Laboratory Astrophysics Experiments to Study Star Formation

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Applied Physics) in The University of Michigan 2017

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ACKNOWLEDGEMENTS

My path to graduate school is an unconventional one: after completing my undergraduate education I served a tour of duty in the U. S. Navy. I’m not sure I would have returned to school at all had I not had the encouragement of my undergraduate advisor, Dr. Pat Hartigan, so I ought to begin there. Thank you for helping me keep my foot in the door for those years and for giving me the idea to attend the 2008 HEDLA Conference, where I met the University of Michigan research group that I have had the pleasure of working with for my graduate education.

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Mommy likes pie! I like cookies.
You are awesome and I am poop.
Did you know? and I am poop.
6 x 5 = 30 4 x 8 = 32 10 x 10 = 100 40 + 40 = 80
20 = 10 + 10 = that is math you are weird since people what is on stars.
Wrote by, Mommy!
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ABSTRACT

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by

Rachel Pierson Young

Co-chairs: R. Paul Drake and Carolyn C. Kuranz

As a thesis project, I devised and implemented a scaled accretion shock experiment on the OMEGA laser (Laboratory for Laser Energetics). This effort marked the first foray into the growing field of laser-created magnetized flowing plasmas for the Center for Laser Experimental Astrophysical Research (CLEAR) here at the University of Michigan.

Accretion shocks form when streams of accreting material fall to the surface of a young, growing star along magnetic field lines and, due to their supersonic flow, create shocks. As I was concerned with what was happening immediately on the surface of the star where the shock forms, I scaled the system by launching a plasma jet (the accreting flow) and driving it into a solid surface (the stellar surface) in the presence of an imposed magnetic field parallel to the jet flow (locally analogous to the dipole field of the star).

Early work for this thesis project was dedicated to building a magnetized flowing plasma platform at CLEAR. I investigated a method for launching collimated plasma jets and studied them using Thomson scattering, a method which measures parameters such as temperature and density by scattering a probe beam off the experimental
plasma. Although the data were corrupted with probe heating effects, I overcame this problem by finding the mass density of the jets and using it to determine they were isothermal rarefactions with a temperature of 6 eV.

Scaling an astrophysical phenomenon to the laboratory requires tailoring the parameters of the experiment to preserve its physics, rather than creating an experiment that merely superficially resembles it. I ensured this by distilling the driving physical processes of the astrophysical system—accretion shocks—into a list of dimensionless number constraints and mapping these into plasma parameter space.

Due to this project being the first magnetized flowing plasma effort at CLEAR, it suffered the growing pains typical of a young research program. Of my two primary diagnostics for the accretion shock experiment, visible light imaging was successful, but proton radiography, which was intended to probe magnetic field structure, failed twice for two independent reasons. The visible light data show that a shock forms and grows rapidly. However, there are no observable structural differences between the magnetized and un-magnetized shots. It may be that there were subtle structural differences that would have been evident in proton radiographs but did not appear in visible light images.

However, it may also be that the magnetic field was not strong enough to affect the structure; given the plasma and magnetic field parameters of the shot day, the experiment was analogous to a young star with a magnetic field of 325 Gauss, which is weaker than the roughly 1 kilo-Gauss fields typically observed. If this experimental effort continues after my departure, it would benefit from making use of one of the novel low-density plasma stream generation techniques being developed at CLEAR.
CHAPTER I

Introduction

1.1 Overview

While a scaled experimental version of a complicated system might seem a poor substitute for the real thing, it offers researchers several advantages: it can be tested under controlled conditions, altered easily, and fine-tuned to reveal insights in the basic physics of the system. The scaled experiments the general public is most familiar with are model aircraft tested in wind tunnels. What the general public may not be aware of is that wind tunnels predate flight by more than thirty years; the Wright brothers’ historic accomplishment at Kitty Hawk would not have been possible without a generation of researchers investigating the basic physics of flight in a scaled setting.

This thesis pertains to a different sort of scaled experiments, high-energy laser experiments which are scaled to astrophysical systems. Conceptually, scaling an astrophysical system is similar to scaling an aircraft: it is an attempt to make a smaller version of the real thing that preserves its physics and thus will tell the researcher something useful about the system of interest. But model aircraft are only scaled down by two or three orders of magnitude in size, while an astrophysical system might be scaled down by ten or more orders of magnitude. Moreover, some astrophysical phenomena, such as gravitation, cannot be reproduced in the laboratory.
Scaling an astrophysical system, therefore, requires choices and tradeoffs: what are the most important physical processes of the astrophysical system and how might they be reproduced—or approximated—in a laboratory setting?

Fluid dynamicists have long used dimensionless numbers to distill the behavior of a fluid system down to its essentials. To return to the model aircraft example above, a researcher wishing to test a model wing in an wind tunnel would adjust the air flow such that the Reynolds number\(^1\) of the wind tunnel system matched the Reynolds number expected when the actual aircraft took flight. This basic process—fiddling with experimental parameters to make dimensionless numbers line up—is what researchers mean when they say a system is “well-scaled.”

For my thesis project, I designed and implemented a laser experiment which I argue is well-scaled version of an accretion shock. Accretion shocks form in any accreting system; I focused on those that occur during star formation at the surfaces of young, growing stars. All stars form at the center of accretion disks, see Figure 1.1. The most widely accepted accretion model is magnetospheric accretion, wherein the magnetic field of the young star is thought to control the accretion process, lifting material out of the plane of the disk and funneling it to the stellar surface along magnetic field lines. When the accreting material impacts at the surface of the star, it creates a shock. From the perspective of a local observer on the surface of the star, it would appear that accreting material was falling to the surface along field lines that ran perpendicular to the surface (that is, up and down).

It was this specific part of the star formation process that I decided to scale to laboratory experiment, see Figure 1.2. In the astrophysical system, a stream of accreting material flows down along stellar magnetic field lines, impacts at the stellar surface, and forms a shock. In the laboratory experiment, a plasma jet (the “accreting flow”) is driven into a solid surface (the “stellar surface”) in the presence of an imposed

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\(^1\)The Reynolds number captures the importance of viscous effects.
magnetic field that runs parallel to the flow (analogous to the local field of the star). To argue that the experiment was well-scaled, I tailored the plasma conditions of the experiment to make a dimensionless-number-based scaling argument.

The primary objective of this project was to investigate the role of the magnetic field in the structure and evolution of accretion shocks. Based on existing astrophysical simulation work, I hypothesized that magnetic fields would play a crucial role in the structure of the post-shock material. I expected a strong field to trap the shock
in a tight column of post-shock material, whereas a weak field would fail to contain it, and it would splash out to the sides, much like a stream of water does when it hits a surface.

1.2 Laboratory Astrophysics

My work in laboratory astrophysics stands on the shoulders of nearly twenty years of work in scaling astrophysical systems to laboratory experiments with dimensionless numbers (Ryutov et al., 1999; Remington et al., 2000, 2006). This project was conducted under the auspices of The Center for Laser Experimental Astrophysical Research (CLEAR). CLEAR is based at the University of Michigan and is lead in part by my co-advisors, Paul Drake and Carolyn Kuranz. Examples of laboratory astrophysics work previously conducted by CLEAR and its predecessor include the work of Kuranz et al. (2009), who created Rayleigh-Taylor blast waves relevant to supernovae remnants; and the work of Krauland et al. (2013), who created reverse shocks relevant to interacting binaries.

This section will lay out hydrodynamic/magnetohydrodynamic (MHD) laboratory astrophysics work in the sub-field of star formation. As related in the last section, stars form at the center of accretion disks; these star-disk systems are accompanied by bipolar jets that extend several light-years into the interstellar medium. Most star-formation-related laboratory astrophysics focuses on the launch mechanism and their structure of these jets. In addition to the wealth of experiments aimed at exploring jet behavior, there are several studies of accretion disk behavior and one other experimental team studying accretion shocks.

1.2.1 MHD Jets on MAGPIE

For over fifteen years, the Plasma Physics group at Imperial College London has lead an effort to study astrophysically relevant jets on MAGPIE, a large pulsed-power
generator. Pulsed-power devices such as MAGPIE create experimental plasmas by discharging high current through some array of conductors (wires or thin metal foils), completely vaporizing them. *Lebedev et al.* (2002) devised a new way to create plasma jets that could be relevant for laboratory astrophysics: they used a conical array of wires to launch a collimated plasma jet with velocity of $\sim 200 \text{ km s}^{-1}$ and a Mach number of $\sim 20$. They found that higher $Z$ materials had more radiative cooling and produced tighter jets. These jets became the basis for later work, including launching a conical-wire MAGPIE jet into a cross wind analogous to an astrophysical jet encountering background movement in the interstellar medium (*Lebedev et al.*, 2004).

In 2005, *Lebedev et al.* built off the conical-wire idea to develop a platform that has been the basis for over a decade of work. They substituted a flat radial array of wires for the conical array. When MAGPIE fires, the wires are completely vaporized, producing a magnetic tower above the wires with a toroidal magnetic field inside. The toroidal field compresses plasma within the bubble into a jet along the axis. The tower grows with time until the jet inside finally breaks free. These jets are radiatively cooled (cooling parameter $\sim 1$) and resultantly have very high Mach numbers ($\sim 30$) (*Lebedev et al.*, 2005b). *Ciardi et al.* (2007) sent such jets into a background plasma in a jet-encounters-interstellar-medium experiment similar to that of (*Lebedev et al.*, 2004) earlier.

The genius of the radial-wires idea is that tweaking the experiment can make the jet episodic like an astrophysical jet. When the radial wire vaporize, they leave a small gap at the center. *Ciardi et al.* (2009) adjusted the experiment such that when the jet breaks free, the plasma is able to fill-in that gap, see Figure 1.3. This sets up conditions identical to those in place when MAGPIE originally fired and the filled-in configuration is able to “refire.” Every time the experiment refires, the magnetic tower grows once more, a jet forms within it and eventually breaks free. Later *Suzuki-Vidal*
et al. (2010) replaced the radial wires with a thin circular conducting foil and achieved three to four eruptions per experiment.

Figure 1.3: Plasma jet data from Ciardi et al. (2009). Over a period of roughly 200 ns, a jet forms inside a magnetic bubble, breaks up, new magnetic bubbles form, and the process repeats.

1.2.2 Jet-Obstacle Collisions on OMEGA

In 2005, Foster et al. began a series of experiments aimed at exploring the interaction of dense plasma jets with a surrounding medium on OMEGA, a large laser facility located at the University of Rochester. The Foster et al. jets (see also Coker et al., 2007) were launched by irradiating a thin piece of titanium with a hohlraum, a metal cylinder which its inner walls irradiated to create a radiative cavity. The jet was collimated by a titanium washer and sent into a foam-filled cavity meant to be analogous to the interstellar medium. The resulting structures show clear bow shocks and turbulence, the same structures observed in the jets than emanate from young star systems.

While experiments that send an astrophysically relevant jet into an ambient medium are fairly common in laboratory astrophysics, the collaboration then seized on a novel variation to it: they collided their jets with polystyrene (plastic) spheres
meant to be analogous to large molecular cores in the interstellar medium (Hartigan et al., 2009).

One remarkable thing about this collaboration is the lengths they have gone to to connect their laboratory results to astronomical observations and vice versa. Hartigan et al. (2011) used the Hubble Space Telescope to obtain time-progression data of several jets from young stars\(^2\) and observed structures similar to those seen in the jet-foam experiments, see Figure 1.4.

![Figure 1.4: Comparison of Hartigan et al. (2009) experimental data (left) and Hartigan et al. (2011) observational data (right).](image)

1.2.3 Jets on LULI

In 2007, Loupias et al. began a series of experiments that were aimed at created astrophysically relevant jets on the LULI laser at L’Ecole Polytechnique. Their experiments used an “ablator” to send a shock wave into foam. By driving the resulting foam shock through a “conical washer” (basically, a converging nozzle), they created a collimated plasma jet.

The ablator in this case was a thin piece of CH irradiated by the LULI laser. Just as a rocket is propelled forward by ejecting material out the back, irradiated material

\(^2\)Jets from young stars are known as “Herbig-Haro objects” in honor of the scientists who originally identified them. Hartigan et al. (2011) observed three HH objects, HH 1, HH 34, and HH 47.
dissipating off the surface of the CH launches a shock forward through the foam. The resultant jets have Mach number of $\sim 10$, Reynolds number $\sim 1$, and Péclet number $\sim 1$, making them good candidates for astrophysical jet studies. The Loupias et al. jets were later launched into an ambient medium of argon meant to be analogous to a jet erupting into the interstellar medium (Gregory et al., 2010; Loupias et al., 2009).

### 1.2.4 MHD Jet Launching at CalTech

In the memorably titled *Why current-carrying magnetic flux tubes gobble up plasma and become thin as a result*, Bellan (2003) proposed that MHD pumping explains an array of phenomenon in the Universe. In You et al. (2005), the collaboration states their concept thusly, “an MHD force resulting from the flared current profile drives axial plasma flows along the flux tube; the flows convect frozen-in magnetic flux from strong magnetic field regions to weak magnetic field regions; flow stagnation then piles up this embedded magnetic flux, increasing the local magnetic field and collimating the flux tube via the pinch effect.”

![Figure 1.5: Evolution of an astrophysically relevant jet made with the Caltech plasma gun (Bellan et al., 2009).](image)

Since they proposed these ideas, this team has performed numerous experiments using the Caltech plasma gun (Yun and Bellan, 2010). Unlike the other jet experiments discussed in this section, these experiments are envy-inducingly large, reaching 20 cm or more, and the results resemble astrophysical jets or solar coronal loops, see Figure 1.5. They have also experimented with sending their jets into an ambient
medium (Moser and Bellan, 2012).

1.2.5 Accretion Disk Instabilities

These are not plasma physics experiments but I have included them because they seek to understand star-formation-related hydrodynamic and MHD behavior. For decades, accretion disk theorists have been plagued by a very basic problem: why does disk material spiral in? The disk material must be losing angular momentum to drag forces, much in the same way satellites in low-Earth-orbit lose angular momentum due to atmospheric drag—without repositioning they would spiral in to Earth. But whereas hydrodynamic viscosity is sufficient to explain the rate at which low-Earth-orbit satellites lose angular momentum, it is insufficient to explain the angular momentum loss in an accretion disk. Instead, the leading candidate is MHD viscosity stemming from the magnetorotational instability.

Ji et al. (2006) used Taylor-Couette apparatus to create a quasi-Keplerian rotating disk with Reynolds numbers up to $2 \times 10^6$. These experiments were not magnetic; they used water or a water/glycerol mixture. Even at such high Reynolds numbers, the flow was stable, underscoring the impossibility of explaining accretion disks without MHD.

Other teams have used Taylor-Couette apparatus (or its spherical equivalent) to pursue the magnetorotational instability. These experiments are more complicated than the water/glycol experiment of Ji et al.; they required liquid metal and an imposed magnetic field. Sisan et al. (2004) and Stefani et al. (2006) have observed the magnetorotational instability, the latter at Reynolds numbers as low as 1000, in stark contrast to the high-Reynolds-number stability of the non-magnetic system.
1.2.6 POLAR Accretion Shocks

Finally, there is one laboratory-astrophysics project that complements my own because it also pertains to accretion shocks. My work was aimed at producing a scaled version of an accretion shock on the surface of a young star and exploring the role of the surrounding magnetic field in containing the shock. The POLAR project is aimed at producing a scaled version of an accretion shock on the surface of a white dwarf\(^3\) and exploring the growth of the resulting column of radiatively cooled post-shock material (Bouquet et al., 2010; Falize et al., 2012; Busschaert et al., 2013). There are two crucial differences between their project and mine. First, their work uses high-Z material to produce a shock with significant radiative cooling. Second, their work relies on artificial means to collimate their “accretion shock.” While actual white dwarf accretion shocks are collimated by the dwarf’s intense magnetic field, the POLAR team used a shock tube to contain their experiment. Laboratory magnetic fields high enough to be analogous to a white dwarf field are simply not achievable with current technology. The first results of this effort are contained in Cross et al. (2016), which found that the growth of the scaled radiative accretion column matches numerical predictions.

Although the POLAR team is concerned with the growth of a radiating “accretion shock column,” it does not appear that they expected to observe the famous Chevalier and Imamura cooling instability.\(^4\) Their papers cite the work of Chevalier and Imamura (1982) in passing but make no mention of seeing the instability in a laboratory experiment. I suspect that the cooling timescale for their plasma cond-

\(^3\)White dwarfs are late-in-life stars; our own Sun will one day be one. While all young stars experience accretion during their formation, only binary white dwarfs experience accretion—without captured material from a binary companion there would be nothing to accrete onto them. A sub-set of these accreting white dwarfs are known as polar stars, hence the clever name of the laboratory-astrophysics project.

\(^4\)The story of the Chevalier and Imamura (1982) cooling instability is worth relating briefly. Within a handful of years, it was observed in numerical simulations, described by analytic predictions, and observed in the x-ray spectra of accreting white dwarfs, making it a lovely example of numeric simulations actually leading the way in astrophysics.
tions was too long for the instability to appear in their experiment; I calculated the cooling timescale of my own experiment once and found that it was on the order $10^{-5}$ s—short by human standards but far to long for a field where experiments are measured in nanoseconds.

To date, there is one plausible laboratory observation of the cooling instability. Hohenberger et al. (2010) observed velocity oscillations in a radiatively cooled shock, which they attribute to the cooling instability. However, their experiment was intended to be a roughly scaled version of the cooling instability in supernovae remnants, not accretion shocks.

### 1.3 The OMEGA Laser

All of the experiments included in this project were performed on the OMEGA laser at the Laboratory for Laser Energetics (LLE) in Rochester, NY. Built in 1970 as part of the national effort to achieve fusion energy, OMEGA is a 30-kilojoule 60-beam frequency-tripled neodymium:glass (Nd:glass) laser system ideal for high-energy physics investigations (Soures et al., 1996). As the laser was designed to implode fuel capsules in fusion experiments, the beams are distributed around the target chamber isotropically (or nearly so) making OMEGA flexible to configure for non-fusion applications. It has a wavelength of 351 nm, the third harmonic ($3\omega$) of Nd:glass (Boehly et al., 1997).

While the OMEGA facility is run by its staff scientists, engineers and technicians, experimental decisions are made on a shot-to-shot basis by the visiting experimental team. It is standard practice at the Center for Laser Experimental Astrophysical Research (CLEAR) to allow the graduate student primary investigator (PI) to make these decisions, albeit with the advice of more senior scientists. The metaphor I would use is student driving: senior scientists give advice and could in theory hit the brakes if they thought it necessary, but the graduate student PI is driving the car. As a
As a graduate student PI, I was responsible for coordinating each shot day from its beginning—planning normally begins about a year in advance—to analyzing the data collected. I defined the goals of the experiment, designed targets using a computer aided design (CAD) program, and coordinated with the target fabrication team here.
at the University of Michigan to have the targets built.

1.4 Description of Chapters

This thesis progresses from the motivation of the work, to early scoping studies of plasma jets, and finally to the full accretion shock experiment. The chapters are as follows:

- Chapter II discusses the process for scaling accretion shocks to a laboratory experiment. I begin with the history of our understanding of star formation, including the currently accepted models and the direct evidence of accretion shocks. I discuss how I determined the plasma conditions in astrophysical accretion shocks. I explain the dominant physics of the astrophysical accretion system and related dimensionless numbers. I enumerate the dimensionless number constraints needed to scale the system and plot each one in plasma parameter space, delineating the regions where the constraint is met and where it is not met. I conclude with two options, each of which would produce a well-scaled experiment.

- Chapter III analyzes the data obtained from collimated jet experiments in April 2012. Visible light imaging revealed that the jets were indeed collimated and that they formed easily visible shocks when collided in a head-on configuration. Thomson scattering was used to plot a mass vs. time profile for the jets, which was compared to analytic predictions. Based on those comparisons, I concluded the jets were behaving as isothermal rarefactions with $T_e \approx 6$ eV.

- Chapter IV presents the results of the accretion shock work. Unfortunately, I was not able to observe a difference between the field and no-field shots due to repeated failures of our primary diagnostic, proton radiography. However,
visible light imaging was successful and I use this to prove that we were successful in creating a shock. I relate the timing of shock formation to the scaling arguments presented in Chapter II. I also connect this work to the timing of shock formation for the collimated jet work presented in Chapter III.

- Chapter V presents all the proton radiography data. I used proton radiography for three shot day, one day devoted to a multiple jet experiment and two devoted to the accretion shock experiment. Unfortunately, proton radiography failed for both accretion shock shot days. I discuss these failures and explain the data that were obtained.

- Chapter VI presents the conclusions of this investigation and considers the future of this work. In particular, I discuss the lack of an observable difference between the field and no-field shots. This may be because proton radiography failed, but it also may be that the magnetic field was too weak to affect the flow. I consider both possibilities and their implications going forward.

- Appendix A provides background on the OMEGA laser and the OMEGA systems used for this thesis project, which include the Magneto-Inertial Fusion Electrical Discharge System (MIFEDS), a system for imposing magnetic fields; proton radiography using a D³He proton back-lighter, which images magnetic field structure; Thomson scattering, a technique which probes parameters such as temperature and density by scattering a probe beam off the experimental plasma; and visible light imaging, in layman’s terms, taking a picture of the experiment with self-emitted radiation.

- Appendix B provides a narrative of the four shot days involved in this thesis project. Much of the effort of this project was dedicated to developing the magnetized flowing plasma platform at CLEAR and our experimental team experienced the growing pains typical of a young research program. This chap-
ter summarizes each shot day, including what was attempted, what data was
gained, and what did not work as expected and resulted in a lesson learned for
the next shot day.

• Each shot day has an appendix dedicated to it which contains all the data,
  including data that failed or was not useful.
CHAPTER II

Scaling Accretion Shocks

This chapter introduces the driving question of this thesis project, “How does magnetic field strength affect accretion shock structure and evolution?”, and the strategy to address it with a scaled laboratory-astrophysics experiment. As discussed in Chapter I, a laboratory-astrophysics experiment is considered well scaled when it preserves the dominant physics of the astrophysical system. To ensure this, I developed a six step process, illustrated in Figure 2.1.

1. Qualitatively describe the astrophysical system and define the driving questions of the investigation. These should be questions that the astrophysical community needs answered and, ideally, they should currently elude direct observation and accurate simulation from first principles. See Section 2.1.

2. Qualitatively describe the experiment and define its goals. What flows, objects, and/or fields from Step 1 must be recreated in the lab? Ensure there is a strong visual connection and determine what it is that one intends to measure. See Section 2.2.

3. Research observational studies to determine astrophysical fluid parameters, such as density, temperature, velocity, and so forth. See Section 2.3.
4. Identify the important physical processes and their associated dimensionless parameters. Because these numbers are dimensionless, they can be used to compare systems on different length scales, such as the astrophysical system and the laboratory experiment. See Section 2.4.

5. Define a list of dimensionless number constraints. These constraints are based on the conditions that exist in the astrophysical system; for the experiment to be well-scaled they must hold true there as well. It is not always necessary to make the dimensionless numbers match exactly, but they should be in similar regimes. See Section 2.5.

6. Map the dimensionless number constraints into the experimental plasma parameter space using region plots that show where the parameter is and is not satisfied. The overlap region where all constraints are satisfied at once defines the parameter range where the experiment will be well-scaled. See Section 2.6.

Figure 2.1: The six steps for scaling an astrophysical system to a laboratory experiment.
2.1 Accretion shocks

2.1.1 Evidence for accretion shocks

All stars form at the center of a rotating accretion disks. Our own Sun once passed through this phase of life, and our Solar System is all that remains of the original disk. At that point, the Sun could not sustain hydrogen to helium fusion in its core. Instead it was powered by gravitational contraction and like all young stars, was much more active and variable than it is today. Low mass ($M < 2M_\odot$) pre-main-sequence stars are called T Tauri stars (Joy, 1945; Herbig, 1962), while higher mass ones ($2M_\odot < M < 8M_\odot$) are called Herbig Ae/Be stars (Herbig, 1960), see Table 2.1. (Note: $M_\odot$ is the solar mass; $R_\odot$ is the solar radius.)

![Figure 2.2: Conception of accreting star (left) and diagram of magnetospheric accretion (right).](Image credit: left, Australian National University, and, right, Camenzind (1990.).)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>T Tauri</th>
<th>Herbig Ae/Be</th>
</tr>
</thead>
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<td>A2</td>
</tr>
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</tr>
<tr>
<td>Stellar radius, $R_*$</td>
<td>$R_\odot$</td>
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<td>3.0</td>
</tr>
<tr>
<td>Magnetic field, $B$</td>
<td>G</td>
<td>2000</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2.1: Vital statistics for prototypic T Tauri and Herbig Ae/Be stars.

Both T Tauri and Herbig Ae/Be stars are thought to experience magnetospheric
accretion. Originally proposed by Koenigl (1991), who extended the compact object work of Ghosh and Lamb (1979a,b) to T Tauri stars, the magnetospheric accretion model has material from the accretion disk lifted out of the plane of the disk and “funneled” along the star’s magnetic field lines to its surface. (Figure 2.2 depicts a beautiful illustration of this phenomenon.) Today, there is ample evidence that magnetospheric accretion occurs on T Tauri stars (see Bouvier et al. (2007) and references therein).

For Herbig Ae/Be stars, the picture is fuzzier. While T Tauri stars have intense magnetic fields of several kiloGauss (Johns-Krull, 2007), Herbig Ae/Be stars have magnetic fields of a few hundred Gauss or less (Hubrig et al., 2004, 2006). These magnetic fields are too weak to truncate the star’s accretion disk, yet observations suggest that there are gaps between Herbig Ae/Be stars and their disks (Hillenbrand et al., 1992; Dullemond et al., 2001; Natta et al., 2001). There is also some evidence of magnetospheric accretion—namely, emission lines that indicate accreting matter is falling rapidly to the stellar surface (Muzerolle et al., 2004; Natta et al., 2000; Grinin et al., 2001).

When the supersonic material impacts the surface of the young star—T Tauri or Herbig Ae/Be—an accretion shock hot enough ($T \sim 10^6 - 10^7$ K) to emit soft X-rays forms. There is ample evidence of this in the X-ray spectra of T Tauri stars (Kastner et al., 2002; Stelzer and Schmitt, 2004; Schmitt et al., 2005; Günther et al., 2006; Argiroffi et al., 2007; Robrade and Schmitt, 2007; Brickhouse et al., 2010; Argiroffi et al., 2011), and evidence is growing that at least some Herbig Ae/Be stars exhibit X-ray-emitting accretion shocks as well (Swartz et al., 2005; Testa et al., 2008; Grady et al., 2010; Drake et al., 2014).
2.1.2 Implications of accretion shocks

The mass accretion rate of a star ($\dot{M}$, usually on the order of $10^{-8}M_\odot$ per year) can be determined from the effect that these X-ray emitting accretion shocks have on the star’s spectrum. The X-rays heat the surrounding photosphere, producing spots of hot plasma (Calvet and Gullbring, 1998). Compared to a similar non-accreting star, an accreting star ought to have excess emission in the optical and UV due to these spots. From the amount of optical and UV excess, researchers can calculate the fraction of the star’s surface covered with accretion streams of a given energy flux (the traditional way to describe accretion streams; $F = \frac{1}{2}\rho u_s^3$, where $u_s$ is the velocity of the incoming material relative to the shock front), and from there get $\dot{M}$. Using this method, accretion rates for a large population of T Tauri stars are now available (Hartigan et al., 1991; Valenti et al., 1993; Hartmann et al., 1998; Muzerolle et al., 2005; Natta et al., 2006).

In principle, the optical/UV excess method ought to work for Herbig Ae/Be stars as well (the physics is the same), but there is a complication: while T Tauri stars peak in the red or infrared, Herbig Ae/Be stars peak in the blue or UV (see Table 2.1). Discerning their optical or UV excess, therefore, is difficult. Instead, the most common method for measuring Herbig Ae/Be accretion rates depends on the Balmer-$\gamma$ (Br$_\gamma$) luminosity (Garcia Lopez et al., 2006; Mendigutía et al., 2011; Donehew and Brittain, 2011). However, it should be noted that this method was calibrated using the optical/UV excess method on low and intermediate-mass T Tauri stars (Muzerolle et al., 1998; Calvet et al., 2004).

2.1.3 Open questions regarding structure

These accretion rate calculations are only as good as the understanding of accretion shock structure behind them. Because the surfaces of young stars cannot be spatially resolved, the structure of accretion shocks has not been directly studied.
For example, do accretion shocks penetrate the star’s photosphere, potentially hiding much of the accretion shock’s energy from observers? Or, do accretion shocks create large “splashes” when they hit the surface of the star, making it appear the shock covers more surface area than it actually does? Either of these scenarios would potentially change the calculated accretion rate significantly.

*Brickhouse et al.* (2010) addresses this problem head-on for one T Tauri star in particular, TW Hydrae. (Because of its relative closeness and its “pole-on” orientation, TW Hydrae is easily the best studied T Tauri star.) *Brickhouse et al.* estimates that 1.5% of the surface of TW Hydrae is covered with 3-MK plasma, and an additional 6.8% of the surface with 2-MK plasma.

Figure 2.3 illustrates two possible ways to interpret this finding. In Figure 2.3, the cartoons above show a cross section view of accretion shocks hitting stellar surfaces; the one on the left is uncontained and splashes outward violently (see arrows), while the one on the right is contained by the magnetic field (field not shown). The cartoons below correspond to the surface of the star in either scenario. One might have a handful of “splashy,” uncontained shocks (see left), or many well-contained shocks (see right). Both cartoon stars have an equal area covered by medium and dark pink, and thus would have the same spectra.

*Brickhouse et al.* contend that the scenario on the left in Figure 2.3 explains their data: the 3-MK plasma they observed is accretion shocks (dark pink) and the 2-MK plasma they observed is rings (or donuts) of heated stellar atmosphere surrounding the shocks, not additional accretion streams. They note that 3-D simulations by *Romanova et al.* (2004) predict that accretion hotspots should be inhomogenous and irregularly shaped. Similarly, simulations by *Orlando et al.* (2010) found that T Tauri accretion shocks would produce violent outflows, particularly when the magnetic field strength is too low to the contain the accretion shock, see Figure 2.4.

This question is by no means limited to TW Hydrae. In their study of accretion
Figure 2.3: Comparison of two different accretion shock scenarios. Are accretion shocks surrounded by violent splashes (left) or are they well-contained (right)?

rates of intermediate-mass T Tauri stars, Calvet et al. (2004) write, “Shock models also fail to explain the overall level of the far UV fluxes... An additional source of emission must be contributing in this range, which we still have to identify.” They suggest that the emission source might be the pre-shock portion of the accretion column, but the simulations of Orlando et al. (2010) suggest that the outflows from accretion shocks might have temperatures and densities similar to those in the pre-shock plasma.

More recently, Ardila et al. (2013) published a study of hot gas lines of 28 T Tauri stars and concluded that, “overall, the observations are consistent with the presence of multiple accretion columns with different densities or with accretion models that predict a slow-moving, low-density region in the periphery of the accretion column [emphasis added].” Similarly, Ingleby et al. (2013) studied 21 T Tauri stars and found that to explain both the UV and the optical excesses, the models required accretion streams ranging from $10^{10}$ to $10^{12}$ erg s$^{-1}$ cm$^{-2}$. 
This completes Step 1 of the scaling process, “Qualitatively describe the astrophysical system and define the driving questions of the investigation.” The system of interest is the region at the surface of the young star when an accretion shock forms and the driving question is how well magnetic fields contain accretion shocks. Ideally, the community needs some way of relating magnetic field strength (which can be directly measured, see Section 2.3) to the degree of containment or the size of the surrounding splash zone.

### 2.2 Defining the laboratory experiment

Creating an accretion shock motivated experiment requires reproducing the major features of the astrophysical system in the laboratory. Based on the magnetospheric accretion model, accreting flow funnels to the surface of the star along magnetic field lines. It is neither possible nor necessary to reproduce all the aspects of magnetospheric accretion in an experiment. The scope of this experiment is restricted to the area on the stellar surface where the accretion stream impacts to create a shock.
From the frame of reference of an observer on the surface of the star, the stream of accreting material falls (flows down) towards the surface along magnetic field lines that run perpendicular to the stellar surface. (Farther away from the surface of the star, both the streams and the field become more complicated, but this is excluded from the experiment.) Figure 2.5 illustrates the accretion shock system (left) and the laboratory experiment meant to emulate it (right). The experiment requires a plasma jet (the “accreting material”) which flows toward a solid block (the “stellar surface”) in the presence of a magnetic field running parallel to the jet and perpendicular to the surface (the “stellar field”).

Figure 2.5: Diagram of astrophysical and laboratory accretion shock systems. In the astrophysical system (left), accreting plasma falls to the stellar surface along magnetic field lines (depicted here as a magnetic dipole at the pole of the star). In the lab experiment (right), a plasma jet collides with a solid block with a parallel background magnetic field.

The over-arching goal of the experiment was to determine the connection between magnetic field strength and accretion structure. This was broken down into three subgoals, which are illustrated in Figure 2.6: 1) create an accretion shock in a laboratory experiment (that is a bright/hot/dense region that is distinct from the incoming flow), 2) observe a splash moving out to the sides as time progresses, 3) vary magnetic field to observe a difference in the size and/or outward velocity of the splash.

This completes Step 2 of the scaling process, “Qualitatively describe the exper-
iment and define its goals.” Our experiment required a plasma jet, a solid block to
drive it into, and a surrounding magnetic field. The goals were to 1) observe a shock,
2) observe outflows from the shock zone (“splashes”) that move with time, and 3) observe a difference in outflow based on magnetic field strength.

2.3 Plasma parameters in accretion shocks

Section 2.1 described the accreting star system on a qualitative level. Understanding the accretion shock in detail requires delving into observational studies of young stars.

X-ray spectra data from T Tauri stars offer important information about accretion shocks, as the X-rays are emitted by the shocked matter. Astronomers typically measure the intensities of many emission lines, anywhere from a dozen to several dozen. The lines are known to be sensitive to the electron density and temperature of the plasma emitting them, so by comparing their relative strengths to a relevant database (generally, the Astrophysical Plasma Emission Database), the astronomers can infer the plasma conditions in the accretion shock. This is not exact science; every spectrum has a range of plasma conditions that could in theory cause it, and that contributes to the error bars astronomers put on their electron density and temperature measurements.

Mass density and incoming velocity can be calculated from incoming velocity as
follows. Mass density is

\[ \rho = \frac{A m_p n_e}{Z}, \]  

(2.1)

where \( A m_p \) is the atomic mass, \( n_e \) is electron density, and \( Z \) is the average ionization. The post-shock temperature is

\[ k_B T = \frac{A m_p 1 + Z^2 u_s^2 (\gamma - 1)}{1 + Z^2 u_s^2 (\gamma + 1)^2}, \]  

(2.2)

where \( u_s \) is the velocity of the incoming flow \textit{with respect to the shock front}, \( k_B \) is the Boltzmann constant, \( T \) is temperature, and \( \gamma \) is the adiabatic index. The velocity of the accreting material with respect to the star, \( u_{\text{acc}} \), and the velocity of the accreting material with respect to the shock front, \( u_s \), are not the same. (For a complete derivation of this see Section 4.3.3.)

\[ u_s = u_{\text{acc}} \frac{\gamma - 1}{2}. \]  

(2.3)

Therefore, incoming velocity of the accreting material with respect to the star can be calculated as,

\[ u_{\text{acc}} = \left[ \frac{2(1 + Z)k_B T}{(\gamma - 1)A m_p} \right]^{1/2}, \]  

(2.4)

assuming that the average atomic number and average mass number in the accretion shock are assumed to be that of the sun: \( Z_s = 1.1 \) and \( A_s = 1.3 \). Table 2.2 presents the findings of eight T Tauri spectral studies and calculated values for mass density, \( \rho \), and incoming velocity, \( u_{\text{acc}} \).

The velocity values in Table 2.2 are calculated from shock temperature, but in-fall velocities can also be directly measured from Doppler shifts or calculated from the free-fall velocity formula. Edwards et al. (1994) found that absorption lines in T Tauri
spectra were redshifted 200 to 300 km s\(^{-1}\). The free-fall formula is

\[ u_{\text{ff}} = \sqrt{\frac{2GM}{R_f}} \left(1 - \frac{R_f}{R_i}\right), \]

where \(G\) is the gravitational constant, \(M\) is the mass of the star, \(R_f\) is the final radius, and \(R_i\) is the initial radius. For typical T Tauri values of \(R_\ast = 2R_\odot\) and \(M_\ast = 0.8M_\odot\) (see Table 2.1), and assuming \(R_i = 5R_8\), \(u_{\text{ff}} = 350\) km s\(^{-1}\), so this is consistent.

Accretion shock studies quantify accretion stream strengths in terms of energy flux, \(F = \frac{1}{2}\rho_1u_1^3\), where \(\rho_1\) and \(u_1\) are the density and velocity upstream of the accretion shock. Calculated values of \(F\) range from \(10^{10}\) to \(10^{12}\) erg s\(^{-1}\) cm\(^{-3}\) (Ingleby et al., 2013). If incoming velocities range from 200 to 400 km s\(^{-1}\), this corresponds to \(\rho_1 \approx 10^{-13} - 10^{-10}\) g cm\(^{-3}\), which is consistent with the post-shock density values found in Table 2.2.

Pre-shock temperature is difficult to observe directly, but can be estimated. Calvet and Gullbring (1998) used a numerical simulation to determine the temperature of the pre-shock region and found that it was 15,000–25,000 K, due to preheating from X-ray emission from the accretion shock itself. Meanwhile, the background temperature of a T Tauri star puts the lower limit of the incoming temperature at around 4000 K.

The last parameter is magnetic field strength, which can be determined from
Zeeman broadening. The Zeeman effect is a single spectral line splitting due to the presence of a magnetic field; in this application the split lines blur together. Johns-Krull et al. (1999) measured Zeeman broadening in the infra-red spectrum of BP Tau to determine that its field is 2.6 kG. Valenti and Johns-Krull (2004) applied the same technique to seventeen T Tauri stars and found magnetic field strengths from 1 to 3 kG. This is consistent with later findings by Yang et al. (2005) and Johns-Krull (2007).

Wade et al. (2007) studied circularly polarized light from a wide sample of Herbig Ae/Be stars and found that most do not have a measurable field, although a handful have fields on par with T Tauri stars (a kG or more). In general, Herbig Ae/Be stars have fields of a few hundred G, if they have any at all.

Table 2.3 summarizes the findings of this section and completes Step 3, “Research observational studies to determine astrophysical plasma parameters.”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
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<td>Incoming velocity, $u$</td>
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</tr>
<tr>
<td>Incoming energy flux, $\mathcal{F}$</td>
<td>erg s$^{-1}$ cm$^{-2}$</td>
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</tr>
<tr>
<td>Incoming mass density, $\rho$</td>
<td>g cm$^{-3}$</td>
<td>$10^{-13}$–$10^{-10}$</td>
</tr>
<tr>
<td>Incoming temperature, $T$</td>
<td>K</td>
<td>4000–25000</td>
</tr>
<tr>
<td>Magnetic field, $B$</td>
<td>G</td>
<td>0–3000</td>
</tr>
</tbody>
</table>

Table 2.3: Plasma parameter ranges for accretion shocks

2.4 Physical processes and dimensionless numbers

Astrophysical systems can never be scaled and reproduced perfectly in the lab. Having a worthwhile experiment, therefore, hinges on discerning which physical processes are most important and translating them into an experiment appropriately. Ryutov et al. (1999) lays out a theoretical basis for doing so: one must ensure that dimensionless numbers (for example, Reynolds number) that define the system are at least in similar regimes.
To review from Section 2.2, our goals are 1) create an accretion shock in a laboratory experiment (that is a bright/hot/dense region that is distinct from the incoming flow), 2) observe a splash moving out to the sides as time progresses, 3) vary magnetic field to observe a difference in the size and/or outward velocity of the splash.

Accomplishing this requires, first and foremost, that plasma conditions allow a shock to form in the first place. This requires a supersonic flow (see Section 2.4.1) and, because the shock will form on the length scale of the ion-ion mean free path (MFP), a relatively short MFP (see Section 2.4.2). In order to observe the effects of a magnetic field, the magnetic diffusion length must be short enough to allow the field to persist during the experiment (see Section 2.4.3). The ram plasma $\beta$ (see Section 2.4.4) is the ratio of field strength pressure to material pressure. Translating this accurately into the lab is crucial to understanding the connection between field strength and shock containment. Finally the Reynolds numbers must be in the same rough regime (see Section 2.4.5).

2.4.1 Mach number

$M$ is the Mach number, the ratio of the flow velocity of the jet to the speed of sound inside the jet, $M = u/c_s$. Sound speed was calculated according to

$$c_s = 9.79 \times 10^{5} \sqrt{\frac{\gamma (Z + 1)T_e}{A}} \text{ cm s}^{-1},$$

where $\gamma$ is the adiabatic index, $Z$ is the average ionization, $T_e$ is the temperature in eV, and $A$ is the atomic mass in proton masses.

2.4.2 Mean free path

$\lambda_{\text{MFP}}$ is the ion-ion mean free path inside the plasma. Any mean free path can be expressed as $\lambda = 1/(n\sigma)$, where $n$ is the number density and $\sigma$ is the cross-section.
The ion-ion mean free path is

$$\lambda_{\text{MFP}} = \frac{1}{n_i \sigma_{ii}^9 4 \ln \Lambda_{ii}}$$

(2.7)

where \(n_i\) is the ion density and \(\sigma_{ii}^9 4 \ln \Lambda_{ii}\) is the total cross section expressed as the 90° cross-section, \(\sigma_{ii}^9\), with a correction factor of \(4 \ln \Lambda_{ii}\) to account for collisions between ions that fail to deflect an ion a full 90°. The 90° cross-section was calculated according to

$$\sigma_{ii}^9 = \frac{\pi e^4 Z^4}{m_i u^4},$$

(2.8)

where \(e\) is the charge of an electron, \(Z\) is the average ionization, \(m_i\) is the ion mass, and \(u\) is the relevant velocity (in this case the flow velocity).

### 2.4.3 Magnetic diffusion length

\(\ell_M\) is the magnetic diffusion length scale. Any diffusion length scale can be written as \(\nu/u\), where \(\nu\) is the diffusion coefficient and \(u\) is the relevant velocity. Here we are concerned with magnetic diffusion in the post-shock region, so the diffusion coefficient is \(\nu_M\) and the velocity is \(u_2 = u_1/4\), where \(u_1\) is pre-shock velocity and \(u_2\) is post-shock velocity, taking the strong shock limit of the Rankine-Hugoniot shock conditions. Therefore we have

$$\ell_M = \frac{\nu_M}{u_2} = \frac{4 \nu_M}{u_1},$$

(2.9)

The magnetic diffusivity in Gaussian CGS units is

$$\nu_M = \frac{c^2 \eta_\perp}{4 \pi},$$

(2.10)

where \(\eta_\perp\) is the transverse Spitzer resistivity, yielding

$$\ell_M = \frac{c^2 \eta_\perp}{\pi u_1}.$$  

(2.11)
The expression for transverse Spitzer resistivity is taken from the *Plasma Formulary*, (Huba et al., 2009):

\[
\eta_\perp = 1.15 \times 10^{-14} Z \ln \Lambda \frac{T_e^{3/2}}{e \sec},
\]  

(2.12)

where \( Z \) is the ionization, \( \ln \Lambda \) is the Coulomb logarithm, and \( T_e \) is the electron temperature in eV.

### 2.4.4 Ram plasma \( \beta \)

\( \beta_{\text{ram}} \) is the ratio of ram pressure of the jet to the magnetic pressure of the field

\[
\beta_{\text{ram}} = \frac{\rho u^2}{B^2/8\pi},
\]  

(2.13)

where \( B \) is magnetic field strength.

### 2.4.5 Viscosity and Reynolds number

\( Re \) is the Reynolds number, the ratio of the viscous timescale to the dynamic timescale, \( Re = Lu/\nu \), where \( L \) is the relevant length scale, \( u \) is the relevant velocity, and \( \nu \) is the ion-ion viscosity, which was calculated according to

\[
\nu_i = \frac{u_{th,i}^2}{\nu_{ii}} = 2 \times 10^{19} \frac{T_i^{5/2}}{n_i Z^4 \sqrt{A} \ln \Lambda} \text{cm}^2 \text{s}^{-1},
\]  

(2.14)

where \( u_{th,i} \) and \( \nu_{ii} \) are the ion thermal velocity and the ion-ion collisional frequency, respectively, and expressions for both were taken from the *Plasma Formulary*, (Huba et al., 2009). In the expression for \( \nu_i \), \( T_i \) is the ion temperature in eV, \( n_i \) is the ion density in cm\(^{-3}\), \( Z \) is the ionization, \( A \) is the atomic mass, and \( \ln \Lambda \) is the Coulomb logarithm.

This completes Step 4 of the scaling process, “Identify the important physical process and their associated dimensionless numbers.” The five dimensionless numbers
of interest are Mach number, ion-ion mean free path, magnetic diffusion length scale, ram plasma beta, and Reynolds number.

2.5 Constraints for the experiment

Section 2.4 laid out five dimensionless numbers that capture the relevant physics of the accretion shock: Mach number, ion-ion mean free path, magnetic diffusion length scale, ram plasma beta, and Reynolds number. Table 2.3 listed the ranges of plasma parameters that one might expect in accretion shocks. Figure 2.7 shows the five dimensionless numbers from Section 2.4 plotted over the range of inputs typical of accreting star systems.
Figure 2.7: Density-velocity space plots of dimensionless numbers in astrophysical accretion shocks. Plots of ion-ion MFP, Mach number, magnetic diffusion length, ram plasma $\beta$, and Reynolds number for accretion shock conditions.
We can draw the following conclusions from Figure 2.7:

1. The flow is highly supersonic. Over the range of velocities and temperatures possible for the incoming flow, Mach numbers ranging from 5 to 50. This is expected as accretion shock appear to be common on actively accreting stars. We can translate this into the lab by imposing $\mathcal{M} > 1$.

2. Ion-ion MFP is much less than the length scale of the system over the whole range of inputs. For the ranges of incoming velocity and incoming density possible, the ion-ion MFP ranges from $10^4$–$10^8$ cm; the length scale of the astrophysical system is $10^9$ cm. We can translate this into the lab by imposing $\lambda_{\text{MFP}} < L$.

3. Magnetic diffusion length is much less than the length scale of the system. For the ranges of incoming velocity and incoming density possible, the magnetic diffusion length is 0.1–1 cm. We can translate this into the lab by imposing $\ell_{M} < L$.

4. Ram plasma beta, $\beta_{\text{ram}}$ is plotted for magnetic field strength and incoming material energy flux, which was defined in Section 2.3. Over the ranges of field strengths and energy fluxes possible, $\beta_{\text{ram}} = 10^{-3}$–$10^{3}$. That covers three regimes: $\beta_{\text{ram}} \gg 1$, $\beta_{\text{ram}} \approx 1$, and $\beta_{\text{ram}} \ll 1$. The high beta case is easy to achieve; one can always run a control with a low field. Therefore the scaling arguments presented in this thesis are for $\beta_{\text{ram}} \approx 1$ and this was done by imposing $0.1 < \beta_{\text{ram}} < 10$.

5. Reynolds numbers are much greater than a thousand across the input range. We can translate this into the lab by imposing $\text{Re} > 10^3$.

This completes Step 5, “Define a list of dimensionless number constraints.” The constraints that will be imposed on the laboratory experiment are listed in bold above.
2.6 Mapping the constraints to parameter space

To be well-scaled, the experiment must have the five criteria listed at the end of Section 2.5 be true at once. For every material, there is some four-dimensional volume in $T_e - u - \rho - B$ space where all five of these criteria are simultaneously met.

A four dimensional space is difficult to visualize, much less translate into a figure. In order to investigate the parameter space, I held $T_e$ and $B$ constant and considered the 2-D $u - \rho$ space; this is illustrated in Figures 2.8 and 2.9. In each of the plots in these figures, the shaded area represents the region in $u - \rho$ space where the criterion is not met. Obviously, this area will shift depending on material type, temperature and magnetic field strength. Figures 2.8 and 2.9 give two temperature options for a CH (plastic) plasma in a 10-T magnetic field. Plastic is a commonly used material for target fabrication; it seemed a reasonable assumption for an experimental plasma. MIFEDS can impose magnetic fields in the range of 5–15 T Fiksel et al. (2015); but from the perspective of scaling, there is no disadvantage to having a high magnetic field.

Considering Figures 2.8 and 2.9, one can see what conditions each criterion favors and whether high or low temperatures are more limiting. Along the left hand side of the plots, the first criterion, Mach number, and the third criterion, magnetic diffusion length, rule out very low-velocity flows. Both favor high velocity because $M \propto u$ and $\ell_M \propto 1/u$. At low temperatures, $\ell_M$ is more limiting. As the temperature rises, Mach number becomes more limiting as sound speed rises and $\ell_M$ drops according to $\ell_M \propto 1/T^{3/2}$.

Along the bottom of the plots, the second criterion, ion-ion mean free path, and the fifth criterion, Reynolds number, rule out low-density flows. The mean-free-path constraint favors high density, low velocity conditions, because $\lambda_{MFP} \propto 1/n_i$ and $\lambda_{MFP} \propto u^4$. Reynolds number favors high velocity, high density conditions because $Re \propto u$ and $\nu_i \propto n_i$. At low temperatures, mean free path is more limiting, while
at high temperatures Reynolds number is more limiting. The mean-free-path trend is due to ionization. Higher ionization raises the collisional cross-section of the ions; larger cross section means more collisions. The Reynolds number trend is due to ionization and the direct effects of temperature itself; the ion viscosity is thermal velocity squared over ion-ion collisional frequency. Although ion-ion collisional frequency increases with increasing temperature, the thermal velocity dependence wins out and increasing temperature increases the viscosity, thus decreasing the Reynolds number.

Finally, the fourth criterion, ram plasma $\beta$, rules out both low-density, low-velocity flows due to the $\beta_{\text{ram}} > 0.1$ constraint, and high-velocity, high-density flows due to
The layout and color-coding are the same as Figure 2.8. The $\beta_{\text{ram}} < 10$ constraint. Of the two, the $\beta_{\text{ram}} < 10$ constraint is more limiting; in practice low-density, low-velocity flows are difficult to achieve on a laser. Because $\beta_{\text{ram}}$ has no temperature dependence, it does not change between Figures 2.8 and 2.9.

Taking all five constraints together, a 10-eV CH plasma, see Figure 2.8, would require $\rho \sim 10^{-5}$ g cm$^{-3}$ and $u \sim 100$ km s$^{-1}$, while a 30-eV CH plasma, see Figure 2.9, would require $\rho \sim 3 \times 10^{-6}$ g cm$^{-3}$ and $u \sim 150$ km s$^{-1}$.

Table 2.4 presents the plasma parameters and calculated length scales and dimensionless numbers for the astrophysical system and both experimental plasma options.

This completes Step 6, “Map the constraints into parameter space and find the volume where all of them are satisfied.” When the highest plausible magnetic field on OMEGA, 10 T, is imposed, the constraints are satisfied for a 10-eV CH plasma with $\rho \sim 10^{-5}$ g cm$^{-3}$ and $u \sim 100$ km s$^{-1}$, or a 30-eV CH plasma with $\rho \sim 3 \times 10^{-6}$ g cm$^{-3}$.
<table>
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<tr>
<th>Parameter</th>
<th>Unit</th>
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<th>10 eV</th>
<th>30 eV</th>
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<td>3.5</td>
<td>3.5</td>
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<td>3.5</td>
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<tr>
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<td>Reynolds number, Re</td>
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</tr>
</tbody>
</table>

Table 2.4: Comparing typical numbers in an accretion stream to two options for experimental jets.

and $u \sim 150$ km s$^{-1}$. If the incoming plasma jet has parameters in either of these ranges, or something in between, an experiment resembling Figure 2.5 will be well-scaled.
CHAPTER III

Collimated Jet Experiments

Chapter II related the process for scaling an astrophysical accretion shock to the laboratory and ended with two sets of plasma parameters, either of which would yield a well-scaled accretion shock experiment.

In April 2012, our collaboration dedicated a day of experiments on OMEGA to testing a method for creating collimated jets with plasma parameters similar to those determined in Chapter II.\(^1\) We conceived of a simple experiment: we would irradiate the rear side of thin cones of acrylic to launch collimated plasma jets and characterize them with optical Thomson scattering and 2-D visible light imaging. This chapter discusses those experiments, the results we obtained, and my analysis of the jet structure.

Section 3.1 discusses the motivation for developing collimated plasma jets and related jet work by other researchers. Section 3.2 delves into my analytical theory of how a conical target collimates the jet. Section 3.3 presents the experimental set-up, experimental parameters used, and discusses what data were obtained.

Section 3.5 presents the Thomson data and its analysis. Thomson scattering is a method for ascertaining parameters such as temperature and density of an experimental plasma by scattering a laser beam of known wavelength off the experimental

\(^1\) Chronologically, this work was completed before the accretion shock experiment was undertaken, but even in April 2012 our collaboration anticipated needing steady, collimated jets for more complex future experiments.
plasma and analyzing the scattered spectrum. We obtained density, temperature and velocity data from seven shots, two colliding jet and five single jet.

Section 3.4 presents the 2-D visible light images obtained; these self-emission images clearly show the jets, their collimation, and how they evolve when collided with each other.

Section 3.6 presents my conclusions.

3.1 Previous Work

Collimated plasma jets are an essential building block in more complicated experiments. One commonly used technique for creating a collimated jet is irradiating either side of a conical or V-shaped target. While plasma from a flat target will expand in all directions without encountering any opposing flow, plasma from a V-shaped or conical target will collide with the plasma flowing away from the opposite side of the target, creating a collimated plasma jet, see Figure 3.1.

![Image of plasma flows from flat vs. V-shaped or conical targets.](image)

Figure 3.1: Plasma flows from flat vs. V-shaped or conical targets. Unlike a plasma front emanating from a flat target (top), a V-shaped or conical target, produces a collimated plasma jet (bottom). The yellow represents the laser beams irradiating the rear side of the target, the gray represents the target (seen here in cross-section), and the pink represents the plasma created.

When a laser pulse hits a thin target, it immediately releases plasma on the
irradiated surface and drives a shock wave into the target. The shock wave heats the material as it passes through, vaporizing it and creating a hot, dense reservoir of plasma that expands in both directions. The surface the laser hit is known as the front surface; the opposite surface is known as the rear surface. The flow from the front surface is the hot, fast initial release followed by the slower, denser expanding rarefaction. However, when this surface is used to create jets (known as “front-surface” jets) is it usually the hot, fast initial flow that is of interest. Thus front-surface jets are typically hotter and faster than rear-surface jets. Table 3.1 presents the results of four other teams that used V-shaped or conical targets. One team, *Li et al.* (2013), had yet to publish when these experiments were designed, but is included here because it represents a medium-Z material.

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>Shigemori</th>
<th>Gregory</th>
<th>Li</th>
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<td>Front</td>
<td>Rear</td>
<td>Front</td>
</tr>
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<td>Al</td>
<td>CH</td>
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</tr>
<tr>
<td>Electron temperature, $T_e$</td>
<td>eV</td>
<td>250</td>
<td>200</td>
<td>10</td>
<td>750</td>
</tr>
<tr>
<td>Velocity, $v$</td>
<td>km s$^{-1}$</td>
<td>500</td>
<td>700</td>
<td>300</td>
<td>1700</td>
</tr>
</tbody>
</table>

Table 3.1: Results of V-shaped or conical experiments. Studies cited are *Farley et al.* (1999); *Shigemori et al.* (2000); *Gregory et al.* (2008); *Li et al.* (2013).

### 3.2 Theory

This section presents analytical calculations for the shape of the collimated jet that were done prior to the April 2012 experiment. The underlying assumption is that a stagnation shock forms. Outside the stagnation shock, the plasma flows perpendicular to the original surface of the target (that is, towards the axis of the cone); inside the shock, the radial flow is stagnated and the flow is entirely in the axial direction.

As illustrated in Figure 3.2, when the flow encounters the shock front, described by $r(z)$, its direction bends to be parallel to the axis. Locally, the incoming flow
approaches an oblique shock with some angle $\phi_1$ with respect to the surface normal, $\hat{n}$, and leaves the shock with angle $\phi_2$ with respect to $\hat{n}$. Some basic geometry yields $\phi_1 = \theta - \alpha$ and $\phi_2 = 90^\circ - \alpha$, where $\alpha$ is the local angle between the $z$-axis and the shock profile and $\theta$ is the opening half-angle of the cone.

Figure 3.2: Collimating shock profile diagram. When plasma encounters the shock profile, described by $r(z)$, it bends to become parallel to the $z$-axis. The diagram on the right is a zoomed-in view of the dotted line box in the diagram on the left.

From equation 4.33 of Drake (2006), the flow at the oblique shock front will bend according to,

$$\cot \alpha = \tan(\theta - \alpha) \frac{M_n^2(\gamma + 1)}{M_n^2(\gamma - 1) + 2},$$

(3.1)

where $M_n$ is the normal upstream Mach number, $M_n = M \cos(\theta - \alpha)$.

Solutions to Equation 3.1 are illustrated in Figure 3.3 for $\theta = 80^\circ$ and $\gamma = 1.5$. At low Mach numbers, there are no solutions to Equation 3.1. Physically, this is due to the assumption that $u_r = 0$ in the post-shock region; the shock is not strong enough to "bend" the flow all the way to the direction of the $z$-axis and the assumptions behind Equation 3.1 no longer hold. At some critical Mach number, $M_c$, there is exactly one solution and for $M > M_c$ there are two solutions. Of these two solutions, the lower branch is physical; a higher Mach number will produce a tighter jet. As $M \to \infty$, $cota = \tan(\theta - \alpha)(\gamma + 1)/(\gamma - 1)$, which has the solution $2.5^\circ$ for $\gamma = 1.5$ and $\theta = 80^\circ$.

There is one final assumption for this problem: the flow coming off the surface of the target (or more accurately, where the target was prior to the laser pulse) can be
described as a drifting rarefaction, that is, \( u = u_{\text{rare}} + u_{\text{drift}} \), where \( u \) is the velocity, \( u_{\text{rare}} \) is the velocity in the frame of reference of the plasma reservoir, and \( u_{\text{drift}} \) is a drift velocity. \( u_{\text{drift}} \) accounts for the added momentum the laser pulse imparts to the system; it is the velocity of the plasma reservoir with respect to the lab.

I found \( r(z) \) using an iterative scheme in Mathematica:

1. Assume some shock profile, \( r_i(z) \). This could in principle be any profile, but for simplicity I used a straight line with an opening half-angle of \( \theta/2 \).

2. For every point along \( r_i(z) \), calculate its distance from the target wall, \( x_i(z) \). Calculate the Mach number, \( M_i(z) \), based on analytic models of rarefactions.

3. Having \( M_i(z) \), calculate the bending angle along the shock profile, \( \alpha_i(z) \).

4. Use \( \alpha_i(z) \) to construct a more refined shock profile, \( r_{i+1}(z) \).

5. Repeat Steps 1–4 until \( r_n(z) \) converges.

The Mach number will be a function of distance from the original target surface and time. For an isothermal rarefaction with a drift velocity, \( u_d \), Mach number is

\[
M_{\text{iso}}(x, t) = 1 + \frac{x}{c_s t} + \frac{u_d}{c_s}, \tag{3.2}
\]
where \( c_s \) is the speed of sound. For an adiabatic rarefaction with a drift velocity, \( u_d \), Mach number is

\[
M_{ad}(x, t) = \frac{2}{\gamma + 1} \left( c_o + \frac{x}{t} \right) + u_d
\]

\[
c_o - \frac{\gamma - 1}{2} \frac{x}{t}
\]

(3.3)

where \( c_o \) is the speed of sound in the original reservoir. Figure 3.4 compares shock profiles, \( r(z) \), created by comparable adiabatic and isothermal rarefactions. Because the adiabatic rarefaction cools as it expands, it has higher Mach numbers and creates a more collimated jet.

![Shock profiles](image)

Figure 3.4: Calculated collimating shock profiles for adiabatic and isothermal rarefactions. Blue represents the shock profile created by an adiabatic rarefaction with \( t = 30 \text{ ns} \), \( c_o = 40 \text{ km s}^{-1} \), and \( u_d = 20 \text{ km s}^{-1} \). Red represents the shock profile created by an isothermal rarefaction with \( t = 30 \text{ ns} \), \( c_s = 40 \text{ km s}^{-1} \), and \( u_d = 20 \text{ km s}^{-1} \).

This analysis rests on several simplifying assumptions: that the flow off the sides of the target was a perfect rarefaction (isothermal or adiabatic), that the reservoir of plasma that launched the rarefaction never ran out, and that the flow stagnated completely inside the shock structure. The reality will inevitably be more complicated, but the analysis of this chapter underscores the validity of using conical targets to create a collimated jet.
3.3 Experiment

In April 2012, our experimental team devoted a day of shots to launching jets by irradiating thin cones similar to those sketched in Figure 3.1. We chose to use Poly(methyl methacrylate) or PMMA ($C_5H_8O_2$), hereafter referred to simply as acrylic, to create the jets. Acrylic is a moderate $Z$-number material that is non-toxic and lends itself to micro-machining. Using acrylic allowed us to have the targets machined in-house at the University of Michigan, which provided flexibility during the shot planning process.

As discussed in Section 3.1, if a thin target is irradiated, the resulting rarefaction from either the front or the rear side may be used. Front-side jets tend to be hotter, faster and shorter-lived, while rear-side jets are colder, slower and longer-lived. We chose rear-side irradiation because we anticipated needing long-lived jets for experiments lasting 10’s of nanoseconds. The experimental scheme is seen in Figure 3.5. Two cones 6 mm apart, and each 3 mm from target chamber center, were rear-irradiated, launching collimated jets. These jets could each be launched individually or they could be launched together to form a head-on collision; all three possibilities were shot multiple times.

![Experimental configuration from April 2012.](image)

The primary diagnostic used was $2\omega$ (526.5 nm) Thomson scattering aimed at the
Thomson scattering is a technique for measuring plasma parameters such as density and temperature by scattering a probe laser beam at the experimental plasma and collecting and analyzing the scattered spectrum. As a secondary diagnostic, we recorded self-emission images of our jets with a 2-D visible light imager. The imager was gated to 3 ns (the shortest possible gating time) and filtered with a $3\omega$ long pass filter, which blocks wavelengths shorter than 385 nm, and a 1.0 neutral density filter. Both of these diagnostics are discussed in detail in Appendix A.

Table B.1 lists the experimental parameters for the collimated jet experiment. Figure 3.6 shows renderings of the experiment done with a CAD program. Targets were machined out of solid acrylic; the bulk of the mass of the target served to anchor the stalk (seen in red in Figure 3.6) and to support the thin cone.

<table>
<thead>
<tr>
<th><strong>Target</strong></th>
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</thead>
<tbody>
<tr>
<td>Material</td>
<td>PMMA $C_5H_8O_2$</td>
</tr>
<tr>
<td>Solid density</td>
<td>1.18 g cm$^{-3}$</td>
</tr>
<tr>
<td>Cone opening angle</td>
<td>160°</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Cone thickness</td>
<td>100 µm</td>
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<tr>
<td>Distance to TCC</td>
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<table>
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<tr>
<th><strong>Drive Beams</strong></th>
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<tr>
<td>Drive beam wavelength</td>
<td>351 nm ($3\omega$)</td>
</tr>
<tr>
<td>Number beams</td>
<td>7 per cone</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>3150 J</td>
</tr>
<tr>
<td>Drive beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>Drive beam radius</td>
<td>352 µm (SG4)</td>
</tr>
<tr>
<td>Drive irradiance</td>
<td>$8 \times 10^{14}$ W cm$^{-2}$</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>$2\omega$ Thomson beam</strong></th>
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</tr>
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<tbody>
<tr>
<td>Wavelength</td>
<td>526.5 nm</td>
</tr>
<tr>
<td>Energy</td>
<td>120 J</td>
</tr>
<tr>
<td>Shape</td>
<td>3 ns, square</td>
</tr>
<tr>
<td>Radius</td>
<td>70 µm (best focus)</td>
</tr>
<tr>
<td>Angle between probe and collector</td>
<td>116.8°</td>
</tr>
</tbody>
</table>

Table 3.2: Experimental parameters for April 2012.
Figure 3.6: CAD renderings of the targets from April 2012 as seen from the point-of-view of the 2-D imager.
3.4 2-D Image Results and Analysis

Out of nine shots, we gained clear images of single jets on two shots and of colliding jets on three shots. For the remaining four shots, the jet was moving away from the imager and the target itself blocked the view. From a technical standpoint, these images were successful (they are in focus), but they contain nothing useful; they can be seen in Appendix C, which contains all of the data from this shot day. The visible light images prove that we were successful in creating collimated jets and that these jets formed well-defined shock structures when collided head-on.

The emission seen in the visible light images is free-free self-emission, or bremsstrahlung, wherein a free electron passes a free ion and has its path diverted. The electron loses kinetic energy in this encounter and to conserve overall energy a photon is emitted.

When this experiment was designed, the jets were expected to have a temperature of \( \sim 10 \, \text{eV} \), which would make their blackbody spectra peak around 25 nm. In the colliding jet configuration, the shocked material would have a temperature of \( \sim 80 \, \text{eV} \) and a blackbody peak of 3 nm. Despite these radiation peaks being in the far ultraviolet and soft x-ray, respectively, we chose to image the experiment in the optical. Systems for magnifying and focusing images in the optical are vastly easier to build than similar systems for x-rays and resultantly OMEGA has an optical light imaging system.

3.4.1 Single Jets

Figure 3.7 shows the two successful single-jet images as well as Computer Aided Design (CAD) renderings of the target for reference.

In Figure 3.7, single jets are visible emerging from the counterbore. Some of the features seen in the visible light images in Figure 3.7 are edges of the target: the inner edge of the counterbore is glowing, as well as the surface of the target facing
the jet. Although we were interested in the rear-surface rarefaction, when a target is irradiated it completely vaporizes and rarefactions expand from both of its surfaces. Thus, this experiment produced both a rear-surface rarefaction, which was responsible for the collimated jet, and a front-surface rarefaction, which appears in the image as an indistinct background halo.

Figure 3.7 shows well-collimated jets. In the images, the edge of the jet appears brightest. This agrees with the analysis of Section 3.2, which shows that a surrounding shock structure collimates the jet. Figure 3.7 also shows the tip of the jet broadening between 20 ns and 25 ns. This could be the tip of the jet escaping the region where the collimation effects of the cone are still felt and beginning to broaden. I estimate that at their widest, the jets seen in Figure 3.7 were roughly 1 mm in diameter.
3.4.2 Colliding Jets

Figure 3.8 shows colliding-jet images. Figure 3.7 (single jets) is useful for orientation here. Both targets are used in the colliding jet shots, the target used in Figure 3.7, and an additional target is placed in opposition to it. The glow in the foreground is coming off the near side of the near target. This is the front surface irradiation discussed above; with the near target involved in the experiment, it is visible. The laser spot is marked in the CAD rendering in Figure 3.8. Behind that the sides of the near target are dark, and behind one can see the jet from the near target emerging (moving away from the viewer) and the jet from the far target coming to meet it.

![Figure 3.8: Colliding jet self-emission images from April 2012. Above and bottom left: Self-emission images of colliding jet shots at 20 ns, 25 ns, and 30 ns after drive. A bright, shocked region is visible that grows with time. Bottom right: CAD renderings of both targets together.](image)

In the 20 ns image, there is a bright area of shocked plasma where the jets meet.
Unfortunately, we did not take an earlier image, so there is no way to know how early this shock forms. However, judging from how quickly the shocked region appears to grow in the 25 ns and 30 ns images, the shock cannot have been there long in the 20 ns image. This suggests the leading edge of the material forming the shock is moving somewhat faster than \(3 \text{ mm}/20 \text{ ns} \sim 150 \text{ km s}^{-1}\).

### 3.5 Thomson Scattering Results

#### 3.5.1 Velocity, Temperature and Density Data

Streaked \(2\omega\ (526.5 \text{ nm})\) Thomson scattering, the method employed here, uses a long probe pulse, in our case 3 ns. We staggered the timing of the Thomson probe beam between shots to gain data over extended amount of time. Firing the probe beam from 7 ns to 10 ns did not return any scattered spectra; if any plasma had reached 3 mm at that time, it was not dense enough to scatter the probe beam. Good data was obtained from 12 ns to 15 ns and from 15 ns to 18 ns. We conducted one shot from 20 ns to 23 ns, but the probe beam reflected uselessly off the plasma, a sign that density was approaching the critical density (see Appendix A).

Figures A.8 and A.9 show examples of scattered Thomson spectra extracted from a single-jet experiment 13.5 ns after drive. Both the Electron Plasma Wave or EPW, and the Ion Acoustic Wave, or IAW, are driven by electron density fluctuations. The EPW is the case where the ions are stationary and the electron oscillate; the IAW is the case where the ions oscillate and thereby force the electrons to oscillate as well, see Appendix A for a complete derivation.

The EPW data, seen in Figure A.8, show the intensity falling to zero in between the two peaks. This is artificial; the EPW set-up uses a beam blocker to block wavelengths around the probe beam (526.5 nm).

Every experimental spectrum obtained was hand fit using the spectrum generator
Figure 3.9: Fitting EPW data. Single jet spectrum taken 13.5 ns after drive. Above: the full spectrum with three potential $T_e$ values (left) and zoomed view of the higher peak (right). Below: the full spectrum with three potential $n_e$ values (left) and zoomed view of the higher peak (right). This spectrum (taken 13.5 ns after drive) had the best fit with $T_e = 110$ eV and $n_e = 1.6 \times 10^{18}$.

included in Froula et al. (2011), which is explained in detail in Appendix A. The spectrum generator uses electron number density, $n_e$, electron temperature, $T_e$, ion temperature, $T_i$, and velocity, $v_a$, as inputs and these are varied until a close fit is obtained, see Figures A.8 and A.9. The electron plasma wave spectrum is used to determine $n_e$ and $T_e$, while the ion acoustic wave spectrum is used to determine $v_a$ and $T_i$. As seen in Figure A.9, the IAW spectra were not clear enough to distinguish between different values of $T_i$; therefore data for $T_i$ are not included here.
Figure 3.10: Fitting IAW data. Many IAW appeared to have erroneous peaks due to reflected light, but velocity data could still be obtained by fitting the Doppler shift. Left: the IAW data corresponding to Figure A.8. Right: One of the clearest examples of a IAW data we obtained.
Figure 3.11 presents electron density, electron temperature, velocity, and mass density data for the five single jet shots for which Thomson scattering was successful. The error bars for $n_e$, $T_e$, and $v_o$ seen in Figure 3.11 were customized for each individual time-specific spectrum; they represent the limits of passable fitting as shown for example in Figures A.8 and A.9.

Of the four parameters shown in Figure 3.11, the first three were directly obtained from the Thomson data, but the fourth, mass density, was calculated according to

$$\rho = n_i A m_p = \frac{n_e A m_p}{Z(T_e)},$$

where $A$ is the average ion mass in proton masses, $m_p$ is the proton mass, and $Z$ is the average ionization. Average ionization is a function of temperature and was obtained by solving the Saha equation (Drake, 2006)

$$Z_{\text{bal}} = \sqrt{\frac{k_B T_e}{E_H}} \ln \left[ \frac{1}{n_e 4 g_k a_o^3} \left( \frac{k_B T_e}{\pi E_H} \right)^{3/2} \right] - \frac{1}{2},$$

where $Z_{\text{bal}}$ is the average ionization assuming recombination balance, $k_B$ is the Boltzmann constant, $E_H$ is the hydrogen ionization energy, $g_j$ and $g_k$ are the statistical weighting factors for states $j$ and $k$ (we assumed $g_j = g_k$), and $a_o$ is the Bohr radius. Since our temperatures are already in energy units, we have

$$Z_{\text{bal}} = \sqrt{\frac{[T_e \text{ eV}]}{13.6}} \ln \left[ \frac{1}{4 n_e a_o^3} \left( \frac{[T_e \text{ eV}]}{13.6 \pi} \right)^{3/2} \right] - \frac{1}{2}.$$  

As seen in Figure 3.11, electron number density ranges from $10^{17}$ cm$^{-3}$ to $10^{19}$ cm$^{-3}$; electron temperature ranges from 50 eV to 400 eV; velocity ranges from 300 km s$^{-1}$ to 100 km s$^{-1}$, and mass density ranges from $10^{-6.5}$ g cm$^{-3}$ to $10^{-4}$ g cm$^{-3}$. 

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Figure 3.11: Thomson data from April 2012. Electron density and electron temperature increase with time, while velocity decreases. The electron density and temperature numbers are corrupted by probe heating but mass density derived from them ought to be accurate.
3.5.2 Probe Heating

The measured electron temperatures seemed implausibly high—generally temperatures of rear-surface ablations are on the order of 10 eV (Gregory et al., 2008). Froula et al. (2011) estimates the increase in plasma temperature due to heating from the Thomson probe beam as

$$\frac{\Delta T_e}{T_e} \simeq 1.28 \times 10^5 \frac{n_i \ln \Lambda}{\omega_{pe}^2 A [T_e]^{5/2}} \int_0^\tau P_i dt, \quad (3.7)$$

where $\ln \Lambda$ is Coulomb lambda, $A$ is the mean ion mass in $m_p$, and $\int_0^\tau P_i dt$ is the incident power integrated over the pulse length. All quantities in Eq. 3.7 are in CGS units except $T_e$, which is in eV. See Appendix A for more background on Equation 3.7.

When the plasma parameters from Shot 65770 (the example given in Figures A.8 and A.9) are used in Equation 3.7, the probe heating is estimated as $\Delta T_e/T_e = 8.7$. Moreover, if the original (unheated) $T_e$ were much lower, perhaps $\sim 15$ eV, then Equation 3.7 would yield $\Delta T_e/T_e = 1300$.

To further investigate the effect of probe heating, I built a simple model, assuming that a plasma with electron density $n_e$ is irradiated by a laser beam with incident wavelength $\lambda_i$, incident frequency $\omega_i$, total energy $E_{beam}$, laser pulse time length $\tau$, and laser beam diameter $D$. After some distance $d$, the original intensity, $I_o$, will be reduced according to

$$I = I_o e^{-\kappa_{EM} d}, \quad (3.8)$$

where $\kappa_{EM}$ is the spatial rate of absorption of laser energy (Drake, 2006),

$$\kappa_{EM} = \nu_{ie} \frac{\omega_{pe}^2}{c \omega_i^2} \frac{1}{\sqrt{1 - n_e/n_c}}, \quad (3.9)$$

where $\nu_{ie}$ is the ion-electron collisional frequency, $\omega_{pe}$ is the electron plasma frequency,
\( \omega_i \) is the frequency of the incident probe beam, and \( n_c \) is the critical density of the plasma. The ion-electron collisional frequency is

\[
\nu_{ie} = 3 \times 10^{-6} n_e \frac{\ln \Lambda Z}{T_e^{3/2}} \, \text{s}^{-1},
\]

(3.10)

where \( \ln \Lambda \) is the Coulomb logarithm, and all quantities are in CGS except \( T_e \), which is in eV (Drake, 2006). The electron plasma frequency, taken from the Plasma Formulary (Huba et al., 2009), is

\[
\omega_{pe} = 5.64 \times 10^4 n_e^{1/2} \, \text{rad s}^{-1}.
\]

(3.11)

The critical density is the electron density at which the electron plasma frequency is equal to the incident laser frequency, \( n_c = 1.1 \times 10^{21}/\lambda \mu \text{cm}^{-3} \), where \( \lambda \mu \) is the incident laser wavelength in microns.

For average plasma conditions, \( n_e = 10^{18} \, \text{cm}^{-3} \) and \( T_e = 15 \, \text{eV} \), the fraction of energy absorbed is low,

\[
\frac{I}{I_o} = e^{-\kappa_{EM}(1 \text{cm})} = 0.9913.
\]

(3.12)

Taking a Taylor expansion, the incident laser energy absorbed by the plasma over length \( d \) is \( E_{ab} \approx \kappa_{EM} d E_{beam}/\tau \).

In the case of the probe heating problem, energy is also lost at the edges of the volume heated by the probe beam due to electron heat flux. Using the free-streaming heat flux model found in Drake (2006), which assumes that energy is carried away at the electron thermal velocity, \( v_{th} \),

\[
Q_{FS} = f_e n_e T_e v_{th},
\]

(3.13)

where \( Q_{FS} \) has units of energy per area per time, and \( T_e \), once again, is in energy units. The factor \( f_e \) is known as the flux-limiter and is usually on the order of 0.1.
Consider some cylinder of plasma with diameter $D$, defined by the focus of the probe beam, and an arbitrary length $d$. In a steady state, energy rate in is equal to energy rate out.

$$\kappa_{EM} d \frac{E_{\text{beam}}}{\tau} = f_e n_e T_e v_{th} \pi D d,$$

assuming that energy flows out of the cylinder across its sides ($A = \pi D d$) but not across its top or bottom. Figure 3.12 shows the left (red) and right (blue) hand sides of Equation 3.14 plotted for a 527-nm, 3-ns, 120-J probe incident on a plasma with $n_e = 10^{18}$ cm$^{-3}$. As seen in Figure 3.12, Equation 3.14 has a solution at $T_e = 109$ eV.

I solved Equation 3.14 numerically over a range of inputs, fit the solution, and found that the steady-state temperature the plasma reaches can be estimated by

$$T [\text{eV}] \approx 145 \left( \frac{E [\text{J}] n_e [10^{18} \text{ cm}^{-3}]}{\tau [\text{ns}] D [\mu\text{m}]} \right)^{0.345},$$

where $T$ is the temperature, $E$ is the energy of the probe beam, $n_e$ is the electron number density, $\tau$ is the time length of the probe beam and $D$ is the diameter of
the probe beam. Substituting the values of this problem, \( E = 120 \text{ J} \), \( \tau = 3 \text{ ns} \), and \( D = 60 \mu \text{m} \), I found

\[
TeV \approx 126 (n_e [10^{18} \text{ cm}^{-3}])^{0.345}.
\] (3.16)

Figure 3.13 compares the electron temperatures predicted by 3.16 (a function of electron density) and the electron temperatures taken directly from the Thomson data. The dashed line indicates perfect agreement between expected temperatures found with 3.16 and the Thomson-measured temperatures. In general, there seems to be agreement. The simple model in Equation 3.14 predicts the measured temperatures reasonably well. This substantiated the contention that the measured temperature data are the result of probe heating; they do not reflect the plasma conditions before the probe turned on.

![Figure 3.13: Probe heating model predictions vs. measurements. Measured \( T_e \) (from Thomson data) agree with temperatures predicted by the probe heating model, Equation 3.16.](image)

3.5.3 Isothermal Rarefactions

A great deal of physical understanding can be gleaned from the mass density data in Figure 3.11. By comparing the data to analytical expressions for rarefactions, I
was able to determine that the jets were behaving as isothermal rarefactions and infer their temperature.

A rarefaction forms when a reservoir of material with some initial density and pressure is released and allowed to expand freely. The material may either cool adiabatically as it expands or it may maintain some constant temperature. If it cools adiabatically, then its density and velocity can be written as

\[ \rho(x, t) = \rho_0 \left( \frac{2}{\gamma + 1} - \frac{\gamma - 1}{\gamma + 1} \frac{x}{c_o t} \right), \text{ and} \]

\[ u(x, t) = \frac{2}{\gamma + 1} \left( c_o + \frac{x}{t} \right), \]

where \( \rho_0 \) is the initial density in the pre-expansion plasma, \( x \) is the distance from the boundary of the initial reservoir, \( c_o \) is the speed of sound in the initial reservoir, and \( \gamma \) is the adiabatic index (Drake, 2006). The speed of sound is taken from Huba et al. (2009),

\[ c_s = 9.79 \times 10^5 \sqrt{\frac{\gamma (Z + 1) T_e}{A}} \text{ cm s}^{-1}. \]

If, rather than cooling adiabatically as it expands, the rarefaction maintains a constant temperature, it is isothermal and its density and velocity can be written as

\[ \rho(x, t) = \rho_o e^{-\left(1 + \frac{x}{c_s t}\right)}, \text{ and} \]

\[ u(x, t) = c_s + \frac{x}{t}, \]

where \( \rho_o \), \( x \), and \( t \) are the same as in the isothermal case, and \( c_s \) is the speed of sound in the system (Drake, 2006).

Figures 3.14 and 3.15 compare the mass density and velocity data to analytic predictions for adiabatic and isothermal rarefactions, respectively. For both figures, \( \rho_o = 1.18 \text{ g cm}^{-3} \), the solid density of CH, and \( x = 3 \text{ mm} \), the distance between the
target and the Thomson probe beam. For the adiabatic case, I assumed $\gamma = 1.5$.

![Graph](image)

**Figure 3.14:** Adiabatic rarefactions compared to single jet Thomson data. Density (left) and velocity (right) of adiabatic rarefaction with initial reservoir temperatures of 28 eV, 35 eV and 42 eV. Regardless of the choice of $T_o$, an adiabatic mass density profile does not match the data.

As seen in Figure 3.14, the basic shape of the adiabatic mass density profile does not match the data and varying the initial temperature does not salvage the situation. The isothermal case, seen in Figure 3.15, is good match. Moreover, because the isothermal density profile is highly sensitive to temperature, I was able to infer the temperature of the jets: $6 \pm 1$ eV. This is far more reasonable than the previously obtained values of 50 to 400 eV; Gregory et al. (2008) measured temperatures of 10 eV for their rear-irradiation-launched aluminum jets.

(I should note, however, that our choice of $\rho_o$ impacts the inferred temperature. If we assume that $\rho_o$ is $10\rho_{CH}$, then the inferred temperature falls from 6 eV to 4.5 eV.)

Velocity profiles, as seen in Figures 3.14 and 3.15, do not change much between the adiabatic and isothermal cases. Neither are they particularly sensitive to temperature. The data show a faster decline in velocity than either the adiabatic or isothermal expression; this is expected of rarefactions expanding into imperfect vacuums.

The isothermal behavior of the jets seems reasonable in light of the electron heat conduction timescale. Drake (2011) shows that when $t_{\text{equil}}/t_{\text{exp}}$ remains small, where
$t_{\text{equil}}$ is the electron heat conduction timescale and $t_{\text{exp}}$ is the experimental timescale, a rarefaction will be isothermal. As conditions approach $t_{\text{equil}} \approx t_{\text{exp}}$, the rarefaction will transition to adiabatic expansion.

Following Drake (2011), the electron heat conduction timescale, $t_{\text{equil}}$, may be found by applying unit analysis to the heat conduction equation, yielding

$$
t_{\text{equil}} = \frac{\rho C_v L^2}{\kappa}, \quad (3.22)
$$

where $C_v$ is the specific heat at constant volume, $C_v = (1 + Z)k_B/(Am_p)$, $L$ is the characteristic length scale, and $\kappa$ is the heat conduction coefficient. The heat conduction coefficient is defined by

$$
\kappa = \frac{128 \, n_e k_B T_e}{3\pi \, m_e \nu_{ei} k_B}, \quad (3.23)
$$

where $\nu_{ei}$ is the electron-ion collision rate, defined as

$$
\nu_{ei} = 3 \times 10^{-6} \ln \Lambda \frac{n_e Z}{T_e^{3/2}} \, \text{s}^{-1}, \quad (3.24)
$$
where $\ln \Lambda$ is the Coulomb logarithm and $T_e$ is in eV. Thus, the heat conduction equilibrium timescale is defined by the density, temperature, material and length scale. Table 3.3 shows the equilibrium timescale calculated for a range of $L$ from 0.1 mm to 1 mm and a range of $\rho$ from $10^{-7}$ to $10^{-4}$ g cm$^{-3}$.

<table>
<thead>
<tr>
<th>$\rho$ [g cm$^{-3}$]</th>
<th>$10^{-7}$</th>
<th>$10^{-6}$</th>
<th>$10^{-5}$</th>
<th>$10^{-4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$ [mm] ↓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>0.04</td>
<td>0.3</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>0.3</td>
<td>0.9</td>
<td>8</td>
<td>60</td>
<td>500</td>
</tr>
<tr>
<td>1.0</td>
<td>4</td>
<td>30</td>
<td>300</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 3.3: Heat conduction equilibrium timescales, $t_{\text{equil}}$, in nanoseconds, for ranges of density and length scale for a CH plasma at 6 eV.

From Table 3.3, $t_{\text{equil}} < 10$ ns for low densities and short length scales. Therefore isothermal behavior would be expected at early times, which was the case for this shot day. It would be beneficial to study jets such as these at later times to see if the isothermal behavior endures, but this was precluded on shot day because we reached the density limit of 2$\omega$ Thomson scattering.

### 3.6 Conclusion

The April 2012 shot day was my first day of experiments at OMEGA. Our collaboration was successful in creating collimated plasma jets by rear-irradiating 100 $\mu$m-thick CH conical targets. We found the following, which would prove useful in developing the accretion shock experiment later:

1. Both single-jet experiments and colliding-jet experiments show clear signs of collimation in 2D self-emission images.

2. Colliding-jet images show a shock forming between them. This shock was evident in our earliest image (20 ns after drive) and appears to grow with time.
3. Thomson scattering data were corrupted by probe heating, but velocity data were unaffected and mass density data (derived from electron density and temperature) are still accurate.

4. The mass density profile matches that of an isothermal rarefaction with $T_e = 6 \pm 1\text{ eV}$, giving an alternate approach to temperature measurement in light of our difficulties with probe heating.
CHAPTER IV

Accretion Shock Experiments

Chapter II introduced the scaled accretion shock experiment and concluded that it would be well-scaled if a 10-T field were imposed on a 10-eV CH plasma with \( \rho \sim 10^{-5} \text{ g cm}^{-3} \) and \( u \sim 100 \text{ km s}^{-1} \), or if a 30-eV CH plasma with \( \rho \sim 3 \times 10^{-6} \text{ g cm}^{-3} \) and \( u \sim 150 \text{ km s}^{-1} \).

Chapter III presented experiments done to characterize collimated jets made by rear-irradiating thin acrylic cones. It concluded that the jets were behaving like 6-eV isothermal rarefactions with \( \rho \sim 10^{-6.5} - 10^{-4.5} \text{ g cm}^{-3} \) and \( u \sim 100 - 250 \text{ km s}^{-1} \).

This chapter presents the results of the accretion shock experiment, which used jets similar to those developed in Chapter III to accomplish the experimental concept articulated in Chapter II. Section 4.1 presents the experimental set-up. To translate this system into a laboratory experiment, I designed an experiment with an incoming plasma jet (the “accreting flow”), an impact surface for it to collide with (the “stellar surface”) and a surrounding magnetic field which ran parallel to the jet velocity and perpendicular to the impact surface.

This experiment used two primary diagnostics: 2-D visible light imaging (the technique employed successfully for the collimated-jet experiments in Chapter III) and proton radiography. Section 4.2 presents the visible light data of the accretion shock experiment. The data show a jet clearly emerging, meeting the impact surface.
and creating a bright shock structure.

Section 4.3 puts the accretion shock visible light data into context by comparing it to the collimated jet visible light data from Chapter III. The experiments are similar; the collimated jets collided head-on with each other, while the accretion shock jet collides with a wall.

Section 4.4 revisits the scaling argument made in Chapter II, and Section 4.5 presents my conclusions.

Unfortunately, while proton radiography was intended to be a primary diagnostic, we encountered repeated difficulties with it and were never able to obtain conclusive data. This is discussed in full in Chapter V.

### 4.1 Experimental Set-up

To scale an accretion shock to a laboratory experiment requires both reproducing the basic elements of the astrophysical system and tailoring the plasma parameters to preserve its physics. Scaling concerns for the actual experiment, as opposed to the ideal experiments presented in Chapter II, are discussed in Section 4.4. This section discusses the configuration of the experiment, which required an incoming plasma jet (the “accreting flow”), an impact surface (the “stellar surface”) for it to collide with, and a surrounding magnetic field which ran parallel to the jet velocity and perpendicular to the impact surface, see Figure 4.1.

As seen in Figure 4.2, rear irradiation launches a single plasma jet, which travels “down” to collide with the impact surface “below.” (Because the experiment lasts less than 100 nanoseconds, gravity does not play a significant role; in the target chamber it does not matter which way is literally down. I have used the terms “down” and “below” to emphasize the connection to the astrophysical system of Figure 4.1.) The experiment is suspended inside two MIFEDS current coils. Beginning before the shot is fired, the high-voltage MIFEDS capacitors discharge through the wire loops, shown
Figure 4.1: Translating the astrophysical system to the lab. This requires a plasma flow, magnetic field and impact surface.

in 4.2 in cross-section. See Appendix A for more information on MIFEDS.

Figure 4.2: Schematic for the accretion shock experiment.

The accretion shock target, seen in Figure 4.3, was entirely constructed from acrylic and was micro-machined in-house at the University of Michigan, like the collimated-jet targets from Chapter III. The target was made in two pieces: a large acrylic block with two walls protruding from it on one end and an acrylic “roof,” with a thin cone machined into it, that rested on the walls.

The two primary diagnostics for this experiment were visible light imaging and proton radiography. We failed to obtain conclusive data for proton radiography; Chapter V or Appendix B discusses this in full.
Figure 4.3: Engineering rendering and photograph of the accretion shock target. Both the drawing and the photo are of 2014 targets; it lacks the fiducial that was added for the 2015 shot days.

Figure 4.4 shows CAD renderings of the accretion shock targets in the target chamber and it highlights one of the fundamental difficulties of imaging this experiment. The target must be maneuvered inside the current coils and behind the proton backlighter and its associated shield, which protects the imaging system from the backlighter blast. Thus there at least three things potentially standing between the experiment and the imager: the coils, the backlighter, and shield protecting the backlighter. The experiment is designed to give the imager a clear line of sight, but if any of these things shift unexpectedly data could be lost.

Table 4.1 provides a summary of experimental parameters. As seen in Table 4.1, the accretion shock experiment was done with either one or seven drive beams launching the plasma jet. For the 2014 shot day, we used seven beams consistent with the collimated jet work of Chapter III. For the 2015 shot days, we dropped down to one drive beam in an attempt to reduce the density and velocity of the incoming jet and thereby improve the scaling of the experiment. The ramifications of this are discussed in Section 4.4.
4.2 Visible Light Data

Figure 4.5 shows all the visible light data from the accretion shock experiment. These images were taken using the 2-D imager that performed so well for the collimated jet work of Chapter III). As with the collimated jet images, the system was gated to 3 ns and a long pass filter was used to block the drive beam frequency ($\lambda < 385 \text{ nm}$) along with one or more neutral density filters. Appendix A contains more detail on the visible light imager and Appendix B lists the filtering for each shot.

Shots 77250 and 77251 were used to get filtering right. Shot 77254 was a control and Shot 77255 was the first good experimental data. After Shot 77255, we decided to reduce the laser intensity by dropping from seven beams to one in order to reduce the density and velocity of the incoming jet.

The top two rows (Shots 77250 to 77259) had MIFEDS inserted into the chamber to impose a magnetic field, while the bottom row did not. The effect of MIFEDS on the visible light images is easiest to see by observing 77254, a control shot for
<table>
<thead>
<tr>
<th>Target</th>
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</tr>
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<tbody>
<tr>
<td>Material</td>
<td>PMMA</td>
</tr>
<tr>
<td>Solid density</td>
<td>1.18 g cm$^{-3}$</td>
</tr>
<tr>
<td>Cone opening angle</td>
<td>160°</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Cone thickness</td>
<td>100 µm</td>
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<table>
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<tr>
<td>Drive beam wavelength</td>
<td>351 nm (3ω)</td>
</tr>
<tr>
<td>Number beams</td>
<td>7 or 1</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>3150 J or 450 J</td>
</tr>
<tr>
<td>Drive beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>Drive beam radius</td>
<td>352 µm (SG4)</td>
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</tbody>
</table>

<table>
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<tbody>
<tr>
<td>BL beam wavelength</td>
<td>351 nm (3ω)</td>
</tr>
<tr>
<td>Number beams</td>
<td>15 (2014) or 18 (2015)</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>6750 (2014) or 8100 (2015) J</td>
</tr>
<tr>
<td>BL beam shape</td>
<td>1 ns, square</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MIFEDS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of field</td>
<td>Parallel</td>
</tr>
<tr>
<td>Max field strength</td>
<td>7 T</td>
</tr>
</tbody>
</table>

Table 4.1: Experimental parameters for the accretion shock experiments. The makeup shots in October 2015 shots were the same as the May 2014 and May 2015 experiments, except the MIFEDS and proton backlighting were dropped. Appendix B gives a complete synopsis of this.

which the drive beam(s) were not fired. Ideally, 77254 would be completely dark and neither MIFEDS nor proton radiography would produce light to interfere with the experimental image. Instead, the image for Shot 77254 shows glowing shapes above and below the experimental region—either the MIFEDS coils are glowing or they are reflecting light from the proton backlighter. There is also a dark shape cutting across the top left corner; this is the stalk that supported the visible-light-system shield mentioned in Section 4.1. These glowing shapes above and below the experimental volume are seen on all of the other shots for which MIFEDS and proton radiography were used, Shots 77254 through 77259.

The best visible light data obtained were the two time-series of shots, with and without an imposed magnetic field. The magnetic-field shots (middle row of Figure
Figure 4.5: All visible light data from the accretion shock experiment. The top row shows initial shots used to establish experimental parameters such as number of drive beams and timing. The middle and bottom row each show a time series of shots either with a magnetic field (middle row) or without (bottom row).

Figure 4.5) and the no-field shots (bottom row of Figure 4.5), show some obvious differences because they were taken with slightly different configurations. The magnetic-field shots used MIFEDS, while the no-field shots did not. Thus, the no-field shots lack the glowing shapes above and below the experimental volume.
The fiducial, illustrated in Figure 4.2 and seen in the CAD renderings of Figure 4.4, is clearly visible in all three no-field shots, but is not evident in the magnetic-field shots. This is troubling; the experiment was designed such that the fiducial ought to have been visible with or without MIFEDS in use. Its disappearance suggests that the MIFEDS coils might have been squeezing together when the current was driven through them and thereby obscuring part of the experimental volume. This is plausible; MIFEDS wires are bent completely out of shape when the coil is fired, see Figure 4.6. Finally, the viewer will notice that Shot 79222 has a much crisper image than all of the other shots. Shot 79222 is a makeup shot from October 2015; no proton radiography was used and all the neutral density filters were removed, so the imager was able to capture more detail.

Figure 4.6: A typical MIFEDS coil before being fired (left) and after (right). This project used a similar design to the MIFEDS device pictured above; while the above device has a thin wall of plastic connecting the upper and lower coils, the accretion shock design did not. (Image credit: Sallee Klein)

Beyond the differences in experimental set-up between the magnetic-field and no-field shots, there is very little observably different between two time series. Both show a jet emerging from the top of the target at 23 ns (Shot 77256/77260), making contact with the impact surface at 43 ns (Shot 77258/79222), and forming a hot, bright region at 63 ns (Shot 77259/77262). Because of the MIFEDS distortion problem discussed above, we cannot see the bottom of the experimental volume in the magnetic field
Figure 4.7 shows intensity along the center line of two visible light images: Shot 79222, no field at 43 ns, and Shot 77262, no field at 63 ns. At 43 ns, the jet has reached the impact surface. The impact surface is glowing brightly, as seen in the intensity peak at $x = 3$ mm ($x = 0$ is the tip of the cone that launched the jet); this could be a shock just beginning to form or it could be the surface itself glowing after being heated by X-rays. The lineout at 63 ns, however, shows two clear zones of differing intensity, which split at $x = 1.8$ mm, where $x = 0$ mm is the original position of the target and $x = 3$ mm is the position of the impact surface. The discontinuity between the two zones is 0.2 mm wide, making the height measurement with error $x = 1.8 \pm 0.1$ mm. There is a bright zone near the impact surface, which I conclude is shocked material, and a less bright zone above it, which ought to be unshocked material.

### 4.3 Shock Evolution

Visible light imaging was used successfully for both the collimated jet campaign and the accretion shock campaign. This section compares the data from both campaigns to better understand the structure of incoming jets in the accretion shock experiment and the evolution of the shocks that formed in both experiments.

#### 4.3.1 Comparisons to Collimated Jets

In April 2012 our experimental team dedicated a day of shots to testing a method for creating collimated plasma jets: rear irradiation of a thin cone of PMMA. As presented in Chapter III, we launched these jets singly and in head-on collision configurations; the primary diagnostics were Thomson scattering and visible light imaging. Due to probe heating, the temperature data obtained were unreliable. However, I was able to create mass density profiles based on the Thomson data, which I used to determine that the jets were behaving as isothermal rarefactions with $T_e = 6 \pm 1$ eV.
As stated in Section 4.1, while we used seven drive beams for the collimated jet shots, we fell back to one drive beam for the second accretion shock shot day. Thus, most of the visible light data are for shots with only one drive beam. These one-beam jets were never probed with Thomson scattering, so their plasma properties must be determined via scaling laws, see Table 4.2. The dependence of temperature on direct laser irradiation intensity is $T_e \propto I_2^{2/3}$ (Drake, 2006), which would make the temperature of the one-beam jets $T_e = (1/7)^{2/3}(6 \pm 1 \text{ eV}) = 1.6 \pm 0.4 \text{ eV}$.

The dependence of ablation pressure on direct laser intensity is $P_{abl} \propto I_2^{2/3}$ (Drake, 2006). Since $P_{abl} \propto u^2$, this yields $u \propto I_1^{1/3}$. The 23–43–63 ns time series for 1-beam accretion shock experiments would correspond to a hypothetical 12–22–33 ns time...
Collimated Jets | Accretion Shock
---|---
Date | April 2012 | May/Oct 2015
Jets creation method | rear-irradiation, thin cone | rear-irradiation, thin cone
Cone thickness | 100 µm | 100 µm
Cone material | acrylic (PMMA) | acrylic (PMMA)
Drive beams | 7, full power | 1, full power
Configuration | collided head on | collided with solid surface
Distance to collision | 3 mm | 3 mm
Visible light imager | TPDI | TPDI
Thomson scattering used | yes | no
Jet behavior | isothermal | isothermal*
Jet temperature | 6 ± 1 eV | 1.6 ± 0.4 eV*

Table 4.2: Comparing the collimated jet experiments and the accretion shock experiments. *The 1-beam jets are assumed to be isothermal like the 7-beam jets and their temperature is inferred from $T_e \propto I^{2/3}$.

series for 7-beam colliding jet experiments. The actual time series taken the colliding jet experiments was 20–25–30 ns, but there is good correspondence between both time series as seen in Figure 4.8.

The earliest accretion shock image, 23 ns, is not equivalent to any of the colliding jet images. The second accretion shock image, 43 ns, would be equivalent to 22 ns and resembles the 20 ns colliding jet image. In both images, the jet(s) have just reached the impact surface/collision point. In the colliding jet image, the bright spot at the collision point is clearly a shock—there is nothing else for it to be. In the accretion shock image, it could be a nascent shock structure forming or it could be the impact surface itself glowing. If it is a shock, it has just formed. The final accretion shock image, 63 ns, would be equivalent to 33 ns for the 7-beam case and resembles the 30-ns colliding jet image. There is a bright volume of shocked material in both, although it is harder to see its outline clearly in the colliding jet work because those images were taken from an angle.
Figure 4.8: Comparing the collimated jet experiments (above) and the accretion shock experiments (below). These images have been rotated, cropped, and adjusted for brightness.
4.3.2 Shock formation timing

In Chapter II, I argued that a shock would become possible when the ion-ion mean free path, $\lambda_{\text{MFP}}$, became less than the scale length of the system, $L$. This visible light data of both the colliding jet experiments and the accretion shock experiments provide an opportunity to test that argument. Figure 4.9 shows region plots in $\rho-u$ space. The blue area is the region where $\lambda_{\text{MFP}} > L$ and a shock should not be able to form; the blank space is the area where $\lambda_{\text{MFP}} < L$ and a shock should be possible. The plots differ due to temperature because of ionization; all other things being equal, higher ionization lowers the MFP and a shock would be possible at lower density/higher velocity. The black points in Figure 4.9 show the trajectory of an isothermal rarefaction at the given temperature across $\rho-u$ space. As seen in Figure 4.9, the 6-eV rarefaction crosses into shock territory at 18 ns, while the 1.6-eV rarefaction crosses at 40 ns. This is in good agreement with the visible image data presented in 4.8.

![Figure 4.9: Isothermal rarefactions move from the $\lambda_{\text{MFP}} > L$ region into the $\lambda_{\text{MFP}} < L$ region with time.](image-url)
4.3.3 Shock growth

As seen the no-field series of shots, the scaled accretion shock begins growing around $\sim 40$ ns and reaches a height of 1.2 mm above above the impact surface by 63 ns. This suggests that the shock surface is rising by $\sim 50$ km s$^{-1}$. Is this reasonable?

Figure 4.10 illustrates two frames of reference for the experiment. In the laboratory frame, the incoming velocity is $u_{jet}$, the velocity downstream of the shock is zero, and the shock front is moving towards the incoming flow (“upward,” if the incoming flow is falling “down”) at $u_s$. This is necessary to fulfill the boundary condition at the surface of the block. In the shock frame, the incoming velocity is $u_1$, the shock is stationary, and the outgoing velocity is $u_2$. (In the shock frame, the block would have velocity $u_2$ as well.)

According to the strong shock limit (Drake, 2006),

$$u_2 = u_1 \frac{\gamma - 1}{\gamma + 1},$$

(4.1)

where $\gamma$ is the adiabatic index.

Therefore the laboratory frame is moving up at $u_1(\gamma - 1)/(\gamma + 1)$ relative to the shock frame. The downward velocity of the incoming jet is

$$u_{jet} = u_1 - u_1 \frac{\gamma - 1}{\gamma + 1} = u_1 \frac{2}{\gamma + 1}.$$  \hspace{1cm} (4.2)

The upward velocity of the shock is

$$u_s = u_1 \frac{\gamma - 1}{\gamma + 1} = u_{jet} \frac{\gamma - 1}{2}.$$  \hspace{1cm} (4.3)

So the rough $\sim 50$ km s$^{-1}$ upwards growth estimated above would be expected if $u_{jet} = 150$ km s$^{-1}$ and $\gamma = 5/3$, but that jet velocity is well above the velocity of an isothermal 1.6-eV jet over this time range, $u_{jet} = 60$–80 km s$^{-1}$. 

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Figure 4.10: The lab vs. the shock frame. In the lab frame, the block is stationary, while in the shock frame, the shock is.

A more precise calculation of shock column height does not solve the discrepancy between predicted and observed growth. I calculated the growth of the shock column by taking

\[ h_n = h_{n-1} + dtu_s(h_{n-1}, t_{n-1}) , \]  

(4.4)

where \( h_n \) is the height at time \( t_n \), \( dt \) is the time step, and \( u_s \) is a function of height and time,

\[ u_s(h, t) = \frac{\gamma - 1}{2} u_{iso}(0.3 \text{ mm} - h, t) , \]  

(4.5)

where \( u_{iso} \) is the velocity of an isothermal rarefaction.

Using this method I found that the shock column ought to grow to 0.5 mm between the shock forming at 39 ns and the final image being taken at 63 ns. Consistent with the rough growth estimated above, the measured height of 1.2 \( \pm \) 0.1 mm is roughly twice the predicted height. Why? It is possible that the intensity jump around \( x = 1.8 \pm 0.1 \text{ mm} \) is not a shock at all; the visible light images seen in Figure 4.7 show variation in emitted intensity, which does not necessarily translate to density. It it also possible that flows are coming off the walls of the target and squeezing the shock column and to make it taller than it would otherwise be; this is discussed in Chapter V.
because proton radiography data supports the presence of flows coming off the walls. A third possibility is that x-ray pre-heating of the solid impact surface produced yet another plasma rarefaction that expands upward. This rarefaction would collide with the incoming “accreting material” and contribute to the observed height of the “accretion shock column.”

4.4 Scaling Revisited

This section revisits the scaling arguments presented in Chapter II. In Chapter II, I argued that the experiment would be well-scaled if five dimensionless number criteria were met; these related to Mach number, ion-ion mean free path, magnetic diffusion length, ram plasma $\beta$, and Reynolds number. I constructed region plots showing the area where all five were simultaneously met for either a 10-eV CH plasma or a 30-eV CH plasma in an imposed magnetic field of 10 T.

But the experiment that was actually performed did not involve a 10-T field or a 10-eV or 30-eV plasma. The maximum field that we were able to impose was 7 T, and, as discussed in Section 4.3, for the visible light time series data, the incoming jets had $T_e = 1.6$ eV (one drive beams). Figures 4.11 shows criteria region plots for the 10-T, 10-eV experiment from Chapter II and Figure 4.12 shows the 7-T, 1.6-eV experiment that was performed, respectively.

Lowering the imposed field and the temperature of the flow has several effects on the criteria region plots. First, the yellow region (Mach number too low) is blank in the 1.6-eV plot. At $T_e = 1.6$ eV the entire plot region is acceptable; lower temperature yields a higher Mach number for a given velocity. Second, the blue region (mean free path too large) is larger in the 1.6-eV plot than the original 6-eV one. As temperature falls, ionization goes down and MFP will increase, so the area where MFP is too large with expand. Third, the allowed region where $\beta_{\text{ram}}$ is neither too low nor too high shifts toward lower left corner (low density, low velocity) because the magnetic field
strength has dropped. Together, these changes dramatically shrink the allowed region.
(The magnetic diffusion length and the Reynolds number plots seem little affected.)
Figure 4.11: Experimental criteria region plots for $T_e = 10$ eV and $B = 10$ T.

Figure 4.12: Experimental criteria region plots for $T_e = 1.6$ eV and $B = 7$ T.
So if the allowed region shrank, did that mean we were less likely to have a well-scaled experiment when only using one drive beam? Not necessarily. Figure 4.13 shows the trajectories of isothermal rarefactions across experimental criteria region plots. Conceptually, these plots are identical to Figure 4.9; here the individual constraint plots have been omitted and only the plots with all five constraints are shown. Although the 6-eV case has the largest allowable region in $\rho - u$ space, a 6-eV isothermal rarefaction does not come close to crossing it. The 1.6-eV isothermal rarefaction just touches the allowable region; it crosses directly from “ion-ion MFP too long to allow a shock” to “$\beta_{\text{ram}}$ too low.”

This explains the accretion shock visible light results: as soon as the experiment was able to create a shock, the flow was too dense for the field to affect it. As was seen in Figure 4.5, the magnetic field had no appreciable effect on the shock structures that are observable by visible light imaging.

![Figure 4.13: Comparisons of isothermal rarefaction trajectories across criteria region plots. For readability, region labels have been omitted but the color coding of Figure 4.11 and 4.12 applies here.](image)

Finally, for comparison’s sake I included a 1-eV case in Figure 4.13, although that does not correspond to any experiment shot. The 1-eV does indeed cross into the allowable space, but only stays there for about 5 ns.

This finding has serious implications for the entire field of magnetized flowing
plasma experiments. I devised my scaling requirements specifically for the accretion shock experiment, but any magnetized shock experiment would use both my $\lambda_{\text{MFP}} < L$ and my $0.1 < \beta_{\text{ram}} < 10$ constraints. The former is required to have a shock at all and the later is required to have a field strong enough to do something observable to that shock; these are very general requirements. As seen in Figure 4.13, together two requirements block off much of the $\rho-u$ space. Even if an isothermal rarefaction crosses its allowed area, it will not stay there very long. There are only two ways out of this predicament: increase the imposed field strength or use some other type of incoming jet; both of these are discussed in Chapter VI.

Table 4.3 revisits Table 2.4 from Chapter II, comparing the accretion shock system, the 10-eV experiment with an imposed 10-T field, and the actual 1.6-eV experiment with an imposed 7-T field. The actual experiment produced $\beta_{\text{ram}} = 10$, which is equivalent to an accreting young star with $B = 325 \text{ G}$. As discussed in Chapter II, this is below the expected range of magnetic fields in T Tauri stars (usually one to several kiloGauss), but within the range of expected magnetic fields for Herbig Ae/Be stars (less than 400 Gauss).

4.5 Conclusions

I made the following conclusions about the accretion shock experiment:

1. Visible light images of the accretion shock experiment show a jet emerging, making contact with the impact surface around 43 ns, and a bright volume of shocked plasma forming. Lineouts of the intensity confirm that a shock is present and has grown to a height of 1.2 mm above the impact surface by 63 ns.

2. Based on a simple scaling law, $T \propto I^{2/3}$, if jets driven by seven full-power beams have $T_e = 6 \pm 1 \text{ eV}$, then jets driven by one full-power beam would have $T_e = 1.6 \pm 0.4 \text{ eV}$. Comparisons of colliding jet visible light images and accretion
Table 4.3: Comparing the accretion shock system, the original 6-eV experiment with an imposed 10-T field, and the actual 1.6-eV experiment with an imposed 7-T field.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Accreting Star</th>
<th>10-eV Scoped Experiment</th>
<th>Actual Experiment</th>
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<tr>
<td>Mass density, $\rho$</td>
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<td>$10^{-5}$</td>
<td>$3 \times 10^{-5}$</td>
</tr>
<tr>
<td>Average atomic number</td>
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<td>1.1</td>
<td>6.5</td>
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</tr>
<tr>
<td>Average mass number</td>
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<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Average ionization</td>
<td>-</td>
<td>0.7</td>
<td>2.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Electron density, $n_e$</td>
<td>cm$^{-3}$</td>
<td>$7 \times 10^{12}$</td>
<td>$2 \times 10^{18}$</td>
<td>$1.4 \times 10^{16}$</td>
</tr>
<tr>
<td>Electron temperature, $T_e$</td>
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<td>10</td>
<td>1.6</td>
</tr>
<tr>
<td>Velocity, $u$</td>
<td>km s$^{-1}$</td>
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<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Magnetic field strength, $B$</td>
<td>G</td>
<td>1000</td>
<td>$10^5$</td>
<td>$7 \times 10^4$</td>
</tr>
<tr>
<td>Post-shock temperature, $T_s$</td>
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<td>300</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Length scale, $L$</td>
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<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Ion collisional MFP, $\lambda_{MFP,i}$</td>
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<td>0.02</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Magnetic diffusion length, $\ell_M$</td>
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<td>200</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Mach number, $\mathcal{M}$</td>
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<td>30</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Collisionality, $\lambda_{MFP,i}/L$</td>
<td>- 0.002</td>
<td>0.2</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Magnetic diffusion length ratio, $\lambda_M/L$</td>
<td>- $2 \times 10^{-7}$</td>
<td>0.3</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Ram Plasma Beta, $\beta_{ram}$</td>
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<td>1.0</td>
<td>2.5</td>
<td>10</td>
</tr>
<tr>
<td>Reynolds number, $\text{Re}$</td>
<td>-</td>
<td>$10^{10}$</td>
<td>$3 \times 10^4$</td>
<td>$7 \times 10^4$</td>
</tr>
</tbody>
</table>

3. Visible light images confirm that shocks do form when the ion-ion mean free path falls below the length scale of the system. For the colliding jet experiments from April 2012, this is predicted to occur at 18 ns; visible light images show a shock forming shortly before 20 ns. For the accretion shock experiments, this is predicted around 40 ns; a shock may be evident in the 43-ns image but cannot be distinguished from glow from the impact surface.

4. As shot, the experiment had $\beta_{ram} \approx 10$, which is above the $\beta_{ram} \approx 1$ regime we were aiming for. Instead of scaling a young star with $B = 1000$ G, our experiment was equivalent to a young star with $B = 325$ G.

5. No difference in evolution or morphology was seen in the magnetic-field time.
series versus the no-field time series. This is attributed to the magnetic field being too low to effect morphology. There may be subtle differences in structure, but as proton radiography failed it is difficult to say.

6. No isothermal jet will ever be acceptable for a magnetized shock experiment when the imposed field is on the order of \( B \approx 10 \, \text{T} \). The low temperature required to bring down density and velocity to achieve \( \beta_{\text{ram}} \approx 1 \) make shock formation impossible.
Proton radiography is analogous to x-ray radiography, with which most people are familiar (dental x-rays, etc.). In x-ray radiography, x-rays pass through a subject and strike a piece of film. When the film is developed, a density-based image of the subject emerges.

In proton radiography, a stream of energetic protons pass through a subject and strike a collector, in our case a thin piece of a type of plastic. Like x-rays, protons are absorbed by dense materials, but as charged particles, protons are also deflected by electro-magnetic fields. When the plastic, which is analogous to the x-ray film, is developed, an image affected by both density and field-strength emerges.

Our experimental team intended to use proton radiography to study magnetic field structures in the scaled accretion shock. Astrophysical simulations have found gross distortions in magnetic field lines surrounding accretion shocks. Figure 5.1 shows the simulation results of Orlando et al. (2010); notice how the laterally expanding accretion shock is sweeping magnetic field lines before it (the field was initially straight up and down). We hoped our scaled accretion shock would produce a similar distortion in the field and proton radiography is ideal for capturing such concentrations in field strength.

Section 5.1 presents the background on the type of proton radiography used, a
Figure 5.1: Simulation results of Orlando et al. (2010). In the weak field case, the (white) magnetic field lines are pushed in front of the accretion shock as it “splashes” out. (This figure was previously used as Figure 2.4 in Chapter II.)

laser-imploded D³He backlighter paired with CR-39. Although we were successful using proton radiography on a related experiment, the multi-jet experiment, we encountered multiple difficulties when applying it to the accretion shock experiment. Section 5.2 discusses the multi-jet experiment and the associated proton radiography data. I was the graduate student PI for the multi-jet experiment in 2013 but chose to go in a different direction for my thesis work. The multi-jet data are included here to aid in understanding the accretion shock proton radiography data.

Section 5.3 discusses the proton radiography data obtained for the accretion shock experiment. Section 5.4 discusses the difficulties encountered: for the May 2014 shot day the protons were deflected away from the CR-39 and for the May 2015 shot day the proton backlighter was improperly illuminated and proton counts were an order of magnitude lower than expected. Section 5.5 presents my conclusions.
5.1 Proton Radiography Background

5.1.1 Proton generation

This project relied on a monoenergetic proton backlighter developed by Seguin et al. (2003) and Li et al. (2006). A spherical glass (SiO$_2$) capsule with a diameter of 427 $\mu$m and a shell thickness of 2 $\mu$m is filled with deuterium-helium-3 ($D^3He$) gas at nominal pressures of 12 atm ($^3He$) and 6 atm ($D_2$).

When the capsule is subjected to direct laser irradiation, the shell ablates away, driving a shock wave through the capsule. The implosion produces protons via the following fission processes:

$$D + D \rightarrow T [1.01 \text{ MeV}] + p [3.02 \text{ MeV}], \text{ and}$$

$$D + ^3He \rightarrow \alpha [3.6 \text{ MeV}] + p [14.7 \text{ MeV}].$$

(5.1)

(5.2)

These proton populations are referred to as the 3-MeV DD protons and the 14-MeV $D^3$He protons (Seguin et al., 2003).

The velocity of the protons is

$$u_p = c \sqrt{1 - \left(\frac{1}{1 + \frac{E_p}{E_o}}\right)^2},$$

(5.3)

where $E_p$ is the energy of the proton and $E_o$ is the rest mass of the proton in energy units. The 3-MeV DD protons have a velocity of $2.4 \times 10^9 \text{ cm s}^{-1}$ (0.08$c$) and pass through the experiment (roughly 3 mm across) within 0.1 ns. The 14-MeV $D^3$He protons have a velocity of $5.3 \times 10^9 \text{ cm s}^{-1}$ (0.18$c$) and pass through the experiment within 0.06 ns.
5.1.2 Proton detection

The protons are detected with CR-39, a clear plastic (chemical composition $C_{12}H_{18}O_7$) whose long polymer chains are damaged by the bombarding protons. The CR-39 is later etched in NaOH. Because the damaged areas are eaten away by the NaOH faster than the intact areas, an images of proton irradiance emerges.

When protons pass through CR-39, they deposit their energy in a highly non-linear manner, depositing very little until the end of their flight, and then depositing all their energy at once.\footnote{This always reminds me of the Hemingway quote on going bankrupt: “Two ways. Gradually, then suddenly.”} This means that the incoming energy of a proton determines its fate. If its energy is high enough, it will pass through the CR-39 unscathed; CR-39 is only 100% efficient at detecting protons in the 0.5–6 MeV range. Otherwise, it will deposit the bulk of its energy, and thus cause most of its damage, at a depth specific to its incoming energy. When the researcher etches the CR-39, the exposure time to the NaOH determines what level of proton damage are left on the surface. By adjusting NaOH exposure time, the researcher can ensure that only protons of a specific energy are seen in the final developed image. Likewise, if the protons above 6 MeV are of interest, the experimenter can place a filter before the CR-39 to bring the proton energy down to something that can be detected by CR-39 (Séguin et al., 2003).

For this project, a stack of 1) 75 µm tantalum; 2) 1500 µm CR-39; 3) 50 µm aluminium; and 4) 1500 µm CR-39 was placed in a Wedge Range Filter, a target chamber apparatus for holding the CR-39.\footnote{The “wedge” in the name refers to the wedge-shaped filters that are often used for proton spectrometry, but no wedge-shaped filters were used for this project.}

Typically, the proton backlighter is placed 1 cm from the subject and the CR-39 is placed $\sim 30$ cm on the other side of the subject, giving a magnification of $\sim 30 \times$. As the sheets of CR-39 are 10 cm across, this provides a field of view roughly 3 mm...
across. To obtain a wider field of view, the CR-39 can be brought closer to TCC; 20 cm from TCC is the closest possible, giving a field of view 5 mm across.

5.2 Multi-Jet Experiment

5.2.1 Motivation

Chronologically, the multi-jet experiment falls between the collimated jet work of Chapter III and the accretion shock work of Chapter IV and this chapter. It represents a road not taken; our collaboration considered pursuing a laser-created rotating plasma disk and chose to go a different direction after this day of experiments.

The idea for creating a rotating plasma disk with a “twisted wagon wheel” was laid out in Ryutov (2011). As sketched in Figure 5.2, half a dozen or more equally spaced jets would be launched inward (the “wagon wheel” part of the design), but they would each be aimed slightly off-center (the “twisted” part of the design). Thus, the system would have some overall angular momentum and rotation about the central axis would be expected.

Additionally, Ryutov intended to impose an external cusp magnetic field on the experiment. A cusp field, see Figure 5.2, uses two current loops in opposite directions to create a field that points in radially, then points outward along the central axis. According to Ryutov, the plasma jets would become coupled with the field when they were launched at the edge of the experiment, then drag the field to the center, where it would effect the creation of a rotating plasma disk.

5.2.2 Configuration

The multi-jet experiment was conceived as a stepping stone towards the configuration seen in Figure 5.2. Instead of a whole wagon wheel of jets, we designed a target with only three, which could be shot individually or in some combination, using the
Figure 5.2: Schematic for creating a rotating plasma disk. Left: Each colliding jet is aimed slightly off-center, giving the system overall angular momentum. Right: Two current loops (shown in cross section) create a cusp magnetic field (blue).

jet-creation method tested in April 2012 and discussed in Chapter III. Consistent with the goal of eventually creating a rotating disk, we imposed a cusp field on this experiment.

Figure 5.3 shows the multi-jet experimental scheme. The three cones, which we referred to as “A,” “B,” and “C,” were positioned 4 mm from target chamber center and were separated by 45°. (That is, A and C were 90° apart and B was halfway in between.) The jets were launched with the rear-irradiation method tested in April 2012 and discussed in Chapter III. The plane of the jets was positioned at the mid-plane of the cusp field, “sandwiched” between the two current coils. A proton-generating backlighter was placed 1 cm below the experiment; a 10 cm × 10 cm piece of CR-39 was positioned 30 cm above the experiment, giving a 3 mm × 3 mm field of view. Table 5.1 lists all the vital statistics for the experiment.

5.2.3 Results

On the August 2013 day of experiments dedicated to the multi-jet configuration, we attempted to use proton radiography on seven shots. For six of those shots,
Figure 5.3: Schematic for the multi-jet experiment. Left: A top-down view of the three colliding jets. For clarity, the current coils and proton backlighter have been omitted. Right: A side-on view of the experiment. For clarity, only one jet has been included.

Proton radiography was successful, five one-jet shots and one two-jet shot. (We were intending to work towards a three-jet shot and did not get there.) Those proton radiography data were seen in Figure 5.4. These images are from the lower layer of CR-39 in the module which records the 3 MeV protons, as that layer consistently showed a brighter image for this shot day.

Several patterns are evident in the images. First, the three shots for which no magnetic field was imposed, Shots 70673, 70674, and 70681, have a smooth background, while the three shots where a 4-T cusp field was imposed have a wrinkled pattern, almost like a cloth were pinched at the center of the field of view. Second, at least four of the shots show a clear bubble moving into the field of view. These bubbles are easiest to see in the no-field shots, but they also appear, albeit somewhat disrupted, in the cusp-field shots. These bubbles seen on the proton radiographs represent the leading edges of expanding jet rarefactions; both the bubbles and as-
Target
Material CH
Solid density 1.18 g cm$^{-3}$
Cone opening angle 160°
Cone diameter 2 mm
Cone thickness 100 µm
Distance to TCC 4 mm
Spacing between cones 45°

Drive Beams
Drive beam wavelength 351 nm (3ω)
Number beams 4 per cone
Total drive energy 1800 J
Drive beam shape 1 ns, square
Drive beam radius 352 µm (SG4)
Drive irradiance $5 \times 10^{14}$ W cm$^{-2}$

Proton Backlighter Beams
BL beam wavelength 351 nm (3ω)
Number beams 16
Total drive energy 7200 J
BL beam shape 1 ns, square
BL beam focus 1.81 mm

Table 5.1: Experimental parameters for the multi-jet experiment of August 15, 2013.

associated jet directions have been labeled in Figure 5.4. Third, the orientation of the proton radiograph appears to have been wrong in several shots. We know for certain which cone was fired; this information is stored in the OMEGA online data system, so there is no doubt that Shots 70672 and 70673, for example, fired the same lasers and launched the same jets. That the jets appear to come from the opposite directions in the two radiographs is undoubtedly due to the CR-39 being inadvertently rotated.
Figure 5.4: Proton radiography data from August 2013. These images show the lower layer of CR-39, which records 3 MeV protons.
5.3 Accretion Shock Experiment

5.3.1 Configuration

The motivations and experimental set-up for the accretion shock experiment have been discussed extensively in Chapters II and IV.

5.3.2 Results

Despite conducting proton radiography on two full days of shots, we saw the distinctive bubble pattern discussed in Section 5.2 only once: on Shot 77255 from May 2015. Since this is the only case of accretion shock proton radiography data with recognizable plasma or field features, it bears its own discussion. Figure 5.5 shows the data of this shot alongside that of a control shot.

The jet in Shot 77254 was launched with seven drive beams and the proton backlighter was fired 10 ns after drive. The visible light imager was gated to 13–16 ns. Figure 5.5 shows both proton radiography and visible light data for the control shot (Shot 77254, top row) and the jet shot (Shot 77255, bottom row). When the jet is seen barely touching the impact surface in the visible light image, there are three bubbles evident in the proton radiography image. The first is the primary bubble made by in the incoming jet, while the second and third are made by blow-off from both sides of the wall. The field of view was at the edge of the CR-39, so the opposite wall and its blow-offs were not evident in the proton radiography image.\(^3\)

These bubbles are remnants of the magnetic field transferred to the plasma while the laser is on. During the laser pulse, some portion of the laser magnetic field propagates into the newly formed plasma, where it is convected to the edge of the plasma. This local field appears at the edge of the expanding cloud of plasma as a

\(^3\)The field of view was not centered on the CR-39 because we knew that we would be using different magnetic field strengths on shot day and needed to allow for differing proton deflections, see Section 5.4.
distinct line in proton radiographs (Eliezer, 2002; Li et al., 2007).

Once the laser turns off, the magnetic field at the bubble surface begins to diffuse away. If the time scale of interest is $\tau$, the amount of time elapsed since the laser turned off, then the magnetic diffusion length by simple unit analysis is $\ell_m = \sqrt{\tau \nu_M}$, where $\nu_M$ is the magnetic diffusivity. As seen in Chapter II,

$$\nu_M = \frac{c^2 \eta_{\perp}}{4\pi},$$

(5.4)

where $c$ is the speed of light, and $\eta_{\perp}$ is the transverse Spitzer resistivity, defined in
Equation 2.12.\textsuperscript{4}

Table 5.2 lists the shot configurations from August 2013, May 2014 and May 2015, whether radiographic bubbles were observed, and, for those configurations where they were absent, why. For the 1-beam shots, plasma bubbles are never seen. For the 4-beam shots, plasma bubbles are seen at all timings, 27–42 ns. For the 7-beam shots, a plasma bubble is seen in the 10-ns shot, but not the later 30-ns and 70-ns shots. Why are bubbles absent from so many shots? They must have either 1) diffused away, 2) moved out of the field of view, or 3) ceased to exist because they struck a solid surface.

The one accretion shock shot to show a plasma bubble is the 7-beam shot at 10 ns. At 10 ns, the plasma bubble has nearly reached the impact surface. Thus, it not surprising that no plasma bubbles are evident at later times, 30 ns and 70 ns; the bubbles have moved out of the field of view or collided with the impact surface or walls of the target. Similarly, the late-time 1-beams shots do not show plasma bubbles either.

However, the 20-ns 1-beam shot ought to be similar to the 10-ns 7-beam shot; based on the scaling arguments of Chapter IV, a 10-ns 7-beam shot would be equivalent to a 19-ns 1-beam shot. What became of the plasma bubble? Table 5.2 shows the length the magnetic field has diffused based on $\ell_m$, where $\tau$ is the length of time elapsed since the laser was fired. By 20 ns, the magnetic field in the 1-beam experiment has diffused 0.3 mm and the bubble has disappeared. Not only has more time elapsed in the 1-beam shot, but the field will diffuse more quickly in a colder plasma because $\eta_\perp \propto T_e^{-2/3}$.

\textsuperscript{4}There is one crucial difference between this discussion and that of Chapter II. There the plasma of interest was the heated post-shock plasma; here the interest is in pre-shock plasma.
<table>
<thead>
<tr>
<th>Drive</th>
<th>Timing</th>
<th>Bubbles?</th>
<th>Reason</th>
<th>$\ell_m$</th>
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<tbody>
<tr>
<td>1 beam</td>
<td>20 ns</td>
<td>☒</td>
<td>Diffusion</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>1 beam</td>
<td>40 ns</td>
<td>☒</td>
<td>Out of range</td>
<td>-</td>
</tr>
<tr>
<td>1 beam</td>
<td>60 ns</td>
<td>☒</td>
<td>Out of range</td>
<td>-</td>
</tr>
<tr>
<td>4 beams</td>
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<td>✔</td>
<td></td>
<td>1.4 mm</td>
</tr>
<tr>
<td>4 beams</td>
<td>32 ns</td>
<td>✔</td>
<td></td>
<td>1.4 mm</td>
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<td>42 ns</td>
<td>✔</td>
<td></td>
<td>1.5 mm</td>
</tr>
<tr>
<td>7 beams</td>
<td>10 ns</td>
<td>✔</td>
<td></td>
<td>0.9 mm</td>
</tr>
<tr>
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<td>30 ns</td>
<td>☒</td>
<td>Out of range</td>
<td>-</td>
</tr>
<tr>
<td>7 beams</td>
<td>70 ns</td>
<td>☒</td>
<td>Out of range</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5.2: Plasma bubbles in proton radiograph data.
Figure 5.6: Inconclusive proton radiography data for the accretion shock experiment. The top two shots are from 2014; the rest are from 2015.
5.4 Difficulties Encountered

5.4.1 Proton Deflection Issues

5.4.1.1 Issue

Many of the proton radiographs obtained in May 2014 were extremely odd and riddled with strange shapes, see Figure 5.7. The no-field proton radiographs showed a thick white frame surrounding a flat gray background. The frame is the target; the walls, roof and impact surface create the appearance of a frame in the proton radiograph. The uniform gray inside the frame is due to the lack an imposed magnetic field. In the magnetic-field shots, the frame itself is either gone or distorted and other odd looking structures appear.

This, I have concluded, is due to proton deflection. The protons are being diverted by the magnetic field; those that passed through the experiment did not arrive at the CR-39. The protons that did arrive at the CR-39 did not pass through the experiment, but instead pass off to its side. The images in the proton radiographs taken with the field on are of a non-experimental part of the target.

Figure 5.7: Comparing no-field and 7-T proton radiographs. May 2014 proton radiography data from a no-field shot, Shot 73335 (left), and a 7 T shot, Shot 73337 (right).
5.4.1.2 Deflection Calculation

If a charged particle travels through a magnetic field, it will experience a Lorentz force, which, in CGS units, is

\[ \mathbf{F} = q\frac{\mathbf{v}}{c} \times \mathbf{B} = -\frac{qv_x B_z}{c} \hat{y}, \]  

(5.5)

where \( q \) is the charge, \( v_x \) is the velocity in the x-direction, \( B_z \) is the magnetic field in the z-direction, and \( c \) is the speed of light. Therefore the acceleration is

\[ \mathbf{a} = -\frac{qv_x B_z}{mc} \hat{y}, \]  

(5.6)

where \( m \) is the particle mass. Therefore we can find the total deflection from the original path, \( \Delta y \), by integrating for any arbitrary \( B_z \) and any two points, \( x_1 \) and \( x_2 \), see Figure 5.8. The velocity during its flight will be

\[ v_y(t) = \int_0^t a_y(t) dt = \int_0^t \frac{B_z(t)}{mc} dt, \]  

(5.7)

and the deflection will be

\[ \Delta y(t) = \int_0^t v_y(t) dt. \]  

(5.8)

The experiment had a solenoidal field. The magnetic field in the z-direction as a function of x was

\[ B_z(x) = \frac{B_0}{0.715\pi\sqrt{Q}} \left[ E(m) \frac{1 - \alpha^2 - \beta^2}{Q - 4\alpha} + K(m) \right], \]  

(5.9)

where \( E(m) \) and \( K(m) \) are complete elliptic integrals of the second and first kind, respectively, and

\[ \alpha = x/R, \]  

(5.10)

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Figure 5.8: Proton deflection diagram. The proton is emitted at $x_1$, flies through the set-up with $\hat{x}$ velocity $v_x$, and is absorbed at $x_2$ by the CR-39.

$$\beta = \frac{h}{R},$$  \hspace{1cm} (5.11) \\
$$Q = (1 + \alpha)^2 + \beta^2, \text{ and}$$  \hspace{1cm} (5.12) \\
$$m = \frac{4\alpha}{Q}. \hspace{1cm} (5.13)$$

Figure 5.9 shows the B-field normalized to arbitrary units, such that $B = 1$ at $x = 0$, for our experiment, where the protons are generated at $x_1 = -1 \text{ cm}$ and collected at $x_2 = 27 \text{ cm}$.

Figure 5.9: [Magnetic field strength and deflected velocity vs. position. Left: the field strength along the x-axis between two coils of current. Right: the deflection velocity. Note that the x-axis only goes to $x = 3 \text{ cm}$ even though the protons are collected at 27 cm.

We expect the deflection on the CR-39 to be $\Delta y_{\text{tot}} = -1.16B_T \text{ cm}$, where $B_T$
is the field strength in Teslas. Or roughly speaking, we expect the protons to be diverted one centimeter per Tesla of field strength. Applying this to Figure 5.7, we would expect Shot 73335 to have a shift of 0 cm, which is what we appear to see. Shot 73337 would be shifted by 8.1 cm, so the window seen in Shot 73335 that spans roughly −2.5 cm to 2.5 cm would be shifted to +5.6 cm to +10.6 cm, completely off the CR-39. This is consistent with the earlier statement that the image captured for Shot 73337 shows the wires connecting the MIFEDS loops.

5.4.1.3 Solving the Problem

To solve this problem for the May 2015 shot day, we offset the proton backlighter from the line of sight. With this configuration, rather than deflecting the protons off the CR-39, the field deflected them onto it.

Figure 5.10: Offsetting the proton backlighter solved the deflection problem by making the protons deflected onto the CR-39.

5.4.2 Backlighter Focus Issues

In May 2015, we consistently got low neutron counts from the Nuclear Diagnostic Inserter (NDI), with an average of $8 \times 10^7$ neutrons per shot, compared to an average of $5 \times 10^8$ neutrons per shot in May 2014. During the October 2015 day (which was largely devoted to another campaign), we discovered during conversations with
OMEGA that we had had the backlighter beams focused incorrectly. We had selected a focus of 0.00 mm (that is, best focus) while we should have set the focus to 1.81 mm. That would de-focus the backlighter beams such that they evenly irradiate the backlighter capsule. At best focus, the backlighter beams act as pin pricks, cracking the capsule before it implodes. Fusion is disrupted, and the proton count drops.

5.5 Conclusions

I made the following conclusions about the accretion shock experiment:

1. At early times, plasma jets appear in proton radiography as “bubbles.” These are readily visible with or without an imposed magnetic field, and actually appear crisper without a field.

2. With time, the magnetic field that causes the proton radiograph bubbles will diffuse away. The magnetic diffusion length is a function of time and temperature; later times and colder temperatures will show more diffusion. For the data collected in this project, bubbles are still evident when $\ell_m = 0.1 \, mm$, but not when $\ell_m = 0.3 \, mm$.

3. Only one accretion shock experiment, a seven-beam shot with proton radiography 10 ns after drive, shows the distinctive bubble pattern. This shot reveals a bubble caused by the incoming plasma jet, but also secondary bubbles caused by blow-off coming from the wall. We must conclude that the presence of the walls affects the physics of the accretion shock experiment.
CHAPTER VI

Conclusion

6.1 Accomplishments

This thesis captures seven years of work on laser-driven plasma experiments, including four shot days on the OMEGA laser. As the graduate student principal investigator, I was responsible for each shot day from start to finish. I determined the physical questions driving each investigation, designed the experiments, worked with engineers at the University of Michigan to build the targets, oversaw the shot day in the control room at OMEGA, and analyzed the data that resulted. I worked under the supervision and guidance of Carolyn Kuranz and Paul Drake, but the work presented in this thesis is mine except where explicitly stated otherwise.

The idea of a laboratory astrophysics experiment aimed at creating a scaled accretion shock was the result of discussions I had with Patrick Hartigan (Rice University) in early 2011. (Dr. Hartigan was my undergraduate advisor; my undergraduate thesis was the jets that emanate from young star systems.) A collaboration between the University of Michigan and Rice University became feasible in the late 2013/early 2014 and it was then that we began to plan the accretion shock experiment in earnest. By that point, I had gained two shot days worth of experience on OMEGA and had worked with all of the systems and diagnostics that would be needed for the accretion shock system, including launching collimated plasma jets, imposing magnetic fields on
experiments, using the 2-D visible light imager, and using proton D$_3$He radiography.

This research encountered numerous experimental problems: both $4\omega$ Thomson scattering and proton radiography failed repeatedly. These experiences provided me with life lessons on doing research, but unfortunately they did not provide me with data. The question that drove the investigation, “How does magnetic field strength affect accretion shock structure and evolution?,” is yet unanswered. As discussed in Chapter IV, the actual experiment had $\beta_{\text{ram}} \approx 10$. At such a $\beta_{\text{ram}}$, the magnetic field is not high enough to produce differences in gross structure.$^{1}$ There may have been nuanced differences due to the imposed field, but as proton radiography failed these went unrecorded.

Despite this, I believe this thesis project is a meaningful contribution to the field of laboratory astrophysics. The experiences gained in this research project have advanced other projects at CLEAR, particularly projects in the magnetized flowing plasma group. I was also able to complete many of the smaller goals I set as part of the overarching accretion shock endeavor. Listed below are what I consider my major accomplishments:

1. I scaled accretion shocks observed in star formation to a laboratory experiments and in doing so developed a visual process for scaling laboratory astrophysics experiments.

2. I successfully tested a method for creating collimated plasma jets and found them to behave like isothermal rarefactions.

3. I found a way to overcome probe beam heating in Thomson scattering by inferring the pre-heating temperature of the jets from their mass density profile.

4. Despite repeated failures involving key diagnostics, I proved that a scaled accretion shock was created in the laboratory. The plasma parameters of this scaled

$^{1}\beta_{\text{ram}}$ is the ratio of plasma pressure to magnetic pressure, see Chapter II.
shock would correspond to a young accreting star with $B = 325$ G.

5. I found that shocks form when the ion-ion mean-free-path falls below the scale length of the system.

6.1.1 Scaling process

For a laboratory astrophysics experiment to be valid, it is not enough to superficially resemble the astrophysical phenomenon in question. It must be well-scaled, which requires that the relevant dimensionless numbers be in the same regime for both the astrophysical phenomenon and the experiment. Using dimensionless numbers to scale experiments is a well-established approach, but the graphical approach I used is, as far as I know, unique in laboratory astrophysics. I created region plots in plasma parameter space for each dimensionless number constraint; each plot showed the area where the constraint was and was not met. By graphing these regions simultaneously, I was able to visually represent the area where all the constraints were satisfied at once. This method allows a researcher to see how an experiment is moving through allowed parameter region with time and to determine for what time range the experiment will be well-scaled. See Chapter II.

6.1.2 Collimated jets

In April 2012 our experimental team tested a method for creating collimated plasma jets on OMEGA by rear-irradiating a thin cone of acrylic. Two-dimensional visible light self-emission images proved that we were successful; the jets were well collimated. We used Thomson scattering for each shot and successfully collected scattered spectra from 12 ns to 18 ns. I analyzed these data to find the mass density profile of the experimental jets and compared it analytically predicted mass density profiles for adiabatic and isothermal rarefactions. There was a clear match between the experimental mass density profile and that of the isothermal rarefaction. There-
fore, I concluded that the jets were behaving like isothermal rarefactions. See Chapter III.

6.1.3 Overcoming Thomson probe heating

If the experimental plasma absorbs some of the Thomson probe beam energy, it can be heated to a temperature well above its initial temperature, corrupting the resulting Thomson scattering data. This occurred during the April 2012 experiments. The measured temperatures are on the order of 50–400 eV; temperatures on the order of 10 eV are typical of rear-irradiated jets. I built a simple steady-state probe-heating model and found that there was good agreement between the temperature predicted by my probe-heating model and the temperatures found from Thomson scattering.

I was, however, able to overcome the probe heating problem with the mass density profile approach described in Section 6.1.2. I compared the experimental mass density profile to analytic predictions of the mass density profile for isothermal rarefactions at varying temperatures. I found that an isothermal rarefaction of \( T_e = 6 \pm 1 \text{ eV} \) bounded the mass density data. See Chapter III.

6.1.4 Scaled accretion shock

Young stars are thought to grow via magnetospheric accretion, wherein material from the accretion disk is funneled to the stellar surface along magnetic field lines. To create a scaled version of this system, I drove a plasma jet (the “accreting flow”) into a solid block (the “stellar surface”) in the presence of a parallel magnetic field (analogous to the local stellar field). The imposed field was intended to resemble the stellar magnetic field which runs perpendicular to the stellar surface where the accretion shocks form. I performed this experiment on two days of shots at OMEGA. Although proton radiography failed on both days (for independent reasons), 2-D visible light imaging was successful.
Visible light images show the jet colliding with the impact surface and a bright shock structure forming. Previous experiments had shown that jets launched with seven full-power beams were isothermal rarefactions with $T_e \approx 6$ eV (see above). The scaling expression, $T_e \propto I^{2/3}$, suggests that the jets used for the accretion shock experiments, which were launched with one beam, would be isothermal rarefactions with $T_e \approx 1.6$ eV. Using the density and velocity analytically predicted for a 1.6-eV isothermal rarefaction, I concluded that the scaled accretion I created would be equivalent to a young star with $B \approx 325$ G. See Chapter IV.

6.1.5 Shock formation and mean free path

Both of the major experiments presented in this thesis, the collimated jet experiment and the accretion shock experiment, involved collisions and resultant shocks. When designing the accretion shock experiment, one of the scaling arguments I used was the prediction that a shock would not be observed unless the ion-ion mean-free-path was less than the scale length of the experiment. The collimated jet experiment produced jets with $T_e = 6$ eV and collided two jets head-on (that is, 180°). Plotting the $\rho - u$ trajectory of a 6-eV isothermal rarefaction on the mean-free-path region plots developed in Chapter II, a shock ought to form at roughly 18 ns, consistent with visible light images.

The accretion shock experiment drove a single jet into an impact surface perpendicular to the jet. Scaling arguments suggest these jets were isothermal rarefactions with $T_e = 1.6$ eV, and the $\rho - u$ trajectory plotting strategy described above predicts that a shock becomes possible for the accretion shock experiment around 40 ns. Again, this is consistent with visible light images. See Chapter IV.
6.2 Future Work

As stated earlier in the Chapter, the driving question for this investigation, “How does magnetic field strength affect accretion shock structure and evolution?,” has not been answered. No difference in shock structure was observed between the shots with an imposed field and one without. This section explores why that might be and how it could fixed for future work. In short, the lack of an observed difference for field and no-field shots could be due to the repeated experimental failures, or it could be due scaling problems. If the fault lies with the experimental failures, then repeating the experiment with the problems fixed would yield useful data. However, if the experiment failed to observe a difference between the field and no-field cases due to scaling, then major design changes would be necessary.

6.2.1 Experimental failures

Proton radiography failed for both the May 2014 and the May 2015 shot days. The May 2014 loss was due to protons being deflected off the CR-39, while the May 2015 loss was due to the wrong beam focus being used to implode the backlighter capsule. With both of these failure modes well understood, CLEAR has recently used D³He proton radiography successfully for another magnetized flowing plasma shot day. In that sense, the problem is solved. However, it is worth considering the proton radiography failures here to avoid similar failures in the future.

Of all the things that went wrong in this thesis project, the hardest to get over is the loss of proton radiography data in May 2014. After we got the data, I calculated the expected path of a proton through my May 2014 experiment and discovered my mistake. The necessary change to that problem was very simple: we moved the proton backlighter 1 mm to avoid the same mistake in May 2015. (In theory, we could have asked to have the beams redirected as late as the night before the shot day, had we known about the problem.) The only lesson that I can takeaway form this is the
importance of doing such calculations in advance, which I would emphasize to future students.

By contrast, I did predict my Thomson data for the April 2012 shot day and in doing so caught a critical mistake. When I calculated the Doppler shift and Thomson peak separations, my predicted Doppler shift was nearly zero. Surprised, I ran the same calculation for an experiment published in the literature, Ross et al. (2012), and discovered the error I had made in designing my experiment: I had made the velocity and the Thomson scattering k-vector nearly perpendicular when they ought to be parallel. Having discovered this mistake, I reoriented the experiment in the chamber to make the jet velocity parallel to the k-vector (which is determined by the entry point of the probe and the location of the collection telescope and cannot be altered), and redesigned the targets accordingly. This mistake was caught fairly late in the planning process—a portion of the targets had already been partially machined and new ones had to be made with the correct stalk angle. But had this mistake not been caught at all, we would have lost velocity data on shot day.

6.2.2 Scaling issues

Scaling issues are harder to rectify than experimental issues. The validity of this genre of work hinges on getting $\beta_{\text{ram}}$ into the coveted $\beta_{\text{ram}} \approx 1$ regime. There are, obviously, two ways to do that: increase the magnetic field or decrease the incoming jet density and velocity. Both of those are difficult.

OMEGA uses a TIM-based\(^2\) system, MIFEDS, to generate magnetic fields. Thus, the capacitors that power MIFEDS must fit in a fixed volume—and most of the space is already devoted to capacitors and their associated charging system. The Laboratory for Laser Energetics (OMEGA) is currently funding Gennady Fiksel here at the University of Michigan to develop a 30-T, and later a 50-T, version of MIFEDS,

\(^2\)TIMs, or Ten-Inch-Manipulators, are basically portals into the target chamber, see Appendix A.
but until these are completed and qualified, the maximum capability will remain fields on the order of 10 T when an experimental volume several millimeters across is required.

The other way to increase field strength, making the current loop smaller, is unfeasible with this experiment. The target has to fit inside the current loop, so there is a limit to how small the current loop can be made without making target positioning impossible. This is something we already pushed to the limit in designing the May 2014 and May 2015 experiments.

Creating a low-density, low-velocity plasma stream with a laser is likewise difficult. Lasers deposit a lot of energy in a short amount of time; they therefore lend themselves to creating high-velocity jets that do not last very long. Irradiating the rear side of the target creates reservoir of hot plasma which can then expand over a longer period of time, which is why we chose to using rear irradiation instead of front irradiation. This is also why we chose to fall back to one beam (instead of the seven we had previously been using) for the second day of accretion shock experiments. Even so, plasma $\beta_{\text{ram}}$ was on the order of ten. One potential solution would be to use a heater beam, exposing the incoming jet to an additional laser beam that heat it. Then one could have the advantages of a low-temperature isothermal jet (low density, low velocity) with the advantages of higher temperature (easier shock formation due to higher ionization).

There is also work ongoing to find other ways to create low-density, low-velocity plasma streams. The collaboration established for this thesis project (Michigan, Rice, MIT, and LLNL) has grown to include other magnetized flowing plasma projects. One project, which created magnetized bow shocks, developed a new method for creating low-density, low-velocity plasma streams. They launched two jets via rear-irradiation, collided them head-on, then used the expanding plasma from the central collision as the flow of interest. Conceptually, their method was similar to the April 2012 colliding
jet project, except they were looking at the flow emanating from the central collision, not the central collision itself. Perhaps this path forward would get the accretion shock experiment into the $\beta_{\text{ram}} \approx 1$ regime.

6.3 In closing

Despite the difficulties encountered in this thesis project, I still feel astonishingly fortunate. Not every graduate student is permitted to essentially design her own experimental campaign from the ground up and I am grateful for the opportunity to do so. It is bittersweet to walk away from an endeavor just as it seems all the problems are solved and everything is looking up, but I suppose that is the nature of graduate school. It is my hope that these experiments will be continued on in some form; the proton radiography problems are solved and the low-density, low-velocity drives being developed could reduce $\beta_{\text{ram}}$ to something genuinely useful. But regardless of whether this particular experiment continues, I know that CLEAR will continue to do this genre of work and that is gratifying.
APPENDICES
This appendix provides background on OMEGA, including the planning process for a day of OMEGA experiments, called a shot day, and background on the major systems used for this project.

OMEGA provides diagnostic flexibility with its six Ten-Inch Manipulators or TIMs, basically portals into the target chamber that can accept any one of more than 150 different diagnostics. While many OMEGA diagnostics can be placed in any of the six TIMs, some newer diagnostics have only been qualified in one or two. If the researcher wishes to use such a diagnostic—as was the case with my experiments using Thomson scattering—the experiment must be planned around it. In addition to the TIM-based diagnostics, OMEGA has roughly 30 diagnostics built into the target chamber.

Section A.1 explains the process for planning an OMEGA shot day. Section A.2 provides background on the system used to impose magnetic fields on experiments, Magneto-Inertial Fusion Electrical Discharge System or MIFEDS. Section A.3 presents Thomson scattering, a technique which probes parameters such as temperature and density by scattering a probe laser beam off the experimental plasma. Section A.4 explains visible light imaging, which is as straightforward as it sounds,
simply taking a picture of the experiment using self-emitted light.

A.1 Planning an OMEGA Shot Day

A.1.1 12 months out

Planning for an OMEGA shot day begins a year in advance. The research team has a rough idea of what the day will be used for since OMEGA, like all major facilities, allocates time based on proposals. At this point, the particulars need to be hammered out. What are the specific goals of this shot day and how do they relate to the campaign as a whole? What will the experimental scheme look like? What major diagnostics or other systems will be needed?

At this point, the research team creates a brief (3 slide) presentation for planning purposes at LLE. OMEGA functions most efficiently if days that use similar diagnostics are grouped together. For example, because Thomson scattering requires a dedicated beam (see Section A.3), it is only done during dedicated $2\omega/4\omega$ Thomson weeks.

Around this time preliminary target design begins. A final design will not be necessary until about three months out, but if the target includes any long-lead items, the CLEAR target fabrication engineer needs to know so that she can source it. (CLEAR is unique in that all of our targets are made in-house; most research programs order them from an outside source.)

Targets are designed in VisRad, a computer-aided design program that has the OMEGA target chamber built into it. VisRad allows the designer to view the target from any point of view in the chamber and has the coordinates of the TIMs and fixed diagnostics built in. VisRad is also used to assign beams to the experiment.

Part of the planning process is completing Shot Request Forms, or SRFs. Every shot has a unique SRF which lays out all the necessary information about targets,
beams, drivers, TIM assignments (which diagnostics are going where), and diagnostic set-up. The OMEGA staff will follow the SRF verbatim, and the SRF will serve as a record of precisely what settings were used on the shot. Work begins on these 4 to 6 months in advance. At this point, there is no need to have an entire shot day’s worth of SRFs complete; only one SRF per unique configuration is needed.

As the graduate student PI, much of this work was my responsibility. I helped to determine the goals of each shot day, did the background research necessary to design the experiment (see Chapter II), prepared the 3-page planning presentation for LLE, designed the experiments in VisRad, and completed the SRFs.

### A.1.2 3 months out

Three months before the shot day, the experiment is largely designed and the responsibilities shift to coordinating the logistics of the shot day.

At this point, the experimental team submits a proposal, which includes an SRF and associated VisRad for each unique configuration that will be used on shot day. The purpose of the proposal is to allow the facility to identify any problems well in advance. Changes can still be made to the experiment, but they require corresponding with the facility engineers and then resubmitting the proposal.

Target fabrication is completed in this time frame. Engineering drawings of the target are made. Because my targets were machined in-house, I worked closely with our micro-machinist in creating my drawings and made changes based on his suggestions, for example rounding out inside corners to accommodate the size of the drill bit. After the targets are made, they must be measured using the CLEAR metrology system.

As the graduate student PI, I completed VisRads and associated SRFs for each configuration and made engineering drawings. I also metrologized (measured) the resulting targets to ensure that they were built to specification.
A.1.3 2 weeks out

At this point, the logistical details have been hammered out and this time period in the cycle is dedicated to addressing late-breaking problems. Experimental teams are expected to brief LLE staff two weeks before the shot day and again one week before. (These briefs are conducted over the phone with prepared slides.) During this time period, a rough shot sequence is laid out. Generally, it is a good idea to work from basic to complicated configurations and to put off using equipment that is prone to failure until late in the day.

A.1.4 Shot day

Shot days last about twelve hours, spanning two shifts of OMEGA personnel. As the grad student PI, I briefed each shift of OMEGA staff (engineers and technicians) about the experimental goals, configurations that would be shot and diagnostics that would be needed. Although all of the hands-on work is done by OMEGA staff, I was responsible for granting my approval. For example, target are aligned by OMEGA to meet the specifications of the submitted VisRad, but I was expected to approve (or not) the aligned target based on its view in the camera.

OMEGA is remarkably flexible. Changes to a shot can be made up until a few minutes before the shot is fired. This means that the experimental team can decide what the next shot will be based on the last shot’s results. As a good shot day only has about a dozen shots, it is crucial to think through the “flow-chart” of what shots will be needed based on early results.
A.2 Imposing Magnetic Fields with MIFEDS

A.2.1 Capabilities

The Magneto-Inertial Fusion Electrical Discharge System (MIFEDS) is a TIM-based electric discharge system used to generate experimental magnetic fields on OMEGA (Gotchev et al., 2009; Knauer et al., 2010). MIFEDS was recently redesigned to be “more user-friendly” while meeting all of its original requirements (Fiksel et al., 2015). Energy is stored in high-voltage capacitors, then discharged through a wire coil when a laser-based trigger is fired, achieving voltages of 10–20 kV. This achieves magnetic fields of 5–15 T extending over several cubic centimeters and lasting for $1 \mu s = 1000\,\text{ns}$.

As seen in Figure A.1, much of the volume inside the TIM is dedicated to the high voltage (HV) capacitors and their associated charging supply. When MIFEDS is fired, the spark-gap switch connects and the capacitors discharge through the high voltage transmission line leading to the magnetic coil.

The zoomed section shows the magnetic coil itself. Each coil design is unique its experimental configuration. Coils are 3-D printed by LLE (the white plastic seen in Figure A.1), then insulated copper wire is wrapped around them as shown. When MIFEDS is fired, the heat of the current discharge destroys the coil; these are single use items. When the used coils are removed from the target chamber, the plastic part is gone and the wire has been mangled by the intensity of the magnetic field.

A.2.2 Development and Use

As its name would suggest, MIFEDS was developed to improve inertial confinement fusion yields by magnetizing the capsule prior to implosion (Gotchev et al., 2009). According to Knauer et al. (2010), “the benefits of this approach are twofold: The hot spot can reach ignition temperatures because of the reduced electron thermal
conductivity. When the nuclear burn develops, the alpha particles can be confined, by a strong magnetic field, to the burn region delivering the energy where it is needed to support the burn wave.” Since being developed for fusion research, it has been used on many experimental platforms, including experiments to study the Weibel instability (Fox et al., 2013) and magnetic recombination (Fiksel et al., 2014).

A.3 Thomson Scattering

Thomson scattering is a method for probing the condition of an experimental plasma by making use of a laser-plasma instability. When a laser beam is incident on an experimental plasma with an underlying density perturbation (and all experimental plasmas have underlying perturbations), wave beating results. In this case, the two waves that beat together are the incident laser wave and the electron density fluctuation wave. This will produce two scattered light waves, one with the sum of the frequencies and wave numbers and one with their differences (Drake, 2006).

Because the scattered light waves are driven by the density fluctuation, the scattered spectrum is dependent on the density and temperature of the plasma. An experimenter may collect the scattered spectrum and compare it to analytically pre-
dicted spectra and thereby determine the plasma conditions that produced it. There will also be an overall Doppler shift to the spectra which indicates the bulk velocity of the plasma.

This section discusses Thomson scattering in depth. Section A.3.1 discusses the conceptual differences between streaked and imaging Thomson scattering, which are both fielded on OMEGA. Section A.3.2 presents the Thomson scattering set-up at OMEGA.

There are two electron density fluctuation waves of interest: the Electron Plasma Wave, or EPW, and the Ion Acoustic Wave, or IAW. The sources of these waves, from which they derive their names, are discussed in Section A.3.4.

To analyze the scattered spectrum, the experimenter compares it to analytically predicted scattered spectra, which are obtained from a numerical code, explained in Section A.3.5. Section A.3.6 presents an example of Thomson data being fit.

Section A.3.7 discusses problems one might encounter in Thomson scattering.

A.3.1 Streaked vs. Imaging Thomson

OMEGA has the ability to field either streaked or imaging Thomson scattering, and the facility is flexible enough to switch from one to the other in the midst of a shot day. Streaked Thomson scattering gathers information about the plasma in a fixed location over an extended period of time. Conceptually, it is similar to installing a flow meter and recording the density, temperature and velocity of the plasma going past it. Imaging Thomson scattering gathers information about a long tube of plasma at a fixed time.

Figure A.2 illustrates the differences in configuration necessary to produce either streaked or imaging Thomson. For streaked Thomson, the probe beam intersects with the experimental plasma, illustrated here as a jet. The volume studied is small, $50 \mu m \times 50 \mu m \times 50 \mu m$. For imaging Thomson, the probe beam illuminates an ex-
tended region, $50 \mu m \times 50 \mu m \times 1000 \mu m$, for a short period of time.

![Figure A.2: A comparison of streaked Thomson scattering (left) and imaging Thomson scattering (right). The probe beam (green) illuminates some portion of the jet (pink). (In practice, the drive beams (yellow) would not fire at the same time as the probe.)](image)

### A.3.2 OMEGA Thomson Set-up

OMEGA has the ability to field either a $2\omega$ (526.5 nm) or $4\omega$ (263.25 nm) probe beam. The OMEGA probe laser pulse can be anywhere from 100 ps to 3.5 ns long with total energy $10^{-200}$ J (Katz et al., 2013).

The system is not permanently installed. On weeks where Thomson is supported, Beam 25 is shifted in frequency and redirected so that it enters the chamber through Port 9. It scatters off experimental plasma at TCC and the scattered light is collected by a telescope TIM 6. Light from the telescope is directed to the Thomson scattering set-up cart about 8 m away, where the beam is broken into a spectrum and recorded. This basic geometry, Port 9 to TCC to TIM 6, cannot be altered; the experimenter must design around it, see Figure A.3.

Once the scattered light is collected and directed to the Thomson scattering set-up, it is split into three legs: one for the EPW feature, one for the IAW feature, and one for
the 2-D imager. The first two legs are illustrated in Figure A.4. (See Section A.4 for a discussion of the third leg.) Both the EPW and the IAW legs rely on Czerny-Turner spectrometers, see Figure A.5, which use a grating to split a broadband light beam into a spectrum. The EPW leg uses a 0.3-m (f/5) Czerny-Turner spectrometer; one of three different gratings can be used to obtain a spectral window of 40, 80 or 160 nm. The IAW leg uses a 1-m (f/9) Czerny-Turner spectrometer; its three gratings provide spectral windows of 40, 80 or 160 nm. For both the 0.3-m and the 1-m spectrometers, spectral resolution is about 0.7% of the spectral window (Katz et al., 2012, 2013). When running $2\omega$ scattering, a long-pass filter that blocks wavelengths $< 400$ nm is used to protect the Thomson set-up from $3\omega$ light (Katz et al., 2013).
Figure A.4: Beam path diagram for Thomson scattering on OMEGA. The scattered spectrum is split; one leg leads to the EPW 1/3-meter spectrometer and another leads to the IAW 1-m spectrometer. Not shown is the optical path leading to the 2-D optical imager. Optical paths and angles are not to scale. (Image credit: diagram from Laboratory for Laser Energetics; my own data added as examples.)

Figure A.5: An unfolded Czerny-Turner spectrograph. A Czerny-Turner spectrograph uses a grating to resolve a spectrum by wavelength. (Image credit: Laser Focus World)
A.3.3 The Electron Plasma and Ion Acoustic Waves

This derivation of the electron plasma wave and ion acoustic wave frequencies follows that of Bellan (2006), which begins by assuming an unmagnetized two-fluid plasma.

\[
m_{\sigma}n_{\sigma 0}\frac{du_{\sigma 1}}{dt} = q_{\sigma}n_{\sigma 0}E_{\sigma 1} - \nabla P_{\sigma 1} \quad \text{Linearized Eq. of Motion} \quad (A.1a)
\]

\[
\frac{dn_{\sigma 1}}{dt} + n_{0}\nabla \cdot u_{\sigma 1} = 0 \quad \text{Linearized Continuity} \quad (A.1b)
\]

\[
E_{1} = -\nabla \phi_{1} - \frac{\partial A_{1}}{\partial t} \quad \text{Linearized Electric Field} \quad (A.1c)
\]

\[
\frac{P_{\sigma 1}}{P_{\sigma 0}} = \gamma \frac{n_{\sigma 1}}{n_{\sigma 0}} \quad \text{Linearized Eq. of State} \quad (A.1d)
\]

Taking the divergence of the linearized equation of motion, substituting both the linearized continuity and the linearized equation of state into it, and making use of the ideal gas law \(P_{\sigma 0} = n_{\sigma 0}\kappa T_{\sigma 0}\), where \(\kappa\) is the Boltzmann constant\(^1\)) yields

\[
m_{\sigma} \frac{\partial^{2}n_{\sigma 1}}{\partial t^{2}} = q_{\sigma}n_{\sigma 0}\nabla^{2}\phi_{1} + \gamma\kappa T_{\sigma 0}\nabla^{2}.n_{\sigma 1} \quad (A.2)
\]

Assuming that both \(n\) and \(\phi\) are proportional to \(\exp(i \mathbf{k} \cdot \mathbf{x} - i \omega t)\), means that \(\nabla \rightarrow i \mathbf{k}\) and \(\partial/\partial t \rightarrow -i \omega\); using these in Equation A.2 yields a purely algebraic form

\[
m_{\sigma}\omega^{2}n_{\sigma 1} = q_{\sigma}n_{\sigma 0}k^{2}\phi_{1} + \gamma\kappa T_{\sigma 0}k^{2}n_{\sigma 1}. \quad (A.3)
\]

Poisson’s equation relates \(n\) and \(\phi\)

\[
k^{2}\phi_{1} = \frac{n_{e 1}q_{e}}{\epsilon_{0}} + \frac{n_{i 1}q_{i}}{\epsilon_{0}}. \quad (A.4)
\]

\(^1\)Although \(k\) is traditional, it is already taken by wave number.
Solving Equation A.3 for \( n_{\sigma 1} \) and plugging it into Poisson’s equation yields

\[ (1 + \chi_e + \chi_i)\phi_1 = 0, \quad (A.5) \]

where \( \chi_\sigma \) is known as the susceptibility, defined as

\[ \chi_\sigma = -\frac{\omega_{p\sigma}^2}{\omega^2 - \gamma k^2 \kappa T_{\sigma 0}/m_\sigma}, \quad (A.6) \]

and \( \omega_{p\sigma} \) is the plasma frequency. For Equation A.5 to be true for all \( \phi_1 \), then

\[ 1 + \chi_e + \chi_i = 0, \quad (A.7) \]

this is known as the dispersion relation.

There are two limiting behaviors of the susceptibility, Equation A.6. If the phase velocity of the density fluctuation, \( \omega/k \), is much greater than the thermal velocity, \( \sqrt{\kappa T_{\sigma 0}/m_\sigma} \), the behavior is said to be adiabatic. In this scenario, the density fluctuation travels faster than the thermal velocity, so isothermal conditions cannot be maintained and adiabatic conditions exist. On the other hand, if phase velocity of the density fluctuation, \( \omega/k \), is much less than the thermal velocity, \( \sqrt{\kappa T_{\sigma 0}/m_\sigma} \), the behavior is said to be isothermal. In this scenario, the density fluctuation travels slower than the thermal velocity, so the plasma can maintain a constant temperature. In these cases, the susceptibility reduces as follows

\[ \chi_\sigma = -\frac{1}{k^2 \lambda_{D\sigma}^2 \omega^2 m_\sigma} \left( 1 + 3 \frac{k^2 \kappa T_{\sigma 0}}{\omega^2 m_\sigma} \right) \quad \text{for Adiabatic: } \omega/k \gg \sqrt{\kappa T_{\sigma 0}/m_\sigma}, \quad (A.8a) \]

\[ \chi_\sigma = \frac{\sigma_{\nu\sigma}^2}{k^2 \kappa T_{\sigma 0}/m_\sigma} = \frac{1}{k^2 \lambda_{D\sigma}^2} \quad \text{for Isothermal: } \omega/k \ll \sqrt{\kappa T_{\sigma 0}/m_\sigma}. \quad (A.8b) \]

There are two electron density fluctuations of interest, which are discussed here.
qualitatively before being addressed mathematically. For the first scenario, the electron density fluctuation is assumed to travel much faster than either the electron or the ion thermal velocity and both the electron and ion behavior are treated adiabatically. Because electrons are so much lower in mass, their behavior dominates and the ion behavior can be neglected in this case entirely. Physically, in this case where the ions are stationary and the electrons oscillate. This is the Electron Plasma Wave, or EPW.

For the second scenario, the density fluctuation velocity is assumed to be between the electron and ion thermal velocity; that is, greater than the ion thermal velocity and less than the electron thermal velocity. Therefore the ions are treated adiabatically and the electrons are treated isothermally. Physically, this is the case where the ions oscillate and thereby force the electrons to oscillate as well. (Because of the difference in mass, ions can ignore electrons, but not vice versa.) This is the Ion Acoustic Wave, or IAW.

To address the EPW, both electrons and ions are taken to be adiabatic. After substituting Equation A.8a into Equation A.7, dropping the ion contribution because \( \omega_{pe}^2 \gg \omega_{pi}^2 \), and using the zeroth order solution, \( \omega = \omega_{pe} \), in the thermal term, the expression for the electron plasma wave frequency becomes

\[
\omega^2 = \omega_{pe}^2 + 3k^2 \frac{kT_e0}{m_e}.
\]  

To address the IAW, the ions are taken to be adiabatic and the electrons are taken to be isothermal. Substituting Equation eq:suscept-iso for the electron contribution and Equation eq:suscept-ad for the ion contribution to the dispersion relation, defining an ion acoustic velocity, \( c_s^2 = kT_e/m_i \), and once again using the zeroth order solution
in the thermal term yields the expression for the ion acoustic wave frequency,

\[ \omega^2 = \frac{k_i^2 c_i^2}{1 + k^2 \lambda_{De}^2} + 3k^2 k T_{i0} \frac{\kappa T_{i0}}{m_i}. \]  
(A.10)

**A.3.4 Predicting EPW and IAW Peaks**

As seen in Figure A.6, an incident wave with k-vector \( \mathbf{k}_i \) scatters off a moving charge to create \( \mathbf{k}_s = \mathbf{k}_s - \mathbf{k}_i \); there is an angle \( \theta \) between the two k-vectors. For Thomson scattering, there will be an overall Doppler shift depending on \( \mathbf{k} \mathbf{v} \) where \( \mathbf{v} \) is the bulk velocity of the plasma. Ideally, the experiment is designed such that \( \mathbf{k} \) and \( \mathbf{v} \) are parallel. The \( \mathbf{k} \), therefore, is also fixed and the experiment is typically designed around it.

![Figure A.6: Scattering k-vector diagram. (Image credit Froula et al. (2011))](image)

This derivation follows Froula et al. (2011). The incident and scattered waves are governed by the dispersion relations,

\[ k_i^2 c_i^2 - \omega_i^2 + \omega_{pe}^2 = 0, \]  
(A.11a)

\[ k_s^2 c_s^2 - \omega_s^2 + \omega_{pe}^2 = 0, \]  
(A.11b)

where \( k \) is the wavenumber, \( c \) is the speed of light, \( \omega \) is the frequency, and \( \omega_{pe} \) is the electron plasma frequency.
From the law of cosines, we see that $|k| = (k_s^2 + k_i^2 - 2k_sk_i \cos \theta)^{1/2}$. For $v/c \ll 1$, the difference between $k_s$ and $k_i$ is small (small Doppler shift), and this reduces to

$$|k| \simeq 2|k_i| \sin(\theta/2).$$  \hspace{1cm} (A.12)

### A.3.4.1 Ion Acoustic Wave

The spectrum will have an overall Doppler shift according to

$$\frac{\Delta \lambda}{\lambda_i} = \sqrt{\frac{1 - v/c}{1 + v/c}} - 1,$$  \hspace{1cm} (A.13)

where $v$ is the velocity parallel to $k$ and $c$ is the speed of light. For an incident wave of $\lambda_i = 526.5$, the Doppler shift will range from about 0.1 nm for a plasma flowing at 50 km s$^{-1}$ to a shift of 1 nm for a plasma flowing at 500 km s$^{-1}$. Although technically, the Doppler shift affects both the IAW and EPW portions of the spectra, in practice the shifts are too small to be visible in the EPW spectra.

The ion acoustic dispersion relation from Froula et al. (2011) (Eq. 5.3.9) is,

$$\omega_{iaw} \simeq \pm k \left( \frac{\alpha^2 Z \kappa T_e}{(1 + \alpha^2)m_i} + \frac{3\kappa T_i}{m_i} \right)^{1/2},$$  \hspace{1cm} (A.14)

where $\omega_{iaw}$ is the IAW frequency, $\alpha = 1/k\lambda_{De}$ where $\lambda_{De}$ is the Debye length, $Z$ is the ionization, and $\kappa$ is the Boltzmann constant; this is simply a rearrangement of Equation A.14. The frequency separation between the peaks will be twice this. Substituting the expression for $k$, $k_{iaw} \simeq 2k_i \sin(\theta/2)$ (Eq. A.12), into Equation A.14 results in

$$\Delta \omega_{iaw} \simeq 4k_i \sin \left( \frac{\theta}{2} \right) \left( \frac{Z \kappa T_e}{(1 + k_{ia}^2 \lambda_{De}^2)m_i} + \frac{3\kappa T_i}{m_i} \right)^{1/2},$$  \hspace{1cm} (A.15)

This is expression is easier to use when written in terms of wavelength. Because
\[ \Delta \lambda / \lambda = \Delta \omega / \omega, \text{ and } k = \omega / c, \]

\[ \frac{\Delta \lambda_{\text{IAW}}}{\lambda_i} \simeq \frac{4}{c} \sin \left( \frac{\theta}{2} \right) \sqrt{\frac{\kappa T_e}{m_i} \left[ \frac{Z}{1 + k_{\text{IAW}}^2 \lambda_{De}^2} + \frac{3 T_i}{T_e} \right]} . \tag{A.16} \]

which is Eq. 5.4.4 from Froula et al. (2011).

As seen from Equation A.16, the separation between the IAW peaks depends on \( T_e \) and \( T_i \), not \( n_e \), and as seen in Figure A.7 the separation varies from roughly 0.1 to 1 nm in the range of temperatures of interest. As noted above, this is on the same scale as the Doppler shift.

### A.3.4.2 Electron Plasma Wave

Beginning with the electron plasma wave dispersion relation, Equation A.9, and substituting Eq. A.11a and A.11b, and assuming that,

\[ \frac{\omega_{pe}^2}{c^2 k_i^2} = \frac{4 \pi n_e e^2}{m_e c^2 k_i^2} = \frac{n_e}{n_c}, \tag{A.17} \]

where \( n_c \) is the critical electron density (see Section A.3.7), yields the separation expression for EPW waves, Eq. 5.4.6 in Froula et al. (2011):

\[ \frac{\Delta \lambda_{\text{EPW}}}{\lambda_i} \simeq 2 \left[ \frac{n_e}{n_c} + \frac{3 \kappa T_e}{m_e c^2} \right]^{1/2} \left( 1 + \frac{3 n_e}{2 n_c} \right) . \tag{A.18} \]

As seen from Equation A.18, the separation between the EPW peaks depends increases with increasing \( n_e \) and \( T_e \), and as seen in Figure A.7, in the range of plasma parameters we care about ranges from 20 to 200 nm. Earlier we stated that 0.1\( n_c \) was a rule of thumb limit for Thomson scattering. As seen from Figure A.7, as the electron density approaches this limit, the \( n_e / n_c \) term dominates and the separation does not change much with \( T_e \). This is another indication that Thomson scattering is becoming less useful as the limit is approached.
Figure A.7: Typical IAW and EPW peak differences. $\Delta \lambda_{\text{iaw}}$ (left) and $\Delta \lambda_{\text{epw}}$ (right) for typical ranges of experimental plasma parameters.

A.3.5 Numerically Calculating the Form Factor

A.3.5.1 Formulae

The form factor, Eq. D.1 in Froula et al. (2011), is

$$S(k, \omega) = \left| \frac{1 + \chi_i}{\epsilon} \right|^2 f_e(\omega/k) + Z \left| \frac{\chi_e}{\epsilon} \right|^2 f_i(\omega/k),$$  \hspace{1cm} (A.19)

where $k$ is the wave number, $\omega$ is the frequency, $f_e(\omega/k)$ and $f_i(\omega/k)$ are the normalized, one-dimensional electron, and $\chi_e$ and $\chi_i$ are the electron and ion contributions to the dielectric function, $\epsilon = \chi_e + \chi_i + 1$.

The velocity distributions, $f_e(\omega/k)$ and $f_i(\omega/k)$, are

$$f_\alpha(\omega/k) = \left( \frac{1}{2\pi} \right)^{1/2} \frac{c}{v_{\text{th},\alpha}} e^{-\omega^2/(2k^2v_{\text{th},\alpha}^2)},$$  \hspace{1cm} (A.20)

where $\alpha$ may either be $e$ or $i$, and $v_{\text{th},\alpha}$ is the thermal velocity.
The dielectric function components, \( \chi_e \) and \( \chi_i \), are

\[
\chi_\alpha(\omega, k) = -\frac{1}{2} \frac{1}{(k \lambda_{d,\alpha})^2} \frac{1}{\delta} W(\xi),
\]

where \( \lambda_{d,\alpha} \) is the Debye length and \( W \) is the plasma dispersion function, expressed as a function of the parameter \( \xi = \omega / \sqrt{2 k v_{th,\alpha}} \),

\[
W(\xi) = \left(\frac{1}{\pi}\right)^{1/2} \int_{-\infty}^{\infty} dz \frac{e^{-z^2}}{z - \xi}.
\]

A.3.5.2 Numerical Code

Thomson spectrum calculator takes the following inputs:

- The electron temperature, \( T_e \), in eV.
- The ion temperature, \( T_i \), in eV.
- A vector with the maximum ionization state, \( Z \), for each species in the plasma. For CH plasma, \( Z = [1, 6] \).
- A vector with the atomic weight (in proton masses), \( A \), for each species in the plasma. For CH plasma, \( A = [1, 12] \).
- A vector with the fractional composition of each species in the plasma. For CH plasma, \( \text{fract} = [0.5, 0.5] \).
- The electron number density, \( n_e \), in cm\(^{-3} \).
- The velocity parallel to the k-vector, \( v_a \), in cm s\(^{-1} \).
- The drift velocity of the electrons relative to the ions, \( u_d \), in cm s\(^{-1} \).
- The scattered frequency, \( \omega_s \), in rad s\(^{-1} \). \( \omega_s \) is an array with several thousand values centered on \( \omega_L \), the frequency of the incident laser probe beam. The
purpose of the code is to obtain a vector $S$, the scattered power spectrum, as a functions of $\omega_s$.

- The frequency of the incident laser probe beam, $\omega_L$, in rad s$^{-1}$.
- The scattering angle, $\theta$, in degrees. (The code calls this “sa”.) For the set-up at OMEGA, $\theta = 63^\circ$.
- The angle between the plane of polarization and the scattering plane, $\phi$, in degrees. For the set-up at OMEGA, $\phi = 90^\circ$.
- The angle in degrees, $\gamma$, between the drift velocity, $u_d$, and the k-vector. For the set-up at OMEGA, $\gamma = 0^\circ$.

The code published in Froula et al. (2011) takes the following steps:

1. Before running the Thomson predictor, run a separate code to create a table $\xi \rightarrow (k\lambda_{d,\alpha})^2\chi_\alpha$.

2. The code takes in $\omega_L$, the frequency of the incident laser, and $\omega_s$, an array of scattered frequencies centered on $\omega_L$, as inputs. It finds $\omega = \omega_s - \omega_L$, where $\omega$, like $\omega_s$ is an array.

3. Find $k_s$ by solving $\omega_s^2 = \omega_{pe}^2 + c^2 k_s^2$. $k_s$ is also an array.

4. Find $k$ using the Law of Cosines and the scattering angle $k^2 = k_s^2 + k_i^2 - 2k_s k_i \cos \theta$. At this point, the code has four arrays: $\omega_s$, the range of scattered frequencies for which we want to find $S(k, \omega)$, and arrays with the corresponding values of $\omega$, $k_s$, $k$.

5. Calculate the various plasma quantities such as $v_{th}$ and $\lambda_D$.

6. For every value in the array $\omega_s$,

   (a) Get the corresponding values of $\omega$ and $k$. 

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(b) Calculate $\xi$.

(c) Use the $\xi \rightarrow (k\lambda_{d,\alpha})^2\chi_\alpha$ table to find $(k\lambda_{d,\alpha})^2\chi_\alpha$.

(d) Plug everything into Equation A.19 to find $S(k,\omega)$.

7. Convert $\omega_s$ to $\lambda_s$. Normalize the scattered spectrum and plot it against $\lambda_s$.

A.3.6 Example of Spectra Fitting

Every experimental spectrum is hand fit using the spectrum generator discussed in Section A.3.5. The plasma parameters ($n_e$, $T_e$, $T_i$, and $v_a$) are varied and the predicted spectrum is plotted alongside the experimental data until a close fit is obtained, see Figures A.8 and A.9, which show a pair of spectra obtained in April 2012.

The electron plasma wave spectrum is used to determine $n_e$ and $T_e$, while the ion acoustic wave spectrum is used to determine $v_a$ and $T_i$. As seen in Figure A.9, the IAW spectra from April 2012 were not clear enough to distinguish between different values of $T_i$.

A.3.7 Problems Encountered in Thomson Scattering

In addition to the geometry concerns discussed in Section A.3.2, there are four additional concerns to consider:

1. The density is too low and the plasma is not in the collection scattering regime.

2. The density is too high and the probe beam reflects off the plasma.

3. The probe energy is too high and heats the experimental plasma significantly.

A.3.7.1 Collective vs. Non-Collective

At what density does a plasma scatter incident radiation collectively? Consider two scale lengths: the wavelength of incident wave and the Debye wavelength, “the
Figure A.8: An example of fitting EPW data. Fitting single jet spectrum taken 13.5 ns after drive. Above: the full spectrum with three potential $T_e$ values (left) and zoomed view of the higher peak (right). Below: the full spectrum with three potential $n_e$ values (left) and zoomed view of the higher peak (right). This spectrum (taken 13.5 ns after drive) had the best fit with $T_e = 110$ eV and $n_e = 1.6 \times 10^{18}$.

Figure A.9: An example of fitting IAW data. Many IAW appeared to have erroneous peaks of reflected light, but velocity data could still be obtained by fitting the Doppler shift. Left: the IAW data corresponding to Figure A.8. Right: One of the clearest examples of a IAW data we obtained.
characteristic distance over which the potential of a charge is shielded by neighboring charges” (Froula et al., 2011).

If the Debye wavelength is smaller than the wavelength of the incident wave, the wave “sees” many charges together and the scattering will be collective. If the wavelength of the incident wave is smaller than the Debye wavelength, the wave “sees” the charges individually and the scattering will be non-collective.

If we introduce a parameter $\alpha$,

$$\alpha = \frac{1}{k\lambda_{De}} = \frac{1.08 \times 10^{-4} \lambda_i \text{ cm}}{\sin \theta/2} \left[ \frac{n_e \text{ cm}^{-3}}{T_e \text{ eV}} \right]^{1/2},$$

(A.23)

then $\alpha \ll 1$ is non-collective and $\alpha \gg 1$ is collective. Here we have once again made use of $k \approx 2k_i \sin(\theta/2)$.

Figure A.10 shows $\alpha$ over a range of typical experimental parameters for a $2\omega$ (526.5 nm), $\theta = 63^\circ$ Thomson scattering set-up. For low temperatures ($T_e < 20 \text{ eV}$), collective ($\alpha > 1$) scattering occurs at electron densities above $10^{17} \text{ g cm}^{-3}$. At higher temperatures, the electron density must be somewhat higher ($> 10^{18}$) for collective scattering.

**A.3.7.2 Critical Density**

At what point does the plasma become too dense for the incident wave to penetrate it? Referring to A.11a,

$$k_i^2 c^2 - \omega_i^2 + \omega_{pe}^2 = 0$$

(A.24)

for $\omega_i > \omega_{pe}$, the wavenumber $k_i$ is real and the wave is transmitted through the plasma; for $\omega_i < \omega_{pe}$ the wavenumber is imaginary and the wave is not transmitted. The electron density at which $\omega_{pe} = \omega_i$ is the critical density,

$$n_c = \frac{\omega_i^2 m_e}{4\pi e^2} = \frac{\pi c^2 m_e}{\lambda_i^2 e^2}.$$  

(A.25)
As an example, for 526.5 nm, \( n_e = 4 \times 10^{21} \text{ cm}^{-3} \). As a rule of thumb, densities below 0.1\( n_e \) are considered reasonable to attempt with Thomson scattering.

### A.3.7.3 Probe Heating

As the probe beam scatters off the experimental plasma, some fraction of it is absorbed and heats the plasma. At what point does this become significant enough to interfere with Thomson scattering? The maximum temperature increase can be estimated by comparing the energy deposited per unit volume to the thermal energy per unit volume. For example, if the energy deposited is equal to the initial thermal energy then we might expect the temperature to double, at most.

Average power dissipated (in MKS, eq. 6.6.3 from Froula et al. (2011))

\[
W_D = \frac{n_e^2 \nu_{el} P_i}{m_e c \epsilon_0 \omega_i^2 A}
\]  

(A.26)

Dividing this by the \( \frac{3}{2} \kappa T_e n_e \), yields the estimated fractional temperature increase, Eq. 6.6.6 in Froula et al. (2011)

\[
\frac{\Delta T_e}{T_e} \approx 1.28 \times 10^5 \frac{n_i \ln \Lambda}{\omega_i^2 A [T_e]^{3/2}} \int_0^\tau P_i dt,
\]  

(A.27)

where \( \ln \Lambda \) is Coulomb lambda, \( A \) is the mean ion mass in \( m_p \), and \( \int_0^\tau P_i dt \) is the incident power integrated over the pulse length. All quantities in Eq. A.27 are in CGS units except \( T_e \), which is in eV. As seen in Figure A.10, probe heating will exceed 10% for most experimental plasma conditions.

### A.4 Visible Light Imaging

As related in Section A.3.2, when the Thomson scattering set-up is installed, a telescope in TIM 6 collects light from TCC and directs it the Thomson cart, where it
is split into three legs: one for EPW, one for IAW, and one for the 2-D imager. This 2D imager is known as the Two Plasmon Decay Imager, or TPDI. The 2-D imager was originally added to the cart as ride-along diagnostic, something that could provide a bit of extra data and that could help to troubleshoot problems with Thomson scattering. However, it has since become the most reliable 2-D visible light imager at OMEGA.

In layman’s terms, TPDI simply takes a picture of TCC. Its field of view depends on which telescope is installed; the experimenter can request either a 2 mm or 4 mm field of view. TPDI is typically filtered with a long-pass filter to protect it from 3ω light and one or several neutral density filters.

TPDI has a minimum gate length of 3 ns. Timing of TPDI does not need to be coincident with the drive beams or the probe beam. Nor does the rest of the Thomson set-up need to be used with TPDI; for this thesis project, TPDI was used alone for the accretion shock experiment.
Summary of Shot Days

This appendix provides a detailed summary of the shot days themselves. The motivations of the experiments, the data collected, and the analysis of that data were addressed in Chapters III, IV, and V. This appendix includes information that would be of interest to a fellow OMEGA user: the TIM assignments, shot sequences, and so forth. The shot days are as follows:

1. April 2012—A full shot day devoted to testing a new method of creating collimated plasma jets. Jets were fired individually and in head-on collisions and were probed with $2\omega$ Thomson scattering. Both the jet-creation method and $2\omega$ Thomson scattering proved successful and both were used on subsequent shot days. See Section B.1. Complete data for this day are in Appendix C.

2. August 2013—A full shot day devoted to the idea of creating a scaled accretion disk inside an imposed cusp magnetic field. Difficulties encountered during this shot day, along with questions about the inherent feasibility of scaling an entire accretion disk in a laboratory experiment, lead to the scope of the project narrowing. Section B.2. Complete data for this day are in Appendix D.
3. May 2014—The first shot day devoted to pursuing the idea of creating a scaled accretion shock in the laboratory. Half the day was devoted to the accretion shock experiment, half was devoted to continued probing of plasma jets with Thomson scattering. Unfortunately, the primary diagnostic on this shot day, proton radiography, failed. See Section B.3. Complete data for this day are in Appendix E.

4. May 2015—A second full shot day devoted to improving on the design of the May 2014 experiments. The targets were redesigned to allow proton both radiography and visible light imaging along opposite (180° apart) lines of sight. Unfortunately, proton radiography failed once again, albeit for a different reason than in May 2014. Visible light imaging was successful. See Section B.4. Complete data for this day are in Appendix F.

5. October 2015—Visible light imaging failed for one shot in May 2014. To fill in this data gap, we used two shots from a shot day devoted to a different campaign to retake the data. These shots have been included in Section B.4 as well. Complete data for this day are in Appendix F.

B.1 April 2012

B.1.1 Collaboration

I served as the graduate student primary investigator for this shot day under the guidance of Carolyn Kuranz and R. Paul Drake (both University of Michigan). The lead engineer for target manufacturing was Sallee Klein (Michigan) and CRASH simulations to help time the shots were performed by Ryan Sweeney (Michigan). Christine Krauland, then a senior graduate student at Michigan, was not deeply involved in the science of the shot day, but accompanied us to OMEGA and acted as a graduate student mentor for my first shot day.
The primary diagnostic for this shot day was Thomson scattering, and two Lawrence Livermore National Laboratory (LLNL) scientists joined the collaboration as experts in Thomson scattering: Dustin Froula (who has since moved to LLE) and Steve Ross.

B.1.2 Configuration

As discussed in Chapter III, the purpose of the April 2012 shot day was to test a method for creating collimated plasma jets. We launched jets through rear irradiation singly and in head-on collisions. Table B.1 lists the experimental parameters for April 18, 2012.

B.1.3 Shot Sequence

As noted in Table B.1, the two experimental targets were positioned using the dedicated target positioner in H2 and a TIM-based target positioner in TIM 4. We began shooting the H2 target alone. On shot days that use Thomson scattering as a diagnostic, TIM 4 (which sits opposite to TIM 6, the Thomson scattering TIM) is reserved for aligning the Thomson scattering set-up. Once Thomson scattering is aligned and several shots have used it successfully, the facility feels comfortable removing the alignment cart and using the TIM for something else. The first four shots of the day, 65762-65, were H2-only shots at various timings. We found that firing the Thomson probe 7 ns after drive was too early, but good data was obtained at 12 ns and 15 ns.

The facility was satisfied that alignment was complete and we were able to switch to using TIM 4 for target positioning. We shot the TIM 4 target alone at 15 ns, Shot 65766, for comparison with the 15-ns H2-only shots, then moved on to shooting both targets at once. We shot head-on collision shots at 15 ns and 20 ns, Shots 65767 and 65769; Shot 65769 was too late and the probe beam reflected off the plasma instead of penetrating and scattering. Finally, we filled out our data with two shots at 12 ns,
Shot 65770, a TIM 4-only shot, and 65774, a collision shot.

Table B.3 contains a list of shots and Table B.3 lists whether data was successfully taken for each one. This was a very successful day; losing a few shots due to probing too early or late is not only expected but desirable: it sets boundaries for where good data can be obtained. All told, we were able to use Thomson scattering to measure electron density, electron temperature and velocity from 12 ns to 18 ns, and we obtained multiple clear images of single and colliding jets evolving with time. Appendix C contains the complete data for this shot day and Chapter III provides discussion of the data.

B.1.4 Difficulties Encountered

We were remarkably fortunate and few difficulties were encountered. We found that the Gated Optical Imager produced poor images, while the imager attached to the Thomson scattering set-up (TPDI) produced high-quality images, see Figure B.1. Resultantly, we chose to never use GOI again.

![Figure B.1: A comparison of GOI (left) and TPDI (right) for shot 65766. The images are not expected to be identical, as the lines of sight and timings are different, but it is immediately obvious that one is either blur or lens flare, while the other is a recognizable jet.](image)
<table>
<thead>
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<th><strong>Target</strong></th>
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<tbody>
<tr>
<td>Material</td>
<td>CH</td>
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<tr>
<td>Solid density</td>
<td>1.18 g cm$^{-3}$</td>
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<tr>
<td>Cone opening angle</td>
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<td>Cone diameter</td>
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<tr>
<td>Cone thickness</td>
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<td>Distance to TCC</td>
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<table>
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<td>Number beams</td>
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<tr>
<td>Total drive energy</td>
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<td>Drive beam radius</td>
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<td>Wavelength</td>
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</tr>
<tr>
<td>Energy</td>
<td>120 J</td>
</tr>
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<tr>
<td>Radius</td>
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<td>TIM 2</td>
<td>Empty</td>
</tr>
<tr>
<td>TIM 3</td>
<td>Empty</td>
</tr>
<tr>
<td>TIM 4</td>
<td>TSS alignment or Target positioner</td>
</tr>
<tr>
<td>TIM 5</td>
<td>Off-axis ASBO telescope</td>
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<tr>
<td>TIM 6</td>
<td>Thomson scattering set-up (TSS)</td>
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<tr>
<td>H2</td>
<td>Target positioner (Thom. exp.)</td>
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Table B.1: Experimental parameters for April 2012. (Note: TIMs 2 and 3 were devoted to the other campaign, which utilized two shots out of this shot day.)
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<th>Cone(s)</th>
<th>Driver Timing</th>
<th>Thomson Timing</th>
<th>TPDI Timing</th>
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<td>10 ns</td>
<td>120 J</td>
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<td>39305</td>
<td>H2</td>
<td>−12 ns</td>
<td>0 ns</td>
<td>10 ns</td>
<td>120 J</td>
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<td>39306</td>
<td>H2</td>
<td>−15 ns</td>
<td>0 ns</td>
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<td>39389</td>
<td>H2</td>
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<td>0 ns</td>
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<td>120 J</td>
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<td>65766</td>
<td>38543</td>
<td>TIM 4</td>
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<td>0 ns</td>
<td>10 ns</td>
<td>120 J</td>
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<td>38493</td>
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<td>0 ns</td>
<td>10 ns</td>
<td>120 J</td>
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<td>65774</td>
<td>39303</td>
<td>Both</td>
<td>−12 ns</td>
<td>0 ns</td>
<td>8 ns</td>
<td>120 J</td>
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Table B.2: Shots on April 18, 2012. TPDI filtering was ND 1.0 plus long pass filter for all shots. (Note: two shots on this day (65772 and 65773) were devoted to another campaign and are not included here.)

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<th>SRF</th>
<th>EPW Data?</th>
<th>IAW Data?</th>
<th>TPDI Data?</th>
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<td>65762</td>
<td>38542</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>Too early</td>
</tr>
<tr>
<td>65763</td>
<td>39305</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>Target blocked view (see note)</td>
</tr>
<tr>
<td>65764</td>
<td>39306</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>Target blocked view (see note)</td>
</tr>
<tr>
<td>65765</td>
<td>39389</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>Target blocked view (see note)</td>
</tr>
<tr>
<td>65766</td>
<td>38543</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Good single jet image</td>
</tr>
<tr>
<td>65767</td>
<td>38493</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Good colliding jet image</td>
</tr>
<tr>
<td>65769</td>
<td>39302</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>Density too high; probe reflected</td>
</tr>
<tr>
<td>65770</td>
<td>39307</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Good single jet image</td>
</tr>
<tr>
<td>65774</td>
<td>39303</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Best colliding jet image</td>
</tr>
</tbody>
</table>

Table B.3: Data taken on April 18, 2012. Note: For single jet experiments with the target mounted in H2, the target itself blocks the view of the jet. These images are clear, but there is little to see.
B.2 August 2013

B.2.1 Collaboration

The collaboration for this shot day was built off of that of April 2012. Once again, I was the graduate student primary investigator, working under Carolyn Kuranz and R. Paul Drake. The target manufacturing was lead by Sallee Klein and CRASH simulations were performed in support of the project by Matthew Trantham and Michael Grosskopf. The Thomson scattering collaboration from April 2012 also carried over; both Dustin Froula and Steve Ross were involved.

As this shot day added two additional systems at OMEGA, we expanded our collaboration. Gennady Fiksel was the lead scientist at OMEGA for MIFEDS, with Po-Yu Chang (an OMEGA post-doc) and graduate student Daniel Barnak (University of Rochester) working underneath him. Chikang Li (Massachusetts Institute of Technology) joined the collaboration to lead proton radiography, with then-graduate student Alex Zylstra working with him.

B.2.2 Configuration

As discussed in Chapter V, the August 2013 shot day was intended to serve as a stepping stone towards creating a rotating plasma disk with a “twisted wagon wheel” design.

We built two configurations for August 2013, both intended to work towards the Ryutov (2011) disk scheme. As seen in Table B.4, both configurations were designed to launch three jets, alone or in a colliding experiment. Table B.5 lists all the vital statistics for the experiment.

For imaging Thomson, the probe beam must illuminate an extended (in space) section of the experiment, which means the experimenter has fewer choices about how to position the experiment relative to the fixed Thomson probe beam. Generally,
<table>
<thead>
<tr>
<th>Imaging Thom. Config.</th>
<th>MIFEDS Config.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary purpose</td>
<td>Imaging Thomson</td>
</tr>
<tr>
<td>Launch mechanism</td>
<td>Rear irrad., 4 beams</td>
</tr>
<tr>
<td>Number jets</td>
<td>3</td>
</tr>
<tr>
<td>Magnetic field?</td>
<td>No</td>
</tr>
<tr>
<td>Thomson scattering?</td>
<td>Imaging</td>
</tr>
<tr>
<td>Proton radiography?</td>
<td>No</td>
</tr>
<tr>
<td>Targets in chamber</td>
<td>1 (exp.)</td>
</tr>
</tbody>
</table>

Table B.4: Similarities and differences for the two configurations of August 2013

Experimenters choose to align the probe with the flow direction of the experiment; we chose to align the probe beam with Jet B, the central jet. Because the probe beam was aligned with Jet B, imaging Thomson could only be used with this Jet. It was, however, possible to use streaked Thomson with any of the three jets, since for streaked Thomson to work the jet and the beam only have to overlap at TCC.

The Imaging Thomson Configuration described in Table B.4 used a semi-circular target with three cones; a CAD (VisRad) rendering of this target from two different angles can be seen in Figure B.2. Whereas the April 2012 targets were machined out of solid CH, these targets were 3-D printed, except for the cones, which were attached later with glue.

Figure B.2: The imaging Thomson target of August 2013. Three jets can be launched, together or individually, and the imaging Thomson probe is aligned with the central jet, B.
The MIFEDS Configuration described in Table B.4 also had the capability to launch as many as three plasma jets and was designed around magnetic field generation and proton radiography. Like the Imaging Thomson Configuration, it consisted of three cones each 45° apart, which lay in the midplane of a cusp field, with a proton-generating backlighter 1 cm below the experiment and CR-39 30 cm above the experiment.

To build the target for this configuration, the entire support apparatus (the support for the MIFEDS wires, the semi-circular cone base and the stalk/support arm mounting it in TIM 1) was 3-D printed as one piece, then the cones were glued on and wire for the MIFEDS coils was wrapped around it. This (3-D printing followed by wire wrapping) is the normal way to make MIFEDS coils, but building the experimental target into the MIFEDS coil was something that had not been tried before, see Section B.2.4.2. This configuration also called for a proton backlighter, which was mounted in TIM 3.

Figure B.3: CAD renderings of the MIFEDS Configuration of August 2013. In the left image, the laser beams have been included; in the right they have been omitted.
B.2.3 Shot Sequence

Table B.6 lists the shots from August 15, 2013 and Table B.7 indicates whether data was obtained. Proton radiography data is not available until weeks later, so the only feedback we had on shot day was Thomson scattering.

We began the shot day with the MIFEDS Configuration. The Thomson probe beam in on the same leg as the proton backlighter beams, and all beams on a given leg must use the same pulse shape. Therefore because the backlighter needed a 1-ns pulse, the streaked Thomson scattering was required to use one as well. We shot Jet B only, first with drive beams 18 ns before the Thomson probe (Shot 70672) and then with drive 25 ns before (Shot 70673). Neither of these shots produced good Thomson data.

We decided to switch to Jet C and go later still, to 30 ns (Shot 70674). This shot produced good Thomson data, both EPW and IAW. At that point we decided to try to obtain imaging Thomson data. To pinpoint the timing we would need, we began shooting the Imaging Thomson Configuration with a long probe pulse, 3 ns. Our intention was to determine optimal timing, then do a shot or two with imaging Thomson. We tried shooting Jet B (the only jet that had the potential to work with imaging Thomson) with a 3-ns probe that lasted 30 ns to 33 ns (Shot 70678). Oddly, while Jet C had obtained good EPW data at 30 ns, Jet B did not. Curious to see if timing could solve the problem, we moved the probe to 40 ns to 43 ns (Shot 70679). The IAW signal became clearer, but EPW did not appear. We went later still, to 50 ns to 53 ns (Shot 70680), but the IAW showed signs of reflection, an indication that the density had climbed too high.

Frustrated at our inability to get imaging Thomson data, we switched back to the MIFEDS Configuration. Because we had gotten the best Thomson data at 40 ns, we decided to shoot B individually and B and C colliding, with and without a magnetic field, all at 40 ns, four shots at all (Shots 70681, 70682, 70683, and 70684). We shot
the shots with B field first, because MIFEDS has a tendency to fail and a shot where MIFEDS failed could be used as “no field” shot if we hadn’t already done it. This turned out to a wise decision; MIFEDS failed for Shot 70681, but this did not prevent us from getting the four shot matrix we wanted.

B.2.4 Difficulties Encountered

B.2.4.1 Electron Plasma Wave Data

EPW data consistently failed when shooting Jet B alone. When Jets B and C were shot together, good data EPW data obtained. Likewise, when Jet C was shot alone good EPW data was obtained. Since we were able to get good EPW data on several shots throughout day, this clears LLE of any blame for the problem. Clearly, the Thomson scattering set-up was aligned properly. So why did Jet B—and only Jet B—fail to produce EPW data?

One possible explanation is that there was a miscalculation in target design and/or alignment and somehow Jet B was not aimed at TCC. This would explain why experiments with B and C together and the single shot with C alone worked, while the shots with B alone failed. But the IAW data from shots with B alone were successful. In particular, Shots 70681 and 70682 returned very clear data, so there must have been some plasma at TCC to scatter the probe beam.

B.2.4.2 Target Design

As noted above, the MIFEDS Configuration target was built in one pice with the MIFEDS support, something that had not been done before. We were dissatisfied with the alignment precision this decision afforded us. While the MIFEDS system is sufficiently precise to align a current loop in the target chamber, it cannot rotate the target and turned out not to be precise enough to align an experimental target. For subsequent experiments using MIFEDS, we built experimental targets that were
separate from the MIFEDS coils.

However, it seems unlikely that this alignment problem was responsible for the missed EPW data discussed in B.2.4.1. Both configurations, Imaging Thomson and MIFEDS, failed to get EPW data when Jet B was shot alone, and the Imaging Thomson Configuration was mounted in the H2 target positioner, which has excellent precision.

B.2.4.3 Timing

Once we obtained the proton radiography data (several weeks after shot day) we regretted not going later in time. The images seem to show plasma structures beginning to move into the field of view, but did not show the structures that form at TCC when they collide. This problem underscores the need to do simulations of data prior to shot day to aid in shot timings.
<table>
<thead>
<tr>
<th>Target</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>CH</td>
</tr>
<tr>
<td>Solid density</td>
<td>1.18 g cm$^{-3}$</td>
</tr>
<tr>
<td>Cone opening angle</td>
<td>160°</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Cone thickness</td>
<td>100 µm</td>
</tr>
<tr>
<td>Distance to TCC</td>
<td>4 mm</td>
</tr>
<tr>
<td>Spacing between cones</td>
<td>45°</td>
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</table>

<table>
<thead>
<tr>
<th>Drive Beams</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive beam wavelength</td>
<td>351 nm ($3\omega$)</td>
</tr>
<tr>
<td>Number beams</td>
<td>4 per cone</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>1800 J</td>
</tr>
<tr>
<td>Drive beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>Drive beam radius</td>
<td>352 µm (SG4)</td>
</tr>
<tr>
<td>Drive irradiance</td>
<td>$5 \times 10^{14}$ W cm$^{-2}$</td>
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<table>
<thead>
<tr>
<th>Proton Backlighter Beams</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BL beam wavelength</td>
<td>351 nm ($3\omega$)</td>
</tr>
<tr>
<td>Number beams</td>
<td>16</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>7200 J</td>
</tr>
<tr>
<td>BL beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>BL beam focus</td>
<td>1.81 mm</td>
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<table>
<thead>
<tr>
<th>$4\omega$ Thomson beam</th>
<th></th>
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<tbody>
<tr>
<td>Wavelength</td>
<td>263.25 nm</td>
</tr>
<tr>
<td>Energy</td>
<td>50 J</td>
</tr>
<tr>
<td>Shape</td>
<td>1 ns or 3 ns, square</td>
</tr>
<tr>
<td>Radius</td>
<td>70 µm (best focus)</td>
</tr>
<tr>
<td>Angle between probe and collector</td>
<td>116.8°</td>
</tr>
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<table>
<thead>
<tr>
<th>TIM assignments</th>
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<tr>
<td>TIM 1</td>
<td>MIFEDS</td>
</tr>
<tr>
<td>TIM 2</td>
<td>Empty</td>
</tr>
<tr>
<td>TIM 3</td>
<td>Target positioner (BL)</td>
</tr>
<tr>
<td>TIM 4</td>
<td>TSS alignment</td>
</tr>
<tr>
<td>TIM 5</td>
<td>CR-39 (Wedge Range Filter)</td>
</tr>
<tr>
<td>TIM 6</td>
<td>Thomson scattering set-up (TSS)</td>
</tr>
<tr>
<td>H2</td>
<td>Target positioner (Thom. exp.)</td>
</tr>
</tbody>
</table>

Table B.5: Experimental parameters for August 15, 2013.
### Table B.6: Shots on August 15, 2013.

*MIFEDS was charged for Shot 70681, but it failed and this was a no-field shot.*

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>SRF</th>
<th>Cone(s)</th>
<th>Driver Timing</th>
<th>Thomson Timing</th>
<th>Proton Timing</th>
<th>Thomson Length</th>
<th>MIFEDS Charged?</th>
</tr>
</thead>
<tbody>
<tr>
<td>70672</td>
<td>44444</td>
<td>B</td>
<td>−18 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>Yes</td>
</tr>
<tr>
<td>70673</td>
<td>45203</td>
<td>B</td>
<td>−25 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>No</td>
</tr>
<tr>
<td>70674</td>
<td>45204</td>
<td>C</td>
<td>−30 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>No</td>
</tr>
<tr>
<td>70678</td>
<td>45211</td>
<td>B</td>
<td>−30 ns</td>
<td>0 ns</td>
<td>-</td>
<td>3 ns</td>
<td>-</td>
</tr>
<tr>
<td>70679</td>
<td>43746</td>
<td>B</td>
<td>−40 ns</td>
<td>0 ns</td>
<td>-</td>
<td>3 ns</td>
<td>-</td>
</tr>
<tr>
<td>70680</td>
<td>45210</td>
<td>B</td>
<td>−50 ns</td>
<td>0 ns</td>
<td>-</td>
<td>3 ns</td>
<td>-</td>
</tr>
<tr>
<td>70681</td>
<td>45205</td>
<td>B</td>
<td>−40 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>Yes*</td>
</tr>
<tr>
<td>70682</td>
<td>45206</td>
<td>B</td>
<td>−40 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>Yes</td>
</tr>
<tr>
<td>70683</td>
<td>45207</td>
<td>B&amp;C</td>
<td>−40 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>Yes</td>
</tr>
<tr>
<td>70684</td>
<td>44574</td>
<td>B&amp;C</td>
<td>−40 ns</td>
<td>0 ns</td>
<td>2 ns</td>
<td>1 ns</td>
<td>No</td>
</tr>
</tbody>
</table>

### Table B.7: Data from August 15, 2013.

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>SRF</th>
<th>EPW Data?</th>
<th>IAW Data?</th>
<th>PR Data?</th>
<th>MIFEDS?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>70672</td>
<td>44444</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>Charged</td>
<td>Too early</td>
</tr>
<tr>
<td>70673</td>
<td>45203</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>Not charged</td>
<td>Faint “bubble” on PR</td>
</tr>
<tr>
<td>70674</td>
<td>45204</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Not charged</td>
<td>Good TS, bubble on PR</td>
</tr>
<tr>
<td>70678</td>
<td>45211</td>
<td>✗</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>Marginal IAW data</td>
</tr>
<tr>
<td>70679</td>
<td>43746</td>
<td>✗</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>Very good IAW data</td>
</tr>
<tr>
<td>70680</td>
<td>45210</td>
<td>✗</td>
<td>✓</td>
<td>-</td>
<td>-</td>
<td>Marginal IAW data</td>
</tr>
<tr>
<td>70681</td>
<td>45205</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>Failed</td>
<td>Good IAW, crisp bubble</td>
</tr>
<tr>
<td>70682</td>
<td>45206</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>Charged</td>
<td>Good IAW, garbled bubble</td>
</tr>
<tr>
<td>70683</td>
<td>45207</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>Charged</td>
<td>Good TS, two bubbles</td>
</tr>
<tr>
<td>70684</td>
<td>44574</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>Not charged</td>
<td>Good TS, PR failed</td>
</tr>
</tbody>
</table>

Table B.7: Data from August 15, 2013.
B.3 May 2014 Shot Day

B.3.1 Collaboration

The decision to pursue a scaled accretion shock in the laboratory was made with the intention of building a collaboration with Patrick Hartigan, an astrophysicist from Rice University who became a Co-Primary Investigator with Carolyn Kuranz. Mario Manuel also joined our group as a post-doctoral fellow around that time. The scaling work detailed in Chapter II was completed during this time period. Andy Liao, a graduate student from Rice, completed some simulations related to timing using the code EPOCH.

Other than the addition of Rice, little about the collaboration changed from August 2013 (Section B.2.1). Sallee Klein lead target manufacturing; Chikang Li lead proton radiography; Gennady Fiksel lead MIFEDS support; and Dustin Froula and Steve Ross provided insights for Thomson scattering.

B.3.2 Configuration

There were two configurations for the May 2014 shot day: an Imaging Thomson Configuration and an Accretion Configuration, see Table B.8. Both configurations created plasma jets under identical conditions: a thin CH cone was rear irradiated by seven full power OMEGA beams. The Imaging Thomson Configuration, which we shot for the first half of the day, aimed the jet along the $4\omega$ Thomson probe beam in order to study plasma properties. The Accretion Shock Configuration, which we shot for the second half of the day, aimed the jet towards a solid block and imaged the resulting shock with proton radiography. Table B.9 lists the experimental parameters of May 8, 2014.

The Imaging Thomson Configuration consisted single target in the chamber to create a plasma jet, see Figure B.4. The design was based on the successful design of
Table B.8: Similarities and differences for the two configurations on May 8, 2014.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary purpose</td>
<td>Imaging Thomson</td>
<td>Scaled Acc. Shock</td>
</tr>
<tr>
<td>Launch mechanism</td>
<td>Rear irrad., 7 beams</td>
<td>Rear irrad., 7 beams</td>
</tr>
<tr>
<td>Number jets</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Impact surface?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Magnetic field?</td>
<td>Yes, MIFEDS</td>
<td>No</td>
</tr>
<tr>
<td>Thomson scattering?</td>
<td>Imaging</td>
<td>No</td>
</tr>
<tr>
<td>Proton radiography?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Targets in chamber</td>
<td>1 (exp.)</td>
<td>3 (exp., BL, MIFEDS)</td>
</tr>
</tbody>
</table>

April 2012 (see Figure 3.6): a cone was machined into one side of an acrylic block. With such a simple target design, alignment errors such as we experienced in August 2013 were nearly impossible. As seen in Figure B.4, the Thomson probe beam fired along the length of the jet; this set-up is identical to that of Figure A.2.

The Accretion Shock Configuration has been discussed at length in Chapter IV.

Figure B.4: CAD renderings of the Imaging Thomson Configuration from May 8, 2014. Laser beams are shown in the left view, but omitted from the right view.

B.3.3 Shot Sequence

We began the day with the Imaging Thomson Configuration (OMEGA staff always prefer to have Thomson shots early because of the set-up time needed). We experimented with different timings to find the lower and upper timing limits to get-
ting Thomson scattering data. We found that 16 ns was too early. The following shot found that 20 ns produced good IAW data, but our attempt to jump much later, 28 ns failed. The uneven image that we saw suggested that the density had risen too high and the plasma was reflecting the probe beam. We fell back to 24 ns but there was still evidence of reflection. For our fifth and final Thomson shot we repeated the 20 ns shot and again obtained good IAW data.

Frustratingly, we were never able to get EPW data. Our experience was somewhat like that of August 2013, except that shot day used streaked Thomson scattering as well, whereas this shot used imaging Thomson exclusively. This failure is discussed in more detail in the next section.

The second half of the day was dedicated to the Accretion Shock Configuration. We began with a control shot; no field was imposed. We then decided to complete a three by two matrix of shots: 30, 50, and 70 ns, with either a high field (7 T) or a low field (3 T). We did completed the 30-ns and 50-ns shots first. We were told that MIFEDS failed for Shot 73336 (which was intended to be high field, 30 ns), so that shot was repeated, but the proton radiography suggests that there was a field. Having completed the 30-ns and 50-ns portion of the matrix, we moved on to the 70-ns shots, but unfortunately MIFEDS failed for the high field 70-ns shot.

Table B.10 lists the parameters for the thirteen shots on May 8, 2014 and Table B.11 lists whether data was successful.
### Target

<table>
<thead>
<tr>
<th>Material</th>
<th>CH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid density</td>
<td>1.18 g cm$^{-3}$</td>
</tr>
<tr>
<td>Cone opening angle</td>
<td>160°</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Cone thickness</td>
<td>100 µm</td>
</tr>
<tr>
<td>Distance to TCC</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

### Drive Beams

<table>
<thead>
<tr>
<th>Drive beam wavelength</th>
<th>351 nm (3ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number beams</td>
<td>7</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>3150 J</td>
</tr>
<tr>
<td>Drive beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>Drive beam radius</td>
<td>352 µm (SG4)</td>
</tr>
<tr>
<td>Drive irradiance</td>
<td>$8 \times 10^{14}$ W cm$^{-2}$</td>
</tr>
</tbody>
</table>

### Backlighter Beams

<table>
<thead>
<tr>
<th>Drive beam wavelength</th>
<th>351 nm (3ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number beams</td>
<td>15</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>6750 J</td>
</tr>
<tr>
<td>Drive beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>Drive beam focus</td>
<td>1.81 mm</td>
</tr>
</tbody>
</table>

### Imaging Thomson Beam

| Wavelength | 263.25 nm |
| Energy | 50 J |
| Shape | 0.5 ns, square |
| Radius | 70 µm (best focus) |
| Angle between probe and collector | 116.8° |

### TIM assignments

<table>
<thead>
<tr>
<th>TIM</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM 1</td>
<td>MIFEDS</td>
</tr>
<tr>
<td>TIM 2</td>
<td>CR-39</td>
</tr>
<tr>
<td>TIM 3</td>
<td>Target positioner (Shock Exp)</td>
</tr>
<tr>
<td>TIM 4</td>
<td>TSS alignment/Target positioner (BL)</td>
</tr>
<tr>
<td>TIM 5</td>
<td>Particle temporal diagnostic</td>
</tr>
<tr>
<td>TIM 6</td>
<td>Thomson scattering set-up (TSS)</td>
</tr>
<tr>
<td>H2</td>
<td>Target positioner (Thomson Exp)</td>
</tr>
</tbody>
</table>

---

Table B.9: Experimental parameters for May 8, 2014. The first half of the day was the Thomson experiment; the second half was the accretion shock experiment.
<table>
<thead>
<tr>
<th>Shot Number</th>
<th>SRF</th>
<th>Primary Diagnostics</th>
<th>Timing</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>73327</td>
<td>47377</td>
<td>$4\omega$ TSS</td>
<td>16 ns</td>
<td>Jet barely in range</td>
</tr>
<tr>
<td>73328</td>
<td>48648</td>
<td>$4\omega$ TSS</td>
<td>20 ns</td>
<td>Good timing</td>
</tr>
<tr>
<td>73330</td>
<td>48649</td>
<td>$4\omega$ TSS</td>
<td>28 ns</td>
<td>Probe reflected</td>
</tr>
<tr>
<td>73331</td>
<td>48650</td>
<td>$4\omega$ TSS</td>
<td>24 ns</td>
<td>Probe reflected</td>
</tr>
<tr>
<td>73334</td>
<td>48651</td>
<td>$4\omega$ TSS</td>
<td>20 ns</td>
<td>Best data</td>
</tr>
<tr>
<td>73335</td>
<td>47405</td>
<td>Prot. radio.</td>
<td>30 ns</td>
<td>No MIFEDS</td>
</tr>
<tr>
<td>73336</td>
<td>47376</td>
<td>Prot. radio.</td>
<td>30 ns</td>
<td>MIFEDS failed</td>
</tr>
<tr>
<td>73337</td>
<td>48652</td>
<td>Prot. radio.</td>
<td>30 ns</td>
<td>MIFEDS, 3 turns, 7 T</td>
</tr>
<tr>
<td>73338</td>
<td>48653</td>
<td>Prot. radio.</td>
<td>50 ns</td>
<td>MIFEDS, 3 turns, 7 T</td>
</tr>
<tr>
<td>73339</td>
<td>48654</td>
<td>Prot. radio.</td>
<td>30 ns</td>
<td>MIFEDS, 1 turn, 3 T</td>
</tr>
<tr>
<td>73340</td>
<td>48655</td>
<td>Prot. radio.</td>
<td>50 ns</td>
<td>MIFEDS, 1 turn, 2.4 T</td>
</tr>
<tr>
<td>73341</td>
<td>48656</td>
<td>Prot. radio.</td>
<td>70 ns</td>
<td>MIFEDS, 1 turn, 3 T</td>
</tr>
<tr>
<td>73344</td>
<td>48825</td>
<td>Prot. radio.</td>
<td>70 ns</td>
<td>MIFEDS, field failed</td>
</tr>
</tbody>
</table>

Table B.10: Shots on May 8, 2014. Halfway through the day, the configuration changed from imaging Thomson scattering to accretion shock with magnetic field.

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>SRF</th>
<th>EPW Data?</th>
<th>IAW Data?</th>
<th>TPDI Data?</th>
<th>PR Data</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>73327</td>
<td>47377</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>-</td>
<td>Barely in range</td>
</tr>
<tr>
<td>73328</td>
<td>48648</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>-</td>
<td>In range</td>
</tr>
<tr>
<td>73330</td>
<td>48649</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>-</td>
<td>Too dense</td>
</tr>
<tr>
<td>73331</td>
<td>48650</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>-</td>
<td>Too dense</td>
</tr>
<tr>
<td>73334</td>
<td>48651</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
<td>-</td>
<td>In range</td>
</tr>
<tr>
<td>73335</td>
<td>47405</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>Control; no field</td>
</tr>
<tr>
<td>73336</td>
<td>47376</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✗</td>
<td>Protons off CR-39</td>
</tr>
<tr>
<td>73337</td>
<td>48652</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✗</td>
<td>Protons off CR-39</td>
</tr>
<tr>
<td>73338</td>
<td>48653</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✗</td>
<td>Protons off CR-39</td>
</tr>
<tr>
<td>73339</td>
<td>48654</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✗</td>
<td>Protons off CR-39</td>
</tr>
<tr>
<td>73340</td>
<td>48655</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✗</td>
<td>Protons off CR-39</td>
</tr>
<tr>
<td>73341</td>
<td>48656</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✗</td>
<td>Protons off CR-39</td>
</tr>
<tr>
<td>73344</td>
<td>48825</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>✓</td>
<td>Field failed</td>
</tr>
</tbody>
</table>

Table B.11: Data on May 8, 2014.
B.3.4 Difficulties Encountered

B.3.4.1 EPW Data Failure

Our experience with EPW data was similar to that of August 2013: when the jet was aligned along the $4\omega$ probe beam, IAW data was obtained but not EPW. In August 2013, both streaked and imaging Thomson scattering were attempted in the probe-parallel-to-jet configuration; both failed. In May 2014 only imaging Thomson scattering was attempted in the probe-parallel-to-jet configuration, and once again it failed. In August 2013, because we had three potential jets, we had the option of falling back to a slightly different configuration with the jet coming on from the side. That configuration worked, although it only worked for streaked Thomson, obviously.

Figure B.5 compares failed EPW data from August 2013 and May 2014. The August 2013 data shows the time fiducial (the dots along the top and bottom of the image) because this is streaked data, and no discernible scattered spectrum. The May 2014 data shows no time fiducial—this is imaging data—but there is a mysterious extended shape in the middle of the image that looks nothing like a scattered EPW spectrum.

Figure B.5: EPW data from August 2013 and May 2014. Left: EPW data from Shot 70678, August 2013. Right: EPW data from Shot 73334, May 2014.
B.3.4.2 Proton Deflection

The images obtained from May 2014 are, with the exception of the control shots for which there was no magnetic field, extremely odd and riddled with strange shapes that look nothing like the data we were expecting, see Figure 5.7. This turned out to be due to protons being deflected off the CR-39; see Section 5.4.

B.4 May and October 2015 Shot Days

B.4.1 Collaboration

Because May 2015 was a repeat of May 2014 with the proton radiography deflection problem fixed, the collaboration was basically unchanged from May 2014, see Section B.3.1. Michigan graduate student Joseph Levesque joined the CLEAR magnetized plasmas projects and MIT graduate student Hong Sio joined to assist with proton radiography.

B.4.2 Configuration

The configuration in May 2015 was nearly identical to that of May 2014, see Chapter IV. Table B.12 lists the experimental parameters; some TIM assignments were changed compared to May 2014.
<table>
<thead>
<tr>
<th><strong>Target</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>CH</td>
</tr>
<tr>
<td>Solid density</td>
<td>1.18 g cm$^{-3}$</td>
</tr>
<tr>
<td>Cone opening angle</td>
<td>160°</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>2 mm</td>
</tr>
<tr>
<td>Cone thickness</td>
<td>100 μm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Drive Beams</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive beam wavelength</td>
<td>351 nm (3$\omega$)</td>
</tr>
<tr>
<td>Number beams</td>
<td>7 or 1</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>3150 J or 450 J</td>
</tr>
<tr>
<td>Drive beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>Drive beam radius</td>
<td>352 μm (SG4)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Proton Backlighter Beams</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BL beam wavelength</td>
<td>351 nm (3$\omega$)</td>
</tr>
<tr>
<td>Number beams</td>
<td>18</td>
</tr>
<tr>
<td>Total drive energy</td>
<td>8100 J</td>
</tr>
<tr>
<td>BL beam shape</td>
<td>1 ns, square</td>
</tr>
<tr>
<td>BL beam focus</td>
<td>0 mm, best focus (see note)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>TIM assignments</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>TIM 1</td>
<td>MIFEDS</td>
</tr>
<tr>
<td>TIM 2</td>
<td>Target positioner (BL.)</td>
</tr>
<tr>
<td>TIM 3</td>
<td>Target positioner (Exp.)</td>
</tr>
<tr>
<td>TIM 4</td>
<td>CR-39 (Wedge range filter)</td>
</tr>
<tr>
<td>TIM 5</td>
<td>Target positioner (Shield)</td>
</tr>
<tr>
<td>TIM 6</td>
<td>Thomson scattering (TPDI only)</td>
</tr>
<tr>
<td>H2</td>
<td>Not used</td>
</tr>
</tbody>
</table>

Table B.12: Experimental parameters for May 14, 2015. The October 27, 2015 shots were the same, except the experiment was moved to the H2 target positioner and MIFEDS and proton backlighting were dropped. Note: using best focus for the proton backlighter was a mistake that was not caught until well after shot day, see Section B.4.4.3.
B.4.3 Shot Sequence

On previous shot days, we had used seven full power drive beams to launch the plasma jets. We initially used seven beams on this shot day as well, see Shots 77250 and 77251, see Table B.13. Shot 77254 was a control shot of proton radiography without a jet. During that shot cycle, we reassessed our results from the first two shots and decided to fall back to using one full power drive beam in order to reduce the velocity of the incoming and thereby bring down the plasma $\beta$. After using one shot to get timing right, we settled on doing six shots at 20 ns, 40 ns, and 60 ns, with and without magnetic fields.

Table B.14 contains a list of successful data taken. While TPDI data was generally good, we consistently had problems with proton generation, see Section B.4.4.3. We found that most of the proton images obtained are identical to the control shot. The one exception is Shot 77254, the only seven-beam shot to use proton radiography.

<table>
<thead>
<tr>
<th>Shot Number</th>
<th>SRF</th>
<th>Field Imposed</th>
<th>Drive Beams</th>
<th>Driver Timing</th>
<th>Proton Timing</th>
<th>TPDI Timing</th>
</tr>
</thead>
<tbody>
<tr>
<td>77250</td>
<td>51957</td>
<td>0 T</td>
<td>7</td>
<td>-20 ns</td>
<td>-</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77251</td>
<td>53198</td>
<td>0 T</td>
<td>7</td>
<td>-10 ns</td>
<td>-</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77254</td>
<td>51955</td>
<td>8 T</td>
<td>-</td>
<td>-</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77255</td>
<td>51544</td>
<td>8 T</td>
<td>7</td>
<td>-10 ns</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77256</td>
<td>53202</td>
<td>8 T</td>
<td>1</td>
<td>-20 ns</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77258</td>
<td>53203</td>
<td>8 T</td>
<td>1</td>
<td>-40 ns</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77259</td>
<td>53205</td>
<td>8 T</td>
<td>1</td>
<td>-60 ns</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77260</td>
<td>51954</td>
<td>0 T</td>
<td>1</td>
<td>-20 ns</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>77261</td>
<td>53199</td>
<td>0 T</td>
<td>1</td>
<td>-47 ns</td>
<td>0 ns</td>
<td>-4 ns</td>
</tr>
<tr>
<td>77262</td>
<td>53200</td>
<td>0 T</td>
<td>1</td>
<td>-60 ns</td>
<td>0 ns</td>
<td>+3 ns</td>
</tr>
<tr>
<td>79221</td>
<td>54550</td>
<td>0 T</td>
<td>1</td>
<td>-43 ns</td>
<td>-</td>
<td>0 ns</td>
</tr>
<tr>
<td>79222</td>
<td>55517</td>
<td>0 T</td>
<td>1</td>
<td>-43 ns</td>
<td>-</td>
<td>0 ns</td>
</tr>
</tbody>
</table>

Table B.13: Shots on May 2015 and October 2015. Shots on May 14, 2015 (Shots 77250 through 77262) and October 27, 2015 (Shots 79221 and 79222).
<table>
<thead>
<tr>
<th>Shot Number</th>
<th>SRF</th>
<th>TPDI Filtering</th>
<th>TPDI Data?</th>
<th>PR Data?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>77250</td>
<td>51957</td>
<td>ND 2.0 (see note)</td>
<td>✓</td>
<td>-</td>
<td>Damaged camera</td>
</tr>
<tr>
<td>77251</td>
<td>53198</td>
<td>ND 3.0+LP385</td>
<td>x</td>
<td>-</td>
<td>Too early</td>
</tr>
<tr>
<td>77254</td>
<td>51955</td>
<td>ND 3.0+LP385</td>
<td>✓</td>
<td>✓</td>
<td>Control shot</td>
</tr>
<tr>
<td>77255</td>
<td>51544</td>
<td>ND 3.0+LP385+VG380</td>
<td>✓</td>
<td>✓</td>
<td>Only good PR image</td>
</tr>
<tr>
<td>77256</td>
<td>53202</td>
<td>ND 3.0+LP385+VG380</td>
<td>✓</td>
<td>x</td>
<td>No protons</td>
</tr>
<tr>
<td>77258</td>
<td>53203</td>
<td>ND 3.0+LP385+VG380</td>
<td>✓</td>
<td>x</td>
<td>No protons</td>
</tr>
<tr>
<td>77259</td>
<td>53205</td>
<td>ND 3.0+LP385+VG380</td>
<td>✓</td>
<td>x</td>
<td>No protons</td>
</tr>
<tr>
<td>77260</td>
<td>51954</td>
<td>ND 3.0+LP385+VG380</td>
<td>✓</td>
<td>x</td>
<td>Clear TPDI</td>
</tr>
<tr>
<td>77261</td>
<td>53199</td>
<td>ND 3.0+LP385+VG380</td>
<td>x</td>
<td>x</td>
<td>TPDI failed</td>
</tr>
<tr>
<td>77262</td>
<td>53200</td>
<td>ND 3.0+LP385+VG380</td>
<td>✓</td>
<td>x</td>
<td>Clear TPDI</td>
</tr>
<tr>
<td>79221</td>
<td>54550</td>
<td>ND 2.0+LP385</td>
<td>x</td>
<td>-</td>
<td>Overfiltered</td>
</tr>
<tr>
<td>79222</td>
<td>55517</td>
<td>LP385</td>
<td>✓</td>
<td>-</td>
<td>Overfiltered</td>
</tr>
</tbody>
</table>

Table B.14: Data from May 2015 and October 2015. Data on May 14, 2015 (Shots 77250 through 77262) and October 27, 2015 (Shots 79221 and 79222). Note: the CCD sustained damage during Shot 77250 due to under-filtering.
B.4.4 Difficulties Encountered

B.4.4.1 Target Positioning

We encountered a problem with target positioning. While the source of this problem was LLE, not our experimental design, it underscored the need to do test alignments on OMEGA. During the test alignment the day before shot day, LLE discovered an interference between the MIFEDS support arm and the shield stalk. This interference was not present in the aligned configuration, but it made alignment impossible. (There was no way for our research group to anticipate this as LLE designs their own alignment procedures.) Fortunately, we were able to move the shield to a different target positioner and shots the next day were unaffected.

B.4.4.2 Visible Light Imaging

There is evidence that the MIFEDS coils obscured the view of the experiments. The experiment was designed such that the entire experimental volume was visible from TIM 6 (TPDI). However, the fiducial notch is readily observed in the no-field shots (where MIFEDS was not inserted into the chamber) and appears obscured in the shots with MIFEDS, see Figure B.6. This is either due to the coils squeezing together as MIFEDS is fired or to glow from the coils themselves drowning out the light coming from the experimental target.

B.4.4.3 Proton Radiography

We consistently got low neutron counts from the Nuclear Diagnostic Inserter (NDI), about $8 \times 10^7$ neutrons compared to $5 \times 10^8$ neutrons in May 2014. We were unable to track down the root of the problem on shot day. During the October 2015 day (which was largely devoted to another campaign), we discovered during conversations with OMEGA that we had had the backlighter beams focused incor-
Figure B.6: Visible light images from May 2015 with and without the fiducial visible.

Left: The fiducial notch is not visible in Shot 77256, which used MIFEDS.
Right: The fiducial notch is visible in the lower right-hand corner of Shot 77260, a no-field shot where MIFEDS was not inserted into the chamber.

rectly. We had selected a focus of 0.00 mm (that is, best focus) while we should have set the focus to 1.81 mm. That would de-focus the backlighter beams such that they evenly irradiate the backlighter capsule. At best focus, they crack the capsule before it implodes, fusion is disrupted, and the proton count drops.
APPENDIX C

Data from April 2012

C.1 65762

Figure C.1: GOI and TPDI of 65762. GOI (left), 7 ns after drive, and TPDI (right), 17 ns after drive, images from 65762. A single jet shot moving away from the viewer in TIM 6. Compare this TPDI to that of 65763. Here the laser spot is brighter and the jet, which is peeking out from behind the target, is barely visible.
Figure C.2: Thomson spectra of 65762. EPW (left) and IAW (right) images from 65762. Probe beam fired from 7 to 10 ns after drive. No usable spectra from this shot; the probe beam was fired too early. The jet had yet to reach TCC.
Figure C.3: GOI and TPDI of 65763. GOI (left), 9 ns after drive, and TPDI (right), 22 ns after drive, images from 65763. A single jet shot moving away from the viewer in TIM 6. Compare this TPDI to that of 65762. Because this shot was 5 ns later, the laser spot is dimmer and the jet has moved farther out from behind the target.

Figure C.4: Thomson spectra of 65763. EPW (left) and IAW (right) images from 65763. Probe beam fired from 12 to 15 ns after drive. Note that the IAW fits show a negative velocity; this is because the jet is moving away from the spectrograph in TIM 6.
Figure C.5: 65763 EPW data at 12.5 ns

Figure C.6: 65763 IAW data at 12.5 ns

Figure C.7: 65763 EPW data at 13.5 ns
Figure C.8: 65763 IAW data at 13.5 ns

Figure C.9: 65763 EPW data at 14.5 ns

Figure C.10: 65763 IAW data at 14.5 ns
C.3 65764

Figure C.11: GOI and TPDI of 65764. GOI (left), 12 ns after drive, and TPDI (right), 25 ns after drive, images from 65764. Single jet moving away from the viewer in TIM 6. This TPDI is very similar to 65763, as it is only 3 ns later.

Figure C.12: Thomson spectra for 65764. EPW (left) and IAW (right) images from 65764. Probe beam fired from 15 to 18 ns. Note that no IAW data was obtained at the earliest time, 15.5 ns.
Figure C.13: 65764 EPW data at 15.5 ns

Figure C.14: 65764 EPW data at 16.5 ns

Figure C.15: 65764 IAW data at 16.5 ns
Figure C.16: 65764 EPW data at 17.5 ns

Figure C.17: 65764 IAW data at 17.5 ns
Figure C.18: OI and TPDI of 65765. GOI (left), 20 ns after drive, and TPDI (right), 25 ns after drive, images from 65765. Single jet moving away from the viewer in TIM 6. The TPDI ought to be identical to 65764.

Figure C.19: Thomson spectra for 65765. EPW (left) and IAW (right) images from 65765. Probe beam fired from 15 to 18 ns. Note that there is no IAW data at 15.5 ns.
Figure C.20: 65765 IAW data at 15.5 ns

Figure C.21: 65765 EPW data at 16.5 ns

Figure C.22: 65765 IAW data at 16.5 ns
Figure C.23: 65765 EPW data at 17.5 ns

Figure C.24: 65765 IAW data at 17.5 ns
C.5 65766

Figure C.25: GOI and TPDI of 65766. GOI (left), 20 ns after drive, and TPDI (right), 25 ns after drive, images from 65766. Single jet traveling toward the viewer in TIM 6. This was the first shot of the day that was traveling towards TIM 6. Here you can see the jet, the ring of the hole in the block from which it’s emerging, and the faint glow of the laser-hit side in the background.

Figure C.26: Thomson spectra for 65766. EPW (left) and IAW (right) images from 65766. Probe beam fired from 15 to 18 ns.
Figure C.27: 65766 EPW data at 15.5 ns

Figure C.28: 65766 IAW data at 15.5 ns

Figure C.29: 65766 EPW data at 16.5 ns
Figure C.30: 65766 IAW data at 16.5 ns

Figure C.31: 65766 EPW data at 17.5 ns

Figure C.32: 65766 EPW data at 17.5 ns
Figure C.33: GOI and TPDI of 65767. GOI (left), 20 ns after drive, and TPDI (right), 25 ns after drive, images from 65767. This was the first colliding jet shot of the day. Compare this TPDI to 65766 (jet coming towards the viewer) and 65764/65765 (jet going away from the viewer). In the foreground we see the glow of the laser-hit side of the near target. Behind that target we see one jet—the jet moving away from the viewer—emerging. In the background we see the other jet—the one coming towards the viewer—coming out. The bright spot in the middle is the collision.

Figure C.34: Thomson spectra of 65767. EPW (left) and IAW (right) images from 65767. Probe beam fired from 15 to 18 ns. The IAW data from this shot and the other colliding jet shot are peculiar and have been relegated to their own section.
Figure C.35: 65767 EPW data at 15.5 ns

Figure C.36: 65767 EPW data at 16.5 ns

Figure C.37: 65767 EPW data at 17.5 ns
Figure C.38: GOI and TPDI of 65769. GOI (left), 25 ns after drive, and TPDI (right), 30 ns after drive, images from 65769. Colliding jet shot. The bright areas from the previous shot (at 25 ns) have grown.

Figure C.39: Thomson spectra of 65769. EPW (left) and IAW (right) images from 65769. Probe beam fired from 20 to 23 ns. The electron density was too high and the plasma reflected the probe beam; no usable data were obtained.
Figure C.40: GOI and TPDI of 65770. TPDI (right), 20 ns after drive, images from 65770. Single jet moving away from the viewer in TIM 6. No GOI image was obtained for this shot.

Figure C.41: Thomson spectra of 65770. EPW (left) and IAW (right) images from 65770. Probe beam fired from 12 to 15 ns.
Figure C.42: 65770 EPW data at 12.5 ns

Figure C.43: 65770 IAW data at 12.5 ns

Figure C.44: 65770 EPW data at 13.5 ns
Figure C.45: 65770 IAW data at 13.5 ns

Figure C.46: 65770 EPW data at 14.5 ns

Figure C.47: 65770 EPW data at 14.5 ns
Figure C.48: GOI and TPDI of 65774. GOI (left), 30 ns after drive, and TPDI (right), 20 ns after drive, images from 65774. Colliding jets shot. Compared to the later colliding shots (65767 at 25 ns and 65769 at 30 ns) this TPDI image is clearer; the hot collision zone regions have yet to get really bright.

Figure C.49: Thomson spectra of 65774. EPW (left) and IAW (right) images from 65774. Probe beam fired from 12 to 15 ns. As with 65767, the IAW data are peculiar and have been relegated to their own section.
Figure C.50: 65774 EPW data at 12.5 ns

Figure C.51: 65774 EPW data at 13.5 ns

Figure C.52: 65774 EPW data at 14.5 ns
C.10 Colliding Jet Shot IAW Data

The colliding jet IAW data show signs of interpenetrating flows moving at different velocities.

Figure C.53: 65774 IAW data at 12.5 and 13.5 ns

Figure C.54: 65774 IAW data at 14.5 and 65767 IAW data at 15.5 ns
Figure C.55: 65767 IAW data at 16.5 and 17.5 ns
APPENDIX D

Data from August 2013

D.1 70672

Figure D.1: Thomson data for Shot 70672; EPW (left) and IAW (right). Jet B was launched 18 ns before Thomson probe; probe length was 1 ns. The probe beam was fired much too early; later shots indicate that it needed to be around 40 ns.
Figure D.2: Proton radiography data for Shot 70672. Backlighter fired 20 ns after drive beams. MIFEDS charged for this shot. No evidence of jets is seen, probably because the data were collected too early.
Figure D.3: Thomson data for Shot 70673; EPW (left) and IAW (right). Jet B was launched 25 ns before Thomson probe; probe length was 1 ns. No good data was obtained, probe was still timed too early.

Figure D.4: Proton radiography data for Shot 70673. Backlighter fired 27 ns after drive beams. MIFEDS did not charge for this shot. A faint “bubble” from the jet emerging into the field of view is visible.
D.3  70674

Figure D.5: Thomson data for Shot 70674; EPW (left) and IAW (right). Jet C was launched 30 ns before Thomson probe; probe length was 1 ns. Good data obtained.

Figure D.6: Proton radiography data for Shot 70674. Backlighter fired 32 ns after drive beams. MIFEDS did not charge for this shot. Oddly, this bubble is oriented the same way it was for Shot 70673, even though Jet B was fired that shot and Jet C was fired for this shot.
Figure D.7: Thomson data for Shot 70678; EPW (left) and IAW (right). Jet B was launched 30 ns before Thomson probe; probe length was increased 3 ns and no proton backlighter was used. This configuration did not use MIFEDS. Problems with the EPW data persist, but the IAW data appears clear over the 3-ns pulse.

Figure D.8: Thomson data for Shot 70679; EPW (left) and IAW (right). Jet B was launched 40 ns before Thomson probe; probe length remained at 3 ns and no proton backlighter was used. This configuration did not use MIFEDS. This is some of the best IAW data obtained for this shot day.
Figure D.9: Thomson data for Shot 70680; EPW (left) and IAW (right). Jet B was launched 50 ns before Thomson probe; probe length remained at 3 ns and no proton backlighter was used. This configuration did not use MIFEDS. Some IAW data is visible, but there is significant interference from reflected light.
D.7 70681

Figure D.10: Thomson data for Shot 70681; EPW (left) and IAW (right). Jet B was launched 40 ns before Thomson probe; probe length was decreased back to 1 ns. Good IAW data obtained.

Figure D.11: Proton radiography data for Shot 70681. Backlighter fired 42 ns after drive. MIFEDS was charged for this shot, but failed. The orientation is odd—were the blocks inadvertently rotated in the developing process?
D.8  70682

Figure D.12: Thomson data for Shot 70682; EPW (left) and IAW (right). Jet B was launched 40 ns before Thomson probe; probe length remained at 1 ns. IAW data is good.

Figure D.13: Proton radiography data for Shot 70682. Backlighter fired 42 ns after drive. MIFEDS was charged for this shot. A fainter bubble is visible—the imposed field seems to interfere with the self-generated field.
Figure D.14: Thomson data for Shot 70683; EPW (left) and IAW (right). Jets B and C were launched 40 ns before Thomson probe; probe length remained at 1 ns. Interestingly, both EPW and IAW worked on this shot.

Figure D.15: Proton radiography data for Shot 70683. Backlighter fired 42 ns after drive. MIFEDS was charged for this shot. Only one bubble is visible even though two were fired.
Figure D.16: Thomson data for Shot 70684; EPW (left) and IAW (right). Jets B and C were launched 40 ns before Thomson probe; probe length remained at 1 ns. Good EPW and IAW data obtained.

Figure D.17: Proton radiography data for Shot 70684. Backlighter fired 42 ns after drive. MIFEDS was not charged for this shot. Proton radiography appears to have failed.
APPENDIX E

Data from May 2014

E.1 73327

Figure E.1: Thomson data from 73327. Thomson data taken 16 ns after drive; EPW (left) and IAW (right). As seen in the IAW image, the jet is barely in range.
Figure E.2: Visible light data from 73327. No discernible structures observed.
Figure E.3: Thomson data from 73328. Thomson data taken 20 ns after drive; EPW (left) and IAW (right). The timing of this shot was good.

Figure E.4: Visible light data from 73328. No discernible structures observed.
Figure E.5: Thomson data from 73330. Thomson data taken 28 ns after drive; EPW (left) and IAW (right). Densities were too high; the probe reflected off the experimental plasma.

Figure E.6: Visible light data from 73330. No discernible structures observed.
E.4 73331

Figure E.7: Thomson data from 73331. Thomson data taken 28 ns after drive; EPW (left) and IAW (right). Densities were too high; the probe reflected off the experimental plasma.

Figure E.8: Visible light data from 73331. No discernible structures observed.
Figure E.9: Thomson data from 73334. Thomson data taken 20 ns after drive; EPW (left) and IAW (right). The timing of this shot was good.

Figure E.10: Visible light data from 73334. No discernible structures observed.
Figure E.11: Proton radiography data from 73335. Shot 73335 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 30 ns after drive, no field imposed.

Figure E.12: Proton radiography data from 73336. Shot 73336 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 30 ns after drive, no field imposed.
Figure E.13: Proton radiography data from 73337. Shot 73337 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 30 ns after drive, 7 T field imposed.

Figure E.14: Proton radiography data from 73338. Shot 73338 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 50 ns after drive, 7 T field imposed.
E.10  73339

Figure E.15: Proton radiography data from 73339. Shot 73339 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 30 ns after drive, 3 T field imposed.

E.11  73340

Figure E.16: Proton radiography data from 73340. Shot 73340 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 50 ns after drive, 2.4 T field imposed.
Figure E.17: Proton radiography data from 73341. Shot 73341 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 70 ns after drive, 3 T field imposed.

Figure E.18: Proton radiography data from 73344. Shot 73344 Particle Temporal Diagnostic (PTD) data on left; proton radiography on right. Data taken 70 ns after drive, field failed.
APPENDIX F

Data from May and October 2015

F.1  77250

Figure F.1: Visible light data for 77250. Seven beam drive; images taken 23 ns later. This image used only an ND 2.0 filter, which resulted in damage to the camera. No proton radiography or magnetic field used on this shot. Left is the image from the CDD; right is the rotated, cropped image. This format will be used on all subsequent shots.
Figure F.2: Visible light data for 77251. Seven beam drive; images taken 13 ns later. Filtering was increased to ND 3.0+LP385 due to damage sustained during the previous shot (77250). No proton radiography or magnetic field used on this shot.
Figure F.3: Visible light data for 77254. A control shot; no jet was created but an 8 T magnetic field was imposed and proton radiography was used. In addition to the ND 3.0 and LP385 filters used previously, a VG380 was added. The dark splotch in the upper right of the cropped image is the damage to the CCD from earlier in the day. It is seen in all subsequent images.

Figure F.4: Proton radiography data for 77254; 3 eV image failed (CR-39 frosted), 15 eV image shown above. Notice the fiducial notch is not visible in this image as it is in some of the others. We suspect this is because the MIFEDS coils “squeezed together” during the shot.
Figure F.5: Visible light data for 77255. Image was taken 13 ns after drive (one beam). An 8 T magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380).

Figure F.6: Proton radiography data for 77255; 3 eV image left, 15 eV image right.
Figure F.7: Visible light data for 77256. Image was taken 23 ns after drive (one beam). An 8 T magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380).

Figure F.8: Proton radiography data for 77256; 3 eV image left, 15 eV image right.
Figure F.9: Visible light data for 77258. Image was taken 43 ns after drive (one beam). An 8 T magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380).

Figure F.10: Proton radiography data for 77258; 3 eV image left, 15 eV image right. In this pair of images, the fiducial notch is clearly visible.
Figure F.11: Visible light data for 77259. Image was taken 63 ns after drive (one beam). An 8 T magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380).

Figure F.12: Proton radiography data for 77259; 3 eV image left, 15 eV image right. Again, the fiducial notch is visible.
Figure F.13: Visible light data for 77260. Image was taken 23 ns after drive (one beam). No magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380). The fiducial notch is visible in these images; we hypothesize that it was not visible in previous images because the MIFEDS coils obscured it.

Figure F.14: Proton radiography data for 77260; 3 eV image left, 15 eV image right.
Figure F.15: Visible light data for 77261. Image was taken 43 ns after drive (one beam). No magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380). This TPDI image failed, perhaps because it was timed to be ahead of the proton backlighter and could not make use of the reflected glow of the backlighter.

Figure F.16: Proton radiography data for 77261; 3 eV image left, 15 eV image right.
Figure F.17: Visible light data for 77262. Image was taken 63 ns after drive (one beam). No magnetic field was imposed and proton radiography was used. Filtering was unchanged from the previous shot (ND 3.0+LP385 +VG380). Again, the fiducial notch is visible.

Figure F.18: Proton radiography data for 77262; 3 eV image left, 15 eV image right.
Figure F.19: Visible light data for 79221. Attempted re-do of Shot Shot 77261, the shot where TPDI failed in May 2015. Image was taken 43 ns after drive (one beam). No magnetic field was imposed and no proton radiography was used. Filtering was ND 2.0+LP385; image appears to be over-filtered.

Figure F.20: Visible light data for 79222. Second attempted re-do of Shot Shot 77261. Image was taken 43 ns after drive (one beam). No magnetic field was imposed and no proton radiography was used. Filtering was reduced to LP385 (ND 2.0 was dropped).


Cross, J. E., et al. (2016), Laboratory analogue of a supersonic accretion column in a binary star system, Nature Communications, 7, 11899, doi:10.1038/ncomms11899.


