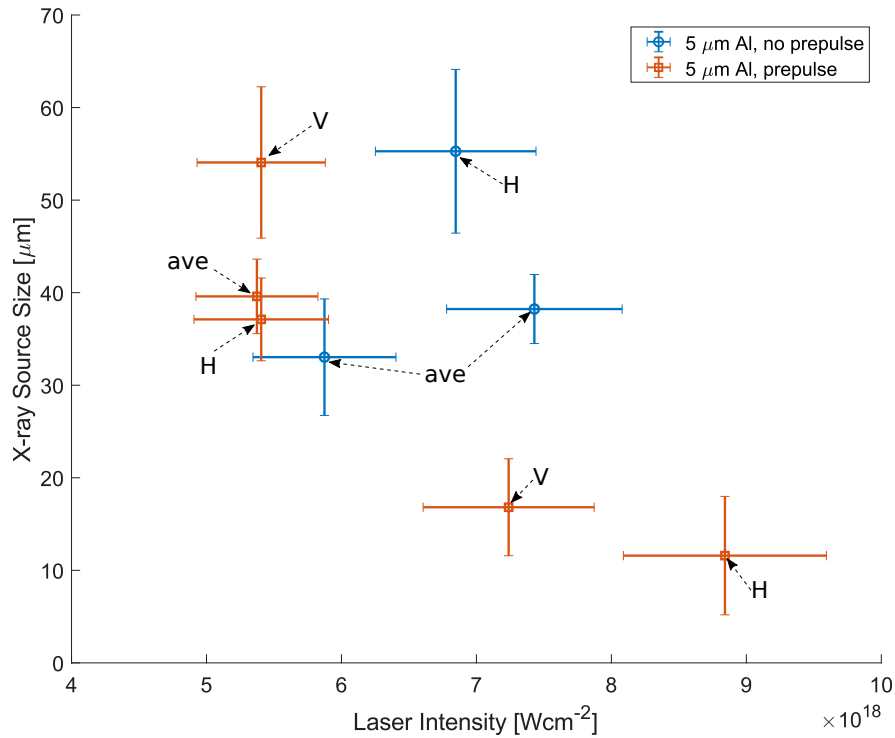


Figure 5.21: Graph showing the results of X-ray source size measurements for the Cerberus laser pulse focused onto 5 μm thick aluminium, without a prepulse (blue points) and with a prepulse (red points). The prepulse was less intense than the main beam by a factor 10^5 and arrived 50 ps before the main beam.

Wire Shots

As was mentioned before, there were two wire shaped targets shot upon using the Cerberus main beam. These were 5 μm diameter carbon fibre and a much larger 200 μm diameter tungsten wire. The carbon fibre was chosen as it should exhibit a difference between vertical and horizontal source size. The tungsten wire is significantly larger so it was expected not to

show a strong horizontal and vertical difference. Since there were only a few shots taken with these targets the results are presented in a table as opposed to graphically, a shot with and without prepulse for each target is shown in Table 5.1. The prepulse arrived 50 ps before the main beam and was 10^5 times less intense than the main beam in both shots.

We first consider the tungsten wire shots. For the prepulse and no-prepulse shot the vertical and horizontal source sizes are similar as we would expect. For the no-prepulse shot, the source is large compared with other result we have seen previously. This is not unreasonable however, as the wire is much thicker than any foil meaning that the electron beam can diverge a significantly larger amount than for a $15\text{ }\mu\text{m}$ foil for example. The prepulse shot on tungsten shows a much smaller source than the shot with no prepulse. This is in line with the effect seen on $15\text{ }\mu\text{m}$ foil shots but a lot stronger. It could be that the preplasma self-focusing influenced the result. Another, possibly more likely, reason for the large difference in size could be that the laser was incident upon the wire at different points on the circumference of the wire. In the case of foils, the angle of incidence of the laser is optimised for coupling the laser energy into the target. As described in Section 5.2.1, the transfer of energy from the laser into the hot electron beam in the target is essentially controlled by the component of the laser electric field normal to the surface of the target (technically the electron density gradient). Dependent on where the laser is incident upon the circumference of the wire, the energy coupling will change considerably. In which case one may expect the source size to be influenced. With only two results it is only possible to speculate on the reason for the difference in source size. In order to test the theory, more shots would need to be carried out where different points on the circumference of the wire are targeted.

Finally, we will discuss the carbon fibre shots. The carbon fibre is unique amongst the targets considered here since its diameter is smaller than the size of the laser focal spot in one direction which was typically $7\text{ }\mu\text{m}$ at optimum. As such, hitting it was not as easy as the other targets. The results show a smaller size for the prepulse shot as with other targets and importantly there is a clear difference between vertical and horizontal source sizes as was expected. The main problem with analysing the data for this shot was due to the low X-ray flux which combined with the naturally small source size/penumbra width to cause relatively much larger errors than for other source size measurements. The horizontal source sizes are actually so small that they should be considered somewhat cautiously as they are at the edge of the capability of the source size diagnostic. This means that errors from sources such as detector resolution and diffraction are considerable. This will be addressed in the next section

along with other error sources. Since the fibre is smaller than the laser focus it is basically certain that the laser only partially hit the fibre. A slight fluctuation in the position of either on-shot would lead to a glancing hit and lower laser absorption which could also explain a sub-5 μm horizontal source size.

Target	Prepulse?	Intensity [Wcm ⁻²]	Vert. Source Size [μm]	Horiz. Source Size [μm]
W wire	N	5.96×10^{18}	151 ± 13	123 ± 17
W wire	Y	6.22×10^{18}	32.6 ± 5.4	30.4 ± 4.6
C fibre	N	7.35×10^{18}	13.5 ± 5.2	2.2 ± 1.4
C fibre	Y	7.81×10^{18}	8.8 ± 3.9	1.35 ± 1.35

Table 5.1: Table showing the vertical and horizontal X-ray source size measurements from Cerberus main beam shots upon 5 μm diameter carbon fibre and 200 μm diameter tungsten wire. Two shots are presented for each target, one utilising a prepulse and one without.

Error Analysis

The largest sources of error for the measurement of source sizes arose from the physical orientation of the diagnostic. The awkward angle at which the diagnostic line of sight was elevated and its location within the target chamber meant measurement of the distances from TCC of the ball-bearings and image plate (and hence absolute magnification of the system) and the elevation angles had large errors. These are systematic errors which would be common to every measurement. A further source of error was in the measurement of the width of the penumbra from the image plate data. This was evaluated for each individual measurement of source size by imposing lines of “worst-fit” over the penumbra transition on a lineout and assessing the difference in penumbra width. This error was different for every case and was a bigger factor for low flux shots which were more susceptible to shot noise. Another factor contributing to the error in measuring penumbra width was a limitation of the ball-bearings. Due to their curvature, a lineout taken from an image plate scan had to be relatively narrow to avoid incorporating the difference in adjacent pixels caused by said curvature. As a result, a random pixel fluctuation on the image plate scan could have a larger influence on a lineout which would otherwise have been averaged out over a wider lineout. Overall, these error sources were quantified and propagated through for each source size measurement and form the errors presented in this results section.

As was mentioned in Section 5.3.2, there are a number of error sources which arise from finite detector resolution, diffraction and transmission through the ball-bearings. Generally, for this experiment these error sources are always negligible when compared to errors arising from measurements as described above. In the case of X-ray source sizes less than $5\mu\text{m}$ however, they can no longer be ignored. The magnitude of these error sources is dependent on the limiting aperture of the system (the source size itself in this case), the positioning of the ball-bearings and detector, and the energy of X-ray radiation present. For completeness, we shall consider the error sources for the diagnostic layout in which the results presented here were taken. Using the theory outlined in Section 5.3.2 a code was written to evaluate the sum of all these contributions over a range of energies for a particular positioning of ball and detector and source size.

Fig. 5.22a and Fig. 5.22b respectively show these total error contributions evaluated for the vertical and horizontal arms of the diagnostic, as seen in Fig. 5.15. The graphs show the size of the “fake” source which would be inferred by the blurring on an image plate due to these error sources, essentially giving the minimum source size measurable by that set-up. The contribution from diffraction is influenced by the source size itself so the graphs show separate lines for different source sizes. The graphs were deliberately cut off below 4 keV which is filtered out by $15\mu\text{m}$ aluminium which was used to protect the image plates. According to work by Eardley [54], the temperature of X-ray emission from a typical Cerberus shot upon aluminium foil was ~ 20 keV so the contribution from higher energy X-rays is likely small but the minimum source size increasing at high energies is controlled by an increase in transmission around the K-edge of tungsten in the balls. The base of the curves at ~ 20 keV is controlled by magnification and an absolute limit imposed by finite detector resolution; the horizontal axis has a lower minimum source size because it has a larger magnification. The increase in minimum source at low energies is caused by the Fraunhofer diffraction limit and becomes more of an issue for smaller sources. This reasoning is why the horizontal measurements of source size for carbon fibre are likely to be unreliable.

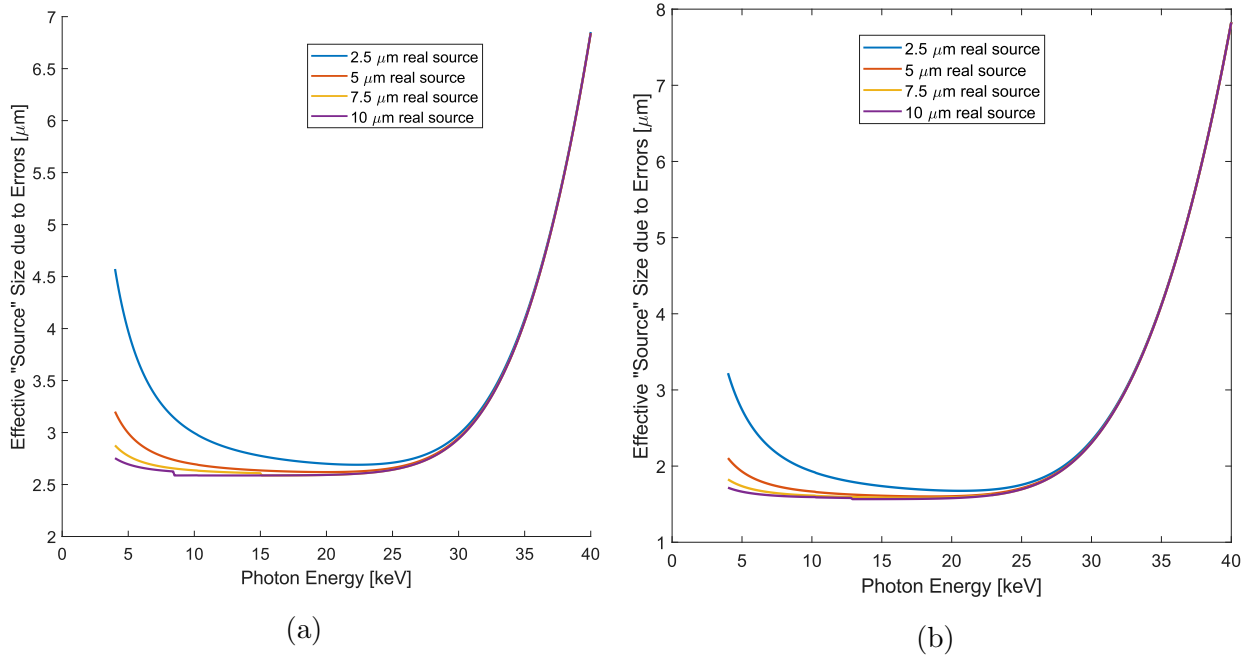


Figure 5.22: Graphs showing the size of an imaginary source created by blurring on an image plate from error sources inherent in the layout of the vertical (a) and horizontal (b) arms of the source size diagnostic shown in Fig. 5.15. These error sources arise from diffraction, transmission through the tungsten carbide balls and absolute spatial resolution of the image plates. They combine to effectively give a limit on the minimum source size measurable by a specific diagnostic layout.

5.5 Application of the X-ray Source Size Diagnostic to X-pinch

5.5.1 X-ray Source Size Measurement on Nene

After some development of the X-ray source size diagnostic on Cerberus, it was decided to apply the use of tungsten carbide ball-bearings (WCBBs) as an edge for penumbral imaging on an X-pinch. As such, a small mounting assembly was produced to hold a horizontally and a vertically aligned ball-bearing, which could fit inside an X-pinch. The first X-pinch this was attempted on was a pulsed-power generator developed at Imperial named “Nene”, see Section 3.2.1 for details on its functionality. An image of the inside of Nene and a close-up of the WCBB mount is shown in Fig. 5.23. In this layout the vertically aligned WCBB was positioned 67 ± 1 mm from the source and the horizontally aligned WCBB was positioned 97 ± 1 mm from the source. The source-detector distance was 213 ± 1 cm giving magnifications of 30.8 and 21.0 for the vertical and horizontal axes respectively.

Data from the first shot is shown in Fig. 5.24, note here that all shots on Nene used $4 \times 5 \mu\text{m}$ tungsten wires as the X-pinch load and a layer of $12.5 \mu\text{m}$ thick titanium foil protecting the IP. As can be seen from the IP data, the horizontal WCBB was mostly obscured, preventing a horizontal measurement of source size. A lineout was taken over the vertical WCBB which yielded a value of $11.4 \pm 2.4 \mu\text{m}$ for vertical source size. This value is slightly larger than expected for the soft X-ray source but smaller than expected for the hard X-ray source, see Section 5.2.2. It was not immediately clear what this penumbra was imaging.

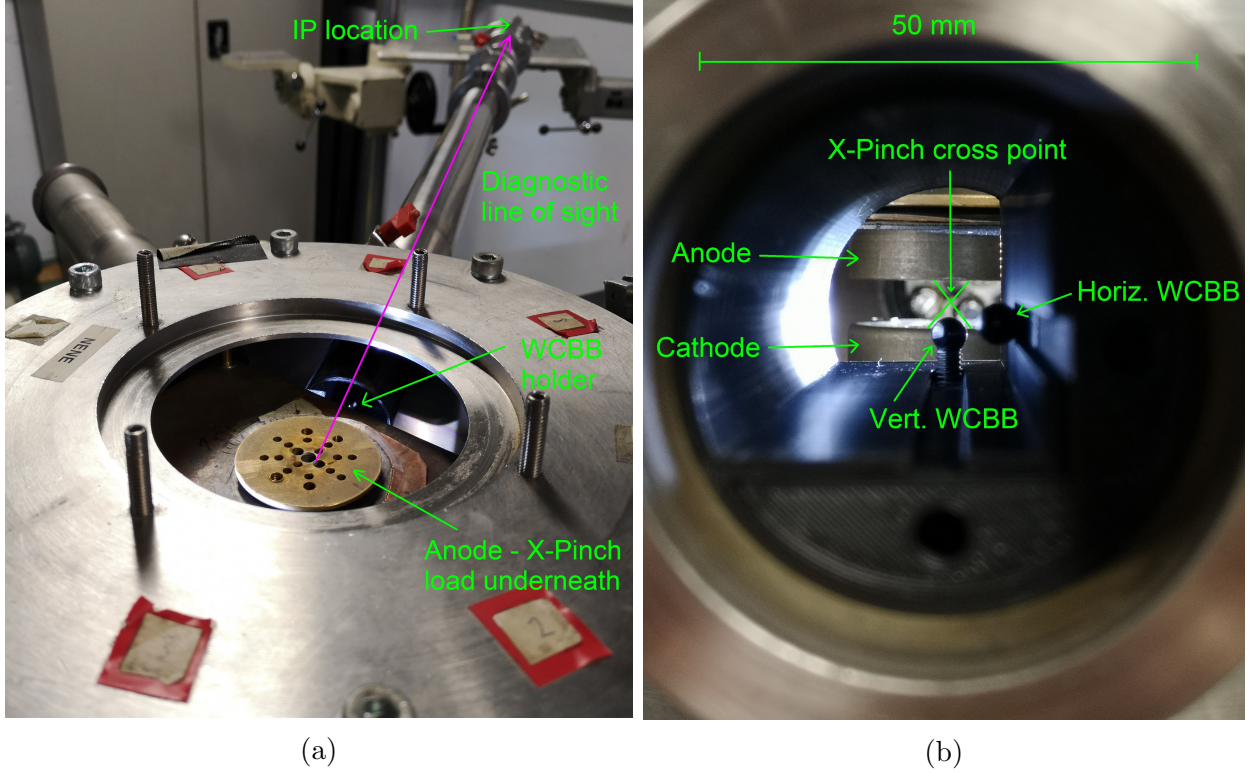


Figure 5.23: Photographs of (a), the whole X-ray source size measurement diagnostic on the Nene X-pinch and (b), a close-up of the WCBB holder with a view of the centre of Nene where the X-pinch wires cross. Picture (a) also shows the location of the image plate on shots at the end of a 2 m long vacuum tube.

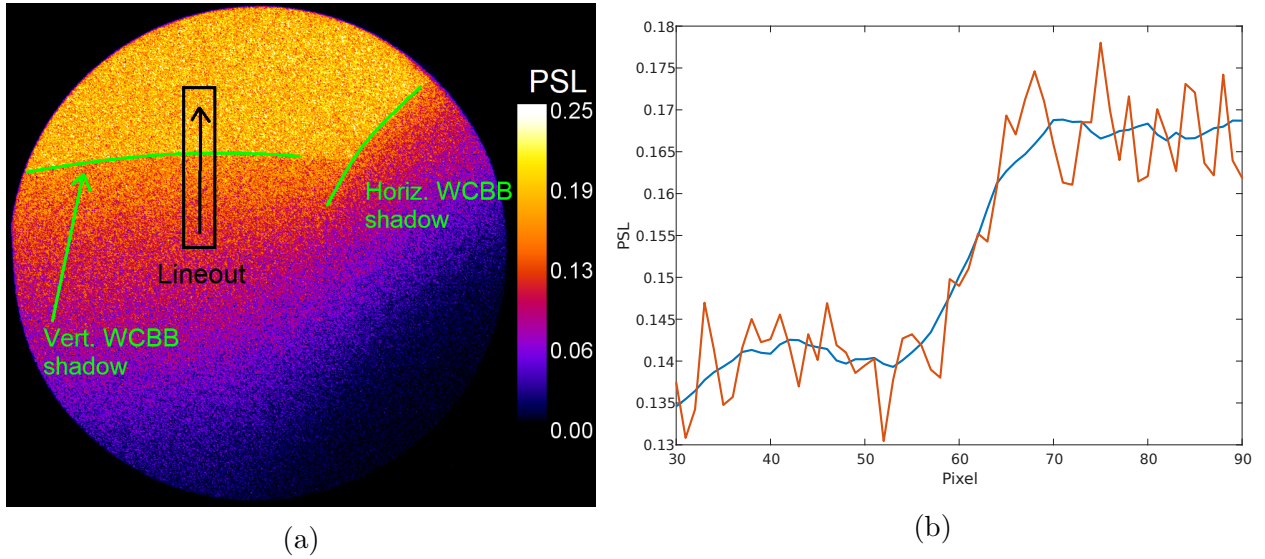


Figure 5.24: Image plate scan showing the penumbral shadows cast by two, orthogonally oriented tungsten carbide ball-bearings on a Nene X-pinch shot using $4 \times 5 \mu\text{m}$ tungsten wires. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows the real data (red line) along with a smoothed profile (blue line) which assisted in measuring the transition width. The transition or penumbra width in (b) was found to be 7 ± 1.5 pixels, yielding a source size of $11.4 \pm 2.4 \mu\text{m}$.

It was decided to reduce the source-detector distance by ~ 1 m to 108 cm to make alignment easier as the previous 2 m vacuum tube was prone to flexing. Also the horizontal WCBB was removed since it was heavily obscured in the first shot. An identical shot to the first was taken after these two changes and is shown in Fig. 5.24. This shot showed the expected penumbral transition which indicated a source of size $42.8 \pm 6.7 \mu\text{m}$, which is a reasonable value expected for an X-pinch hard source. Along with this was an extra feature in the lineout, an unexpected drop in signal after the initial plateau which was interesting. The cause of this tail-off became a focal point for the next shots.

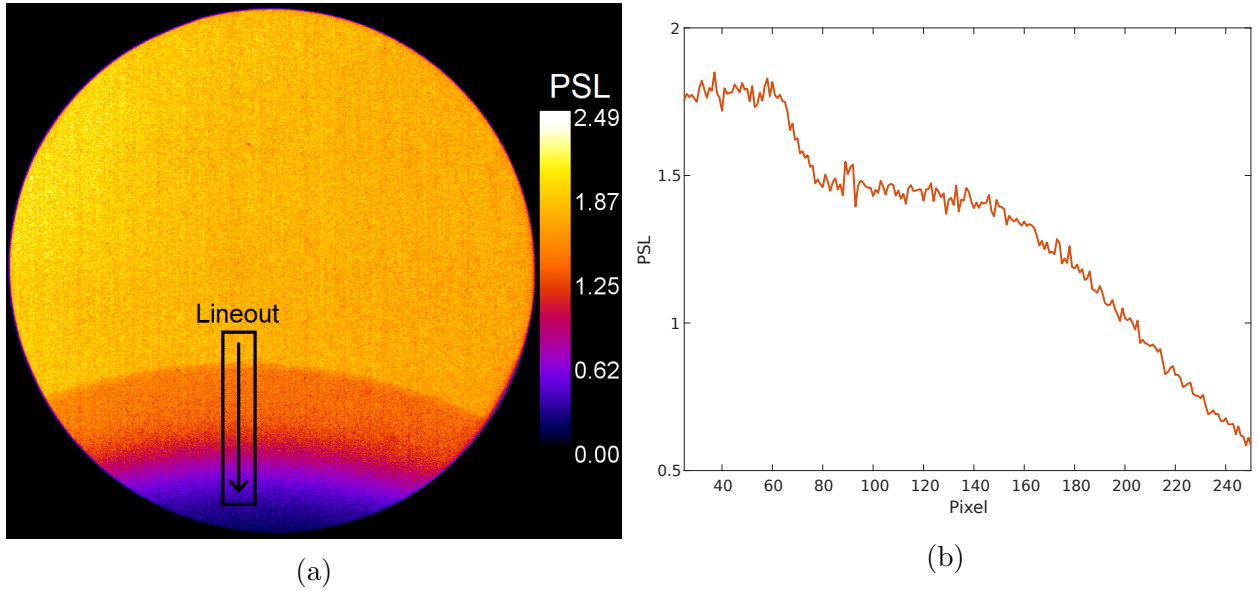


Figure 5.25: Image plate scan showing the penumbral shadows cast by a vertically oriented tungsten carbide ball-bearing on a Nene X-pinch shot using $4 \times 5 \mu\text{m}$ tungsten wires. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows the expected penumbral shadow along with an unexpected decrease in signal after an initial plateau. The width of the “first” penumbra in (b) was found to be 12.9 ± 2 pixels, indicating a source size of $42.8 \pm 6.7 \mu\text{m}$.

The first option considered to explain the additional plateau and second fall off for the signal was scatter of low energy X-rays, incident on the inside of the vacuum tube at shallow angles. A layer of Mylar was added to the inside of the tube on the next shot to absorb any incident low energy X-rays. The position of the vertical WCBB was moved to cover more of the IP in order to see more of the signal drop if it was still present. The results from a shot with this layout is shown in Fig. 5.26. As seen from the lineout in this data the addition of Mylar did not eliminate the unusual signal drop but may have reduced some of the plateau seen after the expected penumbral transition when compared with Fig. 5.25. The size of the transition from this lineout indicates a source of size $20.2 \pm 3.3 \mu\text{m}$. The lineout data from this shot was next used to determine whether direct hard X-ray penetration through the WCBB could have caused the gradual drop off.

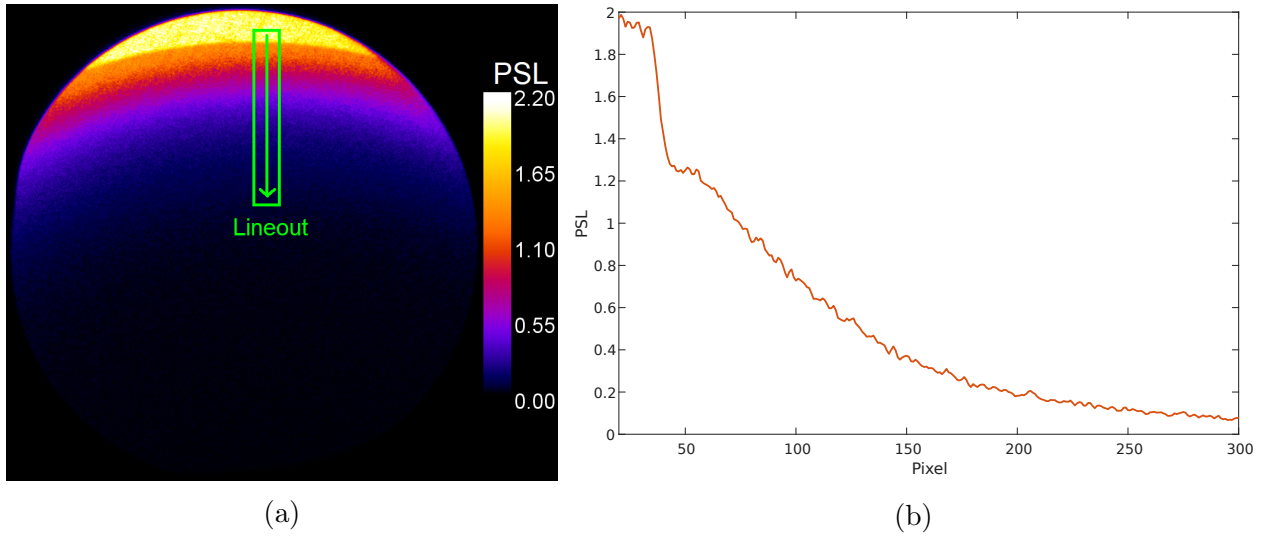


Figure 5.26: Image plate scan showing the penumbral shadows cast by a vertically oriented tungsten carbide ball-bearing on a Nene X-pinch shot using $4 \times 5 \mu\text{m}$ tungsten wires. The green box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows the expected penumbral shadow along with a similar unexpected decrease in signal “deeper” into the shadow of the ball-bearing, as seen in the previous shot. The width of the penumbra in (b) was found to be 6.1 ± 1 pixels, indicating a source size of $20.2 \pm 3.3 \mu\text{m}$.

In order to test the penetration theory, the lineout x -axis shown in Fig. 5.26 was converted from pixels to a corresponding position on the IP (in mm) where zero is the location of the penumbra transition at the edge of the WCBB. The thickness of tungsten carbide that would need to be penetrated by an X-ray in order to arrive at a given IP position was then plotted on the same graph, which is shown in Fig. 5.27.

Choosing the point at which the PSL drops to half its maximum value (~ 0.95), if we assume that all PSL has arisen from WCBB penetration, an X-ray would have had to penetrate 1.5 mm of tungsten carbide to arrive at that IP position. According to the CXRO database we would require X-rays with energy 308 keV to achieve this. To investigate the possibility of the generation of such X-rays a shot was taken with a diagnostic formed from series of filters that would identify any high energy X-ray emission. These were $100 \mu\text{m}$ iron, $25 \mu\text{m}$ tantalum and $250 \mu\text{m}$ zirconium. The transmission curves for these filters are shown in Fig. 5.28. These transmission curves illustrate that the difference in observed PSL behind iron and tantalum will be caused by X-rays between ~ 20 keV and 67 keV (the tantalum K-edge) and the difference in observed PSL behind tantalum and zirconium will be from X-rays between 67 keV and ~ 150 keV. Above this energy the filters will essentially appear transparent to the radiation.

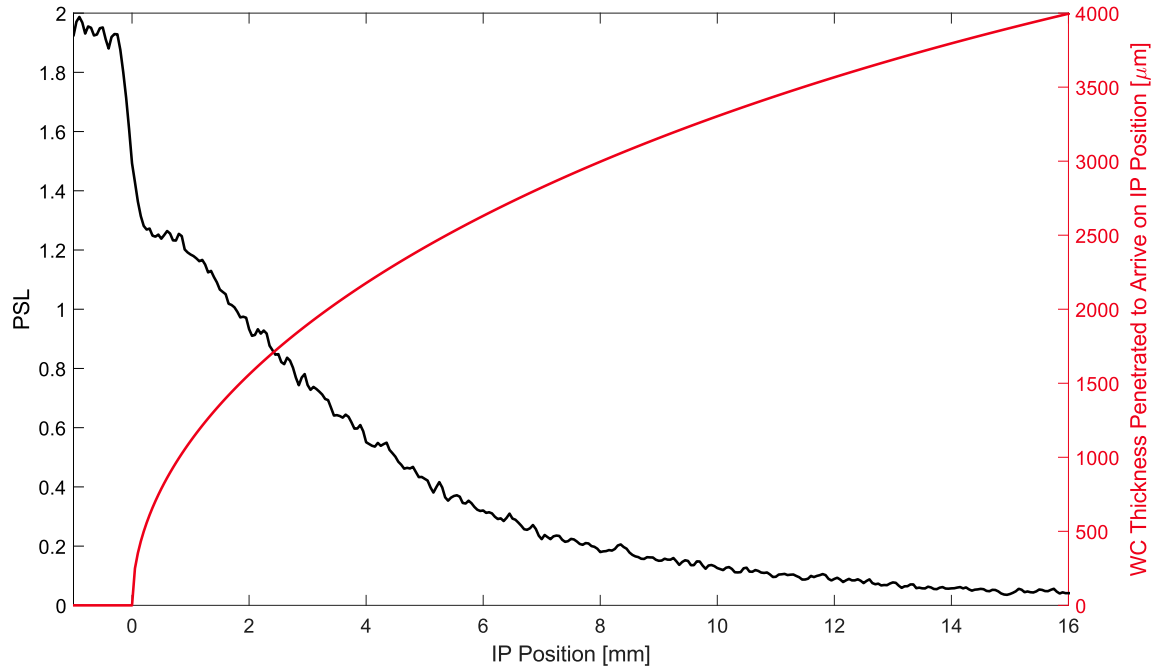


Figure 5.27: Lineout from Fig. 5.26 plotted against equivalent position on IP. Alongside this is the thickness of tungsten carbide an X-ray photon would have to penetrate to cause the observed PSL at a particular IP position. The zero point of IP position was defined as the centre of the penumbra created by the WCB edge.

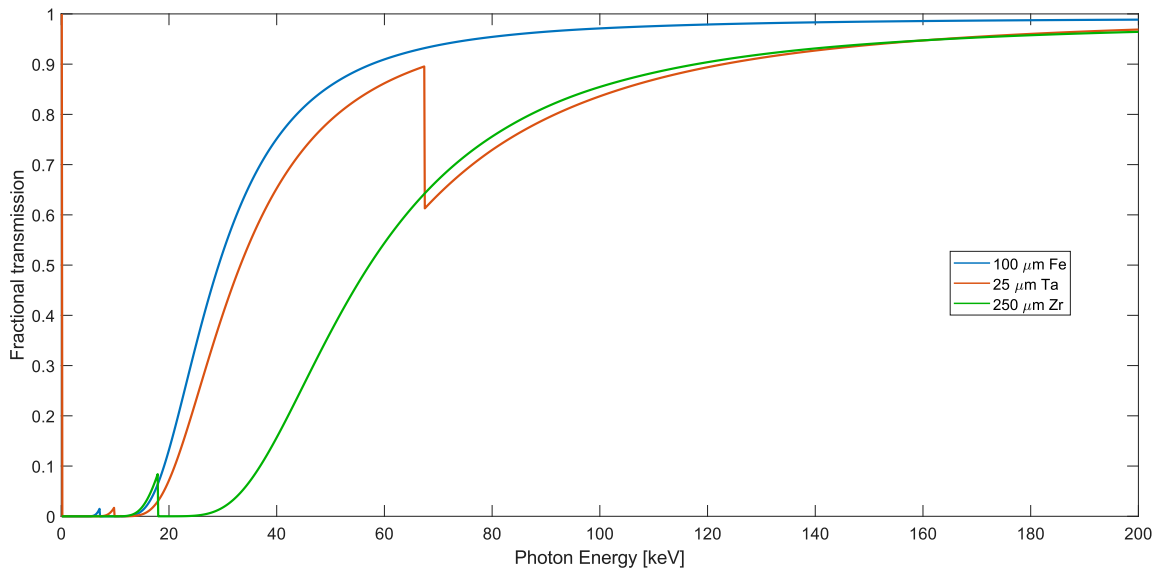


Figure 5.28: Graph showing the transmission of X-rays between 0 and 200 keV through three different metal filters against photon energy. The filters are 100 μm thick iron, 25 μm thick tantalum and 250 μm thick zirconium.

The IP data from a Nene shot taken with the filters is shown in Fig. 5.29. Behind all three filters, the PSL was measured to be essentially zero implying that the gradual decrease in PSL seen in Fig. 5.26 is likely not due to transmission of X-rays through the WCBB. Moreover, from the transmission curves in Fig. 5.28 we can infer that the majority of radiation in this shot must have been below ~ 20 keV.

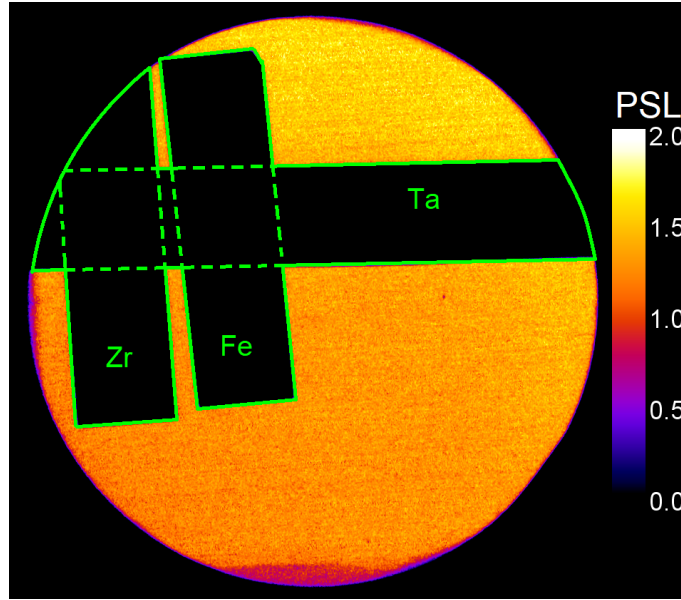


Figure 5.29: Image plate scan showing the (lack of) transmission of X-rays through 100 μm thick iron, 25 μm thick tantalum and 250 μm thick zirconium. The shot was taken with the Nene X-pinch using 4×5 μm tungsten wires.

It is possible to selectively detect X-rays of different energies in an approximate manner by manipulating the detector(s) used in an experiment. To give context, a detector such as Kodak DEF is almost entirely sensitive to X-rays between 1 and 10 keV while IP is sensitive over a much larger energy range, see Section 5.3.3. As such, by putting a layer of Kodak DEF in front of some IP it should be possible to separate contributions from the soft thermal X-pinch source ($E < 5$ keV) and the hard X-pinch source ($E > 10$ keV) as contribution from the latter source should penetrate the DEF and be seen only the IP. A Nene shot was carried out using a layer of DEF in front of the usual IP, Fig. 5.30 shows the DEF results and Fig. 5.31 shows the IP results. Firstly, we shall consider the DEF image. A lineout taken from the DEF scan immediately shows a penumbral transition and an absence of the gradual signal drop seen in previous Nene shots. This immediately suggests that the phenomenon which causes the gradual signal drop seen in image plate data is from an X-ray source with photon energy greater than 10 keV. Crucially, this suggests that it does not originate from the soft X-ray source. The quality of data obtained with DEF is somewhat reduced due to difficulties associated with a wetroom development process. Despite this, it was possible to measure the width of the

penumbra, in the same way as with IP in this project, to yield a source size of $7.7 \pm 2.1 \mu\text{m}$. This is a typical value expected for the small, soft X-pinch source. Moving on to the IP data, we see the radiation which was not absorbed by the DEF, which is immediately reminiscent of the signal drop (it also occurs at a similar PSL) when compared with previous shots. This result further suggests that the gradual drop may come from a hard X-pinch source and not the soft. We shall explore this in further detail in the next section. This shot concluded the data taken with Nene after which other project avenues were explored. An opportunity later arose in the project to carry out source size measurements on a second X-pinch — Dry Pinch which comprises the next portion of this chapter.

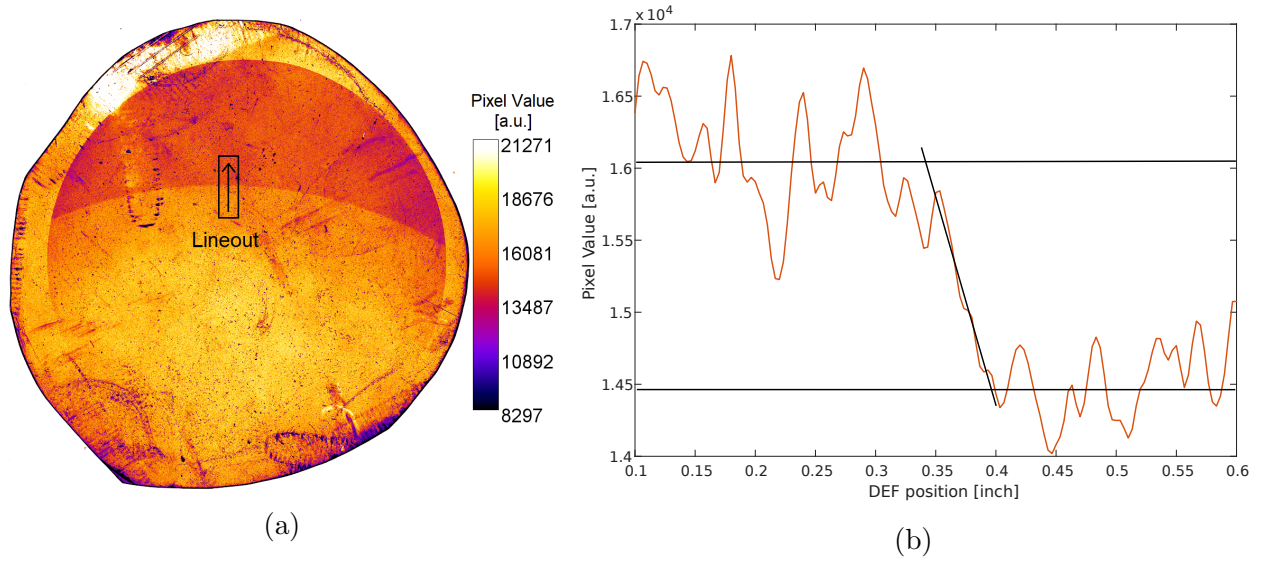


Figure 5.30: Kodak DEF scan showing the penumbral shadows cast by a vertically oriented tungsten carbide ball-bearing on a Nene X-pinch shot using $4 \times 5 \mu\text{m}$ tungsten wires. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows a penumbral transition along with annotated lines which were used to aid in measuring the transition width. The width of the penumbra in (b) was found to indicate a source size of $7.7 \pm 2.1 \mu\text{m}$.

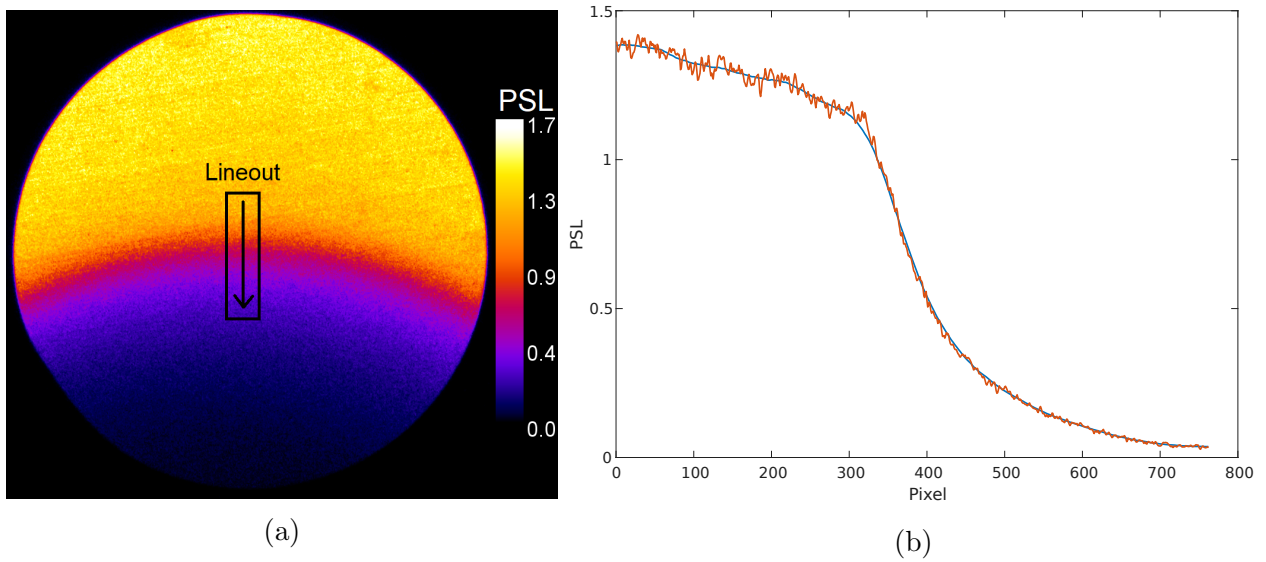


Figure 5.31: Image plate scan from the same shot shown in Fig. 5.30. The IP was positioned immediately behind the DEF and as such recieved X-ray radiation which penetrated the DEF. The black box on (a) shows the direction in which the lineout shown in (b) was taken. The lineout (b) shows a transition matching the observed slow drop in signal from previous shots.

5.5.2 X-ray Source Size Measurement on Dry Pinch

The final source size measurements in this chapter were carried out on a separate pulsed-power generator named “Dry Pinch”. See Section 3.2.2 for more detail on Dry Pinch but, for this section, the crucial difference to note between Dry Pinch and Nene is that Dry Pinch delivers a lower voltage into the X-pinch load: 85 kV versus 250 kV. The load for all shots using Dry Pinch was $4 \times 30 \mu\text{m}$ crossed silver wires. Despite the dual axis capability for source size measurement being present for Nene, horizontal measurements of source size were never taken due to difficulties with alignment. As such dual axis measurement was prioritised for Dry Pinch shots. The simplest way to manage this was to lower the magnification of the WCBs. A second port on the X-pinch was also used for source size measurement with a ball centred relative to the image plate. Using this second port, it was possible to measure horizontal and vertical source size with a single ball bearing when correctly aligned.

An image of the dual balls from an example shot is shown in Fig. 5.32. The colour gradients in the image have been manipulated to show a difference between the vertical and horizontal edges of the ball, indicating an asymmetry in vertical and horizontal X-ray source size. This was noticed in all shots on Dry Pinch. In order to investigate this further, lineouts were taken over the regions shown in Fig. 5.32. These lineouts are shown in Fig. 5.33. In both of these we can see a sharp transition which we would expect to see due to the presence of an X-ray source, these are bounded by black lines annotated on each lineout. The vertical lineout

(Fig. 5.33a) shows a source of vertical size $33.8 \pm 15.3 \mu\text{m}$ and the horizontal lineout (Fig. 5.33b) shows a source of horizontal size $39.7 \pm 15.3 \mu\text{m}$. These source sizes are similar and reasonable measurements for the size of the hard X-pinch source. The errors on these measurements are proportionally larger than previous X-pinch results as the transition width is smaller due to the lower magnification of ~ 6 in this set-up.

An interesting result from this shot is the difference between the horizontal and vertical lineout. The vertical lineout is reminiscent of the vertical lineouts taken on Nene, with a gradual reduction of signal behind the WCBB over at least ~ 100 pixels. Although the tail-off here is less pronounced than for Nene. The horizontal lineout however, shows a more rapid reduction of signal with the signal behind the ball dropping to zero after 40 pixels and the lineout overall appears more symmetrical either side of the main transition than for the vertical. This effect is observed on all Dry Pinch shots and indicates a difference in X-ray emission between the vertical and horizontal axes. These results, combined with the evidence provided by the Nene shots allows a potential explanation for this gradual signal reduction. We shall handle this along with a compilation of all X-pinch source size measurements in the final results section.

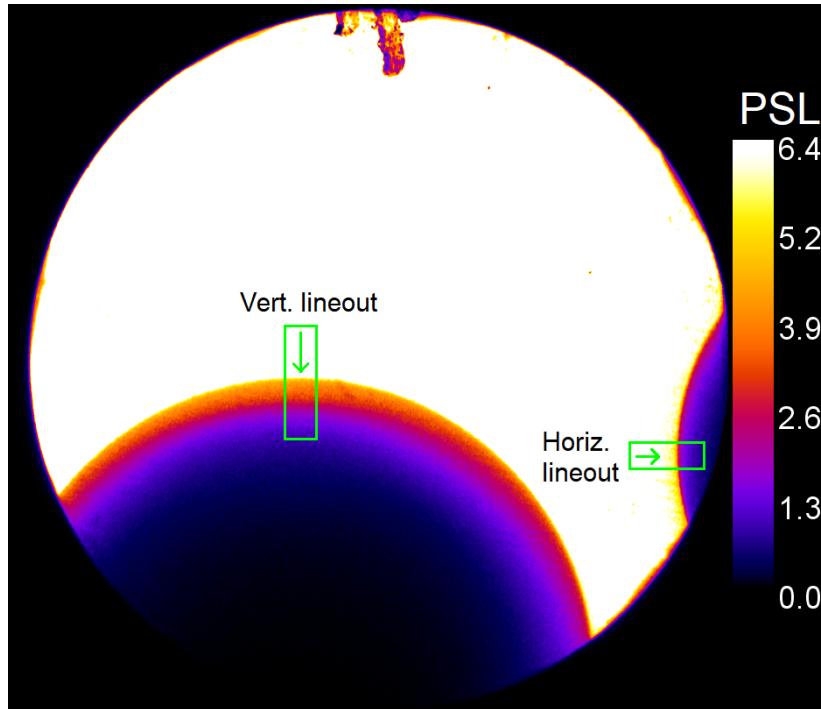
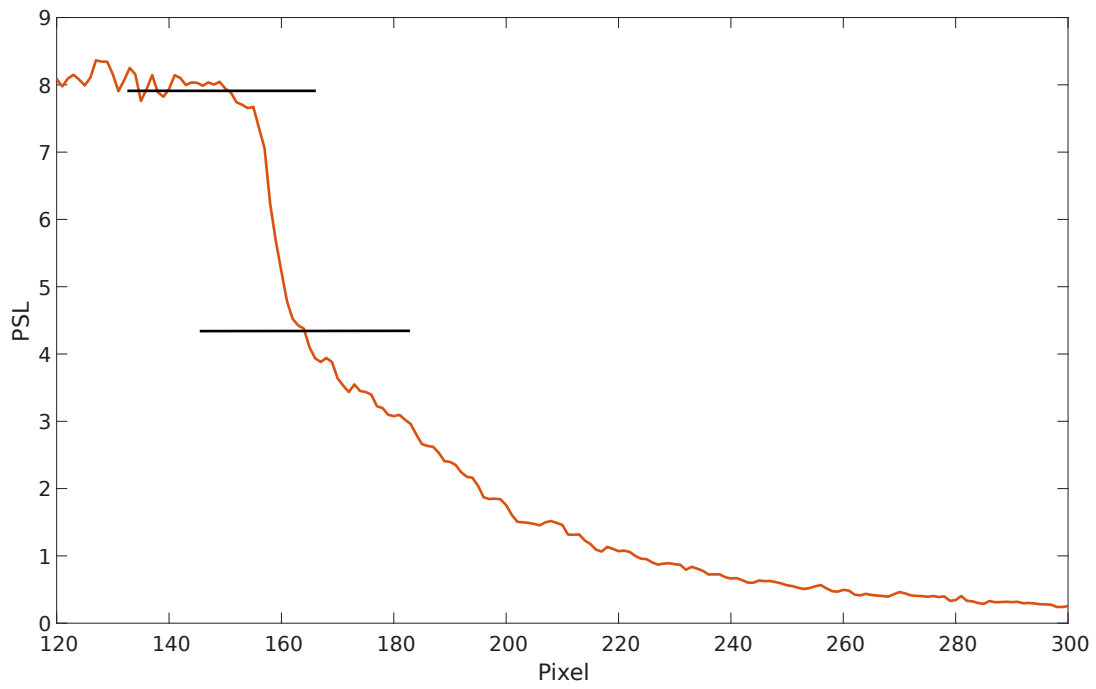
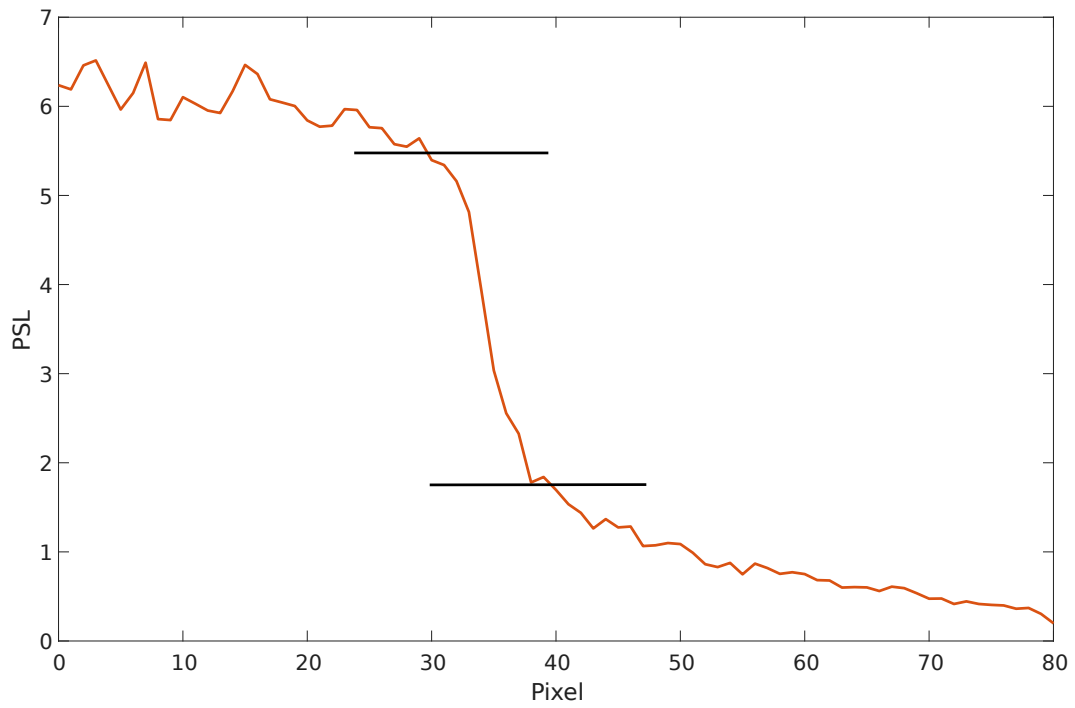


Figure 5.32: Image plate scan showing the shadows cast by two tungsten carbide ball-bearings (see Section 5.4.2) on a Dry Pinch shot using $4 \times 30 \mu\text{m}$ silver wires. The green boxes indicate the directions of lineouts taken which are shown in Fig. 5.33.



(a)



(b)

Figure 5.33: Graphs showing lineouts taken from the image shown in Fig. 5.32. Graph (a) shows the vertical lineout and graph (b) shows the horizontal lineout. The black lines annotated on each graph show the bounds of a transition in each which corresponds to an X-ray source of $\sim 35 \mu\text{m}$.

5.5.3 Results and Discussion

To begin we review what has been determined about the “structured” penumbral image data in which a rapid fall off is then followed by a gradual signal reduction seen across X-pinch source size measurements. Firstly, we know that it is an effect which influences vertical source size measurements (the direction of current propagation), most strongly. The asymmetry seen in vertical lineouts (the drop reliably occurs on one side of the main source size transition) could also suggest that the origin of signal reduction is located at a different vertical position to the main source. From a shot using DEF we determined that the radiation that causes the tail-off is likely from X-rays with energy >10 keV. This would mean that the radiation does not originate from the point of the first soft X-ray burst. Finally we noticed that the effect is more pronounced on Nene shots than Dry Pinch, hence the effect may be influenced by voltage since Nene uses a higher voltage (250 kV vs 85 kV) than Dry Pinch.

A proposed reason for the signal drop that reconciles all of the above is a tertiary source which occurs after the initial soft and hard X-ray burst. Recalling from Section 5.2.2 the secondary, harder X-ray source is generated by electrons accelerated by a strong electric field that develops between two electrodes at the centre of the X-pinch. These electrodes form after the development of the primary soft source which breaks the X-pinch wires apart at the cross point. After the hard burst, the electrons can potentially continue travelling through the cooler wire plasma away from the wire crossing point and toward the anode plate in the X-pinch. In doing so the electrons can continue emitting X-rays e.g. through collisions with ions, with similar energies as the hard burst (hence it is seen on IP but not seen on DEF) but over an extended region and with a gradually decreasing signal as only the most energetic electrons can travel further through the wire plasma and convert their kinetic energy into X-ray radiation. This emission would give the appearance of a signal positioned behind the WCBB shadow where we would normally expect to see darkness. This would also be shifted away from the penumbra caused by the central sources which concurs with observations. An illustration to help visualise this is shown in Fig. 5.34. A possible reason why this effect is less obvious on Dry Pinch compared to Nene is that Nene has a higher voltage. This larger voltage would set up a larger electric field between the electrodes before the hard source is produced, hence accelerating electrons to higher velocities which can travel further through the wire plasmas.

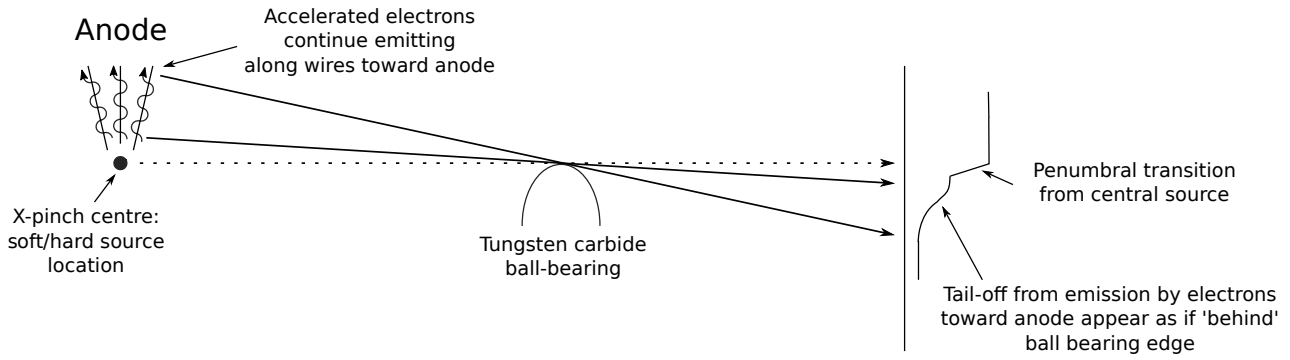


Figure 5.34: Diagram illustrating a potential explanation for the gradual signal reduction observed on vertical X-ray source size measurements for X-pinchs in this thesis.

Since the signal drop is not a sharp transition, it is hard to measure the exact length over which this emission occurs, it is however possible to estimate the size. In all cases, this source is at least $\sim 100 \mu\text{m}$ and can extend up to $\sim 1 \text{ mm}$. According to the theory outlined in Section 5.1.1, this will have a detrimental effect on the spatial resolution when using the X-pinch source for imaging, as such we would want to suppress the effect as much as possible. This effect has been observed before on Nene by Shelkovenko et al. [50] and inferred from results with pin-hole images. The size of the source was much larger than the size of the pin-holes meaning an inverted image of the glowing wires was cast by the pin-holes. A similar pin-hole set-up was employed on the shots from this project. To provide further evidence for the arguments presented in this section, Fig. 5.35a shows a pin-hole image from the Nene shot which yielded the results shown in Fig. 5.25 and Fig. 5.35b shows a pin-hole image from the Dry Pinch shot which provided the results shown in Fig. 5.32 and Fig. 5.33. Both images show an extended “glow” on the anode side of the central X-pinch source. The Nene pin-hole image shows a brighter and more extended emission from the wires than the Dry Pinch image which was typical for all shots. The images of the individual wires are also visible in the Nene pin-hole image.

By using the sizes of the central sources shown in pinhole images such as those in Fig. 5.35, it should be possible to yield a second measurement for the central source size. This follows from the theory for a source which is smaller than the pinhole diameter described in Section 5.3.1. Analysis shows that the central source size measured from pinhole images can vary by 10s of μm from those measured from the equivalent WCBB penumbra but it is possible that the discrepancy arises from the low magnification of the pinhole systems. The magnification of ~ 2 for the pinholes means that the penumbra cast by the pinhole spans only a few pixels on the image plate and hence, an error of even a single pixel (equivalent to $50 \mu\text{m}$) gives a variation in source size of $\sim 25 \mu\text{m}$. As well as for the central source, it is possible to find a second

measurement for the tertiary source by measuring the size of the wire glows in the pinhole images. This follows from the theory for a source which is larger than the pinhole diameter described in Section 5.3.1. In each case, the tertiary source size estimates show a source of at least $\sim 100 \mu\text{m}$, up to $\sim 1 \text{ mm}$ and in agreement with those found using the equivalent WCBB penumbra. Again, due to low magnification and also that the start and end of the source is difficult to determine, these tertiary source sizes can only be approximated.

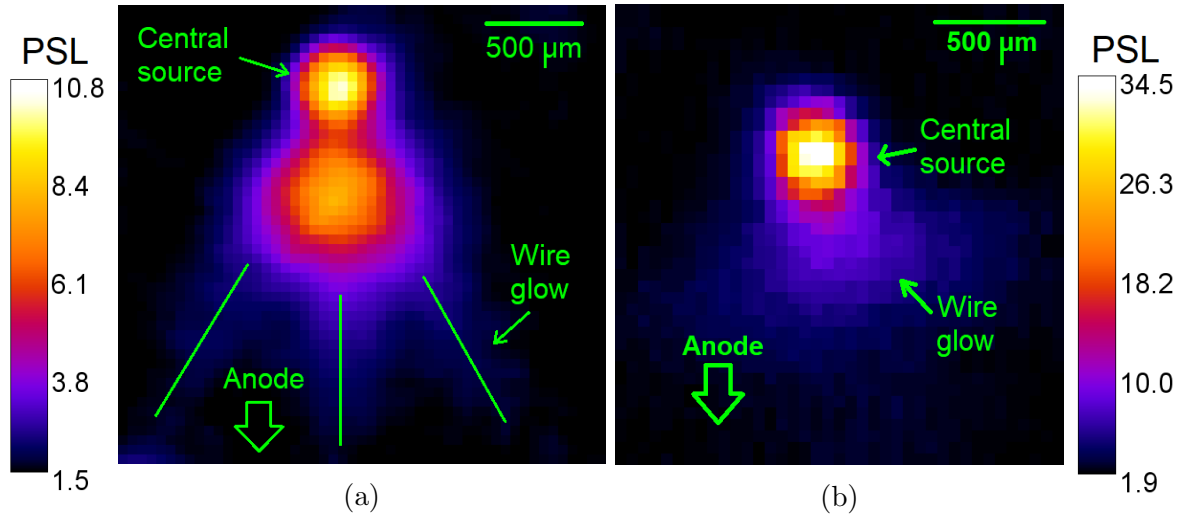


Figure 5.35: Pin-hole images taken for the X-pinch source of Nene (a) and Dry Pinch (b). Both images show a bright spot caused by the central X-pinch source followed by a glow from wires on the anode-side of the X-pinch wire crosss point. The Nene pin-hole image exhibits a stronger glow than Dry Pinch and an image of the wires is formed.

The full set of source size measurements for Nene and Dry Pinch is shown in Table 5.2. Each shot specifies the X-pinch, detector type, vertical and horizontal sizes of the central source and an estimate for the vertical size of the larger tertiary source which gives rise to the gradual signal reduction in the shadow region of penumbral imaging data described above. In some cases, measurements were not able to be made, for example, on Nene shots there was no horizontal axis and only one port used for measurements and are noted with a dash in Table 5.2. The Dry Pinch main vertical and horizontal source size measurements show a symmetrical central source as expected and also show more consistency between shots than for Nene. This may be due to inexperience in operation of X-pinchs when the Nene shots were taken. It should be noted again that the errors on Dry Pinch shots are larger than Nene shots due to lower magnification. It is likely that all measurements using IP represent the size of the hard X-pinch source, due to the fact that IP can not isolate the soft source from the hard source. This is a combination of the fact that IP is more sensitive to the $>10 \text{ keV}$ radiation emitted by the hard source and that both sources occur at the centre of the X-pinch. In order to measure the size

of the soft source it is necessary to use a detector which is selectively sensitive to the <5 keV radiation from the soft source, as evidenced by the source size measured using DEF on Nene. It appears that the tertiary source is overall larger for Nene than Dry Pinch however these values should only be used as a guide due to the difficulty in analysing the signal. Overall, the use of tungsten carbide ball bearings as an edge for penumbral imaging on X-pinchs has been successful. Similar results could however be achieved with a simpler rolled-edge since alignment of an edge in an X-pinch is much easier than for the elevated alignment which necessitated their use in the Cerberus target chamber.

X-pinch	Detector	Horiz. Size [μm] (port 1)	Horiz. Size [μm] (port 2)	Vert. Size [μm] (port 1)	Vert. Size [μm] (port 2)	Tertiary Source Size [μm]
Nene	IP	-	-	11.4 ± 2.4	-	-
Nene	IP	-	-	42.8 ± 6.7	-	~ 560
Nene	IP	-	-	20.2 ± 3.3	-	~ 300
Nene	DEF	-	-	7.7 ± 2.1	-	-
	IP	-	-	-	-	~ 374
Nene	IP	-	-	20.9 ± 5.0	-	-
Dry Pinch	IP	25.4 ± 8.5	31.3 ± 7.8	34.7 ± 8.6	-	~ 200
Dry Pinch	IP	39.7 ± 12.8	38.2 ± 19.2	33.8 ± 15.3	39.3 ± 7.9	~ 300
Dry Pinch	IP	-	40.3 ± 6.4	-	39.1 ± 12.4	~ 100

Table 5.2: Table showing the set of X-ray source size measurements taken on X-pinch shots for this project.

5.6 Chapter Summary and Conclusions

We began this chapter by considering the important characteristics of an X-ray source for use in probing materials undergoing dynamic compression. The important characteristics are spectral brightness, pulse duration and source size. Measuring the latter was the focus of the experimental work in this chapter. For this objective, methods for measuring X-ray source size including penumbral imaging and pin-hole cameras were explored. A penumbral imaging system was then developed for the Cerberus target chamber incorporating vertical and horizontal axis measurement and magnets for charged particle deflection. Due to the footprint of other diagnostics within the chamber, the only available line-of-sight for the diagnostic was one with horizontal and vertical elevation away from the target normal. This made alignment of a flat edge difficult which inspired the use of tungsten carbide ball-bearings as a penumbral edge. The reasons for their use were multiple, firstly being spherical made alignment at awkward angles much easier, the curved tungsten carbide surface was smooth with little surface defects and furthermore presented excellent X-ray absorption properties, due to higher Z and rapid increase in line of sight thickness, when compared to a steel blade edge.

Source size measurements were made for the Cerberus laser shots on foil and wire targets. Initial results showed sizes for foil and tungsten wire shots with the majority of results being between 10 and 100 μm . Measurements of source sizes from 5 μm diameter carbon fibre were possible and the capability of measuring sources <5 μm in size were demonstrated, however the low flux emitted by the target made accurate measurements difficult. Due to the inherent curvature of shadows cast by the ball-bearings used in penumbral imaging in X-ray radiographs, the width of lineouts used to measure source size had to be relatively narrow. This however means that the method is more susceptible to noise and random fluctuations in the radiograph than a flat edge for example. The error caused by this issue could be partially mitigated by creating an image processing code to transpose the curved edge of the ball to a flat edge similar to those given by traditional knife edges. Thus allowing a wider lineout to be taken. In order to test the capabilities of the tungsten carbide ball-bearings for accurate measurements of small sources, shooting levitated targets would be an appropriate direction for further work.

After this, the tungsten carbide ball-bearings were employed on X-pinchs in order to test their capabilities on another piece of equipment, and to allow direct benchmarking of laser and X-pinch driven sources. Values for the size of the hard X-ray sources on X-pinchs were found on both Nene and Dry Pinch between 10 and 50 μm . In order to measure the size of the smaller, soft X-ray source it was necessary to use a detector which could selectively detect the lower energy radiation emitted by the soft source. By manipulating the detector the tungsten carbide ball-bearings allowed measurement of the soft source $<10 \mu\text{m}$ in size.

The final important point to address in this chapter is the evaluation of these sources for use in a FLF-style experiment. A crucial aspect is penetration of the probe through shocked PMMA and we must first calculate the increase in density we expect to see due to shock compression by gas gun impact. From measurements of shock and particle velocity in PMMA (impacted at $\sim 4.5 \text{ km s}^{-1}$) provided by Escauriza et al. [34] and the Hugoniot relation for conservation of mass across a shock (Equation (2.1)) we can infer a minimum increase in density of factor ~ 1.5 . This is a minimum value as the projectile velocities attained by Escauriza et al. were low compared to the $>7 \text{ km s}^{-1}$ expected in FLF gas gun experiments. Using this increased density factor and data provided by the CXRO database we find that 10 mm of PMMA will require X-rays of at least 10 keV in order to transmit any radiation. This means that the soft X-pinch source with energy $<5 \text{ keV}$ is unfortunately unsuitable for a FLF experiment. The hard X-pinch source with energy $>10 \text{ keV}$ will however be sufficient to penetrate this PMMA along with Cerberus generated X-rays, the spectrum of which has a temperature $\sim 20 \text{ keV}$ according to Eardley [54].

All of the sources described in this chapter are capable of producing sources of size $\sim 10 \mu\text{m}$ or less. According to Equation (5.5), our minimum resolvable detail (i.e. spatial resolution) in a radiograph will tend to the source size for a system with increasing magnification. For a cavity of $\sim \text{mm}$ size a $10 \mu\text{m}$ spatial resolution is excellent. Despite this, the X-pinch hard source holds an advantage over Cerberus generated X-rays as results from this project show a lower average source size and less variability for the X-pinch hard source when compared with Cerberus X-rays. On the other hand, the spectrum and source size of Cerberus X-rays can be manipulated through use of different target materials and shapes giving further reason to characterise the X-ray source generated by shooting the Cerberus pulse onto spatially-limited optically-levitated targets.

Chapter 6

Laser-Generated Proton Beams Driven by Cerberus

6.1 Laser-Generated Proton Sources and Application to FLF-Style Experiments

Laser-generated proton beams, relevant to this project, were first demonstrated at the beginning of this century in a series of experiments by Clark [87, 88], Maksimchuk [89] and Snavely [90]. These experiments used a laser beam with intensity $>3 \times 10^{18} \text{ Wcm}^{-2}$, focused onto a foil (polymer or metallic) target, to generate multi-Mev proton beams. The particular mechanism by which these beams are generated is now known as target normal sheath acceleration (TNSA). These early results were significant as the protons were found to be emitted in a low divergence laminar beam [91] (individual protons do not cross paths). Furthermore, the beam was emitted normal to the target on the opposite side to the laser irradiation. A second beam was also shown to be emitted from the same side as the laser was incident but the quality of this beam was found to be lower [92].

One of the major interests in proton beams arises from their energy deposition mechanism in matter: most of the energy of a proton is released at the end of its path at the Bragg peak [93]. For protons of varying energy, the depth at which the Bragg peak occurs within matter is dependent on the energy of the proton, with little energy given to the matter the proton passes through prior to the location of the Bragg peak. In medical science, this has resulted in interest in using proton beams for cancer treatments [94–96]. In physics research, proton beams are appealing for use in imaging through radiography — in a similar manner to X-rays [97, 98] — where stopping or scattering of protons can be used to detect small

changes in thickness and density within a sample. A further use is in the measurement of electromagnetic fields [99], by measuring the deflection of a proton beam by a region containing such fields. Using proton beams for radiography and measuring electromagnetic fields are the most interesting applications for a FLF experiment as a collapsing cavity is a rich environment containing variable densities, material, energy flow and electromagnetic fields. Furthermore, as will be shortly described, the method by which lasers generate proton beams results in a short duration proton pulse which is ideal for imaging the fast processes occurring in a FLF experiment.

As with X-ray sources described in the previous chapter, characterisation of laser-generated proton sources is crucial for assessing their application to a FLF experiment. Therefore, in this chapter we will begin by describing the generation of laser-generated proton beams which will lead onto a discussion of parameters such as energy, pulse duration and source size. The type of detector used for observing protons will then be discussed, before describing experimental work carried out with Cerberus generated proton beams.

6.2 Proton Beam Generation by Cerberus

In this section we shall outline the dominant mechanism by which Cerberus generates beams of protons. This mechanism is directly linked to the theory for X-ray production by lasers given in Section 5.2.1. As mentioned in the last section, the mechanism we will focus on here is TNSA. The theory for TNSA was first established by Wilks [100], which reviewed the preceding experimental work [87–90] and a comprehensive review paper was later written by Macchi [92]. As in Section 5.2.1, we begin with a Cerberus pulse with peak intensity $\sim 10^{19}$ Wcm⁻² focused onto a foil target, see Fig. 6.1 for an illustration of this explanation. The inherent pre-pulses are sufficient to cause an ionisation of the surface of the foil before the main beam arrives, liberating a cloud of hot electrons around the front of the target. Through vacuum, or Brunel, heating (see Section 5.2.1) some of these electrons are accelerated through the target by the main beam. The passage of this electron beam is also the source of X-rays described in Section 5.2.1. Upon reaching the rear side of the target, these electrons form a second, hot electron cloud.

Once these electron clouds are formed, intense electric fields are set up on both sides of the target in the direction of target normal. These electric fields are strong enough to accelerate predominantly protons, but also heavier ions, located within a thin layer of contaminants present on a foil used in a lab environment. These contaminants are typically water molecules

and hydrocarbons from vacuum pump oil, for instance. The acceleration is sufficient to generate a beam of protons and ions with energies up to many 10s of MeV [90]. For Cerberus, the energy spectrum of protons has previously been measured by Eardley to be <10 MeV [54], this will later inform the setup of the detector described in the next section. The temporal duration of the proton pulse is initially on the timescale of the drive laser pulse [92, 99]. The beams are generally emitted in a cone with a low angle of divergence, Maksimchuk measured a divergence angle 40 ± 10 degrees [89]. The source size of these proton beams has been measured to be lower than $10 \mu\text{m}$ [92, 99] and arises from a virtual source located behind the target at a distance $\sim 400 \mu\text{m}$ from the point of laser incidence [99]. This results in a region of proton emission larger than the perceived source size.

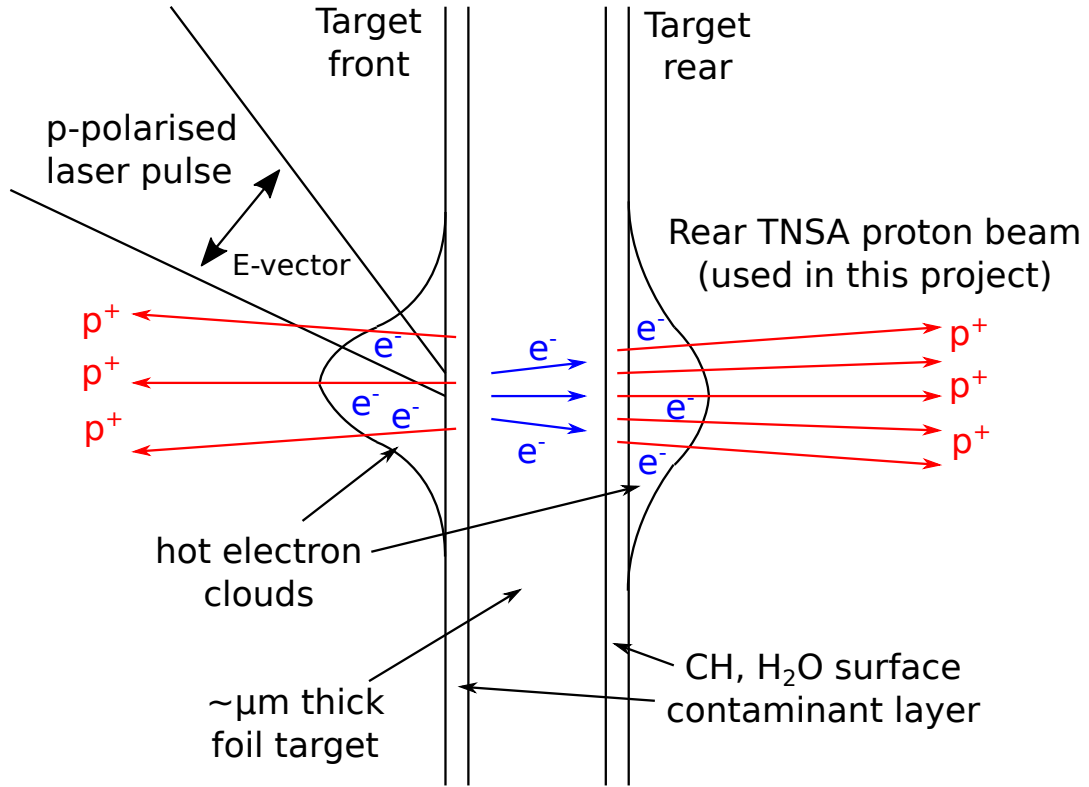
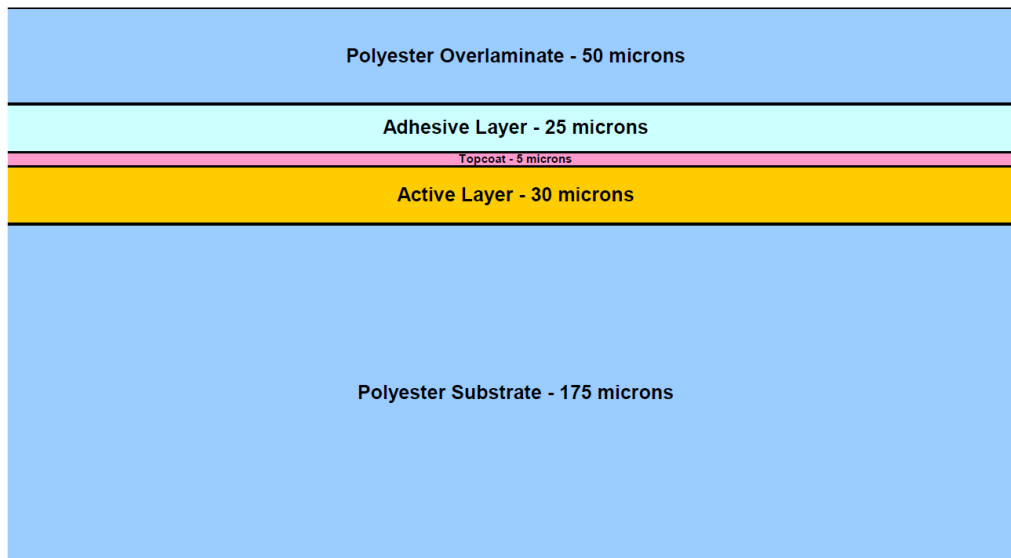


Figure 6.1: Diagram illustrating the target normal sheath acceleration mechanism (TNSA) for proton generation by a laser. A laser beam approaches from the upper left and is focused onto a foil. A hot electron cloud is produced on the front of the target being ionised by the laser before the main beam arrives. Absorption of the main pulse in this region by vacuum heating causes an electron beam to pass through the target and generate a second hot electron cloud on the rear of the target. These hot electron clouds create a large potential difference and electric field in the direction of target normal which accelerates protons and heavier ions located in layers of surface contaminants on the foil. These accelerated ions form the TNSA beams which are observed in experiments.

6.3 Proton Detection

The detector used to observe proton beams in this project was Gafchromic EBT2, a type of radiochromic film (RCF) [101–103]. The active component of the detector is a yellow dye within a 30 μm layer, held between two protective layers of polyester. EBT2 is sensitive to ionising radiation and particles such as electrons, X-rays and protons in particular. The yellow dye rapidly changes colour to blue when exposed to ionising radiation and particles, with no need for the film to be developed. The two outer polyester layers are not of the same thickness (50 μm and 175 μm), hence orientation of the side facing a proton source is crucial for understanding the energy of protons arriving at the active layer. A schematic showing the different layers and thicknesses, along with estimates for the atomic composition of each layer by percentage is shown in Fig. 6.2.



(a)

Layer	Thickness*** microns	Approximate density g/cm ²	COMPOSITION (ATOM%)									
			H	Li	C	N	O	Na	S	Cl	K	Br
Polyester film base*	50	1.35	36.4%	0.0%	45.5%	0.0%	18.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Adhesive*	25	1.2	57.1%	0.0%	33.3%	0.0%	9.5%	0.0%	0.0%	0.0%	0.0%	0.0%
Surface layer (assumes 7.5% moisture)**	5	1.2	56.9%	0.9%	25.7%	0.0%	15.6%	0.0%	0.0%	0.9%	0.0%	0.0%
Active layer (assumes 7.5% moisture)**	30	1.2	58.3%	0.8%	29.6%	0.1%	10.7%	0.0%	0.0%	0.3%	0.1%	0.1%
Polyester film base*	175	1.35	36.4%	0.0%	45.5%	0.0%	18.2%	0.0%	0.0%	0.0%	0.0%	0.0%
Overall Composition			40.85%	0.10%	42.37%	0.01%	16.59%	0.00%	0.00%	0.04%	0.01%	0.01%

(b)

Figure 6.2: Schematic showing the thicknesses of different layers (a) and table listing estimates for the atomic composition of each layer by percentage (b) for Gafchromic EBT2 RCF. Image and table both produced by the manufacturer [102].

Using the composition information from Fig. 6.2b and software which simulates the penetration of different energy ions known as SRIM (Stopping Range of Ions in Matter) [104], it was possible to estimate the kinetic energy of a proton arriving at the active layer in EBT2.

In proton imaging shots in this thesis, the RCF detector pack was made of up to three stacked layers of EBT2 wrapped in a single layer of 5 μm aluminium foil. All EBT2 layers were positioned such that the thinner, 50 μm thick polyester side faced the proton source. As such, using SRIM it was found that the active layer in the first EBT2 layer was sensitive to ~ 2.5 MeV - ~ 2.95 MeV protons. The second, sensitive to ~ 5.85 MeV - ~ 6.15 MeV protons and the third, sensitive to ~ 8.15 MeV - ~ 8.4 MeV protons. Since the Cerberus proton energy spectrum has been measured to be predominantly < 10 MeV, it is unlikely that a fourth layer could be activated in this experiment.

Following determination of the energy bands each layer of EBT2 is sensitive to, it is possible to estimate the velocities of the protons, v_P , which arrive at each layer. Beginning with the equation for relativistic kinetic energy, E_K ,

$$E_K = (\gamma - 1)m_P c^2, \quad (6.1)$$

where γ is the Lorentz factor, m_P is the proton mass and c is the speed of light. We can substitute in $m_P = 938 \text{ MeV}/c^2$ and $\gamma = 1/\sqrt{1 - v_P^2/c^2}$, then rearrange Equation (6.1) to yield,

$$\gamma - 1 = E_K[\text{MeV}]/938 \quad (6.2)$$

$$\frac{1}{\sqrt{1 - v_P^2/c^2}} = 1 + E_K[\text{MeV}]/938 \quad (6.3)$$

$$v_P = c \sqrt{1 - \left(1 + \frac{E_K[\text{MeV}]}{938}\right)^{-2}} \quad (6.4)$$

Using Equation (6.4), we can estimate the velocities of protons arriving at each EBT2 layer with the kinetic energies we calculated above. Therefore, the velocity of protons arriving in the first, second and third layers of EBT2 will be $\sim 0.075c$, $\sim 0.112c$ and $\sim 0.131c$ respectively. Since the protons for each of these layers are travelling at different speeds, it is apparent that they will arrive at each EBT2 layer at different times. We can estimate the time of arrival for the protons in each layer with knowledge of the source-detector distance, l_0 , and applying the Lorentz contraction to calculate the distance observed by the protons, l , i.e. $l = l_0/\gamma$. Thus the time of arrival, t_{layer} , will be given by,

$$t_{\text{layer}} = \frac{l_0}{\gamma v_P}, \quad (6.5)$$

If we take an example source-detector distance of 47 mm and compensate for the thickness of each layer as ~ 0.3 mm, we find the arrival time of protons at the first, second and third layers of EBT2 is 2.1 ns, 1.4 ns and 1.2 ns after emission from the source. From this we can conclude that while the proton beam emission will initially be of a similar duration to the laser pulse [92], a $\sim$ ns spread will develop in the pulse within a few 10s of mm propagation. This also means it may be possible to witness the evolution of a sample, radiographed by a sufficiently energetic proton source, simply by using stacked layers of EBT2 (provided the sample evolves on a $\sim$ ns timescale). Another interesting consequence is that we would see the rear layers activate before the front layers, if we could witness events on that timescale.

A final consideration on proton detectors for this section is the spatial resolution of an image. All EBT2 data in this project was digitised using a scanner (Minolta Dimage Scan Multi PRO Scanner) which provides a resolution of 4800 pixels per inch. This translates to a pixel size of 0.005292 mm/pixel.

6.4 Characterisation of Cerberus Proton Beams

As was described above, the energy of Cerberus proton beams has previously been found to be <10 MeV and the pulse duration will be on the order of the laser pulse which is ~ 700 fs. We however find that the pulse duration is less important as the pulse will rapidly attain a $\sim$ ns duration during propagation, over a distance of 10s of mm, due to the energy bandwidth of the pulse. Therefore, in this section we will discuss efforts to constrain the source size of Cerberus proton beams. These characteristics are important to proton imaging in general but in order to potentially measure electromagnetic fields we must additionally imprint a regular pattern into a beam. This is typically done using a wire mesh of which some were evaluated for this project.

6.4.1 Proton Source Size Measurement

The first shot in this experiment used a woven, copper mesh. Through point projection imaging of the grid, the diameter of the wires was estimated to be 0.25 mm and the apertures between the wires, 0.4 mm. The grid was set up 9.5 mm from the source and RCF 38.5 mm from the source, giving a magnification of the grid ~ 3 . The first shot using this grid used a Cerberus pulse with energy 3.4 J and intensity $\sim 6.8 \times 10^{18}$ Wcm $^{-2}$ onto 15 μ m aluminium foil and one layer of RCF as the detector. The resulting proton beam profile is shown in Fig. 6.3a.

After producing the image, it was realised that the many orthogonal edges of the grid lines would be appropriate for source size measurements, by determining the widths of the penumbra at each edge using the knife-edge method described in Section 5.3.1. Fig. 6.3b shows a lineout taken from the region highlighted in green on Fig. 6.3a, the lineout exhibits a penumbral transition similar to those seen throughout Chapter 5. As before, the source size was found by measuring the width of the penumbra in mm between 90% and 10% of the maximum pixel value of the lineout. This width was then divided by the magnification of the system to find the source size. The source size from the transition in Fig. 6.3b was found to be $13\ \mu\text{m}$. This process was repeated over the two vertical lines in every grid square, noting the position on the RCF of each lineout, to yield a spatially varying map of effective horizontal proton source size, in μm , which is shown in Fig. 6.3c. The equivalent map of effective vertical source, in μm , was found by repeating this whole process at every horizontal line in each grid square and is shown in Fig. 6.3d. The largest source of error in the source size was expected to arise from uncertainty in measuring the width of the penumbra. This error was quantified by applying lines of “worst fit” to the lineouts and calculating the variation in source size. This error was estimated to be $\pm 0.9\ \mu\text{m}$.

Fig. 6.3c and Fig. 6.3d show that the effective source size varies across the spatial profile of the beam between 5 and $25\ \mu\text{m}$ for both horizontal and vertical measurements. This means that the maximum spatial resolution of an image of a sample radiographed by a laser-generated proton beam depends on its position in the proton beam. Furthermore, the horizontal and vertical source sizes are not equal in most locations, meaning an image of a sample radiographed by a small portion of the beam will have different maximum vertical and horizontal spatial resolution. The location of largest source size was compared to the brightness of the beam by extracting the scan brightness value and comparing to saturation, this is shown in Fig. 6.4a and also to the change in brightness by differentiating over the horizontal or vertical direction. The change in brightness horizontally is shown in Fig. 6.4b for context. Comparing the brightness map Fig. 6.4a to either source size map does not seem to show a pattern and the change in brightness horizontally Fig. 6.4b does not seem to show any correlation with the horizontal source sizes.

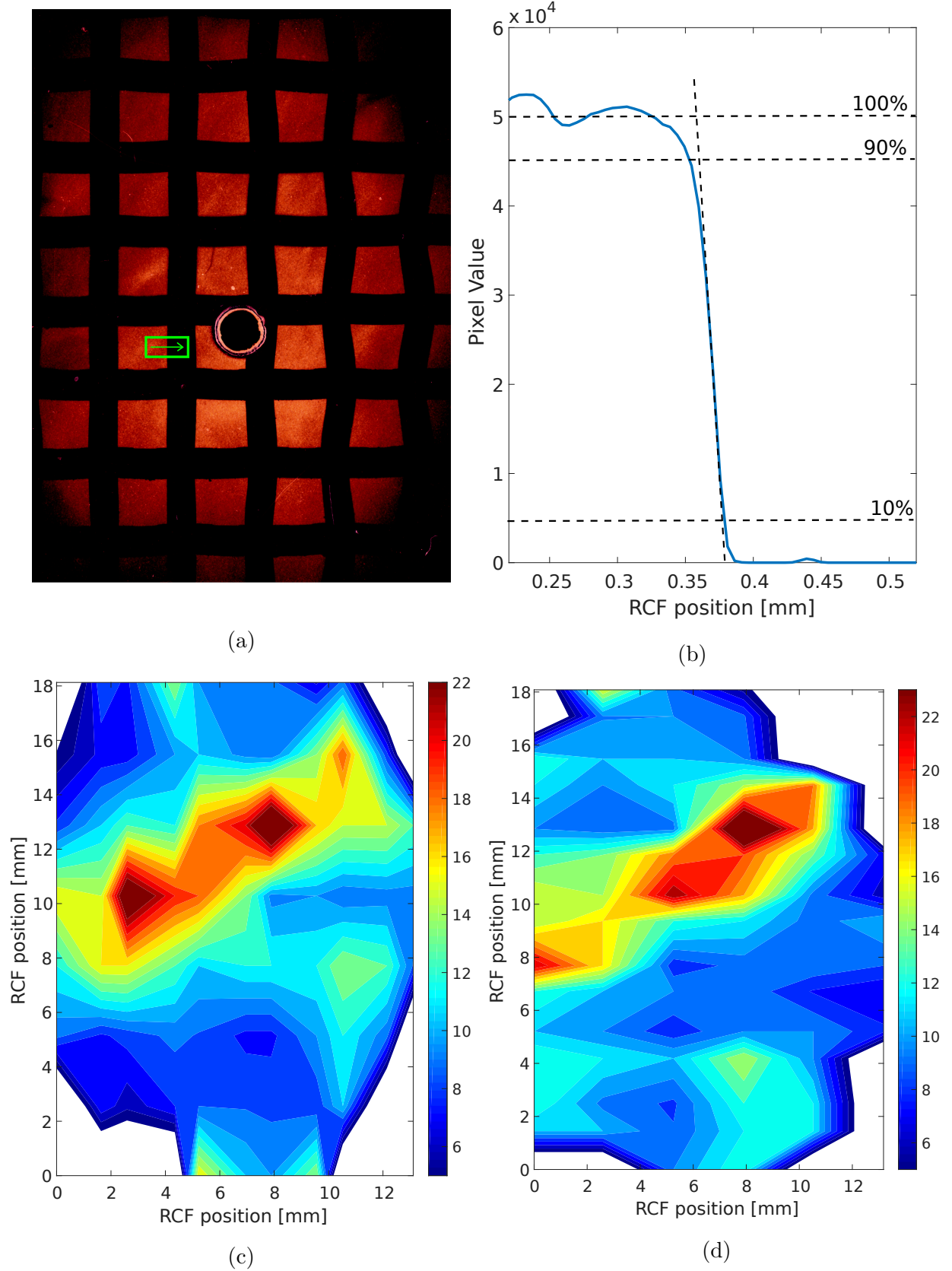


Figure 6.3: RCF image of a Cerberus-generated proton beam (a) and lineout showing a penumbral transition (b) taken across a region, highlighted in green, on the RCF image. The grid pattern of shadows was cast by the wires of a copper wire grid. Lineouts as in (b) were taken over every vertically and horizontally oriented line in each grid square, the penumbra from each was measured to spatially map the variation in effective horizontal (c) and vertical (d) proton source size in μm respectively. The shot used a Cerberus pulse with energy 3.4 J and intensity $\sim 6.8 \times 10^{18} \text{ Wcm}^{-2}$ onto $15 \mu\text{m}$ aluminium foil and one layer of RCF as the detector.

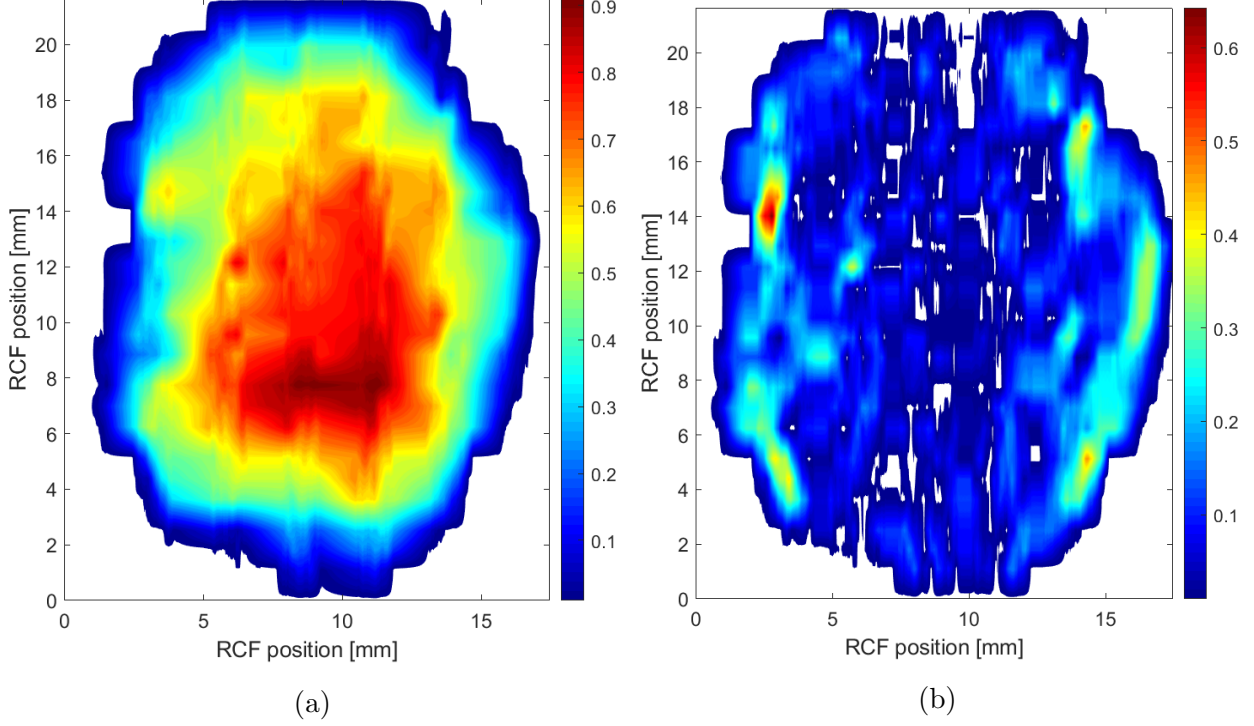


Figure 6.4: Map of image brightness relative to saturation values (a) extracted from Fig. 6.3a and change in brightness in the horizontal direction (b) found by differentiating image (a) horizontally. These images were produced to ascertain if either parameter correlated with the source size maps in Fig. 6.3.

This shot was then replicated but with the addition of a pre-pulse with 1×10^{-5} intensity of the main beam, 50 ps prior to the main beam to see the effect of a pre-pulse. The laser beam had an energy 3.8 J and an estimated intensity $\sim 9.8 \times 10^{18} \text{ Wcm}^{-2}$ but otherwise the shot procedure was carried out in exactly the same way. The resulting RCF image is shown in Fig. 6.5a. As before, the effective horizontal and vertical source sizes were measured across the image and the resulting maps are shown in Fig. 6.5b and Fig. 6.5c for the horizontal and vertical source sizes respectively. These maps show a slightly larger range of source sizes, between 5 and 40 μm , but the smaller source sizes are located within the central portions of the beam. These were the only two shots which were used to measure source size so it is difficult to draw a definite conclusion on the larger perceived source without more data, be it an effect of pre-pulse or the slightly larger intensity used in the latter shot. Since these shots used a single layer these are source sizes for $\sim 2.5 \text{ MeV}$ - $\sim 2.95 \text{ MeV}$ protons. It is possible that source size would be different for different energies/layers.

To conclude from these results, we have at least constrained the effective source size of Cerberus proton beams to between 5 and 40 μm . From the analysis in Section 5.1.1 we can determine that the smallest measurable feature in a radiograph (imaging system spatial resolution) tends to the source size as magnification is increased with smaller magnifications improving this. As such, in a worst-case scenario of imaging a several mm diameter FLF cavity, a maximum source size/resolution of 40 μm is still a positive result.

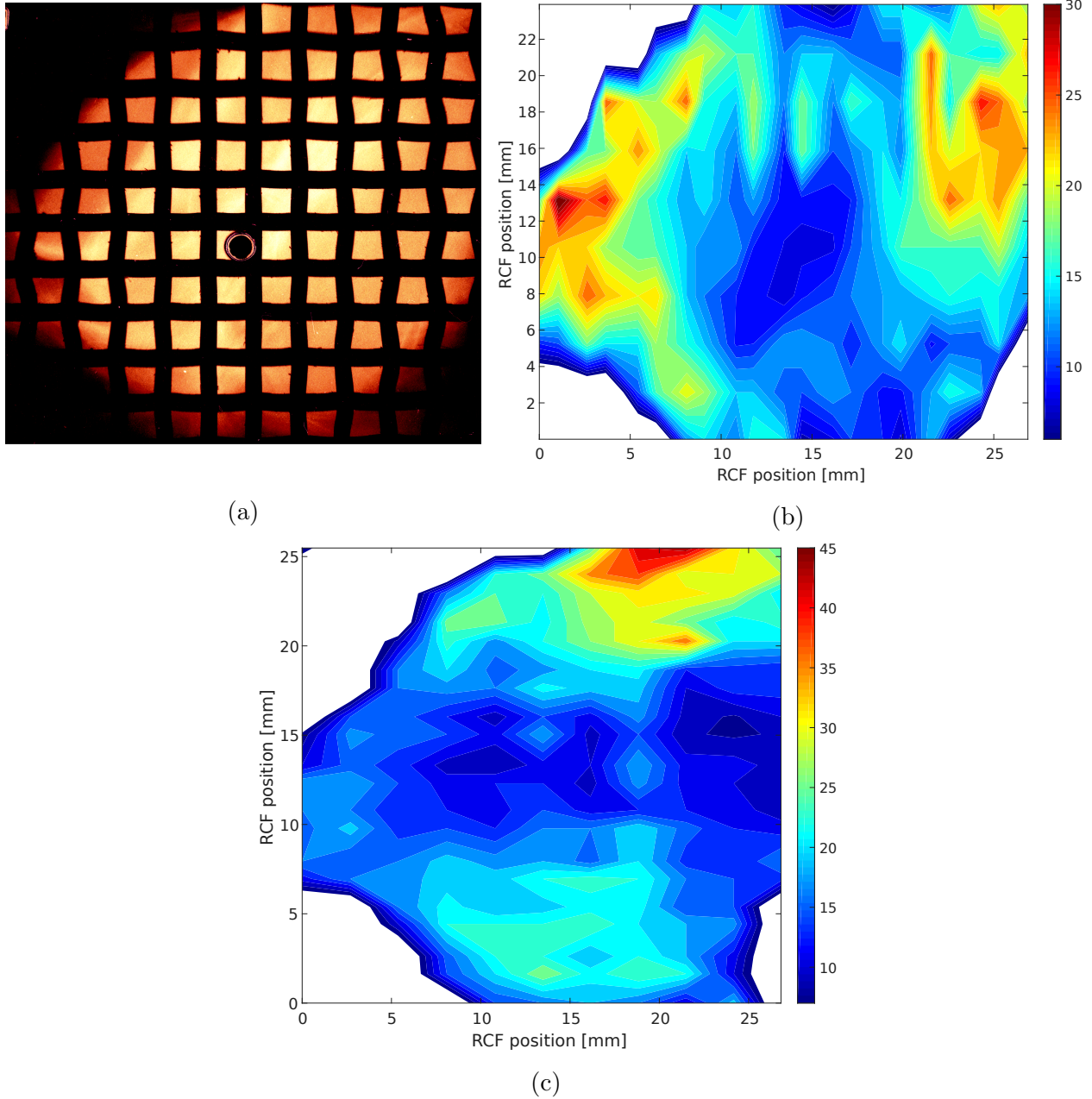
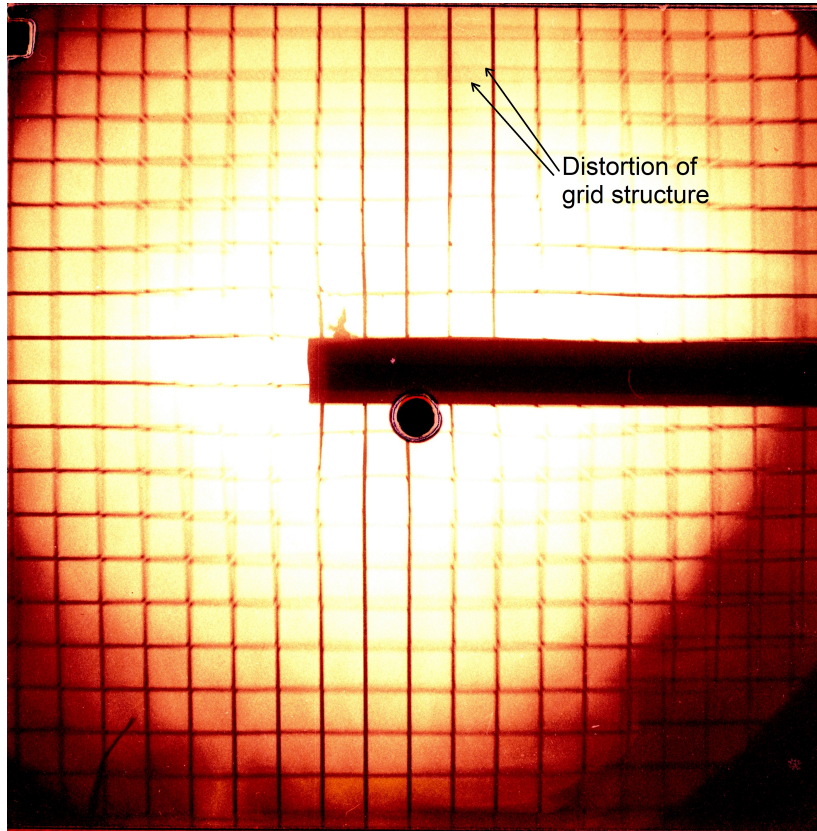


Figure 6.5: RCF image of a Cerberus-generated proton beam (a) along with maps of effective horizontal (b) and vertical (c) source size in μm measured using the penumbra produced by the shadows cast by the vertical and horizontal wires of a copper wire grid. The shot used a Cerberus pulse with energy 3.8 J and intensity $\sim 9.8 \times 10^{18} \text{ Wcm}^{-2}$ onto 15 μm aluminium foil and one layer of RCF as the detector.

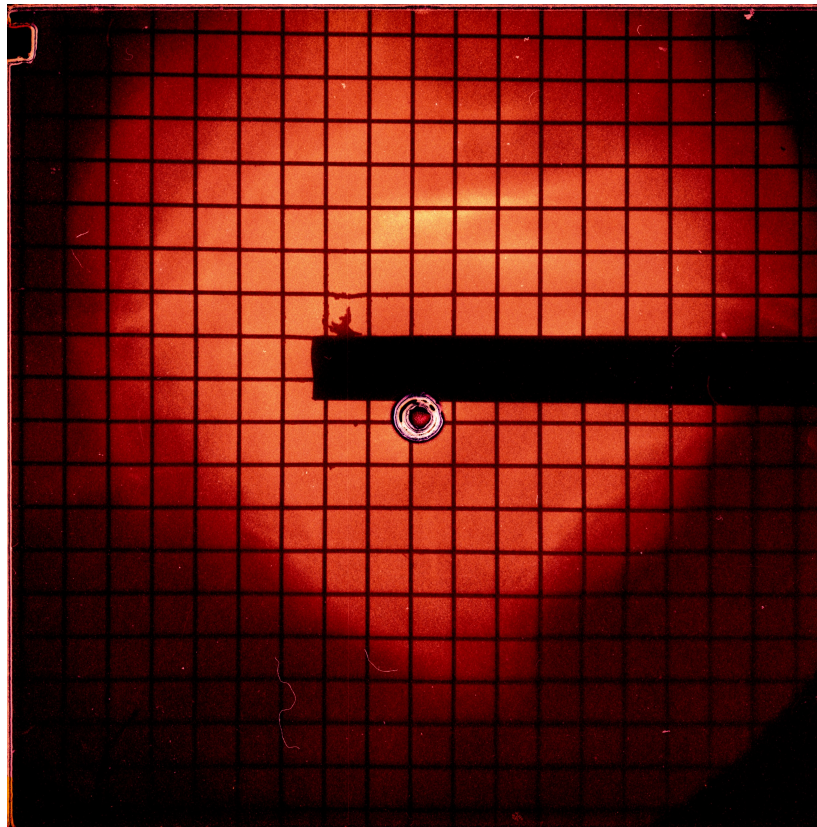
6.4.2 Evaluation of Grid Types

The results shown in Figs. 6.3 and 6.5 use the same woven copper grid. The ratio of dark and exposed RCF in these images would be useful for observing samples which cause a deflection. This is since the larger the separation between adjacent bright regions, the less likely it is there would be overlap. Any overlap would result in uncertainty in determining exactly how far protons are deflected and loss of data in the worst case. On the other hand, it can be seen that the weave of the grid is visible and has caused a deformation of the regular grid pattern in places. This arises from the laminar emission of the protons from a point source which is why the deformation becomes more exaggerated further from the beam centre. The irregularity is detrimental as, in order to calculate a deflection, we must know exactly where the proton would have been which is less predictable with the deformations seen using the woven grid.

In order to avoid this problem, a second commercially available grid was located [105] which is not woven but electroformed. This is a grid that is produced by removing regions from a nominally uniform thickness piece of material resulting in no weave. The grid chosen was a nickel grid with a thickness of $25\text{ }\mu\text{m}$, a wire width of $41\text{ }\mu\text{m}$ and an aperture size of $340\text{ }\mu\text{m}$. The grid was set up 11 mm from the proton source and the RCF 44 mm from the source. A piece of optical fibre with diameter 1 mm was also placed ~ 20 mm from the source as a test object. Two RCF layers from a shot taken with this grid is shown in Fig. 6.6. This shot used a Cerberus pulse of 4.6 J, with intensity $\sim 1.1 \times 10^{19}\text{ Wcm}^{-2}$ and no deliberate pre-pulse onto a $15\text{ }\mu\text{m}$ aluminium foil. Three layers of RCF were used and two were activated. By comparing the two layers, it is clear that the top layer, shown in Fig. 6.6a has experienced some sort of strong grid pattern deformation and protons have arrived in the shadow of the fibre while the second layer Fig. 6.6b does not exhibit either of these effects. Reasons for this will be discussed shortly but the clear grid structure in Fig. 6.6b shows that the electroformed material has behaved as we expect with no distortions arising from a weave. The wire width is however small enough that overlapping of grid sections is a concern. Unfortunately, the only other grid with a larger wire size available with the means at the time was made of beryllium which was decided against due to the destructive environment it was to be placed in.



(a)



(b)

Figure 6.6: RCF images from the same shot of a Cerberus-generated proton beam. With a 1 mm diameter fibre fiducial in the centre. Image (a) shows the first layer of RCF with protons mainly of energy ~ 2.7 MeV and image (b) shows the next layer with protons mainly of energy ~ 6 MeV. The shot used a Cerberus pulse with energy 4.6 J and intensity $\sim 1.1 \times 10^{19} \text{ Wcm}^{-2}$ onto 15 μm aluminium foil.

The strong distortions, and signal behind the fibre, seen in Fig. 6.6a are believed to be caused by deflection of protons caused by ionisation and charge up of the grid and fibre. There are several candidates which could be argued to be the source of the charging: X-rays, electrons and protons/heavier ions. We can likely rule out X-rays as the distortion effect is localised to the brightest, central parts of the beam and X-ray emission from these foil shots is not strongly beam-like. Next, if we consider that the effect is only seen on the top layer of RCF, we can determine that the deflection influences the lower energy protons the most. Recalling from Section 6.3, we also determined that the first layer mostly shows protons that arrive at the detector later than those in the second layer by hundreds of ps. Therefore, we can infer that the charge is possibly caused by the passage of the higher energy protons ionising the grid before the low energy ones arrive at the grid. Without knowledge of the energy of the electrons, and hence velocity, it is not possible to know whether they would have caused the ionisation to deflect only the lower energy protons, however electrons are expected to be “prompt” compared to the proton beam due to their significantly lower mass. Regardless of the origin, this distortion is a detrimental effect which was not observed in shots using the copper grid which has larger size wires by a factor 10. It is possible that the larger wires suppress the effect, further supporting the usage of larger size wire grids. Alternatively, it could be that the effect was not observed on the copper grid shots due to a lower energy proton spectrum/yield as the laser pulse had a lower intensity and energy. These hypotheses could be constrained with a series of shots using different grids with varying wire sizes and varying laser intensity and energy.

6.5 Chapter Summary and Conclusions

We began this chapter by discussing the important characteristics of a laser-generated proton beam for use as a diagnostic probe in a FLF experiment, namely energy, pulse duration and source. Previous work had constrained the spectrum of Cerberus proton beams to be <10 MeV [54], meaning that pulse duration and source size were the priority in this project. Using EBT2 type RCF as a detector it was determined that 3 layers of EBT2 should be sufficient to observe Cerberus proton emission as the active regions in each layer would be sensitive to ~ 2.5 MeV - ~ 2.95 MeV, ~ 5.85 MeV - ~ 6.15 MeV protons and ~ 8.15 MeV - ~ 8.4 MeV protons. The production of protons occurs on a timescale comparable with the Cerberus laser pulse however we determined that, due to the spectrum of proton energies and therefore velocities, the temporal profile of the beam will spread to several hundreds of ps over 10s of mm.

As well as radiography of a sample using the attenuation of protons to image a potential FLF experiment, another use of proton beams is to measure the magnitude of electromagnetic fields from the deflection they cause. In order to do this a pattern is imprinted onto the beam to best measure the precise distance of deflection. This is usually achieved using a grid hence a woven copper grid was located through which a Cerberus proton beam was launched. Using the image produced it was possible to measure and map the effective source size by using the edges formed by the grid for penumbral imaging. Preliminary results indicate that the source size of the beam is between 5 and 40 μm dependent on position in the beam. The reason for the locations of smallest/largest source size has not yet been constrained. Comparing maps of source size to both beam brightness, and local variation in brightness seemed to show no correlation with effective source size.

The weave of the copper grid was found to lead to a deformation of a uniform grid structure when imaged by the proton beam. This is undesirable as, in the situation where the grid is deformed by deflection, it would be unclear where an original grid square would have been. An alternative grid which minimised this effect was identified and tested. This was an electroformed nickel grid which has no weave by being produced from a single piece of material. The size of the grid square separation relative to size of the squares (arising from wire thickness) was however small enough that overlap of adjacent spaces would be of concern. Using this grid it was found that there was a strong, detrimental deformation of the grid pattern on the first layer of RCF. This would render any data taken in a deflection experiment with “live” fields more problematic to analyse. The effect did not extend to the second layer which would be more usable when determining electromagnetic field effects. The cause of the deformation is likely due to ionisation and charge up of the grid. Since the first layer sees protons with energy $\sim 2.5 \text{ MeV} - \sim 2.95 \text{ MeV}$, which arrive at a later time than the second layer we can conclude that the charge up may arise from passage of the faster protons or possibly electron emission. The electrons would have to be slower than the $\sim 5.85 \text{ MeV} - \sim 6.15 \text{ MeV}$ protons otherwise we may expect to see deflection on the second layer.

To build on the work carried out here it would be useful to locate several other electroformed or similar grids with no weave. These should have varying wire sizes in order to see if the distortion originating from grid charge can be suppressed by larger wires. Locating grids with larger wires compared to grid aperture size would also be useful for avoiding the overlap of adjacent grid spaces for real deflection experiment.

Chapter 7

Synchronisation of a Shock Driver and the Cerberus Laser

7.1 Review of PhD Project and Chapter Introduction

Following the work carried out so far for this project, we can revisit the overarching impact-driven fusion-related objectives set out in the introduction and fill in some unknowns. Fig. 7.1 shows a modified version of Fig. 1.1. In order to establish a final FLF-relevant experiment, we add in important numerical details which underpin the experiment. The first being that a projectile travelling at several kms^{-1} traverses the $\sim\text{m}$ long barrel of a gas gun in ~ 1 ms. This projectile impacts a ~ 10 mm scale polymethyl methacrylate (PMMA) target, containing a mm scale cavity, and launches a several kms^{-1} shock wave into the PMMA. The shock traverses the block and cavity, which implodes over a timescale of a few μs , with sub- μs events such as jet impact on the rear surface of the cavity occurring on ns or sub-ns timescales. In order to predict projectile impact and synchronise a probe to this implosion as early as possible, the use of a potential projectile sensor known as a Faraday gate was explored in Chapter 4. This has been added to Fig. 7.1.

We next consider work on characterisation of different probe methodologies and evaluation of their suitability for a full scale FLF experiment. Beginning with X-ray sources, the important characteristics described in Chapter 5 — and Section 5.6 in particular — have been included in Fig. 7.1. We have found that only the X-pinch soft source is incapable of penetrating 10 mm of PMMA at $1.5\times$ density while the hard X-pinch source and Cerberus X-rays should be able to be partially transmitted. The sub-ns time resolution of each X-ray source will be satisfactory for imaging μs timescale processes involved in cavity collapse. The source size of

the hard X-pinch and Cerberus X-ray sources can be as low as $10\text{ }\mu\text{m}$ which will be ideal for imaging mm scale cavities.

Detail on proton beams generated by Cerberus were first discussed in Chapter 6 and have been included in Fig. 7.1. The most important point to note is that the spectrum is under 10 MeV, which means that a penetration of depth no greater than $700\text{ }\mu\text{m}$ can be achieved. As such, proton radiography of a full cavity collapse is currently unfeasible with Cerberus. If the beam is increased in energy to 40 MeV we would be able to penetrate 8.3 mm of shocked PMMA at $1.5\times$ density. Another option may be to isolate the jet generated in the cavity collapse by impacting an “open-backed” cavity which would be a hemisphere or half-cylinder machined into a PMMA block. Protons could be used to investigate electromagnetic fields around the released jet through deflection. Similar to Cerberus generated X-ray pulses, the duration (time resolution) of Cerberus generated proton pulses are of order ps length which are good for observing events in μs timescale cavity collapses and the $5 - 40\text{ }\mu\text{m}$ observed source sizes are ideal for imaging the mm scale cavities.

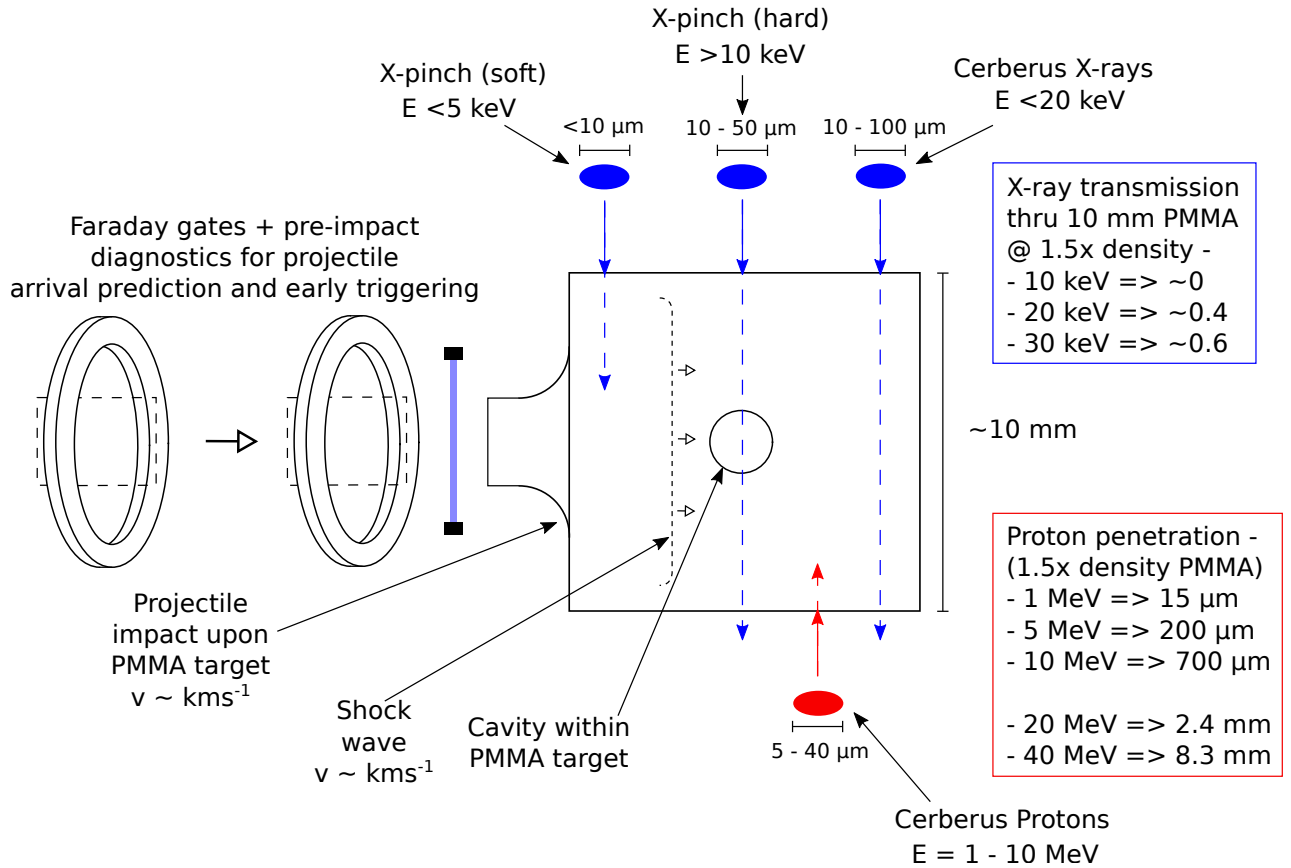


Figure 7.1: Idealised diagram showing an example FLF experiment. A PMMA block, containing a spherical cavity, is impacted from the left by a projectile. A shock wave is launched into the PMMA block. This is a developed version of the diagram shown in Fig. 1.1 which has added information gathered over the course of this PhD.

Over the course of this PhD, challenges were encountered with regards to combining the Cerberus laser system (or any comparable multi-TW laser) and a gas gun. Firstly, Cerberus is constructed from delicate optics, some of which would need to be in close proximity ($\sim$ centimetres) to a gas gun impact in order to probe a collapse with protons or X-rays. Protecting optics from this extremely violent process is both crucially important and difficult, which would entail invasive changes or use of “consumable” optics for final beam delivery. A second issue arises from the fact that the time taken from triggering to a pulse arrival in the Cerberus target chamber is 100 ms. The time taken for a projectile to travel the length of a gas gun barrel will be on the order 1 ms. This means that the Cerberus trigger system would have to be modified. However, the biggest obstacle to the goal of combining a gas gun and Cerberus arose from the time at which we were attempting to realise this experiment. Global events which occurred during the first quarter of 2020 imposed enormous limitations on experimental science. Since the portable two-stage light-gas gun described earlier in this project was based in Oxford at the time, it became impractical to wait for normality to resume.

Driven by the the limited time remaining for the project, other options were explored. While creating a potential experiment, the design was informed by the important aspects of synchronisation of a probe with launch/impact of a projectile, as well as the time/length scales and velocities which underpin a FLF-style experiment as described above. After some thought, two initial ideas were proposed which made use of the availability of lasers in our lab. The first proposal was to imitate an impact by directly driving a $\sim \text{kms}^{-1}$ velocity shock into PMMA using a laser pulse, which could then be synchronised to a Cerberus-generated probe in order to investigate the conditions generated behind the shock. The second was to create an analogue of a gas gun projectile by launching a thin flyer at $\sim \text{kms}^{-1}$ with a laser pulse which could then be radiographed or probed for electromagnetic fields using a probe generated by the Cerberus laser. Therefore this chapter will focus on exploring the possibility of executing each of these options.

7.2 Direct Laser-Driven Shock Waves

Pulsed lasers can be used to generate shock waves in a target, achieving pressures >10 Mbar post shock, even in low atomic number (Z) materials such as polystyrene [106]. Prior to the advent of lasers, the only way to create a shock wave capable of imparting this pressure was to initiate a nuclear explosion [107]. In this section we shall discuss the process of shock wave generation by a laser pulse, the consequences of the shock pressures that can be created to a wider field of research, as well as the scope of this thesis. We shall then consider the crucial aspects of a laser-driven shock experiment focusing particularly on laser conditions in previous work. Finally we shall draw together the constraints on laser parameters and target designs to explore the possibility of conducting such an experiment with the Cerberus laser.

A laser pulse incident upon an absorbing (or initially reflective) target will penetrate to the target's skin depth, ~ 4.9 nm for Cerberus laser radiation ($\lambda = 1053$ nm) with aluminium. The energy required to fully ionise the aluminium atoms within a cylinder of depth 4.9 nm and diameter equal to the laser focal spot — say 1 mm — is $\sim 10^{-4}$ J. As such a Cerberus pulse with energy >3 J will rapidly create a hot and dense plasma at almost solid density [108]. For this density plasma, the plasma frequency (see Equation (5.6)) is larger than the frequency of the laser radiation i.e. the plasma is over-dense. As was described in Section 5.2.1, laser propagation is inhibited in the over-dense plasma and the laser radiation is partially absorbed by the thin layer of plasma via collisional inverse bremsstrahlung [108] (only for intensities below $\sim 10^{15}$ Wcm $^{-2}$, above this intensity we begin to trigger additional absorption mechanisms such as resonance absorption vacuum heating [69] as described in Section 5.2.1). The absorption of the laser pulse generates a temperature and pressure gradient which in turn causes a rapid adiabatic expansion of the plasma [108], launching a stress pulse into the target material. If the laser intensity is high enough to create a stress pulse propagating with a velocity higher than the sound speed in the target, the pulse is a shock wave.

Recalling the content from Chapter 2, similar to other shock drivers, an appeal of laser-driven shocks is in the measurement of the equation of state (EoS) of materials. Knowledge of the EoS of a material allows us to predict its behaviour under extreme pressure and temperature conditions. Hydrodynamic and thermodynamic models make use of EoS, however there exists relatively little experimental data to verify the calculations at high pressure regimes [109]. Therefore, use of a laser-driven shock is particularly exciting as the high pressures behind the shocks allow the study of material behaviour in a regime less easily attained by shock drivers such as gas guns. Gas guns typically attain a dynamic pressure ≤ 1 Mbar (100 GPa) [39, 41, 58]

whereas laser-driven shocks have been observed to attain pressures as high as 30-40 Mbar (3-4 TPa) [107, 110]. For context, the pressures within the core of the Earth reaches ~ 3 Mbar (300 GPa) hence laser-driven shocks are useful to geophysics in the measurement of the EoS of materials such as iron at high pressure [111, 112]. Another crucial use is in the EoS measurements of plastics such as polystyrene (CH) at high pressure which is a primary material used for inertial confinement fusion (ICF) capsules [106, 110]. As such, an application of direct laser-driven shocks relevant to FLF would be in measuring the EoS of PMMA at high pressure states which would be useful for the validation and refinement of hydrodynamic codes used by FLF. Before discussing an experiment using Cerberus we shall consider constraints on target design and laser parameters provided by the literature.

7.2.1 Literature Review

Chaurasia et al. [113] give a succinct summary for four crucial design aspects of a laser-driven shock experiment. These are: the peak laser intensity, the laser pulse length, the target material and depth at which we wish to observe the effect of the shock within the target. In addition, it can be argued that the uniformity of the spatial intensity profile of the laser pulse must also be considered as this directly influences the quality of the shock front, and that quantitative data can be extracted with good confidence. We shall now address and summarise each point separately.

Target Design — Materials and Thickness A target material should not be transmissive to the driving laser and radiation emitted by the laser produced plasma. Ideally we would eliminate transmission of X-rays and electron radiation ahead of the shock. This is however difficult due to their penetrative nature. Transmission of radiation can cause preheating of target material ahead of the shock wave and changes the initial density and temperature state of the target material. Since EoS measurements require knowledge of the initial state of a target, preheating poses undesirable consequences to these types of experiments [114, 115]. Moreover, the level of preheating will not necessarily be spatially uniform and as such can introduce perturbations in an otherwise flat shock front due to different parts of the shock encountering different density material. Previous work [106, 112] has shown success in suppressing preheating by attaching a simple two layer base to targets. An ablator layer of polystyrene (several μm thick) and a layer of ~ 100 nm thick aluminium on the side closest to the laser is used to absorb high intensity radiation and prevent shine through into the main target respectively.

In a general shock experiment there will be a point within the target which is being observed, for example in a cavity collapse this would be the depth of the cavity within the target plastic. Due to the effect of preheating it may seem logical to make a target as thick as possible. This however is unwise. Upon launch of a shock, a relaxation wave begins travelling laterally from the outer edge of the shock propagating to the centre of the wave. This relaxation wave tends to turn an initially flat wave front spherical on a long enough timescale [115]. Therefore, if we have a target with a point of observation at depth d where we wish to have a shock wave front with a flat surface of characteristic size (diameter in this case) ϕ_d , we impose limitations on the size of the laser focal spot ϕ_0 which creates the shock,

$$\begin{aligned}\phi_0 &\geq \phi_d + d \\ &\geq 10d\end{aligned}\tag{7.1}$$

where we use whichever form provides the largest value for ϕ_0 [115].

Laser Pulse Length Upon cessation of the shock-driving laser pulse, another relaxation wave (see Section 2.1.2) begins to propagate from the irradiation zone through the target. The relaxation wave travels at a velocity greater than the shock wave so at some time the relaxation wave will overtake the shock wave front which then begins to decrease in velocity [115]. This effect imposes a maximum target thickness or a depth at which we can observe a shock within a target d and is given by,

$$d \leq 2D\tau,\tag{7.2}$$

which depends on the shock velocity D and laser pulse duration τ [115]. From Equation (7.2) we therefore see that a longer laser pulse length is desirable. For a given energy budget and focal spot size, extending a laser pulse duration will decrease intensity, the consequences of which will now be considered.

Laser Peak Intensity The intensity of a laser pulse with energy E and duration τ focused onto a circular spot of radius r is given by,

$$I = \frac{E}{\tau\pi r^2}.\tag{7.3}$$

Peak intensity is a crucial parameter to constrain as it directly affects the mechanisms by which a laser pulse will interact with a target. As discussed in previous chapters for X-ray and proton generation, at intensities greater than $\sim 10^{15}$ Wcm $^{-2}$ we begin to access ion acceleration mechanisms and X-ray production which can drastically alter the structure of a target and cause a large amount of preheating which makes observation of the effects of a shock wave difficult. Too low an intensity will not generate a shock wave however.

Laser Spatial Intensity Profile A uniform spatial distribution of intensity in the laser pulse will result in an initially flat shock wave front and is therefore desirable. Several experimenters [107, 109, 111] have made use of an optical elements known as a phase zone plate. These are used in conjunction with a focusing lens to produce an approximate flat top profile of intensity and drive a planar shock into a target. Controlling laser spatial intensity profiles is a significant subject which will be referred to in multiple parts of this thesis, as such please see Section 7.2.2 for detail on phase zone plates and other methods for achieving a uniform laser spatial intensity profile.

7.2.2 Laser Spatial Intensity Profile Smoothing

Creating a laser with a spatially smooth intensity profile at focus is of importance to ICF where non-uniformities can lead to instabilities in the collapse of a fusion pellet [116, 117] and to processes such as laser cutting and welding [118]. For the scope of this thesis, intensity profile smoothing is pertinent to creating flat laser-driven shocks propagating into materials and for launching planar flyer plates, see Section 7.2 and Section 7.3 respectively. We shall now discuss several methods for achieving spatial intensity profile smoothness.

Induced Spatial Incoherence One can impose an optical delay upon different parts of the spatial profile of a laser beam by propagating portions of the beam through different thicknesses of a transparent medium. Induced spatial incoherence (ISI) harnesses this method with an optical element such as an echelon [117], a type of wedge shaped optic where the thickness of the wedge increases in discrete increments (steps). One stipulation of ISI requires that the laser, with central wavelength λ , has a large wavelength bandwidth $\Delta\lambda$ such that the coherence time be short compared to the laser pulse duration [117], where the laser coherence time τ_c is,

$$\tau_c \approx \frac{\lambda^2}{c\Delta\lambda}. \quad (7.4)$$

After passage through the echelon a beam is split into a series of beamlets which are temporally delayed by different amounts. Upon focusing of these beamlets by a main lens, an interference pattern is created within an envelope given by the diffraction pattern of a single beamlet. Over time scales large compared to the coherence time, the interference pattern averages out and a smooth intensity profile independent of any nonuniformity in the initial beam can be created [117]. The central area of the envelope essentially becomes the size of the new focal spot, the width of which is given by,

$$\phi_s = \frac{2\lambda f}{d}, \quad (7.5)$$

where f is the focal length of the main focusing lens and d is the width of an echelon step [117]. While this method creates a smooth intensity profile, it is not ideal for making a flat top beam due to the curved profile of the central part of diffraction pattern.

Random Phase Plates This method, demonstrated by Kato et al. [119], achieves intensity smoothing by using an optical element known as a random phase plate (RPP). A RPP contains an array of elements which divide a beam into smaller beamlets and impart a random phase difference of either 0 or π upon each beamlet. Similarly to ISI these beamlets are then focused and an interference pattern of intensity is created from the rays diffracted by each element of the RPP. The interference pattern is superposed upon a sinc^2 envelope function and the overall profile is insensitive to any initial intensity nonuniformity [119]. As with ISI the width of the central part of this envelope function is given by Equation (7.5) but d is now the width of an element of the RPP. As with ISI, RPPs will not form a flat top profile.

Phase Zone Plates This is an adaptation of the RPP where each element is specifically a binary zone plate and the overall optic is known as a phase zone plate (PZP). Binary zone plates can be seen in Fig. 7.2 as the individual cells making up the PZP; the light and dark rings making up a binary zone plate have the same area. As with an RPP, elements of the PZP diffract passing light, separating the beam into a series of beamlets and apply a phase shift of either 0 or π [116]. Fig. 7.2 shows the intermediate focal plane where beamlets diffracted by each binary zone plate are focused. These beamlets then defocus slightly and coincide at the principal focal plane of the main focusing lens. As with ISI and RPP the intensity profile of the beam at the principal focal plane is given by the superposition and averaging of all beamlets and is independent of the initial beam intensity profile [116]. The size of the focus at the principle focal plane ϕ_s is given by,

$$\phi_s \sim \frac{df_p}{f_z}, \quad (7.6)$$

where d is the width of a single binary zone plate, f_p and f_z are focal lengths of the principal focusing lens and binary zone plate respectively [116]. This method is preferable to RPP and ISI as it creates an approximately flat top profile.

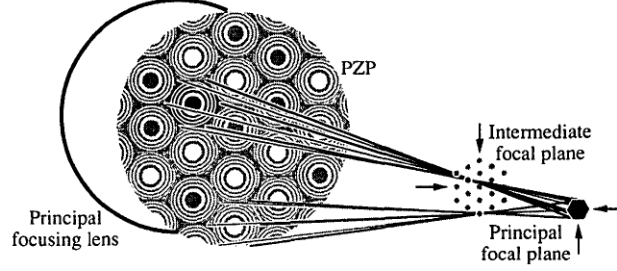


Figure 7.2: Schematic from Stevenson et al. [116] showing the focusing of light through a PZP by a principal focusing lens. The structure of individual binary zone plates can be observed. The intermediate focal plane is created by the focusing of beamlets by individual binary zone plates. The beamlets then defocus and are coincident upon the same point in the focal plane of the principal focusing lens.

Lens Arrays This method uses an optical element comprising of an array of small lenses to achieve a result similar to the PZP. The lens array separates the main beam into an array of beamlets and a main focusing lens is used to combine these beamlets [118]. An intermediate focal surface and principal focus is formed similarly to that shown in Fig. 7.2 and the width of the principal focus can be found using Equation (7.6) replacing d and f_z respectively with the width and focal length of a lens within the lens array. Like PZP this is a more attractive method for intensity profile smoothing than either ISI or RPP as an approximate flat top profile is created.

7.2.3 Laser-Driven Shock Waves with Cerberus

In this section we determine the laser pulse parameters we would need to use to generate a shock wave using the Cerberus laser. The laser parameters and pressures attained by previous experiments are displayed in Table 7.1. Firstly we shall establish that in order to emulate a gas gun impact, we require a shock pressure ~ 1 Mbar. From Table 7.1, we can see that to create a shock pressure of at least 1 Mbar in a material such as polystyrene (CH), we should use a pulse intensity in the range $\sim 10^{13} - 10^{14} \text{ Wcm}^{-2}$.

Using Equation (7.3), we can see that the intensity of a laser pulse with a given energy and duration will be maximised by finding the minimum focal spot size. That way we have the option to stretch the pulse, or more likely expand the beam, in the event of the intensity being larger than the desired range. In order to determine the minimum focal spot size for a Cerberus laser pulse we must consider the scale of the target and apply Equation (7.1). We wish to image the collapse of a spherical cavity or the jet generated by an open-backed, hemispherical cavity; this requires that the flat part of the shock front be at least the size of the cavity diameter, at the depth of the widest part cavity in the target. Realistically the minimum cavity diameter will be ~ 1 mm. Applying this to Equation (7.1) requires $\phi_d = 1$ mm and also sets a minimum observation depth for d as the cavity radius, 0.5 mm. The dominant form of Equation (7.1) informs us that the spot size will need to be at least 5 mm.

Experiment	Pulse energy [J]	Pulse duration [ns]	Spot size [mm]	Intensity [Wcm^{-2}]	Target	Pressure [Mbar]
Krehl (1975) [108]	4 - 11.5	25	5	$8 \times 10^8 - 2 \times 10^9$	Al	8×10^{-4}
Benuzzi (2002) [111]	<100	0.72	0.5	$8 \times 10^{12} - 6 \times 10^{13}$	Fe	1 - 8
Koenig (1998) [109]	<70	0.6	0.4	$< 5 \times 10^{13}$	CH	1 - 3
Koenig (1995) [107]	<100	0.6	0.4	$3 \times 10^{13} - 1 \times 10^{14}$	Au	10 - 35

Table 7.1: Compilation of laser pulse parameters, target materials and resulting shock parameters from previous experiments which used direct laser-driven shock waves.

Assuming a minimum observation depth d of 0.5 mm, we can apply Equation (7.2) to determine the laser pulse duration which would cause the rear relaxation wave and shock front to arrive simultaneously at the observation depth. This essentially gives the minimum pulse length. From data provided by previous EoS studies upon polymers of similar densities to PMMA [106, 109, 120], we can estimate that a shock of velocity $\sim 10 \text{ kms}^{-1}$ would generate a dynamic pressure of ~ 1 Mbar in PMMA. This provides the value of D in Equation (7.2) and in turn gives a minimum pulse length of 25 ns. This will be difficult to achieve with Cerberus as the existing long pulse beam line has a pulse duration of ~ 1.4 ns.

Suppose we are able to stretch the Cerberus pulse length to a minimum of ~ 25 ns and we have a focal spot size of 5 mm, what is the requirement on the pulse energy to create a given intensity? Fig. 7.3 shows the variation of laser pulse energy with pulse duration along lines

of constant intensity. The intensity region which laser-driven shock experiments [107, 109, 111] use to create dynamic shock pressures of at least 1 Mbar is labelled between 10^{13} and 10^{14} Wcm^{-2} . From Fig. 7.3 we can see that in order to reach this intensity region with a 25 ns pulse duration we will need energy exceeding 40 kJ, 4 orders of magnitude larger than the energy currently accessible by Cerberus.

In conclusion, using a Cerberus laser pulse to directly drive a shock wave through and collapse a full scale FLF-style cavity target is currently impractical for several reasons. Firstly the relatively large, >1 mm, scale of a cavity collapse target requires a pulse length of at least 25 ns to avoid deceleration of the shock front before we can observe its effect by a rear relaxation wave. The relaxation wave is released from the irradiation zone after cessation of the laser pulse, travels faster than the shock wave and causes deceleration of the shock upon overtaking it. The scale of the cavity also requires that the laser focal spot have at least a 5 mm diameter in order to create a flat shock front that is the size of the cavity. From previous work [107, 109, 111] we require an intensity between 10^{13} and 10^{14} Wcm^{-2} . The intensity, pulse length and focal spot size restrictions lead to a required pulse energy of at least 40 kJ. As such we should investigate other means of shock generation.

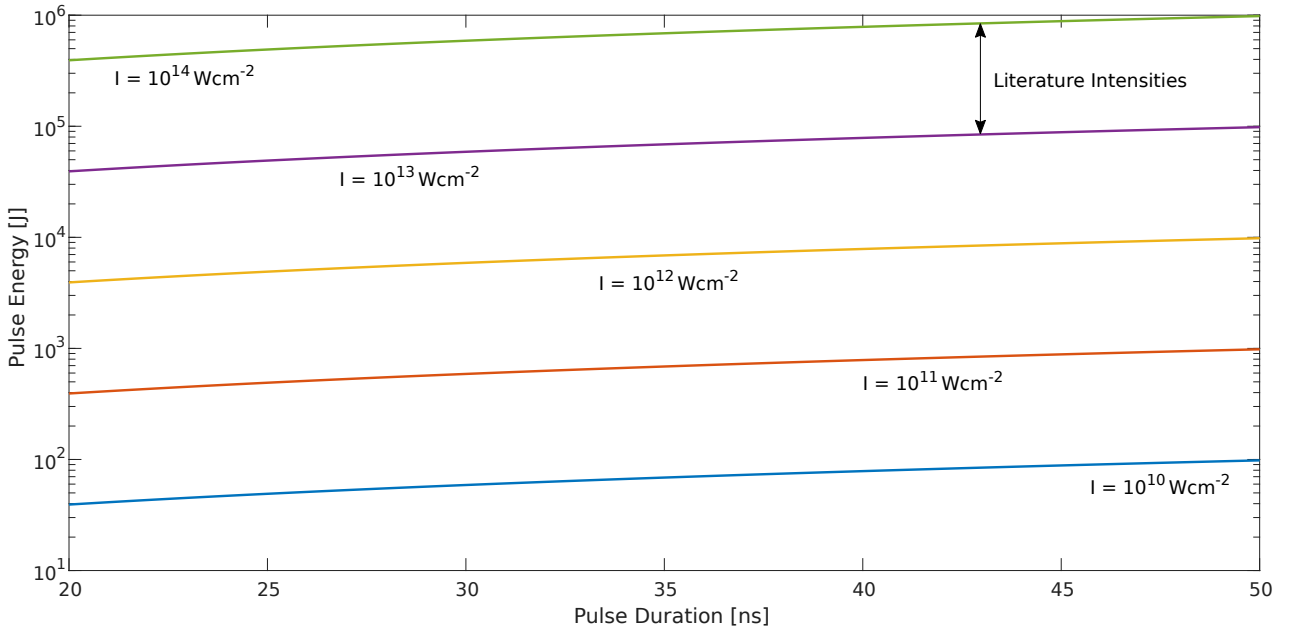


Figure 7.3: Theoretical plot of laser pulse energy versus pulse duration. Upon the graph are lines of constant intensity between 10^{10} and 10^{14} Wcm^{-2} . The purpose of the graph is to show the energy and duration requirements on a laser pulse to create an intensity given by the line upon a 5 mm diameter circular focal spot. Also specified is the intensity region used in laser-driven shock experiments [107, 109, 111] to create dynamic shock pressures of at least 1 Mbar.

7.3 Laser-Driven Launch of Miniature Flyer Plates

A laser-driven flyer plate is a type of projectile which can be created by focusing a relatively short ($\sim$ ns duration) laser pulse onto an absorbing material. This material is typically a micron-scale thickness metal foil. The foil can be constructed of either a single layer, or a composite of multiple layers, designed to control the resulting characteristics of the launched flyer. Using this method, flyer plates with velocities of the order 1 kms^{-1} can be attained using a modest laser system ($<30 \text{ mJ}$ pulse energy) [121]. The foil is often first mounted upon a transparent substrate which provides both a robust mount for the thin flyer to be launched from, and improves the coupling of laser energy into the flyer itself. The coupling is improved as the substrate tamps, or directs, the energy from the laser into the launch of the flyer more effectively than if the foil was simply suspended in air or vacuum [122]. We will now discuss the physics involved in a flyer plate launch, their uses in physics research and what has been discovered so far in target design and characterisation of flyer plates.

The physical process by which a flyer plate is launched can be explained thusly. In the same manner as in Section 7.2, the energy of the incident laser pulse is absorbed by a target forming a plasma which is rapidly heated and begins to expand. The process then deviates from solely launching a shock into the target as the expansion eventually forces the foil to rupture around the plasma and launch a section of the foil [123]. The size of the resultant flyer can be controlled by either changing the laser focal spot size or by physically limiting the size of the flyer foil to be smaller than the focal spot. Post launch, some of the plasma has been shown to remain attached to the flyer for up to $15 \mu\text{s}$ [123] and can actually increase in size immediately after launch as portions of the flyer are further ionised during flight [125]. This aspect will be of interest to the work in this thesis and explained below.

Laser-driven flyer plates are interesting to multiple streams of physics. Primarily, the ability to “tune” the velocity and size of a flyer plate by selecting certain laser parameters and target designs allows the driving of short and controlled shocks in a target impacted by the flyer plate [121]. This allows for high-strain rate material testing and measurements of spall strength in a test material impacted by a flyer plate [122], material testing for the spacecraft industry by simulating hypervelocity impacts (velocity $>3 \text{ kms}^{-1}$) caused by space debris [126] and the shock initiation of explosives. The latter has been demonstrated by Paisley [124] who detonated fine grain explosives with $2 \mu\text{m}$ thick Al flyer plates launched at $\sim 1.8 \text{ kms}^{-1}$. Furthermore, laser-driven flyer plates are of interest to the defense industry as they represent an analogue for larger weapons systems and the testing of high energy density munitions [123].

Laser-driven flyer plate impacts are effectively a compact version of a gas gun impact. Thus they are an ideal subject for the work in this thesis in lieu of being able to install an actual gas gun into the Cerberus target area. Moreover, a laser-driven system holds a number of advantages over a gas gun for our current work: it would require less lab-space by comparison, be capable of more tests in a given time period, said tests would be cheaper and there is a lower risk of debris obliterating a delicate diagnostic system allowing the inclusion of a larger suite of diagnostics [123]. An experiment whereby a shock is driven into an impactor by a laser-driven flyer relies on creating a planar flyer [127] at high velocity ($>1 \text{ kms}^{-1}$). As such, the major body of research on laser-driven flyer plates is focused on the measurements of velocity, planarity, integrity and how each varies with target designs and input laser parameters. We shall now review what has been recorded in the literature.

7.3.1 Literature Review

Target Design and Mounting From previous work there are two established methods for adhering a pre-launch flyer foil to a substrate. Firstly, physical vapour deposition (PVD) whereby a material is first vapourised and μm thickness foil layers are condensed and deposited upon the substrate under vacuum [121, 122, 124, 125, 127, 128]. Alternatively, a foil can simply be held in contact with a substrate using an adhesive such as epoxy [123], or a physical rig to hold the foil and substrate in contact and silicone grease is used to optically couple the two with no air/vacuum gap [129]. PVD removes the need for an adhesive which has been shown to improve coupling efficiency of laser energy into the flyer to $\geq 30\%$ [122, 127] however it does require more specialist equipment in order to create, and layer thickness greater than a few μm can be subject to significant internal stress and peeling.

There are also two different substrates commonly used in the literature. The most common is UV-grade fused silica glass or quartz (high purity, non-crystalline and high transmittance in the UV, optical and low to mid-IR ranges) of thickness 1-3 mm [123–128]. The other is multi-mode optical fibres [121, 122, 129]. The advantage of a multi-mode fibre is that a spatially uniform energy profile, and hence a planar flyer launch, can be achieved by virtue of many internal reflections of the laser within the fibre [122]. The fibre diameter also tightly controls the size of the laser spot which is useful for controlling fluence, intensity and size of the flyer plate, whereas for a larger substrate the fluence and flyer size depend on focusing the laser and knowing the size of the beam at the substrate-foil interface. A disadvantage of using fibre is that there is a limit on the energy supplied to a flyer at the point where the fibre core breaks

down, and can be triggered by self-focusing within the fibre for B-integral values ≥ 3 . This was observed to occur when pulse intensity reached $\sim 4 - 5 \text{ GWcm}^{-2}$ [129]. A hybrid version, combining aspects of both of these methods was created by Greenaway [130]. This method used the spatially uniform energy profile and beam size control provided by a multi-mode fibre which was then directed onto a separate, substrate-backed foil. This allows reuse of the same fibre for several shots without having to repolish and reattach a foil to a fibre after every shot which can be a time-consuming process. Furthermore, in a separate paper [131], Greenaway found that the transmission at the front surface of such fibres would improve with repeated use thanks to laser-produced plasma annealing the fibre surface. This improvement would be “reset” if the fibre has to be repolished after every use.

Finally the foils themselves are typically made from a single layer of material or constructed of a composite of two or three layers. The majority of the literature focuses on single layers [125–127, 129] and comparing the performance of different elemental foils [123]. The result of this comparison work demonstrated that aluminium will attain a higher final velocity than copper of the same thickness, for the same laser conditions. This is likely because aluminium has a lower total ionisation energy and density than copper. Thus, for the aluminium, more laser energy is available to be converted to kinetic energy of the flyer, and the flyer also has a smaller mass leading to a higher final velocity. This hypothesis could be tested using carbon or magnesium foils which have lower density and ionisation energy than aluminium. Also the degree of annealing was found to have no effect on final velocity [123]. For a given laser pulse energy and fluence, it has been found that higher velocities can be obtained using a composite foil of two or more layers as opposed to a single one [121, 124, 128]. These flyers are typically created using PVD to create a thin layer of a metal at the substrate interface followed by a dielectric layer such as a metal oxide and sometimes a final metal layer on top of the oxide. These layers are all typically $\sim 1 \mu\text{m}$ thick. The crucial aspects of a composite flyer are the first metal layer such as aluminium which acts as an efficient laser energy absorber and is designed to vapourise entirely and become a driving plasma, a dielectric layer such as aluminium oxide acts as a thermal barrier preventing diffusion of heat into the latter layer (if present) and conversion of the whole flyer into plasma, ensuring some of the flyer always remains solid [121]. This design results in an efficiency of $\geq 50\%$ for conversion of laser energy into flyer kinetic energy and an increase in kinetic energy of $\sim 30\%$ over equivalent thickness single layer flyers [124, 128].

Flyer Plate Planarity and Integrity In order to generate a planar, uniform shock wave with an impactor, the flyer plate must also be planar and remain intact throughout its flight. The integrity of flyer plates has been studied by observing light from the plasma build-up behind a flyer, penetrating through the flyer as the front surface is compromised. Watson and Field [125] used this method and showed that the time at which this occurred depended upon the flyer thickness and laser energy. It is suggested penetration occurs in thin flyers due to Rayleigh-Taylor instabilities where a significant portion of the flyer is converted to an expanding plasma which exhibits fluid-like behaviour and pushes into the remaining solid density flyer material [132]. In flyers containing a dielectric layer, as discussed in the previous sub-section, it is possible the dielectric layer can fail if the laser fluence is too high. What this means is the dielectric layer is vapourised rather than acting as a thermal barrier, compromising the integrity of latter layers. This occurred at a fluence of $\geq 15 \text{ Jcm}^{-2}$ for a $< 4 \mu\text{m}$ flyer composed of aluminium oxide sandwiched between two layers of aluminium [128], the exact layer thicknesses are not specified. The integrity of flyers may also be compromised due to shear forces caused by a velocity gradient across the flyer caused by a non-uniform laser beam for example [125]. We shall discuss methods for achieving uniform laser spatial energy distribution below.

The planarity of a flyer is mainly influenced by the driving laser used to create it. If the laser has a non-uniform spatial energy distribution, containing hotspots for example the launched flyer plate will be accelerated more where the hotspots exist, leading to shear forces and a non-planar flyer. As such, a flat-top laser beam is crucial. This can be achieved by using a multi-mode fibre optic delivery system with core sizes up to 1 mm diameter [129] as discussed in the target mounting section above. Alternatively a crude flat-top profile can be attained by physically cutting the edges of the beam profile with an opaque filter and using spatial filtering to improve beam quality or more elegantly by using an optic which reduces non-uniformities in laser spatial intensity distributions [123]. The example shown by Dean [123] is a lens array which converts a Gaussian spatial profile beam into an approximate flat-top profile by breaking the beam into a series of beamlets which are recombined by a focusing lens. Section 7.2.2 covers the function of lens arrays along with other methods for intensity profile smoothing in further detail. One result has shown flyer planarity is maintained over flight distances $\sim 300 \mu\text{m}$ by using multi-layer flyers rather than single layers [121]. Therefore in order to ensure a planar impact we should have a flat-top laser profile, a flyer with thickness $\geq 4 \mu\text{m}$ to avoid vapourisation by the laser and a short flight length, preferably $< 500 \mu\text{m}$. Previous work has observed planarity by photography with a high-speed camera [123] or a

streak camera [121, 124, 125, 127] to image the full width of flyers viewed perpendicular to the direction of flight. These diagnostics can also be used to measure the velocity of flyers since the time between frames and photos is known. This leads us directly into the next section.

Flyer Plate Velocity Measurement and Prediction There exists a number of established methods for the measurement of flyer plate velocities. These include streak and high-speed photography, which give average velocity between frames. VISAR [123, 124, 127] and ORVIS [121, 129] are types of velocity interferometry which provide full velocity history and acceleration information for the flyer. VISAR results have revealed that accelerations of $>10^9\text{g}$ can be seen and flyers attain 90% of their maximum velocity in ~ 2 FWHMs of the laser pulse duration (typically in the range 10 - 50 ns for most laser-driven flyer experiments). Laser fluence (pulse energy per unit area) appears to be the crucial parameter to constrain in order to determine the velocity of a flyer plate. One experiment [123] shows a linear scaling of velocity with fluence between 7 and 15 Jcm^{-2} for 25 μm thick flyers. Above this fluence, velocity plateaued which was suspected to be due to energy loss to substrate damage.

A theoretical model [133] has been created which determines a flyer plate final velocity from laser and flyer material properties as well as threshold fluence required to launch the flyer. The flyer velocity can be found using,

$$v = \sqrt{\frac{3E_{tot}/x_d}{(3x_0/2x_d) - 1}}, \quad (7.7)$$

where E_{tot} is the kinetic energy given to the flyer, x_0 is initial flyer thickness and x_d is the thickness of vapourised flyer material [133]. Equations for finding E_{tot} and x_d are provided,

$$x_d = \frac{1}{\mu_{eff}\rho} \ln \left(\frac{\mu_{eff}F_0(1-r)}{\epsilon_d} \right) \quad (7.8)$$

$$E_{tot} = \frac{F_0(1-r)}{\rho} - \frac{\epsilon_d}{\mu_{eff}\rho} \left(1 + \ln \left(\frac{\mu_{eff}F_0(1-r)}{\epsilon_d} \right) \right) \quad (7.9)$$

where F_0 is the laser fluence in Jcm^{-2} , ρ is the flyer material density, r is the effective energy loss (including radiative and reflective losses), ϵ_d is the flyer material vapourisation energy and μ_{eff} is flyer effective absorption coefficient [133]. Finally, μ_{eff} is given by,

$$\mu_{eff} = \frac{\mu_a}{1 + k\mu_a\rho\sqrt{\alpha\tau}}, \quad (7.10)$$

where μ_a is the flyer true absorption coefficient, k is an absorption coefficient constant, α is the thermal diffusivity of the flyer material and τ is the laser pulse duration [133]. Equations (7.7) to (7.10) allow the prediction of flyer velocity if we constrain all the required input parameters. Some of these are readily available including laser pulse duration and fluence, target thickness and density. The effective energy loss r and effective absorption coefficient μ_{eff} of the flyer must be retrieved experimentally however. Fortunately the values for the aluminium used as a test case in the study are supplied and shown in Table 7.2. Therefore this model can be tested against results from other experimenters using aluminium and broadly constrain its expected accuracy for predicting the velocity of a flyer launched by the lasers used in this project.

MATERIAL PROPERTIES FOR ALUMINUM	
Material Density, ρ (g/cm ³)	2.7
Decomposition Energy, ϵ_d (kJ/g)	12
Thermal Diffusivity, α (cm ² /s)	0.8
True Absorption Coefficient, μ_a (cm ² /g)	4.4×10^5
Absorption Coefficient Constant, k (Dimensionless)	0.2533
Effective Energy Loss, r (Dimensionless)	0.6

Table 7.2: Material properties of aluminium supplied by Lawrence [133]. This is included for convenience as the last 3 parameters must normally be calculated experimentally.

Laser parameters, target details and attained velocities have been retrieved from experiments reported in the literature and are shown in Table 7.3. Also included is the velocity calculated using Equations (7.7) to (7.10) for pure aluminium targets. From the predicted velocities in Table 7.3, we see the model is accurate to within 20% for optical fibre-launched flyers. The discrepancy may be caused by differences in coupling of laser energy caused by oxidation or machining marks on the surfaces of different pieces of aluminium. The velocity prediction for aluminium fixed by PVD upon a large fused glass substrate appears to be significantly underestimated. This could suggest that large, rigid substrates (compared to an optical fibre core) are more efficient for coupling laser energy into a flyer, perhaps through tamping of the shock into the flyer. Coincidentally, the velocity predicted for a foil, adhered onto a large glass substrate by epoxy is close to the observed values for fluences of 7.5 and 15 Jcm⁻². This could be due to the epoxy layer decreasing the coupling efficiency of laser energy to the flyer which effectively counters the increase in coupling efficiency provided by the large glass substrate. Finally, the model overestimates for a fluence of 30 Jcm⁻². This is likely due to the model not compensating for energy loss due to substrate damage as shown by Dean [123].

Experiment	Pulse energy [mJ]	Spot size [mm]	Fluence [Jcm^{-2}]	Pulse length [ns]	Intensity [Wcm^{-2}]	Target	Adhesion, Substrate Type	Thickness [μm]	Flyer vel. [kms^{-1}]	Predicted vel. [kms^{-1}]	Flyer K.E. [mJ]	Efficiency [%]
Trott (1994) [121]	~ 6	0.4	~ 5	18	$\sim 3 \times 10^8$	Al	PVD, 0.4 mm diam. multi-mode fibre	4	~ 0.7	0.8	0.3	5.6
	~ 20		~ 17		$\sim 1 \times 10^9$				~ 3.2	2.8	7	35
	~ 6		~ 5		$\sim 3 \times 10^8$	Al/ Al_2O_3			~ 1.7	N/A	N/A	N/A
	~ 20		~ 17		$\sim 1 \times 10^9$				~ 3.5	N/A	N/A	N/A
Trott and Meeks (1990) [129]	20	0.4	~ 16	25	$\sim 6 \times 10^8$	Al	Grease, 0.4 mm multi-mode fibre	25	~ 1.2	1.0	6	31
								5	~ 2.7	2.3	6	31
Watson and Field (2000) [125]	56	~ 1	~ 7	10	$\sim 7 \times 10^8$	Al	PVD, fused silica	4	2.0	1.5	17	30
	103		~ 13		$\sim 1.3 \times 10^9$				4.0	2.5	68	66
	153		~ 19.5		$\sim 2.0 \times 10^9$				4.6	3.3	90	59
Dean, Gottfried et al. (2016) [123]	~ 100	1.3	7.5	6	$\sim 1.25 \times 10^9$	Cu	Epoxy, glass slide	25	0.25	N/A	9	9
	~ 200		15		$\sim 2.5 \times 10^9$	Al			0.6	0.67	16	16
									~ 400	30	$\sim 5.0 \times 10^9$	1.2

Table 7.3: Compilation of results retrieved from a number of laser-driven flyer plate experiments reported in the literature. Important laser parameters and target details are specified. The final four columns show attained flyer plate velocity, final velocity predicted by the theoretical model described by Lawrence and Trott [133], kinetic energy held by the flyer and finally the efficiency of conversion of laser pulse energy into flyer kinetic energy.

7.3.2 Laser-Driven Flyer Plates with Cerberus and Experiment Proposal

We now have enough information to discuss a laser-driven flyer plate experiment conducted using the Cerberus laser. Due to the design of the Cerberus target chamber, the most convenient method for launching a flyer will be from the end of a fibre. A pulse can be injected into a fibre of ~ 1 m length and the flexible nature of the fibre means that the flyer end can be placed in close proximity to the target chamber centre. This will allow relatively easy probing of the flyer using a proton or X-ray beam generated by the Cerberus main beam. The fibre propagation will also aid in spatial intensity profile smoothing. Commonly available aluminium foil adhered to the fibre end with epoxy glue would make a good first target for flyer launch since this target is simple to create compared to a target made using PVD. The model discussed in the previous section predicts the velocity fairly accurately and prediction of the velocity and position of the flyer post-launch will allow the timing of a probe to observe the flyer. Moreover, using a target of thickness $\sim 15 \mu\text{m}$ (the thickness of a common aluminium kitchen foil) should provide sufficient integrity as observation of the breakdown of single layer flyers occurred for flyers of thickness $4 \mu\text{m}$ [121]. Planarity of the flyer will have to be controlled by beam shaping such as using a diffusive optic, and multi-mode propagation in a large core fibre.

The model provided by Lawrence [133] gives an equation for the calculation of threshold fluence, F_{th} ,

$$F_{th} = \frac{\epsilon_d}{\mu_{eff}(1 - r)}. \quad (7.11)$$

As we can see from Equations (7.10) and (7.11), for flyers of the same material, the threshold fluence is dependent only on laser pulse duration. One result found that the threshold fluence required to launch a $25 \mu\text{m}$ aluminium flyer plate with a 26 ns pulse was 2.4 Jcm^{-2} [129]. Application of Equation (7.11) for a pulse length of 26 ns result shows agreement with this value of threshold fluence. With some modification the Cerberus long-pulse duration can be extended to ~ 2 ns, the threshold fluence for an aluminium flyer is then $\sim 1 \text{ Jcm}^{-2}$, according to Equation (7.11). From Table 7.3 we see typical laser intensities for these experiments sit in the range $\sim 5 \times 10^8$ to $\sim 5 \times 10^9 \text{ Wcm}^{-2}$, with a pulse length of 2 ns this range yields a laser fluence between ~ 1 - 10 Jcm^{-2} . Theoretically sufficient to drive a flyer. The focal spot size would depend on the diameter of the core of a multi-mode fibre. A 1 mm diameter core fibre would be large enough to make injection a relatively simple task and still allow some bending

of the fibre length without snapping the core. With this core diameter and a pulse length of 2 ns, an intensity of $1 \times 10^9 \text{ Wcm}^{-2}$ would be achieved with 16 mJ and yields a fluence of 2 Jcm^{-2} . Again, theoretically sufficient to drive a flyer.

There are interesting possibilities for probing in a potential experiment. As described earlier in this chapter, plasma can remain attached to the rear of a flyer plate and the electromagnetic fields surrounding a flyer caused by this plasma have not been measured previously. Other important aspects which are not well understood include flyer material tearing/deformation and the initial laser launch process. By generating protons using the Cerberus short pulse and observing deflection in the beam these fields could be quantified, or at least constrained if they are too small to observe directly. Scaling to a FLF experiment, if plasma/electromagnetic fields are present around gas gun or magnetically driven projectiles during impact with a cavity, it is possible that they could interfere in unexpected ways with plasma generated during collapse dynamics, by for example modifying electron thermal transport. Therefore paving a way for measuring fields around a projectile in-flight could be of merit to FLF. Using the flyer to drive a secondary shock wave into a mm scale diameter cavity would be the natural progression of this method in lieu of a gas gun, however this is dependent on a number of parameters. Namely the production of a planar flyer of width and momentum to drive a shock pulse with sufficient velocity (several kms^{-1}) and physical width ($\sim \text{mm}$) to drive a cavity collapse which takes several μs .

Chapter 8

Probing Laser-Driven Flyers with the Cerberus Laser

8.1 Development of the Flyer-Drive Laser Beamline

8.1.1 Laser-Launched Flyers with the Cerberus Long-Pulse Beamline

In this section we discuss the development of the laser beamline used to launch foil flyer plates from the end of a large diameter multi-mode optical fibre, as proposed in the previous chapter. The first laser we attempted to use to launch flyer plates was derived from the Cerberus long pulse beam. This beam is covered in Section 3.3 and the important characteristics are that it is a 1054 nm wavelength pulse of 1.4 ns duration with a beam diameter ~ 10 mm and tunable energy up to ~ 180 mJ. In order to execute a flyer launch from the end of a fibre, two main sections had to be developed: firstly a beamline ending in a fibre injection method to remain constant throughout multiple shots and secondly an optical fibre with a foil attached to the end which would be replaced after each shot, a consumable aspect of the flyer launch.

A simplified diagram showing the main parts of the beamline up to fibre injection is shown in Fig. 8.1. The first main component of the beamline was a pair of lenses used to up-expand the beam to $\sim 2''$ diameter in order to prevent damage to the target chamber window. This was placed as a precautionary safety measure since it was unknown how much energy would eventually be used on the beamline. The next component was formed of a $\lambda/2$ waveplate and a plate polariser. When used together, the waveplate rotated the polarisation of incoming light, a component of which was rejected by the polariser in order to create a convenient method for

tuning the energy of the driving laser pulse. Beyond the plate polariser was a $\lambda/4$ waveplate which, when double passed, rotates the polarisation of a pulse by 90 degrees. As such any light reflected after the $\lambda/4$ waveplate (off the chamber window or fibre input or output faces) would double pass the $\lambda/4$ waveplate before encountering the polariser once again. At which point it would be rejected by the polariser, preventing propagation of light back down the beamline as a safety measure. Finally a focusing lens was placed ~ 1 cm from a target chamber window and used to direct light onto an optical fibre. The focusing lens was placed within a 3-dimensional kinematic mount, allowing direction of the beam to optimise coupling of light into the fibre. The fibre was placed after the focus of the laser to try to mitigate unwanted damage from initial geometric focusing within the fibre. This meant that high power shots had to be conducted with the chamber under vacuum to prevent breakdown of the laser in air prior to injection.

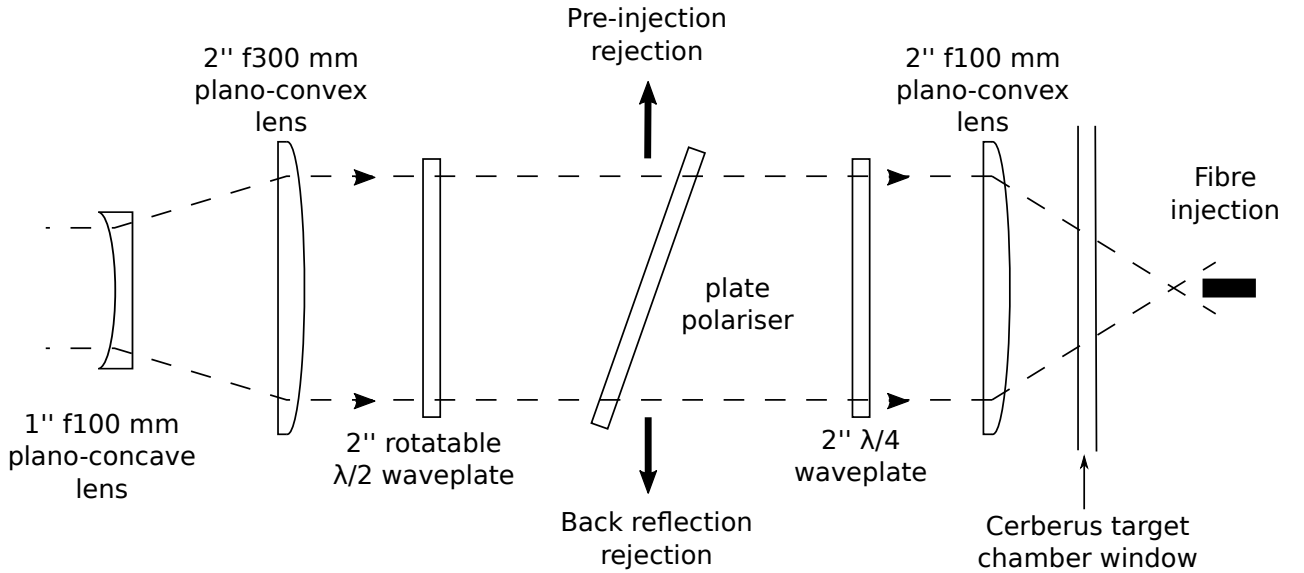


Figure 8.1: Diagram illustrating the optical layout for the main components of the beamline used to inject laser pulses into an optical fibre. A foil flyer was attached to the other end, which was launched by the injected beam.

The next aspect to be designed was the production of fibres for launch. A $1000\ \mu\text{m}$ diameter core multimode optical fibre was selected [134] as a compromise so the fibre would be flexible enough to allow bending in the chamber and large enough to simplify coupling of light into the fibre compared to a smaller core. Also the core diameter defines the final flyer diameter of ~ 1 mm which is more convenient to image than a smaller flyer. The fibres were cut to ~ 1 m lengths and each end was glued into a SMA ferrule [135] which allowed reliable mounting and polishing of the laser-injection and output ends of the fibre. The glue used to adhere the fibres to the ferrules was a heat curing 2-part epoxy [136] which was cured for a minimum of 1 hour at $150\ \text{deg. C}$. A microscope image of a typical fibre face after polishing is shown in Fig. 8.2.

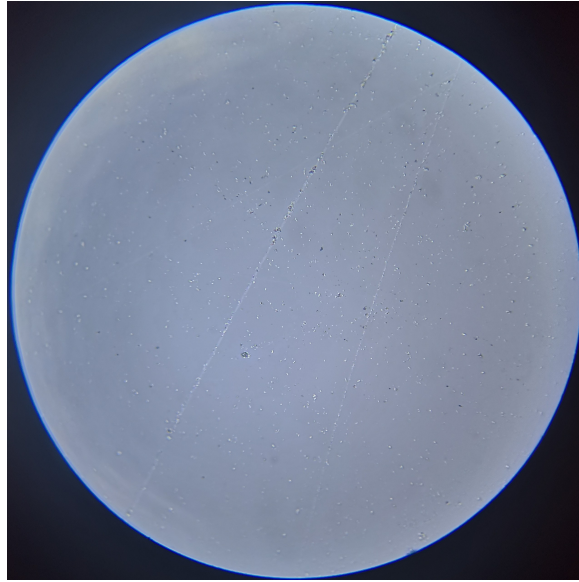


Figure 8.2: Microscope image of a polished 1mm core diameter multi-mode optical fibre face. Minor imperfections are visible upon the face and transmission efficiency tests were conducted using fibres with varying degrees of final polish quality. Imperfections as shown in this image were found to have minimal effect on transmission.

Once a beamline had been established and several blank fibres had been prepared (i.e. with no foil attached yet), we began with the first alignment and efficiency tests for coupling light into a fibre. From this point, at least one blank fibre was kept for alignment purposes. In order to measure the overall transmission through a fibre, an energy meter was used to find the laser pulse energy inside the target chamber before injection. A fibre was then installed close to the laser focus inside the target chamber (see Fig. 8.1) and the energy meter placed viewing the output end of the fibre. The lens used for injection was then moved using its kinematic mount to optimise coupling into the fibre. Using this method, and ensuring the laser focus occurred before injection, a maximum transmission of $\sim 90\%$ was achieved.

Following alignment, the first damage test on a fibre was conducted in order to establish the maximum energy we could use without destroying a fibre on shot. This was an especially useful exercise as an important (and with retrospect, quite obvious) lesson was learned. That is, one should begin with low laser energy and gradually increase when conducting a damage test. Not considering this at the time and driven by enthusiasm, the Cerberus long-pulse beam was initially configured to deliver ~ 180 mJ to the fibre launch beamline with the expectation that the energy tuning capability in the new beamline would control the supplied energy. In this initial test with the Cerberus beam, not only were both ends of the fibre instantly destroyed but optics earlier in the beamline were also burnt. Images of the destroyed fibre faces are shown in Fig. 8.3 which exhibit heavy surface damage. Despite this mistake, an upper limit

for the damage threshold was estimated at ~ 30 mJ, from the energy supplied when the fibre was destroyed and the setting of the $\lambda/2$ waveplate.

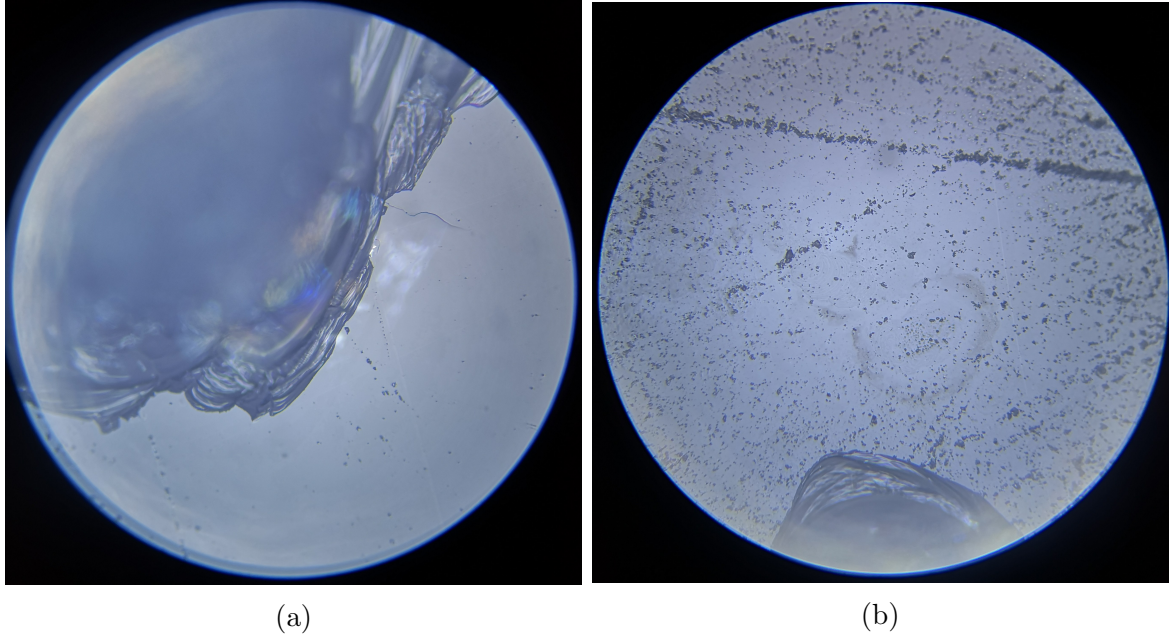


Figure 8.3: Microscope images of a fibre injection face (a) and output face (b) following the first damage test. The test was not fully conclusive but an upper energy limit was established at ~ 30 mJ.

Since the results of the first damage test did not provide a definitive energy limit for a fibre in the current setup, a second fibre was installed. Prior to this, the fibre was backed away from the laser focus to ensure the laser would not focus on the surface of the fibre, lowering peak transmission to $\sim 69\%$. For this damage test the energy began low and increased with Cerberus operated in 10 Hz mode. This time, damage to the fibre was observed at ~ 25 mJ and an intensity of $2.3 \times 10^9 \text{ Wcm}^{-2}$. Interestingly, upon examination of the fibre, there was no clear damage to the fibre input face but there was a significant external burn to the fibre cladding ~ 4.7 cm beyond the injection face, see Fig. 8.4b. Microscope imaging of the injection face showed no surface damage but did show interesting internal damage patterns, see Fig. 8.4a. Similar damage effects were observed by Trott and Meeks [129] between 50 and 100 mm after the input face. This was attributed to the near-Gaussian beam profile of their laser beam. Cerberus also uses a near-Gaussian beam profile and a d-cam image of the spatial beam profile of the Cerberus long-pulse beam is shown in Fig. 8.5.

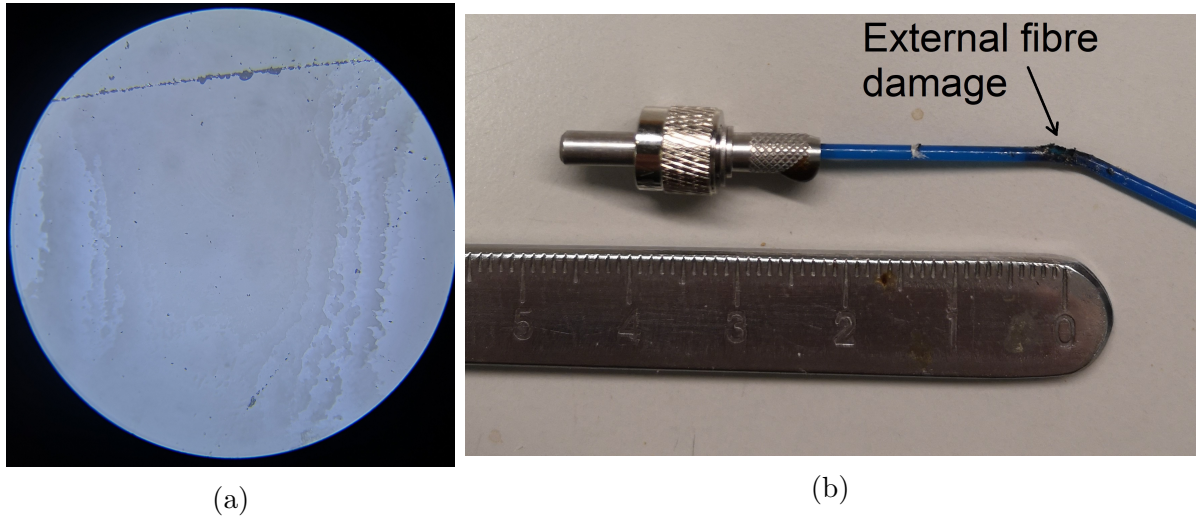


Figure 8.4: Microscope image of a fibre injection face (a) and photo of first ~ 7 cm of the same end of fibre showing catastrophic damage to the external cladding and indication of a complete fibre break (b) following the first successful damage test. The test determined that the maximum energy from the Cerberus long-pulse beam able to be delivered into a fibre was ~ 25 mJ.

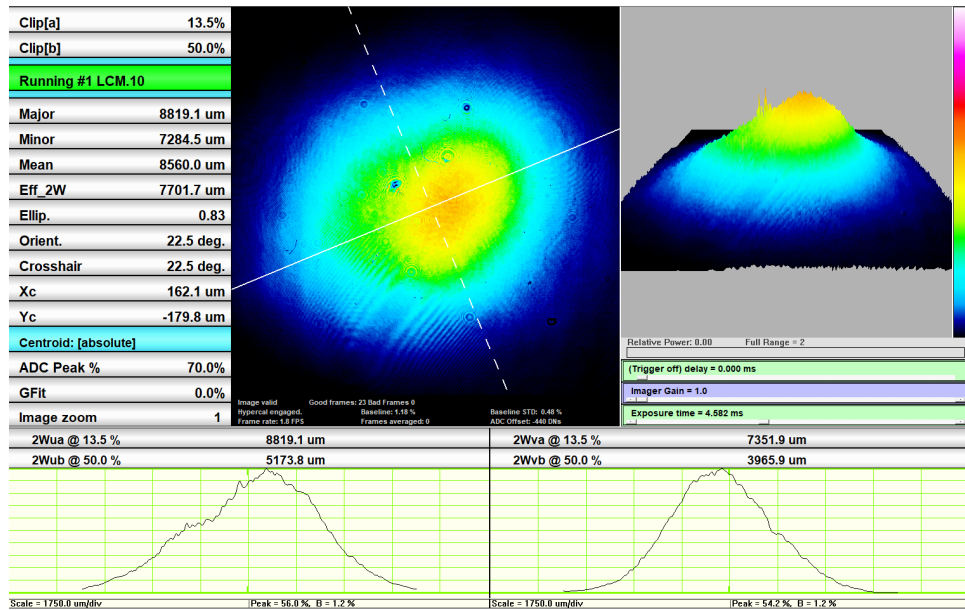


Figure 8.5: D-cam image of the Cerberus long-pulse beam input to the launch fibre exhibiting the near-Gaussian shape of the spatial profile.

After the first quantitative damage test, it was possible to begin setup for imaging a flyer launch. Conveniently, a beamline already existed which uses a small portion of the main Cerberus short-pulse beam for optical diagnostics (see Section 3.3 for its generation), this beam is frequency doubled before the Cerberus target chamber to 527 nm wavelength and has a pulse length of 500 fs and will be referred to as the optical probe from here onward. This is a low energy beamline as it is purely for imaging purposes and the exact energy was never characterised. Crucially, this beam was measured to pass the target chamber centre (TCC)

~ 100 ns after the arrival of a Cerberus long-pulse at the output end of a fibre. Before aligning a fibre to be imaged, a foil was glued to the end of the output end of the fibre, Table 8.1 lists the details of all glues used in this experiment. Glue C was used for this first shot and a $15\text{ }\mu\text{m}$ aluminium foil was used for the flyer. With the expectation that 25 mJ would destroy the fibre, a lower energy of 15 mJ was selected. Upon firing, no flyer movement was observed by the optical probe but the flyer had partially detached following inspection of the output end post-shot. Also damage similar to that shown in Fig. 8.4b occurred close to the input end. A suspected cause for this damage mechanism was self-focusing of the Gaussian beam profile within the fibre. Also the reason for damage occurring below the damage test threshold was suspected to be due to the damage test being conducted with Cerberus operated at 10 Hz repetition rate. At this repetition rate, the fibre would have been gradually heated by Cerberus altering the refractive index of the fibre.

Adhesive	Thesis Ref.	Description
Loctite Double-bubble [137]	“Glue A”	2-part epoxy, room temp. curing
NOA 61 [138]	“Glue B”	UV-curing, optical adhesive
EPOTEK 353ND [136]	“Glue C”	2-part epoxy, hi-temp. curing

Table 8.1: Compilation of adhesives used for bonding foils to fibre ends in this experiment.

Suspecting that the Gaussian beam profile of Cerberus was limiting the energy we could supply into a fibre, a holographic beam diffuser was identified which would convert the Gaussian beam to an approximate flat-top beam profile (with the addition of some high frequency “noise” from sub-aperture beamlets) [139]. This was a 1” diameter optic added into the beamline before the plano-concave lens optics shown in Fig. 8.1. A d-cam image of the beam profile produced by the diffuser at the location of fibre injection is shown in Fig. 8.6. Following the introduction of the diffuser, another damage test was conducted to see if more energy could be supplied into the fibre. In this test, the laser was fired in single shot mode so the fibre would be able to cool between tests. A maximum of 30 mJ was supplied into the fibre and no damage was observed confirming the diffuser had raised the damage threshold by at least 15 mJ. An unfortunate side effect of the diffuser was energy loss during propagation prior to fibre injection, hence 30 mJ was the maximum energy supplied by Cerberus in this test. It was later found that the loss

could be reduced by changing the relative positions of the diffuser and lenses however another damage test was not conducted with the current arrangement. Following the damage test a shot was taken with 19 mJ supplied onto a 15 μm thickness aluminium foil flyer adhered with glue A. The optical probe showed no movement of the flyer but the flyer was found to have launched after the arrival time of the optical probe by inspecting the fibre post-shot. This suggested that some unexpected launch physics was happening but on a much longer timescale than anticipated.

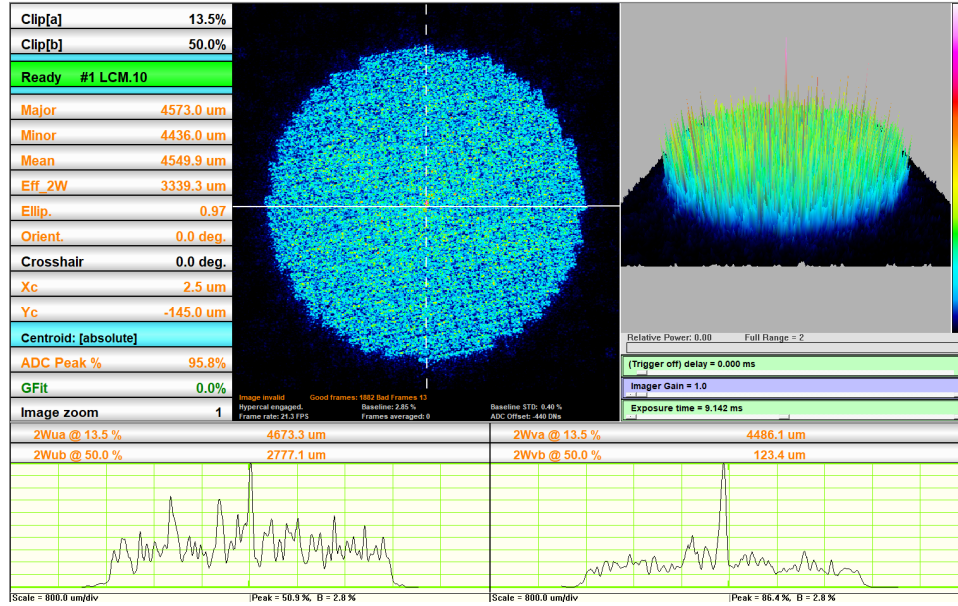


Figure 8.6: D-cam image of the near flat-top spatial profile of the Cerberus long-pulse beam, at fibre injection, after introduction of a holographic beam diffuser.

At this point, the only monitor on the flyer launch was the single 500 fs window provided by the single shot optical probe, ~ 100 ns after the drive laser arrived at the flyer position. In order to better characterise the response of a flyer over a much longer time, a setup was devised, consisting of a continuous wave HeNe laser and a photodiode. The HeNe laser was reflected from the fibre launch face with a foil attached and the reflection viewed by a photodiode connected to an oscilloscope. An infrared filter was placed in front of the photodiode to minimise signal from scattered launch light from behind the flyer. A second photodiode viewed light leakage through the back of a beam steering mirror prior to fibre injection. This photodiode was used as a trigger for the oscilloscope. A diagram showing this setup in the context of the Cerberus target chamber is seen in Fig. 8.7.

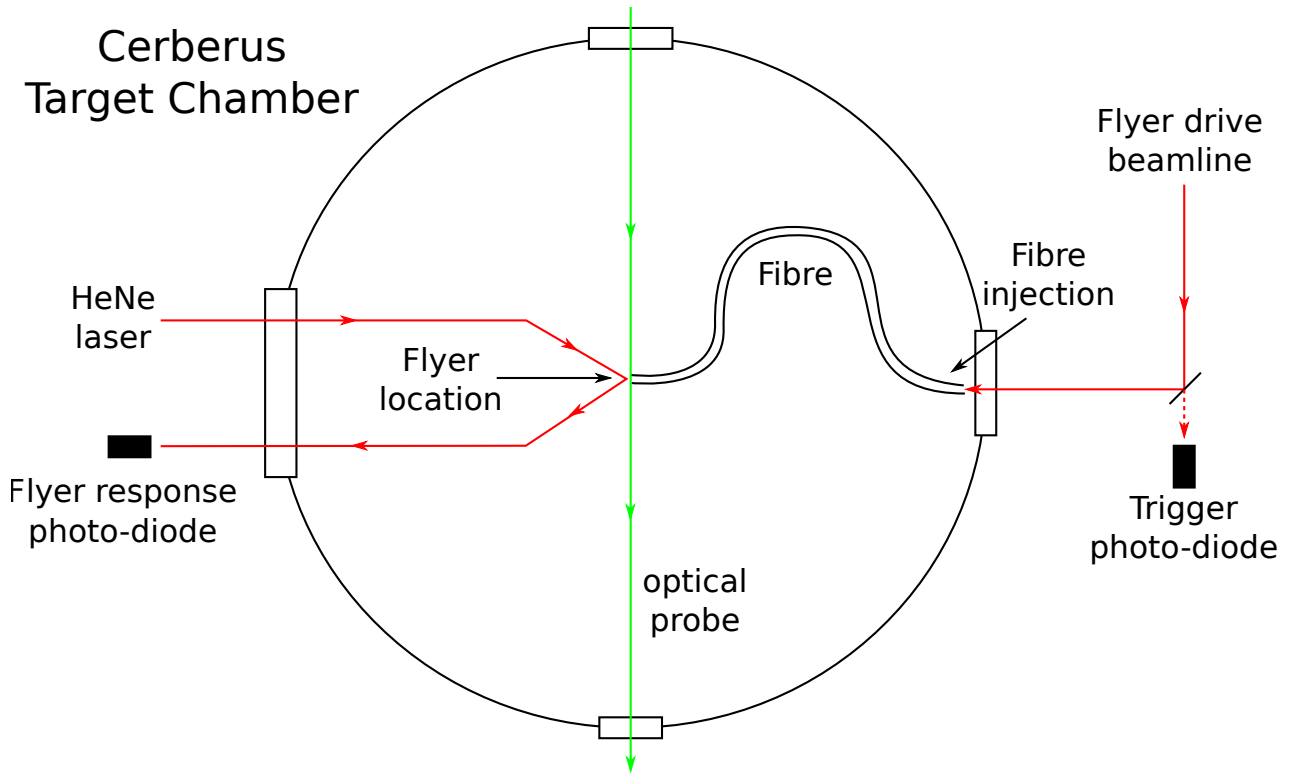


Figure 8.7: Diagram showing the layout of the Cerberus target chamber. This includes the flyer drive beamline and optical fibre with injection and flyer sides annotated. Also shown is the HeNe laser beam which was used to monitor the response of the flyer end of the fibre. Photo-diodes connected to the same oscilloscope are shown, one of which witnesses the leakage of light from the drive beamline and is used as a trigger for the oscilloscope while the second photo-diode monitors the reflection of the HeNe beam from the flyer foil. The optical probe line is shown for additional context.

Once the HeNe beamline had been installed, a fibre was prepared with $15\ \mu\text{m}$ thickness aluminium foil flyer adhered with glue A. The shot used $\sim 12\ \text{mJ}$ onto the flyer foil and the resulting response of the HeNe photo-diode is shown in Fig. 8.8. This photo-diode response first shows an increase in voltage from contamination by a background reflection of the Cerberus long-pulse drive beam from elsewhere in the lab i.e. not from the fibre end. Following this, the photo-diode output voltage decreases as the HeNe beam reflection is disturbed by the flyer beginning to move. If the flyer was to respond as expected (with a layer of rapidly expanding plasma generated as described in Section 7.3) we would likely expect an initial response on a few ns timescale. Fig. 8.8 however shows a response of the flyer over several μs . The physics causing this effect is still unknown but one suspected reason for the result arises from the laser pulse length. Comparing this with other experiments using laser launched flyers (see Table 7.3), we see that the Cerberus pulse length of $1.4\ \text{ns}$ is shorter by a factor >4 . To test this hypothesis the next step was to employ a secondary long pulse laser to drive the flyer launch which is the subject of the next section.

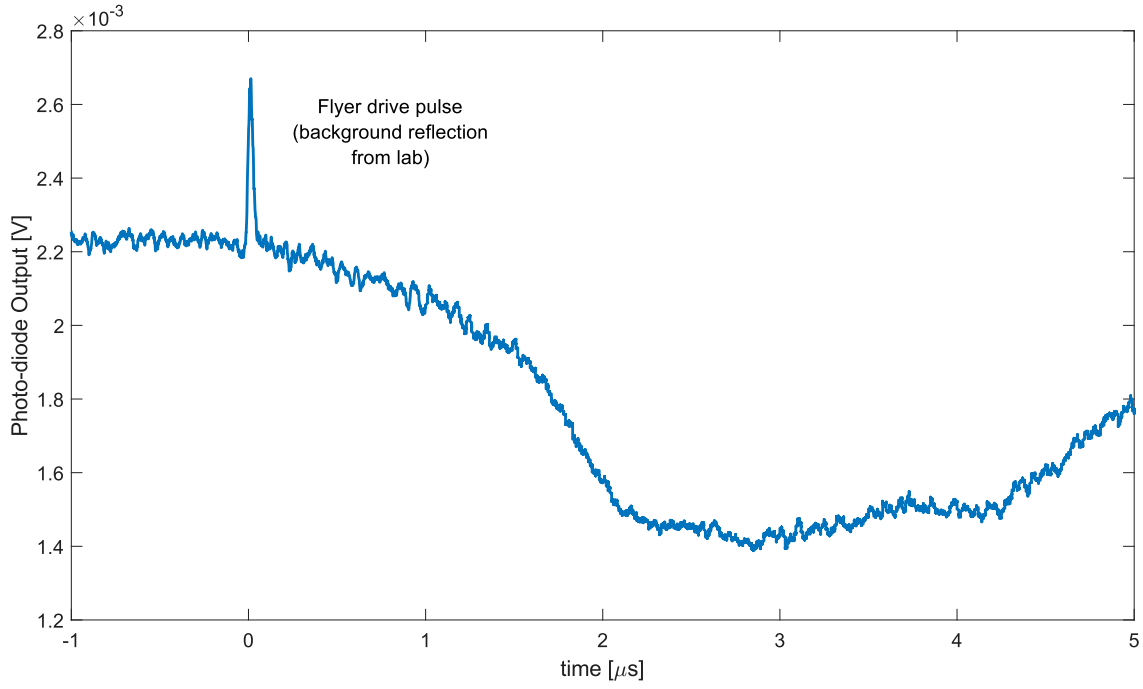


Figure 8.8: Plot showing the response of a photo-diode witnessing the reflection of a continuous wave HeNe laser from the surface of a laser launched flyer plate. The initial spike in voltage is caused by contamination from the flyer drive pulse reflected from elsewhere in the lab. The initial response of the flyer occurs over an extended period of time $\sim 2 \mu\text{s}$ with extended dynamics taking another $\sim 5 \mu\text{s}$.

8.1.2 Laser-Launched Flyers with a Secondary (non-Cerberus) Laser

Following the problems encountered in using Cerberus to drive laser-launched foil flyers from the end of an optical fibre, we move on to the use of a second laser system to fulfil this purpose. This laser is described in detail in Section 3.4 and is a Q-switched, Nd:YAG laser operated at 1064 nm which produces a pulse of duration ~ 20 ns and has variable energy control which allowed up to ~ 150 mJ to be supplied to a fibre. As with the previous section, the diameter of the beam on target was defined by the 1 mm fibre core diameter. For simplicity we will refer to this laser as the “YAG” from here. An immediate advantage the YAG had over the Cerberus long-pulse arose from using a timing system external to the main Cerberus optically locked beam. A trigger sent from Cerberus was used to synchronise the firing of the YAG but a separate delay could be added which allowed selection of an arbitrary time difference between the YAG pulse and the Cerberus main beam. For context, in the previous section there was a maximum 100 ns delay between the arrival of the Cerberus long-pulse for flyer drive and the optical probe beam from the Cerberus main short-pulse beamline. Changing this time difference is constrained by the practical length of optical delay lines so using a secondary timing system for the YAG gave the option to more easily select an arbitrary point at which to

probe a flyer launch with an optical probe pulse. The main Cerberus short-pulse beam, used for proton and X-ray generation has not yet been considered in this chapter but the arrival of this pulse at TCC is synchronised with the optical probe which will become important later.

The YAG was installed into the fibre injection beamline which otherwise remained unchanged from the end of the previous section. Due to being a system not directly optically locked to the Cerberus laser, the first task was to determine the jitter on the arrival of a YAG pulse relative to a Cerberus pulse, at TCC. This was quantified by measuring the standard deviation on the difference between arrival of each pulse on an oscilloscope over several shots. The jitter was found to be 3.8 ns. Prior to attempting to launch a flyer, a damage test was conducted using the new laser. With the YAG, over 85 mJ could be coupled into a fibre with no damage, damage was observed at 130 mJ, higher than the previous maximum of 30 mJ supplied with the Cerberus long-pulse. As in the last section, a photo-diode observed the drive (YAG) pulse before injection to trigger an oscilloscope, while a second photodiode observed the HeNe reflection. A shot was then fired using 50 mJ onto a 15 μm Al flyer adhered with glue A. The resulting photo-diode responses are shown in Fig. 8.9. The HeNe photo-diode shows that the flyer responded to the drive laser on a more rapid timescale when compared to the response shown in Fig. 8.8, suggesting that we were engaging a different mechanism/physics with the new laser.

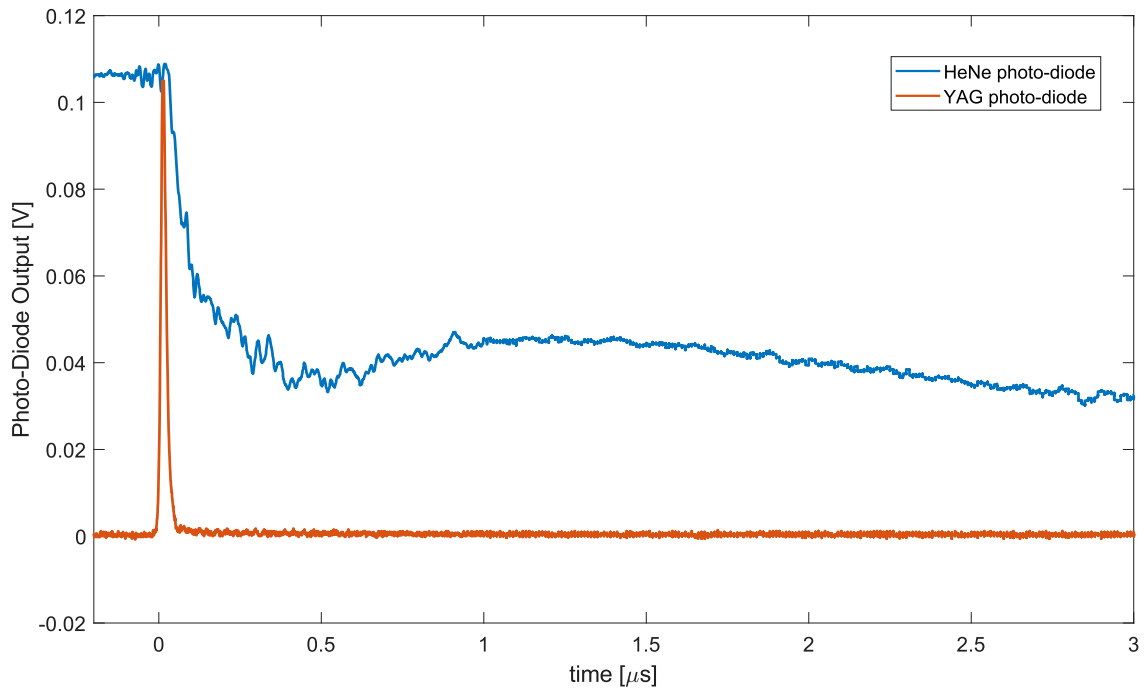


Figure 8.9: Plot showing the response of a photo-diode witnessing the reflection of a continuous wave HeNe laser from the surface of a laser launched flyer plate. The response of a different photo-diode is also shown that witnessed leakage through a mirror of the the flyer launch pulse prior to injection. A rapid response occurs on the HeNe photo-diode within 1 μ s in contrast to the response shown in Fig. 8.8.

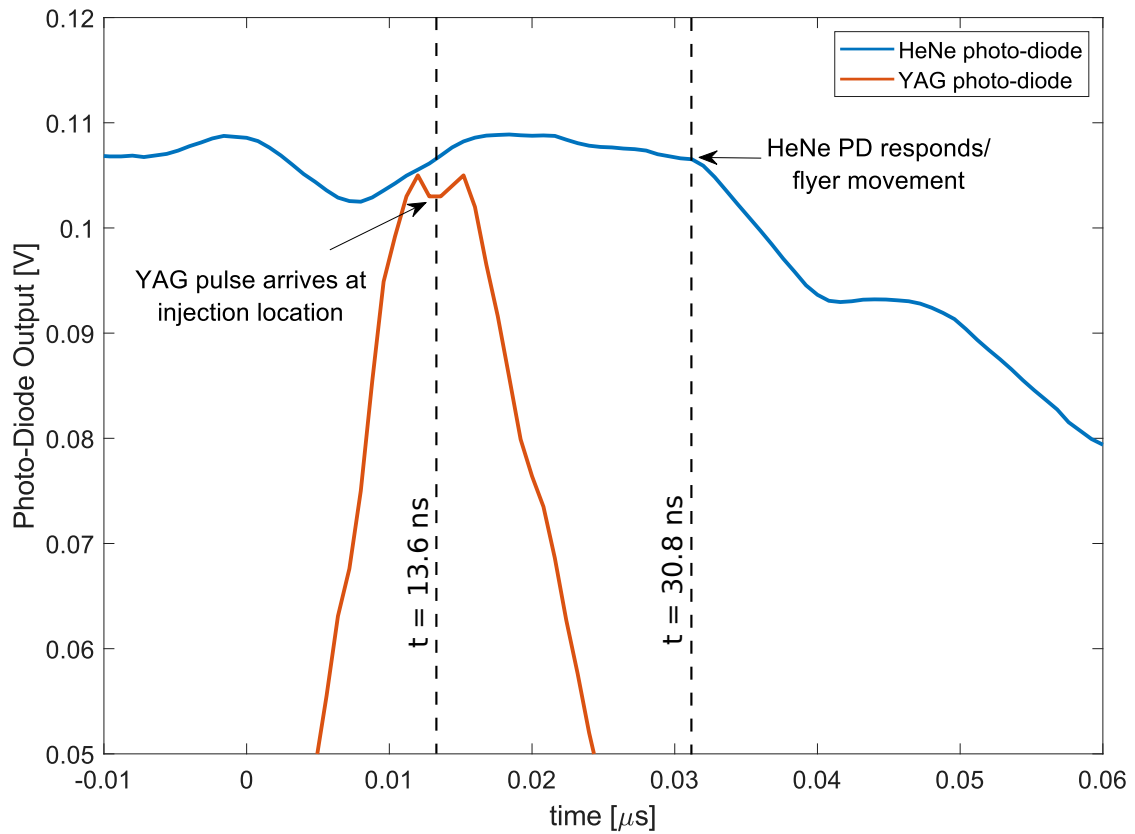


Figure 8.10: Plot showing a magnified version of the graph in Fig. 8.9. The time difference between arrival of the YAG pulse and response of the HeNe on this plot is ~ 17.6 ns.

The next step was to measure the time between the YAG pulse arrival (YAG photo-diode) and the start of the response of the flyer (HeNe photo-diode). A second, magnified version of Fig. 8.9 is shown in Fig. 8.10. Using the cursors on this graph we can measure that the time difference between the aforementioned events is ~ 17.6 ns. In spite of the sub-nanosecond precision of the oscilloscope, in reality, we can not be precise to less than 1 ns. This is due to uncertainty in the location of the peak of the YAG pulse and the time of the flyer response, which were the most significant sources of error in the measurement. Regardless, this time is much faster than the ~ 2 μ s we saw for the response using the Cerberus long-pulse as a driver and more within expectations for the response from generating a rapidly expanding plasma with a laser. If we wish to find the exact response time of the flyers after arrival of the YAG pulse, we must also consider the propagation time of signals through BNC cables and light propagation in the lab. To aid in visualising this problem a version of the layout of the Cerberus target chamber is shown in Fig. 8.11.

The response of the YAG photo-diode observing the YAG laser (trigger photo-diode) is delayed in time by 23.2 ns due to the BNC but also occurs 8 ns earlier than arrival at the flyer position due to propagation through the fibre/air. The response of the HeNe photo-diode is delayed by 25.3 ns due to the BNC connection and is also delayed by the time taken for information to travel from the flyer moving from fibre face to the photo-diode by another 3 ns. Similar to before, even though we can measure the BNC delays to sub-nanosecond precision, measuring the propagation time of light in the lab limits our overall precision to a minimum of 1 ns. Accounting for these factors yields a final delay between the YAG pulse arriving at the flyer position, and the movement of the flyer, of 4 ± 3 ns. At the time, there was no on-shot optical imaging to confirm that a flyer had been launched, due to issues with Cerberus. However, inspection of the fibre post shot indicated a flyer had launched leaving a neat hole in the foil, a before and after image of the fibre end is shown in Fig. 8.12.

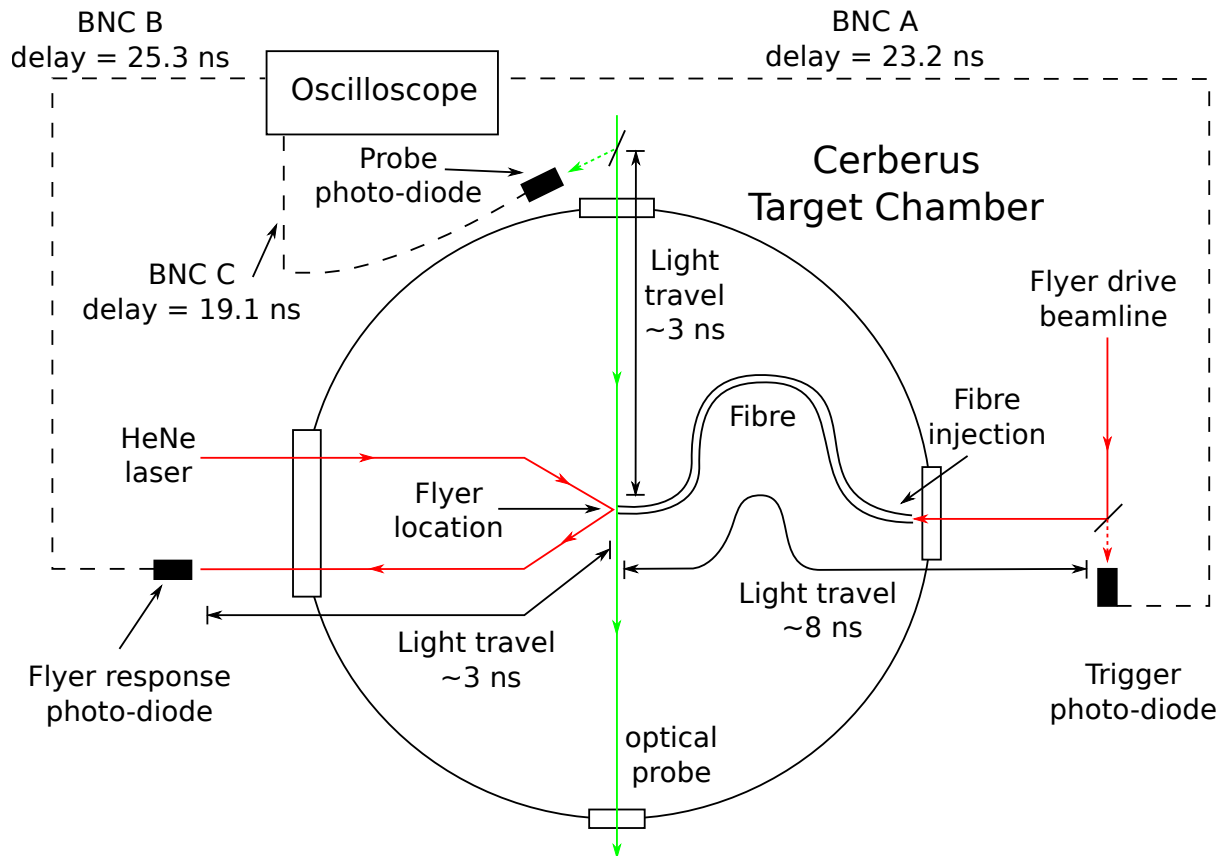


Figure 8.11: Diagram showing the layout of the Cerberus target chamber. This includes the three main beamlines used in this experiment, the positions of photo-diodes used to observe the arrival of each beamline and the timing delays involved in the propagation of light in each beamline between the photo-diode and TCC. Also annotated are the delays of each BNC cable which connects the photo-diode to a single oscilloscope.

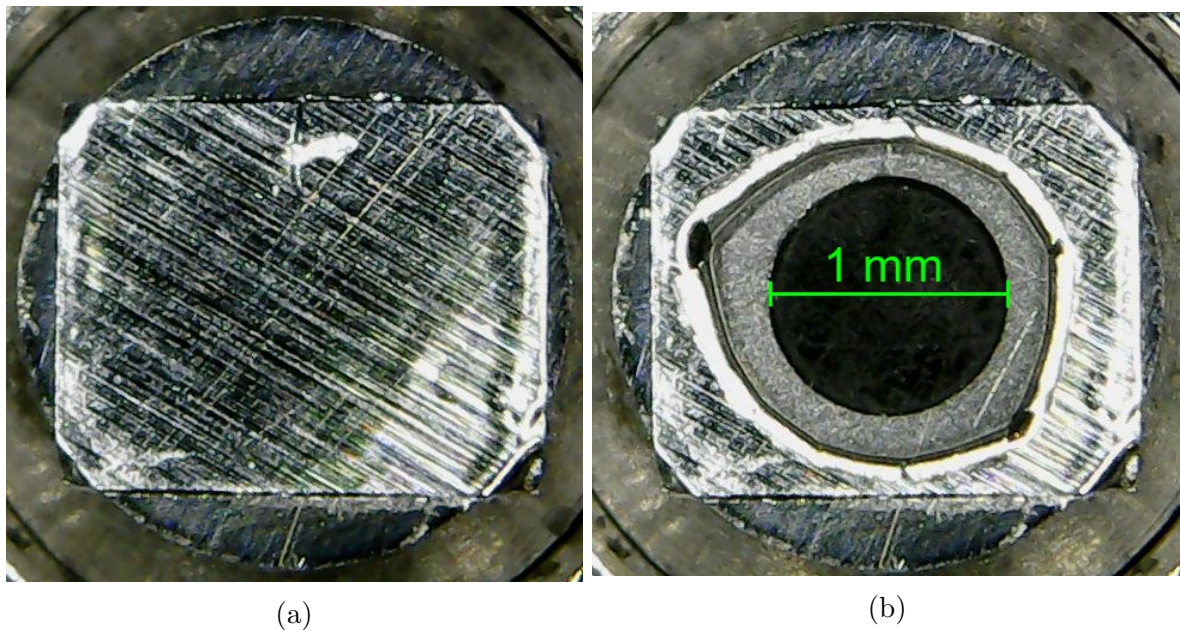


Figure 8.12: Microscope images of the end of fibre output face before (a) and after (b) the launching of a $15\ \mu\text{m}$ Al foil. The laser pulse launched the flyer with 50 mJ energy. Note the curling of the edges of the foil shown in the after image.

Using this current setup it is possible to estimate the response time of the flyer after the YAG pulse arrives and we can now be confident that the a flyer is launching rapidly on a ns timescale. It is however difficult to determine what is physically occurring from the HeNe photo-diode response and accurate velocity measurement, for example, is not feasible. A series of shots were undertaken to see how flyers responded using different glues, flyer materials and energies. The opportunity was also taken to better quantify the threshold launch energy for a 15 μm Al flyer experimentally. The results are compiled in Table 8.2.

The results do not show a clear relation between laser energy and flyer response time, nor does there seem to be a significant change caused by different glues and flyer materials from the data provided. There was considerable variation in the sizes in the sources of error for these response time measurements. On many shots there was an increase in signal seen by the HeNe photo-diode around the time the flyer began to respond, likely due to leakage of drive laser from the edges of the flyer. This made exact measurement of the time at which the flyer started to move difficult, adding an error on measurements of ± 10 ns in the most extreme cases. In conclusion, it is difficult to know the exact response time of the flyer after arrival of the YAG pulse due to the error sources which are greater than 50% the size of the measurement in all but one shot. Despite this, it does appear that the flyers respond on the timescale of the YAG pulse ~ 20 ns. The threshold fluence for launch was also calculated for the 15 μm Al flyers using Equation (7.11) from the predictive model by Lawrence and Trott [133]. From these results we can see that the observed launches mostly occur only when the fluence is above the threshold fluence determined from the model. One discrepancy is in the 20 mJ shot which was below the predicted threshold fluence but showed a launch. It is however, very close to the threshold which could be accounted for by uncertainties in the measurement of the laser pulse duration and energy. The rise-time of the photo-diode used to measure the pulse duration is ~ 1 ns, which is sufficient to lower the threshold below the observed fluence and the energy was measured pre-shot and could vary by a few mJ for the shot itself.

Flyer	Glue	Laser Energy [mJ]	Fluence [Jcm^{-2}]	Threshold Fluence [Jcm^{-2}]	Launch?	Flyer Response Time [ns]
15 μm Al	A	50	6.4	2.6	Y	4 ± 3
15 μm Al	B	50	6.4	2.6	Y	5 ± 3
15 μm Al	B	50	6.4	2.6	Y	4 ± 3
35 μm Cu	C	50	6.4	N/A	Y	7 ± 5
15 μm Al	A	10	1.3	2.6	N	13 ± 3
15 μm Al	A	20	2.5	2.6	Y	5 ± 10
15 μm Al	A	30	3.8	2.6	Y	1 ± 3
15 μm Al	A	50	6.4	2.6	Y	17 ± 10
15 μm Al	A	70	8.9	2.6	Y	1 ± 3

Table 8.2: Compilation of results from the laser launched flyer experiment where the response time of flyer launch after arrival of the drive pulse was measured. Important laser parameters, flyer and glue details are specified. The threshold fluence predicted by the theoretical model described by Lawrence and Trott [133] (see Equation (7.11)) is provided for each shot where possible.

A final interesting result occurred in the shot with 10 mJ which did not launch the flyer. The HeNe photo-diode response is shown in Fig. 8.13, which exhibited a clear and unexpected oscillation after an initial drop in the HeNe reflection. Inspection of the fibre after the shot showed a bulge in the foil. This result shows that the laser likely caused an expansion of glue and/or foil rear surface which oscillated with an approximately constant frequency which was measured at 2.1×10^5 Hz. Furthermore, the initial drop is consistently seen on all shots which successfully launched a flyer, i.e. Fig. 8.9. Thus we can conclude that the drop likely indicates initial dynamics from the foil bulging before detaching. This concludes the establishment of the laser launched flyer experiment and preliminary results, next we shall discuss results from imaging of the flyers.

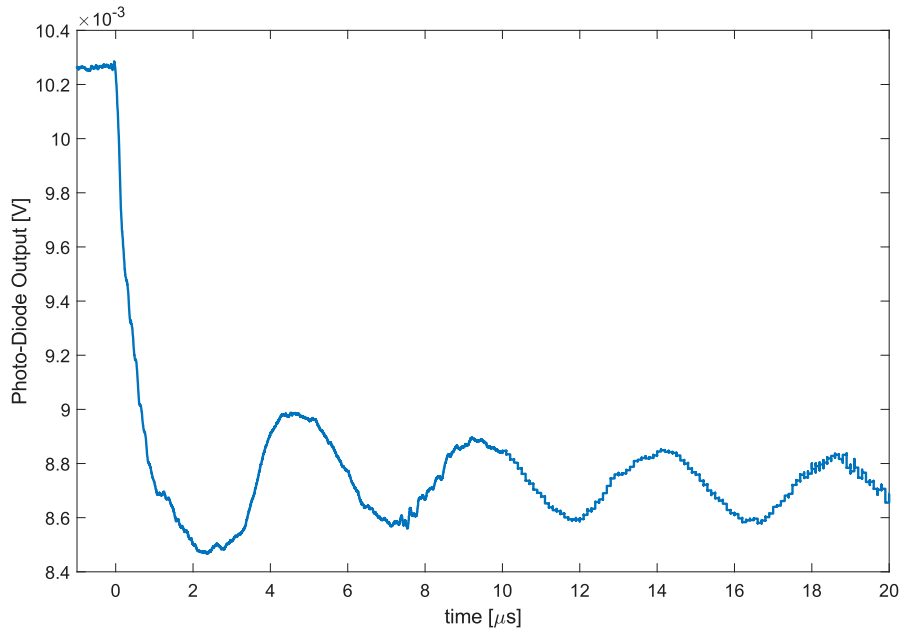


Figure 8.13: Plot showing the response of a photo-diode witnessing the reflection of a continuous wave HeNe laser from the surface of a foil driven by 10 mJ laser energy, insufficient to fully launch the flyer plate. This response exhibits an interesting oscillation at 2.1×10^5 Hz likely caused by the surface of the unlaunched flyer oscillating due to the drive laser.

8.2 Optical Imaging of Laser-Launched Flyers

In this section we discuss results in which the Cerberus laser was used to optically image a flyer launched by the YAG laser. To begin, the Cerberus optical probe beam (which was initially used in Section 8.1.1 before the YAG laser had been installed) was reintroduced to the experimental setup. Referring back to Fig. 8.11 for context, this section mostly makes use of the optical probe beamline and the flyer drive beamline. The HeNe laser was used to initially confirm the flyer responded as expected and a launch had occurred but is not emphasised in these results. The optical probe line used a photo-diode to measure the arrival of a probe pulse which was compared to the arrival of the YAG pulse in order to precisely measure a time difference between launch of the flyer and the probe arrival. As before, the various delays inherent in the probe photo-diode setup is significant for measuring this time difference, the arrival of the probe at TCC occurred 19.1 ns earlier than an oscilloscope reading suggests due to the BNC connection between photo-diode and oscilloscope but then 3 ns later due to the distance between the probe photo-diode and TCC. An expected delay was set by changing the firing time of the YAG but the actual delay was always measured on shot. The YAG photo-diode and beamline setup remained unchanged.

A shot was taken with the YAG supplying 75 mJ to a 15 μm Al foil and an expected time difference between flyer launch and probe arrival at TCC of $\sim 1.1 \mu\text{s}$. The image created by the probe is shown in Fig. 8.14, which is the first visual confirmation that we were successfully launching flyers. This image can be used to determine an average velocity of the flyer by measuring the displacement of the flyer and dividing by the time of arrival of the probe after launch of the flyer. A calibration must first be found for the probe image for converting pixels to distance. This was found by imaging an object of known size with the probe, at TCC. A calibration of $5.49 \times 10^{-4} \text{ mm/pixel}$ was determined. From this an average velocity for the flyer was found at 1.2 kms^{-1} . Using this velocity it is also possible to estimate the kinetic energy of the flyer and hence the conversion of laser energy into flyer kinetic energy. The conversion for this shot was estimated at 30.8%.

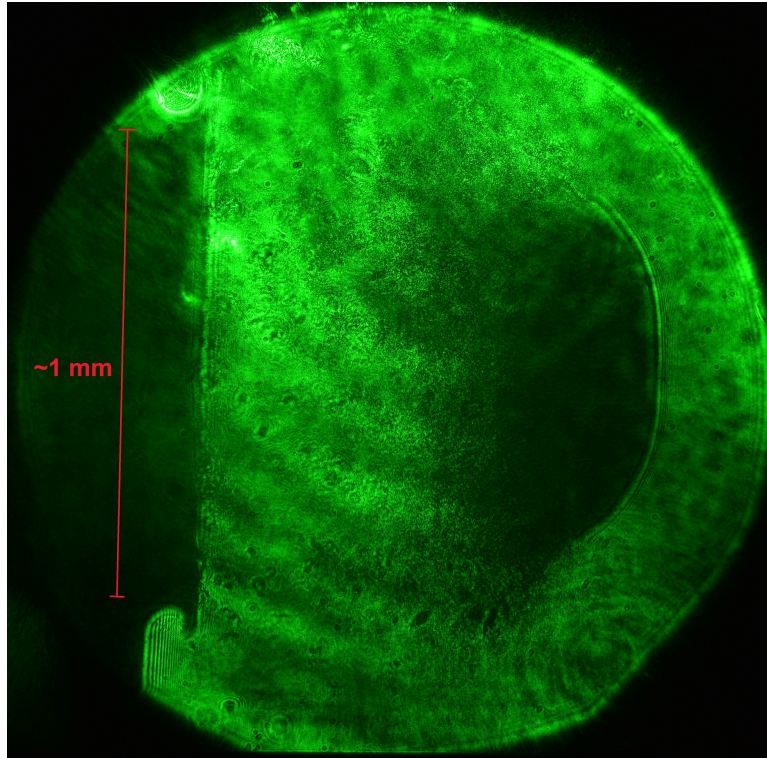


Figure 8.14: Optical probe image of a laser launched flyer. The flyer is formed of an approximately 1 mm diameter 15 μm Al circular foil which was initially flat and adhered to a fibre using glue A. A 75 mJ YAG pulse launched the flyer and the probe light is a 527 nm wavelength, 500 fs pulse provided by Cerberus which arrived $\sim 1.1 \mu\text{s}$ after the YAG pulse. After the flyer is released from the foil, curling of the edges of the foil which remains attached to the flyer can also be seen. Measurement of the displacement of the flyer and the delay of the probe beam yields an average velocity for the flyer of 1.2 kms^{-1} .

Following this, a series of shots were taken where a single parameter was varied each time. Beginning with an energy scan using the same $1.1 \mu\text{s}$ time delay, flyer material, thickness and glue. Then a scan in time by varying the delay of the YAG for the same laser energy, flyer material, thickness and glue. Then finally some shots where the effect of changing glue/flyer could be investigated. As with the first shot the average velocity was measured along with kinetic energy and laser energy conversion efficiency. These results are compiled in Table 8.3. Errors are incorporated for the displacement of the flyer on each shot which was affected by the image quality and ability to measure the position of the front of the flyer. The YAG/probe time difference for each shot had a consistent error estimated at 5 ns which arose from uncertainty in measuring the time of arrival of the YAG and uncertainties in measuring the delays due to laser propagation between TCC and each photo-diode. These were propagated to find errors on each velocity, kinetic energy and conversion efficiency.

Flyer	Glue	Laser E. [mJ]	Delay [ns]	Flyer Vel. [kms^{-1}]	Pred. Vel. [kms^{-1}]	Flyer K.E. [mJ]	Conversion Eff. [%]
15 μm Al	A	50	115 $\pm$ 5	0.74 $\pm$ 0.05	0.55	8.8 $\pm$ 1.1	17.7 $\pm$ 2.5
15 μm Al	A	50	640 $\pm$ 5	0.64 $\pm$ 0.07	0.55	6.6 $\pm$ 1.4	13.1 $\pm$ 2.9
15 μm Al	A	50	1110 $\pm$ 5	0.86 $\pm$ 0.03	0.55	11.9 $\pm$ 0.7	23.7 $\pm$ 2.0
15 μm Al	B	50	1125 $\pm$ 5	0.71 $\pm$ 0.03	0.55	8.0 $\pm$ 0.6	16.0 $\pm$ 1.5
15 μm Al	A	50	1920 $\pm$ 5	0.84 $\pm$ 0.03	0.55	11.4 $\pm$ 0.8	22.7 $\pm$ 2.1
5 μm Al	A	25	1180 $\pm$ 5	0.95 $\pm$ 0.01	0.20	4.8 $\pm$ 0.1	19.2 $\pm$ 2.3
15 μm Al	A	25	1130 $\pm$ 5	0.45 $\pm$ 0.02	0.12	3.3 $\pm$ 0.3	13.2 $\pm$ 1.9
15 μm Al	A	50	1145 $\pm$ 5	0.63 $\pm$ 0.02	0.55	6.3 $\pm$ 0.4	12.7 $\pm$ 1.1
15 μm Al	A	75	1130 $\pm$ 5	1.20 $\pm$ 0.01	0.86	23.1 $\pm$ 0.3	30.8 $\pm$ 1.3
35 μm Cu	A	75	1125 $\pm$ 5	0.28 $\pm$ 0.01	N/A	9.9 $\pm$ 0.4	13.3 $\pm$ 0.7

Table 8.3: Compilation of results from the optical probing experiment for laser launched flyers. Important laser parameters, time delay between YAG and optical probe arrival, flyer and glue details are specified. The average velocity of the flyer from each image is measured along with the estimated kinetic energy for each flyer. The efficiency of conversion of laser energy into flyer kinetic energy is also provided. The final velocity predicted by the theoretical model described by Lawrence and Trott [133] is provided for each shot where possible.

Beginning with the time scan, 15 μm Al foils and glue A were used; the YAG laser delivered 50 mJ to each foil. The results from these shots were plotted on a graph of flyer displacement versus YAG/probe time difference, see Fig. 8.15. From this we can see an approximate linear relationship, a fitting of the graph yields a gradient of 0.85 kms^{-1} , this is a measure of the expected final velocity for a 15 μm Al flyer glued with glue A and driven by a 50 mJ laser pulse. According to previous experiments [123, 124, 129] a flyer should attain its final velocity

within a few FWHM of the drive laser pulse duration. For us that is under 100 ns. Therefore we would expect to see a straight line as the earliest probe time was at 115 ns after the drive pulse. Since each of these points is from a separate shot other sources of error arise from shot to shot energy variations which are not quantified in this graph. A much better method for measuring the final velocity of a flyer launched like this would be to use either a high-speed camera, which can take multiple images of the same shot or an interferometry setup such as VISAR which directly provides a full velocity history for the shot.

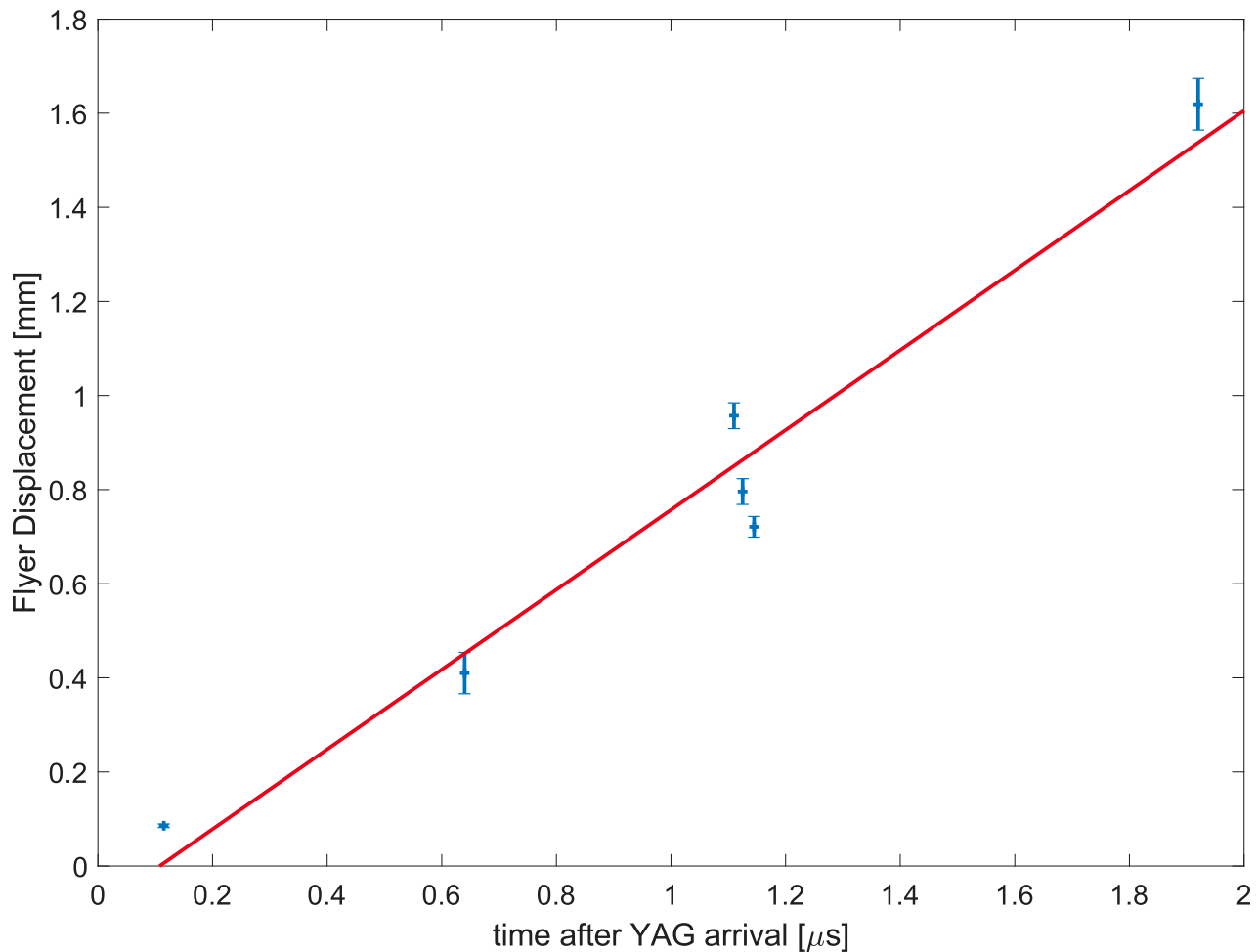


Figure 8.15: Plot showing the variation of flyer displacement with time probed after launch/arrival of the YAG at the foil. Each point is from a separate shot where the laser energy was 50 mJ and the flyer was a 15 μ m Al foil adhered with glue A.

Next we consider the effect of varying glue. Three shots were taken with similar laser and flyer parameters (50 mJ, 15 μ m Al foils and a 1.1 μ s YAG/probe time difference) but differed by the choice of glue. Results in Table 8.3 show that the flyer with glue B had a velocity in between the two shots with glue A. The differences are not significant enough to conclude whether the use of either glue affects resulting flyer velocity. However, an interesting result can be seen in the optical images of the flyer, see Fig. 8.16. Fig. 8.16a shows a flyer made using

glue A and Fig. 8.16b shows a flyer made with glue B which shows more flyer curvature than with glue A. Glue B is UV-curing and affixed by shining UV light into the other end of the fibre. It is likely that some of the glue did not cure at the edges of the foil due to being shaded from the UV. It is possible that poor curing at the edges could give rise to higher curvature flyers which is undesirable for driving a flat shock into a target.

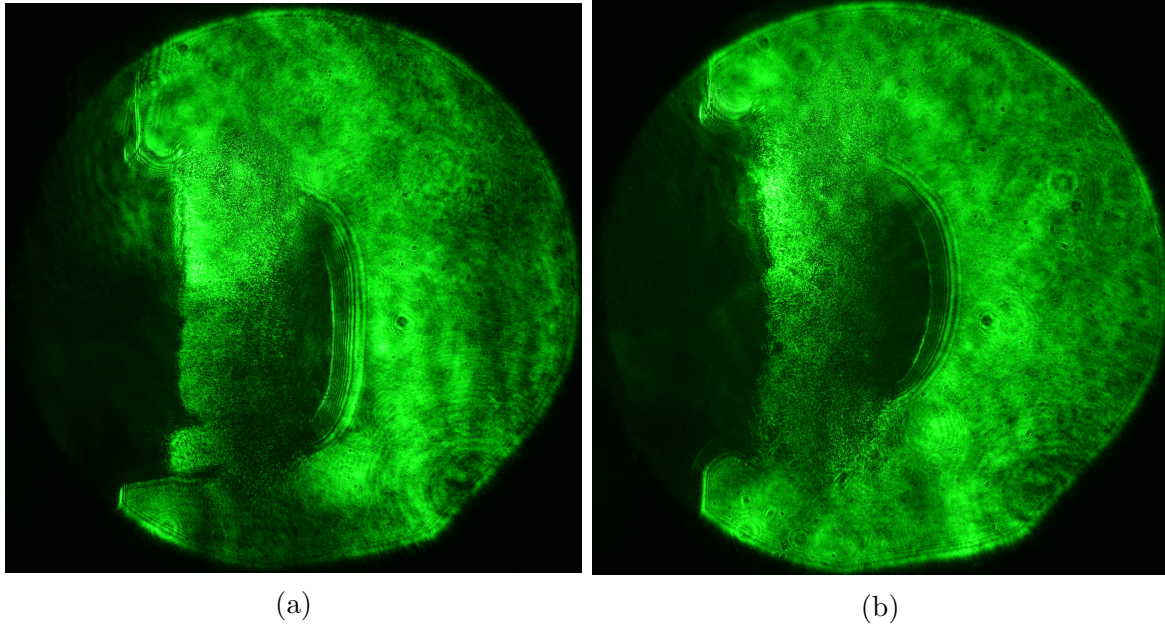


Figure 8.16: Optical probe image of two flyers launched with a 50 mJ YAG pulse. Both flyers were made from a 15 μm Al foil and probed at the same time after launch, 1.1 μs . The two shots differed in the choice of glue adhering the foils, the shot in image (a) used glue A and (b) used glue B. Image (b) exhibits more flyer curvature than (a). Note also the strong diffraction pattern observed at the front of the flyer. These were the most prominent examples of diffraction resulting from imaging of an extended object which was uncommon. The diffraction made precise measurement of the flyer front more difficult which is reflected in errors.

The effect of varying flyer thickness is shown by two shots, one using 5 μm Al foil and one with 15 μm Al foil. For these shots, laser energy was 25 mJ, glue A was used and the YAG/probe time difference was 1.1 μs . As shown in Table 8.3 the thinner foil attained a higher velocity as expected and by a factor ~ 2 . The optical probe images of both of these shots is shown in Fig. 8.17. Fig. 8.17a shows the 15 μm flyer and provides interesting insight into the early dynamics of flyer launch. The rupturing of the flyer can be observed which is not symmetric. The reason for the asymmetry is not fully known but a potential cause could be an inhomogeneous YAG beam profile. Fig. 8.17b shows the 5 μm flyer. This is the only example of significant rotation of a flyer seen on this experiment. The rotation is estimated at 16 degrees and is an undesirable effect. The cause for rotation is not known but could be due to thinner foils being more susceptible. Unfortunately, no other 5 μm flyers were able to be imaged to

test this hypothesis. A thicker, $35\text{ }\mu\text{m}$ Cu foil which has a higher density than Al was also used in a shot but with 75 mJ. Despite the relatively high energy, a lower velocity was attained than in any other shot. This is likely due the increased flyer mass due to increased volume and density.

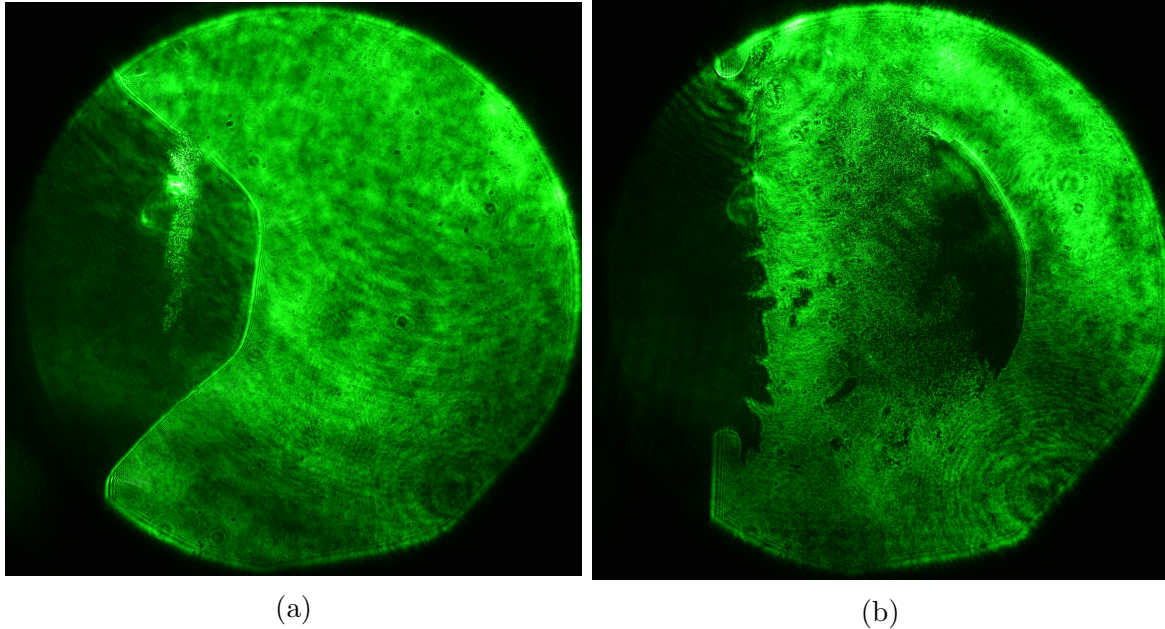


Figure 8.17: Optical probe images showing the difference between a $15\text{ }\mu\text{m}$ Al flyer (a) and a $5\text{ }\mu\text{m}$ Al flyer (b). The YAG provided a 25 mJ pulse in both cases and each flyer was probed $1.1\mu\text{s}$ after launch. Glue A was used for both. Image (a) shows early time dynamics during a launch and rupturing of the foil. Image (b) shows rotation of a flyer by approximately 16 degrees.

An energy scan was carried out on $15\text{ }\mu\text{m}$ Al foils where the same glue was used and the YAG/probe time difference was kept at $1.1\text{ }\mu\text{s}$. The average flyer velocity was plotted against laser energy and is shown in Fig. 8.18. Also shown on the graph are the various other shots with a YAG/probe delay of $1.1\text{ }\mu\text{s}$ described above for visual context. A previous experiment [129] measured final velocity versus drive energy for fibre launched flyers and found a square root dependence. To test this data, a square root fit has been added to the blue points in Fig. 8.18 which does not fit the data well. It appears that the data would however be fit better by a linear relation. The reason we do not find a good square root fit here may be due to uncertainties in energy and the aforementioned inaccuracies in velocity measurement.

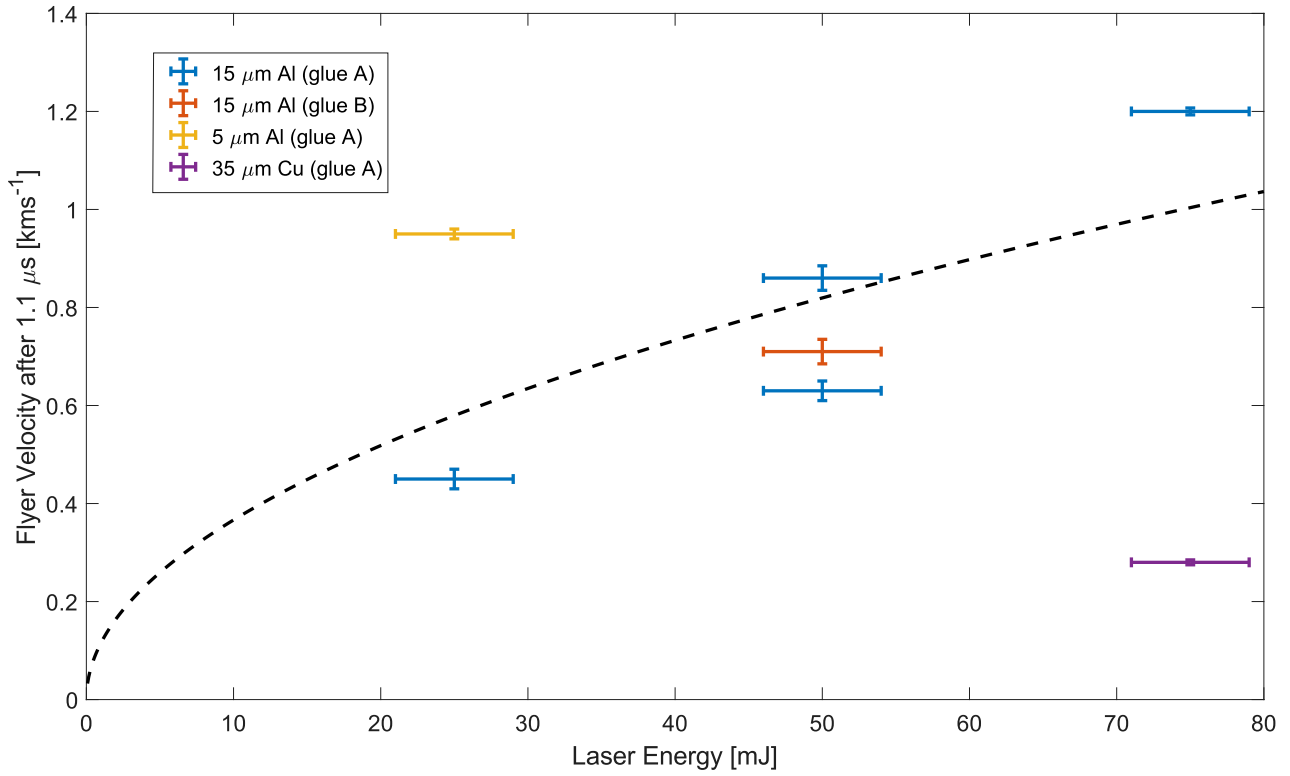


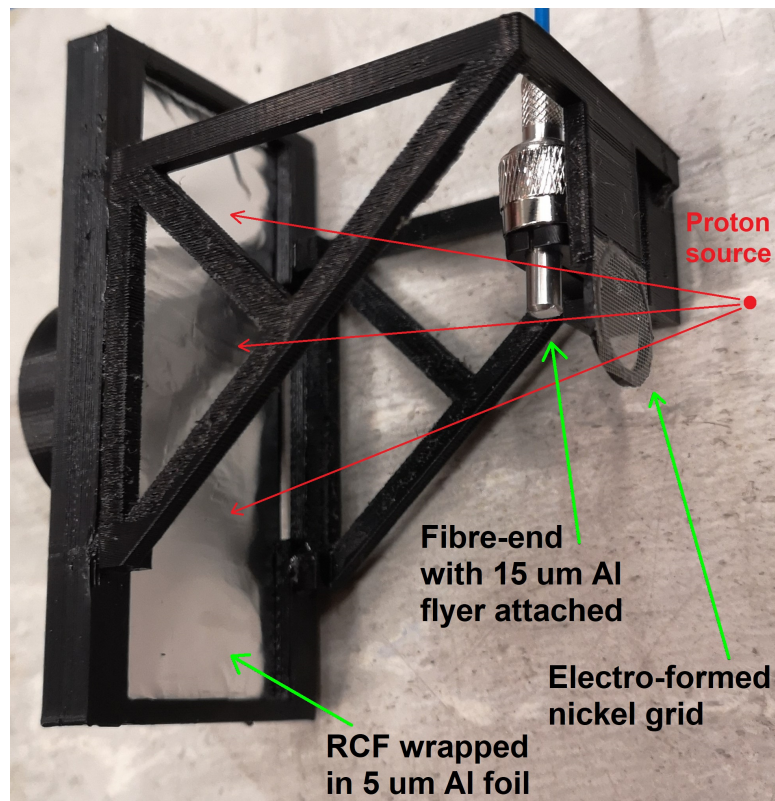
Figure 8.18: Plot showing the variation in measured flyer velocity with laser pulse energy for 15 μm Al flyers attached with glue A (blue points). Each point represents a different shot. Every flyer was probed 1.1 μs after launch. A square-root fit (dashed black line) has been applied to the blue data points. Also added to the graph are shots which varied either glue (red point), Al thickness (yellow point) or flyer material and thickness (purple point).

One column in Table 8.3 we have not discussed yet is the velocity predicted for each flyer by the model by Lawrence and Trott [133], see Section 7.3.1. In all cases the model underestimates the velocity we see which is also reflected in much of the literature results shown in Table 7.3. This is further confusing as we would expect our average velocity measurements to be smaller than the actual flyer velocities due to the early acceleration of flyers. The model does not however, account for adhesives which may be causing energy to couple into the flyer in unexpected ways. This does not explain the underestimation of foils attached by vapour deposition (no adhesive) in Table 7.3. Despite this, the predictions are mostly within a few hundred ms^{-1} which is a reasonable approximation. Accounting for the uncertainties in measuring laser energy and flyer velocity in this experiment, the predictions and results are still promising.

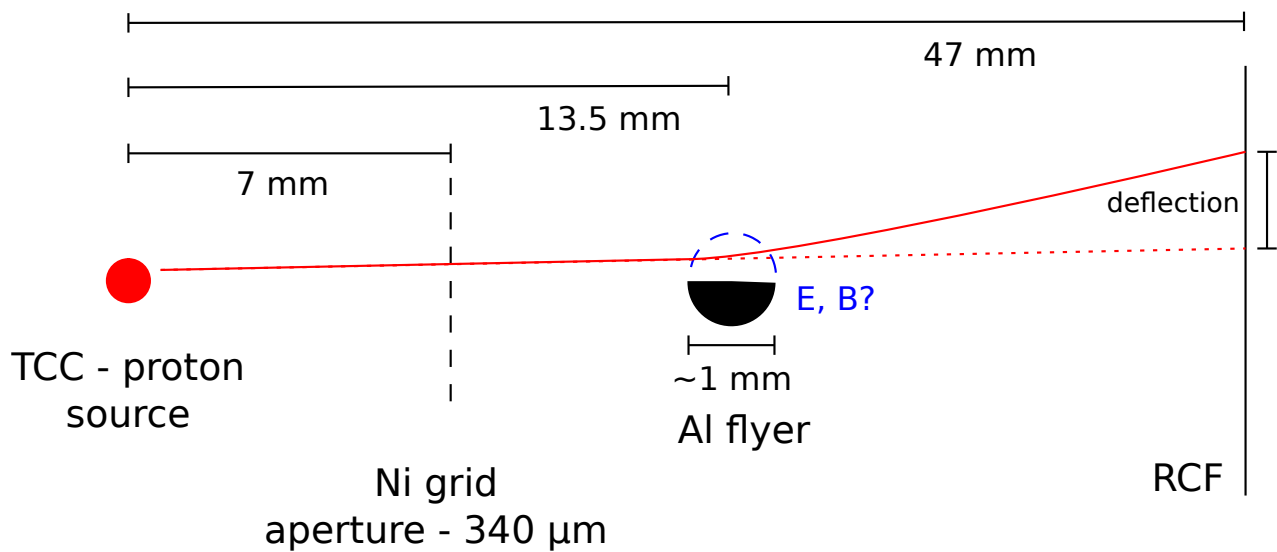
8.3 Proton Radiography of Laser-Launched Flyers

In order to radiograph a laser-launched flyer with a proton beam, the existing experimental setup had to be slightly modified. In the last section, the flyer was launched from TCC which is the location of targets for the Cerberus main short pulse which is used to generate protons by focusing onto a foil target. As such, the flyer launch fibre end was moved away from TCC. This was not a problem however it did mean that simultaneous optical probing of flyers and the use of a HeNe beam to monitor the surface of the foil at launch was no longer feasible. The time of arrival of the Cerberus main short pulse at TCC was synchronised to the optical probe beam. As such, the time difference between the launch of the flyer and generation of the probe beam was measurable using the probe and trigger photo-diodes shown in Fig. 8.11. Important parameters in this experiment will be listed but for details on mechanisms for proton generation, detectors and previous experiments characterising Cerberus generated proton beams, see Chapter 6.

The goal of this experiment was to investigate the presence (or lack of) of electromagnetic fields around or carried by a laser-launched flyer. For this we would need: a proton beam, a grid to imprint a regular pattern into the beam, a launched flyer which could distort the pattern imprinted in the beam and radio-chromic film (RCF) to detect the protons. A 3D-printed mount was designed in order to hold a grid, a fibre for flyer launch and the RCF. This could then be positioned in front of a foil target at TCC from which the proton beam would be generated. A photo of the holder with all components installed and a diagram showing the distances between each is shown in Fig. 8.19.



(a)



(b)

Figure 8.19: Photo showing the 3D-printed holder used to mount a grid, fibre for launching a foil flyer and RCF detector (a) which aided in proton radiographing the flyer upon launch. A schematic (b) shows the distances between each of these components relative to the the location of the proton source at TCC.

For the shot conducted with this setup, the Cerberus main beam was focused onto $5\text{ }\mu\text{m}$ thick Al foil. The main pulse had energy, 2.77 J , providing an intensity of $\sim 6 \times 10^{18}\text{ Wcm}^{-2}$. A nickel electro-formed mesh (flat unlike a woven mesh) [105] with aperture size 0.34 mm and wire width $41\text{ }\mu\text{m}$ was placed between the proton source and the flyer. The flyer was a $15\text{ }\mu\text{m}$ Al foil glued on to a fibre end with glue A and launched with the YAG laser providing 75 mJ and $1.6\text{ }\mu\text{s}$ prior to the arrival of the proton beam. The detector pack was 3 layers of EBT2 RCF (see Section 6.3), wrapped in $5\text{ }\mu\text{m}$ Al foil. Images of the RCF from this shot are shown in Fig. 8.20.

In these images we can see the launched flyer along with a trail of debris behind it, the imprint of the nickel grid and we see the curling of the foil remaining on the fibre holder as with optical images of these flyers. We can infer the velocity of the flyer by measuring the known width of the fibre holder (3.2 mm) [135] and using this calibration to measure the distance travelled by the flyer in $1.6\text{ }\mu\text{s}$. The velocity was found to be 1.2 kms^{-1} . Estimating the kinetic energy of the flyer yields a laser energy conversion efficiency of 30.6% .

As discussed in Section 6.3 the separate layers of RCF are most sensitive to distinct energy bands of protons. According to SRIM analysis, Fig. 8.20a shows mostly signal from 2.5 MeV to 2.95 MeV protons, Fig. 8.20b is mostly sensitive to 5.85 MeV to 6.15 MeV protons while Fig. 8.20c is sensitive to 8.15 MeV to 8.4 MeV protons. Since the highest energy protons travel faster than the slower ones the different layers are images of the flyer at different times. As calculated in Section 6.3, layer 3 Fig. 8.20c shows the flyer $\sim 900\text{ ps}$ earlier in time than layer 1. At a flyer speed of 1.2 kms^{-1} the flyer would move a distance of $\sim 1080\text{ nm}$. Compensating for the magnification of the system ($M = 47/13$) this movement on the RCF is $\sim 3.9\text{ }\mu\text{m}$ which is smaller than the scanner/RCF resolution of $5.292\text{ }\mu\text{m/pixel}$ hence we cannot measure flyer velocity from separate layers.

A second consequence of the difference in arrival time for protons at each layer is the distortion of grid lines seen on Fig. 8.20a. This effect was first covered in Section 6.4. Since layer 1 observes the slowest protons, the faster ones (and other ionising particles such as electrons) will partially ionise the grid by knocking electrons out, and charge up the nickel grid before the layer 1 protons pass the grid. It seems unlikely that X-ray emission could cause this since the effect is concentrated at the centre of the proton beam (which is also where the higher energy protons pass due to a lower divergence) and X-rays are not emitted in the same beam-like manner. The distortion is not desirable as it makes deflection effects caused by a sample such as a flyer less clear.

The distortion effect has been reiterated here as it has consequences for the original purpose of this experiment, measuring electromagnetic fields around a flyer. In Fig. 8.20b we can see that the proton beam passing the debris trail of the flyer undergoes no observable deflection, in Fig. 8.20a it is less clear due to the overall grid-charge distortion but also appears to show no clear distortion. Applied to a FLF projectile, a lack of deflection would be a positive result as a projectile driving an external field into a target could drive electromagnetic instabilities in the collapsing cavity of an FLF experiment. In addition to this result, we can use the size of one pixel to find the minimum field strength we are sensitive to by calculating the field strength required to deflect a proton by the pixel size of $5.292 \mu\text{m}$, or the sensitivity of our experiment.

8.3.1 Minimum Quantifiable Field Strengths — Sensitivity

Here we will determine the required electric or magnetic field to cause a proton to deflect by a distance smaller than the size of a pixel on an RCF image. This amount is $5.292 \mu\text{m}$ as determined in Section 6.3.

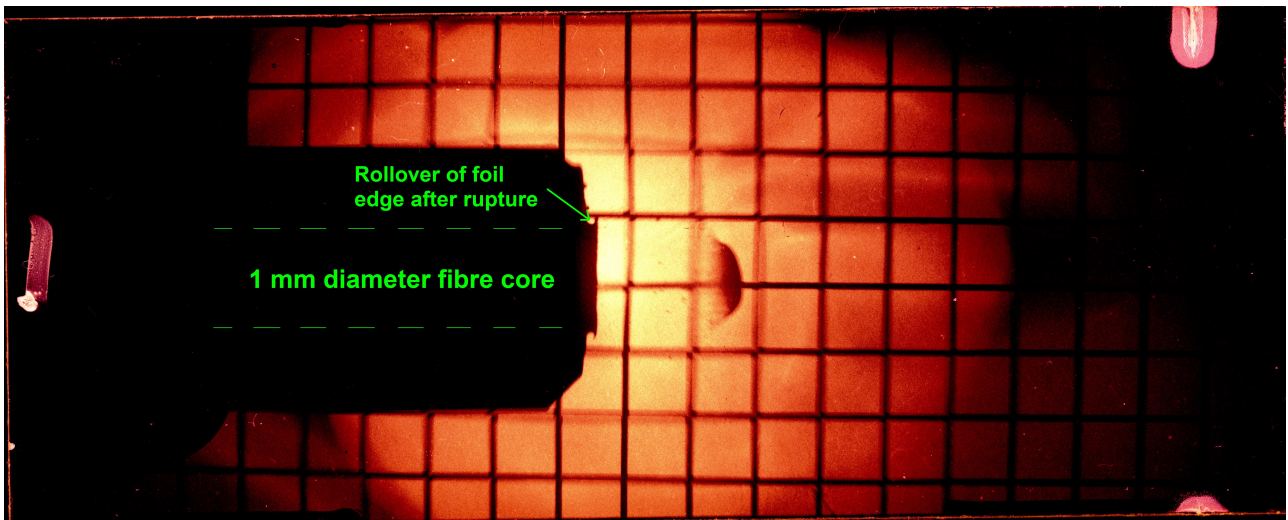
Electric Field Deflection In order to deflect a proton with an electric field within a plasma there would have to be a strong charge separation which is unlikely given that plasmas are generally quasi-neutral. Regardless, the calculation to find the minimum measurable electric field is relatively simple. We begin by defining a region of electric field at the size of a flyer: a $\sim 1 \text{ mm}$ circular region. The strongest response would be experienced by a proton travelling through the centre of this region, at velocity v_P and travelling perpendicular to the electric field. This problem is visualised in Fig. 8.21. After leaving the electric field the proton will approximately remain on the same trajectory till it reaches the RCF position 34 mm from the flyer, see Fig. 8.19b. We know the proton must drift $5.292 \mu\text{m}$ in the electric field direction so we can define a deflection angle, θ ,

$$\theta = \tan^{-1} \left(\frac{5.292 \times 10^{-3}}{34} \right) = 8.9 \times 10^{-3} \text{deg.} \quad (8.1)$$

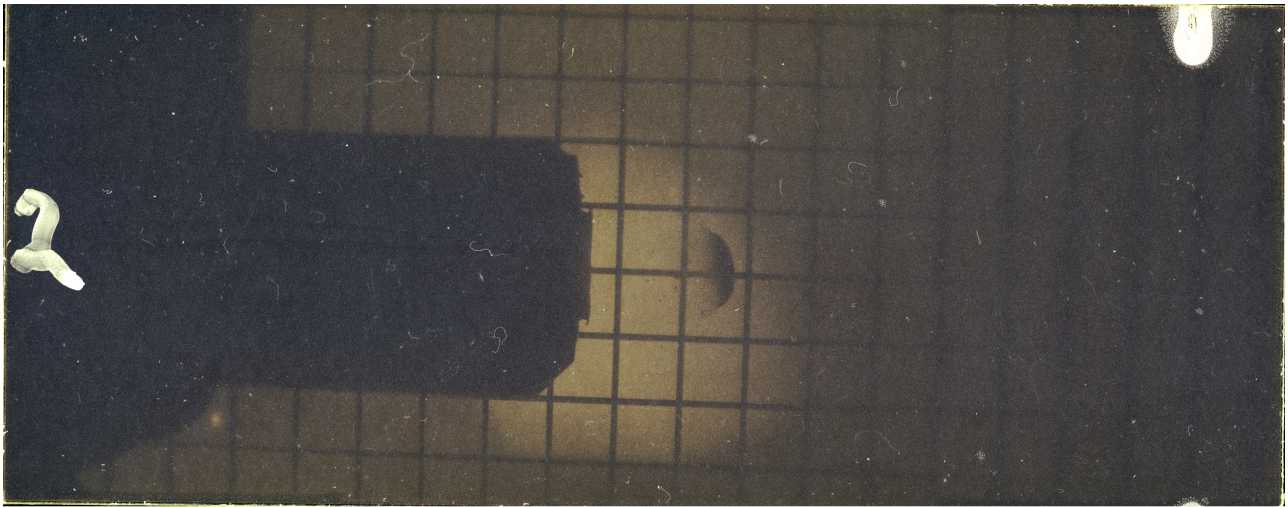
Traversing the electric field, the proton will experience an acceleration $a = eE/m_P$, where e is the charge on an electron and m_P is the mass of a proton. Assuming that the acceleration is constant, the velocity imparted on the proton by the electric field, v_E is,

$$v_E = \frac{eEt}{m_P}, \quad (8.2)$$

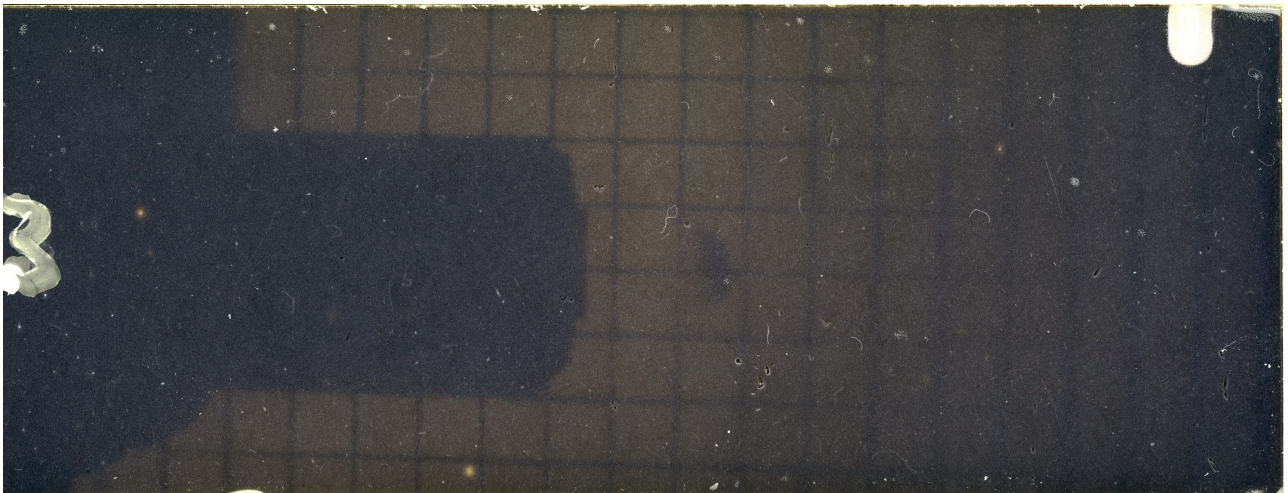
where t is the time the proton remains in the electric field i.e. $t = 1\text{mm}/v_P$.



(a)



(b)



(c)

Figure 8.20: Images of the 3 RCF layers showing proton radiography of a laser launched flyer plate shot, the bright regions being mostly protons. Image (a) is the top layer (closest to source). Images (b) and (c) are the middle and rear layers respectively. These latter layers recieved a lower signal and showed a weaker response for which the scanner compensated producing the different appearance. A $15\text{ }\mu\text{m}$ Al foil was launched by a 75 mJ YAG laser pulse which was imaged by a proton beam $1.6\text{ }\mu\text{s}$ later.

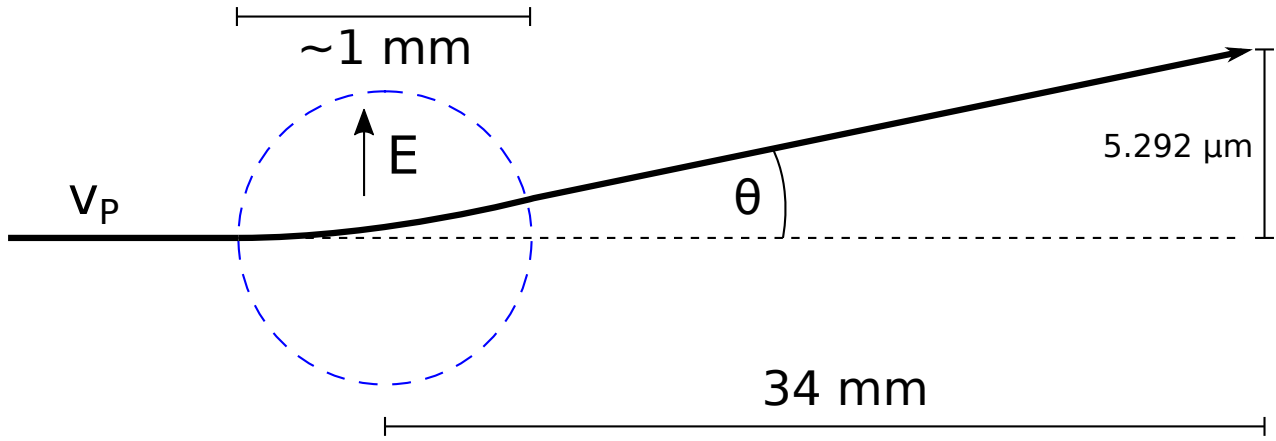


Figure 8.21: Diagram showing the deflection of a proton, travelling at v_P , by an electric field E , which results in a deflection from its original trajectory by an angle θ . This deflection results in a drift in the direction of E by a distance $5.292 \mu\text{m}$.

We now have an expression for the velocity given to the proton by the electric field from Equation (8.2), given the deflection is small we can assume that the velocity of proton in the direction of its original trajectory remains approximately the same at v_P . The resulting velocity of the proton is in the direction of deflection hence, the components must form a triangle with the deflection angle in Equation (8.1), such that,

$$\tan(\theta) = \frac{v_E}{v_P} = \frac{eE(1\text{mm})}{m_P v_P^2}. \quad (8.3)$$

Using Equation (8.3) we can find the minimum measurable electric field using Equation (8.1) and the initial velocity of a proton v_P . In Section 6.3 the velocity of protons reaching the first RCF layer was determined to be $\sim 0.075c$. The minimum measurable electric field will then be $\sim 8 \times 10^5 \text{ Vm}^{-1}$.

Magnetic Field Deflection Similar to the electric field analysis, we begin with a 1 mm region of magnetic field, B , through which a proton travelling at v_P is deflected. The deflection occurs through the same angle given by Equation (8.1) which is visualised in Fig. 8.22. The difference now is that the deflection is caused by a force perpendicular to the magnetic field resulting in circular motion about the field with a radius given by the Larmor radius, r_L ,

$$r_L = \frac{\gamma m_P v_P}{Be}, \quad (8.4)$$

where γ is the Lorentz factor. If we assume the region of magnetic field is circular, tangents at the points at which the proton enters and exits the field and the trajectory of the proton in the field will form a sector of a circle with radius r_L . Geometrically, this sector must subtend an

angle equal to the deflection angle θ . If the proton passes through the centre of the magnetic field and that the deflection is small, we can assume the trajectory of the proton in the field is approximately the same length as the diameter of the field region ~ 1 mm. We can then use knowledge of the deflection angle, Equation (8.1), and the cosine rule to determine r_L ,

$$(1\text{mm})^2 = r_L^2 + r_L^2 - 2r_L^2 \cos(\theta) \quad (8.5)$$

$$r_L = 1\text{mm} / \sqrt{2(1 - \cos(\theta))} = 6.4\text{m}. \quad (8.6)$$

We now have the capability to calculate the minimum measurable magnetic field using Equation (8.4) and Equation (8.4) and the proton velocity $v_P = 0.075c$. The minimum measurable magnetic field was found to be 37 mT.

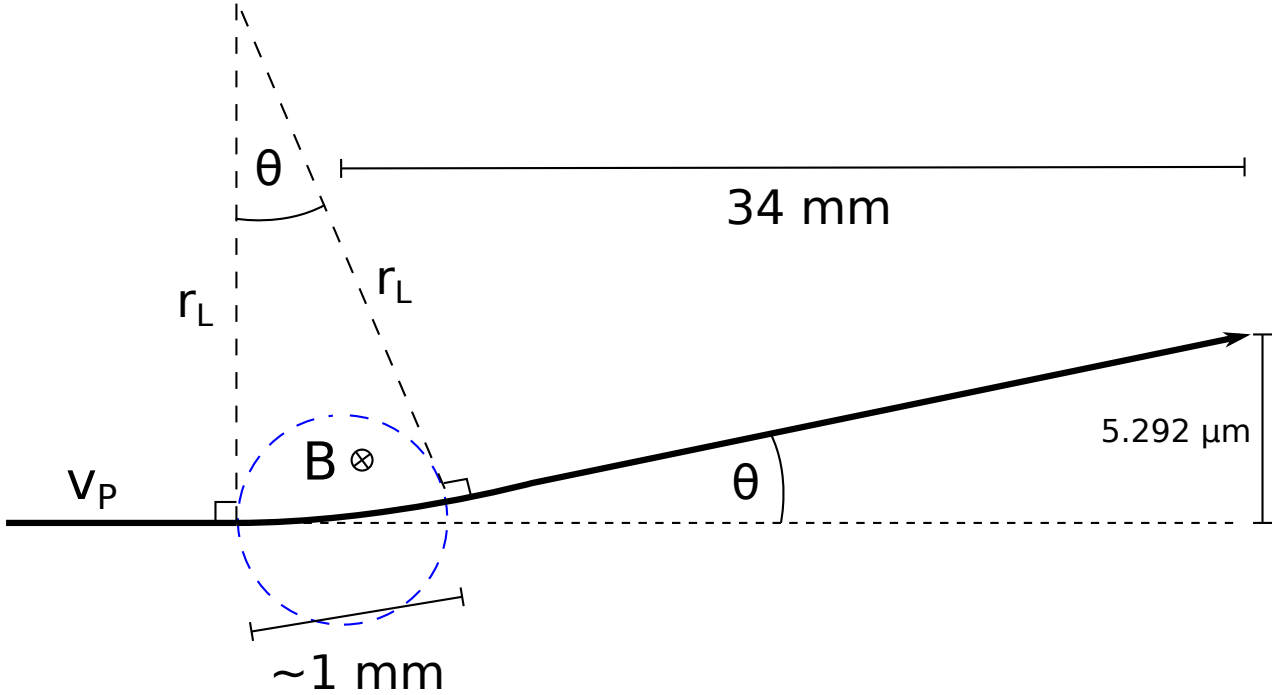


Figure 8.22: Diagram showing the deflection of a proton, travelling at v_P , by a magnetic field B , which results in a deflection from its original trajectory by an angle θ . This deflection results in a drift in the direction perpendicular to B by a distance $5.292 \mu\text{m}$.

8.4 Chapter Summary and Conclusions

We began this chapter by attempting to launch a foil flyer from the end of an optical fibre using the Cerberus long pulse beam as the drive laser. The first objective was to simultaneously establish a new beamline which would be used to inject laser light into the end of an optical fibre and develop a reliable method for mounting a fibre and affixing a foil to the output end of the fibre. After several damage tests and failed attempts to observe the launch of a flyer using a portion of the Cerberus main short pulse as an optical probe, the Gaussian beam profile of Cerberus was suspected to be limiting the amount of energy we could input into the fibre due to self-focusing ($B \sim 4$). To rectify this a beam diffuser was used to homogenise and flatten the beam profile prior to injection. While this allowed more energy to be injected into the fibre, flyers launch was still not observed.

An auxilliary HeNe beam was then installed which was reflected off the surface of the output end of a fibre and used to monitor response of foils to the arrival Cerberus long pulse beam. It was found that the foils were responding unexpectedly slowly ($>2 \mu\text{s}$) and a suspected reason for this arose from the 1.4 ns pulse duration of the Cerberus long pulse. This pulse length was short compared with pulses used in literature. As such, a secondary Q-switched Nd:YAG laser system was installed in place of the Cerberus long pulse which had a longer pulse length of ~ 20 ns. Initial results from the HeNe laser, showed that the YAG laser pulse was causing the flyers to respond within a period of time comparable with the YAG laser pulse duration. A further advantage of the YAG system over the Cerberus long pulse allowed the relative time between firing of the YAG and arrival of the optical probe to be varied more widely.

With the system better optimised, the first experimental results were taken by using the optical probe to capture images of flyers launching. Flyer launch was first confirmed to be occurring successfully creating an analogue of the optical imaging of a FLF gas gun launch using a probe generated by Cerberus. From this first image the average velocity of the flyer was inferred from the flyer displacement and delay between launch of the flyer and probe arrival, yielding a velocity 1.2 kms^{-1} . Flyer launch was then conducted for varying probe times, launch energy and for varying foil materials, thicknesses and glues.

Results for varying probe times and constant launch energy and flyer material/glue showed an almost linear relationship between flyer displacement and time. Which was expected as previous experiments [123, 124, 129] showed a constant velocity for flyers more than a few drive laser pulse lengths after launch. Regardless, this method only allowed one image per shot, a more efficient way to measure flyer velocity is by using high speed multiple-image photography

or a time resolved interferometry system which can yield full velocity history such as VISAR. Results for probing flyers the same time after launch but varying drive energy showed an increase in flyer velocity with drive energy. A previous experiment [129] observed a square root dependence of velocity on energy but results in this experiment had too few statistics with errors too large to see the same relation. By using different types of glue to adhere the same type of flyer to fibres, no significant change in resultant flyer velocity was found. Whereas, decreasing flyer thickness increased flyer velocity and more dense flyer materials decreased flyer velocity.

The final experiment used the Cerberus main short pulse to generate a proton beam which was used to radiograph a flyer in a first proof of principle experiment [Paper in preparation, with author as first author]. This was to emulate the proton radiography of a FLF gas gun projectile. If electromagnetic fields are present around a flyer (or FLF projectile) the proton beam would be deflected which could be measure by imprinting a grid into the proton beam and measuring the deflection of the beamlets. A shot taken with the proton beam arriving $1.6 \mu\text{s}$ after flyer launch showed no observable deflection behind the flyer. This would be a positive result for an FLF projectile as fields driven into a target could cause electromagnetic instabilities in and interfere with the dynamics of a fusion capsule undergoing collapse. From this result a minimum measurable value for an electric or magnetic field was able to be determined setting an upper limit on the fields present in the experimental shot. These were found to be an electric field with strength $\sim 9 \times 10^5 \text{ Vm}^{-1}$ or a magnetic field with strength 38 mT.

In order to progress this experiment, the next step is to take more data with a proton probe time earlier than $1.6 \mu\text{s}$ as it is possible that the plasma attached to the back of the flyer had recombined in the shot shown. Also by increasing the drive energy, we may be able to detect an attached plasma — there could be a threshold energy, below which a plasma is not detectable with our setup due to sensitivity and/or plasma recombination. The grid spacing on the shot shown is also large compared with the flyer (~ 2 grid squares cover the whole flyer). Therefore a finer grid should also be used.

Chapter 9

Thesis Conclusions

First Light Fusion (FLF) are a company attempting to harness fusion energy through hypersonic impact of targets containing voids filled with fusion fuel. These voids are imploded by the passage of a shock, driving the contents to high instantaneous pressure and temperature. A problem they encounter is in the diagnosis of such conditions within the void undergoing rapid and extreme shock compression. This is due to the fact that the system evolves rapidly and, by virtue of the increased density, becomes opaque to all but the most energetic probes: X-rays and energetic particles for example. Development of novel methods to solve this problem was the motivation for this PhD project. A suitable probe was determined to need a duration (or effective shutter speed to draw a parallel with a camera) which is below the μs timescales involved in an impact experiment, provide a spatial resolution of the order $10\text{ }\mu\text{m}$ in order to adequately image mm scale objects and have sufficient energy to penetrate the shock compressed target. Possible candidates were identified as X-rays emitted by X-pinches and X-rays and particles beams generated by high power lasers such as the Cerberus laser at Imperial College.

We began this thesis by breaking down the pathway to this goal and establishing the crucial objectives. The first was finding a method to synchronise the impact and subsequent shock driven collapse of a void with the arrival of a probe pulse. The next goal was to characterise parameters such as energy, source size and generation for each probe. Then finally to execute a FLF-style experiment using a probe and some form of synchronisation with the launch of a shock-driving projectile.

9.1 Methods for Probe Synchronisation

To synchronise diagnostic probe with a FLF impact, the time from trigger of a diagnostic probe to arrival at target was established. For an X-pinch, this time is $\sim$ ns meaning the diagnostic can be triggered by sensors close to an impact target. For a laser like Cerberus, the time is $\sim$ 0.1 s (constrained by the long internal optical path of a pulse and amplifier trigger times) which requires triggering as early as possible after projectile launch. A type of shock-driver used by FLF is a two-stage light-gas gun. Early diagnostic triggering then requires sensing a projectile through the gun barrel, ideally at multiple positions to more accurately determine acceleration and predict arrival time. A pre-existing type of electromagnetic sensor known as a Faraday gate was developed for this goal. Consisting of an annular magnet with a coil of wire inside its inner radius, the Faraday gate can sense a projectile passing through its centre by the current electromagnetically induced in the coil, even with an obstacle such as a gun barrel between the projectile and gate.

Experimental work to characterise the behaviour of Faraday gates included measuring a linear relation between projectile velocity and output voltage for identical projectiles. Gates were found to be sensitive to projectiles with a variety of velocities ranging between a few ms^{-1} and several kms^{-1} . They were fielded upon two different gas guns, the results from which indicate that an experiment which intends to use a Faraday gate is dependent upon the material the gun barrel is made from. Faraday gates were found to work with a barrel of 10.5 mm thickness, demagnetised steel but not with a magnetic, 32.2 mm thickness steel barrel. An investigation into the skin effect suggests that the issue could arise from the latter barrel being impermeable to the oscillating magnetic field produced around a projectile when passing a Faraday gate. Potential solutions to this problem include reducing the thickness of the barrel and using a demagnetised or non-electrically conductive material for the barrel.

It was also known that the output signal of a Faraday gate is dependent on the velocity of the projectile generating the signal (amongst other material properties). As such it should be possible to determine the velocity from a single gate response. Hence, work began in order to develop and benchmark a theoretical model to simulate the voltage induced within a Faraday gate. Finding the velocity through this method would aim to further aid in impact prediction for a projectile. The process was broken down into several steps which need to be modelled over a projectile flight: induction within the projectile, generation of a magnetic field around the projectile and change in magnetic flux through the coil within the Faraday gate and induction within the Faraday gate coil due to the changing flux. Progress was made toward simulating

the first of these steps and a simple experiment was devised to test the validity of the model which initially showed good agreement to within 10%.

Further work toward optimising the use of Faraday gates for probe synchronisation would include development of a fast response system to predict an impact from a single gate or a series of gates. A body of data from previous shots to feed into this system could also aid in prediction. Furthermore, continuation of the development of a model to predict velocity of a single gate would be useful.

9.2 Characterisation of Diagnostic Probes

Characterisation of probes began with X-ray pulses generated using the Cerberus laser. Previous work indicated an energy spectrum up to ~ 20 keV [54] and a pulse length on the timescale of the laser pulse (~ 700 fs) as with all laser generated X-ray pulses. Therefore, measuring X-ray source size became the priority for the experimental work in this project. To achieve this, a penumbral imaging system was developed on the Cerberus target chamber incorporating vertical and horizontal axis measurement. The positioning of other diagnostics within the chamber made alignment of the penumbral imaging system difficult. This inspired the novel use of tungsten carbide ball-bearings as an edge which, by virtue of being spherical, made alignment at awkward angles much easier, the curved tungsten carbide surface was smooth with little surface defects (average deviation of surface profile from nominal diameter of 5 mm is $0.025 \mu\text{m}$) and presented excellent spatially varying X-ray absorption properties when compared to a steel blade edge.

Source size measurements were made for Cerberus laser shots onto foil and wire targets. Initial results showed sizes for foil and tungsten wire shots mostly between 10 and $100 \mu\text{m}$. Source sizes from $5 \mu\text{m}$ diameter carbon fibre were measured and the capability of measuring sources $< 5 \mu\text{m}$ in size were demonstrated but the low flux emitted by the target made accurate measurements difficult. Due to the curvature in shadows cast by the balls in X-ray radiographs, the ball method is more susceptible to shot noise and random fluctuations in the radiograph than a flat edge. To test the capabilities of the tungsten carbide ball-bearings for accurate measurements of small sources, shooting levitated targets would be an extension to this work. Levitated targets, unlike foils and wires, are spatially limited. This means that, when a levitated target is irradiated by the Cerberus laser, the beam of hot electrons which is liberated and directly control the size of a X-ray source are mostly held within the few μm diameter of the target. This is in contrast to a foil or wire, for example, where the electrons can

freely spread out transverse to the beam direction, directly increasing the X-ray source size. To test this source size measurement diagnostic on another piece of equipment, the tungsten carbide ball-bearings were used on X-pinchs. Values for the size of the hard X-ray sources on X-pinchs were found between 10 and 50 μm . To measure the size of the smaller, soft X-ray source it was necessary to use a detector which could selectively detect the lower energy radiation emitted by the source. By manipulating the detector the tungsten carbide ball-bearings allowed measurement of the soft source $<10\text{ }\mu\text{m}$ in size.

In order to evaluate these sources for use on an FLF-style experiment, we must consider penetration of the probe through a shocked target, the source size and pulse duration. Firstly both sources have a duration providing temporal resolution of at least $\sim\text{ns}$, ideal for imaging μs scale collapse events, with the laser providing marginally better performance. By calculating the expected increase in density during an impact and data provided by the CXRO database we found X-rays of at least 10 keV are required to transmit any radiation through a 10 mm FLF target. This means that the soft X-pinch source with energy $<5\text{ keV}$ is unfortunately unsuitable for a FLF experiment. The hard X-pinch source with energy $>10\text{ keV}$ should however be sufficient to penetrate this PMMA along with Cerberus generated X-rays. The separating factor between these two sources is then the size which is typically lower for the X-pinch hard source and less variable than the laser produced source. Therefore the X-pinch is a preferable source for imaging FLF targets in this regard, particularly given the relatively low cost of an X-pinch compared to a multi-TW laser. One advantage of the laser however is that the spectrum and source size of Cerberus X-rays can be manipulated through use of different target materials and shapes. This gives further motivation to characterise the X-ray source generated by shooting spatially-limited optically-levitated targets, while an X-pinch requires that the emitting material can be fabricated into a relatively thin, self-supporting wire.

This same characterisation work was extended to proton beams generated by Cerberus. Previous work with $<5\text{ J}$, 700 fs shots had constrained the proton spectrum to be predominantly $<10\text{ MeV}$ [54] meaning that pulse duration and source size were the priority in this project. Similar to X-rays the production of protons occurs on a timescale comparable with the Cerberus laser pulse however we determined that, due to the spectrum of proton energies and therefore an inherent range of velocities, the temporal profile of the beam will spread to several hundreds of ps over 10s of mm. A woven copper grid was located through which a Cerberus proton beam was launched. Using the image produced it was possible to measure and map the effective source size by using the edges formed by the grid for penumbral imaging. Preliminary results

indicate that the source size of the beam is between 5 and 40 μm dependent on position in the beam. The reason for the locations of smallest/largest source size has not yet been constrained. Comparing maps of source size to both beam brightness, and local variation in brightness seemed to show no correlation with source size.

Applied to a FLF experiment it was found that the energy of the protons made by Cerberus would not be able to penetrate beyond a mm of FLF target. Penetration would require protons with energy >40 MeV which would require at least a near PW laser system, compared with Cerberus which is currently operating at ~ 10 TW. It would be interesting to diagnose the energy of proton beams generated by Cerberus after it undergoes planned upgrades to 50 TW. Despite this, the pulse length and source size of the proton beam are appropriate for FLF experiments.

9.3 Execution of an FLF-Style Experiment

In lieu of being able to bring a gas gun into Cerberus, an experiment was devised to drive a laser launched flyer as an analogue to an FLF projectile. This flyer could then be probed using Cerberus. The first objective was to establish a new beamline which would be used to inject laser light into the end of an optical fibre and develop a reliable method for mounting a fibre and affixing a foil to the output end of the fibre. The first drive laser considered was the Cerberus long pulse with duration ~ 1.4 ns and energy up to 200 mJ. It was found that the Gaussian beam profile and short pulse duration lead to fibre destruction through self-focusing within the fibre core and unexpected slow (>2 μs), flyer responses.

To remedy the above, the Gaussian profile was modified to produce a near flat-top spatial beam profile using a holographic beam diffuser and a secondary Q-switched Nd:YAG laser system was installed in place of the Cerberus long pulse which had a larger pulse length of ~ 20 ns. Initial results showed that the YAG laser pulse was causing the flyers to respond within a period of time comparable with the YAG laser pulse duration. With the new launch system, the first experimental results were taken by using optical light to image flyers. From these images the average velocity of flyers was inferred, showing velocities up to 1.2 kms^{-1} and laser energy conversion efficiencies up to $\sim 30\%$. Flyer launch was then conducted for varying probe times, launch energy and for varying foil materials, thicknesses and glues.

Results for varying probe times showed an almost linear relationship between flyer displacement and time. Which was expected as previous experiments showed a constant velocity for flyers more than a few drive laser pulse lengths after launch. This method however, only

allowed one image per shot, a more efficient way to measure flyer velocity is by using high speed multiple-image photography or an interferometry system which can yield full velocity history. Results for probing flyers the same time after launch but varying drive energy showed an increase in flyer velocity with drive energy. Previous experiments reported in the literature have observed a square root dependence of velocity on energy but results in this experiment had too few statistics with errors too large to conclusively demonstrate the same relation. Results from varying foil glue type showed no significant change in flyer velocity while decreasing flyer thickness increased flyer velocity and as expected, more dense materials decreased velocity.

The final experiment used a Cerberus-generated proton beam to radiograph a laser-launched flyer for the first time, with a diagnostic technique predominantly confined to large national lab facilities up to this point. This was to emulate the proton radiography of a FLF gas gun projectile. If electromagnetic fields are present around a flyer (or FLF projectile) the proton beam would be deflected which could be measured by imprinting a grid into the proton beam and measuring any deflections. A shot taken with the proton beam arriving $1.6 \mu\text{s}$ after flyer launch showed no observable deflection behind the flyer. This would be a positive result for an FLF projectile as fields driven into a target could cause electromagnetic instabilities in an FLF target. From this result an upper limit on the fields present in the experimental shot was determined. These were found to be an electric field with strength $\sim 9 \times 10^5 \text{ Vm}^{-1}$ or a magnetic field with strength 38 mT.

In order to progress this experiment the next logical step is to take more data with a proton probe time earlier than $1.6 \mu\text{s}$ as it is possible that the plasma attached to the back of the flyer had recombined in the shot shown, and any launch driven electric currents within the flyer (generating magnetic fields) had resistively damped. Also increasing the drive energy should be explored as there may be a threshold for energy, which we have not exceeded in this project, that causes a plasma to remain attached to the back of a flyer. The grid spacing on the shot shown is also large compared with the flyer (~ 2 grid squares cover the whole flyer). Therefore a finer grid should also be used in future to better resolve small field structures.

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