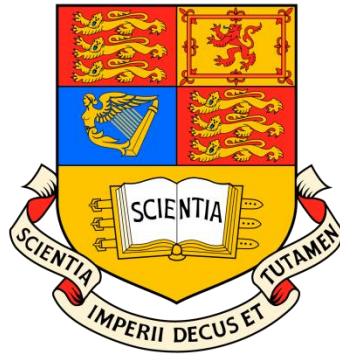


An experimental investigation of the azimuthal structures formed during the ablation phase of wire array z-pinches

George Swadling



Imperial College London

Department of Physics

Plasma Physics Group

Submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy in Science
of the University of London and the Diploma of
Imperial College

2011

Declaration

I hereby certify the material in this thesis, which I submit for the degree of Doctor of Philosophy, is entirely original unless otherwise cited or acknowledged in the text.

George Forrester Swadling

24/10/11

Acknowledgments

The work presented in this thesis could not have been completed without the help and advice of my supervisor, Professor Sergey “The Admiral” Lebedev. Always on hand to provide his invaluable insights, his support and enthusiasm have been of tremendous help throughout my PhD.

I must also thank the senior members of the MAGPIE experimental team, particularly Dr. Francisco “Fran-Chan” Suzuki-Vidal, Dr. Gareth “Captain fun-times” Hall and Dr. Simon “Five minutes” Bland, who taught me so much about both the operation of the MAGPIE generator and the various diagnostic techniques. Without their patience none of this work would have been possible. I would also like to thank Prof. Jeremy “Uncle Jerry” Chittenden for taking time to explain many of the principals underlying the physics of wire arrays, and also for providing data from GORGON simulations for comparison with my experimental results.

I must thank the rest of the MAGPIE experimental team for their help in running the experiments presented in this thesis, including Dr. Adam “Prizewinning” Harvey-Thompson, Guy “Guybrush Threepwood” Burdiak, Louisa Pickworth, “Fireball!” Phil de Grouchi, Jon “Skiddles” Skidmore, Essa Khoory and Lee Suttle.

Thanks also to Alan Finch for all of his help during my experiments, and also to Paul Brown and the staff of the Physics Mechanical Instrumentation Workshop for producing much of required the apparatus.

I must thank my house mates Rachel ‘tiddles’ Dbis, David Worrall and Brian Appelbe for “volunteering” to proof read my thesis, and my officemate Nicolas “mission impossible” Niasse for keeping me cheerfully distracted throughout the writing process.

Finally I must thank my parent for their constant support and encouragement throughout my education. I’m sure they are pleased I have finally finished school.

Abstract

A series of wire array implosion experiments have been carried out on MAGPIE, a 1.4MA peak current, 240ns rise-time pulsed power generator located at Imperial College London. The aim of these experiments was to investigate the azimuthal structure of ablation plasma produced during the early stages of wire array implosions. Previous work [Lebedev, S.V., et al., PoP, 2001] has demonstrated that a significant portion of the implosion time is dominated by the ablation phase, during which the dense wire cores remain at their initial radius and ablate streams of plasma towards the array axis. This ablation plasma prefills the array, and its distribution forms the initial conditions for the eventual snowplough-like implosion.

In order to carry out this investigation a new two-colour end-on interferometry system was constructed. A custom software suite was developed in order to analyse the resulting data, enabling the conversion of the raw interferograms into 2D electron density maps.

The experiments focused on cylindrical tungsten and aluminium arrays of between 8 and 128 wires. The structures observed in aluminium arrays were dominated by collisional features. Networks of oblique shocks were formed as the ablation streams interacted with their neighbours. Analysis of these shock structures allowed an estimate to be made for the Mach number of the ablation streams, $M=7.9-8.2$. In contrast, the structures observed in the tungsten experiments were characterised by smooth density profiles, consistent with relatively long ion mean free paths. The quantitative nature of the dataset makes it ideal for comparison with the results of numerical simulations.

Also reported in this thesis is the development of two CW laser diagnostics, a quadrature interferometer, and a Faraday current diagnostic. The design of these diagnostics is discussed and some examples of the analysis are presented.

Table of Contents

List of Figures	9
List of Tables	16
Chapter 1 Introduction and Review of Wire Array Physics	17
1.1) Background and Motivation	17
1.1.1) Inertial confinement fusion	17
1.1.2) Energy compression and X-ray production in pulsed power driven Z-pinch implosions	19
1.1.3) Introduction to the implosion dynamics of wire array Z-pinchs	20
1.1.4) The MAGPIE pulsed power generator	20
1.2) Outline of work	21
1.3) The Authors Contribution	23
1.4) Review of the physics of wire array implosions	24
1.4.1) The dynamic Z-pinch	24
1.4.2) Evolution regimes – O-D implosion vs. the discrete wire mode	25
1.4.3) OD trajectory and the rocket model	27
1.4.4) The fundamental perturbation	29
1.4.5) Precursor column formation	30
1.4.6) Snowplough implosion	31
1.4.7) Magneto-Rayleigh-Taylor instability	32
1.4.8) Stagnation	33
Chapter 2 Pulsed power technology & the MAGPIE generator	35
2.1) Introduction to pulsed power technology	36
2.1.1) The capacitor discharge	36
2.1.2) The effect of loading on the rise time and peak current of the generator	38
2.1.3) Adding generators in series – the Marx bank	38
2.1.4) Effect of adding generators in parallel	41
2.1.5) The characteristic impedance of the generator	42
2.1.6) Water filled coaxial transmission lines as a pulsed power source	43
2.2) The MAGPIE generator	46
2.2.1) Load specification and power delivery	47
2.2.2) Pulse Forming Lines	48
2.2.3) Marx Banks	49
2.3) Table of key MAGPIE parameters	50
2.1) Introduction to the Z-R generator	51
Chapter 3 The MAGPIE plasma diagnostics suite	53
3.1) Signal transmission and recording	53
3.2) Current/magnetic field diagnostics	55

3.2.1) B-dot magnetic field probe	55
3.2.2) Rogowski groove current monitors	57
3.3) Resistive voltage probe	58
3.4) Radiation diagnostics	59
3.4.1) Diamond photo-conducting detectors (PCDs)	59
3.4.2) Nickel bolometer	61
3.5) Pinhole imaging of radiative emission	61
3.5.1) The pinhole camera	62
3.5.2) Time integrated imaging	63
3.5.3) Micro-channel plates	64
3.5.4) 4-frame XUV MCP cameras field on MAGPIE	65
3.6) Optical streak imaging	66
3.7) Laser probing diagnostics	67
3.7.1) The laser imaging system	67
3.7.2) The refractive index of a plasma due to free electrons	67
3.7.3) Refractive index of neutral gas	70
3.7.4) Shadowgraphy	72
3.7.5) Schlieren imaging	74
3.7.6) Imaging interferometry	76
3.7.7) Faraday rotation	79
Chapter 4 The development of CW laser diagnostics	81
4.1) CW quadrature interferometer	82
4.1.1) Quadrature analysis	82
4.1.2) Optical layout	83
4.1.3) Intensity function of the quadrature signals	83
4.1.4) The benefits of quadrature analysis	83
4.1.5) Apparatus and experimental setup	88
4.1.6) Results	90
4.1.7) Improvements and further work	94
4.2) CW Faraday rotation	96
4.2.1) The Faraday Effect	96
4.2.1) Experimental setup	98
4.2.2) Path integral calibration	99
4.2.3) Measurement of the rotation angle	101
4.2.4) Results	102
4.2.5) Possible improvements	107
Chapter 5 End-on laser interferometry of ablation structures in wire array Z-pinches	111
5.1) Advantages of a Mach-Zender interferometer	111
5.2) Experimental setup for end-on probing	114
5.3) Analysis technique	116
5.4) Zero fringe shift	120
5.4.1) Zero-fringe calibration using a rocket model calculations	121

Table of Contents

5.4.2) Calibration using CW interferometer	122
5.5) Dynamics of tungsten wire array implosions	124
5.5.1) Validation of the Free Electron model	124
5.5.2) 8 wire array data analysis	126
5.5.1) 16 wire array data analysis	131
5.5.2) 32 wire array data	134
5.5.3) 128 wire array data	139
5.6) Dynamics of aluminium wire arrays	142
5.6.1) Oblique shocks in aluminium array ablation plasma	142
5.6.2) The mathematics of oblique shock-waves	143
5.6.3) 16 wire arrays.....	147
5.6.4) 32 wire arrays.....	149
5.7) Collisionality of adjacent ablation streams	154
5.8) Comparisons to GORGON 3D MHD simulations.....	158
5.8.1) Aluminium 32 wire array.....	158
5.8.2) Tungsten 32 wire array	162
Chapter 6 Conclusions and Future Work.....	167
6.1) End-on interferometry -the azimuthal structure of ablation plasma	167
6.1.1) Overview of W results	168
6.1.2) Overview of Aluminium wire array results.....	172
6.2) Quadrature Interferometry	175
6.3) Faraday rotation current diagnostic	176
6.4) Future Work	177
Appendix A: Raw Interferograms	179
Bibliography	183

List of Figures

Figure 1 A schematic of the double wire-array hohlraum concept.	18
Figure 2 Diagram of the current, magnetic field and force structure of a wire array Z-pinch. The red arrow shows the direction of the current, blue arrows show associated magnetic field and the green arrows show examples of the resulting $j \times B$ forces acting on the wires. The current feed electrodes have been omitted for clarity.	21
Figure 3 A schematic of the initial stages of wire array evolution, as seen from above (end-on). The wire cores expand and ablate low density coronal plasma. This coronal plasma is swept towards the axis, forming ablation streams.	24
Figure 4 Taken from [9]. On the left, an example of an optical streak image, captured during an experiment on a 32 wire W array. This image demonstrates that the wire cores remain static for a large portion of the experiment. On the right, implosion trajectories from a selection of experiments. The solid line shows the trajectory predicted by the 0D model. This is only observed experimentally in the 64 wire Al arrays.	25
Figure 5 Taken from reference [8]. Mono-chromatic X-ray imaging of wire array experiments at the Z facility in Sandia National Laboratories. In a) dense wire cores and ablation streams are visible. This confirms that the core-corona ablation dynamics are present in wire arrays at the 20MA level. In b) and c) we see that the implosion instabilities have been seeded by the axial modulations of the wire ablation.	26
Figure 6 Cylindrical polar geometry used to calculate expected density from rocket model.....	28
Figure 7 Taken from reference [9]. One the left is an X-pinch radiograph, showing the dense wire cores (white). Their radius is modulated at the ablation fundamental wavelength. On the right, a series of laser shadowgrams, illustrating the modulation of the ablation streams at the fundamental wavelength for aluminium, titanium and tungsten.....	29
Figure 8 Taken from reference [1]. XUV emission images of a wire array, showing the formation of the precursor column. The initially broad central object collapses to form a dense, highly emitting column.	30
Figure 9 Taken from reference [7]. A series of XUV images illustrating the implosion of a wire array Z-pinch. Large Rayleigh-Taylor ‘bubbles’ are blown into the array mass by the magnetic field.	32
Figure 10 Left, taken from reference [2], an x-ray power trace for an experiment on Z, taken as an average of four shots. Centre, taken from reference [10], a comparison of x-ray power traces for an 8wire array and a 32 wire array. Right taken from reference [11] x-ray yield of an experiment on MAGPIE through a variety of filters.....	33

Figure 11 Circuit diagram for a capacitor discharge pulsed power system.	36
Figure 12 Diagram of a four stage Marx bank. Capacitors are bipolar charged to minimise the inductance introduced by the switches. The current paths for both the charge and discharge cycles are highlighted.....	39
Figure 13 Graph of the current driven into a load by a Marx generator with various numbers of stages. The nominal load inductance was four times the inductance of a single stage.	40
Figure 14 Circuit diagram showing a set of capacitor discharges in parallel. In this diagram the charging circuit has been ignored for simplicity.	41
Figure 15 Circuit diagram for a coaxial line discharge circuit.....	44
Figure 16 a) An equivalent circuit diagram of MAGPIE b) A CAD rendering of the MAGPIE generator, with a human figure for scale. The four Marx banks are painted red, while the pulse forming lines and power feed are silver.....	46
Figure 17 Cross section of the Magpie Generator, showing the load, MITL, Transfer Line, pulse forming line and Marx Bank. Only one of the Marx Bank/ Pulse forming line sets is shown.....	47
Figure 18 Graph showing a scope trace for the switch voltage and current. The switch closes at around 480 ns scope time. At this point there is a rapid fall in switch voltage and rise in the switch current. After the pulse the current reflects back into the pulse forming line.	48
Figure 19 Taken from reference [5].A cross-section of ZR accelerator, showing the pulsed power architecture.	51
Figure 20 A comparison of typical loads fielded on the Z generator (left) and MAGPIE (right).....	52
Figure 21 A diagrams of a B-dot magnetic field probe and a cross sectional diagram of a Rogowski grove in place around a return post.	55
Figure 22 Cross section of the MAGPIE MITL, showing the positions of the current diagnostics.....	56
Figure 23 A schematic for a resistive Voltage divider circuit. The voltmeter measures only a small portion of the actual load voltage.	58
Figure 24 Transmission curves of various radiation filters as a function of photon energy.	59
Figure 25 Cross-section of a PCD, showing the diamond, electrodes and filter, and a diagram showing the biasing and recording circuits.	60
Figure 26 Diagram of a pinhole camera, showing the different design parameters.....	62
Figure 27 Diagram of a micro-channel plate (MCP) image gating system.	64

List of Figures

Figure 28 Schematic of the 4-Frame XUV MCP camera system fielded on MAGPIE.....	65
Figure 29 Diagram of an optical streak camera.	66
Figure 30 Schematic of the side-on laser probing system used in most magpie experiments. This diagram is not to scale. This system allows images to be captured at two separate times.....	68
Figure 31 Shadowgraphy effects: The effects of different phase objects on the intensity distribution of the probing beam at a screen.	73
Figure 32 Diagram explaining various Schlieren imaging techniques.	75
Figure 33 Two commonly used Interferometer layouts, the Mach-Zender and Michelson-Morley layouts.	77
Figure 34 Example of a side-on interferogram, captured during shot s0517_11. This was 16 wire aluminium array. On the left is the pre-shot background image, and on the right the experimental image. The fringes have been distorted and portions of the image have been occluded due to the strong density gradients.	78
Figure 35 A schematic of the quadrature interferometer. The focusing optics have been omitted in order to simplify the diagram.	82
Figure 36 Plot demonstrating how the direction of the phase shift can be interpreted from the quadrature signals.	86
Figure 37 Signal and differential sensitivity of the single phase and quadrature analysis schemes. Sensitivity nulls are only present in the single phase analysis.....	87
Figure 38 Photograph of the quadrature interferometer mounted over the chamber ready for an experiment.....	88
Figure 39 Diagrams of the optical layouts for the quadrature interferometer. Top is the side on arrangement. Bottom is the end on arrangement.	89
Figure 40 Top, an annotated photograph of a radial foil load. Bottom, a schematic of radial foil evolution. Both reproduced with the kind permission of Dr Francisco Suzuki-Vidal [3].	90
Figure 41 A series of XUV self-emission images illustrating the time evolution of the hydrodynamic jet produced by a radial foil as it propagates into an ambient gas medium. Reproduced with the kind permission of Dr Francisco Suzuki-Vidal [3].	91
Figure 42 Raw quadrature data from shot s0603_10. Top, short time-base recording, showing the experimental signal. Bottom, long time-base used to measure the mean intensity. The fine dotted blue lines mark the measured amplitudes used to calculate I_0 . The dotted red and black lines mark the calculated values of I_0 . The measurement fails at $t=305\text{ns}$	92

Figure 43 Electron density signal for shot s0603_10, calculated from the raw data in Figure 42. Top, analysis based on measurements of I_0 from the long time-base signal. Bottom, analysis based on an estimated value of I_0 , based on inspection of the signal.	93
Figure 44 Experimental setup for the Faraday rotation current diagnostic.	97
Figure 45 Plot of the Verdet constant for fused silica. The data points were taken from reference [4]. The red line a power series fit.	98
Figure 46 Left, a diagram of the magnetic field formed around a current carrying conductor, right, a schematic of the experimental setup, showing the relative positions of the conductors and the fused silica bar.	100
Figure 47 Current plots from three different current diagnostics from s0118_10.	102
Figure 48 Diagram of the current switch experiment. Initially the magnetic field is contained within the inverse array. After this array explodes, magnetic field fills the entire cavity.	103
Figure 49 Current measurements from shot s0121_10.	104
Figure 50 Schematic showing how a distributed return current could explain why the Faraday probe and return Rogowski failed to measure the full current delivered to the load.	105
Figure 51 A streak image from shot s0121_10. The current in the imploding array can be inferred from the implosion trajectory.	106
Figure 52 An optical layout for improved analysis of the Faraday current signal. The half-wave plate fast axis is inclined at 22.5° from the plane of the image, so that it rotates the polarisation of the probing beam by 45°	107
Figure 53 Diagram showing beam path through a complete loop faraday current probe.	108
Figure 54 Schematics of two different optical setups for end-on interferometry. Focusing and image forming optics have been omitted.	112
Figure 55 A Photograph of the a typical end-on interferometry load, taken during pump-down for shot s0520_11 – a $31 \times 10 \mu\text{m}$ W wire array, as viewed through one of the vacuum windows. The return post Rogowski grooves can be seen mounted around two of the current return posts.	113
Figure 56 Diagrams of the end-on interferometer optical layout.	115
Figure 57 Examples of end-on interferograms and traced fringe maps: -	117
Figure 58 Example of shadowgraphy effects on an interferogram. The image is brightened and darkened around regions with large density gradients, making fringe tracing difficult.	118

List of Figures

Figure 59 The analysis process for end-on interferograms. On the left, the traced fringes are assigned phase values; in the middle, the space between the fringes is interpolated; on the right, the interpolated phase maps are subtracted. +.....	119
Figure 60 An example of a side on interferogram. The fringes outside the array are undisturbed, and can be used as a reference for the zero fringe shift, allowing measurements of the absolute electron density.	120
Figure 61 Top, the smoothed data used in the analysis. Bottom, the raw voltage signals from the quadrature interferometer.	121
Figure 62 Top, fringe shift as a function of time, bottom, areal electron density as a function of time.	122
Figure 63 Electron density plots from shot s0125_11. The image on the left is the 532nm frame and the image on the right is the 355nm frame. These interferograms were captured simultaneously. A zero fringe shift of 2 fringes was applied to the 532 nm image. The two images appear qualitatively similar. Below are line-profiles through these datasets, both along the ablation streams and between them.	125
Figure 64 End-On Interferogram of an 8 wire tungsten arrays at 128ns. Red dots mark the initial wire positions.	126
Figure 65 Line Profiles from shot s0804_10, an 8 wire W array at 128ns.....	127
Figure 66 Line profiles of 8 wire tungsten arrays. No zero shifts have been applied	128
Figure 67 Current traces from shots s0802_10 and s0804_10. The dI/dt signals are highlighted in yellow. Dashed lines correspond to the return Rogowski signals, the solid lines to the MITL B-dot signals. In both experiments the Rogowski probe has failed. The point of failure is highlighted by black arrows. The green dots mark the timings for the two interferograms.	129
Figure 68 Density profiles for 16 wire tungsten arrays. Red circles indicate the initial wire positions. The corresponding current traces are shown Figure 70. Colour scales vary between plots.	131
Figure 69 Series of line profiles taken through the ablation stream profiles of 16 wire arrays at 101 and 157 ns.	132
Figure 70 Data from 16 wire tungsten array shots	133
Figure 71 Density Maps captured in experiments on 32 wire W arrays. Red circles indicate the initial wire positions. Colour scales vary between the plots.	134
Figure 72 Current traces for 32 wire tungsten arrays, taken from MITL B-dot traces. Timings for the four interferograms are marked. The currents compare well between the two experiments. Raw signals from the MITL B-dots are shown highlighted in yellow.	135

Figure 73 Comparison of line profiles taken from the electron density profiles shown in Figure 71, showing the evolution of the precursor column.	136
Figure 74 Current drive and XUV emission images positioned in time order to compare the dynamics of the two arrays. The array axes are aligned with the image timing.	137
Figure 75 Comparison of stream profiles of earliest and latest time image. Top, 532nm image from s0519_11 (112ns). Bottom, 355nm image from s1013_10 (162ns).	138
Figure 76 Data from an experiment on 128 wire array.	139
Figure 77 Line profiles of 128 wire arrays.	140
Figure 78 Current and diagnostic timings for s0202_11, a 128 x 7.5 μ m W array. XUV images have array axis aligned with image times.	141
Figure 79 Examples of electron density distributions for 16 and 32 wire aluminium arrays.....	142
Figure 80 A Schematic of an oblique shock. A wedge turns a supersonic flow through an angle θ . The oblique shock front forms at an angle β . The hydrodynamic and thermodynamic properties of the flow change abruptly over the shock front.	145
Figure 81 A series of electron density plots captured for 16 wire aluminium arrays. Red circles mark wire positions. Shock structures can be observed at 120ns and later. The imaging times are marked on a series of current traces, as measured by a MITL B-dot.....	147
Figure 82 Line profiles of the ablation stream electron density, showing the hollow nature of the shocked region.	148
Figure 83 Electron density plots for 32 wire aluminium arrays. Shock formation is evident in all three plots. In the final two plots we can make out tertiary and event quaternary shocks. Timings are marked on the current plots, as measured by a MITL B-dot.	149
Figure 84 Diagrams of the shock structure observed in 32 wire aluminium arrays.....	150
Figure 85 Plots for the oblique shock relations.	151
Figure 86 Contours from Figure 57 a) are assigned phase numbers and the spaces between are interpolated. The interpolated phase maps can then be subtracted to remove the background phase gradient, leaving just the phase delay due to the plasma.....	152
Figure 87 Comparison of experimental and simulated data for a 32 wire Al array. The simulated data has been cropped for better comparison.	158

List of Figures

Figure 88 Comparison of the density profiles observed in the primary shock, from experimental data (top) and simulated data (bottom).....	159
Figure 89 Comparison of both on and off stream line profiles for simulated data and experimental measurement.	160
Figure 90 Full plot of a GORGON simulation of 32 wire aluminium array. Electron density plot at 146ns.	161
Figure 91 Comparison of an experimental (left) electron density profile for a 32 wire tungsten array with an electron density profile taken from GORGON simulation data (right).	162
Figure 92 On-stream line profiles of the experimental and GORGON simulation electron density maps. With the addition of a single zero fringe-shift the data matches reasonably well.	163
Figure 93 Comparison of stream profiles for simulated and experimental data for a 32 wire tungsten array. Simulated data is at the top while the experimental data is at the bottom.....	164
Figure 94 Plot showing how the precursor radius changes with time. Data was taken from line profiles of the electron density. Colours indicate arrays of the same wire number, shapes indicate measurements from the same shot.	170
Figure 95 Snowplough trajectories for on and off stream profiles, demonstrating the implosion stretching effect. The stagnation times predicted here are separated by 3ns.	171
Figure 96 Overlay of the oblique shock structure on 32 wire aluminium array data, showing the various angles.	173
Figure 97 Plots of the plasma parameters across the oblique shocks formed in 32 wire arrays. These demonstrate the low sensitivity of the density ratio and the incoming Mach number to changes in Gamma and the shock angle.	174
Figure 98 532nm interferogram of a 32 wire aluminium array, from shot s0518_11.	179
Figure 99 355nm interferogram of a 32 wire aluminium array, from shot s0518_11.	180
Figure 100 532nm interferogram of a 32 wire tungsten array, from shot s0519_11.	181
Figure 101 355 nm interferogram of a 32 wire tungsten array from shot s0519_11.	182

List of Tables

Table 1 List of reference parameters for the MAGPIE generator. Values are quoted for both before and after the upgrade.....	50
Table 2 Table of relative cable delays for key diagnostics. These define the relative difference between the time an event is recorded by a scope and actual experimental timing of the event for each diagnostic. Positive delay means that signals appear later than actual time.	54
Table 3 Table of polarisabilities for some common neutral atoms [6]	72
Table 4 Table of estimated collision interaction velocities for wire arrays with a range of wire numbers.	156
Table 5 A table of the ion mean free path in mm, calculated using the Spitzer slowing down formula.	157

Chapter 1

Introduction and Review of Wire Array Physics

1.1) Background and Motivation

Wire array Z-pinch implosions are powerful and energetic sources of soft X-ray radiation. Experiments at the Z facility in Sandia National Laboratories have resulted in implosions producing a peak radiative power of 280TW, with a pulse width of 4ns and total yield of 1.8MJ [12]. They are extremely efficient, converting up to 20% of the stored electrical energy into soft X-rays. As such they are an ideal radiation source for driving inertial confinement fusion [13-15], high energy density physics and laboratory astrophysics experiments [16-18]. The exact mechanisms that lead to such powerful bursts of radiation are not fully understood. It is hoped that further study of array dynamics may lead to even greater X-ray power and yield.

1.1.1) Inertial confinement fusion

As mentioned above, one of the major applications of wire array Z-pinch is as drivers for indirect Inertial Confinement Fusion (ICF) experiments. ICF is the science of producing controlled nuclear fusion in the laboratory.

This is achieved by compressing spherical fuel capsules to critical density. At this density the fuel ‘ignites’ resulting in a self-sustaining fusion burn. During the burn the fuel assembly is held together by its own inertia.

Compression is achieved by radiatively heating the surface of the capsule, resulting in ablation and a rocket reaction force. In direct drive ICF, the radiation source is coupled directly onto the fuel capsule, whereas indirect drive ICF uses the radiation source to heat a hohlraum, which then re-radiates as a blackbody onto the capsule. The main advantage of direct drive is energy efficiency. Coupling efficiency from a source to the hohlraum and then onto the capsule is often low, due to the many potential energy loss paths. The advantage of indirect drive is the improved drive uniformity. Any modulations of the drive intensity on the surface of the capsule will be imprinted on the implosion. These drive imprints act as seeds for hydrodynamic instabilities, limiting the potential compression of the capsule.

A number of approaches have been proposed for harnessing the radiative power of Z-pinches to drive ICF [13, 14, 19-21]. Figure 1 shows a schematic of just one of these approaches, the double wire-array hohlraum concept. This is an indirect drive approach. The fusion fuel capsule is mounted between a pair of wire arrays inside a large hohlraum. The radiation produced by the two arrays energises this hohlraum. The capsule is protected from di-

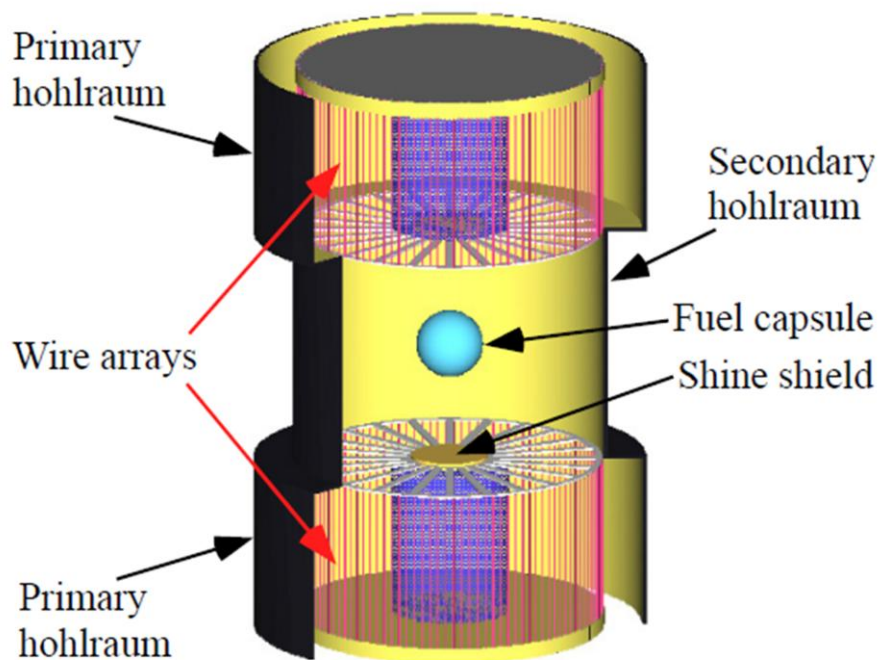


Figure 1 A schematic of the double wire-array hohlraum concept.

rect exposure to the stagnating pinches by shine shields. Shaping of the radiation pulse is essential in order to drive efficient compression of the capsule. Experiments have demonstrated that this can be achieved using nested wire arrays and/or foams on axis[22].

The large volume of the hohlraum means that more drive energy is needed to produce the necessary radiation temperature. Hohlräume used in laser driven ICF experiments are normally much smaller. This disadvantage is more than made up for by the benefits gained in both the cost and efficiency of the drivers. Z-pinches are extremely efficient at converting electrical energy into radiative yield. By comparison the current generation of laser drivers are extremely inefficient (<1%). Much of this inefficiency is due to flash-lamp pumping of the laser gain mediums; however even with the introduction of diode pumping it is unlikely that lasers will overtake Z-pinches in terms of wall plug efficiency. In terms of cost, comparing like for like X-ray yields, Z-pinch drivers are an order of magnitude cheaper [23].

1.1.2) Energy compression and X-ray production in pulsed power driven Z-pinch implosions

A Z-pinch produces radiation through the stagnation of accelerated mass. The complete system, including both the pulsed power driver and load, acts as a multi-stage energy compressor. Electrical energy from the grid is stored in capacitor banks over a period of minutes. Marx bank pulsed power circuitry is capable of discharging this energy over a period of around 1 μ s. Intermediate energy storage lines are used to further compress the pulse, resulting in current rise times in the load on the order of 100ns. The energy contained in this current pulse is used to accelerate the load mass towards the axis. The collision and stagnation of this mass occurs over a period measured in nanoseconds. The kinetic energy of the accelerated mass is thermalized in the pinch, and this thermal energy is rapidly radiated, resulting in the soft X-ray yield. By the end of the process energy has been compressed temporally by a factor of $\sim 10^{10}$.

The symmetry of the implosion is very important [24]. Greater symmetry results in a larger fraction of the kinetic energy of the implosion being thermalized. It is this requirement that originally led to the interest in wire arrays.

Wire arrays allow for much more precise control of the initial mass distribution compared with gas puffs, while allowing much lower mass per unit lengths than can be achieved with solid metal liners.

1.1.3) Introduction to the implosion dynamics of wire array Z-pinch

Figure 2 shows the relative orientations of the current, magnetic field and the Lorentz ($\mathbf{j} \times \mathbf{B}$) force acting on a wire array Z-pinch. A multi-mega-Ampere current is driven through the array, inducing an azimuthal magnetic field around it. The interaction of this field with the current results a radial $\mathbf{j} \times \mathbf{B}$ force acting on the wires. It is this force that drives the implosion.

The wire cores remain stationary for a significant portion of the implosion time (50 – 80%) [2, 9]. During this time the drive current is conducted by a low density coronal plasma, formed by ablation from the surfaces of the cold dense cores. This coronal plasma is continually swept away from the cores, forming streams of ablated plasma which propagate towards the axis, resulting in a radial redistribution of the original array mass. This period is normally referred to as the ablation phase.

At some point the wires run out of mass with which to sustain ablation and the implosion begins. The implosion proceeds as a “snowplough” [25, 26]. The interface between the array plasma and the magnetic field acts as a piston which sweeps up and accrues mass as it moves towards the axis. Thus the radial trajectory of this surface is to some extent set by the mass distribution that it encounters on its way to the axis. Any azimuthal density variations produced during the ablation phase will have an impact on the symmetry of the implosion. As has already been mentioned, the peak radiative power is very sensitive to the symmetry of the implosion. The differences in the mass distribution could result in an effective increase in the thickness of the imploding shell, resulting in a longer period of stagnation, and therefore a lower peak radiative power. For these reasons it is worthwhile to investigate the ablation dynamics and the azimuthal density structure in greater detail.

1.1.4) The MAGPIE pulsed power generator

The experimental work described in this thesis was carried out on the Mega-Ampere Generator for Plasma Implosion Experiments (MAGPIE) [27] at Imperial College London. MAGPIE is a 1.4MA peak current, 240ns rise time

pulsed power generator. Originally developed to drive radiative collapse experiments, for the last decade MAGPIE has been used to investigate the physics of wire array implosions. Although significantly less powerful than the Z-generator, which drives 26MA in 100ns, MAGPIE's main advantage is the excellent diagnostic access it affords and its unusually high drive impedance. A set of 16 radial ports are available, allowing an extensive suite of diagnostics to be fielded with unobstructed views of the experiment. Diagnostics can also be fielded aligned down the axis of the array. The high drive impedance of the generator means that the peak current is reasonably insensitive to changes in the inductance of the load hardware. This makes it easier to field interesting or exotic new load configurations. On MAGPIE the standard arrays used to produce high X-ray yields are cylindrical arrays, with a radius of 16mm and a length of 20mm. Wire numbers will vary between 8 and 64 wires, with wire diameters between 5 - 30 μ m.

1.2) Outline of work

The main body of work presented in this thesis is a large dataset of end-on electron density distributions. This

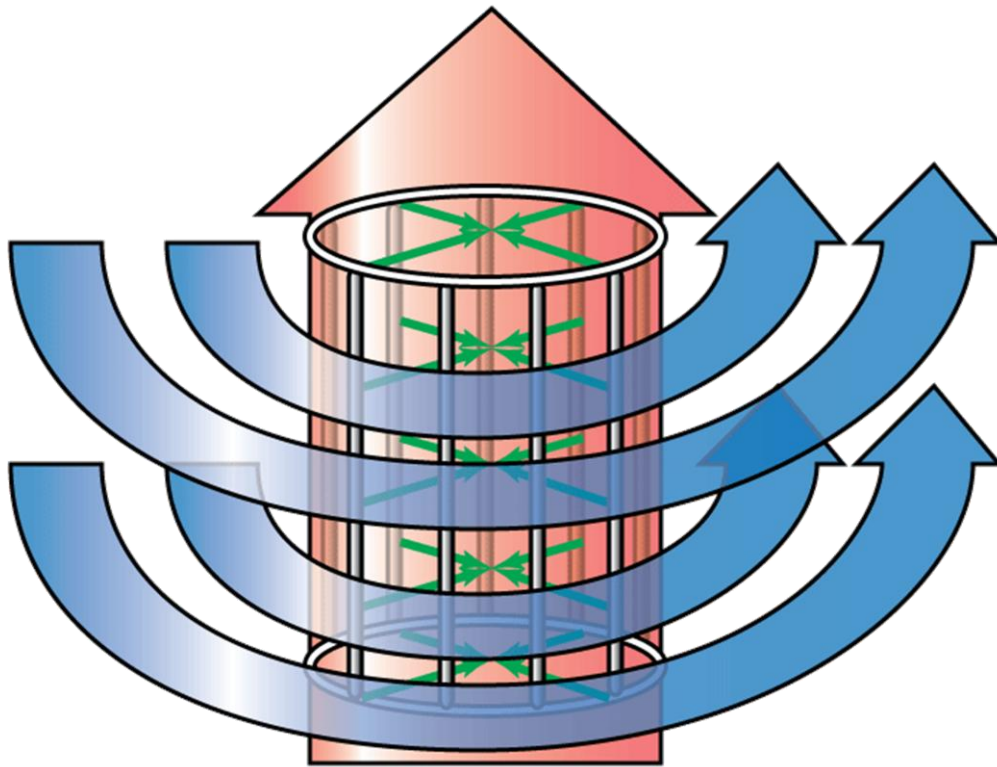


Figure 2 Diagram of the current, magnetic field and force structure of a wire array Z-pinch. The red arrow shows the direction of the current, blue arrows show associated magnetic field and the green arrows show examples of the resulting $\mathbf{j} \times \mathbf{B}$ forces acting on the wires. The current feed electrodes have been omitted for clarity.

data is the result of the analysis of images captured during a series of end-on interferometry experiments carried out on the MAGPIE generator. The data is resolved in the r, θ plane and provides new information about the flow structures that are formed during the ablation phase of wire array Z-pinches.

End-on interferometry has been fielded in previous MAGPIE experiments [28]. The aim of this work was both to improve the quality of the interferometry data and analysis process and to make a detailed survey over a range of materials and wire numbers. Much of the improvement in the quality of the interferograms was achieved by moving over to a Mach-Zender probing scheme. This required only a single pass of the laser probing beam through the array, a great improvement on the previous Michelson-Morley design which required a double pass. The interferometer uses two probing wavelengths, a 532nm and a 355nm probing beam. These beams can be synchronised or timed separately in order to capture two experimental frames. This is useful when investigating the dynamics of an experiment.

Experiments were carried out on aluminium and tungsten arrays with wire numbers varying between 8 and 128 wires. The data reveal differences in the structures formed by these materials. Aluminium arrays produce oblique shock structures, indicating a high degree of collisionality between the ablation streams. Tungsten arrays produce smooth density distributions which are indicative of a less collisional flow.

A number of other diagnostics were also been developed in the course of these studies. A quadrature CW interferometer was developed to make time resolved measurements of free electron line densities through various experiments. Most interferometry systems fielded in wire array experiments are imaging interferometers. These produce spatially resolved density maps, but provide only limited information on the dynamics of arrays. A time resolved interferometer allows comparisons of the temporal dynamics of the plasma with models and simulations. It also provides a potential method of measuring the zero fringe shifts in the end-on interferometry images. This is very important for the proper calibration of the data. The diagnostic was fielded in a variety of different experiments. It has been used to investigate the formation of precursor plasmas in cylindrical wire arrays, and used end-on to measure the time resolved density plot in order to estimate zero fringe shift in some of the end

on interferograms. It was also fielded in a series of experiments on radial arrays and radial foils, investigating the formation of supersonic plasma jets

A Faraday rotation diagnostic was developed to measure the current in Z-pinch loads. This diagnostic was designed specifically to measure the rapid current switch produced in experiments which used inverse arrays as a current switch. While ultimately this diagnostic failed to make an accurate current measurement in the current switch experiments, it does provide an excellent method of measuring magnetic fields in pulse power experiments.

1.3) The Authors Contribution

All of the experiments reported in this thesis were performed on the MAGPIE generator with the assistance of the MAGPIE experimental team. The end-on interferometry system, CW quadrature interferometer and Faraday current diagnostic were developed by the author and the experiments in which the end-on electron density data was captured were designed and managed by the author, including the design of the loads, experimental hardware and overall diagnostic setup, as well as the maintenance and frequent repair of the pulsed power systems used to drive the experiments.

The software used to analyse the interferograms was designed and implemented by the author, and all of the analysis of the data was completed by the author. This software was written using MATLAB, and is currently in use by many members of the group for general analysis of interferometry data.

The CW interferometer and Faraday current diagnostic have largely been fielded as an additional diagnostic for experiments managed by other member of the MAGPIE team. The quadrature interferometer has been used in experiments investigating hydrodynamic jets [29, 30], while the Faraday diagnostic was fielded in experiments investigating the application of inverse wire arrays as fast current switches [31].

The results of this work have been presented at a series of international conferences. End-on probing data was presented at both the 2011 DZP conference in Biarritz and 2011 ICOPS conference in Chicago. They will also be presented at the 2011 APS DPP conference in Salt Lake City.

1.4) Review of the physics of wire array implosions

1.4.1) The dynamic Z-pinch

For many years the Z-pinch configuration was investigated as the method of steady-state containment for magnetic confinement fusion experiments. Unfortunately this configuration turned out to be unstable, resulting in very short confinement times and relegating this approach to history. Interest was renewed with the introduction of pulsed power technology. This allowed the Z-pinch to be driven as a dynamic implosion, with no attempt to produce a steady state plasma. Instead a powerful current is driven through the plasma, producing an inward $\mathbf{j} \times \mathbf{B}$ force which overwhelms the thermal pressure and implodes the plasma. The imploding plasma collides on axis, where it stagnates and releases a burst of radiation. In order to produce short, powerful burst of radiation, it was believed that a narrow, symmetrical mass shell was required as the starting point. One approach to producing such a shell is by using an array of fine metal wires ($\sim \mu\text{m}$). This allows a symmetrical mass distribution with a much lower mass than could be manufactured as a solid liner.

The physics of wire array Z-pinch has been studied for a number of years. The motivation for much of this work was the rapid progress made in increasing the peak radiative power and radiative yields achieved in experiments. These increases were driven firstly by increases in the wire number of arrays [32, 33], and later by the introduc-

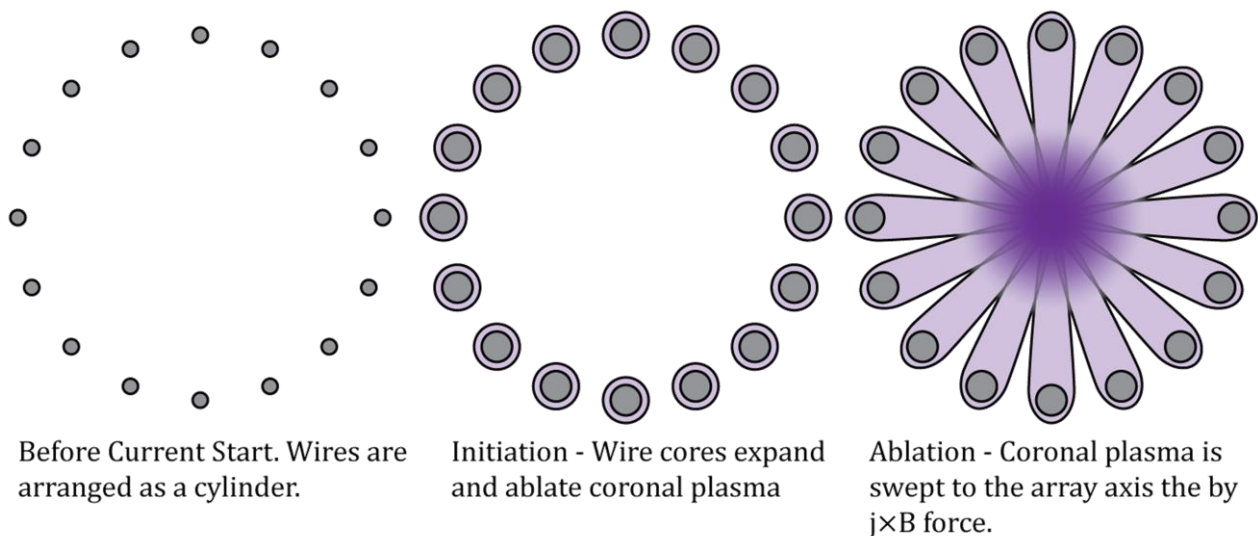


Figure 3 A schematic of the initial stages of wire array evolution, as seen from above (end-on). The wire cores expand and ablate low density coronal plasma. This coronal plasma is swept towards the axis, forming ablation streams.

tion of nested wire arrays (two concentric cylindrical wire arrays)[12]. A record peak radiative power of 180TW, with a pulse width of 4ns and a total yield of 1.8MJ was achieved in experiments on high wire number tungsten nested arrays fielded on the Z-machine. The great improvements in power and yield were unexpected and poorly understood. As a result, research into the dynamics of wire array implosions became a priority.

1.4.2) Evolution regimes – 0-D implosion vs. the discrete wire mode

For a long time it was believed that wire arrays implode as a discrete, uniform plasma shell [24, 26]. Energy deposition in the wires would cause them to expand to a point where they would merge with their neighbours. This merged shell would then be accelerated to the axis by the $j \times B$ force. This model is commonly referred to as the OD model for a Z-pinch implosion.

Work by Lebedev et al. [9, 28, 34] on the 1 MA MAGPIE generator in the late 90's and early 2000s showed that wire array dynamics, even for high wire number array, are often dominated by three-dimensional effects. The combination of these effects is often referred to as the discrete wire regime. Electrical breakdown of plasma formed on the surface of the wires halts energy deposition into the wire cores and hence their expansion. This means they do not necessarily merge to form a homogeneous shell as had previously been postulated [24]. Instead each wire evolved into a heterogeneous core-corona structure. X-pinch backlighting experiments have demonstrated the formation of dense wire cores with a characteristic diameter dependent upon the wire materi-

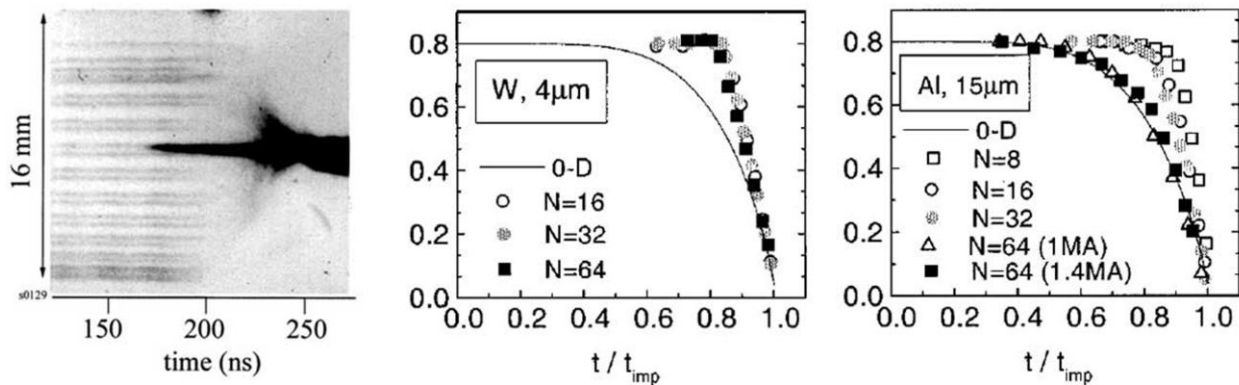


Figure 4 Taken from [9]. On the left, an example of an optical streak image, captured during an experiment on a 32 wire W array. This image demonstrates that the wire cores remain static for a large portion of the experiment. On the right, implosion trajectories from a selection of experiments. The solid line shows the trajectory predicted by the OD model. This is only observed experimentally in the 64 wire Al arrays.

al (250 μ m for Al, 100 μ m for W). Experiments over a wide range of wire numbers have shown that this core diameter is independent of the current per wire and initial wire diameter. The cores remain relatively cold, dense and non-conductive, in what is believed to be a hybrid liquid/vapour state. A low density, highly conductive coronal plasma is continuously ablated from their surfaces. The majority of the drive current flows in this corona. Experimental evidence of this is provided by implosion trajectories measured via optical streak imaging. These show that for a large portion of the drive period (80% in MAGPIE experiments) the dense cores formed by the initial expansion of the wires remain stationary. The $j \times B$ force acts only on the coronal plasma, sweeping it towards the axis as ablation streams. Therefore the current conducted in the cores must be negligible. Figure 7 contains an X-pinch radiograph of the dense wire cores, captured in an experiment on MAGPIE. Figure 5 shows mono-chromatic backlighting images of wire arrays fielded on the Z machine, demonstrating the formation of dense cores at 20MA.

The 0-D trajectory expected by the homogenous shell model is only recovered in the case where the inter-wire gap is reduced to less than three times the characteristic core expansion diameter. It can be shown that when this ratio of interwire gap to wire diameter approaches π the local field around the individual wires falls to zero [34,

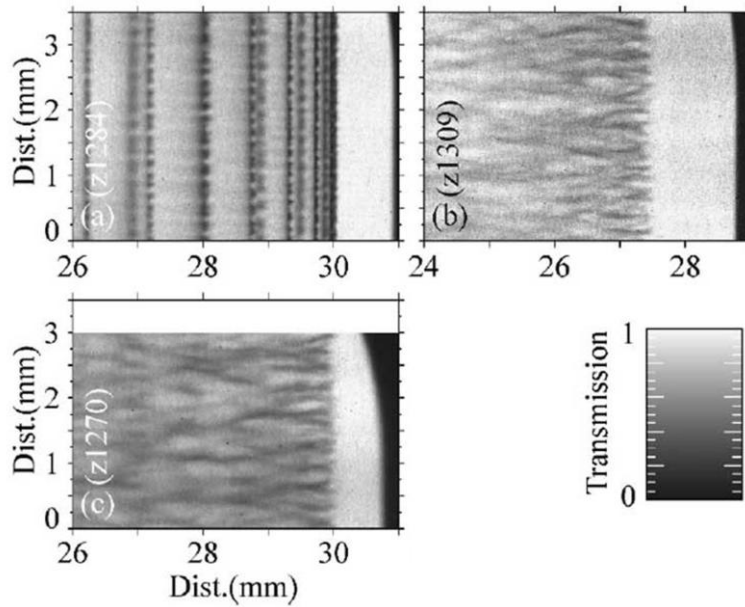


Figure 5 Taken from reference [8]. Mono-chromatic X-ray imaging of wire array experiments at the Z facility in Sandia National Laboratories. In a) dense wire cores and ablation streams are visible. This confirms that the core-corona ablation dynamics are present in wire arrays at the 20MA level. In b) and c) we see that the implosion instabilities have been seeded by the axial modulations of the wire ablation.

35]. No local field means there are no local containing forces to prevent further wire expansion and merge. The OD implosion mode was observed in an experiment on a 16mm diameter, 64-wire Al array. The inter-wire gap in this experiment is 800 μm , compared to the expected expanded wire core diameter of 250 μm . For tungsten arrays the inter-wire gap required to produce a OD implosions is around 300 μm . This corresponds to only the very smallest gaps used in the Z experiments. Experimental observations have confirmed the presence of an ablation phase in Z-pinches at both the 3MA level in experiments on the Angara-5-1 facility [36] and at 20MA level in experiments on the Z-generator [2, 8], demonstrating that a delayed implosion is a ubiquitous feature of wire array implosions over a large range of drive currents. Figure 4 shows an example of an optical streak image and graphs of the implosion trajectories measured from streak images for a variety of arrays.

1.4.3) OD trajectory and the rocket model

The equation describing the OD implosion trajectory is based on a very simple force balance argument:

$$\begin{aligned}
 F &= ma \\
 BI(t)l &= m \frac{d^2 r_{shell}}{dt^2} \\
 \frac{d^2 r_{shell}}{dt^2} &= \frac{\mu_0 I^2 L}{2\pi r_{shell} m}
 \end{aligned}
 \tag{1.4.1}$$

In this equation m is the total array mass, l is the array length, r_{shell} is the radial position of the plasma shell and I is the drive current.

Based on the observations of static wires cores, a phenomenological model was developed in order to estimate the wire ablation rate [9]. This is known as the rocket model. The model makes the assumption that the radial ablation velocity (v_{abl}) that coronal plasma is accelerated to as it leaves the wire cores is a constant. The force equation is now balanced by the mass ablation rate ($\dot{m}$), and the acceleration term is neglected:

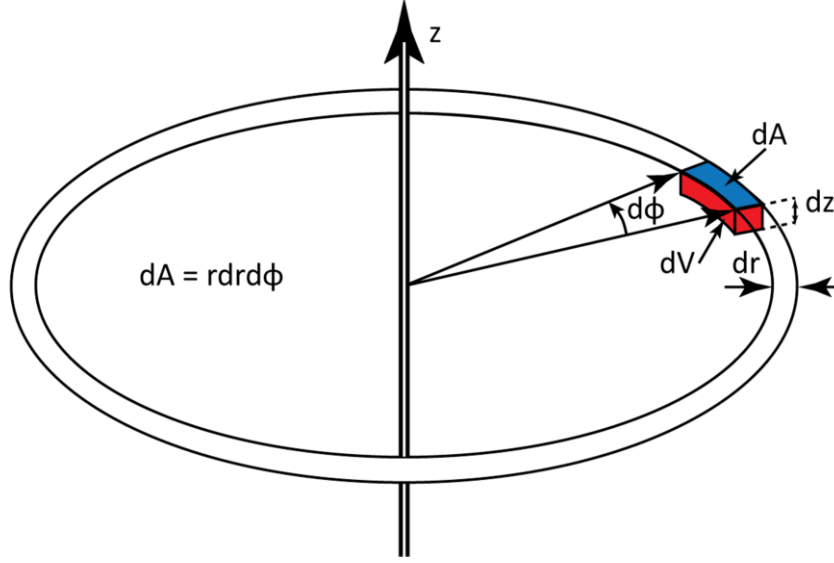


Figure 6 Cylindrical polar geometry used to calculate expected density from rocket model.

$$F = ma + \dot{m}v_{abl} = \dot{m}v_{abl} = BIL$$

$$\dot{m}(t) = \frac{\mu_0 I(t)^2 L}{2\pi R v_{abl}} \quad (1.4.2)$$

The ablation velocity appears to be a remarkably stable and universal parameter, and may be taken as $v_{abl} \sim 1.5 \times 10^5 \text{ ms}^{-1}$ (0.15mm/ns in units on the order of experimental scale). This number is based on measurements of the velocity of the density profile taken from multiple end on interferograms [28]. Fitting to the results of experiments at the Z facility indicate that there is little change in the ablation velocity when scaling for 1 to 20MA[37].

The azimuthally averaged plasma density may be calculated by dividing the time-of-flight corrected value of the ablation rate $\dot{m}$ from equation (1.4.2) by the radially converging volume $dV(r)$. In the following derivation this volume is described using cylindrical polar coordinates as shown in Figure 6:

$$\begin{aligned} \rho(r) &= \frac{dm(r,t)}{dV} = \frac{1}{L} \frac{dm(r,t)}{dA} \\ \frac{dm}{dA} &= \frac{dm}{dt} \frac{dt}{dr} \frac{dr}{dA} \\ \frac{dr}{dt} &= v_{abl}; \quad \frac{dm}{dt} = \dot{m}(r,t) = \dot{m}(t_{delayed}); \quad \frac{dA}{dr} = 2\pi r \\ t_{delayed} &= \left(t - \frac{R-r}{v_{abl}} \right) \end{aligned} \quad (1.4.3)$$

$$\rho(r, t) = \frac{\mu_0 I^2 \left(t - \frac{R-r}{v_{abl}} \right)}{4\pi^2 v_{abl}^2 R r}$$

1.4.4) The fundamental perturbation

The ablation of each individual wire is modulated by an m=0-like Z-pinch instability. These instabilities are ubiquitous, and form at characteristic wavelengths, which like the expanded core diameter, appears to be dependent only on the wire material. In tungsten arrays they form with a wavelength of $\sim 250\mu\text{m}$ and in aluminium arrays the wavelength is $\sim 500\mu\text{m}$ [34]. They appear to scale roughly the same as the wire core diameters. Figure 7 shows examples of X-pinch and optical laser shadowgraphy images of these structures. They are often referred to as the fundamental instability of the wire array, and are remarkable in that they remain axially stationary, with a constant wavelength for the duration of the experiment. It should however be noted that the positions of these instabilities are not correlated between the wires. X-pinch radiography confirms that the ablation modulation seen in the coronal plasma corresponds to axial modulations in the wire cores. However the modulations observed in the wire cores are anti-correlated with the ablation stream density modulations, indicating some form of axial mass transport [9]. 3D simulations have shed light on the mechanism which both forms and stabilises this instability[38]. The addition of a global magnetic field to the local field of the wire sweeps ablated plasma away,

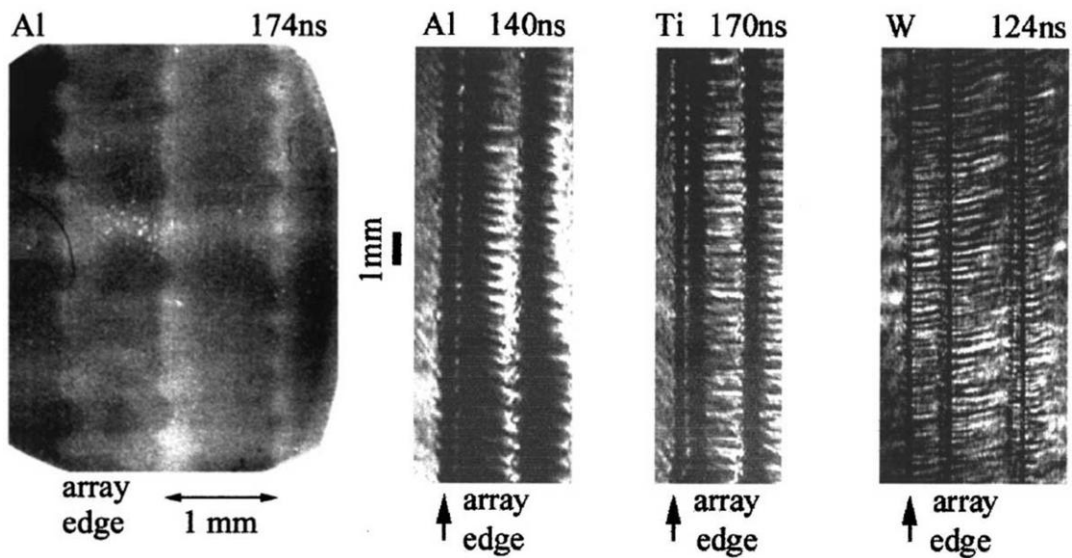


Figure 7 Taken from reference [9]. On the left is an X-pinch radiograph, showing the dense wire cores (white). Their radius is modulated at the ablation fundamental wavelength. On the right, a series of laser shadowgrams, illustrating the modulation of the ablation streams at the fundamental wavelength for aluminium, titanium and tungsten.

removing the positive feedback would that normally drives the growth of the instability wavelength. Non-axial and non-azimuthal magnetic field components result in axial transport of material ablated from the outer surface of the wire core, producing the density modulation observed in the stream. The wavelength of the fundamental perturbation appears to be controlled by the diameter of the wire cores, as this sets the scale over which material from the back of the core must travel in a non-radial direction. The size of the core is thought to be set by the initial energy deposition into the core at the start of current drive. This process is poorly understood and occurs on scale lengths much smaller than those probed in current MHD simulations.

1.4.5) Precursor column formation

The precursor is a well-defined, strongly emitting and stable column of relatively dense plasma that forms on the axis of wire arrays during the ablation phase. A review of precursor dynamics is presented in a review by Bott et al.[1]. The precursor is formed by the collision and interaction of the plasma ablated from each of the wires. Its radius is controlled by the balance between its thermal pressure and the momentum flux of the incoming ablation flows. Initially a broad, low density distribution forms about the axis. At some point the plasma density becomes critical. The rate of radiative cooling is proportional to the square of the ion density. When it exceeds the

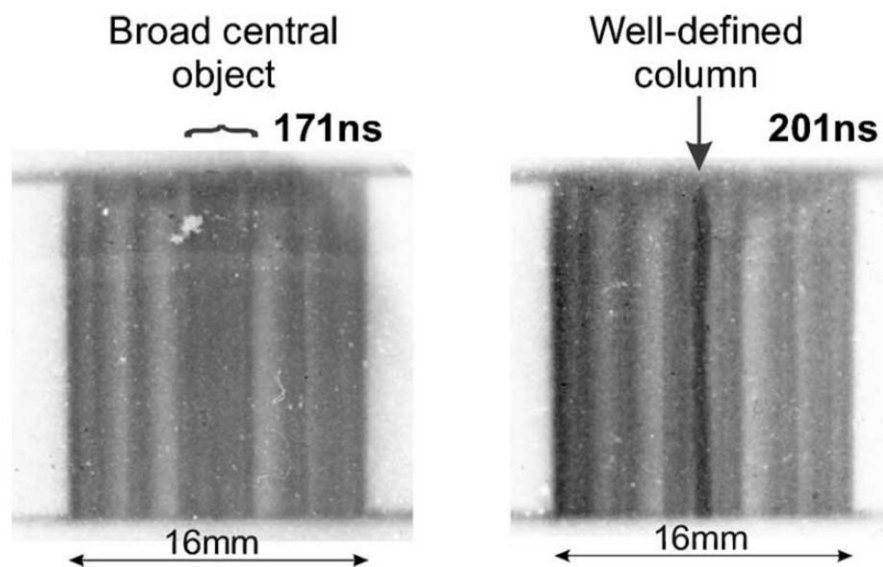


Figure 8 Taken from reference [1]. XUV emission images of a wire array, showing the formation of the precursor column. The initially broad central object collapses to form a dense, highly emitting column.

rate of heating due to the kinetic energy flux from the ablation-flows the pressure of the column falls and it contracts. Contraction drives a positive feedback loop, increasing the column density and therefore further increasing the cooling rate. The result is a runaway collapse of the broad density distribution. Experimentally, this is observed as a combination of a pulse of X-ray emission on radiation diagnostics and the formation of a compact plasma column on axis seen in side-on XUV emission imaging. Examples of XUV images captured both before and after the collapse are shown in Figure 8. The final radius of the precursor is likely set by the balance of radiative loss to kinetic energy input into the precursor. It has been observed to grow in radius slowly after the initial collapse. The lack of evidence of the growth of $m=0$ instabilities in the precursor column has been used to estimate that the precursor may, at the very most carry 2% of the drive current [1].

1.4.6) Snowplough implosion

Assuming that the array implodes in the discrete wire regime, the implosion phase begins at the point when breaks begin to form in the wires. Thanks to the axial perturbations in the mass ablation rate of the wire cores, breakage tends to occur when around 40-50% of the wire material has been ablated. Breaks in the wires are rarely azimuthally correlated, and may not occur simultaneously at precisely the fundamental wavelength, due to variations in the intensity of ablation perturbation[25]. With the source of coronal plasma removed, the ablation phase abruptly ends and the array implodes.

The implosion proceeds as a “snowplough”. The implosion front is accelerated towards the axis by the $\mathbf{j} \times \mathbf{B}$ force, sweeping up the mass that was redistributed during the ablation phase. Therefore the mass of the implosion front increases as it propagates. The mathematics describing snowplough implosions are discussed in references [25, 26, 39]. The equation of motion is written as follows:

$$\begin{aligned}
 F &= ma + \dot{m}v \\
 m &= \int_R^r 2\pi r \rho(r, t_d) dr & \dot{m} &= \frac{dm}{dr} \frac{dr}{dt} \\
 -\frac{\mu_0 I^2}{2\pi r} &= \int_R^r 2\pi r \rho(r, t) dr \frac{d^2 r}{dt^2} - 2\pi r \rho(r, t) \left(\frac{dr}{dt} \right)^2
 \end{aligned} \tag{1.4.4}$$

Where m is current mass of the implosion front and $\rho(r, t_d)$ is the delay-adjusted rocket model density profile, given by equation (1.4.3), which can be solved numerically. The only free parameter of this equation is the proportion of the unablated mass that takes part in the implosion. Comparisons of calculated snowplough trajectories to those measured by streak photography indicates that roughly a tenth of the unablated mass takes part in this implosion, with the rest (some 54% of the total array mass) left as so called trailing mass [25].

1.4.7) Magneto-Rayleigh-Taylor instability

The snowplough like implosion described in the previous section is simplistic. The magneto-Rayleigh-Taylor instability makes the interface between the magnetic field and the plasma highly unstable. The Rayleigh-Taylor instability, ubiquitous in fluid dynamics, is the instability of any interface between a light and a heavy fluid where the light fluid is exerting a greater force on heavy fluid than the heavy fluid exerts upon it. This is easiest to understand from an energy standpoint. The overall system energy is minimised with the heavy fluid on the 'bottom'. In the case of the Magneto-Rayleigh-Taylor instability, the role of the light fluid is taken by the driving magnetic field. A detailed derivation of the dynamics of these interfaces is beyond the scope of this review but an overview can be found in [26].

Rayleigh-Taylor instabilities are a problem as they tend to increase the effective width of the imploding plasma sheath, leading to a longer stagnation and lower peak X-ray. Figure 9 shows an example of a series of XUV emission images captured during the implosion of a wire array. Even at stagnation a large portion of the array mass

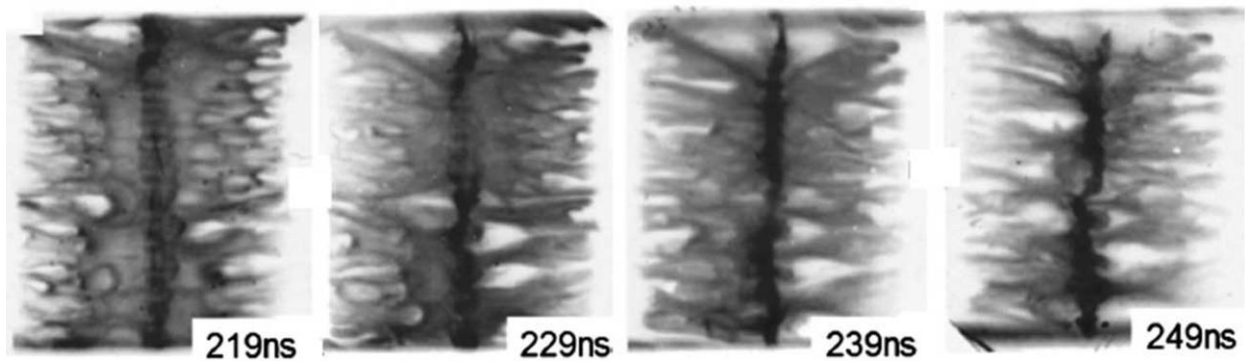


Figure 9 Taken from reference [7]. A series of XUV images illustrating the implosion of a wire array Z-pinch. Large Rayleigh-Taylor 'bubbles' are blown into the array mass by the magnetic field.

remains at large radius.

In order for the instability to form, a seed perturbation to the interface is required. The rate of growth of the instability is related to the effective wavelength and amplitude of this initial perturbation. The most obvious seed perturbation in wire array Z-pinches is the fundamental ablation perturbation wavelength. Increasing the wire number of the array can help to better azimuthally average the seed perturbation, as the axial positions of the fundamental wavelengths between the wires are uncorrelated. The result is better stagnation symmetry and more efficient conversion of kinetic energy into radiation [38].

1.4.8) Stagnation

Stagnation is the final stage of the wire array implosion. The imploding plasma shell impacts on the precursor column and the sudden increase in kinetic pressure causes it to compress. The directed kinetic energy of the shell stagnates against the column producing heat which is promptly radiated away as soft X-rays [10]. The pinch continues to compress and the radiative power increases, reaching its maximum when the pinch radius reaches its minimum. 'Hot-spots' form along the length of the pinch, acting as sources of hard radiation [10]. Figure 10 shows plots of the X-ray pulse shape from experiments on MAGPIE at 1.4 MA and Z at 20MA.

A large portion of the radiated energy comes directly from the stagnated kinetic energy of the imploding plasma shell. Observations of higher than expected radiation temperatures and yields have led to some debate as to the

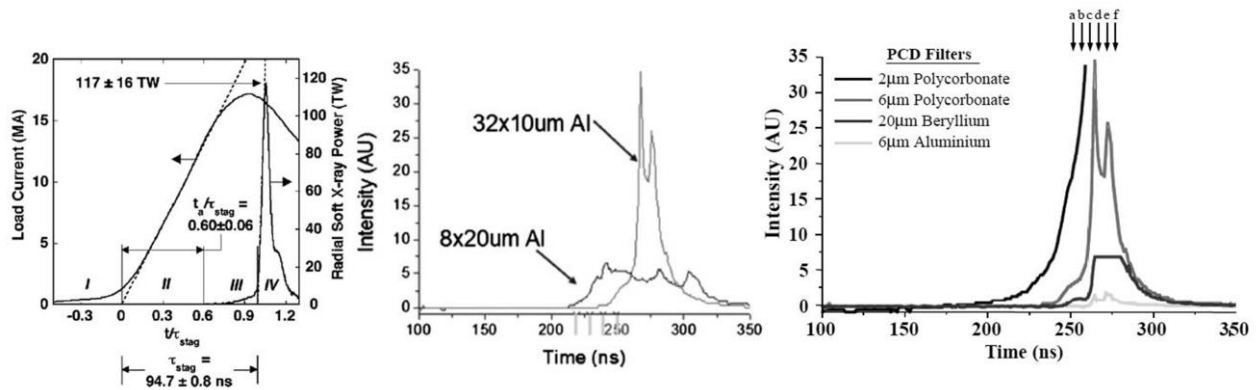


Figure 10 Left, taken from reference [2], an x-ray power trace for an experiment on Z, taken as an average of four shots. Centre, taken from reference [10], a comparison of x-ray power traces for an 8-wire array and a 32-wire array. Right taken from reference [11] x-ray yield of an experiment on MAGPIE through a variety of filters.

importance of alternative heating mechanisms [40, 41].

As Figure 9 shows, the stagnating column rapidly becomes unstable, developing $m=0$ and $m=1$ type instabilities. Trailing mass left behind due to the Rayleigh-Taylor instabilities of the implosion can produce alternative current paths during stagnation, due to the increasing inductive voltage across the pinch. This may cause secondary implosions, resulting in secondary x-ray peaks.

In general it has been found that the radiative yield from the stagnation column is very sensitive to the implosion symmetry. Greater symmetry results in higher peak X-ray power. This has been demonstrated on experiments on wire arrays of differing wire number [7, 10], and an example of the difference that wire number can make to the peak power is shown in Figure 10. Since the ablation plasma will to some extent seed instabilities in the implosion front, it is important to gain a better understanding of the azimuthal structure of this plasma.

Chapter 2

Pulsed power technology & the MAGPIE generator

Wire array Z-pinch experiments require drivers capable of generating very large currents over extremely short time scales. This chapter contains an overview of pulsed power technology, and a discussion of the design characteristics of MAGPIE. MAGPIE was originally designed to drive radiative-collapse experiments, with a view to inducing thermonuclear fusion in deuterium fibre loads. The rapid increase in the load inductance expected during radiative collapse led to a generator design that has a much higher characteristic drive impedance compared to pulsed power drivers designed for other applications. This high drive impedance not only allows a great deal of flexibility in terms of load design, but also provides the opportunity for excellent diagnostic access. A detailed description of the generator design can be found in reference [27] and a table of the key pulsed power characteristics is included at the end of the chapter for quick reference.

2.1) Introduction to pulsed power technology

This section presents an overview of pulsed power technology, introducing some of the key characteristics of pulsed power generators. Starting from a basic capacitor discharge, it goes on to describe how the characteristics of a generator can be modified by adding multiple units together, both in parallel and in series as a Marx bank. The effect of the loading on the peak current and rise-time are discussed, as well as pulse compression techniques using transmission lines as intermediate storage. The discussion below is based on concepts taken from references [27, 42, 43].

2.1.1) The capacitor discharge

The most basic pulsed power device is the capacitor discharge. Many of the more complex pulsed power designs can be understood in terms of an equivalent circuit of this form. As such it is useful to have a basic understanding of this circuit. A basic diagram of this circuit is shown in Figure 11. The capacitor is charged by a high voltage power supply via a charging resistor. Once the capacitor is fully charged, the spark gap switch is closed. The capacitor is connected across the load and begins to discharge. The resistance of the charging resistor is selected such that the charging circuit is effectively isolated over the timescale of the discharge. The discharge circuit has a finite inductance, which acts to limit the rate of current rise. This inductance is normally dominated by the spark

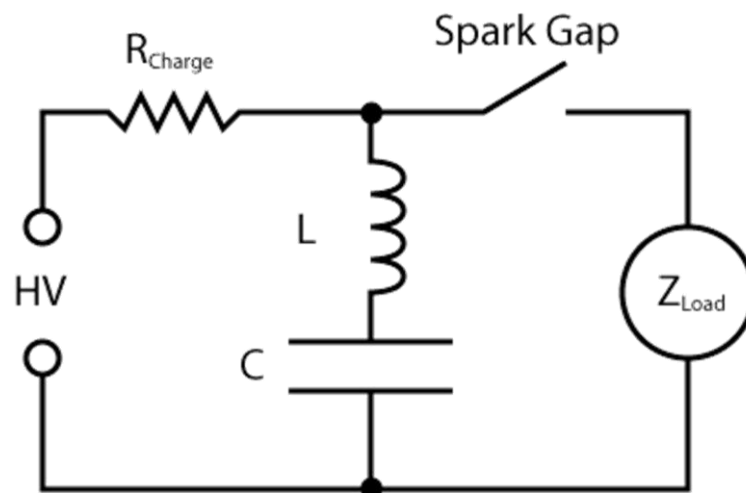


Figure 11 Circuit diagram for a capacitor discharge pulsed power system.

gap, with a smaller contribution from the capacitor.

As a starting point, the circuit can be modelled with a short-circuit load. For a short circuit the load impedance (Z_{Load}) can be set to zero. Constructing Kirchhoff's circuit law results in the following expression:

$$L \frac{dI(t)}{dt} + \frac{1}{C} \int_{-\infty}^t I(\tau) d\tau = 0 \quad (2.1.1)$$

Defining $V(t)$ as the voltage across the capacitor and differentiating yields the following expressions:

$$\begin{aligned} \frac{1}{C} \int_{-\infty}^t I(\tau) d\tau &= V(t) \\ I(t) &= \frac{CdV(t)}{dt} \end{aligned} \quad (2.1.2)$$

$$\frac{dI(t)}{dt} = C \frac{d^2V(t)}{dt^2}$$

Substituting these results into equation (2.1.1) leads to an expression for the generator voltage. This takes the form of a homogenous second order differential equation, for which the general solutions are well known:

$$\frac{d^2V(t)}{dt^2} + \frac{1}{LC} V(t) = 0 \quad (2.1.3)$$

$$V(t) = V_1 e^{i\omega t} + V_2 e^{-i\omega t} \quad (2.1.4)$$

$$\omega = \frac{1}{\sqrt{LC}} \quad (2.1.5)$$

The initial conditions for the discharge are that at $t=0$, the charging voltage $V(0)=V_0$ and the current $I(0)=0$. Applying these leads to a specific solution for the discharge:

$$V(t) = V_0 \cos(\omega t) \quad (2.1.6)$$

For a pulsed power generator the most important characteristics are the peak current, I_{max} and the rise time t_{rise}

Substituting equation (2.1.6) into (2.1.2), and rearranging gives the equation for the current:

$$I(t) = C \frac{dV(t)}{dt} = -C\omega V_0 \sin(\omega t) = -\sqrt{\frac{C}{L}} V_0 \sin \omega t \quad (2.1.7)$$

Maximum current occurs when $\omega t = \frac{\pi}{2}$:

$$I_{max} = -\sqrt{\frac{C}{L}} V_0 \quad (2.1.8)$$

$$t_{rise} = \frac{\pi}{2\omega} = \frac{\pi}{2} \sqrt{LC} \quad (2.1.9)$$

2.1.2) The effect of loading on the rise time and peak current of the generator

The results derived in the previous section should be considered as the ideal, limiting case for the maximum current and minimum rise time. Any real pulsed power generator will be required to drive some form of load impedance. In the case of Z-pinch loads, the impedance of the load will be dominated by its inductance. Therefore for this analysis the load impedance is approximated as a simple inductance. The solution will be of the same form as equation (2.1.7), with the driver inductance replaced by the total inductance, the sum of the load and capacitor inductances ($L_{Total}=L_{Cap}+L_{Load}$). This leads to new expressions for the peak current and rise time:

$$I_{Max} = \frac{1}{f_{load}} \sqrt{\frac{C_{cap}}{L_{Cap}}} V_{charge} \quad t_{rise} = f_{load} \frac{\pi \sqrt{L_{Cap} C_{Cap}}}{2} \quad (2.1.10)$$

$$f_{Load} = \sqrt{1 + \frac{L_{Load}}{L_{Cap}}} \quad (2.1.11)$$

The maximum current and rise time have been modified by the factor f_{load} . This factor describes the degree of circuit loading, and is controlled by the relative inductance of the driver and load.

2.1.3) Adding generators in series – the Marx bank

A number of capacitor discharge circuits may be arranged in series. This results in a circuit known as a Marx bank. Figure 12 shows a typical circuit diagram for a Marx bank. The charging and discharging cycles of this circuit are highlighted. During the charging cycle the spark-gap switches remain open and current flows through the charging and grounding resistors (R_C and R_G respectively). As in the single capacitor case, the resistance of the charging and grounding resistors is large enough to isolate the charging circuit over the discharge timescale ($\tau_{RC} \gg \tau_{LC}$). Once the capacitors are fully charged, the spark-gaps are triggered and the bank discharges.

An equivalent circuit for the discharging Marx can be constructed by calculating the total resultant charge voltage, capacitance and inductance. The charge voltage increases by a factor equal to the number of capacitor stages, while the overall capacitance decreases by the same factor.

$$V_{\text{Marx}} = NV_0 \quad (2.1.12)$$

$$C_{\text{Marx}} = \frac{C_{\text{Cap}}}{N} \quad (2.1.13)$$

The inductance of the Marx bank is dominated by the switches, with a small component from the capacitors. The number of switches increases with the number of capacitors, so that it can be argued that the overall inductance of the bank will scale linearly with the number of capacitors. To minimise this contribution many designs take advantage of bipolar charging. This arrangement halves the number of spark-gaps required. We therefore define L_{Cap} as the inductance associated with each capacitor stage.

$$L_{\text{Marx}} = NL_{\text{Cap}} \quad (2.1.14)$$

These equivalent values can be inserted into the simple capacitor discharge equations:

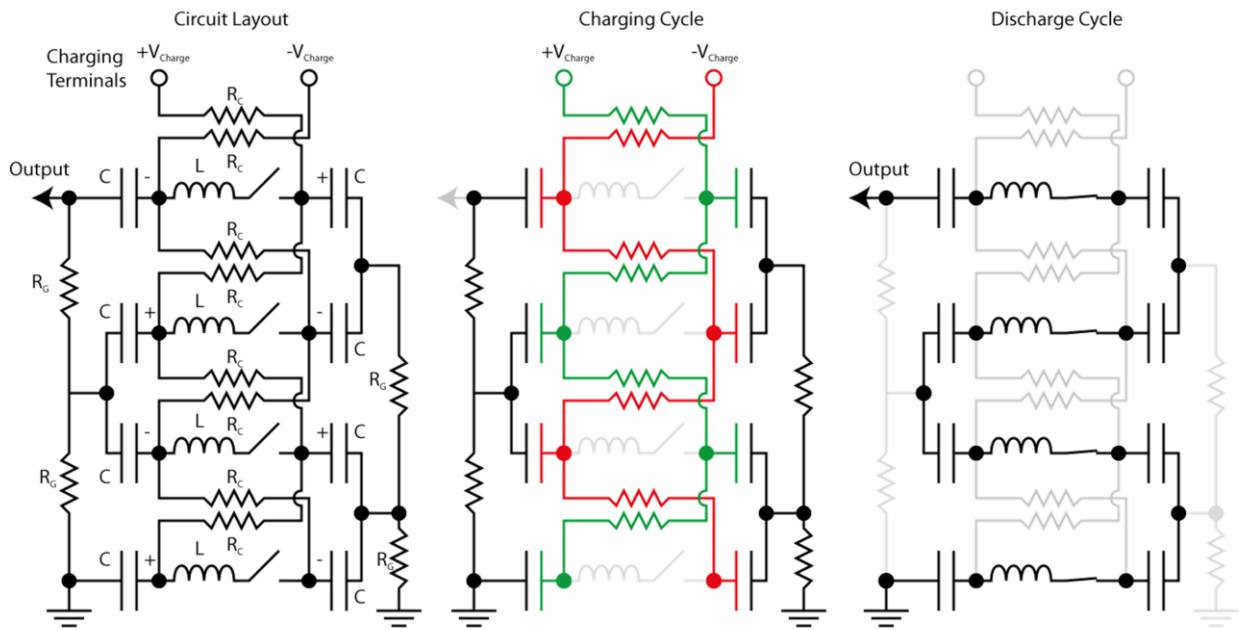


Figure 12 Diagram of a four stage Marx bank. Capacitors are bipolar charged to minimise the inductance introduced by the switches. The current paths for both the charge and discharge cycles are highlighted.

$$I_{Max} = \sqrt{\frac{C_{Marx}}{L_{Marx}}} V_{Charge} = \sqrt{\frac{\frac{C_{Cap}}{N_{Cap}}}{L_{Cap} N_{Cap}}} N_{Cap} V_{Cap} = \sqrt{\frac{C_{Cap}}{L_{Cap}}} V_{Cap} \quad (2.1.15)$$

$$t_{rise} = \frac{\pi}{2} \sqrt{L_{Marx} C_{Marx}} = \frac{\pi}{2} \sqrt{L_{Cap} N_{Cap} \frac{C_{Cap}}{N_{Cap}}} = \frac{\pi}{2} \sqrt{L_{Cap} C_{Cap}} \quad (2.1.16)$$

These equations reveal that the Marx bank configuration provides no benefit in terms of peak current and rise time. Looking at the loaded case, substituting $L_{Total}=NL_{Cap}+L_{Load}$, $C_{Total}=C_{Cap}/N$, $V_{Total}=NV_0$ into equations (2.1.8) and (2.1.9) results in the following expressions:

$$I_{max} = \sqrt{\frac{\frac{C_{Cap}}{N_{Cap}}}{(NL_{Cap} + L_{Load})}} NV_0 = \frac{1}{\sqrt{1 + \frac{L_{Load}}{NL_{Cap}}}} \sqrt{\frac{C_{Cap}}{L_{Cap}}} V_0 \quad (2.1.17)$$

$$t_{rise} = \frac{\pi}{2} \sqrt{(NL_{Cap} + L_{Load}) \frac{C_{Cap}}{N}} = \sqrt{\left(1 + \frac{L_{Load}}{NL_{Cap}}\right)} \frac{\pi}{2} \sqrt{L_{Cap} C_{Cap}} \quad (2.1.18)$$

We can define a modified inductive loading factor:

Plot showing the effect of increasing number of Marx stages on current pulse shape

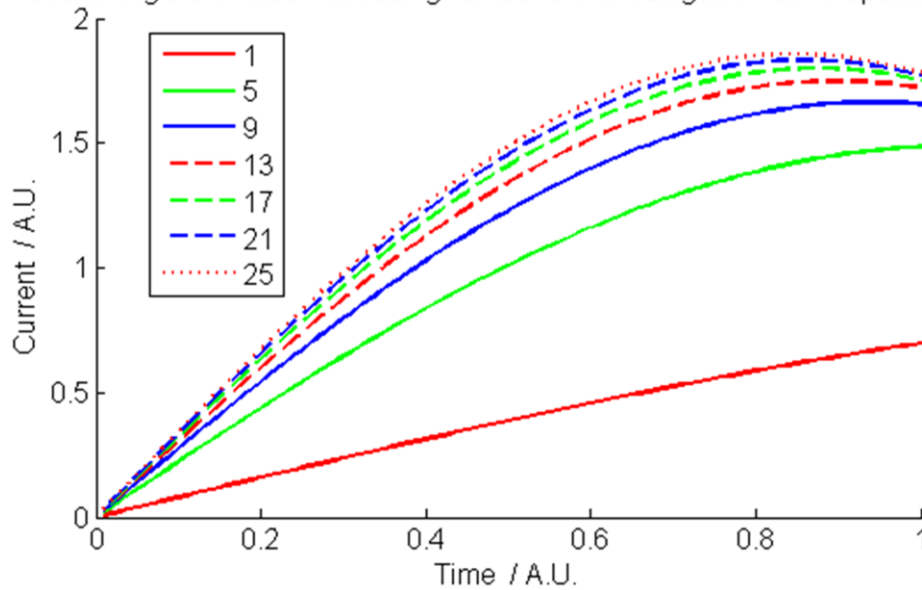


Figure 13 Graph of the current driven into a load by a Marx generator with various numbers of stages. The nominal load inductance was four times the inductance of a single stage.

$$f_{load} = \sqrt{\left(1 + \frac{L_{Load}}{L_{Cap}N_{Cap}}\right)} \quad (2.1.19)$$

From this analysis, we can see that with each extra stage added to the Marx bank, the inductive loading factor decreases. This means that the generator will drive closer to its ideal current maximum and rise time. The Marx bank arrangement therefore allows the generator to drive larger loads. The effect of increasing the number of Marx stages driving into an inductive load is illustrated in Figure 13.

2.1.4) Effect of adding generators in parallel

Generator stages can also be added in parallel. A diagram of this layout is shown in Figure 14. Again an equivalent circuit can be constructed. The capacitances and inductances of each generator can now be added in parallel. The charging voltage is unaffected.

$$C_{Par} = N_{Par}C_0 \quad (2.1.20)$$

$$L_{Par} = \frac{L_0}{N_{Par}} \quad (2.1.21)$$

$$V_{Par} = V_0 \quad (2.1.22)$$

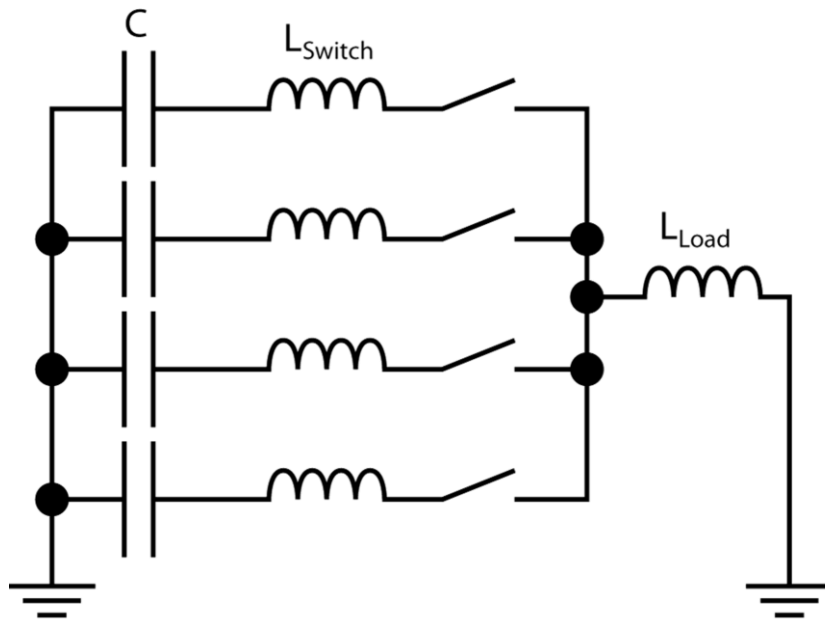


Figure 14 Circuit diagram showing a set of capacitor discharges in parallel. In this diagram the charging circuit has been ignored for simplicity.

$$I_{Max} = \sqrt{\frac{C_{Par}}{L_{Par}}} V_0 = \sqrt{\frac{N_{Par} C_0}{L_0 / N_{Par}}} V_0 = N_{Par} \sqrt{\frac{C_0}{L_0}} V_0 \quad (2.1.23)$$

$$t_{rise} = \frac{\pi}{2} \sqrt{L_{Par} C_{Par}} = \frac{\pi}{2} \sqrt{\frac{L_0}{N_{Par}} C_0 N_{Par}} = \frac{\pi}{2} \sqrt{L_0 C_0} \quad (2.1.24)$$

Thus this arrangement increases the peak current by a factor equal to the number of generators in parallel. Applying the inductively loaded equations results in the following equations:

$$I_{Max} = \sqrt{\frac{C_{Par}}{L_{Total}}} V_0 = \sqrt{\frac{N_{Par} C_0}{\frac{L_0}{N_{Par}} + L_{Load}}} V_0 = \frac{N_{Par}}{\sqrt{1 + \frac{N_{Par} L_{Load}}{L_0}}} \sqrt{\frac{C_0}{L_0}} V_0 \quad (2.1.25)$$

$$t_{rise} = \frac{\pi}{2} \sqrt{\left(\frac{L_0}{N_{Par}} + L_{Load}\right) N_{Par} C_0} = \sqrt{\left(1 + \frac{N_{Par} L_{Load}}{L_0}\right) \frac{\pi}{2} \sqrt{L_0 C_0}} \quad (2.1.26)$$

$$f_{load} = \sqrt{\left(1 + \frac{N_{Par} L_{Load}}{L_0}\right)} \quad (2.1.27)$$

The modified loading factor increases with the number of generators added in series. This means that with each additional stage, the inductance of the load that the generator is capable of driving decreases.

2.1.5) The characteristic impedance of the generator

The ability of the generator to drive a given load can be quantified by the characteristic drive impedance. The characteristic impedance is the ratio of the amplitudes of the voltage and current waves produced by the generator when driving a short circuit load. Dividing the expressions for the ideal voltage and current waves:

$$Z_{Output} = \frac{V(t)}{I(t)} = \frac{V_0 \cos \omega t}{\sqrt{\frac{C}{L}} V_0 \cos\left(\omega t - \frac{\pi}{2}\right)} = \sqrt{\frac{L}{C}} e^{-\frac{i\pi}{2}} \quad (2.1.28)$$

For a generator made up of N_{Caps} capacitors arranged in N_{Marx} Marx banks, where each bank contains $N = N_{Caps} / N_{Marx}$ the impedance and maximum current of the driver can be expressed with the following equations:

$$|Z_{Output}| = \frac{N_{Caps}}{N_{Marx}^2} \sqrt{\frac{L_{Cap}}{C_{Cap}}} \quad (2.1.29)$$

$$I_{Max} = N_{Marx} \sqrt{\frac{C_{Cap}}{L_{Cap}}} V_{Charge} = \frac{N_{Marx} V_{Charge}}{N_{Caps} |Z_{Output}|} \quad (2.1.30)$$

For a given number of capacitors the drive impedance decreases as the square of the number of Marx banks, while the peak current increases proportionally to the number of banks. In order for the generator to drive its ideal maximum current through the load, the drive impedance must be significantly larger than the load impedance. However, if the aim is to deliver maximum energy to the load, then the impedance of the Load should be matched to the impedance of the generator.

2.1.6) Water filled coaxial transmission lines as a pulsed power source

The main conclusion that can be drawn from the analysis so far is that whilst the peak current and characteristic impedance of a pulsed power generator can be modified by the arrangement of capacitors and switches, the rise time of the pulse is essentially limited by the characteristics of these most basic units. Improvements in the rise time require either lower inductance capacitors and switches or capacitors capable of withstanding a higher charging voltage. Marx bank systems designed using available high voltage capacitor and switch technology result in rise times of around a microsecond. To produce faster pulses a different approach is required.

Transmission lines can be used to generate fast rising current pulses. A basic diagram of this circuit is shown in Figure 15. The line acts as a combination of storage capacitor and inductor. Once switched, it drives a flat-top voltage wave with amplitude equal to half the charging voltage for a period equal to twice its transit time. Transmission lines used for this purpose are normally referred to as pulse forming lines (PFLs). Coaxial lines are an ideal choice for designing PFLs. The equations for the inductance and capacitance per unit length of a coaxial line are:

$$L'_{Coax} = \frac{\mu_0 \mu_r}{2\pi} \ln \left(\frac{R_{outer}}{R_{inner}} \right) \quad (2.1.31)$$

$$C'_{Coax} = \frac{2\pi\epsilon_0\epsilon_r}{\ln\left(\frac{R_{outer}}{R_{inner}}\right)} \quad (2.1.32)$$

The inductance and capacitance per unit length are both set by the aspect ratio of the cable (R_{Outer}/R_{Inner}). So long as this ratio is maintained a coaxial line can be scaled up to any radius while maintaining these characteristics. The electric field at the surface of the electrodes decreases as the radius of the lines increases. This is useful as a lower electric field at the conductor surface reduces the probability of the electrical breakdown of the line. As a result coaxial lines can be designed to withstand extremely high charging voltages. This allows single coaxial lines to effectively replace entire Marx banks. Since only a single switch is required for the line, inductance is minimised and extremely fast rise times are possible. The characteristic impedance and transmission speed of the line is given by the following expression:

$$Z = \sqrt{\frac{L'_{Coax}}{C'_{Coax}}} = \frac{1}{2\pi} \sqrt{\frac{\mu_0\mu_r}{\epsilon_0\epsilon_r}} \ln\left(\frac{R_{outer}}{R_{inner}}\right) = 60 \sqrt{\frac{\mu_r}{\epsilon_r}} \ln\left(\frac{R_{outer}}{R_{inner}}\right) \quad (2.1.33)$$

$$c_{PFL} = \frac{c}{\sqrt{\epsilon_r\mu_r}} \quad (2.1.34)$$

In order to maximise voltage tolerance, the coaxial aspect ratio should be as large as possible. In order to produce a large current in general the impedance needs to be minimised. Therefore dielectric constant, ϵ_r , must be maximised. At the frequencies of interest deionised water has an extremely large dielectric constant ($\epsilon_r=80$), due to the polarisability of the water molecules. This makes it an ideal dielectric medium for high current pulsed power applications. Unfortunately deionised water is only capable of holding off electrical breakdown for short periods,

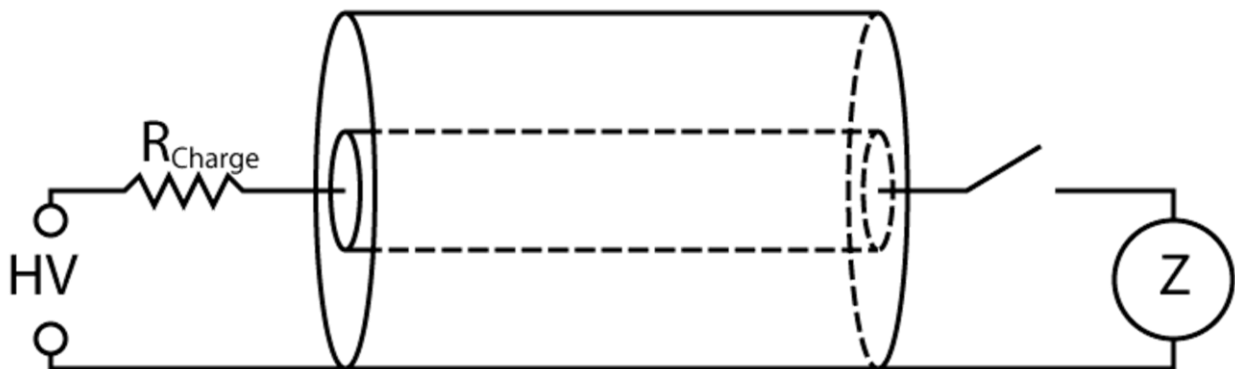


Figure 15 Circuit diagram for a coaxial line discharge circuit.

on the order of microseconds. As a result water filled coaxial lines must be pulse-charged by a secondary pulsed power generator, typically a Marx bank. The inductance of the pulse forming line is small enough that during the charging cycle it may be treated simply as a capacitor. The capacitance can be calculated using equation (2.1.32).

The equation for the charging time for a pulse forming line charged by a Marx bank is:

$$t_{charge} = \pi \sqrt{\frac{L_{Marx} C_{Coax} C_{Marx}}{C_{Coax} + C_{Marx}}} = \frac{\pi \sqrt{L_{Marx} C_{Marx}}}{\sqrt{1 + \frac{C_{Marx}}{C_{Coax}}}} \quad (2.1.35)$$

The peak voltage reached on the PFL is set by the relative capacitance of the line and the Marx Bank source. If the capacitance of the Marx is larger than the capacitance of the line, the voltage on the line will ‘ring up’ to a higher voltage than the Marx charging voltage. It should be noted however that this ring up is accompanied by a reduction in the energy transfer efficiency from the Marx to the PFL.

$$V_{PFL} = \frac{2C_{Marx}V_{Marx}}{C_{PFL} + C_{Marx}} = \frac{2V_{Marx}}{\left(1 + \frac{C_{PFL}}{C_{Marx}}\right)} \quad (2.1.36)$$

$$\eta_{Transfer} = \frac{\frac{1}{2}C_{PFL}V_{PFL}^2}{\frac{1}{2}C_{Marx}V_{Marx}^2} = \frac{4C_{PFL}}{C_{Marx} \left(1 + \frac{C_{PFL}}{C_{Marx}}\right)^2} \quad (2.1.37)$$

For maximum energy efficiency, the capacitance of the Marx bank should be matched to the PFL.

Once the switch is closed, the PFL must be treated as a transmission line. This is because transmission time of line becomes comparable to the LC time of the equivalent capacitor discharge. Transmission lines are governed by the telegrapher’s equations. The impedance of the Marx bank is normally large enough that on the discharge time-scale of the PFL it can be treated as an open circuit, reflecting the voltage wave back towards the load. This results in the line driving a flat-top voltage wave of half the charge voltage for a period equal to twice line transit time into the load.

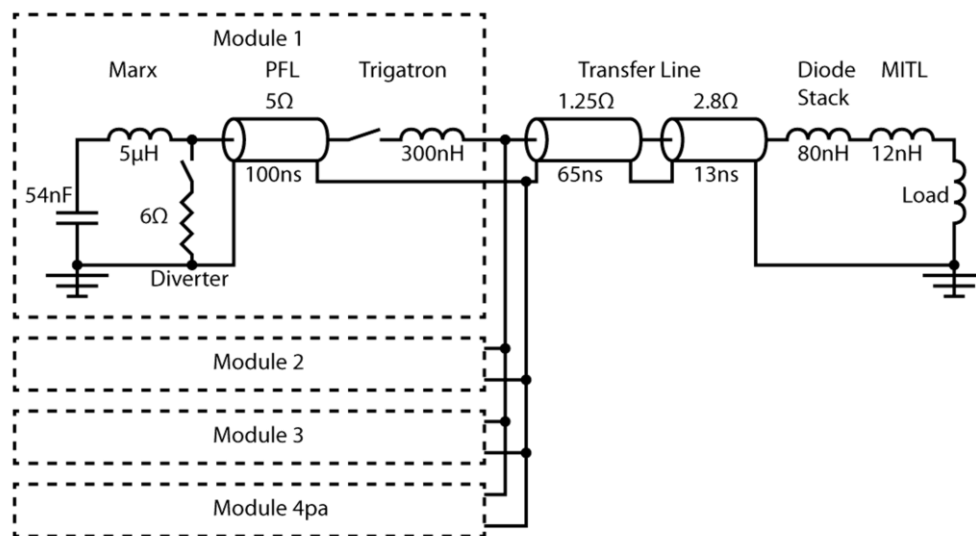
$$\tau_{drive} = \frac{2l}{c_{pfl}} = \frac{2l\sqrt{\epsilon_r}}{C} \quad (2.1.38)$$

$$V_{out} = \frac{V_{PFL}}{2} \quad (2.1.39)$$

2.2) The MAGPIE generator

This section describes the design and characteristics of the MAGPIE generator. Figure 16 shows an equivalent circuit diagram and a CAD rendering of the generator. A cross-section diagram of the various components is shown in Figure 17. The design of the generator is described in detail in reference [27]. Current is driven by a set of four

a)



b)

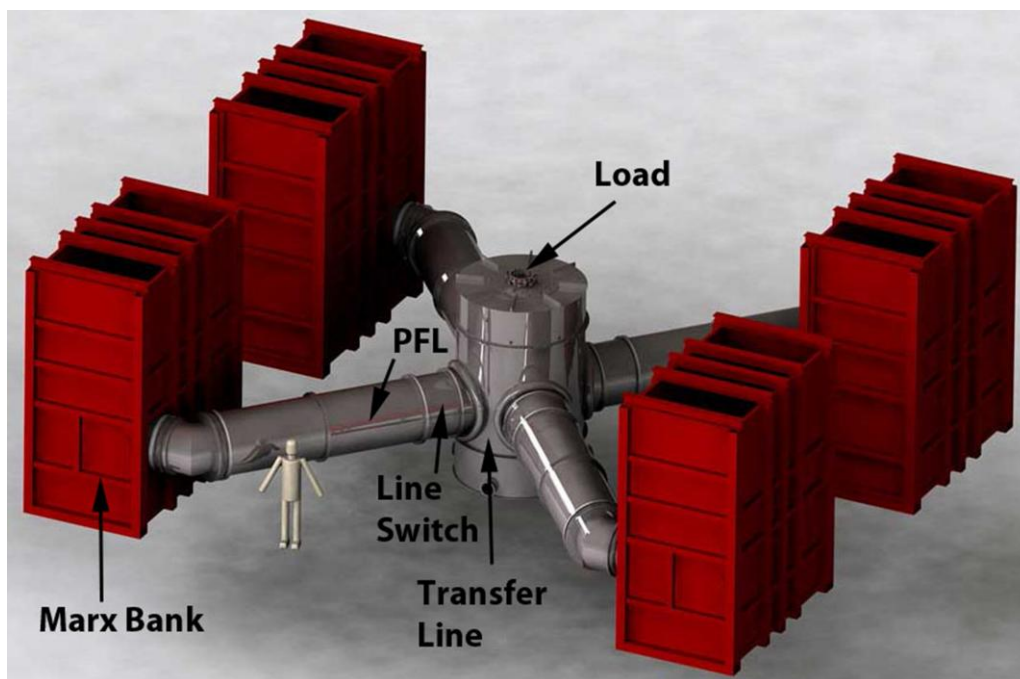


Figure 16 a) An equivalent circuit diagram of MAGPIE b) A CAD rendering of the MAGPIE generator, with a human figure for scale. The four Marx banks are painted red, while the pulse forming lines and power feed are silver.

parallel water filled coaxial pulse forming lines. These lines are charged by Marx banks, and the current is combined via a vertical transfer line, itself a water-filled coaxial line. This section described the design of the generator, working back from the drive characteristics required by the load.

2.2.1) Load specification and power delivery

MAGPIE was originally designed to drive cryogenic deuterium fibre implosion experiments. To drive these loads it was calculated that a total generator output impedance of 1.25Ω would be required. The vertical transfer line is a water-filled coaxial line whose purpose is to combine the current feeds from the four lines and azimuthally smooth the current before it is delivered to the load. Since it is the final current feed to the load it was designed with an output impedance of 1.25Ω . The diode stack is mounted at the top of the transfer line. The stack acts as a non-conducting vacuum chamber wall, allowing the current to be transferred from the water filled line into the evacuated experimental chamber without shorting the load. The design is tailored to minimise the risk of vacuum breakdown. It consists of a stack of metal and Perspex disks. The metal disks help to divide the applied voltage, resulting in an even electric field over the Perspex insulators. The insulators have surfaces cut at 45° to take advantage of an effect known as magnetic flashover inhibition (MFI). Surface emitted electrons are directed away from the insulator surface by the Lorentz force, reducing the risk of runaway avalanche induced electrical break-

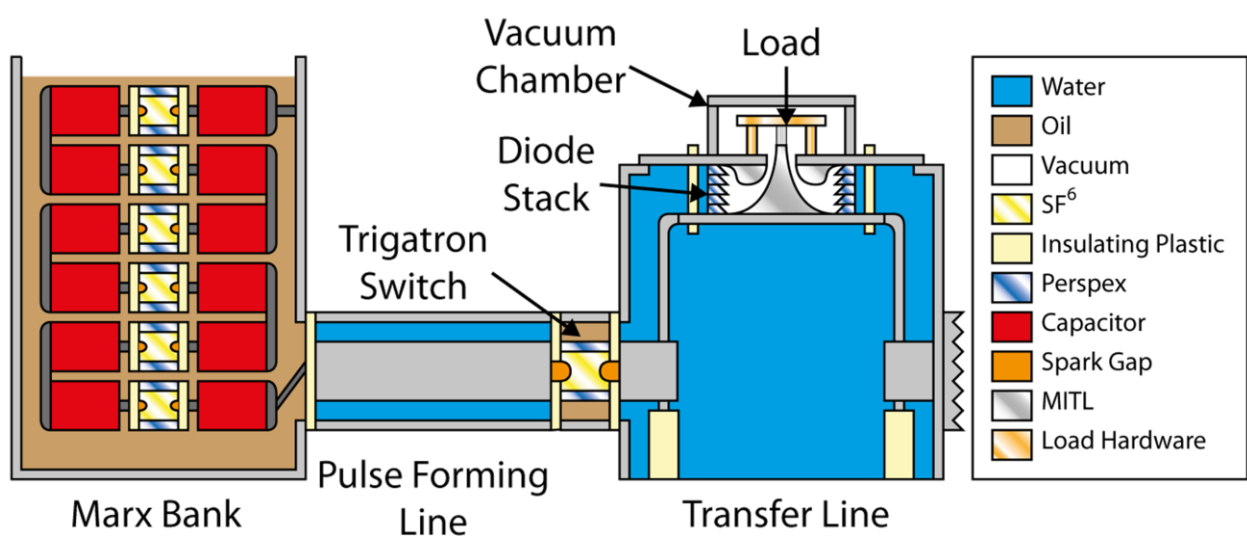


Figure 17 Cross section of the Magpie Generator, showing the load, MITL, Transfer Line, pulse forming line and Marx Bank. Only one of the Marx Bank/ Pulse forming line sets is shown.

down. The Magnetically Insulated Transmission Line (MITL) is mounted inside the diode stack. This is designed to transfer current from the large radius of the transfer line electrode ($\sim 0.8\text{m}$) to the smaller radius of the load ($\sim 8\text{mm}$). As the conductor radius is reduced, the magnitude of the surface electric field will increase. Breakdown across the MITL is prevented by magnetic insulation – the magnetic field between the electrodes is shaped to result in a characteristic Larmor radius for emitted electrons small enough to prevent them crossing the anode-cathode gap. The inductance of the MITL and diode stack combined is $\sim 90\text{nH}$.

2.2.2) Pulse Forming Lines

Current is fed into the vertical transfer line by a set of four separate pulse forming lines (PFLs). In order to fulfil the impedance match condition into the transfer line, the lines were designed with an impedance of 5Ω . Each PFL is connected to the vertical transfer line via a high current switch (a Trigatron). The lines are charged up and when switched produce a flat top voltage pulse of half the charge voltage for a period equal to twice the line transmission time. The transmission speed of the line is $\sim \frac{c}{9}$, so a rise time of 200ns corresponds to a PFL length of

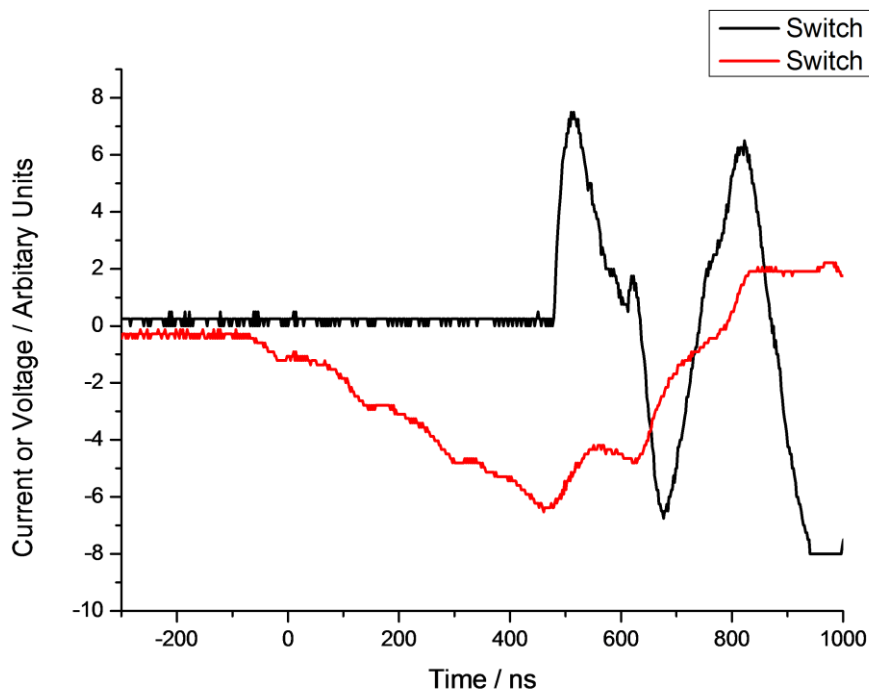


Figure 18 Graph showing a scope trace for the switch voltage and current. The switch closes at around 480 ns scope time. At this point there is a rapid fall in switch voltage and rise in the switch current. After the pulse the current reflects back into the pulse forming line.

3.3m. The required impedance sets the coaxial line aspect ratio according to equation (2.1.33). For $5\ \Omega$ this ratio $r_{\text{Outer}}/r_{\text{Inner}} = 2.1$. The total capacitance and inductance of the lines are calculated according to equations (2.1.31) and (2.1.32), resulting in $C_{\text{Coax}}=20\text{nF}$ and $L_{\text{Coax}}=12.4\text{nH}$. The four trigatron switches are triggered from a single source, via cables of identical length in order to guarantee switch synchronisation.

2.2.3) Marx Banks

Each pulse forming line is charged by a Marx bank located at its far end. Each bank consists of 24 $1.3\mu\text{F}$, 100kV rated low inductance capacitors. These capacitors are arranged such that they can be charged in parallel, as shown in the circuit diagram in Figure 12. Normally these capacitors are charged to $\pm 65\text{kV}$. At this charge voltage each bank stores $\sim 66\text{kJ}$. A high voltage pulse is used to trigger the Marx switches, inducing the bank to erect. Once erected the bank can be treated as a single capacitor with an effective charging voltage $V_{\text{Marx}} = 1.56\text{MV}$, total capacitance of $C_{\text{Marx}} = 54\text{nF}$, and a total inductance $L_{\text{Marx}} = 5\mu\text{H}$. The Marx charges the PFL to a peak voltage of $V_{\text{PFL}} = 2.28\text{MV}$ in a period $\tau_{\text{Charge}} = 890\text{ ns}$. At peak charge the energy stored in the PFL is 52 kJ , corresponding to an energy-transfer-efficiency from Marx to PFL of 80%. The Marx banks were refurbished in 2008 to increase the overall generator current for 1MA to 1.4MA .

2.3) Table of key MAGPIE parameters

The following table contains a range of reference values for MAGPIE, and summaries the improvements made during the Marx bank refurbishments. Many values taken from reference [27]. During the refurbishment the capacitors were replaced with newer, higher capacitance models.

Overall Values	Before Upgrade	After Upgrade
Peak Current	1MA	1.4MA
Current Rise Time	240ns	240ns
Max. Drivable Load Inductance	150nH	150nH
Transfer Line		
Transfer Line Characteristic Impedance	1.25Ω	1.25Ω
Transfer Line Transit Time	65ns	65ns
Marx Bank		
Capacitance of Individual Capacitor	0.7μF	1.3μF
Marx Bank Erect Capacitance	29nF	54nF
Marx Bank Erect Inductance	5.5μH	5.5μH
Standard Marx Charging Voltage	65kV	65kV
Marx Bank Erect Voltage	1.56MV	1.56MV
Energy Stored per Marx Bank	35.5kJ	66kJ
Charging time into PFL	0.8μs	0.89μs
Pulse Forming Lines (PFL)		
PFL Characteristic Impedance	5Ω	5Ω
PFL Capacitance	20nF	20nF
PFL Inductance	12.4nH	12.4nH
PFL Length	3.3m	3.3m
PFL Transit Time	120ns	120ns
Max Line Voltage (With Ring-up)	1.85MV	2.28MV
Energy transferred to each PFL	34kJ	52kJ
Energy transfer efficiency (η)	0.96	0.79

Table 1 List of reference parameters for the MAGPIE generator. Values are quoted for both before and after the upgrade.

2.1) Introduction to the Z-R generator

The Z machine [5, 44, 45] is based at Sandia National Labs, Albuquerque, New Mexico. When configured for wire array experiments the generator is capable of driving peak currents of 26MA with a rise time of 100ns. The machine is also capable of operating in a long-pulse mode. This mode is typically used for material physics experiments and is characterised by a peak current of 20MA, with a rise time of 500ns.

Originally built as the Particle Beam Fusion Accelerator II, (PBF-II), it was designed to produce the high voltages required to drive ion beam diodes (10 – 30MV) for ion beam driven inertial confinement fusion experiments. The accelerator was completed in 1985. In 1996 the machine was modified to enhance the current delivered to the load. Peak currents of 18 – 20 MA were achieved. This was originally a temporary modification for a short series of experiments to investigate the effects of current scaling for Z-pinch loads. The experiments at high current were so successful that the decision was made to keep the machine in this configuration permanently. The machine was renamed Z in 1997. In 2002 the ZR project was initiated. This involved a major refurbishment of the

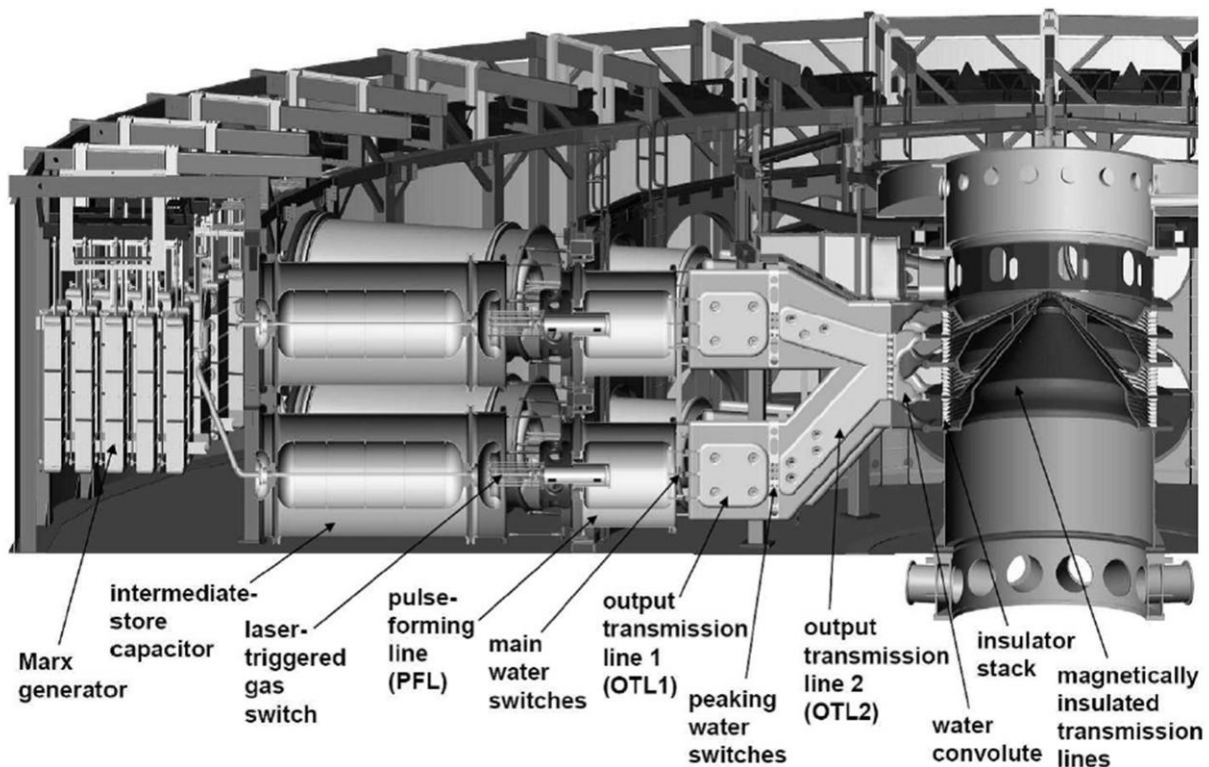


Figure 19 Taken from reference [5]. A cross-section of ZR accelerator, showing the pulsed power architecture.

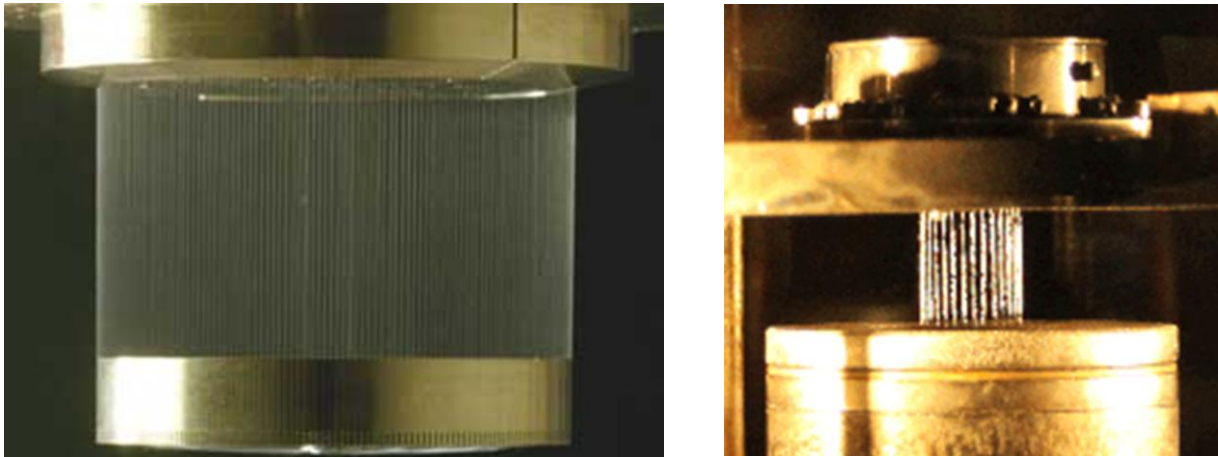


Figure 20 A comparison of typical loads fielded on the Z generator (left) and MAGPIE (right).

facility. The machine was almost entirely rebuilt. The project was completed in 2007, with construction work taking around 14 months.

Figure 19 shows a cross section of the generator. It consists of a set of 36 Marx Generators, each charging one of 36 multistage pulse forming lines. These lines are stacked two high and distributed in a circle around the generator. The lines are connected to a four level diode stack, and feed into a post hole convolute via magnetically insulated transmission lines. The currents are combined and delivered to the load.

Arrays fielded on Z are typically 10-20mm in radius with ~ 300 wires, with typically 60kA current per wire. This is compared with 8mm radius 32 wire arrays fielded on MAGPIE, resulting in ~ 30 kA per wire. Examples of these arrays are shown in Figure 20.

Chapter 3

The MAGPIE plasma diagnostics suite

Plasma physics experiments rely on a wide range of diagnostic techniques. Experiments evolve over short time scales (ns) and generate extremely strong, rapidly changing electric and magnetic fields. Plasma parameters such as the density and temperature often vary over many orders of magnitude within a single experiment. Radiation is emitted over a very wide spectral range, from the optical all the way up to the hard x-ray. This chapter provides an introduction to some of the key techniques that are regularly used to diagnose experiments on MAGPIE.

3.1) Signal transmission and recording

Many of the diagnostics described in this chapter rely on transmitting voltage signals from a diagnostic device to a remote recording device. Various effects must be taken into account due to this transmission. Signal delays and attenuation will change the apparent timing and magnitude of recorded signals. Recording effects can also be important. The temporal resolution of the recording device may obscure detail in the signal, and the limited dynamic range means care must be taken in the selection and setup of the recording device.

Signals are transmitted via coaxial transmission lines. These coaxial lines have a characteristic impedance of 50Ω . The characteristic impedance of a transmission line dictates the amplitude ratio between the voltage and current

waves transmitted down the line. In an electromagnetically noisy environment such as a pulsed power lab relatively large voltage signals are preferable in order to maximise the signal to noise ratio. Care must be taken with diagnostics which are capable of driving only a small current, for example photodiodes. In some cases, local buffer amplification may be required in order to drive a sufficiently large voltage wave into the transmission line.

The signals are recorded by fast digitising oscilloscopes located in the screened room. The screened room provides a high quality Faraday cage environment, protecting the recording equipment from electro-magnetic noise generated during the MAGPIE discharge. Optical timing signals for the laser probing system are fed in via fibre optic cables where they are coupled into photodiodes so that the signal may be electronically recorded. MAGPIE is equipped with a bank of 6 HP16500B/C oscilloscopes. Two of these are dedicated to diagnostics monitoring the generator, while the other four are dedicated to the experimental diagnostic suite. As has already been mentioned all signals are routed to the digitiser inputs via 50Ω coaxial cables. These cables are terminated at the scopes with 50Ω resistive terminators to prevent signals reflecting off of the oscilloscope due to an impedance mismatch.

All transmission lines have associated frequency dependent signal attenuation. At high frequencies this effect is mostly due to dielectric losses. In order to make accurate measurements of voltages at the experiments, these effects should be taken into account in any analysis.

The transmission velocity of signals in the coaxial lines is $\sim 2/3$ speed of light. This is reasonably slow on the time-scale of the experiment. The transmission time along 1m of cable is $\sim 5\text{ns}$, and so cable delay becomes an im-

Diagnostic	Relative delay
Rogowski Grooves & MITL B-dots	Defined as $t = 0$ Reference
XUV Framing Cameras	$-2\text{ ns} + \text{Time of Flight} \approx 0\text{ ns}$
PCD Signals	$+4\text{ ns} + \text{Time of Flight} \approx 7\text{ ns}$
Laser Timing Signal	-10 ns

Table 2 Table of relative cable delays for key diagnostics. These define the relative difference between the time an event is recorded by a scope and actual experimental timing of the event for each diagnostic. Positive delay means that signals appear later than actual time.

portant factor in the timing of measurements. Time of flight for light is also a factor in many diagnostics; transmission over 1 m takes $\sim 3.3\text{ns}$. In order to simplify analysis as far as possible, cable lengths from the diagnostics to the digitisers have been standardised. Even so, some diagnostics have a relative time offset, normally referred to as delay. A selection of these are summarised in Table 2.

3.2) Current/magnetic field diagnostics

The accurate measurement of current is very important in pulse power experiments. MAGPIE fields multiple diagnostics monitoring the current in many different locations across the generator. The two key diagnostic devices used are B-dots and Rogowski grooves. B-dots are also used to probe the magnetic fields produced in experimental plasmas. The positions at which these diagnostics are fielded are shown in the schematic of the MITL shown in Figure 22.

3.2.1) B-dot magnetic field probe

B-dot probes are used both to measure the magnetic fields generated in experiments and also to monitor current

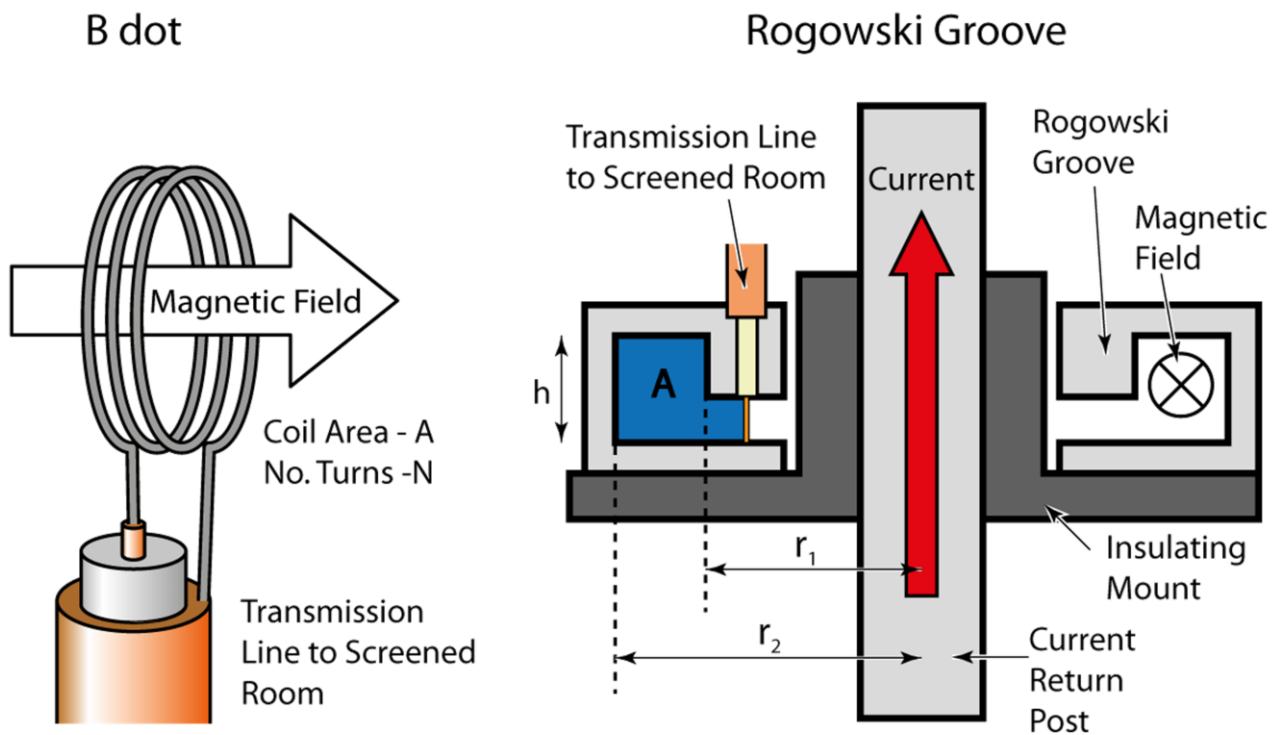


Figure 21 A diagrams of a B-dot magnetic field probe and a cross sectional diagram of a Rogowski groove in place around a return post.

pulse shape at different points in the generator. Probes are used to monitor the Marx output current, the current through the line switches and in the current fed through the MITL. Figure 21 shows a diagram of a typical B-dot. The probe consists of a small wire coil, usually only a few turns, mounted on the end of a coaxial transmission line. The changing magnetic field linking the B-dot induces a voltage signal across the coil. This voltage is proportional to the rate of change of flux linkage through the coil. This voltage drives current into the transmission line, and the transmitted signal is recorded by an oscilloscope. The following equations describe the voltage signal:

$$V = - \frac{d\Phi(t)}{dt} \quad (3.2.1)$$

$$\phi(t) = \iint \vec{B}(t) \cdot d\vec{A} = NA\bar{B}_{\perp}(t) \quad (3.2.2)$$

$$\frac{d\bar{B}_{\perp}(t)}{dt} = - \frac{1}{NA} V(t) \quad (3.2.3)$$

Where N is the number of turns, A is the probe area and V(t) is the voltage recorded across the coil, and $\bar{B}_{\perp}$ is the average magnetic field strength perpendicular to the coil.

Care must be taken when using B-dot probes to measure the magnetic fields inside a plasma. Firstly, the probe can become capacitive coupled. Magnetic field data can be retrieved by fielding pairs of counter-coiled probes. The signal from each probe due to the magnetic field will be of the opposite polarity, but the signal due to the

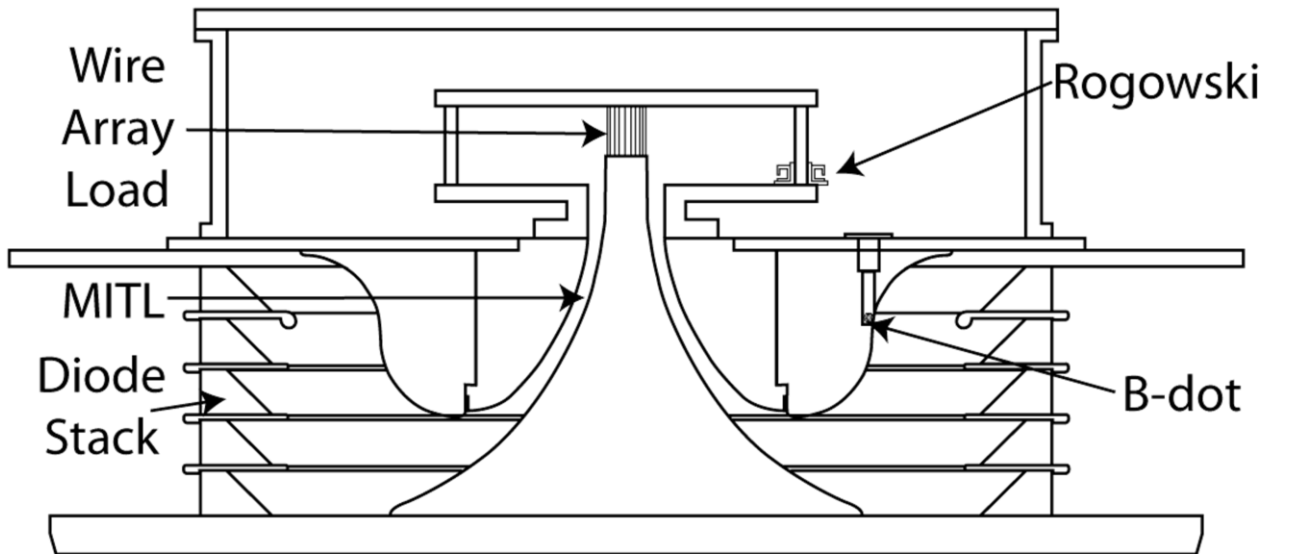


Figure 22 Cross section of the MAGPIE MITL, showing the positions of the current diagnostics.

electric field should remain of the same polarity. The two signals can be subtracted to remove the capacitive component. B-dots can also be susceptible to electrical pickup from the free charges in plasma, and must be carefully insulated in order to prevent this.

On MAGPIE we field a set of four B-dots mounted in the MITL. These monitor the current delivered to the generators anode-cathode (AK) gap. It should be noted that they will be insensitive to any electrical breakdown that may occur in the array hardware before the current is delivered to the load. The B-dots are mounted in recesses just beneath the MITL's conducting surface, as shown in the diagram in Figure 22. As such a geometric calibration is difficult to calculate. Instead calibration is carried out via comparison with the return Rogowski signals. While this cross calibration is not ideal, it still provides information on the drive current in the case where the return Rogowskis fail.

3.2.2) Rogowski groove current monitors

Rogowski grooves are used to measure the current delivered to the load during experiments. They are sensitive to the rate of change of current in the conductor that they surround. The equations for the magnetic flux through the Rogowski probe and corresponding induced voltage are:

$$\phi = \oint \vec{B} \cdot d\vec{A} = \int_0^h \int_{r_1}^{r_2} \frac{\mu_0 I(t)}{2\pi r} dr dz = \frac{\mu_0 I(t)}{2\pi} h \ln\left(\frac{r_2}{r_1}\right) \quad (3.2.4)$$

$$V(t) = -\frac{d\phi}{dt} = -\left[\frac{\mu_0}{2\pi} h \ln\left(\frac{r_2}{r_1}\right)\right] \frac{dI(t)}{dt} \quad (3.2.5)$$

Where the various dimensions correspond to those labelled in Figure 21. Rearranging and integrating results in an expression for the total current:

$$I(t) = -\frac{\int_0^t V(t) dt}{\left[\frac{\mu_0}{2\pi} h \ln\left(\frac{r_2}{r_1}\right)\right]} \quad (3.2.6)$$

In most MAGPIE experiments two Rogowski grooves are fielded, each mounted around one of the four return posts. In addition, a larger Rogowski groove is occasionally mounted around the load. Unlike standard Rogowski coils, the Rogowski groove does require the conductor to be mounted at the centre of the probe.

3.3) Resistive voltage probe

Voltage measurements are essential for both monitoring the generator and the diagnosis of energy flow into the experiment. The voltages produced in these experiments are extremely large, and therefore special measurement techniques are required.

Resistive dividers provide an extremely simple method of measuring high voltages. On MAGPIE they are used to monitor the Marx bank output voltage and to monitor the voltage across the load. Figure 23 shows a circuit diagram for a typical divider. Current is driven through the divider by the voltage of interest. The voltage drop across a small portion of the divider is recorded, giving a signal which is proportional to the total voltage drop. The relative values of the R_1 and R_2 can be selected to produce a suitable signal voltage for recording. The formula for the total voltage is given below:

$$V_{Total} = V_{Scope} \frac{R_1 + R_2}{R_2} \quad (3.3.1)$$

Care must be taken when fielding resistive dividers, as inductive coupling from the load current can introduce an extra component to the signal. The high voltages involved in pulsed power mean that care must also be taken to prevent electrical breakdown along the divider.

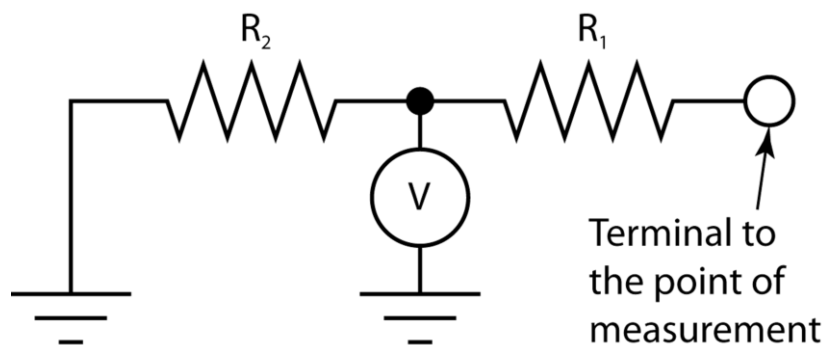


Figure 23 A schematic for a resistive Voltage divider circuit. The voltmeter measures only a small portion of the actual load voltage.

3.4) Radiation diagnostics

Wire array z-pinch experiments produce high temperature, high density plasma physics conditions. A single experiment will generate electromagnetic radiation over a wide range of energies. One of the key drives in wire array research is maximising the yield of soft x-ray radiation. A number of diagnostics are used to measure radiation pulse shape and the total yield in wire array experiments.

3.4.1) Diamond photo-conducting detectors (PCDs)

Diamond photo-conducting detectors (PCDs) are regularly used as a radiative power diagnostic. The PCDs fielded on MAGPIE originated from Sandia National Labs, Albuquerque and thier design is discussed in detail in reference [46]. Often in order to analyse the emission spectrum a pack of five PCDs with different filters are fielded. PCDs have a flat response to radiative power over a wide range of wavelengths (10eV–6keV). They also have an excellent temporal response, due to the fast electron-hole recombination time (~ 200 ps). Carriers are quickly reab-

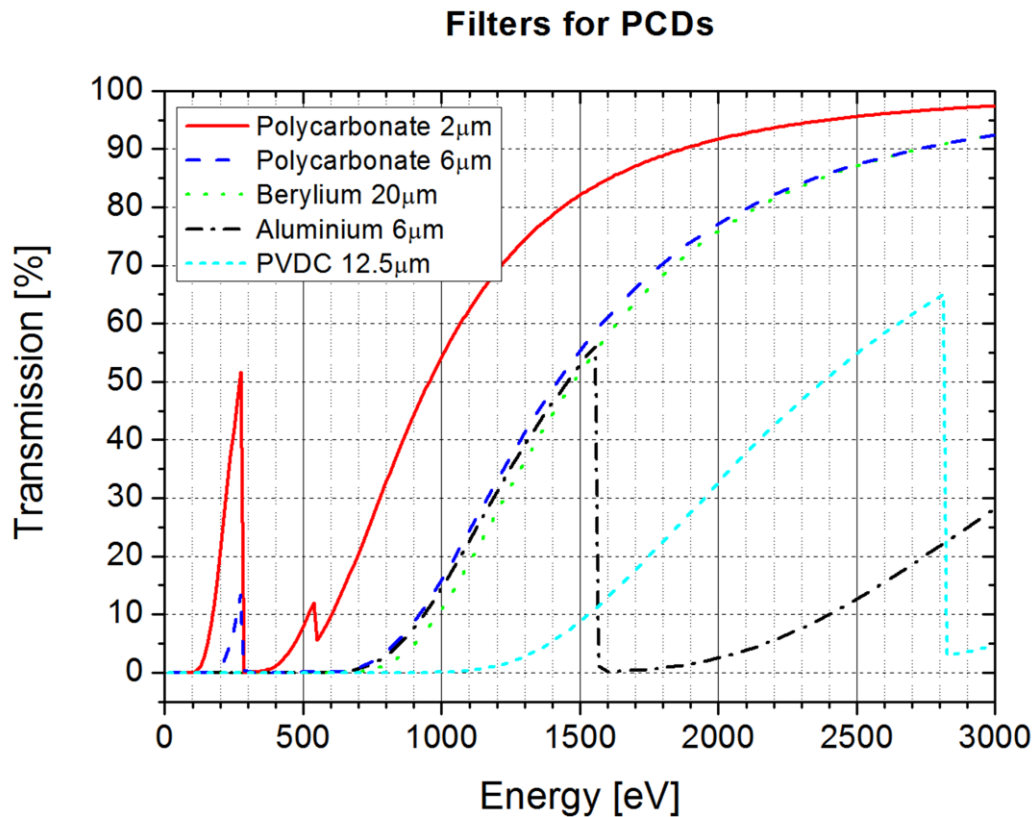


Figure 24 Transmission curves of various radiation filters as a function of photon energy.

sorbed as the incident radiative power decreases. The standard pack fielded on MAGPIE shots consists of a set of five PCDs. Figure 24 shows transmission curves for a selection of filters regularly used in wire array experiments. Filter choice is dictated by the particular experimental aims. The hard surface of diamond is naturally very resilient to debris impact, making it an ideal material for the construction of wire array diagnostics.

Figure 25 shows a cross section of a PCD and a basic circuit diagram showing how they are biased. A PCD consists of a diamond crystal sandwiched between two electrodes. The surface of the diamond facing the experiment has a cross section of $3 \times 1 \text{ mm}$ and is 0.5 mm deep. A biasing voltage of $\sim 350 \text{ V}$ is applied across it. The number of current carriers in the diamond at any moment in time is set by the balance between the photo-excitation rate and recombination-rate. This balance results in the conductivity of the diamond being approximately proportional to the radiative power falling on it. Current is driven through the diamond by the biasing voltage. The resistive voltage drop provides the signal.

PCDs are susceptible to saturation. Cable transmission times are normally longer than the signal length so that the biasing voltage across the probe can start to fall off as charge stored across the diamond is depleted. This effect is described in more detail in reference [47]. Saturation can be useful as it can increase the effective dynamic range of the PCD. Early, lower power signals may be accurately recorded in the same experiment as a later higher power peak. The corrected signal can be recovered using the following formula:

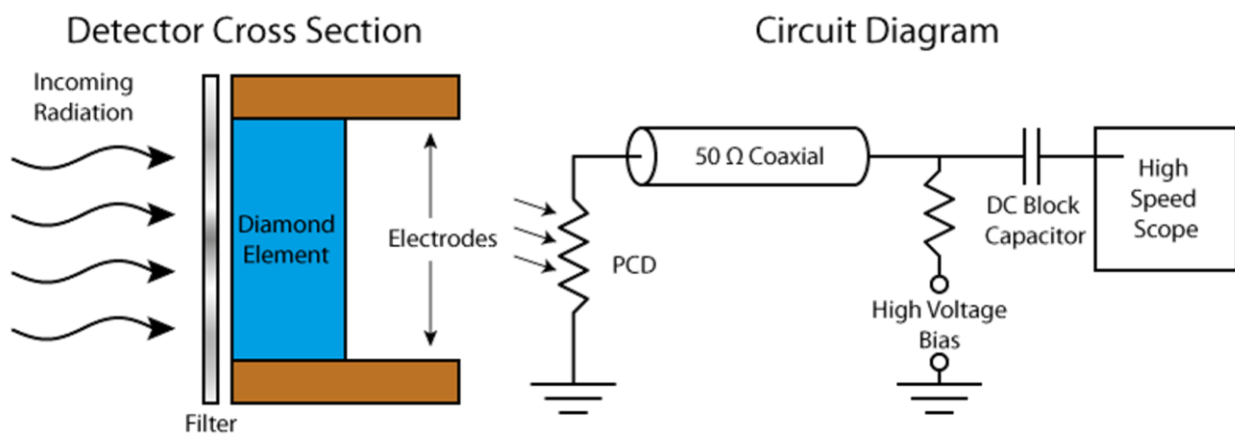


Figure 25 Cross-section of a PCD, showing the diamond, electrodes and filter, and a diagram showing the biasing and recording circuits.

$$V_c = \frac{V_m}{1 - \frac{V_m}{V_b}} \quad (3.4.1)$$

Where V_c is the corrected voltage, V_m is the measured voltage, and V_b is the biasing voltage.

3.4.2) Nickel bolometer

A bolometer is a diagnostic which measures the time resolved radiative yield of the experiment. Ideally a bolometer has a fast response (ns) and is insensitive to the spectral profile of the radiation. It is a useful diagnostic for investigating the energy balance of wire array experiments. The bolometer fielded on MAGPIE consists of a thin Nickel foil. The design is described in detail in reference [48]. The foil absorbs radiation from the experiment. This increases the foil temperature resulting in a corresponding increase in its resistance. A power supply drives a constant current through the foil. The ohmic voltage drop across the foil is recorded, and from this signal the foil resistance can be calculated. From the resistance signal the absorbed energy can be calculated and finally the radiative flux can be calculated:

$$\begin{aligned} \Delta E &= \frac{\Delta R}{(dR/d\epsilon)} = \frac{\Delta V}{I} (wl) \left(\frac{w}{l}\right) \rho_m t^2 c_p \left(\frac{d\rho}{d\epsilon}\right)^{-1} \\ F &= \frac{\Delta R}{(dR/d\epsilon)} = \frac{\Delta V}{I} \left(\frac{w}{l}\right) \rho_m t^2 \left(\frac{d\rho}{d\epsilon}\right)^{-1} \end{aligned} \quad (3.4.2)$$

Where E is the energy absorbed by the foil, R is the resistance, T is the temperature and ϵ is the internal energy of the foil. w , l and t are the foil width, length and thickness respectively, ρ_m is the density of the foil and ρ is the foil resistivity.

The foil is mounted between a pair of strong permanent magnets. These magnets act to contain the photo-excited electrons within the foil by limiting their Larmor radius.

3.5) Pinhole imaging of radiative emission

Imaging the radiation emitted by the plasma is a useful technique for investigating the dynamics of wire array implosions. Typical wavelengths of interest range from the extreme ultra-violet (XUV) to the hard X-ray. At these

wavelengths standard optical components such as lenses and mirrors are either difficult to field, prohibitively expensive or unavailable. The solution is to use a pinhole camera. Producing temporally resolved images is more difficult. The short duration of the experiment (~ 250 ns) rules out the use of physical shutters. Electro-optic micro-channel plates (MCPs) provide the solution. This section describes the principles behind both the pinhole cameras and the MCPs. It goes on to discuss the specific design of the cameras fielded on MAGPIE.

3.5.1) The pinhole camera

A pinhole camera is an extremely simple method for producing a focused image. Figure 26 shows a diagram of a basic pinhole camera. No focusing optics are required. Instead, a pinhole is used to limit the possible paths that rays can take to the imaging surface. Pinhole imaging is particularly useful for imaging radiation at wavelengths for which focusing optics are either unavailable or prohibitively expensive. The major drawback of using a pinhole camera system is that the intensity of the image is much lower than for a comparable lens based camera. This is because the optical acceptance angle of the camera is limited by the small aperture provided by the pinhole. The intensity and magnification of the image formed by a pinhole camera are set by the combination of pinhole diameter, distance from the object to the pinhole and distance from the pinhole to the detector surface:

$$I \sim \frac{\Delta^2}{q^2} \quad (3.5.1)$$

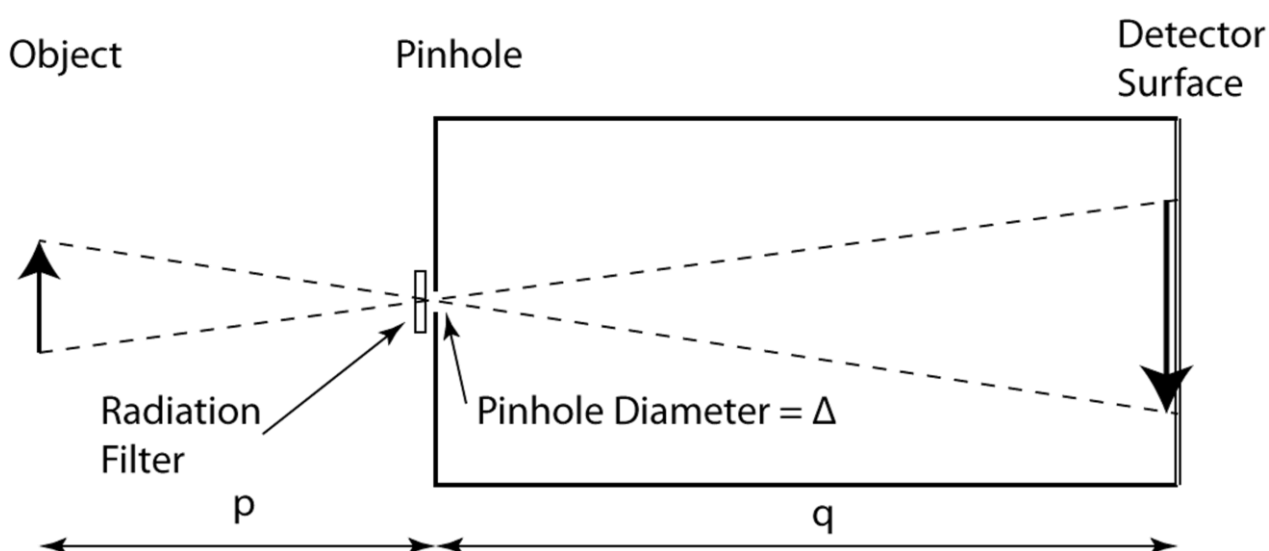


Figure 26 Diagram of a pinhole camera, showing the different design parameters.

$$M = \frac{q}{p} \quad (3.5.2)$$

The intensity of the image is dependent on the size of the pinhole and the distance from the pinhole to the detector surface. Changes in the distance from the pinhole to the object only change the magnification, not the image intensity. As with the PCD diagnostic discussed in section 3.4.1), radiation filters can be used to select specific bands of radiation to image.

The resolution of the camera is limited by two separate effects. For a pinhole diameter much larger than the radiation wavelength the spatial resolution is geometrically limited. As the pinhole diameter approaches the wavelength of the radiation the resolution becomes diffraction limited. These resolution limits can be calculated using the following equations:

$$\delta_{Geo} = \frac{\Delta(M + 1)}{M} = \Delta \frac{(p + q)}{q} \quad (3.5.3)$$

$$\delta_{Diff} = 1.22 \frac{\lambda q}{\Delta} \frac{1}{M} \quad (3.5.4)$$

For any pinhole camera design there will be a cut-off wavelength above which an image will not be formed. Instead the radiation will be smeared out over the detector surface. In cases where the geometric and diffraction limited resolutions are both small, the resolution of the recorded image can be limited by the detector resolution.

3.5.2) Time integrated imaging

The simplest application of the pinhole camera described above is time integrated imaging. In this case the detecting surface of the camera is simply a piece of film. Very hard X-ray radiation is produced for only a brief period (of order ns) during the stagnation of the pinch. This means that by filtering the radiation entering the camera it is possible to produce pseudo-time resolved image of the stagnated pinch. Films commonly used for X-ray imaging are Kodak Biomax MS and Kodak DEF.

The major drawback of this diagnostic method is that there is no way of telling when any event that appears in the image actually happened. The only way to estimate the timing of the image is to use a PCD with a matched filter to pick out the points in time when the radiation in that particular range was at its most intense.

3.5.3) Micro-channel plates

In order to produce time resolved images a fast shuttering system is required. Physical shutters are incapable of operating on the time scales of wire array experiments. The solution is an electro-optical micro-channel plate (MCP) imager. Figure 27 shows a diagram of a typical multichannel plate. Radiation impinges upon a thin film photo-cathode, producing free electrons via the photo-electric effect. The photocathode is mounted atop a densely packed array of fine silica capillaries ($\sim 12\mu\text{m}$ internal diameter). A high voltage gating pulse is used to shutter the MCP. This pulse produces an electric field along the capillaries, accelerating the free electrons from the photo-cathode towards a scintillating surface mounted on the opposite side of the plate. Amplification takes place in two stages. Firstly the electron current is amplified in the MCP. As the electrons travel through the plate, they collide with the walls of the capillaries, freeing further electrons and resulting in an avalanche amplification process. Secondly the amplified electron beams is accelerated from the back surface of the MCP to the scintillator by an acceleration potential. The kinetic energy of these accelerated electrons is converted into light in the optical spectrum. The image is captured by placing a piece of film over the scintillating surface, or by using a CCD camera. The time resolution of the MCP relies on a combination of a fast electron recombination time at the pho-

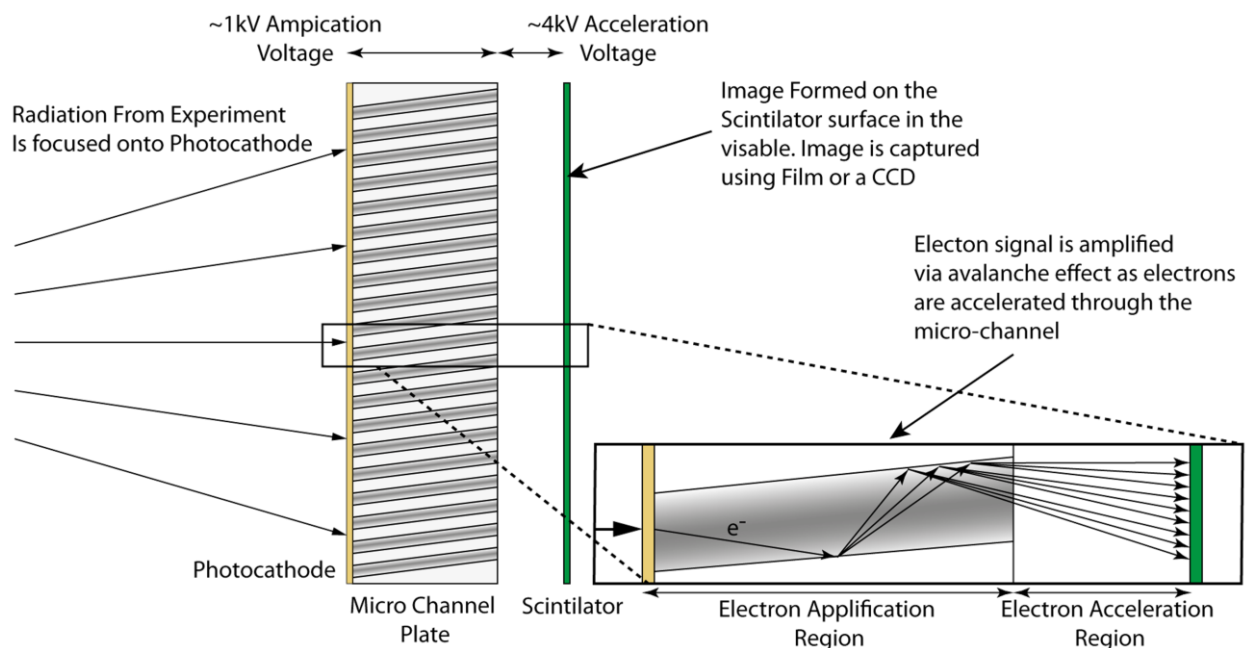


Figure 27 Diagram of a micro-channel plate (MCP) image gating system.

to-cathode and a short gating pulse.

3.5.4) 4-frame XUV MCP cameras field on MAGPIE

4-frame micro-channel plate (MCP) pinhole cameras are fielded in almost all MAGPIE experiments. Their design is discussed in detail in reference [49]. The MCPs were supplied by Schultz Scientific and have a detector surface special resolution of $\sim 70\mu\text{m}$. They are sensitive to radiation in the extreme ultraviolet (XUV) spectral band ($\sim 10\text{-}100\text{eV}$). The MCP plates are circular and divided into 4 separately gated frames.

Gating pulses are generated by a high voltage coaxial cable discharge, typically peaking at 6kV with a period of $\sim 2\text{ns}$. The four frames on each camera are triggered from the same power supply, and the gating pulses are fed to the cameras via high voltage coaxial cables. Frame timing is controlled by varying the cable lengths. As the cable length increases, the gating voltage falls off due to attenuation. This can be a problem as the MCP gain scales approximately as V^{5+} . After passing through the MCP the gating pulses are combined into a single cable which is routed to the screen room so that the frame timings can be recorded.

Figure 28 shows a schematic of the XUV 4-frame camera system. A set of four pinholes are used to form a separate image in each frame. The cameras can be fielded both radially and end-on. In most experiments $100\mu\text{m}$ pinholes are used. In situations where the image is likely to be larger than the individual frames, baffles may be in-

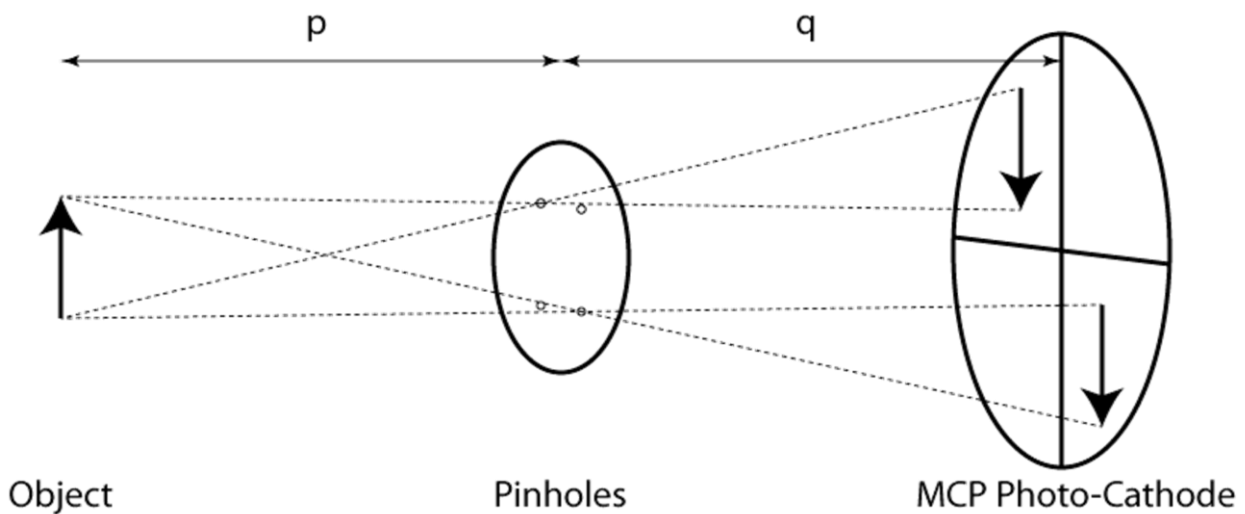


Figure 28 Schematic of the 4-Frame XUV MCP camera system fielded on MAGPIE.

stalled to prevent image overlap.

Originally the cameras were designed to be film backed. The standard film used for this was Ilford HP5. Recently the cameras have been modified so that the images can be captured on Canon SLR CCD cameras. This method is more reliable, faster, and reduces the risk of damage to data during film handling and processing.

3.6) Optical streak imaging

Optical streak cameras are used to measure the temporal dynamics of the experiment. A schematic diagram of a streak camera is shown in Figure 29. An optical imaging system projects an image of the object onto the photocathode. The photocathode is masked by a slit so that it is only exposed to a thin strip of the image radiation. Electrons are freed from the photocathode by the radiation via the photoelectric effect and accelerated by an electric field produced by a high voltage acceleration grid. Once accelerated to a known velocity, the electrons are deflected by a time dependent electric field. Electro-optics are used to form the image on the MCP. The electrons strike an MCP and undergo an avalanche amplification process before impinging onto a scintillator which converts the electron signal back to visible light. This results in the image strip being streaked in time to produce an image with one time and one spatial dimension. An example of a streak image of a wire array is shown in Figure 4. In this case the image strip is across the array diameter and the resulting image shows the implosion trajectory

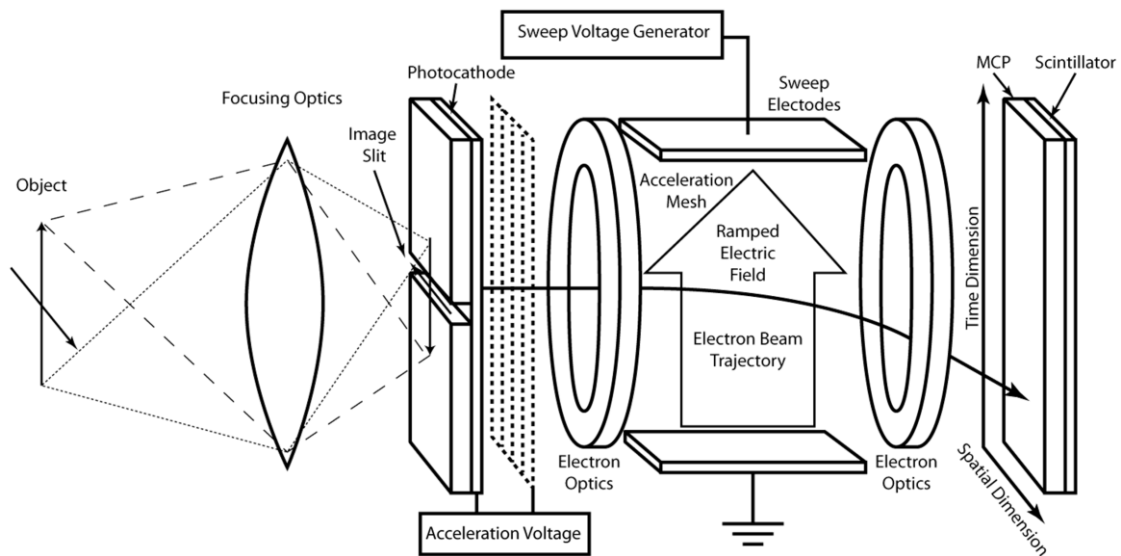


Figure 29 Diagram of an optical streak camera.

of the array.

3.7) Laser probing diagnostics

Laser probing diagnostics take advantage of the dependency of the optical properties of the plasma on its various physical parameters. In the simplest case changes in the free electron density of the plasma can be measured via their effect on the plasma refractive index. The probing beam is directed through the plasma and an optical delay proportional to the areal refractive index is imprinted on the beam phase front. A variety of different techniques can be used to analyse the distorted phase front. The main methods commonly used are Shadowgraphy, Interferometry and Schlieren.

Other optical effects can also be used to make measurements of the plasma. Faraday rotation techniques measure how the polarisation angle of a probing beam is rotated while passing through the plasma. This provides a measurement of the magnetic field strength inside the plasma. Thompson scattering techniques take advantage of the Doppler shifting of scattered probe radiation to measure the velocity distribution function of the plasma.

3.7.1) The laser imaging system

The beam used for laser imaging is provided by an EKSPLA SL312P. This is a flash-lamp pumped Nd:YAG laser. The pulse is SBS compressed, resulting in a pulse duration of $\sim 500\text{ps}$. The beam is coupled into non-linear crystals tuned to produce both the second (532nm) and third (355nm) harmonics. This laser is the driver for two side-on imaging systems, and also powers the new end-on laser probing setup discussed later in this thesis. Figure 30 shows a schematic of the optical setup used for the side on cameras. The imaging times for the two cameras are separated by 22ns. This is produced by a time-of-flight delay.

3.7.2) The refractive index of a plasma due to free electrons

Most laser probing techniques rely on the dependence of the refractive index on the plasma free electron density. The refractive index of a plasma is made up of two components, the neutral gas refractive index due to electrons in bound orbitals, which is positive, and the refractive index due to free electrons, which is negative. The

free electron refractive index tends to dominate in high Z wire array experiments due to high degrees of ionisation. In most cases the neutral gas refractive index component may be ignored. To derive the refractive index of plasma we first write the equation of motion for an electron moving in the optical field.

$$-e\vec{E} - \nu_{col}m_e\vec{V}_e = m_e \frac{d\vec{V}_e}{dt} \quad (3.7.1)$$

The optical electric field is of the following form:

$$\vec{E} = \vec{E}_0 e^{i(\omega t - kz)} \quad (3.7.2)$$

$\vec{V}_e$ is the electron velocity, and ν_{col} is the electron collision rate. The motion of the electrons will be of the same form as the driving field, with some amplitude and phase shift:

$$\vec{V}_e = \vec{V}_0 e^{i(\omega t - kz)} \quad (3.7.3)$$

Where the $\vec{V}_0$ is the complex amplitude, containing both the amplitude of the oscillation and the phase shift from the drive field. By substituting equation (3.7.3) into equation (3.7.1) can be rewritten as:

$$\vec{V}_e = \frac{ie\vec{E}}{m_e(\omega - i\nu_{col})}; \quad \vec{V}_0 = \frac{ie\vec{E}_0}{m_e(\omega - i\nu_{col})} \quad (3.7.4)$$

This is the equation of motion for a single free electron. In the case where collisions are neglected the velocity

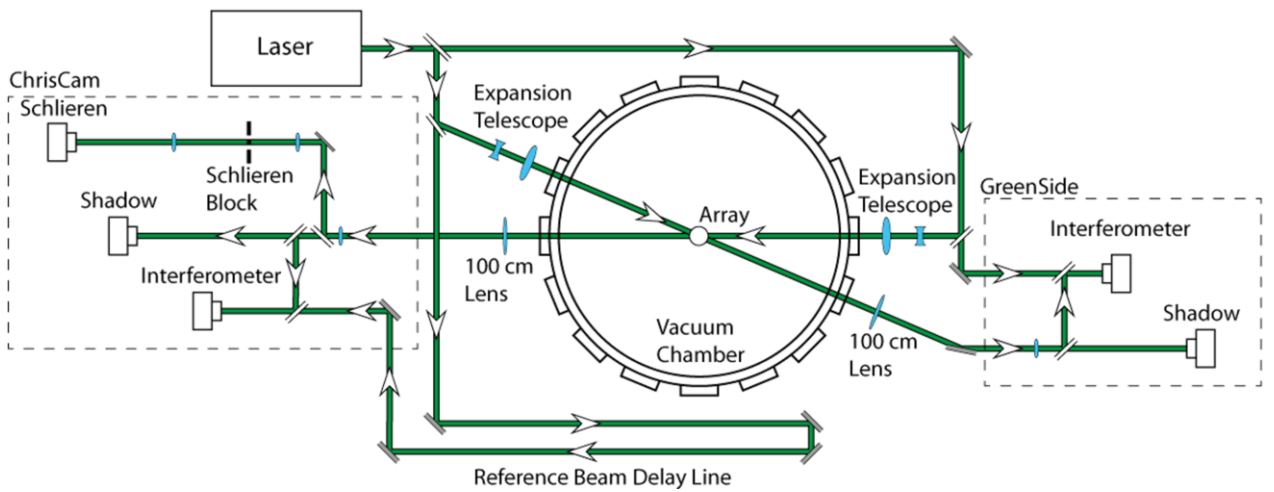


Figure 30 Schematic of the side-on laser probing system used in most magpie experiments. This diagram is not to scale. This system allows images to be captured at two separate times.

lags behind the drive by $\pi/2$. The current density driven in the plasma can be calculated from this as follows:

$$\vec{J} = \frac{-in_e e^2 \vec{E}}{m_e(\omega - i\nu_{col})} \quad (3.7.5)$$

Next this current density can be substituted into the equation for Amperes Law:

$$\begin{aligned} \nabla \times \vec{B} &= \mu_0 \left(\vec{J} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right) \\ \nabla \times \vec{B} &= \mu_0 \left(\frac{-in_e e^2 \vec{E}}{m_e(\omega - i\nu_{col})} + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \right) \end{aligned} \quad (3.7.6)$$

Now we can substitute in the expression for the electric field given in equation (3.7.2).

$$\nabla \times \vec{B} = -\epsilon_0 \mu_0 \omega \left(1 - \frac{n_e e^2}{(\omega - i\nu_{col}) \omega \epsilon_0 m_e} \right) \vec{E} \quad (3.7.7)$$

Using the identity for the plasma frequency and assuming $\omega \gg \nu_{col}$:

$$\nabla \times \vec{B} = -\epsilon_0 \mu_0 \omega \left(1 - \frac{\omega_p^2}{\omega^2} \right) \vec{E}; \quad \omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (3.7.8)$$

Differentiating this equation and substituting into the Faraday-Maxwell equation produces a wave equation:

$$\begin{aligned} \nabla^2 \vec{E} &= \epsilon_0 \mu_0 \left(1 - \frac{\omega_p^2}{\omega^2} \right) \frac{d^2 \vec{E}}{dt^2} \\ \nabla^2 \vec{E} &= \frac{1}{c^2} \left(1 - \frac{\omega_p^2}{\omega^2} \right) \frac{d^2 \vec{E}}{dt^2} \end{aligned} \quad (3.7.9)$$

From the wave equation we can extract the wave velocity, and thus the refractive index:

$$\begin{aligned} \frac{1}{v^2} &= \frac{1}{c^2} \left(1 - \frac{\omega_p^2}{\omega^2} \right) \\ v &= \frac{c}{\left(1 - \frac{\omega_p^2}{\omega^2} \right)^{\frac{1}{2}}} = \frac{c}{\eta} \end{aligned} \quad (3.7.10)$$

$$\eta = \left(1 - \frac{\omega_p^2}{\omega^2} \right)^{\frac{1}{2}} \quad (3.7.11)$$

This can be rewritten in terms of the electron density of the plasma and the critical density, n_c corresponding to the laser probing wavelength:

$$n_c = \frac{\omega^2 \epsilon_0 m_e}{e^2} \quad (3.7.12)$$

$$\eta = \left(1 - \frac{n_e}{n_c}\right)^{\frac{1}{2}} \quad (3.7.13)$$

Finally assuming that $n_c \gg n_e$ we can use the binomial expansion to approximate the refractive index linearly:

$$\eta = 1 - \frac{n_e}{2n_c} + \dots \quad (3.7.14)$$

3.7.3) Refractive index of neutral gas

In order to calculate the refractive index of a neutral gas we must model the medium as an ensemble of many atomic dipoles. Each dipole corresponds to an electron bound to the nucleus with a characteristic spring constant, k_E . The resonant frequency for each electron is given by equation (3.7.15). Since we are interested in the refractive index of gases at reasonably low pressures, the damping forces have been ignored.

$$\omega_0 = \left(\frac{k_E}{m_e}\right) \quad (3.7.15)$$

The system is driven by the electric field of the probing beam, which we will assume is again of the form given in equation (3.7.2). We can therefore write the equation of motion for each electron:

$$-e\vec{E}(t) - m_e \omega_0^2 \vec{x} = m_e \frac{d^2 \vec{x}}{dt^2} \quad (3.7.16)$$

Assuming that the solution for the electron motion is also of sinusoidal form:

$$\vec{x} = \vec{x}_0 e^{i(\omega t - kz)} \quad (3.7.17)$$

We can substitute, differentiate and rearrange to obtain the equation for the displacement of each electron:

$$\vec{x}(t) = -\frac{e}{m_e(\omega_0^2 - \omega^2)} \vec{E}(t) \quad (3.7.18)$$

Any given atom will be made up of an ensemble of electron oscillators, so to calculate the polarisation of the medium we must sum over all of the electron oscillators.

$$P = n_{atom} \sum_j^M \frac{N_j e^2 \vec{E}(x)}{m_e (\omega_{0j}^2 - \omega^2)} \quad (3.7.19)$$

The equation relating the permittivity to the polarisation of a medium is

$$(\epsilon - \epsilon_0) \vec{E} = \vec{P} \quad (3.7.20)$$

Thus:-

$$\epsilon = \epsilon_0 + \frac{\vec{P}}{\vec{E}} \quad (3.7.21)$$

$$\epsilon = \epsilon_0 + n_{atom} \sum_j^M \frac{N_j e^2 \vec{E}(x)}{m_e (\omega_{0j}^2 - \omega^2)}$$

And the refractive index is:

$$\eta = \left(1 + \frac{n_{atom} e^2}{\epsilon_0 m_e} \sum_j^M \frac{N_j}{(\omega_{0j}^2 - \omega^2)} \right)^{\frac{1}{2}} \quad (3.7.22)$$

This model is over-simplified. In reality each electron is associated with multiple possible ω_0 values, with each of these values associated to a different electronic transition. To calculate the refractive index we need to introduce the concept of the oscillator strength. This is quantum mechanical weighting for a transition from state i to state j equivalent to the number of classical electron oscillators ‘associated’ with it. In practice this number is often less than one. To get the total refractive index we must sum over all possible transitions. The formula quoted for the oscillator strength is the ideal for the hydrogenic case.

$$\eta = \left(1 + \frac{n_{atom} e^2}{\epsilon_0 m_e} \sum_{i,k} \frac{f_{i,j}}{(\omega_{0i,j}^2 - \omega^2)} \right)^{\frac{1}{2}} \quad (3.7.23)$$

$$\omega_{0i,j} = \frac{E_{i,j}}{\hbar} \quad (3.7.24)$$

Atom	$2\pi\alpha$
He	$1.3 \times 10^{-24} \text{cm}^3$
H ₂	$5 \times 10^{-24} \text{cm}^3$
Air	$1.1 \times 10^{-23} \text{cm}^3$
Ar	$1.1 \times 10^{-23} \text{cm}^3$
Al	$4.4 \times 10^{-23} \text{cm}^3$

Table 3 Table of polarisabilities for some common neutral atoms [6]

$$f_{i,j} = \frac{32}{3\pi\sqrt{3}} \frac{1}{i^5} \frac{1}{j^3} \frac{1}{\left(\frac{1}{i^2} - \frac{1}{j^2}\right)^3} \quad (3.7.25)$$

Assuming that the refractive index is close to unity, and the correction due to our gas atoms is small, the binomial expansion can be used to approximate the refractive index.

$$\eta = 1 + \frac{n_{atom}e^2}{2\epsilon_0 m_e} \sum_{i,k} \frac{f_{i,j}}{(\omega_{0i,j}^2 - \omega^2)} + \dots$$

$$\alpha = \frac{e^2}{4\pi\epsilon_0 m_e} \sum_{i,k} \frac{f_{i,j}}{(\omega_{0i,j}^2 - \omega^2)} \quad (3.7.26)$$

$$\eta \approx 1 + 2\pi\alpha n_{atom}$$

α is defined as the polarisability of a specific atom. Assuming that our probing beam frequency is well away from any resonances, we can use the values given in Table 3. For high Z ions, calculation of the neutral component of the refractive index can become computationally intense, so that only experimentally determined values for the polarisability are available.

3.7.4) Shadowgraphy

Shadowgraphy is a simple technique for analysing a laser probing beam. It is easy to set up and the images are simple to interpret. This makes it a very popular technique. The probing beam is passed through the plasma and onto a detecting surface. This produces a 'shadow' due to the deflection of the beam by density gradients in the

areal plasma density profile. While it is difficult to retrieve accurate quantitative density data from shadowgrams, they are useful for qualitative analysis of experimental dynamics.

Figure 31 shows the effect of a variety of different phase objects on a collimated probing beam. Each object has a different characteristic spatial variance of its optical path length. (a) is an object of constant path length. The rays of light are not deflected by this object, only retarded. The image on the screen is unchanged. It remains in the same position, and of same intensity. (b) has a constant gradient of path length. The probing beam is deflected and the image on the screen is shifted down a small amount. The overall intensity of the image remains the same. (c) shows the effect of an object with a constantly varying path length gradient. The angular deflection of the rays varies continuously across the object. At the screen this is observed as a redistribution of the probing beam intensity. Positive curvature of the path length causes divergence of the probing beam, resulting in lower intensity at the screen. Negative curvature results in focusing of the probing beam and therefore higher image intensity. The equation for the angular deviation of a ray is[50]:

$$\theta_{dev} = \frac{d}{dy} \int \eta dl \quad (3.7.27)$$

The equation for the contrast ratio of the shadow cast on a screen a distance g from the object is:

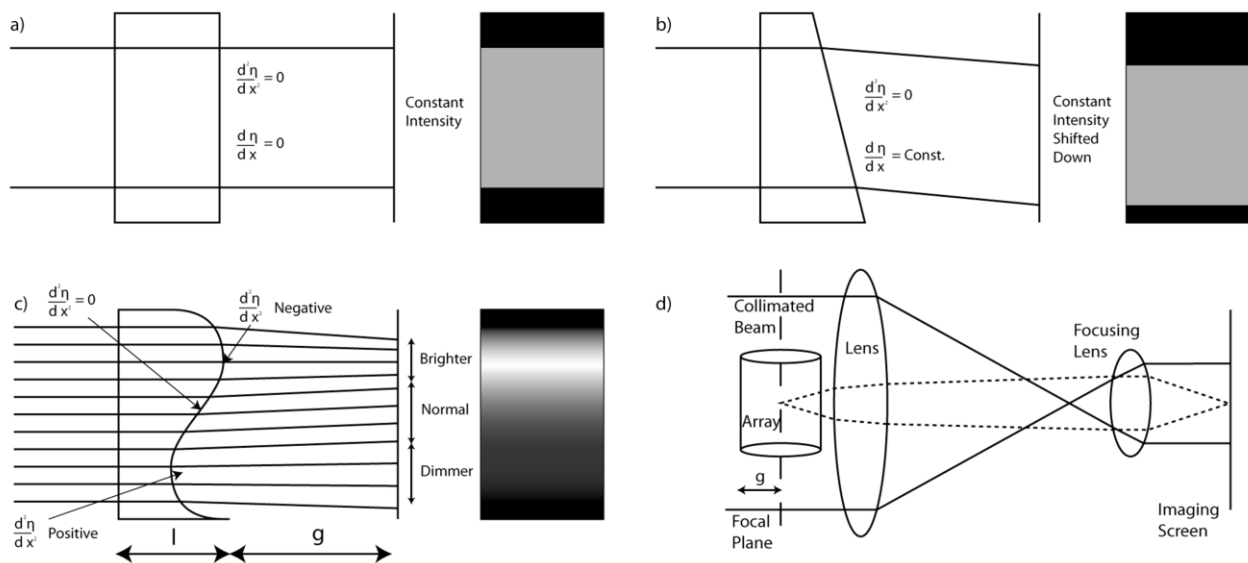


Figure 31 Shadowgraphy effects: The effects of different phase objects on the intensity distribution of the probing beam at a screen.

$$\frac{\Delta I}{I} = g \left[\frac{d^2}{dx^2} + \frac{d^2}{dy^2} \right] \int \eta \, dl \quad (3.7.28)$$

The above equation represents a simplification. It assumes that the length of the plasma is much smaller than the distance to the screen.

Figure 31 (d) shows the setup used for shadowgraphy in MAGPIE experiments. This is an example of a focused shadowgraphy system. The image captured by the camera is the shadow effect at the focal plane of the optical system. This plane is usually placed as close to the array axis as possible. The plasma on either side of the focal plane contributes to the shadowgraphy effect, and the strength of that contribution is dependent on its displacement from the focal plane. The expected intensity of the image is described by the following equation:

$$\frac{\Delta I}{I} = \int g(l) \left[\frac{d^2}{dx^2} + \frac{d^2}{dy^2} \right] \eta \, dl \quad (3.7.29)$$

Where l is the length of the object and $g(l)$ is the displacement of a specific point from the focal plane. Unwanted shadowgraphy effects can cause problems when analysing interferograms. Regions corresponding to strong gradients in the refractive index may be brightened or darkened, leading to confusion of the fringe positions. The effect is accentuated if the image is poorly focused. To minimise this effect, these diagnostics should be focused as sharply as possible.

3.7.5) Schlieren imaging

The Schlieren technique is used to image gradients of the path length of the plasma. As explained in the previous section, gradients in the plasma path length result in the angular deflection of the probing beam. Selecting coordinates such that the z -axis is aligned along the direction of probing beam propagation, the following equations describe the angular deflection in the x and y planes respectively[50]:

$$\theta_x = \frac{1}{\eta} \int \frac{\partial \eta}{\partial x} dz \quad \theta_y = \frac{1}{\eta} \int \frac{\partial \eta}{\partial y} dz \quad (3.7.30)$$

In the limit $n_c \gg n_e$, we can use equation (3.7.14) for the plasma refractive index. This equation can be differentiated in both x and y directions, leading to the following expressions for the refractive index gradients:

$$\frac{\partial \eta}{\partial x} = \frac{1}{2n_c} \frac{\partial n_e}{\partial x} \quad \frac{\partial \eta}{\partial y} = \frac{1}{2n_c} \frac{\partial n_e}{\partial y} \quad (3.7.31)$$

Substituting of these expressions into equation (3.7.30) leads to the equation for the angular deflection in terms of the areal electron density:

$$\theta_x = \frac{1}{(2n_c - n_e)} \int \frac{\partial n_e}{\partial x} dz$$

$$\theta_y = \frac{1}{(2n_c - n_e)} \int \frac{\partial n_e}{\partial y} dz \quad (3.7.32)$$

Figure 32 shows a series of ray diagrams for a Schlieren system. (a) shows the path of an unperturbed collimated probing beam. A lens is used to image the array. Since the probing beam is collimated, it is brought to a focus at a distance equal to the focal length of the lens. Any angular disturbances in the probing beam produced by the plasma are transformed into displacements from this central focal spot. This effect is illustrated in Figure 32 (b).

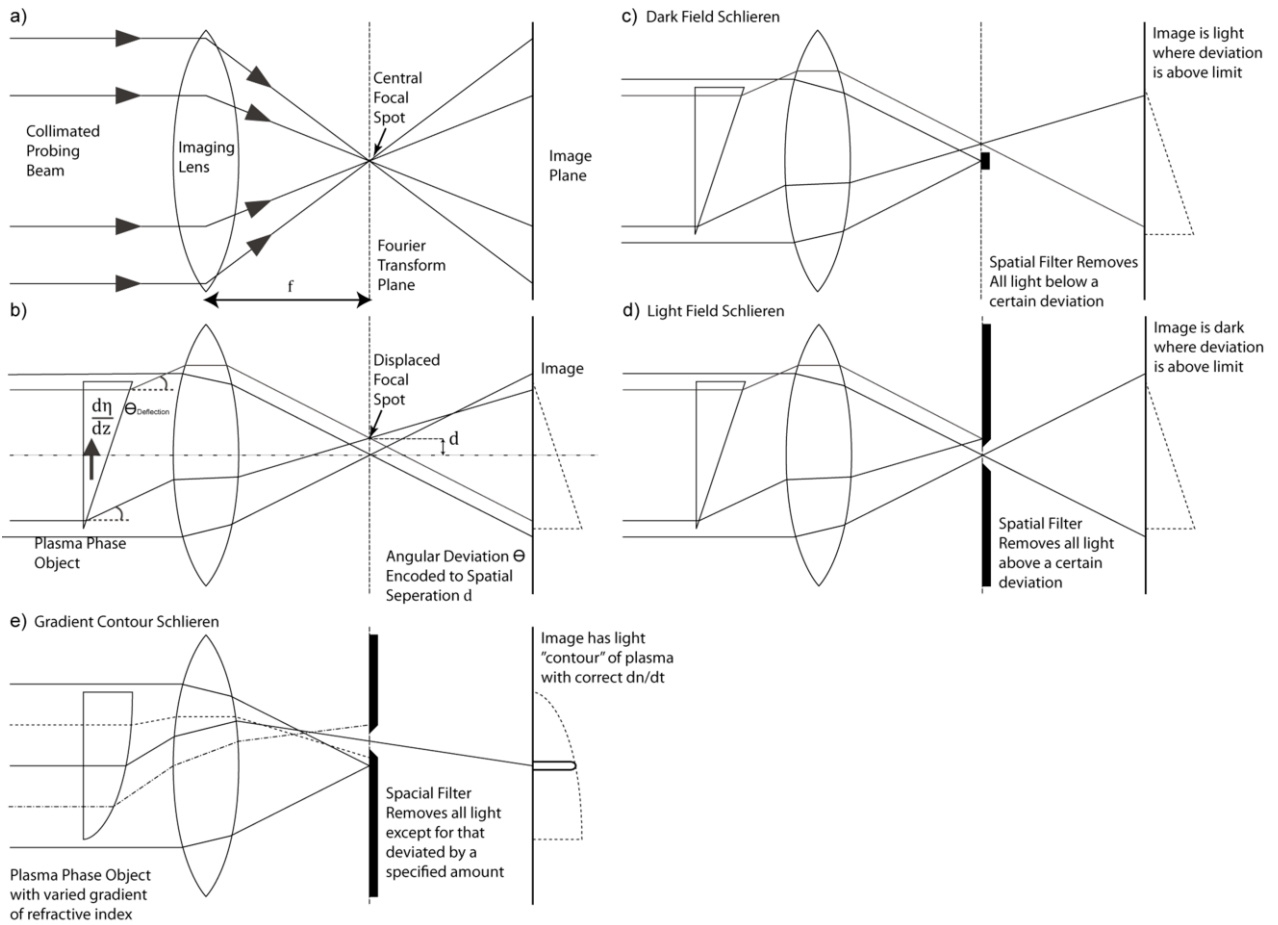


Figure 32 Diagram explaining various Schlieren imaging techniques.

Rays passing through the object are deflected, while rays passing either side of the object are not. The displacement of the ray from central spot is governed by the following equations:

$$d_x = f \tan(\theta_x) \quad d_y = f \tan(\theta_y) \quad (3.7.33)$$

A variety of different Schlieren imaging techniques can be used. Diagram Figure 32 (c) shows the setup for dark-field Schlieren. A small beam block is placed at the lens focal point. This blocks all of the un-deflected rays. Only rays deflected by the object reach the detecting screen. The opposite arrangement is light field Schlieren, as shown in Figure 32 (d). An aperture prevents any light deflected by more than a predetermined cut-off angle from reaching the detector, forming what appears to be a shadow of the object. The Gradient contour Schlieren scheme is shown in Figure 32 (e). In this case the object has a continually varying path length gradient. A slit is placed at the lens focal plane. It allows through only rays whose deflection falls within a small range of angles. This range translates to a corresponding range of areal electron density gradients. The direction of the gradient measurement is the direction in which the slit is displaced from the focal point. A ring shaped slit can be used to look for gradients of a specific magnitude in any direction. This technique can produce quantitative measurements of the density gradients in the plasma.

Unwanted Schlieren effects are often observed in images produced using other laser probing techniques. This is caused by the limited acceptance angle of the optical imaging system. The acceptance angle corresponds to the maximum angle a ray can be deflected and still reach the detecting surface. The acceptance angle therefore imposes a limit on the maximum gradient that can be viewed.

3.7.6) Imaging interferometry

Imaging interferometry is a powerful technique for directly measuring the areal electron density distribution of the plasma. The phase front of the probing beam is distorted by the areal refractive index of plasma. This beam is superimposed with a reference beam and produces a fringe pattern via interference of the optical waves. Each of the resulting fringes follows a line of constant phase difference between the probe and reference beams. An example of a side on interferogram is shown in Figure 34.

There are two interferometer layouts which are commonly used, the Michelson-Morley and Mach-Zender interferometers. Diagrams of these layouts are shown in Figure 33. The main difference between the two is that the Michelson-Morley layout requires two passes of the plasma, while the Mach-Zender only requires one. A single pass is preferable in many plasma physics applications. It allows for more accurate focusing of the interferogram and helps to simplify alignment. The main benefits of the Michelson-Morley layout are that it requires optical access from only one side of the experiment and the sensitivity of the interferometer is increased due to the double pass of the plasma.

The following section describes the mathematics of interferometry. The derivation given below is written in terms of the electric field component of the optical field. The general equation for the probing beam electric field at the detector surface is:

$$E = E_0(x, y)e^{i(\omega t)}e^{i(\phi(x, y))} \quad (3.7.34)$$

$E_0(x, y)$ is a function which describes the cross-sectional intensity profile of the beam. We shall assume for simplicity that the probing beam is wide and of constant intensity over the area of interest, so that we can write $E_0(x, y) = E_0$. The function $\phi(x, y)$ describes the spatial variance of phase shift across the beam. For the probing beam, $\phi(x, y)$ is set by the phase delay due to the free electron density of the plasma. For the reference beam it is set by the shearing angle, θ_s . This is the angle by which the reference and probing beam are misaligned. The co-

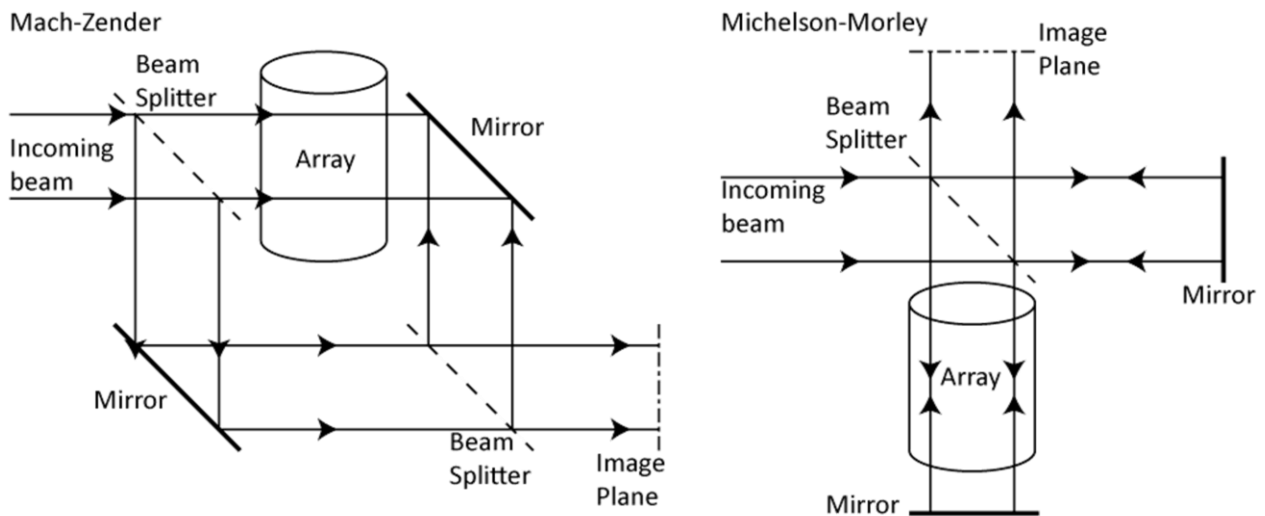


Figure 33 Two commonly used Interferometer layouts, the Mach-Zender and Michelson-Morley layouts.

ordinate system is selected such that both beams lie in the x-z plane. It is assumed that the shear angle is small so that the reference phase can be written:

$$\phi_{ref}(y) \cong ky\theta_s \quad (3.7.35)$$

The intensity recorded by the detector is set by the superposition of the electric fields due to the probing and reference beams:

$$\begin{aligned} E_{Total} &= E_{Probe} + E_{Ref} \\ E_{Total} &= E_0 e^{i(\omega t)} e^{i\phi_{plas}(x,y)} + E_0 e^{i(\omega t)} e^{iky\theta_s} \\ E_{Total} &= E_0 e^{i(\omega t)} (e^{i\phi_{plas}(x,y)} + e^{iky\theta_s}) \end{aligned} \quad (3.7.36)$$

The detector is sensitive only to the light intensity. The equation for the intensity on the detector is derived as follows:

$$\begin{aligned} I &= \langle E^2 \rangle = EE^* = E_0^2 (e^{i\phi_{plas}} + e^{iky\theta_s})(e^{-i\phi_{plas}} + e^{-iky\theta_s}) \\ I &= E_0^2 (2 + e^{i(ky\theta_s - \phi_{plas})} + e^{-i(ky\theta_s - \phi_{plas})}) \\ I &= 2E_0^2 \left(1 + \cos(ky\theta_s - \phi_{plas}) \right) = 4E_0^2 \cos^2 \left(\frac{ky\theta_s - \phi_{plas}}{2} \right) \end{aligned} \quad (3.7.37)$$

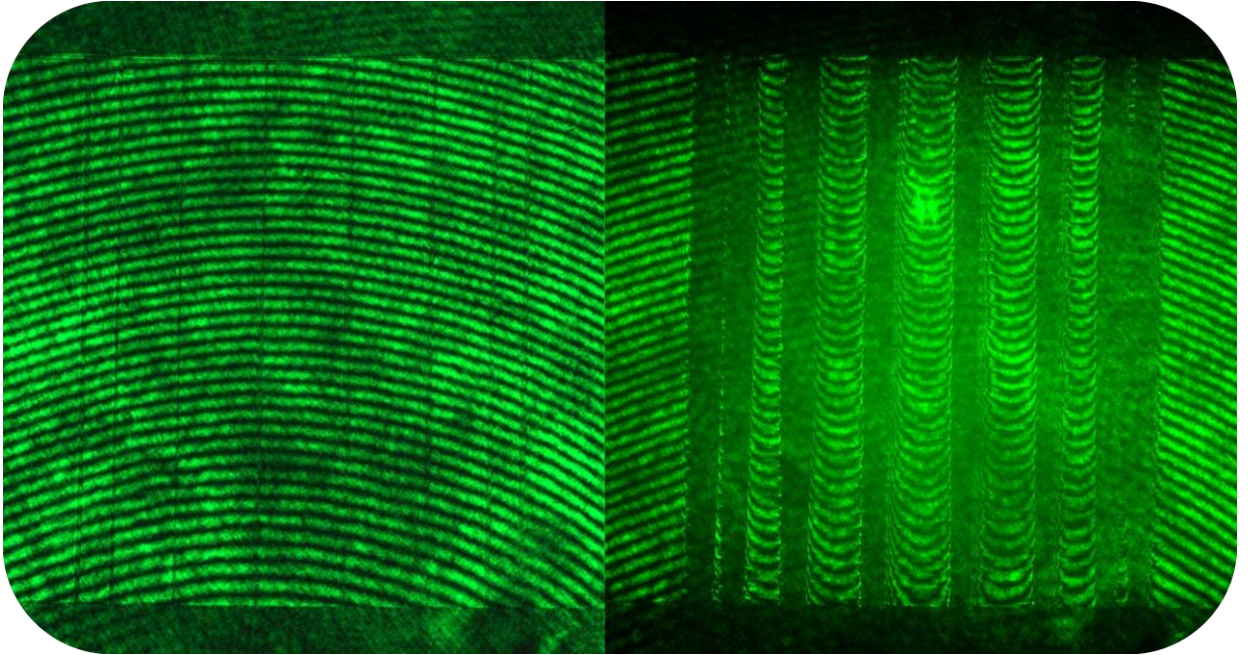


Figure 34 Example of a side-on interferogram, captured during shot s0517_11. This was 16 wire aluminium array. On the left is the pre-shot background image, and on the right the experimental image. The fringes have been distorted and portions of the image have been occluded due to the strong density gradients.

Dark fringes are observed when the intensity is zero, so the position of each fringe can be calculated as follows:

$$\begin{aligned} \frac{ky\theta_s - \phi_{plas}}{2} &= \left(n + \frac{1}{2}\right)\pi \\ y &= \left(\frac{\pi(2n + 1)}{k\theta_s} + \frac{\phi_{plas}(x, y)}{k\theta_s}\right) \end{aligned} \tag{3.7.38}$$

Where n is the fringe number. For a background image where no plasma is present, $\phi_{plas}=0$ and this results in straight fringes separated by $\frac{2\pi}{k\theta_s} = \frac{\lambda}{\theta_s}$. Fringe density increases with the shear angle. In the experimental image these fringes will be distorted by ϕ_{plas} . The distance that the fringe appears to be displaced scales with the fringe separation.

The analysis of interferograms is discussed in detail in Chapter 5. This chapter is mostly focused on the analysis of a large number of end-on interferograms.

3.7.7) Faraday rotation

Faraday rotation techniques are different from the techniques discussed above. Instead of imaging the effects of the plasma refractive index, Faraday rotation measures the circular birefringence induced in magnetised plasma. A material which exhibits circular birefringence will cause a relative phase delay between the two counter-rotating circular polarisations of light. The effect of this relative delay on a plane polarised ray of light is that the plane of polarisation will rotate about the ray axis by an angle proportional to the field strength and electron density of the plasma. The electron density can be measured using the interferometry technique discussed above. If this is combined with a Faraday rotation system, it is possible to measure the areal magnetic field strength. From this the radial magnetic field distribution can be calculated, and from that the current distribution on the array.

CW Faraday rotation has also been used to measure the output current of the generator. This is discussed in more detail in section 4.2).

Chapter 4

The development of CW laser diagnostics

The laser based diagnostics discussed in Chapter 3 used short pulse lasers to capture data from single moments in time during the experiment. Lasers can also be used to make time resolved measurements of plasma parameters throughout the experiment. These diagnostics require a continuous wave (CW) laser. The CW laser beam is directed through the experiment and remains on for the duration of the experiment. Information is encoded into the beam by the optical properties of the media it passes through. This information can then be extracted via optical analysis.

Two diagnostic systems have been developed in the course of this PhD. A quadrature interferometer was developed to measure changes in the electron density along a line through the experiment. This diagnostic takes advantage of the dependence of the plasma refractive index on the free electron density. A Faraday rotation diagnostic was developed to measure the current delivered to the load. This diagnostic takes advantage of magnetically induced circular birefringence in a piece of glass in order to measure the magnetic field induced by the current.

4.1) CW quadrature interferometer

A CW interferometer was constructed in order to make time resolved measurements of the plasma electron density. MAGPIE already fields a number of imaging interferometers, however these can capture data at only a single point in time during the experiment. A CW interferometer can measure the electron density integrated along a single line through the experiment for the entire duration, and provide new insights into the experimental dynamics.

4.1.1) Quadrature analysis

Quadrature analysis is a method of measuring changes in the phase delay of a probing beam. This technique provides a number of benefits compared with the analysis of a single phase interference signal. It introduces directional sensitivity, improves the differential sensitivity over the full interference cycle, and introduces the ability to take account of changes in the fringe contrast ratio. In order to perform quadrature analysis two interference signals must be recorded. These signals should be in quadrature phase with one another, meaning that the relative phase of the interference states is separated by $\pi/2$. These two phases are produced by manipulating the

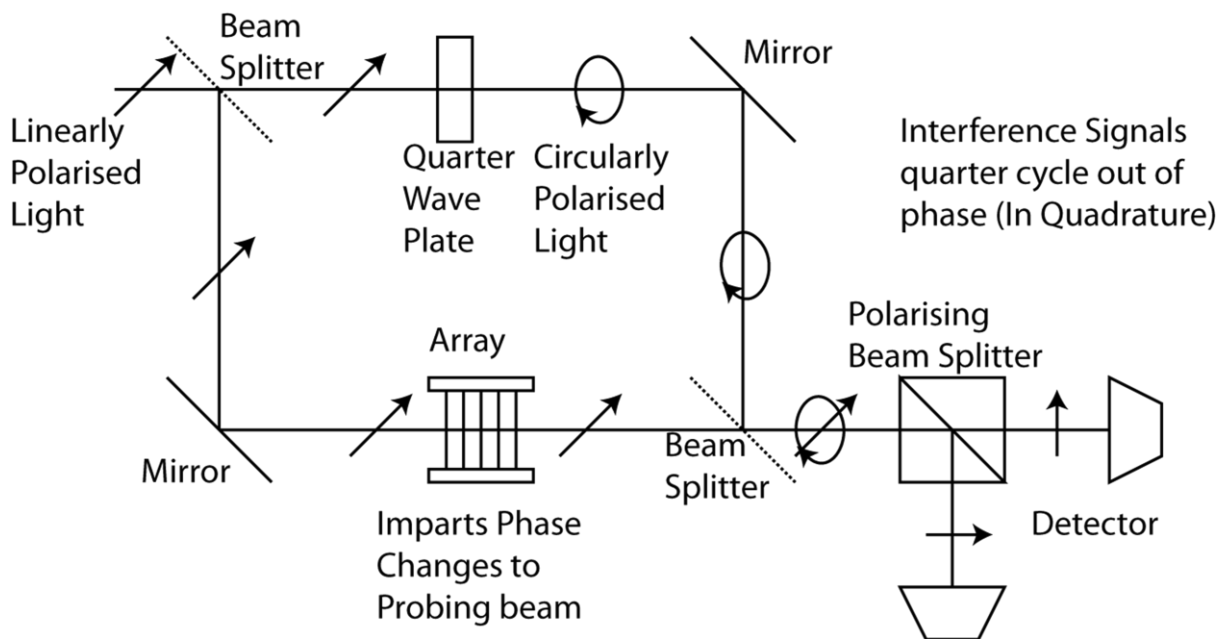


Figure 35 A schematic of the quadrature interferometer. The focusing optics have been omitted in order to simplify the diagram.

polarisation of the probing and reference beams using wave-plates.

4.1.2) Optical layout

The quadrature interferometer was built along the lines of the design described in reference [51]. This is a Mach-Zender style interferometer. Figure 35 shows a schematic of the optical design. Initially the beam is linearly polarised, with the polarisation angle inclined at 45°. This beam is split into probing and reference beams by a non-polarising beamsplitter. The probing beam is directed through the plasma, while the reference beam is directed around the experiment. The reference beam is passed through a quarter wave plate, the fast axis of which is aligned vertically, resulting in a circular polarisation. The two beams are then recombined, taking care to match the path lengths as closely as possible. The combined beam is analysed by a polarising beam splitter, again aligned vertically. The vertical and horizontal polarisation components of the combined beams are separated, and their respective intensities are recorded by fast photodiodes. This arrangement ensures that the two signals remain in quadrature.

4.1.3) Intensity function of the quadrature signals

In order to interpret the signals recorded by the two diodes, we must analyse the effects of the optical processing described above. Initially the probing and reference beams have the same polarisation, inclined at 45° with respect to the vertical. This polarisation state can be written as a superposition of vertical and horizontal polarisation components, with the two components in phase. The Jones vector the initial polarisation state is given by the following expression:

$$E_{\rightarrow}(z, t) = E \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad (4.1.1)$$
$$E = E_0 e^{i(\omega t - kz)}$$

The reference beam is then passed through a quarter wave plate. The horizontal component of the polarisation is delayed in phase by a quarter-cycle with respect to the vertical polarisation component, resulting in a circular polarisation state. The reference field may be calculated by multiplying by the Jones matrix for the quarter wave plate:

$$E_{Ref}(z, t) = \begin{pmatrix} 1 & 0 \\ 0 & -i \end{pmatrix} E \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$E_{Ref}(z, t) = E \begin{pmatrix} 1 \\ -i \end{pmatrix} \quad (4.1.2)$$

The probing beam is passed through the plasma which introduces a time varying phase delay, $\phi(t)$, to both the vertical and horizontal components. Again this field is calculated by multiplying by the Jones matrix for an arbitrary phase shift:

$$E_{Probe}(z, t) = \begin{pmatrix} e^{i\phi(t)} & 0 \\ 0 & e^{i\phi(t)} \end{pmatrix} E \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

$$E_{Probe}(z, t) = E \begin{pmatrix} e^{i\phi(t)} \\ e^{i\phi(t)} \end{pmatrix} \quad (4.1.3)$$

The beams are then recombined, and the fields from the two beams are superimposed. For simplicity the relative phase between the beams due to any difference in path length has been neglected, as it only introduces a static phase term:

$$E(z, t) = E_{Probe}(z, t) + E_{Ref}(z, t) = E \begin{pmatrix} e^{i\phi(t)} \\ e^{i\phi(t)} \end{pmatrix} + E \begin{pmatrix} 1 \\ -i \end{pmatrix}$$

$$E(z, t) = E \begin{pmatrix} e^{i\phi(t)} + 1 \\ e^{i\phi(t)} - i \end{pmatrix} \quad (4.1.4)$$

The polarising beam splitter divides the beam into the vertical and horizontal polarisations and photodiodes record the intensities of the two beams. These are calculated by multiplying by the Jones Matrices for the polariser channels and taking the squared magnitude of the resulting vector:

$$E_{\uparrow} = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} E \begin{pmatrix} e^{i\phi(t)} + 1 \\ e^{i\phi(t)} - i \end{pmatrix} = E \begin{pmatrix} 0 \\ e^{i\phi(t)} - i \end{pmatrix}$$

$$I_{\uparrow}(t) = E_{\uparrow} E_{\uparrow}^* = \left\| E^2 \begin{pmatrix} 0 \\ e^{i\phi(t)} - i \end{pmatrix} \begin{pmatrix} 0 \\ e^{-i\phi(t)} + i \end{pmatrix} \right\|$$

$$I_{\uparrow}(t) = \frac{E_0^2}{2} (2 + ie^{i\phi(t)} - ie^{-i\phi(t)})$$

$$I_{\uparrow}(t) = E_0^2 (1 - \sin \phi(t)) \quad (4.1.5)$$

$$\begin{aligned}
 E_{\rightarrow} &= \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} E \begin{pmatrix} e^{i\phi(t)} + 1 \\ e^{i\phi(t)} - i \end{pmatrix} = E \begin{pmatrix} e^{i\phi(t)} + 1 \\ 0 \end{pmatrix} \\
 I_{\rightarrow}(t) &= E_{\rightarrow} E_{\rightarrow}^* = \left\| E^2 \begin{pmatrix} 0 \\ e^{i\phi(t)} - i \end{pmatrix} \begin{pmatrix} 0 \\ e^{-i\phi(t)} + i \end{pmatrix} \right\| \\
 I_{\rightarrow}(t) &= \frac{E_0^2}{2} (2 + e^{i\phi(t)} + e^{-i\phi(t)}) \\
 I_{\rightarrow}(t) &= E_0^2 (1 + \cos \phi(t))
 \end{aligned} \tag{4.1.6}$$

The signals take the form of the sine and cosine of the plasma phase delay. The degree of interference between the two beams, referred to as the fringe contrast ratio, is usually less than the ideal represented by these equations. This is the result of the imperfect superposition of the two beams, combined with any mismatch in the path lengths of the probing and reference beams. A factor $k(t)$ is introduced to quantify this contrast ratio; this factor should be the same across the two channels. Errors in the initial polarisation can result in slightly different mean intensities for the two channels. These must be taken account of in the analysis. A static phase term is also introduced to take into account the initial phase of the signal at $t=0$.

$$\begin{aligned}
 0 &< k(t) < 1 \\
 I_{\uparrow}(t) &= I_{0\uparrow} (1 - k(t) \sin(\phi(t) + \phi_0)) \\
 I_{\rightarrow}(t) &= I_{0\rightarrow} (1 + k(t) \cos(\phi(t) + \phi_0))
 \end{aligned} \tag{4.1.7}$$

The phase delay can be extracted from these signals using the following equations.

$$\begin{aligned}
 \frac{I_{\uparrow}(t) - I_{0\uparrow}}{I_{\rightarrow}(t) - I_{0\rightarrow}} \left(\frac{I_{0\rightarrow}}{I_{0\uparrow}} \right) &= \frac{(\sin(\phi(t) + \phi_0))}{(\cos(\phi(t) + \phi_0))} = \tan(\phi(t) + \phi_0) \\
 \phi(t) &= \text{atan} \left(\frac{I_{\uparrow}(t) - I_{0\uparrow}}{I_{\rightarrow}(t) - I_{0\rightarrow}} \left(\frac{I_{0\rightarrow}}{I_{0\uparrow}} \right) \right) + n2\pi - \phi_0
 \end{aligned} \tag{4.1.8}$$

This analysis is independent of $k(t)$. It does however require values for the mean intensity at each channel. Vibrations of the optical table introduce a second time varying phase difference term. The timescale (500ns) of the experiments is short enough that this time varying phase is approximately static for the duration, and so this term can easily be subtracted out. A long time-base recording can measure the fringe contrast envelope from this vibration signal, which can be used to calculate values for the I_0 of each channel.

4.1.4) The benefits of quadrature analysis

As explained in the previous sections, quadrature analysis uses two signals to calculate the phase. These two signals are a quarter cycle out of phase. It is possible to analyse the phase using only one signal. The following equations describe how the phase can be calculated from the intensity signal measured at the photodiode:

$$I(t) = I_0(1 + k(t) \cos(\phi(t) + \phi_0))$$

$$\phi(t) = \arccos\left(\frac{1}{k(t)}\left(\frac{I(t)}{I_0} - 1\right)\right) + 2\pi n - \phi_0 \quad (4.1.9)$$

Quadrature analysis provides a number of advantages over the analysis of a single phase component. Firstly, quadrature analysis introduces directional sensitivity to the phase measurement. Figure 36 shows a synthetic phase signal and the sin and cosine phases of the interference signals that it corresponds to. With only one of the interference signals it is impossible to tell whether the phase delay is increasing or decreasing. With two signals the direction of the phase shift is unambiguous. In the example shown in Figure 36, as the phase shift (black) increases the red interference signal leads the blue one. As the direction of the phase shift changes, the blue interference signal overtakes the red one, and begins to lead as the phase difference decreases. The lead is reversed again as the phase difference begins to increase again.

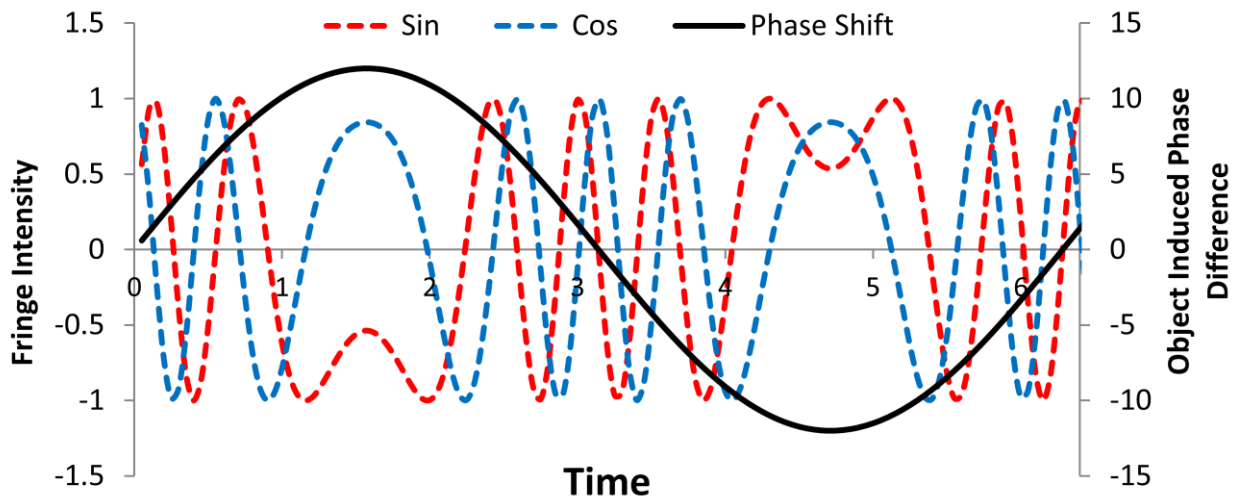


Figure 36 Plot demonstrating how the direction of the phase shift can be interpreted from the quadrature signals.

The second advantage of quadrature analysis is that it improves the overall differential sensitivity of the diagnostic. The differential sensitivity describes how sensitive the signal is to changes in phase. When analysing only a single phase, the intensity varies as a sinusoid:

$$I \propto \sin(\phi) \quad \frac{dI}{d\phi} \propto \cos(\phi) \quad (4.1.10)$$

This signal has sensitivity nulls where $dI/d\phi=0$. This is illustrated by the plot shown in Figure 37. In the quadrature scheme the overall signal is found by dividing the two quadrature signals. Thus the overall signal is proportional to the tan of the phase:

$$I \propto \tan(\phi) \quad \frac{dI}{d\phi} \propto \sec^2 \phi \quad (4.1.11)$$

As Figure 37 shows, while the sensitivity of this signal varies significantly, it never falls to zero.

The final advantage of quadrature analysis is that the signal is insensitive to the changes in the fringe contrast ratio, $k(t)$ as this factor is divided out during the analysis. This is extremely useful in plasma physics experiments. The contrast ratio can vary significantly during the experiment due to the deflection of the probing beam by re-

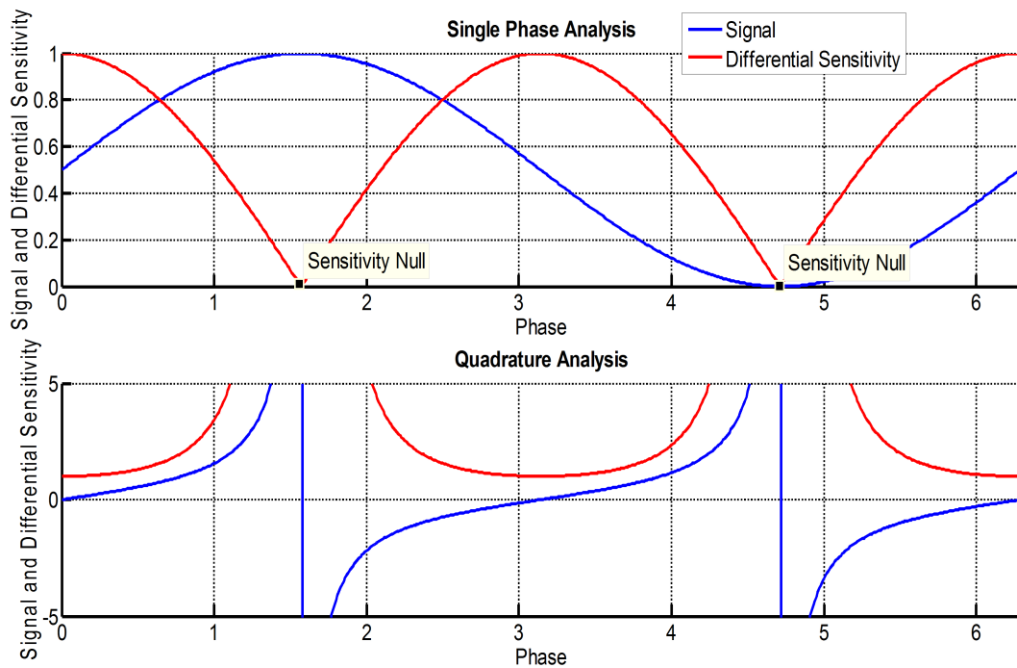


Figure 37 Signal and differential sensitivity of the single phase and quadrature analysis schemes. Sensitivity nulls are only present in the single phase analysis.

fractive index gradients in the plasma. With a single phase analysis, changes in the contrast ratio would appear no different than changes in the phase difference, confusing the analysis.

4.1.5) Apparatus and experimental setup

A photograph of the quadrature apparatus is shown in Figure 38. The probing beam is provided by a 70mW diode pumped Nd:YAG laser. The beam is frequency doubled, resulting in a wavelength of 532nm. The intensity signals are recorded by fast (ns) photodiodes. In order to minimise electrical noise pick-up the photodiodes are mounted in a screened box and the diode outputs are amplified so as to drive larger currents into the 50 Ω transmission lines.

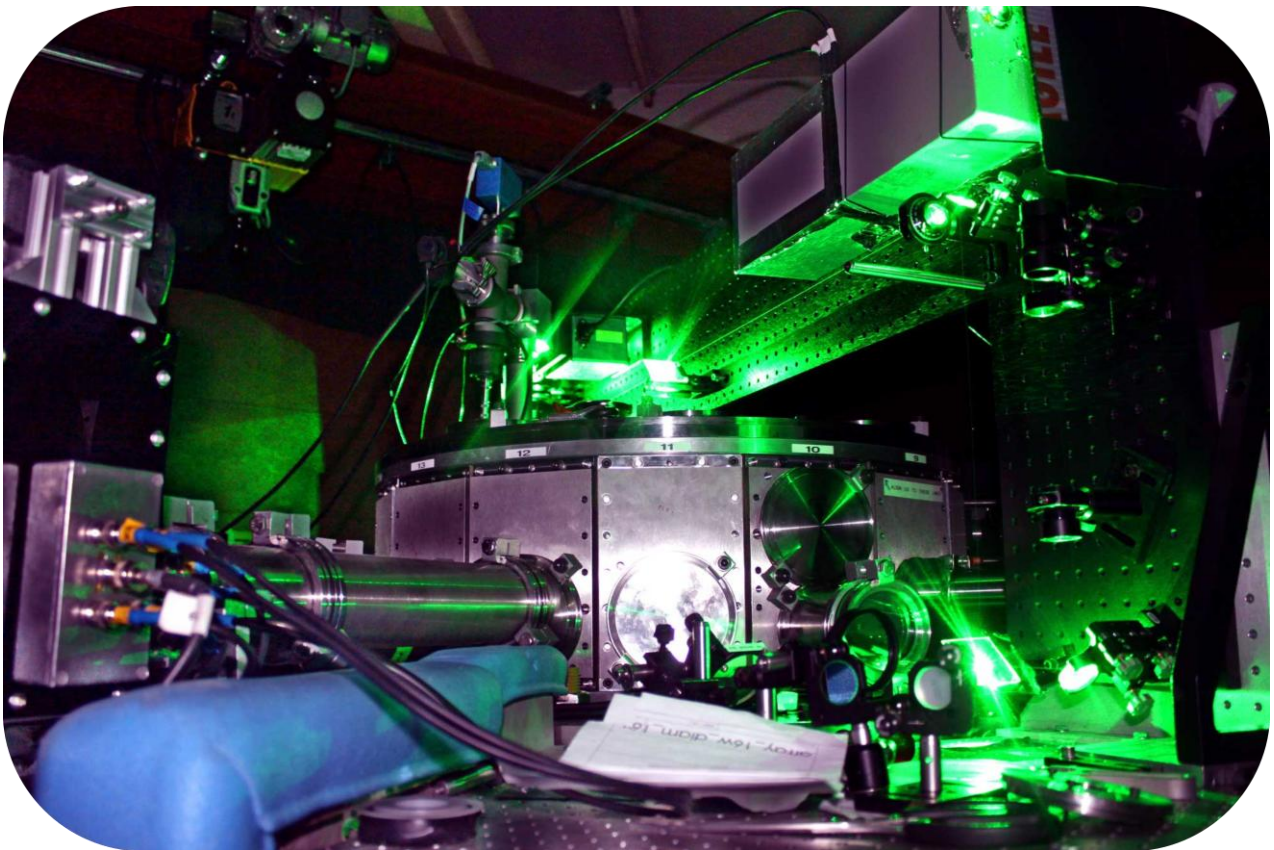


Figure 38 Photograph of the quadrature interferometer mounted over the chamber ready for an experiment.

The quadrature interferometer optics are mounted on a horseshoe shaped optical breadboard, designed to straddle the vacuum chamber. The entire interferometer assembly can be lifted by two people, and needs to be removed between each shot. Bearing in mind this intense handling the optical alignment is surprisingly robust, with little realignment required between shots. The optical layout for the interferometer board is shown in Figure 39. It shows the layouts used for both side-on and end-on probing of wire arrays.

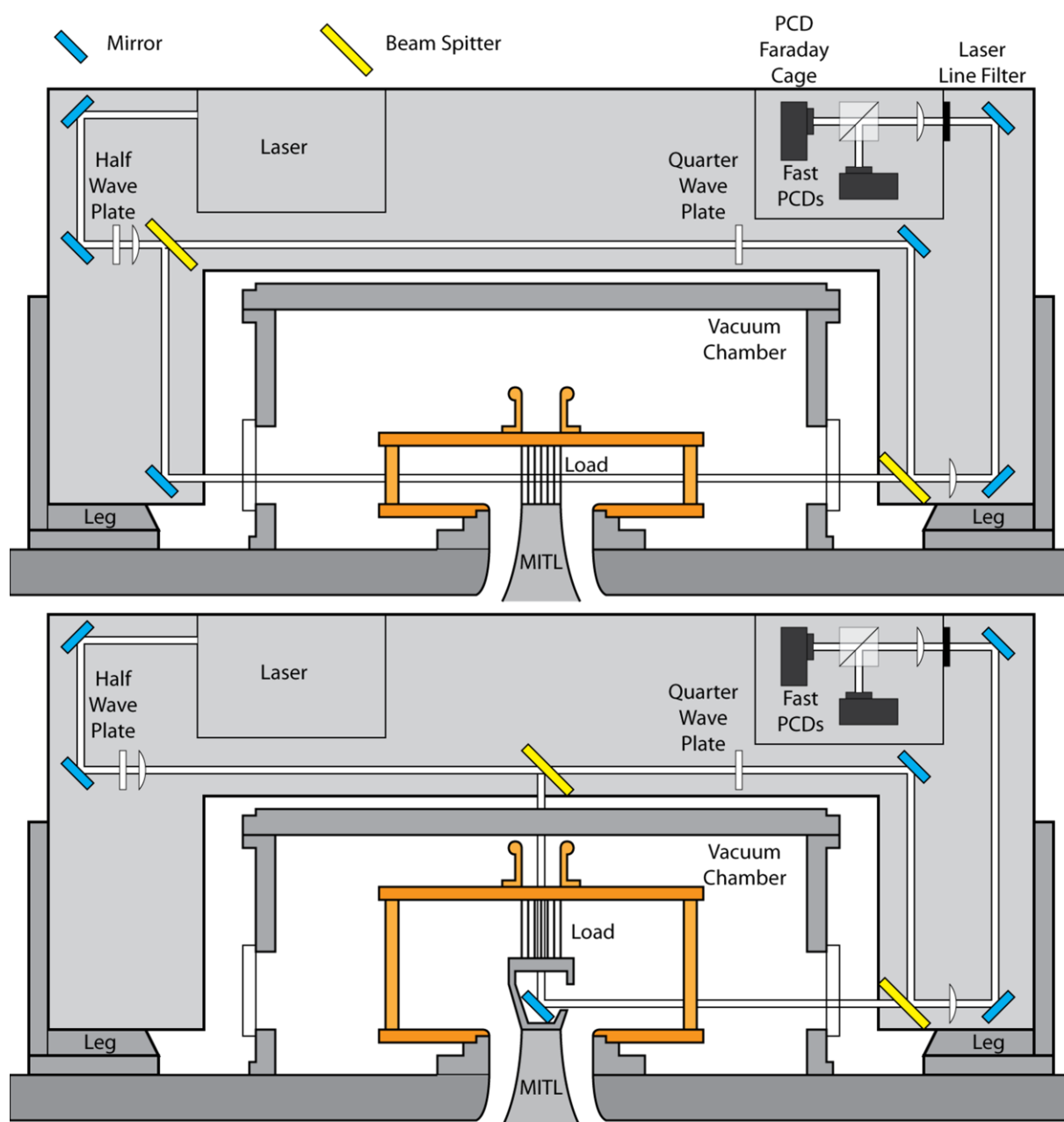


Figure 39 Diagrams of the optical layouts for the quadrature interferometer. Top is the side on arrangement. Bottom is the end on arrangement.

4.1.6) Results

The quadrature interferometer was fielded in experiments investigating hypersonic jets launched from radial foils [29, 30, 52, 53]. These experiments were directed by Dr. Francisco Suzuki-Vidal, in collaboration with Dr. Mahadevan Krishnan. The interferometer was used to make time resolved measurements of the jet density above the array axis.

An annotated photograph of a typical radial foil load and a diagram illustrating the formation and evolution of hypersonic plasma jets is shown in Figure 40. In a radial foil experiment current is driven through a thin metal foil

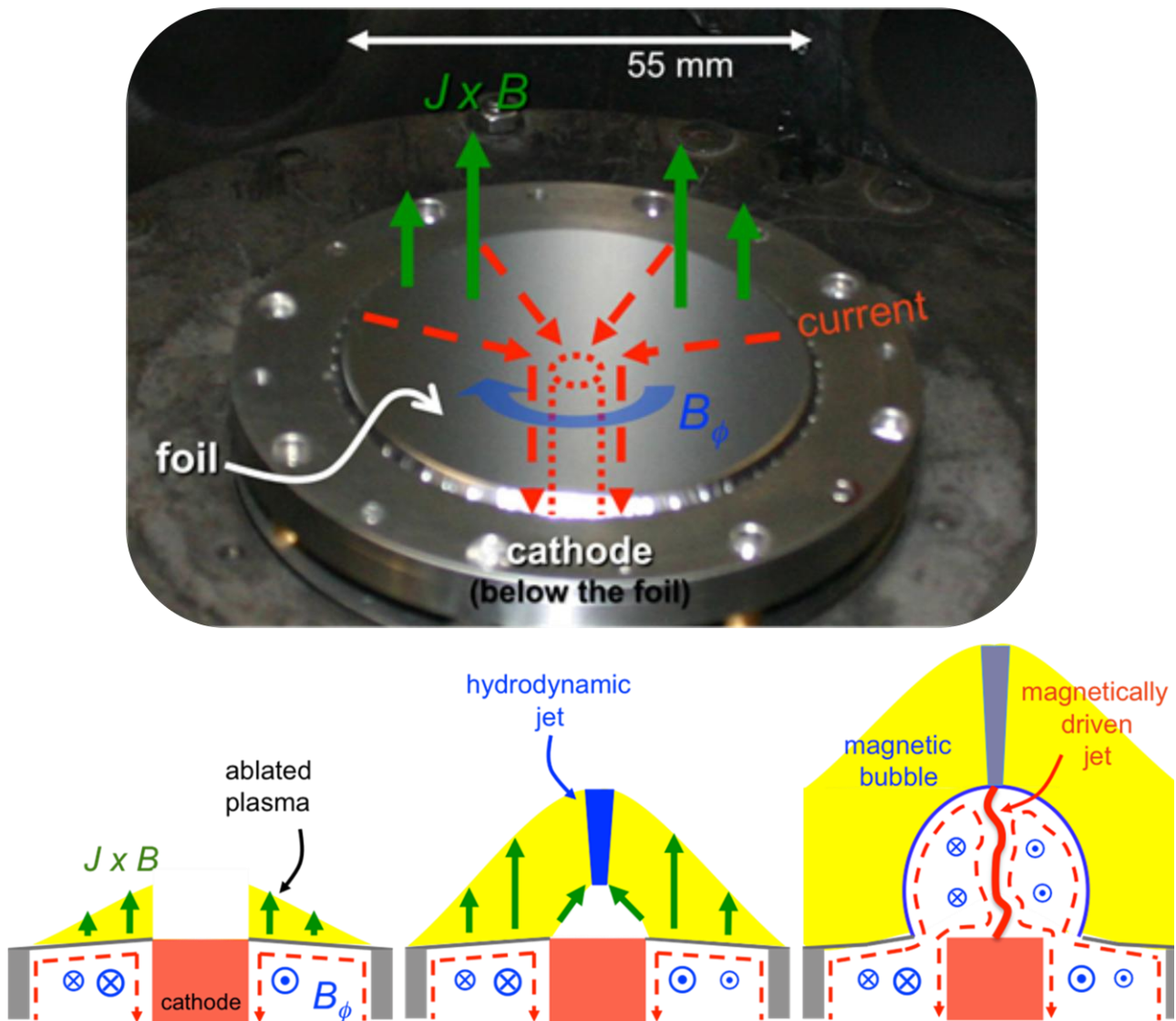


Figure 40 Top, an annotated photograph of a radial foil load. Bottom, a schematic of radial foil evolution. Both reproduced with the kind permission of Dr Francisco Suzuki-Vidal [3].

stretched radially between a pair of concentric electrodes. The central electrode is the cathode, with an annular anode surrounding it. The current heats the foil, resulting in the ablation of plasma from its surface. This plasma expands, forming a hydrodynamic jet which is launched along the axis. Due to the radial convergence of the current, the foil ablation rate is greatest near the axis. The foil mass is exhausted here first, resulting in breakage and the formation a magnetic cavity. The cavity expands due to the magnetic pressure inside it, accelerating axially and pinching a dense column of plasma onto the axis. This process launches a high density jet of plasma from the axis. Current reconnection at the cathode can lead to the formation of secondary magnetic cavities, resulting in a series of episodic jets.

The experiment reported here was focused on the hydrodynamic jet that forms before the foil breaks. This jet was directed into a gas target produced by a fast opening hypersonic gas jet valve [54]. The aim of the experiment was to investigate the dynamics of the interaction between the jet and the ambient medium. In order to extend the hydrodynamic jet regime, relatively thick foils ($15\mu\text{Al}$) and large radius cathodes (6.4mm) were used

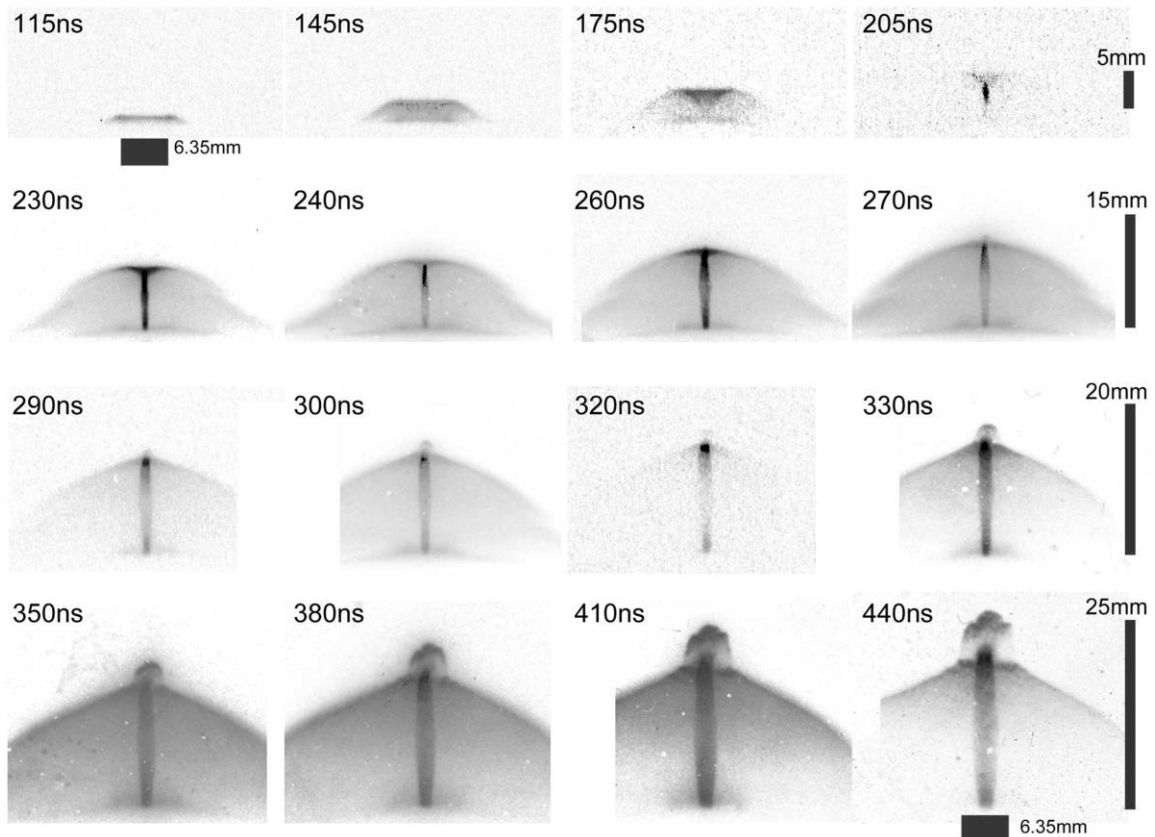


Figure 41 A series of XUV self-emission images illustrating the time evolution of the hydrodynamic jet produced by a radial foil as it propagates into an ambient gas medium. Reproduced with the kind permission of Dr Francisco Suzuki-Vidal [3].

in these experiments. Both of these help to delay breakage of the foil around the cathode. A series of XUV self-emission images depicting the evolution of the hydrodynamic jet and its interactions with an ambient medium are shown in Figure 41.

The experimental data presented here was captured in experiment s0603_10. In this experiment the quadrature interferometer probe beam was aligned through the axis of the experiment, at a position $\sim 31\text{mm}$ above the foil. The aim was to measure the time-resolved density profile of the jet. The signal from each photodiode was recorded on two oscilloscopes, one set with a long time-base and the other set to a short time-base. The long time-base signal is sensitive to pre-shot vibrations and allows measurement of the mean beam intensity, which is required for the analysis. The vibrations are slow on the time scale of the experiment, and so do not interfere with the experimental measurement.

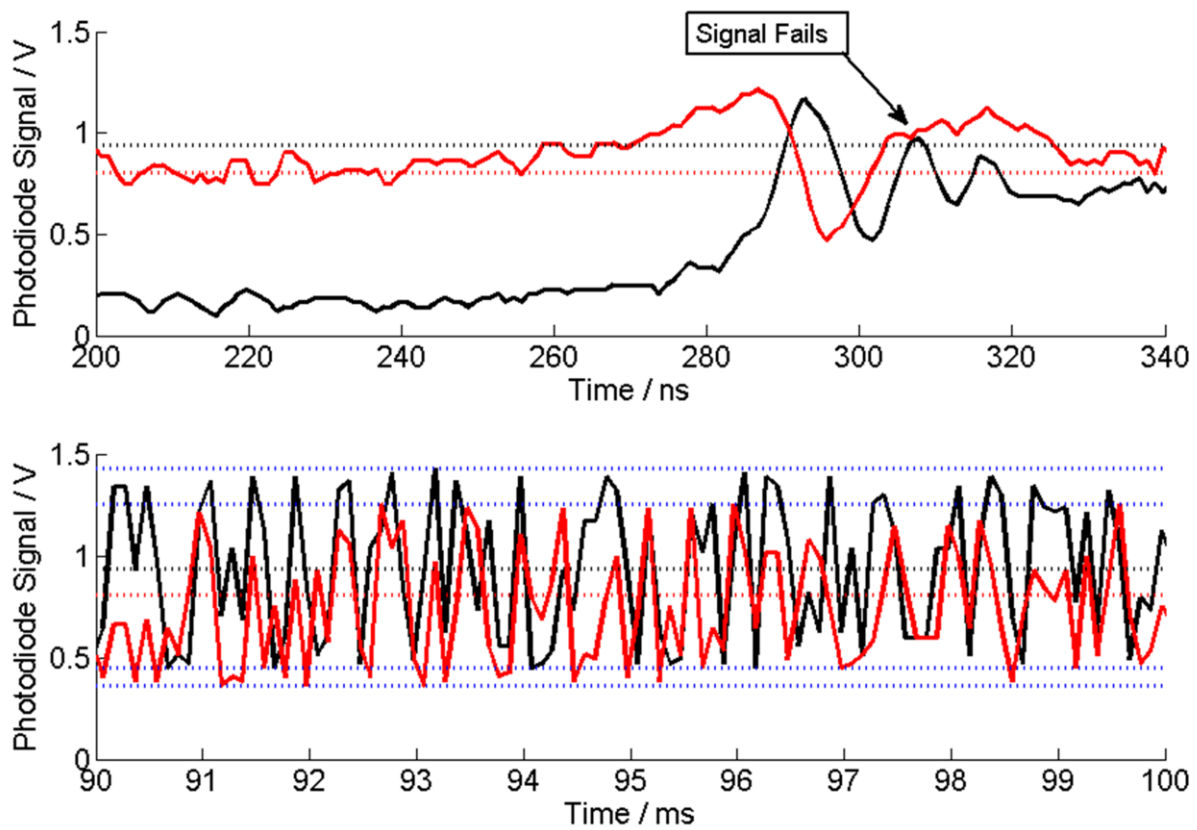


Figure 42 Raw quadrature data from shot s0603_10. Top, short time-base recording, showing the experimental signal. Bottom, long time-base used to measure the mean intensity. The fine dotted blue lines mark the measured amplitudes used to calculate I_0 . The dotted red and black lines mark the calculated values of I_0 . The measurement fails at $t=305\text{ns}$.

The raw voltage signals recorded in these experiments are shown in Figure 42. The short time-base data is on the top, and the long time-base data on the bottom. The mean intensity, I_0 , was calculated for each channel as the mean of the signal amplitude observed in the long time base signal. The red and black dotted lines in the short time-base plot mark the calculated I_0 for the two signals. Analysis of these signals using equation (4.1.8) results in the data shown in the top half of Figure 43. A calibration for the electron density was calculated using the free electron model for the refractive index (Section 3.7.2)). Looking again at the short time base plot of the raw data

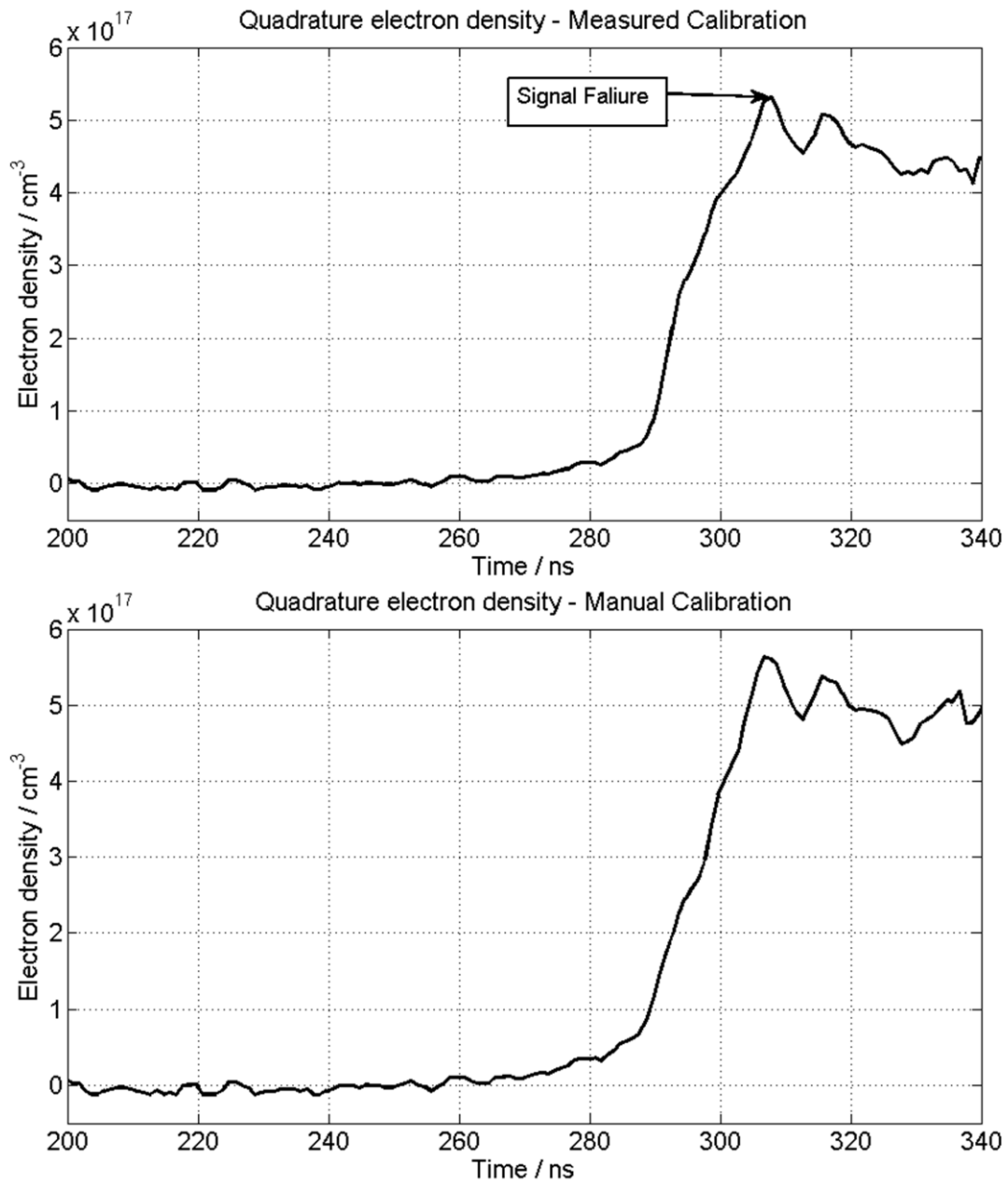


Figure 43 Electron density signal for shot s0603_10, calculated from the raw data in Figure 42. Top, analysis based on measurements of I_0 from the long time-base signal. Bottom, analysis based on an estimated value of I_0 , based on inspection of the signal.

(top of Figure 42) the calibration lines appears to be incorrect, as they do not run through the middle of the oscillations. The analysis was repeated using manually selected value for I_0 . The resulting electron density plot is shown in the bottom half of Figure 43. This plot shows a much more linear ramp of the electron density than was observed in the plot calculated using the measured I_0 calibrations. The differences between the two analyses are however minor.

Looking carefully again at the short time base data in Figure 42, we notice a number of effects. Firstly, the amplitude of the signal oscillation decreases with time. This is most likely the result of refractive bending of the probing beam reducing the degree of beam overlap at the detector. The quadrature analysis technique takes account of this changing fringe contrast ratio. Secondly, the signal recorded on the red channel appears to fail at around 305ns. The point of failure is marked on the plots in Figure 42 and Figure 43. The reason for this failure is as yet unclear; it is possible that the probe beam has been deflected away from the photodiodes detecting surface.

This interferometer was also used to make measurements of the zero-fringe shift during the end-on interferometry experiments. This is important in order to produce reliable absolute quantitative data from the interferograms. The details of this experiment and the results are discussed in Chapter 5.

4.1.7) Improvements and further work

There are a number of improvements that could be made to this diagnostic. The first would be to replace the laser used to power the interferometer. The current laser is only 70mW, low enough that self-emission from the plasma can still be a significant source of noise. A more powerful laser with a longer coherence length would greatly improve the quality of the signals recorded during the experiment, and simplify alignment by increasing the tolerance to path difference between the probing and reference beams. Matching the path lengths is currently the most time consuming part of the alignment process.

The second improvement would be to use photo-diodes with a larger active surface area. The diodes used in these experiments were Thorlabs PDA10A amplified fast photodiodes. The surface area of the detector on these diodes is only 0.8mm^2 . This is almost the same size as the focused probing beam. It is believed that the small detec-

tor surface area may result in loss of measured intensity as the beams are refractively bent. This loss of some of the intensity complicates the analysis by introducing a changing signal baseline, I_0 .

The final improvement that could be made to this diagnostic would be to move the photodiodes into the screened room. The two beams analysed by the beam splitter could be coupled into multi-mode fibres and routed to the photodiodes. The photodiodes are extremely sensitive to electrical noise and in their current position, mounted directly above the generator is far from ideal. If the photodiodes were placed in the screened room they could be better protected from electrical noise, resulting in cleaner data which would be much simpler to analyse.

4.2) CW Faraday rotation

A diagnostic was required to make accurate measurements of rapid current switching produced in experiments on inverse wire arrays. The standard MAGPIE current diagnostics were believed to fail during these experiments due to the large voltages induced across them by the rapid increase of the magnetic field.

Most pulsed power current diagnostics exploit Faradays law of induction. As a result these diagnostics are sensitive only to the rate of change of current. A different approach to the problem of current measurements is to exploit the optical Faraday Effect. This is sensitive to the current magnetic field, and therefore the current. The following discussion is based on information from reference [50].

4.2.1) The Faraday Effect

The Faraday Effect describes how an externally applied magnetic field induces circular birefringence in an optical medium. This circular birefringence results in a rotation of the plane of linearly polarised light. This birefringence is due to the introduction of a $\mathbf{j} \times \mathbf{B}$ force acting on the electrons as they orbit due to a rotating optical field. To explain how this birefringence results in a rotation, the expression for a linearly polarised optical field must be decomposed into a pair of counter-rotating circularly polarised fields. Each of these fields experiences a different refractive index, and therefore has a different wave vector:

$$E_{\uparrow} = E \begin{pmatrix} 1 \\ 0 \end{pmatrix} = \frac{E}{2} \begin{pmatrix} 1 \\ i \end{pmatrix} + \frac{E}{2} \begin{pmatrix} 1 \\ -i \end{pmatrix} = E_{\psi} + E_{\psi} \quad (4.2.1)$$

$$E = E_0 e^{i\omega t}$$

$$k_{\psi} = \left(\frac{\eta_{\psi} \omega}{c} \right) \quad k_{\psi} = \left(\frac{\eta_{\psi} \omega}{c} \right) \quad (4.2.2)$$

$$E_{\uparrow} = E_{\psi} + E_{\psi} = \frac{E}{2} \left(e^{ik_{\psi}z} \begin{pmatrix} 1 \\ i \end{pmatrix} + e^{ik_{\psi}z} \begin{pmatrix} 1 \\ -i \end{pmatrix} \right) \quad (4.2.3)$$

$$E_{\uparrow} = \frac{E}{2} e^{-\frac{i(k_{\psi} + k_{\psi})z}{2}} \begin{pmatrix} \cos \left(\frac{(k_{\psi} - k_{\psi})}{2} z \right) \\ \sin \left(\frac{(k_{\psi} - k_{\psi})}{2} z \right) \end{pmatrix}$$

The angle of the plane of polarisation is encoded as the phase shift between the two circularly polarised components. Examining equation (4.2.3) reveals that the change in the angle ($\Delta\theta$) is equal to half the accumulated phase shift ($\Delta\phi$):

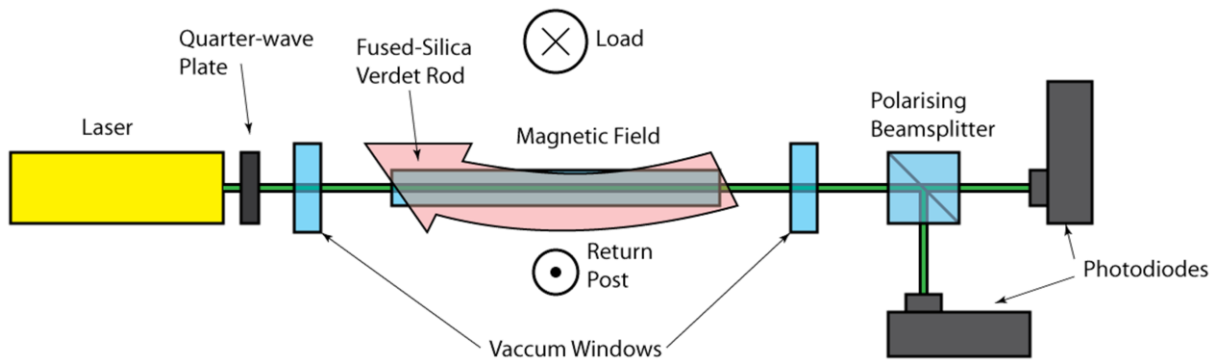
$$\Delta\theta = \frac{\Delta\phi}{2} = \frac{(k_v - k_o)z}{2} = \frac{(\eta_v - \eta_o)\frac{\omega z}{c}}{2} = \frac{\Delta\eta\omega z}{c} \quad (4.2.4)$$

Thus the angle of rotation increases with both the distance of propagation (z) and the degree of circular birefringence ($\Delta\eta$). Since the degree of circular birefringence is controlled by the magnetic field strength, the effect can be parameterised by the following equation:

$$\theta = V \int B \cdot dl \quad (4.2.5)$$

The Verdet constant (V) describes the strength of the Faraday Effect. It takes into account both the wavelength of

a)



b)

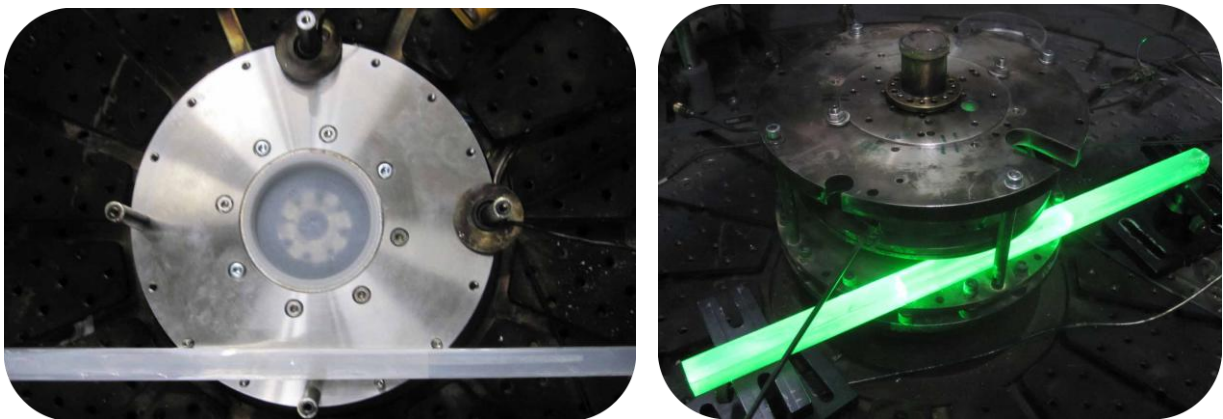


Figure 44 Experimental setup for the Faraday rotation current diagnostic.

- a) Schematic of optical layout used to measure the angle of rotation.
- b) Photographs of fused silica rod mounted in experimental hardware. The rod is wrapped in protective plastic. In the left image the load and top anode plate has been removed to provide a clearer view of the arrangement. In the right image the load has been installed and the beam has been aligned through the glass.

the probe and the susceptibility of the medium to the Faraday Effect.

4.2.1) Experimental setup

A plane polarised 532nm CW laser beam was directed through a 100mm long fused silica rod mounted within the current return structure between the load and one of the current return posts. The position of the rod is shown in Figure 46 in the right hand diagram. After passing through the rod, the beam leaves the vacuum chamber via a window. A polarising beamsplitter was used to analyse the beam into two orthogonal linear polarisations, and these are then focused onto photodiodes in order to record their intensities. Figure 44 a) shows a schematic of this optical setup and Figure 44 b) shows photographs of the fused silica rod mounted in the load hardware before a shot.

A dataset of the Verdet constant for fused silica over a range of wavelengths was found in reference [4]. The data from this paper is plotted in Figure 45. A power series fit is plotted over this data. At 532nm the value for the Verdet constant interpolated from this fit line is $5.04 \text{ rad (Tm)}^{-1}$.

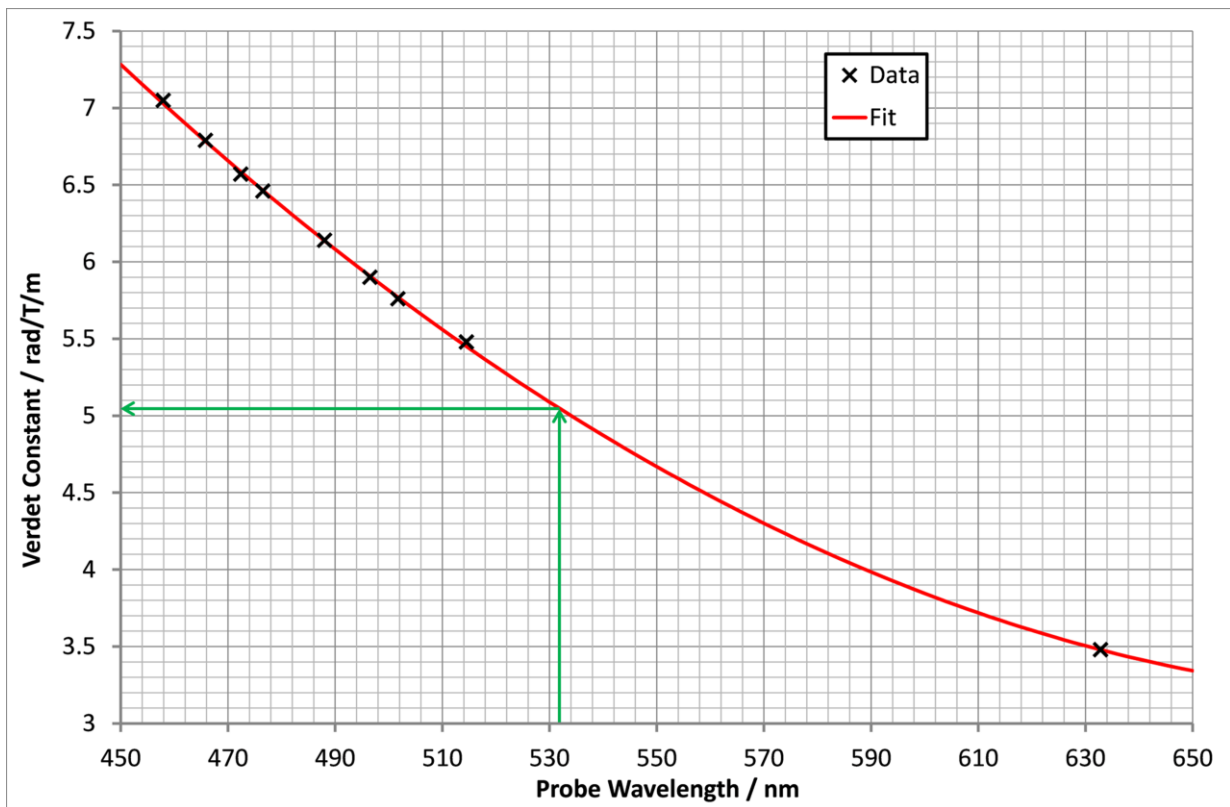


Figure 45 Plot of the Verdet constant for fused silica. The data points were taken from reference [4]. The red line a power series fit.

4.2.2) Path integral calibration

A geometric calibration factor is required in order to calculate the load current from the measured magnetic field path integral:

$$k_{geo} = \frac{\int B \cdot dl}{I} \quad (4.2.6)$$

The magnetic field at a given radius from a cylindrical conductor can be calculated using the Biot-Savart Law. The magnitude of the tangential field at a given radius is:

$$B = \frac{\mu_0 I}{4\pi r} \frac{\int dl \times \hat{r}}{|r|^2} \quad (4.2.7)$$

$$|B| = \frac{\mu_0 I}{2\pi r}$$

Figure 46 shows a schematic of the relative positions of the glass rod, load and return posts. We need to calculate the component of the magnetic field along the glass rod, in the direction of laser propagation. For this calculation it is easiest to rewrite the above equation in terms of a Cartesian coordinate system. The orientation of the axes is selected such that the probing beam propagates in the y-direction. The axis of the load is defined as the origin. The field calculated in equation (4.2.7) is tangential to the displacement vector r . The geometry of the field is shown in left hand diagram in Figure 46. The y component of the field at a point (x,y) is described by the following equations:

$$B_y(r, \theta) = |B| \sin \theta = \frac{\mu_0 I}{2\pi r} \sin \theta$$

$$\sin \theta = \frac{y}{r} \quad r = (x^2 + y^2)^{\frac{1}{2}} \quad (4.2.8)$$

$$B_y(x, y) = \frac{\mu_0 I}{2\pi} \frac{y}{(x^2 + y^2)^{\frac{3}{2}}}$$

This expression gives the y component of the magnetic field due to a conductor passing through the origin of the coordinate system. It can be generalised for a conductor passing through any point in the coordinate system by applying the following substitutions:

$$\begin{aligned} x &\rightarrow (x - x_i) \\ y &\rightarrow (y - y_i) \end{aligned} \quad (4.2.9)$$

Where (x_i, y_i) are the coordinates of the conductor. The total field due to an ensemble of conductors can be calculated as the linear superposition of the field due to each individual conductor:

$$B_y(x, y) = \sum_i \frac{\mu_0 I_i}{2\pi} \frac{(x - x_i)}{((x - x_i)^2 + (y - y_i)^2)} \quad (4.2.10)$$

This expression must be integrated along the length (l) of the glass rod:

$$\begin{aligned} \int B \cdot dl &= \int_{-\frac{l}{2}}^{\frac{l}{2}} B_y dy = \frac{\mu_0}{2\pi} \int_{y_1}^{y_2} \sum_i \frac{I_i(x - x_i)}{(x - x_i)^2 + (y - y_i)^2} dy \\ \int B \cdot dl &= \frac{\mu_0}{2\pi} \sum_i I_i(x - x_i) \int_{y_1}^{y_2} \frac{dy_i}{(x - x_i)^2 + (y - y_i)^2} \\ \int B \cdot dl &= \frac{\mu_0}{2\pi} \sum_i I_i \left[\text{atan} \frac{(y - y_i)}{(x - x_i)} \right]_{y=-l/2}^{y=l/2} \end{aligned} \quad (4.2.11)$$

The positions of the conductors are marked in Figure 46. r_G is the distance of the glass rod from the axis of the load and r_0 is the distance from the return posts to the axis of the load. The return current is assumed to be equally divided such that each carries a quarter of the load current. The current and position of each conductor is

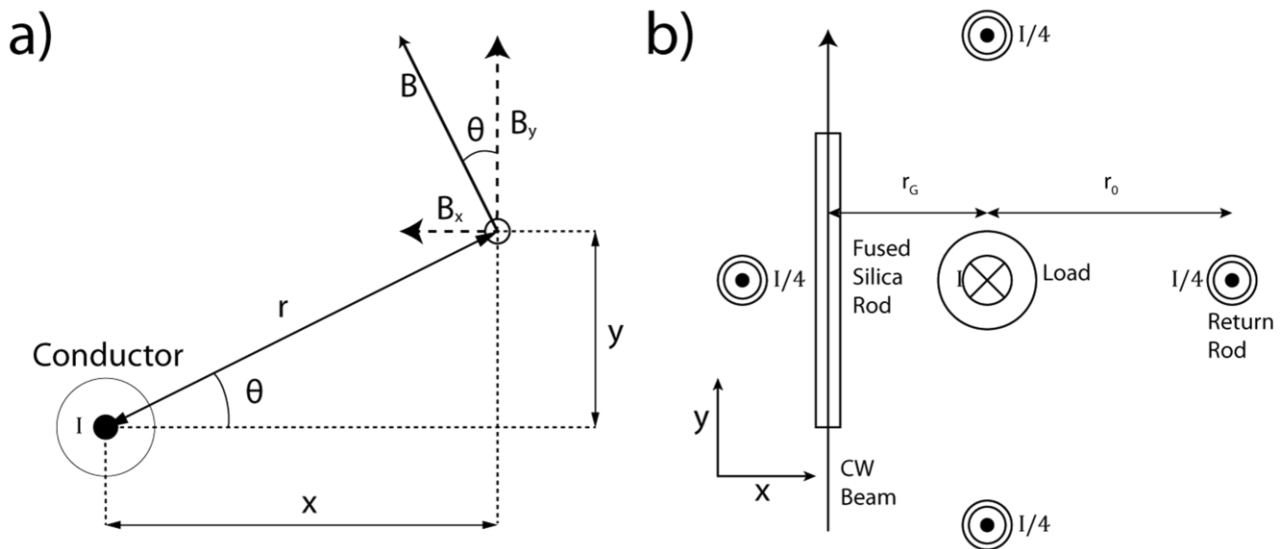


Figure 46 Left, a diagram of the magnetic field formed around a current carrying conductor, right, a schematic of the experimental setup, showing the relative positions of the conductors and the fused silica bar.

substituted into equation (4.2.11) to get an expression for the magnetic field path integral.

$$\int B \cdot dl = \frac{\mu_0}{2\pi} \sum_i I_i \left[\operatorname{atan} \frac{l/2}{r_G} - \frac{1}{4} \left\{ \operatorname{atan} \frac{(l/2 + r_0)}{r_G} + \operatorname{atan} \frac{l/2 - r_0}{r_G} + \operatorname{atan} \frac{l/2}{r_G + r_0} + \operatorname{atan} \frac{l/2}{r_G - r_0} \right\} \right] \quad (4.2.12)$$

Substitution of this into equation (4.2.6) results in following expression for the geometric calibration.

$$k_{geo} = \frac{\mu_0}{\pi} \left[\operatorname{atan} \frac{l/2}{r_G} - \frac{1}{4} \left\{ \operatorname{atan} \frac{(l/2 + r_0)}{r_G} + \operatorname{atan} \frac{l/2 - r_0}{r_G} + \operatorname{atan} \frac{l/2}{r_G + r_0} + \operatorname{atan} \frac{l/2}{r_G - r_0} \right\} \right] \quad (4.2.13)$$

4.2.3) Measurement of the rotation angle

The probing beam was analysed using a polarising beam splitter. This divided the beam into a pair of orthogonal linear polarisations. The intensity of these beams was measured by fast photodiodes. The intensity of the light falling on each photodiode is a function of the angle of rotation θ :

$$\begin{aligned} I_{\parallel}(\theta) &= I_0 \cos^2(\theta + \phi) \\ I_{\perp}(\theta) &= I_0 (1 - \cos^2(\theta + \phi)) \end{aligned} \quad (4.2.14)$$

Where I_0 is the intensity of the CW beam that enters the polarising beamsplitter and ϕ is the initial angle of the plane of polarisation. The angle of rotation can be extracted from the intensity data using the following formula:

$$\theta(t) = \operatorname{acos} \sqrt{\frac{1}{2} \left(\frac{I_{\parallel}(t) - I_{\perp}(t)}{I_{\parallel}(t) + I_{\perp}(t)} \right) - 1} + n\pi - \phi \quad (4.2.15)$$

The sensitivity of this measurement system varies over the cycle:

$$\frac{dI_{\parallel}}{d\theta} = \frac{dI_{\perp}}{d\theta} = \frac{I_0}{2} \sin(\theta + \phi) \quad (4.2.16)$$

As $(\theta + \phi)$ approaches zero or a multiple of π , the differential sensitivity goes to zero. This means that at these points a change in the polarisation angle results in no change in intensity. It also means that the analysis becomes extremely sensitive to signal noise. To minimise the problems associated with this a half-wave plate was used to adjust the initial polarisation angle of the input beam. The plane of polarisation was oriented at 45° to the polariser, so that initially the intensity of the beam is split between the two channels equally. This maximised the differential sensitivity of the diagnostic at current start.

4.2.4) Results

A series of experiments were carried out to test the calibration of this diagnostic. The best example of these shots was shot s0118_10. The load for this shot was $32 \times 13\mu\text{m}$ tungsten arrays on a 16mm diameter. The raw data from this shot is shown in Figure 47 a). The plot shows the raw voltage signals measured directly from the photo-diodes. These signals are very noisy. Before analysis, a nearest neighbour smoothing algorithm was used to remove a large portion of this noise.

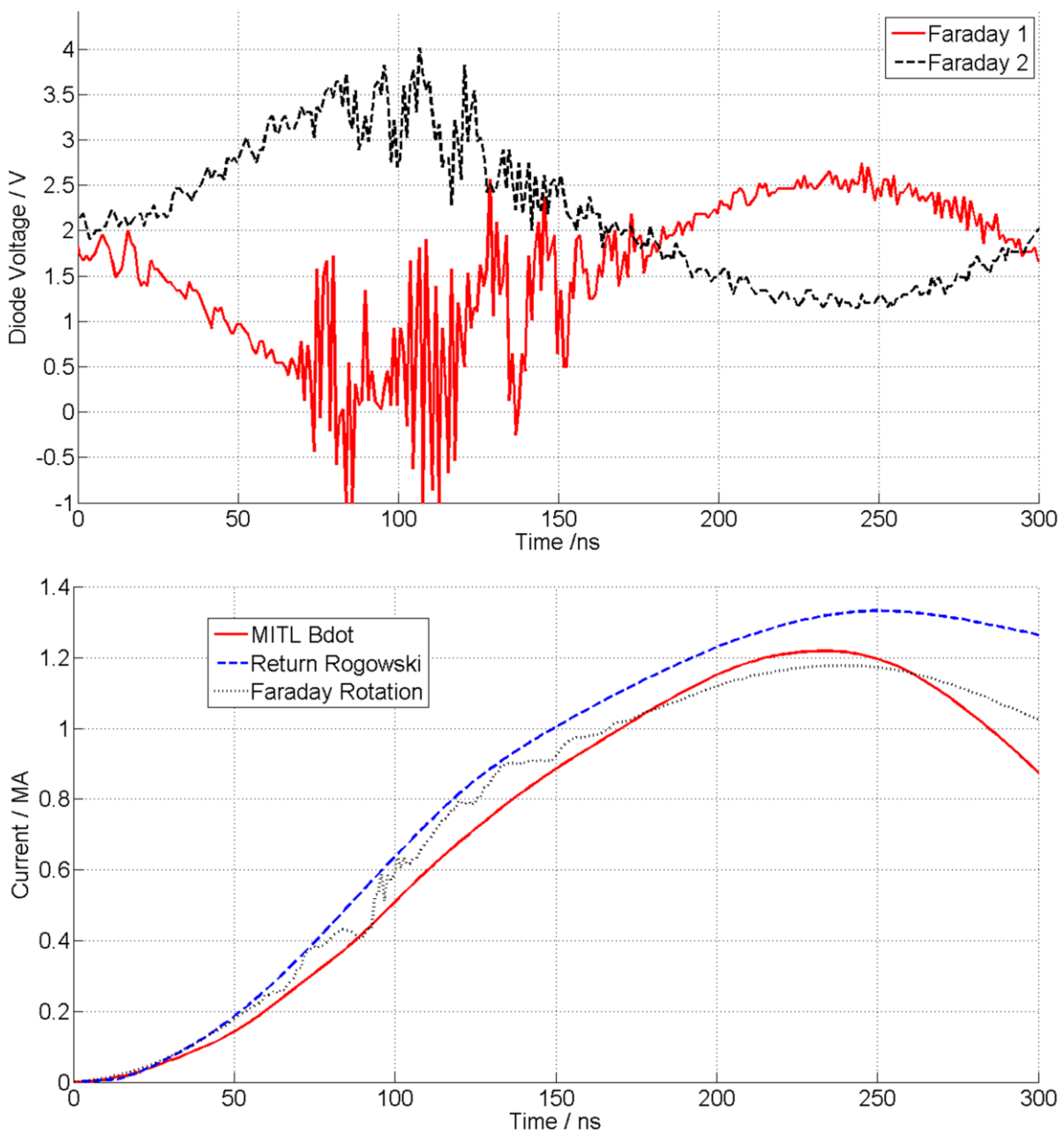


Figure 47 Current plots from three different current diagnostics from s0118_10.

In this experiment the glass rod was placed at a radius of 65mm, with the return posts at a radius of 77.5mm from the return. The rod was 100mm long. Substituting these parameters into equation (4.2.13) results in a geometric calibration of $k_{\text{geo}} = 2.912 \times 10^{-7} \text{A(Tm)}^{-1}$. The current signal was calculated using equation (4.2.15). The resulting current trace is plotted in Figure 47 b). The Faraday current measurement appears to agree well with the measurements taken by the return Rogowski and MITL B-Dot. It shows a peak current of 1.18MA, at 240ns from current start. The current signal at early and late times appears smooth but there is a region of signal in the middle which appears to fluctuate a lot. This region corresponds to the sensitivity null of the instrument. At this angle changes in current produce only small changes in the measured intensity, while noise signals are amplified by the analysis algorithm. Based on the evidence of this shot it would appear the diagnostic works as expected.

The diagnostic was next applied to a current switching experiment driven by an inverse wire array [31]. The experimental setup is rather more complicated than that in the previous experiment. A schematic of the experiment is shown in Figure 48. A standard imploding wire array is mounted on top of an inverse exploding wire array. In the inverse array configuration current flows up through a central conductor and returns via the wires. As a result the magnetic forces are reversed and plasma is ablated outwards instead of inwards. When the wires are exhausted the array explodes outwards. This breaks the circuit, providing the switching effect.

At the beginning of the experiment the distribution of the current between the two arrays is set by resistive division. At some point the arrays undergo breakdown and their resistance becomes negligible. From this point on the current is distributed inductively. The circuit cavity and therefore inductance associated with the standard

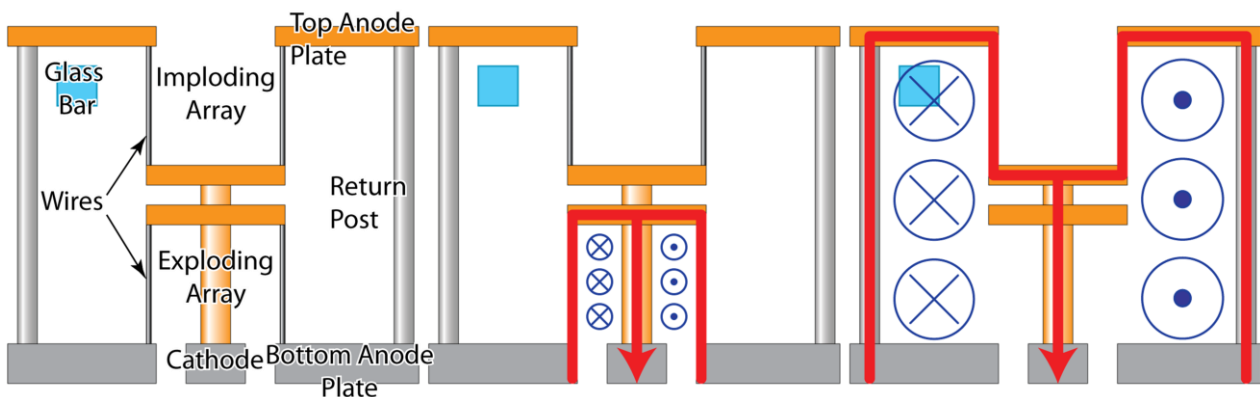


Figure 48 Diagram of the current switch experiment. Initially the magnetic field is contained within the inverse array. After this array explodes, magnetic field fills the entire cavity.

array is much larger than that associated with the inverse array. As a result most of the drive current is conducted through the inverse array.

At some point the ablation of inverse array results in depletion of the wire mass. The array explodes, driven by magnetic pressure blowing out the wire material. This breaks the circuit path through the inverse array, forcing the current to switch to the imploding wire array above. The high inductive drive voltage results in an extremely rapid current rise.

For this experiment the fused silica bar was placed in the return structure associated with the imploding wire array. As Figure 48 shows, while the current is flowing in the inverse array the majority of the magnetic field should be contained within it. After it explodes, the field will fill the full return volume. The strength of this field will be proportional to the current in the standard cylindrical array.

Shot s1021_10 provides a good example of the data taken during these experiments. The load consisted of a 20mm long $8 \times 12.5\mu\text{m}$ cylindrical Al wire array, with current switching performed by a 30mm long, $8 \times 12.5\mu\text{m}$ Al inverse wire array. The fused silica bar was placed high in the return structure, near the top anode plate. The dis-

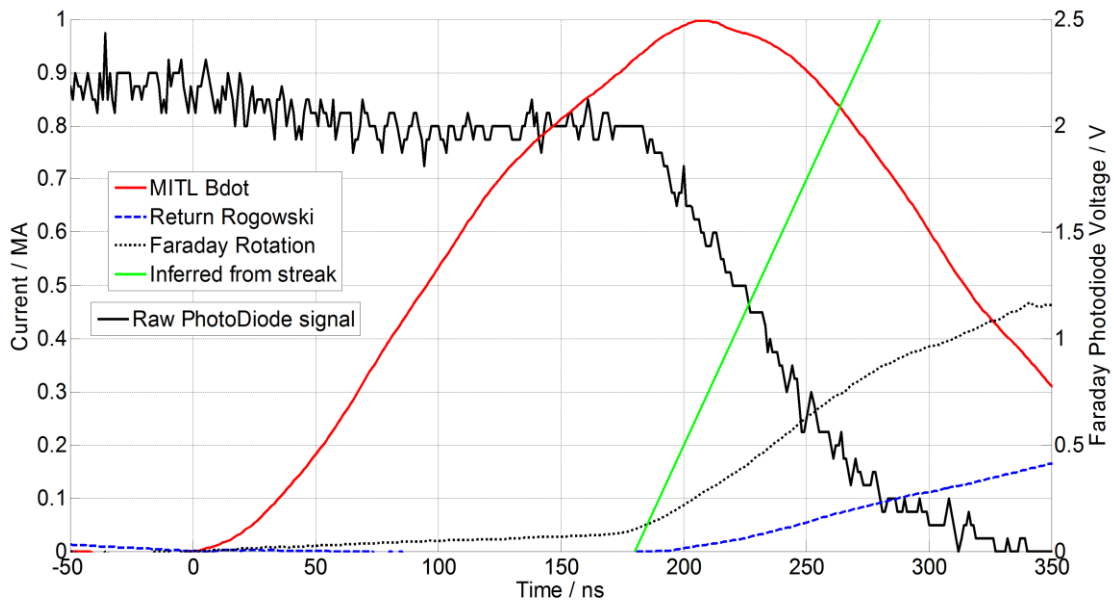


Figure 49 Current measurements from shot s0121_10.

The current through the imploding array was measured by the Faraday rotation diagnostic, and a Return post Rogowski probe. The MITL B-dot indicated the total current delivered by the generator. The green line shows the current in the imploding array as inferred from the streak data. The solid black line is the raw Faraday signal.

tance from the middle of the bar to load axis was maintained at 65mm. As a result the geometric calibration for this experiment remains the same as that in shot s0118_10, $k_{\text{geo}} = 2.912 \times 10^{-77} \text{A(Tm)}^{-1}$.

The results of this experiment are plotted in Figure 48. This graph shows the current as measured by the Faraday rotation diagnostic, a Rogowski groove placed around the return post for the imploding array and a MITL B-dot. The MITL B-dot measures the total current driven into the experiment. The Rogowski and Faraday probes should only show measurements of the current driven into the imploding array. The Faraday signal shows a small initial rise in current. This is most obvious in the raw Faraday voltage signal, where there is a definite decrease in the measured voltage just after current start. This current is the result of the initial resistive division and later inductive division between the arrays. The current in the imploding array appears to remain at a steady level until around 180ns, when the current beings a linear rise. The X-ray peak produced by the stagnation of the top array occurred at around 300ns. At this time the current measured by the Faraday probe has only reached 0.4MA. The rate of current rise after switching appeared to be slower than the current rise due to the standard current drive. The Rogowski signal indicated an even slower rate of current rise. An optical streak image captured during this experiment is shown in Figure 51. This image shows the trajectory of the imploding array. By analysing this trajec-

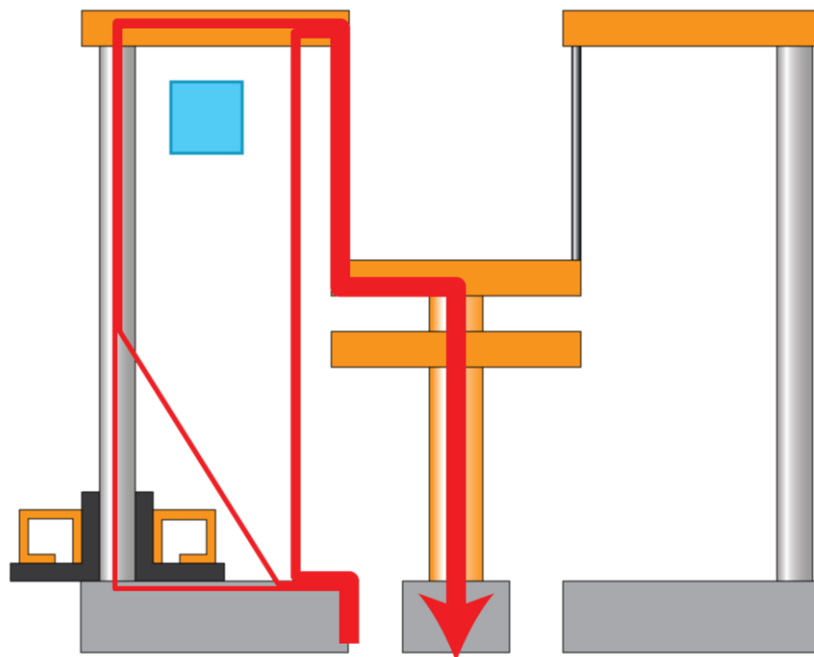


Figure 50 Schematic showing how a distributed return current could explain why the Faraday probe and return Rogowski failed to measure the full current delivered to the load.

tory it is possible to infer the drive current profile required to drive it; a peak current of 1.12MA is required, with a rise time of 112ns from the time of current switch[55]. This current profile is also plotted in Figure 49.

The data appears to indicate that the Faraday current diagnostic has failed. The current measurement is too small to explain the observed implosion trajectory. The most probable explanation for this is that some portion of the return current for the cylindrical array was not flowing in the return hardware. The inverse array 'switch' explosion produces a large volume of plasma which may provide alternative return paths, allow current to circumvent the return posts. This explanation is particularly persuasive as the return post Rogowski in this experiment was mounted at the bottom of the return posts. Figure 50 illustrates how a distributed alternative current return path could explain why the current measured by these diagnostic is not large enough. Experiments which are in progress now appear to support this interpretation.

The development of this diagnostic was put on hold due to its failure to measure the current in these experiments. It remains an interesting technique for current measurement, since it is one of the few techniques that directly measure the current and magnetic fields produced in pulse power experiments.

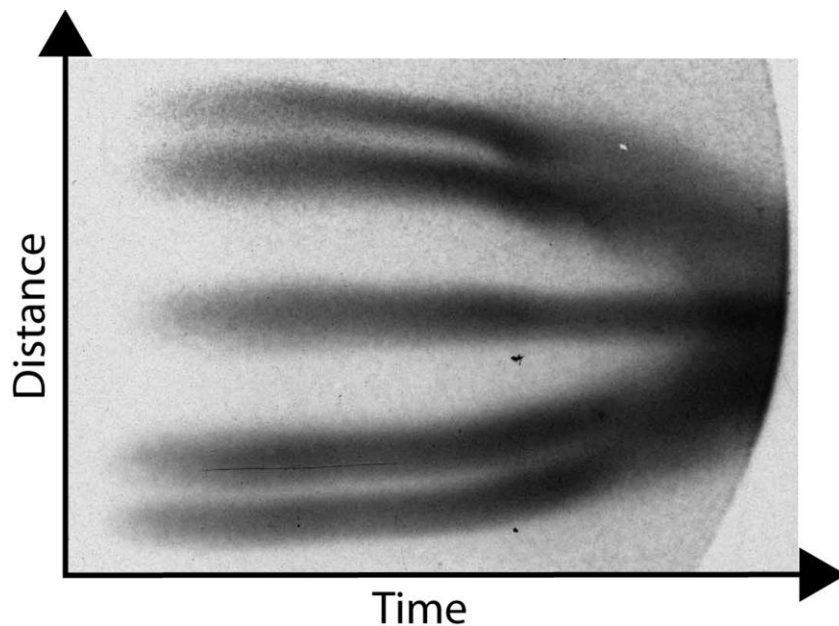


Figure 51 A streak image from shot s0121_10. The current in the imploding array can be inferred from the implosion trajectory.

4.2.5) Possible improvements

There are two improvements [56, 57] that could be made to improve the accuracy and simplify the calibration of this diagnostic.

The first is an improved method to measure the angle of polarisation. Analysing the beam at only a single polariser angle means there will always be some rotation angles at which the differential sensitivity of the diagnostic will fall to zero. Also the direction of the rotation will often be ambiguous. A better technique is to analyse the beam using two polarisers, with the angles at which the beam is analysed separated by 45°. Ideally four response matched photodiodes can be used to measure the resulting light intensity signals. By combining these signals it is possible to remove the sensitivity nulls and also to extract information about the direction of the rotation. Figure 52 shows a schematic of an optical layout for this analysis. Expanding on the expressions for the theoretical signals given in equation (4.2.14), we get expressions for each pair of signals:

$$\begin{aligned}
 I_{\parallel 1}(\theta) &= I_0 \cos^2(\theta + \phi) \\
 I_{\perp 1}(\theta) &= I_0 (1 - \cos^2(\theta + \phi)) \\
 I_{\parallel 2}(\theta) &= I_0 \cos^2\left(\theta + \phi + \frac{\pi}{2}\right) = I_0 \sin^2(\theta + \phi) \\
 I_{\perp 2}(\theta) &= I_0 (1 - \sin^2(\theta + \phi))
 \end{aligned}
 \tag{4.2.17}$$

A normalised signal (S) can be calculated from each these signal pairs. These normalised signals can then be combined as follows to extract the current signal:

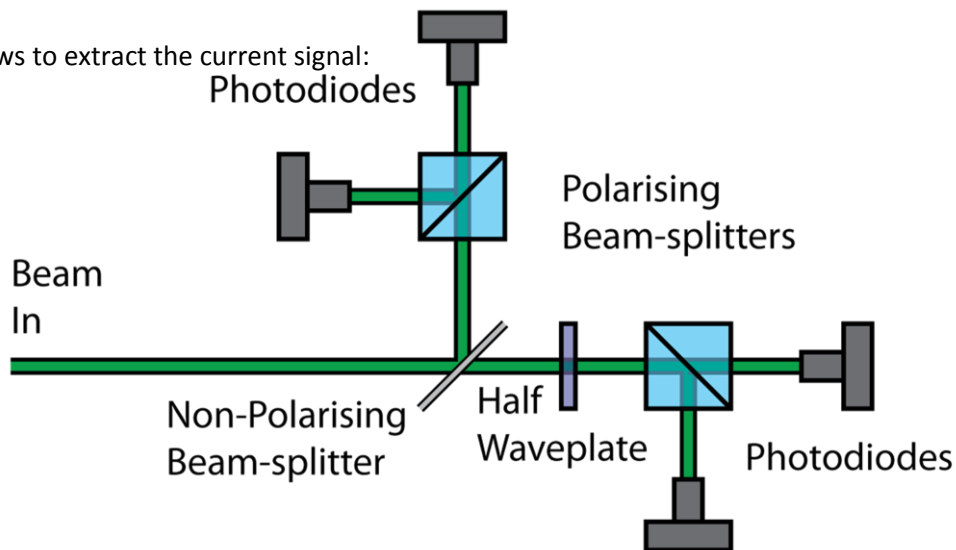


Figure 52 An optical layout for improved analysis of the Faraday current signal. The half-wave plate fast axis is inclined at 22.5° from the plane of the image, so that it rotates the polarisation of the probing beam by 45°.

$$S = \frac{I_{\parallel} - I_{\perp}}{I_{\parallel} + I_{\perp}} \quad (4.2.18)$$

$$S_1 = \cos^2(\theta)$$

$$S_2 = \sin^2(\theta) \quad (4.2.19)$$

$$\frac{S_2}{S_1} = \tan^2 \theta$$

$$\theta = \text{atan} \sqrt{\frac{S_2}{S_1}} = \text{atan} \sqrt{\frac{I_{\parallel 1} + I_{\perp 1}}{I_{\parallel 1} - I_{\perp 1}} \frac{I_{\parallel 2} - I_{\perp 2}}{I_{\parallel 2} + I_{\perp 2}}} \quad (4.2.20)$$

This analysis technique is very similar to the quadrature analysis method used for the CW interferometer, described in section 4.1). Section 4.1.3) describes the benefits of this type of analysis in greater detail. The major drawback of this approach is the extra complication involved in the experimental setup and the extra equipment that is needed to collect the data.

The second improvement that can be made to this diagnostic is to remove the requirement for the geometric calibration. If the probing beam path can be steered all the way around the conductor then Amperes law may be used to calculate the relationship between the magnetic field path integral and the current:

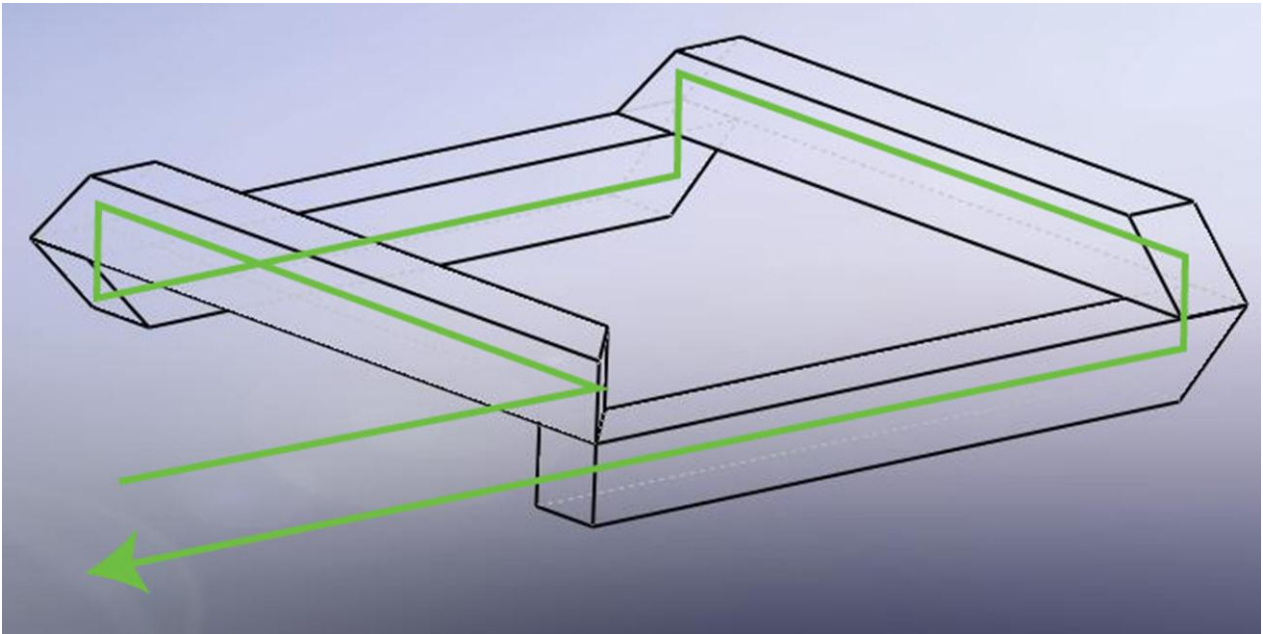


Figure 53 Diagram showing beam path through a complete loop faraday current probe.

$$\oint B \cdot dl = \mu_0 \iint_s J \cdot dA = \mu_0 I_{Enc} \quad (4.2.21)$$

Substituting Amperes law in equation (4.2.5) and rearranging for the current gives the following expression:

$$I = \frac{\theta}{\mu_0 V} \quad (4.2.22)$$

Now the only calibration required is a value for the Verdet constant. A complete current loop can be formed by taking advantage of total internal reflection in glass. Care must be taken, as total internal reflection can result in phase shifts between the s and p polarisations in the beam. This could induce elliptical polarisation in the beam. Double reflection corners can be used to cancel out much of this effect. A diagram showing the beam path through such an apparatus is shown in Figure 53.

Chapter 5

End-on laser interferometry of ablation structures in wire array Z-pinches

A series of experiments was carried out to investigate the azimuthal structure of the ablation plasma produced during wire array implosion experiments. An end-on imaging interferometer and analysis system was developed specifically for these experiments. The laser probing beam is directed down the axis of the array. End-on probing of wire array implosions reveals structures and dynamics which are hidden from a side-on view. It is a powerful technique for investigating both the ablation stream structure and the build-up of mass on axis as the precursor column is formed.

5.1) Advantages of a Mach-Zender interferometer

End-on laser interferometry has been fielded as a diagnostic in previous MAGPIE experiments [28]. A Michelson-Morley interferometer design was used in these experiments. The probing beam was directed down the array axis and retro-reflected by a mirror embedded in the cathode. This required the beam to perform a double-pass of the plasma. The array hardware was modified for the experiments described in this chapter to allow a Mach-Zender interferometer to be used instead. Figure 54 shows basic schematics of the two designs. The most im-

portant difference is that the Mach-Zender scheme allows a single-pass through the plasma by reflecting the probing beam out through a hole cut in the side of the cathode.

A single pass interferometer has a number of advantages over a double pass design. Firstly alignment of the probing beam down the axis of the array is simplified. With a double pass system there is a danger that any minor misalignment may cause the beam to 'walk off' before the second pass, resulting in a double image. This is a particular problem in wire array experiments as it is very difficult to make adjustments to the cathode mirror alignment once the load is in place. The effect of the 'walk off' is to smear out detail in the image, reducing the effective resolution.

The second advantage is related to the depth of field of the optical system. The depth of field describes the range of object displacements either side of the plane of focus that are brought to an acceptable focus at the imaging surface. A double-pass will more than double the effective length of the object that needs to be in focus. A good quality focus is essential in order to minimise shadowgraphy effects in the resulting interferograms. Shadowgraphy effects result in a redistribution of the probe beam intensity around regions corresponding to strong areal electron density gradients and produce confusing intensity patterns in the interferograms. The strength of the effect is controlled by the depth of focus of the optics and the distance from the plane of focus of the contributing plasma. Shadowgraphy effects are discussed in greater detail in section 3.7.4). In order to minimise disturb-

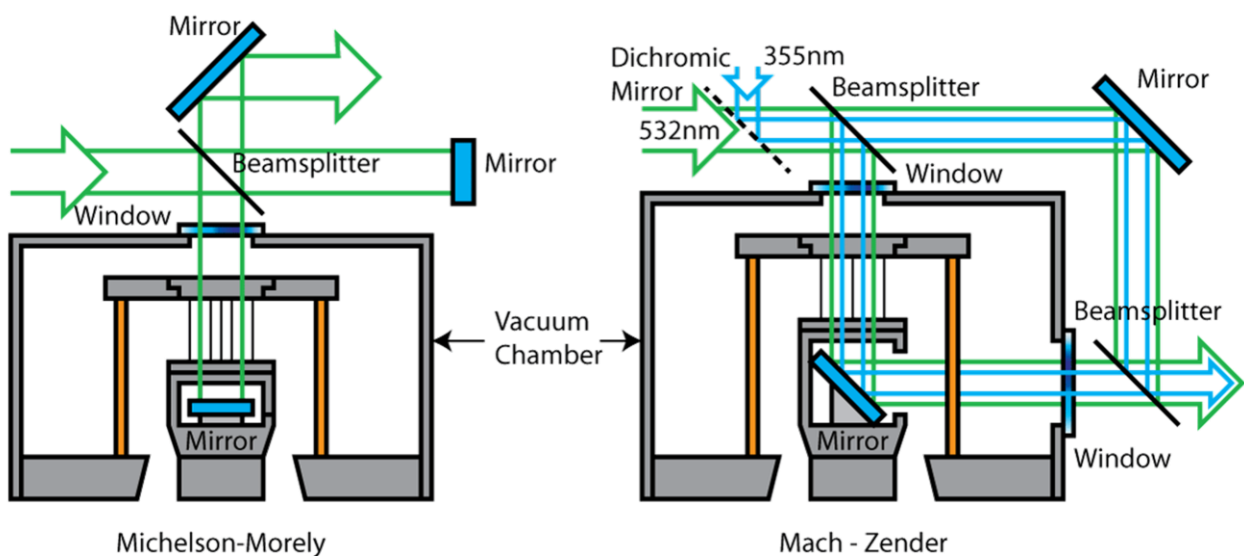


Figure 54 Schematics of two different optical setups for end-on interferometry. Focusing and image forming optics have been omitted.

ance of the interferograms the focusing optics should be adjusted in order to minimise the average displacement of the object from the focal plane. For a single-pass this means the focal plane should be placed halfway through the object while for a double pass it is placed at the retro-reflecting mirror. The average distance from the focal plane to the plasma is therefore unavoidably larger in the double-pass case.

Another consequence of this depth of focus requirement is that the mirror in the Michelson-Morley setup must be placed as close as possible to the array. The upper limit for the imaging time is set by the melt time of the cathode mirror surface. Melting is driven by heating by radiation produced as the precursor column is formed. With the Mach-Zender design it is possible to move the cathode mirror further from the array, reducing the radiation flux and effectively delaying the melt time, allowing the interferometer to access later points in the array evolution.

The third advantage of the single pass system is that it reduces the sensitivity of the interferometer. This is simply

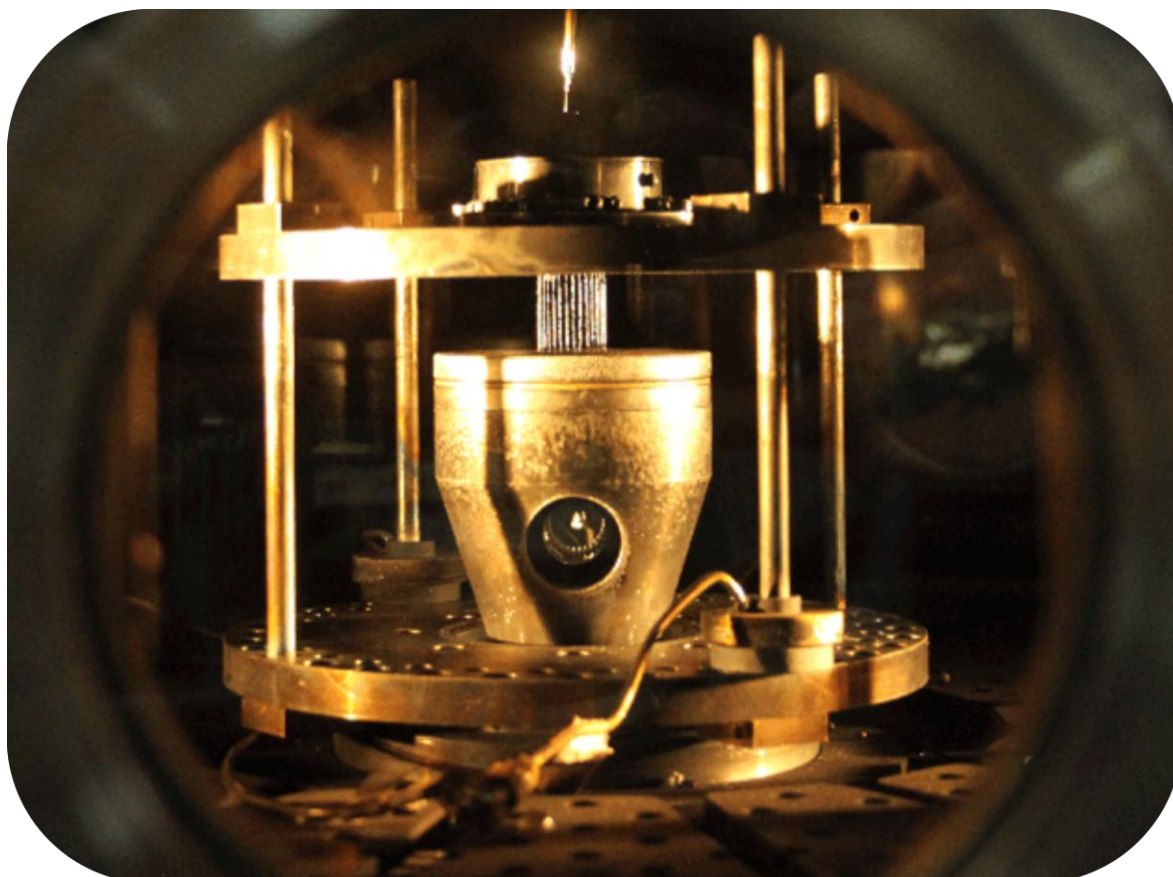


Figure 55 A Photograph of the a typical end-on interferometry load, taken during pump-down for shot s0520_11 – a $31 \times 10 \mu\text{m}$ W wire array, as viewed through one of the vacuum windows. The return post Rogowski grooves can be seen mounted around two of the current return posts.

because the probing beam now passes through less plasma. A lower sensitivity makes the interferometer more suitable for imaging at later times when the plasma density variations are larger.

5.2) Experimental setup for end-on probing

Fielding a Mach-Zender interferometer down the array axis required a major redesign of the array hardware. The diameter of the cathode needed to be significantly expanded in order to accommodate a mirror large enough to image the entire array. A photograph of an array loaded into the new hardware is shown in Figure 55. The laser exit hole can be seen directly below the array, and a wire mounting ring can be seen through it reflected in the mirror. The entire array had to be moved up with respect to its position in previous shots in order for the probing beams to be able to exit the vacuum chamber without the aid of further steering optics. This resulted in an increase in the height at which the standard side-on diagnostics suite was centred.

Delivering the probing beam down the array axis initially proved difficult. Mounting the required optics on the vacuum chamber lid was not ideal. The lid is removed between each experiment and once the lid is closed, access to the experiment is very limited, making further alignment adjustments difficult. Also, the lid deflects slightly during vacuum pump-down, adding a further complication to the alignment procedure. The problem was solved by mounting the beam delivery optics onto the ceiling above the experiment. This allows the interferometer to be aligned and the imaging optics to be focused before the lid is put in place, greatly simplifying setup. As has already been shown, a good quality focus is very important. An end-on view provides no obvious object to focus on. Therefore a special focusing target was designed to assist in the accurate positioning of the focal plane.

The optical setup for the interferometer is reasonably simple. Figure 56 a) shows a schematic of the full beam-line, including the beam delivery optics, the chamber and the image focusing optics. Figure 56 b) focuses on a schematic of the image forming optics. These optics result in an image magnification of $M=0.75$. This magnification was selected so the entire array diameter could fit onto the CCD surface. The spatial filter iris was set to 1cm, corresponding to a depth of field of $\sim 1\text{cm}$, and optical acceptance angle of 0.005 rad.

The end-on beam delivery optics were designed to allow two wavelength probing, at the second and third (532nm & 355nm) harmonics of the Nd:YAG probing laser. These two wavelengths can be fielded simultaneously, or at separate times in order to produce two image frames per shot. The extra optics required to deliver the second probing wavelength increases the time required for alignment between shots, but the large amount preparation required between each experiment means that the extra alignment time is easily outweighed by the benefits of producing two interferograms per shot.

The interferograms were captured on commercial Canon SLR cameras. The 532nm images were captured on a Canon 500D. The CCD dimensions are $22.3 \times 14.9\text{mm}$, with an array of 4752×3168 pixels. The 355nm images were captured on a Canon 350D with a $22.2\text{mm} \times 14.8\text{mm}$ CCD made up of $3,456 \times 2,304$ pixels. In order to detect 355nm light the IR/UV filter was removed from the CCD surface. The time resolution of the interferometer is set by the probing laser pulse duration which is approximately $\sim 500\text{ps}$. The camera shutter is held open for 1.3s ,

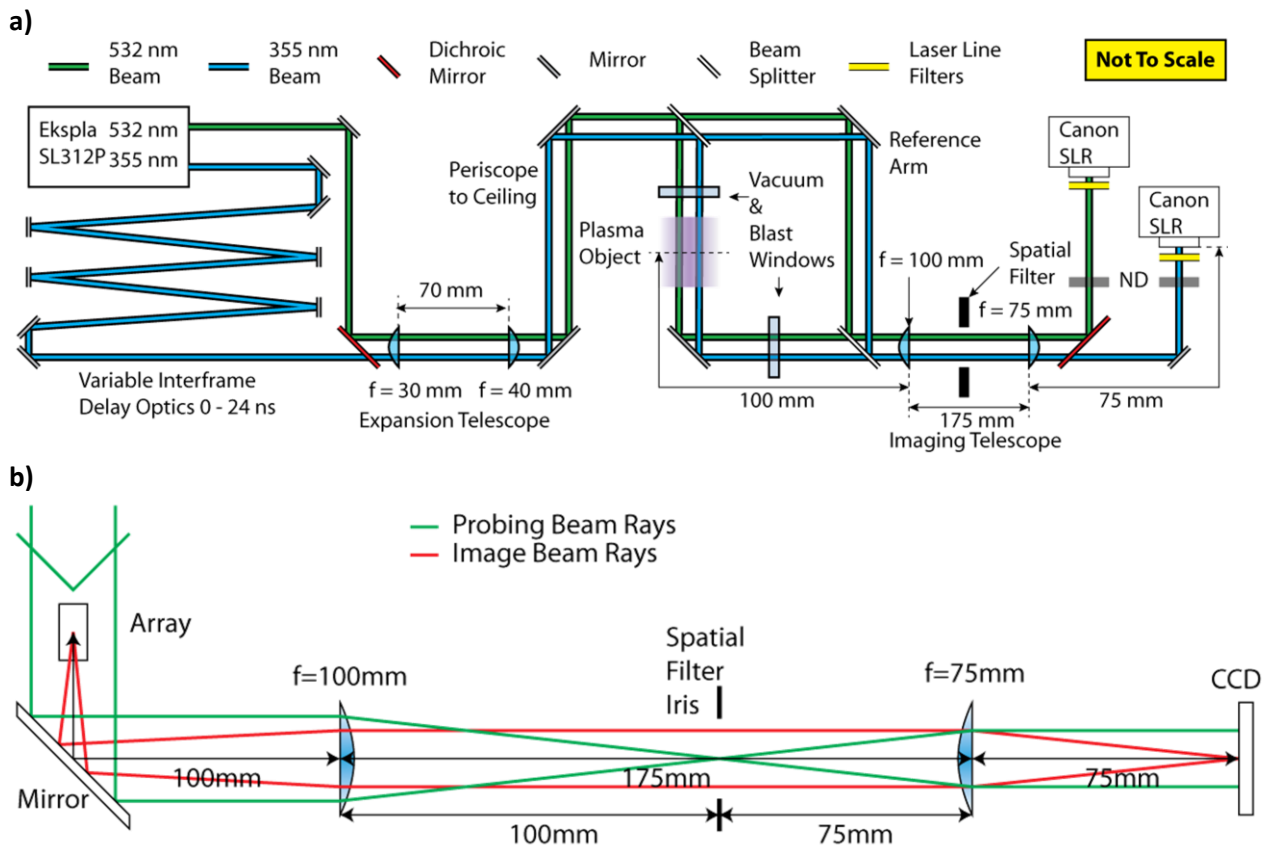


Figure 56 Diagrams of the end-on interferometer optical layout.

- a) A schematic of the end-on probing beam-line, showing beam delivery for the two wavelengths and imaging optics layout.
- b) Diagram of the end-on Imaging optics. The green lines show the effect of the optics acting on the undisturbed probing rays, while the red lines show the path of rays scattered by the array plasma.

long enough to cover the full duration of the experiment. Self-emission from the plasma is suppressed using a combination of multi-layer laser line filters on the cameras and spatial filtering to limit the acceptance angle of the optics. Neutral density filters are used to reduce the probe intensity before the image is captured.

The arrays fielded in these experiments are very similar to the standard arrays used in many other cylindrical wire array z-pinch experiments carried out on MAGPIE. The array diameter was maintained at 16mm, with wire number varying between 8 and 128 wires. Array lengths of both 1cm and 2cm were fielded. The main array materials used were tungsten and aluminium.

In addition to the end-on interferometer, side on laser diagnostics were also fielded in these experiments. Two probing beams were used, providing two separately timed frames. The beams were analysed using shadowgraphy, schlieren and interferometry techniques. A pair of 4-frame XUV MCP cameras were also fielded. These cameras each capture a set of four images of the plasma XUV emission, with 30ns between each frame. The data is used to produce a time histories of the array dynamics from a side on perspective. An X-ray PCD pack was used to monitor the radiative output of the arrays. In some of the later experiments a Thompson scattering diagnostic was fielded to measure the radial velocity profile of the ablation plasma. These measurements were synchronised with the end-on interferometry measurements.

5.3) Analysis technique

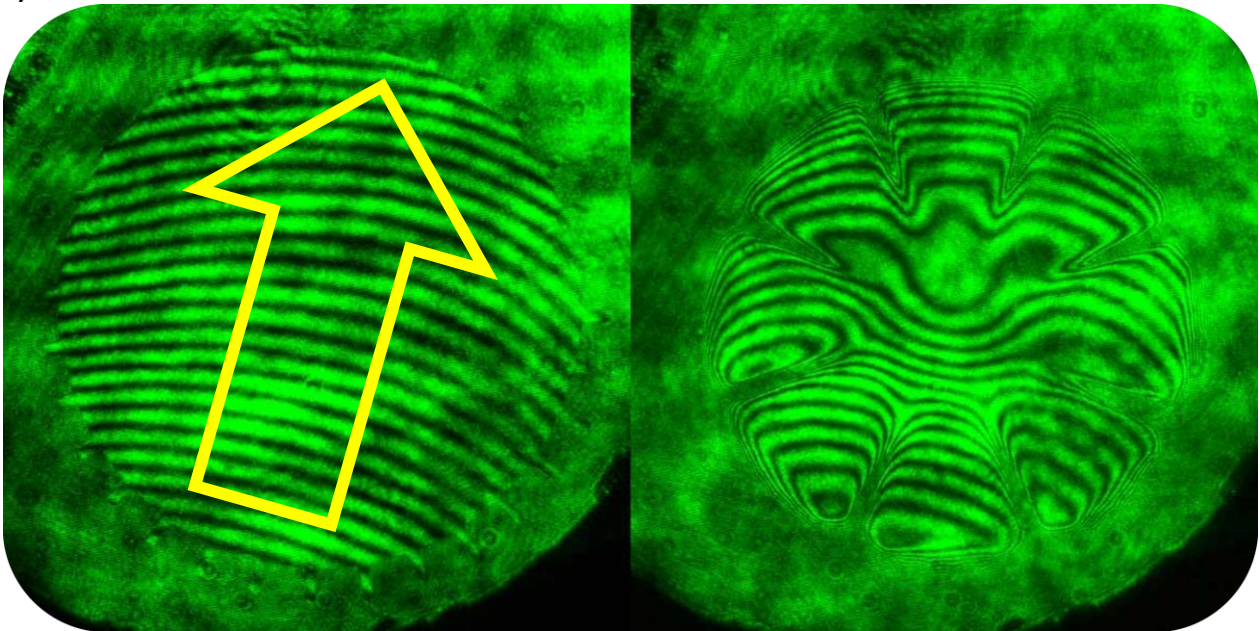
The technique used to analyse the interferograms was developed specifically for these experiments. The mathematics describing the interference of two laser beams is discussed in detail section 3.7.6). The fringe lines making up an interferogram follow lines of constant phase difference between the probe and reference beams. The phase difference separating consecutive fringes is 2π . Thus the interferogram may be interpreted as a contour map of the phase difference between the probe and reference beams.

Figure 57 a) shows examples of background and experimental interferograms of the ablation streams produced by an eight wire tungsten array. The background image is made up of a series of relatively straight fringes. These fringes are produced by introducing a small shearing angle between the reference and probing beams. The result-

ing pattern corresponds to a linearly increasing phase difference across the image. The direction is indicated by the yellow arrow. The spacing of the background fringes is controlled by the shearing angle. A larger shearing angle results in a higher background fringe density and vice-versa.

The beams used to produce the interferograms in these experiments are often of low optical quality, with large spatial variations in their intensity. As Figure 58 shows, secondary shadowgraphy effects due to the finite depth

a)



b)

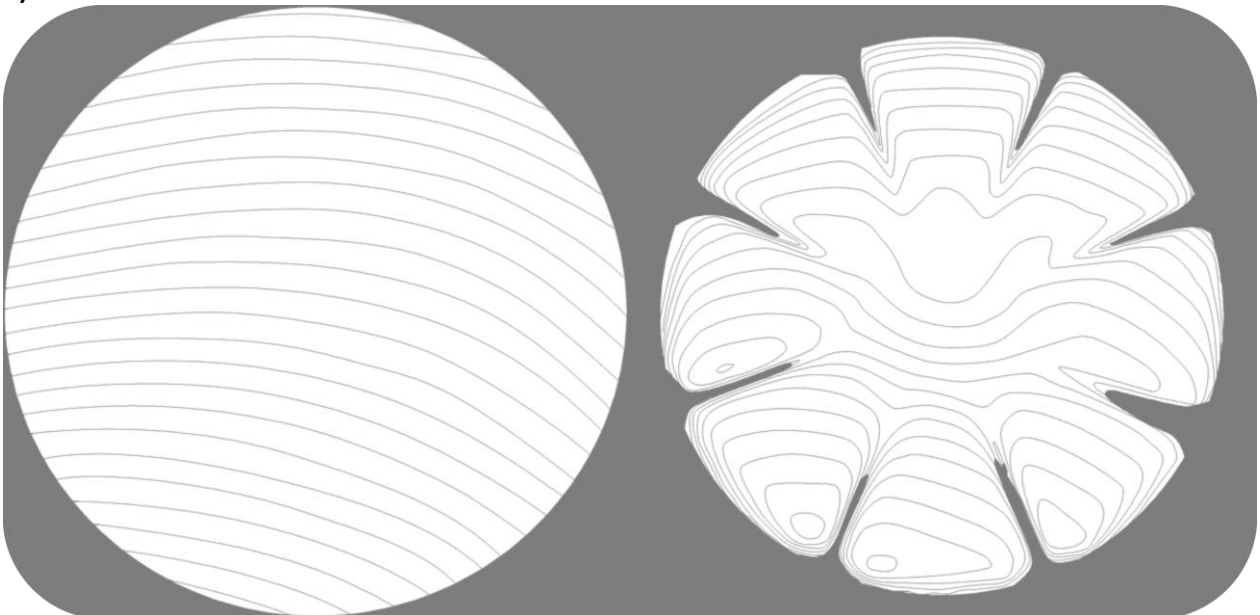


Figure 57 Examples of end-on interferograms and traced fringe maps: -

- a) Background and Experimental Interferograms for 532 nm channel. Taken from shot no. s0201_11, an 8 wire W array.
- b) Contour maps produced by tracings the lines of minimum fringe intensity. These Images are formatted as the input for the fringe numbering program. Fringe minima are marked in black, untraceable regions are masked in grey and regions to be interpolated are marked white.

of focus of the imaging optic cause brightening and darkening of the image around regions corresponding to strong density gradients. Accurately extracting the full phase information based on how the intensity changes between these two states is difficult and unreliable. As a result this analysis has focused on extracting information by tracing the lines of minimum fringe intensity (dark fringes).

The first step to extracting the data from an interferogram is to trace the fringes. The tracing has been done manually, as the fringe patterns produced are often complicated (see Figure 58) and the signal to noise ratio too poor to allow a computer to make an accurate tracing. Adobe Photoshop software was used to trace the fringes, as it provides a powerful set of drawing tools as well as an extensive library of filters for adjusting the brightness and contrast of the interferograms. Figure 57 b) shows the contour maps that resulted from tracing the interferograms shown in Figure 57 a). The fringe tracing process is by far the most time consuming stage of the analysis. There is an on-going effort to improving the quality of the laser optics so that computerised fringe tracing algo-

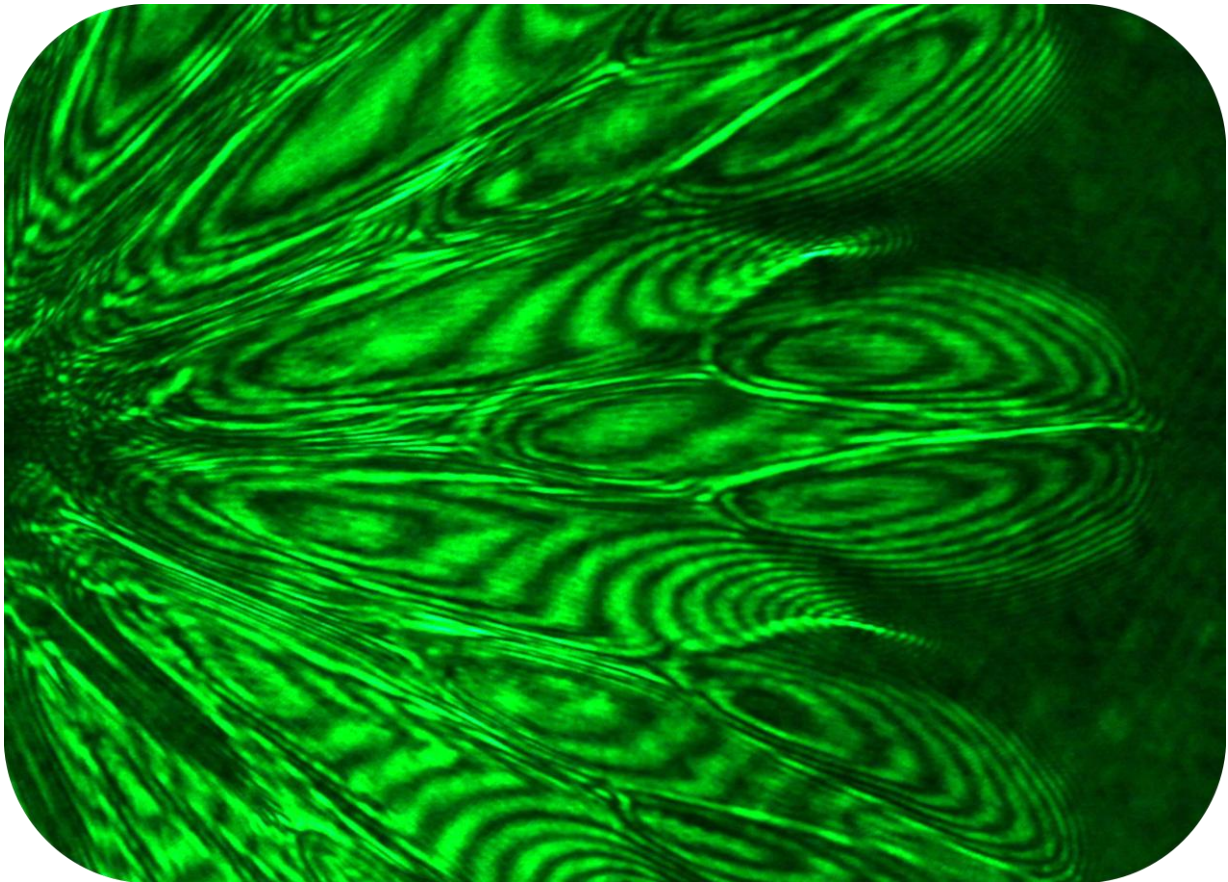


Figure 58 Example of shadowgraphy effects on an interferogram. The image is brightened and darkened around regions with large density gradients, making fringe tracing difficult.

rithms may be used.

Once all the fringes have been traced, a specially formatted contour map is produced. This contour map is then loaded into the fringe numbering program. This program assists in assigning each of the contours a relative phase-shift index. The process is analogous to assigning height values to the contour lines on a map. The fringe numbering is also done by hand as in many situations the direction of phase change can be ambiguous and require some interpretation. Once all the fringes have been correctly numbered the phase contour map is complete. The left-hand column of Figure 59 shows the completed background and experimental phase contour maps for the interferograms shown in Figure 57.

In order to retrieve the phase due to the plasma, the background phase must be subtracted from the probing phase map. This process poses a problem; the spatial distribution of the data contained in the background and experimental contour maps does not match. The solution is to interpolate the data between the contours, producing complete phase maps for both the experimental and background images. The process is illustrated from left to right in Figure 59. Interpolation is carried out using a Delaunay triangulation algorithm, which is designed to interpolate data-points based on a scattered input dataset. The interpolation method is linear and implemented using the built-in 'triscatteredintep' class in Matlab. Once the interpolation is completed, the phase maps are

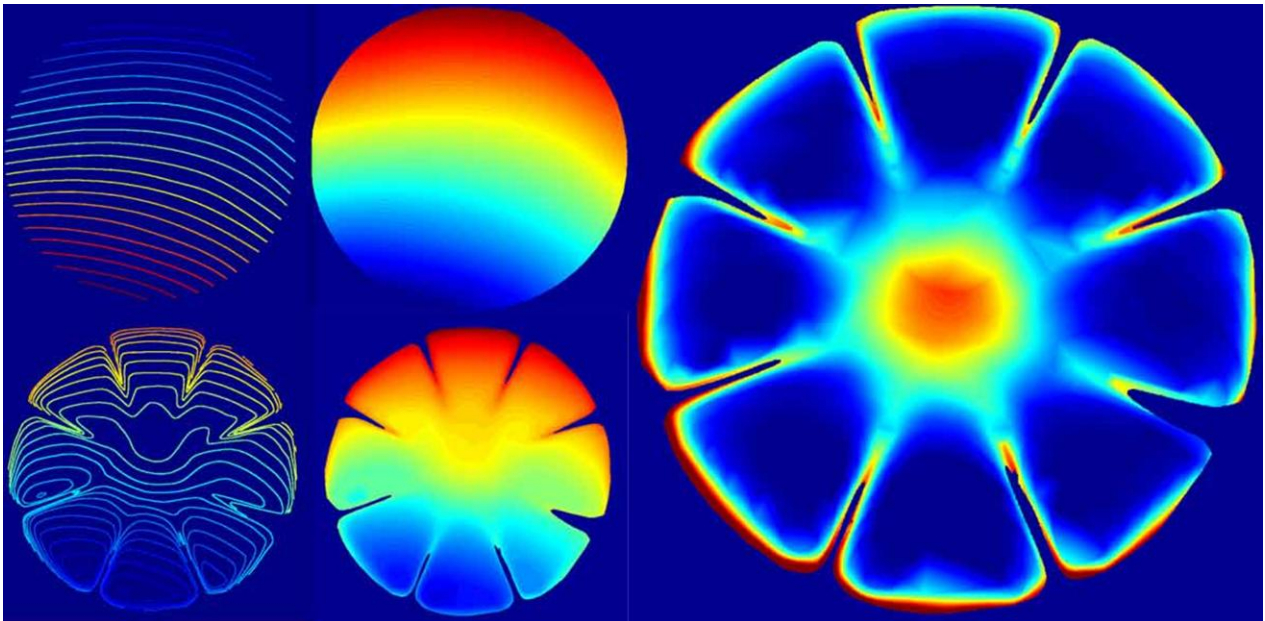


Figure 59 The analysis process for end-on interferograms. On the left, the traced fringes are assigned phase values; in the middle, the space between the fringes is interpolated; on the right, the interpolated phase maps are subtracted.+

subtracted, to produce a map of the phase imparted by the plasma. A zero fringe shift value must be assigned to the phase map. This is discussed in more detail in the next section.

The final step of the analysis is to convert the phase map into an electron density map. A calibration factor is required to convert the phase delay into areal electron density. The derivation for the free electron model of the plasma refractive index is in section 3.7.2). Calculations using equation (3.7.14) yield areal electron densities per fringe shift of $6.3 \times 10^{17} \text{ cm}^{-2}$ for 355nm and $4.2 \times 10^{17} \text{ cm}^{-2}$ for 532nm images. The electron density map is calculated by multiplying the relative phase map by the corresponding areal density calibration and then dividing by the array length.

Appendix A contain a number of raw interferograms, included as examples of the typical data captured during the experimental series.

5.4) Zero fringe shift

In side on interferograms fringes can often be traced out to large radius where it is safe to assume that the electron density is zero, an example of this is shown in Figure 60. This region can be used to set a baseline for measuring the relative fringe shift in the rest of the image. This baseline is referred to as the zero-fringe. With an end-on interferogram the mounting electrode acts as a mask, so that fringes can only be seen within the array radius.

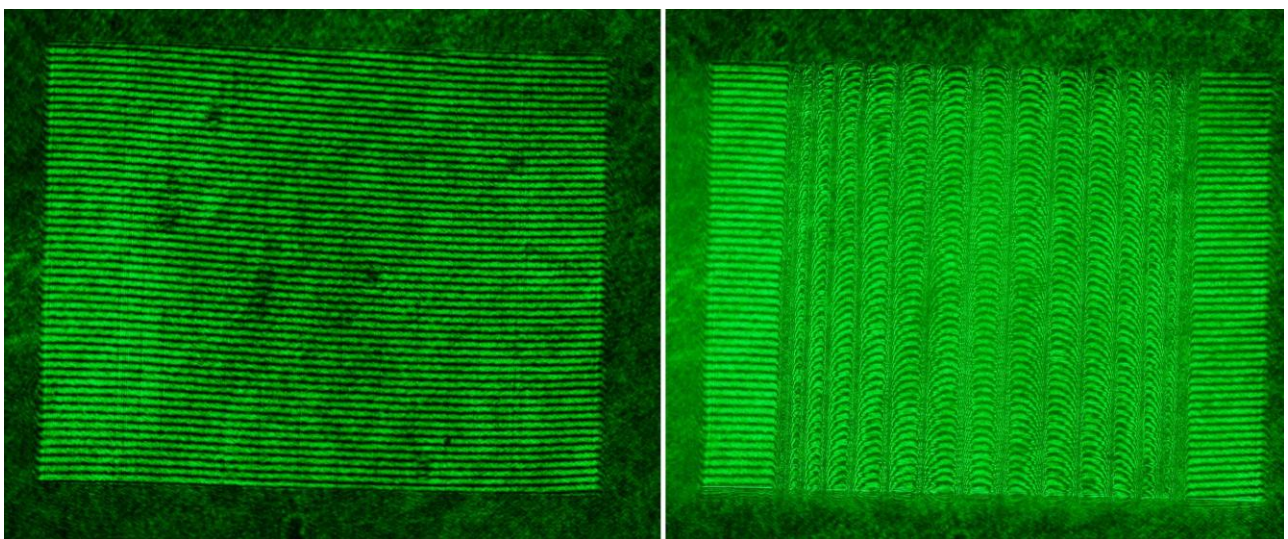


Figure 60 An example of a side on interferogram. The fringes outside the array are undisturbed, and can be used as a reference for the zero fringe shift, allowing measurements of the absolute electron density.

Other methods must be used to estimate the zero fringe-shift.

5.4.1) Zero-fringe calibration using a rocket model calculations

Rocket model calculations can be used to estimate the density profile that we would expect to see at a given time during the experiment. If no other method is available, this estimate may be used as a crude calibration for the zero-fringe shift. Details of the mathematical arguments and derivations for the rocket model are given in section 1.4.3). The resulting equation for the plasma density is:

$$\rho(r, t) = \frac{dm}{dV} = \frac{dm}{dt} \frac{dt}{dr} \frac{dr}{dV} = \frac{\mu_0 I(t_d)^2}{4\pi^2 r R V_{abl}^2} \quad (5.4.1)$$

$$t_d = \left(t - \frac{(R - r)}{V_{abl}} \right)$$

To extract the electron density, this density must be divided by the ion mass and multiplied by the expected value of the average ionisation.

$$n_e(r, t) = \rho(r, t) \frac{\bar{Z}}{A} \quad (5.4.2)$$

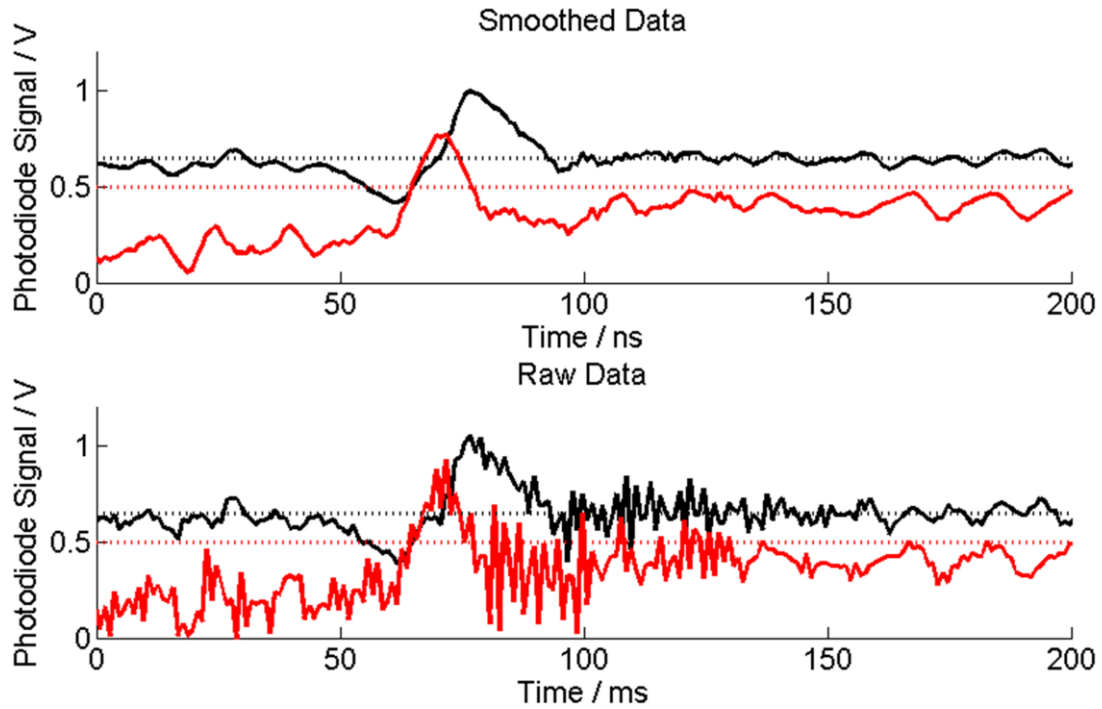


Figure 61 Top, the smoothed data used in the analysis. Bottom, the raw voltage signals from the quadrature interferometer.

The zero fringe-shift can then be adjusted to match the experimental line profiles to the computed profiles as closely as possible. This method is far from ideal, and care must be taken to account for azimuthal density profile variations that are ignored by the rocket model.

5.4.2) Calibration using CW interferometer

A better technique for measuring the zero-fringe shift is to use a CW interferometer. This is an interferometer that measures fringe shift for a single line through the plasma as a function of time. A CW quadrature interferometry system was developed by the author, and is discussed in detail in section 4.1). In order to measure the

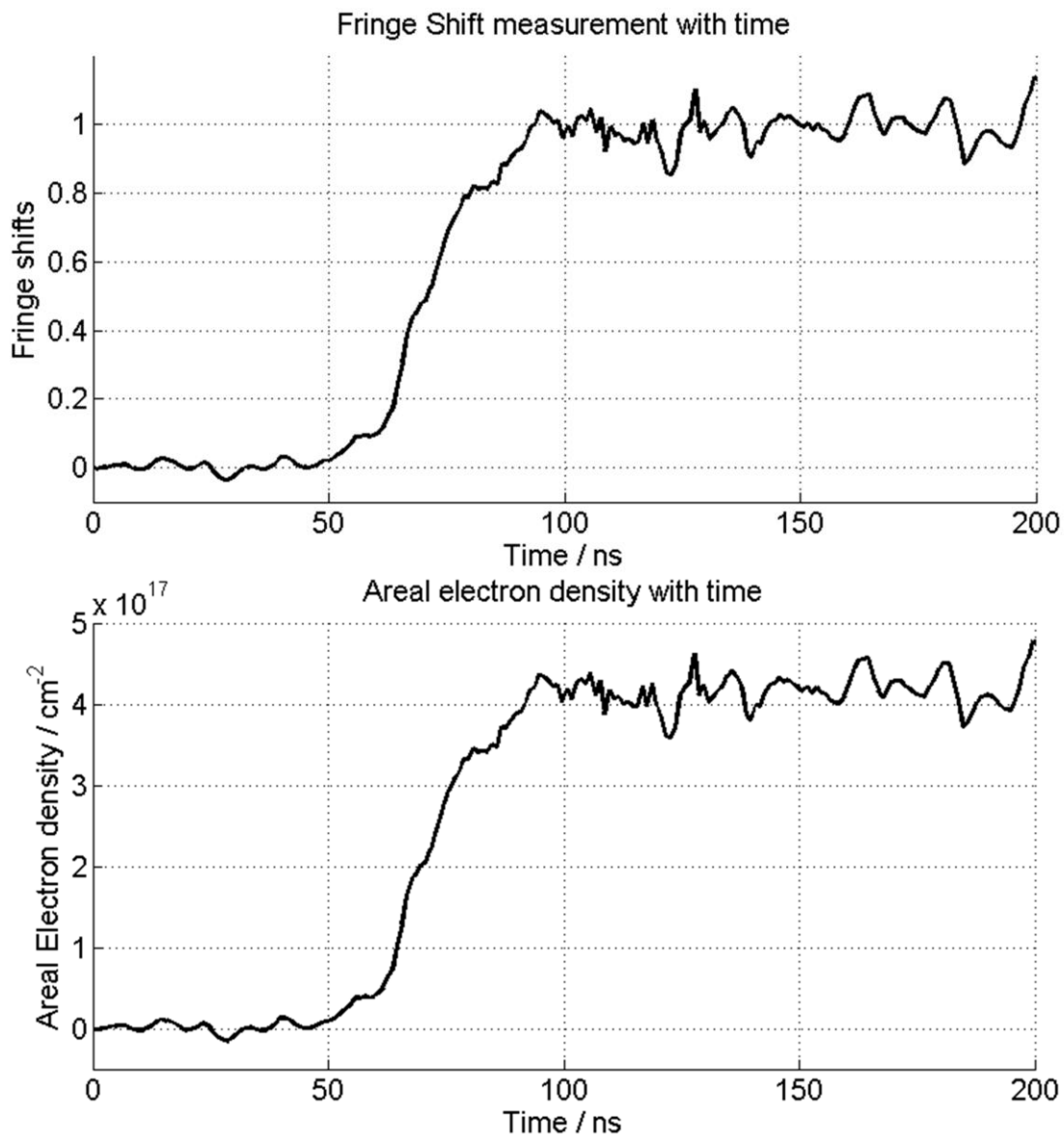


Figure 62 Top, fringe shift as a function of time, bottom, areal electron density as a function of time.

zero fringe-shift, the CW beam must be aligned parallel to the axis of the array at some known radius. Ideally the radial position of this line is selected so that the beam passes through the region with a reasonably flat electron density profile. This minimises the sensitivity of the measurement to the exact position of the beam. The experimental configuration used for this measurement is shown in the bottom half of Figure 39. Once the data has been analysed, the zero-fringe shift of the interferogram can be read by cross-referencing the image timing.

A zero-fringe measurement using this technique was carried out on a 32 wire tungsten array, shot s0209_11. The 32 wire tungsten array was selected as it provides a large region where the density profile is radial and azimuthally flat. As Figure 73 illustrate, this region retains a flat profile over a large fraction of the experimental time and extends over a radial range of 3-5mm. For the experiment the beam was placed at a radius of 4mm from the axis of the array. Figure 61 shows the signal both before and after the application of a nearest neighbour smoothing algorithm. The I_0 mean intensity calibration was estimated by eye, and is plotted as a dotted line in Figure 61.

The data was analysed using the algorithm discussed in section 4.1.3). The results of this analysis are shown in Figure 62. The top plot shows the fringe shift as a function of time, while the bottom plot shows the corresponding areal electron density.

The signal is extremely noisy, making it difficult to assess whether the measurement has failed. The sudden end to the rise in density at ~ 90 ns suggests that the measurement has failed here. Further work is required to perfect this technique for measuring the zero-fringe shift. The current measurement does not extent far enough to accurately estimate the fringe shift of the interferograms captured later than 90ns into the experiment. It is at least useful in that it places a lower limit of 1 for the zero-fringe shift.

5.5) Dynamics of tungsten wire array implosions

The end-on interferometer was used to investigate the ablation dynamics of tungsten wire arrays. The upper limit of the probing times accessible to the interferometer was limited by the melt time for the surface of the cathode mirror. This normally occurred around the time of precursor collapse. The details of precursor formation physics are discussed in reference [1]. For most of the experiments it formed at $\sim 160\text{ns}$ from current start. The arrays used in these experiments were designed to be over-massed for the generator. This meant that they did not implode and hence there was no stagnation. As a result, the x-ray signals measured in these experiments are relatively small. The wire numbers of the arrays fielded ranged from 8 to 128 wires, with a standardised 16mm array diameter. Both 1cm and 2cm long arrays were fielded.

5.5.1) Validation of the Free Electron model

The refractive index of the plasma was calculated using the free electron model. This model is described in some detail in section 3.7.2). By using this model we are making the assumption that the bound electron component of the refractive index is negligible. The calculations required to find the bound electron contribution, especially for tungsten, are extremely complex. An experiment was conducted in order to investigate whether the bound electron effects were significant. In this experiment the timing of the two end-on laser probing channels was synchronised. The two interferograms obtained were analysed, and the electron density maps were calculated using the free electron refractive index calibrations. The areal electron densities associated with a single fringe shift, calculated using the free electron model, are $4.2 \times 10^{-17} \text{cm}^{-2}$ and $6.3 \times 10^{-17} \text{cm}^{-2}$ for 532nm and 355nm probe wavelengths respectively.

Figure 63 shows the electron density plots for two interferograms obtained in this experiment (shot s0125_11). The load was a of $32 \times 10\mu\text{m}$ tungsten wire array and the interferograms were captured at 150ns from current start. A zero fringe shift of 2 was applied to the 532nm image. It should be noted that the current in this shot was significantly below average due to the failure of part of the generator.

The two electron density plots appear qualitatively very similar. A quantitative comparison was made by taking line profiles through each of them. The profiles were taken both along the ablation streams and between them. The resulting data, shown in the lower half of Figure 63, illustrates the excellent agreement between the two measurements. The scale of the density variations matches extremely well and by adding a zero-fringe shift of two to the 532nm data we have managed to very closely match the precise density values. As expected, the harder 355 nm probe penetrates better into the higher density gradients at the edges of the array.

From this data we can conclude that the ion component of the refractive index for this plasma is at the very least small in the regime of interest. At the very least, the data calculated from 532 and 355nm phase maps using the-

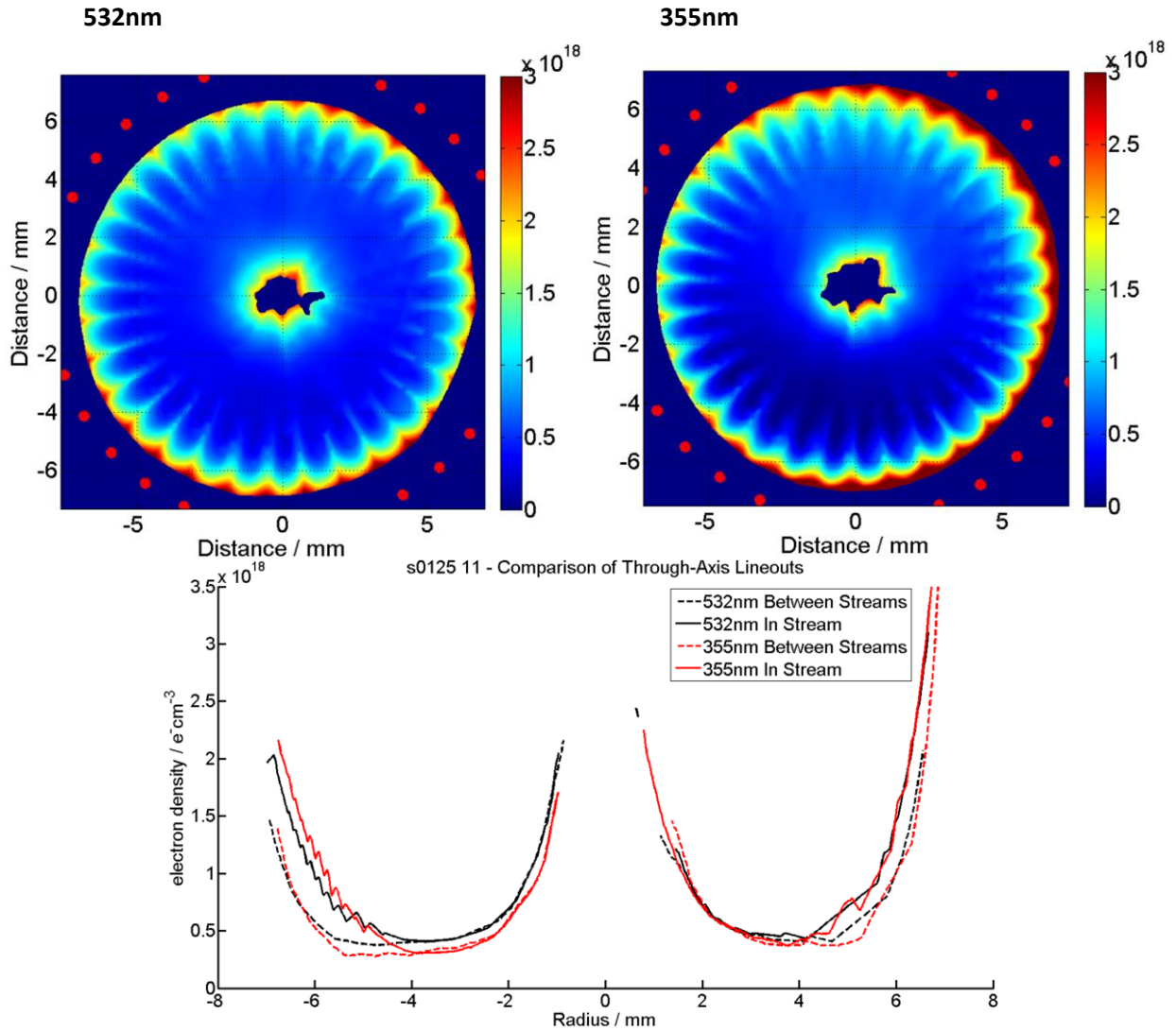


Figure 63 Electron density plots from shot s0125_11. The image on the left is the 532nm frame and the image on the right is the 355nm frame. These interferograms were captured simultaneously. A zero fringe shift of 2 fringes was applied to the 532 nm image. The two images appear qualitatively similar. Below are line-profiles through these datasets, both along the ablation streams and between them.

se calibrations should produce comparable results for making arguments about the evolution of ablation structures.

5.5.2) 8 wire array data analysis

Initial experiments using the end-on interferometer were carried out on 8 wire tungsten arrays. These arrays were constructed from $18\mu\text{m}$ wire. Figure 64 shows the result from shot number s0804_10. This image was captured at 128ns. The ablation dynamics are dominated by sharply defined ablation streams flowing from each of the wires. Very little plasma is observed in the inter-stream region. The strong density gradients across the ablation streams meant that the fringes could not be traced through large portions of them and therefore these regions have been masked in the plot. At this time the density distribution about the axis appears broad and

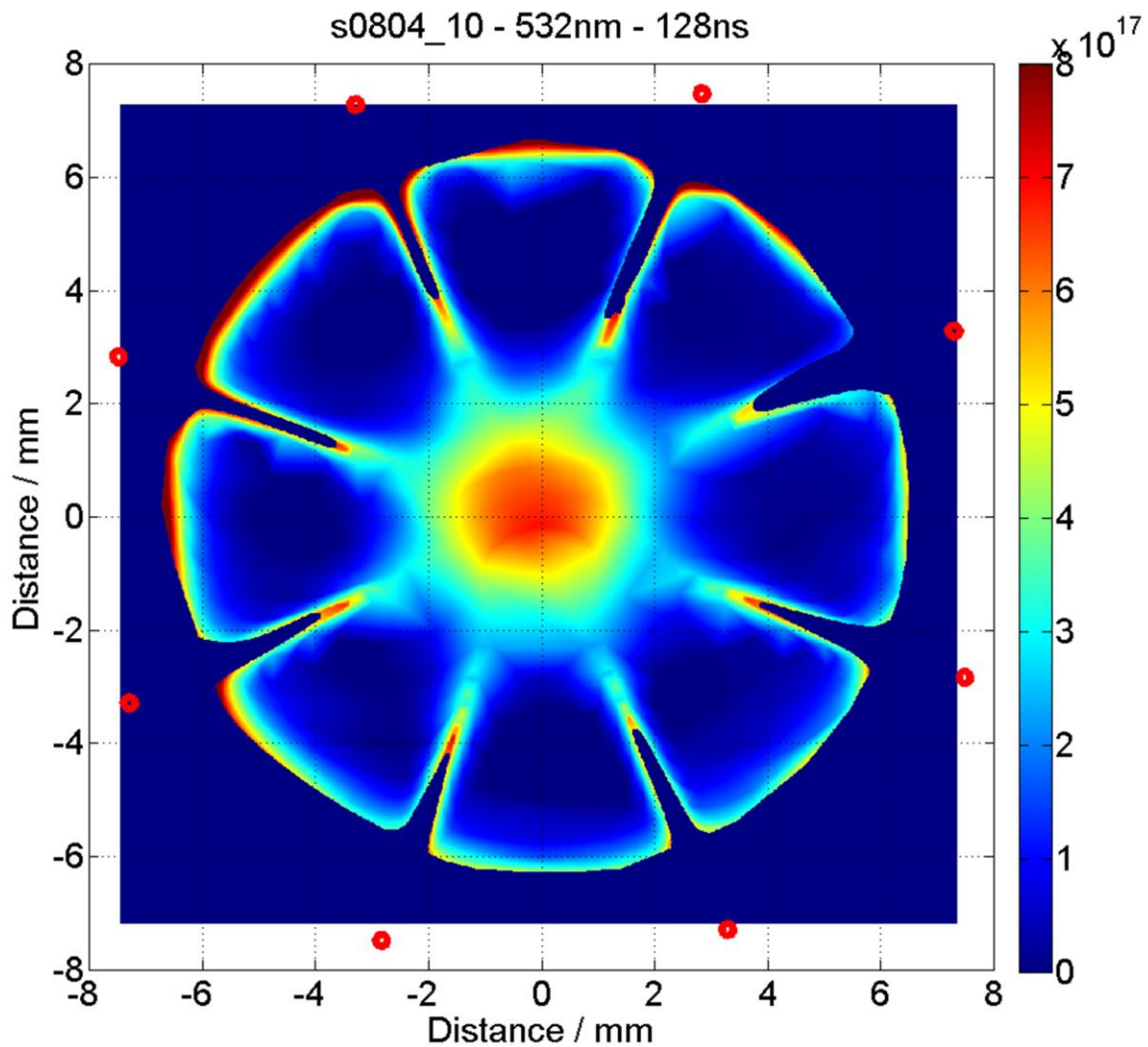


Figure 64 End-On Interferogram of an 8 wire tungsten arrays at 128ns. Red dots mark the initial wire positions.

smooth. This is before collapse and formation of the narrow, dense precursor column. It is interesting to note that although the ablation streams initially appear well defined and sharp, there appears to be very little azimuthal variation near the axis.

Around the outer radius of the array there appears to be a halo of high density plasma. This is believed to be due to plasma emitted from the wire mounting rings. A similar effect is observed near the electrodes in side on interferograms. High density plasma expands from the electrode surfaces, producing a sharp density ramp. The wire

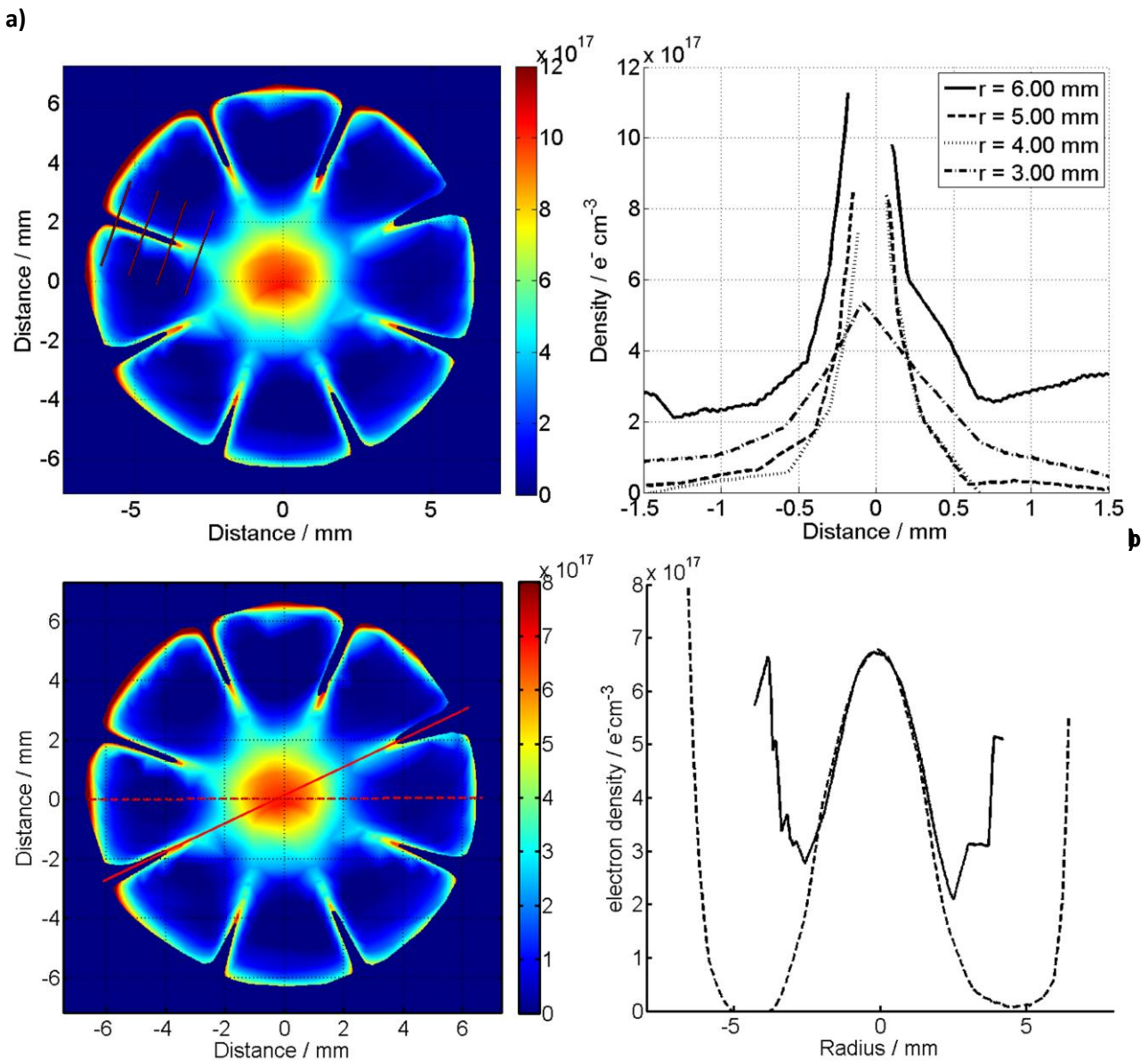


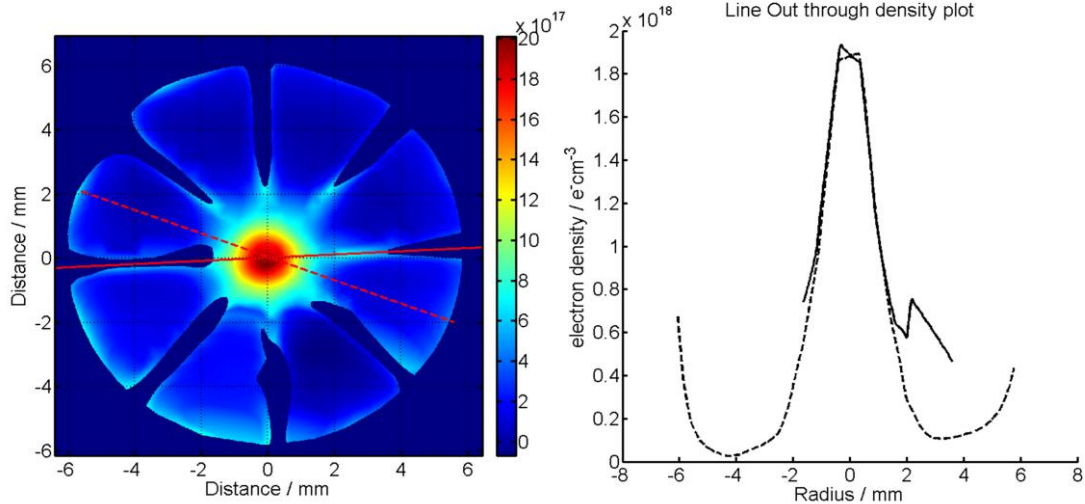
Figure 65 Line Profiles from shot s0804_10, an 8 wire W array at 128ns

- Series of line-profiles through the ablation streams.
- Line-profiles through the precursor distribution. The solid line passes through the ablation stream while the dashed line is placed off axis.

notches extend out to a radius of 7mm, so that combined with the plasma expansion effect, the visible plasma is limited to a radius of between 6–7mm.

Figure 65 a) shows plots of a series of line profiles taken across one of the ablation streams. The measurements indicate a stream FWHM of ~ 0.5 mm. Figure 65 b) shows a pair of line profiles taken through the array axis. The solid line is taken along one of the ablation streams while the dashed line is a profile taken between them. These profiles reveal a broad precursor column which appears to be azimuthally isotropic within a radius of approximately 2.5mm. It is characterised by a full width half maximum of 3.8mm. The isotropy of the precursor column is especially remarkable given the sharp density profiles of the ablation streams that form it. This is strong evidence

a)



b)

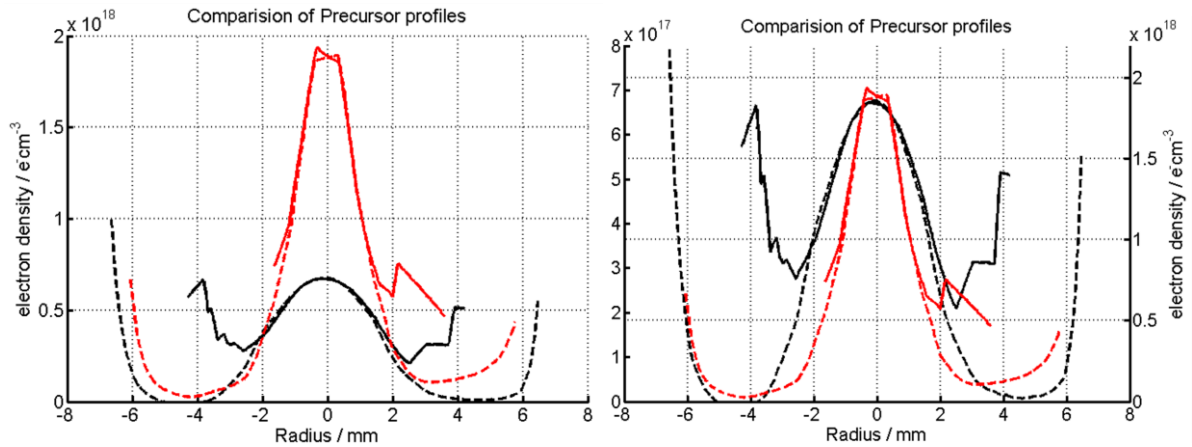


Figure 66 Line profiles of 8 wire tungsten arrays. No zero shifts have been applied

- Shot number s0802_10, an 8 wire W array. Image captured at 145 ns. The solid line plot is the on-stream line profile and the dashed line is the off-wire line profile.
- Comparisons of the precursor density profile for 128ns (Black Lines) and 145ns (Red Lines). The Plot of the left is scaled while in the right hand plot the peaks have been matched to compare the distributions.

for some form of collisional redistribution of the incoming mass.

Shot s0802_10 was taken slightly later, at 145ns. Figure 66 a) shows plots of the precursor electron density profile at this time. The peak density on axis has increased but the FWHM of the distribution has reduced to ~ 2 mm. Figure 66 b) illustrates the change in the shape of the profile. On the left, the two profiles are plotted to the same scale while on the right they are plotted on separate scales in order to compare their profiles. The data is consistent with the model for a precursor column formed by the compression of mass onto the axis by the pressure due to the incoming streams. Again, the strong density gradients present in this shot mean large portions of the ablation streams in the interferogram were not traceable.

Measurements of the current pulses for these two shots are shown for comparison in Figure 67. The solid lines show the raw MITL signal and integrated current, while the dashed lines show the same data for the return

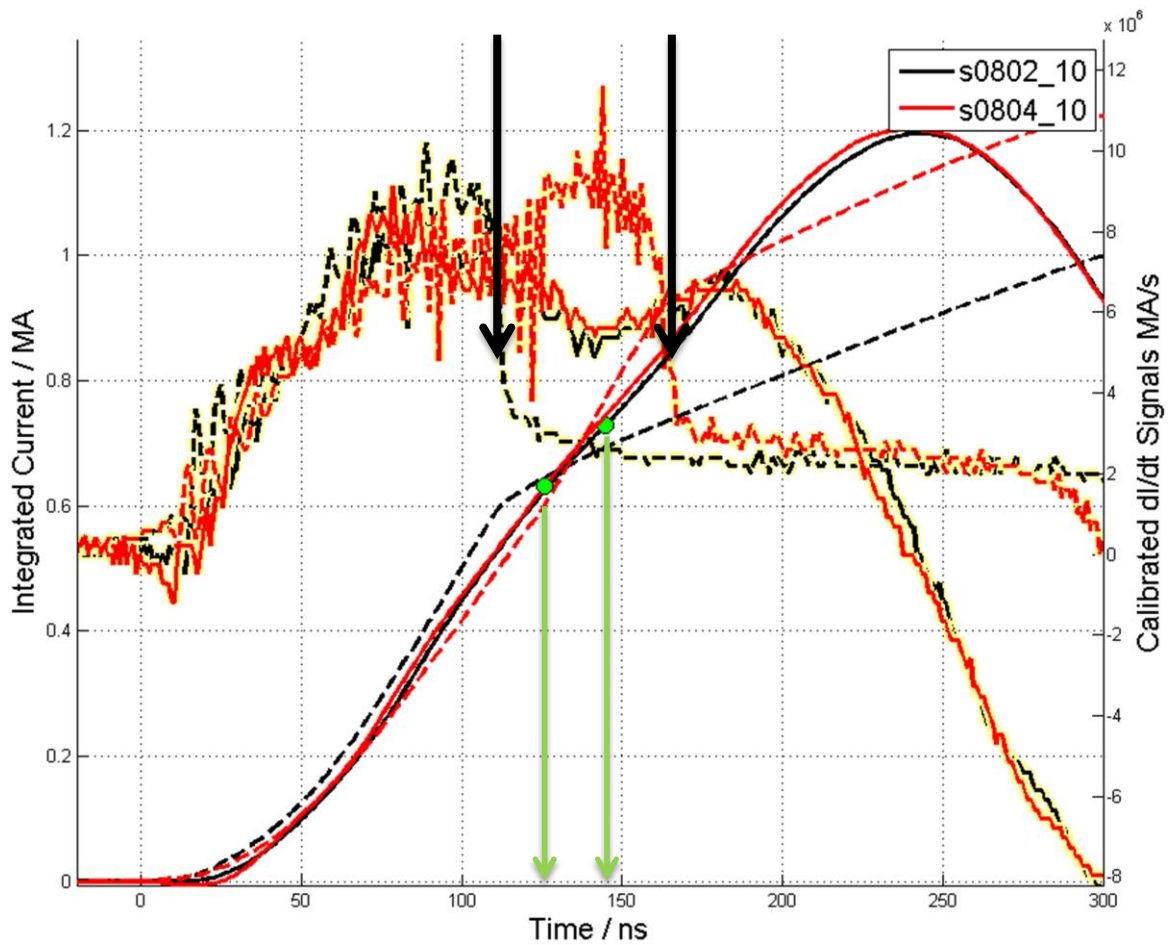


Figure 67 Current traces from shots s0802_10 and s0804_10. The $\frac{dI}{dt}$ signals are highlighted in yellow. Dashed lines correspond to the return Rogowski signals, the solid lines to the MITL B-dot signals. In both experiments the Rogowski probe has failed. The point of failure is highlighted by black arrows. The green dots mark the timings for the two interferograms.

Rogowski probes. The current measured by the return Rogowski probe shows strong discontinuities in both shots, appearing at different times in each. It is believed that this is due to electrical breakdown of the Rogowski probe. Surface plasma produced when radiation produced by the load ablates the exposed surfaces of the probe can provide an alternative current path, circumventing the diagnostic. The current measured by the MITL B-dots does not show this discontinuity. Therefore the MITL B-dot trace has been used in an attempt to reproduce the current delivered to the load. The B-dots were calibrated by matching the MITL current to the early return Rogowski current, in the region before it failed. This calibration of the B-dot was maintained between the two calculations, demonstrating the reproducibility of the signal.

While the MITL B-dots are not the ideal probe for the load current, they produce more reliable and reproducible data than that obtained from the Rogowski signal. The main reasons for this are that they are very rarely moved between shots, and undergo much less stress during each shot. Also, since each return Rogowski measures the current in only one of the four return posts, there may be an error in the measurement due to unequal division of the return current. It should be noted that the MITL current signals are not sensitive to any current losses beyond the MITL neck. Since the MITL B-dot signal shows the current in the two shots to be very similar, we can assume a similar dynamic timescale for the two experiments.

The density gradients in the ablation streams produced by 8 wire arrays proved too strong to probe using the end-on interferometer. Therefore it was decided to focus further study on arrays of greater wire number as this reduces the current per wire and therefore the density of each stream. The end-on probing system used at the time that these experiments were conducted used only a single colour probe. Focusing techniques used to improve image quality had not been developed. It may be interesting to do further experiments with the improved apparatus to get better measurements of the ablation stream profiles.

5.5.1) 16 wire array data analysis

Two experiments were carried out on 16 wire tungsten arrays. Figure 68 shows plots of the electron density distributions extracted from the four interferograms captured in these experiments. Shot s1007_10 was a 20mm long array using 7.5 μ m diameter tungsten wire. Interferograms were captured at 101ns and 125ns. Shot s1012_10 was a 10mm long array, with 13 μ m wires. Image times were 133ns and 157ns. The wire mass was increased between these shots in order to better suppress implosion and reduce early radiation yield, as the second interferogram captured in s1007_10 showed signs of the onset of mirror melt.

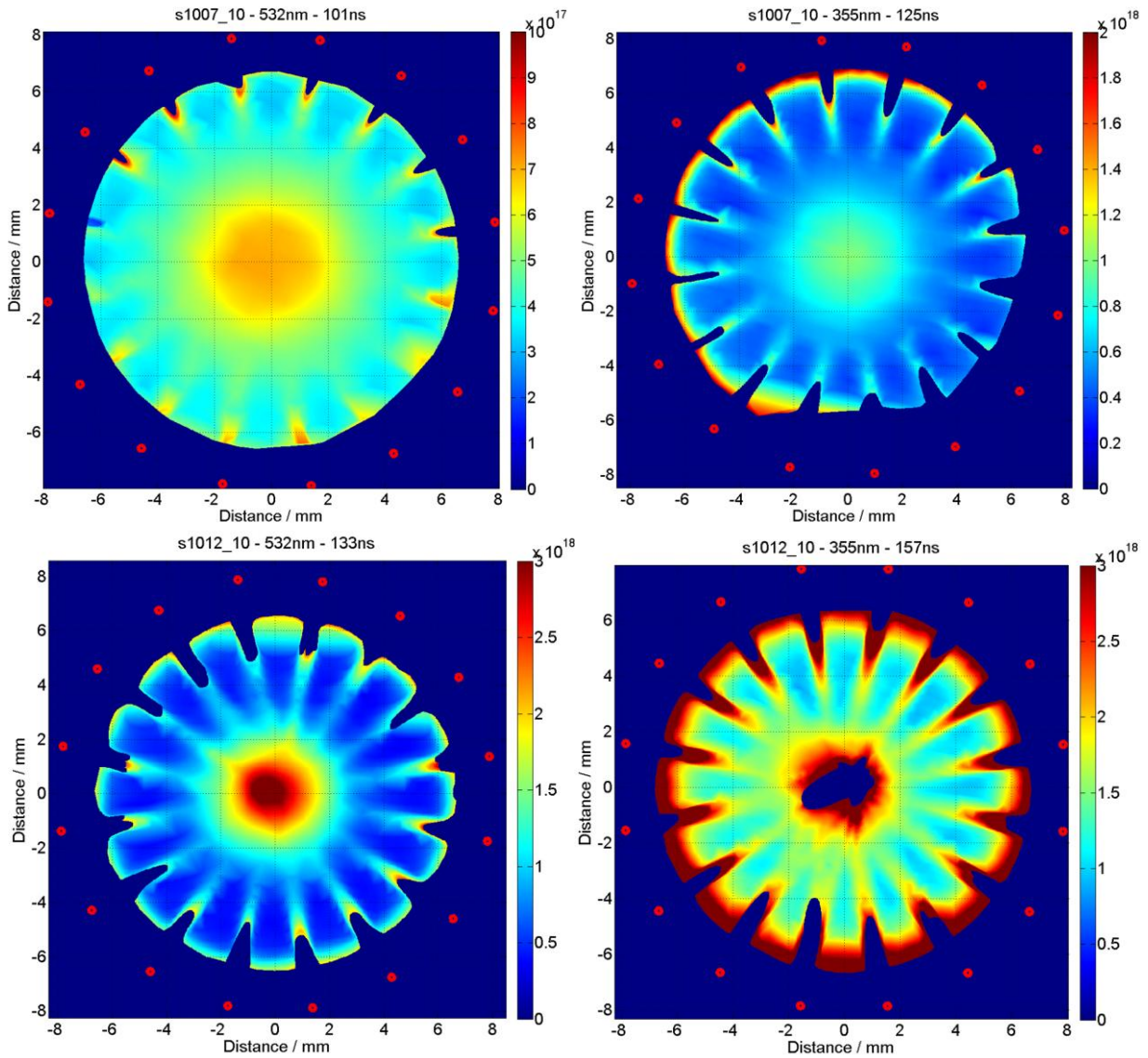


Figure 68 Density profiles for 16 wire tungsten arrays. Red circles indicate the initial wire positions. The corresponding current traces are shown Figure 70. Colour scales vary between plots.

On the left hand side of Figure 70 is a plot of the load current measured in these experiments by one of the return Rogowski probes (dashed lines) and by one of the MITL b-dots (solid lines). A radiative power trace is also included, taken from PCD1. This was filtered by a 2 μ m polycarbonate film. The timings of the four interferograms are marked on the corresponding current traces. In shot s1007_10 we can see a radiative peak around 160ns, with a small ramp of radiation leading up to it. This may be the pulse which has caused the mirror to begin melting by the time of the 355nm interferogram. The trace for shot s1012_10 does not show this, indicating that the increase in mass has successfully suppressed radiation production.

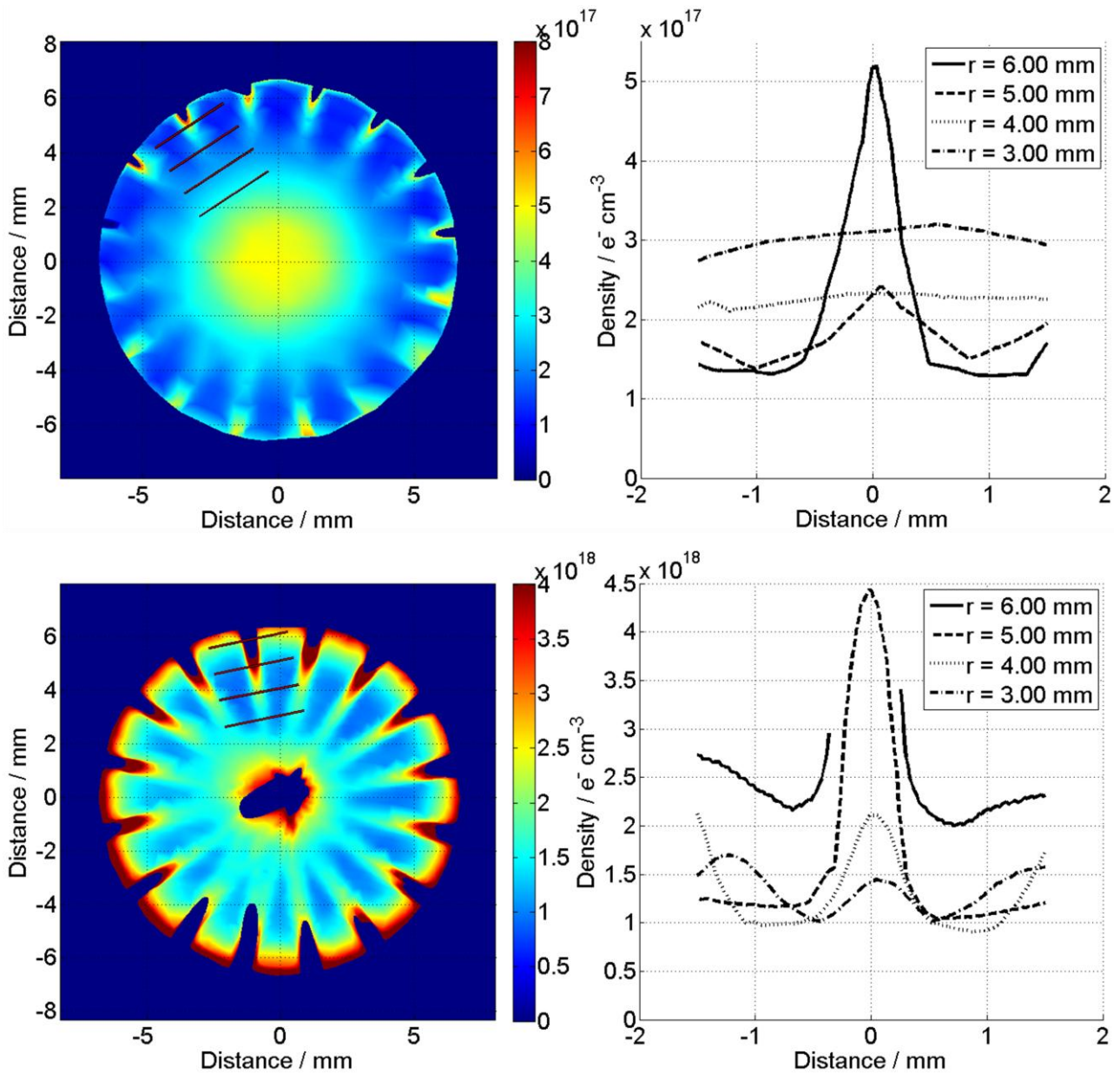


Figure 69 Series of line profiles taken through the ablation stream profiles of 16 wire arrays at 101 and 157 ns.

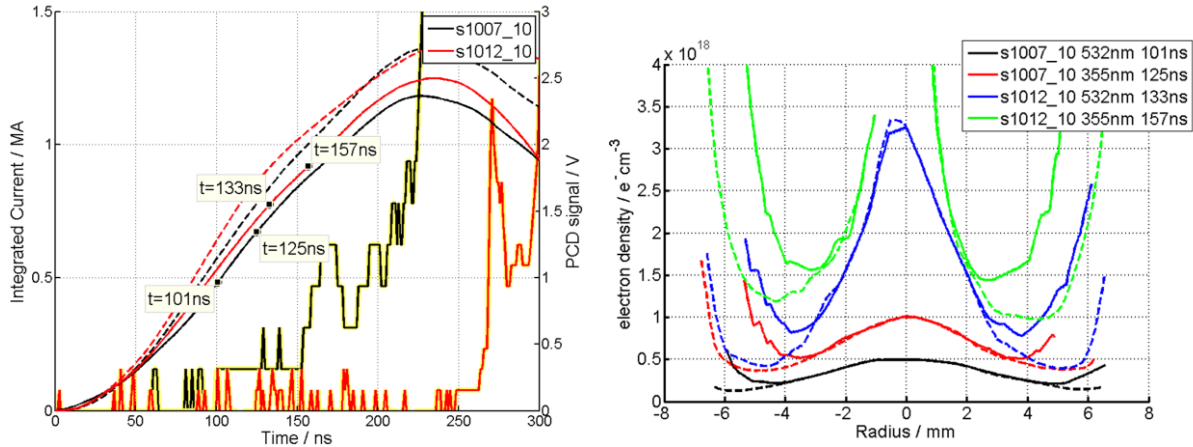


Figure 70 Data from 16 wire tungsten array shots

Left Graph: Current curves, calculated MITL B-dot (Solid Line) and Return Rogowski (Dashed line) signals. Yellow highlighted plots show the signals recorded by PCD1. End-On interferogram image timings are marked on the respective current traces. The data extracted from these interferograms is displayed in Figure 68.

Right Graph: Electron density line profiles for the 4 density maps in Figure 68. Solid line is through ablation streams, dotted line is between ablation streams.

On right side of Figure 70 are a series of line profiles taken through the axis of each of the interferograms in Figure 68. As in previous plots, the solid lines in this plot show profiles through the ablation streams while the dashed lines are for profiles that pass between them. As time progresses the electron density on axis increases. As was seen earlier in the 8 wire case, the density profile of the precursor column is remarkably isotropic. The on and off stream density profiles match well within the precursor region. The FWHM of the precursor distribution appears to decrease with time.

Figure 69 shows a series of line profiles taken through the ablation streams from the interferograms taken at 106ns and 162ns. The first observation is that in the later image the well-defined ablation streams penetrate further towards the array axis. This corresponds with the decreasing radius of the isotropic density profile, as observed in the lineouts shown in Figure 70. Secondly, while the peak stream density has increase by a factor of 10 in the time between the two interferograms, the overall structure of the ablation streams appears to have remained very similar. The FWHM of the streams in both cases is $\sim 0.5\text{mm}$, and the contrast ratio between the stream and the inter-stream region is ~ 10 . In both cases the contrast falls away as we approach the axis of the array.

5.5.2) 32 wire array data

Three experiments were conducted on 32 wire tungsten arrays. Good current signals were recorded in only two of these, shots s1013_10 and s0519_11. In the third shot, s0125_11, the peak current is significantly reduced. This was caused by delayed firing of one of the four line switches. For this reason it has been excluded from this analysis. The data from this shot is presented in section 5.5.1), as the two images were timed simultaneously. The data has been used to investigate the validity of the free electron model of the refractive index for the plasmas produced in these experiments.

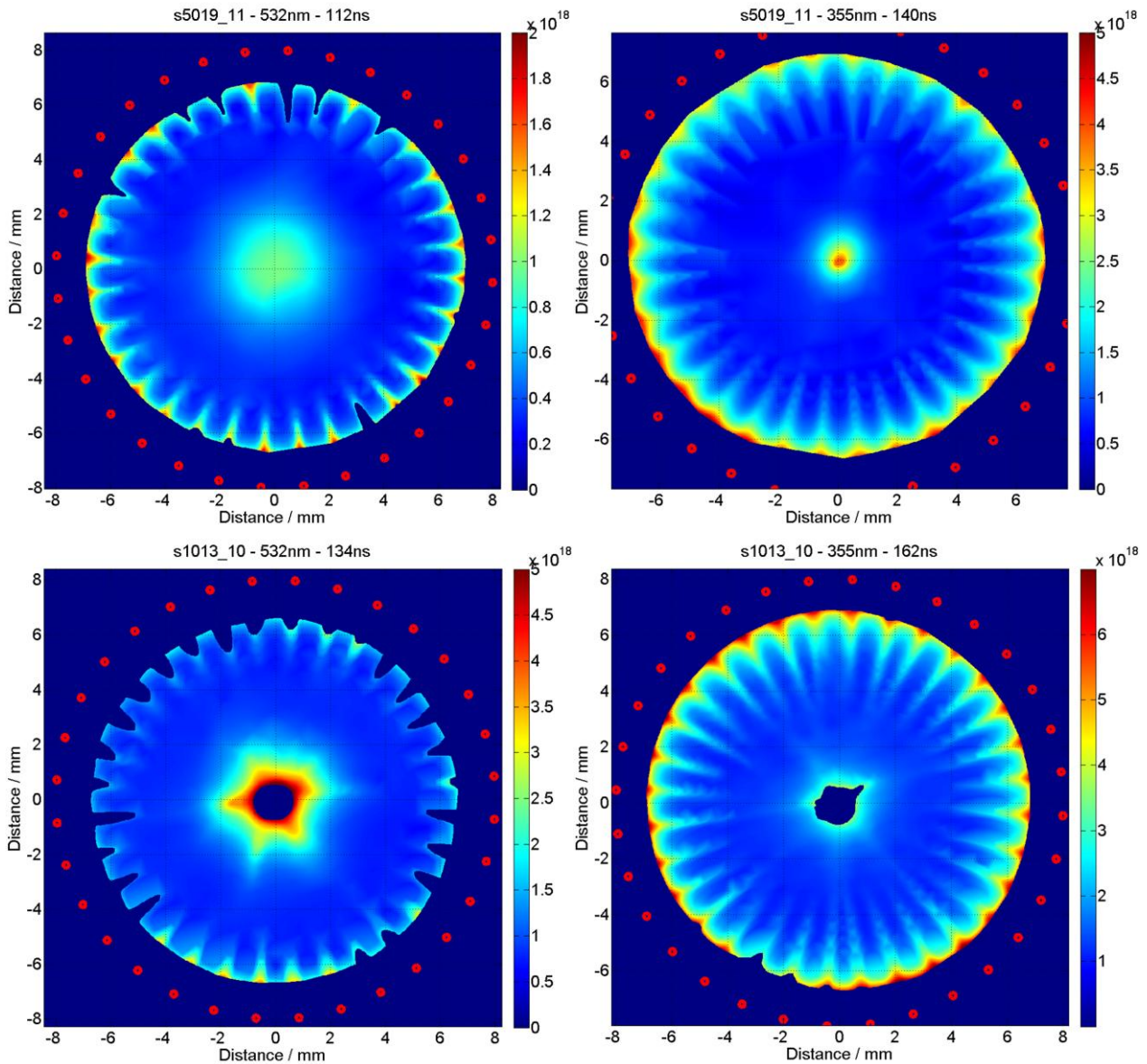


Figure 71 Density Maps captured in experiments on 32 wire W arrays. Red circles indicate the initial wire positions. Colour scales vary between the plots.

Four Interferograms were captured and the resulting electron density maps are shown in Figure 71. The interferogram timings were 112ns, 134ns, 140ns and 162ns. The current pulses generated in these experiments are plotted in Figure 72. These were calculated using the MITL B-dot signal, as the Rogowski signal showed strong discontinuities similar to those observed in the 8 wire experiments described in section 5.5.2). There is a slight difference in the peak current achieved, but for the period during which the interferograms were captured the current drives appear to be very similar.

Both loads were constructed using 10 μ m diameter tungsten wires. The array used for s1013_10 was 1cm long, while the one used for s0519_11 was 2cm long. The difference in array length has been taken into account in the calculation of the electron density maps. As in the 8 and 16 wire cases, these loads were designed to be over-massed.

The main change we see from the 16 wire arrays in Figure 71 is that neighbouring ablation streams are now in contact at much larger radius. Even so, the density profiles show no signs of shock formation. The streams are still characterised by smooth density gradients, indicating that the mean free path of ions is reasonably large compared with the stream scale lengths. The increase in wire number means there are no longer regions be-

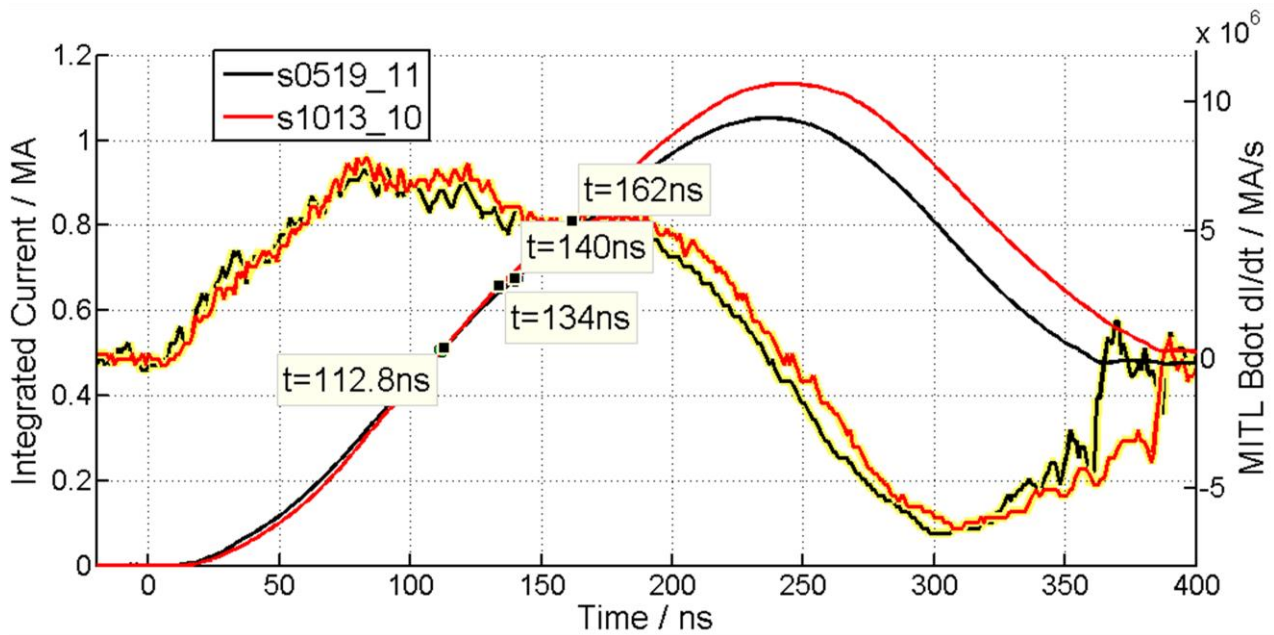


Figure 72 Current traces for 32 wire tungsten arrays, taken from MITL B-dot traces. Timings for the four interferograms are marked. The currents compare well between the two experiments. Raw signals from the MITL B-dots are shown highlighted in yellow.

tween the ablation streams where the density falls away and the density profile flattens, as was observed in the 8 and 16 wire cases. Individual ablation streams are observed up to a certain radius. As in 8 and 16 wire arrays, after this point the density distribution becomes azimuthally isotropic. The precursor FWHM is observed to reduce with time.

Looking quantitatively, Figure 73 shows a set of line profiles taken through the axis of the density plots displayed in Figure 71. The legend is organised in time order. As before, solid lines are taken through the ablation streams while the dashed lines are profiles between the streams. As in the previous cases the on and off-stream profiles match well near the array axis but diverge at a certain radius. The lineouts from the two shots appear to show different dynamics. s0519_11 shows a broad density profile that is collapsing to form a narrow precursor column. At the time of the 355nm interferogram the precursor has not fully collapsed, and fringes can be traced all the way to the axis. In shot s1013_10, the precursor column appears to have already formed – fringes cannot be traced into the array axis due to the strong gradients present. The 532nm image from s1013_10 and 355nm im-

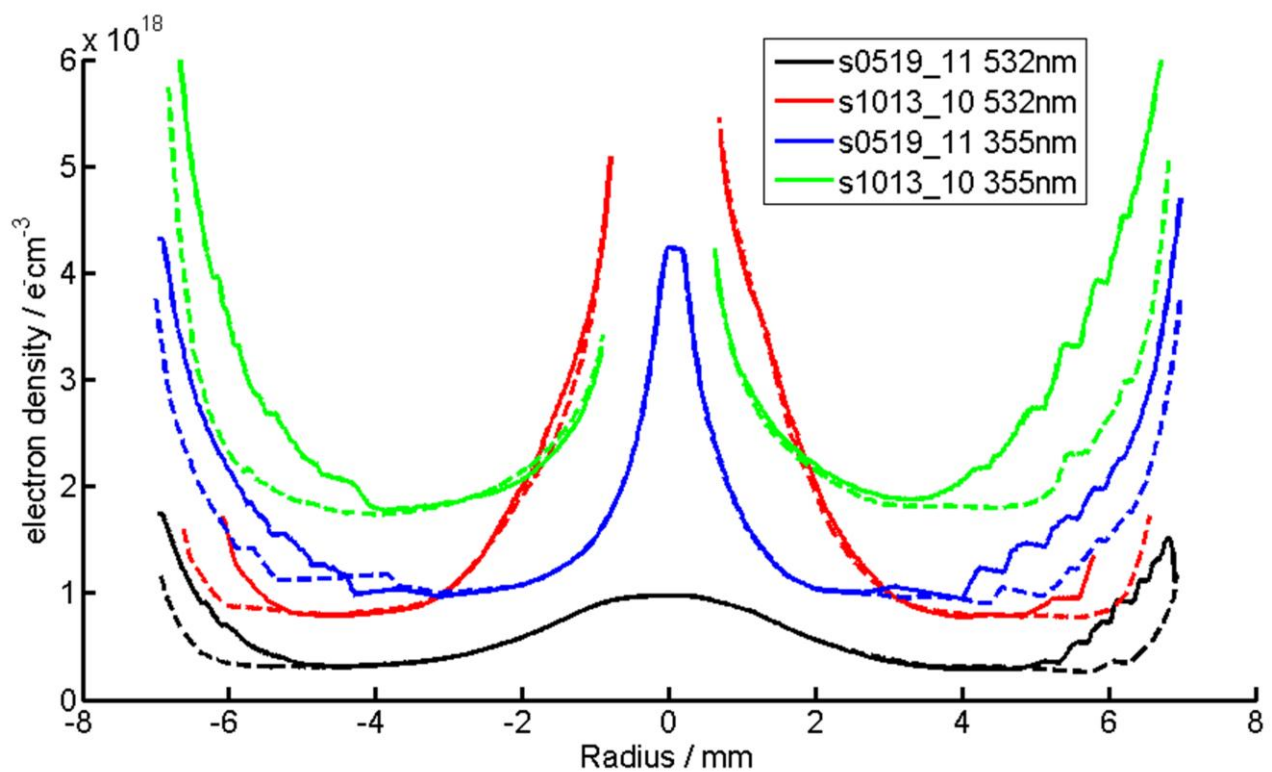


Figure 73 Comparison of line profiles taken from the electron density profiles shown in Figure 71, showing the evolution of the precursor column.

age from s0519_11 have very similar timings and yet the density profiles look very different.

In order to investigate this further we can look at the XUV time resolved imaging. Figure 74 shows the XUV images captured during these experiments. The images are positioned such that the array axes are aligned at the time at which they were captured. The drive current and diagnostic timings are marked on the corresponding current traces. This data shows that the precursor is formed earlier in the shorter array, at around 125ns compared to 145ns in the longer array. This agrees well with the interferometry data, which shows a dense column on axis at 134ns for shot s1013_10, but not at 140ns in shot s0519_11. The cause of this difference in the precursor formation time has yet to be identified. It could be due to some form of current loss before the load. The Rogowski signals give conflicting evidence on whether this current loss occurred. Better current diagnosis is required to answer these questions. Another potential cause could be differences in the electrical breakdown characteristics of the arrays. Since the shorter array will have a smaller resistance, it may behave slightly differently at very early times. This could increase the amount of mass that is ablated early in time, resulting in earlier precursor for-

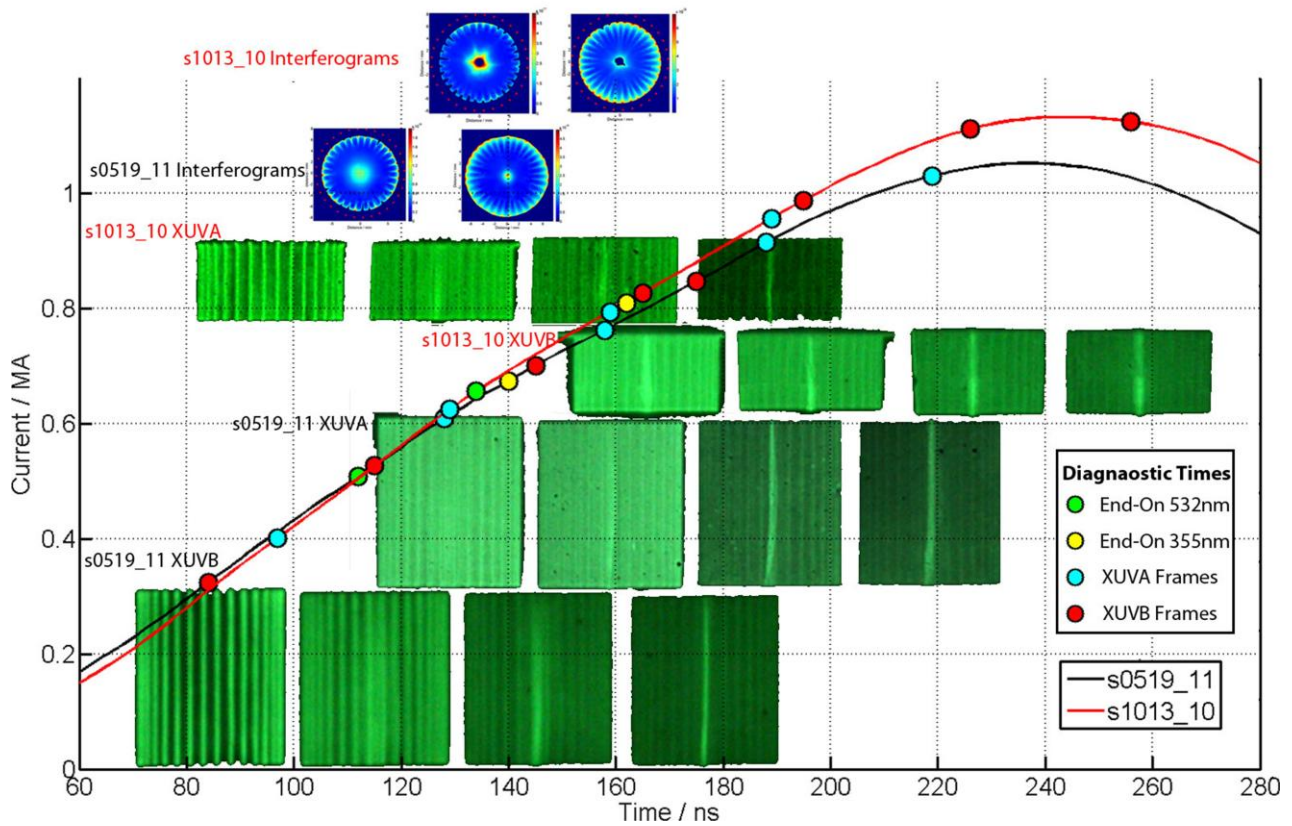


Figure 74 Current drive and XUV emission images positioned in time order to compare the dynamics of the two arrays. The array axes are aligned with the image timing.

mation.

Line profiles through the ablation streams of the 32 wire arrays are shown in Figure 75. This data shows how the radius to which the well-defined ablation streams penetrate increases as the experiment goes on. In the earlier plot (112ns), there is no sign of ablation streams at $r=5\text{mm}$, however in the later image (162ns), we can observe some signs of ablation stream penetration up to a radius of at least 4mm. Also interesting to note from this data is that the density contrast ratio from mid-stream to between stream remains almost constant between these two images. This is despite the overall density increasing by a factor of 5.

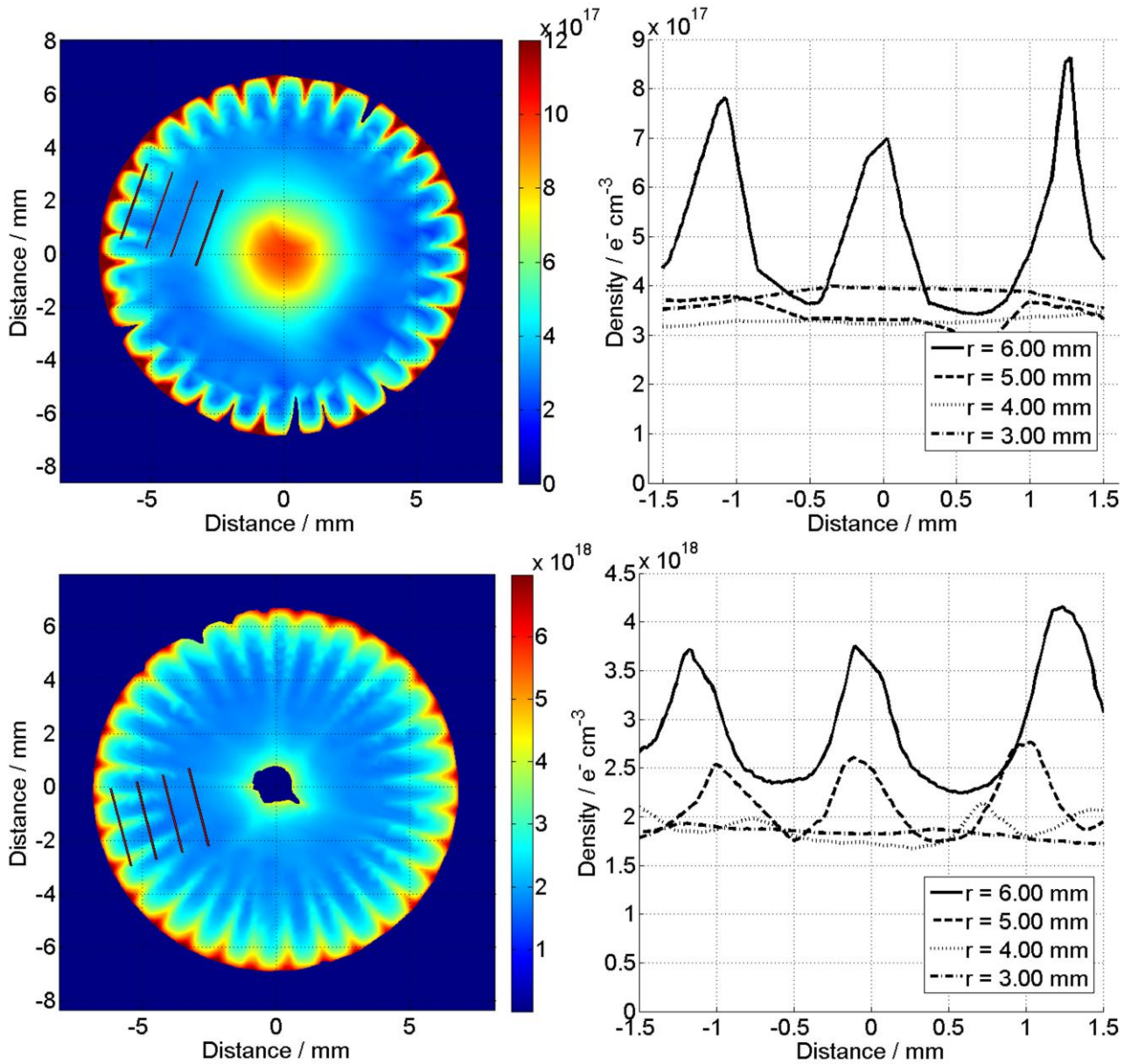


Figure 75 Comparison of stream profiles of earliest and latest time image. Top, 532nm image from s0519_11 (112ns). Bottom, 355nm image from s1013_10 (162ns).

5.5.3) 128 wire array data

An experiment was carried out on a 128 wire Tungsten array. The array had a 16mm diameter, was constructed from 7.5 μm diameter wires and was 2cm long. Two interferograms were captured, at 129 and 157ns respectively. A plot of the current pulse for this experiment and interferogram timings are shown in Figure 78. The density maps are displayed in Figure 76 a). The density distributions for 128 wires appear very smooth compared with the lower wire number experiments discussed earlier. Ablation streams are only visible at the very edges of the density plots. A dense precursor column has formed by the time of the first interferogram, at 128ns.

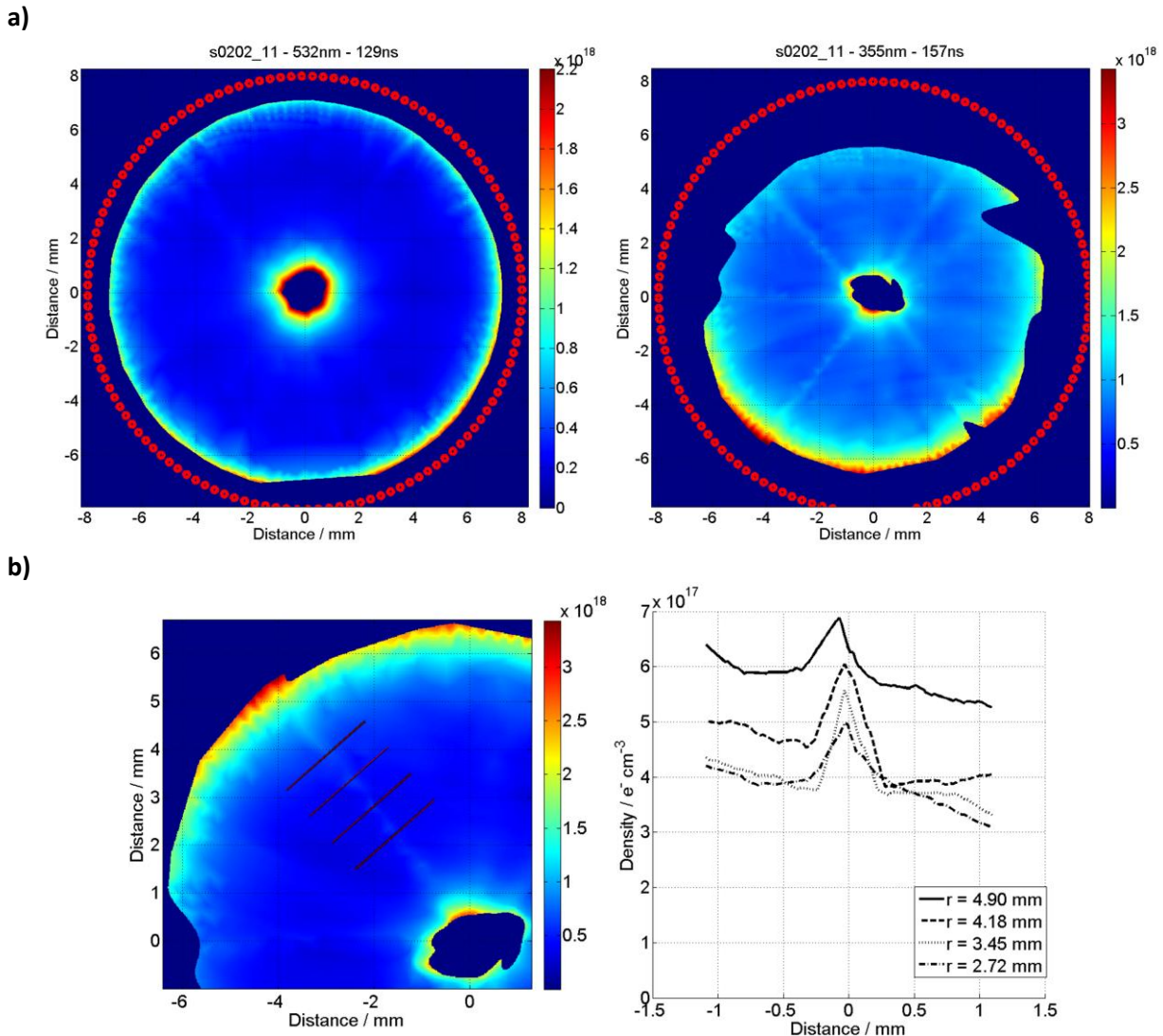


Figure 76 Data from an experiment on 128 wire array.

- a) Electron density maps from shot no. s0202_11, a 128 wire W wire array. The image on the left shows the data extracted from the 532 nm image, captured at 129 ns 1 fringe shift has been added to this data. The image on the right is taken from the 355nm image taken at 157 ns, and also has 1 fringe shift added to it.
- b) Stream profiles showing one of the regions of enhanced ablation.

Careful scrutiny of the second (355 nm interferogram) density plot reveals four streams of enhanced electron density. The four streams fall at angles of 80° and 100° from one another. These angles correspond to the separation angles between the four pulse forming lines that feed the MAGPIE current pulse (see section 2.2)). Looking in a little more detail, Figure 76 b) shows a series line profiles across one of these streams. The ablation stream density enhancement appears to vary between ~ 15 and $\sim 50\%$. In terms of electron density, this corresponds to an enhancement of around $1\text{--}1.5 \times 10^{17} \text{ cm}^{-3}$ and the width of the enhanced region is approximately 0.3 mm. This

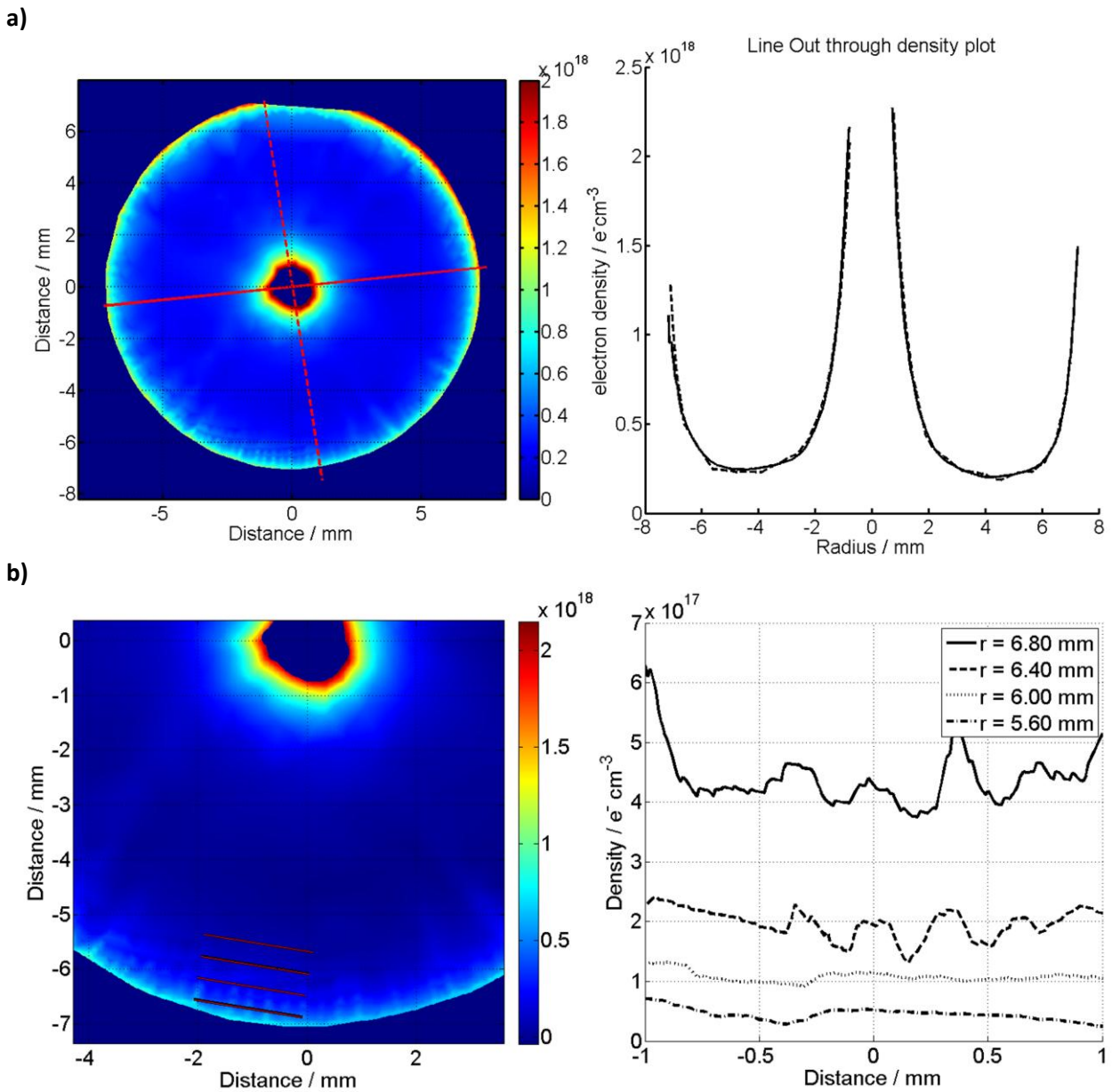


Figure 77 Line profiles of 128 wire arrays.

a) Line profiles through the axis of the 532nm interferogram from shot s0202_11.

b) Ablation stream profiles through the same dataset, showing how the ablation modulation decreases as the flow travels towards axis.

non-uniformity is very strange, as the transfer line should be long enough to allow the current waves from the four pulse forming lines to smooth out azimuthally by the time that they reach the load. It has been suggested that differences in the switching times for the four line gaps may result in a standing wave that could produce this pattern of current enhancement.

Figure 77 a) shows line profiles through the axis of the array taken through two almost orthogonal lines. The profiles match extremely well, demonstrating the isotropy of the electron density distribution. Figure 77 b) shows a series of ablation stream profiles. The modulation wavelength at the largest radius is $\sim 0.4\text{mm}$, agreeing well with expected ablation modulation for a 128 wire array. The ablation stream electron density enhancement can still be made out at $r = 6.4\text{ mm}$, but has smoothed out by 6.0 mm .

Figure 78 shows XUV emission images captured during the experiment, with imaging diagnostic timings marked on the current curve. The current was calculated from the MITL B-dot signal. The first evidence of the formation of the precursor column is seen at around 120ns . At this point the precursor shows up as a broad emission region. The end-on images were captured at 128ns , when this column is already formed.

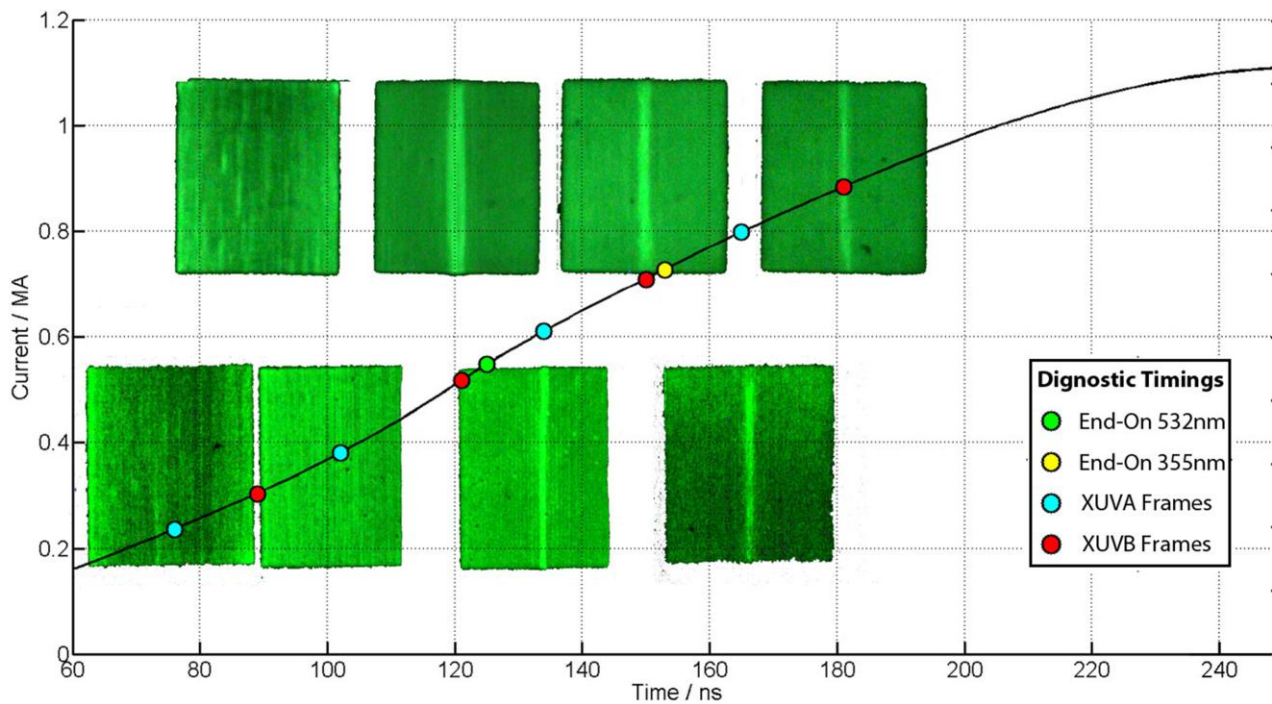


Figure 78 Current and diagnostic timings for s0202_11, a $128 \times 7.5\mu\text{m}$ W array. XUV images have array axis aligned with image times.

5.6) Dynamics of aluminium wire arrays

Experiments were carried out on 16 and 32 wire aluminium arrays, with the radius maintained at 8mm. To prevent implosion, the loads were designed to be over-massed. This helped to suppress the x-ray pulse, reducing damage to the array hardware. The wire diameters were kept to a minimum while maintaining the over-massed condition in order to minimise disturbance to the wire expansion dynamics.

The structures formed during the ablation phase of aluminium wire arrays are very different from those observed in the tungsten wire arrays. Oblique shocks are formed at the points where the plasma streams ablated from each of the wires collide.

5.6.1) Oblique shocks in aluminium array ablation plasma

Figure 79 shows a pair electron density plots extracted from interferograms captured during an experiments on 16 and 32 wire aluminium arrays. The most immediate difference from the electron density profiles captured in experiments on tungsten arrays is that these profiles feature sharp discontinuities in the electron density. These discontinuities are the tell-tale signs of the formation of oblique standing shocks in the flow of the ablated plasma. They contrast with the smooth spatial profiles observed in experiments on tungsten arrays.

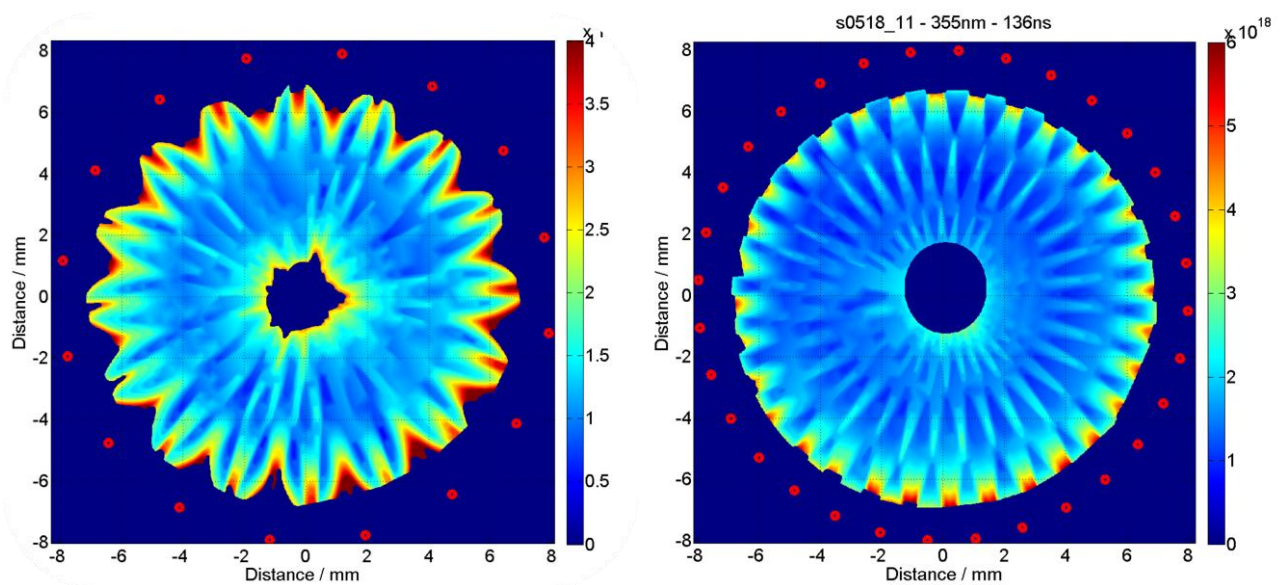


Figure 79 Examples of electron density distributions for 16 and 32 wire aluminium arrays.

An example of oblique shock formation is seen in the 32 wire data. The regions of highest density around the edges of this plot actually fall midway between the wire positions. In experiments on tungsten arrays these regions of highest density correspond to the ablation streams flowing directly from the wires. The high density regions in the aluminium plot are not the ablation streams flowing directly from the wire cores but instead are formed from the collision of the ablated material. The sharp edges of this region mark the shock fronts where new material from the ablation streams impinges on the shock. Similar shock structures are observed in 16 wire arrays.

In both datasets the material which passes into these ‘primary’ shocks continues to travel toward the array axis, going on to form further shock structures as the plasma flow radially converges. In order to properly understand the dynamics of these interactions we need a better understanding in the physics of oblique shocks.

5.6.2) The mathematics of oblique shock-waves

The derivations for the oblique shock relations can be found in detail in reference [58]. Shock waves are a phenomena associated with supersonic flows. When an obstruction is placed in a subsonic flow, sound waves in the fluid pass information up the flow stream allowing the fluid to flow smoothly around it. In a supersonic flow this information cannot be passed upstream as the sound waves travel slower than the flow velocity. Instead a shock front is formed. The shock front marks a sudden discontinuity in the flow parameters. In general, the velocity of the flow is reduced, while the temperature, density and pressure of the flow increase.

For this analysis we are interested specifically in oblique shocks. Oblique shocks form when a supersonic flow is forced to turn. Figure 80 contains a schematic of this flow configuration. A supersonic flow enters from the left side of the diagram. A wedge shaped obstruction is introduced into the flow. In order to turn the flow parallel to the wedge surface an oblique shock front is formed. The shock is attached to the tip of the wedge, but separated from it by some angle. The angle at which the oblique shock is formed is dictated by the upstream Mach number M , and the turning angle of the obstacle. The Mach number of a flow is defined as the ratio of the bulk flow velocity to the local sound speed, c_s :

$$M = \frac{v}{c_s} \quad (5.6.1)$$

The solution for the angle at which an oblique shock is formed is obtained by applying the hydrodynamic equations across the shock front. These equations encode the laws of mass conservation, momentum conservation and energy conservation. The equation governing mass conservation is known as the mass continuity equation:

$$\nabla \cdot (\vec{v}\rho) = 0 \quad (5.6.2)$$

That equation states that the mass flux entering the shock front must equal the mass flux leaving it. This is applied to the component of the flow vector normal to the shock front:

$$v_{\perp 1}\rho_1 = v_{\perp 2}\rho_2 \quad (5.6.3)$$

The equation governing momentum conservation is the force/momentum equation:

$$\frac{d}{dt}(\rho v) = -\nabla P \quad (5.6.4)$$

The equation implies that any change in the momentum of the flow over the shock must be balanced by a change in the pressure in that direction. The momentum is split into components normal and tangential to the shock front:

$$P_1 + \rho_1 v_{\perp 1}^2 = P_2 + \rho_2 v_{\perp 2}^2 \quad (5.6.5)$$

$$(\rho_2 v_{\parallel 2})v_{\perp 2} = (\rho_1 v_{\parallel 1})v_{\perp 1} \quad (5.6.6)$$

Substituting equation (5.6.3) into (5.6.17) reveals that the tangential component of the flow velocity is unaffected by the shock front. The steering of the flow is therefore achieved entirely through the slowing of the normal component.

Energy conservation is governed by the energy equation (neglecting thermal diffusion):

$$\rho \left(\frac{\partial \epsilon}{\partial t} + v \cdot \nabla \epsilon \right) + \rho \nabla \cdot v = 0 \quad (5.6.7)$$

This equation states that the energy flux into a point must be equal to the energy flux out minus the increase in the fluid internal energy. Again this equation is applied across the shock front:

$$-(P_2 u_2 - P_1 u_1) - \left(\left(\rho_2 \epsilon_2 + \frac{\rho v_2^2}{2} \right) u_2 - \left(\rho_1 \epsilon_1 + \frac{\rho_1 v_1^2}{2} \right) u_1 \right) = 0 \quad (5.6.8)$$

$$\left(\left(\frac{P_1}{\rho_1} + \epsilon_1 \right) + \frac{v_1^2}{2} \right) \rho_1 u_1 = \left(\left(\frac{P_2}{\rho_2} + \epsilon_2 \right) + \frac{v_2^2}{2} \right) \rho_2 u_2$$

This equation equates the fluid energy across the shock. The form of this energy may shift between potential energy, internal energy and directed kinetic energy. Substituting in the mass conservation equation, (5.6.15):

$$\left(\frac{P_1}{\rho_1} + \epsilon_1 \right) + \frac{v_1^2}{2} = \left(\frac{P_2}{\rho_2} + \epsilon_2 \right) + \frac{v_2^2}{2} \quad (5.6.9)$$

Then applying the fact that the tangential velocity is unchanged:

$$\left(\frac{P_1}{\rho_1} + e_1 \right) + \frac{v_{11}^2}{2} = \left(\frac{P_2}{\rho_2} + e_2 \right) + \frac{v_{12}^2}{2} \quad (5.6.10)$$

Combining these relations with the ideal gas law allows us to derive the shock angle. The turning angle (β), shock angle (θ) and upstream Mach number (M) are related by the θ - β - M relation:

$$\tan \theta = 2 \cot \beta \left[\frac{(M_1^2 \sin^2 \beta - 1)}{(M_1^2 (\gamma + \cos 2\beta) + 2)} \right] \quad (5.6.11)$$

θ and β are labelled in Figure 80 for greater clarity. Assuming they can be measured from the data, an expression for the upstream Mach number can be obtained by rearranging the above equation.

$$M_1 = \sqrt{\frac{2(\cot \beta + \tan \theta)}{\sin 2\beta - \tan \theta (\gamma + \cos 2\beta)}} \quad (5.6.12)$$

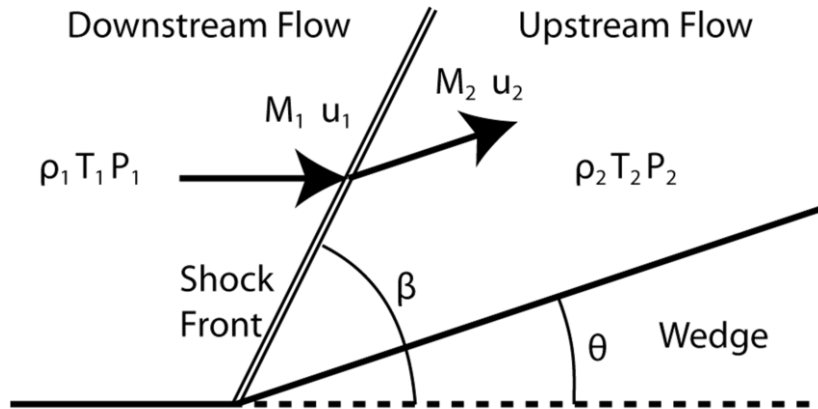


Figure 80 A Schematic of an oblique shock. A wedge turns a supersonic flow through an angle θ . The oblique shock front forms at an angle β . The hydrodynamic and thermodynamic properties of the flow change abruptly over the shock front.

This still leaves one unknown parameter, γ , the adiabatic index; however we know the range in which it should lie. Once the upstream Mach number is known the downstream Mach number can be calculated:

$$M_{\perp 2} = \sqrt{\frac{M_1 \sin^2 \beta + \frac{2}{\gamma - 1}}{\frac{2\gamma M_1^2 \sin^2 \beta}{\gamma - 1} - 1}} \quad (5.6.13)$$

$$M_2 = \frac{M_{\perp 2}}{\sin(\beta - \theta)}$$

Ratios of the various thermodynamic parameters are given by the following expressions:

$$\frac{\rho_2}{\rho_1} = \frac{u_1}{u_2} = \frac{(\gamma + 1)M_{\perp 1}^2}{2 + (\gamma - 1)M_{\perp 1}^2} \quad (5.6.14)$$

$$\frac{P_2}{P_1} = 1 + \frac{2\gamma}{\gamma + 1}(M_{\perp 1}^2 - 1) \quad (5.6.15)$$

$$\frac{T_2}{T_1} = \frac{P_2 \rho_1}{P_1 \rho_2} = \left[1 + \frac{2\gamma}{\gamma + 1}(M_{\perp 1}^2 - 1) \right] \left[\frac{2 + (\gamma - 1)M_{\perp 1}^2}{(\gamma + 1)M_{\perp 1}^2} \right] \quad (5.6.16)$$

These relations can be used to calculate the expected jump conditions for a given oblique shock. They shall be applied in the following sections. It is useful to consider the effects of the different parameters on the flow:

The component of the upstream flow velocity normal to the downstream flow velocity is stagnated in the shock.

The associated kinetic energy is converted to heat:

- Larger turning angle - greater heating – lower downstream velocity.

The shock angle (β) is dependent on upstream Mach number (M) and turning angle (θ):

- As M increases beyond unity, β decreases.
- As θ increases, β also increases.
- If θ increases beyond some angle, θ_{MAX} , the β - θ - M relation does not provide any solution. The shock front becomes detached, and a bow shock is formed. θ_{MAX} is a function of the upstream Mach number.

The downstream density is controlled by the shock angle (β), turning angle (θ) and upstream Mach number (M).

- Smaller shock angle – smaller downstream flow cross-section - higher density
- Larger turning angle – smaller downstream velocity – higher density

5.6.3) 16 wire arrays

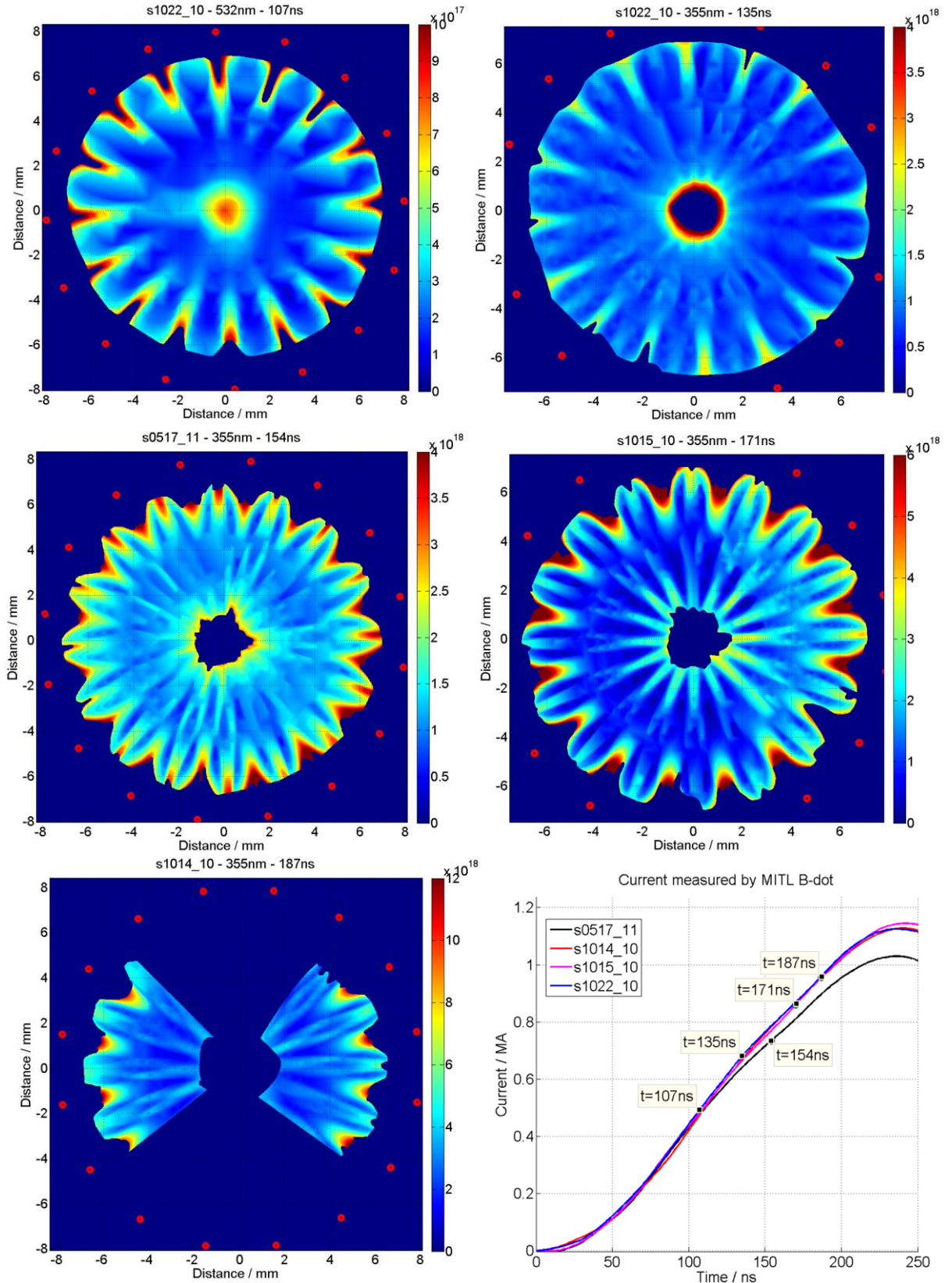


Figure 81 A series of electron density plots captured for 16 wire aluminium arrays. Red circles mark wire positions. Shock structures can be observed at 120ns and later. The imaging times are marked on a series of current traces, as measured by a MITL B-dot.

Four experiments were conducted on 16 wire aluminium arrays. All of these arrays were constructed from 30 μ m aluminium wire. Shots s1014_10 and s1015_10 were 1cm long arrays, while s1022_10 and s0517_11 were 2cm long. During these experiments a total of five good end-on interferograms were captured. Interferograms were captured at 107ns, 135ns, 154ns, 171ns and 187ns. This provides a good spread of data throughout the evolution of the ablation structures.

Shock structures are observed in all of the interferograms except for the one captured at 107ns. It appears that at this point in time the plasma is not yet collisional. By 135ns a high density region has formed between the main ablation streams. This region is bounded by shock fronts. Closer to the array axis the density profile of this shocked region appears to become hollow. Figure 82 shows a series of line profiles taken through one of these shocks to illustrate the hollowing effect. This profile may be evidence of higher temperature plasma in this region, due to the more abrupt angle at which this material has joined the shocked region. As a result a greater portion of the kinetic energy would be expected to be thermalized. The increase in temperature in this region would provide pressure to support this region of lower density. As time progresses the shock structure becomes more evident. The hollowed shock structure is observed all the way to latest image, captured at 187ns. The detailed structure observed in the 16 wire arrays appears highly complex. It is discussed in more detail later when compared with the results of simulations.

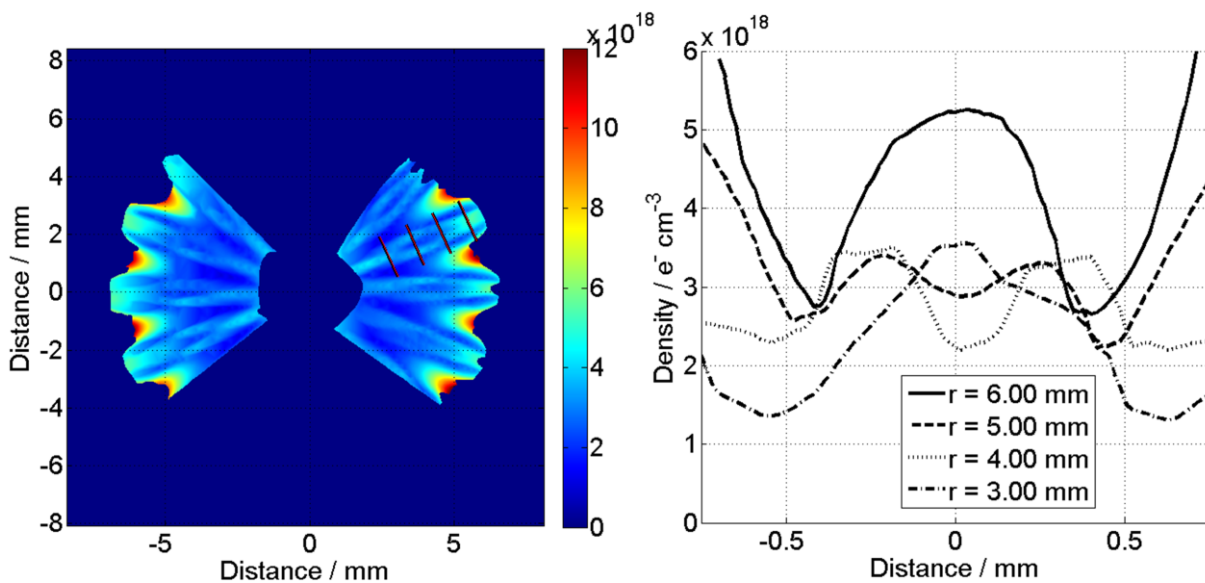


Figure 82 Line profiles of the ablation stream electron density, showing the hollow nature of the shocked region.

5.6.4) 32 wire arrays

Two experiments were conducted using 32 wire aluminium arrays, shots s0201_11 and s0518_11. Both arrays were constructed from 25 μ m aluminium wire. Figure 83 shows plots of the electron density calculated from three of the interferograms captured. These Interferograms were timed at 120ns, 142ns and 147ns. In all three plots oblique shock structures dominate the ablation dynamics.

Figure 84 a) illustrates this structure. A high density region is formed between each pair of adjacent wire cores. This is formed by the collision of the ablated plasma and is bounded on either side by shock fronts. From here on it is referred to as the primary shock region. As plasma passes through the shock fronts it is turned such that all

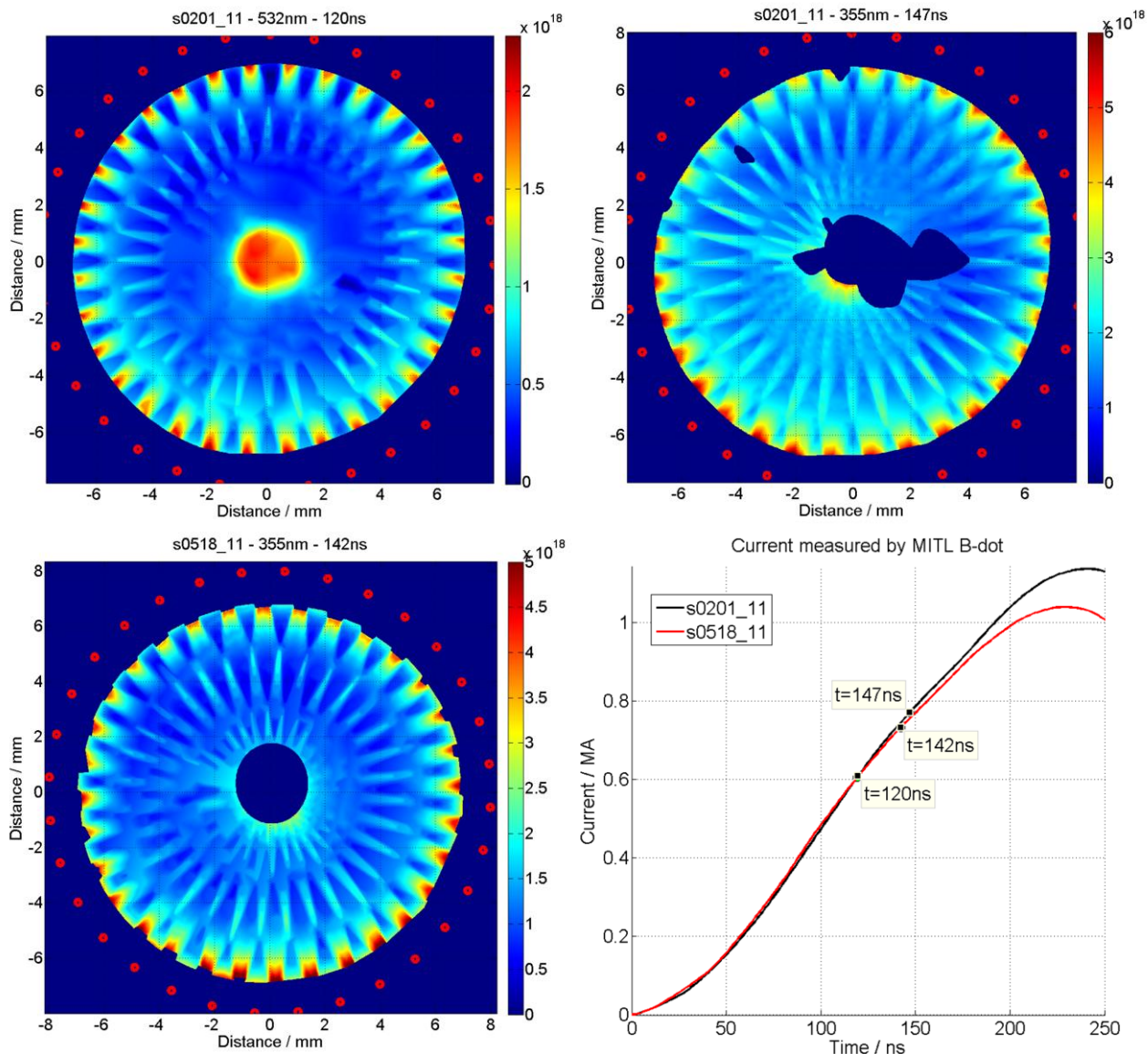


Figure 83 Electron density plots for 32 wire aluminium arrays. Shock formation is evident in all three plots. In the final two plots we can make out tertiary and event quaternary shocks. Timings are marked on the current plots, as measured by a MITL B-dot.

the plasma in this region flows parallel. The centre line of the shock region is oriented towards the array axis. More material enters this region as we move towards the axis. This increases the width of the primary shock. Combined with the radial convergence of the flows, this means that the adjacent primary shocks eventually meet one another. The collision between two primary shocks results in the formation of a secondary shock flow region. The process repeats, with these regions going on to collide and form tertiary shocks. The plot from shot s0518_11 even shows some evidence of the formation of quaternary shocks.

The shocks observed in this dataset are extremely oblique. The flows are being turned by an angle of just 5.625° with each interaction. As a result, the magnitude of the flow velocity is only reduced by a factor of 1.004 by each shock. This is a very small change. The increase in the density of the flows is therefore dominated by the reduction in the effective cross-section of the flow. This process is shown schematically in Figure 84 b). This diagram plots the flows vectors for a single 32nd portion of the structure. The shock angles have been exaggerated for

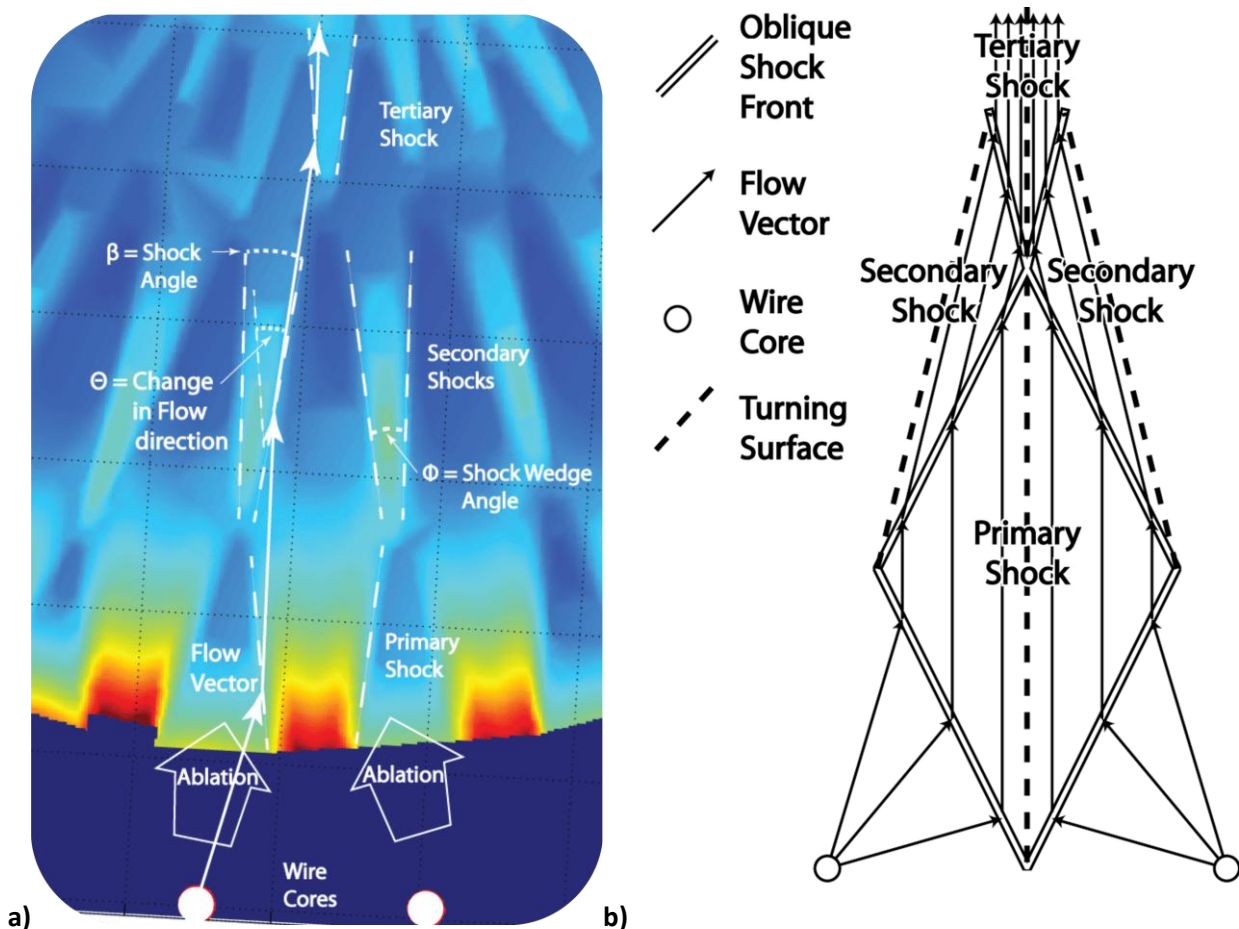


Figure 84 Diagrams of the shock structure observed in 32 wire aluminium arrays.

a) The shock structure overlaid on an electron density profile.

b) A diagram of the interpreted ablation flow structure. Angles have been accentuated for clarity.

clarity. As the flow passes through each shock front, stream lines are forced closer and closer together. Since the velocity remains approximately constant, this results in an increase in the flow density.

The relations derived in section 5.6.2) can now be applied to this dataset. Figure 84 a) shows a schematic of the oblique shocks identified in these experiments. In the theoretical treatment a solid wedge redirected the flow. In this case the flow collides with and is redirected by the neighbouring flow. Assuming the two flows are identical and fully collisional, the interface between them will remain in force balance. This results in an interface that acts to turn the flow in a similar manner to a solid wedge object. The mean wedge angle of the secondary shock fronts measured from the interferograms is $\phi = 0.227 \pm 0.007$ rad. The flow turning angle θ can be calculated from the number of wires in the array:

$$\theta = \frac{\pi}{N} \quad (5.6.17)$$

The expression for the shock angle is then simply:

$$\beta = \theta + \frac{\phi}{2} \quad (5.6.18)$$

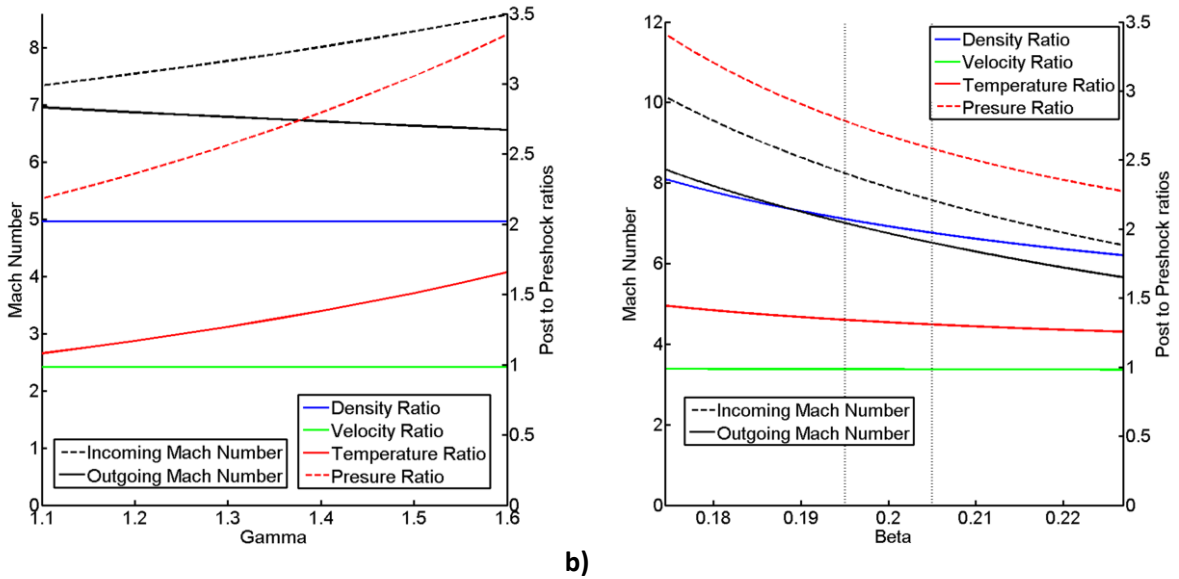


Figure 85 Plots for the oblique shock relations.

- a) Plot of various fluid variables over a range of gamma for an oblique shock with turning angle $\theta=0.1$ and shock angle $\beta=0.2$.
- b) Plot of the same variables for the same turning angle, with constant $\gamma=1.35$, over a range of shock angle values. The vertical lines mark the error of the angle measurement.

Calculation results in values of $\theta = 0.098$ rad and $\beta = 0.208 \pm 0.004$ rad. To accurately calculate the Mach number, and therefore the ratios of the flows parameters, a suitable value for γ is required. In order to investigate the

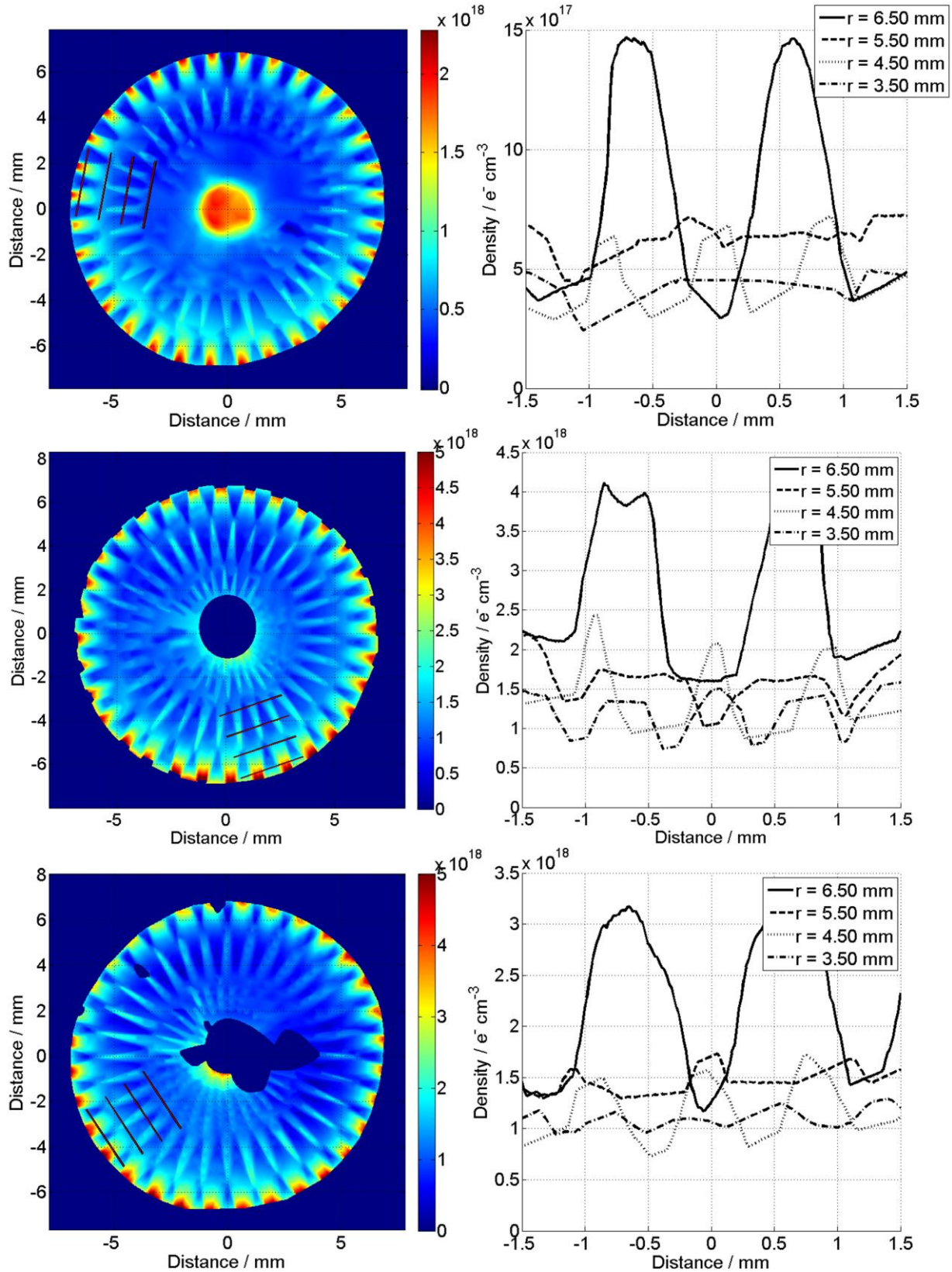


Figure 86 Contours from Figure 57 a) are assigned phase numbers and the spaces between are interpolated. The interpolated phase maps can then be subtracted to remove the background phase gradient, leaving just the phase delay due to the plasma.

sensitivity of calculations in this angle range to γ , the upstream and downstream Mach numbers and thermodynamic parameter ratios were calculated for a range of γ values. The results are plotted in Figure 85 a). The incoming and outgoing Mach numbers do not vary significantly over the range of γ , remaining relatively large. More interestingly, although the temperature/pressure ratios vary a reasonable amount over the range of γ , the density ratio across the shock remains very stable. We are also interested in the sensitivity of the flow parameters to the shock angle. Figure 85 b) shows a plot of the density, velocity, temperature and pressure ratios for a range of shock angles. This plot indicated that the density contrast is a weak function of the shock angle. Also interesting is that the temperature ratio varies little with shock angle under these conditions. With a ratio of around 1.2-1.3, we should not expect to observe a great deal of heating across these shocks. This is useful, as heating could cause an increase in the average ionisation level of the plasma, increasing the free electron density without a commensurate increase in the plasma ion density.

The Mach number of the flow inside the primary shock region is estimated to be in the range $M=7.9-8.2$, and the density contrast over the shock front is approximately 2. The density contrast appears to be pretty robust to any errors in measurement of the shock angles, or to the value of γ used. This is extremely useful as it provides a means of calculating the zero fringe-shift for the interferogram. This method was used to estimate the zero fringe shifts for all of the interferograms plotted in Figure 83. Electron density line profiles of the ablation stream in the calibrated plots are displayed in Figure 86. The zero fringe-shift was selected to best meet the requirement for the density to double over the secondary shock front.

Although primary and secondary shocks are observed in 120ns interferogram, the central region around the precursor appears to be reasonably smooth. This may indicate that the mean free path is longer in this region, so that shocks are not formed here. There appears to be no evidence of the formation tertiary shocks, as seen in the other, later interferograms. We will look in more detail at these structures when we look for comparison with simulation data.

5.7) Collisionality of adjacent ablation streams

The azimuthal dynamics of tungsten and aluminium wire arrays show what appear to be very different collisional properties. Oblique shock fronts form between the ablation streams of aluminium arrays, while the ablation streams formed by tungsten arrays appear to merge together to form smooth density profiles. Oblique shocks are a hydrodynamic phenomenon, requiring a collisional fluid with sufficient viscosity to stagnate the flow over the shock front scale length ($\sim 100\mu\text{m}$). The data suggests that in the regimes accessed by these experiments, the aluminium plasma can be considered as a fluid, while the tungsten plasma must be modelled using a particle model, as investigated in reference [59].

In order to gain a greater understanding of these differences in the azimuthal structure, it is interesting to calculate the expected mean free paths of the ions in each case. Calculations were carried out using the Spitzer slowing down formula, taken from the NRL plasma physics formulary [60]. This equation models the collisions for a test particle of species α , traveling at a velocity v_α , into a stationary background distribution of particles of species β .

$$\frac{dv_\alpha}{dt} = -v_s^{\alpha\beta} v_\alpha \quad (5.7.1)$$

Here $v_s^{\alpha\beta}$ is defined as the slowing frequency for the test ion. This is calculated as follows:

$$v_s^{\alpha\beta} = \left(1 + \frac{m_\alpha}{m_\beta}\right) \psi(x^{\alpha\beta}) v_0^{\alpha\beta} \quad (5.7.2)$$

$$v_0^{\alpha\beta} = \frac{4\pi \bar{z}_\alpha^2 \bar{z}_\beta^2 e^4 \lambda_{\alpha\beta} n_\beta}{m_\alpha^2 v_\alpha^3} \quad (5.7.3)$$

$$x^{\alpha\beta} = \frac{m_\beta v_\alpha^2}{2kT_\beta} \quad (5.7.4)$$

$$\psi(x) = \frac{2}{\sqrt{\pi}} \int_0^x dt t^{1/2} e^{-t} \quad (5.7.5)$$

$$\psi'(x) = \frac{d\psi}{dt} \quad (5.7.6)$$

The Coulomb logarithm ($\lambda_{\alpha\beta}$) is a factor that describes the relative contributions of small angle coulomb scattering interactions and large angle scattering events. Expressions for both the Coulomb logarithm and the slowing frequency at various limits where found in the NRL plasma formulary [60]. The mean free path (L_{mfp}) of the ions is calculated using the following equation:

$$L_{mfp} = v_{\alpha}/v_s^{\alpha\beta} \quad (5.7.7)$$

It is interesting to note, inspecting equations (5.7.3) and (5.7.7), the strong dependence of the mean free path to both the ion velocity (v_{α}^4) and average ionisation ($\bar{z}^4$). A small change in these parameters may result in a large change in the mean free path.

The equations for the mean free path have been written into a Fortran Code that was kindly provided by Dr Mark Sherlock. For the following calculations, it was assumed that the electron temperature in the ablation streams was 15eV, as this agrees with the temperature range found in many simulations of these experiments. For simplicity, it was assumed that the ion temperature and electron temperature were equal. The velocity of the ions was set to $1.5 \times 10^5 \text{ ms}^{-1}$. This is a generally agreed value for the ablation velocity, consistent with rocket model approximations and previous experimental measurements[9]. An estimate of the average ionisation of the two materials was made using an approximation to the Saha equation argued in [61]. The following is an expression approximating the average ionisation level, $\bar{z}$ to the plasma temperature, T.

$$\bar{z} = 2 \left(\frac{2\pi m_e k_B}{h^2} \right)^{\frac{3}{2}} \frac{T^{\frac{3}{2}}}{n_i} e^{-\frac{\bar{I}(\bar{z}+1)}{k_B T}} \quad (5.7.8)$$

Where h is the Plank constant n_i is the ion density and $\bar{I}(\bar{z}+1)$ is the ionisation potential, the energy required to promote the ion to the next ionisation level. For these calculations the ionisation potentials were taken from tabulated data sources [62, 63]. The values for $\bar{z}$ were then found using a trial and error technique, adjusting $\bar{z}$ to find the best match between the two sides of this equation. The resulting estimated values for $\bar{z}$ were 11 for tungsten and 6 for aluminium.

The mean free path was calculated for a variety of collision geometries. The shock structures observed in the aluminium experiments were formed where adjacent streams of ablated plasma collided. Since the inter-stream

approach velocity is lower than the relative counter streaming velocity at the axis, the inter-stream case should be the most collisional. To approximations of the likely interaction velocities between adjacent streams we must look to the geometry of the array. The angle describing the azimuthal separation between each adjacent pair of the wires is given by the following expression:

$$\theta_{adj} = \frac{2\pi}{N_{wire}} \quad (5.7.9)$$

Where N_{wire} is the number of wires making up the array. The approach velocity of two adjacent streams is calculated by taking components of the stream ablation velocity (typically $V_{abl} = 1.5 \times 10^5 \text{ ms}^{-1}$). The approach velocity is calculated in the rest frame of one of the ablation stream resulting in the following expression:

$$V_{int} = 2V_{abl} \sin\left(\frac{\theta_{adj}}{2}\right) \quad (5.7.10)$$

The angular separation between adjacent flows and the expected approach velocity of the adjacent flows is summarised in the table below. The approach velocity decreases with increasing wire number, and thus it would be expected that the ablation flows of higher wire number arrays would be more collisional than the flows observed in arrays of lower wire number.

Wire Number N_{wire}	Inter-stream Angle /rads θ_{adj}	Interaction Velocity /m/s V_{int}
8	0.79	1.1E+05
16	0.39	5.9E+04
32	0.20	2.9E+04
64	0.10	1.5E+04
128	0.05	7.4E+03

Table 4 Table of estimated collision interaction velocities for wire arrays with a range of wire numbers.

The corresponding ion-ion and ion-electron mean free paths were calculated and the resulting mean free paths are tabulated below. For these calculations the ion density was assumed to be $\sim 1 \times 10^{17} \text{ cm}^{-3}$ for tungsten. The same mass density was assumed for the aluminium wire arrays, resulting in an ion density of $\sim 7 \times 10^{17} \text{ cm}^{-3}$. The widths of the shock fronts observed in the aluminium experiments were on the order of $100 \mu\text{m}$. Therefore in the

table of results, the mean free paths greater than $100\mu\text{m}$ have been highlighted green, while mean free paths less than $100\mu\text{m}$ have been highlighted red.

W	T=15eV Z=11 n = $1\text{e}17 / \text{cc}$	Wire Number Relative Velocity / m/s	8	16	32	64	128
			1.1E+05	5.9E+04	2.9E+04	1.5E+04	7.4E+03
Al	T=15eV Z=6 n = $7\text{e}17 / \text{cc}$	W:					
		ion - ion / mm	1.70000	0.15000	0.00870	0.00064	0.00004
		ion - electron / mm	1.41000	0.75000	0.37500	0.19000	0.09500
		Al:					
		ion - ion / mm	0.06300	0.00520	0.00032	0.00003	0.00001
		ion - electron / mm	0.18000	0.09900	0.04900	0.02500	0.00000

Table 5 A table of the ion mean free path in mm, calculated using the Spitzer slowing down formula.

This table provides some interesting results. Firstly, the aluminium streams are shown here to be collisional in both the 16 and 32 wire cases, as observed in experiments. The table suggests that 8 wire aluminium arrays may access the non-collisional regime. The ion-electron mean free path is significantly larger than $100\mu\text{m}$, however the ion-ion mean free path here is $63\mu\text{m}$. It would therefore be interesting to do an experiment at this wire number.

Secondly while this data supports the low collisionality observed in 8 and 16 wire tungsten, it suggests that tungsten ablation streams should be collisional in both the 32 and 128 wire cases. In both of these cases the ion-ion mean free path is significantly smaller than $100\mu\text{m}$. In the 128 wire case even the ion-electron mean free path is border-line, with a mean free path of only $95\mu\text{m}$. In the case of 128 wire arrays, there may have been some shock formation; however the expected scale of these shocks could have fallen below the spatial resolution of the interferometer. Combined with some small degree of azimuthal integration introduced by the imperfect alignment of the probing beam, this may help to explain why no shock formation was observed in the 128 wire data. In the 32 wire data there is definitely no sign of shock formation. The experimental data therefore contradicts this calculation. It should be noted that the mean free path calculation is extremely sensitive to changes to its inputs, particularly $\bar{z}$ and v_{ion} . Better estimates of these inputs may help to clarify the situation. Further work is required, ideal-

ly to make measurements of temperature, velocity and mean ionisation distributions. Work is already underway using a new Thompson scattering diagnostic to attempt to make some of these measurements.

5.8) Comparisons to GORGON 3D MHD simulations

A series of MHD simulations have been run in order to produce data for comparison with the dataset produced in the end-on probing experiments. The simulations were run using the Gorgon [64, 65] resistive MHD code, both in 2D and 3D. The quantitative nature of the data resulting from these experiments lends itself well to comparison with these simulations. It provides an excellent source for both model validation and code verification. The simulations presented in this section were provided by Prof Jeremy Chittenden.

5.8.1) Aluminium 32 wire array

A 3D Gorgon MHD simulation of a 32 wire aluminium wire array was run in order to make comparisons with the data captured in shot no. s0518_11. The experimental and simulated density plots $t \sim 146\text{ns}$ are plotted side by side in Figure 87. The simulated data has been masked in this plot in order to provide a better comparison with the field of view available to the end-on interferometer. Qualitatively, the two plots appear extremely similar. In both images there is evidence of the formation of primary, secondary and tertiary shock structures. The wedge

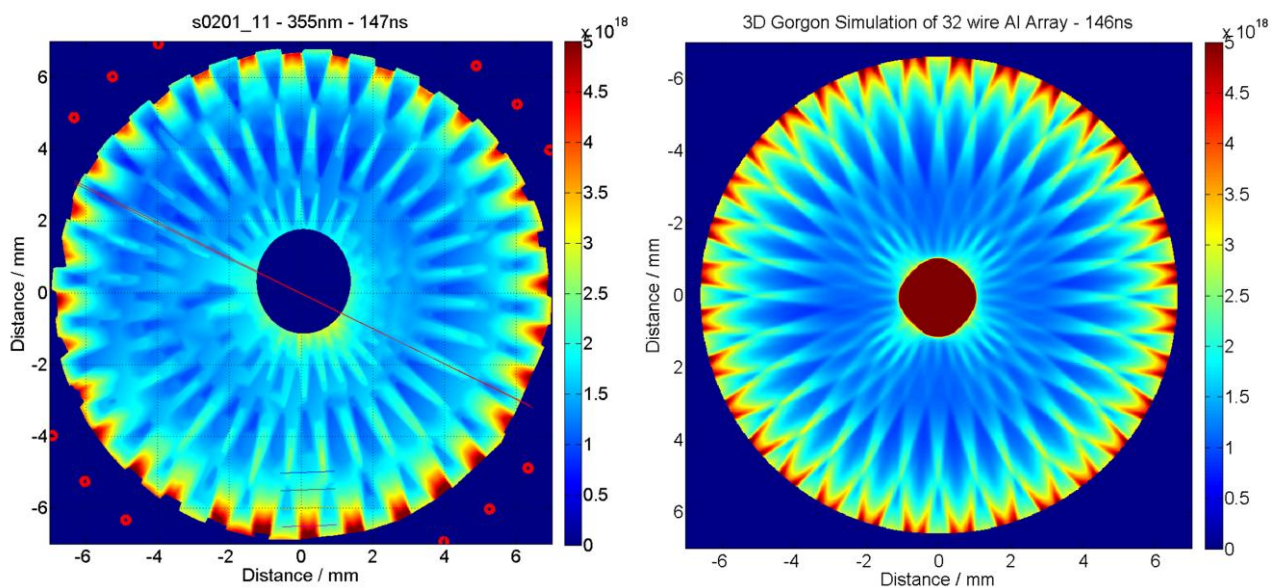


Figure 87 Comparison of experimental and simulated data for a 32 wire Al array. The simulated data has been cropped for better comparison.

angles of the secondary shocks agree to within the measurement errors. As in the experimental data, the regions of highest density at the perimeter of the plot correspond to the inter-wire gaps, and are formed by the collision of ablated plasma. It should be noted that there is some evidence of grid imprint visible in the simulated data. The simulations are performed on a Cartesian grid, which tends to produce a degree of imprint on the azimuthal distribution on the data. This is particularly evident in the density contrasts of the quaternary shocks.

There are some differences between the two data sets. Figure 88 shows a series of line profiles through the primary shocks, for $r=5\text{mm} - 6\text{mm}$. The primary shock streams observed in the simulated data are characterised by

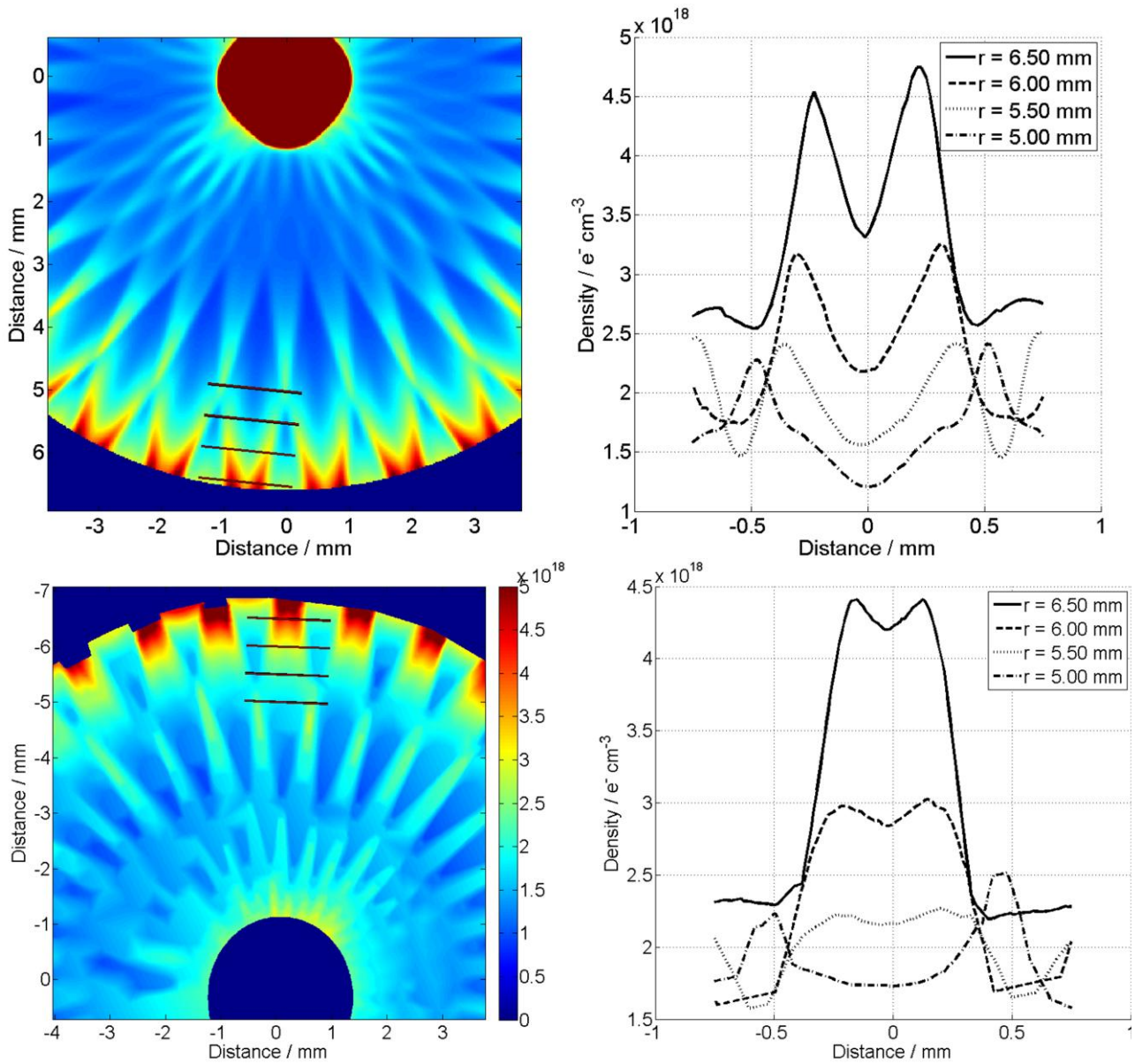


Figure 88 Comparison of the density profiles observed in the primary shock, from experimental data (top) and simulated data (bottom).

a wider and more hollow density profile than those observed in the experimental data. At $r = 6\text{mm}$, the width between the peaks of this profile is $\sim 0.5\text{mm}$, while in the experiment this width is $\sim 0.25\text{mm}$. This could indicate that the degree of heating of the plasma in the primary shock is being exaggerated in the simulation, leading to higher internal shock pressure. The secondary shocks appear to form at roughly the same radius in both, at around 5 mm .

Figure 89 shows on and off stream line profiles for both the experimental and simulated electron density profiles. Comparing these line profiles, we see that the experimental data is extremely noisy. This is due to the complex fringe pattern produced by this electron density distribution. Similar structures can be made out in the two pro-

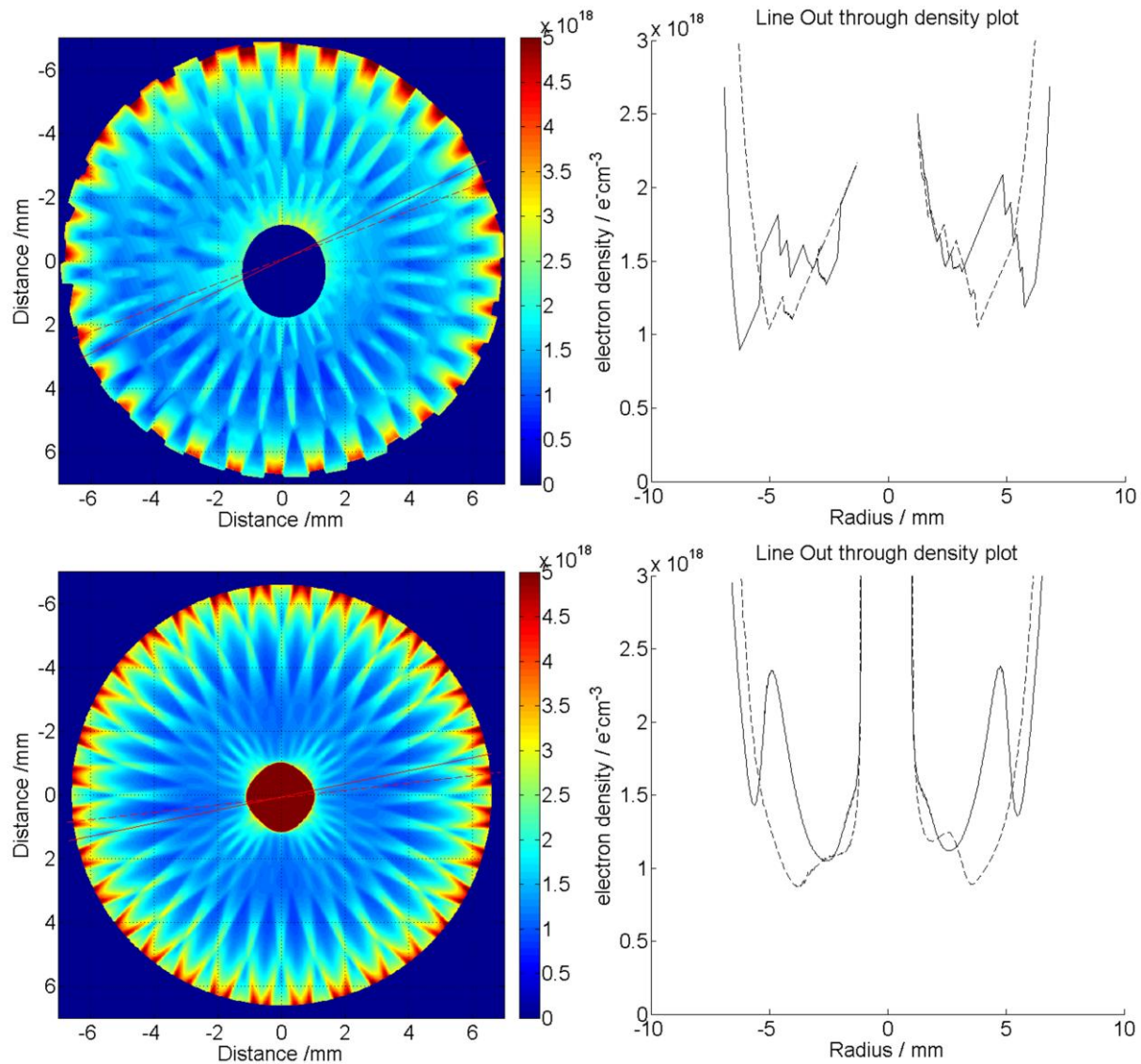


Figure 89 Comparison of both on and off stream line profiles for simulated data and experimental measurement.

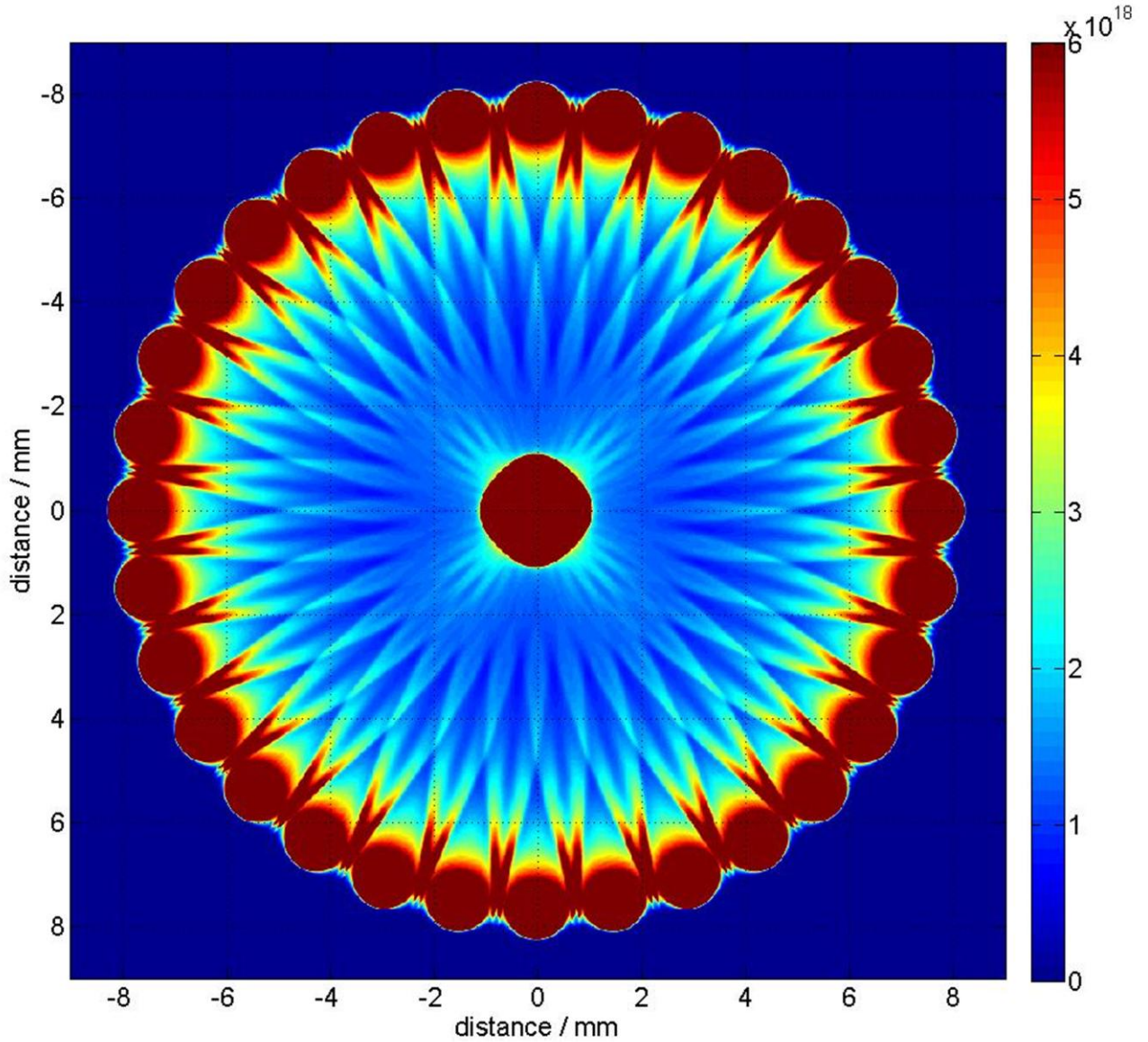


Figure 90 Full plot of a GORGON simulation of 32 wire aluminium array. Electron density plot at 146ns.

files, and the electron density scale over which the two sets of profiles vary is also similar. Otherwise, it is difficult to make any significant conclusions from this comparison.

Overall the experimental data appears to agree well with the simulation. The dynamics of the ablated plasma are well described using the fluid approximation inherent in a MHD code and the datasets appear to agree numerically. Figure 90 shows an unmasked version of the plot shown in Figure 87, demonstrating the origins of the primary shock streams. The large high density circles correspond to the expanded wire cores.

5.8.2) Tungsten 32 wire array

Figure 91 shows a comparison of an experimental and simulated electron density profile for a 32 wire tungsten array at 140ns. The azimuthal ablation structures observed in these two plots are very different; the ablation streams in the simulated profile appear much more focused than those observed in the experimental data, and shock fronts have clearly formed between the streams. By contrast the experimental data is characterised by smooth density gradients throughout.

Strong azimuthal density variations are present in the simulated data right up to the array axis, while in the experimental data the density profile becomes azimuthally isotropic within a radius ~ 4 mm of the axis. This smoothing of the density profile indicates some form of diffusive process is taking place, acting to transport the electron density azimuthally as the ablation streams propagate towards the axis. Whether this is a collisional process or due to the slow expansion and overlap of the ablation stream is unclear.

Gorgon is an MHD code, which means that it treats the plasma as a fully collisional fluid, and cannot model non-collisional, interpenetrating flows. The experimental data indicates that the interaction of the adjacent tungsten ablation flows is non-fluid like. The mean free path of the tungsten ions must be at least on the scale of the ablation stream widths. Particle based simulations are required in order to model these dynamics more accurately.

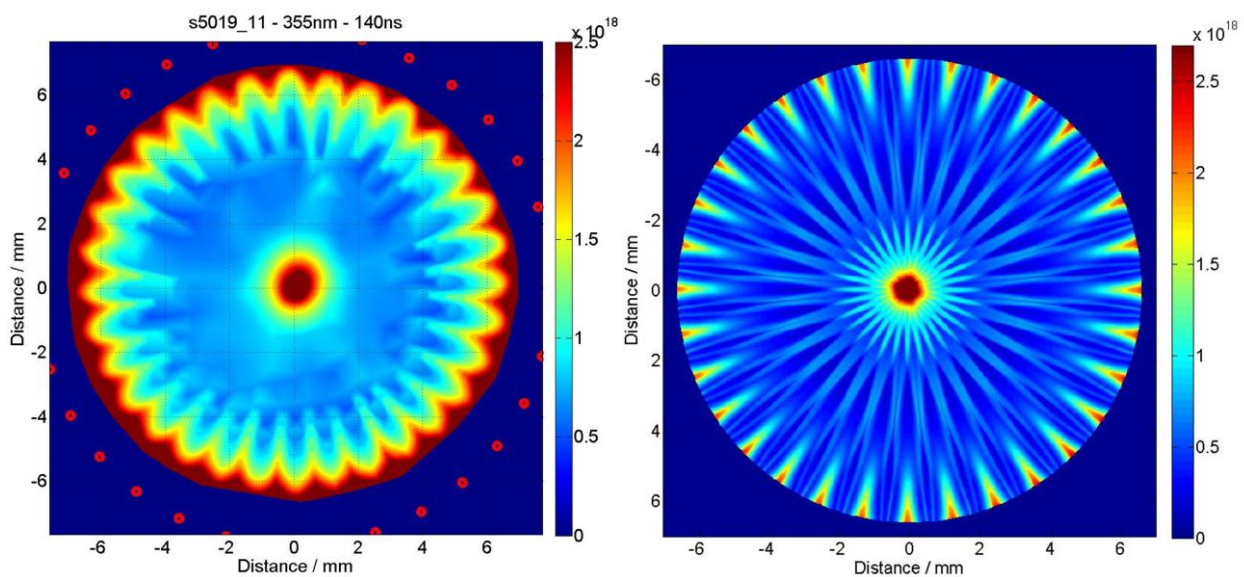


Figure 91 Comparison of an experimental (left) electron density profile for a 32 wire tungsten array with an electron density profile taken from GORGON simulation data (right).

A quantitative comparison can be made by taking line profiles through the two data sets. Figure 92 shows electron density profiles along the ablation streams, taken from the electron density profiles shown in Figure 91. While the electron density profile of the experimental and simulated data appear to agree broadly, the profile from the experimental data appears much smoother. In the simulated data shoulders are observed in the profile between $r=1.5$ - 2 mm. These correspond to the sudden increase in density due to formation of a shock front formed near the axis.

Due to the MHD modelling, radial convergence occurs as a staged process in the simulation, with each stage taking place across an oblique shock. In the experimental data this appears to be a continuous process. In Figure 91 the experimental profile is shown with two different zero fringe shifts, illustrating how the zero fringe shift can be

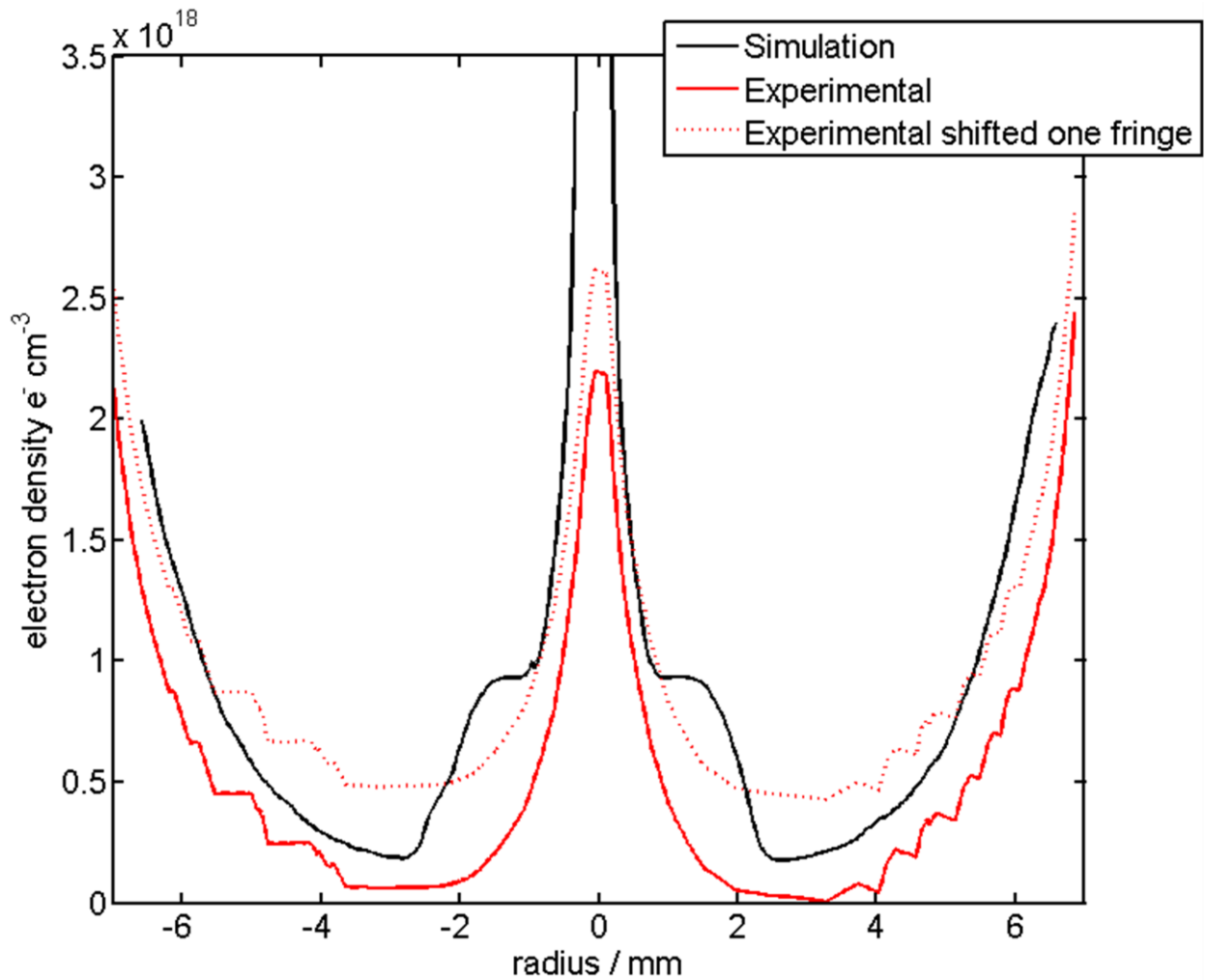


Figure 92 On-stream line profiles of the experimental and GORGON simulation electron density maps. With the addition of a single zero fringe-shift the data matches reasonably well.

used as a free parameter for matching the experimental and simulated profiles. In this case a better match is found by increasing the zero fringe shift by one.

Figure 93 shows a comparison of the profiles taken through the ablation streams for the two density profiles. The profiles are each 1.5mm long and are taken at radii varying between 3-6mm. Comparing the profiles taken at the 6mm, we can see that the initial ablation stream is much narrower in the simulation. The FWHM of the simulated stream is ~ 0.3 mm, compared with ~ 0.5 mm for the experimentally measured stream. The degree of azimuthal

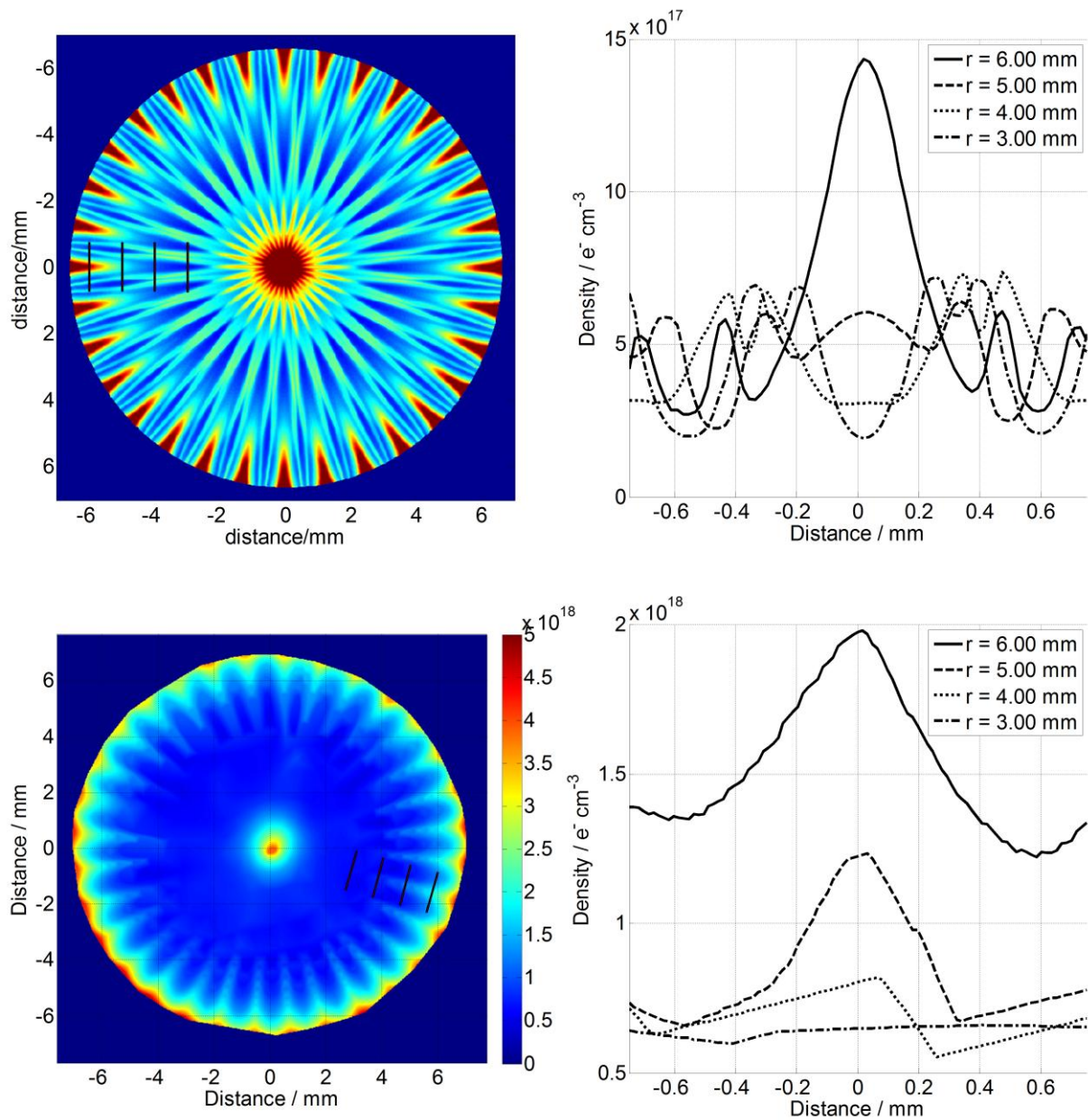


Figure 93 Comparison of stream profiles for simulated and experimental data for a 32 wire tungsten array. Simulated data is at the top while the experimental data is at the bottom.

variation in electron density remains strong in the simulated data up to a radius of 3mm. In the experimental data the profile appears azimuthally smoothed by this radius.

Chapter 6

Conclusions and Future Work

6.1) End-on interferometry -the azimuthal structure of ablation plasma

An end-on imaging interferometer has been developed in order to make measurements of the azimuthal variations in the electron density of ablation plasma produced during wire array Z-pinch implosion experiments. The apparatus developed for this work is a significant improvement on interferometers used in previous end-on laser probing experiments. The addition of a laser exit hole in the side of the cathode allows a Mach-Zender layout to be used for end-probing for the first time. The interferometer features dichromic beam combination and separation optics, allowing two probing wavelengths to be used to produce two separately timed interferograms during each shot

Experiments were conducted on aluminium wire arrays with 16 and 32 wires, and tungsten wire arrays with 8, 16, 32 and 128 wires. The results of these experiments are discussed in detail in Chapter 5. End-on interferometry reveals a great deal of azimuthal structure. This structure is the result of the formation of ablation streams from each of the wires and the interactions of these streams as they radially converge towards the axis. A significant

change in dynamics is observed between aluminium and tungsten wire arrays. Aluminium wire arrays produce collisional electron density structures, characterised by the formation of a network of oblique shock fronts. This structure contrasts with observations of the tungsten arrays, which produce smooth density distributions, consistent with reasonably large inter-stream ion mean free paths, at least on the scale of the ablation stream widths.

One of the most interesting applications of this highly quantitative dataset is as a resource for model validation and code verification exercises. Numerical simulations codes must be benchmarked against known problems in order to evaluate their accuracy and validity. Comparison of the end-on laser probing data with MHD simulations has produced excellent agreement in the case of aluminium arrays; however the finite mean free path dynamics observed in the tungsten density distributions are not captured by the MHD code due to its fluid approximation of the plasma. A particle-in-cell treatment of these arrays may result in better agreement with the data.

6.1.1) Overview of W results

Experiments were carried out on tungsten wire arrays with 8, 16, 32 and 128 wires. The end-on interferometry data captured in these experiments is generally characterised by smooth electron density profiles, with no sharp discontinuities in gradient. The wires each produce sharp, high Mach number ablation streams. These streams are seen particularly clearly in the data from the 8 wire arrays, where the azimuthal separation of the streams is at its greatest. The streams are characterised by a FWHM of $\sim 0.5\text{mm}$, and there is very little plasma observed in the regions between them.

As the number of wires increases, the azimuthal separation between the ablation streams decreases. The electron density profiles for 16 wire arrays indicate that the ablation streams make contact towards the array axis, and in the 32 wire data the ablation streams are in contact from almost the outset. Despite this there is no evidence of the formation of oblique shocks at the points where the ablation streams overlap, indicating that the collision of these flows is characterised by relatively long ion mean free paths.

The data from the eight wire arrays allows us to get a handle on the Mach number of the ablation streams based on the observed expansion of the ablation streams. The stream profiles in Figure 65 show that the ablation streams are highly collimated. The expansion angle measured is smaller than the error associated with the measurement, indicating a high Mach number, unlikely to be lower than 10. An estimate of the expected Mach number can be made by comparing the ablation velocity, V_{abl} with the thermal expansion velocity V_{th} and ion sound speed c_{ion} as given by the equations below, taken from the NRL formulary [60]. This analysis indicates a lower limit Mach number of $M \sim 10$, set by the ion sound speed. This is consistent with our observations of the streams.

$$\begin{aligned} V_{abl} \sim 10^5 \text{ms}^{-1} \quad V_{th} \sim 10^4 \sqrt{\frac{T_i}{A}} \sim 10^6 \frac{\sqrt{15eV}}{183} \sim 10^3 \text{ms}^{-1} \quad M = \frac{V_{abl}}{V_{th}} = 100 \\ c_{ion} \sim 10^4 \sqrt{\frac{ZT_e}{A}} \sim 10^4 \sqrt{\frac{10 \cdot 20}{183}} \sim 10^4 \text{ms}^{-1} \quad M = \frac{V_{abl}}{c_{ion}} = 10 \end{aligned} \quad (6.1.1)$$

In all tungsten wire array profiles presented the electron density profile becomes azimuthally isotropic within a certain radius, which we shall define as the precursor radius. There are two possible mechanisms that could lead to this smoothing of the profile: either the ablation flows expand thermally as they propagate towards the axis, smoothing the profile as a result of their superposition, or there is some form of collisional process that azimuthally transports mass as the streams approach the axis.

The azimuthal smoothing of the density profile in the 8 wire data appears to occur rapidly at a well-defined radius, supporting the theory that this is a collisionally driven process. The overlap of radially converging, gradually broadening ablation streams would be expected to be a more gradual process. In any case there is no evidence that the streams have significantly broadened before they reach the precursor radius. Since no shocks are observed, the ion mean free path must be long enough that this scattering process is diffusive.

The same azimuthal smoothing effect is also observed in the 16 and 32 wire data. The radius at which the density profile becomes azimuthally isotropic (the precursor radius) can be measured by comparing the on and off stream electron density line profiles. Figure 94 shows a plot of the precursor radius as measured from the line profiles for 8 (Figure 65, Figure 66), 16 (Figure 70) and 32 (Figure 73) wire tungsten arrays. This plot demonstrates

how this radius decreases with time. This is consistent with the model for the initial precursor distribution being compressed by the momentum flux of the incoming ablation streams as the rate of ablation increases with rising drive current [1]. Interestingly, this radius also increases with wire number. Perhaps the azimuthal smoothing is the result of a combination of both collisional and superposition effects.

At the axis the mean free path for the collisions of opposing flows should be long, as the relative velocity of the ions at the axis is large ($\sim 3 \times 10^5 \text{ ms}^{-1}$). The ions would therefore be expected to slow down only over relatively long distances. An increase in the average ionisation state on axis may act to reduce the mean free path, as the collision frequency scales with Z^4 . The energy required to further ionise the plasma could be provided by the stagnation of the streams onto the axis. Recent Thompson scattering measurements of the radial velocity profile indicate that the velocity of the ablation streams does start to decrease as they approach the axis. It's possible that this slowing results in the scattering of stream as it 'piles up' upon itself, driving the azimuthal smoothing effect. Further experimental measurements and particle based simulations are required.

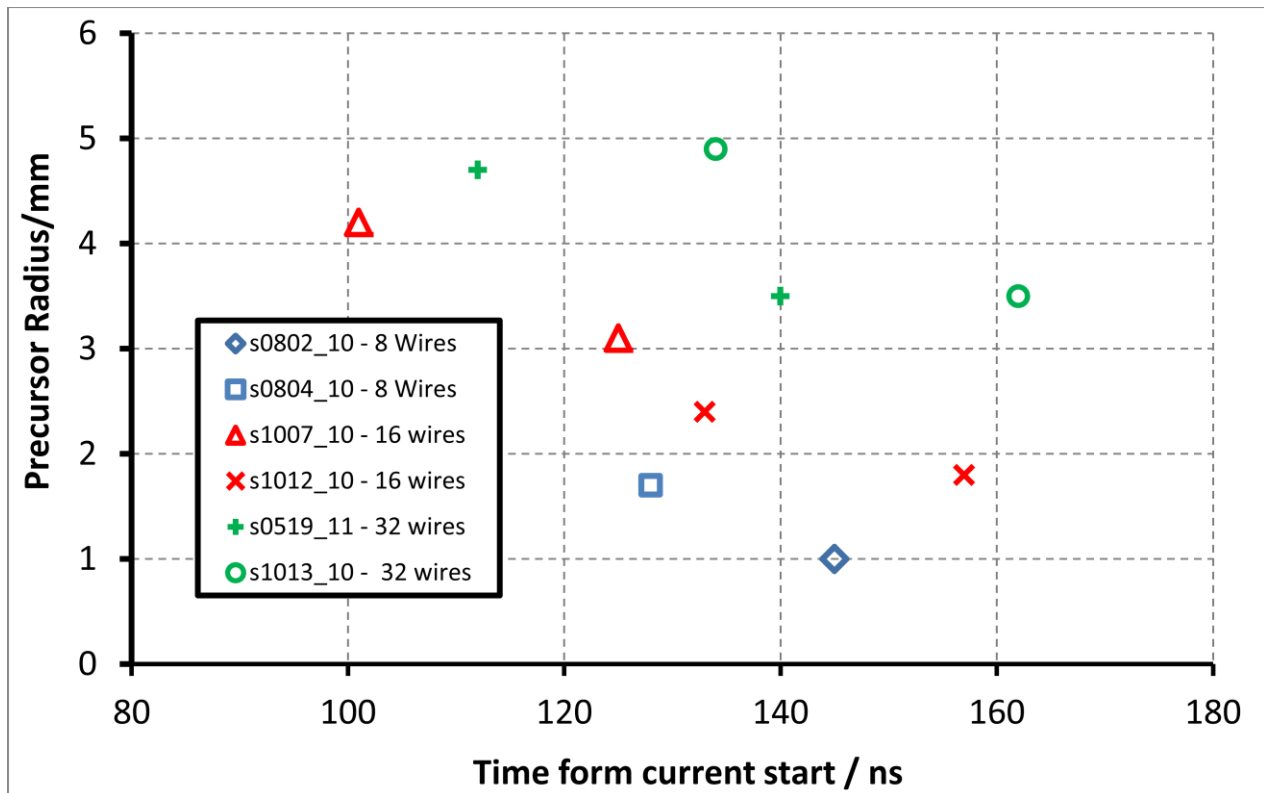


Figure 94 Plot showing how the precursor radius changes with time. Data was taken from line profiles of the electron density. Colours indicate arrays of the same wire number, shapes indicate measurements from the same shot.

The smoothed precursor distribution eventually collapses to form the dense precursor column. The formation mechanisms of the dense precursor column are discussed in detail in reference [1]. Collapse is believed to be triggered by ion-electron equilibration brought on by the increasing plasma density. Rapid equilibration allows the electrons to radiatively cool the ions. 1D particle codes have been used to investigate this process [59].

Modulations in the azimuthal density profile may have an impact on the peak X-ray power output. In tungsten arrays the modulations in the density of the precursor fill can reach deep towards the axis. These variations may increase the effective width of the snowplough piston, which in turn may reduce the peak radiative power achieved by the pinch. Snowplough trajectory calculations, based on the model put forward in reference [25], can be made by modulating the rocket model density profile to take account of differences between on-stream and off-stream profiles. The modifications to the calculations in reference [25] were made as simple as possible. The

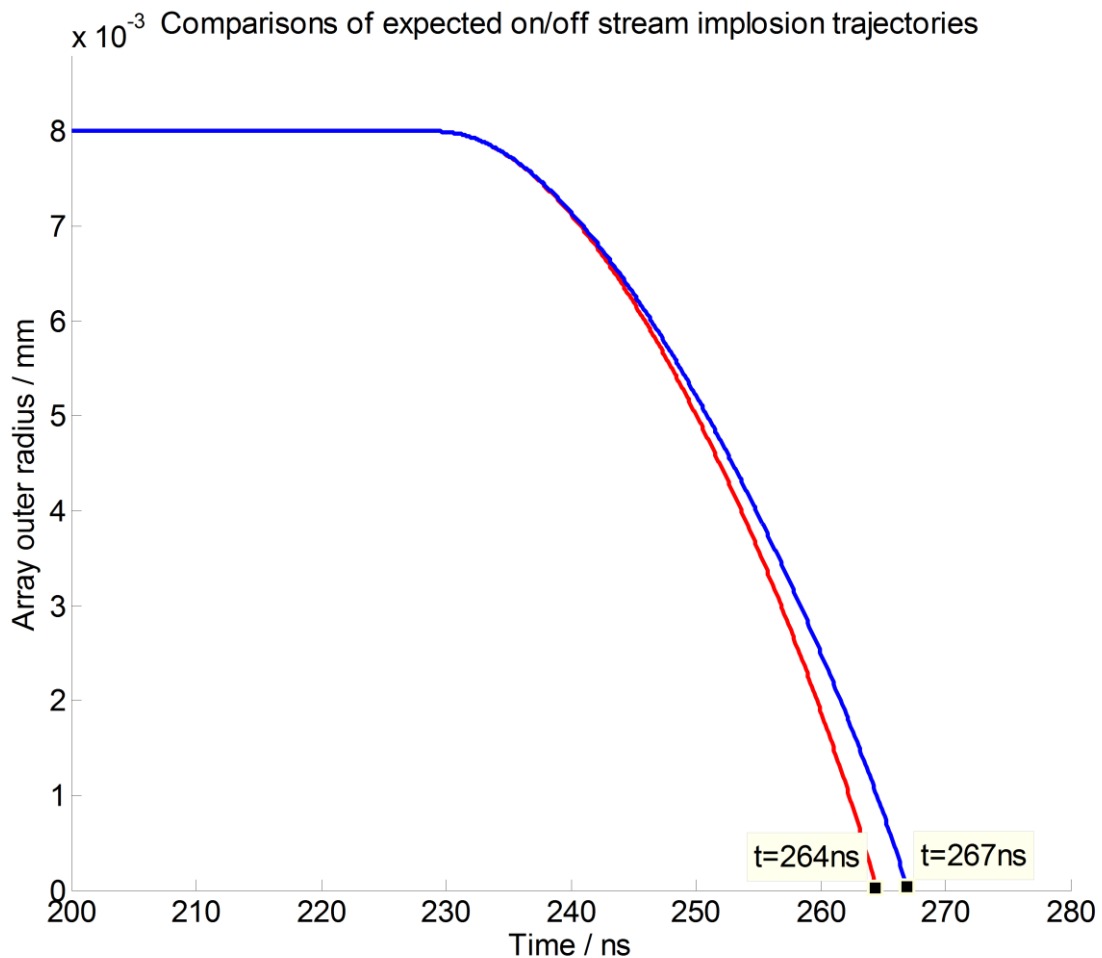


Figure 95 Snowplough trajectories for on and off stream profiles, demonstrating the implosion stretching effect. The stagnation times predicted here are separated by 3ns.

same current profile and mass per unit length ($4.77\mu\text{g}/\text{cm}$) were used.

$$I = I_0 \sin^2 \left(\frac{\pi t}{500\text{ns}} \right) \quad (6.1.2)$$

The implosion was assumed to begin when 40% of the mass had been ablated, and 1/6 of the remaining wire mass was assumed to implode with the piston. Estimates for the on-stream density enhancement and off-stream density reduction were made from the stream profiles shown in Figure 75. This data is from a 32 wire array, and resulted in modulation factors of $k_{\text{on}}=1.2$ for on-stream and $k_{\text{off}}=0.8$ for off-stream. The only change to the calculation was that the prefill annular-density was calculated using the following modified expression:

$$\rho = k\rho(r, t_{\text{delay}}) = \frac{k\mu_0}{4\pi R_0 V_{\text{abl}}} I \left[\left(t - \frac{(R_0 - r)}{V_{\text{abl}}} \right) \right]^2 \quad (6.1.3)$$

The results of these calculations are shown in Figure 95, and indicate that this effect could stretch the implosion time to around 3ns. This is on the order of the width of the radiation peak.

6.1.2) Overview of Aluminium wire array results

Experiments were carried out on aluminium wire arrays with 16 and 32 wires. The ablation structures produced in these experiments are dominated by collisional features. A network of oblique shocks is formed as the ablation streams launched from the wires interact with their neighbours. Secondary, tertiary and even quaternary shocks have been observed in the 32 wire array data. Because of the collisional nature of the flows, radial convergence of the density occurs in discrete steps, mediated by the oblique shock fronts. Between shock fronts the ablated plasma flows as parallel streams, and the radial density distribution is set only by the current waveform.

The ablation streams formed by the aluminium wires appear much broader than those formed by tungsten arrays, indicating the Mach number of these flows is smaller. In the 16 wire data the ablation streams interact to form collisional shock structures all the way out to the array perimeter. The primary shocks formed in the 16 wire data appear to hollow as they propagate towards the axis, indicating that the plasma at the cores of these shocks has a higher temperature than that at the edge. The increased temperature results in a higher thermal pressure, which acts to balance the kinetic forces at the shock front. The angle at which material from the wire cores joins

the shock is highest at large radius. A larger turning angle results in a greater portion of the kinetic energy being stagnated and a higher post-shock temperature. As the wire number increases the angle at which the plasma streams meet the primary shock decreases, and as a result the amount of kinetic energy stagnated into the shock is reduced. This interpretation is consistent with the data; the primary shocks observed in the 32 wire data have a much flatter density profile compared with the shocks formed by the 16 wire arrays.

The shock structures in the 32 wire data were analysed in greater detail than those for the 16 wire array. This was mainly due to the much simpler structure that was observed. Analysis of the angles at which the secondary shock fronts formed allowed estimates of the Mach number of these flows to be made. A diagram of the shock structure is shown in Figure 96. For a 32 wire array the expected turning angle for the flow is $\theta = 0.098 \text{ rad}$. The angle at which the secondary shocks formed in the 32 wire arrays was measured as $\beta = 0.208 \pm 0.004 \text{ rad}$. Using the θ - β -M relation introduced in section 5.6.2) it is possible to estimate the Mach number of the primary streams. As is demonstrated by the plots in Figure 97, the incoming Mach number is remarkably insensitive to both the Gamma

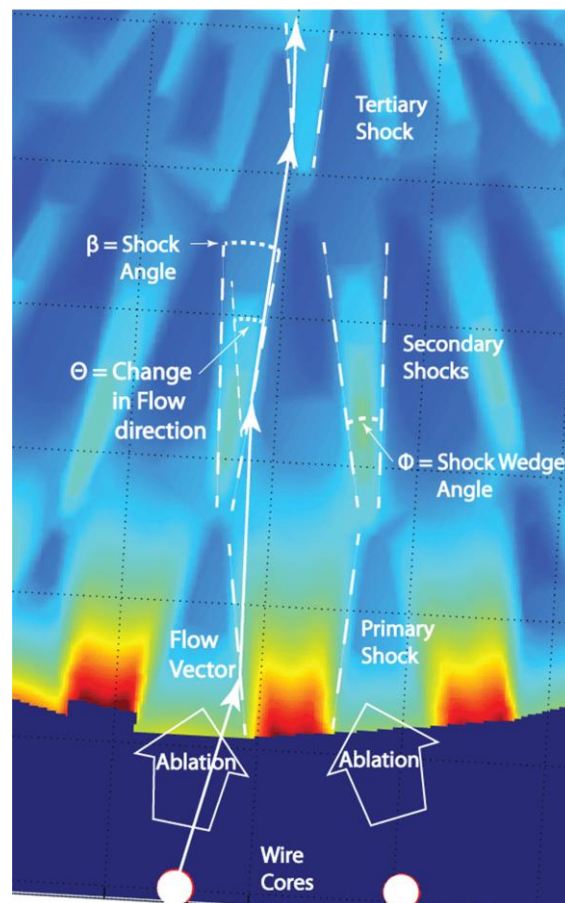


Figure 96 Overlay of the oblique shock structure on 32 wire aluminium array data, showing the various angles.

of the plasma and small errors in the measurement of the shock angle. The analysis results in an estimate of $M=7.9-8.2$ for the Mach number of the primary shock flows. Using equations from the NRL formulary [60] for the ion sound speed allows us to estimate the $T\bar{Z}$ product for this plasma.

$$M = \frac{V_{abl}}{c_{ion}} \quad V_{abl} = 1.5 \times 10^5 \text{ ms}^{-1} \quad c_{ion} \sim 10^4 \sqrt{\frac{zT_e}{A}} \text{ ms}^{-1} \quad (6.1.4)$$

$$zT_e = \left(\frac{V_{abl}}{10^4 M} \right)^2 A = 90 - 97 \text{ eV}$$

This agrees reasonably well with the values that were estimated for the collisionality calculations in section 5.7), $\bar{Z}=7$, $T_e=15\text{eV}$, $T\bar{Z} = 105\text{eV}$.

The aluminium array data is in good agreement with data from Gorgon 3D MHD simulations, indicating that the fluid approximation is valid in this regime. The data therefore provides an excellent resource for testing the accuracy of MHD codes. Initial comparisons with simulations indicate that GORGON may overestimates both the width and degree of heating that occurs in the primary shocks formed in 32 wire arrays. Further analysis is required in order to make more in-depth comparisons.

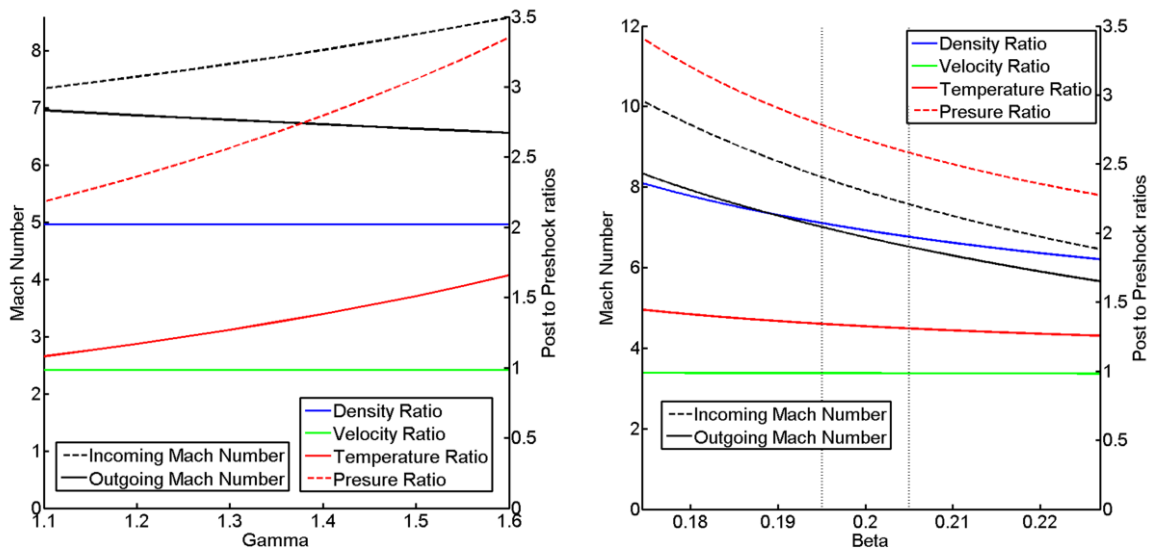


Figure 97 Plots of the plasma parameters across the oblique shocks formed in 32 wire arrays. These demonstrate the low sensitivity of the density ratio and the incoming Mach number to changes in Gamma and the shock angle.

6.2) Quadrature Interferometry

A quadrature interferometer was developed in order to make time resolved measurements of the line integrated plasma electron density. The apparatus was designed to be fielded in both side-on and end-on configurations. It has been used in a number of experimental applications, including monitoring the density of the hypersonic plasma jets launched from radial foils and measuring the zero fringe-shift in end-on interferometry experiments.

The quadrature analysis technique was presented and its various benefits discussed. Quadrature analysis provides three major benefits over analysis of a single phase signal; it introduces directional sensitivity, improves the differential sensitivity over the full phase cycle and allows for changes in the fringe contrast ratio introduced by refractive bending of the probing beam. The tolerance to changes in the contrast ratio is particularly important in wire array experiments, as the probing beams are often deflected by strong refractive index gradients generated in the plasma.

The design and implementation of this diagnostic was discussed in detail. The interferometer was constructed on a special 'horse shoe' shaped optical breadboard. The design allows the interferometer to be placed over the top of the experimental chamber. While this means that the diagnostic must be removed between each shot, it also means that the interferometer is very compact, helping to maximise the number of diagnostics that can be fielded in each experiment.

An example of the experimental data was analysed. This data was from a radial foil experiment, investigating the evolution of hydrodynamic jets launched into an ambient medium. The analysis of this data highlighted the insensitivity of the analysis to small errors in the calibration. The data from the radial foil experiment showed what appeared to be a linear ramp in the density of the jet.

The diagnostic was also used to measure the zero fringe-shift for a 32 wire tungsten array experiment. This data was used to help calibrate the interferograms in section 5.6.4). The quality of the data produced in this experiment was not very good, and therefore further work is required to perfect this technique.

A number of potential improvements to this diagnostic were discussed. The interferometer signal suffers from a number of problems, associated with electrical noise in the signal and changes in the average intensity measured by the photodiodes during the shot.

6.3) Faraday rotation current diagnostic

A Faraday rotation diagnostics was developed in order to make measurements of rapid changes in current produced in experiments where an inverse wire array was used as a switch. The detail of the design of this diagnostic is discussed in section 4.2). The current is measured by exploiting the Faraday Effect, which described how an externally applied magnetic field may induce circular birefringence in optical transmission medium. A circularly birefringent transmission medium will induce a rotation in the plane of polarisation of a linearly polarised beam of light that passes through it. The angle of rotation is directly proportional to the magnetic field strength, which in turn is proportional to the current. Therefore the current may be measured by recording how the angle of rotation changes during the experiment. The major benefit of the Faraday technique over other current diagnostic devices is that the signal is proportional to the current itself, rather than the rate of change of the current.

A fused silica rod was used as the Faraday rotation medium, and a 532nm CW Nd:YAG laser was used as the beam source. Experiments were first carried out on standard wire array loads in order to test the diagnostic. This resulted in current measurements that were in good agreement with the standard diagnostic suite. In the current switching experiments however the diagnostic measured significantly less current than expected. It is believed that this low measurement was due to a distributed return current. The return current is normally conducted through a set of four return posts. The inverse array injects a large volume of plasma into the return structure that may provide alternative return paths for the current, circumventing the faraday probe. As a result of the failure of this measurement the development of this diagnostic was put on hold. It remains a powerful technique for making accurate measurements of a fast changing current.

6.4) Future Work

The work presented in this thesis has revealed a great deal of detail in the azimuthal structure of the ablation plasmas produced by wire array z-pinches. Interferometry provides a simple and powerful technique for probing the density of these plasmas, however in order to gain a better understanding of the dynamics further measurements of the plasma parameters such as plasma temperature, velocity, and mean ionisation are required.

A new diagnostic laser system is currently being installed. The Cerberus project aims to install three new laser beam-lines, which will be available to power diagnostics on MAGPIE. The first beam-line is already online and is currently being used to make Thompson scattering measurements. The beam energy is 2-3J, with a pulse length of ~ 8 ns and a wavelength of 532nm. The Thompson scattering diagnostic has already been applied to wire array experiments, in order to measure the velocity curves of the ablation streams. Further experiments using the Thompson scattering diagnostic are required in order to build up a full picture of the velocity distribution. Of special interest are the acceleration zones around the wires, where the ablation streams are launched, and the region around the axis, where the plasma interacts to form the broad initial precursor distribution.

The second laser to come online will be a fast pulse beam designed to power an X-ray point-backlighting system. Conservative estimates suggest this will have total beam energy of ~ 20 J, with a pulse length of ~ 1 ns and wavelength of 527nm. X-ray radiography could be applied to tungsten wire arrays to directly measure the mass distribution of the ablation plasma. With both the electron density distribution and mass density distribution known, it should be possible to calculate a map of the average ionisation, $\bar{Z}$. End-on backlighting experiments have already been carried out at the Cobra facility at Cornell university [66]. The X-ray source used for these experiments was an X-pinch. While X-pinch radiography is a convenient and inexpensive diagnostic for pulse power experiments, it provides only limited control of the image timing, making experiments difficult to reproduce.

Finally the third beam-line will be designed to drive proton probing experiments. While the total beam energy is likely to be similar to the radiography beam described above, this beam will use Chirped Pulsed Amplification (CPA) techniques to produce a pulse duration of ~ 500 fs. This reduction in the pulse duration will result in a mas-

sive increase in the peak optical power, enough to drive high energy proton beams. Proton probing is used to probe the magnetic fields present in the plasma by observing the deflection of the beam. End-on proton probing measurements could be used to measure the degree of current penetration into the ablation plasma.

Appendix A:

Raw Interferograms

This appendix contains a selection of raw end-on interferograms, and is included as a reference to the complexity of the analysis. These images selected represent the most recent data collected, during a series of shots from May 2011.



Figure 98 532nm interferogram of a 32 wire aluminium array, from shot s0518_11.



Figure 99 355nm interferogram of a 32 wire aluminium array, from shot s0518_11.



Figure 100 532nm interferogram of a 32 wire tungsten array, from shot s0519_11.



Figure 101 355 nm interferogram of a 32 wire tungsten array from shot s0519_11.

Bibliography

1. Bott, S.C., et al., *Dynamics of cylindrically converging precursor plasma flow in wire-array Z-pinch experiments*. Physical Review E, 2006. **74**(4): p. -.
2. Cuneo, M.E., et al., *Characteristics and scaling of tungsten-wire-array z-pinch implosion dynamics at 20 MA*. Physical Review E, 2005. **71**(4).
3. Suzuki-Vidal, F., *Private Correspondence*.
4. Munin, E., J.A. Roversi, and A.B. Villaverde, *Faraday-Effect and Energy-Gap in Optical-Materials*. Journal of Physics D-Applied Physics, 1992. **25**(11): p. 1635-1639.
5. Matzen, M.K., et al., *The Refurbished Z Facility: Capabilities and Recent Experiments*. Acta Physica Polonica A, 2009. **115**(6): p. 956-958.
6. Sarkisov, G.S., et al., *Interferometric measurements of dynamic polarizabilities for metal atoms using electrically exploding wires in vacuum*. Physical Review A, 2006. **73**(4).
7. Bland, S.N., et al., *Implosion and stagnation of wire array Z pinches*. Physics of Plasmas, 2007. **14**(5).
8. Sinars, D.B., et al., *Measurements of the mass distribution and instability growth for wire-array Z-pinch implosions driven by 14-20 MA*. Physics of Plasmas, 2005. **12**(5).
9. Lebedev, S.V., et al., *Effect of discrete wires on the implosion dynamics of wire array Z pinches*. Physics of Plasmas, 2001. **8**(8): p. 3734-3747.
10. Hall, G.N., et al., *Structure of stagnated plasma in aluminum wire array Z pinches*. Physics of Plasmas, 2006. **13**(8).
11. Hall, G.N., *The relationship between implosion dynamics and stagnation structure in aluminium wire-array Z-pinches*. 2007.
12. Deeney, C., et al., *Enhancement of X-ray power from a Z pinch using nested-wire arrays*. Physical Review Letters, 1998. **81**(22): p. 4883-4886.
13. Cuneo, M.E., et al., *Double Z-pinch hohlraum drive with excellent temperature balance for symmetric inertial confinement fusion capsule implosions*. Physical Review Letters, 2002. **88**(21).

14. Hammer, J.H., et al., *High yield inertial confinement fusion target design for a z-pinch-driven hohlraum*. Physics of Plasmas, 1999. **6**(5): p. 2129-2136.
15. Bennett, G.R., et al., *Symmetric inertial confinement fusion capsule implosions in a high-yield-scale double-Z-pinch-driven hohlraum on Z*. Physics of Plasmas, 2003. **10**(9): p. 3717-3727.
16. Frank, A., et al., *A HED laboratory astrophysics testbed comes of age: JET deflection via cross winds*. Astrophysics and Space Science, 2005. **298**(1-2): p. 107-114.
17. Lebedev, S.V., et al., *Production of radiatively cooled hypersonic plasma jets and links to astrophysical jets*. Plasma Physics and Controlled Fusion, 2005. **47**: p. B465-B479.
18. Lebedev, S.V., et al., *Magnetic tower outflows from a radial wire array Z-pinch*. Monthly Notices of the Royal Astronomical Society, 2005. **361**(1): p. 97-108.
19. Jones, B., et al., *Planar Wire-Array Z-Pinch Implosion Dynamics and X-Ray Scaling*. Physical Review Letters, 2010. **104**(12).
20. Bailey, J.E., et al., *X-ray imaging measurements of capsule implosions driven by a Z-pinch dynamic hohlraum*. Physical Review Letters, 2002. **89**(9).
21. Lash, J.S., et al., *The prospects for high yield ICF with a Z-pinch driven dynamic hohlraum*. Comptes Rendus De L Academie Des Sciences Serie Iv Physique Astrophysique, 2000. **1**(6): p. 759-765.
22. Cuneo, M.E., et al., *Demonstration of radiation pulse shaping with nested-tungsten-wire-array Z pinches for high-yield inertial confinement fusion*. Physical Review Letters, 2005. **95**(18).
23. Cuneo, M.E., et al., *Compact single and nested tungsten-wire-array dynamics at 14-19 MA and applications to inertial confinement fusion*. Physics of Plasmas, 2006. **13**(5).
24. Sanford, T.W.L., et al., *Improved symmetry greatly increases X-ray power from wire-array Z-pinches*. Physical Review Letters, 1996. **77**(25): p. 5063-5066.
25. Lebedev, S.V., et al., *Snowplow-like behavior in the implosion phase of wire array Z pinches*. Physics of Plasmas, 2002. **9**(5): p. 2293-2301.
26. Ryutov, D.D., M.S. Derzon, and M.K. Matzen, *The physics of fast Z pinches*. Reviews of Modern Physics, 2000. **72**(1): p. 167-223.
27. Mitchell, I.H., et al., *A high impedance mega-ampere generator for fiber z-pinch experiments*. Review of Scientific Instruments, 1996. **67**(4): p. 1533-1541.

28. Lebedev, S.V., et al., *The dynamics of wire array Z-pinch implosions*. Physics of Plasmas, 1999. **6**(5): p. 2016-2022.
29. Suzuki-Vidal, F., et al., *Generation of episodic magnetically driven plasma jets in a radial foil Z-pinch*. Physics of Plasmas, 2010. **17**(11).
30. Suzuki-Vidal, F., et al., *Formation of episodic magnetically driven radiatively cooled plasma jets in the laboratory*. Astrophysics and Space Science, 2009. **322**(1-4): p. 19-23.
31. Harvey-Thompson, A.J., et al., *Suppression of the Ablation Phase in Wire Array Z Pinches Using a Tailored Current Prepulse*. Physical Review Letters, 2011. **106**(20).
32. Deeney, C., et al., *Power enhancement by increasing the initial array radius and wire number of tungsten Z pinches*. Physical Review E, 1997. **56**(5): p. 5945-5958.
33. Spielman, R.B., et al., *Tungsten wire-array Z-pinch experiments at 200 TW and 2 MJ*. Physics of Plasmas, 1998. **5**(5): p. 2105-2111.
34. Lebedev, S.V., et al., *Effect of core-corona plasma structure on seeding of instabilities in wire array Z pinches*. Physical Review Letters, 2000. **85**(1): p. 98-101.
35. Velikovich, A.L., I.V. Sokolov, and A.A. Esaulov, *Perfectly conducting incompressible fluid model of a wire array implosion*. Physics of Plasmas, 2002. **9**(4): p. 1366-1380.
36. Alexandrov, V.V., et al., *Prolonged plasma production at current-driven implosion of wire arrays on Angara-5-1 facility*. IEEE Transactions on Plasma Science, 2002. **30**(2): p. 559-566.
37. Sinars, D.B., et al., *Measurements and simulations of the ablation stage of wire arrays with different initial wire sizes*. Physics of Plasmas, 2006. **13**(4).
38. Chittenden, J.P. and C.A. Jennings, *Development of instabilities in wire-array Z pinches*. Physical Review Letters, 2008. **101**(5).
39. Velikovich, A.L., et al., *Stabilized radiative Z-pinch loads with tailored density profiles*. Physics of Plasmas, 1998. **5**(9): p. 3377-3388.
40. Haines, M.G., et al., *Ion viscous heating in a magnetohydrodynamically unstable Z pinch at over 2×10^9 Kelvin*. Physical Review Letters, 2006. **96**(7).
41. Velikovich, A.L., et al., *Model of enhanced energy deposition in a Z-pinch plasma*. Physics of Plasmas, 2000. **7**(8): p. 3265-3277.

42. Martin, J.C., et al., *J.C. Martin on pulsed power*. Advances in pulsed power technology 1996, New York: Plenum Press. xix, 546 p.
43. Mesiaats, G.A., *Pulsed power* 2005, New York: Kluwer Academic/Plenum Publishers. xvii, 568 p.
44. Weinbrecht, E.A., et al., *Update of the Z refurbishment project (ZR) at sandia national laboratories*. 2007 IEEE Pulsed Power Conference, Vols 1-4, 2007: p. 975-978, 1843.
45. Weinbrecht, E.A., D.H. McDaniel, and D.D. Bloomquist, *The Z refurbishment project (ZR) at Sandia National Laboratories*. Ppc-2003: 14th IEEE International Pulsed Power Conference, Vols 1 and 2, Digest of Technical Papers, 2003: p. 157-162, 1464.
46. Spielman, R.B., *Diamond Photoconducting Detectors as High-Power Z-Pinch Diagnostics (Invited)*. Review of Scientific Instruments, 1995. **66**(1): p. 867-870.
47. Spielman, R.B., W.W. Hsing, and D.L. Hanson, *Photoconducting X-Ray-Detectors for Z-Pinch Experiments*. Review of Scientific Instruments, 1988. **59**(8): p. 1804-1806.
48. Spielman, R.B., et al., *Fast resistive bolometry*. Review of Scientific Instruments, 1999. **70**(1): p. 651-655.
49. Bland, S.N., et al., *Extreme ultraviolet imaging of wire array z-pinch experiments*. Review of Scientific Instruments, 2004. **75**(10): p. 3941-3943.
50. Hutchinson, I.H., *Principles of plasma diagnostics*. 2nd ed 2002, Cambridge ; New York: Cambridge University Press. xvii, 440 p.
51. Buchenauer, C.J. and A.R. Jacobson, *Quadrature interferometer for plasma density measurements*. Review of Scientific Instruments, 1977. **48**(7): p. 769-774.
52. Gourdain, P.A., et al., *Initial experiments using radial foils on the Cornell Beam Research Accelerator pulsed power generator*. Physics of Plasmas, 2010. **17**(1).
53. Ciardi, A., et al., *Episodic Magnetic Bubbles and Jets: Astrophysical Implications from Laboratory Experiments*. Astrophysical Journal Letters, 2009. **691**(2): p. L147-L150.
54. Krishnan, M., et al., *Electromagnetically driven, fast opening and closing gas jet valve*. Physical Review Special Topics-Accelerators and Beams, 2011. **14**(3).
55. Harvey-Thompson, A., *Private Correspondance*.
56. Deng, X.Y., et al., *Research on the magneto-optic current sensor for high-current pulses*. Review of Scientific Instruments, 2008. **79**(8).

57. Ning, Y.N., et al., *Recent Progress in Optical Current Sensing Techniques*. Review of Scientific Instruments, 1995. **66**(5): p. 3097-3111.
58. Anderson, J.D., *Modern compressible flow : with historical perspective*. 3rd ed. McGraw-Hill series in aeronautical and aerospace engineering 2003, Boston: McGraw-Hill. xvi, 760 p.
59. Sherlock, M., et al., *Ion collisions and the Z-pinch precursor column*. Physics of Plasmas, 2004. **11**(4): p. 1609-1616.
60. Naval Research Laboratory (U.S.) and United States. Office of Naval Research., *NRL plasma formulary*. Nrl/Pu, Washington, DC: Naval Research Laboratory. v.
61. Zel*dovich, I.A.B. and I.U.P. Ra*izer, *Physics of shock waves and high-temperature hydrodynamic phenomena* 2002, Mineola, N.Y.: Dover Publications. xxvii, 916 p.
62. Kramida, A.E. and J. Reader, *Ionization energies of tungsten ions: W2+ through W71+*. Atomic Data and Nuclear Data Tables, 2006. **92**(4): p. 457-479.
63. Martin, W.C. and R. Zalubas, *Energy-Levels of Aluminum, Al-I through Al-Xiii*. Journal of Physical and Chemical Reference Data, 1979. **8**(3): p. 817-864.
64. Chittenden, J.P., et al., *One-, two-, and three-dimensional modeling of the different phases of wire array Z-pinch evolution*. Physics of Plasmas, 2001. **8**(5): p. 2305-2314.
65. Chittenden, J.P., et al., *Two- and three-dimensional modeling of the different phases of wire-array z-pinch evolution*. Laser and Particle Beams, 2001. **19**(3): p. 323-343.
66. Blesener, I.C., et al., *Axial x-ray backlighting of wire-array Z-pinchs using X pinches*. Review of Scientific Instruments, 2009. **80**(12).