High-Power Laser Systems for Driving and Probing High Energy Density Physics Experiments

Siddharth Patankar

Imperial College London

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Declaration

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

Siddharth Patankar

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Abstract

This thesis describes the construction of a hybrid OPCPA and Nd:Glass based laser system to provide advanced diagnostic capabilities for the MAGPIE pulsed power facility at Imperial College London. The laser system (named Cerberus) is designed to provide one short pulse 500 fs beam for proton probing and two long pulse beams, one for x-ray backlighting and one for Thomson scattering. The aim of this project is to accurately determine plasma parameters in a range of demanding experimental environments.

The thesis is split into two sections; the first section provides details about the design and implementation of the laser system while the latter chapters present experimental data obtained on the MAGPIE facility. The front end for the laser system is based on optically synchronised Optical Parametric Chirped Puled Amplification (OPCPA) which is supplemented by large aperture flashlamp pumped Nd:Glass power amplifiers in the latter stages to increase the energy to the Joule level. The use of optical parametric amplifiers (OPAs) in the pre-amplifier stages reduces gain narrowing, B-integral and improves contrast. Simulations of the dispersive optics for the Chirped Pulse Amplification (CPA) system are described in detail.

Spatially resolved Thomson scattering was used to measure temperature and velocity of ablation streams in aluminium and tungsten cylindrical wire arrays. The measurements show a peak flow velocity of 120 km/s and agree well with 3D MHD simulations for the case of aluminium. There is discrepancy with the tungsten data caused by the difficulty in handling of collisionality calculations.

Novel data showing the self-emission of ions from tungsten radial wire arrays is presented as a key step towards laser driven proton probing of MAGPIE. It is observed that the bulk of the emission corresponds to low energy protons with energies of ~ 100 keV. Protons with energy > 600 keV were observed to emanate from the collapsing magnetic jet using a coded aperture camera. These results offer interesting new prospects in diagnosing wire arrays.
Acknowledgements

Given the large collaborative nature of the work presented in this thesis, I would like to take this opportunity to acknowledge the help and contributions of all the people involved in this project over the past few years. The work described in this thesis would not have been possible without the continuing guidance and advice of my supervisor Prof Roland Smith and I am very grateful for the opportunity to have worked on the Cerberus laser. I have very much enjoyed the coffee time conversations on lasers, tv shows and kids. I would also like to thank Prof. Sergey Lebedev who has been a co-supervisor for over five years. His insight into plasma physics and intuitive explanations has never ceased to impress me.

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Also a special thanks for my fellow ‘scientists’ Jordan and Cyprian who have been with me since undegraduate days. Drinking Everyday... Thank you Boon for
organising tons of nights out and coming to all those chelsea games!!

And finally, I would like to thank my parents for providing food money house and love for this most enjoyable laser escapade!!!
### Fundamental Physical Constants

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<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value (SI)</th>
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<tbody>
<tr>
<td>$c$</td>
<td>Speed of light in vacuum</td>
<td>$3 \times 10^8$ m s$^{-1}$</td>
</tr>
<tr>
<td>$e$</td>
<td>Unit of charge</td>
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</tr>
<tr>
<td>$h$</td>
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<td>Boltzmann constant</td>
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<td>Proton mass</td>
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<td>$8.85 \times 10^{-12}$ F m$^{-1}$</td>
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<tr>
<td>$\mu_0$</td>
<td>Permeability of free space</td>
<td>$4\pi \times 10^{-7}$ N A$^{-2}$</td>
</tr>
</tbody>
</table>
Contents

1 Introduction 31
   1.1 Organisation of Thesis 33
   1.2 Contributors and Publications 35
   1.3 Experimental Overview 36
   1.4 Cerberus Laser Outline 40

2 Concepts in High Power Lasers 43
   2.1 Laser Technology 43
      2.1.1 Mode-Locking 43
      2.1.2 Nonlinear Optical Effects 45
   2.2 Light Amplification Methods 50
      2.2.1 Chirped Pulse Amplification 51
      2.2.2 Optical Parametric Amplification and Contrast 66
   2.3 Optical Synchronisation 72
   2.4 Laser Diagnostics 76
      2.4.1 Pulse Measurement 76
      2.4.2 Beam Profiles 81

3 Design and Implementation of an OPCPA Nd:Glass Laser 84
   3.1 Modelling and Design Parameters for the CPA System 85
      3.1.1 Short Pulse CPA 87
      3.1.2 OPA Pump CPA System 97
   3.2 Cerberus Laser System Configuration 104
List of Figures

1.1 The increase in laser intensities available over the past five decades along with the physics regimes they can access. CPA - Chirped Pulse Amplification; OPCPA - Optical Parametric Chirped Pulse Amplification. QED - Quantum Electro-Dynamics; $E_q$ - Electron quiver energy; $m_e$ - Electron mass; $m_p$ - Proton mass. ........................................ 32

1.2 An overview of the Cerberus beamlines including the approximate physical organisation of the laser system. Measured parameters are included where possible. OPAs - Optical Parametric Amplifiers; NLC - Nonlinear Crystals; SHG - Second Harmonic Generation. Red arrows correspond to infra-red and green arrows represent the second harmonic (527 nm). It should be noted that the shown laser parameters are design point values based on experimental requirements. .... 42

2.1 Functional diagram of the Nd:Glass oscillator used on the Cerberus front end. The yellow regions correspond to heating elements used to control the breadboard temperature to minimise thermal drift over long timescales. SESAM = Semi-conductor saturable absorption mirror; AM = Actuated mirror to control cavity length; TS = Tuning slit; OC = Output coupler. The two prisms are used to compensate for intra-cavity dispersion and also control the width of the oscillator spectrum. The tuning slit can be tweaked to control the central wavelength of the oscillator. ................................................................. 44
2.2 The CPA concept. Chirped pulse amplification involves stretching the pulse temporally, amplifying it and then compressing it to deliver a high energy pulse with nearly the same temporal width as the original pulse.

2.3 Left) A standard two lens Martinez-style stretcher adds chirp due to blue wavelength components travelling a greater distance compared to red [89]. Right) Treacy-style two grating compressor in which red wavelengths travel more than blue removes an equal amount of chirp [143]. In their shown configuration, the outputs of these arrangements will be spatially chirped which is usually undesirable. This is remedied by retro-reflecting the beam back through the system.

2.4 Effect of spectral phase (red) on laser pulses (blue = input, black = output). a) Unchirped pulse with a corresponding flat spectral phase. b) Pulse with large a second order phase ($\phi''$) term gives uniform broadening. c) Addition of third order dispersion ($\phi'''$) introduces side lobes to the pulse and causes distortion. d) Residual second and third order phase terms will gives a broader pulse with poor contrast more visible here on a log scale. In practice, this effect will exacerbated due to clipping of the spectrum on dispersive optics.

2.5 Various factors can affect pulse contrast over different timescales. On a nanosecond timescale, amplified spontaneous emission (ASE) from flashlamp pumped gain storage amplifiers is dominant. On a picosecond timescale, discrete pre-pulses from multiple reflections and ringing from spectral clipping affect contrast.

2.6 The effect of gain narrowing of the input spectrum of a typical Nd:Glass laser as a function of gain.
2.7 The effect of shaping seed spectrum on the amplified output bandwidth. Left) An input spectrum from a Nd:Glass laser (black, centered at 1054 nm) is amplified in a lower bandwidth Nd:YLF amplifier (blue, centered at 1053 nm). The output spectrum (red) has a FWHM of 0.3 nm. Right) In this simulation, the input spectrum has been selectively attenuated at 1053 nm to part compensate for the reduced gain in the wings. The output spectrum is now 0.1 nm wider compared the unshaped scenario.

2.8 Grating conventions used in CPTrace3D and also in this thesis. Angles and distances are defined as per diagram.

2.9 A simplified block diagram of the operation of CPTrace3D code. Blue lines represent temporal/spectral phase and red lines are temporal/spectral intensities. FT represents the Fourier transform.

2.10 3D ray trace output of a two grating compressor performed using CP-Trace3D. Different wavelengths follow different paths through the system and this can be visualised and analysed easily from the output of the code. Only end points of the vectors are plotted for clarity.

2.11 2D projection of the compressor viewed from the top. The path of the rays is plotted for clarity. Location of the gratings and the double pass mirror are shown.

2.12 A simplified representation of optical parametric amplification of a weak seed by a strong pump in nonlinear crystal. A third beam called the idler is also produced in this interaction to conserve energy.

2.13 Energy level diagram for OPAs (left) and traditional gain storage amplifiers (right). In parametric amplification, a higher frequency energetic pump ($\omega_1$) is used to amplify a lower energy and frequency seed ($\omega_2$). A third photon corresponding to the energy difference is produce to conserve energy. For gain storage amplifiers, a population inversion is required in the lasing transition. Typically flashlamps or other lasers are used for this purpose which has the effect of heating up the medium.
2.14 Block diagram of the optically synchronised short pulse OPAs. The use of a CPA pump pulse reduces the final pulse duration and therefore, the fluorescence window around the signal. Red arrows correspond to the fundamental wavelength and the green arrows the second harmonic. 69

2.15 Simulations of the short pulse OPAs performed by Nick Stuart using Geoff New’s OPA code. Left) Output profiles of the signal and the pump from the modelling of the OPA stages. Right) Gain as a function of the crystal length. Parameters were adjusted to reach near saturation performance. 71

2.16 Left) Input and output spectra from the 1st OPA crystal show very little spectral narrowing and only minor modulation in the wings which is likely to be a numerical artifact from a finite size FFT window. Right) Gain is near uniform over the centre of the spectrum. The gain is higher in the wings due to signal strength being substantially lower. 72

2.17 A common oscillator can be used to generate both the seed for the signal and the pump. In this scheme, a Pockels cell is used to select a pulse for amplification. This becomes the pump and amplifies a signal later in time from the oscillator pulse train. Synchronisation is achieved by matching the optical path lengths and maintained by controlling the oscillator frequency. SHG - Second Harmonic Generation; OPA - Optical Parametric Amplification. 72

2.18 Diagram of the closed loop feedback system for the Cerberus oscillator. Yellow regions correspond to heating pads which are used to maintain oscillator temperature. AM - Actuated Mirror to control cavity length. PD - Photodiode. TM - thermometer. 75

2.19 Control systems for the Cerberus oscillator. Left) Variation of oscillator frequency with and without temperature control. Right) Oscillator frequency offset with control loop enabled. The gap in the frequency offset data is due to a system restart. 75
2.20 Typical measurement from a fast 6 GHz Bandwidth, 50 ps rise time diode detector from Newport. The stretched pulse duration from a stretcher is measured. The double peak corresponds to a real spectral modulation which is visible in the time domain measurement. Measured using a Newport Model 1437 photoreceiver and 50 Gigasamples/s Tektronix oscilloscope.

2.21 Left) Diagram of a scanning autocorrelator; SHG = Second harmonic generation crystal; SM = Spherical mirror; BS = Beam splitter. Right) Geometry of non-collinear overlap in a nonlinear crystal used in a single shot autocorrelator.

2.22 Graph showing the profile of a 250 fs $sech^2$ laser pulse (black) and the envelopes of the interferometric autocorrelation of the pulse (blue and red). The relationship between the FWHM of the pulse and width of the autocorrelation is established.

2.23 Beam profile of a laser taken using the WinCamD camera. The clipping in the outer regions of the laser would typically be hard to visualise on a low dynamic range detector (typically 8 bit) used in many commercial CCDs.

2.24 Diagram of a far-field monitor consisting of a lens to focus the laser beam, a microscope objective and a CCD camera.

3.1 Simplified block diagram of the Cerberus OPCPA setup. The primary short pulse beam consists of two OPA amplifiers stages along with flashlamp pumped power amplifiers. The pumps for the OPA system are derived from a common oscillator and require a separate CPA system for its amplifiers. Red arrows correspond to $1\omega$ laser wavelength and green arrows $2\omega$. SHG - Second Harmonic Generation.
3.2 Schematic of the stretcher used for the short pulse OPA section. It is based on the two-grating delay line. A parallel geometry is achieved by using a prism mirror to retro reflect the beam through the system at a different height. ................................. 88

3.3 Simulations for the first grating stretcher. Left) Simulated stretched pulse duration after a double pass of the stretcher described in figure 3.2. Right) Output spectrum on a logarithmic scale. .................. 88

3.4 Visualisation of the reflective doublet stretcher with relative positions of the main components. The injection and inversion optics are not shown. ..................................................... 90

3.5 CPTrace3D simulations of the reflective doublet stretcher. Top) Contrast as a function of angle for a given grating size. Bottom) Contrast as a function of grating size at an angle of 77°. Note that only the leading edge of the pulse profiles are plotted as they are symmetric in time. These pulses were compressed with an extra large grating size compressor to isolate stretcher performance. ...................... 92

3.6 Final specifications of the reflective doublet stretcher as view from above. M1 - 200 mm diameter concave mirror with 1175 mm radius of curvature. M2 - convex mirror with - 1000 mm radius of curvature (135 mm × 30 mm). M3 - flat folding mirror (120 mm × 30 mm). . . 93

3.7 Photograph of the implemented reflected doublet stretcher on the Cerberus front end. The dielectric grating is seen on the left in the foreground with the gold coated mirrors in the background. ............ 94

3.8 Compressed pulse durations as a function of grating size and beam diameter (flat top spatial profile) for 500 fs transform limited input pulses. ................................................................. 96

3.9 Proposed layout of the short pulse compressor. FR - Faraday rotator. 97
3.10 Simulation of the main stretcher-compressor pair with the final specification optics. Stretcher grating size is set to 175 mm × 75 mm and the compressor size is 285 mm × 140 mm. It should be noted that the effect of the small first stage stretcher is not included in this simulation. Results showing the effect of surface roughness are included using known optical flatness measurements of λ/25 for the stretcher.

3.11 Schematic of the OPCPA pump stretcher which is based upon a quad pass version of the single lens folded Martinez design.

3.12 Simulated stretched pulse duration from the OPCPA pump stretcher as calculated for the design shown in figure 3.11.

3.13 Diagram of the folded OPA pump compressor. The dashed line indicates effective grating separation.

3.14 Contrast as a function of grating size for the OPA pump compressor. A wider grating is able to support a greater spectral bandwidth. This additional bandwidth translates into better contrast in the time domain. The pulse in this simulation was stretched using stretcher parameters shown in figure 3.11. Note that the curve for the 140 × 100 mm grating is exactly overlapped on the curve for the 140 × 50 mm grating. This is because the performance is not dependent on vertical extent of the grating.

3.15 Stretched pulse duration of the long pulse OPA pump as a function of angle and bandwidth for a given grating separation (6 m). It should be noted that only the allowed diffraction angles as per the grating equation are included.

3.16 Schematic of the long pulse stretcher showing the input and output section. VSF - Vacuum Spatial Filter. AP - Apodiser. Cylindrical lenses at the input (1) have focal lengths of -100 mm and 200 mm for a 2:1 up-collimation. The lenses at the output have focal lengths of 250 mm and 150 mm to reshape the elongated output profile.
3.17 Pulse selection for the OPA signal and pump system seed. FR - Faraday rotator, PC1 and PC2 - Pockels cell. Firing either Pockels cell allows a pulse to be selected and designated as pump or signal.  

3.18 Diagram of the amplification system for the OPCPA Pump beam. FR - Faraday rotator, PC, PC2 - Pockels cell. PC2 is used to select a 10 Hz pulse train from the 400 Hz regen output to see flashlamp pumped Nd:YLF amplifiers. Up and down collimation optics used to limit B-integral into the Faraday rotators are not shown for clarity.  

3.19 Photo of the regenerative amplifier (foreground) which has been built using 1” thick Invar [40] rods. The Nd:Glass based oscillator (GLX-200-HP) is located in the background.  

3.20 Left) Typical pulse energy build up inside the regen cavity measured via leakage in the end cavity mirror. Right) Energy stability as a function of cavity round trips. Saturation of the amplifier offers significantly increased energy stability.  

3.21 Input spectrum of the stretched pulse along with the amplified output spectrum. The 'spiky' modulation on the spectra is due to interference from a double reflection off a polariser.  

3.22 Amplification section for the long pulse OPA pumps. This section contains two flashlamp pumped Nd:YLF amplifiers operating at 10 Hz. Each amplifier is double passed using a Faraday isolation stage for increased gain. FR- Faraday Rotator. VSF - Vacuum spatial filter.  

3.23 High power Nd:Glass amplifier section for long and short pulse beamlines. FR - Faraday rotator; VSF - Vacuum spatial filter. Crossed circle represents a periscope.  

3.24 Photo of the large aperture Nd:Glass amplifiers (red, in foreground) donated by AWE for the Cerberus project. A large aperture vacuum spatial filter for beam expansion and image relaying is also visible in the background.
3.25 Diagram showing the short pulse OPA setup. Lens pairs are used to control beam sizes in the crystals and a small angular walk-off is used to separate the three output beams. TS - Translation stage; DM - Dichroic mirror. SF - Spatial filter.

3.26 Simplified diagram of the triggering system for the Cerberus laser system. SRS - Stanford Research Systems timing unit; QC - Quantum Composer timing unit. Orange arrows correspond to optical links and dashed blue line represents clock sharing. Black arrows are standard BNC cables. It should be noted that not all details are included for the sake of clarity.

3.27 Photo of the Cerberus laser front end in July 2013. It is worth noting that optics are closely spaced to reduce beam propagation lengths and improve robustness.

3.28 Single shot autocorrelation of the short pulse stretcher. Note that the small asymmetry in the leading edge of the pulse is probably due to misalignment of the autocorrelator. Data courtesy of D.Bigourd.

3.29 Left) Measured pulse duration for the reflective doublet stretcher under typical conditions. Right) Input and output spectra after quad pass of the stretcher. The slight shift in wavelength is due to small amount of residual spatial chirp. It should be noted that these measurements were taken under different oscillator conditions which explains their inconsistency. The reason for loss in stretcher bandwidth is to be investigated in the future.

3.30 Left) Typical autocorrelation measurement of the unamplified laser. Right) A scan of the compressor separation along with the pulse durations obtained. Zero distance corresponds to the optimum distance found experimentally.

3.31 2nd order autocorrelation of the amplified 400 Hz OPA pump beam with a Gaussian fit. The sharp drops in background signal at each end are for temporal axis calibration.
3.32 Compressed pulse duration as a function of grating separation for a range of input regen energies. The effect of shaping the spectrum of the amplified pulses results in shorter compressed pulses compared to unshaped spectra. The unshaped higher energy pulses have shorter pulse durations and consequently suffer from SPM which results in poor compression. Zero grating separation corresponds to the optimum position achieved without amplification (as per figure 3.30).

3.33 Left) Oval output at the exit of the long pulse stretcher. The beam profile aberrations are currently unexplained. Right) Beam profile after correcting using cylindrical lenses and VSF.

3.34 Measured stretched pulse duration from the long pulse stretcher. A fast photodiode (Newport model 1437) with a 50 ps rise time was coupled to a Tektronix 70000 series oscilloscope capable of digitising signals at 50 Gigasamples/s to perform this measurement.

3.35 Left) Gain as a function of pump energy of OPA 1 and 2 with a constant seed energy of 600 pJ. Right) Gain as a function of signal energy with a constant total pump energy of 2.4 mJ.

3.36 Amplified output spectra from the short pulse OPA setup. The input spectrum (blue) corresponds to the output of the oscillator and has a FWHM of ~ 6 nm. Group velocity mismatch between the pump and the negatively chirped signal of ~ 580 fs results in preferential amplification of the shorter wavelength components of the spectrum (which lie on the leading edge of the pulse).

3.37 Gain contrast from the first OPA stage obtained by scanning the OPA seed beam through a temporally fixed OPA pump beam. The modulated temporal profile is due to a combination of pre and post pulses on the pump and the seed. This measurement cannot distinguish between the modulations on the seed and the pump. The temporal profiles of the pump and seed will be investigated in the future with a scanning third order autocorrelator. Data courtesy of N.Stuart.
4.1 Solidworks render showing the MAGPIE generator with a human figure for scale. MITL - Magnetically Insulated Transfer Line; PFL - Pulse Forming Line. A significantly larger target chamber has now been installed to allow better diagnostic access for probe lasers. Image courtesy of Gareth Hall.

4.2 A typical scan of a post-etch CR-39 slide showing pits formed by ion interactions. This was imaged under a 40× magnification optical microscope with a CCD camera attachment.

4.3 Stopping range of various ions in aluminium filters as a function of energy. The dashed line correspond to typical filter thicknesses used in experiments described in this thesis. For example, protons would need an energy of \( \sim 1 \text{ MeV} \) to penetrate 12.5 \( \mu \text{m} \) Aluminium.

4.4 Diagram of a typical pinhole imaging setup. For the case of ions emitted from a source, an appropriate detector such as CR-39 (shown in grey box) can be used. The magnification is given by image distance divided by object distance.

4.5 Side-on view of the flyeye camera. The length of the tubes set the distance to the detector (CR-39 in this case) and distance to the target sets the field of view of the tubes.

4.6 SolidWorks render of the high resolution flyeye camera. It consists of a 24 × 24 array with 1.2 mm diameter holes printed using UV cured epoxy resin. 3D printing system manufactured by OBJET (Model - Eden 250).

4.7 Schematic of a magnetic spectrometer used on MAGPIE. Incoming protons (red) are deflected by a strong 0.8 T magnet and detected on four pieces of CR-39 (indicated in blue). The slits are orientated perpendicular to the plane of dispersion.

4.8 Simplified schematic of the amplification setup of the Thomson probe beamline. VSF - Vacuum Spatial Filter; SHG - Second Harmonic Generation; IR - Infra-red; Pol - Polariser.
4.9 Photo of the Thomson probe beam line developed by the author (foreground). The large aperture amplifiers (in red casings) in the background are provisioned for use with the Cerberus front end.

4.10 Typical temporal performance of the Nd:YAG laser at various power settings. Seeding the cavity gives smoother temporal profiles while increasing the pump power reduces the pulse duration. Note - '10-10' corresponds to an energy setting where the cavity and the subsequent power amplifier are pumped at full power. The pulse duration is only dependent on cavity pump power. The post amplifier is not used in normal operation as the additional energy is not required.

4.11 Relative timings of the $\alpha$ rod amplifier compared to the Nd:YAG. The blue curve shows the current through the amplifier flashlamps. The large amplifier is fired first at 380 $\mu$s prior to lasing to allow the gain to reach its peak value which is not coincident with the peak of the current pulse.

4.12 Schematic of the Thomson scattering data acquisition setup and techniques used to reduce stray light in the imaging system. The red dot represents location from which scattered light is collected. FL - Focusing Lens; Spectrometer is a Shamrock SR500i system from Andor.

5.1 Thomson scattering form factors. a) Low alpha spectrum is Gaussian like with a width proportional to the $T_e$. b) Transition region around $\alpha \sim 1$ shows both ion and electron components present. c) High alpha spectra showing twin peaks corresponding to ion acoustic waves. d) For constant plasma parameters, the variation of $\alpha$ with viewing angle is shown. Green arrow corresponds to the laser probing direction while black lines are angles where $\alpha = 1$. The forward direction is more suitable for viewing high $\alpha$ spectra but is experimentally prone to stray light. Graph courtesy of A. Coliatis.
5.2 a) Wave scattering geometry relative to velocity $\mathbf{v}$ [81]. The x axis bisects the angle between $k_{\text{in}}$ and $k_{\text{out}}$ and $\mathbf{v}$ is in an arbitrary direction.  

b) Vector diagram representation of $\mathbf{k} = k_{\text{in}} - k_{\text{out}}$.  

5.3 End on view of a CWA. A typical array contains 16 wires with an array width of 16 mm. Left) End on view showing the position of the wires. Right) Single wire image showing the ablating plasma stream accumulating on the axis due to the $\mathbf{J} \times \mathbf{B}$ force.  

5.4 Left) Photo of a 16 wire aluminium CWA along with the scattering pin used to align the Thomson laser on to specific points inside the array. Right) Diagram of the end-on scattering setup. A dichroic mirror (DM) is used to simultaneously allow 355 nm laser probing for 2D interferometry. An F/10 imaging lens (IL) is used to image the scattering volume (red) on to the fibre bundle which is connected to a gated spectrometer (TS).  

5.5 Left) End-on interferogram of CWA. Scattered light from the alignment pin can be imaged by the laser probing optics to give an accurate position of the scattering volume. Laser direction is shown by white arrow with the red spot marking the position of the scattering volume. Right) Diagram showing the imaging of scattering volumes at different positions along the fibre bundle. IL - Imaging Lens.  

5.6 Views of Thomson scattering geometry relative to the CWA from end-on and side-on directions. a) Side-on view of the collection volumes (red dots) with respect to the array dimensions and axis. b) The scattering vector diagram from the orientation shown in a). c) End-on view of the scattering volumes.  

5.7 Typical scattered spectra obtained from CWA shots. A) Background spectrum taken before the shot. B) Spectra from individual fibres show visible doppler shifting and broadening. C) Data from each fibre (black curves) integrated along with the Gaussian fits (red dash) and the background spectrum (blue).
5.8 End-on interferogram (355 nm) showing the 2D electron density distribution in a 16 wire aluminium CWA. The black line corresponds to the region where Thomson scattering was performed. Data courtesy of G.F. Swadling [139].

5.9 Line out of the measured electron density along the black line marked in figure 5.8. There is an increase in density close to the wires (small radius) and the axis where the ablated plasma accumulates.

5.10 Effect of varying plasma parameters on the fit ($\bar{Z}T_e, T_i$). Data (black line) from fibre 2 of shot s051711 which was a $16 \times 30 \, \mu m$ aluminium array. The best fit (red) corresponds to a $\bar{Z}T_e$ of 140 eV and $T_i$ of 20 eV. Changes to these parameters at the $\pm 20\%$ level produces significantly different fits that are clearly less well matched to the experimental data, both in width and in the details of the peak structure.

5.11 Effect of varying ion temperature on the tungsten spectrum. Data from fibre 2 of shot s051911 which was a $32 \times 10 \, \mu m$ tungsten array. Changes to the temperature at $\pm 33\%$ create a broader or narrower curve.

5.12 A comparison of measured and simulated radial velocity profiles for aluminium CWAs between ablation streams. The measurements show that the ablated plasma is accelerated towards the axis reaching a peak velocity of $\sim 120 \, km/s$. Simulations performed with Gorgon code are also included (simulated data courtesy of J.Chittenden).

5.13 Data from shot s051711 which was a 16 wire aluminium array. Left) Individual fits (red) for each fibre (black). The blue curve on fibre channel 5 is the unshifted pre-shot spectrum. Left) Fitting theoretical curves to scattered aluminium spectra is used to extract values of $\bar{Z}T_e$ and $T_i$ as a function of radial position.

5.14 Velocity profiles from tungsten CWAs. Left) Radial velocity profiles at 150 ns for tungsten wire arrays measured between and within flows. Right) Velocity profiles at 210 ns. Gorgon simulations are included for both cases (data courtesy of J.Chittenden).
5.15 Thomson scattering data is used here to evaluate radial temperature profiles for tungsten CWAs. Top) Measured widths from broadened tungsten spectra as a function of array diameter with zero referring to the array axis. Measurements are provided at two different times and an early time measurement inside the flow is also shown for comparison. Bottom) Ion temperature extracted from fits to the spectra as a function of array diameter. The errors are larger for higher temperature measurements due to a lack of sensitivity to the $T_i$ parameter. At early times ($\sim 150$ ns), the temperature is higher on axis due to thermalisation of individual ablation streams. At later times ($\sim 200$ ns), the temperature is uniformly low as the excess energy has been radiated away as x-rays.

6.1 Diagram of a RWA load. Thin metallic wires are held between the anode and the cathode. The application of a powerful pulsed current (blue arrow) creates a strong magnetic field around the cathode (red arrows). The ablated plasma is accelerated vertically by the $\mathbf{J} \times \mathbf{B}$ force (green arrow). Further evolution is heavily influenced by this magnetic field topology.

6.2 Simple schematic showing the stages of evolution of radial wire arrays. The dynamics are dominated by the interaction of the current (red) with the magnetic field (green). a) Early time behaviour is governed by ablation of plasma from the wires which is accelerated vertically and driven into the region above the cathode due to pressure gradients. b) This ablated plasma forms a hydrodynamically collimated jet (orange). Additionally, the breaking of the wires leads to a reconfiguration of the current path and the formation of a magnetic cavity. c) At late times, the reconfigured current path is susceptible to MHD instabilities and forms a ‘clumpy’ jet.
6.3 Evolution of the magnetic cavity. Top) Gated XUV self-emission images from s071406 which was a $16 \times 13 \, \mu m$ tungsten array. Bottom) Synthetic x-ray images from 3DMHD code Gorgon[33]. The evolution of the magnetic cavity and the instabilities in the jet (‘sausage’ and ‘kink’ modes) are reproduced accurately in the simulations. Images adapted from [35].

6.4 3D MHD simulations using the Gorgon code can show the complicated magnetic field topology around the central jet (230ns). This is a close-up of the magnetic jet in its unstable phase. Structures of this type would be a prime target for a laser driven proton probe. Reprinted from [36].

6.5 Experimental setup for ion self-emission diagnostics. 1 - Thomson Parabola; 2 - Magnetic Spectrometer; 3 and 4 - Ion pinhole Cameras; 5 - High resolution Flyeye; 6 - Ion pinhole camera with low magnification; 7 - XUV pinhole cameras; TCC - Target chamber centre. It should be noted that not all diagnostics were used for each shot.

6.6 False colour ion pinhole images obtained as a function of pinhole diameter. The distances shown on the graphs are real sizes of the plasma being imaged while the axis scale corresponds to the size on the CR-39. Smaller pinholes reduce the flux reaching the detector. This reveals the region of highest ion emission. Pinhole diameters were a) 1 mm, b) 300 $\mu m$, c) 100 $\mu m$ and d) 300 $\mu m$. It is not possible to be certain where the cathode lies in these images as there is no pre-shot to compare with but the direction of propagation of the jet can be inferred (dashed arrow on a).

6.7 Images from figure 6.6c-d with axes scaled to plasma size rather than detector. It is interesting to note that the emission region appears to be larger in the low magnification image. This is believed to be an artifact of a long etching duration on a low flux image.
6.8 Left) Diagram showing position of line scan in dashed relative to the dimensions of the CR-39 detector. Right) Line-out of total number of pits in each image from a unsaturated CR-39 film used in a pinhole camera. Area covered by each image is $\sim 0.5 \ mm^2$. It should be noted that unsaturated CR-39 looks clear to the naked eye and the position of the jet is for illustrative purposes only.

6.9 Comparison of ion emission region (c) with time resolved optical Schlieren (b) and XUV diagnostics (a,d) at key points during its evolution. The loads for all the shots were $16 \times 10 \ \mu m$ tungsten RWAs. The cathode position is shown in red dashed line and is estimated for the ion image (black dash). The grey area in subfigure d) is the dead region between MCP detector frames.

6.10 Comparison between time integrated ion pinhole image and time resolved XUV at 369 ns after current start from the same shot. The deflection seen on the time integrated image is consistent with 'clumps' of plasma propagating at an angle to the axis. This can be a result of small angular deviations in the load mounting.

6.11 Close-up of the shadow pattern in a single flyeye channel with the black ring marking aperture entrance size. a) When the source occupies the complete field of view of the tube, the region enclosed by the black ring is filled. b) When the source is partially offset from the tube’s field of view, the front edge of the tube casts a shadow on the detector depending on the relative positions of the source and the tube.

6.12 Methodology to work out the position of proton source from shadow pattern. The grey region corresponds to the shadow. The co-ordinates of the points in the red are used to generate a direction perpendicular to the shadow (blue arrow). For example $r_3 - r_2$. Additional geometric parameters such the tube length and target distance can be used to scale the direction to the target plane.
6.13 End on view of the flyeye camera geometry. The shadow caused by the aperture of the tube is indicated in dashed lines. The red line connects the edge of the emitting source to the rim of the tube. The grey region is where protons are detected. 186

6.14 Results obtained with the low resolution flyeye. Left) False colour image of etched CR-39 showing flyeye shadow pattern from RWA. Right) The blue arrows are the calculated directions of the shadows accounting for the distance to the target projected in the plane of the detector. The black dots are the end positions of the vector which represent the edge of the source. 188

6.15 Figure 6.14 with the direction data super posed on the shadow pattern. The position of the aperture rims are indicated on few points for the sake of additional clarity. Each shadow is used to extract a position for the source edge. 188

6.16 Side-on projection of shadow data in figure 6.14 compared with an optical Schlieren image to potentially isolate the source of the emission. The known distance between the load and the flyeye aperture has been used to project the arrows on to the source plane. The Schlieren diagnostic is designed to image spatial structure during the early phase of the RWA evolution and has a limited field of view. The arrows (time-integrated) point to region where the plasma has not reached at 244 ns after start of current. This suggests the emission occurs transiently at a later point during the evolution of the RWA. The cathode position is shown in red. Vertical axis is on the same spatial scale in both images. 189

6.17 End-on projection of the flyeye data from figure 6.14 allows the width of the source to be determined. In this case, the emission width is 6 mm which is the same as the aperture of the tubes. It is interesting to note that the measured width of the emission is narrower than the total width of the magnetic cavity as seen from optical Schlieren imaging. 189
6.18 High resolution flyeye data along with a Schlieren image for comparison. Left) plot showing high resolution flyeye pattern along with vectors pointing (blue arrows) towards the source. Schlieren image taken at 237 ns shows on the same plot in red the region enclosed by the blue arrows. The cathode position is indicated in red below. The results indicate that the higher energy protons appear to originate from the top of the magnetic cavity.

6.19 Projections of the high resolution flyeye data Left) Side projection of the ion source vectors in figure 6.18 gives a width of $\sim 3.5$ mm on the source plane. Right) End-on projection of the vectors in figure 6.18. SP - Source Plane.

6.20 Proton spectrum from $16 \times 10 \mu$m tungsten RWA measured using the magnetic spectrometer. The slits were located at height of 31 mm above the cathode.

6.21 Photograph showing the relative position of the load and the inductive voltage probe.

6.22 Diagram showing inductive probe setup used to measure load voltages. a) Illustration of the starting configuration b) Configuration during the magnetic cavity phase.

6.23 Voltage probe signal showing the effect of change in load inductance on measured voltage for a RWA shot. Peak voltage inside the cavity exists during the same period as peak x-ray emission. They both occur due to the 'pinching' of the plasma on axis. It should be noted that the effect of stray magnetic fluxes are accounted for in the calculation of $V_{array}$.
6.24 Graph showing the expected variation of magnetic field (dashed black) against the radius of the magnetic cavity. The proton Larmor radius as function of distance for a range of energies is also plotted. Protons are assumed to be trapped when their larmor radius is less than twice the cavity radius. This condition is illustrated by the pink line on the graph and arrows correspond to region where the condition is fulfilled.

6.25 a) Schematic of the gated proton pinhole imaging setup consisting of charged electrodes (grey) to deflect ions on the CR-39 (blue) detector. The deflection would result in a secondary image next to the normal pinhole image from the undeflected ions. b) Deflection as a function of energy for protons. Due to time of flight dispersion, protons with different energies arrive at different times which would make gating difficult. The aim was to gate only the low energy protons.

7.1 Design for single shot spatially resolved spectra of the jet. A series of collimating tubes with a narrow field of view can be used to select emission at different vertical positions from the jet. A dispersive magnet setup can then be used to obtain a series of spectra on a single detector in a single shot.

7.2 Scan of an unsaturated proton pinhole image using an automated system by made by Track Analysis Systems Ltd (TASL) installed at the Rutherford Appleton Laboratory.

7.3 Left) Diagram of the radial foil experiment. Red circles represent Thomson scattering volumes. The hydrodynamic jet is shown in orange and the supersonic gas valve is set at a position above the foil, perpendicular to the direction of the jet. The Thomson laser beam is focused at the centre of the jet from the axial direction and scattered light is collected perpendicular to the laser. Right) Axial velocity profile of the jet. The large drop in velocity corresponds to the interface between the gas stream and the jet. Data courtesy of F. Suzuki-Vidal.
7.4 X-ray backlit image (shown in false colour) of a resolution grid using the long pulse laser beam of the Cerberus system. A silicon target was irradiated with 6 J of laser light in a 1.4 ns FWHM pulse duration. The grid was illuminated by the He-\(\alpha\) line of the silicon at 1.865 keV which was imaged using a spherically bent crystal on to a Fuji image plate detector (BAS-TR). The results show that features as small as 4 \(\mu m\) can be discerned. Data courtesy of G.N.Hall.

7.5 Monochromatic x-ray backlight image (in false colour) of a fly’s wings reveals the intricate wing structure with excellent detail. The magnification of the imaging system is 6\(\times\). Data courtesy of G.N.Hall.

7.6 Monochromatic x-ray backlight image (in false colour) of a 16 \(\times\) 25 \(\mu m\) tungsten CWA during the ablation phase. The modulations in the ablation streams are clearly visible. A metal rod was placed on axis to suppress an implosion and limit background x-rays. Data courtesy of G.N.Hall.

7.7 Photo of Nd:Glass disc amplifiers of 108 mm (top two) and 150 mm diameter (bottom) which are available for future energy upgrades.

7.8 Diagram showing the original Cerberus project (Labs 1-3) along with the planned additional target areas (Labs 4 + 5) which will all share the front end described in this thesis.
List of Tables

2.1 Summary table of second order nonlinear optical effects pertinent to high power lasers. ........................................... 46

3.1 Summary of the CPA system on Cerberus. Both the signal and the pump sections have two stretchers and one compressor. Measured values are used where possible and simulated numbers are italicised. BW - FWHM Bandwidth. ........................................... 106

3.2 Summary of the flashlamp pumped amplifiers on Cerberus. The B-integral calculation assume a flat top spatial profile and a 1 ns temporal duration (also assumed to be flat) which is a good approximation given measurements of these parameters. ........................................... 113

3.3 Summary of the OPA crystals in each stage. It should be noted that the short pulse OPAs will be pumped with a 5 ps pulse and the long pulse OPAs with a 1.3 ns pulse. ........................................... 115

3.4 Summary of parameters for the short pulse OPAs. ........................................... 126

4.1 Table of summary for the flyeye cameras used ........................................... 140
Chapter 1

Introduction

The advent of new laser amplifications methods over the past 25 years, particularly Chirped Pulse Amplification (CPA) [132] has resulted in a large increase in attainable laser intensities. This has allowed novel and exotic experiments to be performed such as laser driven particle acceleration [87] with potential applications in hadron therapy for treating cancer[23]. Figure 1.1 plots the increases in laser intensities over the decades along with the types of physical phenomena which can be accessed. National facility class laser systems are already capable of providing focused intensities up to $10^{22} \text{ W cm}^{-2}$ [65] and the up-coming 'European Extreme Light Infrastructure' (ELI) [28] laser system includes provisions for a 200 PW laser which will potentially be capable of reaching $10^{25} \text{ W cm}^{-2}$. It is anticipated that Quantum Electrodynamic (QED) effects such as vacuum polarisation could be measured using such a system [64].

Another consequence of these advances in laser technology has been the reduction in the size of high power laser systems from 'facility scale' to 'university scale'. As a result, high energy density (HED) conditions can now be accessed transiently (typically over picoseconds to nanoseconds) in small scale laboratories. The emerging field of HED laboratory astrophysics [47, 114] has particularly benefitted from this and aims to simulate experimentally the physics of astrophysical phenomena. Such comparisons between events occuring over vastly different spatial and temporal scales has been made feasible using hydrodynamic scaling laws based on dimensionless parame-
Introduction

ters [118, 18]. Whilst entire events on complex systems such as supernovae explosions and their subsequent dynamics cannot be recreated, it is possible to study aspects of their behaviour such radiative shocks in the remnant [151]. The results from such experiments can be used to benchmark simulations, test models and provide physical insight.

The ability to measure the aspects of the conditions created in HED studies is often a limiting factor in the applicability of experiments. Many large HED facilities such as the National Ignition Facility (NIF) [63] have a low repetition rate (∼ one shot/day) which makes it imperative to capture all the required data in a single experiment. Such a diagnostic driven approach to experiments is also used on the MAGPIE pulsed power facility [94] and serves as one of the primary motivations for this project along with a key goal of measuring plasma conditions in a range of experimental configurations such as wire arrays implosions.

![Graph showing the increase in laser intensities available over the past five decades along with the physics regimes they can access.](image)

Figure 1.1: The increase in laser intensities available over the past five decades along with the physics regimes they can access. CPA - Chirped Pulse Amplification; OPCPA - Optical Parametric Chirped Pulse Amplification. QED - Quantum Electro-Dynamics; $E_q$ - Electron quiver energy; $m_e$ - Electron mass; $m_p$ - Proton mass.
1.1 Organisation of Thesis

The work described in this thesis covers a collaborative project between the laser science and plasma physics groups and presents the first results arising out of it. As a result, the thesis is split into two sections to cover both topic areas. The first half of the thesis details the construction of the three-beamline laser system, many aspects of which were done from scratch. A particular emphasis is placed on the simulation, design and implementation of the CPA system which was carried out by the author. The cost of the gratings represented the single biggest expense on this project, therefore detailed simulations were important to ascertain ‘price-performance’ merits of different systems. Due to budget constraints, some systems could not be implemented whilst others were scaled back. Nevertheless details are provided about simulations and designs to assist future upgrades to the system. The second half of the thesis presents experiments carried out from the implementation of the laser system on the MAGPIE generator. Although experiments using the two primary beams of this laser was not carried as of writing of this thesis, significant progress has been made towards achieving results.

This introductory chapter gives an overview of the Cerberus laser system along with the three planned HED experiments based on its ability to drive advanced plasma diagnostics. The scientific context and the wider application of the laser system to high energy density physics and plasma diagnostics is also discussed. It should be noted that the International System of Units (SI) is used throughout this thesis and the fundamental constants which are used are listed in the opening section. Graphs shown in the latter part of this thesis which describe data have been allocated unique shot numbers in the format (s(month)(day)(year)). This is useful in indicating which piece of data has been collected from the same shot from a suite of diagnostics.

Chapter 2 describes the laser technology relevant to the construction of a short pulse laser system. Theoretical background in the topics of nonlinear optics and ultrashort pulse amplification are provided with a particular emphasis on the methodology used to attain good pulse contrast. Also included in this chapter are descriptions of
the diagnostics used during the implementation of the laser such as autocorrelators.

Chapter 3 contains a detailed description of the simulations performed for the important dispersive components of the laser system used to implement CPA such as the stretchers and compressors. These were carried out using a custom ray tracing code CPTrace3D [91]. The results from the implementation of the stretchers and compressors are provided where possible along with initial results from Optical Parametric Amplifiers (OPAs) used in the front end of the laser system.

The experiments described in thesis were performed in the MAGPIE pulsed power facility at Imperial College using cylindrical and radial wire arrays (CWA and RWA respectively). Chapter 4 begins with a brief introduction to the pulsed power facility and the plasma diagnostics used during the experiments. The diagnostic setup for the Thomson scattering and the ion self-emission experiments which represent the bulk of the experimental results described in this thesis are described in greater detail.

Chapter 5 presents data obtained from the Thomson scattering diagnostic used to measure ablation velocities of plasma streams from CWAs. The data analysis procedure and the methodology used to interpret the various plasma parameters such temperature and density is described. Results from aluminium and tungsten wire arrays are presented along with supporting simulations from 3D MHD code Gorgon [33].

Chapter 6 shows novel ion self-emission data obtained from RWAs which is particularly relevant in the context of laser driven proton probing. This was measured using diagnostics such as coded aperture ‘flyeye’ cameras. Measurements reveal the spatial distribution of the self-emission which is compared with time resolved laser probing.

The final chapter concludes this thesis by reviewing the aims and the experimental data. Additional work is also suggested for the main experiments conducted during this thesis.
1.2 Contributors and Publications

The Cerberus laser system described in this thesis was proposed and funded by Prof. Roland A. Smith in collaboration with Prof. S. Lebedev. The author’s primary contribution to the development of this large CPA laser was the simulation and implementation of the optical stretchers and compressors. This was carried out with assistance of D. Bigourd. The implementation of the short pulse OPA and subsequent gain measurements which are included in this thesis were performed primarily by D. Bigourd.

The MAGPIE pulsed power facility is a large and complex experimental system which is run by a dedicated team from the plasma physics group at Imperial College led by S. Lebedev. The author collaborated with the MAGPIE team on a range of experiments but was primarily responsible for the Cerberus laser system, and not the daily operations of MAGPIE.

The Thomson scattering experiment (Chapter 5) from pulsed power driven CWAs was led by A. Harvey-Thompson with the assistance of the author. The laser system was constructed and commissioned by the author with the help of M. Hohenberger. The key data described in this thesis was analysed by the author with the guidance of S. V. Lebedev. The supporting interferometry data was provided and analysed by G. F. Swadling.

The ion self-emission experiments were carried out by H. W. Doyle and the author. All the data shown except the energy spectrum was analysed by the author. The laser probing images shown in this chapter were courtesy of the F. Suzuki-Vidal.

Publications arising out of work presented in this thesis.


These publications represent additional work which is not discussed in this thesis


### 1.3 Experimental Overview

The Cerberus laser system consists of three major beamlines which are capable of providing three independent advanced diagnostic capabilities to the MAGPIE pulsed power laboratory. The combined capability of pulsed power and high power lasers
in a university setting described here is currently the only one of its kind in existence will allow novel experimental configurations to be realised. A particular emphasis of this project is obtaining high quality quantitative measurements of the dynamics of magnetically driven plasma jets. This would allow comparisons to be made with simulation codes and astrophysical observations of jets. This section provides background information on the planned experiments which underpin the primary design constraints of the laser system. The overall aim of this project is to build one short pulse (<ps) and two long pulse (∼ ns) beamlines and integrate them with MAGPIE diagnostic capabilities.

**Thomson Scattering**

The scattering of electromagnetic radiation from free charged particles offers a powerful non-invasive technique to measure key plasma parameters [81, 122]. The availability of powerful optical laser sources has made this experiment feasible in low density plasmas. Furthermore, use of pulsed lasers allows this measurement to be temporally resolved which improves signal to noise ratio and focusing improves spatial resolution which is important as the macroscopic size of laboratory plasmas is small. Plasma temperature is an important parameter of interest where Thomson scattering particularly excels compared to x-ray self-emission due to its greater applicability and accuracy. For solid density plasmas, x-rays can be used as a Thomson probe [58] instead of optical lasers but this is currently not in the scope of this project.

**X-ray Backlighting**

Along with optical probing, energetic x-rays offer a complementary way to probe high energy density plasmas. Backlighting refers to a general method of illuminating a transparent object to study it. Owing to their greater photon energy, x-ray can penetrate significantly higher density plasmas (which would be termed overdense at optical wavelengths) which would make them ideal for investigating implosions where peak mass and electron densities can be near solid or higher. Despite their
obvious advantages, generating sufficiently bright short duration x-ray pulses in the laboratory is not easy. Although x-ray lasers do exist, pumping them is difficult and consequently, they are difficult to use in a university setting. X-ray based diagnostics on pulsed power systems have traditionally used a configuration known as an x-pinch as an x-ray source for imaging plasmas [76]. This consists of two fine metallic wires which intersect in a cross-shaped configuration. Upon the application of a pulsed current, the intersection region implodes and emits a short pulse of x-rays which can be used to backlight the main experiment. Such configurations are typically driven by the same current pulse which drives the load and consequently, it is difficult to time the x-ray pulse arbitrarily compared to the load experiment. In comparison, laser irradiation of solid targets can act as transient x-ray sources with a temporal resolution which of the order of the laser pulse. A laser based system offer numerous advantages such as the ability to change the spectrum by varying the target element and controllable temporal duration [127].

The incoherent x-ray source generated from laser irradiated targets can be used to image a secondary experiment. A simple way to do this would be point projection imaging where the x-ray source casts a shadow of the plasma on to the detector. Unfortunately, Z-pinch plasmas tend to be bright x-ray sources themselves which increases the background on the detector. Clearly, it would be ideal to discriminate the laser produced x-rays from the self-emission. Monochromatic backlighting has been demonstrated as a way of achieving this [127]. In this scheme, the x-ray optics are used to image the plasma on to a detector. Through careful choice of optics (typically spherically bent crystals such as quartz or mica) and x-ray wavelengths, it possible to design the system such that it only images a single x-ray line on to the detector. This means that the plasma self-emission is also only imaged over a narrow spectral bandwidth. Additionally, the detector can be placed out of direct line of sight of the plasma which also improves signal to noise ratio. Such an imaging system driven by one arm of the Cerberus laser has been implemented on MAGPIE to for x-ray radiography of dense plasmas. The laser requirements for such a system are quite modest and good results have been obtained from Nd:Glass lasers with 15
Introduction

J of energy in 2 ns pulse [112]. In addition to imaging dense plasmas on MAGPIE, it is hoped that such a monochromatic imaging system could also be used to measure plasma opacity [110] by observing the attenuation in the image in comparison with a calibrated density step-wedge. As of writing of this thesis, initial results with x-ray backlighting system are being obtained, however, these will be the subject of a future publication.

Proton Probing

Analogous to photon based imaging, particle imaging has been recently demonstrated to offer complementary information about plasma dynamics [85]. It has been shown that interactions of intense light pulses with thin foils (usually gold or aluminium) produces beams of poly-energetic protons with a narrow divergence angle [62]. It has been observed via experiments and simulations that these protons are accelerated from the rear surface by a strong space charge field created by fast electrons expanding into vacuum [113].

The quality of these protons beams is sufficient such that it possible to use for point projection imaging of plasmas in a similar fashion to x-rays. The produced beams have demonstrated high spatial resolution and temporal resolution which of the order of a few picoseconds. An advantage of using charged particles for imaging is that, it is possible to interpret their deflection as interactions due to the strong electromagnetic fields in the plasma. Such deflectometry measurements have already been performed to measure magnetic field strengths in a transient plasma [146], although only in laser driven experiments at large facilities. The unique use of such a diagnostic technique on magnetised jets in MAGPIE [77] is one of the primary aims of this laser system.

It is expected that the combined diagnostic capabilities of all three beams will offer a comprehensive and uniquely power set of measurements of plasma conditions in a range of challenging experimental configurations.
1.4 Cerberus Laser Outline

Figure 1.2 provides a complete overview of the planned laser system. Due to restrictions on space, the system is currently split over three adjacent laboratory areas to house the front end, the power amplifiers and the final beam delivery optics. Known laser parameters and design point values for various components are stated where possible. Neodymium doped glass (Nd:Glass) has been chosen as the lasing medium over Ti:Sapphire for a range of technical and practical reasons. The most important of these is the availability of large aperture amplifiers released by the decommissioning of the Helen laser system [103], which were donated by the Atomic Weapons Establishment (AWE) for long term use. In addition to this, Cerberus also integrates components from an older Nd:Glass system such as rod amplifiers, gratings and optics, all of which require wavelength compatibility.

Short duration laser pulses with peak powers up to a petawatt have already been demonstrated using Nd:Glass [109] and Ti:Sapphire [5] as the gain media. Systems based on Nd:Glass benefit from large aperture amplifiers which draw upon technology originally developed for inertial confinement fusion (ICF) whereas the broader gain bandwidth of Ti:Sapphire supports shorter pulse durations and consequently requires less energy to reach a given power level. Despite this, scaling Ti:Sapphire systems to higher peak powers has been difficult due to challenges in manufacturing large aperture crystals and pumping them. More recently, hybrid lasers incorporating the advantages of both system have been demonstrated [156]. In such setups, the front end consists of Ti:Sapphire amplifiers which support greater bandwidth during the early stages of amplification. This is supplemented by Nd:Glass power amplifiers to increase the energy to petawatt levels [88]. Optical parametric amplifiers (OPAs) have also been shown to be capable of broadband gain along with the added advantage of improved contrast [44]. Such a scheme is utilised on the Cerberus front end along with larger flashlamp pumped amplifiers to increase the energy to the > 20 J. A separate long pulse beamline derived from the same front end is also incorporated into the system to offer additional flexibility of simultaneous long and short pulse
probing to multiple target areas. The third beam line will be an independent narrow
band Nd:YAG and Nd:Silicate based system operating separately from the main front
end.
Figure 1.2: An overview of the Cerberus beamlines including the approximate physical organisation of the laser system. Measured parameters are included where possible. OPAs - Optical Parametric Amplifiers; NLC - Nonlinear Crystals; SHG - Second Harmonic Generation. Red arrows correspond to infra-red and green arrows represent the second harmonic (527 nm). It should be noted that the shown laser parameters are design point values based on experimental requirements.
Chapter 2

Concepts in High Power Lasers

This chapter provides background information on current laser technology and modern methods of laser light amplification. The two main ways of amplifying ultrashort pulses of light, Chirped Pulse Amplification (CPA) and Optical Parametric Amplification (OPA) (often used in conjunction with the former), are compared in the context of high contrast lasers. Both techniques are relevant to the Cerberus laser system described in this thesis. Accurate measurements of key laser parameters such as pulse duration and spatial profiles are important to verify simulations and check correct implementation of stretcher and compressor systems. The diagnostic techniques used during the construction of the laser are also described.

2.1 Laser Technology

2.1.1 Mode-Locking

A laser cavity of length $L$ is able to support a potentially infinite range of standing waves separated in frequency by $d\nu = c/2L$. The laser medium itself has a finite gain bandwidth ($\Delta\nu$) which limits the number of longitudinal modes which can be present. The laser output would then correspond to a comb of allowed modes modulated by the gain profile assuming the cavity optics have a flat spectral response. Typically, these modes will oscillate out of phase, which produces an output which is unstable and
quasi-periodic in time. ’Mode-locking’ is a method which allows these longitudinal
modes to be locked together in phase so that they constructively produce a single
pulse whose minimum width is given by \( \Delta T \sim \Delta \nu^{-1} \). Most modern oscillators use a
technique known as passive mode-locking where non-linear effects (such as saturable
absorption) can be used to produce a robust ’turn-key’ device [105]. Figure 2.1 shows
the diagram of the Nd:Glass (Time-Bandwidth Products Ltds GLX-200-HP) based
oscillator used in the front end of the Cerberus laser. In this system, mode-locking is
achieved through the use of a saturable absorption mirror (SESAM) which selectively
reflects higher intensity spikes (corresponding to shorter pulses) [72]. This allows a
pulse train to build up with a spacing given by \( \Delta T_{\text{sep}} = 2L/c \).

Figure 2.1: Functional diagram of the Nd:Glass oscillator used on the Cerberus front end.
The yellow regions correspond to heating elements used to control the breadboard temper-
ature to minimise thermal drift over long timescales. SESAM = Semi-conductor saturable
absorption mirror; AM = Actuated mirror to control cavity length ; TS = Tuning slit; OC
= Output coupler. The two prisms are used to compensate for intra cavity dispersion and
also control the width of the oscillator spectrum. The tuning slit can be tweaked to control
the central wavelength of the oscillator.

Q-switching is another technique which is routinely used to produce pulses of the
order of few nanoseconds, commonly from Nd:YAG based lasers. In this scheme, a
fast electro-optic device such as Pockels cell is used to modulate the loss in the cavity
(typically in conjunction with a Brewster angle polariser). This allows gain and stored
energy in the active medium to build up to its maximum value before lasing occurs.
Since the gain is very high, the pulse builds up quickly with pulse durations which can be of the order of the cavity round trip time.

### 2.1.2 Nonlinear Optical Effects

A system responds linearly if its output depends linearly on the input. In the case of nonlinear optics, the response of a material is modified by the presence of a strong electric field which results in a range of interesting and potentially useful phenomena pertinent to lasers. For small applied electric fields, the oscillating electric field creates an oscillating dipole in the material which acts as a source term to re-emit the same wave. In this regime, the polarisation of matter, $P$, can be expressed as

$$P(t) = \epsilon_0 \chi_1 E(t)$$  \hspace{1cm} (2.1)

where $\epsilon_0$ is the permittivity of free space and $\chi_1$ is the first order or linear susceptibility [20]. For anisotropic materials such as crystals, $P$ is typically a tensor, however, the essential physics can be understood under the scalar approximation. Short pulse lasers are capable of generating strong transient electric fields which can perturb the atomic potential significantly. Hence, the linear approximation quoted above is no longer valid and induced polarisation can be expanded as a power series in the electric field.

$$P(t) = \epsilon_0 (\chi_1 E(t) + \chi_2 E^2(t) + \chi_3 E^3(t) + ..)$$  \hspace{1cm} (2.2)

$$\equiv P^{(1)}(t) + P^{(2)}(t) + P^{(3)}(t) + ..$$  \hspace{1cm} (2.3)

where the quantities $\chi(n)$ are the $n^{th}$ order susceptibilities and $P^{(n)}(t)$ refer to the order of polarisation induced by that susceptibility. This nonlinear polarisation acts as the source term for the various phenomena described below. It should be noted that the quantities $\chi(n)$ are usually rank $n$ tensors.

The range of effects generated by the second term in equation 2.3 can be extracted by substituting an optical field composed of two arbitrary frequencies ($\omega_1$ and $\omega_2$) into
\[ P^2(t). \]
\[ E(t) = E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t} + \text{c.c.} \]  
(2.4)

where c.c. refers to the complex conjugates of the field.

\[ P^{(2)}(t) = \epsilon_0 \chi^2 (E_1^2 e^{-i2\omega_1 t} + E_2^2 e^{-i2\omega_2 t} + 2E_1 E_2 e^{-i(\omega_1+\omega_2)t} + 2E_1 E_2^* e^{-i(\omega_1-\omega_2)t} + \text{c.c.}) + 2\epsilon_0 \chi^2 (E_1 E_1^* + E_2 E_2^*) \]  
(2.5)

The effect corresponding to each term is summarised in table 2.1 below. It is possible to obtain an intuitive picture of these processes in terms of the creation and destruction of photons. For example, second harmonic generation can be thought of as two photons excitation to a virtual state which decays to give a single photon at twice the frequency. Optical parametric amplification, an effect around which this laser system is designed, can be understood as a case of difference frequency generation where a higher frequency pump wave (\( \omega_1 \)) amplifies a lower frequency seed (\( \omega_2 \)) through the creation of an idler wave at the frequency difference (\( \omega_1 - \omega_2 \)).

It should be noted that not all materials are capable of producing these effects and for second order processes only non-centrosymmetric crystals have \( \chi^2 \neq 0 \).

<table>
<thead>
<tr>
<th>Term</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P(2\omega_1) )</td>
<td>Second Harmonic Generation at ( 2\omega_1 )</td>
</tr>
<tr>
<td>( P(2\omega_2) )</td>
<td>Second Harmonic Generation at ( 2\omega_2 )</td>
</tr>
<tr>
<td>( P(\omega_1 + \omega_2) )</td>
<td>Sum Frequency Generation at ( \omega_1 + \omega_2 )</td>
</tr>
<tr>
<td>( P(\omega_1 - \omega_2) )</td>
<td>Difference Frequency Generation at ( \omega_1 - \omega_2 )</td>
</tr>
<tr>
<td>( P(0) )</td>
<td>Optical Rectification</td>
</tr>
</tbody>
</table>

Table 2.1: Summary table of second order nonlinear optical effects pertinent to high power lasers.

Usually, only one of the effects in table 2.1 is desired and this can be achieved through careful selection of polarisation, phase matching and choice of material. For efficient conversion into the required process, it is important for the driving field and the generated field to stay locked in phase. Since the refractive index is a function of wavelength, poly-chromatic light disperses inside crystals, and consequently, two
difference frequencies will typically ‘walk-off’ temporally as they propagate through
the crystal. Birefringent crystals are a commonly used technique to achieve phase
matching for non-linear process. These crystals which exhibit polarisation depen-
dent refractive index which can be used to obtain a common refractive index for
the two different frequency components. This allows the phase matching condition
\( \Delta k = k_2 - k_1 = 0 \) to be fulfilled. In practice, this is achieved by tuning the angle
of the crystal such that \( n_e(\omega_2, \theta) = n_o(\omega_1) \), where \( n_e \) and \( n_o \) are the extra-
ordinary and ordinary refractive indices. This is known as critical phase matching and is typ-
ically very sensitive to angular misalignment or thermal drift. From an experimental
perspective, regular alignment is necessary to optimise the output. Other methods
such a temperature tuning depend upon the temperature dependent refractive index
of certain crystals to match the phase velocities at a fixed angle \([20]\). This lack of
angular sensitivity can make them more robust, but requires additional closed loop
control systems to implement.

In parallel with second order processes, a range of third order optical effects can
be understood by expanding this \( P^3 \) term from equation 2.3.

\[
P^{(3)}(t) = \epsilon_0 \chi_3 (E_1 e^{-i\omega_1 t} + E_2 e^{-i\omega_2 t})^3
\]  

(2.7)

An exhaustive combination of all the terms and the corresponding effects is provided
by Boyd in \([20]\). Third order effects are prevalent in all centrosymmetric media and
therefore present in most optical elements of a high power laser system. In the context
of this thesis, the optical Kerr effect \([20]\) is the most pertinent and is discussed in the
following section

The second order nonlinearities described above can be exploited usefully, whereas
others such intensity dependent refractive index (optical Kerr effect) can have nega-
tive consequences particularly in the context of high power laser amplifiers. For an
intense laser pulse travelling through the medium, the modified refractive index can
be expressed as an intensity dependent modification of the ordinary refractive index
Concepts in High Power Lasers

\[ n_{\text{total}} = n_0 + n_2 I \]  \hspace{1cm} (2.8)

where \( n_2 \) is the nonlinear refractive index \([\text{cm}^2/\text{W}]\) and \( I \) is the intensity.

High intensity laser beams are often characterised by a Gaussian or Super-Gaussian spatial and temporal profile which have the highest intensity along the axis of propagation. This results in a non-uniform refractive index profile which can act as a positive lens to focus the beam. This creates regions of higher intensity and positive feedback can then result in collapse of an energetic beam into a diffraction limited filament. The medium is usually permanently damaged due to this. Spatial non-uniformities in the laser beam such as 'hot-spots' and 'clips' can also result in enhanced local intensity and self-focusing. These effects are particularly important to consider for long amplifier rods where there is gain available in a long piece of transmissive optic. The use of spatial filters can help to remove high spatial frequency components arising from 'hot-spots' and 'clips' but they cannot reduce the overall intensity of the pulse during amplification. This requires the use of a technique such as CPA which is described in detail in the next section. The build-up of the nonlinear effects can be expressed through the so called 'B-integral'

\[ B = \frac{2\pi}{\lambda_0} \int_0^z n_2 I(z) \, dz \]  \hspace{1cm} (2.9)

where \( \lambda_0 \) is the laser wavelength and the integral is evaluated over path \( z \) through the optic. If the intensity is constant along the propagation path (typically true for many non-amplifying optics), then the integral simplifies to

\[ B = \frac{2\pi n_2 I z}{\lambda_0} \]  \hspace{1cm} (2.10)

For non-saturated amplifiers where the intensity increases as \( I(z) = I_0 e^{\alpha z} \), the equation can be expressed as

\[ B = \frac{2I_0 \pi}{\lambda_0} \int_0^l n_2 e^{\alpha z} \, dz = \frac{2I_0 \pi n_2}{\lambda_0 \alpha} (e^{\alpha l} - 1) \]  \hspace{1cm} (2.11)
where $\alpha$ is the gain per unit length, $l$ is the length of the amplifier. Experimental evidence and theory stated in [19] indicate that B-integral values of $< 5$ should be maintained to prevent catastrophic damage to amplifiers and optics. It should be noted that the calculated value is typically an estimate as spatio-temporal non-uniformities in the laser act to increase it. While self-focusing is a spatial effect of the intensity dependent refractive index, self-phase modulation (SPM) acts in the time domain. Since the intensity of a laser pulse is not constant in time, the refractive index also changes with time. This imposes an instantaneous frequency shift at each point in time given by [20]

$$\Delta \omega = -\frac{n_2 \omega_0 l}{c} \frac{dI(t)}{dt}$$

(2.12)

where $n_2$ is the second order refractive index, $\omega_0$ is the laser frequency and $l$ is the propagation distance. This results in the formation of new frequency components and spectral broadening of the pulse. This effect is used now routinely exploited in gas filled hollow fibres to generate spectra spanning hundreds of nanometres which can subsequently be compressed using chirped mirrors to produce few-cycle pulses below 4 fs [101, 147]. However, in the context of good recompression and high contrast, the nonlinear chirp introduced by SPM can be difficult to compensate for [22]. Simulations done by M.D. Perry et al [107] have shown that for CPA lasers, even total B-integral values of $\sim 1$ can reduce peak intensities by spreading the energy more into the wings of the pulse.

In addition to nonlinear effects such as those described above, damage threshold of optical materials and coatings also limits achievable intensity. For uncoated glass, this can be as high as $40 \, J \, cm^{-2}$ (10 ns pulses) but dielectric anti-reflection coatings typically reduce this by a factor of four. The empirical $t^{0.5}$ law can be used to scale damage threshold for pulse durations between 10 ps to 10 ns [150] where the adjusted threshold $= Q_t \sqrt{\frac{\Delta Q_p}{\Delta t_p}}$, where $Q_t$ is the damage threshold measured at a pulse duration of $\Delta Q_p$ and $\Delta t_p$ is the actual pulse duration.

The electric field of an ultrashort laser pulse can be written as a product of a slowly varying amplitude ($A(t)$) and a carrier frequency, $\omega_0$, at a fixed position in
where $\phi(t)$ is the temporal phase of the pulse. For longer pulses ($> 50$ fs), the oscillations of the carrier frequency can be ignored as the intensity envelope and temporal phase terms suffice. The measured quantity, intensity, is defined as

$$I(t) \propto |E(t)|^2$$  \hspace{1cm} (2.14)

Similarly, the frequency domain expression can be written as

$$E(\omega) = A(\omega)e^{i(\phi(\omega))}$$  \hspace{1cm} (2.15)

where $\phi(\omega)$ is the spectral phase and $A(\omega)$ is the spectral amplitude. The quantities $E(t)$ and $E(\omega)$ are Fourier transform pairs. This is a particularly important relationship as we often want to control the laser pulse in the time domain but this is only readily achieved through the frequency domain for ultrashort pulses. In the next section, the concept of CPA will be introduced which involves direct control of the temporal duration of a light through changes to the spectral phase.

### 2.2 Light Amplification Methods

Many short pulse laser systems use commercial oscillators as the primary light source. Whilst these devices are capable of delivering sub-ps or in some cases even few-cycle pulses at the press of a button, individual pulse energies are typically only of the order of nanojoules. For a typical Nd:Glass oscillator delivering 200 fs pulses with 5 nJ of energy, the focused intensity of a single pulse could easily exceed $10^{10} \text{Wcm}^{-2}$. This means that many of the nonlinear effects described in the preceding section can be accessed. However, many laser driven plasma physics experiments require substantially higher peak intensities (typically $10^{18} \text{Wcm}^{-2}$ to access the ‘relativistic regime’ which is defined as the value at which the ponderomotive energy of electron
in the laser field is equal to its rest mass.) and greater drive energies in order to interact with larger samples of material. This requires pulses from the oscillator to be amplified by a factor of $10^9 - 10^{12}$, taking them to up to the J - kJ level. The next section explores the methods and challenges of achieving such large amplification factors.

### 2.2.1 Chirped Pulse Amplification

The effects of nonlinearities described in the preceding chapter make direction amplification of short pulse lasers problematic. For example, a 250 fs pulse amplified in a 1 cm diameter Nd:Glass rod of length 15 cm will reach a B of 1 when the pulse energy reaches a mere $\sim 0.55$ mJ. This is substantially less than the saturation energies of high gain amplifiers (typically $\sim J \text{ cm}^{-2}$). One way to reduce intensity is to increase the area of the laser beam and increase the aperture of the amplifiers. For pulses which are of the order of nanoseconds, this is routinely employed. The only limiting factor in this case is the damage threshold of optics. Large laser-driven ICF facilities such as the National Ignition Facility (NIF) [63] are capable of producing $> 40 \text{ kJ}$ per laser beam using 40 cm aperture square amplifiers. This results in peak powers of $\sim 3 \text{ TW}$ on a nanosecond timescale and by combining 192 such lasers, $\sim 0.5 \text{ PW}$ can be delivered to the fusion capsule. Whilst such large aperture amplifiers are not commercially available (nor would they be easily affordable!), they still would not represent an efficient way to extract energy with short pulse lasers. The solution to this problem is to stretch the pulses temporally rather than spatially to reduce peak intensities and consequently nonlinear damage. This was first demonstrated by Strickland and Mourou [132]. They used laser pulses with a near linear variation of frequency with time (chirped) to increase their temporal duration before amplifying. Hence, this method of amplification is known as chirped pulse amplification or CPA.

The methodology is shown in figure 2.2 and essentially involves stretching the pulse temporally to reduce intensities during amplification and then compressing it back to near its original form to reproduce the short pulse which now contains substantially more energy and power. This technique has allowed peak powers to reach up to a
Figure 2.2: The CPA concept. Chirped pulse amplification involves stretching the pulse temporally, amplifying it and then compressing it to deliver a high energy pulse with nearly the same temporal width as the original pulse.

petawatt with focused intensities reaching $\sim 10^{21} \text{ W cm}^{-2}$ [109].

The optical systems used to stretch and compress lasers pulses are illustrated in figure 2.3. Intuitively, an unchirped broad bandwidth pulse can be thought of as having all frequency components distributed uniformly in time. It is clear that if one frequency component is delayed with respect to another, then the pulse would be temporally stretched. An optical arrangement which does this is called a 'stretcher'. Similarly, an arrangement which allows the frequency components to be overlapped again in time is called a 'compressor'. The inter-wavelength delaying can be implemented by a wavelength dependent transit time through the system. When the pulse is stretched before amplification, individual frequency components are amplified in series as opposed to parallel (in the case of unchirped pulses) and thus short pulse lasers can now be amplified in a similar fashion to long pulse lasers without destroying optical elements.

The effects of adding or removing chirp can be understood in terms of modifications to the spectral phase profile $\phi(\omega)$. This can be expanded into a Taylor series
Concepts in High Power Lasers

Figure 2.3: Left) A standard two lens Martinez-style stretcher adds chirp due to blue wavelength components travelling a greater distance compared to red [89]. Right) Treacy-style two grating compressor in which red wavelengths travel more than blue removes an equal amount of chirp [143]. In their shown configuration, the outputs of these arrangements will be spatially chirped which is usually undesirable. This is remedied by retro-reflecting the beam back through the system.

around the central wavelength $\omega_0$ [125]

$$\phi(\omega) = \phi_0 + (\omega - \omega_0) \frac{d\phi}{d\omega}|_{\omega_0} + \frac{(\omega - \omega_0)^2}{2!} \frac{d^2\phi}{d\omega^2}|_{\omega_0} + \frac{(\omega - \omega_0)^3}{3!} \frac{d^3\phi}{d\omega^3}|_{\omega_0} + \ldots \quad (2.16)$$

where the first term $\phi_0$ is known as the carrier envelope phase (CEP) which is the phase between the oscillations of the electric field and its amplitude envelope. Controlling this is important for experiments with few-cycle pulses [70] but it is not applicable for this laser system. The second term is called group delay and results in a temporal shift of the envelope. Neither of these two terms have effects on the shape of the pulse. The third term, which is of particular interest, is called the group delay dispersion (GDD) and is responsible for stretching and compressing laser pulses. Since the group delay is itself a function of the phase, the second derivative is linear and consequently results in a linear relationship between frequency and time. The sign of this term defines whether the dispersion is positive or negative. The effect of this term on an unchirped pulse will result in temporal broadening, irrespective of the sign (figure 2.4b). The type of dispersion determines whether longer wavelengths are on the leading or trailing edge of the pulse. The fourth term is called third order dispersion (TOD) and results in a quadratic chirp on the pulse. This can create wings and side-lobes on the shoulder of the laser pulse (figure 2.4c) if uncompensated. It is clear from inspecting the above equation that the effects of higher order terms is more important as pulse bandwidth increases since $\omega_0 - \omega$ gets large. For the longer
pulses (∼ 200 fs) from an Nd:Glass laser, the effect of these higher order terms is typically seen to affect 'contrast', which can be defined as the ratio of the intensity of the main peak compared to next highest peak in the time window ahead of the main pulse (figure 2.4d). The effect of these various phase terms on the pulse profile is shown in figure 2.4a-d. A pulse with a flat or a constant spectral phase is termed transform-limited. The minimum possible duration which can be obtained is given by the time-bandwidth product $\Delta \nu \Delta t = K$ where $K = 0.441$ for Gaussian pulses and 0.315 for $Sech^2$ pulses. In theory, if all the phase terms could be perfectly matched, then the original pulse could be re-created faithfully. However, a range of issues occur during the implementation of a CPA setup which make 'perfect' compression difficult and these will discussed in the next section.

![Figure 2.4: Effect of spectral phase (red) on laser pulses (blue = input, black = output).](image)

- a) Unchirped pulse with a corresponding flat spectral phase.
- b) Pulse with large a second order phase ($\phi''$) term gives uniform broadening.
- c) Addition of third order dispersion ($\phi'''$) introduces side lobes to the pulse and causes distortion.
- d) Residual second and third order phase terms will gives a broader pulse with poor contrast more visible here on a log scale.

In practice, this effect will exacerbated due to clipping of the spectrum on dispersive optics.


**Design Considerations for CPA**

The final ‘quality’ of the compressed laser pulse is affected strongly by the ability to properly overlap spectral components in time. Intuitively, if any spectral components get ‘lost’ in the laser chain, then the ability to reconstruct the pulse exactly is compromised. This is known as spectral clipping and is a key design consideration for any CPA setup. The loss of frequency information translates directly into a longer pulse and can also deteriorate the contrast. In practice, clipping at some level is hard to avoid especially on dispersive optics of a finite size. If it were possible to have extremely large optics and gratings throughout the system, then any clipping would be negligible. In reality, the cost of optics rarely increases linearly with size therefore maximising the benefit from available components is important. A ‘hard’ spectral clip corresponds to a high frequency structure in the spectrum and results in ‘ringing’ in the wings of the temporal profile. The use of larger beam diameters is preferred as this spreads the equivalent energy over a larger area which results in spatial averaging or ‘softening’ of any clipping. This ‘soft’ clip will typically result in a pulse shoulder in the time domain. Surface quality of optics can also affect pulse quality especially in stretchers and compressors where the spectral content is dispersed over a large area. Aberrations on the optics translate into phase errors which can be very hard to compensate and can limit contrast dramatically. For typical optics in the stretcher and compressor, a RMS flatness of $\lambda/30$ is required to minimise phase distortions [7]. Although simulations show tangible improvements can be had by using $\lambda/50$ or better surfaces, the effects of other factors such beam divergence or misalignment become more important. Stretchers with transmissive optics such as the one shown in figure 2.3 suffer from chromatic aberrations and material dispersion effects and will typically result in worse performance compared to the all-reflective systems such as the one described in [90]. The contrast of a laser pulse can be affected by a range issues apart from incomplete compression. On the long timescale ($\mu s$ to ns), amplified spontaneous emission (ASE) from amplifiers gives a smooth pedestal. Discrete pre-pulses on this time scale can also occur due to leakage from
regenerative amplifiers and stray reflections but fast Pockels cells can be used to clean them. On a shorter time scale, multiple reflections from mirrors and uncoated optics can result in pre-pulses on the tens of picosecond scale. These can be difficult to diagnose and optical elements need to be carefully selected and positioned to avoid them (e.g. wedged windows). Frequency doubling the laser pulse is a good way to improve pulse contrast as conversion depends on the square of the intensity and is therefore poor in the wings of the pulse. Plasma mirrors [142] are another technique often used post compression to improve pulse contrast. In this method, the laser pulse is focused on to a glass plate where pre-pulses are transmitted through but the main pulse is reflected by the plasma formed from its leading edge [45, 48]. This removes any pre-pulses and pedestal from the leading edge of the pulse. This is a single shot technique as the glass plate is damaged after each shot. Therefore, it would be better to have good contrast implemented in the design, so that there is more flexibility and higher efficiency in experimental setups.
Grating Damage Thresholds

Although the use of CPA allows energy to be efficiently extracted from amplifiers, the ability to compress this energy in time (via the use of gratings in high-energy systems) still limits achievable peak powers. For a two grating compressor system, the final reflection off the grating experiences the highest intensities due to the compressed pulse and consequently limits the input energy. Traditionally, gold gratings have been used in CPA setups due to good reflectivity and reasonable cost. For any metallic layer, the absorption of laser light at the reflecting surface reduces damage threshold. Typically, modern gold gratings have a maximum damage threshold of \( \sim 0.6 \, \text{Jcm}^{-2} \) at 500 fs [99]. Usable fluences can be much lower as energy distribution is rarely uniform across the laser beam. Recent advances in the fabrication of multi-layer dielectric (MLD) stacks have resulted in the creation of dielectric gratings which offer significant improvements over metallic equivalents [124]. The most significant of these is the increase in damage thresholds which have been measured to be an order of magnitude higher (\( \sim 5 \, \text{Jcm}^{-2} \) projected on to the grating surface) under equivalent conditions [99, 108]. This has been realised through the use of MLD stacks which use interference to reflect light. It is possible to maximise this interference effect for a particular wavelength range which means gratings can reach close to 100 % efficiency into a specified diffraction order. Such gratings have been successfully used on high energy short pulse systems such as OMEGA-EP [73] which can deliver up to 2.6 kJ in a 10 ps pulse. To achieve such a high energy throughput, three sub-aperture MLD gratings are tiled to produce a single large effective grating. A deformable mirror is used post compression to compensate for tiling of the grating.

Despite their additional cost per given area, the Cerberus short pulse beamline will make use of the technological improvements of MLD gratings to maximise energy throughput. Due to cost considerations, only gratings of a certain size were affordable and modelling was used throughout to decide final specifications. The MLD gratings described in thesis were custom made by Plymouth Grating Laboratory. This is detailed in chapter 3.
Gain Narrowing

![Graph showing gain narrowing](image)

Figure 2.6: The effect of gain narrowing of the input spectrum of a typical Nd:Glass laser as a function of gain.

Conventional amplifiers are limited in their spectral gain profile and consequently suffer from gain narrowing. Due to a non-uniform gain profile, the centre of the spectrum is amplified more than the wings which has the effect of narrowing the width of the spectrum. This loss of bandwidth effectively places a limit on minimum pulse duration. The effect of this is shown in figure 2.6 where a 5.6 nm output spectrum of a Nd:glass laser is amplified in Nd:glass amplifiers (line width is 20 nm) by different amounts. A gain of $10^9$ is the minimum typically required to reach from nanojoules to joules and in reality, losses can mean that total gain needed can be substantially more. It is possible to mitigate this effect to an extent by shaping of the spectrum to account for the non-uniformity in the amplification process. For example, it is possible to selectively attenuate the peak of the wavelength dependent gain curve such that there is greater net gain in the wings of the spectrum. Another method which has been demonstrated for Nd:Glass based systems is to mix different glasses (usually silicate with phospate) with different gain profiles to obtain an overall wider gain profile [116]. For many CPA lasers, the bulk of the gain ($\sim 10^6$) occurs in multi-pass regenerative amplifiers. Here, spectral shaping of the seed or modulation
Figure 2.7: The effect of shaping seed spectrum on the amplified output bandwidth. Left) An input spectrum from a Nd:Glass laser (black, centered at 1054 nm) is amplified in a lower bandwidth Nd:YLF amplifier (blue, centered at 1053 nm). The output spectrum (red) has a FWHM of 0.3 nm. Right) In this simulation, the input spectrum has been selectively attenuated at 1053 nm to part compensate for the reduced gain in the wings. The output spectrum is now 0.1 nm wider compared the unshaped scenario.

of gain profile have been particularly effective. Experiments with both Nd:Glass [106] and Ti:Sapphire [8] have shown improvements by a factor of up to three in output bandwidths.

Figure 2.7 shows the effect of spectral shaping on the input Nd:Glass spectrum (black curve centered at 1054 nm, Gaussian shape) which is amplified in a Nd:YLF amplifier by factor of $10^6$. The gain curve for Nd:YLF is shown in blue and is centered at 1053 nm with a FWHM of 1.3 nm. With a ‘dip’ in the spectrum at peak of the Nd:YLF gain curve, the output spectrum (red) is wider by 0.1 nm compared to the no shaping case. It should be noted that saturation effects are ignored in this calculation.

**CPtrace3D Modelling Suite**

Given the large range of parameters affecting CPA systems and pulse contrast, simple analytical calculations do not suffice and it is important to use a model which incorporates all the relevent physics so that informed decisions can be made about system parameters. This section describes a 3D ray tracing code called ‘CPTrace3D’ which was developed by Mike Mason and is described in detail in [91]. This code was used extensively by the author to model the CPA components of the Cerberus
laser system. It allows quantitative comparisons to be made between different configurations which is essential given the large parameter space for CPA systems and the considerable cost of diffraction gratings.

For certain aspects of CPA design, it is not necessary to use full 3D modelling. For example, the choice of stretched pulse duration is often set by the target value of the system’s B-integral. For Nd:glass based CPA systems, 1 ns is a typical stretched pulse duration as it allows energy extraction of the order of $\sim \text{Joules cm}^{-2}$ without exceeding damage thresholds. The stretched pulse duration ($\Delta T$) can be calculated using an analytic assessment of the standard two grating compressor geometry as described in [52]. The difference in path lengths for two wavelength components separated by the FWHM of the spectrum can be related to their separation in time after traversing the two grating delay line. This allows the pulse duration to be expressed in terms of common grating parameters as

$$\Delta T = \frac{2\lambda_0bd^2\Delta \lambda}{c \cos^2 \theta}$$

(2.17)

where $\lambda_0$ is the central wavelength, $b$ is the perpendicular grating separation, $d$ is the grating constant (in lines/m), $c$ is the speed of light, $\Delta \lambda$ is the FWHM bandwidth and $\theta$ is the angle between the grating normal and the diffracted ray for $\lambda_0$ (figure 2.8). It should be noted that the factor of 2 is added to account for the double pass geometry which both doubles the dispersion and removes spatial chirp. For example, a 250 fs $sech^2$ pulse traversing through a double pass compressor with a grating separation of 1 m, a ruling density of 1740 l/mm and incident at an angle of $77^\circ$, would be stretched to $\sim 375$ ps. A stretcher with an equivalent grating separation would provide the same dispersion but with an sign opposite chirp. This means that designing a compressor to match the stretcher should in principle be straightforward.

The grating angle conventions used in this thesis are identical to those employed by the CPTrace3D program to maintain consistency. The diffracted angle ($\theta$) is can
be calculated from the grating equation as -

\[ \sin \theta + \sin \gamma = m \lambda \]

(2.18)

where \( m \) is the diffraction order and the angles \( \gamma \) and \( \theta \) are measured with respect to the grating normal and defined as per figure 2.8. The difference between \( \gamma \) and \( \theta \) is defined as \( \phi \). This will be referred to as the input angle and is useful when building grating based setups.

\[ \text{Grating separation} = d \]

\[ \text{Input angle} = \phi \]

\[ \text{Diffraction angle} = \theta \]

\[ \text{Optical axis} \]

Figure 2.8: Grating conventions used in CPTrace3D and also in this thesis. Angles and distances are defined as per diagram.

Since CPA setups are heavily dependent on spectral components and their phase, CPTrace3D has been specifically designed to ray trace bundles of different frequency components through an optical system. The code begins with a time domain description of the pulse (limited to Gaussian or \( \text{Sech}^2 \) profiles) (see figure 2.9a). To create a 2D beam profile, a grid of 1D pulses is used and weighted by the spatial profile (again Gaussian) to create a realistic description of a real laser pulse. A discrete Fourier transform is then performed to convert to a frequency domain description. Each 1D beam is now split into thousands of frequency components (these are called rays)(figure 2.9b). The code then transports individual frequency components through the stretcher and the compressor where individual phase contributions can be calculated using the path length between components (figure 2.9c-d). Finite size optics are used to apodise the spectrum and simulate spatial clipping (figure
2.9e) and rays which fall outside the optics are marked 'lost'. The remaining rays are recombined using a 'perfect lens' and an inverse Fourier transform is taken to give the expected output in the time domain (see figure 2.9f). The pulse duration can be readily extracted from the intensity profile and plotting the intensity on a log scale allows the contrast to be determined. Contrast in the code is defined as the ratio of the main peak to other second highest peak in the time window of the pulse. This was often strongly affected by small amounts of residual third order phase and proved to be an inconsistent way to compare designs. It was often more useful to plot different profiles and compare them visually.

![Figure 2.9: A simplified block diagram of the operation of CPTrace3D code. Blue lines represent temporal/spectral phase and red lines are temporal/spectral intensities. FT represents the Fourier transform.](image)

**Code Features and Limitations**

- Since stretchers and compressors often require beams to be injected at an angle which are not parallel to the dispersion plane, a full 3D ray-trace of the system is carried out. This makes it particularly sensitive to off-axis aberrations in
stretcher for example.

- Changing the size of optics is handled intuitively in the design files and this allows the effect of a single optical parameter (e.g. grating width) on the pulse quality to be examined. This was done extensively for many of the CPA setups described in this thesis as component sizes had to fall within a constrained budget.

- The surface quality of optics also has an effect on final pulse quality. Imperfections in optics can introduce phase errors which can build up over multiple bounces from mirrors. CPTrace3D is able to simulate the effect of the surface roughness of optics using a technique called ‘pistoning’ [91]. In this method, the optical surface is divided into small sections which are displaced from their ideal positions to direct rays away from their original path. The amount of ‘pistoning’ is set at a level based on empirical evidence by Antonetti et al [4] who conducted pulse duration measurements as a function of surface flatness. The code allows surface roughness to be set at some fraction of the incident wavelength which is a common commercial standard for describing optical elements.

- In addition to ray tracing the stretcher and compressor, a range of additional physics can also be included. This includes material dispersion from optics in the amplification chain and also the amplifiers themselves which can have a substantial path length due to multiple passes. It is also possible to simulate gain narrowing, SPM and ‘pulse shapers’ and study their effects on the pulse. While this gives a more realistic model of the system, it was rarely done in practice as often we were looking to compare stretcher configurations rather than model the entire laser system.

- It is possible to plot the path of each individual ray through the system which allows for visualisation and analysis of advanced CPA setups. Figure 2.10 shows a 3D ray trace of a standard two grating compressor. The individual rays are not plotted for the sake of clarity but the positions of each individual rays
on the surface of optics can be analysed intuitively. Figure 2.11 shows the 2D projection of the compressor as viewed from above. The path followed by each component can be seen along different projections of the compressor. The position of the gratings is shown for orientation and clarity.

- The CPA setup on the Cerberus laser system is designed to complement the expected performance requirement of the OPAs and traditional flashlamp pumped amplifiers. The modelling of OPA gain requires the use of additional codes and is not explicitly handled in CPTrace3D.

- Optimisation routines are not implemented to maximise a particular parameter such as pulse duration or contrast. This can make parameter scans tedious to perform in practice.
Figure 2.10: 3D ray trace output of a two grating compressor performed using CPTrace3D. Different wavelengths follow different paths through the system and this can be visualised and analysed easily from the output of the code. Only end points of the vectors are plotted for clarity.

Figure 2.11: 2D projection of the compressor viewed from the top. The path of the rays is plotted for clarity. Location of the gratings and the double pass mirror are shown.
2.2.2 Optical Parametric Amplification and Contrast

Optical parametric amplification is a term used to describe the process of difference frequency generation when a strong higher frequency wave (pump) is mixed with a weaker low frequency wave (signal) to amplify the lower frequency wave and produce a third wave (idler) which is the difference between their frequencies. This process typically takes place in a nonlinear birefringent crystal so that the interaction can be phase matched. This is illustrated in figure 2.12. The frequency of the third generated wave is given by the energy conservation equation

\[ \omega_3 = \omega_1 - \omega_2 \]  

(2.19)

where \( \omega_1 \), \( \omega_2 \) and \( \omega_3 \) are defined as per figure 2.12.

![Diagram](image)

Figure 2.12: A simplified representation of optical parametric amplification of a weak seed by a strong pump in nonlinear crystal. A third beam called the idler is also produced in this interaction to conserve energy.

The mechanism of parametric amplification is fundamentally different to conventional laser amplifiers based upon gain storage. They typically consist of a 4-level (see
figure 2.13) system in which energy is pumped into the lasing medium (via flashlamps or other lasers) which excites electrons into a long lifetime energy states known as a pumping band. This is followed by a fast non-radiative decay to the upper level of the lasing transition. The presence of a photon with an energy corresponding to this transition stimulates it to decay releasing an identical photon in the process. The system then returns to the original state via additional non-radiative decays. Energy absorbed into the medium via these non-radiative transitions heats the amplifying medium and limits the repetition rate of the system. Amplifiers based on crystalline media such as Ti:Sapphire and Nd:YAG exhibit better thermal conductivity compared to the glass based amplifiers and consequently support higher repetition rates.

Figure 2.13: Energy level diagram for OPAs (left) and traditional gain storage amplifiers (right). In parametric amplification, a higher frequency energetic pump ($\omega_1$) is used to amplify a lower energy and frequency seed ($\omega_2$). A third photon corresponding to the energy difference is produce to conserve energy. For gain storage amplifiers, a population inversion is required in the lasing transition. Typically flashlamps or other lasers are used for this purpose which has the effect of heating up the medium.

The variables defined in equation 2.19 can take on any range of values which are only limited by the transparency window of the nonlinear crystal and the range over which nonlinear processes can be phase matched (for example, BBO has a transparency window which spans from 189 nm to 3500 nm [100]). In principle, it is possible to amplify a much wider range of frequencies than is possible with conventional amplifiers which are based on a fixed transition in the material. The amplification method
is termed ‘parametric’ in the sense that the system returns to the same energy state it started (see figure 2.13) with no net energy coupled into the gain medium. The pump photon ($\omega_1$) is transiently absorbed by the medium, which is then stimulated to decay at the signal frequency given by $\omega_2$ and an idler frequency corresponding to the difference between the pump and the signal. An important property of this mechanism is that no energy is transferred to the amplifying medium itself, hence, thermal loading of amplifiers is almost negligible and repetition rates are only limited the pump laser rather than crystal cooling times. Additionally, gain in the medium only exists on the timescale of the pump pulse duration which is important in suppressing long timescale amplified spontaneous emission (ASE) which is typical in gain storage amplifiers and exists for longer than the gain medium is pumped. This can be for timescales of many hundreds of microseconds before and after the arrival of the pulse to be amplified. This is important from a pulse contrast perspective and the implementation of this property into the Cerberus short pulse beam is discussed in the next section. Since the width of the gain profile can also be significantly greater than the width of the seed pulse spectrum, gain narrowing is limited and it is possible to obtain very large gain factors without any loss in bandwidth. For OPAs operating in a saturated mode, the bandwidth can actually be increased [13]. This was found to be the case on the Cerberus short pulse OPAs and is discussed in the next chapter.

A particular effect limiting the contrast of OPAs is parametric fluorescence from the pump beam, which is a spontaneous emission process (akin to ASE in conventional amplifiers) which occurs when a signal beam is not present. While this occurs on a significantly short time (ns to ps) compared to upper state lifetimes of conventional amplifiers, it still creates a pedestal on a timescale which may affect many experiments. Noise on the temporal profile of the pump can also imprint itself on the spectrum of the chirped seed which can then create a pedestal during compression [55]. Hence it is favourable to have as short a pump as possible to restrict the gain window around the signal. This method has been successfully demonstrated to improve contrast by a factor of the order of the OPA gain at the University of Rochester [44]. Their setup utilised a 200 fs signal pulse at 1053 nm which was directly ampli-
fied in an OPA with a $\sim 8$ ps 526.5 nm pump pulse with 2 mJ of energy. A total gain of $10^5$ was obtained using a single lithium triborate (LBO) crystal [30]. High dynamic range contrast measurements showed that the amplified OPA pulse had a contrast of $10^{-11}$ in the window ahead of the pump pulse profile. This measurement was actually limited by the dynamic range of the diagnostic for 100 $\mu$J, 300 fs pulses.

The short pulse OPA setup on Cerberus is based upon a similar design concept to create an energetic seed with excellent contrast for further amplification. A schematic of our modified setup is shown in figure 2.14. A complete CPA setup is deployed on the OPA pump section in order to extract the maximum possible energy and deliver the shortest possible pulse durations. The signal pulse is stretched slightly to improve temporal overlap with the pump and provide better conversion efficiency. The amplified pulse is then stretched again using an Offner-style stretcher for further amplification in the long pulse pumped OPA stages.

Figure 2.14: Block diagram of the optically synchronised short pulse OPAs. The use of a CPA pump pulse reduces the final pulse duration and therefore, the fluorescence window around the signal. Red arrows correspond to the fundamental wavelength and the green arrows the second harmonic.

It is possible to implement OPAs as a part of a CPA system which allows the advantages of both techniques to be exploited simultaneously. The use of a chirped seed in the process described in figure 2.12 allows intensities to be lowered during amplification and greater energies to be extracted. This method has been used in

69
a wide range of laser systems to produce few-cycle [68] pulses and also high energy pulses approaching a petawatt [29]. In the context of the Cerberus short pulse setup, parametric amplification stages will be used to amplify laser pulses from the oscillator to the tens of millijoule level. The aim is to restrict gain narrowing and improve contrast in the early stages of amplification where bulk of the gain narrowing occurs. The parametric amplification will be split into two stages; the first OPAs will use short (∼ ps) pump pulses and the latter stages will use long (∼ ns) pump pulses. This will then be supplemented in the final stages by flashlamp pumped rod amplifiers to increase pulse energy to the multi-Joule level.

**Design considerations**

Optimisation of OPAs requires numerical modelling of the coupled wave equations governing the signal, pump and idler. The simulations of amplifier performance were carried out by a number of masters students over the course of several projects and this is described in more detail in [133, 80, 59]. Much of the preliminary modelling was done using a freely available code from Newlight Photonics known as Select Non-linear Optics (SNLO) [6] and also an 'in-house' code written in Fortran by Prof. Geoff New. These codes allow the gain to be evaluated as function of the spatial and temporal characteristics of the input beams and also crystal type and length. The amplifiers are designed to be operated in a saturated regime as signal gain varies exponentially with the pump and energy stability is a key requirement of the system. It should be noted that strong saturation can lead to spectral modulation via back conversion and other nonlinear processes such as second harmonic generation of the signal. Each stage (long and short pulse pumped) consists of two amplifiers to increase stability to the pump energy fluctuations. BBO crystals are used due to their higher nonlinear susceptibility which reduces crystal length required for a given gain compared to KDP and LBO. Whilst keeping intensities below damage thresholds, the crystal lengths were optimised such that the signal output was maximal for given pump conditions. Modelling can provide a useful guide to system design, but in practice, the beam sizes, peak intensities, etc must be adjusted to control the actual performance of each
crystal.

Exhaustive details about the simulations of nonlinear crystal are not provided here as they were not performed by the author, however, a typical crystal simulation result is shown in figure 2.15. In this simulation, a 900 fs signal at 1054 nm is pumped by a 400 µJ 6 ps laser beam in a 6.5 mm BBO crystal. The time domain profiles in figure 2.15 show strong pump depletion but there is no back conversion visible. The gain as a function of the crystal length is also plotted and is close to the regime where saturation is reached. Figure 2.16 shows the spectral gain profiles on a logarithmic scale. The simulations show that the output spectrum matches closest the input spectrum up to the $10^{-15}$ level and that the gain profile is flat around the centre wavelength of 1054 nm. The spectral gain is higher in the wings as the input spectrum there is weaker and thus can be amplified substantially more before approaching saturation. It should be noted that OPA crystals were simulated before the construction of the OPA pump system and adjustments to controllable parameters such as beam sizes are anticipated when the pump amplifiers are fully optimised.

Figure 2.15: Simulations of the short pulse OPAs performed by Nick Stuart using Geoff New’s OPA code. Left) Output profiles of the signal and the pump from the modelling of the OPA stages. Right) Gain as a function of the crystal length. Parameters were adjusted to reach near saturation performance.
Figure 2.16: Left) Input and output spectra from the 1st OPA crystal show very little spectral narrowing and only minor modulation in the wings which is likely to be a numerical artifact from a finite size FFT window. Right) Gain is near uniform over the centre of the spectrum. The gain is higher in the wings due to signal strength being substantially lower.

Figure 2.17: A common oscillator can be used to generate both the seed for the signal and the pump. In this scheme, a Pockels cell is used to select a pulse for amplification. This becomes the pump and amplifies a signal later in time from the oscillator pulse train. Synchronisation is achieved by matching the optical path lengths and maintained by controlling the oscillator frequency. SHG - Second Harmonic Generation; OPA - Optical Parametric Amplification.

### 2.3 Optical Synchronisation

Stable use of parametric amplifiers requires stringent control of a large range of laser parameters due to the instantaneous and nonlinear nature of the gain. This is exacerbated by the use of a short pump pulse where maintaining temporal overlap at the picosecond level is now an additional concern. The system described in here [9] (from our group) used different lasers for signal and pump and synchronised it using electronic triggering. Measurements with this setup showed that it was possible
to obtain timing jitters of as low a 5 ps RMS. This required the use of two cavity stabilised oscillators along with sophisticated electronics to lock their relative phase. Jitters as low as 20 fs have been reported in literature [71] using different oscillators, however, such technology is expensive and increases the complexity of the project. Sensitive electronics are also susceptible to noise from high voltage sources commonly found in lasers such as Pockels cell drivers and pulsed power banks. Therefore, an optical synchronisation scheme is utilised on Cerberus where the pump and signal pulses are derived from a common oscillator. A simple way to do this would be to split a single pulse into using a beamsplitter and use one for the pump and other for the signal. Although this is straightforward to implement, it requires a large optical delay on the signal as the amplified pump will typically take 500 ns to be amplified to the millijoule level in a regenerative amplifier. Such a long optical delay would need a path length of over 150 m to compensate! Clearly this would be difficult to implement practically given the dimensions of optics table and would introduce a multitude of issues with daily alignment. Additionally, splitting a pulse reduces the energy for the signal and pump as well. A solution to this is to use the oscillator to compensate for the optical delay by picking a pulse later in time for the signal. This method has been successfully implemented for short pulse pumped OPAs and is described in detail here [141] for the case of a Ti:Sapphire oscillator based OPCPA setup. In their setup, a Photonic Crystal Fibre (PCF)[49] was used to shift the spectrum of Ti:sapphire laser pulses from \( \sim 800 \) nm to 1053 nm to allow it to more efficiently seed Nd:YLF amplifiers operating at 1053 nm. The output of these was then frequency doubled and used to amplify seed pulses from the same oscillator in nonlinear crystals. Since Cerberus is a Nd:Glass based laser, direct seeding of Nd:YLF amplifiers is possible without wavelength shifting.

Figure 2.17 shows a schematic of the method utilised on the front end of Cerberus. Individual pulses from the oscillator pulse train are selected using a Pockels cell and directed along different paths to become either signal or pump. The amplified pulse can then be frequency doubled to pump OPAs. Since the signal pulse can be picked from the oscillator pulse train, the maximum optical path difference that needs
compensating is the half the pulse spacing. (e.g. a 70 MHz pulse train corresponds to a pulse spacing of \(\sim 12.5\) ns. Since there is freedom in choosing a seed to amplify, a maximum of \(\sim 2\) m of path length would be required). Such a scheme has shown to have negligible jitter even on a femtosecond timescale \([141, 69]\) and is ideally suited to our requirements.

Along with jitter, long term drift of pump-seed timing is also a concern for OPAs employing a short pulse pump which need to operate reliably for long durations during experimental campaigns. Since the oscillator now acts as an optical delay line, it is important to stringently control its parameters such as temperature and cavity length to prevent drift. Locking the repetition rate (equivalent to fixing the cavity length) is important to prevent temporal slipping between the pump and the signal pulses. For example, if there is a change in oscillator repetition rate of 1 Hz out of 70 MHz, then, the corresponding time between two consecutive pulses (\(\Delta t_{pt}\)) changes by

\[
\Delta t_{pt} = \frac{1}{7 \times 10^6} \pm \frac{1}{7 \times 10^6} \pm 1 = \pm 200\text{ as}
\]  

(2.20)

Since the pulse for the seed is not the next pulse in the train but typically the 40th (to allow sufficient time for pump pulse amplification), the actual increase is \(\sim 8\) fs, which is negligible given the typical durations of pump and signal pulses even in short pulse OPAs. However, a relatively minor cavity drift of hundreds of Hertz will result in picosecond level drift which is a substantial fraction of the pump pulse duration on Cerberus. Controlling the oscillator temperature is also an essential component of controlling cavity length as temperature changes result in the expansion of metals. A closed loop temperature control system is installed on the Cerberus oscillator and is able to main temperature at a constant \(26 \pm 0.2^\circ\) (see figure 2.19).

Figure 2.18 shows the schematic of the closed loop control implemented on Cerberus oscillator. The frequency of the oscillator is measured using a frequency counter (Stanford Research Systems (SRS) SR-400 which is referenced to a 10 MHz clock signal from a SRS DG645 digital delay generator), and any changes are compensated for by adjusting the cavity length using a piezo actuated mirror inside the cavity. The
Figure 2.18: Diagram of the closed loop feedback system for the Cerberus oscillator. Yellow regions correspond to heating pads which are used to maintain oscillator temperature. AM - Actuated Mirror to control cavity length. PD - Photodiode. TM - thermometer.

Figure 2.19: Control systems for the Cerberus oscillator. Left) Variation of oscillator frequency with and without temperature control. Right) Oscillator frequency offset with control loop enabled. The gap in the frequency offset data is due to a system restart.

temperature is similarly measured and maintained using heating pads stuck on to the oscillator breadboard. The results of this control are shown in figure 2.19 where we see that the system is able to maintain the oscillator to set a frequency with an accuracy of 0.38 Hz over time periods of 2 hours. Whilst the frequency can be locked independently of temperature control, it was noticed that the use of temperature control was able to maintain the frequency offset within a range in which it could be more easily compensated for by the limited range piezo stage. Since the oscillator is rigorously controlled, the major source of drift is likely to come from expansion of beam paths for the pump and signal.
2.4 Laser Diagnostics

Implementation and optimisation of laser setups requires accurate measurements to be made of the pulse duration and beam quality throughout the laser system. Misalignment of the laser beam on optics can result in geometric aberrations which can translate into poor recompression and contrast. This section introduces some of the techniques used in the next chapter to implement and characterise the laser system.

2.4.1 Pulse Measurement

Pulse duration is a critical parameter for any laser system as it has a very direct impact on the peak achievable intensity. Although the energy in a laser pulse is rather straightforward to measure using a calorimeter, pulse duration measurements for ultrashort laser pulses can be significantly more complicated. It is much easier to measure a distance travelled at the speed of light in a time duration equal to the laser pulse. For a 250 fs laser pulse, this is equal to $75 \, \mu m$ which is easily measured using motorised translation stages. The rise-times of fast diode detectors is limited by finite capacitance to $\sim 50 \, ps$ which is orders of magnitude longer than short pulse lasers (typically sub-ps). State of the art high-speed detectors (such as Newport model 1400 series) are able to achieve rise times of $\leq 20 \, ps$ but these require the use of oscilloscopes with 50 GHz of bandwidth which are prohibitively expensive. For lasers pulses of the order of nanoseconds from Q-switched YAG lasers or stretched pulses from a stretcher, fast diode measurements can resolve the temporal profile and are routinely referenced to in this thesis (see figure 2.20). The rise time of such diodes is limited by their finite capacitance. For pulses duration in the 5-1000 ps range, streak cameras are a useful way to measure pulse durations, although they are extremely expensive compared to the other methods described. Even shorter pulses require the use of self-referencing techniques which involve splitting the pulse into two and measuring it against itself. Numerous methods have been developed over the years for accurate measurements of ultrashort laser pulses. These include simple autocorrelation methods [149] or more sophisticated time-frequency techniques such
as FROG [144] or SPIDER [67].

Figure 2.20: Typical measurement from a fast 6 GHz Bandwidth, 50 ps rise time diode detector from Newport. The stretched pulse duration from a stretcher is measured. The double peak corresponds to a real spectral modulation which is visible in the time domain measurement. Measured using a Newport Model 1437 photoreceiver and 50 Gigasamples/s Tektronix oscilloscope

**Autocorrelation**

Autocorrelation is a well established method of measuring pulse durations of ultrashort laser pulses. A diagram of a scanning second order autocorrelation is shown in figure 2.21 and is based on the Michelson interferometer. In this scheme, an input laser pulse is split into two identical replicas using a thin pellicle beamsplitter. The reference arm is at a fixed delay and the scanning arm is used to interfere the replica with the reference pulse as a function of variable delay. The combined signal can be focused on to a nonlinear detector so the measured signal is proportional to the square of the instantaneous intensity. The detector can be a nonlinear crystal such as BBO with a spectral acceptance which is wider than the input bandwidth or a two photon sensitive diode [117]. A cheap light emitting diode (LED) can be used in reverse bias as a nonlinear two-photon detector because the band gap energy is typically in the visible part of the spectrum. This makes it insensitive to single lower energy IR photons. When two pulses are spatially and temporally overlapped on the
diode, the photon flux is high enough to excite an electron in the conduction band via a two-photon process. This creates a voltage signal which can be monitored with a standard oscilloscope. The type of signal measured depends on the speed on the detector, a slow detector will average the interference fringes and only be sensitive to the envelope (Intensity autocorrelation) whereas a fast detector can resolve the fringes (Interferometric autocorrelation). The fringe resolved signal can potentially reveal information about spectral phase through the use of an iterative algorithm [120] but this was not performed during this project. For short pulse oscillators producing pulse trains at tens of megahertz, autocorrelation is an effective way to measure the pulse duration, though it requires an assumption to be made about the pulse shape. For amplified pulses which typically run at much lower repetition rates, a scanning technique is no longer possible and single-shot version based on non-collinear overlap in a nonlinear crystal can be used (figure 2.21).

![Diagram of a scanning autocorrelator](image)

Figure 2.21: Left) Diagram of a scanning autocorrelator; SHG = Second harmonic generation crystal; SM = Spherical mirror; BS = Beam splitter. Right) Geometry of non-collinear overlap in a nonlinear crystal used in a single shot autocorrelator.

The measured signal from the second order collinear autocorrelation can expressed as

\[
I_{ac}^{(2)}(t) \propto \int_{-\infty}^{\infty} ((E(t) + E(t + \tau))^2)^2 dt
\]  

(2.21)

As mentioned already, the type of signal obtained also depends on the detector.
An intensity autocorrelation in a collinear geometry is characterised by a peak to background ratio of 3:1 while an interferometric autocorrelation has a centre to background ratio of 8:1. These relative ratios are a good indicator of the alignment of the system. For bandwidth limited pulses, there is a simple relationship between the FWHM of the measured autocorrelation and the FWHM of the input pulse. For intensity autocorrelations, the factors are

\[ \Delta t_{\text{gauss}} = \frac{\Delta t_{\text{intac}}}{1.411} \]  

(2.22)

\[ \Delta t_{\text{sech}^2} = \frac{\Delta t_{\text{intac}}}{1.543} \]  

(2.23)

where \( \Delta t_{\text{intac}} \) is the FWHM of the intensity autocorrelation and the subscripts gauss and \( \text{sech}^2 \) are assumed pulse shapes. For interferometric autocorrelations the corresponding factors are

\[ \Delta t_{\text{gauss}} = \frac{\Delta t_{\text{infac}}}{1.693} \]  

(2.24)

\[ \Delta t_{\text{sech}^2} = \frac{\Delta t_{\text{infac}}}{1.896} \]  

(2.25)

where \( \Delta t_{\text{infac}} \) is the FWHM of the interferometric autocorrelation. Figure 2.22 shows the envelopes of an interferometric autocorrelation of a input pulse with a \( \text{sech}^2 \) profile. The envelopes of the autocorrelation are shown in red and blue and the FWHM is defined at a normalised intensity of 4. Since the autocorrelation function is symmetric in time, it is not possible to ascertain whether the observed features are before or after the main pulse. This makes the diagnostic insufficient for measurements involving pulse contrast where pre-pulse is typically of much more concern than a post-pulse. Additionally, it is also necessary to assume a pulse shape in the calculations. For typical pulse parameters of the Nd:Glass based laser described in this thesis, the accuracy of this measurement is enough as the assumed pulse shapes are realistic.

For the single-shot geometry shown in figure 2.21, the measured FWHM spatial width of the signal on the detector (\( \Delta x \)) can be related to the FWHM temporal width.
(\(\Delta t\)) of the pulses by the equation

\[ \Delta t = \frac{\gamma \Delta x \sin (\theta/2)}{c} \]  

(2.26)

where \(\gamma\) is a pulse shape dependent factor as defined for the intensity autocorrelations and \(\theta\) is the angle between the pulses (defined as per figure 2.21). It should be noted that non-collinear measurements are background free and the signal contrast is limited by scattering of second harmonic light in the crystal.

![Graph showing the profile of a 250 fs sech^2 laser pulse (black) and the envelopes of the interferometric autocorrelation of the pulse (blue and red). The relationship between the FWHM of the pulse and width of the autocorrelation is established.](image)

**Figure 2.22**: Graph showing the profile of a 250 fs \(\text{sech}^2\) laser pulse (black) and the envelopes of the interferometric autocorrelation of the pulse (blue and red). The relationship between the FWHM of the pulse and width of the autocorrelation is established.

**Contrast Measurements**

The second order autocorrelation described above is capable of giving a useful pulse duration measurement, however, for many experiments which involve interactions with solids targets or clustered gas sources, intensity contrast is an important property of the laser beam. It is possible to get a background free measurement of the pulse by adapting the autocorrelator to a non-collinear geometry and careful imaging of the crystal. A measurement dynamic range of 8 orders of magnitude has been demonstrated using such methods [21]. This still does not resolve the inherent limi-
tations of the second order autocorrelation measurements which is a need to assume a pulse shape. Although, it should be noted it is possible to break the ambiguity in time by adding chirp to one arm of the interferometer. The experiments described above are particularly sensitive to pre-pulses compared to post-pulses. The solution to this problem is to use a third-order autocorrelation with a high dynamic range detection system. This can be achieved by mixing the fundamental of the laser pulse with its second harmonic in an appropriate crystal (such as BBO) to produce a signal which is the third harmonic of the laser. The use of laser line filters and calibrated attenuators can reduce background to a negligible amount and improve the detection dynamic range of the system to $> 10^8$. Such a setup is described in detail in [82]. Unfortunately, no data with amplified pulses was obtained hence the system is not described in detail.

2.4.2 Beam Profiles

Measurements of the spatial profile of the beam are an important diagnostic tool for setting up a laser system. Traditionally, photographic paper (such as Kodak Linograph 1894) was used to take 'burns' of the laser beam profile during alignment. This has the disadvantage of being single use and having a nonlinear response to beam energy. Nevertheless, it is a useful way to visualise clipping and hot-spots in the profile. Modern systems based on CCD technology are capable of delivering high resolution beam profiles ($\sim \mu m$ resolution) along with a high dynamic range (16 bit) to visualise energy distribution in the beam. The WinCamD system from Dataray Inc. was extensively used on the Cerberus laser system for alignment and setup. Through the use of appropriate down-collimation optics and attenuation, centimetre sized beam could be imaged in realtime and optimised. The sensor is also capable operating in a wide wavelength band (350 to 1150 nm) which allows it to be used for checking spatial overlap of OPA pump and signal beams.

A far-field monitor is a simple technique used to image the focal spot of the laser beam. It is called a far-field monitor as the incoming collimated laser beam has parallel rays and is effectively an image of a far away source (figure 2.24). To
Figure 2.23: Beam profile of a laser taken using the WinCamD camera. The clipping in the outer regions of the laser would typically be hard to visualise on a low dynamic range detector (typically 8 bit) used in many commercial CCDs.

perform this measurement, the laser beam is focused using a lens and the focal spot is imaged onto a CCD detector using a high magnification microscope (typically 40×) objective lens. The size of the focal spot can be measured by placing a wire or grid of known dimensions in the focal spot, thus allowing the exact magnification to be determined. A measurement of the focal spot is a useful way to check the alignment of the laser beam and also to calculate the peak intensity of the laser pulse. Assuming that the far-field measurement optics have a negligible effect on the beam, any aberrations in the laser beam will be evident in the quality of the focal spot. For example, spatial chirp is a common problem due to misalignment of the stretcher or compressor and would result in a focal spot which is elongated in the dispersion direction. By monitoring the the spot quality in realtime, small tweaks can be made to alignment the system to rectify problems.

Summary

This chapter provides the theoretical background for the laser technology and modelling tools used during the building of the Cerberus laser system. A brief introduction to nonlinear optics is provided along with methods used to generate ultrashort light
The optical synchronisation setup used to maintain pump-signal overlap is explained along with results of the oscillator stabilisation system. Diagnostics tools which are essential to measure ultrashort light pulses such as autocorrelation as discussed.
Chapter 3

Design and Implementation of an OPCPA Nd:Glass Laser

This chapter describes the modelling and implementation of the Cerberus laser system. As mentioned in the introductory chapter, this large laser system is hosted in three separate labs and utilises a two-stage optically synchronised OPCPA front end. The modelling for the CPA systems of the short pulse beam and its OPA pump laser were performed by the author using a 3D ray-tracing code called CPTrace3D which is described in chapter 2. Due to the large cost of pulse compression gratings, it was imperative to maximise the performance of affordable optics. Quotes were obtained for sensibly sized gold gratings from Jobin Yvon and for dielectric gratings from Plymouth Grating Laboratory and their performance was simulated using CPTrace3D. Despite their higher cost per unit area, the higher damage threshold of dielectric gratings offer better value per 'joule of energy compressed'. Initial component size estimates were based on prior experiences of CPA setups and were used as a starting point for simulations. Due to cost overruns, certain components could not be purchased and compromises were made by purchasing readily available gold gratings for the pump laser and reducing the dimensions of the primary compressor gratings.

A detailed description of the laser amplifiers used is also provided in this chapter. Given the size of the laser system, every single optical component is not described, instead, the system is split into large functional components to maintain clarity. The
implementation of the stretchers and compressors was done primarily by the author, while the amplifiers in the pump section were worked on by Prof. R. Smith and the short pulse OPAs were implemented by Dr. D. Bigourd. The power amplifiers and the Thomson beamline were worked on by the author and the latter is described in the next chapter as it is an independent system.

Whilst at this present time, the system is by no means complete, measurements obtained from the implementation of the amplifiers, the stretchers/compressors and the OPAs are included in this chapter. As of writing of this thesis, the short pulse arm is still in development while the long pulse section is being commissioned for x-ray imaging experiments on MAGPIE. Since the system configuration changes frequently for testing, the aim of this chapter is to represent a snapshot of it and explain the settings used for the initial results.

3.1 Modelling and Design Parameters for the CPA System

Figure 3.1: Simplified block diagram of the Cerberus OPCPA setup. The primary short pulse beam consists of two OPA amplifiers stages along with flashlamp pumped power amplifiers. The pumps for the OPA system are derived from a common oscillator and require a separate CPA system for its amplifiers. Red arrows correspond to $1\omega$ laser wavelength and green arrows $2\omega$. SHG - Second Harmonic Generation.

A functional block diagram of the Cerberus front end is shown in figure 3.1 and consists of a total of six stretcher and compressor sections. It should be noted that
the design of some of the stretchers is actually a geometry more usually used in a
compressor. These will be referred to as stretchers during the thesis as their ac-
tion is to increase the pulse duration rather than reduce it. The main short pulse
beamline which is designed for laser driven proton probing on MAGPIE, consists of
two stretchers and one final compressor. Additionally, the long pulse beamline which
is derived from the same oscillator, also contains two stretchers and a compressor.
This section of Cerberus will be 'dual use' in that it can be simultaneously used for
pumping OPA stages. In this scheme, a fraction of the pump pulse energy will be
compressed for pumping OPAs (these will be referred to as short pulse OPAs) and the
remainder will be stretched once more for further amplification. This will again be
split to pump OPAs (long pulse OPAs) and seed power amplifiers to provide a \( \sim \) ns
pulse for x-ray backlighting and other long pulse experiments. Whilst this combined
setup is complicated, it offers the advantage of optical synchronisation for the OPAs
and the ability to have simultaneous short and long pulse beamlines which are locked
to a common oscillator. This is useful in the context of triggering the laser system
relative to MAGPIE and also saves on the cost of additional components by reusing
the same amplifiers.

Simulating the entire laser system including the amplifiers was not possible as
a code which integrates all the relevant physics was not available. As a results the
amplifiers (primarily OPA stage) and dispersive optics were treated independently.
Each CPA component (i.e. stretcher or compressor) was modelled to maximise the
performance of affordable components. For the short pulse section, it was decided to
use custom made dielectric gratings for their higher efficiency and damage threshold.
Contrast and clipping was more of a concern here than on the long pulse beamline
where attaining necessary stretched pulse durations for maximum energy extraction
was pertinent. The following section describes the modelling parameters for each
CPA section.
3.1.1 Short Pulse CPA

The short pulse OPA setup described in C.Dorrer et al [44] did not use a stretcher on the signal beam (200 fs seed pulse). This has the disadvantage of reducing the energy overlap with pump which was estimated at 6 ps in their setup. Consequently, the energy extracted was limited to 100 $\mu$J. For the Cerberus short pulse setup, simulations done in [133] have shown small improvements can be made in gain bandwidth by the use of a chirped signal with a pulse duration of 900 fs. Stretching the signal also lowers the B-integral for subsequent optics which is an important factor for contrast in CPA system.

The original specification for this stretcher was to accommodate a Liquid Crystal Spatial Light Modulator (LC-SLM) into a 4$f$-stretcher system which would allow active control over the stretched pulse duration with flexibility to work in zero dispersion mode if required. The 4$f$ stretcher consists of two gratings and two lens with focal length $f$ with the distance between each optical component set to $f$. Such a configuration contains a Fourier plane at the 2$f$ position where frequency components are arranged linearly in the dispersion plane. By placing a SLM at this position, additional optical path can be added to different frequency components which can be used to compensate for residual phase terms through the laser chain and can potentially be used to improve the compressed pulse durations [10].

Unfortunately, the dielectric gratings purchased for this setup were found to suffer from imperfections such as ghosts, hence the planned 4$f$ setup was not implemented in this way due to concerns regarding contrast and compressibility. It was replaced with a simpler two-grating delay line. Figure 3.2 shows a diagram of this setup. Holographic gratings with a ruling density of 600 lines/mm were used to obtain stretch factors between 3 and 4. Given the small stretch factor required, the grating separation is small and the size of the gratings is 50 mm $\times$ 50 mm. The grating separation was chosen to give optimum pulse duration for the subsequent OPA stages and the size of optical components was chosen to ensure a very wide spectral bandpass. The simulated output spectrum from a raytrace of the stretcher is shown in figure 3.3 and
extends over a bandwidth which is substantially wider than of the Nd:Glass oscillator. The stretched pulse durations are also included in the same figure. This stretcher has now been replaced with a solid high dispersion glass block (SF6) which is multi-passed to give an effective path length of \(~ 1\) m. The monolithic glass block is more stable and offers better spatial beam quality compared to the gratings. It should be noted that the OPA results shown in the latter part of this chapter were obtained with the grating stretcher.

![Figure 3.2: Schematic of the stretcher used for the short pulse OPA section. It is based on the two-grating delay line. A parallel geometry is achieved by using a prism mirror to retro reflect the beam through the system at a different height.](image)

Figure 3.3: Simulations for the first grating stretcher. Left) Simulated stretched pulse duration after a double pass of the stretcher described in figure 3.2. Right) Output spectrum on a logarithmic scale.

![Figure 3.3: Simulations for the first grating stretcher. Left) Simulated stretched pulse duration after a double pass of the stretcher described in figure 3.2. Right) Output spectrum on a logarithmic scale.](image)
Primary Short Pulse Stretcher

The main stretcher on the short pulse section is based on a reflective doublet system which was originally designed by Mike Mason for use with a 800 nm Ti:Sapphire laser and is described in detail in [91]. The original gold coated mirrors were refurbished and a new dielectric grating was added to build this stretcher. The original specifications for this stretcher allowed for faithful compression of Ti:Sapphire laser pulses down to 30 fs. To achieve such short compressed pulses, the stretcher is carefully designed around a high degree of aberration compensation through the use of all reflective optics and symmetry. Figure 3.4 shows a representation of the stretcher along with the optical path. Although the stretcher is arranged similar to an Offner triplet configuration which is commonly utilised for ultrashort pulses [32], it is effectively a reflective version of the standard Martinez design. The Offner design is only aberration free at the null stretch position for the grating whereas this reflective doublet design has been optimised for the grating in the dispersive position. The concave and convex mirrors form an aberration compensated doublet with the flat mirror acting to fold the system about its axis. These mirrors were refurbished to > λ/30 (at 1054 nm) flatness to minimise random phase errors.

The focal lengths of the optics and their relative positions have been optimised by Mike Mason to give a flat residual phase profile after compression. Although this was an excellent starting point to design the stretcher, the critical parameters such as the grating separation were already fixed. In a double pass configuration, the effective grating separation of this stretcher is \( \sim 1142 \) mm. For a 250 fs sech\(^2\) pulses from the oscillator, this would correspond to a stretched pulse duration of only \( \sim 434 \) ps (calculated for grating with a ruling density of 1740 l/mm and a grating angle of 77°). This is below the target requirement of 1 ns and would result in a high B-integral value during amplification. To remedy this, a quad pass design with double the dispersion was proposed. Although such a design adds substantial complexity in terms of alignment and additional energy loss, it also offers a few advantages. By spreading the total required dispersion over two identical passes, the spectral
clipping is reduced compared to an equivalent double pass design with twice the effective grating separation. This means quad pass designs in general offer better contrast compared to double pass ones. Additionally, it is also possible to invert the face of the beam such that any asymmetric aberrations are applied inversely across the spatial profile of the beam on the second pass, giving some degree of cancellation. This is not possible with a double pass design as inverting the spatially chirped beam on the double pass would change the path lengths of the various spectral components through the system.

Figure 3.4: Visualisation of the reflective doublet stretcher with relative positions of the main components. The injection and inversion optics are not shown.

The main component of this stretcher which has changed from the original design is the grating. Although the position of the grating relative to the optics is set from the original stretcher design, the angle is a free parameter, and therefore offers some control over the stretched pulse duration. Since a quad pass design was required, there was no need to realise the full dispersion in double pass. A steeper grating angle also reduces the spatial clipping of spectral components and improves contrast. Figure 3.5a shows the intensity profiles of the compressed pulses on a log scale for a limited range of candidate angles (simulations used an infinite sized compressor so that stretcher performance can be evaluated). They indicate good contrast for all angles with steeper angles being approximately a factor of two better in the wings of the pulse. As a compromise between contrast and stretched pulse duration, $77^\circ$ was chosen as the grating angle. This angle is also physically feasible for this system.
in that it is possible to inject and extract beams without being obstructed by the large mirror mounts demanded for the major optical components. It should be noted that simulations performed by Alaistair Moore on a previous Nd:Glass laser system had also indicated that the angle range between 76° and 78° offers the best contrast and pulse quality [96]. For the given grating parameters and a quad pass geometry, the stretched pulse duration can be calculated as \( \sim 870 \text{ ps} \). This assumes a nominal input bandwidth of 4.66 nm which is actually below the specifications of the Nd:Glass oscillator. The actual stretched pulse duration is likely to exceed a nanosecond if the input bandwidth is larger. In addition to the angle, the size of the grating is a critical factor which sets the amount of spectral clipping. Wider gratings always offer better performance and component costs is usually a deciding factor. Hence, only ‘affordable’ grating sizes were simulated. Figure 3.5b shows the intensity contrast as a function of grating size with a grating angle of 77°. As expected, the wider gratings perform better but the 175 mm wide gratings is almost a factor of two better than the 150 mm one. The ‘ringing’ visible in the wings of the pulse originates from the ‘hard’ spectral clip in the stretcher. This can be mitigated by using larger diameter beams but this requires the use of larger optics which were not available for this project. A similar stretcher configuration deployed on the Vulcan Petawatt laser at the Rutherford Appleton Laboratory (RAL) uses 3 cm beams and two Offner stretcher stacked on top of each other to obtain the required dispersion [37]. The height of the grating does not affect the clipping performance, although this stretcher design needs a tall grating as only the top and bottom areas are used. The 175 \times 75 \text{ mm} grating was chosen as the best compromise between price and performance. The diffraction efficiency for the dielectric gratings would be optimised for an angle of 77° by the manufacturer (Plymouth Grating Laboratory).

The final specification diagram of the reflective doublet stretcher is shown in figure 3.6 along with the distances between the important optics. The beam is injected off-axis at a height of 25 mm above the axis of system at a height of 17.5 cm off the optics table. The combination of the concave and convex mirrors act to focus the beam on to the flat mirror where a Fourier plane exists. The returning beam goes through
Figure 3.5: CPTrace3D simulations of the reflective doublet stretcher. Top) Contrast as a function of angle for a given grating size. Bottom) Contrast as a function of grating size at an angle of 77°. Note that only the leading edge of the pulse profiles are plotted as they are symmetric in time. These pulses were compressed with an extra large grating size compressor to isolate stretcher performance.
the bottom half of the stretcher which is symmetric with the top (at a height of 12.5 cm). A prism mirror is used to double pass the stretcher with such that the returning beam is offset from the input beam by more than the beam diameter. This allows a cut mirror to pick-off the beam for the image inversion and quad pass re-injection. A F/100 lens is used to focus the beam onto a zero degree mirror which acts to invert the face of the beam before re-injecting back into the stretcher. A Faraday isolation stage is used to separate the quad pass output of the stretcher from the input beam. Additionally, to reduce the B-integral through the Faraday rotator, up and down collimation optics are used on either side to maximise the 8 mm clear aperture.

Figure 3.6: Final specifications of the reflective doublet stretcher as view from above. M1 - 200 mm diameter concave mirror with 1175 mm radius of curvature. M2 - convex mirror with - 1000 mm radius of curvature (135 mm × 30 mm). M3 - flat folding mirror (120 mm × 30 mm).

**Primary Short Pulse Compressor**

Once the stretcher is specified, designing a two-grating compressor to match it is straightforward. The angle and the separation between the gratings is fixed as per the stretcher. As with the stretcher, a range of affordable grating sizes were available for purchase. Simulations were carried out the designed stretcher so that a realistic representation of the final compressed pulse could be obtained.

An important parameter for the compressor is the beam size which has direct
consequences on compressible energy and also spectra clipping. Due to the choice of dielectric gratings with higher damage threshold rather than gold, it is possible to compress more energy in a given beam diameter for greater peak powers. Since compressor setup does not operate at normal incidence, the projected beam area on the grating is larger by a factor of cosine of the grating angle. For example, with a 40 mm beam diameter, the total projected area on the grating is $\sim 55 \text{ cm}^2$. If a safe and conservative value of the grating damage threshold is used (1 $\text{ J cm}^{-2}$ (500 fs)), then the maximum incident energy can be $\sim 55 \text{ J}$ (In reality, input pulse is a nanosecond long and the damage threshold at this pulse duration will be higher. the actual limit is on the final bounce off the grating where the intensity is the greatest). With an assumed grating efficiency of 95% (a guaranteed value by the manufacturer), the compressor will be capable of a throughput energy of $> 44 \text{ J}$ in a pulse duration of the order of 0.5 ps, resulting a peak power of 88 TW. If this were to be focused into a modest spot size with FWHM of 30 $\mu$m then a peak intensity exceeding $10^{18} \text{ W cm}^{-2}$ will be achieved. Ion acceleration experiments performed on similar specification laser systems [27, 153] has indicated that protons with energies of 3 - 5 MeV can be
achieved. This would be sufficient to begin the commissioning of a proton imaging diagnostic.

The amplified input pulse to the compressor is likely to have less bandwidth than the original oscillator pulse. Despite the use of OPAs as pre-amplifiers, gain narrowing and clipping is expected. Hence a design point value of 500 fs (3.5 nm FWHM bandwidth) was used for the compressor simulations. This value is typical of many large scale Nd:Glass CPA systems [39, 95]. Figure 3.8 shows simulations of the compressor grating sizes against different beam diameters. It is clear from the graph that larger beam diameters result in additional clipping and consequently, worse pulse durations for a finite size compressor. Although larger beam areas would allow more energy to be compressed, there is a trade-off with contrast. The example shown above indicates that even smaller beams can deliver pulses with sufficient power to perform the experiment. Due to financial considerations, the 285 mm $\times$ 140 mm gratings were purchased for use in the compressor along with an 8” diameter zero degree mirror to double pass the system.

The planned layout of the compressor is shown in figure 3.9. The input beam to the compressor is injected at a small angle upwards so that path through the compressor is slightly tilted, this allows the output beam to be spatially separated from the input beam. This angle (0.25°) is not expected to affect performance. At the input to the compressor, a Faraday isolation stage will be used to protect the amplifiers from light reflected back from the target. This is particularly crucial as experiments are planned at the fundamental wavelength and the duration of gain in the Nd:Glass power amplifiers can extend for hundreds of microseconds after the laser pulse has passed. The compressor will be located directly adjacent to the MAGPIE target area to reduce the propagation length for the short pulse beam. The compressed pulse will have very high intensity and to maintain spatial profile during propagation, helium filled pipes will be used to the target chamber due to the high ionisation threshold of helium. MAGPIE shots typically produce a large amount of debris, as a result it is not planned to connect the compressor to the target chamber via vacuum pipes so that optics can be isolated.
Figure 3.8: Compressed pulse durations as a function of grating size and beam diameter (flat top spatial profile) for 500 fs transform limited input pulses.

Figure 3.10 shows the final expected pulse profile from the short pulse section. This simulation uses known optical dimensions and flatness values along with a flat-top beam diameter of 40 mm for the compressor. The effect of the small stretcher and additional optics in the beam path is not included. The effect of the surface flatness of optical components on the pulse profile is included using the relevant options in the CPTrace3D code. The results show that the contrast ratio with realistic optical flatness is expected to be $10^5$ around the 10 picosecond window. The use of short pulse OPAs is likely to push this value much higher.
3.1.2 OPA Pump CPA System

The issues of contrast and clipping were secondary considerations on the long pulse section of Cerberus as it was designed to pump OPA crystals. The planned experimental outlook on the long pulse beamline is not particularly affected by contrast either. The amplifiers in the pump section are based on Nd:YLF which has a significantly lower bandwidth compared to the Nd:Glass based oscillator. Therefore, the optics sizes for the OPA pump stretcher and compressor were chosen with a reduced spectral bandpass which is sufficient for Nd:YLF. The calculations and simulations shown below are performed at a central wavelength of 1053 nm rather than 1054 nm to match the gain profile of Nd:YLF.

OPA Pump Stretcher

The output pulses from the master oscillator which are designated for the pump section are stretched in a single grating folded Martinez-style stretcher. Figure 3.11 show a simplified diagram of the setup. This was designed using easily available components to give as large a stretch factor as possible in a compact, stable setup.
This was achieved through the use of a quad pass design which effectively doubles the dispersion. The grating is set at a shallow angle of 70.23° which is limited by the width of the doublet lens. The diffracted beam is focused using a 2” diameter 1 m focal length achromatic doublet lens to a zero degree folding mirror. The Fourier plane of this stretcher lies on the mirror itself, nevertheless, a spatial mask assembly is installed slightly in front of the mirror to modulate the seed spectrum for the Nd:YLF amplifiers. This is described in more detail in the amplification section. A cut mirror is used to pick the beam off after the double pass so that it can be injected back upon itself for an additional double pass. A F/100 lens is used to focus the double passed beam onto a zero degree mirror so that the face of the beam can be inverted spatially before re-injection into the stretcher. Analogous to the reflective doublet stretcher described above, this has the effect of evening out asymmetric abberations in the stretcher. The output of the stretcher returns directly along the input path and a Faraday isolation stage and polariser is used to separate the returning beam for injection into the amplifier chain.

The effective grating separation for this stretcher is $\sim 2.8$ m. The large bandwidth
of the Nd:Glass oscillator clips heavily in this stretcher, however, as long as output spectral width is greater than the gain bandwidth of Nd:YLF (1.3 nm FWHM), the amplifiers can be successfully seeded. Figure 3.12 shows the output time domain profile of a 2 ps Gaussian input pulse after the stretcher. This pulse has a bandwidth of 0.8 nm which is typically larger than that achieved by Nd:YLF oscillators and represents a design point value. The pulse duration out of the stretcher is thus effectively only over this 0.8 nm bandwidth, and is calculated as 240 ps which is sufficient to avoid damage by nonlinear effects in the planned amplification stages.

**OPA Pump Compressor**

As shown in figure 3.1, the amplified output of the pump section is split into two beamlines, for both, compression and further stretching. Compressing the pump pulses would reduce their duration down to the few ps level and as has been shown in here [44], this reduces the parametric fluorescence of the first two OPAs to a narrow time window around the signal. Simulations were performed of this compressor to ascertain the ideal grating dimensions. For the sake of simplicity and lower costs, a single grating folded compressor geometry was used. The system is specified to allow
faithful compression of the amplified Nd:YLF bandwidth. A design point value of 0.8 nm (2 ps Gaussian pulse equivalent) was used as per the stretcher. Since gain narrowing in the amplifiers is expected to be significant, this value is likely to be much larger than in reality and thus, a good upper estimate. The parameters of this

Figure 3.12: Simulated stretched pulse duration from the OPCPA pump stretcher as calculated for the design shown in figure 3.11.

Figure 3.13: Diagram of the folded OPA pump compressor. The dashed line indicates effective grating separation.

compressor have been setup to provide equal and opposite chirp to compress pulses from the stretcher shown in figure 3.11. The original design plan for this was to use
a high efficiency dielectric grating. Due to the choice of grating angle (77°) made for the short pulse section, all the dielectric gratings from the manufacturer were to be optimised (for diffraction efficiency) at this angle as a part of a bulk order. As a result the compressor was designed around a grating angle of 77° instead of the stretcher angle. Whilst mis-matched angles can affect compressed pulse quality, simulations showed that this effect would be small and negligible within the time window of the signal. For OPA pumping, the compressed output would also be frequency doubled which will further improve contrast. Additionally, as long as the pump profile is smooth over the temporal duration of the signal, there should be no modulation of the chirped signal’s spectrum. It should be noted that the dielectric grating was not implemented for financial reasons and a holographically ruled gold grating with 1740 l/mm (140 mm × 50 mm) was used in the configuration as per the diagram.

Figure 3.14: Contrast as a function of grating size for the OPA pump compressor. A wider grating is able to support a greater spectral bandwidth. This additional bandwidth translates into better contrast in the time domain. The pulse in this simulation was stretched using stretcher parameters shown in figure 3.11. Note that the curve for the 140 × 100 mm grating is exactly overlapped on the curve for the 140 × 50 mm grating. This is because the performance is not dependent on vertical extent of the grating.

Figure 3.14 shows a logarithmic intensity plot of the compressed OPA pump pulses using the design shown above. The grating separation has been increased to compensate for the grating angle mis-match with the stretcher. It should be noted that the
expected FWHM pulse durations from the different size gratings were approximately the same (∼2 ps) given the required performance. The simulations show that the contrast improves by two orders of magnitude for an additional 20 mm of grating width and is acceptable on all available gratings. The 140 × 50 mm grating was chosen for the final specification as it is easier to implement the folded single grating configuration with a wider grating. In this setup, the input beam is injected off a D-cut mirror on to the far edge of the grating. This allows the diffracted beam to be reflected back on to the centre of the grating when at its widest. To maintain the spectral components in the correct orientation for a compressor, a prism mirror is used to fold the compressor. This is mounted a long translation stage to facilitate scanning of the optimum grating separation. The diffracted beam is again doubled passed using a second prism mirror which translates the beam vertically such that the output beam passes over the cut injection mirror. This prism mirror is also mounted on a translation stage which allows the grating position to be scanned whilst keeping the total optical path length in the compressor constant. This is important for maintaining temporal overlap with the OPA stages.

**Long Pulse OPA pump/X-ray Backlighter Stretcher**

The remainder of the pump beam is stretched again so it can be further amplified for use as a pump for the long pulse OPAs and a seed for x-ray backlighter beamline. Although this additional stretch factor could have been incorporated into the first stretcher, the actual implementation would have required custom focal length optics and a physically large design, together with a much larger OPA pump compressor. The input pulses for this stretcher were approximated ∼80 ps long due to gain narrowing in the Nd:YLF amplifiers. However, their bandwidth was only 0.4 nm. Since the stretched pulse duration is linearly proportional to the bandwidth, obtaining a large stretch factor to the nanosecond level is difficult. Although a positive dispersion stretcher would have been advantageous given the sign of the dispersion on the input pulse, this would have required custom made long focal length lenses. A twograting Treacy-style compressor geometry does not contain any focusing optics and
would have been simpler to implement. It should be noted that since there is no requirement to recompress this stretched pulse, the sign of dispersion is not important, simply its magnitude.

Figure 3.15 shows the parameter space for the stretched pulse duration as function of bandwidth and grating angle for a fixed grating separation (set to a large value of 6 m which is limited by the dimensions of the optical tables). The graph shows that shallower grating angles disperses the pulse more which results in a longer stretched pulse duration. Using the equation for the stretched pulse duration from 2.17, the physical limitations on grating separation and required pulse duration, the angle which best satisfies the constraints was determined to be \( \sim 59^\circ \). Since this pulse is not intended to be compressed, spectral clipping and contrast were not simulated. Although it would have been possible to quad pass this design to make the system more compact, a range of issues were encountered with the beam quality during the implementation which resulted in a simpler double pass design being implemented. This is discussed further in the next section.

![Figure 3.15: Stretched pulse duration of the long pulse OPA pump as a function of angle and bandwidth for a given grating separation (6 m). It should be noted that only the allowed diffraction angles as per the grating equation are included.](image)

Since the gratings used for this stretcher were procured from an old Nd:Glass laser
system, simulations were not performed to assess component sizes. Two \(140 \times 120\) mm gold gratings (Jobin Yvon) were available for this stretcher. The geometry of this setup is similar to the compressor shown in figure 3.11 apart from the use of two discrete gratings which are placed in parallel, adjacent to each other. It should be noted that due to mounting restrictions, it was not possible to tile the gratings to make a single effective grating. The setup has been folded this way to accommodate the large inter-grating separation (\(\sim 5.6\) m) on a standard length optical table. The beam is injected at an angle of \(59^\circ\) on to the stretcher using a motorised mirror (Newport Agilis AG-M100) which maintains the stretcher alignment using a closed loop feedback mechanism. An elongated beam with an aspect ratio of 2:1 (width \(\sim 12\) mm, height 6 mm) is used for injection to increase the projected beam area on to the gratings which have low damage threshold owing to their age. One advantage of the two grating geometry compared to the single grating is that the full aperture of the grating is available for each bounce. The diffracted beam is folded around using two \(45^\circ\) mirrors to maintain correct orientation of spectral components. The returning beam then hits the centre of the second grating and the whole setup is double passed using a 3” zero degree mirror. A small tilt is applied to the injected beam in the vertical direction such that returning beam can be picked off using a D-cut mirror. The output beam profile is elongated \(\sim 3:1\) in the horizontal plane and this is corrected using a cylindrical lens pair and Vacuum Spatial Filter (VSF) assembly.

3.2 Cerberus Laser System Configuration

This section contains a description of the primary laser system components and the amplification sections for the OPA pump and signal. To reduce the complexity of the diagrams, multiple collimation optics and transport mirrors are not included. As has been mentioned in the introductory sections, the amplifiers for the short pulse section will consist of BBO based OPAs which are split into four stages with the first two stages being pumped with picosecond pump pulses and the two latter with
Figure 3.16: Schematic of the long pulse stretcher showing the input and output section. VSF - Vacuum Spatial Filter. AP - Apodiser. Cylindrical lenses at the input (1) have focal lengths of -100 mm and 200 mm for a 2:1 up-collimation. The lenses at the output have focal lengths of 250 mm and 150 mm to reshape the elongated output profile.

nanosecond. The remainder of the energy requirements after the OPA stages will be fulfilled by large scale flashlamp pumped Nd:Glass power amplifiers.

The OPA pump/long pulse section consists of a combination of Nd:YLF amplifiers supplemented by Nd:Glass power amplifiers. For OPA pumping, a diode pumped regenerative amplifiers (regen) operating at 400 Hz is used used to bring energy to the millijoule level and the latter stages consists of three flashlamp pumped Nd:YLF rod amplifiers which operate at 10 Hz. Nd:Glass power amplifiers for the short and long pulse beam lines have long cool down times and operate on a single shot basis.

The Cerberus laser system is designed to be a stable and a robust system, therefore particular attention has been given to the mechanical design of the laser. The beam height off the optics table is kept to 8 cm and solid stainless posts of a specific cut length are used for monolithic construction. The number of degrees of freedom for optics has also been reduced through the use of fixed mounts where possible which reduces the daily alignment duration. The entire front end is very compact to minimise optical path lengths and is designed to fit inside a footprint of 1.5 m × 6 m.
### Table 3.1: Summary of the CPA system on Cerberus. Both the signal and the pump sections have two stretchers and one compressor. Measured values are used where possible and simulated numbers are italicised. BW - FWHM Bandwidth.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Signal CPA</th>
<th>Pump CPA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stretcher (small)</td>
<td>Stretcher</td>
</tr>
<tr>
<td>Grating Size (W x H) mm</td>
<td>50 x 50</td>
<td>140 x 50</td>
</tr>
<tr>
<td>Grating Line Spacing l/mm</td>
<td>600</td>
<td>1740</td>
</tr>
<tr>
<td>Input Pulse Duration</td>
<td>250 fs</td>
<td>2 ps (0.8 nm BW)</td>
</tr>
<tr>
<td>Output Pulse Duration</td>
<td>900 fs</td>
<td>240 ps</td>
</tr>
<tr>
<td></td>
<td>Stretcher (Primary)</td>
<td>Compressor</td>
</tr>
<tr>
<td>Grating Size (W x H) mm</td>
<td>175 x 75</td>
<td>140 x 50</td>
</tr>
<tr>
<td>Grating Line Spacing l/mm</td>
<td>1740</td>
<td>1740</td>
</tr>
<tr>
<td>Input Pulse Duration</td>
<td>900 fs</td>
<td>~ 80 ps</td>
</tr>
<tr>
<td>Output Pulse Duration</td>
<td>~ 870 ps (4.66 nm BW)</td>
<td>6 ps</td>
</tr>
<tr>
<td></td>
<td>Compressor</td>
<td>Long Pulse Stretcher</td>
</tr>
<tr>
<td>Grating Size (W x H) mm</td>
<td>285 x 140 (Two gratings)</td>
<td>140 x 120 (Two gratings)</td>
</tr>
<tr>
<td>Grating Line Spacing l/mm</td>
<td>1740</td>
<td>1740</td>
</tr>
<tr>
<td>Input Pulse Duration</td>
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<td>80 ps</td>
</tr>
<tr>
<td>Output Pulse Duration</td>
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<td>~ 1 ns</td>
</tr>
<tr>
<td></td>
<td>~ 546 fs (amplified)</td>
<td></td>
</tr>
</tbody>
</table>

#### 3.2.1 Front-end and Pulse Selection

The Nd:Glass based oscillator used on the front end is described in chapter 2 and a functional diagram is shown in figure 2.1. Under daily operating conditions, it is capable of average powers exceeding 400 mW with pulse durations of ~ 250 fs. The output of the oscillator is split between two sections corresponding to the pump and signal. This is achieved through the use of polarisers and Pockels cells. A diagram of the pulse selection setup is shown in figure 3.17. A Faraday isolation stage is used to protect the oscillator from back reflections of the amplified OPA pulse and OPA pump system. A second Faraday isolation stage is used to separate the input and output pulses from the quad pass OPA pump stretcher. A combination of a polarising cube beamsplitter and a Pockels cell are used to select a pulse to go to the signal section or pump section at different times. This has the advantage that both the pump and signal pulses have the full energy, whilst allowing the bulk of the oscillator pulses to be used routinely for diagnostic purposes (such as spectrum, power or pulse duration...
Figure 3.17: Pulse selection for the OPA signal and pump system seed. FR - Faraday rotator, PC1 and PC2 - Pockels cell. Firing either Pockels cell allows a pulse to be selected and designated as pump or signal.

3.2.2 OPCPA Pump Section

Figure 3.18: Diagram of the amplification system for the OPCPA Pump beam. FR - Faraday rotator, PC, PC2 - Pockels cell. PC2 is used to select a 10 Hz pulse train from the 400 Hz regen output to see flashlamp pumped Nd:YLF amplifiers. Up and down collimation optics used to limit B-integral into the Faraday rotators are not shown for clarity.

The output of the pump stretcher described in section 3.1.2 is injected into a homemade linear cavity regen (see figure 3.18) for amplification. The regen is designed using 1” thick Invar [40] rods which have a low thermal expansion coefficient for long
timescale thermal stabilisation. The regen cavity consists of a convex mirror (−5 m focal length) and a concave mirror (2 m focal length) which were decided upon through simulations and testing. The seed pulse is injected into the cavity off a Brewster angle thin film plate polariser. A combination of a quarter waveplate and a BBO Pockel cell with fast switching time is used to trap one pulse into the cavity. The amplifier is a diode pumped (50 W) Nd:YLF module (Northorp Grumman RBA35-1C2) with a 3 mm rod diameter. The switched-in pulse needs ∼ 40 round trips to reach saturation in the regen which corresponds to a total net gain of ∼ 10^7 (∼ 1.25 gain per pass). The Pockel cell is driven at 400 Hz which offers the best compromise for beam profile and energy output. The regen outputs ∼ 3 mJ pulses of ∼ 80 ps duration. A Faraday isolation system is used to separate the input seed from the amplified output pulse.

Figure 3.20 shows the typical performance of the regen in terms of build up and energy stability. The system is operated at saturation so that energy stability is maximised. This is particularly important for pumping OPAs which are sensitive to pump intensities. The leakage from the end cavity mirror is used to monitor the build up of pulse energy inside the cavity. A series of pulses spaced by the cavity round
trip time (9.3 ns) are seen. The final pulse with the maximum energy is extracted by triggering the Pockel cell again. A RMS stability of 1.4% is obtained with output energy of 3 mJ. In more recent work not described in this thesis, the stability has been improved further to $\sim 0.4\%$ by using a low finesse intra-cavity etalon.

Gain narrowing in the regen results in a loss of bandwidth which makes subsequent stretching and compression more difficult. To mitigate this effect, the spectrum of the seed pulse is modulated to part-compensate for non-uniform spectral gain. This spectral shaping is done through the use of a spatial mask at the Fourier plane of the OPA pump stretcher (see figure 3.11. The seed spectrum at the peak of Nd:YLF gain curve is attenuated. Figure 3.21 shows the input and output spectra of the regen. The fine scale modulation of the spectra is an artifact due to double reflections off a polariser and should be ignored. It should be noted that the input spectrum is substantially wider than the gain width of Nd:YLF as indicated by the simulations of the stretcher.

![Graph showing typical pulse energy build up inside the regen cavity](image1.png)

![Graph showing energy stability as a function of cavity round trips](image2.png)

Figure 3.20: Left) Typical pulse energy build up inside the regen cavity measured via leakage in the end cavity mirror. Right) Energy stability as a function of cavity round trips. Saturation of the amplifier offers significantly increased energy stability.

The output of the regen alone lacks sufficient energy to pump all the OPA stages and an additional 7.5 mm Nd:YLF rod amplifier is used in a double pass configuration to increase the pulse energy to 30 mJ. The pulse repetition rate is lowered to 10 Hz as this system is flashlamp pumped. This amplifier is built around a heavily modified Nd:YAG laser system which has been retro-fitted with Nd:YLF rods. Due to the
birefringence of Nd:YLF crystals, a Faraday isolation stage is again required for a double pass and separation of the input and output beams. The measured maximum double pass gain of the amplifier is actually $\sim 25$ and it is only limited to 30 mJ by the B-integral in the Faraday rotator which uses a material called Terbium Gallium Garnet (TGG) with a high nonlinear refractive index ($n_2$) value ($1.7 \times 10^{15} \text{cm}^2\text{W}^{-1}$). Despite pulse picking a 10 Hz train from the 400 Hz regen and not saturating this amplifier, the output energy stability is still 2% RMS. A waveplate polariser combination is used to split the 30 mJ output between the pump compressor for the short pulse OPAs and the stretcher for the long pulse OPA stages and x-ray backlighter beamline.

![Figure 3.21: Input spectrum of the stretched pulse along with the amplified output spectrum. The 'spiky' modulation on the spectra is due to interference from a double reflection off a polariser.](image)

### 3.2.3 Long Pulse Beamline and Power Amplifiers

The next stage of amplifiers are designed to pump long pulse OPAs and seed power amplifiers for the long pulse beamline at the $\sim 0.4$ J level. Due to losses in the long pulse stretcher and spatial filters, a 1.4 ns pulse with 5 mJ of energy is used to seed a flashlamp pumped Nd:YLF amplifier chain (see figure 3.22. These amplifiers operate at 10 Hz and contain 7.5 mm (Amp 2) and 9.5 mm (Amp 3) diameter rods.
They also share a common pulsed power drive system as the 10 Hz power amplifier described in section 3.2.2. Therefore, the pump power of the first amplifier (Amp 2 in diagram) cannot be set independently, which, limits the overall energy output of this system. Each amplifier is double passed using a Faraday isolation stage to maximise the energy extraction. Under typical operating conditions, the double pass gain of each amplifier is $\sim 10$ which gives a total output energy of $\sim 400 \text{ mJ}$ after accounting for the losses. Although the amplifiers are not fully saturated, the RMS stability is improved from $\sim 2\%$ to 0.8\% at the output. A waveplate and polariser combination is used to split the output to pump OPA stages and seed the single shot power amplifiers.

Figure 3.23: High power Nd:Glass amplifier section for long and short pulse beamlines. FR - Faraday rotator; VSF - Vacuum spatial filter. Crossed circle represents a periscope.

The large aperture power amplifiers for the Cerberus laser system are located in a dedicated room which is located adjacent to the front end laboratory. Although this
Figure 3.24: Photo of the large aperture Nd:Glass amplifiers (red, in foreground) donated by AWE for the Cerberus project. A large aperture vacuum spatial filter for beam expansion and image relaying is also visible in the background.

requires laser beams to be sent between rooms (also separate buildings in our case), it was necessary due to space requirements for the large pulsed power banks and allow Cerberus to be linked to MAGPIE. Nd:Glass (Phosphate) rods were available with apertures of 25 mm (These will be referred to as alpha) and 50 mm (beta). Each amplifier is housed in its original configuration used on the HELEN laser system [103] which consist of 6 xenon flashlamps arranged concentrically around a 40 cm long laser rod. The flashlamps are capable of being driven with $\sim 10\ \text{kJ}$ (alpha) and $\sim 30\ \text{kJ}$ (beta) of electrical energy with a charge voltage of up to 20 kV. The optical layout of these amplifiers is shown in figure 3.23. VSFs are used to expand the beam to fill the aperture of the rod and a Faraday isolation stage is used in between the amplifiers to isolate the residual gain from back reflections. It should be noted that these same amplifiers will be used for the short pulse beamline as well in the future. Although this means that simultaneous use of the long and short pulse beamlines will not initially be available, it saves on the cost of additional large aperture optics.

The measured single pass gain of the alpha amplifier with a 17 kV charge (minimum voltage required to fire flashlamps) is $\sim 25\times$ and for the beta, it is $\sim 8\times$. This
combined gain of 400 would require a seed pulse with 100 mJ of energy to reach the 40 J output which is readily available from the previous Nd:YLF amplifiers. Table 3.2 summarises the typical parameters of the amplifiers. Calculations for the B-integral show that it possible to reach upto the 40 J with a total accumulated $B < 1$ using available amplifiers (It should be noted that B-integral values through other optics such as lenses have been neglected).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Nd:YLF</th>
<th>Nd:YLF</th>
<th>Nd:Glass rod</th>
<th>Nd:Glass rod</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>7.5 mm</td>
<td>9.5 mm</td>
<td>25 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>Input Energy</td>
<td>4 mJ</td>
<td>40 mJ</td>
<td>200 mJ</td>
<td>4 J</td>
</tr>
<tr>
<td>Output Energy</td>
<td>40 mJ</td>
<td>200 mJ</td>
<td>4 J</td>
<td>40 J</td>
</tr>
<tr>
<td>B-integral</td>
<td>0.015</td>
<td>0.054</td>
<td>0.27</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 3.2: Summary of the flashlamp pumped amplifiers on Cerberus. The B-integral calculation assume a flat top spatial profile and a 1 ns temporal duration (also assumed to be flat) which is a good approximation given measurements of these parameters.

### 3.2.4 Short Pulse Section and OPAs

This section describes the layout of the short pulse amplification setup. Figure 3.25 shows a diagram of the short pulse OPAs which utilise two type 1 BBO crystals. The lengths of the crystals are 6.5 mm and 2 mm respectively. The compressed output of the OPA pump beam is frequency doubled to 526.5 nm using a 2.5 mm BBO crystal and is capable of a maximum pump energy of 3 mJ in a 5 ps pulse duration. The pump is separated from the residual IR using a dichroic mirror followed by a Pellin-Broca prism to ensure that no residual pump IR remains to seed the OPA stages. A waveplate and polariser combination allows the pump pulse to be split with an arbitrary ratio to vary the energy delivered to each crystal. Translation stages are used to precisely set the delay between the pump and signal pulses. Collimations optics are used on the pump and signal at each crystal to set the beam sizes and consequently the input intensities. Signal beams are set to slightly overfill the pumped volume of the crystal to limit parametric fluorescence. A small angle ($\sim 0.5^\circ$) is introduced between the pump and signal to separate them spatially. This angle is in the direction of the pump spatial walk-off to maintain better overlap and it also suppresses second
harmonic generation (SHG) of the signal beam as the phase matching angles for both nonlinear processes are similar. The signal SHG actually proved to be a good way to approximately set the required phase matching angle during the OPA setup. Spatial overlap of the pump and signal is achieved using dichroic mirrors which reflect the pump and transmit the signal. Although there is choice in selecting the first pulse to amplify, the optical path length for the signal and pump between the first and second stage is exactly the same to ensure the same pulse is amplified again. The

Figure 3.25: Diagram showing the short pulse OPA setup. Lens pairs are used to control beam sizes in the crystals and a small angular walk-off is used to separate the three output beams. TS - Translation stage; DM - Dichroic mirror. SF - Spatial filter.

output of the two OPA stages is monitored using a spectrometer (Ocean Optics USB2000+) and the gain is measured using a photodiode (Thorlabs DET10A). It should be noted that gain is defined as the ratio of the input energy to the output energy. Since small values of energy are difficult to measure, the amplified output signal was focused on to the photodiode and the relative values of the measured signals were used to infer gain (with the use of calibrated neutral density (ND) filters to improve dynamic range). Energy measurements in >10 $\mu$J range were made using an calibrated energy meter (Gentec QE-12) and beam profiles were measured using the WinCamD camera described in chapter 2. As of writing of this thesis, contrast measurements are available, however, compression of first two OPA stages down to $\sim$ 400 fs has been demonstrated. The initial results from the OPA stages is shown in
The long pulse OPA section is still in the implementation phase but simulations have already been performed [80]. The preliminary design assumed that 500 mJ of pump light will be available but initial measurements from the pump amplifiers indicates it is likely to be $\sim 2 \times$ lower. If the output of the long pulse OPA is not sufficient to seed the larger amplifiers shown in figure 3.23, then additional flashlamp pumped Nd:Glass rod amplifiers are available to increase the energy to the 100 mJ level. A summary of the OPA stages is given in table 3.3

<table>
<thead>
<tr>
<th>Short Pulse OPAs</th>
<th>Crystal</th>
<th>Pump Energy</th>
<th>Simulated Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1</td>
<td>6.5 mm BBO</td>
<td>0.4 mJ</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Stage 2</td>
<td>2 mm BBO</td>
<td>2 mJ</td>
<td>100</td>
</tr>
<tr>
<td>Long Pulse OPAs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage 1</td>
<td>12 mm BBO</td>
<td>50 mJ</td>
<td>$\sim 80$</td>
</tr>
<tr>
<td>Stage 2</td>
<td>8 mm BBO</td>
<td>450 mJ</td>
<td>$\sim 15$</td>
</tr>
</tbody>
</table>

Table 3.3: Summary of the OPA crystals in each stage. It should be noted that the short pulse OPAs will be pumped with a 5 ps pulse and the long pulse OPAs with a 1.3 ns pulse.

3.2.5 Triggering and Synchronisation

Given the large and complex nature of the Cerberus laser system and its implementation as a diagnostic driver on another equally large experiment, accurate triggering and synchronisation between the two systems was essential before any experiments could be attempted. The MAGPIE facility uses a custom made ‘single shot sequence’ synchronisation setup which fires the generator and diagnostics sequentially at specified timings relative to the current pulse. From the context of lasers, Q-switched systems can be fired on demand which makes synchronisation straightforward, however, the Cerberus front end uses a modelocked oscillator as the reference signal for subsequent triggering of Pockels cells, amplifiers, etc. required to be accurate to better than 1 ns relative to the mode locked pulse train. To remedy this, an external trigger mode was implemented on MAPGIE to allow it to be fired in sync with an available laser pulse. Since laser pulses are available for amplification at 10 Hz, this
signal was used to synchronise the two systems. Electrically noisy pulsed power environments can result in misfiring of the triggering system. Fibre optic cables are used to trigger critical components such as amplifiers and Q-switches as they are much more resistant to electrical noise.

Figure 3.26 shows a simple diagram of the synchronisation system used on the laser. The photodiode in the oscillator is used to trigger a high accuracy digital delay box (Stanford Research System (SRS) DG645) with an internal rubidium atomic clock timebase (This reduces jitter substantially on longer counting delays). The 10 MHz signal from this clock is shared between all delay boxes to reduce jitter. Since the repetition rate of the front end laser oscillator is locked, the input trigger rate is constant and can be divided (by 175,000) to give an effective 400 Hz trigger for the regen Pockels cell. The flashlamped pumped amplifiers operate at 10 Hz and this can be derived from the 400 Hz trigger by dividing it by 40. The 'long timescale' flashlamps are triggered from the previous 10 Hz pulse train such that the gain is at its peak value when the laser pulse arrives (long delays SRS - DG535) and Pockel cells are triggered with a short counting delays to reduce jitter. To achieve a single laser shot on demand in MAGPIE, a trigger sequence synchronised to 10 Hz clock is used. The fire signal from MAGPIE is used to initiate the laser shot sequence (Quantum Composer 9518). This sequence uses a fast blade shutter (Thorlabs SH05) to select a single pulse from the 10 Hz pulse train and also fires the Nd:Glass power amplifiers. This synchronisation system allows the laser to be timed with an accuracy of ± 2 ns relative to pulsed current drive in MAGPIE. For most experiments on the MAGPIE generator, this is a sufficient level of timing accuracy as plasma evolution timescales from the 250 ns current drive are significantly longer (≈ 10 - 100 ns).
Design and Implementation of an OPCPA Nd:Glass Laser

Figure 3.26: Simplified diagram of the triggering system for the Cerberus laser system. SRS - Stanford Research Systems timing unit; QC - Quantum Composer timing unit. Orange arrows correspond to optical links and dashed blue line represents clock sharing. Black arrows are standard BNC cables. It should be noted that not all details are included for the sake of clarity.
3.3 Implementation and Verification of the Cerberus Laser System

This section presents the results of the implementation of the core CPA systems and their performance is compared with simulations. The pulse duration measurements are important in order to verify the proper alignment of the stretcher before any further laser amplification is attempted. It should be noted that the measurements presented below were taken over the course of two years and are representative of daily performance. Initial results obtained from the short pulse OPA section are also included.

Figure 3.27: Photo of the Cerberus laser front end in July 2013. It is worth noting that optics are closely spaced to reduce beam propagation lengths and improve robustness.

3.3.1 Short Pulse Section

Stretchers and compressors are very sensitive to any angular misalignment due to their use of dispersive optics. Some of the designs mentioned above utilise a quad pass geometry in which the system is folded back upon itself. This typically requires beams to be effectively stacked on top of each other to maximise the aperture of the optics. To facilitate the alignment of the stretchers, a mechanical scribe was constructed for
Design and Implementation of an OPCPA Nd:Glass Laser

each stretcher and compressor to effectively act as a precision alignment removable iris. Such a method of alignment was described by Mike Mason in [91]. Carefully positioned apertures allow laser beams to pass through, which eases the alignment of multiple closely spaced beams travelling in both directions. An infra-red (IR) viewer can be used to spot any misalignment by checking for clipping on the apertures. This alignment method proved to be particularly useful with the reflective doublet stretcher where the beams follow an angled path between the curved mirrors. In addition to the scribe, large triangles were drawn on the optic tables using a fine marker to provide a reference geometry to inject beams on to the gratings. This provides a very high angular accuracy (± 54 arcseconds for 1 m injection length). Since stability is paramount in long optical path length stretchers, the motion axes (XY) of the grating mount were removed to increase rigidity. Although the system takes longer to setup in this mode, stretchers and compressors typically do not require daily alignment from scratch. The detailed methodology used to align the stretchers and compressors is not included in thesis.

Figure 3.28: Single shot autocorrelation of the output of the first stretcher. Note that the small asymmetry in the leading edge of the pulse is probably due to misalignment of the autocorrelator. Data courtesy of D.Bigourd.

Figure 3.28 shows a single-shot autocorrelation of the output of the first stretcher.
Design and Implementation of an OCPA Nd:Glass Laser

on the short pulse beamline. The measured FWHM of the pulse is $\sim 870$ fs compared to the design value of $925$ fs. This discrepancy is due to the output bandwidth of the oscillator being less than specified. This value is still close to the required stretched pulse duration for optimum OPA bandwidth. No measurable spectral clipping was observed which is consistent with what was simulated.

The stretched pulse duration out of the reflective doublet stretcher was long enough to be measured directly using a fast photodiode and oscilloscope. The quad pass output of the stretcher was focused on to a small area photodiode (Newport model 1437) with 6 GHz of analog bandwidth and a 50 ps risetime. The signal was digitised at 50 Gigasamples/s using a Tektronix 70000 series oscilloscope with a 20 GHz of bandwidth. The measured trace is shown in figure 3.29 and has a FWHM of $1.35$ ns which is longer than the calculated width of $\sim 870$ ps. The calculated stretched pulse duration assumes a nominal bandwidth of 4.66 nm (corresponding to a transform limited 250 fs $\text{sech}^2$ pulse) from the oscillator. It is in fact capable of delivering up to 8 nm when ’tweaked’ for maximum performance. The longer pulse duration is consistent with additional bandwidth ($7\text{ nm} \times 186\text{ ps/nm} \approx 1.3\text{ ns}$) which the oscillator is capable of. It should be noted that the oscillator cavity is not optimised regularly to reduce alignment duration and the measurements shown here were not taken on a single day. The output spectrum is also given in the same figure and shows a small reduction in bandwidth from 5.37 nm to 4.72 nm. Since clipping on a linear scale is not expected due to the wide bandpass of the stretcher, the reason for the bandwidth reduction is due to be investigated. The small change in the central wavelength of 0.3 nm is indicative of residual spatial chirp in the stretcher. Despite the use of high efficiency dielectric grating, the stretcher only has input/output efficiency of $\sim 30\%$.

3.3.2 OPA Pump Section

The pump beam for the short pulse OPAs consists of an entire CPA setup with a stretcher, two amplifiers and a compressor. A pulse duration measurement for the pump stretcher is unavailable as $\sim 240$ ps is difficult to measure accurately even us-
Design and Implementation of an OPCPA Nd:Glass Laser

Figure 3.29: Left) Measured pulse duration for the reflective doublet stretcher under typical conditions. Right) Input and output spectra after quad pass of the stretcher. The slight shift in wavelength is due to small amount of residual spatial chirp. It should be noted that these measurements were taken under different oscillator conditions which explains their inconsistency. The reason for loss in stretcher bandwidth is to be investigated in the future.

Figure 3.29: Left) Measured pulse duration for the reflective doublet stretcher under typical conditions. Right) Input and output spectra after quad pass of the stretcher. The slight shift in wavelength is due to small amount of residual spatial chirp. It should be noted that these measurements were taken under different oscillator conditions which explains their inconsistency. The reason for loss in stretcher bandwidth is to be investigated in the future.

Using a fast photodiode is outside the range of the scanning autocorrelation system (80 ps time window). As shown in figure 3.21 the spectral bandwidth of the stretcher is sufficient for seeding Nd:YLF amplifiers. The amplified pulse undergoes substantial gain narrowing in the regen which shortens its pulse width to \( \sim 40 \) ps. The use of spectral shaping on the seed pulse improves this by a factor of 2 to \( \sim 80 \) ps. This CPA system is designed to faithfully compress pulses down to 2 ps when amplified. To obtain a starting point for the optimum compressor grating separation, it was setup with the unamplified beam from the oscillator. This pulse train contains more bandwidth than is expected from the Nd:YLF amplifiers but will allow the maximum performance of the CPA system to be evaluated. The measurements shown below were taken with a scanning 2nd order LED based autocorrelator. Figure 3.30 shows the best interferometric autocorrelation obtained from the distance scan of the compressor along with a graph showing the pulse duration as function of the grating separation. Using equation 2.25, the FWHM of the interferometric autocorrelation can be used to deduce the FWHM of the input pulses as \( \sim 880 \) fs. This performance exceeds the design point value of 2 ps by more than a factor of 2. The asymmetry in the autocorrelation trace is believed to be due to residual third order phase from the mismatched grating angles while the ringing nodal structure are due to a strong
Figure 3.30: Left) Typical autocorrelation measurement of the unamplified laser. Right) A scan of the compressor separation along with the pulse durations obtained. Zero distance corresponds to the optimum distance found experimentally.

symmetric clip in the stretcher. Since only the central part of the pulse will pump the seed, structure in the wings of the pulse is not important and expected to be lost when using the gain narrowed output of the OPA pump amplifier chain. The pulse duration measurements of the amplified pulses were performed differently due to the low damage threshold of the photodiode in the scanning autocorrelator. The output of the scanning autocorrelator was frequency doubled in a BBO crystal with a large acceptance bandwidth and the second harmonic signal produced was filtered and de-
tected on a photodiode. Due to the lower repetition rate of the amplified pulses (400 Hz compared to 70 MHz), an intensity autocorrelation was obtained. It should be noted that measurements below were obtained without the use of the 10 Hz flashlamp pumped amplifier as the diagnostic is particularly sensitive to small energy fluctuations. Figure 3.31 shows an intensity autocorrelation of the amplified pulse with the grating separation optimised. The FWHM of the autocorrelation is 7.8 ps. Assuming a Gaussian temporal profile (typical of amplified pulses), the pulse duration of the original pulses can be estimated to be $\sim 5.5$ ps. If the pulse is transform limited, then this would correspond to a required bandwidth of 0.29 nm. The energy throughput of this compressor is found experimentally to be 50% which gives 5 mJ of compressed pulses with a 10 mJ input. The pulse duration obtained is almost identical to the one used by C.Dorrer et al for pumping high contrast OPAs (6 ps) for the OMEGA-EP front end [44].

![Figure 3.32: Compressed pulse duration as a function of grating separation for a range of input regen energies.
](image)

Figure 3.32: Compressed pulse duration as a function of grating separation for a range of input regen energies. The effect of shaping the spectrum of the amplified pulses results in shorter compressed pulses compared to unshaped spectra. The unshaped higher energy pulses have shorter pulse durations and consequently suffer from SPM which results in poor compression. Zero grating separation corresponds to the optimum position achieved without amplification (as per figure 3.30).
It was observed experimentally that the output bandwidth of the amplified pulse was actually lower with spectral shaping rather than without. A possible reason for this is that the shorter chirped pulse durations produced without spectral shaping of the seed resulted in self phase modulation (SPM) in the regen. This created additional frequency components which broadened the spectrum and introduced nonlinear chirp which cannot be compressed. The effect of spectral shaping therefore reduces intensity dependent effects such as SPM and yields a more compressible amplified pulse. This results in compression close to the transform limit. This is illustrated in figure 3.32 where grating separation scans are performed as a function of regen energy. The results show that the shortest pulse durations are indeed obtained when the seed pulse is shaped. Reducing the energy output also reduces the compressed pulse duration as lower intensities reduce SPM. Estimates of B-integral values in the regen based upon calculations of the mode size in the cavity indicate that strong SPM is expected for saturated mode of operation (B \sim 6) [92]. Damage to the optical components is prevented by locating them in region where mode area is larger.

The setup of the long pulse stretcher was more challenging as an input pulse with limited bandwidth and opposite sign chirp had to be stretched by a substantial amount. This stretcher was designed with very large dispersion value of 3 ns/nm which is an order of magnitude greater than the reflective doublet stretcher (186 ps/nm). The combination of high dispersion with a large grating separation resulted in a spatially elongated beam profile. This ellipticity was in the plane parallel to the dispersion plane, however, it could not be attributed to spatial chirp or misalignment. This aberration in the stretcher remains unexplained. A pair of cylindrical lenses were used to correct for this aberration at the output of the stretcher and the spatial clipping was corrected for using an apodising aperture and vacuum spatial filter. Figure 3.33 shows the output spatial profiles from the stretcher before and after correction.

The pulse duration from the 'long' OPA pump stretcher was measured using the same diode based instruments as the reflective doublet stretcher. Figure 3.34 shows the temporal profile of the stretcher. The measured pulse duration of 1.36 ns is greater
Figure 3.33: Left) Oval output at the exit of the long pulse stretcher. The beam profile aberrations are currently unexplained. Right) Beam profile after correcting using cylindrical lenses and VSF.

than the calculated value but this is highly sensitive to input bandwidth as previously mentioned. Although this pulse duration is optimal for seeding the power amplifiers for the long pulse arm, it is roughly the same value as the short pulse seed (output of the reflective doublet). Consequently, the pump temporal profile may spectrally window the chirped short pulse seed spectrum.
3.3.3 Initial OPA Results

The short pulse OPA stages were designed to generate a clean high contrast seed for further amplification whilst retaining the full bandwidth of the 250 fs input pulses. This amplification stage effectively replaces the high gain regenerative amplifier in a traditional CPA setups that boosts seed pulses from nJ to mJ level. Although these OPA stages remain a work in progress at this time, the initial results shown here are promising. Table 3.4 shows a summary of the OPA setup parameters. It should be noted that the measurements in this section were made by D.Bigourd.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Signal</th>
<th>Pump</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration</td>
<td>900 fs</td>
<td>5 ps</td>
</tr>
<tr>
<td>Wavelength</td>
<td>1054 nm</td>
<td>526.5 nm</td>
</tr>
<tr>
<td>Energy</td>
<td>up to 600 pJ</td>
<td>up to 3 mJ (combined)</td>
</tr>
<tr>
<td>Beam diameter</td>
<td>700 µm (stage 1)</td>
<td>650 µm</td>
</tr>
<tr>
<td></td>
<td>1120 µm (stage 2)</td>
<td>550 µm</td>
</tr>
<tr>
<td>Crystals</td>
<td>6.5 mm (stage 1)</td>
<td>2.5 mm (SHG)</td>
</tr>
<tr>
<td></td>
<td>2.0 mm (stage 2)</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4: Summary of parameters for the short pulse OPAs.

The stability of the setup to fluctuations in the pump energy were measured by varying the pump energy. The variation of the gain as a function of pump and signal...
Design and Implementation of an OCPA Nd:Glass Laser

energies is shown in figure 3.35. With the signal energy constant at 600 pJ, the gain increases exponentially (linearly on a log scale graph) for higher pump energies, and begins to reach a plateau with a pump energy of 1.5 mJ. This is true for both the first stage and both combined. From the perspective of stability, the combined output of the two stages shows good stability with pump energies from 1.8 mJ to 2.8 mJ. For example, increasing the pump energy from 2.16 mJ to 2.64 mJ only results in a 17% change in gain. Given that the pump amplifiers have typically 2% RMS stability, the shot to shot variation in the gain was expected to be low. In fact, measurements showed that output energies of > 100 µJ are readily possible with an RMS stability of 4%. The variation of gain with input signal energy shows a similar trend of saturated behaviour. The gain decreases for higher signal energies as saturation is reached faster (for a constant pump intensity). It should be noted that the signal energy is inferred by dividing the average power by the repetition rate. In addition to output stability, it was observed that active control of the oscillator was able to maintain good temporal overlap for the duration of the day.

![Figure 3.35: Left) Gain as a function of pump energy of OPA 1 and 2 with a constant seed energy of 600 pJ. Right) Gain as a function of signal energy with a constant total pump energy of 2.4 mJ.](image)

The output spectrum of the OPAs (both stages) is shown in figure 3.36. The amplified spectrum exhibits significant broadening (from 6 nm input to ~ 11 nm) which is asymmetric towards the shorter wavelengths. The increase in spectral bandwidth is not due to SPM but is a consequence of operating the OPA stages in deep saturation.
with a slightly chirped seed. This results in a larger gain in the wings of the pulse and consequent reshaping of the spectral profile. Group velocity mismatch (∼ 90 fs/mm) between the pump and signal results in a 580 fs temporal slip of the negatively chirped seed relative to the pump. This results in the frequencies on the leading edge of the chirped seed being amplified slightly more. Although these additional frequency components are likely to be clipped in the subsequent reflective doublet stretcher, it is important to note there has been no spectral narrowing from the OPA stages. This highlights a key advantage of the OPAs compared to a gain storage amplifier with gain narrowing.

As stated already, detailed contrast measurements have not been performed as of writing of this thesis, however, it is worth stating that a gain contrast exceeding $10^3$ was seen in a 9 ps time window around the signal after the first OPA amplifier. This measurement is shown in figure 3.37 and was performed by scanning temporally the shorter (∼ 1 ps) seed through the longer 5 ps pump pulse to effectively measure the cross correlation between the pump and the seed with optical parametric amplification as the nonlinear process. The gain profile contains pre and post pulses which will be investigated in the future to determine whether they are on the pump or the seed. It is also worth noting that the 'dip' at the peak of the gain implies that the most intense part of the pump is back converting. This likely to broaden the pulse and increase the gain window. These gain scan measurements indicate that significant improvements to the temporal contrast of the pulse are possible, as seen in literature [44]. It was also observed that the measured parameters were typically lower than simulations by a factor of ∼ $2\times$. This is attributed to 1D simulations over-estimating the intensity.

**Summary**

This chapter presents the details of the initial build phase of the Cerberus laser system and particularly its multiple CPA sub-systems and OPA amplifiers. The simulations performed using CPTrace3D for the CPA system are shown in the opening the section. A total of six dispersive systems are modelled consisting of four stretchers and two
Figure 3.36: Amplified output spectra from the short pulse OPA setup. The input spectrum (blue) corresponds to the output of the oscillator and has a FWHM of $\sim 6$ nm. Group velocity mismatch between the pump and the negatively chirped signal of $\sim 580$ fs results in preferential amplification of the shorter wavelength components of the spectrum (which lie on the leading edge of the pulse).

Figure 3.37: Gain contrast from the first OPA stage obtained by scanning the OPA seed beam through a temporally fixed OPA pump beam. The modulated temporal profile is due to a combination of pre and post pulses on the pump and the seed. This measurement cannot distinguish between the modulations on the seed and the pump. The temporal profiles of the pump and seed will be investigated in the future with a scanning third order autocorrelator. Data courtesy of N.Stuart.
compressors. A detailed description of the amplification system for the short and long pulse beamlines is given. The final part of the chapter presents results from the implementation of the system by the author such as pulse duration measurements. It is observed that there is good agreement with the CPTrace3D simulation. Initial results from the short pulse OPAs are presented which show that at least 100 µJ of energy (10^5 gain) can be extracted with a 4% RMS stability.
Chapter 4

Instrumentation and Experimental Methods

This chapter gives an overview of the MAGPIE pulsed power facility which is the primary target area for the Cerberus laser system when run as a diagnostic driver and where all the experiments described in this thesis were carried out. The diagnostics which the author worked on and developed are described in greater detail compared to range of other diagnostics which are referred to in the experimental chapters. The first section describes the diagnostics used to study ion self emission from radial wire arrays (RWAs). The latter part describes the high energy narrow-band Nd:YAG based beamline built by the author to perform Thomson scattering experiments on cylindrical wire arrays CWAs.

4.1 Overview of MAGPIE Pulsed Power Facility

Pulsed power generators are a commonly used way of achieving high energy density conditions in the laboratory, particularly when large deposited energies are required [119]. Similar to CPA lasers in a broad concept, the aim is to compress energy in time to achieve high peak powers (∼ terawatt in the case of MAGPIE) for 'short' durations, albeit using electricity rather than light. The pulses are typically much longer (tens to hundreds of nanoseconds compared to < ps for CPA lasers) but are
capable of delivering substantially more energy (kJ to MJ) than a laser of equivalent cost and size. Spatial energy compression is achieved by discharging the generator via a target load, typically consisting of (∼ um) fine wires or thin foils. This step is conceptually equivalent to focusing a laser on a target.

![Diagram of the MAGPIE generator](image)

**Figure 4.1: Solidworks render showing the MAGPIE generator with a human figure for scale.**

MITL - Magnetically Insulated Transfer Line; PFL - Pulse Forming Line. A significantly larger target chamber has now been installed to allow better diagnostic access for probe lasers. Image courtesy of Gareth Hall.

The MAGPIE generator, illustrated in figure 4.1, is a 'medium sized' pulsed power facility comprising of 4 Marx banks. Each bank houses 24 × 1.3 μF capacitors which are charged in parallel and discharged in series via spark gaps which contain Sulphur Hexafluoride (SF₆) gas. For a standard shot, the capacitors are charged to ± 65 kV. This delivers a combined stored energy of $4 \times \frac{1}{2}CV^2 = 264 \text{kJ}$.

The output of each Marx bank is transferred to a water filled co-axial pulse forming line (PFL, a ∼ 1 m cross section water filled cylinder with a central conductor) which sets the rise time ($\tau$, 250 ns) and duration of the current pulse ($I$). It is well modelled by the following form

$$I(t) = I_0 \sin \left(\frac{\pi t}{2\tau}\right)$$

(4.1)
where $I_0$ is the peak current. A vertical transfer line combines the outputs of the four individual PFLs and directs it to a magnetically insulated transfer line (MITL) which is designed to prevent breakdown under high voltages. The tapered MITL reduces the physical aperture of the conductor and allows experimental loads of a few cm in size to be placed on top. Since MAGPIE is a high impedance generator, the load inductance does not affect the load current significantly which allows many different types of arrays to be fielded. Additional technical information about the construction of MAGPIE and its design specification are provided in [138, 94] and references therein. The target chamber on the generator has a sixteen fold symmetry with $32 \times 100$ mm viewing ports distributed over two layers. There are also ports on the chamber lid for end-on viewing. As a result, unobstructed views of the target are available for laser probing from all angles allowing for good diagnostic access for the Cerberus laser system.

4.2 Diagnostic Capabilities in MAGPIE

Due to the low repetition rate and single shot nature of experiments on Magpie, a wide array of plasma diagnostic capabilities are installed to collect the maximum amount of data during each shot. Since the dynamical features of the electrically driven plasma typically evolve on timescale of $\sim$ ns and are traveling at $\sim 100$ km/s, the use of fast time resolved diagnostics such as pulsed lasers and low rise time diodes are needed to 'freeze motion'. An overview of the plasma diagnostics package on MAGPIE is provided in here [14].

4.2.1 Fast Ion Detection

Columbia Resin - 39 (CR-39) is a colourless clear plastic which is commonly used as a solid state nuclear track detector (SSNTD) [53] and was the primary ion detector used in experiments described in chapter 6. Energetic ions deposit energy in the bulk material as they traverse through it. The deposited energy breaks the bonds within the polymer material causing localised damage. The damage can be visualised by
Instrumentation and Experimental Methods

etching in a solution of 6.25 Molar (M) Sodium Hydroxide (NaOH) at 85°C. The etching occurs at a preferential rate in regions where there is ion radiation damage compared to bulk material. This results in the formation of pits at each interaction site which can be observed under a microscope and counted. Since each ion forms one pit, the detector offers nearly \(\sim 100\%\) quantum efficiency. A typical unsaturated CR-39 scan is shown in figure 4.2. Saturation occurs when the pit density is sufficiently high that individual pits merge together and cannot be accurately counted. Since the size of the pits depends on the etching duration, saturation can occur due to high fluence or long etching duration. A lower threshold for saturation is \(\sim 10^6\) particles per cm\(^{-2}\) [56] and recent work in our group shows that ions with energy as low at \(\sim 85\) keV can be detected [46].

![Figure 4.2: A typical scan of a post-etch CR-39 slide showing pits formed by ion interactions. This was imaged under a 40× magnification optical microscope with a CCD camera attachment.](image)

The deposition of energy by ions in bulk materials is different to that of photons and electrons. Energy is deposited initially near uniformly along the path, ending in a characteristic peak called the Bragg peak where most of the energy is deposited. This is caused by an increase in electronic stopping as ions lose their energy [155]. Ions which are lighter and have more kinetic energy penetrate deeper into the material. Thus filters of various thicknesses can be used to transmit ions above a threshold energy. The stopping range of ions in matter can be calculated using a Monte Carlo code, for example SRIM2008 [154] and the stopping range for various ions in alu-
minium is shown in figure 4.3. The transmission energies for various filters used during experiments were calculated using this code.

![Graph showing stopping range of various ions in aluminium filters as a function of energy.](image)

Figure 4.3: Stopping range of various ions in aluminium filters as a function of energy. The dashed line correspond to typical filter thicknesses used in experiments described in this thesis. For example, protons would need an energy of $\sim 1$ MeV to penetrate 12.5 $\mu$m Aluminium.

Since electrons and photons cannot cause localised damage via the same mechanism as ions, CR-39 is exclusively sensitive to ions, which is a unique feature compared to other detectors such as Radiochromatic film (RCF). By counting pits under a microscope, it is also possible to obtain absolute fluence values, although this tends to be tedious in practice. Automated pit counting systems (e.g. Track Analysis Systems Ltd.) exist but have issues distinguishing between pits and dust. A key issue encountered with their use was that the etching process bends the CR-39 nonuniformly and the system was unable to maintain focus during scan. Therefore such systems were not used to analyse data and it was deemed unfeasible to rasterise large images by counting manually. For measurements such as energy spectra, where it is possible to interpolate between points, pit counting can be done manually at regular intervals. Image analysis software such as *ImageJ* was also used to batch process data where
manual analysis was not possible. Although the software cannot distinguish between every pit correctly, the error is typically less than 1%. It should be noted that this method still requires images to be taken manually using a microscope and designing an automated counting system was beyond the scope of this project.

A note on saturation of CR-39

When CR-39 is fully saturated, the pits are indistinguishable and the clear plastic turns milky white to the naked eye. In this regime, the optical density response of CR-39 is highly nonlinear [56] and it is hard to obtain any fully quantitative measurements. Nevertheless, it is still possible to interpret the size and shape of the emission region. An optical flatbed scanner was used to scan etched CR-39 pieces for the data obtained (in reflectance). The scanned images often show internal structure which is an artifact of CR-39 saturation and cannot be interpreted as being linearly proportional to fluence. Due to the technical difficulties of counting pits on CR-39, the plastic was deliberately etched until the saturated pattern was visible to the eye.

4.2.2 Pinhole Imaging

A pinhole camera is a simple device which can be used to make images. In the context of plasma physics, it is particularly valuable as no simple lenses are available for imaging hard x-rays, ions, etc. Through the use of appropriate detectors and filters, a range of radiation can be imaged. Such an image can notionally be aberration free and recorded with an infinite depth of field but, often very dim as small aperture sizes are required for good resolution. A diagram of a pinhole camera is shown in figure 4.4.

The pinhole camera creates an inverted image of the object with a magnification (M) given by the ratio of the image distance to object distance.

\[
M = \frac{\text{ImageDistance}}{\text{ObjectDistance}} = \frac{v}{u} \quad (4.2)
\]

For the specific context of ion imaging which is relevant to this thesis, a sealed
box with a small aperture was used as a vacuum compatible, radiation ’hard’ camera system. Sensitivity to ions is achieved through the use of a 5 cm × 5 cm piece of CR-39 detector. A range of pinhole sizes from 1 mm to 50 µm were used to control the ion flux into the detector. For pinhole imaging, the resolution of the system is affected by diffraction, pinhole diameter and the resolution of the detector itself. Given that only the boundary of the emission region can be interpreted from a saturated detector, resolution was not an important design parameter. The pinhole limited resolution varied from 1.5 mm to 150 µm for apertures 1 mm to 100 µm wide. The time-integrated information obtained from this diagnostic is able to reveal the size of the region from which ion self-emission is maximal. An attempt to further develop this device to allow time resolved imaging is also described in chapter 6.

In addition to imaging ions, time resolved XUV (> 40 eV) pinhole cameras backed by a micro channel plate (MCP) detector [148] were also deployed to image the soft x-ray self emission from the plasma. The MCP detector is divided into four quadrants capable of giving four independent 2D frames in a single shot with ∼ 2 ns temporal resolution. Additional information on this setup can be found in [14].
4.2.3 Flyeye Ion Camera

The *flyeye* camera consists of an array of hollow tubes with a detector placed at one end. It is based on the principle of coded aperture imaging whereby information about the source can be inferred from the pattern which a known aperture mask leaves on the image. Like pinhole cameras, it is a potentially useful way of imaging radiation which is difficult to focus using a lens or mirror system and is widely used in astronomy for example [26]. Another common form of coded aperture imaging is the technique of penumbral imaging which is often used to estimate the size of imploding fusion capsules via their particle self-emission [31]. The technique used on MAGPIE is similar to this, however, care must be taken in interpreting saturated CR-39 data. The tubes of the flyeye camera aperture are made from a material which is thick enough to block ions, hence, the geometry of the tubes sets a range of angles through which ions can reach the detector at the back. This allows the direction of the source to be visualised providing information complementary to a pinhole camera and potentially able probe ion self-emission in the presence of a large magnetic field which may perturb ion trajectories. A diagram of the flyeye camera is shown in figure 4.5.

![Diagram of flyeye camera](image)

**Figure 4.5**: Side-on view of the flyeye camera. The length of the tubes set the distance to the detector (CR-39 in this case) and distance to the target sets the field of view of the tubes.

The initial design of this camera developed over the course of the project by the author consisted of a $5 \times 5$ tube array drilled into an aluminium block. The
length of the tubes was 55 mm and they had a 6 mm aperture. For the experiments conducted in September 2010, this camera was used. An interesting and unexpected shadow pattern was observed in the data, which is explained in Chapter 6. A higher resolution version of this device was made for experiments conducted in 2011. This consisted of a 24 × 24 tube array which was created by a 3D printer (material - ultraviolet light cured epoxy resin) as the long narrow holes (1.2 mm) were difficult to drill mechanically. The stopping power of epoxy resin is still high enough for the ion energies concerned so the same principle in Figure 4.5 applies. A 3D render of this device is shown in Figure 4.6.

The angle subtended by the tubes to the source is very small. As a result the detector only has a 6 mm field of view of the jet and is designed to only image ions travelling along paths closely aligned to the tube structure. For emitting plasma jets which are moving in excess of ~200 km/s, 6 mm can be covered in ~30 ns. This, along with the direction information, offers a way to estimate a timescale on which emission occurs.

![SolidWorks render of the high resolution flyeye camera. It consists of a 24 × 24 array with 1.2 mm diameter holes printed using UV cured epoxy resin. 3D printing system manufactured by OBJET (Model - Eden 250).](image)

**Figure 4.6:** SolidWorks render of the high resolution flyeye camera. It consists of a 24 × 24 array with 1.2 mm diameter holes printed using UV cured epoxy resin. 3D printing system manufactured by OBJET (Model - Eden 250).

### 4.2.4 Magnetic Ion Spectrometer

A charged particle travelling in a magnetic field is deflected by the Lorentz force \((\mathbf{v} \times \mathbf{B})\) which results in a trajectory along the gyroradius given by \(r = \frac{mv}{qB}\), where \(m\) is the mass of the particle, \(v\) is the velocity and \(q\) is the charge. Since this force
Table 4.1: Table of summary for the flyeye cameras used

<table>
<thead>
<tr>
<th></th>
<th>Low Resolution</th>
<th>High Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>25</td>
<td>496</td>
</tr>
<tr>
<td>Tube diameter</td>
<td>6 mm</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Material</td>
<td>Aluminium</td>
<td>Epoxy Resin</td>
</tr>
<tr>
<td>Target View</td>
<td>5.4 cm</td>
<td>6 mm</td>
</tr>
</tbody>
</table>

is directly proportional to velocity (which itself is proportional to the square root of energy), an energy spectrum can be obtained by deflecting a charged ion beam. Unlike a Thomson Parabola, which uses parallel electric and magnetic fields to give 2D dispersion proportional to the charge to mass ratio, a magnetic spectrometer can only deflect in one dimension. Consequently, it cannot differentiate between different charged species which have to be inferred via other means. A simple schematic of the spectrometer is shown in figure 4.7. The incoming ion beam is collimated using slits and passed between a pair of strong magnets ( ~ 0.85 T) which disperses the ions perpendicular to the field. A large detection area is achieved through the use of four CR-39 sheets arranged as per the diagram.

Figure 4.7: Schematic of a magnetic spectrometer used on MAGPIE. Incoming protons (red) are deflected by a strong 0.8 T magnet and detected on four pieces of CR-39 (indicated in blue). The slits are orientated perpendicular to the plane of dispersion

For purposes of the experiment described in chapter 6, a custom built magnetic spectrometer designed to resolve relatively lower energy (0.1 - 5 MeV) protons was
used. The deflection is greatest for particles with lower mass and kinetic energy. This means small errors from fringe fields and an analytic calibration have a large effect when trying to resolve lower energies. The spectrometer used was calibrated by Dr. Hugo Doyle at the Surrey Tandetron [126] which offers monoenergetic proton beams with energy control of ± 10 keV [46]. This calibration gives precise distance to energy relationship along the dispersion curve with errors of less than 1%. It should be noted that this spectrometer was not designed specifically for this experiment and was on loan from the Atomic Weapons Establishment (AWE).

4.2.5 Laser Probing

Pulsed lasers are a common diagnostic tool for freeze frame imaging of rapidly evolving plasma dynamics. Nanosecond pulses from Q-switched Nd:YAG lasers are readily available commercially and can offer very good reliability and ‘turn-key’ operation. Such a system (EKSPLA SL312P) is deployed in MAGPIE for spatially resolved 2D time framed imaging through the means of shadowgraphy, interferometry and Schlieren techniques [66]. All of these techniques depend upon the effect of free electrons on the plasma refractive index which affects the phase front of the laser beam. These methods are applicable as long as the plasma is optically transparent to the incoming laser. The threshold for this condition is that the local free electron density must be below the critical density for propagation for the laser wavelength [74]. The critical density is given by

$$n_c = \frac{\omega_0^2 \epsilon_0 m_e}{e^2}$$  \hspace{1cm} (4.3)

where $\omega_0$ is the laser frequency. Exceeding this density renders the plasma opaque to light at frequency $\omega_0$. For the second harmonic of Nd:YAG operating at a wavelength of 532 nm, this gives a cut-off density of $\sim 4 \times 10^{21} \text{ cm}^{-3}$. Many plasma phenomena such as shocks contain strong density gradients. The refraction of light which occurs at such density gradients can bend light out of the finite aperture of the optical measurement system. Therefore practical measureable limits are typically significantly
lower than the critical density.

Shadowgraphy and Schlieren imaging are sensitive to density gradients in the plasma and are ideal for imaging shocks due to their strong gradients. Time resolved images can be obtained from spatial structures (and global dynamics) and it is possible to see features evolve by taking multiple 2D frames separated in time. Interferometry allows free electron density images to be obtained by tracking fringe shifts after traversing a plasma. An independent measurement of the electron density is particularly important for analysing Thomson scattering spectra. A detailed study of the interferometry techniques used on CWAs is presented here [138]. The term 'electron density' will be used to refer to the free electron density as contributions from ions and bound electrons were deemed negligible experimentally [138].

Two laser channels derived from a common system are available for side-on probing on MAGPIE with a fixed time separation of 22 ns. Each channel allows shadowgraphy, interferometry and Schlieren imaging to be performed simultaneously. All images shown in this thesis were obtained at the second harmonic of Nd:YAG at 532 nm and commercial Canon digital single lens reflex (D-SLRs) cameras were used as detectors of the laser probe. Certain loads such as CWAs exhibit a strong symmetry about the axis of rotation. In these cases, end-on laser probing is used to give average cross sectional images of the electron density. This was used on the Thomson scattering experiment described in the next chapter. To obtain electron density measurement simultaneously with Thomson scattering, the third harmonic (355 nm) of the Nd:YAG was used instead of the second to eliminate stray light at the Thomson probing wavelength.

4.2.6 Additional Diagnostic Channels

Monitoring current is essential in pulsed power systems as it can help diagnose faults with the machine and also aids post shot analysis of relative timings between the current pulse and other plasma diagnostics. It should be noted that \( t_0 \) is defined as the start of the current (for the particular shot) and diagnostic timings refer to time elapsed since \( t_0 \). The current delivered is monitored on MAGPIE using B-dot probes
and Rogowski coils. From Faraday’s law of induction, a time varying magnetic field induces a voltage. This effect is utilised in B-dot probes which measure the rate of change of magnetic flux through a loop of wire (proportional to the rate of change of current $\frac{dI}{dt}$). For an absolute measurement of current during a shot, a Rogowski coil is fitted around the return current post. It consists of a square toroidal channel which is sensitive to the azimuthal component of the magnetic field (caused by an axial current) around the conductor. A voltage is induced by the changing magnetic flux and this can be measured using an oscilloscope. The total current can then be calculated analytically from the known geometry of the pulse power setup and dimensions of the Rogowski coil. Further information on the geometric calibration constants and the design of the coils can be found in [137].

Z-pinch plasmas are very often extremely bright in the x-ray region of the spectrum. A time history of the dynamics of the array can be obtained through the use of x-ray sensitive diodes such as diamond photosconducting detectors (PCDs). These have a flat response between 10 eV and 6 keV [130] and can be filtered to provide sensitivity in certain spectral regions. It is particularly useful to compare the x-ray emission timescales with time resolved laser images to ascertain the physical process responsible for the emission such as an instability driven collapse of the pinch.

### 4.3 Thomson Probing Beamline

This section gives a description of a high energy Nd:YAG based beamline which was developed by author to perform Thomson scattering on the MAGPIE generator. Additional information about the scattering process and the experimental techniques are provided in the next chapter. This system is standalone from the rest of the Cerberus beams (it does not share a common front end) and is also independently housed in a dedicated lab adjacent to MAGPIE. The laser setup is relatively straightforward, consisting of a commercial flashlamp pumped Q-switched Nd:YAG (SpectraPhysics QuantaRay GCR-200) which is then amplified in a 25 mm diameter Nd:Glass (Silicate) rod amplifier. The amplification and data acquisition systems are housed in
separate laboratories. A simplified diagram of the laser amplification system is shown in figure 4.8.

![Simplified schematic of the amplification setup of the Thomson probe beamline. VSF - Vacuum Spatial Filter; SHG - Second Harmonic Generation; IR - Infra-red; Pol - Polariser.](image)

**Figure 4.8: Simplified schematic of the amplification setup of the Thomson probe beamline. VSF - Vacuum Spatial Filter; SHG - Second Harmonic Generation; IR - Infra-red; Pol - Polariser.**

### Thomson Probe Laser Setup

The commercial Nd:YAG system used as the front end of the Thomson beam line operates at 10 Hz and is capable of delivering up to $\sim 1\text{J}$ in pulses as short as $\sim 7\text{ns}$. The cavity inside the laser is injection seeded by a diode laser which allows the system to operate in single longitudinal mode (SLM). The seeding allows a dominant cavity mode to develop and significantly reduces the line width of the laser ($\sim 0.003 \text{ cm}^{-1}$ or 0.34 pm). This narrowband source is essential for use in Thomson scattering where changes to the spectrum of the laser source is the measured parameter. The temporal profile of the source is also smooth due to suppression of adjacent cavity modes. The effect of this is shown in figure 4.10. It was observed that pulse characteristics depended heavily on the pump power. The shortest pulses could only be obtained by pumping the laser cavity at full power, however, this risked damage to the laser cavity. As a result, typical operation was at pulse durations of 9 ns instead of 7 ns. This resulted in 200 mJ of energy to seed the silicate rod amplifier. The gain bandwidth of silicate glass is centered at 1062 nm (c.f. Phosphate glass which is $\sim 1054$ nm. Note - the exact glass specifications are unknown. Large aperture silicate laser glass is currently impossible to source commercially and the rod used here was donated to
the project by AWE Aldermaston and may be several decades old. Therefore, typical values are quoted and were used for calculations.) which makes it sufficiently close in wavelength for use with Nd:YAG based system operating at 1064 nm [75].

The output of the Nd:YAG based setup is spatially filtered under vacuum and up-collimated to 21 mm to match the size of the large amplifier rod (25 mm diameter, 400 mm length). The rod is double passed using a quarter-waveplate and a polariser to maximise energy extraction. Typical single pass gain of the rod is \( \sim 30 \) and double passing results in near saturated operation with good shot to shot energy stability (Double pass gain of \( \sim 60 \)). The geometrically folded double pass does risk damage to the seeding laser from leakage through the polarisers so a Faraday isolation stage is installed at the output of the laser to reject returning light. Standard shots deliver \( 10 \pm 1 \) J of light at 1064 nm. This is converted to second harmonic (532 nm) in a 4 cm long type 2 KDP crystal and delivered to MAGPIE. On target energy of \( \sim 4 \) J is obtained in pulsewidth of 8 ns FWHM delivering a peak power of 500 MW.

The laser is synchronised to a 5 Hz trigger from MAGPIE via optical cables to
Figure 4.10: Typical temporal performance of the Nd:YAG laser at various power settings. Seeding the cavity gives smoother temporal profiles while increasing the pump power reduces the pulse duration. Note - '10-10' corresponds to an energy setting where the cavity and the subsequent power amplifier are pumped at full power. The pulse duration is only dependent on cavity pump power. The post amplifier is not used in normal operation as the additional energy is not required.

suppress pre-triggering from noise created by large scale pulsed power equipment. A single pulse is selected for amplification using a fast blade shutter and the shot rate is limited to one shot every 10 minutes to allow the rod to cool. The cautious shot rate includes a substantial safety margin as silicate glass rods are effectively irreplaceable at the current time. The timing sequence for the laser is showing in figure 4.11. The flashlamp discharge for the silicate rod amplifier occurs over a longer timescale and is therefore fired first. The Q-switch for the YAG laser is fired $\sim 380 \mu s$ later to extract maximum energy.

**Experimental Considerations for Thomson Scattering**

Since the signal from Thomson scattering is small, it is important to minimise stray light and maximise collection efficiency. Although the spectral characteristics of stray light may allow it to be discriminated from Thomson scattered light, its intensity can
simple saturate the camera system or potentially damage it. The trigger system for the laser has approximately \( \sim 3 \) ns of jitter which is small enough to not miss dynamics on MAGPIE but too large for electronic triggering of the gated camera. As a result, the Andor camera (iStar ICCD 300 series) on the spectrometer is triggered by laser itself by sampling a small section of the beam on a fast photodiode detector (Thorlabs DET10A). Due to triggering delays inside the gated camera, an optical delay is added to laser to ensure scattered light arrives exactly as the spectrometer triggers. The final experimental setup varies depending on the target array and the geometry of probing (see figure 4.12). Typically, a 2.5 m focal length lens is used to make a large, long focus at the centre of the chamber (F/125 focusing, \( \sim 4 \) cm Rayleigh length). Brewster windows are installed at the entrance and exit of the laser beam path to maximise the transmission of polarised light entering and exiting the chamber. Whilst these offer contrast ratios (Tp/Rs) of 1000:1, multiple internal reflections inside the thick windows still proved to be an issue. Baffles consisting of concentric circular apertures of decreasing radii were used to guide the focusing beam in and out of the chamber. The focus of the laser is imaged at 90° (usually from two opposite sides) by a lens on to a fibre bundle (typically 7 fibres in a line with 200 pixels each).
µm cores spaced by 490 µm). This allows measurements to be performed at different points along the laser focus. The spatial resolution is set by the magnification of the imaging lens at ∼700 µm. Whilst this is larger than the laser focus, it makes the system more resistant to misalignment. The fibre setup allows light to be conveniently directed on to a spectrometer without additional optics. A 3-axis vacuum XYZ stage is used to position a thin pin to align the fibres under vacuum and allows absolute scattering position relative to the target load to be determined (to within ∼100 µm).

Figure 4.12: Schematic of the Thomson scattering data acquisition setup and techniques used to reduce stray light in the imaging system. The red dot represents location from which scattered light is collected. FL - Focusing Lens; Spectrometer is a Shamrock SR500i system from Andor.

The imaging Czerny-Turner spectrometer comes with a three grating turret which gives a choice of wavelength ranges and resolution. The spectral resolution is limited by the aperture on the fibre to 0.45 Å for 200 µm fibre and 0.25 Å for 100 µm fibre. The Andor camera is capable of 2 ns temporal gating which means scattering occurring during the FWHM of the laser pulse is recorded and background self-emission of the plasma over other timescales is removed. Since the path length for the scattered light is fixed by the fibre length (and the path for triggering is fixed by the coaxial cable), the spectrometer is always triggered at the correct time with effectively no jitter.

Summary

This chapter outlines the experimental tools that are pertinent to the experiments described in the subsequent chapters. An overview of the MAGPIE pulsed power
facility is presented here which is where the experiments were carried out. The diagnostic capabilities available are also discussed with a particular emphasis on the those developed by the laser and relevant to the measurement of ion self-emission described in chapter 6. A technical description of the Thomson scattering beam line is also given which includes setup parameters and characterisation of the laser.
Chapter 5

Optical Thomson Scattering in Wire Arrays

This chapter describes experiments conducted using the Thomson probe laser system detailed earlier to accurately measure plasma parameters of cylindrical wire arrays (CWAs). The experiments described below were led by Adam Harvey-Thompson and the author was involved in developing the high energy Thomson laser, setting up the diagnostic and analysing the data. The parameters measured include velocity profiles and temperature for aluminium and tungsten CWAs during the ablation phase of their evolution.

5.1 Thomson Scattering Theory

Thomson scattering is a process in which an electromagnetic wave scatters off a free charged particle. The incoming wave interacts with charged particles via Lorentz forces, making them oscillate. This oscillating charge emits dipole radiation which acts to scatter the incident wave in all directions. Due to their increased mass, ions are accelerated less than electrons and their contribution to the scattered power is typically negligible. This classical description of Thomson scattering is valid as long as the photon momentum is small compared to that of the electron’s ($\hbar \omega \ll m_e c^2$). For small oscillations, the magnetic field component of the Lorentz force can also be
The total scattering cross section from a single electron is given by

$$\sigma_T = \frac{8\pi}{3} r_e^2 = 0.665 \times 10^{-24} \text{ cm}^2$$

(5.1)

where $r_e$ is the classical electron radius. The cross section is proportional to the square of the electron radius and consequently very small in practice. It is also interesting to note that the cross section is independent of the frequency of the incident wave. Since the wave is emitted as a dipole, the scattered power is maximum in the plane perpendicular to the dipole and drops to zero in the parallel direction. To generalise the cross-section to multiple charges in a plasma, the scattering properties of individual electrons and their interactions must be included [81]. The total scattered intensity is proportional to the number of scatterers which is readily accounted for in calculations by the electron number density, $n_e$. The dependence on the collective plasma interactions such as electron plasma waves is introduced through the scattering form factor, $S(k, \omega)$, which is based on the time and space Fourier transform of the electron density fluctuations in the plasma [81]. Combining these allows the differential scattering cross section ($d\sigma$) per unit volume to be defined as

$$\frac{d\sigma}{d\omega d\Omega} = n_e \sigma_e S(k, \omega)$$

(5.2)

where $d\Omega$ is a volume element, $n_e$ is the free electron number density and $\sigma_e$ is the Thomson cross-section. The effect of the scattering form factor on the measured spectrum is discussed in the next section.

5.1.1 Scattering Regimes

The scattering from a group of charges in a plasma can depend on collective effects such as Debye shielding and a comprehensive theoretical treatment is provided by John Sheffield in [122]. Scattered spectra correspond to two broad regimes depending on the ratio of the scattering wavelength ($k^{-1}$) to the Debye length ($\lambda_D$). This ratio
Optical Thomson Scattering in Wire Arrays

is often expressed through the parameter $\alpha$,

$$\alpha = \frac{1}{k\lambda_D}$$  \hspace{1cm} (5.3)

For values of $\alpha < 1$, i.e. $k\lambda_D > 1$, the incoming wave 'sees' free charges which are undergoing random motion (assuming thermal equilibrium). This regime is known as incoherent scattering due to the random distribution of charges within the scattering volume. For the cases of a non-relativistic plasma (electron temperature, $T_e < keV$) with a Maxwellian distribution, it is possible to evaluate the electron density ($n_e$) and the electron temperature from the scattered spectrum.

In the other regime where $k\lambda_D < 1$, the scattering occurs from the collective motion of the electrons which are localised on the scale length of the Debye length. Hence this regime is known as 'coherent' or 'collective' scattering. It is possible to measure ion temperature ($T_i$) and also the average ionisation state ($\langle Z \rangle$). Typically, interferometry is used to obtain local electron density independently as not all plasma parameters can be evaluated simultaneously from a single Thomson scattering measurement. For plasmas of interest in MAGPIE, $T_e \sim 100$ eV and densities range from $10^{17} cm^{-3}$ to $10^{19} cm^{-3}$. For measurements taken at 90°, $\alpha$ ranges from 1 to 3 which implies that collective scattering dominates. The parameter $\alpha$ represents a continuous scale in which scattered power transitions from incoherent to collective regimes (at $\alpha = 1$, equal contributions from each mode).

The total scattered spectrum ($S(k, \omega)$) can be expressed as sum of the scattering from electrons which move randomly ($S_e(k, \omega)$) and those whose motion is correlated with the ions ($S_i(k, \omega)$).

$$S(k, \omega) = S_e(k, \omega) + S_i(k, \omega)$$  \hspace{1cm} (5.4)

$S_i(k, \omega)$ is often called the 'ion component' although this not related to scattering from the ions themselves which is still negligible. This approximation was first put forward by Salpeter in 1960 [121] and is valid under the following conditions. The velocity distributions for the electrons and ions needs to be Maxwellian and $T_e/T_i \simeq 1$.
Additionally, effects of collisions, magnetic fields and laser dispersion are also not included. A complete theoretical description is beyond the scope of this thesis, however, further detail on the approximate model used to fit data is included in appendix A. Figure 5.1 shows the analytical version of the scattered spectra for a range of different alpha parameters. When scattering from electrons undergoing random thermal motion is dominant, their velocity distribution can be assumed to be Maxwellian. The small scale random motion creates small doppler shifts which acts to broaden the laser spectrum to reflect the Gaussian velocity distribution of the electrons (figure 5.1a). The transition region where $\alpha \simeq 1$ is the most interesting as it possible to infer a range of important parameters including both $T_i$ and $T_e$ (figure 5.1b). The shape of the ion feature depends on the ratio of $\bar{Z} T_e / T_i$ [122, 50]. For the case where $\bar{Z} T_e / T_i > 1$, twin peaks corresponding to resonant scattering from ion acoustic waves is observed (figure 5.1c) and when $\bar{Z} T_e / T_i < 1$, a single peak broadened by the ion thermal distribution is seen. Only the ion temperature can be evaluated in this regime. Some experimental control of the scattering regime is possible by changing the angle of observation (figure 5.1d) as $\alpha$ is dependent on angle. Experimentally, it can be hard to choose arbitrary viewing angles due availability of vacuum ports and more importantly, stray light from refraction is also an issue when viewing from a forward direction.

**Doppler shift**

In addition to the plasma parameters described above, the bulk motion of the plasma can impart a Doppler shift to the central wavelength of the spectrum. This shift occurs due to the relative motion of the electron and the incoming/scattered wave. The magnitude of this shift can be used to evaluate the local plasma flow velocity.

The moving electron sees an incoming wave ($k_{\text{in}}$) with a frequency shift given by $\omega' = \omega_0 - k_{\text{in}}.V$. The wave is then re-emitted at a Doppler shifted frequency given by $\omega'_{\text{out}} = \omega' + k_{\text{out}}.V = \omega_0 + (k_{\text{out}} - k_{\text{in}}.V)$. The total Doppler shift measured is then given by

$$\delta \omega = \omega_{\text{out}} - \omega_0 = (k_{\text{out}} - k_{\text{in}}).V = k.V \quad (5.5)$$
Figure 5.1: Thomson scattering form factors. a) Low alpha spectrum is Gaussian like with a width proportional to the $T_e$. b) Transition region around $\alpha \sim 1$ shows both ion and electron components present. c) High alpha spectra showing twin peaks corresponding to ion acoustic waves. d) For constant plasma parameters, the variation of $\alpha$ with viewing angle is shown. Green arrow corresponds to the laser probing direction while black lines are angles where $\alpha = 1$. The forward direction is more suitable for viewing high $\alpha$ spectra but is experimentally prone to stray light. Graph courtesy of A. Coliatis.

Figure 5.2 shows a diagram of the scattering geometry with scattering vector $\mathbf{k}$ defined as $\mathbf{k} = \mathbf{k}_{\text{out}} - \mathbf{k}_{\text{in}}$. An interesting point to note is that Doppler shift measures the component of velocity along the scattering vector ($\mathbf{k}$) not the viewing direction ($\mathbf{k}_{\text{out}}$).

For Thomson scattering where photon energy is small, $\mathbf{k}_{\text{out}} \approx \mathbf{k}_{\text{in}}$ and the scattering geometry in figure 5.2b is an isosceles triangle. The scattering vector $\mathbf{k}$ can then be expressed as

$$\mathbf{k} \approx \frac{2\omega_0}{c} \sin \frac{\theta}{2}$$

(5.6)
The doppler shift can then be used to work out the component of the velocity parallel to k ($V_\parallel k$)

$$V_\parallel k = \frac{w_{out}c}{2\omega_0sin\frac{\theta}{2}}$$  (5.7)

The relative orientation of V and k determine whether the observed spectrum is red-shifted or blue-shifted. The known geometry of the setup can then be used to work out the full velocity. For example, a wavelength shift of 0.2 nm corresponds to a $v_\parallel$ of 79.8 km/s. Errors in this measurement are introduced due to a range of k vectors being collected by the lens ($\Delta k = 0.025$) and uncertainties in the viewing angle ($\pm, 3^\circ$) [61]. This results in an experimental error of $\pm 4$ km/s in the work described here. In comparison, flow velocities in MAGPIE CWA experiments typically exceed 100 km/s [17], therefore the overall error is small.

### 5.2 Overview of Cylindrical Wire Arrays

Recent interest in CWAs has been driven by their ability to efficiently generate short bursts of thermal x-rays. Experiments conducted on the 20 MA Z generator at Sandia have shown that it is possible to generate peak x-ray powers of 280 TW (4 ns pulse duration) and yields in excess of 2 MJ [41, 131]. The electrical conversion efficiency
Optical Thomson Scattering in Wire Arrays

is very high (20 percent) compared to laser driven sources, making wire array Z-pinches the most powerful and energetic laboratory x-ray sources available. The x-rays generated in this way can then be used to drive secondary experiments such as Hohlraums for inertial confinement fusion (ICF) \cite{60, 38}. Quantitative measurements provided in this section are important to understand the dynamics of x-ray production and to test the validity of complex numerical simulation codes.

CWAs consist of a series of fine wires ($\sim \mu m$) which are arranged vertically at a constant radius between two circular electrodes. A large current from a pulsed power source is driven through the wires. The current causes ohmic heating of the wires which expand and form a two component plasma consisting of a cold dense inner region and hot coronal shell. The wires stay approximately stationary and act as a mass reservoir for up to 80% of the drive time \cite{138}. The ablated mass is accelerated radially inwards by the $J \times B$ force. Figure 5.3 shows a diagram of the wire array ablation geometry. Streams from each individual wire collide on axis to form a precursor. The implosion phase begins when breaks appear in the wire and they are unable to support the current. This results in the current sheath imploding on axis and impacting the precursor. The large x-ray yield measured experimentally is attributed to the kinetic energy of the imploding sheath as it collides against the precursor plasma being thermalised (This process is often called 'stagnation'). Measurements of flow velocity and acceleration are therefore a key component in understanding the emitted x-ray powers. Current generation simulations of wire arrays do not model the initial heating of the wires and start with cylinders of plasma with initial conditions chosen to give agreement with experiments \cite{33}. Direct measurements of plasma parameters shown in this chapter allow for the verification of the models used in simulations and represent the state of the art in such studies.

5.3 Experimental Setup for Thomson Scattering

Thomson scattering was performed on CWAs made from aluminium or tungsten wires with an array diameter of 16 mm and a height of 23 mm. Since the ablation velocity
and the conditions of the precursor plasma are of interest, the arrays were 'overmassed' to prevent implosion. The extra mass prevents wires from breaking within the duration of the current pulse and the typical evolution described earlier is suppressed. The total mass in the aluminium and tungstens arrays was kept similar.

In addition to Thomson scattering, imaging 2D interferometry was used to measure the 2D electron density distribution from the end-on direction which gave an unobstructed view of the array interior. The details of the Nd:YAG based laser system used for Thomson scattering diagnostic along with the stray light suppression system are provided in chapter 4.3. The side-on view of the array is obstructed by the expanded wires during the experiment, hence, for ablation measurements along the wire, an end on light collection system is used (see diagram in figure 5.4). In this setup, the laser beam is focused using a 2.5 m focal length lens (F/125) to give a large $\sim 500 \mu m$ focal spot which is approximately constant along the length of the array (The Rayleigh length of 8 mm is comparable to the array radius). The beam is focused in between the wires and allowed to pass through unimpeded out of the chamber. This geometry allows plasma conditions inbetween the wires to be measured. For end-on measurements, a F/10 lens is used to image the scattering volume on to a fibre array off a dichroic mirror (this allows 355 nm probing light to pass through). The fibre bundle consists of $7 \times 200 \mu m$ fibres which are placed 490 $\mu m$ 

Figure 5.3: End on view of a CWA. A typical array contains 16 wires with an array width of 16 mm. Left) End on view showing the position of the wires. Right) Single wire image showing the ablating plasma stream accumulating on the axis due to the $J \times B$ force.
Figure 5.4: Left) Photo of a 16 wire aluminium CWA along with the scattering pin used to align the Thomson laser on to specific points inside the array. Right) Diagram of the end-on scattering setup. A dichroic mirror (DM) is used to simultaneously allow 355 nm laser probing for 2D interferometry. An F/10 imaging lens (IL) is used to image the scattering volume (red) on to the fibre bundle which is connected to a gated spectrometer (TS) apart in a line. Each fibre images a different spatial location from the object plane and with careful alignment, it is possible to orientate the fibre bundle such that each position lies along the input laser axis. Given the magnification of the setup (typically $\sim 0.3$), 7 points, over a distance of 7.8 mm on the object plane, are imaged on to the fibre bundle with a spatial resolution of $\sim 700 \ \mu m$ (figure 5.5). Changing the magnification could in principle increase the spatial resolution, however, the amount of scattered light collected is also lowered along with additional sensitivity to alignment of the fibres. The use of fibre optics allows different spatial positions to be imaged in a single shot conveniently. The combination of 200 $\mu m$ fibres and a 0.5 m imaging spectrometer with 2400 lines/mm grating is able so deliver a spectral resolution of 0.045 nm. This is limited by the aperture of the individual fibres which act as an effective slit. Alignment of the laser at the required locations was performed in vacuum before the shot using a thin needle attached to a precision XYZ vacuum stage. Since the width of the needle is less than the focal spot size, it is possible to
centre the laser on it by looking at the diffraction pattern in the transmitted beam from the pin. The fibres are aligned individually by imaging the scattered light off the pin before the shot. The light scattering off the pin was also imaged via the end-on imaging optics for laser probing to accurately photograph the scattering volume (figure 5.5). Thus, each scattering volume could be determined with an accuracy of 100 $\mu m$. Additionally, the use of the third harmonic of Nd:YAG (355 nm) allows laser probing to occur simultaneously with Thomson scattering without the risk of stray light saturating the spectrometer. The time resolution of the diagnostic was set by the 4 ns temporal gate on the ANDOR intensified charge coupled device camera (Andor iCCD).

![Figure 5.5: Left) End-on interferogram of CWA. Scattered light from the alignment pin can be imaged by the laser probing optics to give an accurate position of the scattering volume. Laser direction is shown by white arrow with the red spot marking the position of the scattering volume. Right) Diagram showing the imaging of scattering volumes at different positions along the fibre bundle. IL - Imaging Lens.](image)

### 5.3.1 Thomson Data Analysis Procedure

With the end-on light collection geometry, the measurement direction vector ($k_{out}$) is at 90° to the laser input vector ($k_{in}$) which means that scattering vector ($k$) is at 45° to both and also the velocity. As mentioned previously, the measured velocity
is the component parallel to \( k \) so the angle between them must be known in order to calculate the full velocity vector. Figure 5.6a-c shows how the scattering volumes were arranged relative to the wire array. Since the CWA is 16 mm in diameter, 7 fibres can effectively cover the radius of the array from the wire to the precursor with a \( \sim 1.3 \) mm spacing between scattering volumes. Typically, the fibres were set up to observe radial positions between 6.5 mm to - 1.3 mm with 0 mm corresponding to the axis of the array.

Figure 5.6: Views of Thomson scattering geometry relative to the CWA from end-on and side-on directions. a) Side-on view of the collection volumes (red dots) with respect to the array dimensions and axis. b) The scattering vector diagram from the orientation shown in a). c) End-on view of the scattering volumes.

Figure 5.7 shows typical spectra obtained from a tungsten CWA. The background image shows the pre-shot spectrum which is taken by scattering the light off the alignment pin in vacuum. It is important to note here that only a single fibre is illuminated from a single scattering location which makes the data interpretation unambiguous. The shot image shows individual spectra from each fibre which appear as a series of dots which are shifted in frequency and broadened with respect to the background. Since the spectrometer is spatially resolved, the signal from each fibre can be spatially integrated and then normalised (figure 5.7c). Fitting a Gaussian curve to each spectra allows the mean wavelength to be determined. This can be compared with the background signal to infer the wavelength shift which can be attributed directly to the bulk motion of the plasma. The increase in scattered signal which is seen along
the radial direction of the array is typically due to increased local plasma density. Although it is possible to obtain electron density values from the total signal, this was not attempted due to difficulties in absolute calibration. The broadening of the spectrum is due to the random motion of scatterers within the observed volume and can be interpreted as an effective temperature. For tungsten ablation streams where the ion temperature is very high \((T_i > \bar{Z}T_e)\), a single peaked spectrum is recorded. A theoretical spectrum is generated using the equations described in appendix A to best fit the data and obtain a temperature. This is more accurate than a simple Doppler broadening calculation as the spectrum is not expected to be purely Gaussian in the collective scattering regime. Sensible estimates of plasma parameters (from the Gorgon code and previous experiments) were used as starting values for the fits. The number of free parameters in the spectrum equation made the use of an algorithmic fitting

Figure 5.7: Typical scattered spectra obtained from CWA shots. A) Background spectrum taken before the shot. B) Spectra from individual fibres show visible doppler shifting and broadening. C) Data from each fibre (black curves) integrated along with the Gaussian fits (red dash) and the background spectrum (blue).
function difficult as it was possible to fit unrealistic plasma values to the curves. Since
the datasets obtained from each shot are not large, it was possible to fit each curve
manually by iterating the parameters until a good fit is obtained. The quality of the
fit was assessed by changing the dependent plasma parameters (such as $\bar{Z} T_e$ and $T_i$)
until the shape of the curve clearly did not match the data. This is explained further
in the next section. Although this is not potentially as accurate as might be obtained
with an ideal analytical fitting function, the level of accuracy obtained is sufficient to
support the conclusions drawn. To ease comparisons with the measured spectra, the
theoretical spectra were convolved with the measured spectrometer response so that
boardening due to the instrument is accounted for. The simultaneously measured
value for electron density from interferometry was used to generate the spectrum but
no independent measurement of the average ionisation ($\bar{Z}$) exists. Consequently, the
electron temperature is stated as the product, $\bar{Z} T_e$. For tungsten spectra, it is not
possible to calculate $\bar{Z} T_e$ as the measured shape is only very weakly dependent on it.
As a result, $T_i$ was varied to fit to the width of the measured spectrum.

![Figure 5.8: End-on interferogram (355 nm) showing the 2D electron density distribution
in a 16 wire aluminium CWA. The black line corresponds to the region where Thomson
scattering was performed. Data courtesy of G.F. Swadling [139].](image)

For aluminium CWAs, a twin-peaked spectrum is recorded due to the ratio $\bar{Z} T_e/T_i > 1$. In this case, the separation between the twin peaks is dependent upon $\bar{Z} T_e$ and this
value can be adjusted to fit the theoretical spectra to the measured one. The width of
Optical Thomson Scattering in Wire Arrays

the theoretical spectrum is adjusted using the $T_i$ parameter. Pre-shot measurements of the positions of the fibres can be overlaid on top of the interferograms so that the exact electron density values can be used. Figure 5.8 shows an end-on interferogram taken at 162 ns from a 16 wire aluminium CWA. The wires are located at a radius of 8 mm in this image. The black line represents the direction along which Thomson scattering measurements were performed. It should be noted that the measured electron density corresponds to an average value rather than any specific plane in the axial direction. A lineout of the electron density in this direction is indicated in figure 5.9. The electron density is of the order of $10^{18} \text{ cm}^{-3}$ and is greatest at the precursor and close to the ablating wires.

![Image](image_url)

Figure 5.9: Line out of the measured electron density along the black line marked in figure 5.8. There is an increase in density close to the wires (small radius) and the axis where the ablated plasma accumulates.

The sensitivity of the fit to $\bar{Z}T_e$ and $T_i$ can be assessed by changing the parameters by a set percentage as highlighted in [111]. This is used to define a 'worst case scenario' for fitting methodology and states the level of accuracy obtained. Figure 5.10 shows the changes expected to the shape of an aluminium ablation stream spectrum caused by varying $\bar{Z}T_e$ and $T_i$ by $\pm 20\%$. An increase of 20\% (red curve) in temperature creates a broader curve with a greater separation of the ion acoustic peaks while a 20\% decrease (green) creates a thinner curve with an incorrect modulation of the
peaks. The fits to tungsten spectra are not as sensitive as aluminium to changes in temperature. Figure 5.11 shows the effect of changing the ion temperature by ±33% from the 3 KeV best fit. The changes produce a different curve which is either broader or narrower than the best fit. It is also worth noting that the data curve lies inbetween the two extreme simulations.

Figure 5.10: Effect of varying plasma parameters on the fit ($\bar{Z}T_e, T_i$). Data (black line) from fibre 2 of shot s051711 which was a 16 $\times$ 30 $\mu$m aluminium array. The best fit (red) corresponds to a $\bar{Z}T_e$ of 140 eV and $T_i$ of 20 eV. Changes to these parameters at the ±20% level produces significantly different fits that are clearly less well matched to the experimental data, both in width and in the details of the peak structure.
Figure 5.11: Effect of varying ion temperature on the tungsten spectrum. Data from fibre 2 of shot s051911 which was a $32 \times 10$ µm tungsten array. Changes to the temperature at ±33% create a broader or narrower curve.

5.4 Measurements of Plasma Parameters from Aluminium and Tungsten CWAs

Scattering measurements were performed on aluminium and tungsten CWAs with wire numbers of 16 or 32. Velocity profiles were measured inbetween the wires for both CWAs but for tungsten arrays, a direct measurement of the flow velocity was also carried out on a 31 wire array to allow the laser to pass along the axis of the ablation stream. Axially averaged velocity profiles from the 3D MHD code Gorgon are also included for comparison at equivalent times. Additional information about the simulation methodology is found in [33].

5.4.1 Aluminium CWA Measurements

Figure 5.12 shows the radial velocity profiles measured from an aluminium CWA with corresponding simulations. The horizontal axis range represents the radius of the array. The measurements show that the ablated plasma is radially accelerated by
the $\mathbf{J} \times \mathbf{B}$ force. This implies the presence of current flowing in the axial direction along the streams. The accelerating plasma attains a peak velocity of $1.2 \times 10^5$ m/s as it reaches the axis. The velocity profiles are quantitatively similar between 16 and 32 wire arrays which is consistent given that the total mass of the array is constant and they are qualitatively similar at different times as well. When the streams reach the axis, they collide with other streams and the mass of the array accumulates on axis. This is indicated by the drop in velocity for radial positions $< 1$ mm where the precursor column forms. The Gorgon simulations agree well with the data and indicate that the flow velocities are similar between and inside individual ablation streams. In addition to velocity, the fits to the measured spectra also allow electron and ion temperature to be evaluated (see figure 5.13 for evaluated fits to the fibres). Since no independent measurement of the mean ionisation is available, the electron temperature is quoted as $\bar{Z}T_e$. Figure 5.13 shows the radial temperature profile at 162 ns after current start. The data shows that electron and ion temperatures are approximately constant across the radial profile (For $Z = 4$, the electron temperature can be inferred to be between 30-40 eV).
Figure 5.13: Data from shot s051711 which was a 16 wire aluminium array. Left) Individual fits (red) for each fibre (black). The blue curve on fibre channel 5 is the unshifted pre-shot spectrum. Left) Fitting theoretical curves to scattered aluminium spectra is used to extract values of $\bar{Z}T_e$ and $T_i$ as a function of radial position.

### 5.4.2 Tungsten CWA Measurements

A similar set of Thomson scattering measurements were carried out on tungsten CWA and the velocity profiles obtained at two different times ($\sim 150$ ns and $\sim 210$ ns) are shown in figure 5.14. The low density at early times ($\sim 136$ ns) in the ablation stream allows the laser to travel unimpeded and the internal flow velocity has been measured. The results show that velocities are roughly similar between flows compared to within them. The simulations do not agree well with the measured velocity values at 150 ns, predicting a higher peak velocity of $\sim 170$ km/s and a narrower precursor column width of $\sim 0.2$ mm. The agreement on velocity at 210 ns is significantly better in terms of peak value and the radial profile. The velocity difference at early times could be attributed to the lack of inclusion of wire heating in the simulations.

The early time collisionality of tungsten is not treated properly in the fluid de-
Figure 5.14: Velocity profiles from tungsten CWAs. Left) Radial velocity profiles at 150 ns for tungsten wire arrays measured between and within flows. Right) Velocity profiles at 210 ns. Gorgon simulations are included for both cases (data courtesy of J.Chittenden).

scription used in the Gorgon code which results in the large discrepancy in the predicted width of the precursor. The ion-ion mean free path (mfp) calculated for typical plasma parameters in the tungsten ablation stream ($n_e \sim 2 \times 10^{18} \text{cm}^{-3}$, velocity $\sim 1.2 \times 10^5 \text{m/s}$ and $Z = 7$) is $\sim 6 \text{mm}$ [17]. This results in the formation of a broader precursor column which can be inferred from the temperature data shown in figure 5.15. This effect is not seen in aluminium where high collisionality (mfp $\sim 0.4 \text{mm}$ [17]) keeps ion temperatures low at the same time. The low collisionality of tungsten also results in the lack of shocks between adjacent ablation streams (which are in contrast found in aluminium) which has been experimentally seen in results presented in [138].

The increased width of the tungsten spectra compared to the background measurements (such as seen in figure 5.7) is due to thermalisation of the kinetic energy of the ions when they collide on axis. The fits to the spectra are dependent primarily on the ion temperature which can be extracted from these measurements. The accuracy of the fits are typically 20% or better. Figure 5.15 shows the width of the spectra along with the corresponding ion temperature as a function of CWA radius. The results show that at early times ($\sim 150 \text{ ns}$), the ion temperature on axis is very high ($\sim 5 \text{ keV}$). The lower collisionality of tungsten streams and significantly higher kinetic energy ($0.5m_i v_{abl}^2 \sim 9.5 \text{ keV}$) result in high precursor temperatures. This broad
high temperature region extends out with a diameter of approximately 5 mm and has also been observed with end on XUV pinhole imaging [17]. Outside this region, the temperature remains comparatively lower which corresponds to the ablation stream temperature. The drop in temperature is accompanied by a reduction in the width of the precursor column (measured to be 0.6 mm in [17]) which is no longer spatially resolved by the Thomson scattering diagnostic. At later times (207 ns), the temperature is \( \sim 100 \) eV across the radius of the array. The onset of collisionality in tungsten results in high on axis temperatures at \( \sim 150 \) ns as energetic ions collide. The mechanism for radiative collapse is explained in [17]. The high thermal pressure from the hot precursor is able to resist the kinetic pressure from the ablation streams. This process continues until energy loss via radiation (proportional to the square of density) exceeds the thermalisation from the ablation streams. This causes the precursor to collapse (which in turn increases the density and cooling even more) to a narrow column on axis. This is accompanied by an increase in the x-ray emission.
Figure 5.15: Thomson scattering data is used here to evaluate radial temperature profiles for tungsten CWAs. Top) Measured widths from broadened tungsten spectra as a function of array diameter with zero referring to the array axis. Measurements are provided at two different times and an early time measurement inside the flow is also shown for comparison. Bottom) Ion temperature extracted from fits to the spectra as a function of array diameter. The errors are larger for higher temperature measurements due to a lack of sensitivity to the $T_i$ parameter. At early times (∼150 ns), the temperature is higher on axis due to thermalisation of individual ablation streams. At later times (∼200 ns), the temperature is uniformly low as the excess energy has been radiated away as x-rays.

Summary

This chapter presents results from experiments conducted to study in detail the ablation velocities from CWAs. These were measured using spatially resolved Thomson scattering to obtain a velocity profile along the ablation stream. A brief overview of the theory applicable to Thomson scattering is provided along with the dependence of the spectral shape on the parameter $\alpha$. The measurement of plasma parameters from CWAs are important for understanding x-ray yields and testing simulation codes, therefore the measured results are compared with a 3D MHD code Gorgon. The results from aluminium CWAs show good agreement with Gorgon on the value of
peak velocity ($\sim 1.2 \times 10^5$ m/s). The code’s inability to properly handle the lower collisionality of tungsten during the early phase of ablation results in discrepancies in predicting the precursor diameter and peak velocities.

The work presented in this chapter shows the first direct measurements of velocity and temperature in the ablation flows from CWAs and has been published in Physical Review Letters [61].
Chapter 6

Ion Self-Emission from Radial Wire Arrays

This chapter describes initial experiments conducted by the author to characterise ion self-emission from radial wire arrays (RWAs). The initial motivation for these experiments was to measure the background emission which would need to be overcome in the implementation of a laser driven proton probing diagnostic. These results were obtained over several experimental campaigns in 2010 and 2011 on the MAGPIE generator. All the data described in this chapter utilised RWAs as the target load. The dynamics of this array are dominated by strong magnetic fields and are scalable to astrophysical phenomena [77], such as magnetic tower jets.

Measurements of photon self-emission in the optical and x-ray wavelengths are routinely used to infer plasma dynamics and obtain quantitative information about plasma parameters such as temperature and density. Similarly, the emission of charged particle radiation can also be measured with appropriate detectors to offer a complementary knowledge about the experiment in question. For example, neutrons produced during fusion experiments can be measured to improve Hohlraum design and consequently, the yield [98]. Since charged particle radiation travels at subluminal velocities, it is possible to obtain energy spectra using time of flight methods or deflections in electromagnetic fields. This also offers a method to discriminate between particles and photons.
Ion Self-Emission from Radial Wire Arrays

Previous experiments with pulsed power devices such as plasma foci [140, 12] and capillary pinches [129] have shown ion emission to be a common feature of the plasma dynamics. Given the presence of strong electromagnetic fields in Z-pinches and hydrocarbon impurities in the wires, ion (protons in particular) emission could be expected. The experiments presented are the first investigation to look at such properties of RWAs.

Preliminary experiments used a naked piece of CR-39 in a simple witness plate configuration around the target. These were found to be saturated in a short duration of etching despite being located 40 cm from the load array. This suggested fluence levels at least as high as saturation fluence for CR-39 detectors ($\sim 10^6 \text{ cm}^{-2}$). The use of thin aluminium filters ($\sim \mu\text{m}$ thick) reduced the signal dramatically alluding to the predominantly low energy nature of the ions.

The exclusive sensitivity of CR-39 to ions makes it an ideal detector to use in a radiation heavy environment such as MAGPIE where substantial amounts ($> kJ$) of thermal x-rays are emitted during wire array implosions. Other ion detectors such as RCFs and scintillators are sensitive to a wide range of radiation (including both electrons and x-rays) and would make any interpretation ambiguous.

6.1 Overview of Radial Wire Arrays

A RWA is a type of load consisting of thin wires (10 - 20 $\mu\text{m}$) placed perpendicular to concentric electrodes in a planar geometry. A diagram of this is shown in figure 6.1. An even (8, 16 or 32) number of wires ensures each diagnostic window has an identical view of the target. The dynamics of these arrays can produce jets which are collimated both hydrodynamically and magnetically. Previous experiments with such jets have looked at a range of topics surrounding their launching mechanics, collimation [79], propagation and interactions with ambient medium [78]. The dimensionless numbers relevant to these jets such as Mach number, Reynold’s number, etc. are in the correct regime to be astrophysically relevant. This means that a well characterised laboratory experiment can address problems of direct relevance to astrophysical length and time.
scales. Models of astrophysical jets show that the magnetic field plays a crucial role in jet launching and subsequent collimation \cite{83, 84} and the RWA offers a way to integrate a dynamically significant magnetic field into the experiment which is a unique feature compared to purely laser driven jets studies. In addition to magnetic fields, radiative cooling is also thought to play an important role in the collimation of the jet \cite{16}. The loss of energy lowers the internal temperature of the jet, hence it experiences additional axial pressure to maintain density \cite{137}. Modifications to the cooling regime are typically achieved by changing the target material. Higher atomic number (Z) materials exhibit substantially more radiative cooling via increased line emission (scaling as $\sim Z^2$) and offer a way to control the cooling rate without changing the target geometry. This method has been confirmed in experiments with laser driven ablation of conical targets \cite{123} and also conical wire arrays \cite{2, 3}. In both cases, it was observed that higher Z targets resulted in narrower jets. The dynamics of RWAs

![Diagram of a RWA load. Thin metallic wires are held between the anode and the cathode. The application of a powerful pulsed current (blue arrow) creates a strong magnetic field around the cathode (red arrows). The ablated plasma is accelerated vertically by the $J \times B$ force (green arrow). Further evolution is heavily influenced by this magnetic field topology.](image)

Figure 6.1: Diagram of a RWA load. Thin metallic wires are held between the anode and the cathode. The application of a powerful pulsed current (blue arrow) creates a strong magnetic field around the cathode (red arrows). The ablated plasma is accelerated vertically by the $J \times B$ force (green arrow). Further evolution is heavily influenced by this magnetic field topology.

have already been studied experimentally \cite{77} and numerically \cite{36, 35, 34} in some detail. Recent experiments have looked at controlling the initial conditions of the magnetically driven jet by changing cathode diameters and wire thickness \cite{137}. The initial phase of the evolution of this system is governed by the ablation of plasma from the wires which occurs at the edges leaving a solid core behind. The current
flows preferentially at the edges owing to the lower resistivity while the core acts as a mass reservoir for a large duration of the evolution (fig 6.2a). The direction of the ablation is in the vertical direction due to the interaction of a radial current ($J_r$) with azimuthal magnetic field ($B_\phi$). It should be noted that the global magnetic field around the cathode is stronger than the fields around the individual wires as the current is distributed evenly between the wires. The ablation rate is smallest above the cathode (as the magnetic field is strongest on the edge of the cathode). Thus, the ablated plasma converges on axis due to local pressure gradients to form a predominantly hydrodynamic jet (orange). The wires in proximity to the cathode experience a faster ablation rate due to a larger magnetic field. This results in a formation of a gap in the wires which is pushed by the magnetic field to form a cavity (fig 6.2b). The current path is now along the edge of the cavity. The cavity elongates in the axial direction where the strength of the magnetic field remains roughly constant with height. At later times, a combination of increasing magnetic field and radiative losses cause the central plasma column to collapse to a narrow jet. Current driven MHD instabilities make the jet go 'clumpy' ($m=0$ and $m=1$ modes are visible in x-ray images). The disruption of the current path due to these instabilities makes it more
favourable for the current to reconnect at the base than flow through the cavity. The jet is now detached from the base and effectively 'launched' away from it. The re-connecting current can result in the formation of further cavities which has recently been observed by replacing the wires with a radial foil load \[134, 135\].

![Experimental XUV self-emission images](image1)

![Simulated X-ray self emission](image2)

Figure 6.3: Evolution of the magnetic cavity. Top) Gated XUV self-emission images from s071406 which was a $16 \times 13$ $\mu m$ tungsten array. Bottom) Synthetic x-ray images from 3DMHD code Gorgon[33]. The evolution of the magnetic cavity and the instabilities in the jet (‘sausage’ and ‘kink’ modes) are reproduced accurately in the simulations. Images adapted from [35]

Figure 6.3 shows the measured evolution of the magnetic jet via XUV self-emission images along with simulated images from the 3D magneto-hydrodynamic (MHD) code Gorgon [33]. Both sets of images agree on the dynamics observed along with their timescale. Absolute times tend to vary shot to shot depending on the value of the current and relative timing of the Marx banks. 3D MHD simulations can be used to reveal the expected complexity of the magnetic field topology inside the jet. Figure 6.4 shows a simulation performed using a 3D MHD code Gorgon of the the central portion of a magnetic jet from a RWA configuration (same region as figure 6.3). A complicated topology consisting of toroidal and poloidal components is seen. The presence of current driven MHD instabilities twists the field in a manner which
is difficult to measure experimentally. Such challenges are a primary motivation for using laser accelerated protons to make direct measurements of magnetic fields embedded within a high energy density plasma.

The dynamics described above are typical of RWAs without considering the details such as wire thickness or load material which primarily change the time at which particular features evolve. Since the ion self-emission data presented here is time-integrated, variations between different mass arrays can be ignored. The 16 x 10 \( \mu m \) tungsten array (with a 6.35 mm cathode diameter) was the preferred load for the experiments described below. Historical evidence shows that useful comparisons can be made between different shots if the array type is the same.
6.2 Ion Self-Emission Results

The spatial characteristics of the ion self-emission were measured using pinhole and flyeye cameras developed by the author and the energy spectrum was measured using a magnetic spectrometer. Figure 6.5 shows the typical diagnostic arrangement used to obtain data. Since RWAs exhibit good symmetry about the axis, every diagnostic fielded had an equivalent view of the target. The smaller ion diagnostics such as pinhole cameras were placed inbetween viewing ports (as per figure 6.5) so that laser probing diagnostics were not blocked. It should be noted that the Thomson parabola spectrometer used was designed to measure laser accelerated protons in the range of 10 - 50 MeV. Consequently, the significantly lower energy signal observed in these experiments did not fit its measurable energy range.

![Figure 6.5: Experimental setup for ion self-emission diagnostics. 1 - Thomson Parabola; 2 - Magnetic Spectrometer; 3 and 4 - Ion pinhole Cameras; 5 - High resolution Flyeye; 6 - Ion pinhole camera with low magnification; 7 - XUV pinhole cameras; TCC - Target chamber centre. It should be noted that not all diagnostics were used for each shot.]

6.2.1 Spatial Characteristics of Ion Self-Emission

Time-integrated pinhole images obtained for various pinhole diameters are shown in figure 6.6. It should be noted that these plots are in false colour for clarity and as ex-
plained in section 4.2, it is difficult to interpret the internal structure unambiguously. Images 6.6a-c were obtained with a constant magnification of \(\sim 0.5\) and the pinhole diameters were 1 mm, 300 \(\mu m\) and 100 \(\mu m\) respectively. The final figure is a low magnification (\(\sim 0.12\)) image with a 300 \(\mu m\) pinhole. None of the pinhole images were filtered as this reduced the ion flux substantially. The etching times were short, typically up to one hour, which implied a large low energy ion flux. The results show that a reduction in pinhole size reduces the flux reaching the detector and this increases the measured aspect ratio of the jets. This implies that the central portion of the jet is emitting more ions compared to the ambient plasma (for a constant etching duration). To confirm this, the total number of ion pits from an unsaturated image were counted (Figure 6.8) to give absolute fluence levels. Microscope images were taken at 1 mm intervals at a height of 25 mm (along the central axis of the CR-39 as shown in figure 6.8) and pits were counted using the cell counting mode in ImageJ software. A typical scanned image obtained from the microscope is shown in figure 4.2. The manual pit counting shows that the highest emission is along the jet axis. The observed pits under the microscope are circular which is consistent with axial emission normal to the detector. Etching the CR-39 for shorter duration reveals the low energy ion pits only, however, the data from the magnetic spectrometer confirms that this is where most of the emission lies.

The overall emission region (83 mm tall) seen from the low magnification image (figure 6.7b shows the pinhole images with target scale) is very large compared to the typical size of the magnetic cavity. In this setup, the pinhole is much further away from the source, therefore, it is much more sensitive to the weaker emission from the ambient plasma. It is worth noting that timescale of this emission is likely to be much greater than the dynamical timescale of the experiment and can therefore be considered as background signal. The aspect ratio of the ion pinhole image in 6.6c is 1:4.2 and is distinctly 'jet-like' with the emission from the background suppressed. The overall emission region can be compared with other diagnostics to obtain a correlation between regions emitting ions and relevant features of the jet as determined from XUV self-emission and optical probing. Figure 6.9 compares
Figure 6.6: False colour ion pinhole images obtained as a function of pinhole diameter. The distances shown on the graphs are real sizes of the plasma being imaged while the axis scale corresponds to the size on the CR-39. Smaller pinholes reduce the flux reaching the detector. This reveals the region of highest ion emission. Pinhole diameters were a) 1 mm, b) 300 µm, c) 100 µm and d) 300 µm. It is not possible to be certain where the cathode lies in these images as there is no pre-shot to compare with but the direction of propagation of the jet can be inferred (dashed arrow on a)).

Figure 6.7: Images from figure 6.6c-d with axes scaled to plasma size rather than detector. It is interesting to note that the emission region appears to be larger in the low magnification image. This is believed to be an artifact of a long etching duration on a low flux image.
Figure 6.8: Left) Diagram showing position of line scan in dashed relative to the dimensions of the CR-39 detector. Right) Line-out of total number of pits in each image from a unsaturated CR-39 film used in a pinhole camera. Area covered by each image is \( \sim 0.5 \text{ mm}^2 \). It should be noted that unsaturated CR-39 looks clear to the naked eye and the position of the jet is for illustrative purposes only.

The spatial extent of emission from the pinhole camera with time resolved Schlieren and XUV imaging. Schlieren imaging allows free electron density gradients in the plasma to be visualised [66]. The refraction of laser light at these density gradients manifests as changes in brightness levels of an image. It is possible to obtain exclusive sensitivity to these density gradients by blocking the unrefracted light from the plasma with a focal plane beam stop. This results in a dark image with a bright outline corresponding to the density gradients. In the context of RWAs, it can be used to image dense turbulent flows and shocks. Images in figures 6.9a-b are taken during the early phase of evolution of the magnetic jet. The maximum size of the cavity seen in these images is only 25 mm compared to 50 mm extent of the ion emission region. Figure 6.9d is a late time (303 ns) XUV image which has been scaled to fit on the same axis as the ion image. The XUV image was taken after the cavity has 'collapsed' to look at propagation of the launched jet. To increase the field of view on the XUV image, a single pinhole was used to illuminate two quadrants of the MCP (both triggered at different times). The top quadrant (region above the grey bar in the figure) only shows the top part of the cavity which allows the extent of the jet to be measured. Whilst direct comparisons between features is not possible, it is
Figure 6.9: Comparison of ion emission region (c) with time resolved optical Schlieren (b) and XUV diagnostics (a,d) at key points during its evolution. The loads for all the shots were $16 \times 10 \mu m$ tungsten RWAs. The cathode position is shown in red dashed line and is estimated for the ion image (black dash). The grey area in subfigure d) is the dead region between MCP detector frames.

Interesting to note that the extent of the higher flux ion emission is in fact smaller than the dynamical size of the extended plasma. This is suggestive of a transient emission mechanism such as a short timescale plasma instability.

Another interesting feature which was noticed in some of the pinhole images was an angular deviation of the emission away from the vertical. Small changes in the way the central cathode is positioned can result in the jet being formed at an angle. This results in the remnants of the magnetic cavity propagating at an angle to the array axis. Figure 6.10 shows a pinhole image with a tilted jet alongside an XUV image (369 ns) showing 'clumps of plasma' propagating at an angle. For this shot, the array was lowered by 22 mm compared to standard shots which allowed the late
Figure 6.10: Comparison between time integrated ion pinhole image and time resolved XUV at 369 ns after current start from the same shot. The deflection seen on the time integrated image is consistent with ‘clumps’ of plasma propagating at an angle to the axis. This can be a result of small angular deviations in the load mounting.

time dynamics to be captured (this has also resulted in the pinhole image clipping on the CR-39). The plasma density at such times is lower than the detection thresholds of laser probing but the ion pinhole image effectively provides a ‘streak’ of the clump motion. It should be noted that due to saturation, it is not possible to discern the ion species responsible for the emission.
A flyeye camera consisting of a series of tubes was used to image the ion emission. Initial experiments conducted in 2010 used the low resolution version of this device (25 pixels) as it was easier to machine and the aim was to test the concept. The results obtained were promising and images using naked CR-39 showed a distinct shadow pattern despite being saturated. The shadows pointed to a source smaller than the scale of the system which indicates that the process responsible for them is faster than the typical evolution time of the RWA. Filtering with 6.5 µm thick aluminium foil removed the low energy background whilst leaving the shadow pattern intact. A typical image of a shadow is shown in figure 6.11 where the first image corresponds to a region which has been fully illuminated by the source and the second image shows partial illumination. The black ring represents the size of the aperture. The size of the aperture and the known experimental geometry can be used to estimate the location of the source relative to the aperture. Each tube is able to give one point of information which corresponds to the furthest a source can be to give the required pattern. This assumes that the emission is azimuthally symmetric and is shown schematically in figure 6.12. It should be noted that the resolution of the scanner has been used to convert pixels to lengths (47 pixels/mm). The red dots in the figure correspond to key positions as labelled by their co-ordinates. They are chosen to lie along a line perpendicular to the tangent of the shaded region. A displacement vector (shown in blue in figure 6.12) normal to the curve of the shadow can be generated as
Ion Self-Emission from Radial Wire Arrays

\[
\mathbf{r} = \begin{pmatrix} x_3 - x_2 \\ y_3 - y_2 \end{pmatrix}
\]  

(6.1)

where \(x_n, y_n\) are co-ordinates of the point. Since the shadow represents a 2D image, this displacement vector is in the plane parallel to the detector, however, the source lies in the target plane so a \(z\) component is added to the vector. This can simply be approximated as the distance from the target to the front of the tube (as per figure 6.13). Additionally, the angular magnification of the tubes must be accounted for by multiplying with a factor equal to the ratio of the target distance \((d)\) to the tube length \((e)\). This three component vector maps the point on the edge of the tube aperture which causes the shadow on to the edge of the source emitting protons. This is indicated diagrammatically in figure 6.13. The position of the source point \(\mathbf{r}_s\) can then be expressed

\[
\mathbf{r}_s = \begin{pmatrix} (x_3 - x_2) + (x_2 - x_1) \times (d/e) \\ (y_3 - y_2) + (y_2 - y_1) \times (d/e) \\ d \end{pmatrix}
\]  

(6.2)

This procedure is carried out per shadow data point. Due to difficulties in plotting and visualising 3D data on paper, 2D projections are plotted in important planes to elucidate the size of the source.

This allows a locus of points to be plotted which encompass the extended source. Figure 6.14 shows such an image along with the data extracted from the shadow pattern (blue arrows). Unlike pinhole images, the cathode position can worked out from the pre-shot geometry. These images are from the viewpoint of looking down the flyeye tubes towards the target. Figures 6.16 and 6.17 show the side-on and end-on projections of the data relative to the RWA target. The side-on view is plotted alongside a Schlieren image taken at 244 ns (from the same shot) with the same scale on the height axis. The known distance between the target and the aperture of the tubes is used to create a vector which is extended to the source plane. This allows the height of the source to be estimated between 20 and 35 mm above the
Figure 6.12: Methodology to work out the position of proton source from shadow pattern. The grey region corresponds to the shadow. The co-ordinates of the points in the red are used to generate a direction perpendicular to the shadow (blue arrow). For example \( \mathbf{r}_3 - \mathbf{r}_2 \). Additional geometric parameters such the tube length and target distance can be used to scale the direction to the target plane.

Figure 6.13: End on view of the flyeye camera geometry. The shadow caused by the aperture of the tube is indicated in dashed lines. The red line connects the edge of the emitting source to the rim of the tube. The grey region is where protons are detected.
cathode position. This corresponds to a region which is not imaged by the Schlieren diagnostic. Similarly, the width of the source can be calculated from the end-on projection (figure 6.17) as \( \sim 6 \) mm which is limited by the size of the tube aperture. The ability to localise the source spatially in this manner proved to be interesting and was visited again with a higher resolution version of the camera whose construction was prompted by this observation in the next section.
Figure 6.14: Results obtained with the low resolution flyeye. Left) False colour image of etched CR-39 showing flyeye shadow pattern from RWA. Right) The blue arrows are the calculated directions of the shadows accounting for the distance to the target projected in the plane of the detector. The black dots are the end positions of the vector which represent the edge of the source.

Figure 6.15: Figure 6.14 with the direction data super posed on the shadow pattern. The position of the aperture rims are indicated on few points for the sake of additional clarity. Each shadow is used to extract a position for the source edge.
Figure 6.16: Side-on projection of shadow data in figure 6.14 compared with an optical Schlieren image to potentially isolate the source of the emission. The known distance between the load and the flyeye aperture has been used to project the arrows on to the source plane. The Schlieren diagnostic is designed to image spatial structure during the early phase of the RWA evolution and has a limited field of view. The arrows (time-integrated) point to region where the plasma has not reached at 244 ns after start of current. This suggests the emission occurs transiently at a later point during the evolution of the RWA. The cathode position is shown in red. Vertical axis is on the same spatial scale in both images.

Figure 6.17: End-on projection of the flyeye data from figure 6.14 allows the width of the source to be determined. In this case, the emission width is 6 mm which is the same as the aperture of the tubes. It is interesting to note that the measured width of the emission is narrower than the total width of the magnetic cavity as seen from optical Schlieren imaging.
Since the detector was filtered with 6.5 µm thick aluminium foil, only ions above a certain threshold energy can reach the detector (see figure 4.3 for transmission curves). For example, protons would need a minimum energy of \( \sim 600 \text{ keV} \) whereas tungsten ions would require energies in excess of \( > 50 \text{ MeV} \). Other ions which are likely to be present include oxygen and carbon from hydrocarbon impurities in the tungsten wires (typically 99.9 %). Even these would need energies in the 6 - 7 MeV range to penetrate the aluminium foil. Given the specifications of MAGPIE, the required ion energies are unrealistic, and so protons are the only likely source of these 'shadows' on the CR-39 detectors. Impurities are also the source of laser accelerated protons [86]. It should be noted that the CR-39 etching duration was consistent with protons rather than heavy ions. Similar shadows were also seen when the detector was covered with 12.5 µm aluminium foil filter which has an even higher cut-off energy (\( > 900 \text{ keV} \) for protons). This indicates that the number of MeV protons is at least enough to saturate the CR-39 detector.

As mentioned in section in 4.2, the large aperture of the tubes of the low resolution flyeye can only localise the source to its width, which limits the resolution of the system. The same experiment was repeated with the higher resolution version of the flyeye and the data obtained is shown in figure 6.18 along with a Schlieren image for comparison. The shadow pattern present in figure 6.14 is still visible. The region enclosed by the blue arrows is plotted in red on the Schlieren image which has been scaled to the same magnification. The spatial localisation implies that the central magnetic jet could be a source of the higher energy protons. The side-on and end-on projections (figure 6.19) allow the dimensions of the source to be evaluated. The width of the source is \( \sim 3.5 \text{ mm} \) and the vertical extent of the source is a \( \sim 9 \text{ mm} \) region at a height of 15 mm above the cathode.
Figure 6.18: High resolution flyeye data along with a Schlieren image for comparison. Left) plot showing high resolution flyeye pattern along with vectors pointing (blue arrows) towards the source. Schlieren image taken at 237 ns shows on the same plot in red the region enclosed by the blue arrows. The cathode position is indicated in red below. The results indicate that the higher energy protons appear to originate from the top of the magnetic cavity.

Figure 6.19: Projections of the high resolution flyeye data Left) Side projection of the ion source vectors in figure 6.18 gives a width of ~ 3.5 mm on the source plane. Right) End-on projection of the vectors in figure 6.18. SP - Source Plane.
6.2.2 Energy Spectrum of Ion Self-Emission

The energy spectrum of the ions from RWAs was measured using an appropriately calibrated magnetic spectrometer described in chapter 4. Although the spectrometer cannot directly differentiate between ion species, CR-39 etching durations and pit sizes confirmed that the bulk of the signal was from protons. The data for this section was analysed by H.W. Doyle. Figure 6.20 shows the spectrum from a typical RWA shot. The spectrometer slits were located at a height of 9 cm (31 mm above the cathode) which is the region where the higher energy emission was seen to originate from in the flyeye data. The CR-39 counts have been converted into absolute fluence values using cross-calibrated RCF film which measures the dose accurately. The graph reveals a 'low energy' peak at $\sim 100$ keV and a tail which stretches out to $\sim 4$ MeV. The fluence from the source at the energy is comparable with ion acceleration experiments driven by petawatt lasers focused on thin foils [46], although, the proton beams from laser-foil interactions have low emittance and higher cut-off energies [104]. There is no significant 'spike' in the spectrum to account for the higher energy protons seen from the flyeye data. This implies that they are indeed just the tail of the spectrum.

![Proton spectrum graph](image)

Figure 6.20: Proton spectrum from $16 \times 10 \mu m$ tungsten RWA measured using the magnetic spectrometer. The slits were located at height of 31 mm above the cathode.

The lower energy emission is consistent with measurements of the load voltages
Figure 6.21: Photograph showing the relative position of the load and the inductive voltage probe.

Figure 6.22: Diagram showing inductive probe setup used to measure load voltages. a) Illustration of the starting configuration. b) Configuration during the magnetic cavity phase.
Ion Self-Emission from Radial Wire Arrays

present in MAGPIE. Particles are accelerated by the applied voltage to an energy which is of the order of \( \sim qV \) where \( q \) is the charge on the ion. Load voltage measurements were carried out in the same RWA shot series using a vacuum voltage probe designed by G. Burdiak. Additional information on this probe and its calibration can be found here [24]. A photo of the setup can be seen in figure 6.22a. Voltages present inside the anode-cathode (AK) gap can be measured using a voltage probe connected to the cathode below the RWA target assembly (see figure 6.22b). The formation of the magnetic cavity and the associated change in current path modifies the inductance of the load (figure 6.22c). The measured voltage \( (V_m) \) can be written as

\[
V_m = \frac{d}{dt}((L_0 + L_{mag}(t))I(t)) = L_0 \frac{dI_C}{dt} + \frac{d}{dt}(L_{mag}(t)I_C(t))
\]

where \( L_0 \) is the inductance of the load and the \( L_{mag} \) is the cavity inductance. The voltage profile from the load inductance can be calculated from the Rogowski signal while any additional voltage can be attributed to the extra inductance from the magnetic cavity (represented by the second term in the equation above). A figure 6.23 shows a measurement of the voltage profile \( (V_{array}) \) from the voltage probe from a RWA shot alongside a PCD measurement of the x-ray self-emission. At early times, there is good agreement between the voltage probe measurement and the Rogowski signal as the inductance is time independent. The difference between the two signals \( (\Delta V, \text{shown in black}) \) is due to the additional inductance of the magnetic cavity formed in the plasma and corresponds to the voltage between the cathode and the edge of the cavity (illustrated in figure 6.22c). The large spike in the PCD voltage correlates with the peak in the x-ray emission which is caused by the pinching of the plasma on axis and coincides with the peak cavity voltage. The magnitude of the voltage \( (\sim 90 \text{ kV}) \) explains the large fluence of low energy protons observed in the energy spectrum which originate from the jet. The higher energy protons seen in the filtered flyeye image and the tail of the energy spectrum requires additional acceleration mechanisms to explain properly.
The acceleration of charged particles from turbulent magnetic fields is a common mechanism used to explain high energy particle radiation in space and astrophysical plasmas\cite{25, 43}. A dynamic magnetic field can induce electric fields which can then accelerate ions (and protons in particular). The unstable central jet inside the magnetic cavity is known to create turbulent magnetic conditions where such acceleration can occur and offers a plausible explanation for the discovery of the higher energy tail ($\sim$ MeV) in the proton spectrum and also the spatially localised proton emission from the central jet.

The 3D MHD code Gorgon which is used to simulate experiments on MAGPIE is unable to handle particle self-emission in its model of RWA dynamics. Despite the lack of explicit treatment, numerical simulations done by A.\textit{Ciardi et al} on the evolution of magnetic tower jets offers an interesting explanation on the high energy protons\cite{35}. The presence of an axial current creates a strong toroidal magnetic field
inside the cavity (configuration in figure 6.2b). This field is strongest close to the axis with a peak strength up to $\sim 100$ T at a radius of 1 mm (assuming all the peak current is conducted through the jet). A strong magnetic field is able to trap high energy protons if their Larmor radius is smaller than the scale length of the magnetic field. If the jet is assumed to be a conducting cylinder of plasma, then the magnetic field drops as $r^{-1}$. The high energy protons such as those seen to be emanating from the magnetic jet in figure 6.18 can only be accelerated close to the axis. Figure 6.24 shows the variation of the magnetic field with increasing distance along with the proton Larmor radius for a range of test energies. The horizontal spatial scale is of the order of the magnetic cavity radius and the magneta line corresponds to the condition that the Larmor radius is less than the size of the system. The calculations show that only protons with energy less than 8 MeV can be localised to the cavity radius.

The observed height of proton emission from the flyeye data coincides with a region of MHD instabilities. Simulations performed in [35] have shown that the $m = 1$ ‘kink’ instability dominates the late time evolution and is followed by a reconfiguration of the current path to the base of the jet. This process occurs on a time scale of tens of nanoseconds and could explain the transient emission of the energetic ions. Whether the instabilities accelerate the protons or simply allow them to escape would require time resolved measurements to understand. Although the launched jet is thought to retain some of its magnetic field [35], it is unlikely to be strong enough to trap the higher energy protons. Measurements of the trapped field were performed for a radial foil configuration which has largely similar dynamics to the RWA and the trapped field was estimated to be of the order of 1 T [135].

From an astrophysical perspective, the cyclotron radiation emitted by charged particles trapped in magnetic fields can be used to measure its field strength [145, 51]. Due to the high energy nature of cosmic particles, this radiation is in visible and x-ray region where measurements via telescopes are possible. For a typical 100 keV proton trapped in the jet, the gyrofrequency is of the order of $\sim$ GHz. Although measurements in this range are not possible on MAGPIE, it is interesting to note that
Figure 6.24: Graph showing the expected variation of magnetic field (dashed black) against the radius of the magnetic cavity. The proton Larmor radius as function of distance for a range of energies is also plotted. Protons are assumed to be trapped when their larmor radius is less than twice the cavity radius. This condition is illustrated by the pink line on the graph and arrows correspond to region where the condition is fulfilled.

the particles themselves may be observable. This offers new avenues in exploring jet dynamics in the future.

### 6.4 Time resolving the emission

The time-integrated data obtained above has been useful in understanding many aspects of the ion self-emission, however, the addition of time resolution to these diagnostics would allow images to be made during the evolution of RWAs. This would offer a novel and unique diagnostic capability to study their dynamics. Despite the advantages of CR-39 in detecting ions, there is no simple method to time resolve its response on a nanosecond scale. Space and time resolved detectors such as MCPs are sensitive to ions but prohibitively expensive for our use and likely to suffer from significant x-ray background signal. The destructive nature of RWA blast would risk considerable damage to naked MCPs and filtering would suppress the signal. Imaging of particle radiation has been successfully used to diagnose imploding
fusion capsules [42, 115]. In these experiments, the fusion neutrons are imaged using fibres which also act as scintillators. These can then be fed into a time-resolved intensifier and imaged on a standard detector. Long time of flight tubes are used to separate particle radiation from high energy photons which will also be detected by the scintillator. Unfortunately, such a setup was beyond the scope of this project.

Silicon diodes are also capable of detecting ions. The AXUV range of diodes from International Radiation Detectors Inc has Proton responsivity of 0.27 A/W and sub-ns rise times. Such diodes have previously proved useful in spectrometers due to their energy response and efficiency [102]. To separate the proton signal from the photon one, the diode would need to be placed at least 2 m away from the source. Their small surface area (0.8 mm$^2$) would make it hard to get measurable signals at such a distance as the as proton flux is low.

To address the limitation described above, direct time resolution of the proton emission was attempted through the use of a pulsed electric field. In this scheme, (shown in figure 6.25) a pinhole camera was modified by installing two electrodes after the aperture to deflect the protons for 30 ns. This would result in a secondary pinhole image adjacent to the time-integrated one. The magnitude of deflection from the charged plates is a function of incoming ion energy and since we have a poly-energetic spectrum, the low energy (100 keV) emission would be gated where the fluence was the highest. A pulsed high voltage power supply capable of delivering 3 kV for 30 ns was used achieve deflection. The system was used in low magnification to reduce the size of the image on the detector (such that two discrete images could fit on a single piece of CR-39) and an equivalent pinhole imaging setup was placed on the opposite side of the array to give a reference image. The plates were triggered to gate the emission from the collapsing magnetic jet and the time of flight (≈ 250 ns for 100 keV protons) from the jet to the detector was accounted.

Initial experiments have shown no useful results using this diagnostic. The time-integrated image (straight-through) was present on all occasions which implies that the deflection plates did not work as designed. It is not clear whether the emission simply occurs at a different time to the gating pulse or if the protons are space charge
neutral and not sensitive to electric fields. Due to the low shot rate on MAGPIE, it is difficult to test new diagnostics of this kind, and so further testing with a higher repetition rate laser driven proton source is planned.

The large low energy self-emission of protons is unlikely to be an issue when performing future experiments with laser accelerated proton probes. Given the projected specifications of the laser, typical proton energies of $\sim 10$ MeV will be routinely accessible and further improvements can be had by modifying target geometry. [54]. The sub-MeV energy background signal found in the work reported here can easily be filtered using thin aluminium foils (12 $\mu$m) on CR-39 films. RCF (RadioChromic Film) detector stacks will require additional shielding to discriminate x-ray signal from proton signal. A greater obstacle is likely to be protecting the thin foil target used to generate protons from the radiation emitted by the RWA during the early phase of its evolution (a double foil target is planned to overcome this). Additional work to characterise the shielded targets with a double foil geometry are planned.
Summary

This chapter describes experiments conducted to study the self-emission of ions from RWAs on MAGPIE for the first time as a prelude to active probing with laser generated protons. The spatial characteristics were measured using pinhole and flyeye cameras while the energy spectrum was measured with a magnetic spectrometer. It was observed that the bulk of emission consists of low energy protons which are primarily emitted from the axis of the jet along with a tail which stretches out to \( \sim 4 \) MeV. The flyeye data revealed that higher energy protons (\( > 600 \) keV) were emitted from the top of the jet. These could be accelerated by the strong dynamic magnetic field of the jet and escape when current driven instabilities disrupt it. Attempts to time resolve the emission were not successful, however, further testing of the time resolved diagnostic is planned using a higher repetition rate laser driven ion source.
Chapter 7

Conclusions and Future Work

This thesis describes the development of a large multi-beam Nd:Glass based laser system called Cerberus which has been designed to provide advanced plasma diagnostic capabilities for the MAGPIE pulsed power facility. This system is still in active development and initial results from the implementation of the laser system and the plasma diagnostics it drives are provided along with experiments conducted as a part of this project.

The introductory chapter provides an outline of the laser system and justifies its target specification with reference to the planned experiments. The scientific motivation for three planned experiments - Proton probing, x-ray backlighting and Thomson scattering is provided. A brief introduction to laser driven plasma diagnostics is also given.

Since this laser system was developed from scratch, each section had to be designed, simulated and implemented. While an equivalent custom commercial system might be possible to source given a sufficiently large budget, this would not have been a cost effective route as Cerberus uses a significant quantity of existing capital equipment, particularly large aperture amplifiers. Chapter 2 provides the theoretical background pertinent to laser physics and the technological aspects of short pulse lasers. An introduction to the area of nonlinear optics along with the challenges inherent in the amplification of ultrashort light pulses is provided. A description and comparison of the main methods of amplifying ultrashort pulses of light, CPA
Conclusions and Future Work

and OPCPA, is given. Simulations for the core CPA components of the Cerberus sub-system were carried out using a ray tracing code called CPTrace3D and its functionality is also described. This is followed by an overview of the diagnostics used during the implementation of the laser system.

Chapter 3 provides a detailed description of the development of the Cerberus front end used to seed multiple short and long pulse beam linses with very low jitter optical synchronisation. It begins by considering the design parameters and simulations for an advanced CPA setup to complement the optically synchronised OPCPA scheme. A total of six core CPA components were simulated and designs optimised against target specifications, particularly contrast and pulse duration with a constrained equipment budget. Given the large scale of the project, not every single optical component is mentioned but a detailed functional description of the major sections such as the amplifiers, stretchers and compressors is provided. Initial results are presented on the performance of the long pulse beam and results from the first two short pulse pumped OPA stages are also included.

The experiments described in this thesis were performed on the MAGPIE generator, and these required integration of two complex research systems to create a facility only surpassed by the Sandia National Laboratory. This chapter provides an overview of the pulsed power facility along with the diagnostic suite which supports experiments on it. This includes current monitoring diagnostics such as Rogowski coils and also the wide range of laser probing setups such as interferometry. Ion diagnostics used for the experiments in chapter 6 are introduced here in detail. The Thomson probe beam line which was developed as a part of the Cerberus project and used for the experiments described in chapter 5, is discussed in detail along with the data acquisition system and stray light suppression mechanisms.

Chapter 5 provides an introduction to the dynamics of cylindrical wire arrays (CWAs) and shows results of optical Thomson scattering to measure plasma parameters during the ablation phase of their evolution. Such measurements are important to understand mechanisms of x-ray generation in CWAs and to improve their yield. This is of particular relevance to secondary experiments which are driven by x-rays.
such inertial confinement fusion. Velocity profiles and temperature results for aluminium and tungsten CWAs with 16 or 32 wires are presented. These represent the first direct measurements of plasma parameters in a RWA configuration. They are also compared with the 3D MHD code Gorgon which is used to simulate experiments on MAGPIE. Results from both materials are qualitatively similar with peak velocities exceeding $10^5$ m/s. In the case of tungsten, it is noted that the lower collisionality results in a broader precursor at $\sim 150$ ns which is modelled incorrectly in current generation simulations.

The ion self-emission results provided in chapter 6 reveal interesting and novel dynamics about RWAs. Pinhole and flyeye cameras were developed and used to measure the spatial profiles of the emission and a magnetic spectrometer was used to obtain an ion energy spectrum. The pinhole images indicate that the ion self-emission is strongest on axis where the density is also the greatest. The flyeye camera was filtered with a 6.5 $\mu$m aluminium filter to remove low energy ($< 600$ keV) ions. The results imply that protons with energies greater than 600 keV are emitted from the central jet at a height of $\sim 20$ mm above the cathode. The energy spectrum confirms that most of the emission consists of low energy protons which are accelerated to $\sim 100$ keV by typical voltages present inside the magnetic cavity demonstrating that future laser driven proton probes at $\sim 10$ MeV will be able to overcome the noise background. The higher energy protons are believed to be accelerated by the strong dynamic magnetic field of the central jet. These results could open new avenues of studying the dynamics of RWAs from an astrophysical perspective.

7.1 Future Experimental Outlook

As of writing of this thesis, sections of the Cerberus laser system are regularly used for experiments in different configurations on the MAGPIE generator. This section discusses some of the future experiments and planned upgrades for the Cerberus laser system.
Conclusions and Future Work

7.1.1 Proton Self-Emission

The proton self-emission data proved to be an interesting and novel way to look at the evolution of RWAs. The current inability to time resolve the emission limits the range of conclusions which can be drawn, however, improved methods of spatially resolving the data would allow measurements to be performed from a localised region.

Spatially resolving the magnetic spectrometer would allow an energy spectrum to be measured from different regions of the jets. The flyeye data has already indicated that higher energy protons emanate from approximately $\sim 3$ cm above the cathode. By combining the flyeye collimation system with the spectrometer magnets, ions can be collected at different heights in a single shot. Figure 7.1 shows an illustration of this concept. The long narrow tubes act as concentric apertures to select an ion beam with small divergence. The current flyeye data demonstrates that there is enough fluence passing through each aperture to make this experiment feasible. The use of large magnets in an appropriate orientation would give dispersion in the plane parallel to the magnets. The data can be collected using an appropriate detector such as CR-39. Correlations could be made between different spatial features (which change as a function of height as the magnetic jet evolves) and energy spectra. This would be a new and interesting way to elucidate the acceleration methods responsible for the higher energy protons which are seen to significantly exceed the peak voltages expected in MAGPIE.

As mentioned in chapter 4.2, there are substantial technical difficulties in automated scanning of unsaturated CR-39 slides. An attempted scan of an ion pinhole image with high spatial resolution is shown in figure 7.2. The software stores the position of each pit which can be plotted in a scatter graph. As can be seen from the graph, the system is far from being usable in its current state and misses large regions of data. This unreliability of scanning methods meant that saturating the CR-39 was the only way to visualise the data on the slides. The ability to scan in unsaturated pinhole images would allow for more quantitative measurements to be performed and would allow the high spatial resolution of CR-39 detectors to be exploited.
Conclusions and Future Work

Figure 7.1: Design for single shot spatially resolved spectra of the jet. A series of collimating tubes with a narrow field of view can be used to select emission at different vertical positions from the jet. A dispersive magnet setup can then be used to obtain a series of spectra on a single detector in a single shot.

Figure 7.2: Scan of an unsaturated proton pinhole image using an automated system made by Track Analysis Systems Ltd (TASL) installed at the Rutherford Appleton Laboratory.

7.1.2 Thomson Beamline

This thesis describes the first results obtained for optical Thomson scattering in CWAs. The laser system and the data acquisition system was capable of measuring a range of plasma parameters with good signal to noise ratio. In addition to the results described in this thesis, new experiments are planned to investigate additional
features of the dynamics of the precursor plasma such as the onset of collisionality.

Figure 7.3: Left) Diagram of the radial foil experiment. Red circles represent Thomson scattering volumes. The hydrodynamic jet is shown in orange and the supersonic gas valve is set at a position above the foil, perpendicular to the direction of the jet. The Thomson laser beam is focused at the centre of the jet from the axial direction and scattered light is collected perpendicular to the laser. Right) Axial velocity profile of the jet. The large drop in velocity corresponds to the interface between the gas stream and the jet. Data courtesy of F. Suzuki-Vidal.

Since its demonstration on CWAs, this Thomson scattering setup has also been used routinely in a range of other experiments such the interaction of jets from radial foil with a supersonic gas flow. Figure 7.3 shows the experimental setup for this measurement. A pulsed gas valve was used to create a supersonic flow which allows interactions between the jet and the ambient medium to be studied. This is scalable to astrophysical scenarios such as the jet from a protostar impacting on interstellar gas clouds. The laser beam was focused from the end on direction into the centre of the jet and the scattered light was measured from side-on viewing ports. This orientation allowed scattering volumes to lie axially upwards in the jet. Therefore it was possible to obtain a velocity profile of the jet in the axial direction. The measurements show a sharp drop in axial velocity at a height of 14 mm above the cathode where the gas stream collides with the jet. Additional results from this experimental configuration are published in here [136].

It is useful to be able to perform different measurements using the same laser system to minimise setup time and add flexibility to the Cerberus project. The
Nd:YAG system described for the Thomson scattering beamline is capable of giving longer pulses (\(\sim 60 \text{ ns}\)) when running in low power mode. The output energy is approximately 15 mJ and this results in negligible energy conversion to the second harmonic. However, the use of the high gain 25 mm Nd:Silicate rod amplifier results in second harmonic energies of up to \(\sim 100 \text{ mJ}\) which is a useful amount for long timescale laser probing. This longer pulse output of the Thomson probe beamline was used to perform streaked Schlieren measurements\cite{97} of radiative shocks on MAGPIE. This measurement is able to provide a trajectory of the shock wave in a single shot. Such measurements can be useful in searching for velocity domain instabilities in shock waves \cite{97}. The results obtained from these measurements are discussed by J.Skidmore in \cite{128}.

The Thomson beamline is currently capable of delivering \(\sim 3 \text{ J}\) in an 8 ns FWHM pulsewidth. Since the gated spectrometer is capable of integration times as low as 2 ns, it would be ideal to compress the energy of the Thomson beamline into a shorter pulse which will help to improve the signal further and allow lower density plasmas to be probed. Stimulated Brillouin Scattering (SBS) has been used successfully to decrease the temporal widths of Nd:YAG lasers pulses to sub nanosecond durations with minimal loss of energy \cite{1}. A tapered waveguide SBS compressor filled with 40 bar \(SF_6\) was tested for the Thomson probe beamline but it proved difficult to implement given the low shot rate on the system. It could be possible to implement such a compression system based upon liquid heavy fluorocarbons instead which as been demonstrated to deliver 25 J sub-nanosecond pulses with a 80% efficiency \cite{152}. In addition to energy compression, a 50 mm aperture Nd:Silicate rod amplifier is also available as an energy upgrade which should be able to increase the available energy to \(\sim 20 \text{ J}\) at the second harmonic. The corresponding increase in scattered photons could be used to simultaneously measure both the electron and ion components of the scattered spectrum, which would allow additional plasma parameters such as the mean ionisation be measured \cite{57}. As of writing of this thesis, the first results from the monochromatic x-ray backlighting system are being obtained. Although the laser is not operating at target specifications (only 6 J at 527 nm is available at this time),
Conclusions and Future Work

Figure 7.4: X-ray backlit image (shown in false colour) of a resolution grid using the long pulse laser beam of the Cerberus system. A silicon target was irradiated with 6 J of laser light in a 1.4 ns FWHM pulse duration. The grid was illuminated by the He-α line of the silicon at 1.865 keV which was imaged using a spherically bent crystal on to a Fuji image plate detector (BAS-TR). The results show that features as small as 4 µm can be discerned. Data courtesy of G.N.Hall.

The results are still very promising. The monochromatic imaging system is based on a similar design developed at Sandia for ‘Z-machine’ [127] and has been deployed on the MAGPIE generator by G.N.Hall. It is designed to image using a spherically bent quartz crystal, the load plasma in the He-α line (1.865 keV) of silicon. Whilst, the author was not directly involved in taking this data, these measurements are a milestone in the commissioning of the system. Figure 7.4 shows a x-ray radiograph of a resolution test grid produced on the MAGPIE generator using the Cerberus laser system. The 6× magnification of the system is capable of resolving features < 10 µm. Figure 7.5 shows a x-ray radiograph of the wings of a 'common house fly' which reveals the detailed structure of the wings. An experimental campaign to make measurements with different load configurations is now underway and figure 7.6 shows an x-ray backlit image of tungsten cylindrical wire array during the ablation phase. The streams of plasma ablating from the wire are clearly visible. These benchmark images highlight the experimental capabilities of the Ceberus laser system as a diagnostic driver for MAGPIE. The Z-machine at Sandia National labs is the only other facility with such capabilities [11]. These results will be discussed in detail in a future publication.
Figure 7.5: Monochromatic x-ray backlight image (in false colour) of a fly’s wings reveals the intricate wing structure with excellent detail. The magnification of the imaging system is 6×. Data courtesy of G.N.Hall.

Figure 7.6: Monochromatic x-ray backlight image (in false colour) of a 16 × 25 µm tungsten CWA during the ablation phase. The modulations in the ablation streams are clearly visible. A metal rod was placed on axis to suppress an implosion and limit background x-rays. Data courtesy of G.N.Hall.
7.2 Cerberus Laser System Upgrades

Despite Cerberus being very much a work in progress, additional upgrades through the use of larger aperture amplifiers and new target areas are already in the pipeline. As stated in the introduction, the Nd:Glass power amplifiers were donated to this project by AWE and only 25 mm and 50 mm rod amplifiers have been used so far. Larger apertures disc amplifiers of 108 and 150 mm diameter are also available to use as a part of an energy upgrade. These would allow the energy of the long pulse beamline to reach of the order of hundreds of joules. This would allow additional new diagnostic capabilities to be deployed such as two colour x-ray backlighting. On the short pulse beamline, the equivalent energy could be compressed, consequently, peak powers would be able to approach nearly a petawatt, although larger aperture gratings will be necessary to compress the additional energy.

![Photo of Nd:Glass disc amplifiers of 108 mm (top two) and 150 mm diameter (bottom) which are available for future energy upgrades.](image)

Along with the energy upgrades, it is important to have different targets areas to maximise the range of experiments which can driven with a large sophisticated
laser system such as Cerberus (see figure 7.8). To perform laser driven blastwave experiments in gas clusters which are astrophysically relevant, a small (≈ 3 J, < 0.5 ps) short pulse beamline using the existing front end is also under development. This would integrate components of an existing Nd:Glass laser to take advantage of the 10 Hz OPCPA pre-amplifiers. The amplifiers for this laser are capable operating at repetition rate of one shot a minute which would make it ideal as a diagnostic testbed for other experiments. Newly refurbished labs will also allow the Cerberus beam to be used for laser driven shock physics experiments and also assist in equation of state measurements in the MACH facility [15].
Conclusions and Future Work

Additional target areas and planned upgrades

Cerberus Front end and OPCPA Amplifiers
Short Pulse Beam
Phosphate Nd:Glass Amplifiers

Target Chamber

Nd : Glass Power Amplifiers

MAGPIE Beam Delivery
MAGPIE Target Chamber

Nd:Glass Power Amplifiers

Spherical Target Chamber

Lab 1

Lab 2

Lab 3

Lab 4

Lab 5

Figure 7.8: Diagram showing the original Cerberus project (Labs 1-3) along with the planned additional target areas (Labs 4 + 5) which will all share the front end described in this thesis.
7.3 Concluding remarks

The Cerberus laser system described in this thesis offers unique experimental opportunities in high energy density physics through the combination of high power lasers and pulsed magnetic fields. It is expected to operate for a decade or more, providing diagnostic and driver beams to multiple areas and multiple experimental programmes. The development of a sophisticated OPCPA front end allows multiple beam lines to be derived from a common system which can be shared between different experiments. The results on Thomson scattering and ion self-emission offer interesting new avenues of exploring the complex physics of wire arrays in MAGPIE and demonstrate the exciting potential for this project in emerging areas such as laboratory astrophysics.
Appendix A

Derivations for Optical Thomson Scattering

It is useful to be able to compute theoretical spectra for Thomson scattering for fitting with observed data. The approach shown by Salpeter [121] is followed here with collisions, relativistic effects and magnetic fields not being considered. It allows the observed spectrum to be split into the sum of two dimensionless components, the electron \(x\) and ion \(y\). It should be noted that the ion-component refers to scattering from electrons confined to the Debye sphere, not the ions themselves.

\[
x = \frac{\omega - \omega_0}{\sqrt{2k^2k_B T_e/m_e}} \quad (A.1)
\]

\[
y = \frac{\omega - \omega_0}{\sqrt{2k^2k_B T_i/M_i}} \quad (A.2)
\]

where \(\omega - \omega_0\) is the frequency shift, \(k\) is the scattering vector, \(k_B\) is the Boltzmann constant, \(T_e\) and \(m_e\) are the electron temperature and mass, and \(T_i\) and \(M_i\) are the ion temperature and mass. The theoretical spectra for the electron \(S_e(k, \omega)\) and ion component \(S_i(k, \omega)\) can be expressed as

\[
S_e(k, \omega) = \frac{1}{\sqrt{\pi}} \frac{n_e}{\sqrt{2k^2k_B T_e/m_e}} \Gamma_\alpha(x) \quad (A.3)
\]

\[
S_i(k, \omega) = \frac{1}{\sqrt{\pi}} \frac{n_i}{\sqrt{2k^2k_B T_i/M_i}} \Gamma_\beta(y)
\]

214
Derivations for Optical Thomson Scattering

\[ S_i(k, \omega) = Z \left[ \frac{\alpha^2}{1 + \alpha^2} \right]^2 \frac{1}{\sqrt{\pi}} \frac{n_e}{\sqrt{2k^2k_BT_i/M}} \Gamma_\beta(y) \tag{A.4} \]

where \( Z \) is the ionisation state, \( \alpha \) is as defined previously and the \( \Gamma \) functions are as defined below for electron and ion component

\[ \Gamma_\zeta(z) = e^{-z^2} \left[ 1 + \zeta^2(1 - f(z)) \right]^2 + \pi\zeta^2e^{-2z^2} \tag{A.5} \]

In the above equation, \( \zeta \) is equal to \( \alpha \) for the electron part and \( \beta \) for the ion part. Similarly \( z \) is set to \( x \) for the electron component and \( y \) for the ion. The parameter \( \beta \) is defined separately as

\[ \beta^2 = Z \frac{T_e}{T_i} \frac{\alpha^2}{1 + \alpha^2} \tag{A.6} \]

The function \( f \) is defined as

\[ f(z) = 2ze^{-z^2} \int_0^z e^{t^2} dt \tag{A.7} \]

This function is commonly known as the \textit{Dawson’s Integral} and can be evaluated in Matlab by calling a built in library \textit{mfun(‘Dawson’)}. The total spectrum can be obtained by summing the electron and ion parts. The spectrum obtained in this way can then be convolved with the measured spectrometer response function to give a reasonable model for fitting data.
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