Applications of Magnetic Fields in High Energy Density Plasmas

by

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In memoriam

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Biographical Sketch

Daniel Barnak was born in Lansdale, PA in 1987 and raised in the small town of Telford, PA. He graduated from Souderton Area High School in the summer of 2006. He was accepted with a large scholarship to Dickinson College, from where he graduated magna cum laude with a Bachelor of Science degree in Physics and Mathematics with honors. He discovered the mechanism for controlling the position of traveling and stationary intrinsic localized modes in an array of nonlinear electrical oscillators, leading to a featured publication in Physical Review E during his tenure at Dickinson. His honors thesis topic was exploring the optimal depth of an anode in a closed-drift Hall thruster, and this first experience in plasma physics spurred his desire to pursue a PhD in the subject. Upon graduating, he dedicated a year of his time in the service of his country as an Americorps member tutoring students in math and physics at Horace Howard Furness High School in Philadelphia. After completing his Americorps term, he enrolled in the PhD program in physics at the University of Rochester and worked at the Laboratory for Laser Energetics (LLE) at the University of Rochester. He has made contributions to the design and implementation of magnetized high energy density physics experiments through the development of MIFEDS (magneto-inertial fusion electrical discharge system), under the supervision of Dr. Gennady Fiksel and Dr. Po-Yu Chang. He became the
de facto lead experimental physicist of the laser-driven MagLIF (Magnetized Liner Inertial Fusion) experiments at LLE in 2016, which became his main focus of his PhD under the supervision of Professor Riccardo Betti and mentorship of Professor Jonathan Davies.

List of Publications

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6. “Use of external magnetic fields in hohlraum plasmas to improve laser-coupling”
   D. S. Montgomery, B. J. Albright, D. H. Barnak, P.-Y. Chang, J. R. Davies, G. Fiksel,

5. “Diagnosing laser-preheated magnetized plasmas relevant to magnetized liner inertial fusion”
   A. J. Harvey-Thompson, A. B. Sefkow, T. N. Nagayama, M. S. Wei, E. M. Campbell,

4. “Note: Experimental platform for magnetized high-energy-density plasma studies at the OMEGA laser facility”
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Science is ultimately a collaborative enterprise and rarely is it the case that major scientific discoveries are the sole responsibility of the principal investigator. The technicians, laser operators, target fabricators, engineers, instrument principal investigators and specialists, and the lab administration all work harmoniously to produce cutting edge scientific research, including the work presented in this thesis. Many of their names are not included in the publications that result from this research, but their dedication and efforts toward this project have not been forgotten. LLE is a world-class research facility, and it is my opinion that the dominant reason for this is its personnel.

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Abstract

A laser-driven magnetized liner inertial fusion (MagLIF) experiment was designed for the OMEGA laser system by scaling down the original point design for the Z machine. 1-D hydrocode modeling was used to select pulse length, thickness of the cylindrical shell, and initial gas pressure that maximizes the neutron yield within the constraints of convergence ratio and implosion velocity. An implosion velocity of twice that of Z machine implosions was chosen, and other factors in the point design matched the Z design within a factor of 2. 2-D modeling of the point design provides estimates for end losses, total neutron yields, and better estimates of implosion velocity and convergence ratio. Scaling of the OMEGA point design to MJ-class lasers was considered.

Focused experiments to establish laser preheat conditions and implosion uniformity for laser driven cylinders were performed in preparation to integrate each piece in the first ever MagLIF experiments. Implosion uniformity and velocity was determined using x-ray self-emission of the cylinders in flight. A laser balance of 83 % of peak energy for oblique beams overlapped in the center and peak energy of the normal beams irradiating the ends of the cylinder gives the most uniform cylindrical implosion. Implosion velocities were determined for 4 different shell thicknesses. Azimuthal uniformity was corrected prior to discovering a natural Legendre mode
imposed from the default laser pointing, and the effect of the correction will be measured in future experiments.

The laser transmission, backscatter, and sidescatter from laser entrance hole (LEH) windows was measured to understand LEH burn through, which is important in determining preheat timing and quantifying the amount of laser energy that reaches the gas. Backscatter and sidescatter was negligible in both the window only experiments and full cylinder preheat experiments. Analysis of soft x-ray emission from Ne doped deuterium gas filled cylinders indicates that the minimum preheat temperature of 100 eV was achieved in the implosion region. Furthermore, comparison of the x-ray spectra from experiments with simulations indicate that hydrocode predictions of laser preheating are accurate enough to be considered predictive. According to hydrocode predictions, the entirety of the gas region is preheated to an electron and ion temperature of 200 eV by the end of the laser pulse, and the timing is consistent with the 100 eV minimum preheat measured from the implosion region.

The summary of neutron yields obtained from the first integrated MagLIF experiments demonstrate yield enhancement from magnetized cylindrical implosions. Complications of the preheat beam and the Hall parameter estimations show there is no benefit to neutron yield or ion temperature from preheating. Secondary D-T fusion yield was used to infer final $\rho R$, and the ratio of initial to final $\rho R$ is used to estimate convergence ratio. Increasing convergence ratio was shown to decrease yield by the relation $Y_{DD} \sim C^{-0.818}$. Yield decreases due to high convergence causes 1-D results to diverge from experimental measurements. Hall parameter estimations using the neutron-averaged ion temperature as an approximate measurement of the electron and ion temperatures and assuming a fixed number of magnetic flux loss show that integrated shots are weakly magnetized compared to magnetized cylin-
drical compression. Future integrated MagLIF experiments must include integrated shots with higher magnetic field to demonstrate the benefits of preheat. Optimal preheat timing was determined to be 1.0 ns before the start of the laser pulse, but more measurements are required to confirm this result.
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Chapter 1

Introduction

MagLIF is a magnetized target fusion (MTF) or magneto-inertial fusion (MIF) concept first developed at Sandia National Laboratories (SNL) for the expressed purpose of obtaining an efficient Gigajoule fusion yield for electrical energy generation and nuclear weapons testing. MagLIF combines a fast near-adiabatic compression of deuterium gas, a hallmark of inertial confinement fusion, and a magnetic field to insulate against thermal conduction losses, a hallmark of magnetic confinement fusion. The concept was first designed using the classified code LASNEX [42] and first implemented in 2012 on the Z machine at SNL. The first ever MagLIF shots demonstrated an order of magnitude increase in yield over a traditional Z-pinch compression of DD fuel without magnetized preheated gas [19]. The results were promising in that they were replicated with 2-D modeling, though the initial internal energy of the gas needed to be artificially decreased by a factor of 6.

MagLIF is a 3 stage process of axially magnetizing a deuterium gas inside a cylindrical metal liner, preheating the gas axially using a laser, and imploding the metal liner using a large axial current and azimuthal magnetic field similar to a
traditional plasma Z-pinch. Preheating the gas inside the liner provides a higher initial temperature leading to a higher final temperature under near-adiabatic compression for small convergence ratios. The magnetic field provides insulation against thermal conduction losses during the implosion. The Z-pinch compression happens at roughly 1/3 the speed of a traditional ICF implosion and produces only a weak shock, so the liner isn’t as susceptible to fluid instabilities such as Rayleigh-Taylor and Richtmeyer-Meshkov. A sufficient axial magnetic field strength is required to insulate heat losses during this slow implosion time so that the gas is compressed quasi-adiabatically.

Being the only pulsed-power device in the world available today able to produce the currents required for a sufficiently fast implosion, the Z machine lacks a high rate of shots and the ability to produce data with enough statistical relevance for sound scientific studies of the MagLIF parameter space. To this end, a collaborative effort between SNL and the Laboratory for Laser Energetics (LLE) was formed to provide science-based improvements to MagLIF shots on Z. The primary role of LLE was to provide a comprehensive statistical analysis of the MagLIF concept at a scale of 1:1000 of the original SNL point design. This thesis contains all of the work done at LLE for the MagLIF collaboration. It is presented in chronological order of publication of the project in its entirety: 1) The 1-D and 2-D modeling and basic scaling considerations made to formulate a point design for MagLIF at the OMEGA scale, and scaling predictions for MJ class lasers, 2) focused experiments to obtain a predictive model of gas preheat as a function of time and laser energy, 3) focused experiments to obtain a uniform cylindrical compression and in-flight shell trajectories using 40 beams of the OMEGA laser system, and 4) the combination of implosion, magnetization, and preheat culminating in the first scaled down MagLIF
implosions performed on the OMEGA laser system.

The point design for laser-driven MagLIF was scaled down from the original point design[42] for the Z machine by conserving the energy per unit volume in the implosion. Non-scalable physics such as thermal conduction losses and magnetic flux losses prohibit an exact scaling down of the MagLIF design without compromising neutron yield below measurable values. The main objective of the point design is to develop a platform that matches conditions on Z to within a factor of 2 or better. From the energy and volume scaling, the best possible design achievable on OMEGA was determined to be a 600 µm outer diameter 20 µm thick cylindrical shell pressurized to 14 atm with deuterium gas, preheated to a temperature of 200 eV, magnetized with an initial field of 10 T, and imploded using 40 of the 60 beams over a region of ~ 600 µm in length.

A series of 1-D MHD simulations were performed to see how shell thickness, preheat, magnetization, initial fuel density, laser pulse length, and laser energy affected neutron yield and neutron-averaged ion temperatures. Although 1-D simulations will drastically overestimate neutron yield compared to experiment, the overall trends within the parameter space provide meaningful insight for the design and implementation of different MagLIF experiments and act as a good starting point for narrowing the parameter space for experiments and 2-D simulations.

A simple hydrodynamic-equivalence scaling was considered for laser energies up to 1 MJ to motivate future work in the area of laser-driven MagLIF. Scaling was accomplished by multiplying the laser energy by a factor $f$ and adjusting other quantities to conserve hydrodynamic properties such as pressure and implosion velocity. The particulars of specific laser facilities were left out of this scaling and it should not be considered as a different point design for larger laser systems. It should also
be noted that the scaling method used is too crude to conserve hydrodynamic values exactly, and the addition of an axial magnetic field also fundamentally changes the hydrodynamics of cylindrical implosions at different scales. However, the scaling provides an excellent baseline of what to expect from larger laser-driven MagLIF platforms that can be developed for lasers like the National Ignition Facility[35], and demonstrates the ability of a MJ-class laser to provide experimental measurements comparable to full-scale Z machine experiments.

The first series of experiments for laser-driven MagLIF were to empirically determine laser pointing and laser energy balance that produced the most uniform cylindrical implosion. The arrangement of lasers relative to a cylindrical target has 2 groups of 20 beams at 2 different angles of incidence. A series of hollow cylinders were imploded using one group of 20 beams to determine the laser drive versus the angle of incidence. X-ray self-emission images of the shell in flight were used to determine the implosion velocity and the effective drive. The results of these experiments were then used to develop an irradiation pattern for the cylindrical implosions for MagLIF. When all 40 beams were combined, the effective drive for each group of 20 beams were vastly different from the previous experiment. Two more experiments were performed to determine the required adjustments in laser pointing and laser energy to produce a uniform cylindrical compression. Shell shape and velocity were determined from the self-emission x-rays during the laser drive. These experiments were performed for a range of different shell thicknesses, and an implosion velocity for each shell thickness was determined. X-ray images of the end of the cylinder determined that the drive beams for one ring of 10 beams, which illuminate the target in 5 pairs, impose an azimuthal mode 5 non-uniformity in the drive. The beams were then adjusted by a radial shift to fix this, but measurements
of the improvement in azimuthal uniformity have yet to be performed.

MagLIF targets for integrated shots where laser preheating, magnetization, and compression are combined use gas filled cylinders closed by thin windows on the end for laser preheating. A focused experiment was designed to quantify window burn through, backscatter and sidescatter of laser light form the laser-window interaction, and gas preheating using a single OMEGA laser. For the window only shots, full aperture backscatter stations (FABS) and calorimeters were used to measure the total laser energy transmitted, reflected, and absorbed by the window. An array of filtered soft x-ray diodes also measured the the x-ray spectrum of the window and the total x-ray energy emitted by the window. The data collected was compared to 2-D hydrocode simulations to determine their predictive capability.

Fluorinated cylinder targets pressurized with neon-doped deuterium gas were then heated using the same laser pulse used in the window only experiments. A diagnostic window drilled into the side of the cylinder at the center of the implosion region looked at the soft x-ray emission of the neon gas to determine the preheat temperature throughout the duration of the laser pulse. The filtered x-ray diode array also looked at the x-ray spectrum of the window, wall, and the gas and was able to determine the gas temperature versus time for the front 1 mm of the cylinder. FABS determined that there was no significant difference in the backscatter energy and spectrum between window only shots and full cylinder preheat shots. The results were then compared to 2-D hydrocode results and it was determined that the gas preheat predicted matches closely with experiments. One cylinder was magnetized with a 15 T axial magnetic field to see the effect on laser preheat. There was clear evidence that the magnetic field suppresses thermal conduction from the gas and the window to the wall without affecting the gas temperature by more than 10%. 
With both the preheat and compression fully understood, the first integrated MagLIF experiments on OMEGA were performed. Four distinct cases were explored in detail: 1) Compression only to establish a baseline neutron yield and neutron-averaged ion temperature, 2) compression and preheat, 3) compression and magnetization, and 4) integrated shots that combine preheat, magnetization, and compression. A comparison between all of the cases demonstrates a yield increase with the addition of magnetic field. Several complications occurred during the first integrated MagLIF shots including magnetic field coils obstructing drive lasers from the target and a misalignment of the preheat beam to the cylinder axis. Limited scans including different preheat beam timings, initial gas pressure, and magnetic field strength were performed, although lower magnetic field strengths were explored with changing preheat timing and the results are unclear as to what is the dominant effect on neutron yield. Shots that were not corrupted and had measurable DD yields were compared to 1-D simulations that matched implosion velocity. The predicted yield from these simulations greatly exceeds experimental measurements, and the fuel convergence ratios from simulations are far too high to produce believable results.

A measurable secondary DT yield was used to infer the $\rho R$, and the ratio of initial to final $\rho R$ is used to determine the convergence ratio experimentally. DD neutron yield is shown to fall of almost linearly with increasing convergence ratio as expected. This further validates the reasoning behind why 1-D results diverge so much from experiment. Increasing magnetization, preheat, and initial fuel density is predicted to limit large convergence ratios by 1-D simulations, and the requirement of having a convergence ratio less than 25 set by the point design can and should be a goal moving forward for laser-driven MagLIF.
Electron and ion Hall parameters for magnetized compression and integrated shots for 10 T initial axial magnetic fields were estimated assuming a 50% flux loss and an 80% flux loss respectively. The electron and ion temperatures were also taken to be equal to the measured neutron-averaged ion temperatures so as to be self-consistent with the experiments. A loss of initial mass and heat due to axial flow was largely ignored in the interest of calculating a lower bound. There is no discernible increase in electron or ion Hall parameters between magnetized compression and integrated shots, motivating the need to explore higher initial magnetic fields in the future.
Chapter 2

Point Design

2.1 Basic Scaling Considerations and Initial Design Choices

There are 3 intuitive physics-based choices for scaling down MagLIF. The first and most obvious choice is to scale down the volume of the plasma to the energy of the driver. While there are no first principle physics reasons to do this, conserving the energy per unit volume in the implosion can achieve roughly the same hydrodynamic conditions at the end of the implosion. The second choice is to do a full hydro-scaling of MagLIF, conserving implosion velocity and final pressure exactly. The benefits of the latter are obvious, but they come at a cost of stronger conduction losses at smaller length scales that decreases performance. The first choice offers a more intuitive approach to hydro-scaling that can achieve roughly the same results given the excess conduction losses. The third choice would be to scale by conserving the
4 key parameters of a MagLIF system [39]

\[ R_1 = \frac{a}{\rho_i}; \quad R_2 = \frac{a}{\lambda}; \quad R_3 \equiv \beta = \frac{16\pi nT}{B^2}; \quad R_4 = \frac{\ell}{a} \tag{2.1} \]

where \( a \) is the fuel radius, \( \rho_i \) is the gyro radius of deuterium ions in the plasma, \( \lambda \) is the ion mean free path, \( \beta \) is the ratio of hydro pressure to magnetic pressure, and \( \ell \) is the length of the fuel cylinder. While this has obvious physics merits, conserving this number of quantities within the constraints of developing a robust experimental platform is next to impossible. The magnetic field strengths required to conserve \( R_1 \) and \( R_3 \) are as of today impossible to achieve at OMEGA scales.

The first method of energy scaling is suitable for scaling down the Z point design to a point design for OMEGA. The original point design from 1-D magneto-hydrodynamics (MHD) modeling for the Z machine MagLIF platform [42] uses a 3.48 mm outer radius, 0.58 mm thick, 5 mm long beryllium cylinder in a 30 T axial magnetic field, filled with 3 mg cm\(^{-3}\) DT fuel preheated to 250 eV and compressed by a 27 MA current pulse with a 100 ns rise time. The initial fuel density and preheat temperature were chosen to obtain a final fuel convergence ratio of 25 to limit the growth of the magneto-Rayleigh-Taylor instability during the compression. Although 1-D modeling showed higher neutron yields for higher aspect ratio targets, 2D MHD modeling showed that these targets would break up in flight and placed a restriction of the maximum aspect ratio achievable. The aspect ratio of the final point design was chosen to be 6 based on the 2D results [40]. A summary of the differences between the Z point design and first Z experiments are given in Table 2.2.
2.1 Basic Scaling Considerations and Initial Design Choices

2.1.1 Drive Energy, target dimensions, and magnetic field

The targets used in the first Z MagLIF experiments were slightly longer and thinner than the targets specified in the point design, as shown in Table 2.1. The fuel used was D₂, not DT, and at much lower initial densities due to material property constraints. The initial axial magnetic field was also lowered from 30 T to 10 T because a coil design providing the full 30 T blocked all diagnostic access to the target. The drive current was also lower at 19 MA due to the increased inductance of the load and losses in the structure of the current delivery system, which may be improved in the future. A 2.0 kJ, 2ω laser was used to preheat the gas to 120-150 eV. The initial experiments had a DD neutron yield of $2 \times 10^{12}$ with a neutron-averaged ion temperature of 2.5 keV and a BR product of 0.4 T·m. The 2D MHD models predicted higher values of neutron yield, neutron-averaged ion temperature, and BR of $6.1 \times 10^{13}$, 3.2 keV, and 0.53 T·m respectively. The main source of target performance degradation is thought to be decreased coupling of the preheat laser to the gas. The experimental results can be reproduced in the 2D model if the laser energy absorption into the gas is artificially decreased by about a factor of 6, as shown in Table 2.2. Loss of current delivered to the liner due to the geometry of the last part of the transmission line, known as the convolute, is also believed to be a source of yield degradation, and a reduction in the drive can also account for the difference in yield between experiment and 2-D simulations.

Magnetized cylindrical implosions have been carried out previously on OMEGA [20, 29] before the MagLIF point design was conceived, using a device called MIFEDS (Magneto-Inertial Fusion Electrical Discharge System) to provide an axial magnetic field of 6 T [21]. An upgraded version of MIFEDS that is currently in use on OMEGA can provide up to 10 T for MagLIF experiments on OMEGA [12], which matches
Table 2.1: Target parameters for the Z point design, first Z experiments, and the OMEGA point design.

<table>
<thead>
<tr>
<th>Target parameter</th>
<th>Z point design</th>
<th>Z experiments</th>
<th>OMEGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer Radius (mm)</td>
<td>3.48</td>
<td>2.79</td>
<td>0.3</td>
</tr>
<tr>
<td>Shell thickness (mm)</td>
<td>0.58</td>
<td>0.465</td>
<td>0.02 to 0.05</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>5</td>
<td>7.5</td>
<td>0.5 to 0.7</td>
</tr>
<tr>
<td>Shell aspect ratio</td>
<td>6</td>
<td>6</td>
<td>6 to 15</td>
</tr>
<tr>
<td>Fuel aspect ratio</td>
<td>1.72</td>
<td>3.23</td>
<td>1.79 to 2.80</td>
</tr>
</tbody>
</table>

the magnetic field values used in the Z experiments. The only element missing from previous magnetized cylindrical implosions is the use of a laser to preheat the fuel prior to compression. A single $3\omega$ beam of OMEGA has been redirected down an axis of symmetry to accomplish this.

The OMEGA laser system can deliver roughly 1000 times less energy to a target compared to Z, therefore, in order to conserve the ratio of energy and volume, the linear dimensions of an OMEGA MagLIF target need to be reduced by a factor of 10. These scaled down targets provide the first experimental test of MagLIF scaling, while providing a platform with higher repetition rate, better diagnostic access, and diagnostic capabilities that do not yet exist at the Z facility. In particular, axial magnetic field probing to study the dynamics of flux compression within a MagLIF target and time-resolved x-ray self-emission to measure shell trajectory are key diagnostics required to study the important underlying physics of the fusion concept.

The main objective of the point design is to develop an experimental platform that matches conditions on Z within a factor of 2 or better. These parameters are implosion velocity, convergence ratio, initial magnetic field, and initial fuel temperature and density. The results of the 1-D MHD simulations for the Z point design and the point design conditions for Omega can be found in Table 2.2 and Table 2.5.
### 2.1 Basic Scaling Considerations and Initial Design Choices

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Z point design</th>
<th>Z experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preheat temperature (eV)</td>
<td>250</td>
<td>~ 20</td>
</tr>
<tr>
<td>Fuel density (mg/cm$^3$)</td>
<td>3 (DT)</td>
<td>0.7 (D$_2$)</td>
</tr>
<tr>
<td>Axial magnetic field (T)</td>
<td>30</td>
<td>7 to 10</td>
</tr>
<tr>
<td>Implosion velocity (km/s)</td>
<td>70</td>
<td>≈ 70</td>
</tr>
<tr>
<td>Fuel convergence ratio</td>
<td>25</td>
<td>≈ 40</td>
</tr>
<tr>
<td>Peak temperature (keV)</td>
<td>8</td>
<td>≈ 3</td>
</tr>
</tbody>
</table>

Table 2.2: Key parameters from the Z point design and first experiments on Z. The goal of the OMEGA point design is to match these parameters to within a factor of 2. The experimental preheat temperature was the value used in 2-D MHD simulations that reproduced experimental results [40, 43] and is not a direct measurement.

Fixing these initial parameters means that other parameters cannot be matched due to physics effects that do not scale in the same manner as size and energy. A decrease in length of the target while maintaining roughly the same sound speed in the gas means substantially more axial losses. The value of $BR$ will also be reduced in OMEGA targets because the initial axial field will have the same value, but the radius will be significantly smaller. The effect here is two-fold: 1) The final magnetic field strength being equal under ideal flux compression for a fixed convergence ratio will naturally have a smaller $BR$ product for smaller targets and 2) temperature gradients will be larger, leading to more classical magnetic diffusion and excess diffusion by the Nernst effect under non-ideal flux compression. The surface area to volume ratio is larger in OMEGA scale targets, which will increase thermal losses. For a given target radius $r$, the surface area to volume ratio and the temperature gradient both vary as $1/r$, while the implosion time for a fixed implosion speed goes as $r$. Final fuel temperatures are expected to be lower in OMEGA scale targets as a result.

Due to the geometry of the OMEGA laser system, only 40 of the 60 beams can be used in a cylindrical compression effectively because the remaining 20 beams have
grazing angles of incidence and therefore very low absorption. For the optimized pulse length of 1 ns and using smoothing by spectral dispersion (SSD), 40 OMEGA beams can deliver 18 kJ of energy to the target. The intensity of the lasers on target at this energy gives a much higher implosion speed than desired and have the unwanted side-effect of driving strong shocks into the target which lowers the compressibility of the shell. It is therefore more desirable to use a longer laser pulse to reduce the power on target. However, since the frequency conversion crystals (FCC) have a lower conversion efficiency at lower powers. Extending the laser pulse has the effect of also reducing the available energy on target. An example of the ultraviolet energy on target (UVOT) is shown in Table 2.4. A principle objective of the 1-D modeling is to determine the optimal pulse length and laser energy. It is reasonable to estimate that the kinetic energy coupled to the target to be no more than 1 kJ considering UVOT values and a net coupling efficiency of less than 10%. Compared to the 0.5 MJ that the Z designs couple to the target, the volume of the OMEGA targets should be at least 500 times smaller or a factor of 8 reduced in linear dimensions. Dividing the Z point design target and Z experiment target parameters respectively by this factor gives a 435 µm outer radius, 625 µm long target and a 350 µm outer radius, 940 µm long target.

It is also important to consider how the laser energy will be deposited onto the cylinder, namely the proportion of the spot size of each beam relative to the target size. Clearly it is not advantageous to consider a target that is much smaller than the spot size of the laser. Ideally, the target outer diameter should match closely with the size of the laser spot for a uniform and efficient illumination of the target. Distributed Phase Plates (DPPs) determine the spot size of each beam of OMEGA. Manufacturing phase plates to fit the target size of our desires is a costly and time
2.1 Basic Scaling Considerations and Initial Design Choices

consuming process, so these initial experiments had to use existing phase plates and compensate by tuning the target size. Currently there are sets of 40 phase plates that give a spot radius of approximately 150 µm, 300 µm, and 430 µm, containing 95% of the total laser energy. The 300 µm phase plate was selected since the 430 µm is at the upper limit concerning the Z point design and 150 µm is too small. The phase plates chosen are designated as SG2’s since they give a roughly Gaussian intensity profile with a FWHM in intensity of approximately 289 µm.

In OMEGA experiments using spherical geometry, shell aspect ratios are typically 20 or more, which is a huge difference between the restriction of 6 placed on the Z point design. Larger aspect ratio targets can be used on OMEGA because of the ablative stabilization of the Rayleigh-Taylor instability. Furthermore, higher aspect ratio targets can achieve the higher implosion velocities needed for ICF since the laser drive efficiency increases as the ratio of un-ablated mass to ablated mass increases over the region of aspect ratios relevant to MagLIF. Increasing shell aspect ratios for MagLIF targets on OMEGA will have the benefit of increasing implosion speed, mitigating excess axial and radial losses due to small scale, and will not be compromised by instability feedthrough. Shell thicknesses between 20-50 µm will be modeled and a thickness will be chosen based on the implosion velocity and the convergence ratio.

The length of cylinder capable of being driven by OMEGA depends on how far the laser spots can be spread without compromising the illumination uniformity. This is inherently a complex problem, since not all 40 beams have equal angles of incidence. There are 20 beams, 10 per side, that have an angle of incidence ±31.15° (rings 3), and 20 beams that have an angle of incidence of ±8.75° (rings 4). Spot size increases and laser absorption decreases as angle of incidence increases. Achieving a
uniform cylindrical compression is decidedly outside the scope of the point design, but the main principle of achieving a uniform drive is to match the energy delivered by the ring 3 and ring 4 beams. Since ring 3 beams will couple less energy to the target, each side of ring 3 will need to be overlapped to match the intensity of each side of ring 4, which must be used to drive the ends. This means that the average axial intensity on target should be closely approximated by the intensity of one side of ring 4, which is the drive used in subsequent 1-D simulations.

### 2.1.2 Thermal losses, implosion velocity, fuel density, and preheat

One of the hallmarks of MagLIF is the use of an axial magnetic field to reduce radial conduction losses. The reduction in thermal conductivity perpendicular to the axial field is inversely proportional to the Hall parameter $\chi$, which is the ratio of the cyclotron frequency to the collision frequency of the plasma, raised to a power between 1 and 2. For a uniform magnetic field purely in the axial direction, the thermal conductivity perpendicular to the field goes as $1/\chi^2$ (Braginskii conductivity) [11]. As curvature and other non-uniformities are introduced to the magnetic field, the power of the Hall parameter approaches unity (Bohm conductivity) [3]. Intermediate cases between these two extremes have been demonstrated experimentally, theoretically, and empirically [3, 4, 25].

The electron Hall parameter in a hydrogen plasma can be estimated as

$$\chi_e \approx 10^{-5} A \frac{B}{\rho} T_{eV}^{3/2}$$

where $\rho$ is the mass density in (kg m$^{-3}$), $A$ is the average mass number of the ions,
2.1 Basic Scaling Considerations and Initial Design Choices

$B$ is the magnetic field in (Tesla), and $T_{eV}$ is the electron temperature in eV. To simplify this formula $\log \Lambda = 10$ was used. Under ideal MHD, the ratio $B_z/\rho$ is a constant in a cylindrical compression, so initial values can be used to calculate the temperature at which magnetization of the electrons occurs. Taking 10 T to be the field readily achievable and estimating a gas density of 1 mg cm$^{-3}$, $\chi_e > 1$ when $T_{eV} > 292$ eV. Electron magnetization therefore occurs with minimal compression provided the initial temperature is close to the designed 250 eV.

The same calculation can be done for ion magnetization. Following the simple estimation from above

$$\chi_i = \frac{\chi_e}{30.2 A_1^{1/2}}$$

(2.3)

For 10 T and 1 mg cm$^{-3}$, $\chi_i > 1$ occurs at $T_{eV} > 3.6$ keV, which is much hotter than the plasma at stagnation for Z-scale experiments. Suppression of ion thermal conductivity requires a massive magnetic field, especially at the OMEGA scale. This also has the negative side effect of increasing the ratio of magnetic pressure to hydro pressure, making the target harder to compress and ultimately decreasing the performance of the implosion. Suppressing ion thermal conductivity should play a larger role in ignition scale designs.

Increasing the electron Hall parameter to more than 10 has little effect on mitigating thermal losses since the diffusion becomes ion dominated. This can be illustrated by plotting the total thermal conductivity in Fig. 2.1. Therefore, it is not essential to match the Hall parameter in the Z point design. It should also be noted that perturbations to the magnetic field will not effect target performance as long as the Hall parameter is 10 or greater.

Thermal losses are estimated using a sort-of 0-D model. Assuming that the
2.1 Basic Scaling Considerations and Initial Design Choices

Figure 2.1: Total thermal conductivity plotted versus electron hall parameter for both Braginskii and Bohm models, using $1/[1 + (5/3)\chi]$ as an approximation to the Bohm model.

Electrons and ions are ideal gases and the order of magnitude estimate of the temperature gradient $\sim T/r$, where $r$ is the outer radius of the fuel, the energy balance equation including thermal losses and work done in compression is

$$\frac{d}{dt}(3neT\pi r^2) \sim -K_0T^{5/2}T\frac{T}{r}2\pi r - 2neT \frac{d}{dt}(\pi r^2)$$ (2.4)

where $T$ is temperature in eV, $K_0$ represents the temperature independent constants for a Spitzer-like ion thermal conductivity given by $125/\sqrt{A}$ W m$^{-1}$ eV$^{-7/2}$ for $\ln \Lambda = 10$, and $n$ is the electron and ion number density. Assuming a constant implosion velocity $v = -dr/dt$ (m/s) and solving for temperature,

$$\frac{T}{T_c} = \frac{0.7^{2/5}C^{4/3}}{[C^{7/3} - 1 + 0.7(T_c/T_0)^{5/2}]^{2/5}}$$ (2.5)

where $T_0$ is the preheat temperature, $C = r_0/r$ is the fuel convergence ratio, and $T_c$ is the temperature where thermal losses equal the work done by compression.
2.1 Basic Scaling Considerations and Initial Design Choices

\[
T_c = \left( \frac{2\varepsilon n_0 r_0 v}{K_0} \right)^{2/5} \approx 1.6 \left( \sqrt{\frac{2}{A}} \frac{\rho_0}{2.4 \text{mg/cm}^3} \frac{r_0}{0.3 \text{mm}} \frac{v}{140 \text{km/s}} \right) \tag{2.6}
\]

Expanding this for values around \( T_c \) for small convergence ratios gets

\[
T \approx T_0 C^{4/3}; C - 1 << 1 \tag{2.7}
\]

For \( T_0 << T_c \) the adiabatic result is recovered \( T = T_0 C^{4/3} \). In the case of MagLIF, final temperatures are much greater than \( T_c \) so thermal losses will be much larger at the OMEGA scale and will result in lower final temperatures. In the limit of large convergence ratios, Eq. 2.5 yields

\[
T \sim 0.7^{2/5} C^{2/5} T_c \tag{2.8}
\]

\[
C^{7/3} \gg 0.7(T_c/T_0)^{5/2} - 1 \tag{2.8}
\]

\[
\propto (C\rho_0 r_0 v)^{2/5}
\]

This result is an adequate approximation for final temperature scaling for a MagLIF implosion.

A decrease of target radius by a factor of 10 keeping convergence, fuel density, and implosion velocity constant will reduce the final temperature by a factor of 2.5 by Eq. 2.8. To offset the increase in thermal losses, convergence, fuel density, and implosion velocity must somehow compensate this loss. To stay consistent with our original goal of matching experimental conditions to within a factor of 2, the product of these three parameters must be increased by a factor 1.75. The easiest way to accomplish this in terms of experimental design, engineering and material constraints, and limiting instabilities, is to increase the implosion velocity by a factor of 2 by increasing shell aspect ratio. Increasing the convergence ratio
will have the unwanted consequence of increasing instabilities that degrade implosion uniformity and introduce mix. Increasing fuel density will require using thicker laser entrance hole (LEH) windows to hold the gas pressure, which would reduce the laser coupling and preheat temperature. Furthermore, higher gas densities require higher magnetic fields to achieve the same electron Hall parameter and heat conduction suppression.

It is interesting to note that Eq. 2.8 has no dependence on the preheat temperature $T_0$, meaning for a given fuel density and convergence ratio there exists a preheat threshold above which the final temperature does not increase significantly; most of additional preheat energy will be lost. The preheat temperature required to reach 90% of the limiting value from Eq. 2.8 is

$$T_0 > 1.47 \frac{T_c}{C^{14/15}} \sim 120 \left( \sqrt{\frac{2}{A}} \frac{\rho_0}{2.4 \text{ mg/cm}^3} \frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \right)^{2/5} \left( \frac{C}{25} \right)^{-14/15} \text{ eV} \quad (2.9)$$

This means that the preheat threshold for the OMEGA design should be 120 eV whereas the preheat threshold for the Z point design should be 230 eV, which is closer to the 250 eV preheat specified in the Z point design.

Provided the preheat threshold is exceeded, the final temperature is

$$T \sim 5.1 \left( \sqrt{\frac{2}{A}} \frac{\rho_0}{2.4 \text{ mg/cm}^3} \frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \frac{C}{25} \right)^{2/5} \text{ keV} \quad (2.10)$$

Plugging in values from the Z point design gives 10 keV compared to the 8 keV peak ion temperature reported in the 1-D modeling, and 6.5 keV for Z experiments. 1-D modeling predicted a peak ion temperature of roughly 5 keV with sufficient preheat for the Z experiments[19]. It should be noted that this estimate neglects
2.1 Basic Scaling Considerations and Initial Design Choices

Electron thermal conduction and is therefore an upper limit. Based on the results from Z and our simple estimates, it is reasonable to expect that the OMEGA design can achieve a peak temperature of 3.6 keV.

2.1.3 Magnetic field loss mechanisms and estimates

Restricting electron heat flow relies on having sufficient magnetic field within the preheated fuel. During compression, there are several loss mechanisms which can decrease the magnetic field, lower the Hall parameter, and allow unwanted levels of electron conduction losses. These loss mechanisms include classical MHD diffusion and the Nernst effect, both of which will lead to larger magnetic field losses at smaller scales.

Magnetic field loss due to diffusion can be calculated by estimating the associated Ohmic heating dissipation. The current density is concentrated in a peak near the gas/shell boundary as the plasma is compressed. Under lossless frozen-in compression, the compressed field \( B \sim C^2 B_0 \). For a simple order of magnitude estimate of loss under resistive MHD diffusion, \( \mu_0 j \sim (C^2 - 1) B_0 / \Delta r \) with \( \Delta r \sim \sqrt{\eta t / \mu_0 / C} \) can be considered as the conventional diffusion length modified by the compression with resistivity \( \eta \). The power dissipated by the resistance is then calculated to be \( \sim \eta j^2 2\pi (r_0/C) \Delta r \). Using the Spitzer resistivity model and large convergence ratio assumption from Eq. 2.7 and integrating gets the energy dissipated per unit length. Using the square root of the ratio of energy dissipation and magnetic field energy in the absence of loss, the estimated fraction of the magnetic field lost:

\[
f_B \sim 0.5 \left( \sqrt{\frac{2}{A}} \frac{\rho_0}{2.4 \text{ mg/cm}^3} \right)^{-3/20} \left( \frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \right)^{-2/5} \left( \frac{C}{25} \right)^{7/20} \tag{2.11}
\]
2.1 Basic Scaling Considerations and Initial Design Choices

The fraction of magnetic field lost to diffusion has the same scaling with target radius and implosion velocity as the thermal losses derived in Eq. 2.8. The loss fraction scales weakly with initial fuel density and the target radius is fixed by laser parameters, so the clear choice to mitigate magnetic fields losses is to increase the implosion velocity. This will also help limit the thermal losses by the same order and is the most advantageous approach to keeping other parameters within a factor of 2 of the Z point design. Plugging in values from the Z point design into Eq. 2.11 gives $f_B \sim 0.26$ and a 25% flux loss is reported in 1-D MHD modeling without including the Nernst term [42].

The Nernst effect is the other major loss mechanism of magnetic field inside MagLIF implosions. It was discovered that electromotive force could be generated in magnetized heated plates in 1887. In general, the presence of a temperature gradient and a magnetic field creates an electric field perpendicular to both. When included in the generalized Ohm’s Law equation, it introduces an additional velocity to the magnetic field evolution equation[23]:

$$v_N \approx \frac{2}{5} \frac{q_{\perp}}{n_e T_e}$$  \hspace{1cm} (2.12)

Here $q_{\perp}$ is electron heat flux perpendicular to the magnetic field. This formulation of the Nernst effect highlights the underlying physics of the magnetic field being frozen to the conduction electrons rather than the low-energy electrons that comprise the bulk of the plasma, since these conduction electrons experience fewer collisions. The Nernst effect is a major source of degradation in MagLIF implosions by directly counteracting the role the magnetic field plays in suppressing radial conduction losses. There is a delicate balance of the magnetic field and heat front
pushing against each other. The Nernst velocity is proportional to the temperature gradient scale length. If $\nabla T/T \sim 1/r$ as assumed previously, then the Nernst effect will be 10 times worse at the OMEGA scale. This can be compensated for by increasing the implosion speed, but since the Nernst velocity is sensitive to the electron magnetization a simple estimate of the magnetic field loss is difficult to make.

The importance of the Nernst effect can be quantified by introducing the dimensionless quantity $v/v_n$ or the "Nernst number". High values of the Nernst number indicate the magnetic field is compression dominated, and a value less than 1 would indicate that the magnetic field is loss dominated. Using the temperature gradient scale length and the temperature from Eq. 2.5 the Nernst number is

$$\frac{v}{v_N} \sim \frac{0.072 C^{7/3} - 1 + 0.7(T_c/T_0)^{5/2}}{\sqrt{A}} \frac{1}{C^{7/3}} \frac{1}{f(\chi_e)}$$

(2.13)

where $f(\chi_e) \geq 1$ is the factor of reduction in electron thermal conductivity perpendicular to the magnetic field.

The preheat temperature and initial magnetic field for OMEGA scale MagLIF experiments gives $f(\chi_e) \sim 1$, and so

$$\frac{v}{v_N} \sim 7\left(\sqrt{\frac{2}{A}} \frac{\rho}{2.4 \text{ mg/cm}^3} \frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}}\right)\left(\frac{T_0}{200 \text{ eV}}\right)^{-5/2}$$

(2.14)

The Nernst number for the Z point design is 20 whereas the OMEGA point design gives about 7. Indeed, it is reasonable to expect the losses due to the Nernst effect to be at least twice as much on OMEGA than on Z. The Nernst number will decrease as the target is compressed provided the electron heat flow remains unmagnetized. Once the target has been compressed enough to amplify the magnetic
field and increase the fuel temperature, the Nernst number will begin to increase. The minimum Nernst number is estimated by assuming lossless field compression and a temperature when the Hall parameter reaches unity. Taking the convergence from the analytic adiabatic solution \( C = \left( \frac{T}{T_0} \right)^{3/4} \),

\[
\frac{v}{v_N} \sim 1.5 \left( \frac{2}{A} \frac{\rho_0}{2.4 \text{ mg/cm}^3} \right)^{-1/6} \left( \frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \right)^{-3/4} \left( \frac{B_0}{10 \text{ T}} \right)^{7/6} \tag{2.15}
\]

showing that for values close to the OMEGA point design the Nernst number is near unity leading to significant loss of magnetic field compression prior to fuel magnetization. For Z experiments, the Nernst number is approximately 40, and 1-D modeling of experiments performed at Z found that flux loss due to the Nernst effect was not significant at the preheat levels that matched measured neutron yields.

As the target becomes compressed and the fuel begins to heat up, electron heat flow becomes strongly magnetized. Using Eq. 2.5 to estimate temperature, assuming lossless flux compression, and Braginskii’s thermal conductivity,

\[
\frac{v}{v_N} \sim 23 \left( \frac{2}{A} \right)^{9/10} \left( \frac{\rho_0}{2.4 \text{ mg/cm}^3} \right)^{-4/5} \left( \frac{r_0}{0.3 \text{ mm}} \frac{v}{140 \text{ km/s}} \frac{C}{25} \right)^{6/5} \left( \frac{B_0}{10 \text{ T}} \right)^2 \tag{2.16}
\]

and so the loss of magnetic field becomes substantially less later on in the implosion at both the OMEGA and Z scales.

So far, the only strategy to mitigate flux loss due to the Nernst effect is to increase the magnetic field as was done on the Z point design. Modeling was done with and without the Nernst term included, which caused a shift of the optimum magnetic field from 10 T to 30 T. Flux loss was estimated to be 45% when Nernst is
2.2 Preheat: Modeling, Temperature, Window Standoff, and Timing

included. Although the current magnetic field delivery system cannot achieve field strengths this high, there are plans to build such a system. In the meantime, the Nernst number can be lowered by lowering fuel density and preheating only to the threshold preheat value of 100 eV [Eqs. 2.14 and 2.15]. This will be demonstrated in the subsequent 1-D modeling.

2.2 Preheat: Modeling, Temperature, Window Standoff, and Timing

Preheating for MagLIF targets is accomplished by inverse bremsstrahlung absorption of laser light axially incident on the cylindrical liner. As part of the Z point design, the preheating process was modeled using analytic and 2-D hydrocode models with ray tracing [42]. A thin window at the top of the cylinders allows the fuel to be held within the cylinder and provides an entrance hole for the laser to preheat the gas. However, the density and thickness of this window as well as the density of the gas can cause parametric instabilities to occur, leading to sidescatter, backscatter, and mix from ablation of the inner surface of the liner and window material propagating into the implosion region. This is inherently a complex physics problem that goes beyond the scope of this thesis. It will be sufficient to limit the fuel density to be less than one-tenth the critical density of the laser used for preheating, and measure the resulting backscatter and sidescatter from the window disassembly to confirm that enough laser energy is left over for preheating. For a single OMEGA beam with $\lambda = 351$ nm, one-tenth critical density is $2.7 \text{ mg/cm}^3 D_2$. For Z-beamlet, $\lambda = 527$ nm, which corresponds to a one-tenth critical density of $1.2 \text{ mg/cm}^3 D_2$.

Electron temperature scales with inverse bremsstrahlung heating as $(nI\lambda^2t)^{2/5}$,
assuming a fixed number density and neglecting thermal and radiative losses. The product $It$ is in units of energy per area, so for fixed preheat temperature $T_0$, number density, and laser wavelength, the laser energy needed to reach $T_0$ is proportional to the square of the radius, and so it should be $100\times$ less at the OMEGA scale compared to the Z scale. This seems a bit counter-intuitive, but the heated length is proportional to $n^{-7/5}(It)^{3/5}\lambda^{-4/5}$ and does not change, meaning that area and not volume is important and preheating becomes less efficient at smaller scales. The preheating time should scale linearly with radius, and so it will be reduced by $10\times$ at the OMEGA scale, giving a laser intensity that is $10\times$ higher than Z.

The 2-D hydrocode modeling used for the Z point design showed that the 250 eV preheat of a 3 mg/cm$^3$ DT filled liner (or 2.4 mg/cm$^3$ equivalent number density in $D_2$) can be accomplished using a 500 nm, 8 kJ, 10 ns laser pulse with a 1 mm radius spot size. This translates to a beam intensity of $2.5 \times 10^{13}$ W/cm$^2$. A single OMEGA beam can easily deliver laser intensities $10\times$ greater than Z-beamlet, as long as the appropriate beam conditioning optics are used. A 120 J, 1 ns laser pulse with a 100 µm spot size can provide an intensity of $3.8 \times 10^{14}$ W/cm$^2$. Increasing the laser energy and spot size can provide more radial uniformity of the heating as well. The preheating is very inefficient at the OMEGA scale, but the energy required to heat a 0.3 mm radius cylinder filled with 2.4 mg/cm$^3$ of $D_2$ to 200 eV is only 20 J/mm.

Since all 3 legs of the OMEGA laser system will be used for the compression beams, the preheating beam must have the same pulse shape as the compression beams. This means that the preheating beam will be a square pulse with the same length as the drive beams. The design of the OMEGA laser forbids having a different pulse shape for a single beam, however the relative timing of each beam can be varied.
independently, allowing the preheating to occur well in advance of the compression.

The spot size of the preheat beam is dictated by the available phase plate, which has a radial profile described by the function \( \exp\left\{-\left[\frac{r}{126.8 \text{ \mu m}}\right]^2 \right\} \). This is the minimum size of spot a phase plate can achieve while delivering adequate beam smoothing. To match the required intensity from the above calculation, the laser energy can be increased. Increasing the power from 0.12 TW to 0.2 TW will increase the intensity to the required \( 3.8 \times 10^{14} \text{ W/cm}^2 \) using this phase plate.

A critical parameter that was not addressed by the Z point design is the thickness of the laser entrance window and the energy required to disassemble the window. The lack of understanding of this parameter has led to issues on MagLIF shots on the Z machine. Targets to measure window burn through, backscatter and sidescatter, and gas heating as a function of time have been tested using a single OMEGA beam. It was found that a 1.84 \( \mu \text{m} \) thick polyimide window was thick enough to hold the 2.4 mg/cm\(^3\) of D\(_2\) at room temperature, had minimal backscatter and sidescatter during disassembly, and absorbed \( \sim 30\% \) of the laser energy for varying intensities. More information of the results of this experiment and results and setup of the 2-D simulation can be found in the preheat section of this thesis.

From the experimental and simulation results, the distance of window material propagation into the gas cylinder is approximately 1.2 mm from the entrance. Several cases have been explored in simulation and the results are presented in Table 2.3.

The preheat temperatures achieved with minimal window mix, sidescatter, and backscatter exceed the estimated minimum requirement in Eq. 2.9. Using the optimal laser power for preheating is preferred since it will require less window standoff and decrease the precision requirement of preheat beam timing. To quantify,
Table 2.3: Preheating results from DRACO for a range of D$_2$ fuel densities ($\rho$), laser powers ($P$) giving a mean temperature $T$ at time $t$. The distance $s$ is the distance away from the entrance where the fraction of window material in the gas is at or below 0.1.

doubling the laser power increases preheat temperature by only 8% for a fuel density of 2.4 mg/cm$^3$ whereas the standoff distance is increased by 38%.

Radial temperature profiles obtained from 2-D modeling are important to discuss in relation to wall ablation and 1-D modeling. Temperature profiles predicted for the OMEGA scale are much broader in relation to the laser spot than those at the Z scale due to the electron thermal diffusion time

$$t_{\text{dif}} \sim 1.6 \left( \frac{2}{A} \frac{\rho_0}{2.4 \text{ mag/cm}^3} \right) \left( \frac{T}{400 \text{ eV}} \right)^{-5/2} \left( \frac{r}{0.3 \text{ mm}} \right)^2 \text{ns} \quad (2.17)$$

normalized to double the desired temperature since electrons are heated first. The normalization constant is of the same order as the preheat time, ignoring magnetization. This means that it is impossible to heat just the central region of the gas without having thermal conduction to the wall. Trying to avoid interactions and ionization with the wall is a key limiting factor to the amount of preheat that can be achieved at the OMEGA scale. Eq. 2.17 gives 92 ns for the Z point design, and so the limiting factor for preheat is shock propagation rather than thermal conduction.
2.2 Preheat: Modeling, Temperature, Window Standoff, and Timing

Figure 2.2: Radial temperature and density profiles from the 2-D rad MHD code DRACO into the wall.

It is important to estimate the electron-ion equilibration time in relation to the preheat time since it is the ion temperature preheat that must be above threshold. Normalizing to OMEGA point design parameters

\[ t_{ei} \approx 0.68 \left( \frac{A}{2} \right) \left( \frac{\rho}{2.4 \text{ mg/cm}^3} \right)^{-1} \left( \frac{T}{400 \text{ eV}} \right) \text{ ns} \] (2.18)

the equilibration time is slightly less than the preheating time. At smaller scales, this equilibration time does not change and the thermal diffusion time decreases, making preheat harder to accomplish without significant wall heating.

It is worth noting that the radial fuel density profile is modified by the preheating. The preheat laser pushes fuel out of the center of the target and towards the wall by thermal expansion. Since the implosion velocity is much quicker than the thermal expansion of the fuel, this should have a minor impact on the compression. Radial profiles from the 2-D modeling are shown in Fig. 2.2.
2.3 1-D MHD modeling to optimize shell thickness, pulse duration, and fuel density

The 1-D MHD code \textit{LILAC}\textsuperscript{[10]} was used to find the combination of shell thickness, laser pulse length, and fuel density that maximizes neutron yield within the condition of $C \lesssim 25$. Starting from a shell thickness of 50 $\mu$m that gives identical shell aspect ratios for the OMEGA and Z design (Table 2.1), a scan to thinner shells will compensate for increased thermal losses at the smaller scale. Thin cylindrical and spherical shells have already been explored on OMEGA and have demonstrated stable and uniform implosions without shredding under instabilities. Higher shell aspect ratios have yet to be explored on Z for this reason. A magnetic field and preheat temperature were chosen based upon the capabilities of the magnetic field system for OMEGA and from estimates of single beam heating of a gas in \textit{DRACO}. A fixed 10 T initial axial magnetic field and preheat temperature of 200 eV were chosen to test 20, 30, 40, and 50 $\mu$m shells for 5 different densities and 5 pulse lengths shown in the subsequent plots. \textit{LILAC} was run using six-group radiation transport, tabulated opacities, \textit{SESAME} equations of state, a thermal flux limiter of 0.06, and included the Nernst term \textsuperscript{[9]}. In cylindrical geometry, the Nernst term is

$$\frac{dB}{dt} = -\frac{1}{r} \frac{d}{dr} (rv_t B)$$

(2.19)

where $v_t$ is the convection velocity. The Nernst term is calculated using an upwind method for the magnetic gradient part and then by analytical solution for the convection velocity gradient. The convection velocity multiplied by a correction factor gives the Nernst velocity. The Nernst velocity is flux limited in this calculation using
the same flux limiter for thermal diffusion in the hydrodynamics routines. This is an important step to prevent the Nernst velocity from diverging in the calculation from sharp thermal gradients. It is also an intuitive way to limit the Nernst effect in a self-consistent manner.

It should be expected that a 1-D code will overestimate the neutron yield by about a factor of 10 since 2-D and 3-D effects generally degrade the implosion via instabilities, axial losses, and non-uniformities. However, the precision of 1-D modeling should be reasonable enough to predict trends and differences, and so the optimum conditions predicted from the entire MagLIF parameter space should be sufficiently accurate and can be calculated quickly.

To preserve the physicality of preheating without the use of a laser in the simulation, an arbitrary temperature profile with a continuous gradient that is exactly zero at the gas-shell interface is imposed as an initial condition. This avoids having step temperature gradients that cause the Nernst velocity to diverge. The profile is given as

\[ T = \begin{cases} T_0 \cos^2 \left[ \frac{\pi}{2} \left( \frac{r}{R} \right)^4 \right] + T_1, & r \leq R \\ T_1, & r > R \end{cases} \]  \hspace{1cm} (2.20)

where \( r \) is the radial coordinate, \( R \) is the fuel outer radius, \( T_1 = 0.025 \) eV is room temperature. \( T_0 \) is set such that the mean temperature is the preheat temperature desired, i.e. \( T_0 = 292 \) eV for a mean fuel temperature of 200 eV.

It is desirable to drive the shell continuously with no coasting phase as is done on the Z accelerator. This would require a laser pulse of about 2.5 ns for a 0.3 mm target imploding at 140 km/s. Since the frequency conversion crystals of the OMEGA laser system have an efficiency that depends on the incident laser power,
2.3 1-D MHD modeling to optimize shell thickness, pulse duration, and fuel density

going to such long pulses decreases the available UV energy delivered to the target. The UV energy on target (UVOT) has been measured for different length square pulses on the OMEGA laser and the results are summarized in Table 2.4.

<table>
<thead>
<tr>
<th>Pulse duration (ns)</th>
<th>1.0</th>
<th>1.5</th>
<th>1.8</th>
<th>2.0</th>
<th>2.5</th>
<th>2.7</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVOT per beam (J)</td>
<td>450</td>
<td>395</td>
<td>380</td>
<td>360</td>
<td>295</td>
<td>270</td>
<td>260</td>
</tr>
<tr>
<td>Effective drive ($10^{14} \text{ W/cm}^2$)</td>
<td>7.69</td>
<td>4.49</td>
<td>3.60</td>
<td>3.08</td>
<td>2.20</td>
<td>1.71</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Table 2.4: Maximum UVOT per beam measured for square-shaped pulses of different lengths with SSD on. The effective drive is calculated by taking the azimuthally averaged intensity on the target surface of one ring 4 (10 beams).

*LILAC* uses a 2-D ray tracing algorithm in cylindrical geometry with rays of normal incidence on the target surface. *LILAC* will overestimate the drive relative to experiments since the actual illumination of the cylinder occurs at incidence angles of 8.75° and 31.15° for rings 4 and rings 3 respectively. Ring 3 beams will be absorbed less efficiently than ring 4 beams due to the greater angle of incidence of ring 3 compared to ring 4, and so rings 3 need to be overlapped to compensate for this. Regardless of how the beams are arranged axially, a uniform drive profile will have a value that is close to the intensity that a single ring 4 can provide. This effective drive is used for the point design simulations and are reported in Table 2.4.

The maximum neutron yield for each shell is reported in Table 2.5. Peak ion temperatures are significantly lower than the 8 keV calculated for the Z point design, though the 20 µm shells are within a factor of 2. Assuming a factor of 10 reduction from 1-D predictions and assuming a cylinder length of 600 µm, 40 and 50 µm shells will give neutron yields around $10^7$ in experiments, which is too close to the detectable threshold for OMEGA neutronics to determine $T_i$ and bang time. It is desirable to use shell thicknesses of 30 µm or less. Furthermore, the neutron averaged ion temperature for 40 and 50 µm shells compares with the ±500 eV error.
2.3 1-D MHD modeling to optimize shell thickness, pulse duration, and fuel density

bars associated with measuring ion temperatures with neutron time-of-flight (nTOF) detectors.

<table>
<thead>
<tr>
<th>Shell thickness (µm)</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration (ns)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Fuel density (mg/cm³)</td>
<td>2.7</td>
<td>2.4</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Neutron yield (10¹⁰ mm⁻¹)</td>
<td>12.4</td>
<td>3.26</td>
<td>0.709</td>
<td>0.151</td>
</tr>
<tr>
<td>Peak ion temperature (keV)</td>
<td>4.27</td>
<td>2.85</td>
<td>2.34</td>
<td>1.72</td>
</tr>
<tr>
<td>Neutron averaged ion temperature (keV)</td>
<td>3.36</td>
<td>2.28</td>
<td>1.82</td>
<td>1.34</td>
</tr>
<tr>
<td>Implosion velocity (km/s)</td>
<td>188</td>
<td>154</td>
<td>128</td>
<td>113</td>
</tr>
<tr>
<td>Fuel convergence ratio</td>
<td>27.3</td>
<td>25.5</td>
<td>24.6</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Table 2.5: Pulse length and fuel density that maximizes neutron yield for each shell thickness under the constraint that fuel convergence ratio is approximately 25. All reported observables were obtained from 1-D LILAC MHD.

An example trend of neutron yield as a function of pulse length and fuel density for 30 µm is shown in Fig. 2.3. Neutron yield is highest for the lowest fuel density, but the convergences at these densities exceed the constraint of 25. Increasing the fuel density from the lowest to highest value reduces the convergence by a factor of 2 while having a worst-case impact of a 25% decrease on neutron yield. Therefore, tuning the fuel density to satisfy the fuel convergence requirement is a good strategy.

The time evolution of an imploding 30 µm shell is shown in Fig. 2.4. This graph is a reproduction of Fig 4 in Ref. [42] for direct comparison with the Z point design. This illustrates the difference between OMEGA and Z in terms of drive; OMEGA flattens out about halfway through the laser pulse, whereas the current pulse from Z constantly rises throughout the implosion. The Z point design also assumes a fixed rate of energy deposition into the gas shortly before the fuel convergence to model preheat rather than imposing an initial condition. The shorter time scale and sharper rise in drive in the OMEGA design allows us to impose preheat as an initial
Figure 2.3: a) Neutron yield per unit length and b) fuel convergence ratio as a function of pulse length and fuel density for 30 $\mu$m shells. Other shell thicknesses have similar trends with respect to pulse length and fuel density.

Figure 2.4: A 30 $\mu$m shell implosion with initial fuel density of 2.4 mg/cm$^3$ driven by a 1.5 ns pulse is illustrated by absorbed laser power, outer fuel radius, and average ion temperature plotted as a function of time condition without substantial losses prior to compression, unlike Z simulations.

A plot of ion temperature, density, and magnetic field profiles in the fuel at neutron bang time for a 30 $\mu$m shell with and without the Nernst term is included to compare with Fig. 5 of Ref [42]. The profiles for the case without the Nernst effect match closely. However, the increased magnetic flux losses due to Nernst is made apparent by the differences in magnetic field and ion temperature profiles between
the Z and OMEGA point designs. The Nernst effect lowers the magnetic field in the center of OMEGA targets due to shock convergence causing a temperature gradient early in the implosion. The flux pile-up that is seen in the no-Nernst case is swept out by the temperature gradient close to the edge of the shell in the Nernst case resulting in a relatively flat magnetic field profile. There is little to no shock driven by the Z accelerator during its implosion phase causing very little flux loss towards the center. The Z design also loses much less flux than the OMEGA design near the gas-shell boundary. The magnetic field is still large enough to impede heat flow, which causes the ion temperature profile to broaden without being significantly reduced. It is very advantageous to maintain a high magnetic field at the gas-shell interface since that is the region where heat loss takes place. In the OMEGA point design, the Nernst effect case actually has a higher magnetic field at this boundary albeit an overall lower $BR$ product. It was never expected of the OMEGA design to have the $BR$ required to magnetize charged fusion products, and the Nernst effect is not a major issue concerning the success of MagLIF experiments on OMEGA.

Diffusive flux loss calculations were in very good agreement with the predictions from Eq. 2.11. At peak neutron rate, OMEGA lost 85% magnetic flux compared to 70% for Z for a 10 T initial magnetic field with the Nernst term included. Without the Nernst term, OMEGA lost 39% magnetic flux whereas Z lost 25% [42].

2.4 Preheat and Magnetic Field Parameter Space

In the previous section, preheat and axial field were fixed at the highest values that could readily be achieved on the OMEGA laser system. This section provides a look at how different levels of preheat and magnetic field affect the neutron yields for 30
$\mu m$ shells.

Fig. 2.5 shows the effects of preheat for 3 different initial axial magnetic fields. The effects of magnetic field on yield, neutron averaged ion temperature, mean implosion velocity, and fuel convergence ratio are shown in Fig. 2.6.

The yield increases with preheat only up to the threshold value of $\sim 100$ eV in agreement with the estimate from Eq. 2.9. Preheating above this threshold has no added benefit in terms of neutron yield, and in some cases can lead to decreased yield due to higher temperature gradients sweeping out magnetic flux via the Nernst effect. Furthermore, preheating above the threshold temperature carries the risk of excessive wall heating due to thermal conduction and prolonged time for window material to propagate into the implosion region. Without magnetization, increasing preheat has little effect on the neutron yield. Considering the thermal losses early in time, preheating to any higher than 29 eV calculated from Eq. 2.9 is largely wasted energy.

It should be noted that the original choice of 200 eV preheat for optimizing the laser pulse length and initial fuel density was not critical; the value used could have easily differed by $\pm 100$ eV without significantly affecting the result. A potential benefit from increasing preheat comes from the reduction in fuel convergence, particularly in the unmagnetized case. It could very well be the case that preheat with implosion vs. implosion only experiments will produce more neutrons from reduced convergence and reduced perturbation growth and mix.

Both yield and ion temperature increase with magnetic field because energy losses from electron thermal conduction are suppressed. The rate at which neutron yield and temperature increase with magnetic field starts to decrease above 20 T. This is due to the heat flux being ion dominated while the electron conduction falls
2.4 Preheat and Magnetic Field Parameter Space

Figure 2.5: Neutron yield per unit length vs. preheat temperature for 3 initial magnetic field values. Once above the 100 eV threshold temperature, neutron yield does not increase appreciably at higher preheat temperatures.

esentially to zero. Magnetization without preheat allows the target to converge considerably. This compresses the magnetic field to the point where the magnetic pressure becomes comparable to the hydro pressure at stagnation, illustrated in Fig. 2.7. With preheat, magnetic pressure is negligible even in the case of 30 T.

Increasing the initial magnetic field should also reduce the loss of magnetic field compression due to the Nernst effect. This is shown in Fig. 2.8 as well as the impact that preheating has on flux conservation and the Nernst effect. Without an initial temperature profile, there is no temperature gradient to cause flux loss due to Nernst early in time. For the preheat case, increasing the magnetic field from 10 T to 30 T increases the flux conserved by a factor of 2. The Z point design predicts an even greater increase in flux conservation because of the smaller temperature gradient at larger scales as expected from Eq. 2.8; an increase from 30% to 55% from 10 T to 30 T.

Increasing the preheat and the magnetic field decreases both the fuel convergence and the mean implosion speed, thereby changing what the other optimal values may
2.4 Preheat and Magnetic Field Parameter Space

Figure 2.6: a) Yield per unit length, b) neutron averaged ion temperature, c) mean fuel implosion velocity, and d) fuel convergence ratio plotted as a function of magnetic field for no preheat and 200 eV preheat.

Figure 2.7: The ratio of magnetic pressure to hydro pressure at peak neutron rate is plotted as a function of magnetic field for the preheat and no preheat case. High convergence when the gas is not preheated causes the magnetic pressure to become comparable to the hydro pressure at bang time.
2.4 Preheat and Magnetic Field Parameter Space

Figure 2.8: The percentage of flux conserved vs magnetic field. More flux is conserved for higher initial fields due to a reduction of the Nernst effect. Without preheat, Nernst effect is less of an issue and therefore leads to much higher flux percentages.

be. Since there are plans to increase OMEGA’s magnetic field capability to produce fields as strong as 30 T, the optimization scan is repeated using a 30 T initial field and report our findings in Table 2.6. The optimal pulse lengths and trends of initial fuel densities with neutron yields are unchanged for all shell thicknesses except for 20 \( \mu m \). The decrease in convergence is due to the stronger magnetic field further suppressing electron thermal losses from the gas. For the 30 \( \mu m \) shells, the optimal parameters are unchanged, but result in a lower convergence, higher ion temperature, and increased neutron yield compared to the 10 T case. Suppression of heat losses is illustrated best by looking at the volume-averaged pressure at bang time, shown in Fig. 2.9. For thicker shells, the change in scaling of convergence ratio with initial fuel density due to the addition of the magnetic field make it more advantageous to use higher initial fuel densities, although the overall increase in neutron yield is very marginal.

20 \( \mu m \) shell implosions begin to enter a new regime for 30 T initial magnetization. From the 0-D estimate for final temperature in Eq. 2.10, the dependence on final
Figure 2.9: Volume averaged total pressure $nT + B^2/2\mu_0$ plotted versus initial magnetic field. The decrease in convergence due to increasing magnetic field is attributed to hotter core temperatures and greater fuel pressures at stagnation. As preheat temperature increases, convergence decreases enough to lower the gas pressure at stagnation.

<table>
<thead>
<tr>
<th>Shell thickness ($\mu$m)</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse duration (ns)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Fuel density (mg/cm$^3$)</td>
<td>2.0</td>
<td>2.4</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Neutron yield ($10^{10}$ mm$^{-1}$)</td>
<td>27.3</td>
<td>9.26</td>
<td>2.62</td>
<td>0.88</td>
</tr>
<tr>
<td>Peak ion temperature (keV)</td>
<td>10.8</td>
<td>5.26</td>
<td>3.75</td>
<td>3.05</td>
</tr>
<tr>
<td>Neutron averaged ion temperature (keV)</td>
<td>5.91</td>
<td>3.38</td>
<td>2.54</td>
<td>2.11</td>
</tr>
<tr>
<td>Implosion velocity (km/s)</td>
<td>196</td>
<td>158</td>
<td>128</td>
<td>114</td>
</tr>
<tr>
<td>Fuel convergence ratio</td>
<td>25.9</td>
<td>20.9</td>
<td>18.7</td>
<td>19.9</td>
</tr>
</tbody>
</table>

Table 2.6: Pulse length and initial fuel density that maximizes neutron yield for the case of 30 T initial axial field and 200 eV preheat. All observables were calculated using 1-D LILAC MHD
temperature with initial fuel density can be estimated and compared between the 0 T and 30 T cases. For a large initial magnetic field, the scaling should be unchanged from simple adiabatic compression physics. For different initial fuel densities, the average compression velocity is relatively unchanged. Therefore, the stagnation conditions should be the same which gives us

\[ PV^\gamma = nTV^\gamma = \text{const.} \]

\[ T \sim C^{4/3} \]

\[ V \sim C^{-2} \]

\[ n = n_0C^2 \]

\[ \rho_0 \sim \text{const.} \]

for an adiabatic compression. The no magnetic field case is very far from the adiabatic case. An exponential fit of the results from LILAC MHD shows that the actual scaling is \( \rho_0 \sim C^{-0.9} \) for the case of 20 \( \mu \)m thick shells. It is expected to see convergence ratio decrease with increasing initial fuel density as the implosion diverges from the adiabatic case. For example, taking the 0-D approximation in the high convergence case would give a relation of \( C \sim \rho_0^{-0.4} \), ignoring the dependence of \( T_c \) on \( \rho_0 \). As the implosion becomes more insulated from heat losses by the magnetic field, the convergence ratio dependence on initial fuel density approaches the adiabatic limit, which can be seen in Fig. 2.10.

If the convergence ratio scaling from the 1-D results is substituted into the 0-D estimate of final temperature (Eq. 2.10) for the 0 T case, the same scaling relation with initial fuel density is very nearly recovered. However, if the same is done for the 30 T case, a temperature increase with increasing fuel density should be expected rather than a more drastic decrease as seen in Fig. 2.10. The 0-D model
Figure 2.10: Increasing the magnetic field decreases the convergence ratio for a given drive energy and initial fuel density, as well as changing the scaling relation between convergence and initial fuel density. The left hand plot shows the difference for 20 \(\mu\text{m}\) shells driven with a 1.5 ns square pulse with no initial magnetic field and 30 T initial magnetic field. This in turn changes the neutron-averaged ion temperature scaling, seen on the right hand plot.

is incomplete when explaining the temperature trend for the 20 \(\mu\text{m}\) thick shells. The same exercise can be performed for the rest of the shell thicknesses, and in fact, a similar decrease in temperature between the 0 T and 30 T cases is shown. The slight change in scaling of the convergence ratio for the thicker shells makes it advantageous to use higher initial gas densities, which increases the optimal gas density from 1.5 to 2.0 mg/cc in the case of 40 and 50 \(\mu\text{m}\) thick shells.

Since this strange effect is only seen in the case of high initial magnetic field, the 0-D model should be modified using the Braginskii correction to the Spitzer conductivity \((K_0 \rightarrow K_0 K')\). For ions diffusing perpendicular to the magnetic field, the Braginskii correction is given as

\[
K' = \frac{2\chi^2 + 2.645}{\chi^4 + 2.70\chi^2 + 0.677}
\]  

(2.22)

where \(K_0\) is the Spitzer conductivity described in Eq. 2.4 and \(\chi\) is the ion hall
Figure 2.11: The Braginskii correction modifies the critical temperature, which in turn changes how the final temperature scales with initial fuel density. To get an estimate of this scaling, the Braginskii correction is approximated using a least-squares power law fit. The fit is much better at capturing the trend of the correction term over a large range of ion hall parameters compared to a Taylor series expansion about $\chi = 2$. The fit here shows that $(1/k')^{2/5} \sim \chi^{0.72}$ for $1 < \chi < 10$

parameter. For ion hall parameters close to unity, the correction factor is $\sim 0.83$, which is enough to change the temperature by $\sim 10\%$. Unfortunately, the initial field strength is far too low, and $\chi$ only reaches values close to unity around 2/3 peak compression. Considering the only physics missing from the 0-D estimation is the effect of magnetic field modifying the conductivity, the ad-hoc assumption of including the Braginskii correction seems valid.

A power law fit of the Braginskii correction term as a function of the ion hall parameter is used to determine the scaling relation and more easily estimate the trend of final temperature vs initial fuel density obtained from 1-D simulations. The values of $\chi$ that have the most varied impact on temperature are $1 < \chi < 3$. A
5th order expansion is required to obtain a decent approximation to the correction term in this domain. Additionally, the high order terms make the expansion diverge sharply for $\chi > 3$, giving a terrible prediction capability for values outside the domain of interest. By using a power law fit, a much better approximation is achieved in the domain of interest that is still relevant for values of $\chi$ outside the domain. A comparison of the expansion and the power law fit compared to the exact value of the correction term is shown in Fig. 2.11. The power law fit gives a relation of $(1/K')^{2/5} \sim \chi^{-0.72}$.

A relation of $C \sim \rho^{-0.56}$ is obtained from the power law fit in Fig. 2.10. The ion hall parameter is proportional to the magnetic field, and so $B \sim C^2 \sim \rho^{-1.12}$. The shell velocity scales very weakly with increasing initial fuel density, but makes a contribution of $v_0 \sim \rho_0^{-0.04}$. Substituting these relations into the 0-D estimate of final temperature gives

$$T \sim \rho_0^{2/5} v_0^{2/5} C^{2/5} \chi^{0.7} \sim \rho_0^{2/5} (\rho_0^{-0.06})^{2/5} (\rho_0^{-0.56})^{2/5} (\rho_0^{-1.12})^{0.72} \sim \rho_0^{-0.65} \quad (2.23)$$

This very nearly matches the result of $T \sim \rho_0^{-0.7}$ obtained from the power law fit shown in Fig. 2.10. The small discrepancy between the 0-D model and the 1-D results can be explained by the magnetic field modifying the temperature profile, making the assumption of $\nabla T \sim 1/r$ invalid. The temperature dependence of $\chi$ is also not considered. This would require another more detailed look at solving the energy balance equation. It suffices to state the effects seen on the 20 $\mu$m thick shells can be explained to 0th order by the effects of the magnetic field. Ion magnetization is responsible for changing how neutron yield changes with increasing fuel density.
2.5 Two-dimensional modeling of the point design using HYDRA, effects of end losses, and absolute neutron yields

in the case of strongly magnetized 20 µm shell implosions.

2.5 Two-dimensional modeling of the point design using HYDRA, effects of end losses, and absolute neutron yields

Neutron yields calculated from 1-D simulations are all reported per unit length of the cylinder. Realistically, the energy per unit length restriction of the OMEGA laser system will dictate the actual yield seen in experiments. Loss mechanisms such as mass loss due to axial flow, axial thermal conduction, and axial diffusion of magnetic field are not taken into account in a 1-D simulation, which leads to overestimation of the neutron yield. Slutz et al. estimate end losses using an analytical solution for a rarefaction wave, doubling it to calculate loss out of both ends of the cylinder gives:

$$\frac{d}{dt} (\log N) = -2 \left( \frac{3}{4} \right)^4 \frac{c_s}{L}$$

for \( N \) total particles, cylinder length of \( L \), and adiabatic ion sound speed \( c_s = \sqrt{\frac{5ZkT}{3m_i}} \). Substituting Eq. 2.5 into Eq. 2.24 and expanding for initial and final temperatures and convergence ratios of interest,

$$\frac{N}{N_0} \approx \exp \left[ -6 \left( \frac{3}{4} \right)^4 \frac{r_0 c_s(T_0)}{L} \frac{v}{v} \right], \quad C^{7/3} \gg 0.7 \left( \frac{T_c}{T_0} \right)^{5/2} - 1, \quad 0.7 \left( \frac{T_c}{T_0} \right)^{5/2} \gg 1$$

(2.25)

where \( c_s(T_0) \) is the adiabatic sound speed evaluated at the initial temperature.
Eq. 2.25 does not take axial conduction losses into account, which would decrease the sound speed at the ends of the cylinder thereby reducing the total mass loss. Equation 2.25 should be considered as an appropriate upper bound estimation for mass loss out of the ends of the cylinder. For the point design parameters calculated previously and taking $L = 0.5$ mm, Eq. 2.25 gives a 64 % mass loss.

End loss mechanisms can be taken into account in more detail with 2-D MHD modeling using HYDRA [30]. To save on computation time, HYDRA was only used for 20 and 30 $\mu$m shells with a 10 T magnetic field so these gave adequate neutron yields and ion temperatures.

HYDRA uses 35-group radiation transport, tabulated LTE (local thermodynamic equilibrium) opacities and LTE equations of state (LEOS), Epperlein-Haines transport coefficients with a Lee-More degeneracy correction, and a flux limiter of 0.05. The resistivity of $D_2$ was calculated using QLMD (quantum Lee-More-Desjarlais). Unfortunately, the Nernst term was not included in the magnetic field evolution equation at that time. Results from 2-D HYDRA were compared to 1-D HYDRA to ensure an accurate 1-D to 2-D comparison. Results from 1-D HYDRA were within 10 % of the results from LILAC even though HYDRA uses different radiation transport, EOS, thermal conductivities, and resistivities. Magnetic flux conservation from HYDRA matched the 60 % from LILAC when the Nernst term was not included.

An exact pointing for the laser drive was not considered as this goes beyond the scope of the point design. Instead, normal incident rays with a super-Gaussian axial intensity profile with a full width at 95 % intensity of 0.5 mm were used to provide the drive. The length of the implosion region was arbitrarily chosen and is a conservative estimate of OMEGA’s capabilities, while the peak intensity matched the value used in LILAC. The density plot in Fig. 2.12 demonstrates that the
2.5 Two-dimensional modeling of the point design using \textit{HYDRA},
effects of end losses, and absolute neutron yields

Figure 2.12: A snapshot from \textit{HYDRA} 2-D MHD simulation showing the density profile at peak neutron rate for a 30 \( \mu \)m shell.

implemented laser drive provides an axially uniform compression over the entire 0.5 mm length.

An advantage of running a full 2-D simulation is the ability to include an axial laser beam to apply preheating rather than imposing it as an initial condition. The window and standoff distance was not included in these simulations in order to make the calculation more computationally inexpensive. The previous DRACO results are used to calculate the approximate laser energy absorption in the window and the relative timing of the beam irradiating the gas. For a 180 J, 1.5 ns long pulse for a cylinder filled with 2.4 mg/cm\(^3\) \( \text{D}_2 \), the mean temperature from \textit{DRACO} calculations was 219 eV, with the laser burning through the window 0.5 ns into the pulse. An equivalent 120 J, 1 ns pulse was then used in \textit{HYDRA} to approximate the energy loss from the laser-window interaction.

The temperature profiles from this preheating scheme are shown in Fig. 2.13 for a 2.7 mg/cm\(^3\) \( \text{D}_2 \) filled 30 \( \mu \)m shell. The results for a 2.7 mg/cm\(^3\) \( \text{D}_2 \) filled 20 \( \mu \)m thick shell were similar. The radially averaged ion temperature is 200 eV, which
2.5 Two-dimensional modeling of the point design using HYDRA, effects of end losses, and absolute neutron yields

![Figure 2.13: a) Area-averaged electron and ion temperatures and b) radial profiles of electron temperature and density at the center of the implosion region after the preheat laser pulse for a 30 µm shell with 2.4 mg/cm$^3$ of D$_2$ using 2-D Hydra.](image)

is comparable to the pre-imposed conditions used in the 1-D LILAC simulations. However, the electron temperature is a factor of 5 greater than the ion temperature in the HYDRA results, whereas equal ion and electron temperatures were used in LILAC. Much of the excess heat in the electron fluid is lost to axial flow in 2-D, and at peak neutron rate, ion temperature exceeds the electron temperature.

A comparison between 1-D and 2-D HYDRA is shown in Table 2.7. Heat and mass losses due to axial flow are roughly 50% for 30 µm shells and roughly 40% for 20 µm shells, which is close to the estimate from Eq. 2.25 of 64% and 55% respectively, assuming a 200 eV preheat temperature. The net effect on the performance of these losses is a decrease in neutron yield by a factor of 53 for 30 µm shells and a decrease by a factor of 14 for 20 µm, assuming a 0.5 mm long uniform implosion region for the 1-D results.

Area-averaged fuel density and temperature at peak neutron rate show strong axial gradients shown as fractions of the 1-D results in Fig. 2.14. The profiles
2.5 Two-dimensional modeling of the point design using HYDRA, effects of end losses, and absolute neutron yields

<table>
<thead>
<tr>
<th>Shell thickness (µm)</th>
<th>20</th>
<th>20</th>
<th>30</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dimensions</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Neutron yield (10^9)</td>
<td>17.0</td>
<td>1.22 (7.2%)</td>
<td>12</td>
<td>0.224 (1.9%)</td>
</tr>
<tr>
<td>Peak ion temperature (keV)</td>
<td>3.46</td>
<td>2.22 (64%)</td>
<td>3.11</td>
<td>1.52 (49%)</td>
</tr>
<tr>
<td>Neutron average ion temperature (keV)</td>
<td>2.54</td>
<td>1.73 (68%)</td>
<td>2.30</td>
<td>1.27 (55%)</td>
</tr>
<tr>
<td>Implosion velocity (km/s)</td>
<td>205</td>
<td>168 (82%)</td>
<td>163</td>
<td>139 (85%)</td>
</tr>
<tr>
<td>Fuel convergence ratio</td>
<td>26.2</td>
<td>25.6 (98%)</td>
<td>27.3</td>
<td>26.5 (97%)</td>
</tr>
<tr>
<td>Compressed fuel density (g/cm³)</td>
<td>1.81</td>
<td>1.03 (57%)</td>
<td>1.80</td>
<td>0.85 (47%)</td>
</tr>
</tbody>
</table>

Table 2.7: A comparison of 1-D and 2-D HYDRA results for the point design. 1-D neutron yield assumes a cylinder length of 0.5 mm. The convergence ratio is calculated in 2-D from the center of the implosion. The compressed fuel density in 2-D is the average over a length of 0.5 mm around the center of the implosion.

Figure 2.14: a) Radially averaged density and b) temperature plotted as fractions of 1-D results vs axial position for 20 µm (dotted) and 30 µm (solid) shells.

also show that axial heat loss is greater than mass loss, which is expected considering axial flow and thermal conduction. Axial asymmetries are formed from the axial temperature gradient imposed by the absorption of the preheat laser. Axial losses differ between shell thicknesses because of differing implosion velocities and compression times.
2.5 Two-dimensional modeling of the point design using HYDRA, effects of end losses, and absolute neutron yields

Figure 2.15: Axial profiles of radially integrated magnetic field \((BR)\) plotted as fractions of the 1-D result of 0.038 T·m at peak neutron rate.

Axial profiles of the radially integrated magnetic field, or \(BR\) product, at peak neutron rate as fractions of the 1-D result are plotted in Fig. 2.15. The loss of radially integrated magnetic field in the central 0.5 mm of the cylinder is 56% for 30 \(\mu m\) shells and 48% for 20 \(\mu m\) shells going from 1-D to 2-D. This indicates that end losses also provide an additional source of magnetic field diffusion from the central region of the implosion that is comparable to the radial diffusion losses of 40%. Regardless of the additional losses, the \(BR\) product obtained in these implosions are far too small to provide confinement of charged fusion products, but are strong enough to measure using high-energy proton deflectometry [22].

The requirement for measurable neutron yields and neutron-averaged ion temperatures is a neutron yield of \(10^9\) or greater, which can be provided by 20 \(\mu m\) shells. Another requirement of the point design in the 2-D modeling is to maintain a convergence of \(\sim 25\). The implosion velocity and convergence ratio do not change much from 1-D to 2-D with a reduction in convergence caused by axial heat flow in the corona leading to lower ablation pressure, which is offset by an increase in
convergence due to axial losses.

2.6 Scaling to MJ class lasers

The National Ignition Facility (NIF) is a $3\omega$ laser configured for polar drive and can deliver up to 1.9 MJ of laser energy to the outside of a cylinder. Magnetization and preheat capabilities are still missing from the NIF, but magnetic field generation and its application to hohlraums have already been considered [37]. NIF has roughly $10\times$ less energy absorbed by the target than Z, which makes NIF a smaller scale MagLIF scheme like OMEGA, but with the capability of conditions more relevant to full-scale MagLIF.

A scheme similar to Nora et al. [36] of increasing total drive energy in the 1-D modeling by a factor $f$ from 1-100 while increasing linear dimensions and laser pulse duration by factors of $f^{1/3}$ was applied to the 30 $\mu$m shells. This scaling keeps laser intensity, laser energy per unit shell mass, shell aspect ratio, and fuel aspect ratio constant while maintaining 2.4 mg/cm$^3$ D$_2$ fuel density, 10-T axial magnetic field, and a 200 eV preheat with an identical profile to previous LILAC simulations. Magnetic field capabilities on the NIF should produce up to 70 T, so modest magnetic fields up to 30 T will be considered.

All practical details of a design for the NIF such as drive symmetry, magnetization, preheating, phase plates, pulse duration, laser pointing, and laser absorption efficiencies, will not be considered here. A more in-depth point design on the NIF should be considered, and the initial scaling presented here provides the motivation for doing so. The most critical issue for doing MagLIF on the NIF would be adding an extra UV beam to accomplish preheating down a symmetry axis, or providing
an alternative solution for preheating the targets.

In an ideal hydro-equivalent scaling with no changes in thermal and magnetic field losses, implosion velocity, and convergence ratio, the final pressure should remain the same leading to a $f^{4/3}$ increase in total neutron yield. For a spherical implosion of constant pressure, the yield goes as $Y_{1-D} \sim E^{3/2}$ assuming no heating due to local alpha particle deposition[36]. For 1-D calculations of cylinders, the neutron yield and laser energy are given per length of the cylinder, and so the scaling from 1-D spheres must be normalized to the energy per unit length. Since linear dimensions scale as $f^{1/3}$,

$$Y_{1-D} \sim E_L^{3/2} \frac{\ell}{E_L} \sim E^{4/3}$$

Thermal losses should decrease as size increases, thereby increasing the temperature, decreasing the implosion velocity, and lowering the final pressure. Magnetic field losses will also be less as target size approaches the Z scale, leading to better magnetic insulation and higher gas temperatures. A temperature scaling like Eq. 2.8 that does not consider reductions in implosion velocity or final pressure can give an upper bound on scaling.

$$P \sim nT \sim \text{const.}$$

$$nT \sim C^2 \left( C^{2/5} f^{2/15} \right)$$

$$C \sim f^{-1/18}$$

$$T \sim f^{1/9}$$

Final temperature should scale as $f^{1/9}$ and convergence ratio as $f^{-1/18}$, leading to a total neutron yield scaling of $f^{5/3}$ assuming a fusion reactivity of $\langle \sigma v \rangle \propto T^4$
2.6 Scaling to MJ class lasers

Figure 2.16: Neutron yield, neutron-averaged ion temperature, implosion velocity, and convergence ratio as fractions of the $f = 1$ case plotted vs energy scale factor $f$, including power law fits.

relevant for D$_2$ fusion at 2 to 3 keV, and assuming that confinement time goes as $T^{-1/2}$ because of the increase in expansion velocity.

The scaling relations predicted by LILAC 1-D MHD of relative yield, neutron-averaged ion temperature, implosion velocity, and convergence ratio are shown in Fig. 2.16 along with least-squares power law fits with respect to the scaling factor $f$.

Relative yield increases like $f^{1.4}$ regardless of initial magnetic field, between the expectation for fixed temperature of $f^{4/3}$ and fixed velocity and convergence ratio of $f^{5/3}$. Final temperature scales similarly to the prediction from Eq. 2.8 of $f^{1/9}$ at 30 T, and slightly slower for 10 T, but this is due primarily to the decrease in implosion velocity and convergence ratio that were not taken into account. The fall
2.6 Scaling to MJ class lasers

![Graph showing volume averaged pressure vs scale factor](image)

Figure 2.17: Volume averaged pressure vs the scale factor $f$ shows that this rudimentary scheme of scaling is not exactly hydro-equivalent, with the total reduction in final pressure being about a factor of 2.

in convergence ratio is faster than $f^{-1/18}$ for the same reason.

The $\sim 35\%$ decrease in convergence ratio from the ideal goal of 25 indicates that the ideal parameters for MagLIF at NIF-scale energies are different than simply scaling up an optimized design from OMEGA. Finding these optimal parameters should be the goal of the NIF point design in the future. Furthermore, the crude scaling of laser energy is not exactly a hydro-equivalent scheme, since important quantities like implosion velocity and final pressure are not the same as the OMEGA scale case. A plot of the volume-averaged pressure is shown in Fig. 2.17. A constant implosion velocity and pressure would require small changes in shell thickness and initial fuel density. It is quite possible to do this with just the $f = 100$ case to get an idea of the performance of a MagLIF capsule at the NIF scale.

Keeping in the spirit of trying to achieve hydro-equivalence with the 30 $\mu$m shell case, with a gas density of 2.4 mg/cc, initial preheat temperature of 200 eV, initial magnetic field of 30 T, and tune the shell thickness to achieve roughly the same
2.6 Scaling to MJ class lasers

final pressure, convergence ratio and implosion velocity. These calculations can also
go a step further and see how a hydro-equivalent DT implosion compares to a DD
implosion, since NIF is capable of fielding such an experiment. For this simulation,
a 50/50 mixture of DT is used and the results are reported in Table 2.8.

<table>
<thead>
<tr>
<th>Case</th>
<th>20 µm ideal</th>
<th>30 µm ideal</th>
<th>NIF f=100 DT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel density (mg/cm$^3$)</td>
<td>2.0</td>
<td>2.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Neutron yield (10$^{12}$ mm$^{-1}$)</td>
<td>2.73</td>
<td>0.926</td>
<td>39000 (DT)</td>
</tr>
<tr>
<td>Peak ion temperature (keV)</td>
<td>10.8</td>
<td>5.26</td>
<td>16.7</td>
</tr>
<tr>
<td>Neutron averaged ion temperature (keV)</td>
<td>5.91</td>
<td>3.38</td>
<td>10.9</td>
</tr>
<tr>
<td>Implosion velocity (km/s)</td>
<td>196</td>
<td>158</td>
<td>180</td>
</tr>
<tr>
<td>Fuel convergence ratio</td>
<td>25.9</td>
<td>20.9</td>
<td>21.0</td>
</tr>
<tr>
<td>Volume averaged pressure (Gbar)</td>
<td>2.18</td>
<td>3.65</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 2.8: The ideal case, which maximizes neutron yield for 20 and 30 µm thick
shells is compared to a NIF scale design with f=100 and a 50/50 DT mixture with
a tuned shell thickness to match final pressures for the OMEGA scale cases.

Obviously much of the increase in neutron yield is due to the addition of DT. For
DD fuel, the yield for the $f = 100$ case for a tuned shell thickness is $1.2 \times 10^{15}$ mm$^{-1}$,
which is close to the nominal scaling of the 30 µm shell case of $1.1 \times 10^{15}$ mm$^{-1}$. Clearly to achieve true hydro-equivalence, the fuel density must be changed alongside
the shell thickness and laser energy. Such work is outside the scope of this thesis.

Increasing the target size decreases magnetic flux loss from the Nernst effect and
resistive diffusion. Indeed, the percentage of flux conserved increases with increas-
ing $f$ and increasing initial magnetic field as shown in Fig. 2.18. For 10 T, flux
conservation more than doubles from 15% at $f = 1$, to 34% at $f = 100$. At 30
T, the increase in flux conserved with increasing scale is less, but at $f = 100$ the
percent flux conserved reaches 50%, which is comparable to the 55% of the Z point
design.
2.6 Scaling to MJ class lasers

Figure 2.18: The percent of flux remaining in the fuel at peak neutron rate vs energy scale factor $f$. Higher initial fields as well as increasing target size lead to more flux conservation.

This additional flux conservation allows targets at the NIF scale to achieve values of $BR$ that are relevant to confining charged fusion products. The values of $BR$, shown in Fig. 2.19 are still short of the 0.6 T·m required for self heating [2] and the 0.4 T·m measured in Z experiments [40] even at 30 T and $f = 100$, but they are high enough to produce measurable secondary DT yield from D$_2$ fuel [40]. Magnetic confinement of charged fusion products is quintessential to the MagLIF concept and can be studied at the NIF scale.
2.6 Scaling to MJ class lasers

Figure 2.19: Radially integrated magnetic field, or $BR$, parameter vs energy scale factor $f$. At larger magnetic fields and scale factors, the $BR$ product reaches values where confinement of charged fusion products can be easily measured.
Chapter 3

Characterization of OMEGA

MagLIF preheat and LEH (laser entrance hole) burn through and transmission

3.1 Introduction

MagLIF (magnetized liner inertial fusion) is a magnetized target fusion scheme utilizing a cylindrical implosion with an axial magnetic field to compress preheated deuterium fuel to fusion relevant pressures. The magnetic field mitigates the radial conduction losses and allows these implosions to happen $\sim 3 \times$ slower than direct or indirect spherical implosions. The lower volume decrease with equal conversion ratios for cylinders versus spheres requires that the deuterium fuel start at a much higher temperature than in traditional ICF schemes. This is accomplished by using
an axial laser to heat the deuterium via inverse bremsstrahlung absorption. A thin plastic foil or window is used to cover the laser entrance hole (LEH) contain the \(\sim\)10 atmospheres of gas. Characterizing the laser energy required to burn through the LEH foil, determining the preheat temperature of the gas after LEH burn through, and quantifying undesirable laser-plasma interactions (LPI) such as Stimulated Raman Scattering (SRS), Stimulated Brillouin Scattering (SBS), and filamentation are key to reliably preheating MagLIF implosions on OMEGA.

To study the LEH window disassembly in terms of laser transmission, backscatter, sidescatter and x-ray emission, a series of LEH foil only shots were performed along the axis of a single beam of the OMEGA laser. LEH window shots were performed in two configurations: one to measure backscatter, sidescatter, and transmission using beam 25 and the other to measure transmission and forward scatter using beam 46. The beam 25 configuration is then used to heat D\(_2\) gas filled cylinders doped with Neon to measure the temperature of the gas and infer the absorbed laser energy using soft x-ray diagnostics. Six cylinders in total were shot; two with an initial 15 T magnetic field and an initial gas density of 1.5 mg/cc, two without magnetic field at the same gas density, one at 1/2 of the initial gas density, and one at 3/2 the initial gas density.

3.2 LEH window backscatter, sidescatter, and forward transmission

A 2.5 ns square pulse 3\(\omega\) laser with a 200 \(\mu\)m distributed phase plate (DPP) with smoothing by spectral dispersion (SSD) was used in both the LEH window and gas filled cylinder configurations. The laser energy was varied between 60-200 J to
Figure 3.1: a) The backscatter measurement configuration utilizes the beam 25 axis in OMEGA (B25) and FABS diagnostics in ports 25, 30, and H17C. Forward transmission is then measured using a calorimeter in the nearest hex port to the beam 46 axis. b) The forward scatter configuration utilizes beam 46 (B46) and the same FABS to measure forward and side scatter. c) Ne doped D$_2$ gas filled cylinders with the same foil windows were shot using beam 25 to measure the gas preheating and changes to the backscatter and sidescatter.

The foil thickness was chosen based on 2 key parameters. The first being the change the incident laser intensity for LEH window shots and fixed at 200 J for the cylinder shots. The LEH foils were made from 1.84 µm thick polyimide film (C$_{22}$H$_{10}$N$_2$O$_5$). Full-aperture backscatter stations (FABS) were arranged around the LEH foil as shown in Fig. 3.1 to measure time-resolved spectra of scattered light. A calorimeter was used to measure the forward transmission through the foil, and an array of filtered x-ray diodes were used to measure self-emission x-rays to calculate plasma conditions of the LEH disassembly and demonstrate trends in energy absorbed by the window as a function of incident laser energy.

The foil thickness was chosen based on 2 key parameters. The first being the
filamentation figure of merit (FFOM) $Q^{[34]}$. The deuterium gas inside the cylinder needs to be heated without inadvertently heating the wall. This can happen by filamentation which can cause the laser beam to spray at various angles in the forward direction, causing laser-wall interactions. It can also happen by intensely heating the region of the gas that is close to the wall, which will conduct into the wall before the end of the preheat pulse. Any deviation of the laser from a purely forward propagation can cause unwanted wall heating and mix of wall material into the gas.

The FFOM is given as$^{[34]}$

$$Q = \left( \frac{I \lambda^2}{10^{13} \text{ W cm}^{-2} \mu \text{m}^2} \right) \left( \frac{n_e}{n_c} \right) \left( \frac{T_e}{3 \text{keV}} \right)^{-1} \left( \frac{f}{8} \right)^2$$  \hspace{1cm} (3.1)

where $I$ is the incident laser intensity, $\lambda$ is the laser wavelength, $n_e/n_c$ is the fractional critical density, $T_e$ is the electron temperature, and $f_n = 6.7$ is the f-number of a single OMEGA laser. Assuming the window is heated to an even 1 keV electron temperature and evenly expands into a cylinder of height 1 mm and radius 1 mm, $Q \approx 1.0 \times 10^{13}$, which is a factor of 3 lower than the filamentation threshold for using the smoothing techniques available on the OMEGA laser. A change to 2ω light would nearly exceed the FFOM threshold, and this is a huge advantage of the OMEGA laser versus Z-Beamlet used at SNL. It is expected that filamentation will not occur once the laser starts propagating into the implosion region.

The other parameter is staying below quarter critical to abate other LPI phenomenon like SRS and SBS. We can use our model of expanding the window uniformly down the cylinder to calculate the distance that the window material needs to propagate to reach $n_e/n_c < 0.25$. It turns out this distance is $< 200 \mu \text{m}$ or within
3.2 LEH window backscatter, sidescatter, and forward transmission

Figure 3.2: Backscattered laser intensities from the SBS calorimeters. Backscatter signals between LEH foils and cylinders are identical, with cylinders having a small increase in backscatter later in time.

the washer used to support the LEH foil where it mounts to the target, assuming that the window reaches around 1 keV and is fully ionized. This factor of 200 expansion in volume is also the point at which the window material drops below quarter-critical. We expect to initially get a large burst of LPI in the beginning of LEH burn through, but do not expect much as time goes on.

Foil transmission along the original beam path exceeded 50% and increased with laser energy. The preheat requirement of \( T_i > 100\text{eV} \) mandates that more than 5 J of laser energy need to absorbed by the gas for a 600 \( \mu \text{m} \) long 600 \( \mu \text{m} \) diameter cylindrical volume filled with an initial density of 2.0 mg/cc of \( \text{D}_2 \). It therefore follows that any initial laser energy in the range of 60-200 J transmits enough energy into the gas to achieve adequate preheating.

For maximum laser energy, there is only detectable amounts of SBS for both foil-only and cylinders lasting for \( \sim 0.5 \) ns, shown in Fig. 3.2. SRS calorimeters measured nothing above the noise level for the entirety of the laser pulse. Laser
light was backscattered outside of the original beam path, with twice as much laser intensity recorded at 24.8° than at 16.6°. The only difference between cylinders and foils is the small increase in backscattered power at later times. The forward scattering setup measured sidescatter at both angles that lasted 0.5 ns and occurred 0.5 ns after the end of the backscatter.

The three different measurement angles of backscatter and sidescatter of the two 200 J shots were fit with a 2-D Gaussian profile to infer the total backscattered and sidescattered energy fraction, which we report in Fig. 3.3. Knowing that 63.4% of the laser energy was transmitted through the LEH foil, 0.5% was backscattered, and 8.7% was sidescattered, we can calculate that 27% of the laser energy was absorbed by the foil as it disassembled. The assumption that the backscatter is isotropic and fits a 2-D Gaussian profile with a large angular extent makes this an overestimate of the total laser energy absorbed in the foil.

A 2-D hydrodynamics code DRACO reproduces the foil burn through time of ~0.5 ns for the 200 J foil shots and matches the extent and intensity of the sidescat-
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Along with the FABS diagnostics, an array of filtered x-ray diodes called Dante[44] was used to characterize the x-ray spectrum and total energy of x-rays emitted by the exploding window during the laser pulse. Each diode in the array has its own aperture, filter, signal cable, electrical attenuator, power tee, and transient digitizer. The combination of all of these components is referred to as a channel. Traditionally, 11 channels are employed to diagnose radiation temperatures for hohlraums. This makes Dante ideal to use for diagnosing both the LEH window only shots and the full cylinder preheat shots. Voltage signals from Dante are used to recover both time-resolved and time-integrated spectra of an emitting plasma.

Despite having limited channels above the noise threshold available to reconstruct an x-ray spectrum, the fact that some channels cannot see the x-ray emission due to over-filtering can be used to fill in the gaps to the spectral reconstruction. For example, if there is sufficient signal available in a channel within the range of 80 - 120 eV photon energies and a range of 300 - 500 eV but not in the subsequent range of 120 - 300 eV, there is still enough information about the spectral intensity to make bounded restrictions to it.

First, the raw Dante data must be reduced and aligned. The loss of signal from the cabling, attenuators, and aperture needs to be subtracted. For low signal
applications, there is significant drift in the background for each digitized channel making a constant offset subtraction for zeroing impossible. The drift is less obvious for channels with significant signal, but still can affect the shape of the recorded signal and is important to subtract. The main signal is removed from the background by finding the maximum of the signal and removing points within a time window equal to the length of the laser pulse. The remaining points are fitted with a $3^{rd}$ order polynomial using a linear regression. The resulting polynomial function is then subtracted from the entire signal. A visual inspection of the signal after the background subtraction is made is used to verify that background values are close to zero.

Due to the noise inherent in the digitizer, some recorded values are negative. This poses an issue when trying to reconstruct time-resolved spectra. Negative values can easily be replaced by the absolute value mean of the noise instead, allowing signals close to the noise level to still be included in the spectral reconstruction. In the case of solving for a time-integrated spectrum, the inclusion of many additional points of noise can cause an overestimate of integrated signal and severe distortion to the recovered spectrum.

The data is aligned to the maximum of the signal from the exploding LEH window time each channel surpasses a threshold. This is very nearly congruent with aligning to the rising edge of the signal for the LEH only shots, though the slight discrepancy between aligning the rising edge versus the peak values is important and consistent with an *a priori* knowledge of how the spectrum evolves in time. Using the peak of the Dante signals to align the data in time provides a self-consistent method since the x-ray emission from the foil burn through is present in both the cylinder and LEH shots.
With limited signal information, several well-established methods of recovering the x-ray spectrum\cite{31, 41} are impossible to employ. A matrix method cubic spline spectral unfold\cite{28} can be adapted to missing spectral information using a linear spline to make an initial guess about the spectral intensity using the channels that have adequate signal. The linear spline takes the form of an array of constant values that must be solved for at each knot point in the spline. The knot points of the spline are defined by the location of the K-edge of the filter for each channel. The spline is then constructed piecewise between the knot point values using linear interpolation. For $i$ channels, any spline employs $i + 1$ points since the equations involve integrals over a region that necessitate an initial point for the lowest energy channel. In this instance, channel 2 is the lowest energy channel, and so the initial point of the spline occurs at the K-edge for channel 1. The linear spline’s purpose is to formulate a guess of the spectral value for channels with no signal between channels with adequate signal level, so for simplicity the initial point is excluded. In the case of solving for a time-integrated spectrum, the $i^{th}$ equation is

$$\int_{t_L} V_i dt = Y \cdot \int_0^\infty R_i(E) dE$$

(3.2)

where $V_i$ is the signal voltage of the $i^{th}$ channel, $t_L$ is the laser pulse length, $Y$ is the array of values to be solved for, and $R_i(E)$ is the response function of the $i^{th}$ channel. The integration over the response function must be done piecewise in order to determine the contribution from each value in the matrix $Y$. The integration is notated to be over the full energy spectrum as a formality. The method is similar for time-resolved spectra by solving the equations at discrete time points rather than integrating the signal over the laser pulse.
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Following the formula for the cubic spline unfold and using the values generated by the linear spline, the $Y$ array for the cubic spline can be solved using a least squares fitting algorithm. It is still required that the cubic spline has a specified initial point in order to find a solution. This initial value can only take a narrow range of values since the other spline values are constrained within a region of spectral intensity by the linear spline. This significantly improves this method of spectral reconstruction by eliminating the need for guesses and an \textit{a priori} knowledge of the spectra.

Even though this method is successful at reconstructing x-ray spectra, there is only so much that can be done with missing information. The fidelity of the spectral reconstruction can be measured by integrating the recovered spline with the Dante response functions and comparing them to all measured channel signals. For the time-integrated case, spectral fidelity is preserved over single channel gaps, e.g. channel 4 is completely recovered by having information from channel 3 and 5. Larger gaps in information such as channels 7 and 8 are not recovered as accurately. A comparison of the spectral fidelity from the linear spline and cubic spline for a particular shot is shown in Fig. 3.4. This in no way replicates an uncertainty study of the spectral intensity. Rather, it demonstrates improvements in reconstruction by implementing this method, which is an inherent increase in accuracy in the measurement.

Time-integrated x-ray spectra from the LEH window only shots show only a marginal increase in total x-ray energy emitted by the exploding window with increasing laser energy. This is consistent with the laser absorption measurements discussed previously that do not change significantly with laser energy. Total x-ray energy is found by integrating the recovered time-integrated spectrum over photon
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Figure 3.4: The linear spline (blue) and cubic spline (orange) are integrated using each channel’s response function and the value obtained is compared to the experimental results (green dashed). Using the values obtained from the linear spline as the first guess, the cubic spline is able to converge close to experimental values that have little to no usable signal, e.g. channels 4, 7, 8, and 9.

Energy. The error bars on the results shown in Fig. 3.5 are applied using the results from a Monte Carlo error analysis applied to the signal voltages for channels sensitive to photons < 2 keV[32]. This uncertainty analysis is independent of the reconstruction method used, and the error recovered from using the Monte Carlo is summarized by the equation

\[ \Delta F[0 - 2 \text{ keV}] = 0.32462 + 0.084331F - 1.9045 \times 10^{-5}F^2 \]  

(3.3)

where \( F \) is the total flux of x-rays and \( \Delta F \) the uncertainty in x-ray flux both in units of GW/sr.
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Figure 3.5: A summary of the x-ray energy emitted in nJ as a function of the laser energy incident on the LEH window only targets. Total x-ray energy emitted by the foil is minimal and changes very little with respect to initial laser energy incident on the foil. The x-ray energy incident on Dante is also affected by which beam configuration is used. Dante looks directly at the laser-foil interaction in the beam 25 configuration, whereas it is blocked by the foil in the beam 46 configuration.

3.3.1 Comparison of Dante data from LEH window shots to 2-D simulations

Dante can also be used to verify hydrocode results for the LEH foil only experiments. The 4 channels provide an entire spectral range pertinent to both the continuum and line emission relevant to polyimide plastic, and a high confidence in the plasma conditions predicted by hydrocodes can be established by direct comparison.

The 2-D hydrocode FLASH [16] was run using a super-Gaussian laser profile that matches the phase plate used in the experiment. The beam profile is simulated using 32,500 rays randomly distributed throughout the laser profile. The default ray tracing algorithm was modified using a volume-weighted moving average to distribute laser energy over the simulation grid. To further eliminate ray tracing noise and perturbations, a cubic interpolation of plasma temperature and density is used to smooth out the plasma profile after each time step. FLASH is provided
with an asynchronous ray trace algorithm that utilizes a linear interpolation for smoothing, which runs faster but is more susceptible to numerical noise. *FLASH* also uses AMR (adaptive mesh refinement) to handle large gradients in the plasma. The AMR grid is converted to a uniform grid that conserves mass, momentum, and internal energy so that the results can be post-processed.

The 2-D hydrocode *DRACO* was run using over 1 million rays with the same super-Gaussian laser profile used in *FLASH*. These rays are randomly distributed and require no smoothing techniques to produce a numerically stable simulation. *DRACO* uses grid feathering to handle large gradients in the plasma that need no additional refinement for post-processing. The 2 LEH window only shots at 200 J were the only shots modeled by *DRACO*.

Both codes used SESAME tables for equation of state, inverse bremsstrahlung absorption as the mechanism of laser absorption, and a 100% absorption in solid materials in order to initialize plasma conditions from solid state conditions. Ion heat conduction is not tested by the *FLASH* developers and is not used here, although *DRACO* simulations predict that this is not a significant effect. Both codes were used to simulate the beam 25 configuration only, although comparisons with the simulation is done against both configurations.

The output of *FLASH* and *DRACO* is then post-processed using SPECT3D detailed atomic modeling to produce a spectrum. The spectrum is then convolved with the instrument and filter response functions to produce x-ray diode traces that can be compared to the data, seen in Fig. 3.6. For the 200 J LEH window only shots, the *FLASH* code is able to predict the plasma conditions well enough to reproduce the x-ray diode data across all channels with a margin no bigger than 30%. *DRACO* can reproduce time-integrated spectra very well, but cannot reproduce
individual channel curves to the same accuracy as \textit{FLASH}.

Furthermore, it appears that the ray tracing algorithms used for \textit{DRACO} are of much higher quality than \textit{FLASH}, which changes the plasma absorption profile generated by the code. Therefore, \textit{DRACO} produces a highly uniform slowly expanding plasma that continually absorbs over time, whereas \textit{FLASH} generates numerical instabilities forming plasma non-uniformities that do not absorb as well as a uniform plasma. \textit{DRACO} can implement many more rays than \textit{FLASH} and so the laser absorption estimated from \textit{DRACO} is less dependent on plasma uniformity and how the laser energy is distributed among the rays.

The discrepancy between these two codes alludes to a mechanism of channel formation that expands and pushes the plasma generated by the laser-window interaction away. The laser intensities used in this experiment are far below the threshold for plasma channeling\cite{45}, however the power used exceeds the threshold required for relativistic self-focusing\cite{26, 27}. It could very well be the case that the laser is self-focused in a very brief instant in time, causing the sidescatter signal seen shortly after the backscatter signal. The laser is then focused to intensities where the laser ponderomotive pressure exceeds the fluid pressure of the plasma, causing the plasma to be pushed away from the center. This prevents the plasma from absorbing more laser radiation and can explain the drastic increase in laser transmission that is seen after a certain time.

Unfortunately, hydrocodes like \textit{FLASH} and \textit{DRACO} do not have packages that account for relativistic laser self-focusing or ponderomotive effects from laser radiation, so the above theory cannot be tested using hydrocodes. There is also no direct experimental evidence of such an event occurring, but this hypothesis covers all possible observables from the experiment. A possible future improvement is to use a
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Figure 3.6: X-ray diode data compared to results from post-processing the 2-D hydrocode FLASH using SPECT3D detailed atomic physics. The agreement between data and simulation across all x-ray diode channels is within a margin no bigger than 30%.

Figure 3.7: DRACO simulation results compared to Dante experimental data. The laser energy used in the simulation is 200 J, 195.6 J for shot 76676, and 198.4 J for shot 76678

2D PIC (particle in cell) code to accurately simulate LEH window burn through to supplement hydrocode simulations of preheat.

It should be noted that the FLASH code also over-predicts the laser absorption in the window at ~ 30%, with similar LEH burn through times, window material
propagation speed, and preheat temperatures predicted by DRACO. The similarities between the two codes suggests that the source of this over-estimation may be due to EOS table calculations and the numerical methods involved with calculating laser absorption in solid materials early in time.

3.3.2 Inferring gas temperature from Dante measurements of cylinders

The viewing angle of Dante to the cylinder targets suggests that the first 1 mm of the target, which includes a region of gas outside of the implosion region, can be seen by Dante. The neon doping in the gas should contribute to the x-ray spectrum in a region easily measurable by Dante, and so a gas temperature can be recovered from Dante from specific channels. Simulations from DRACO are used to decompose each channel into fractional contributions to the signal in each channel from the window, wall, and gas.

To avoid issues concerning opacity, a series of three simulations from DRACO are post-processed in Spect3D considering x-ray emission from the wall only, the wall and the window, and the wall, window, and gas. A self-consistent decomposition of the percent contribution from wall, window, and gas of the signal in each channel is made. Most channels that have a signal significantly above the noise detect x-rays primarily from either the window or wall plasma during preheating. However, the higher photon energy channels, e.g. channels 9 and above, are dominated by gas emission for a brief moment in time after the window plasma has stopped emitting. Select channels are shown decomposed into the 3 possible contributors along with the raw data of the corresponding channel in Fig. 3.8
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Figure 3.8: Decomposed signals from channels 2, 5, and 9 (top left to top right) are shown in percent contributions from the window, wall, and gas using results from DRACO post-processed in Spect3D. This is compared to the raw signals from the respective channels to determine the composition of the signal at different times. Lower photon energy channels show only window and wall emission, whereas higher energy channels have most of their signal contributed by the gas in the front 1 mm of the cylinder. This allows Dante to be used to estimate a time-resolved gas temperature measurement.

Channel 9 is the only channel with adequate signal to analyze concerning a correct modeling of the gas preheat in the front 1 mm of the cylinder. A direct comparison of the simulated Dante traces from post-processing DRACO simulations can be made for the 3 shots with identical starting conditions. The application of magnetic field prior to preheating has little effect on the gas temperature outside of the typical shot-to-shot variations, and DRACO predictions tend to overestimate the signal in channel 9 as shown in Fig. 3.9.

Instead of comparing signals convoluted with instrument response functions, the adaptive cubic spline unfold method can be used to compare spectra recovered from Dante directly with Spect3D simulation results from Draco to show specific deviations in the spectra as a function of time. Spectra from DRACO simulations
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

are unfolded from the calculated Dante traces in order to have a fair comparison with the spectra from the experiment and to combine contributions from line and background emission from the simulations. Doing this also validates that the unfold method employed is able to recover a spectrum with a high degree of accuracy. In the case of using simulated Dante traces as the input for the unfold process, all channels were used eliminating the need for the linear spline adaptive method to predict spectral contributions of low signal channels.

Based on the signal decomposition of channel 9 from Fig. 3.8, times between 1 and 2.4 ns were considered to be the best times to compare spectra for gas emission. The 1000-1400 eV range of photon energies correspond to neon emission lines from the gas, and photons in this energy band also correlate with the signal in Dante.
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Figure 3.10: The top graph shows a comparison between the DRACO and Dante spectral unfold for shot 76674 over the entire spectral range 2.2 ns into the laser pulse. The bottom 3 graphs show, from left to right, detailed comparisons of the spectral range attributed to neon doped gas emission at 1.2, 1.8, and 2.4 ns. The relatively close agreement of these detailed comparisons, along with the experimental spectra exceeding the simulation spectra towards higher photon energies, indicates that DRACO can be used as a predictive code for determining preheat temperature of the gas as a function of laser energy. It should be noted that spectral behaviors after 1400 eV are artifacts of the spectral unfold process since that portion of the spectra is unbounded by additional Dante channels.

channel 9. A detailed look at the lowest emission shot (76674 highlighted in Fig. 3.9) in this photon energy range reveals a close agreement, and thus comparable electron and ion temperature predictions by DRACO and experiments. Neon line emissions and background levels are highly sensitive to temperature differences, e.g. the spectra changes by an order of magnitude in intensity for a gas temperature difference of $\sim 50$ eV. The comparisons shown in Fig. 3.10 show agreement between simulation and experiments within a factor of 5 at worst, with the largest deviations occurring at lower photon energies where emission from the window and wall are contributing factors. Across all time steps, the total spectral intensity predicted by
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

\[ \text{Te} \]

\[ \text{Ti} \]

Figure 3.11

\[ \text{Te} \]

\[ \text{Ti} \]

\[ T_e \]

\[ T_i \]

\[ \text{DRACO} \]

\[ \text{DRACO} \]

in this energy range is on average 10.2 times higher than the experimental results. Much of the deviation in spectral intensity can be attributed to wall and window emission, which is indicated by the Dante unfolded spectra having higher spectral intensity towards the higher photon energies, and lower spectral intensity towards lower photon energies compared to \text{DRACO}.

Comparison of the window and wall dominated portions of the spectrum (400-800 eV or channels 5 and 6) provide further evidence of the simulation over-predicting the emission from the wall and the window. In the interest of brevity, the comparative analysis of shots 76675 and 76678 are not shown, but have the expected result of stronger spectral intensity and a closer match to simulations since they have higher signal levels in channel 9.

The gas electron and ion temperature predictions by \text{DRACO} between 1 and 2.4 ns are shown in Fig. 3.11. The temperature is calculated as a volumetric average over the front 0.5 mm of the cylinder for the full cylinder radius. The electron
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

temperature quickly saturates at \( \sim 200 \) eV due to a drop in inverse bremsstrahlung absorption and cooling due to expansion. The ion temperature slowly thermalizes with the electron population. By the end of the laser pulse, the entirety of the cylinder including the implosion region reaches an ion temperature of 200 eV. This confirms the ability of a single OMEGA beam to reach adequate preheating conditions for a MagLIF implosion.

3.3.3 Proof of thermal conduction wall heating suppression with magnetic fields

Another useful result of the signal decomposition technique is the demonstration of the reduction in wall emission and wall heating due to magnetic field suppression of thermal conduction from the window and the gas. One of the six cylinder shots that was initially magnetized with a \( \sim 15 \) T magnetic field prior to the start of the laser pulse has enough signal in Dante to make a comparison to the two other unmagnetized shots at equal initial gas pressure.

Knowing the signal composition for each channel from Fig. 3.8, we can see that the magnetic field provides a \( \sim 20-40\% \) reduction in signal for the regions in each channel that correspond to wall emission. Since the portion of the spectrum that contributes to these channels is heavily line dominated, a 20 \% reduction in signal infers a significant decrease in the temperature of the wall blow-off plasma. The main mechanism in the formation of the wall blow-off is thermal conduction from the hot window plasma into the wall according to 2D simulations. This implies that the magnetic field is limiting the amount of thermal energy transfer from the window to the wall.
3.3 Analysis of LEH window disassembly using the filtered x-ray diode array Dante

Figure 3.12: Raw Dante signals for channels 2, 5, and 6 for the cases of 15 T and 0 T. In every channel where wall emission comprises > 50% of the signal (shaded region), the case with 15 T initial field has a ∼ 20-40 % decrease in signal.

The effect is minimal, since there are other mechanisms like thermal and x-ray radiation that also contribute to wall heating. Furthermore, a 15 T magnetic field does not compare to the hydro pressure of the expanding window material, and so eventually the magnetic field is swept away by the window. We can estimate the change in thermal conduction provided by the magnetic field using the Braginskii formulation\[11\]. Taking the ratio of Spitzer conductivity to Braginskii perpendicular thermal conductivity

\[
\frac{K^e_\perp}{K_0} = \frac{3.25\chi^2 + 1.2}{\chi^4 + 7.482\chi^2 + 0.0961} \tag{3.4}
\]

where \(\chi\) is the Hall parameter. If we estimate the \(n_e = 5 \times 10^{20} \text{ cm}^{-3}\) and \(T_e = 500 \text{ eV}\) from DRACO values at the onset of window/wall interaction 1.0 ns into the laser pulse, we can estimate the Hall parameter to be close to unity. This makes the ratio of thermal conductivities ∼ 50 %. In the time it takes the window material to push the magnetic field out of the way, there is a factor of 2 reduction in heat transferred to the wall by thermal conduction.

Looking at Dante signal traces for channels 2, 5, and 6 where wall emission comprises > 50% of the signal in Fig. 3.12, the case of 15 T initial field sees a
3.4 Measuring gas temperature in implosion region using Ne soft x-rays

The cylinder experiments used a diagnostic window drilled into the side and resealed with a 2 µm polyimide film to look at soft x-ray emission from the Ne doped D₂ gas. The cylinders were also made out of a fluorinated plastic Parylene-AF4 (C₈H₄F₄) so that the wall temperature and gas temperature can be measured using the same spectrometer. A 3 channel soft x-ray imager (SXR) used combinations of mirrors and filters to get spectrally integrated, spatially and temporally resolved images of the side diagnostic window. The spectral responses of each channel, shown in Fig. 3.13, were chosen primarily to discern the Ne and F emission in the 800 eV photon energy range. The third channel also serves to look at possible carbon emission if the wall gets heated by thermal conduction from the gas.

There is no possible way to recover the spectrum of the plasma from only 3 channels when the response function K-edges are not adequately coordinated. Furthermore, SXR is not an absolutely calibrated diagnostic, so each channel signal must be compared with another for any useful information to be extracted. There are a limited number of possible gas densities, wall blow-off densities, wall temperatures, and gas temperatures possible from the experimental configuration. Using results from the 2-D hydrocode predictions as a guide, a grid of possible temperatures and densities were used to construct 2-D plasma profiles in SPECT3D. Using detailed atomic modeling, the spectrum for each possible combination of temperature and density was convolved with response functions of SXR. The channel ratios
from the data are then solved for by using the simulated grid under the condition that $T_{\text{gas}} > T_{\text{wall}}$. Since the system is highly degenerate, the main result from this analysis establishes a lower bound on the possible gas temperature of 100 eV at 1.3 ns into the laser pulse, which is shown in Fig. 3.14.

The experimental images and step wedges were taken on Biomax film and digitized using a PDS digitizer with no additional magnification. After digitization the step wedges were used to convert the recorded pixel values into a film response. The portions of each strip containing the diagnostic window image was digitally cut into equal squares centered on the highest value pixel. The image was then filtered using various methods described below. All pixel values are summed to give the channel signal, and each channel signal is divided by another to produce 3 different ratios. These ratios are then compared to the ratios calculated from Spect3D simulation to determine gas temperature.

Several methods of noise reduction including mean, median, and Gaussian fil-
The SXR signal is dominated with line emissions in the entire photon range between 100-1000 eV due to the presence of C, F, and Ne. As a result, the SXR detector quickly saturates in at least one channel per strip. The saturation of a
3.4 Measuring gas temperature in implosion region using Ne soft x-rays

Figure 3.15: Time evolution of the gas heating calculated from the SXR images using a grid of possible gas and wall temperatures and densities.

A channel in any one strip loses 2 of the possible 3 comparisons and greatly limits this analysis technique. Furthermore, the line emission quickly saturates the detection limits of SXR at temperatures above 100 eV, making it impossible to characterize the heating of the gas above this temperature later in time. Signals prior to 1.3 ns are too dim for this analysis, independent of noise reduction or contour used. A summary of the time-evolution of the gas heating from this method is presented in Fig 3.15 and is very unenlightening. Achieving a 100 eV gas temperature at 1.3 ns is consistent with DRACO predictions and analysis of Dante unfolded spectra of the front 1 mm of the cylinder. Achieving a preheat of at least 100 eV is important since it is the threshold preheat temperature to see neutron yield enhancement from integrated MagLIF implosions determined from the point design simulations.
Chapter 4

Implosion optimization: axial uniformity and implosion trajectories

4.1 Angular dependence of laser absorption and drive efficiency

The OMEGA laser is configured to implode spherical targets using 60 beams arranged symmetrically at the vertices of tessellated pentagons and hexagons. Beams that share the same polar angle around a pentagon or hexagon port can be arranged into rings, where each ring is a given number of chamber ports away from the pentagon of interest. An illustration of this arrangement is shown in Fig. 4.1, where a pentagon port is taken to be at the north and south poles. If a cylindrical target were to be aligned to the z-axis in Fig. 4.1, the 4 separate rings will have different axial locations on the cylinder and have unique incidence angles. This poses a prob-
Figure 4.1: Angles of different rings shown along the spherical target chamber for OMEGA. Not shown is the polar angle of Ring 4 of 81.3°.

Problem for trying to achieve an axially and azimuthally uniform cylindrical implosion on OMEGA. Laser absorption will change with laser incidence as $\sim \cos[\theta]$ where $\theta$ is the polar angle shown in Fig 4.1. Beams at very shallow angles to the target normal such as Rings 1 and 2 cannot be used for this reason, and since most of their energy will be refracted away from the target it poses a hazard to laser operation. Furthermore, the laser spot becomes stretched along the cylinder’s surface as incidence angle increases. A beam from ring 3 with the same laser energy and spot size will have a different intensity on the cylinder surface. Axial positions of the laser spots will also change with diameter as a natural consequence of having a cylindrical target.

Ablation and drive are often difficult to predict using existing hydrocodes because of the dependence on flux limiters to control the initial thermal diffusion and the
codes’ inability to simulate laser absorption in solid materials. Changing these parameters in a 2-D code and running an array of possible drives is computationally expensive and 1-D codes like LILAC cannot simulate beams incident at varying angles. It is very likely to have cross-beam energy transfer (CBET) in a polar drive configuration. CBET is the phenomenon of laser energy being exchanged between different beams mediated through a background plasma. This can change the energy balance between rings 3 and 4 and can divert laser energy away from the target. Non-local transport within the coronal plasma can change the plasma conditions affecting the laser absorption as well. Considering all of these complicating factors, it is more practical to measure and derive the proper illumination for a uniform compression empirically.

Hollow cylinders made of polyimide plastic (C\textsubscript{22}H\textsubscript{10}N\textsubscript{2}O\textsubscript{5}) were imploded with overlapping either rings 3 or rings 4 to measure the difference in laser drive for the two angles of incidence. Self-emission x-rays were imaged using x-ray framing cameras to track the trajectory of the shells in flight. Seven equally spaced radial lineouts were taken along the implosion region of the image. The peak x-ray emission was found for each side of the shell. These points were then fit with an exponential decay function of the form

\begin{equation}
A - B \exp\left[-\frac{x - C}{D}\right]^E
\end{equation}

where \(A, B, C, D,\) and \(E\) are free parameters. It matters not how many free parameters are used here since replicating the diameter of the shell with a function is the main goal and maximizing the free parameters increases the certainty of the fit. This function takes into account regions of the shell that are not imploding as
Figure 4.2: Trajectories of shells using either Rings 3 or Rings 4 only to drive the implosion. The difference in laser absorption between the two incidence angles are highlighted by the difference in shell velocities. from the linear fitting of the trajectory points. Error bars are small enough to be engulfed in the points plotted.

fast as the center. Taking the difference between $A$ and $B$ gives a good average of the shell radial position at any axial position along the cylinder. The error is compounded by this operation, but the total error seen in Fig 4.2 is still very small.

Plotting the radius points obtained from this operation versus the time of each image calculated from the timing traces of the x-ray framing cameras gives the shell trajectory. The trajectories are then fit with a linear function to determine the average implosion velocity for the ring 3 and ring 4 cases. The first set of 4 points are clearly too early in time when the shell is still accelerating to it’s final velocity and are not included in the fit. The fits for each ring 3 case are nearly identical, and so the average of the fits is presented in Fig. 4.2.
1-D simulations using *LILAC* for a range of laser powers were then used to match the trajectories measured from experiment. The reduction in drive required by the simulation corresponds to the reduction in drive due to the differing angles of incidence. It was found that rings 4, which had an angle of incidence of 8.2° had a drive efficiency of 89% whereas the rings 3 with an angle of incidence of 31.2° had a drive efficiency of 49%.

### 4.2 Achieving axially uniform cylindrical compression

Based on the simulated values of reduced drive, an axial profile was derived to achieve an axially uniform compression shown in Fig. 4.3. The pointing scheme of this irradiation pattern consists of overlapping rings 3 in the center of the target while using rings 4 to illuminate the sides. In terms of axial position along the cylinder, rings 3 are displaced 180 μm toward the center of the target on either side and rings 4 are displaced by 220 μm away from the center. Since overlapping the rings 3 at the center more than makes up for the factor of 1.8 difference in effective intensity, it is likely to have to decrease the intensity of the rings 4 to achieve an optimal balance.

Since both shell shape and trajectory are of interest, a more complex fitting routine is required. An already established method of determining the inside surface of the x-ray emission developed by Michel *et al.* is used in the analysis. Every lineout from the x-ray images was fit with a double-Gaussian of the form
4.2 Achieving axially uniform cylindrical compression

Figure 4.3: Azimuthally averaged axial intensity profile calculated for all beams. According to measurements from using rings 3 and rings 4 only, this should yield an axially uniform implosion. However, due to other effects that remain unquantified it does not.

\[
E \exp\left[-\frac{|x-B|}{g^2}H\right] + A + I - EA \exp\left[-\frac{|x-b|}{c^2}D\right] + I
\]  \hspace{1cm} (4.2)

for each side of the shell, where all capitalized variables are free parameters as in Eq. 4.1. The functions are such that they have the same value at the peak x-ray emission. This fit of the radial lineout is used to calculate the half peak intensity point on the inside of the shell

\[
\frac{1}{2} \left( A + I + E \exp\left[-\frac{1-B}{g^2}H\right] + (A + I - E) \right)
\]  \hspace{1cm} (4.3)

which corresponds to the inner x-ray surface close to the ablation surface of the cylinder. The points obtained along the entire axis of the cylinder are then fit with an even fourth-order polynomial to reconstruct the shape of the shell as a function of axial position:
4.2 Achieving axially uniform cylindrical compression

![Graph with annotations](image)

Figure 4.4: Shell shape plotted for 40 µm shell implosions for the illumination pattern from Fig. 4.3. The flattest profile achieved was with rings 3 intensity lowered by 80%. An offset of 43.8 µm for the 80% case is introduced for comparison of shell shape only.

\[ a + b(z - z_0)^2 + c(z - z_0)^4 \]  \hspace{1cm} (4.4)

The end result shows that for 40 µm thick shells with a nominal outer diameter of 600 µm that a reduction of the rings 3 intensity of 80% is required to achieve an axially uniform implosion. This result was unexpected and is an indicator of laser-plasma interactions that happen in the presence of all beams. Regardless, the results from this experiment indicated that the length of the implosion region could be increased by simply separating the rings 3 and rings 4 until the drive from rings 4 and rings 3 are approximately equal.

Recalculating the illumination pattern based off of the empirical results from the 40 µm shell implosions gives a relatively uniform axial intensity profile shown in Fig
Figure 4.5: Azimuthally averaged axial energy profile that extends the implosion region rather than decreasing the energy in rings 3 to obtain an axially uniform cylindrical compression

4.5. A large dip in the middle is now present from the increased separation of the rings 3 in the center. The total displacement of the rings 3 is now 285 $\mu$m towards the center so that the rings 3 actually cross at target center and illuminate opposite sides of the cylinder. The rings 4 are displaced 275 $\mu$m away from target center. It is now much more probable that the energy in rings 4 needs to be reduced in order to achieve an axially uniform cylindrical compression. This approach is much more consistent with how the drive was estimated from the point design section of this thesis.

Visually inspecting the shape of the shell has been satisfactory up to this point in the design, but shell shape must be better quantified to achieve the best result in terms of uniformity. From the polynomial fit, the ratio of $b/a$ can be used to show whether the shell is overdriven in the center or the ends. Mathematically speaking, only the parameter $b$ matters as it indicates whether the polynomial has 4 real roots.
or 2 real roots, but normalizing to the parameter $a$ allows a comparison of the time evolution of the shell shape in flight.

Using the axial energy profile in Fig. 4.5, 20, 24, and 30 $\mu$m Parylene-N ($\text{C}_8\text{H}_8$) shells with up to 14 atmospheres of D$_2$ gas were imploded with different reductions of the rings 4 peak energy. Using x-ray framing cameras positioned side on and end on captured both the axial and azimuthal implosion uniformity. The shell boundary was determined using the polynomial in Eq. 4.2 and fit with the polynomial in Eq. 4.4. The ratio of $b/a$ is then plotted as a function of time to determine the most uniform implosion. Select results from the 30 $\mu$m shell are in Fig. 4.6 and 20 $\mu$m shells in Fig. 4.7, highlighting the optimal value of $\sim 84\%$ reduction in the rings 4 peak energy. In particular, shot 79498 gave the most uniform implosion with a 20 $\mu$m thick shell with an outer diameter of 566 $\mu$m, and all subsequent implosions have the same pointing on target and energy balance as this shot. In the case for larger targets, the implosion will be slightly ends overdriven, which is seen as a slight benefit in the 2-D MHD predictions. The nominal axial energy profile that is used for MagLIF on OMEGA is in Fig. 4.8

Being able to resolve the actual shell shape given the resolution limitations of imaging a $\sim 0.7$ mm long cylindrical implosion and the fact that the ablation surface and not the shell surface is imaged with x-rays begs the question as to whether this measurement technique is valid. A 2-D hydrocode SAGE with 3-D ray tracing and multigroup radiation diffusion [8] was used to simulate 30 $\mu$m shell implosions using the axial profile from Fig. 4.5. Three time steps were then post-processed using Spect3D x-ray image simulation and atomic physics package [18] to determine the x-ray self-emission image. A 20 $\mu$m point spread function estimated from the shell width from the images and appropriate beryllium filtering was then applied to the
4.2 Achieving axially uniform cylindrical compression

Figure 4.6: The ratio of $b/a$ from the fit polynomial of x-ray self-emission images of 30 µm shells in flight. The optimal value of $\sim 84\%$ is highlighted against full energy in rings 4. Negative values of $b/a$ denote ends overdriven whereas positive values denote center overdriven.

Figure 4.7: The ratio of $b/a$ for 20 µm
4.2 Achieving axially uniform cylindrical compression

Figure 4.8: The azimuthally averaged axial profile that is used for all MagLIF experiments on OMEGA image output of Spect3D to simulate the instrument response of an x-ray framing camera. This image was then fit using the same techniques used in experiments and the shape and location of the x-ray surface is compared to the shell mass density profile from SAGE, in Fig. 4.9. This helps confirm that the technique for finding the intensity profile that gives the most uniform compression is sound, and is able to recover roughly the outer position of the shell during the implosion.

It is worth noting that the shell shape shown in Fig 4.9 were obtained using an identical laser configuration to the most axially uniform shot (79498), but SAGE over-predicts the drive at the ends of the cylinder by 20%. Furthermore, when using the first irradiation pattern derived from the single ring drive experiments, SAGE predicts an axially uniform implosion. This indirectly suggests that there is some phenomenon causing loss in energy of the rings 4 when all laser beams are illuminating the target. The angles and positions of the beams are such that it is possible to have cross-beam energy transfer (CBET) occurring between the...
Figure 4.9: Simulation results of x-ray surface (green dashed) shape plotted as an overlay to the simulated density profile from SAGE 2-D hydrocode results. The shape of the x-ray surface matches the shape of the shell surface exactly.

Inbound rings 4 and outbound reflections of rings 3 mediated by the coronal plasma from the imploding cylinder. Geometrically, this effect would only be seen when all rings are used, which is consistent with observations. Both HYDRA [30] and SAGE agree in their predictions, though results from HYDRA will not be presented here. This implies that other effects within the simulation such as EOS, flux limiters, and differences in ray tracing do not fully explain the discrepancies with experimental results.

X-ray pinhole images provide a time-integrated image of core emission that can be used to determine shell uniformity. The length and uniformity of the core emis-
sion corresponds directly to the uniformity of the compressed shell. A region of interest was highlighted for each image centered about the signal and then cut. The background of the image is then subtracted from the region of interest, and the image is rotated using a bilinear interpolation to get the core emission well-aligned to the horizontal axis. A smaller region of interest of the reduced rotated image is then cut out. A fitting function of the form

\[ I(r) = \frac{I_0}{1 + (r - r_0^2)/R^2}; \quad r > r_0 \]  

(4.5)

with free parameters \( I_0 \) for intensity amplitude, \( R \) for decay length, and \( r_0 \) for shell position were used to fit the shell emission. Assuming a constant implosion velocity and integrating \( I(r) \) from \( r_0 = r_{in} \) to \( r_0 = r_{out} \) gives a time integrated intensity from the shell of

\[ I(r) \propto \arctan \left( \frac{\max(r - r_{in}, 0)}{R} \right) - \arctan \left( \frac{\max(r - r_{out}, 0)}{R} \right). \]  

(4.6)

The line integration to give the projected signal on the camera is then performed numerically using Gaussian quadrature. The outer radius of the shell is offset by another free parameter \( r_c \) to account for target offset causing x-ray emission offset. The emission up to \( r_{in} \) is then subtracted. To obtain a higher fidelity fitting routine, a Gaussian can be convolved to take instrument response into account, though it makes little difference here and is not included.

Core emission was then fit with a binned Gaussian

\[ f(x) = \frac{\sqrt{\pi} d}{2 \sqrt{R}} A_p \left[ \text{erf}\left( \frac{r_0 - x + d/2}{R} \right) - \text{erf}\left( \frac{r_0 - x - d/2}{R} \right) \right] \]  

(4.7)

where \( d \) is the width of the bin (1 pixel), and \( A_p \) is a free parameter fitting the
core emission amplitude. For $d/2 << R$, $f(x)$ tends rapidly towards a Gaussian function. For thinner core structures with small $R$, the fitting function is still able to obtain a minimal residual fit. Adding up the radial fittings of the core emission fits gives an axial profile of core emission that can be compared to the axial profiles obtained from x-ray framing cameras.

Axial profiles of 30 $\mu$m are more peaked compared to the 20 $\mu$m shells, which show a $\sim 600$ $\mu$m wide region with intensity variations of less than 5%. The width of the core from 30 $\mu$m shells is typically $\sim 1$ pixel wide and is limited by the spatial resolution of the pinhole cameras of 20 $\mu$m. Core emission from the 20 $\mu$m shells are broader by roughly a factor of 2, with peak widths near the center of about $30 \pm 2$ $\mu$m. The outer diameter of the shell emission is roughly constant for all fits and correlates well with shell outer diameter. The axial profile of the inner radius of the shell measured from pinhole images of 30 $\mu$m shells correlates well with the side-on x-ray framing camera shell shape measurements. Unfortunately $r_{in}$ cannot
be determined for 20 \( \mu \text{m} \) shells because it overlaps with the core. Fig. 4.10 shows that the ends were overdriven in shot 79492, which is consistent with having the ratio of ring 4 energy to ring 3 energy at unity and the average \( b/a \) value from both sides of the shell being \(-2.8 \times 10^{-6} \pm -6.64 \times 10^{-6}\). For shot number 79501, the ratio of ring 4 to ring 3 energy was 0.819, close to the ideal value of 0.83. The inner radius analysis of the pinhole images show a shell shape that corresponds to the average \( b/a \) ratio of \(3.65 \times 10^{-7} \pm 8.99 \times 10^{-8}\), indicating a very uniform drive was achieved. The value of \( b/a \) is small, but positive indicating that it is still slightly overdriven in the center. In Fig. 4.10, the opposite appears true, since the error bars from the pinhole analysis are much larger compared to framing camera analysis. It is entirely possible to recover in-flight shell uniformity from time-integrated images, which is a technology that can be easily implemented on Z.
4.3 Azimuthal Uniformity and line-integrated core emission

A single ring of the OMEGA laser system consists of 10 beams arranged in 5 pairs around any pentagon port. If unmoved, a single ring imposes a mode 5 intensity modulation on the surface of the cylinder. The symmetry of the OMEGA laser dictates that beams from the same ring are out of phase by $180^\circ$ on opposite sides of the cylinder. This provides a near perfect overlap of intensity when both sides of ring 3 are used to illuminate the center. However, ring 4 beams are not overlapped, illuminate opposite sides of the cylinder, and are not in phase with the ring 3 beams causing the mode 5 modulation on either side of the cylinder.

An x-ray framing camera was positioned end-on to the cylindrical implosion to track azimuthal uniformity of the implosions, as well as measuring target offset and axially integrated core emission near stagnation. Since the implosion region is not exactly on the tip of the target, the x-ray emission from the shell corona backlights the unimploded portion of the cylinder. The pattern on the inner x-ray surface is primarily from the side of ring 4 closest to the camera, since the corona and plastic shell opacity blocks other emission from the shell while looking end-on. This inner surface is cut out of the image and, using a 1-D interpolation, a 2-D function of pixel intensity is made. This function is then radially averaged from the inner edge of the emission to $1.8\times$ that initial radius. The azimuthal profile $\Psi(\theta)$ is then approximated using a Legendre mode expansion

$$\Psi(\theta) = \sum_{n=0}^{10} A_n P_n(\cos \theta)$$  \hspace{1cm} (4.8)
for the first ten modes. Of course, more modes can be chosen, however there is strong indication that mode amplitude tends to zero very strongly above mode 10. Mode 10 is an intuitive cutoff when expecting mode 5 to be dominant. However there is very little mode 10 present in all shots. The simplicity of our Legendre series negates the possibility of reconstructing the azimuthal profile since our analysis does not calculate the required phase of each mode. The mode amplitudes are found the usual way using Fourier’s trick

\[
A_n = \frac{2n + 1}{2} \int_{0}^{\pi} \Psi(\theta) P_n(\cos \theta) \sin \theta d\theta.
\]  

(4.9)

Since the mode 0 amplitude depends upon the pixel values of the image, all mode amplitudes are normalized to the mode 0 amplitude to give a consistent comparison across all shots. These imposed Legendre modes act as the seeds of the Rayleigh-Taylor (RT) instability, and are therefore expected to grow in time as the outer shell accelerates inward. The framing camera sees the inner x-ray surface, which is the outer ablation surface of the shell. It is unlikely that the image represents the inner shell spikes in the deceleration phase, despite the fact that the images give the appearance of spikes protruding inward.

As expected, the dominant mode is mode 5, which can be seen growing in time for all shots regardless of shell thickness, ring 4 intensity, and outer diameter. For 30 µm thick shells, there exists a mode 2 early in time, which decays quickly. The only mode remaining at later times during the start of core emission is mode 5. For the 20 µm thick shells, many modes are present such as mode 4, 6, and 8, however these modes are only equal or greater than the amplitude of mode 5 in 2 out 5 shots. An interesting case occurs for the 24 µm shell, which shows modes 4 and 6 growing
Figure 4.12: Mode amplitudes for 24 (top) 20 (bottom left) and 30 (bottom right) \( \mu \text{m} \) thick shells. Thinner shells seem to exhibit a wider array of modes compared to thicker shells, which are mode 5 dominated. In the case of the one 24 \( \mu \text{m} \) shell shot, mode 5 decays late in time in favor of modes 4 and 6, which is the result of a bifurcation and merger of one of the x-ray peaks in the image, which may be due to the mode structure of other rings emitting in the background.

as mode 5 decays, indicating a bifurcation and then merger of x-ray intensity in the corona. It is unclear whether this has anything to do with shell thickness since this is only one shot. Typical mode amplitudes are shown in Fig. 4.12 for all shell thicknesses.

It is worth noting that the center of the image is arbitrarily defined, and so error exists in predicting the amplitudes of some modes, especially modes less than 5. Signal noise also contributes to error from modes larger than 10 and can enhance mode amplitudes slightly between mode numbers of 5 and 10. The error associated
with poorly guessing the center of the image is calculated by analyzing a perfect mode 5 image, introducing an offset, and plotting the artificial increase in mode amplitude as a function of mode number and offset. The biggest error from image offset is seen in mode 1, which can vary by 5% depending on how the center of the image is chosen. For modes greater than 1, the effect is far less.

### 4.3.1 Legendre Modes of Azimuthal Laser Intensity Profile

The mode 5 pattern of the nearest ring 4 is easily predicted when considering the beam pointing and azimuthal irradiation pattern. The Legendre mode analysis of the x-ray surface compared with the mode analysis of the azimuthal intensity profile confirms that azimuthal perturbations are dominated by laser drive. Azimuthal intensity of the lasers is calculated as a function of $z$ and an azimuthal line out is taken along the the point where the beam centers intersect the target surface. The Legendre mode amplitudes are found using the same analysis for the experimental data. The modes presented here were for a cylinder diameter of 600 $\mu$m, although initial target diameter has very little impact on the mode amplitudes over the possible target diameters used in the experiments, which is in agreement with the experimental data. There is a strong correlation between the modes in azimuthal laser intensity and the x-ray surface of the target early in time, shown in Fig. 4.13.

The dominant modes are mode 5 and mode 3, with modes higher than 10 going to 0 quickly. The initial imposed modes may seem smaller than the experimental measurements since mode amplitudes grow over time.

A correction to the pointing of the beams can be applied to ensure that beam pairing does not impose a mode 5 to the implosion. A radial shift is applied to each beam so that the beam centers intersect the target with even azimuthal spacing.
This shift achieves a more uniform intensity profile and is also applied to ring 3 beams to ensure that no low-order modes are imposed on the center of the target. The Legendre mode decomposition of a line out along the beam center axial position for one side of the ring 4 beams demonstrates that the new pointing solves the issue of azimuthal uniformity, which is shown in Fig 4.14. Unfortunately, no experimental evidence of this adjustment’s effectiveness exists since it is impossible to achieve end-on imaging of fully-integrated MagLIF implosions. However, this analysis shows a convincing argument that the implosions using the adjusted pointing will be improved.

4.3.2 Line Integrated Core Emission

Continuum x-ray emission from the hot compressed core is also captured on the end-on framing camera. An x-ray temperature cannot be determined since there is
4.3 Azimuthal Uniformity and line-integrated core emission

Figure 4.14: Applying a radial shift to all beams so that the beam centers intersect the target at uniform azimuthal positions eliminates imposed Legendre modes on the target. Radial shifts are applied to all rings to ensure a uniform intensity profile and implosion along the entire length of the cylinder.

No absolute calibration for framing cameras and the opacity and length of the core are not exactly known, but the x-ray bang time can be determined by measuring the maximum emission comparatively in time. The core emission is extracted from the data by visually cutting the core region from the whole image and then refining the fit to a 17% peak intensity contour. The pixel values are then totaled and divided by the number of pixels to get an averaged x-ray emission from the core region. No corrections are made in terms of calculating the core length, the opacity of the plastic cap at the end of the target, the CCD gain, and the bias voltages of the camera. As a result, values reported here cannot be compared shot-to-shot, and the times at which peak emission occurs should be the main takeaway.

Peak emission times for 30 µm shells occur at a mean time of 2.36 ns, excluding shots 79492 and 79497 which were mistimed and did not acquire peak emission.
4.3 Azimuthal Uniformity and line-integrated core emission

Figure 4.15: Pixel-averaged core emission from the end-on framing camera measurements. These images provide a high-fidelity measurement of the x-ray bang time for 20µm and 30µm shells.

time (Fig. 4.15). These shots were analyzed to demonstrate consistency with the other shots, and indeed they show core emission increases and decreases that are comparable to the other 3 shots. From 1D hydrocode predictions, all targets have a discrepancy between x-ray bang time and neutron bang time of ∼100 ps across all shots. Therefore the neutron bang time of a non-mixed implosion is expected to be around 2.2 ns. The presence of carbon within the core will cool the gas and retard the neutron bang time. Unfortunately, mix will not greatly affect the x-ray bang time since it is from continuum emission and not as strong of a function of temperature as the D-D reactivity.

20 µm shells have an x-ray bang time of 1.74 ns, which is much earlier than the 30 µm shells as expected from the higher implosion velocity. X-ray bang time is demonstrated to be independent of initial fuel pressure between 11-14 atmospheres and initial target diameters within the range of 550-600µm. There is little experimental correlation between increasing the outer diameter and increasing the x-ray bang time. This is found to be consistent with 1-D MHD predictions.

It was theorized that the line-integrated core emission would be bright enough to
measure the x-ray burst from shock convergence in the center of the target. However, considering x-ray bang times consistent with 1-D MHD simulation predictions, there is no evidence of an x-ray flash at the expected time of shock convergence in either 20 or 30 $\mu$m implosion only shots.
Chapter 5

First Integrated MagLIF Experiments on OMEGA

5.1 Optimal timing of preheat for integrated shots

The nominal timing of the preheat beam was selected so that preheating finishes just as the inner shell starts to move, and was calculated by *DRACO* to be 1.0 ns prior to the start of the compression beams. A longer delay is much safer in terms of not letting the laser hit the inner liner as it moves inward, but runs the risk of window material propagating down the cylinder and mixing with the D$_2$ in the implosion region causing massive degradation to ion temperature and neutron yield. Timing the preheat beam to be closer to the compression beams runs the risk of not getting sufficient preheat prior to implosion and increasing the wall heating. It has been confirmed by the separate preheat experiments that *DRACO* adequately predicts gas temperature as a function of time during preheat, and the prediction is expected to be close to experimental measurements.
Figure 5.1: The preheat timing that maximizes the neutron yield appears to be 1.0 ns prior to the start of the compression beams at $t = 0$, although preheat shots at -1.3 ns showed significant degradation to the implosion due to magnetic field coils obstructing beam paths. The shots that need repeating are highlighted with a red circle.

Three different preheat timings, 0.7, 1.0, and 1.3, were shot with 11 atm D$_2$ filled cylinders with an initial magnetization of 6 T. The cylinders were then compressed using the same scheme previously optimized from the implosion experiments. The re-entrant tube nTOF was the primary neutron diagnostic used to measure all neutron yields and ion temperatures, except for the 1.0 ns shot that used the 5.4 m nTOF. The 5.4 m nTOF yields are typically 20% lower than the re-entrant tube yields, so that measurement can be considered more of a lower bound.

The results of preheat timing are shown in Fig. 5.1. Error bars reported on these measurements represent total instrument uncertainty and the uncertainty of the fit from the scintillator traces. The experimental points are fit with a quadratic function to estimate the peak neutron yield as a function of preheat laser timing. Preheat timing is reported in negative values given $t = 0$ is the start of the compression beams. The fitted maximum from the quadratic function is -0.95 ns, though a yield
degradation for the 1.3 ns shots would more than explain the shift away from the predicted value of -1.0 ns. Future experiments on preheat beam timing should repeat the shots at 1.3 ns for a more accurate measure of the optimal time. Furthermore, preheat beam timing and energy should be varied for higher magnetic fields and initial gas pressures as well to formulate a more complete and predictive picture of the parameter space.

5.2 Yield Enhancement from magnetized cylindrical implosions

The main goal of the MagLIF fusion scheme is to achieve a greater amount of fusion reactions with moderate implosion velocities and convergence ratios compared to conventional ICF by using preheat and magnetic fields. Neutron yields from a cylindrical compression only, an understanding of preheat vs. time from experiments and simulations, and 1D predictions of neutron yield increases due to preheat and magnetization have been established in previous sections of this thesis. Combining implosion, preheat, and magnetization leads to increased neutron yield for a hydro-equivalent implosion, and the first demonstration of this concept is contained herein.

The experimental setup for fully integrated shots uses the same beam pointing for previous implosion only shots including the azimuthal shift to avoid imposing unwanted mode 5 on the shell. The cylinder axis is aligned with the P9-P4 axis to accommodate the $3\omega$ preheating beam propagating from P9, which does not allow end on imaging of the imploding shell like the implosion only experiments that were aligned to the P6-P7 axis. Magnetic field coils that provided a 5 T initial magnetic field were positioned around the cylinder in a Helmholtz-like geometry to ensure
5.2 Yield Enhancement from magnetized cylindrical implosions

uniform magnetic field in the implosion region of the cylinder. The cylinders were pressurized to 11 atm with D₂ and used the same LEH window and washer assembly used in the preheat experiments. Both the implosion beams and the preheating beam used a 1.5 ns long pulse, differing from previous laser pulse lengths used in the preheat and implosion experiments. In order to preheat the gas in the cylinder prior to compression, the preheat beam is fired 1.0 ns prior to the compression beams. DRACO predictions verify that this preheat beam timing is optimal, and preheat beam timing is explored in more detail later on.

Neutron measurements can vary widely between implosion only, preheat and implosion, magnetization and implosion, and fully integrated shots. An array of nTOF (neutron time of flight) detectors at varying distances from the implosion were used to obtain an accurate measure of the D₂ neutron yield, including a re-entrant tube at 1.0 m, a 3.5m LARD, 4 m, and 8 m nTOFs. This allows a dynamic range suitable for all possible configurations, laser pulse lengths, and shell thicknesses to have detectable levels of neutrons. The 3m LARD allows for the measurement of secondary DT neutrons to be detected, which can be used to infer gas areal densities and shell convergence. A separate diagnostic was able to measure the time of peak neutron rate, which is critical for determining the energetics of the implosion.

X-ray framing cameras were able to capture in-flight shell compression to determine implosion uniformity and velocity for each shot, as well as capture core emission times as was done in the implosion only experiments. An array of pinhole cameras also monitored core uniformity, although only one line of sight is not obstructed during integrated MagLIF shots.

Since the laser pulse length of the implosion beams has changed from the implosion only experiments, a new set of implosion only shots are required to have
a comparative baseline to magnetized, preheated, and integrated shots. Implosion only shots on the integrated platform were done without coils in place to save time on target positioning. This makes the comparison between magnetized and unmagnetized shots a bit tricky because coils can block lasers from the target by being malformed or ill-positioned. Laser beam obstructions can be easily identified with pinhole camera images of core non-uniformities that result from an imbalanced drive, and such magnetized shots can be excluded from the analysis.

In conventional ICF, spherical targets impose a uniform scattering mass for neutrons escaping the hot spot region. Ideally, every nTOF detector looking at a spherical implosion should give identical yields. This degree of symmetry is lost in the case of cylindrical geometry, and neutron yields are expected to vary slightly with differing lines of sight. In addition to there being physics reasons for yield variation across detectors, each nTOF has a unique detection method that has its own intrinsic deviations from measurement accuracy. Different lines of sight are also set at different distances from target chamber center (TCC), and can afford different amounts of shielding, collimation, and dynamic range. To this effect, yields reported for each shot are the $1/\sigma^2$ weighted mean from all scintillator channels that are not clipped or occluded by noise across all detectors, where $\sigma$ is the error reported for each scintillator channel. Neutron-averaged ion temperatures are also averaged in similar fashion with a $1/\chi^2$ weighting, where $\chi$ is the residuals of the best fit of the scintillator signal for each channel.

There is no standardized way to represent error propagation when computing the error weighted mean of measured values. Several methods exist in literature, but are often unjustified or oversimplified. To this end, the error propagation used here is
Figure 5.2: A summary of $1/\sigma^2$ weighted mean DD neutron yields for all shots with a) 11 atm and b) 7 atm initial fill pressure. Shots that include using preheat have significant yield outliers due to preheat beam misalignment to the cylinder. Preheat plus compression shows marginal increases in yield over compression only, which is consistent with 1D predictions. There is marginal difference between integrated and magnetized only shots, also consistent with the lower field limit predicted by 1D simulations in Fig. 2.6 graph a)

\[
\sigma^2_{err} = \frac{\sum_i w_i(x_i - \mu^2)}{\sum_i w_i - (\sum_i w_i^2 / \sum_i w_i)} \quad (5.1)
\]

where $w_i$ are the weights for each measurement, $x_i$ is the measurement value, and $\mu$ is the weighted mean calculated from the set of measurements.

A summary of all shots by category is shown in Fig. 5.2 for initial fill pressures of 7 and 11 atm. It is unclear from this summary as to whether the addition of preheat and magnetic field is beneficial in terms of increasing neutron yield. The spread of points is greatest with the inclusion of preheat. This can be attributed to complications with aligning the cylinder axis to the axis of the preheat laser. A slight deviation in preheat beam pointing can lead to significant laser-wall interaction, which can cause a greater degree of high Z shell mix into the hotspot and decrease the ion temperature and neutron yield. Preheat beam alignment is measured from the start of each series of shots, and so shots that exceed the pointing accuracy
threshold of ±10 µm using the preheat beam can be excluded. It is also worth mentioning that there have been shots performed with very low-quality targets that are an order of magnitude different in yield for all cases compared to those reported in Fig. 5.2 and have been excluded as well. In the integrated plots, there are 2 shots at different magnetic field than the shots shown in the magnetized compression portion of the graph.

After excluding outlier shots and taking the average yield for the 4 cases, a clear trend of yield enhancement is demonstrated between compression only, preheat and compression, and magnetized compression shots shown in Fig. 5.3. The results are also shown as relative yields and compared against 1D predictions that closely matches experimental shell trajectories and bang times. LILAC predicts a much higher increase in yield than shown in experiment. As the initial fill pressure is decreased in 1D simulations, the convergence ratio is increased to unreasonable values, with the lowest convergence of 35.4 being the integrated case. Experimen-
tally, the yield should degrade for such high values of convergence. There is a slight degradation in yield from compression only to compression and preheat according to 1D predictions. This is due to an increase in the internal energy of the gas by introducing preheat, making it harder to compress. The convergence ratio between the two cases drops by 65%. The extra internal energy present from the onset is insufficient to recoup the losses in yield due to a drop in compression.

The advantage of high convergence in 1D simulations is the increase in electron and ion Hall parameter from the compression of the magnetic field. In the case of magnetized compression experiments, the 1D convergence ratio for this case is 51.7. With an assumed flux loss of 50%, the magnetic field would be akin to experimental convergence ratios conserving 100% of the magnetic flux. It would be expected that if experiments conserved 100% of the magnetic flux that the yield would be substantially higher than the measured $1.5 \times$ increase. This overestimation is exacerbated when preheat is added, since much of the initial internal energy cannot escape the strongly compressed magnetic field.

5.2.1 Inferred $\rho R$ and fuel convergence from secondary DT fusion yield

A DT fusion yield just above the detectable threshold was measured for a number of shots in all 4 configurations. The primary confinement and source for DT fusion yield in a MagLIF implosion is due to the $BR$ product, since $\rho R$ is projected to be small. However, in the case of laser-driven MagLIF with initial magnetic fields of 10 T or lower, $\rho R$ is much greater than $BR$ at bang time. The yield of T from DD fusion is equal to the DD neutron yield. For $\rho R << \frac{12T_{keV}^{3/2}}{mg \ cm^{-2}}$, energy loss
5.2 Yield Enhancement from magnetized cylindrical implosions

from the released T nucleus will be minimal. The ratio of the velocity of the DT fusion neutron and the DD fusion T is much greater than unity, which implies that the DT neutrons can be considered an isotropic source. Given these assumptions, the ratio of the DT and DD fusion yields is

\[
\frac{Y_{DT}}{Y_{DD}} = \frac{1}{m_D} \langle \rho R \rangle \sigma \quad (5.2)
\]

where \(\langle \rho R \rangle\) refers to the T path length averaged D \(\rho R\), \(\sigma\) is the DT fusion cross-section, and \(m_D\) is the mass of the deuteron. For a relatively stationary \(\sim 2\) keV D and a 1 MeV T, the center of mass energy for the fusion reaction is 0.4 MeV. This corresponds to a cross-section of \(\sigma = 4.13 \times 10^{-29} \text{ m}^2\)[5]. The actual \(\rho R\) is determined by integrating along all possible path lengths of the T to the edge of the cylinder. For an isotropic point source, the mean path length for a cylinder where \(R << L\) is \((\pi/2)R\), and so

\[
\rho R = \frac{2 m_D Y_{DT}}{\pi \sigma Y_{DD}} \approx 5.18 \frac{Y_{DT}}{Y_{DD}} \text{ (g cm}^{-2}\text{)} \quad (5.3)
\]

A good check on the self-consistency of the calculation can be made by plotting the DD yield versus the ratio of final to initial \(\rho R\), as is done in Fig. 5.4. The ratio of final to initial \(\rho R\) is a lower bound estimate of the fuel convergence ratio. Mass loss out of the ends of the cylinder during preheat and compression contribute to a decrease in final fuel density after compression. This mass loss has been estimated by 2D HYDRA runs in Chapter 5 to be around 40%. The actual values of \(\rho R\) can also change if the source of tritons is extended beyond being considered as a point source at the center of the cylinder.

The overall decrease in DD neutron yield with increasing convergence demon-
5.2 Yield Enhancement from magnetized cylindrical implosions

![Graph showing DD Yield scaling with the ratio of $\rho R$ calculated from the DT/DD yield ratio to the initial $\rho R$ of the uncompressed fuel is fitted with an exponential function. The scaling is close to being inversely proportional, which is a good check of self-consistency in the calculation. Furthermore, the ratio of final to initial $\rho R$ provides a lower bound estimate of fuel convergence ratio, and the resulting yield decrease with increasing convergence demonstrates the benefit the preheat and magnetization in cylindrical implosions that limit the convergence ratio.](image)

Figure 5.4: DD Yield scaling with the ratio of $\rho R$ calculated from the DT/DD yield ratio to the initial $\rho R$ of the uncompressed fuel is fitted with an exponential function. The scaling is close to being inversely proportional, which is a good check of self-consistency in the calculation. Furthermore, the ratio of final to initial $\rho R$ provides a lower bound estimate of fuel convergence ratio, and the resulting yield decrease with increasing convergence demonstrates the benefit the preheat and magnetization in cylindrical implosions that limit the convergence ratio.

...strates the need to limit the convergence ratio of cylindrical implosions in order to maximize fusion yield. Furthermore, 1-D predictions with high yields and convergence ratios should generally not be trusted.

Comparing $\rho R/\rho R_0$ by shot type excluding shots with marginal DT yields in Table 5.1, shows that preheat and magnetization decrease the fuel convergence by a factor of 2 for shots with initial fill pressures of 11 atm. For the two cases at 7 atm initial pressure with a magnetic field of 10 T, the convergence is higher than the case of compression only with 11 atm. Whereas the trends from experiment agree with the trends predicted from the 1D point design (see Figs. 2.6 and 2.3), the percent change in fuel convergence is greater in experiment than is in 1D predictions, suggesting that preheat, magnetization, and higher fuel density are more important...
Table 5.1: Estimated $\rho R$ values from experimental DT fusion yields, the ratio of initial to final $\rho R$ values, relative changes in $\rho R$ values between shot types, and their comparison to 1-D results. Simple estimates and 2-D modeling indicate that 1-D will overestimate $\rho R$ by a factor of 2 because of end losses, but will predict similar convergence ratios to 2-D.

for obtaining low convergence high yield cylindrical implosions than the point design predicts.

### 5.2.2 Estimating the Hall parameter at peak compression

An estimate of the Hall parameter can be made indirectly and independently from proton radiography measurements assuming the flux loss is equivalent to the flux loss from the 1D point design results from Fig. 2.8. There is no viable measurement of electron temperature, but using the neutron-averaged ion temperature as the temperature for both populations provides enough accuracy to formulate an order of magnitude estimate. The error from the estimation of Hall parameter is then the error for the neutron-averaged ion temperature carried through using standard error propagation

$$\Delta \chi_e = \chi_e \frac{1.5 \Delta T_i}{T_i}$$  \hspace{1cm} (5.4)

Multiplying Eq. 2.2 by a flux loss constant of 0.50 for magnetized compression and 0.20 for integrated shots is congruent with 1D predictions from Fig 2.8. Fluc-
tuations of the $\rho R$ ratio from shot to shot for similar shot types are within the reported errors, so mass loss appears to be constant across the different implosion types. Introducing a mass loss term similar to the flux loss term will overestimate the Hall parameter, and in the interest of calculating a lower bound estimate has been ignored. The ion Hall parameter is calculated from the electron Hall parameter using Eq. 2.3.

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>Shot Type</th>
<th>$\chi_e$</th>
<th>$\chi_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>85561</td>
<td>Compress+Mag (11 atm)</td>
<td>7.06 ± 2.53</td>
<td>0.165 ± 0.06</td>
</tr>
<tr>
<td>85562</td>
<td>Compress+Mag (11 atm)</td>
<td>7.65 ± 1.50</td>
<td>0.179 ± 0.04</td>
</tr>
<tr>
<td>85564</td>
<td>Compress+Mag (7 atm)</td>
<td>9.91 ± 1.10</td>
<td>0.232 ± 0.03</td>
</tr>
<tr>
<td>85567</td>
<td>Compress+Mag (7 atm)</td>
<td>9.62 ± 1.76</td>
<td>0.225 ± 0.04</td>
</tr>
<tr>
<td>84313</td>
<td>Integrated (11 atm)</td>
<td>6.22 ± 0.98</td>
<td>0.146 ± 0.02</td>
</tr>
<tr>
<td>85558</td>
<td>Integrated (11 atm)</td>
<td>5.39 ± 0.16</td>
<td>0.126 ± 0.01</td>
</tr>
<tr>
<td>85559</td>
<td>Integrated (7 atm)</td>
<td>9.99 ± 0.92</td>
<td>0.23 ± 0.02</td>
</tr>
<tr>
<td>85560</td>
<td>Integrated (11 atm)</td>
<td>5.51 ± 2.21</td>
<td>0.13 ± 0.05</td>
</tr>
</tbody>
</table>

Table 5.2: Pulse length and fuel density that maximizes neutron yield for each shell thickness under the constraint that fuel convergence ratio is approximately 25. All reported observables were obtained from 1-D $LILAC$ MHD.

The electron Hall parameter for both magnetized compression and integrated shots are shown in Table 5.2. All shots reported are for the same initial magnetic field of 10 T. Compression and magnetization shots easily exceed the requirement of $\chi_e > 7$ for sufficient magnetization of the electrons during the implosion. Integrated shots are just below this level of magnetization due to more flux loss by the Nernst effect from preheating. The discrepancy of magnetization is most likely why there is negligible difference between neutron yield of compression and magnetization and integrated shots. In order to have a significant difference between these two cases, the magnetic field needs to be greater. This is consistent with 1D results obtained from the point design.
Inferred electron and ion Hall parameters and the neutron yield enhancement plateau between magnetized compression and integrated shots motivates the need for higher initial magnetic fields for MagLIF experiments. Several methods of increasing the initial magnetic field are being explored for the future of the platform, and once such method is discussed in the appendix.
Chapter 6

Conclusions

A point design for MagLIF was successfully developed using 1-D and 2-D simulations. The initial design choice was a 0.6 mm outer diameter target, a 30 µm thick plastic shell, an initial DD fuel density of 2.4 mg/cc, preheated by a single OMEGA beam of 180 J delivered in 1.5 ns, an initial magnetic field of 10 T, and compressed by 40 other OMEGA beams delivering a total of 15.8 J in 1.5 ns. Adjustments to the point design were made after initial implosion experiments gave a neutron yield close to the detectable limit. The shell was then thinned down to 20 µm, increasing the implosion velocity from 154 km/s to 190 km/s, a convergence ratio of 27.3, and an a yield per unit length of $1.24 \times 10^{12} \text{ mm}^{-1}$.

The beam pointing and laser energy balance between oblique and normal incidence beams that gives the most uniform cylindrical compression was determined to be full energy for the normal beams and 83% of full energy for oblique beams overlapped in the center. The pointing of the oblique beams cross the center of the cylinder and are pointed 0.285 mm away from the cylinder centroid along the cylinder axis. The normal incidence beams are shifted away from the centroid along
the cylinder axis by 0.275 mm to irradiate the sides of the cylinder. A detailed picture of this pointing configuration can be seen in Fig. 4.8, keeping in mind that the location of the peaks for each ring of beams is on the cylinder surface and do not reflect the axis-based numbers reported here.

A radial shift was applied to each beam to get an azimuthally uniform irradiation pattern and eliminate the mode 5 perturbation that naturally occurs from OMEGA beam geometry. The shifts imposed are the minimum required to achieve a uniform profile so as to minimize the energy lost in the wings of the Gaussian beam profile. The shift imposed decreased the initial mode 5 perturbation amplitude by 50 %. No measurements of azimuthal uniformity were made of the final laser pointing, but experiments to measure this will be conducted in the future.

The preheating experiments determined that DRACO simulations adequately predict gas temperatures over time to be used as a predictive tool, despite the fact that it overestimates the absorption of laser energy in the window. Measurements of soft x-rays in the implosion region establish that at least 100 eV is achieved in the implosion region 1.3 ns into a 200 J, 2.5 ns laser pulse. The predictions from DRACO, which align closely to spectral data from analyzed Dante data, show that the preheating achieves an electron and ion temperature of 200 eV by the end of the laser pulse. Dante spectral analysis of the front portion of the cylinder demonstrates that an initial axial field of 15 T applied to preheating mitigates wall heating due to thermal conduction.

Comparison of FLASH and DRACO simulations of window only experiments shows that when the laser absorption profile is sufficiently perturbed, simulations begin to agree with experiment. This suggests that there is some physical effect that is responsible for pushing the window plasma out of the way. The leading hypothesis
is that there is sufficient laser self-focusing to focus the laser to an intensity where the ponderomotive pressure of the laser is comparable to the hydrodynamic pressure of the expanding window plasma. Simulations have been carried out using DRACO to see if laser speckle could provide a sufficient perturbation that matched experiments, but the results did not match any better.

Compression, preheat, and magnetization were all combined in the first integrated MagLIF shots performed on OMEGA. The major success of integrated shots was the successful demonstration of yield enhancement between compression only and magnetized compression shots. There was no significant difference between magnetized compression and integrated MagLIF shots in terms of neutron yield, and an estimation of the Hall parameters between the two cases demonstrates the need for higher magnetic fields for the platform to see a difference between these two cases. Integrated shots had a lower convergence ratio compared to magnetized compressions, with secondary DT yields at or below detection threshold. Secondary DT fusion yields were used to calculate an experimental convergence ratio. Convergence ratios calculated from experiment followed 1-D predictions, with compression only being the highest convergence and integrated shots giving the lowest. Both preheat and higher initial fuel density were shown to decrease convergence ratio, which is also consistent with 1-D results. DD neutron yield falls almost linearly with increasing convergence ratio as expected. This is contradictory to 1-D results that do not take mix into account from too high of a fuel convergence, and shows when 1-D predictions break down in their ability to predict experimental results.

A small scan of preheat timing was performed, although too many shots were corrupted by magnetic field coils blocking the shots to formulate a sound conclusion. According to DRACO predictions and how well they match the preheating experi-
ments, not much deviation from the prediction is expected experimentally. Despite a yield increase, there was no significant enhancement of the neutron-averaged ion temperature across all cases of MagLIF implosions.

MagLIF is still an ongoing research effort and the success of this platform has garnered a place in the NNSA (National Nuclear Security Administration) cooperative agreement for the LLE. Future shots will include measurements of azimuthal uniformity of the final beam pointing, higher axial magnetic field shots, laser pulse shaping to maximize neutron yield and eliminate strong shocks launched by square pulses, and proton radiography measurements of the compressed magnetic field.
Bibliography


Appendix A

Increasing the Magnetic-Field Capability of the Magneto-Inertial Fusion Electrical Discharge System Using an Inductively Coupled Coil

A.1 Introduction

The goal of producing very large magnetic fields for magnetized HEDP (high energy density physics) experimental platforms is constrained by both space and energy limitations. The MIFEDS (magneto-inertial fusion electrical discharge system) device is capable of efficiently delivering a large magnetic field with very limited energy storage by employing coils of many turns wound around a 3D printed plastic frame[13]. This approach has been effective and has led to many scientific discoveries in the field of magnetized HEDP[6, 14, 33, 24, 15, 7, 1, 46].
However, the number of turns required to generate the largest magnetic field possible occludes the target from diagnostic lines-of-sight and lasers that generate HEDP conditions. Although direct coupling to a coil of many turns is the most efficient way to magnetize experiments, it is impossible to implement such a design. It has been proposed before that inductive coupling rather than a direct connection can be used to compress the current density thereby compressing the magnetic flux, however such methods were deemed too inefficient for any practical application[17]. Nevertheless, this coupling scheme is very effective for HEDP experiments that are constrained by required lines-of-sight. Inductively coupled coils can be made much smaller than current coils, which typically magnetize a volume of $\sim 1 \text{ cm}^3$, and still efficiently convert stored energy into magnetic field.

Inductively coupled coils consist of a primary coil of many turns that is electrically connected to a current generating device (MIFEDS in this instance). The primary is then surrounded by a conducting collar that forms part of an inductive circuit, which is referred to as the secondary coil. The inductive circuit is then completed through a small single loop of wire, which can be used to magnetize the experiment of interest. A 3D model of this type of coil is shown in Fig. A.1. The efficiency of inductively coupled coils hinges greatly on the resistance of the secondary coil and the coupling efficiency between the primary coil and the secondary coil.

**A.2 Theory**

MIFEDS can be modeled as an RLC circuit with an initial charge on the capacitors, shown in Fig. A.2.

The system of equations governing Fig. A.2 is
Figure A.1: A 3D model of an inductively coupled coil. A primary coil of 7 turns of 26 AWG wire is surrounded by a solid copper ring with a cut on the right side. A simple strip line tapers down to a single loop that completes the circuit for the outer secondary structure.

Figure A.2: A circuit-equivalent of MIFEDS with a coil, depicted as the inductor $L_c$ and resistor $R_c$, directly connected.

$$\frac{Q}{C_M} - I R_M - I R_c - L_M \frac{dI}{dt} - L_c \frac{dI}{dt} = 0$$

(A.1)

$$-\dot{Q} = I$$

Where $M$ subscripts refer to internal MIFEDS circuit parameters and $c$ subscripts refer to coil parameters. $Q$ and $I$ are the charge on the capacitor and current through the circuit respectively. We can make a substitution of one equation into
the other to get a single differential equation of order 2

\[ \ddot{Q} + \frac{R}{L} \dot{Q} - \frac{1}{LC} Q = 0 \]  

(A.2)

where \( R = R_M + R_c \) and \( L = L_M + L_c \) are total resistance and inductance of the circuit respectively. We introduce an ansatz solution of \( Q(t) = Q_0 e^{i\omega t} \) and use initial conditions \( Q(0) = V_0 C_M \) and \( I(0) = 0 \) where \( V_0 \) is the initial charge voltage on the capacitors to find both \( Q_0 \) and \( \omega \). Substituting our solution into Eq. A.2 and solving for \( \omega \) gives us

\[ \omega = \sqrt{\omega_0^2 - \gamma^2} + i\gamma \]  

(A.3)

\[ Q_0 = V_0 C_M \]

where \( \omega_0^2 = 1/LC \) and \( \gamma = R/2L \). Now the derivative of the solution gives us the current running through the circuit. However, the initial condition \( I(0) = 0 \) dictates that the sine component is the only surviving term, and since determining the peak current is the objective, only the real part of the current amplitude is considered. Hence the final solution to the current is of the form

\[ I(t) = V_0 C_M \tilde{\omega} e^{-\gamma t} \sin \tilde{\omega} t \]  

(A.4)

where \( \tilde{\omega} = \sqrt{\omega_0^2 - \gamma^2} \). Taking the derivative and setting it to 0 gives us the time at which peak current occurs

\[ t_{peak} = \frac{1}{\tilde{\omega}} \tan^{-1} \left[ \frac{\tilde{\omega}}{\gamma} \right] \]  

(A.5)

We can substitute Eq. A.5 into Eq. A.4 to get the exact solution for peak
Figure A.3: Many turns of copper wire are needed to obtain the highest magnetic field from the MIFEDS device. Shown here is a solenoid of radius 5 mm where each turn is stacked on top of one another. The maximum field strength requires \( \sim 10 \) turns, which makes the minimum length of the coil \( \sim 8 \) mm.

This solution ignores resistance changes in the coil due to wire heating over the discharge time, which in the case of MIFEDS is a non-trivial component. A good estimate of the peak current that best fits empirical data of various coil types from the MIFEDS device is

\[
I_{\text{peak}} = \frac{V_0}{\sqrt{\frac{L_M + L_c}{C_M}} + 0.8 \times (R_M + R_c)}
\]

where the nominal internal MIFEDS values are \( C_M = 1.0 \ \mu \text{F}, \ L_M = 150 \ \text{nH}, \) and \( R_M = 0.20 \ \Omega. \)

Magnetic field can be estimated using the model in Eq.A.6 as a function of the number of turns in the coil as seen in Fig. A.3. Typically, MIFEDS coils are not in a solenoid configuration, but for comparison and ease of calculation, the solenoid inductance and magnetic field do not deviate significantly from more practical designs.
Figure A.4: Circuit diagram of a coil inductively coupled to MIFEDS. Here, $R_1$ and $L_1$ is the primary coil resistance and inductance respectively, $L_2$ is the inductance of the secondary, and $R_c$ is the resistance of the secondary and magnetic coil structure.

For the inductive coupling case, the circuit equivalent is a transformer setup in Fig. A.4. This circuit is governed by a new system of equations

\[ \frac{Q(t)}{C_M} = (R_1 + R_M)I_1 + L_1 \frac{dI_1}{dt} - M \frac{dI_2}{dt} \]
\[ L_c \frac{dI_2}{dt} = -R_c I_2 - M \frac{dI_1}{dt} \]

(A.7)

where the circuit values follow those found in Fig. A.4 and $M = k\sqrt{L_1L_2}$ is the mutual inductance between the primary and secondary of the transformer, with $0 < k < 1$ being the coupling coefficient. These equations can also be solved analytically, although a purely mathematical analysis is complicated and unenlightening. To better compare with the case of direct coupling, there are many free parameters that must be fixed, such as the coupling $k$, the secondary resistance $R_c$, the number of turns in the primary $N_1$, and the radius of the primary coil $r_1$. The latter two parameters will fix the value of $L_1$ and $L_2$ when $k$ is maximum. Thus an estimate of the inductive coupling that is within physical limitations must be made.
Figure A.5: The magnetic field of an inductively coupled coil is compared to the magnetic field produced by the same coil electrically connected to MIFEDS. As long as the coupling efficiency is high, the magnetic field can be more than doubled.

A.2.1 Coupling Efficiency

The coupling efficiency depends upon the cross-section overlap between the secondary and primary coil. Formulating an estimate to the coupling efficiency of the design is reduced to a simple geometric calculation. Assuming both primary and secondary coils conserve flux separately,

\[ M = N_1 N_2 \mathcal{P}_{12} = k \sqrt{L_1 L_2} \quad (A.8) \]

where \( N_2 \) is the number of turns in the secondary and \( \mathcal{P}_{12} \) is the magnetic permeance, which is proportional to the shared cross-sectional area of the overlapping coils, similar to electrical conduction. Substituting this into the formula and assuming the short solenoid case for the separate inductances gives
\[ N_1N_2P_{12} = N_1N_2\mu_0A \frac{\ell}{\ell} = k\sqrt{L_1L_2} \]  
(A.9)

\[ k\sqrt{L_1L_2} \sim \frac{\mu_0\pi kN_1N_2r_1r_2}{\ell} \]

where \( A \) is the cross-sectional area of the primary coil, \( \ell \) is the length of both the secondary coil and the solenoid that comprises the primary coil, and \( r_1 \) and \( r_2 \) are the radii of the primary and secondary coil respectively. This can be simplified down to

\[ k \sim \frac{A}{\pi r_1r_2} \sim \frac{r_1}{r_2} \]  
(A.10)

giving an easy estimation of the coupling constant \( k \) for designing and building transformer coils.

Making this ratio close to unity is critical in assuring minimal energy loss. The achievable magnetic field drops substantially due to poor inductive coupling, and inductively coupled coils quickly become disadvantageous compared to a directly connected coil, as seen in Fig. A.5. Considering manufacturing defects and the dimensions of materials, the inductive coupling cannot practically exceed 90% for the design considered here. The radii can be made to be equal if the primary and secondary coil were both wrapped around an iron core. This adds considerable weight and size to the design and may not be suitable for HEDP applications, but it is possible to have this design exceed the limiting factor for coupling. The reason the collar-like design was chosen was to reduce the resistance in the secondary coil by increasing the cross-sectional area.
A.3 Experiment

A prototype coil was constructed to test the feasibility of the concept. A lightweight plastic core was machined to fit 10 turns of 26 AWG wire to form the primary coil. The secondary coil was made from 125 µm copper shim stock that was wrapped tightly around the primary windings. The estimated coupling efficiency of this design is \( \sim 0.84 \). The predicted magnetic field of this design is \( \sim 20 \) T. It is hard to accurately predict the performance of such coils since they are hand made and have unmeasurable characteristics such as coupling efficiency. A small strip line insulated by 100 µm Kapton® sheeting allowed a 4 mm diameter loop to be soldered to either side of the shim stock collar. A terbium doped Faraday rotator glass is then glued into the center of the small loop for diagnostic purposes. A linearly polarized 532 nm Nd:YAG laser was used to measure the magnetic field by Faraday rotation. An on-board Rogowski coil with passive integration[38] was used to measure the current discharge through the primary coil. The Rogowski coil is calibrated in-situ against a Pearson Model 2093 current monitor for both timing and current amplitude and are taken from a previous publication on the device[13].

A half wave plate rotates the initial polarization of the laser to a known phase. Using two photodiodes to look at the intensity of both S and P polarized light, the magnetic field can be calculated from the intensity relationship

\[
I_{S,P}(t) = I_0 \cos^2(B(t)\nu \ell + \phi_0)
\]  

(A.11)

Where \( I_0 \) is the sum of the intensities of both S and P polarization without the magnetic field present, \( \nu = 0.11 \) rad·T\(^{-1}\)·m\(^{-1} \) is the Verdet constant of the Faraday rotation crystal, \( \ell = 1 \) mm is the length of the Faraday crystal, and \( \phi_0 \) is the initial
The phase is calculated from the initial signal level as

$$\phi_0 = \arccos \left( \sqrt{\frac{I_S(0)}{I_0}} \right)$$

Fitting the peak of the magnetic field in Fig. A.6 with a quadratic function determines that the peak field is $15.2 \pm 1$ T. This implies a current in the secondary coil of $48.4 \pm 1.3$ kA. For a 4 mm diameter coil made of AWG 24 copper wire, the coil inductance is calculated to be 5.43 nH. The energy in the coil is calculated to be $6.36 \pm 0.8$ Joules. At 12 kV, MIFEDS stores 72 Joules, so the ratio of energy stored to energy delivered, or efficiency, is $8.8\% \pm 1\%$. For direct coupling, the predicted efficiency of a 4 mm diameter coil is $1.3\%$, so the increase in efficiency is roughly 7-fold. There is a small discrepancy between the predicted value of magnetic field and the measured value, but no discrepancy between the predicted primary current and the measured. This means that the secondary structure, coupling, or the coil deviated from the model. The size of the structure and the way it is assembled makes it hard to accurately measure resistance and inductance in-situ, and since small deviations in these values greatly affect the magnetic field, this deviation is acceptable and expected.

**A.4 Coil Optimization**

The configuration that achieves the strongest magnetic fields is a coil of many turns directly connected to MIFEDS. However, most experiments utilize laser and diagnostic configurations that prohibit using such coils. A useful exercise is to examine the performance of direct connection vs. inductive coupling as a function of coil
Figure A.6: The magnetic field produced by the coil attached to the secondary and the current through the primary coil as measured by the Rogowski coil as a function of time. The peak of the field is 15.2 T.

inductance. The energy equations show that an inductively coupled coil performance depends upon the number of turns in the primary and the inductance of the secondary. These parameters must be optimized first for a fair comparison.

Minimizing the resistance in the secondary and magnetic field coil is a must for maximizing magnetic field. It seems equally intuitive to keep increasing the number of turns in the primary side of the transformer. However, the resistive losses that come with more turns begins to decrease the energy delivery. The gain from increasing the number of turns comes from making the transformer inductance much larger than the internal inductance of the MIFEDS device without the discharge becoming resistance dominated. The inductance of the transformer can still be increased without also increasing the resistive losses by increasing the radius of the primary coil and thus, the secondary coil as well. The benefits of the increase in system size is illustrated in Fig. A.7. The gains in increasing the system size quickly plateau, but this suggests that possibly a more permanent and larger fixture in the transmission line of MIFEDS could prove to be more efficient than the low-inductance direct transmission line being employed now.
Figure A.7: The energy delivery capability of the inductively coupled coil increases as the radius of the primary and secondary coil $a_0$ increases.

Using the optimized case for the inductive coupled coils, a fair comparison of the energy delivery as a function of coil inductance between direct and inductive coupling can be made. The coil inductance gives the most general look at the geometry and the strength of the magnetic field being produced. In Fig. A.8, the two curves cross at roughly 160 nH. For a single turn coil, this would mean inductive coupling would be more inefficient for coils with a radius larger than $\sim 40$ mm. For a Helmholtz geometry that provides higher field uniformity, a coil of radius and separation of $\sim 10$ mm can be used before inductive coupling becomes less effective than direct connection. For the size of the experiments being performed in HEDP, inductive coupling for the MIFEDS device is generally a more effective approach than a coil geometry directly connected to MIFEDS.

A.5 Conclusions

Using the on-board current monitor system for MIFEDS and the Faraday rotator crystal, a magnetic field of 15 T was measured for a charge voltage of 12 kV.
Figure A.8: Energy delivery as a function of coil inductance reveals when inductive coupling (solid curve) is favorable over direct connection (dashed curve) in terms of coil size and geometry. For coils above 160 nH, MIFEDS delivers more energy, and hence produces more magnetic field, via direct connection.

For comparison, if the same coil was directly connected to MIFEDS, the predicted magnetic field performance is 7 T.

If the impedance of the magnetic field coil is below 160 nH, using an inductive coupling scheme is more efficient than direct electrical connection. This limit is well within the size characteristics of most HEDP experiments on OMEGA.