High-intensity Ultra-fast Laser Interaction Technologies

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HIGH-INTENSITY ULTRA-FAST LASER INTERACTION TECHNOLOGIES

by

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Major Professor: Martin Richardson
ABSTRACT

To our knowledge this is the first comprehensive study of laser-induced effects generated at intermediate distances using self-channeled femtosecond laser pulses. Studies performed were made both experimentally and theoretically with the use of novel modeling techniques. Peak laser pulse powers above 3 GW allow beam propagation without divergence for up to several kilometers. In this regime, experiments were performed at 30 meters from the laser system in a custom propagation and target range, utilizing the Laser Plasma Laboratory’s Terawatt laser system. Experiments included investigations of laser ablation; electromagnetic pulsed (EMP) radiation generation over the 1-18 GHz region; shockwave formation in air and solid media; optical coupling of channeled pulses into transparent media; and, conservation of energy in these interactions. The use of bursts of femtosecond pulses was found to increase the ablation rate significantly over single-pulse ablation in both air and vacuum. EMP generation from near-field focused and distance-propagated pulses was investigated. Field strengths upwards of 400 V/m/λ for vacuum focusing and 25 V/m/λ for self-channeled pulses were observed. The total field strengths over 1-18 GHz measured at distance surpassed 12 kV/m. Shockwaves generated in transparent media at 30 meters were observed as a function of time. It was found that the interaction conditions control the formation and propagation of the shock fronts into the medium. Due to the processes involved in self-channeling, significant fractions of the laser pulse were coupled into the target materials, resulting in internal optical and exit-surface damage. Basic estimations on the conservation of energy in the interaction are presented. The results of the experiments are supported by hydrodynamic plasma physics code and acoustic modeling.
To my family and friends
ACKNOWLEDGMENTS

I would like to thank Dr. Martin Richardson for his support and guidance during this research without which, none of this work would have been possible. I would also like to thank my committee, Dr. Kar, Dr. Moharam, and Dr. Wahid.

During the course of this research, many people have contributed to my work or education in various ways. Thanks to Dr. Nikolai Vorobiev for his tutelage in high-power laser system operation and to Somsak (Tony) Teerawattanasook for helping to keep my laser operating even against insurmountable odds. In addition, all the members of the Laser Plasma Laboratory for their support and help throughout the years for which I am grateful.

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<th>Description</th>
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<td>CPA</td>
<td>Chirped Pulse Amplification</td>
</tr>
<tr>
<td>Cr:LiSAF</td>
<td>Chromium-doped Lithium Strontium Aluminum Fluoride</td>
</tr>
<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>EMP</td>
<td>Electro-Magnetic Pulse</td>
</tr>
<tr>
<td>EOC</td>
<td>End of Charge</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
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<tr>
<td>GVD</td>
<td>Group Velocity Dispersion</td>
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<td>HAZ</td>
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<td>LIBS</td>
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</tr>
<tr>
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<td>RF</td>
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<tr>
<td>TTL</td>
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CHAPTER 1.  OVERVIEW OF FEMTOSECOND LASER TECHNOLOGIES

Since its advent nearly 40 years ago, the laser has revolutionized many different fields, from medicine to consumer electronics, to communication. Each step, or jump maybe, of this evolution has resulted from new ideas and new applications of the laser technology and thereby extending its capabilities. With each avenue taken the laser has started out small and grown quickly. This thesis outlines effects produced in a new step in laser application, self-guiding laser beams and their interaction effects at distance. The theory, conditions for formation, and experimental applications at distance will be explored and demonstrated herein.

1.1.  New phenomenon: Self-guiding laser light

Anyone who has ever used a flashlight knows that no matter how hard one tries to collimate the light, it always diverges with distance. This is a property of all light sources, commonly referred to as the divergence. Since divergence is governed by the wave nature of light, it applies to all light sources including lasers. The biggest advantage of lasers is the ultra-intense collimated beam and the applicability of it. Thus the further from the laser source, the greater the spot size, and the usefulness decreases. Until recently almost all applications have been performed within close proximity to the laser source.

However, within the past 10 years a new methodology for transmitting laser light has developed. Originally noticed in ultra-high-power long-pulse lasers (like Vulcan in the UK and the Nova laser at LLNL), the non-linearities of the air began to distort the beam into an array of
intensity spikes [38]. For this class of laser it was considered an annoyance and was mitigated by any means possible. The practicality of this would not be realized until the availability of ultra-short pulse lasers became commonplace in the laboratory. These lasers are significantly lower energy but due to the ultra-short pulse duration, can still achieve the same peak powers. First noted by Braun et al. at the University of Michigan, these intensity spikes created in the beam, once formed, would propagate significant distances without divergence [8]. The possibility to defy divergence is the combination of several factors but most importantly due to the peak power of the beam itself, thus the beam is said to self-guide (or channel) during the propagation. Self-guiding of laser pulses increases the effective range of the laser to tens of kilometers while maintaining high-power densities.

1.2. **Opportunities**

The ability to propagate a laser beam over long distances without loss of power-density brought with it the question of how to apply it. The laser has been used at long ranges in the past for applications that did not require constant power or precision beam quality. These are applications like laser range finding (for example, measuring the exact distance to the moon) and target illumination. However, beyond these, applications like ablation or energy deposition are impractical. The ability to propagate energy and power in a confined and collimated beam allows for these applications to be performed at distance.

The energy and peak-power of the self-guided laser beam are sufficient to generate plasma on most surfaces. The generation of plasma is extremely useful since the particles that make up the plasma radiate at specific wavelengths and provide an atomic ‘fingerprint’ to the
material. Light Induced Breakdown Spectroscopy (LIBS) is a field of research devoted to the collection of light from these distant plasmas, analyzing the returning spectral ‘fingerprint’, and determining the contents of the target struck by the laser. This is an extremely useful technique for determining everything from what sort of rocks are on the horizon to what type of paint is on a car.

The process of generating plasma at distance is equivalent to local generation in that it ablates the surface of the material. The self-guiding beam is capable of ablating targets at significant distances thus making it applicable in a lot of industrial applications. There are limitations on the amount of energy transported by the self-guiding process. However, this only serves to decrease the overall ablation rate as compared to local ablation.

The nature of self-guiding laser beams is extremely useful for projecting energy at distance, where the deposition can result in ablation, plasma heating, induced effects, and even allow communications. These beams have been considered as a means of interdiction on the battlefield and other arenas. This form of laser propagation can blind sensors for various different combat devices as a means to ensure compliance. In addition, they can be used to prevent communications. The applications in this new regime of laser operation are currently under investigation.

1.3. **New field of study**

The ability to propagate light long distances has generated new many new challenging avenues of research. The Laser Plasma Laboratory (LPL) is pursuing several of these challenges, including LIBS, remote sensing, electromagnetic pulse generation (EMP), terahertz generation,
and other violent interactions at distance. The research is divided up between different segments of the group, with overlap and cross-comparison. Some of the effects are compared to classical approaches (localized approach) and the effect difference is noted.

Remote sensing and LIBS are currently very interesting topics of research. The ability to project light out and detect the presence of specific substances is of great importance. The lab is currently investigating nanosecond based lasers for traditional LIBS detection and the new femtosecond based self-guiding laser pulses for long range LIBS. There are a lot of technical issues involved in the process, however, most of them come from the collection and processing of the return signal. Most of the LIBS information originates from the plasma induced on the target surface, but there are other techniques using the white light generation from the self-guiding mechanism to detect airborne particles [47]. Currently, there are commercial nanosecond based LIBS systems capable of projecting the laser beam to distances of 30 meters using large optics. There are none however that can project to 100 meters, which is only possible due to the ability for self-guiding laser pulses.

All plasmas emit radiation throughout the spectral band. The emission depends on the type of resonances that generated it, the material in the plasma, the temperature, and many other factors. LIBS data is measured in the visible and infrared regions of the spectrum due to the atomic transitions that occur and radiate. These plasmas have also been observed to emit terahertz radiation, a form of emission useful for imaging through solid materials. Some work has been performed in the lab with remote generation of terahertz emission in combination with four-wave mixing as a means to detect specific materials. The radiation extends out of the terahertz region into the gigahertz, where EMP fields are detected. These fields are generated by
the highly transient electron motion in the plasma and can reach significant field strengths. This results in the ability to generate remote EMP pulses.

In addition to the plasma formation and the emission, there is a considerable amount of energy imparted to the target material in the form of concussive force and optical related damage. The concussive force results from the high-pressure plasma generating a pressure wave into the material and the surrounding medium. This form of interaction is under investigation.

1.4. **Focus of study**

The program of research presented in this thesis is the first to focus on the effects that can be generated by self-guiding laser pulses interacting with solid materials at distance. The effects investigated include properties of the self-guiding mechanism, ablation of the target material, and measurement of the frequency spectrum of the RF electromagnetic emission, the shockwave generation, and the optical coupling involved in the interaction of these self-guided pulses with solid materials. Of necessity this study also involves the development of new laser and electronic techniques applied to the LPL Terawatt laser system in order to perform the experiments. In addition the properties of the self-guiding mechanism itself are explored, in order to understand the interaction effects observed at distance. Finally an array of theoretical models are used, and in many cases developed or restructured, in order to analyze the results.

All of the experiments in this thesis were performed using the Terawatt laser system. This system required significant system modifications for the experiments reported here. This included a complete re-design of the electrical triggering backbone, the addition of software based hardware control, and modifications to the infrastructure supporting the optical beam path.
In addition, an entirely new intermediate-range interaction facility, one of the first ever to be constructed was designed and constructed explicitly for these experiments. The upgrades to these facilities are described in detail herein.

Using this new interaction facility, the research focused on understanding the basic interaction science of self-channeled laser beams with solid material at intermediate ranges. Several distinct aspects of this interaction were examined in detail, and for each effect, a supporting theoretical framework constructed, from which an experimental plan was created to take advantage of the best possible methods of analysis. Thus a methodic approach was taken to all aspects of the research.

1.5. **Organization of thesis**

To introduce the novel studies performed for this thesis, the foundations for the work and the background are first presented. The rest of the thesis then follows in a logical sequence beginning with a description of the basic theory for primary interaction mechanisms involved, followed by the development of the laser, diagnostics and the new interaction facility, the results of the experiments, and finally some conclusions are presented. The basic fundamental theory for the experiments described in Chapter 2 is critical for a complete understanding of the processes occurring and for analyses to be performed. The theory is presented as individual sections, in the corresponding order in which they are used in the thesis. It is followed by Chapter 3 which reviews the necessary modifications to the laser system, the design and implementation of the diagnostics and the construction of a new interaction facility. These modifications were essential
to the operation of the experiments and it is hoped that their description helps the reader understand how the experiments were configured.

The following three chapters (Chapters 4 – 6) cover the experiments performed at distance in the secure test range. The first covers ablation studies made both in vacuum and at distance, and makes a comparison of different ablation modalities. Chapter 5 then discusses the EMP detection system, describes some of the data from vacuum experiments, and concludes with a detailed description of the investigation of EMP as measured from the interaction after the self-channeled beam had propagated through the test range. The third of these chapters, (Chapter 6), perhaps the pinnacle of this work, covers the shockwave interactions, energy conservation, and optical effects generated in targets at distance.

This thesis provides the first concise compendium to our knowledge of the interaction effects generated by this novel form of ultrafast laser directed energy. There are profound consequences to these results and the applications that follow will be many fold.
CHAPTER 2. THEORY

The research performed in the following chapters is based upon a new type of laser interaction scheme between ultra-fast lasers and solid materials. Although this is fundamentally an experimental thesis, the aspects of the interactions must be supported by the relevant theory. We start this by describing the basic laser/material interaction physics for both nanosecond and femtosecond laser pulses. This leads to the science of ablation, how electrons are generated, and why electromagnetic pulses occur from plasmas. A result of the ablation and plasma creation are the generation of shockwaves, and a basic formulation for these is presented. Finally, the physics governing the propagation of light over long distances with no divergence is discussed.

2.1. Laser-material interaction science

The majority of micro-machining lasers currently available on the market today are nanosecond-based systems. Nanosecond lasers are preferable for large-scale machining of parts because of their low operating costs, high uptime, and most importantly, their efficiency for machining most materials. This efficiency results from the coupling characteristics of the laser produced plasma and the laser pulse on nanosecond time scales. The characteristics of nanosecond versus femtosecond materials interaction are markedly different. Ultra-short pulse lasers are not as efficient for ablation, but are found to provide cleaner cuts and less surface burning. The difference between the ablation by these two classes of laser can be explained by the plasma formation processes and the dominate ablation mechanisms.
2.1.1. **Plasma generation from nanosecond laser pulses**

As the leading edge of a high-intensity nanosecond laser pulse strikes a solid target, photoelectrons are generated by multi-photon absorption in the material. These electrons leave the material on sub-nanosecond time scales. The remaining portion of the laser pulse (more properly, its strong electromagnetic field) drives the photoelectrons back into the surface, producing localized heating due to collisions which in turn causes ablation via vaporization. Therefore, the depth of material each pulse can ablate is governed by the skin depth, that is, how far the photons can tunnel into the material and generate electrons. The collisions of the photoelectrons and the resulting vapor produce a high-density electron/ion cloud, or plasma. Typical laser-produced plasmas have electron densities in the range of $10^{21}$ electrons/cm$^3$ and temperatures of 10 -100-electron-volts (eV).

As the plasma forms, there is an exponential density gradient extending out along the surface normal. The laser light propagates into the plasma as far as the critical density surface, the surface at which the laser frequency matches the electron plasma frequency. At the plasma frequency, the oscillation of the electrons matches the frequency of the incident laser light and acts like a mirror. In this region, the electron density is sufficiently high that the propagation of laser light is governed by the generated electrons. This propagation must follow the dispersion relation, [27]

$$k = k_0 \sqrt{\varepsilon} = k_0 \sqrt{1 - \frac{(\omega_p)^2}{(\omega_L)^2}},$$  \hspace{1cm} \text{(2-1)}$$

where $\omega_L$ is the angular frequency of the laser radiation and $k_0$ its wave number. $\omega_p$ is the electron plasma frequency and is defined as
where $n_e$ is the electron density in the plasma, $e$ is the elementary charge and $m_e$ is the mass of the electron. The group velocity in the plasma is given as

$$v_g = \frac{\omega}{k} = c \sqrt{1 - \frac{(\omega_p)^2}{(\omega_c)^2}}$$

which decreases with increasing electron density. When the group velocity goes to zero, an expression for the critical density $n_c$ can be found.

$$n_c = \frac{m(\omega_c)^2 \varepsilon_0}{e^2} = 1.1 \times 10^{21} \lambda_L^{-2} \text{ cm}^{-3}$$

Here, the incident laser wavelength is expressed in micrometers. Due to the dispersion relation, light cannot propagate when the propagation factor is not real, when $n_e > n_c$; at this point, all of the remaining incident laser light reflects back through the plasma, and thus for ideal coupling the critical density surface should be deep within the plasma. Long laser pulses (tens of nanoseconds) always satisfy this condition. Lasers with shorter pulse lengths often employ a low energy pre-pulse. The pre-pulse creates a small plasma which rapidly expands, produce electron density fall-off with a long scale length. When the main pulse arrives, the laser light more efficiently couples into this pre-formed low-density, thereby increasing the ablation of the material.
2.1.2. **Ultra-short-pulse laser interactions**

The interaction between laser light and material is significantly different for ultra-short (femtosecond) pulses. The short pulse duration creates extremely high electric field intensities that result in instantaneous ionization of the material’s surface and plasma expansion on the order of picoseconds. The plasma expansion is so small and occurs on such a short time scale that the local electron density is equivalent to solid densities ($10^{23}$ electrons/cm$^3$) and the resulting plasma gradients are very steep. The scale length of the plasma is given by

$$ L = c_s \cdot \Delta t $$

where $\Delta t$ is the temporal width of the laser pulse and $c_s$ is the speed of sound given by,

$$ c_s = \sqrt{\frac{3k_b T_i + Z k_b T_e}{M}} $$

for the charge number $Z$, the ion and electron temperatures $T_i$ and $T_e$, $k_b$ the Boltzmann’s constant, and the ion mass $M$. For femtosecond pulses, $L$ is very small, typically around 10 nanometers. The femtosecond laser pulse rapidly ionizes the target, resulting in an optically opaque plasma due to the electron density being higher than the critical density. This occurs within about one period (reciprocal of optical wave frequency) of the incident laser light.

The plasma that subsequently forms during this brief (~100fs) interaction can be classified into three regions. The first region, typically tens of nanometers in extent, is the low-density outer edge of the plasma comprised of fast electrons that are rapidly expanding into its surroundings. The second region has electron densities equal to that of solids and has a thickness equivalent to the skin depth of the material as a function of wavelength. This region absorbs most of the laser energy through various mechanisms. The last region is in the remaining solid
target and only experiences the laser pulse by way of thermal diffusion; this region can be hundreds of nanometers thick.

2.2. **Plasma related effects**

The plasma generated by laser pulses result in various effects where generally the most commonly known is ablation of the target material. The ablation processes differ with shortening of the pulse length and will be discussed herein. The plasma also generates electrons with high velocities which create current and therefore magnetic fields. Over very short lived plasmas, the rapidly changing fields become electromagnetic pulses and generate emission in the radio frequency (RF) spectrum. These different effects will be discussed.

2.2.1. **Ablation mechanisms**

Using lasers for micro-fabrication in metals has long been difficult due to the high thermal conductivity and low melting points typical of metals. Conventional nanosecond lasers create large heat-affected zones, non-uniform holes, and reformed molten surface debris. Nolte *et al* [51] performed studies on the ablation of metals from the femtosecond pulse-length regime up through picoseconds, including 150 fs with a Ti:sapphire laser at fluences of 0.1–10 J/cm², resulting in the first characterization of the separate ablation regimes as a function of laser pulse length. This increased understanding of ablation modalities provided the ability to fabricate micro-structures on solid targets with better precision, decreased deposited energy, and less surface damage. Silicon (even though a non-metal) and its compounds are also being studied due to the potential to laser-machine silicon wafers during semiconductor chip manufacturing. Using
a Ti:sapphire laser at 790-nm wavelength with 130-fs pulses and fluence above the damage threshold under vacuum, the ablation damage to the surface, including the structural details, has been studied. From this it has been verified that at or just above the damage threshold, the silicon tends to melt, but higher fluences produces ablation [6]. Interestingly enough, this implies that the ablation mechanisms for fs laser pulses apply to metals and to non-metals alike.

The two regimes in laser ablation are the multi-photon (skin depth) and the electron diffusion (thermal) regimes. These originate from the Arrhenius-type evaporation equations, and describe the ablation process by

\[ L = \delta \ln \left( \frac{F_a}{F_{th}^{\text{Skin}}} \right) \text{ where } \delta \approx \alpha^{-1} \]

for low-intensity and

\[ L = l \ln \left( \frac{F_a}{F_{th}^{\text{thermal}}} \right) \text{ where } l \approx \sqrt{D \tau_a} \]

for high-intensity ablation [51]. \( F_{th}^{\text{skin}} \) and \( F_{th}^{\text{thermal}} \) are the threshold ablation fluences for low and high-intensity ablation respectively. These equations describe the effective ablation depth per shot in terms of the incident laser fluence. For low incident fluences, the skin depth (defined above as \( \delta \)) defines the effective depth of absorption. For higher laser fluences, the electron thermal diffusion length (defined as \( l \) where \( D \) is the electron thermal diffusivity and \( \tau_a \) the time of ablation) dominates and increases the ablation rate over that of the skin depth.

Many different metals have been examined by others and ourselves, such as copper and aluminum, which are commonly machined with lasers. Copper is one metal that has been extensively tested due to the frequency of its use, either alone or in combination with other
metals as alloys. Ablation of copper foil in air has been studied with an 800-nm, 70-fs laser in the 0.01–28 J/cm² regime. In this study, an emphasis was placed on determining the effect of changing the pulse duration, in an attempt to minimize the ablation threshold. As expected, the ablation rate decreased as the pulse length increased [31, 32]. The ablation characteristics of silver, gold, and copper have been studied at fluence levels of 0.1–10 J/cm² using the Terawatt laser system [4]. Bulk material samples were used to better simulate and model the effects expected in laser machining, which is usually done on bulk materials rather than foils. In this work, the two ablation regimes (skin depth and electron diffusion) were observed. In addition, the lateral features of the ablated region were studied for use as a precise measurement of ablation ability [25]. The ablation depth was measured and found to be coupled to the pulse energy. It was also observed that as the pulse energy increased, so did the resulting debris on the surface. It can be concluded from this work that to create clean cuts in a metal, the laser pulse energy needs to be in the skin-depth regime, below that which would cause thermal diffusion [67].

In recent studies, and due to the extensive research already performed on the pulse length dependence of ablation, greater focus is being placed on the ablation rate’s dependence on pulse energy. Wynne et al experimented with the ablation rates of aluminum and stainless steel under varying conditions of pulse duration, pulse energy, surface conditions, and ambient atmospheric pressure [69]. They conducted this research with a Ti:sapphire laser at 810-nm wavelength, 1-kHz repetition rate, 150-fs–40-ps pulse length, and 1.5 mJ energy per pulse. They determined that there was a strong decrease in the ablation rate as the depth of the ablated holes increased, due to surface irregularities forming around the ablated region. These structures tend to inhibit the ablation process by reflecting the light and/or absorbing the energy before it reaches the full
depth of the ablated hole, slowing the ablation process. They also found that the ablation rates in air and vacuum are of similar magnitude, but the time required to drill a hole completely through the foil was much shorter in the vacuum regime. They attributed this to the absorption of energy by the plasma plume produced in front of the target, resulting from ionization of the surrounding air [69]. Many groups are currently working on mitigating this effect in order to increase the applied energy and the ablation rate while preserving surface quality [33, 43]. In a related effort, we are investigating the possibility that a multi-pulse scheme might minimize the air ionization, as well as the subsequent parasitic energy absorption and surface degradation; this could result in significantly increased ablation rates.

Zhu et al have shown preliminary results that suggest a correlation between the properties of different metals and their ablation rates [74]. They tested aluminum, tungsten, titanium, copper, iron, silver, gold, and lead foils of different thicknesses using a Ti:sapphire laser at 800 nm and pulse lengths from 60 fs up to nanoseconds. They ablated the samples with equivalent energy but varying pulse length and found three distinct temporal ablation regimes: femtosecond, picosecond, and nanosecond. These regimes correspond to surface shattering; slight melting and ablation of clusters of material; and severe melting of the sample, respectively. From this, they showed that the ablation rates depend on both the laser parameters and the material properties in each of the three different ablation regimes. They report that the material properties most affecting the ablation rate are the thermodynamic properties of the material, especially the latent heat of vaporization [74].
2.2.2. Hot electron generation

In laser produced plasmas there are two dominant absorption processes, inverse Bremsstrahlung and resonant excitation. Laser-produced plasmas on a surface of a material typically exhibit a Maxwellian distribution of electron temperature as a result of various mechanisms. Even in low-temperature plasmas, there is always a small fraction of electrons (usually around 1%) which have higher thermal energies due to other absorption mechanisms.

As described in section 2.1.2 the plasma is separated into different regions depending on the transparency. The optically transparent region is located in front of the critical density front, and the opaque region is located behind. The laser light propagating in the transparent region (also known as the under-dense region) will mostly be absorbed by inverse Bremsstrahlung absorption. This is best described as the three-body process that occurs when an electron absorbs laser light energy when passing through the field of an ion by means of resistive damping [16, 35]. Momentum and energy are conserved in the three body interaction. The result of the electron directly absorbing the laser energy leads to low thermal temperatures of the ions, and low thermal conduction to the material. The absorption coefficient can be calculated by

\[
\kappa_{iba} = 3.4 \frac{(n_e/n_c)^2 Z \ln \Lambda}{\sqrt{1-n_e/n_c \lambda^2 (kT_e)^{2/3}}} \text{ m}^2
\]

where \( Z \) is the mean ion charge, \( \ln \Lambda \) is the Coulomb logarithm for inverse Bremsstrahlung, \( \lambda \) the wavelength of the laser, \( n_e \) the electron density, \( n_c \) the critical density, and \( T_e \) the electron temperature [35, 49]. Numerical simulations have shown that up to 80-90% of the incident laser energy can be absorbed through inverse Bremsstrahlung absorption [72].
Light that passes through the optically transparent region and reaches the critical surface can then be absorbed by resonant excitation. Resonant absorption is the process that occurs at the critical density, when the frequency of the electron oscillation matches that of the incident light frequency, and leads to the acceleration of the electrons and reflects the laser light. If the electrons remain in phase with the electric field there is no energy transfer, but in practice, since the electrons move across a steep electron density gradient they fall out of phase, and therefore draw energy from the field. For instance those electrons that stream into the dense medium beyond the critical surface give rise to a thin layer of material being superheated. The temperature of this layer can be approximated by

\[ T_h \propto \left( I \lambda^2 \right)^{2/3} \]

where \( I \) is the incident laser intensity and \( \lambda \) is the wavelength [26].

The field strength of the incident light is sufficient to excite the electron and accelerate it forwards (or backwards) with energies much greater than thermal electrons. The electrons that are driven down the density gradient of the plasma until it de-phases with the driving electric field. Then the Coulomb (or electrostatic) field set up between these electrons and the slowly moving ions pulls the electron back towards the ions in the plasma. The electrons now retains this energy (at least what is not lost to collisions) and consequently propagating out of the plasma with energies greater than that of thermal electrons.

This direct acceleration of the electrons by the intense electric field can be approximated. For an incident transverse electric field, the maximum electron energy gain is given by

\[ \Delta E_{\text{max}} = \frac{1}{2} m v_e^2 \left( \frac{1}{1 - \frac{v_s}{v_e}} \right)^2 \]

where
where \( m \) is the electron mass, \( v_q \) is the quiver velocity, \( v_x \) is the velocity in the direction of the electric field, and \( v_\phi \) is the phase velocity[10]. The quiver velocity is defined as

\[
v_q = \frac{eE}{m_\omega} \approx 25\lambda(\mu m)\sqrt{I(W/cm^2)}
\]

which is in units of cm/s [26]. For example, if \( \lambda = 850 \text{ nm} \) and \( I = 10^{19} \text{ W/cm}^2 \) then the electron energy gained is approximately 1.28 MeV.

### 2.2.3. Electromagnetic Pulses

An electromagnetic pulse (EMP) is defined as a short-duration broadband burst of electromagnetic energy. EMP radiation can result from dipole radiation, the transient electromagnetic fields, or other mechanisms in the plasma. While there are many methods of generating electromagnetic pulses, only the first two methods will be discussed.

As described in the previous section, the electrons gain energy via inverse Bremsstrahlung and other absorption processes. Electrons that do not have sufficient energy to escape the plasma oscillate as dipoles around an ion at the plasma frequency. As an example, for an electron density of \( 10^{15} \text{ cm}^{-3} \), the dipole frequency is approximately 200 GHz [2]. In the laser material interaction, electrons are both driven into and out of the target [30]. Those that are driven into the material in short bursts result in sharp transient magnetic fields associated with the pulsed current flow [68]. The magnetic fields and current flow induce resonances within the bulk target material which will radiate at the natural frequencies allowed [45]. The electrons that are driven out away from the critical density front experience Coulombic forces pulling them back to the plasma. As the plasma cools, and before recombination, the electron/ ion form a
momentary dipole. This dipole, depending on the length, radiates in the GHz frequency spectrum [11]. For cases where the material is completely vaporized in the laser interaction, surface currents are not applicable. It is surmised that plasma separates via a Lorentz force in a fashion similar to that of a plasma filament [53]. This effectively forms a dipole smaller than the dimension of the plasma.

In addition to the plasma radiating GHz frequencies, filaments themselves have been observed to produce emission. The emission has extremely small conversion efficiency, on the order of $5 \times 10^{-9}$ as was calculated by Penano et al [54]. The source of the emission is surmised to be from the electrons separated from their respective ions inducing a dipole. The length of the dipole has been measured to be as large as 10 cm [55]. Considering that the diameter of the filament is generally accepted to be 100 µm, this conductive region can be treated like a moving dipole antenna. The average electric field along the filament is in the direction of the filament, implies an axially net motion of charge. Thus the radiation characteristics can be reasonably approximated by use of a classical wire antenna model [2].

2.3. Shockwaves

A pressure wave propagating in a medium is considered a shockwave when the group velocity of the wave is faster than the speed of sound in the material for those conditions. The leading edge of the shockwave is essentially discontinuous and results in rapid changes in pressure and temperature across the discontinuity. The energy required for a shockwave to propagate decreases quickly with increasing distance. The decrease in energy is the result of loss
to work on the medium (in the form of heating) and radial expansion. This section presents the
basic physics of shockwaves.

2.3.1. Shockwaves in plasmas

In short-lived plasmas, such as laser-produced plasmas, the electrons and ions are both
stimulated to high energies. Due to their smaller mass, the electrons have a much higher velocity
and escape the plasma quickly. This leaves the remaining plasma with a surplus of ions, and
hence a net positive charge. The development of shockwaves in plasmas is based on the
assumption that the plasma consists entirely of ions. This method follows from Chen’s derivation
[10].

For simplicity it is assumed that the plasma is one-dimensional and collision-less. Most
waves are formed by the steepening of an ion pressure wave, the result of propagating through a
medium experiencing nonlinear effects. The wave initially moves with a velocity \( v_0 \), and the
potential \( \phi(x) \) is constant with respect to the moving wave. Using energy conservation, the ions
in the shockwave have velocity given by

\[
\frac{1}{2} m (v_{ion})^2 = \frac{1}{2} m v_0^2 - e \phi(x)
\]

which solved for the velocity gives

\[
v_{ion} = \sqrt{v_0^2 - \frac{2e \phi}{M}}
\]

where \( e \) is the electron charge, \( \phi \) the potential, and \( M \) the mass of the ions. Then the ion density
\( n_i \) with respect to the main plasma density is
\[ n_0v_0 = n_e(x)u(x) \quad 2-15 \]

\[ n_e(x) = n_0 \left(1 - \frac{2e\phi}{Mv_0^2}\right)^{-1/2}. \quad 2-16 \]

For a steady-state plasma, the electrons are governed by the Boltzmann distribution.

\[ n_e(x) = n_0 e^{\frac{e\phi}{KTe}}. \quad 2-17 \]

Using Poisson’s equation,

\[ \left( \frac{\partial^2}{\partial x^2} \right) \phi(x) = f(x) \quad 2-18 \]

and inserting equation 2-17 gives

\[ \frac{d^2 \phi}{dx^2} = 4\pi e(n_e - n_i) = 4\pi e n_0 \left[ e^{\frac{e\phi}{KTe}} - \left(1 - \frac{2e\phi}{Mv_0^2}\right) \right] \quad 2-19 \]

which is the nonlinear relation for the potential. It is common here to make some substitutions, namely,

\[ \xi \equiv \frac{x}{\lambda_d}, \quad \chi \equiv \frac{e\phi}{KTe}, \quad M_m \equiv \frac{v_0}{\sqrt{KTe/M}} \quad 2-20 \]

where \( M_m \) is known as the Mach number of the shockwave. Making these substitutions gives,

\[ \frac{d^2 \chi}{d\xi^2} = e^\chi - \left(1 - \frac{2\chi}{(M_m)^2}\right)^{-1/2} = -\frac{dV(\chi)}{d\chi} \quad 2-21 \]
where $V$ is the quasipotential and is often referred to as the Sagdeev potential [10]. The potential and density disturbances caused by the shockwave are analogous to a moving depression, where once particles enter they are trapped inside. However, the leading edge acts like a barrier to the electrons and ions, repelling them as it propagates. By reflecting these particles, the density of the leading edge steepens and the trailing edge spreads out. The result of this ‘snowplowing’ is a strong shockwave.

Equation 2-21 for the shockwave is, however, only valid for a certain range of $M_m$. The lower limit is found by expanding equation 2-21 and assuming $\chi \ll 1$. This gives

$$\frac{1}{2} \dot{\chi}^2 - \left( \frac{\chi^2}{2M_m^2} \right) > 0$$

which implies that $M_m^2 > 1$ for all conditions. The upper limit is found by setting $\chi > 1$, where this would be required for particles to be reflected and for the potential to be steep. This assumption gives

$$e^\chi - 1 < M_m^2 \left[ 1 - \sqrt{1 - \frac{2\chi}{M_m^2}} \right]$$

for $\chi > 0$. However, $e\phi$ must be less than $\frac{1}{2} M v_0^2$; otherwise, the ions behind the shockwave are excluded. This implies that $\chi$ has a maximum value of $M_m^2/2$. Setting this in equation 2-23,

$$e^{\left( \frac{M_m^2}{2} \right)} - 1 < M_m^2 \left[ 1 - \sqrt{1 - \frac{2\left( \frac{M_m^2}{2} \right)}{M_m^2}} \right]$$
\[
e^{\left(\frac{M_m^2}{2}\right)} - 1 < M_m^2
\]

Solving numerically gives \( M_m < 1.6 \). Thus the total range for the Mach number in a plasma is \( 0 < M_m < 1.6 \) [10]. Going back to the definition of the Mach number (equation 2-20), the range of allowable velocities is given by,

\[
1 < \frac{v_0}{\sqrt{KT_e / M}} < 1.6
\]

\[
\sqrt{KT_e / M} < v_0 < 1.6 \sqrt{KT_e / M}
\]

As an example, a typical laser-produced plasma has a temperature of 100 eV, and for a metal target of copper, gives the velocity range of, \( 12322 < v_0 < 19715 \) m/s [10].

### 2.3.2. Shockwaves in gases and solids

There are many factors involved in the mathematical description of shockwaves propagating in gases and solids. These range from thermodynamic properties to velocity, pressure, and density, all of which are functions of time. In solids the system behaves hydrodynamically whereas in gases it behaves in a gasdynamic manner. Given the complexity, only the basics of shockwave theory will be examined here, as the full theory is outside the scope of this thesis. The theory will be developed for gases, with the understanding that the derivation applies to solids by merely changing the physical parameters (and, e.g., ignoring compressibility). The derivation here follows the approach of Zeldovich and Raizer [73]. The
derivation begins with sound waves from which can be extrapolated the concept shockwaves due to shockwaves being self-steepened intense sound waves.

We first introduce the basic equations for sound waves in a gas, making the assumptions that the thermodynamic properties are constant in time (e.g., the pressure wave is not heating and cooling the gas as it propagates). In reality, this is not a realistic approximation to most measured values. Conservation of mass in the medium is provided by the fluid equation (here assumed a fluid under high pressures).

\[
\frac{d\rho}{dt} + \rho \nabla \cdot v = 0 \tag{2-28}
\]

where \(\rho\) is the density of the medium and \(v\) is the velocity of a particle under compression. For incompressible fluids, as in hydraulics, \(\rho\) is a constant and the equation becomes

\[
\nabla \cdot v = 0 \tag{2-29}
\]

To express the motion of the fluid we have

\[
\rho \frac{dv}{dt} = -\nabla p \tag{2-30}
\]

where \(p\) is the pressure. Lastly we have to conserve the total energy of the system, which is given by

\[
\frac{d\varepsilon}{dt} + p \frac{dV}{dt} = Q \tag{2-31}
\]

where \(\varepsilon\) is the specific internal energy, \(V\) is the specific volume defined as \(1/\rho\), and \(Q\) is the total energy in the system [73]. Equations 2-28 to 2-31 can be combined into a single equation of state,
\[
\frac{\partial}{\partial t} \left( \rho \varepsilon + \frac{\rho v^2}{2} \right) = -\nabla \cdot \left[ \rho v \left( \frac{\varepsilon + v^2}{2} \right) + pv \right] + \rho Q
\]

This equation now describes the total change of energy in the system per unit volume [73]. For instance if the fluid is compressed (an external input of energy), the internal temperature, density, and total energy \( Q \) will increase as expected.

Equation 2-32 describes the state of a fluid as a function of time. Propagating sound waves are perturbations in the density and pressure in this state so we can make the following approximations

\[
\rho = \rho_0 + \Delta \rho
\]

and

\[
p = p_0 + \Delta p
\]

where the variations due to the acoustic waves are defined as positive deviations from the rest conditions \( p_0 \) and \( \rho_0 \). Due to the initial assumptions that we ignore the pressure adiabatic of the system for simplicity, it is required that the velocity of the waves is slow and no nonlinear effects are present. Then these parameters are interrelated by the ideal gas law,

\[
pV = RT, \quad p = R \rho T
\]

where \( R \) is the universal gas constant. The speed of sound in the gas is found through the continuity equation as

\[
v_s^2 = \frac{\partial p}{\partial \rho}
\]

and is only valid for rest conditions. The wave equation for the change in density is given by
\[ \frac{\partial^2 \Delta \rho}{\partial t^2} = v_s^2 \frac{\partial^2 \Delta \rho}{\partial x^2} \]  

which has the solutions

\[ \Delta \rho = \Delta \rho(x - v_s t) \]  

\[ \Delta p = \Delta p(x - v_s t) \]  

\[ v = v(x - v_s t) \]

that describe the motion of the disturbances after a perturbation [73]. Relating density and particle velocity,

\[ v = \frac{v_s}{\rho_0} \Delta \rho, \quad \Delta p = v_s^2 \Delta \rho = \rho_0 v v_s \]

We can write these equations in the general form for the change in pressure and velocity for a propagating wave.

\[ \Delta \rho = \frac{\rho_0}{v_s} f_1(x - v_s t) + \frac{\rho_0}{v_s} f_2(x + v_s t) \]  

\[ v = f_1(x - v_s t) - f_2(x + v_s t) \]

where the functions \( f_1 \) and \( f_2 \) are given by

\[ f_1 = \frac{1}{2} \left[ \frac{v_s}{\rho_0} \Delta \rho(x, 0) + u(x, 0) \right] \]  

\[ f_2 = \frac{1}{2} \left[ \frac{v_s}{\rho_0} \Delta \rho(x, 0) - u(x, 0) \right] \]
and depend on the initial conditions and distributions of the density and velocity [73].

The derivations so far have been based upon sound waves in gases and the assumption of linear perturbations as proposed in Zeldovich and Raizer [73]. Continuing, consider now that the initial perturbation into the medium becomes increasingly more intense. Under large input system perturbations, the same gas equations can be considered valid assuming that the acoustic wave formed is represented by extremely large gradients over small lengths in the solution (the solutions are considered to be continuous). This large gradient, as the length approaches zero, becomes a discontinuity and is defined as a shockwave.

From the general derivations above, the density, pressure, and velocity can be found for the case of a discontinuity or shockwave (again, this is not entirely valid since adiabatics are ignored). Given an impulse into a fluid with velocity $D$, the conservation of mass in the system is given by

$$\rho_1(D - v)t = \rho_0Dt$$

where the compressed volume is given by the left-hand side and the undisturbed volume is given on the right. Therefore the mass across the discontinuity must be conserved. The momentum of the system is given by

$$\rho_0Dvt = (\rho_1 - \rho_0)t$$

where the force acting on the fluid is equal to the difference in pressure across the boundary. The total kinetic energy of the system, including the internal and external acting energies, is found from

$$\rho_0Dt\left(\varepsilon_1 - \varepsilon_0 + \frac{v^2}{2}\right) = p_1vt$$
where $\varepsilon_i$ is the thermodynamic term for the compressed region, and $\varepsilon_0$ for the uncompressed. These three equations can be used to find the values of $p_1$, $\rho_1$, and $D$ as functions of time using the known values of $p_0$, $\rho_0$, and $v$ [73].

Shockwaves (or discontinuities) do not exhibit constant thermodynamic properties. There are significant differences in the properties across the discontinuity, which are not treated here and are extremely difficult to calculate. Instead, empirical data taken for various conditions and materials are compiled into Hugoniot curves (also known as shockwave adiabatics) that relate volume, pressure, and density. The combination of empirical data with complex derivations for all terms involved can model shockwave behavior. This level of complexity is outside the scope of this thesis.

2.4. **Femtosecond laser propagation (filamentation)**

In this project a specific phenomena that occurs in air when a high intensity femtosecond laser pulse propagates through it known as filamentation is described. Filaments can be generated in any optical material with suitable nonlinear properties. Filamentation through the atmosphere was first observed experimentally by Braun et al [8], who used a 200-femtosecond laser producing peak powers of ~10 GW. They propagated a stable filament tens of meters down a hallway in the lab. This process is possible because of the balance of the air’s nonlinear properties and the propagation of the wave. In the subsequent sections the fundamental science behind this phenomenon is described.

There are many different approaches to describing the process of filamentation. The approaches range from simplistic approximations to rigorous models. Couairon et al. analytically
model the filamentation process using a vector wave equation which accounts for plasma
defocusing, blueshifting of the optical pulses, plasma current density, and the gas parameters
[15]. Broudeur et al. explain the propagation of the laser pulses though a moving focus model as
an alternative to self-channeling [9]. Another approach is to solve the non-linear Schrödinger
equation for filamentation including dispersion, space time focusing, and self-steepening [22].
Kolesik et al. model the filament in fully vectorial form using Maxwell’s equations [40]. All of
these approaches agree well with the experimental results and illustrate that there are many
avenues to approach filamentation.

2.4.1. Filamentation

In order to accurately model the filamentation process, many different effects and
properties must be accounted for. The non-linear properties (including the Kerr response) of the
propagation medium, the ionization potentials of all the molecules in that medium, and the group
velocity dispersion all must be considered. Due to its complexity, this section focuses on the
basic theory for stable propagation and maintenance of the filament structure in any medium,
regardless of material parameters. This approach follows that presented in Non-linear Optics [7].

The basic concept of stable filamentation can be described by a four-wave mixing
process that occurs in media. The phase fronts of the propagating laser light experience
perturbations, the result if propagation in the media and the properties of the laser. The formation
of self-focusing depends strongly on the initial phase front, and these perturbations result in non-
uniform self-focusing of the beam. To obtain a single filament, the phase front of the laser beam
must be clean. The derivation assumes that one filament is created, the result of a clean beam. In
order to understand the confinement of a laser pulse propagating in a medium, we start with the electric field of the pulse. The electric field can be defined as

\[ E(r, t) = E(r)e^{-j\omega t} + c.c. \]  

which is split into three electric field components: the central beam (containing most of the power) and two symmetrical weak side fields. This is illustrated in figure 1. The side fields represent the divergence of the electric field of the laser beam.

Thus for confinement of the pulse, these must be minimized. The electric field is then,

\[ E(r) = E_0(r) + E_1(r) + E_{-1}(r) = \left[ A_0(z) + a_1(z)e^{jqr} + a_{-1}(z)e^{-jqr} \right]e^{jkz} \]

where \( E_0 \) is the central field, \( E_1 \) and \( E_{-1} \) are the side fields, and, once split into amplitudes, \( A_0 \) is the central amplitude, \( a_1 \) and \( a_{-1} \) the side amplitudes and \( q \) is the transverse propagation vector.

For filamentation to occur the side fields must balance one another by operating at the condition where \( q \) cancels out the side fields. The nonlinear polarization of the field in the media is given by,

\[ P = 3\chi^3 |E|^2 \] 

\[ E = P_0 + P_1 + P_{-1} \]
where $\chi^3$ is the 3rd order susceptibility. Now expanding each polarization individually,

$$P_0 = 3\chi^3|E_0|^2 E_0 = 3\chi^3|A_0|^2 A_0 e^{jkz} = p_0 e^{jkz}$$  \hspace{1cm} 2-52$$

for the central mode of the polarization, and

$$P_{\pm 1} = 3\chi^3 \left(2|E_0|^2 E_\pm + E_0^2 E_{\mp1}^*\right) = p_{\pm 1} e^{jkz}$$  \hspace{1cm} 2-53$$

for the polarization for the phase-matched side modes. The propagating central electric field must obey the wave equation as a function of the spatial distribution of $A_0$,

$$2jk \frac{\partial A_0}{\partial z} + \nabla \cdot A_0 = -\frac{4\pi\omega^2}{c^2} p_0$$  \hspace{1cm} 2-54$$

which has the solution

$$A_0(z) = A_{00} e^{j\gamma z}$$  \hspace{1cm} 2-55$$

where

$$\gamma = \frac{6\pi\omega\chi^3}{n_0 c} |A_{00}|^2 = n_2 k I$$  \hspace{1cm} 2-56$$

where $k$ is the vacuum propagation constant, $A_{00}$ the amplitude of the field, $n_2$ the nonlinear refractive index of the medium, and $I$ the intensity. As a result the propagation of the central component only experiences phase shift. For the side components, the nonlinear polarization is given by

$$p_{\pm 1} = 3\chi^3 \left(2|A_{00}|^2 A_{\pm 1} + A_{00}^2 e^{2j\pi} A_{\mp1}^*\right)$$  \hspace{1cm} 2-57$$

and then the wave equation for propagation is given by,
\[ 2jk \frac{\partial A_{\pm 1}}{\partial z} + \nabla_\perp^2 A_{\pm 1} = -\frac{4\pi \omega^2}{c^2} p_{\pm 1} \]  

using \( A_{\pm 1} = a_{\pm 1} e^{\pm jqr} \) and the equation for \( P_{\pm 1} \), the wave equation becomes

\[ 2jk \frac{\partial a_{\pm 1}}{\partial z} - q^2 a_{\pm 1} = -\frac{4\pi \omega^2}{c^2} 3\chi^3 |A_{\pm 0}|^2 \left[ 2a_{\pm 1} + a_{\pm 1}^* e^{\pm jqr} \right] \]

which, when simplified, becomes

\[ \frac{da_{\pm 1}}{dz} + \frac{jq^2}{2k} a_{\pm 1} = j\gamma \left[ 2a_{\pm 1} + a_{\pm 1}^* e^{\pm jqr} \right] \]

This yields a set of equations for \( a_1 \) and \( a_{-1} \). From this set, eigen-solutions are found which represent the solutions in which stable propagation is possible. The result leads to

\[ \Lambda = \pm \sqrt{\frac{q^2}{2k} \left( 2\gamma - \frac{q^2}{2k} \right)} \]

which is the gain of the forward four-wave-mixing solution and depends on the value of \( q \). This results in a minimum \( q \) value of 0 and a maximum value of \( q_{\text{max}} = 2\sqrt{k\gamma} \). Self-channeling will be stable at the peak of the this gain curve when \( q \) is optimal, or \( q_{\text{opt}} = q_{\text{opt}} / \sqrt{2} \). Thus the optimal value of \( q \) for filamentation to occur is given by

\[ q = \sqrt{2k_0 kn_2 I} \]

which is the optimal condition for optical phase matching in the four-wave mixing process.

In practice it is more useful to know the power required for the filamentation process to occur. The power in the filament is simply the cross-section times the intensity,
Here, the diameter $d$ can be approximated by the waist of the beam

$$\omega^2 = \left(\frac{\pi}{q}\right)^2$$

then combining for the waist, and $q$ we get

$$P_{fil} = \alpha \omega^2 I = \alpha \frac{\pi^2}{q^2} I = \alpha \frac{\lambda^2}{4n_0n_2}$$

which is the power contained within each filament. The constant $\alpha$ is a beam shape factor which affects the filamenting process; it is different for each laser. For powers greater than this value, the beam breaks into separate filaments to distribute the power. The critical power required for self-focusing is

$$P_{cr} = \alpha \frac{\pi 61^2 \lambda_0^2}{8n_0n_2}$$

which is calculated to be around 3 GW but experimentally found higher for femtosecond lasers.

### 2.4.2. Filament-induced ionization

Additional factors can help the filamentation process. For femtosecond laser pulses propagating in the atmosphere, the molecules undergo weak ionization due to multi-photon absorption. This ionization results in a localized decrease in the refractive index, thereby counterbalancing the self-focusing. The number of electrons generated by the femtosecond pulse is found from
\[ \frac{dN_e}{dt} = \frac{dN_i}{dt} = (N_T - N_i) \sigma_n T^n - rN_e N_i \]

where \( N_e \) is the number of present electrons per volume, \( N_i \) the number of ions, \( N_T \) the total number of atoms present, \( \sigma_n \) the absorption cross-section for the \( n^{th} \) photon, and \( r \) the recombination rate. For femtosecond lasers, \( r \) can be ignored. The polarizability of an electron is found by

\[ P = \alpha(\omega)E \]

where

\[ \alpha(\omega) = -\frac{e^2}{m\omega^2} \]

\( e \) is the electron charge, and \( m \) is the mass. The dielectric constant of a cloud of electrons is given by

\[ \varepsilon = 1 + 4\pi N\alpha(\omega) = 1 - \frac{4\pi Ne^2}{m\omega^2} \]

where \( N \) is the electron density; thus the refractive index is

\[ n = \sqrt{1 - \frac{4\pi Ne^2}{m\omega^2}} \]

Therefore, as the density of electrons increases, the refractive index decreases.

2.4.3. Filamentation through the atmosphere

Filaments generated in the atmosphere exhibit both four-wave mixing and multi-photon ionization (and other processes not discussed here), resulting in more power transport capability
per filament than just filamentation using four-wave mixing. This is due to the ionization decreasing the refractive index \( n_0 \) as \( N_e \) increases. The power per filament is defined as

\[
P_{fil} = \alpha \frac{\lambda^2}{4m_0(N_e)n_2}
\]

where \( n_0 \) is now a function of \( N_e \), and \( n_2 \) is approximately \( 5.6 \times 10^{-19} \) \( \text{cm}^2/\text{W} \) [59]. As can be seen, decreasing \( n_0 \) increases the total power per filament.

Filaments can propagate over long distances before defocusing, the result of a combination of energy lost in ionizing the air and to positive dispersion, dominates, dispersing the filament. The energy lost to ionization is often referred to as a ‘burn rate,’ or the amount of energy lost per kilometer. Propagation through the atmosphere itself produces positive dispersion that spreads the pulse in space thereby decreasing the peak power. After several kilometers, the net loss and dispersion can cause the filament to destabilize. If channels at a longer distance are desired, it is possible to negatively chirp the pulse such that at a prescribed distance the pulse recompresses and filamentation begins.
CHAPTER 3. THE LPL TERAWATT LASER

The laser system utilized for the majority of experiments detailed in this thesis is the LPL Terawatt laser. At full power this system is capable of producing upwards of 1 Joule in 100 femtoseconds; this equates to 10 terawatts of peak power on target. Several previous Laser Plasma Laboratory students originally designed and built the laser as a team in 1994 [4, 56]. It was built from the ground up, and spreads out over several rooms; however, the main laser system is contained within a single clean room to minimize the danger of dust contamination, which can damage the optics at these power levels. The main target facility is located in the adjacent room and a long-range target facility is now located in the adjacent service chase.

The LPL Terawatt laser (hereafter referred to as TW) is a large laser system with many subsystem components. Each of these separate systems will be discussed in detail, both their individual operation and how they integrate into the system as a whole. In addition, many of the recent improvements will be discussed, including improvements to the fundamental laser operation and the changes necessitated by the experiments performed using the system.
3.1. **Overall design and operation**

The LPL Terawatt laser is based on Chirped Pulse Amplification (CPA) techniques, which involve temporally stretching the pulse, amplifying it, and then recompressing it. The amplifier gain material is Cr\(^{3+}\):LiSrAlF\(_6\) (Cr:LiSAF), a fluoride material with high gain and extremely low non-linear refractive index. The front end utilizes Ti:sapphire (Ti\(^{3+}\):Al\(_2\)O\(_3\)). Cr:LiSAF was chosen as the gain material specifically for its low non-linear index; at higher intensities this becomes critical in avoiding self-focusing in the laser rods.

3.1.1. **Ti:sapphire oscillator**

To generate ultra-short high-intensity laser pulses, the front end of the laser system needs to have sufficiently short pulses and wide bandwidth prior to amplification, as bandwidth is typically lost during the amplification process, leading to longer output pulses. Most systems of this type use a Ti:sapphire oscillator; these oscillators are compact and have large output bandwidths. The Ti:sapphire oscillator was first shown by Spence et al. [60] and is capable of producing pulse lengths of 6 femtoseconds or less [21]. Typical output pulse lengths range from 40 to 100 femtoseconds, depending on the application requirements. Shorter pulse lengths become increasingly hard to achieve since large bandwidths require special optical methods to generate and maintain the bandwidth. The oscillator is so named because it produces a continuous train of pulses with a frequency in the MHz range, similar to that of a crystal oscillator.
These oscillators are usually based on a simple laser cavity in either X-cavity or Z-cavity configurations. This nomenclature refers to the optical path surrounding the crystal as illustrated in Figure 2. In both cases, the crystal is placed between two curved mirrors whose focal lengths are equal; the two mirrors’ foci are located at the same point within the laser crystal. A typical focal length for the mirrors is ~ 100 mm, and they are angled at approximately 15 degrees with respect to the axis of the crystal. The angle of the mirrors is determined by the conditions for optimal operation [39]. For Ti:sapphire, the peak absorption occurs ~ 500 nm, so multi-line argon ion (Ar+) lasers make almost ideal pump sources, with dominant wavelengths of 488 and 514 nm. However, with their better stability, compact size, and longer lifetimes, diode-pumped solid-state (DPSS) lasers are quickly replacing argon ion lasers as pump sources. The most common DPSS pump lasers are frequency-doubled neodymium-doped yttrium orthovanadate (Nd3+:YVO4) lasers, which are available with high output powers at 532 nm from a number of vendors. Despite the lower Ti:sapphire absorption at 532 nm, in most cases the advantages of DPSS lasers outweigh the disadvantages.

Figure 2. a) X-cavity Ti:sapphire oscillator layout. b) Z-cavity oscillator configuration.
The pump laser is focused using a simple plano-convex lens, through one of the curved mirrors into the crystal, and is positioned such that the pump focal spot overlaps the focal regions of the curved mirrors. This overlap region is often referred to as the mode volume of the cavity. It is critical to have high pump intensity inside the crystal, as the intensity directly impacts the power and efficiency of the laser. The intensity is limited by the pump laser’s power, the focal length of the focusing lens (which is itself limited by the physical arrangement of the mirrors and the crystal), and the beam quality. The top arm of the laser passes through a prism pair and onto a highly reflective mirror (usually referred to as a high reflector or HR). Between the prisms is a slit, adjustable in both position and width. This allows for tuning of the center wavelength and bandwidth of the output. In this case, the slit is adjusted for a center wavelength of 845 nm and a bandwidth of ~14 nm, to match the Cr:LiSAF. Output couplers typically have transmissions between 4-15%; the TW oscillator uses 12.5%. The X configuration is identical in operation to that of the Z except the bottom arm is folded upward (in the schematic, that is, the actual beam path is parallel to the optical table). The TW oscillator is in the X configuration due to space constraints. One advantage of the Z cavity over the X is that astigmatism is minimized due to the optical alignment around the crystal. The X configuration has the advantage of minimal coma aberration, as the symmetry of the mirrors around the crystal cancels it out.

Short pulses can be generated by a process known as Kerr-lens modelocking, which occurs when the cavity is configured such that it has a net dispersion of zero and prefers a pulsed mode of operation. Kerr-lens modelocking can be performed in any laser material with sufficient gain bandwidth to produce short pulses. Short pulses must have large spectral widths, and this spectral width experiences positive dispersion (the red travels faster than the blue) while propagating in the cavity. This separation of colors is known as group velocity dispersion.
GVD can be compensated by optical elements that produce negative dispersion, like prism pairs or chirped mirrors [24]. If the amount of positive dispersion and negative dispersion is equal for the different wavelengths in the cavity, then the round-trip optical path length of the cavity is equal for all wavelengths. This allows a unique process to occur: the photons in the cavity start to become locked in phase. Or we can say that the longitudinal modes of the cavity are locked, hence the term ‘modelocking.’ The result is a spectral output which is significantly larger than CW operation and has greater power extraction. Once dispersion is compensated for, a pulse propagating inside the cavity does not experience any net stretching. Then if any random oscillations are introduced to the cavity, they will be preferentially amplified, expand in bandwidth, and lock in phase with one another. This results in a single coherent pulse propagating in the cavity; the output pulse frequency depending on the round-trip path length.

Dispersion compensation can be accomplished by introducing prisms in a specific orientation to provide negative dispersion in the cavity. Most cavities use two prisms, where the spacing between the prisms and the prisms’ material properties set the dispersion compensation. However, this is difficult to adjust, since the prisms spatially separate the beam by frequency. Four prisms are better for adjustment, since only the spacing between each pair needs to be adjusted and the beam in the rest of the cavity is not spatially separated. The prisms provide negative (also called anomalous) dispersion because the red (longer) wavelengths experience longer path lengths than the blue (shorter) wavelengths; this is contrary to the dispersion of most optical materials. The amount of path difference (or GVD) depends on the amount of prism insertion and the distance between prisms \( l_p \), as measured from the apex. A prism pair is illustrated in Figure 3. The prisms are cut such that the minimum deviation angle coincides with
Brewster’s angle, providing near-lossless insertion, since the laser beam is typically already polarized.

The optical path length $P$ of the separate wavelengths after passing through a prism pair can be expressed in terms of the dispersion angle $\alpha$ and the prism separation $l_p$ [24].

$$P = l_p \cos \alpha$$

The amount of dispersion is found from the second derivative of the phase $\phi$ with respect to the frequency $\omega$ expressed using the optical path length $P$ [17].

$$\left. \frac{\partial^2 \phi}{\partial \omega^2} \right|_{\omega_0} = -\frac{l_p}{c} \left[ \sin \alpha \left( 2 \frac{\partial \alpha}{\partial \omega} + \omega \frac{\partial^2 \alpha}{\partial \omega^2} \right) + \omega \cos \alpha \left( \frac{\partial \alpha}{\partial \omega} \right)^2 \right]$$

Since $\alpha$ is small, $\sin \alpha$ is much less than one, so a small-angle approximation may be used to simplify the previous equation.

$$\left. \frac{\partial^2 \phi}{\partial \omega^2} \right|_{\omega_0} = -\frac{\omega_0}{c} l_p \left( \frac{\partial \alpha}{\partial \omega} \right)_{\omega_0}^2$$
For the condition of minimum deviation, the GVD becomes
\[
\left. \frac{\partial^2 \phi}{\partial \omega^2} \right|_{\omega_0} = -4 \frac{\omega_0}{c} I_p \left( \frac{\partial n}{\partial \omega} \right)^2
\]
which can be expressed in terms of wavelength as well. In addition to GVD it is sometimes necessary to take into consideration higher-order dispersion terms, mainly the third-order dispersion. This term must be compensated in order to achieve pulses shorter than 60 fs. It is given by [17]
\[
\left. \frac{\partial^3 \phi}{\partial \omega^3} \right|_{\omega_0} = \frac{3I_p \lambda_0^4}{\pi^2 c^3} \left[ \left( \frac{\partial n}{\partial \lambda} \right)^2 \left[ 1 - \lambda_0 \frac{\partial n}{\partial \lambda} \left( n^{-3} - 2n \right) \right] + \lambda_0 \frac{\partial n}{\partial \lambda} \frac{\partial^2 n}{\partial \lambda^2} \right]_{\lambda_0}
\]
Even-higher-order terms are required to obtain shorter pulses, but these are outside the scope of this text.

Oscillations in the cavity are introduced using the optical Kerr effect or saturable absorbers, both passive modelocking techniques, or active modelocking using acousto-optic elements. The optical Kerr effect is a nonlinear reaction of the Ti:sapphire material to high electric fields, causing a change in the local refractive index. Since the beam inside the cavity has a Gaussian profile, different portions of the beam experience different indices of refraction and thus the material acts much like a lens. By aligning the cavity to lase with this specific alignment (when this “lens” is active), the laser will prefer modelocking to CW operation since the CW alignment experiences higher loss in the cavity.

Since Ti:sapphire has approximately 300 nm of gain bandwidth, and can be tuned to lase over this entire range [48]. The peak gain occurs at 790 nm with a continuous wave (CW) lasing bandwidth of less than a nanometer. In the case of modelocking, the bandwidth is significantly
wider and is typically in the 10-60 nm range. Since the output of a modelocked laser has a broad spectral bandwidth, as a consequence of the Fourier transform, this output has a very narrow temporal width (a very short pulse). Put simply, the wider the spectrum, the shorter the pulse. Since the width of the pulse depends directly on the bandwidth, as well as a number of other factors, this gives rise to the term bandwidth-limited pulses. Ideally, the pulse width would be as short as the Fourier transform of its spectrum allows, and this ideal case is known as transform-limited.

3.1.2. Chirped Pulse Amplification techniques

The idea of chirped pulse amplification (CPA) was developed by Strickland and Mourou [61]. This technique allows for the amplification of ultra-short pulses (considered to be less than a picosecond in length) more easily than the previous Master Oscillator Power Amplifier (MOPA) systems. Amplification of short pulses is difficult to achieve since, as the energy in the pulse increases, the instantaneous power quickly comes close to the damage threshold of the material. In addition, at high intensities, the materials begin to exhibit non-linear effects, and self-focusing can occur, causing severe damage. Thus, in conventional laser amplifiers, the beam has to be expanded significantly to keep the intensity inside the gain media well below the damage threshold. This requires large gain media, which are very expensive and complicated amplifier chains.

The CPA technique involves optically stretching the pulse in time, amplifying, and then re-compressing the pulse back to short time scales. Stretching is typically performed using dispersive optical systems, either a Martinez-type stretcher or a Treacy-type stretcher [44, 63].
By stretching the pulse prior to amplification, the power inside the gain media is significantly lower and thus high energy gain can be achieved at low power. After amplification, the pulse is recompressed, again using dispersive optics, typically a Treacy-type compressor. The resulting pulse is many orders of magnitude greater in energy, while the pulse length is still the same order of the input pulse.

The stretching and compressing processes are dependent on the frequency bandwidth $\Delta \nu$ of the pulse. Since the process is governed by the Fourier transform of the spectrum, we have the limiting case relation $\tau_p \cdot \Delta \nu = a$ where $\tau_p$ is the shortest pulse length possible and $a$ is a constant that depends on the shape of the spectrum. Pulses that obey this relation are referred to as transform-limited pulses. It should be noted that this relationship is only valid if there is equal phase for all of the wavelengths. For typical Ti:sapphire oscillators the spectrum takes the shape of a $\text{sech}^2$ envelope and the corresponding value of $a$ is 0.315. Since we use a slit in the TW oscillator to shift the center wavelength, the spectrum is set by the pass band of the slit [17].

Dispersion is defined as the change in the refractive index $n(\omega)$ of the medium with respect to the wavelength $\lambda$ or angular frequency $\omega$. Thus in an optical system that is transmitting large bandwidths, the different wavelengths experience different optical paths. This is typically analyzed by expanding the propagation constant $\beta(\omega)$ into a Taylor series.

$$\beta(\omega) = n(\omega)\frac{\omega}{c} = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \frac{1}{6}\beta_3(\omega - \omega_0)^3 \ldots$$

where $\beta_m = \left(\frac{d^m \beta}{d\omega^m}\right)_{\omega=\omega_0}$ for $m = 0,1,2,3\ldots$
\[ \beta_1 = \frac{1}{c} \left[ n + \omega \frac{dn}{d\omega} \right] = \frac{1}{v_g} \] 3-8

\[ \beta_2 \approx \frac{\lambda^3}{2\pi^2} \frac{d^2 n}{d\lambda^2} \quad \text{and} \] 3-9

\[ \beta_3 \approx \frac{\lambda^4}{(2\pi)^2 c^3} \left[ \lambda \frac{d^3 n}{d\lambda^3} + 3 \frac{d^2 n}{d\lambda^2} \right] \] 3-10

\( \beta_1 \) is the reciprocal of the group velocity of the light. \( \beta_2 \) is the group velocity dispersion (GVD) term and \( \beta_3 \) is the cubic dispersion term. For most cases, including ours, we only consider the second and third terms when calculating the effects of dispersion. The result of a Gaussian temporal pulse shape experiencing these two terms is found using

\[ \tau_{chirp} = \tau_0 \sqrt{1 + \left[ \beta_2 \frac{Z}{\tau_0^2} \right] + \left[ \beta_3 \frac{Z}{2\tau_0^3} \right]} \] 3-11

where \( \tau_0 \) is the initial pulse width (FWHM) and \( Z \) is the length of the material in which the light is propagating. Using the Sellmeier equation to calculate the wavelength-dependent index, the GVD and third-order term can be calculated and used to find the stretched pulse length. The Sellmeier equation is given as

\[ n^2(\lambda) - 1 = \frac{A_1 \lambda^2}{\lambda^2 - C_1} + \frac{A_2 \lambda^2}{\lambda^2 - C_2} + \frac{A_3 \lambda^2}{\lambda^2 - C_3} \] 3-12

where \( A \) and \( C \) are optical material constants. Thus in principle transmission through any material can be used as a means of pulse stretching. However, for our purposes, the amount of material required would be enormous. In addition, dispersion in material is not always uniform,
so compression is nearly impossible without a material that has the exact opposite dispersion
characteristics. A better approach is to use diffraction gratings.

As noted above, a Martinez stretcher is typically used for stretching optical pulses in a
CPA system because it can provide positive dispersion. If we were to stretch the pulse using
negative dispersion, the pulse will shorten as it propagates through the amplifying media (which
is undesirable). The stretcher consists of two orthogonal gratings and two lenses. The two lenses
act as a telescope and image the input grating and thus effectively change the separation between
the two gratings. The first lens images the first grating to a position of

\[ I = \frac{fx}{x - f} \]  \hspace{1cm} (3-13)

where \( I \) is the distance from the lens to the image plane. Using the thin lens equation,

\[ \frac{1}{f} = \frac{1}{I} + \frac{1}{O} \]  \hspace{1cm} (3-14)
Figure 4. a) Illustration of a Martinez stretcher. b) A folded Martinez stretcher.

The second lens then images this to

\[ I = 2f - x \]  

If \( x < f \) then the image of the grating is \( 2(f-x) \) behind the second grating; this means the separation between the two gratings is negative and thus the stretcher produces positive dispersion. As noted before, positive dispersion is best for stretching the pulse so that it will not recompress in optical propagation. By placing a mirror at the focal length of the first lens the system can be folded as illustrated. The back mirror is now typically placed below the input.
beam and at a slight angle to the beam in the stretcher so that the two paths do not overlap. The Terawatt laser system utilizes a folded Martinez stretcher with an 1800-lines-per-millimeter grating. The lens-to-grating spacing is 30 cm and the focal length of the lens is 58 cm. This configuration provides an increase in pulse length of ~3,000 times the input.

Optical compression is accomplished by use of a Treacy compressor [63]. Using two parallel gratings, the different wavelengths in the bandwidth of the laser pulse experience different optical path lengths, resulting in negative dispersion. The Treacy compressor is illustrated in Figure 5.

![Figure 5. The Treacy compressor.](image)

The first grating separates the wavelengths of the input pulse and spatially disperses them across the second grating. This second grating then effectively collimates the separated spectrum, which is in turn reflected back to a higher position on the gratings, and the dispersion process is reversed. This compressor design causes the longer wavelengths to travel a longer distance in both the forward and backward paths, resulting in negative dispersion. The amount of negative dispersion required should exactly equal the amount of positive dispersion in the stretcher plus
the small amount caused by the gain media. The result should be a net dispersion of zero, such that the original pulse length prior to stretching is obtained. The amount of dispersion is adjusted by moving the second grating relative to the first so that they remain parallel, but move closer together or further apart. The Terawatt stretcher uses 1200-lines-per-millimeter gratings, and a grating separation of about 20 cm.

3.1.3. Amplification

The Terawatt oscillator produces pulses with energies in the range of 2-5 nanojoules, which is too low to send directly to the large amplifiers. To increase the pulse energy, a regenerative amplifier (“regen”) is employed. The output from the stretcher goes directly to the seed-injection Pockels cell. The Pockels cell is between two crossed Glan-Taylor polarizers that reject all the pulses except those when the Pockels cell fires. The timing of the seed injection is synchronized to the rest of the laser system. This will be explained in detail in subsequent sections. The cavity is illustrated in Figure 6.

Figure 6. Layout of the TW regenerative amplifier. The first two polarizers and Pockels Cell (PC) 1 are used for seed injection to the cavity. The seed is injected via Polarizer (Pol) 3. Pockels Cell 2 traps the seed pulse and the cavity lases. The output is a train of pulses.
The seed pulse is injected into the amplifier cavity by reflecting off Polarizer 3, which is a thin-film high-power polarizer set at Brewster’s angle in the cavity to minimize the insertion loss. The amplifier cavity has a highly reflecting curved mirror (radius of 5 meters) and an output coupler with 40% transmission. The combination of the quarter-wave plate (\(\lambda/4\)) and Pockels Cell 2 retains the pulse in the cavity by rotating the seed pulse’s polarization from horizontal to vertical. Pockels Cell 2 is synchronized to Pockels Cell 1 such that it opens just prior to the seed pulse entering and is timed such that it closes before the seed pulse returns from a round trip in the cavity. The round-trip time of the cavity is about 9 nanoseconds and the Pockels cell typically closes in 4 nanoseconds. A Continuum avalanche board drives the first Pockels cell, and a Continuum Marx bank board drives the second. Now that the seed pulse is in the cavity, the pulse is amplified each pass through the Cr:LiSAF rod. Typically, it takes around 40 passes in the cavity before all the gain is extracted. Since there is an output coupler to extract the pulses from the amplifier cavity, the output is a train of pulses, separated by the cavity round-trip time, under a Gaussian envelope. The peak pulse under the envelope contains between 1 and 6 mJ of energy depending on how much flashlamp pumping is applied to the Cr:LiSAF. Measured energies greater than 6 mJ outside the cavity can result in damage to the Cr:LiSAF rod, as the internal power is too close to the damage threshold (for typical stretched pulse lengths; the length of the pulse directly affects this threshold). Generally, any seed pulses shorter than 200 picoseconds can also be very dangerous to the gain media.
Figure 7. a) Output pulse train from the regenerative amplifier. b) Overlap of pulse sliced out and regen output to show which pulse was selected. Relative signals are exaggerated to illustrate position of sliced pulse.

Typically we want to amplify only one pulse in the main amplifiers; however, the output of the regenerative amplifier is a train of pulses. To amplify one pulse, a high-speed pulse slicer is used. The pulse slicer is a combination of two high-power polarizers (again Glan-Taylor) and a Pockels cell with a special driver. This Pockels cell can open on sub-nanosecond time scales and
close in the same amount of time. This allows exact extraction of any pulse under the envelope with nanosecond accuracy. In addition, the time between open and close can be adjusted such that more than one pulse goes through. This is referred to as ‘burst mode,’ and will be detailed in the discussion on material processing. The measured contrast ratio of the pulse slicer is around $10^6$.

By allowing more than one pulse to pass through the pulse slicer, the train of pulses may be amplified further. The leading pulses tend to get more gain than the later, but this can be counteracted by selecting pulses from the leading edge of the Gaussian regen envelope, such that the first pulses initially have less energy. The net result is typically four pulses having energies within 10% of each other. More than four pulses is possible, but the uniformity of the pulse energies is not as good. To obtain more than four pulses with uniform energy, a Michelson interferometer is set up directly after the pulse slicer and the pulses are split and temporally multiplexed. This gives a train of eight pulses with half the time separation and less than half the original energy (due to the loss when recombining the pulses with a beamsplitter). Initially, the pulse separation is set by the round-trip time of the regenerative amplifier, typically ~9 ns, so the multiplexed pulses have a separation of about 4.5 ns. These pulses are passed to the amplifiers and are subsequently amplified further.
Figure 8. a) Sliced-out top five pulses from the regenerative amplifier. b) Measured eight pulses out of interferometer after pulse slicer, using four input pulses.

The main amplifier stages of the Terawatt system are typically reconfigured for each experiment depending on the requirements. The first amplifier is always a double-pass Cr:LiSAF 7-mm \( \times \) 105-mm cylindrical rod, flashlamp-pumped. The double-pass gain is around 12. With the output pulses from the pulse slicer having energies of \( \sim 4 \) mJ, the double-pass produces pulse energies of about 50 mJ. However, the beam profile is typically poor. To keep good beam quality, either an iris is inserted in front of the amplifier or the output beam passes through a vacuum spatial filter. The use of the iris reduces the gain to around 7 by clamping down on the beam. The vacuum spatial filter has better energy performance; however, having this device in the beam path makes alignment difficult. Since the amplifiers are re-configured often, lower performance (\textit{i.e.}, the iris) is typically chosen over alignment issues. After the double-pass, a single-pass Cr:LiSAF rod of the same dimensions provides a single-pass gain of about 3. From here the beam is typically sent to the next room, into a vacuum chamber for optical compression.
3.2. **Vacuum chamber and associated infrastructure**

The Terawatt vacuum chamber assembly consists of two main connected chambers; one contains the Treacy compressor, a single-shot autocorrelator to measure the pulsewidth, and beam-steering optics; the other chamber is where the high intensity vacuum experiments are typically performed. The first chamber is often referred to as the compression chamber, named for the optical compressor contained within, and the second is commonly referred to as the target chamber. The laser beam from the Terawatt system passes through a wall, which separates the clean room from the target bay, and passes directly into the compression chamber through a vacuum-tight window. Once inside, the laser beam goes through the compressor, and the output is steered to the autocorrelator, the target chamber, or the propagation test range. Inside the compression chamber a small portion of the compressed beam is split off and sent to the propagation test range. The autocorrelator is used to align the Treacy compressor for best (shortest) pulse length.

The target chamber is a custom-built MDC chamber with 50 ports, each aligned to the center of the chamber. This arrangement allows easy reconfiguration for almost any experiment and is illustrated in Figure 9. The chamber is equipped with two long-distance microscopes which can be focused onto the target for alignment and process tracking. These can also be moved around the chamber as necessary for the experiment. In the center of the chamber there is a three-axis vacuum-compatible stage with sub-micron accuracy. These stages, Newport MFN25 series, are controlled with a Newport 4006 motion controller, which itself can be controlled either remotely via computer or by using the front panel. For typical experiments, software is written in NI LabVIEW to handle complicated operations.
The Terawatt vacuum system is rather complex, consisting of three rough vacuum pumps and two turbo molecular pumps. The three rough vacuum pumps are all rotary vane oil pumps running with synthetic hydrocarbon fluid. The largest one, a Leybold Sodgenvac 250 series is
capable of pumping out the majority of the atmosphere in the chambers, which is required before starting the other pumps. This pump is limited to an operating pressure of 2 Torr, at which point the other two roughing pumps are used to continue pumping the chambers. These pumps are Welch rotary vane pumps and in combination can bring the chamber to around 150 millitorr. For simple experiments this pressure is adequate as there is little atmosphere to interfere with the laser interaction process. However, for more precise experiments, the Welch 1000 L/s turbo pumps are used. The compression and target chambers have their own independent turbo pumps and can be isolated from each other. This allows one chamber to be brought up to atmospheric pressure while leaving the other at vacuum. Starting at a chamber pressure of less than 300 millitorr, the turbos require approximately 15 minutes to reach operating speed. The chambers can reach pressures of $10^{-6}$ Torr but only after several hours of pumping. Typical operation of $10^{-5}$ Torr can be achieved about 30 minutes after the turbos reach full speed. Once experiments are completed, the turbos require a minimum of 30 minutes to spin down before venting of the chamber can begin. The chamber is always vented with nitrogen to reduce the amount of moisture inside the chamber; this decreases the subsequent pump-down time. The vacuum system has numerous control valves that are all pneumatically powered, and as such requires compressed air. The air for the actuators comes from the building services, but in the case of a malfunction, compressed nitrogen has been used. The default state of all actuators is closed for safety.
3.3. **Improvements and upgrades**

A large portion of the electrical system in the Terawatt laser was used for at least ten years. As a result, the system was prone to failure due to electrical component failures. Between experiments, improvements to the operation of the system have been made, including a recent comprehensive rebuild of almost the entire electrical system. In addition to the necessity of replacing old parts, new areas of research are changing the way in which the Terawatt system is and can be used. Some of the new changes reflect this, and most of the improvements will be described in this section.

In order to perform experiments at distance, a complete new lab and associated infrastructure had to be built. This required upgrades to the laser, and to the compressor chamber to pipe the laser beam to an adjacent service chase. The service chase was reconfigured to allow beam propagation over 30 meters and an experiment station was constructed.

3.3.1. **Previous electrical backbone**

To better describe the changes made to the electrical system, the old system will be discussed first. The previous electrical backbone system, and here backbone meaning the main timing and synchronizing electronics and associated parts, experienced significant jitter, which was the result of noise in the electrical system and jitter in the electronic components themselves. In addition, the RF electronics used to synchronize the oscillator with the rest of the system were not designed to be used for this purpose. This sometimes resulted in a poor lock to the oscillator signal. Since the cavity of the oscillator is designed to run at \(\sim 92\) MHz, the RF electronics must have bandwidths at least twice that in order to track and lock onto the signal. Once locked on, the
electronics would wait until the main control box, a Continuum CU552, entered a ready state. When the CU552 would trigger the laser to fire, it first triggered the power supplies of the amplifiers including the regenerative amplifier; then the RF box locked onto the oscillator. This box then triggered, in synchronism with the output pulses of the cavity, the input pulse slicer Pockels cell and the seed injection Pockels cell. The timing of the pulses to these units was adjusted by cable delay and had to be accurate to about one nanosecond. Additional instruments in the system were triggered via fiber optic cables that came from transmitters connected to the amplifier power supplies. This often resulted in significant jitter because the timing accuracy of the power supplies was in the microsecond range, but the instruments had nanosecond accuracy. The CU552 had to be manually operated from its front panel and only supported continuous operation at 5 Hz on the regenerative amplifier and 1 Hz on the main amps. This operation was not native to the CU552 and had been heavily modified by previous graduate students. However, no documentation remained of the modifications and these were frequently the cause of failures in the system (as was determined after much frustration). Single shots were possible, but pulse-to-pulse energy was unstable and significantly lower than in continuous operation. The pulse slicer (after the regenerative amplifier) was triggered by a photodiode signal at the leading edge of the output pulse. This was necessary to correctly time the slicer, since the build-up time in the regen varied from shot to shot. The overall effect of the poorly-timed electrical system was a measured pulse energy variation of close to 30%, in addition to frequent missed shots. At the time of its replacement, the CU552 had fired the laser system 70 million times, which was well past its expected lifetime. This also explained the problems with the amplifier power supplies themselves.
3.3.2. Current electrical backbone

The entire old electrical backbone has been replaced with a newly designed system which has proved to be much more reliable than the previous system. In addition, Terawatt’s capabilities have been greatly expanded with the introduction of the new design. The new system utilizes some purchased timing components, some homemade parts, and computer interfacing.

Performing experiments at significant distances in the test range required complete control from anywhere in the facility, which necessitated computer control and monitoring of the electronics. Building a control unit from components was not feasible given the needed accuracy of the device, the timing requirements, and the time involved for design and testing. Thus the main timing component chosen for the system is a Masterclock, manufactured by Thales in France. This unit performs the synchronization between the oscillator output pulses and all the components of the system, as well as providing 20 digital outputs with adjustable delay in increments of 250 picoseconds. In addition, the Masterclock monitors the cooling and interlock safety system, and in the case of a failure performs a specific shutdown sequence. Since this device cannot meet the logic levels of the older devices of the system, various electronic interfaces had to be designed and built. These interfaces change the digital TTL levels used by the Masterclock into the 20-volt positive-edge triggers required by the Pockels cell drivers, adapt to 15-volt negative logic for the regen power supply, and interface with the controls for the amplifiers. All of these interfaces provide electrical isolation in case of failure in the power supplies.

The main amplifier power supplies posed a more complicated challenge. Between the CU552 and the main supplies, specialized logic was used for control and status reporting. This
exact logic had to be replicated for use with the new system. To do so, a microcontroller-based interface was constructed. The microcontroller used for this was the Parallax BASIC Stamp 2p40 due to the simplicity and ease of use of the device. The BASIC Stamp was programmed with the logic to mimic the original controller and also provide feedback on the condition and status of the power supplies to the computer via an RS-232 serial interface. In addition, it also has a display screen which provides diagnostic information about the power supplies.

The BASIC Stamp logic needs many safety precautions in order to protect the power supply from self-inflicted damage. To begin a firing cycle, the BASIC Stamp pulls the charge line on the amplifier power supply high, signaling it to begin charging. The Stamp now must listen for the end of charge (EOC) line from the supply to go high when the unit has reached a full charge on the capacitors. Then the Stamp must stop the charge command or risk damaging the charging circuit. This is followed by a hold-off time to allow the supply to settle, typically about 100 microseconds, in which the unit is not allowed to fire. The Stamp now waits for the fire command to come from the Masterclock, and when it does it issues the fire command to the supply. Since the power supply is relatively slow to respond (from beginning of charge to actually firing), the code on the Stamp is designed to anticipate the repetition rate of 1 Hz and reduce the delay by pre-triggering the power supply to begin a charge cycle. It does this by using a hold-off of about 7/10 of a second after the last fire command, then issuing the charge sequence before the next fire command. The result is that the power supply is ready about 100 milliseconds prior to the fire command, greatly increasing the speed and the pulse-to-pulse energy stability. This pre-trigger leads to another problem; the first shot out of the unit typically has no energy because the energy stored in the capacitors is bled off. For safety, the power supplies have bleed resistors across the main capacitors to eliminate charge after the unit is
turned off; it typically takes about a minute for there to be negligible charge remaining. To avoid this problem, the software written on the computer tells the BASIC Stamp to recharge the power supply just before firing for the first time.

Figure 10. Process flow diagram of the redesigned Terawatt control and synchronization system.

The software used to control the whole laser system is written in LabVIEW and can interface with most of the components in the laser system. LabVIEW was chosen for its simplicity in writing code that can communicate with all the various electronics, including its low-level ability to control the COM ports. Low-level control is required when interfacing with the BASIC Stamp as it uses a modified version of the RS-232 protocol, and this had to be specially written. A process diagram of the system is shown in Figure 10. The computer and the Masterclock are the heart of the electrical backbone. The computer running the LabVIEW code also controls the Spectra-Physics Millennia, the solid-state pump laser for the oscillator, so that adjustments can be made remotely to the power output, and it can be turned off to conserve diode life when not in use. LabVIEW also interfaces with both logic interpreters and the BASIC Stamp
logic interface for recharge commands or to read current parameters. The communication between LabVIEW and the Masterclock is more complicated than the rest of the system. It uses a scheme of 256 variables, each of which represents a specific component of the system. These values are then shifted into specific memory registers on the Masterclock for programming. The full description of this process is outside the context of this thesis.

3.3.3. Secure test range and infrastructure

To perform the experiments utilizing atmospheric channeling, a long, straight area is required for propagation. In the past, the front door to the lab was opened and the beam was propagated down the hallway at night and on weekends. However, this is dangerous considering the peak powers employed and the lack of control of the environment. Thus it was logical to move to the adjacent service chase directly behind the lab. This service chase contains all the vacuum pumps, chillers, and other equipment required by the facilities in the Laser Plasma Lab.

In order to use the chase, the beam had to be re-routed from the compressor chamber. This required the addition of a custom-built vacuum tube assembly mounted on the available port of the chamber, and the installation of optics and optical mounts inside the tube. Inside the compressor chamber, the optical routing was re-aligned to allow switching between the target chamber, the autocorrelator, and the service chase. The optical layout inside the chamber required significant planning due to the complexity and space constraints. One of the main steering mirrors to the service chase is only 92% reflecting. The 8% leak from the main beam is used for diagnostic purposes and will be discussed in more detail in Chapter 7. In order to use the diagnostic beam, it has to precede the main beam, thus a delay line was configured to provide 2.5
ns of delay to the main beam. Both beams are aligned through the tube to the service chase and exit the vacuum tube seven feet above the floor through an optical window.

In order to accommodate the propagation of laser beams in the service chase, some modifications to the chase had to be performed. This included re-routing vacuum components, moving equipment, cleaning the chase, and construction of an experiment station. This station is free-standing and constructed from Unistrut® framing. The frame holds a 2×4-foot optical breadboard mounted vertically on the wall of the chase. It is located roughly six feet off the chase floor so that the beams maintain their height. The structure also contains several computers and diagnostics required for the experiments. In order to control the experiments at the end of the chase, five data channels were run from the Masterclock to the experiment station, and a wired network connection and power were also run. These data channels provide pre-triggering of the electronics, CCD cameras, and oscilloscopes at the test station as shown in figure 11.

Figure 11. The diagnostics at the end of the test range. Trigger cables are visible strung on the wall.
3.4. **Summary**

A significant amount of planning and construction was required in order to perform experiments at distance. This included significant electrical design and implementation on the TW laser system, additional vacuum components and optics, modifications to the service chase, and construction of the test station. Without these improvements, none of the experiments described herein would have been possible.
CHAPTER 4. PROPERTIES OF LASER PROPAGATION IN THE ATMOSPHERE

In Chapter two, the theory behind the process of atmospheric channeling was presented. This chapter examines the characteristics of the channels that are produced by the Terawatt laser. In particular four specific, and some cases novel, features are described. We begin by examining the conditions for channel formation, since these are laser- and beam-profile-dependent. We then illustrate the wave guiding features of the self-channeling by a series of experiments in which we observe the effects of obscuring or interfering with the central portion of the channel. Since the self-channeling produces a transient wire of ionization, with obvious implications for directed energy, we explore the possibility of “channel stacking”. Finally a new method of diagnosing the stability of the channels is introduced that is based on silicon ablation markers.

4.1. Measurement of beam collapse

To measure the collapse of the channel (i.e., the onset of channel-like behavior) as a function of pulse energy, the Terawatt laser system was configured such that the amplifiers were set to full power and the output energy was adjusted by means of a half-wave plate and a polarizer (since the beam is already polarized) placed after the last stage of amplification, before the pulse compression. In this manner a consistent beam profile was maintained while varying the energy. For these experiments, the laser beam propagated directly through the target chamber, though a vacuum port to the hallway, and down the hallway (illustrated in Figure 12). In order to protect the last optic in the system (the turning mirror used in the hallway), a 2×
telescope was inserted just prior to the compression gratings. The larger beam profile increased the channel formation distance to beyond the turning mirror.

Figure 12. Illustration of hallway propagation.

A Spiricon® laser beam profiler was used to measure the beam profile. This device allows calibrated measurements of the beam’s intensity distribution. The intensity within the channel is $> 10^{14}$ W/cm$^2$, well above the breakdown threshold of all materials. Therefore to measure its intensity distribution with the Spiricon, a sacrificial 4% Fresnel reflecting glass plate was used to attenuate the intensity to below the breakdown threshold. The diagnostic configuration is shown in Figure 13. For each shot the beam sampling plate suffers damage, but since the effects of the damage mechanism on the reflectivity occur on a time scale longer than the pulse duration, a faithful record of the channel intensity profile was recorded on the detector. All the measurements were made at 30 meters from the turning mirror. Two sets of experiments were performed, the first set using single pulses and the second using bursts of pulses.
Figure 13. Illustration of diagnostics at the end of the hallway.

Figure 14. Beam profiles as a function of laser beam energy. As the laser beam energy increases, the channel begins to form. The image size is 6 × 5 mm.

Figure 14 shows the measured beam profile measurements after 30 meters of propagation. The first image, for an energy of 3 mJ, shows the beam expanding with the classical divergence. As the energy is increased to 5.5 mJ, the beam starts to become smaller and take the shape of a channel. Here we see that two channels are forming; however, one is receiving most of the energy. At 12 mJ, the channel is completely formed along with a small weak secondary channel. The right channel has enough energy to self focus and filament, but much less than the left.
division of energy into separate channels results from several factors. The initial beam
distribution is a critical factor in the formation process as the phase front must be clean for single
filaments to be produced. The energy inside a channel is regulated by the peak power
propagating. Above a certain point (which is calculated for the specific beam quality and pulse
duration) the channel must split to divide the energy such that the formation conditions are
maintained. Mlejnek et al. have modeled the breakup of laser beams into many filaments [46].

Figure 15. Isosurfaces showing the distribution of collapsing light filaments from a single pulse
at various distances [46]

They assumed an initial pulse 200 fs in duration, 775 nm, and a waist of 7 mm. The initial beam
shape was Gaussian, but a 15% field modulation was added to speed up the filamentation and
reduce the computing time. The isosurfaces shown in the above figure illustrate the dynamics of
the laser beam breakup. The initial power contained within the laser pulse was 35 times that of
the critical power which explains the large number of individual pulses formed. The formation of filaments is better observed in cross-section, as shown in Figure 16.

![Figure 16. Modeled intensity distribution across the beam at given distances [46].](image)

The individual time slices shown in the above figure illustrate the distribution of filaments from a single pulse at a distance of 9.9 meters. The top frame shows the collapse near the leading edge of the laser pulse, roughly the center of the pulse in the middle image, and the bottom image is around the trailing edge of the pulse. The images show that the filaments themselves are dynamic within their own length, as it is observed that peripheral filaments exist for shorter times in space.
than the central filaments. It has also been shown that filaments can pass energy between one
another through coupling of the peripheral energies [47].

Due to the fundamental requirements on the processes involved in the channel formation,
the resulting channel is circular, and has a full-width half-maximum (FWHM) diameter of 100
microns. The energy required for channel formation was around 5.5 mJ, for pulse lengths of
~120 fs. This energy is beam—or more precisely phase-dependent, and later it was found that the
insertion of the telescope into the system introduced phase errors in the beam wavefront. These
errors resulted in the two distinct channels that formed and accounted for the high energy
required for channeling. When no telescope was used, single filaments would form.

4.2. Filamented pulse stacking

It was shown by Tzortzakis et al [65] that the ionization of the channel exists for about 4
nanoseconds after the pulse, set by the estimated recombination time of the electrons in the
channel. In order to investigate the properties of multiple filaments traveling in each other’s
ionization trails, the Terawatt laser was configured to produce six pulses with pulse-to-pulse
separations of 4.5 nanoseconds. This separation was just longer than the ionization fall-off time.

Figure 17. Beam profiles of a burst of 6 pulses at 30 meters for various energies. The energy
listed is the sum energy of the group.
Again, for these experiments the telescope was used, sometimes resulting in multiple filaments. Figure 17 shows the beam profiles for different energies. The energy listed for each image is the sum total energy of the six pulses. At lower energies the beam again follows classical diffraction. As the beam energy increases, the channels begin to form. At 20 mJ and 30 mJ, many filaments are forming. This means that each pulse in the train has enough energy to create a filament, and that these separate filaments do not propagate along the same path. Not shown here are the shot-to-shot profiles, which illustrate the unstable nature of the multiple filaments. It should be noted that even the separation of the filaments is less than classical diffraction would predict. The last image shows the rare case where a few of the filaments did follow each other and we observe only two.

The Spiricon® beam profiler does not provide any information on which pulse arrived first. To gain a sense of the time development of these multiple filaments from burst mode propagation, a streak camera was used in place of the Spiricon®. The slit on the streak camera was opened to a few millimeters to accommodate the movement of the channels, and the hallway was completely darkened. The setup is illustrated in Figure 13. Streak camera images of the burst pulses were taken in two different configurations: burst mode, where only the extracted regenerative amplifier pulses with separation of 9 nanoseconds were used; and multiplexed burst mode (MBM), where an interferometer was used to multiplex down to pulse separations of 4.5 nanoseconds. The power falling on the photocathode in the streak camera was carefully monitored and adjusted using neutral density filters to ensure the operation was in the linear regime and not saturated. Since the time span of the streak is fixed to ~30 ns, the trigger was delayed appropriately in order to observe all the pulses that compose the train.
Figure 18. Burst-mode pulses with separation of 9 nanoseconds. The top three images show the channel form as a function of pulse energy. The bottom three show the pulses in a single burst channeling.

Results from the streak camera for both different time delays and different energy levels are shown in Figure 18. At 8 mJ for the set of pulses the beam is clearly diverging, and as a result only illuminating the width of the slit. In previous tests it was found that threshold for channeling was around 5.5 mJ. Thus to achieve channeling for 6 pulses each with 6 mJ of energy, the envelope energy must be 36 mJ. In the images the channel can be identified as the bright point in the middle of the vertical line. In the bottom set of images taken at different delays, the six pulses can be seen individually. The downward drift of the images is due to alignment and not due to channel movement. Note that the first four indicate channels due to the presence of a bright
point; the fifth channel appears weak; and the sixth is almost non-existent. This implies either the pulses from the regenerative amplifier had uneven energy or the gain in the amplifiers was depleted before the sixth pulse. These tests show that it is possible to produce burst filaments from a laser, but it is also clear between the previous images and these that a time delay of 9 ns does not suffice for stacking. Thus decreasing the pulse separation is required.

Figure 19. Multiplexed burst of pulses. The upper left is from the delay arm of the interferometer and the upper right is from the direct path. The bottom two images show all the pulses together.
To increase the temporal density of the pulses for 6 pulses spaced by 9 ns to 8 pulses spaced by 4.5 ns, an interferometer was installed between the regenerative amplifier and the double-pass amplifier in the TW laser. This interferometer was constructed in a Michelson style utilizing a beam splitter dividing the energy in a ratio of 45-55%. Thus typically the delayed beam had less energy than the direct and sometimes these pulses would not always channel. This was verified using the streak camera when every other pulse, originating from the weaker arm of the interferometer would be just at threshold for channeling. At this time the laser system was not capable of increasing the overall energy enough to overcome this issue, since about 50% of the energy was lost through the interferometer. Figure 19 shows the images from the streak camera. The top images show the delay arm only and the direct arm only as a means of gauging which pulses were forming stable channels. The bottom images show the combination of pulses from the interferometer. The strange shape of the pulses is the result of the channel hitting and scattering off the edge of the slit.

Although both experiments did not succeed in demonstrating the stacking of filaments one behind another, this should be viewed as only the first attempt towards this objective. The experiments did show that generating bursts of pulses, as long as the peak power in each pulse is above the critical power, can create many self-channeling pulses. This had never before been demonstrated. The experiments performed here had limiting factors not allowing pulses closer than 4.5 ns, and the reason for the pulse spatial deviation. In order for pulse stitching to succeed, the pulses must be stacked closer together than 4 ns, the ions recombination time. In addition, the experiments were performed in the public hallways not allowing a controlled environment. Future experiments in the new test range are likely.
4.3. **Measurements of silicon ablation**

Material ablation was performed at the same distance as the analysis of the channel formation, ~30 m. The materials investigated were the following: silicon, silicon oxide, shiny aluminum, dull aluminum, polymeric film and some carbon fiber material. The images of the surface damage after exposure to the filament were obtained with an optical microscope. Ablation was performed in the single-pulse mode and the burst mode where the target was irradiated with either 1 or 10 shots (or bursts). During these tests, we were unable to operate the laser in the MBM mode (8 pulses separated by 4.5 ns) because the individual pulse energy could not be assured to be above the filamentation threshold. These test were made early in the experimental series before improvements to the laser permitted higher pulse energies.

The laser-matter interaction or ablation by the filamented laser radiation was first investigated in a preliminary way by simply examining the single pulse damage created on the surface of different materials. All materials tested showed evidence of damage from a single filament. However, whereas all other materials tested showed damage spots that were significant and were material dependent, the effect on Silicon was most distinctive, and was subsequently used as a means of diagnosing the channels.
4.3.1. Using silicon wafers as a diagnostic of filament interaction

The first image in Figure 20 shows a single filamented pulse incident on the silicon wafer. The center gray area indicates the ablated region and the surrounding ring is a thermally-induced change to the silicon dioxide layer. This indicates that it can be useful as a diagnostic in that it shows the shape and approximate size of the filament and a clear pattern of the energy impact. Figure 20 b) shows the result of ten single shots in sequence incident on the same silicon wafer. From this image it can be ascertained (with reasonable certainty) which pulse struck first and the relative stability of the independent channels. It is interesting to note that the overall cluster pattern distributional area is much smaller than the classical divergence of the beam, in like manner to the way (noted above) that the separation of channels within a single burst were more closely packed within a solid angle than the classical diffraction angle. This implies that it is possible to concentrate more energy in a smaller area with burst mode, and with multiple firing
of the laser in the self-channeling regime than with a freely diverging beam. It is also noted that on overlapping spots from successive shot there is now evidence of the ablation of the silicon itself, in like manner to the ablation of other materials. This is attributed to there being a lack of silicon dioxide layer which was ablated by the first in the series of pulses.

Figure 21. a) Damage on silicon using a burst of 4 pulses with total energy of 45 mJ. b) Same sample ablated with 10 bursts of shots, each with 45 mJ total energy.

4.3.2. Burst mode analysis with silicon wafers

Following the analysis of filaments from single pulses utilizing their effect on silicon wafers, the same technique was used to analyze burst mode filamentation. For these tests, a series of four pulses separated by 9 nanoseconds, where the sum energy is 45 mJ, was used. Figure 21 a) shows the impact from a single burst of four pulses. The first thing to note is that there are only three major spots. We learned in the single-pulse tests that the impact always shows up as a near-perfect round spot. Noting this and that the left-most impact is not round, this
implies that two pulses overlapped there. Using the heat-created rings as a reference, it can be seen that the pulses arrived from left to right. The effect of striking the surface with 10 separate bursts is shown in Figure 21 b). The result is something similar to that seen with consecutive single pulse impacts. As with single pulse filaments, the angular encirclement of the distribution of consecutive impacts of burst-mode filaments is still much smaller than that defined by the classical divergence of the laser beam.

For both single-pulse and burst modes regimes, we invariably see spatial movement of one channel relative to another. With these pulse separations we were unable to observe clear evidence of filament-stitching. Also in burst mode each separate filament generally follows its own path and not that of the previous one. This spatial variation is typically attributed to air currents and the formation of the channel. In strong air currents, there are minute changes to the optical properties of the air and as a result the channel moves. Over thirty meters of range, movement was typically not greater than a few millimeters. For a kilometer range this variation in targeting could be several centimeters. In these tests, the beam emanating from the laser forms the channel itself. There was no control over filament formation. Other studies have also observed this instability [5]. To improve the filament formation stability, a long-focal-length lens can be used.

4.4. **Stability of the Self-channeled Beam**

The theory of self-channeling and propagation of light in waveguides shows that in addition to the optical fields inside the waveguide itself, there is a substantial field structure propagating outside the waveguide itself. For this self-generated self-supporting filament in air,
the support field structure outside can be considerable. Numerical modeling of the propagation of multiple filaments [47] show energy can flow from one filament to another through coupling between the fields of closely propagating filaments. An example from Mlejnek’s work is shown in Figure 15. The impact sites created on silicon shown above is supportive of this notion. This raises questions on how stable these filaments are to atmospheric effects, and to impact with dust particles, smoke, aerosols, rain etc. To learn more about this stability at the fundamental level a new set of experiments were performed that tested the stability of individual filaments. These experiments comprised a set of tests that examine the effects of central and annular obscurations on the propagation of the self-channeled beam. These tests were performed in collaboration with Alex Gaeta and his group at Cornell University,

To explore the dependence of the stability of the filament on the peripheral fields, a series of experiments were devised. These were performed with the set-up illustrated in Figure 22.

Figure 22. Illustration of filament passing through substrate.

The first experiment passes the filament through a very thin optical flat, which is to be used as a substrate for the following tests, to determine if it interferes with the filament stability. The
experiment is set up on a pedestal approximately 1 meter after the filament formation. To measure the beam profile, a beam sampler and Spiricon are used on a rolling cart allowing scanning in terms of distance. Movement of the beam spatially is primarily the result of the cart and not instabilities of the beam. Figure 23 shows the Spiricon images taken after the optical flat at various distances.

![Figure 23](image)

Figure 23. Channel measured at different distances after formation. Beam is measured after passing through an optical flat.
From Figure 23 it can be seen that the optical flat has no effect on the filament, as little energy is lost and there is no beam distortion. The blue region next to the filament is the result of the beam profile’s not being perfectly Gaussian.

With the thin optical substrate in place, two tests were made to analyze the stability of the filaments. In the first set of tests the filament itself was blocked, but the surrounding field allowed to propagate past the obscuration. In the second set of tests the peripheral field was prevented from propagating with the filament passing through. To block the filament, a small piece of sand, with a diameter of 365 microns, was attached to the optical flat using high-temperature glue and then positioned into the filament path using a three-axis stage. The Spiricon system was then used to examine the beam profile downstream by scanning the range after the beam block. The setup is illustrated in Figure 24. In order to ensure complete removal of the filament, the sand was chosen to be much larger than the filament dimensions. The peripheral energy is allowed to pass through the glass substrate. The Spiricon is positioned at various points in the re-formation region.

Figure 24. Illustration of blocked filament experiment.
Figure 25. Channel measured at different distances after obscuration. Obscuration is 365 microns in diameter and the laser energy is 14 mJ.

The first image in Figure 25 shows the filament without blocking. The next two images show the piece of sand, which can be identified by the circular diffraction rings, being positioned into the filament’s path. After the sand, the beam profile takes the shape of the diffraction pattern of the sand, effectively destroying the filament. However, within 2 meters the filament is beginning to reform, and in the far field is completely reformed with most of the original energy.
Next, using the same obscuration we examined the energy dependence of this process by using a pulse with an initial energy of 24 mJ. Here the filament reforms significantly faster after the obscuration. The rings of energy surrounding the filament created by diffraction of the sand are also seen to dissipate as the energy is moved back into the filament.

Figure 26. Channel measured at different distances after obscuration. Obscuration is 365 microns in diameter and the laser energy prior to the obscuration is 24 mJ.

It is observed that the filament reformation distance is energy-dependent. This agrees with the theory for the filament formation process, as the distance for self-focusing depends on the peak
laser power. By almost doubling the laser energy, the filament reformation distance is nearly halved.

To examine whether obscuration size has an impact on the reformation of the filament, a second piece of sand was used with a diameter of 580 microns in the same setup. Being significantly larger than the filament, it blocked a substantially greater amount of energy. As a result, only the 24 mJ beam was examined. This was affixed to another optical flat and positioned into the filament path.

Figure 27. Channel measured at different distances after obscuration. Obscuration is 580 microns in diameter and laser energy prior to the obscuration is 24 mJ.
Again, the diffraction rings seen in Figure 27 indicate the piece of sand being aligned to the filament. Similar to the smaller obscuration with lower energy, it takes more than two meters to reform. This is likely the result of both a larger diffraction pattern and more energy being blocked by the sand. The filament is completely reformed in the far field.

Figure 28. Illustration of experiment blocking the peripheral channel energy.

To examine if there is dependence of the filament on the surrounding energy, an iris was positioned such that it passed just the filament, but removed of the surrounding energy as shown in Figure 28. The iris was closed to a diameter of 1 mm and the filament was positioned to pass through its center.
Figure 29. Channel measured at different distances after passing through a 1-mm iris. Energy measured before the iris is 24 mJ and after is 1 mJ.

In Figure 29, the outline of the iris can be seen as the color difference surrounding the filament. With distance it is clearly observed that the filamentation process is stopped, and the beam propagates with classical divergence.

The result of these experiments is that part of the guiding mechanism in the filamentation process relies heavily on the surrounding energy. This can be readily seen in the previous experiments. For two different beam obscurations and two different pulse energies, the filament
reformed within two meters. However, once the surrounding energy was removed, the filament fell apart. This is not surprising since most of the beam energy appears to lie in the surroundings. The energy prior to the iris was 24 mJ and after the iris was 1 mJ, which is insufficient energy to form a filament. Further investigation would require increasing the beam energy such that at least 6 mJ of energy passed through the iris. This, however, would require significant incident beam energy and was not possible at the time of the experiments.

These results agree with the theory developed for the filamentation process. The filament can be considered to behave like that of a wave propagating in a fiber, where there is central energy and a coupled evanescent wave in the cladding. In terms of the filament, a significant portion of the total energy is contained within this evanescent wave, and as a result the removal results in collapse.

### 4.4.1. Modeling

As a first-order approximation of the effects that were observed with the interaction of the channel and beam blocks, the experiment was modeled using ZEMAX®. ZEMAX is a commercially-available ray-tracing software for accurate modeling of propagation through optical systems. This model can only simulate the effects of the light traveling around the block in terms of the wave nature of the light, and not the non-linear physical processes involved. However, it will provide information regarding the reformation of the filament and how diffraction possibly influences this process.
In the first frame of Figure 30, the blocked filament is observed. The block was chosen to be 365 μm in diameter and the incident beam was defined to have the same profile as a filament with an energy of 24 mJ. The subsequent images are taken at increasing distances from the block, until the filament is observed to reform. This model does not predict that the filament should reform in 30 cm, but rather that the diffraction from the beam block can help the reformation of the
filament by guiding the laser light back into the shape of a filament. From this point the non-linear processes should become the dominant reformation mechanism. It should be noted that ZEMAX was not able to model past 30 cm due to limitations of the algorithms used in the model.

4.5. **Summary**

The Terawatt laser is an ideal laser for generating filaments, as compared to many other laser systems. Typical commercial laser systems generate clusters of 10 or more filaments with very little position stability shot-to-shot. As was observed in the filamentation experiments, Terawatt is capable of generating single filaments with stability of a few millimeters over 30 meters. The threshold energy required for filamentation depends on the initial beam quality, due to the formation process depending on the uniformity of the beam. The threshold observed was around 5.5 mJ, which is lower than most other groups have measured with equivalent pulse lengths.

The possibility of energy deposition at distance can be increased by splitting the main pulse into several and propagating in the same atmospheric wake. Pulses were stacked down to 4.5 ns separations with up to 8 pulses in the train, each filamenting. However, it was noted that the pulses tended to self-guide and not follow each other. This can be attributed to the pulse separation being longer than the ionization decay. Silicon wafers were used as a diagnostic to judge the individual filaments’ positions.

Lastly, experiments designed to aid understanding of the fundamental guiding mechanisms were performed. Around the filament there is an evanescent wave propagating
which contains a significant amount of energy. To understand the direction of the dependency (if the filament depends on the evanescent wave or vice-versa), two experiments were performed. The first blocked the filament and passed the outer wave, which led to the filament reforming within a distance dependant on the energy in the beam. The second blocked the evanescent wave and passed the filament, which resulted in the collapse of the filament. The result is the filament depends on the evanescent field for propagation to occur. In addition, it was found from ZEMAX modeling that the reformation of the filament after the block is helped by diffraction.

This work provides a better understanding of how the filamentation process occurs and how filaments behave as they propagate. This information is vital for understanding the applications of and future experiments on filamentation.
CHAPTER 5. ABLATION EXPERIMENTS

It is well known that femtosecond lasers have several advantages over conventional laser systems for materials-processing applications. These advantages include the reduction of collateral damage in dielectrics [62], smaller heat-affected zones (HAZ) [51], a deterministic [43] rather than statistically distributed ablation threshold [3], and the ability to ablate sub-diffraction-limited target regions [50]. These have increased interest in the use of femtosecond lasers for precision micro-structuring of a wide range of materials, with applications in medicine, aerospace, microelectronics, photonics, and other industries.

Numerous research and industry groups are working to determine the ablation thresholds for various common materials, such as copper, aluminum, silicon, carbides, oxides, alloys, and various x-ray filter materials. However, no group had previously (to our knowledge) examined the fundamental aspects of ablation of materials in their pure elemental state. An understanding of the fundamental aspects of a specific element’s ablation could then be applied to compounds made from the elements. With the increased interest in the use of femtosecond-pulse-length lasers as tools for cutting and ablation, it seems appropriate to create a compendium of laser ablation data for many different elements, with comparisons to their physical parameters, and to establish empirical trends which can be useful for future laser ablation. Using the Terawatt laser and its target chamber, a select assortment of elemental materials was ablated under various conditions; the results are discussed following. In addition, the conditions for optimal ablation were examined, including a pulsed regime commonly referred to as ‘burst mode’. Lastly, using filamentation various common materials were ablated at distance.
5.1. **Elemental ablation scan**

To perform this study, the Terawatt laser was configured for low-peak-power operation and aligned into the target chamber. The elements to be ablated were chosen to provide a statistical representation of the elements, avoiding toxic, radioactive, and mechanically unstable (with some exceptions) materials. All of the materials were mounted inside the target chamber with the Terawatt laser beam focused for optimal ablation. The conditions of ablation were varied to provide a statistical set. Once ablated, the materials were examined using an optical microscope.

The samples themselves were various thin foils (from Alfa Aesar and Goodfellow) of at least 99.95% purity, ranging in thickness from 25 μm to 100 μm, depending on availability. Each sample was carefully prepared in a clean, dry environment and cut into ¼-by-1-inch rectangles, which were then mounted on special steel substrates. These substrates were then mounted to the sample holder in the chamber. Once ablated, the samples were stored in a clean room with desiccant to prevent corruption of the surface. The lanthanide materials, which are highly reactive to moisture, required special care and were kept in a positive-pressure dry nitrogen environment to prevent corrosion.
Figure 31. Illustration of chosen elements. These were chosen because of their wide sampling of the table, low toxicity, and natural state.

The samples were chosen to be distributed across the periodic table (Figure 31). For these experiments, the following elements were used: beryllium, titanium, iron, copper, yttrium, molybdenum, silver, gold, tin, lead, neodymium, dysprosium, and ytterbium.

The samples were mounted in the center of the target chamber, affixed to the Terawatt three-axis target stage. The stages are computer-controlled, and the ablation was performed in a grid with 250-μm spacing. This comparatively large spacing was intended to completely isolate each region from debris produced in other regions. A special mount, having an opening directly behind the target region, was designed to allow the detection of the laser beam once it ablated through the foil target. A biconvex 150-mm-focal-length lens was used for this experiment, with
an F/# of approximately 6. This lens was chosen rather than a microscope objective to give a larger focal (Rayleigh) region, decreasing the positioning accuracy required for best focus. The lens produced a focal spot of 30-μm FWHM as measured by the Spiricon beam profiler. A fast electromechanical shutter was installed in front of the lens, triggered by a fast photodiode directly behind the sample. Dedicated electronics controlled the starting and stopping of the ablation process by opening the shutter and then closing it as soon as laser light had penetrated the sample. The total number of shots was determined using another fast photodiode that faces the sample and was connected to a high-speed pulse counter. (Figure 32) Ablation experiments were performed both in vacuum and in air. For the vacuum experiments, a chamber pressure of approximately 10⁻⁴ Torr was used. The polarization of the laser beam was linear TE, and the beam was slightly astigmatic, the effects of which can be seen as a non-uniform hole structure in the sample images.

Figure 32. The experimental setup for elemental ablation scan.
To measure the ablation rates of the selected materials, the foil samples were ablated until the laser beam penetrated completely through to the back surface, counting the number of laser pulses required. For each sample, five different energies were used, each of which was repeated four times for a statistical average. After ablation, the samples were imaged using an Olympus 20× optical microscope. The front and rear hole diameters were recorded, as well as the characteristics of the ablated hole and the surface surrounding the ablation region. From the measured front and rear hole sizes, and knowing that the laser ablates an approximately cone-shaped volume, the total volume of ablated material can be calculated using a conical frustum. The volume of material ablated is given by the following equation:

\[
V = \frac{\pi}{3} \epsilon \left( R_f^2 e + R_f R_b + R_b^2 \right)
\]

Where \( \epsilon \) is the thickness of the material, \( R_f \) is the front radius of the hole, and \( R_b \) is the back radius of the hole.

![Diagram of a conical frustum](image.png)

Figure 33. Volume of material ablated (frustum of a cone).

From this volume and the known density of the materials, the mass removed during ablation can subsequently be calculated. Knowing the number of shots required for break-through and the amount of mass removed, it is then possible to determine the average mass removed per shot.
This approach ignores the fact that the drilling process is non-linear in nature, and that ablation rates decrease with drilled depth [69]; however, such effects would be difficult to account for until more is known about the exact rate dependence. For the purposes of this comparison, the assumed linearity will not affect the results, as all the samples would have similar dependences.

For these experiments effects of the reflectivities of the different materials were ignored. This is reasonable, as the intensity region at focus was sufficiently above the ablation threshold that the reflectivity would only affect the initial part of the pulse, causing minor changes to the total energy deposited. Future experiments will consider reflectivity.

![Image](image.png)

Figure 34. Gold sample ablated by 1-mJ pulses. 73 shots were required for penetration. Left image is the front surface and right image is the back.

Analysis of the samples showed signs of operation well above the ablation threshold, with little debris present on the surface and smooth ablated holes. For the thicker samples, and samples with low melting points, there was noticeable material ejected from the back surface, which is characteristic of high-temperature melting inside the ablation region [69]. Figure 34 shows images of 25-μm-thick gold ablated with 73 shots at 4 mJ in vacuum. The distinct ring around the hole, which is almost twice the hole’s size, is possibly the result of a heat-affected zone or the creation of a thin film on the surface. Since this ablation was performed in vacuum,
an oxide layer is unlikely. However, it is interesting that there is no heat-affected zone noticeable on the back surface, which would be expected from a localized heat buildup. The rough surface inside the hole, which results from tiny beads of reformed molten metal, is characteristic of very hot plasma and the evaporation ablation regime. The lack of debris on the surface indicates that the ablation energies were above those of the melting ablation regime. The asymmetry of the drilled hole can be attributed to two factors: the linear polarization of the laser beam, and a slight astigmatism, which results in an overall oval beam shape, as mentioned above. The size of the hole was measured using a computer algorithm which accounts for the shape and provides a best-fit circle for use in our calculations. The gold ablation shown is typical of the ablation seen in vacuum for all samples.

Each sample was ablated at five different individual pulse energies: 1, 2, 3, 4, and 5 mJ; and the ablation was repeated four times for each energy. The total shot count for each hole was recorded; these counts were averaged and used to calculate the average ablation rate for that energy. The standard deviation of the shot count was used to generate the error bars.

Figure 35. Copper ablation at 5 mJ for air (a) and vacuum (b). The numbers of shots are 64 and 43 respectively.
For most samples, the ablation was performed under both vacuum and atmospheric conditions to observe ablation rate dependences on pressure conditions; we have yet to perform vacuum ablation for a few of the selected elements. The ablation rates were observed to be higher in vacuum than in air and the degree of difference in ablation rate can be observed as variation in the slope of the trend. Figure 35 shows copper ablated at 5 mJ in both atmospheric and vacuum conditions. There was a decrease by a third in the number of shots required to ablate through the sample under vacuum, which agrees with previous results. Note that the surface effects on the copper around the ablated hole are similar to those seen on the gold sample. However, the gold sample only showed a color change with no surface deposition or damage. The copper ablated in air shows signs of surface plasma with extensive surface damage and melting. The unusual shape of the outer burn region is likely the result of the astigmatic beam.

The results from the ablation are shown in Figure 36. Atmospheric and vacuum ablation rates are plotted on separate graphs as a function of laser pulse energy. The 1–5 mJ region corresponds to intensities from $8 \times 10^{14}$ to $4 \times 10^{15}$ W/cm$^2$ for these focal spot sizes, and was chosen since it is above the ablation thresholds of all the samples and easily produced by the laser.
Figure 36. Graphs of mass ablated versus incident energy performed in atmospheric conditions for 13 elements. The top graph shows the full scale while the lower graph shows a close-up of the lower section. Error bars are one standard deviation.

The above graphs show the whole range and a close-up of the lower ablation rates. Note that some of the 5-mJ data points are missing from the chart. This is due to the fact that they did not seem to follow any trend and need to be repeated. This will be performed along with the ablation of additional elements. One noticeable feature in the measurements taken in air is the
large separation of lead and tin from the other elements. The reasons for this are not currently known, but might be due to the low melting points of these two elements. The ablation rate of material as a function of pulse energy in this fluence region tends to be approximately linear. For analysis purposes, a best-fit linear regression was applied to each element’s data. The slope of the trend is an ablation rate in terms of mass per shot per energy, also known as $Q^*$.  

Observations from the vacuum ablation experiments show that lead has significantly higher rates than the other elements, whereas tin has a more typical rate (Figure 37). Again, the higher ablation rate for lead might be due to its low melting point. The ablation rates of the elements in vacuum show higher ablated mass per shot than those ablated at atmospheric pressure, which is consistent with known results [28]. The distinct groupings between certain elements, which can be clearly seen in the vacuum ablation chart, attracted our interest. If there is an inherent mechanism causing this grouping, rather than differences in the laser parameters, then it must be some function of the material properties.
Figure 37. Graph of mass ablated versus incident laser energy for vacuum experiments performed on eight elements. The top graph shows the full scale while the lower graph shows a close-up of the lower section. Error bars are one standard deviation.

A chart was created from the calculated $Q^*$ values for both air and vacuum, in combination with common material properties. (Table 1) Preliminary observations from this chart indicate that the ablation rate increases with decreasing melting point. Using this information, along with the calculated ablation rates, trends begin to appear when all the
elements are plotted. Other studies have observed ablation dependences upon other thermodynamic properties of the material such as melting point and ionization; however, our results are inconclusive in this regard. The preliminary results show groupings of the elements by ablation rate as a function of laser energy. The difference in grouping between vacuum and air data is possibly the result of the air interaction with the plasma.

Table 1. Chart of \( Q^* \) and known physical data of the elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>Be</th>
<th>Ti</th>
<th>Fe</th>
<th>Cu</th>
<th>Y</th>
<th>Mo</th>
<th>Ag</th>
<th>Sn</th>
<th>Nd</th>
<th>Dy</th>
<th>Yb</th>
<th>Au</th>
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<tr>
<td>Z</td>
<td>4</td>
<td>22</td>
<td>26</td>
<td>29</td>
<td>39</td>
<td>42</td>
<td>47</td>
<td>50</td>
<td>60</td>
<td>66</td>
<td>70</td>
<td>79</td>
<td>82</td>
</tr>
<tr>
<td>( Q^* ) air</td>
<td>0.313</td>
<td>1.727</td>
<td>2.151</td>
<td>12.007</td>
<td>6.315</td>
<td>1.347</td>
<td>12.996</td>
<td>52.143</td>
<td>10.743</td>
<td>6.491</td>
<td>22.009</td>
<td>12.704</td>
<td>81.463</td>
</tr>
<tr>
<td>( Q^* ) vac</td>
<td>0.883</td>
<td>9.632</td>
<td>1.370</td>
<td>31.906</td>
<td>-</td>
<td>4.467</td>
<td>34.606</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>38.085</td>
<td>150.440</td>
</tr>
<tr>
<td>Melting Point</td>
<td>C</td>
<td>1278</td>
<td>1660</td>
<td>1535</td>
<td>1083.4</td>
<td>1523</td>
<td>2617</td>
<td>961.93</td>
<td>1010</td>
<td>1499</td>
<td>824</td>
<td>1064.43</td>
<td>327.502</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>C</td>
<td>2970</td>
<td>3287</td>
<td>2750</td>
<td>2567</td>
<td>3337</td>
<td>4612</td>
<td>2212</td>
<td>2270</td>
<td>3127</td>
<td>2335</td>
<td>2807</td>
<td>1740</td>
</tr>
<tr>
<td>Density</td>
<td>g/cm(^3)</td>
<td>1.848</td>
<td>4.507</td>
<td>7.874</td>
<td>8.92</td>
<td>4.472</td>
<td>10.22</td>
<td>10.491</td>
<td>7.29</td>
<td>6.8</td>
<td>8.551</td>
<td>6.57</td>
<td>19.3</td>
</tr>
<tr>
<td>Resistivity</td>
<td>( 10^8 ) W m</td>
<td>4</td>
<td>40</td>
<td>9.7</td>
<td>1.7</td>
<td>56</td>
<td>5</td>
<td>1.6</td>
<td>11</td>
<td>64</td>
<td>91</td>
<td>28</td>
<td>2.2</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>W/(m·K)</td>
<td>190</td>
<td>22</td>
<td>80</td>
<td>400</td>
<td>17</td>
<td>139</td>
<td>430</td>
<td>67</td>
<td>17</td>
<td>11</td>
<td>39</td>
<td>320</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>( 10^6 ) K</td>
<td>11.3</td>
<td>8.6</td>
<td>11.8</td>
<td>16.5</td>
<td>10.6</td>
<td>4.8</td>
<td>18.9</td>
<td>22</td>
<td>9.6</td>
<td>9.9</td>
<td>26.3</td>
<td>14.2</td>
</tr>
<tr>
<td>Enthalpy of fusion</td>
<td>kJ/mol</td>
<td>7.95</td>
<td>18.7</td>
<td>13.8</td>
<td>13.1</td>
<td>11.4</td>
<td>36</td>
<td>11.3</td>
<td>7</td>
<td>7.1</td>
<td>11.1</td>
<td>7.7</td>
<td>12.5</td>
</tr>
<tr>
<td>Enthalpy of vapor</td>
<td>kJ/mol</td>
<td>297</td>
<td>425</td>
<td>347</td>
<td>300</td>
<td>380</td>
<td>600</td>
<td>255</td>
<td>290</td>
<td>285</td>
<td>280</td>
<td>160</td>
<td>330</td>
</tr>
<tr>
<td>Enthalpy of atomization</td>
<td>kJ/mol</td>
<td>324</td>
<td>471</td>
<td>415</td>
<td>338</td>
<td>425</td>
<td>659</td>
<td>285</td>
<td>302</td>
<td>328</td>
<td>290</td>
<td>152</td>
<td>368</td>
</tr>
</tbody>
</table>

5.2. Vacuum versus atmospheric ablation

In the single-pulse ablation experiments it was found that significant surface burning only occurs in the presence of atmosphere and not for vacuum. This implies that the surface burning is the result of the air directly in front of the surface becoming ionized due to the high-intensity electric field of the laser. This air plasma then causes the surface damage as it absorbs a portion of the laser beam and heats the surface. The logical way to eliminate this problem is to decrease the laser energy such that at focus the irradiance does not exceed \( \sim 10^{14} \) W/cm\(^2\) (the ionization potential of air). The easiest way to do this is to split the pulse into many pulses such that each individual pulse does not have enough energy to ionize the air but the sum total energy of the
pulses is still the same, hence a burst-mode ablation. The material effectively integrates the energy, so the ablation rate is similar to that of single pulses.

Figure 38. The left column of images show front and back of a copper sample ablated at \(8 \times 10^{14}\) W/cm\(^2\) at Standard Temperature and Pressure (STP). The right column shows the same sample ablated in burst mode with the same irradiance. Note the image scales differ.

Figure 38 shows samples from the sets of data taken for single-pulse and burst mode for atmospheric conditions. Notice the significant burning of the surface of the copper sample for single-pulse ablation, the result of a significant amount of laser energy which went into creating the surface plasma. The eight-pulse burst ablation shows minor signs of heating of the surface. Since the pulses arrive every 4.5 nanoseconds, the prior plasma has expanded outwards and exists at low density. The next pulse possibly reheats this plasma and transfers that heat to the surface, resulting in the minor burning.
Vacuum experiments were additionally performed, at pressures less than 2 Torr. The same copper sample was used with the same laser and mechanical setup. Sample images of the ablation are shown in Figure 39. Single-pulse ablation shows little thermal surface burning in contrast to the atmospheric ablation. There are some signs of irregular burn marks on the front surface which are probably the result of a non-uniform beam. The burst-mode sample shows almost identical ablation to that in air but has a smaller hole.

Figure 39. The left column of images show front and back of a copper sample ablated at $8 \times 10^{14}$ W/cm$^2$ at 2 Torr. The right column shows the same sample ablated in burst mode with the same irradiance. Note the image scales differ.

These experiments show that burst mode is a viable way of increasing ablation rates in that more closely mimics vacuum ablation under standard atmospheric conditions.
5.3. **Burst-mode ablation of materials**

Burst-mode operation can be performed in two ways with the Terawatt laser system, either using the direct envelope output of the regenerative amplifier or temporally multiplexing and subsequently amplifying pulses derived from the single pulse switched out of the regenerative amplifier. These particular experiments utilized only the multiplexed output with 8 pulses, each separated by 4.5-nanosecond. They were compared with data obtained with, single pulses having the same total energy.

Burst-mode experiments were performed on copper and Lexan (a commonly laser-machined dielectric) for different pressures and different focal spot sizes. These were then compared to single-shot ablations of the same target samples. The results indicate that burst mode in vacuum shows an increase in the ablation rate over single pulses by a factor of five, and in air, approximately the same. This can be attributed to a reduction in the ionization of air, due to the eight-fold reduction of peak intensity from the $\sim 10^{15}$ W/cm$^2$ intensities used for single-shot mode. Moreover, the rate of increase in the ablation rate with incident fluence is significantly increased [58]. Shown below are images of a copper sample from the vacuum experiments (Figure 40). For this particular sample, the laser energy was 3.5 mJ per pulse, 8 pulses per shot, and pressure less than 2 Torr; it required 60 shots to penetrate the sample. Notice the large thermal region on the front face of the sample, which is not expected for femtosecond pulses. This can be attributed to localized heating resulting from the sample’s being very thin ($\sim 30 \mu$m thick) and no atmosphere or substrate to provide cooling.
Using a calibrated optical microscope, we were able to accurately measure the sizes of the ablated holes and then calculate the amount removed per shot as discussed earlier. Testing conducted under atmospheric conditions yielded similar results. See Figure 41. One thing to note of the copper samples ablated in air: the thermal damage area is quite small when compared to the previous results from single-pulse ablation; this is attributed to the burst-mode process.
The ablation of the dielectric Lexan showed similar qualitative results, with burst mode removing more material than the single-pulse mode. Instead of the front surfaces of the Lexan samples burning, the material melted on the front into patterns that typically resembled the laser beam profile, which would be expected due to the material’s relatively low melting point and poor thermal conductivity. As a result, the residual surface quality is poor, and is not shown here.

5.4. **Application to ablation rates**

Using all of the data from the burst-mode ablation experiments of copper and additional single-pulse data, we compared the results to the theoretical model for ablation in this regime. The model was introduced in chapter 2. For burst mode, the model may be extended by taking the equation for high-intensity ablation, multiplying it by \( n \) pulses, and dividing the fluence by \( n \) pulses. The result is the following equation for burst-mode high-intensity ablation \([58]\).

\[
L_n(F) \approx n L_h(F/n) = nd \cdot \ln \left( \frac{F}{n F_{th}} \right)
\]

\( n \) is the number of pulses and \( d \) is the electron diffusion length. Now, plotting these equations, the burst-mode effect can be readily seen. In the figure below, we used the low-intensity equation for irradiances below \( 10^{14} \) W/cm\(^2\) and the high-intensity equation above that.
Figure 42. Top: Ablation model described earlier. Bottom: Extending that model for burst-mode ablation. Note how ablation rate increases as the number of pulses increases.

In Figure 42, the top graph uses equation 5-2 for single-pulse ablation (n=1 case) and the bottom uses equation 5-2 for burst-mode ablation. Plotted for burst mode are 1, 2, 4, and 8 pulses, corresponding to the right shift of the knee in the curve. It is important to note from this that at
fluences above $\sim 2.5 \text{ J/cm}^2$, bursts of pulses remove more material than single pulses. So increasing the number of pulses significantly increases the ablation.

To validate the theory, the burst mode data for copper with 1- and 8-pulse bursts is plotted on the graphs with the theoretical curves. These are shown in Figure 43.

Figure 43. Superimposed theory and data from experiments. 4-mJ in 30-ns burst, 8 pulses, 850-nm wavelength, 120-fs pulse length on Cu target.
Both graphs illustrate a good fit of the experimental data with the theoretical curves. For the single-pulse data in both plots, the knee in the curve is below the 2 J/cm² point and is not visible. It can be seen that ablation in burst mode for higher energies has up to 5 times the ablation over single-pulse mode. It is also interesting to note that the ablation for vacuum is higher for both, but significantly higher for single-pulse conditions. This implies that the single-pulse mode in air is suffering from air ionization and loss of energy. Burst mode is also affected by air ionization but to a lesser degree. This is understandable since each pulse is close to the ionization threshold.

5.5. **Ablation at distance**

In addition to ablating silicon at the end of a channel at 30 meters’ distance as discussed in chapter 4, various other materials were also ablated at distance. These included aluminum foil, Lexan, and a composite carbon fiber material. These are materials common to military applications, and thus the ability to ablate these materials at distance is highly desirable. The channel at 30 meters is 100 microns in diameter and both single-pulse and burst mode were used. Some sample images are shown in Figure 44.
Figure 44. Images of single-pulse and burst-mode ablation performed at 30 meters using a filament.

In these experiments, the materials were mounted on a thin frame for support while leaving clearance for the beam to propagate through. The aluminum chosen was household aluminum foil and was stretched to make it flat. Lexan is a commercially-available plastic (polycarbonate) material; this sample was approximately 500 µm thick. The material had what appeared to be air blown into the plastic making it opaque. The carbon fiber material was a thick sheet reinforced with a large-fiber mesh. All of the targets were shot with single bursts, varying between 1 pulse and 8 pulses. The energy varied according to the number of pulses.

In the experiments, the aluminum ablated quickly for burst-mode operation, as a hole can be seen in the image. The single pulse did not have adequate energy to ablate completely through
the material. The Lexan sample only slightly melted for a single pulse and showed signs of ablation and burning for burst mode. It also showed signs of transmitting a portion of the laser light. The carbon fiber material showed almost no signs of damage even after prolonged periods of exposure. This can be attributed to the high ionization threshold for carbon fiber. Complete qualitative studies could not be performed due to the movement of the filament. At one hertz, and with a movement of several millimeters, ablation through the foil targets is impractical.

5.6. Summary

In order to make laser ablation at distance more useful, it was important to explore the fundamental aspects of femtosecond laser ablation. Starting with experiments to understand the ablation rate as a function of material parameters, the elemental material scan showed that the ablation mechanisms rely mostly on the melting point, and possibly a combination of several other parameters. This information can be used to extrapolate the expected ablation rates for materials at distance through knowledge of the material composition.

To increase ablation rate and decrease thermal surface damage, burst-mode ablation was implemented on the Terawatt laser system. Various energies and numbers of shots per burst were tested on various materials. The result was a significant increase in the ablation rate as the number of pulses was increased. For a fixed energy, the burst of pulses (each pulse below the air ionization threshold) significantly outperformed the equivalent energy in a single pulse. This was attributed to the difference in energy being deposited in the air. Since filaments naturally have peak powers just at the ionization threshold of air, burst mode filamentation makes an almost
ideal way to ablate a target at long distances. The implementation of burst mode on a laser system is relatively simple and the gain in terms of cutting rate is significant.
CHAPTER 6. EMP

The GHz spectrum of radiant emission is relatively un-charted in terms of laser material interaction spectra due largely to the difficulties of measurement. The emission has been studied to some degree; in the past bare copper wires were placed near the plasma and used as detectors to monitor its generation [55]. This however does not provide data beyond the analog bandwidth of the scope and wire (and also aliasing is a significant issue). Mead et al. used both EMC antenna and a Moebius loop antenna to measure laser generated EMP [45]. In another experiment, Mead measured fields of 59 MHz resulting from ringing of the vacuum chamber excited by electrons liberated from Petawatt laser pulses incident on a target [45]. In addition, it has been observed that the filamented laser pulses themselves generate EMP emission. Tzortzakis et al. used a corrugated microwave horn and microwave heterodyne receiver and rectifier to measure filament generated EMP for 93-95 GHz and 117-119 GHz frequency bands [64]. Cheng et al. have observed emission from filaments due to the dipole oscillations in the air molecules [11]. Some of the high frequencies produced by these plasma sources are in a range where no other sources currently exist because generation is difficult by conventional approaches. By means of a completely new detection system, we attempted to analyze and evaluate the strength and spectral components of plasma emission for possible use as a new electromagnetic radiation source both locally and at distance.

The first experiments were performed in the Terawatt target chamber to test and calibrate the electromagnetic pulse (EMP) detection system. These experiments were performed for vacuum conditions using standard focusing techniques and various target materials. The second
set of experiments was conducted in the service chase, exploring the generation of EMP from self-channeled laser beams at distance. Some basic estimations of the source of the emission are explored.

6.1. EMP detection and signal processing

Detection was performed using a novel type of emission receiver, in combination with DSP post-analysis to extract the spectra. A 4-GHz Tektronix oscilloscope was used to collect the signal over 40 GHz of bandwidth in 4-GHz increments. Since the plasma is a pulsed source, the scope must be able to single-shot acquire as large a bandwidth as possible, and was the limiting factor in the collection of the signal. For the initial experiments, the Terawatt laser system was directed onto the target assembly located within the target chamber, and the laser configured for single shots at varying energies up to 15 mJ in 120-femtosecond pulses. This energy was focused onto various targets which face the receiver system as illustrated in Figure 45 with the laser beam incident at 25 degrees to the target surface normal.

![Figure 45. Illustration of setup for vacuum EMP experiments.](image-url)
The GHz spectrum is difficult to detect and measure quantitatively due to the lack of capable detectors. A previous graduate student in LPL designed and built an inverse superheterodyne receiver that is capable of detecting 1 to 40-GHz pulsed emission [2]. Since, to our knowledge, no analog-to-digital converter (ADC) exists that can capture single-shot signals with 40 GHz of bandwidth directly, the system demodulates the high-frequency bands down to lower bands with a calibrated transfer function. The high-frequency signal is detected via one of two different calibrated horn antennas; one covers a range of 1-18 GHz (Sunol Sciences DRH-118) and the other 18-40 GHz (Q-Par Angus QSH180K). An amplifier is connected directly to the horn antenna to minimize noise in the input. The amplified signal then is passed into the first high-frequency high-bandwidth mixer. This mixer performs inverse heterodyning between the input from the horn antenna and a calibrated function generator. Depending on the frequency of the function generator, the mixer either adds or subtracts the input and the reference. For proper mixing, the function generator inputs 13 dBm, at specific frequencies that correspond to sections of 4 GHz in the total 1-40 GHz range. The output of the first mixer has a 4 GHz bandpass filter, to limit the passband to avoid aliasing in the system and oscilloscope. The signal then passes through a variable attenuator and a second amplifier before entering the second mixer. The second mixer subtracts 16 GHz from the input signal, making the output 0-4 GHz. This output is again filtered to remove harmonics in the mixing, and passed to the oscilloscope. The schematic of the inverse heterodyning is shown in Figure 46. The output frequency range \( S_m \) is calculated by,

\[
S_m = S_i \pm S_c - 16
\]
where $S_i$ is the input signal from the horn, $S_e$ is the frequency of the function generator, and the sign of the operation is positive for 1-18 GHz and negative for 18-40 GHz. Thus by sweeping the reference frequency to the mixer, the entire 40-GHz bandwidth can be covered and stored in the oscilloscope as separate frequency segments. These segments are then processed by software to account for attenuation of the system. Details of the processing are in Appendix 1.

Figure 46. Schematic of the Inverse Superheterodyne RF system.

### 6.1.1. System response

To date, the system has been calibrated using two methods. First, the horn antenna was replaced with a calibrated frequency generator with known output power, and a sweep of the entire frequency range was completed and measured. This provides the receiving system’s attenuation over the entire bandwidth, which can be compared to theoretical models. A plot of the response is shown in Figure 47. The gain can be seen to fall off quickly with increasing frequency, the result of attenuation in the microwave electronics.
In addition to calibrating the receiving system, the horn antennas must be calibrated. Horns are typically calibrated using far-field sources, as this simplifies the equations and reduces reflections. However, since when either horn is installed inside a grounded metal vacuum chamber with a source-to-horn distance of approximately 30 cm; the chamber masks most far-field sources. The calibration was instead performed using a known RF point source located at the target position, specifically an LG VX6000 cellular phone. Since cell phones must meet stringent FCC guidelines and all the diagnostic data is freely available, the exact amount of RF power at the antenna was known (in addition, in diagnostic mode the phone knows its exact transmission strength). This particular phone operated in the CDMA 2-GHz band and had a rated electric field of 28 V/m at the antenna. This provides a single scaling factor for the 1-18 GHz horn antenna to calibrate the above curve. The time-domain output from the cell phone as recorded by the RF system is shown in Figure 48. The 18-40 GHz horn antenna was calibrated.
by placing another calibrated horn antenna at the source point and driving with a calibrated RF source at a specific frequency.

![Figure 48](image.png)

Figure 48. Displayed is the CW time domain signal produced by the LG VX6000 cell phone.

6.1.2. Target geometry

Various targets have been used with the current configuration. The first materials tested were metals, mainly to test the EMP system. Most are solid targets were mounted on a three-axis translation stage; the stage moves to provide a fresh surface per laser shot. For a 15 cm focusing lens, the focal spot was measured to be 40 µm FWHM. The laser energy for the experiments was 8-10 mJ at 120 fs in duration, providing a peak laser irradiance in vacuum of ~10^{15} W/cm². Typically, old mirrors, gold- and silver-coated, have been used as targets because of their known thin, uniform surface layer. In addition, the thin layers improve the generation of EMP, as there is less material to quench the fields generated [2]. However, there still remains some interaction
of the substrate (typically glass) and the EMP generated. To eliminate this, a special stretching frame was constructed which accepts thin foils. This frame then holds and stretches the thin foils flat. Experiments using aluminum and copper foils were performed. One of the main problems associated with using solid targets is that the exact amount of material consumed in the plasma is not known due to the large bulk surface. Custom target arrays would be required in order to address this issue.

6.2. Local RF measurements from LPP

To generate EMP in the target chamber, the Terawatt laser was configured to operate in unison with the newly developed inverse heterodyne detection system. This work was jointly performed between the author, Nick Barbieri, and Jason Aspiotis. It is presented here as a reference for comparison between conventional focusing and filamented laser pulses at distance which will be presented in subsequent sections.

Prior to performing laser plasma experiments, the detection system was tested inside the target chamber using a high-speed discharge source placed at the target plane [1]. The voltage across the gap of this source at the point of breakdown could then be compared to the signal obtained from the heterodyne system. This source comprised 3300pF doorknob capacitor connected to a variable voltage supply. The spark gap was connected in parallel with the capacitor where the gap length could be adjusted to change the spark characteristics. The measured electromagnetic pulse from this source existed for less than a nanosecond. The short time signal with no following peaks indicated that there were no reflections within the chamber. Three different voltages were tested across the gap, producing the signals in Figure 49 for 1-18
GHz. For the voltages tested, electric field strengths of 250 V/m are obtained for 8 GHz, and the field strengths become increasingly stronger past 16 GHz.

![Fast Discharge RFE for varying voltages](image)

Figure 49. EMP generated by discharge source for three different voltages.

With the detection system calibrated and tested, the Terawatt laser was aligned into the target chamber. These experiments used copper plates as targets due to their simplicity and copper’s low ionization threshold. Data analysis using the MATLAB software and the calibration curves described above produced Figure 50 for the EMP from the Cu target. The generation of laser produced plasma EMP was performed inside the terawatt target chamber at a pressure of $10^{-4}$ torr. The laser energy was 10 mJ, and the beam was focused to ~ 40 microns in diameter providing a peak laser irradiance of $6 \times 10^{15}$ W/cm².
Figure 50. Copper radio frequency emission (RFE) taken under vacuum.

The emission is observed to be relatively smooth with no sharp peaks, the result of an initially narrow calibration data set. In the vicinity of 35 GHz, the electric field strength is ~400 V/m, a significant field. Integrating the electric field over the frequency band 1-40 GHz, the total field strength is many kV/m, significant by any measure. Further research is required to optimize this emission and to examine the possibility of shifting the energy into a particular frequency band.

Conductive targets may exhibit electron resonance around the laser focus, the result of momentary charge movement along the target surface. Although this effect produces minimal EMP emission it does act as a damping mechanism on the EMP generated in the plasma. To compare this to a situation where there are no conduction electrons in the material, a dielectric target was chosen. Since with the dielectric there is no possibility for surface currents (at least anything appreciable), there will not be damping effect [2]. The material chosen was an optical
substrate (the backside of a mirror) made from fused silica. The dielectric experiments were only performed from 1-18 GHz, but with the same laser and pressure conditions as before, and are plotted against the copper data for this range in Figure 51.

![Copper RFE vs. Dielectric RFE 1-18 GHz](image)

Figure 51. EMP for metal and dielectric from 1-18 GHz.

The functional form of the emission over the 1-18 GHz range is remarkably similar. It is logical to assume then that the emission observed is a property of the plasma itself, rather than a material effect. It has been observed that the electron jets inside of momentary plasmas form infinitesimal radiating dipoles dependent upon the laser matter interaction.

EMP generated using conventional focusing techniques in vacuum produced field strengths upwards of 400 V/m per wavelength. Using a discharge source, electric fields were measured to be ~ 250 V/m at the target plane. To minimize the damping of the electric field in the plasma, a glass target was also shot and was found to produce similar field strengths as that
of copper. Comparing the above plots for discharge, copper, and dielectric it is observed that the functional form of the emission in terms of the peaks is similar. The peaks commonly occur at 4, 8, and 12 GHz possibly implying a harmonic in the detection system. Calibration of the system is an ongoing effort.

6.3. **EMP generated in filament interaction**

To examine the generation of EMP from filaments incident on surfaces at distance, the inverse superheterodyne system was installed on the end station in the test range. The horn antenna was placed 30 cm from the target/filament interaction, the same distance as in the vacuum chamber. A photo of the experiment is shown in Figure 52. Due to the orientation of the setup, the horn was mounted at 20 degrees with respect to the surface normal of the target (the filament propagated along the target normal). Rotating the target such that the normal was along the axis of the horn did not make a significant difference in the measured value. However, a full angular scan was not attempted. For these experiments the filaments had 8 mJ of energy per pulse, a pulse width of approximately 120 femtoseconds, and propagated 30 meters. As compared to the vacuum experiments, the irradiation is at an order of magnitude lower, at $\sim 5 \times 10^{14}$ W/cm². Thus the electric fields are expected to be lower than measured previously in vacuum. In addition, it is expected that the atmosphere will damp the RF emission by damping the electron motion.
These tests were to examine EMP emission from common materials, therefore five materials were chosen: copper, aluminum, glass, plastic, and sapphire. Copper and aluminum are common radiation-shielding materials for electronics; glass and sapphire are common window materials on detectors; and the representative plastic is a common type of encapsulation used for cell phones and other handheld devices. The detection system is polarization-sensitive, so measurements were taken with the system both aligned and orthogonal to the laser electric field of the filamented laser beam [41]. Shown in Figure 53 are the resulting graphs of the EMP as measured from each target in terms of spectral strength aligned to the laser electric field.
Figure 53. EMP emission from targets as measured aligned to the laser e-field.
Each material has its own spectral characteristic emission and intensity level. It must be noted that the peak intensity of the electric field was low (as expected), but when all the electric field emissions are summed, the resulting field is quite significant. Table 2 lists the values of the summed electric field over the 1-18 GHz range for the materials above.

The MATLAB code written for interpreting the raw signal can also stitch the entire spectral range together. From this spectrum, the inverse DFT can be performed to estimate what time domain signal would create such a spectrum. This is not entirely correct to perform, as the plasma is made of individual radiators that depend on their mechanical properties for the radiation spectrum and not a time dependency. It does, however, provide some insight into what the signal might look like. Figure 54 and Figure 55 illustrate the time domain recovery from the software.

![Figure 54. Reconstructed time domain signal for aluminum.](image)
The inverse DFT is explored because time domain signals are not possible to add directly. When recording the signal, the scope has to trigger on two difference events, the trigger signal from the laser and the emission itself. This is due to the jitter in the output of the laser (a maximum of 50 ns). The result is that the time origin of the data is not known, and therefore cannot be added without a known reference.

Since the system is polarization dependent, the orthogonal emission is measured by rotating the horn antenna by 90 degrees. The same material and laser conditions are used as in the previous experiment. The result is shown in Figure 56.
Figure 56. Orthogonal EMP emission for various targets.
The measured electric fields are significantly lower than that measured aligned to the laser electric field. This is reasonable since the laser field polarizes and drives the plasma during its interaction, thus the dipole radiators are also aligned. The summed electric field over 1-18 GHz is provided in Table 2. To our knowledge, the polarization of the radiating emission has not been observed prior to these experiments. This allows the possibility for crude sketching of the motion of the electrons in the plasma and along the surface of the target in a dipole fashion.

Table 2. Total electric field measured for both polarizations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Aligned E-field (V/m)</th>
<th>Ortho E-Field (V/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>12,311</td>
<td>2,484</td>
</tr>
<tr>
<td>Copper</td>
<td>8,123</td>
<td>1,346</td>
</tr>
<tr>
<td>Glass</td>
<td>7,475</td>
<td>1,964</td>
</tr>
<tr>
<td>Plastic</td>
<td>6,430</td>
<td>1,970</td>
</tr>
<tr>
<td>Sapphire</td>
<td>10,631</td>
<td>3,065</td>
</tr>
</tbody>
</table>

To test the effects of multiple pulses (burst mode) on the generation of EMP at distance, the laser system was configured to produce two pulses, first with summed energy of 8 mJ for comparison to previous single-pulse data sets, and then with a total energy of 18 mJ for higher-energy testing. The energy was divided evenly between the two pulses with a relative difference of less than 10%. If multiple pulses interact in the generation of EMP, then the 8 mJ test should produce higher emission strength. The time separation was 9 ns and is probably too long. These tests were only performed for copper targets and the horn antenna is set to measure the field aligned to the laser. The results are shown in Figure 57 and Figure 58.
Figure 57. EMP generated from copper target with 2 filaments, 4 mJ each.

Figure 58. EMP generated from copper, two pulses, 9 mJ each.
For the lower-energy test, where the total energy was kept constant but divided between two pulses, the resulting EMP is lower than that of the single-pulse data. This can be attributed to the lower electric fields generated in the plasma formed and the time separation between pulses. For the higher-energy test, there is an improvement in the emission as a direct result of the increase in the amount of energy per pulse. Due to the time separation of the pulses, bursts of pulses do not significantly increase the amount of EMP flux seen. Increases can be made by increasing the energy per pulse.

It is also interesting to note that the difference in energy did not affect the function form of the emission. The peaks positioned at 4.8, 7, and 12.8 GHz remain fixed and only the level changes. Similar peaks were observed in the spark gap and the vacuum focusing experiments. Considering the difference in peak laser intensity between the different experiments, it seems unlikely that it is a plasma phenomenon. At least one of the peaks is probably real, and the others are harmonics from it. The surrounding spectra are probably due to vibration states of the ablated material.

6.4. Analysis of results

As mentioned earlier the pulsed GHz spectrum from a laser plasma is difficult to directly measure due to the complexities of the measurement process. Until recently, this region of radiation spectrum has remained un-charted in terms of laser material interaction spectra. The present study is probably the first to focus on the analysis of the spectrum itself. This region is outside the atomic radiation region and mostly results from vibrations, rotations, and bending of molecules and from emission resulting from electron and ion motion in the plasma. The
difference between the spectra for metals and non-metals is clearly observed in the above data as
the metals have a more broadband emission whereas the emission from non-metals exhibits
discrete spectral components. Although, this region of molecular spectroscopic analysis is
beyond the context of this thesis some simple ideas and basic conclusions are presented here. For
the basic analysis, only aluminum and plastic are considered. The characteristics of the other
materials can be inferred from these.

The different materials used as targets have notably different spectra, but share the
common emission from the plasma. Short bursts of electrons are generated from the target during
the laser interaction. These electrons are either forced into the material or are driven out of the
plasma. As the plasma cools, the electrons temporarily forms a dipole with the surrounding ions,
and radiates at several different modes [45]. In the case of thin targets, the laser completely
vaporizes the target. The resulting plasma is separated by a Lorentz force smaller than the
filament’s dimensions, and can be approximated by infinitesimal dipoles.

Aluminum has a low ionization potential around 6 eV and electrons are easily liberated.
Thus when irradiated by the laser pulse (having a per photon energy of 1.5 eV), many electrons
are generated into the plasma via multi-photon ionization. In addition to the electrons, aluminum
ions are liberated from the surface. These electrons in the plasma are accelerated by the intense
electric field of the laser pulse, and due to the high density of the plasma, electron collisions are
frequent. As a result of the collisions and the plasma expansion, the electrons stream out of the
plasma. The combination of collisions and electron motion, results in Bremsstrahlung emission
throughout the frequency band where the peak of the emission depends on the electron
temperature. This thick cloud of electron motion gives rise to the emission observed in the
experiments with aluminum and copper.
The plastic’s discrete spectral lines are quite interesting. This particular plastic is a homopolymer form of polyformaldehyde \((\text{CH}_2\text{O})_n\) in chains of \(n\) [20]. The structure is illustrated in Figure 59. In general the ionization potentials of plastics are significantly higher than those of metals and the number of valance electrons is smaller. Interestingly for this material, the hydrogen is weakly bound and is completely ionized at temperatures around 2-3 eV (the plasma generated by the filament has an average temperature of 2 eV) [37]. Thus it can be assumed that the plasma consists of a large portion of hydrogen ions as the carbon oxygen bond is significantly stronger. Certainly carbon and oxygen ions are present in the plasma, but in a lesser concentration. The emission due to the free ions and electrons is naturally in the visible and ir spectrum, well outside the GHz region. Polyformaldehyde is known to emit in the 10-100 THz region due to vibrations of the molecular bonds between carbon and oxygen and carbon and hydrogen [52]. Thus emission into the GHz region has to be the result of macroscopic molecular vibrations and oscillations.

Figure 59. Structure of polyformaldehyde.

This plastic, being a homopolymer, forms into long continuous chains of repeating unit cells. When irritated by a femtosecond laser pulse, the region at focus is ionized and ablated from the surface. A portion of the material ablated is raw material and likely finite chains. These
chains can be set into oscillations and vibrations and can emit radiation at GHz frequencies. These oscillations can consist of bending, flexing, stretching, intramodal vibrations (chain to chain), and rotor. Intramodal vibrations are the result of chains attaching to other chains in non-linear fashions, and energy of vibration passing between them. Rotor is the condition when the ends of the chains rotate about the axis of the chain and thereby emit radiation. The complexity involved in the number of different configurations of molecules and the different types of oscillations make it impossible to estimate the structure that generated a specific frequency. Molecular codes would be required for simulating the different effects. However, the discrete combinations for resonating effects explain the discrete spectra observed.

6.5. Summary

Although EMP has been investigated for many years, this is the first time to our knowledge that the 1-40 GHz range has been explored using a single-shot, high-resolution microwave spectrometer on filament-produced plasmas. The laser plasmas generated in vacuum were observed to emit into a significant portion of the 1-40 GHz region with individual frequency field strengths approaching 400 V/m. The field strengths observed at the end of the channel are significantly lower, which can be attributed to the difference in the plasma conditions. However, the amount of EMP generated by a single filament is still a significant amount with sum totals in the tens of kilovolts.

The differences in the observed spectra taken at 30 meters by the filament-produced plasma are likely the result of the differences in the type of emission mechanisms. For metals, the emission is generated mostly from the free electrons propagating in the plasma whereas for
the non-metals the emission results more from the vibrations of the molecules freed from the target surface. If the EMP system is capable of detecting vibrations of molecules, then this would allow significant enhancements to the diagnosing the complex materials generated in the ablation process.
CHAPTER 7.  SHOCKWAVES

Filament-induced shockwaves are a completely novel application of directed energy. It has been known ever since the advent of the laser that laser-produced plasmas generate shockwaves in the target medium and the surrounding atmosphere. This can be most easily identified by the distinct “crack” sound—the sound itself being a shockwave—heard with each incident laser pulse. This chapter systematically explores the generation of shockwaves in transparent media at distance using a filamented laser beam.

7.1.  Methodology for detection of shockwaves

To observe shockwaves in optical media, the form of the target had to meet some basic criteria. Specifically, it had to be transparent at 425 nm (the probe beam wavelength), optically flat such that no distortions occurred due to the media itself, and very thin in the imaging dimension. The last criterion is set by the imaging system’s ability to focus in the region of the shockwaves. The imaging system utilizes a 10× long-working-distance microscope objective that has a depth of focus of 1 micron. Anything outside this region introduces blur into the image and degrades the ability to image the shockwave.

The first set of test shockwave experiments utilized microscope cover glasses as targets due to their availability, optical transparency, known physical parameters, and small thickness. Two different types of cover glasses were used: number 1 and number 1.5 glasses from Fisher Scientific and Corning, respectively. The number 1 glasses are ~110 microns thick and made of
borosilicate glass, whereas the number 1.5 glasses are ~160 microns thick and made of zinc
titania glass.

Table 3. Material properties of cover glasses used [14].

<table>
<thead>
<tr>
<th></th>
<th>Zinc Titania</th>
<th>Borosilicate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefft. of Expansion</td>
<td>74 x 10^{-7} cm/cm/°C</td>
<td>32.5 x 10^{-7} cm/cm/°C</td>
</tr>
<tr>
<td>Strain Point</td>
<td>508°C</td>
<td>510°C</td>
</tr>
<tr>
<td>Density</td>
<td>2.53 g/cm³</td>
<td>2.22 g/cm³</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>7.6 x 10³ Kg/mm²</td>
<td>6.4 x 10³ Kg/mm²</td>
</tr>
<tr>
<td>Refractive Index</td>
<td>1.523</td>
<td>1.474</td>
</tr>
<tr>
<td>Non-linear refractive index [7]</td>
<td>2.09 x 10^{-15} cm²/W</td>
<td>2.6 x 10^{-15} cm²/W</td>
</tr>
</tbody>
</table>

The use of thin targets places some constraints on the setup. In the tests of ablation at
distance in Chapter 4, silicon wafers were ablated at 30 meters and used to determine the shot
spread of the filaments in time. This included burst modes and standard single-shot mode. In
some cases the point spread of the shot pattern was as large as 5 mm, but was typically around 1-2 mm.
Thus there is a significant problem when aiming for a target that is 100-160 microns wide, and normally would give a low probability of actually striking the target.

To form the filament in the previous experiments, a lens was used directly after the beam left the vacuum chamber. The subsequent propagation through 30 meters of air resulted in the pointing instability. To improve the aim for the cover glass experiments, the lens was placed only a few meters from the test station. This resulted in similar filaments, but with significantly improved pointing stability. Being in the near field of the filament formation does produce some inconsistency in filament diameter; however, this is negligible for the cover glass experiments which will be explained later on. Post-ablation analysis of the targets shows that every filament strikes close to the center of the edge.
7.1.1. Configuration of facility

In order to observe the channel/material interaction at distance, a dedicated test range was constructed using a service chase in the building. The Terawatt laser beam is sent to the service chase via a vacuum tube with beam steering for both the main beam and the probe beam. From the end of the vacuum tube to the end station is roughly 30 meters. The end station is a 2×4-foot optical breadboard mounted vertically on the chase wall, and the experimental setup is attached to this. An illustration of the setup mounted on the breadboard is shown in Figure 61.

![Illustration of the diagnostic setup used for measuring shockwaves.](image)

Both beams propagate down the service chase, the main beam filamented and the probe beam collected via a large lens. The large collection lens forms the front of a beam reducer (the beam at 30 meters is almost 5 cm in diameter). The reducer has an intermediate focus, around which a
BBO crystal is mounted on a translation stage. This allows for movement in and out of the focal region to adjust the beam intensity, which changes the amount of blue, 420 nm (second harmonic) being generated. Inside the TW laser system the main beam is delayed optically to provide extra delay time for the positioning of the probe beam at the end station. To adjust the synchronization between the main pulse and the probe, an optical delay arm is used. This arm stretches out along the service chase for a distance of over 80 meters. Sweeping this delay length allows recording the evolution of the shockwave as a function of time (not on a single-shot basis, of course). Within the delay arm is a beam reducer, which has to be used with long delay distances. Even with the ability to collimate the output of the second harmonic, the beam divergence at large distances does not provide adequate illumination without beam reduction.

The imaging system was first built with parts from a previous project. The objective was a very-long-working-distance 10× objective. However, this particular objective was not designed to be used with coherent light, as it has a roof prism for correcting the image orientation. The seam of the roof prism introduced significant diffraction and blurred the images, and had to be replaced with a more appropriate component. The current system utilizes an Edmund Optics long–working-distance 10× microscope objective. This particular objective was chosen for its large numerical aperture, 0.45 NA, as compared to the typical 0.3 NA, permitting more light collection. This is mounted on a lens tube attached to a custom-built camera that has no window over the CCD chip, to prevent plane-parallel fringes from reflections in the window. A photo is shown in Figure 62. To minimize the amount of stray light and to block the light from the laser and plasma, a narrow bandpass interference filter centered at 420 ± 5 nm is mounted inside the lens tube. Since the laser runs at 1 Hz and the camera acquires for only 40 µs, the camera must be triggered to observe the interaction. The camera has the ability to be externally triggered, with
a short propagation delay. Several pre-trigger lines run to the test station, one of which triggers the custom camera trigger box, and thus the camera. The camera has a minimum gate time of 40 microseconds, so the camera is triggered in advance of the laser pulse such that only the end of the acquisition time is used for the formation of the plasma. This minimizes the amount of plasma light acquired, effectively removing plasma saturation and thus improving the contrast of the image. The camera is connected to a computer with capture software which records each frame. The image data is then post-processed using Photoshop.

![custom CCD camera](image)

Figure 62. Photo of custom CCD camera used for these experiments.

### 7.1.2. Image calibration

Calibration of the imaging system is performed using a 1951 USAF resolution pattern placed at the target position. The probe beam is used to illuminate the slide thereby providing the same imaging conditions as the targets. Measuring the distance between the rectangles of the
separate sections in terms of pixels, then using the calibrated distance between lines, provides the resolution as a function of nm/pixel.

Figure 63. 1951 USAF resolution target.

In the original imaging system, the calibration was 655 nm/pixel; the current imaging system has a resolution of 733 nm/pixel. The camera has pixel size of 6×6 microns, and dimensions of 1280×1024 pixels. This corresponds to an image region of ~1×0.75 mm on the target. Calibration of distance in the images is performed by measuring the pixel distance using Photoshop, then multiplying by the calibration factor.
7.1.3. Plasma Modeling

Plasma modeling is an essential part of understanding the dynamics of the filament interaction. To model the plasma, a one-dimensional hydrodynamic code called MEDUSA is employed [13]. This code was originally developed in the early 1970s for use with the laser fusion program. The program models in one dimension the effects of a pellet irradiated by a high-power laser beam. The pellet is composed of three shells: the inner core, the glass layer, and the plastic layer. These layers are still available in the code; however, for these experiments only the first two layers are utilized.

MEDUSA models density, velocity and ion and electron temperatures throughout the plasma. These are used since they are functions of time and space, and can be implemented in various spatial coordinates. From these the quantities, the remaining plasma parameters are calculated. The input problem is segmented using a Lagrangian difference mesh in a manner explicit for hydrodynamic simulations. Each time step in the code is iterated several times to ensure proper handling of non-linear effects and to obtain convergence of the parameters.

The version of MEDUSA used for this work is MED103, an adaptation from the original version by A. Djaoui [18, 19]. This version has many improvements to the laser coupling calculations such that high-peak-power lasers are better handled by the code. A significant amount of atomic processes (for non-LTE) were also added. Paul Gibbon of the Jülich Supercomputing Centre in Jülich, Germany later added changes to allow modeling of femtosecond laser pulses [26, 36]. The version that was used for these experiments is modified from Paul Gibbon’s code, with additions to allow for multiple pulses incident on target.
The conditions for the experiment are loaded into the code through an input file. This file contains all of the parameters for the laser beam, the interface between materials, and the material properties. The output of the code is passed through a post-processor for extraction of the data (the output is one large file). These files are then imported into MATLAB for further post-processing and plotting of the data. From the initial parameters of the model, MATLAB corrects the time stamp and position axes. The time has to be corrected since, to avoid sudden shocks to the model, the incident laser is delayed from the initial modeled time. As the model consists of separate layers, it is useful to define the boundary between layers as the origin for the graph axes. This is all calculated in the post-processing MATLAB code.

Figure 64. Example of output from MEDUSA for a filament-produced plasma.
The best way to view the output is a spatio-temporal color-coded graph. A sample is given in Figure 64, showing pressure generated in the ablation process. Here the x-axis is time and the y-axis is position in sample space. Two layers are used for this model: the inner layer and the glass layer. The inner layer is given the physical parameters of the glass target and is the region below the white dotted line (negative position) in the above figure. The glass layer (the name only refers to the original use in laser fusion) is the surrounding air. The incident filament is defined to have energy of 8 mJ and a pulse length of 120 fs and is incident from the top, as illustrated by the arrow. MEDUSA predicts that roughly 15 µm is ablated in the first 200 ps, with peak pressures of 180 million PSI. In addition to pressure, MEDUSA can predict the electron and ion temperatures and densities; the material density; velocities; and the average charge state. However, MEDUSA cannot predict the effects of these parameters on the surrounding medium.

7.1.4. Acoustic modeling of shockwave generation

Shockwave modeling under these conditions is a challenging task due to the extremely high pressures and velocities, and the short time scales. In these conditions, the material response is non-linear, which must be adequately implemented in the code. The mathematical implementation in code is outside the scope of this research; however, the Mathematics Department at the University of Washington has a freely available FORTRAN routine that is capable of solving such problems. The Conservation Laws Package (CLAWPACK) is a package of FORTRAN codes that can solve non-linear time-dependant hyperbolic systems of partial differential equations in up to three dimensions [42, 66]. CLAWPACK forms the basis for the acoustic modeling program, and an application code feeds in the data to the package.
The shockwave acoustic model is written in modules and compiled into a single executable. The code currently consists of four major parts: the input parameter file, the application code, mathematical libraries, and CLAWPACK. The input file consists of all the physical space, code execution, and output parameters required for the code operation. This file is read in by the application code, which interprets the parameters and stores them to the correct memory arrays. The problem to be solved is contained within this code, which is passed to the CLAWPACK input arrays for processing. The acoustic portion of the code was partly written by the authors of CLAWPACK for analysis of pressure waves passing cylindrical structures. From this point the code was modified to its current state.

The problem space has been designed to mimic the conditions of the experimental setup. In the region to be analyzed, the code requires defined space and boundaries; the left half of the plane is configured as glass and the right half as air, where a dashed line marks the boundary. The initial conditions for the system are defined by a user-defined subroutine. For this work, the glass and air have initial conditions of standard temperature and pressure (STP) except for a small, extremely high-pressure region in the center at the boundary as illustrated in Figure 65.
Figure 65. Initial pressure distribution input to model. Left half is glass and right half is air.

This pressure region is the equivalent of an instantaneous time after the incident laser pulse. To accurately set this value, MEDUSA is run using the laser and geometry conditions and provides the plasma temperature and pressure as a series of defined time steps. The shape is defined by the incident laser beam dimensions and intensity distribution. These are directly related to the plasma conditions. When we record images of the shockwaves using shadowgraphy, the image is the gradient of the density profile at that instant. Therefore we plot the gradient of the output of the code, in 8-bit grayscale.
Two further modifications to this code need to be made to make it suitable to model laser plasma shock effects. The original version was not capable of handling time scales on the order of nanoseconds or less. This was found to be the result of machine issues, or more probably FORTRAN mathematical problems, with the extremely small numbers that are used in the code. This is a known problem when working with numbers smaller than $10^{-9}$, as the math algorithms are not written to support this. One possible solution would be to scale all the units to a larger value to bypass the small-number issue; however, this has proved to be quite difficult to implement throughout the entire code. In addition, the code is not able to handle gaseous flow and adiabatic processes. For the air side of the model, the model assumes that the material acts similar to a solid in that the acoustic waves pass through and the medium is stationary. However, this provides inaccurate representations of the shockwaves. To compensate, the as-measured atmospheric shockwave velocities are entered as the speed of sound in the medium at that time step. This provides a rough match to that observed in the lab, but is not of great importance since we are more interested in the shockwaves in the solid target material.

Figure 66. Two time steps of the output of the code. Modeled in 2D.
7.2. Filament-generated shockwaves

As described in Chapter 2, shockwaves are acoustic waves whose group velocity is faster than that of the speed of sound in the medium. The generation of shockwaves requires significant energy deposition into the propagation medium. The interaction between the filamented laser pulse and the target material generates enormous pressures from the plasma on the target surface. Pressure is directed into the target material and into the surrounding atmosphere, and results in shockwaves in both media. These effects will be explored in the following sections.

7.2.1. Transverse filament acoustics

As the femtosecond pulse propagates through the atmosphere, the energy lost to the channeling process is deposited into the air in the form of heat. This localized heating generates a weak disturbance in the refractive index of the air, and a very weak acoustic wave. Some groups have measured the parameters of the filament by recoding this weak acoustic wave [70].

As a result of the design of the imaging system, both shockwaves in transparent solid media and shockwaves in the air can be visualized. What is recorded is not the pressure, but rather the gradient of the pressure. This is similar to a Schlieren imaging system, where the change in index is observed rather than the index itself. The shockwaves in the solid media are significantly easier to record since they are in the same in plane in which the imaging system is focused. In addition the shockwaves are confined within a finite semi-2D region overlapping the depth of focus of the imaging system. This confinement provides clearer imaging.
The channels in air are observed as two thin lines propagating coaxially with the laser pulse. Each line represents the edge of the acoustic wave, expanding transversely to the laser axis. This is illustrated in the figure below.

Figure 67. Filament acoustic wave.

In the figure, four different time steps are shown and the filament edges are illustrated to the right. The dark diagonal line is an imaging artifact. As time progresses, the diameter increases at a slowing rate, and significantly slower than that of the plasma. This is attributed to the weak
amount of energy deposited in the air. Even without a target being present, the acoustic waves are observed. As noted in the previous section, the channels were seen to be unstable when shot in bursts (separations less than 10 nanoseconds). In an experiment involving two filaments separated in time by 9 nanoseconds, the air disturbance is observed to be significant and explains the spot patterns seen in ablation of silicon targets at distance.

![Figure 68. Image of multi-filament transverse acoustic waves.](image)

The region in front of the surface plasma is seen to have a significant amount of turbulence that would cause variations in the guiding of adjacent filaments.

### 7.2.2. Filament-produced plasma

Shockwaves form as the result of a large impulse of energy, where the motion of the energy (which is transferred to the shockwave) surpasses the speed of sound in the material. To understand shockwaves being generated by filament-produced plasmas, the initial transfer of
energy must be determined. During the time of the filament/material interaction, conservation of energy must be maintained. The energy contained in the filament must be equal to the sum of the energy transferred to the air, the heating of the material into plasma, the emission of energy throughout the electromagnetic spectrum, and the concussive energy in the form of a shockwave in the medium. To observe these effects, the imaging system was configured to examine times ranging from 100 ps to 2 ns after the filament hit the target.
Figure 69. Evolution of filament-produced plasma (time increasing left-to-right and top-to-bottom).

Figure 69 shows images taken using a 100-fs probe beam with a filament incident on a glass target. The time separations are measured using a fast photodiode and oscilloscope with a
resolution of 50 ps. Each frame is a new section of material, as each filament significantly damages the surface. This results in the non-uniform shot-to-shot characteristics observed in the shape and expansion of the plasma. In the early stages of the plasma expansion, the plasma profile is of equivalent size to the diameter of the channeled beam, including the peripheral energy. The addition of this extra width (beyond the channel itself) verifies that the channel’s evanescent wave carries significant energy. As time progresses, the plasma expands rapidly outwards, at speeds measured up to 80 km/s. The velocity decreases as $r^{-3}$, as would be expected. At times less than 500 ps, additional atmospheric turbulence is observed directly in front of the plasma. This could result from backward-scattering laser light from the plasma, plasma emission, or other thermal effects; the exact cause has not yet been determined. Without performing interferometry, which is not feasible with the current setup, it is not possible to accurately measure the plasma density. However, the critical density for this probe beam is $6 \times 10^{21}$ cm$^{-3}$, implying that any non-transmitting section of the plasma is above this density. At 1.5 ns after the filament impact, the density of the entire plasma has decreased below the critical density. The black streaking observed in the glass is discussed in a following section.
7.2.3. Filament-generated shockwaves

The results from the early plasma evolution show that the expansion is similar to conventional plasma expansions and that there is a significant portion of energy deposited into the air (in order to achieve expansion velocities of 80 km/s). However, at these time scales the shockwaves in the glass have not propagated far enough from the surface for them to be observable. Starting at 1 ns after the filament, images were taken at 5-ns intervals up to 40 ns. These images are shown in Figure 70.

Figure 70. Shockwaves in glass. These images were taken using the old imaging system.
In the set of images, the shockwave becomes noticeable at 5ns as a thin, dark line just behind the plasma. The vertical width of the line is directly correlated to the size of the surface plasma and the pressure it exerts. The shape of the shockwave is seen to depend on the boundary conditions. This will be explored in more detail in a later section. The air shockwave can be observed in the right half-plane of the image, and to some extent in the left half-plane as well. This is due to the plasma’s dimensions being larger than the target and thus wrapping around the target. The shadowgram is sensitive enough to observe these deviations in the density (or refractive index).

Each image acquired in the experiment is post-processed in Photoshop to enhance the contrast (most images are very dark). After processing, the physical features of the image can be measured using the selection tools. Since the imaging system is calibrated as a distance per pixel, Photoshop needs only to measure the number of pixels of the feature. Using the measured distance and dividing by the time at which the image was taken provides the velocity of the shockwave. The error in the velocity is the result of error in the distance measurement. Since the boundary of the glass has an opaque region, it is uncertain where the shockwave originated. Therefore the entire thickness of the opaque region is used as the error for the measurement of the distance.

The velocity of the shockwave in the atmosphere is measured first. The expansion is considered to be like that of a point explosion with extremely high initial velocities that decrease like a power function. Figure 71 is the graph of the measured data for the atmospheric expansion velocity. The initial velocity is upwards of 80 km/s and slowly decreases.
Figure 71. Measured shockwave velocity in air for 1 to 50 ns.

By inputting the filament laser conditions into MEDUSA and plotting as a function of time it is possible to extrapolate the rate of material ablation and therefore the rate at which the material is expanding outwards.

Figure 72. MEDUSA calculation for the filament conditions.
The output shown in Figure 72 is the pressure. Pressure in this case is not particularly useful; however it does show the calculated amount of ablation as a function of time. In this case, ~15 µm is ablated in 200 ps, which equates to an expansion velocity of 75 km/s. Compared to the measured value of 80 km/s, it is in reasonable agreement. This also verifies that the parameters for MEDUSA are correct and that the model is matching the physical conditions well.

The shockwaves in the glass are measured using the same method as for the air shockwaves. The result is plotted in Figure 73.

![Glass shockwave graph](image)

**Figure 73.** Measured shockwave velocity in glass generated from a filament.

For early time measurements the error bars are larger, due to the relatively small distance traveled away from the boundary. For this particular experiment, the glass had a speed of sound of approximately 5420 m/s. The trend of the velocity over time is decreasing, the result of the shockwave’s initially traveling faster than the speed of sound in the glass and energy dissipation. After 40 ns the velocity is observed to continue decreasing with time.
To further investigate all the phenomena observed in the images, a select image is chosen. This image was taken 25 ns after the filament, which contained 8 mJ of energy in a 120 fs pulse.

Figure 74. Filament-produced effects, 25 ns after pulse.

The two faint horizontal lines in the right of the image are the result of the channel acoustics. Both air shockwaves and glass shockwaves are present in the image, which can be readily separated by their respective velocities and shapes. The main shockwave in the glass has a measured velocity of 5461 m/s, as compared to the known material acoustic velocity of 5425 m/s. The plasma formed from the filament interaction expands around the glass slide, due to the dimensions of the target being smaller than the plasma, resulting in the appearance that the air shockwave passes through the interface. The small bump protruding from the top of the air
shockwave results from the decreased atmospheric density in the filament wake. There are two glass shockwaves observed: the main shock front from the filament and a smaller secondary shock. The second shock is under investigation but is likely the result of surface recoil effects or surface material expulsion [12].

At twice the energy, 15 mJ, the glass shockwave is observed to be much larger in vertical length as shown in Figure 75. The increase in length is attributed to the increase in the dimensions of the plasma and the subsequently increased area under extreme pressure. All the same effects can be seen as in the lower energy sample. The low velocity of the shockwave is likely the result of error in defining the origin of the shockwave (the edge is severely damaged and increases the error).

Figure 75. Result of 15mJ filament incident on glass target.
To verify the existence of strong shockwaves in the glass and to provide differentiation between the waves in glass and those in air, polarimetry was implemented on the diagnostic system. Silica glass exhibits birefringence only under high stress, where the amount of birefringence is proportional to the amount of stress, making polarimetry an ideal diagnostic. To achieve optimal imaging of stress/strain, the two crossed polarizers were aligned at 45 degrees to the plane of incidence. The birefringence generates two different polarizations; however, only one is passed through the second polarizer. It is possible to perform this test with just one polarizer, but separating the two images from the noise would be difficult. The angle was found to be the best through successive experiments.

Figure 76. Image of shockwave in glass using polarimetry and stress-induced birefringence.
In Figure 76, the glass slide is the left half, with the thin white line marking the glass/air interface. The white cloud noticeable in the right half is unpolarized emission from the plasma. The shockwaves are clearly seen in the glass as white lines, where intensity correlates to induced stress. Targets exposed to many filaments form cracks orthogonal to the plane of incidence, which can be seen by the resulting material strain. The results confirm that in the previous images where extra waves were visible, these are likely waves in the air surrounding the sample.

7.2.5. Oblique incidence

All the previous experiments have been performed using filaments normal to the target interface. To investigate the properties of the interface geometry on the target interaction, the target was rotated 45 degrees to the filament. These experiments were performed using 8 mJ, 120 fs filaments incident on 150 µm-thick glass slides.

Figure 77 shows one image taken of the interaction at 30 ns after the filament. The filament is incident from the right as indicated by the expansion of the filament acoustic wave. The plasma formed at the interface is seen as the bright region, and the dark spots are remnants of the surface ablation. The air shockwave is clearly visible and has expanded to a radius of 300 µm. At the bottom of the air shockwave there is a small disturbance in the shock front. This is the result of a small secondary pulse that leaked through the optical pulse slicer in the laser system. This pulse arrived 9 ns after the filament and reflected off the plasma downwards and heated the shock front.

The blue dotted line represents the surface normal of the target, along which the shockwave from the interaction is observed. The shockwave from the filament interaction is
produced by the severe increase in pressure along the surface front. The generation of the shockwave in the material is the result of the pressure along the interface; therefore it is logical that the shockwave always propagates normal to the surface interface. The shockwave generated in the glass shows diffraction from the leading edge of the shock front, implying that the leading edge is extremely sharp. The shockwave is measured to have traveled 170 μm in 30 ns, giving it a velocity of 5660 m/s. The calculated speed of sound in the glass is 5640 m/s.

Figure 77. Filament incident on glass target at 45 degrees.
In previous experiments it was noted that there was black streaking into the glass in the region behind the filament interaction. This was originally thought to be optical damage of the glass; however, the black lines dissipated with time, implying a light-induced effect. In the image the dark black line of optical damage is the path that the light propagated through. The large amount of optical damage implies a high degree of coupling of the leading edge of the pulse or of the peripheral energy. If light is coupling into the glass slide, then it must obey Snell’s law at the interface. This sample was made of Zinc Titania glass with a refractive index of 1.5, thus for an incident wave at 45 degrees the refracted wave is predicted to bend 28 degrees from the normal. Analyzing the image shows that indeed the damage path is at this angle.

Along the path of optical damage there are a series of circles. These circles are the acoustic waves produced by the optical damage. There are several prominent circles that correlate with the large optical damage regions. The radius of the circles is measured to be 170 \( \mu \text{m} \), the same distance the main shockwave propagated. After the second large optical damage point, there is a small amount of light still propagating through the material. However, due to the energy required for optical damage and to produce the acoustic waves, the amount of energy remaining must be quite small.

### 7.2.6. Optical filament coupling

As already noted, the dark lines that are observed in the glass after the filament are the result of changes to the optical properties of the material. Specifically, the presence of high-intensity laser light modifies the refractive index of the material due to the non-linear refractive index. This refractive index change, when illuminated from the side as in the imaging system,
appears as a dark region where the light has been refracted away from its direct path. In the situation where the intensity is sufficient to modify the refractive index but not high enough to create optical damage, self-propagation in the material is possible through four-wave mixing (as described in chapter 2). The light can form stable, self-propagating beams in the material, often referred to as solitons. The solution to the wave equation for this condition dictates that the cross-sectional profile of the beam is sech². A method for reconstruction of the beam profile is presented in section 7.3. With all of the experiments, this effect was only observed to last for up to ~40 ns after the pulse and fades with time. This time is presumably the relaxation time of the material. An exact time measurement was not possible as it changes shot to shot due to differences in the interface conditions.

An image taken at 200 ps is shown in Figure 78. In this image the filament is incident from the right as evidenced by the acoustic signature, and the refractive index change is clearly visible behind the plasma interaction region.

Figure 78. Observation of self-focusing of the transmitted light in the glass at 200 ps.

Note the difference in size between the filament acoustic diameter and the region of refractive index change. The difference is caused by the peripheral energy around the filament described previously. Directly behind the center of the plasma, there is a small region where the refractive
index is increasing due to self-focusing. As the light self-focuses, the intensity increases until either stable propagation results (below the optical damage threshold) or the material undergoes damage. In this case, there are three optical damage points along the path of the self-guided pulse. Each time, the pulse propagates around the optical damage site, losing energy. Once the fluence contained is below the damage threshold, it is seen to propagate for significant distances.

To image the distance that these solitons can propagate in the material, two subsequent images were taken and stitched together. They are shown in Figure 79.

![Figure 79. Multiple images showing propagation of filaments in glass.](image)

On the far right of the image the dark black line is the surface of the glass. The incident filament was again 8 mJ, 120 fs in duration. In the region just after the interface the self-focusing effect in the glass is clearly apparent, as the black region narrows with distance into the glass. Two solitons are observed to propagate through the glass. The vertical line in the middle of the image is the point where the imaging system was moved to image further into the glass. The same surface position on the glass was used in order to align the two segments. This accounts for the weaker visibility in the second frame, as more energy was scattered by the damaged interface. However, it does show that these travel upwards of several millimeters and possibly further. To
the eye, they appear to travel up to a centimeter, but this has not yet been observed with the imaging system.

In situations where a wave propagates in a space where one or more dimensions are confined, this confinement affects the propagation of the wave. Since one dimension in the target is on the order of the diameter of the incident laser beam, a thicker sample was chosen for comparison. The typical samples used ranged between 120-200 µm in thickness, so the thick sample was chosen to be an order of magnitude thicker, 1 mm. This sample is an optical flat made of fused silica.

Figure 80 shows an image using the fused silica flat. The thick black region of the edge is due to the thickness of the target and the edge’s not being perpendicular to the side. The imaging system is not completely focused onto the soliton region due to problems focusing into the
material. However, the propagation in the material is clearly visible, implying that the effect is not a boundary effect.

Using knowledge of the material damage properties, it is possible to estimate the refractive index change in the solitons in the material. For fused silica, the optical damage threshold for femtosecond pulses is around 2 J/cm² [7]. Looking back to the image shown in Figure 78, the region in front of the optical damage point can be estimated. The diameter is measured to be ~16 µm, therefore the pulse has a circular cross-section of 200 µm². Dividing the damage threshold by the pulse length, the intensity is found to be 1.6×10¹³ W/cm². The refractive index can be found from

\[ n = n_0 + n_2 I \]

7-1

From Table 3 the non-linear refractive index is 2.09×10⁻¹⁵ cm²/W and the refractive index is 1.543. The change in refractive index can then be estimated as

\[ \Delta n = \left(2.09 \times 10^{-15}\right)\left(1.6 \times 10^{13}\right) = 0.033 \]

7-2

which is a significant amount. Again, this is only an estimate, but it shows that the difference in refractive index is sufficient for guiding light. A refractive index change of this magnitude acts like a small cylindrical lens (that is, with respect to the imaging direction), which explains the dark lines observed in the images. It also explains why the dark lines often have light centers, as the light propagating though the center of a lens is normal to the local surface interface and continues straight propagation. In effect, the glass slide becomes a phase plate in the presence of the propagating light.
7.2.7. Conservation of energy - Custom targets

In order to understand the conservation of energy in the filament/glass interaction, a series of tests was devised. Since the laser does not have enough coherence (after 30 meters of propagation) to perform interferometry, the measurements of energy had to be made using information from the atmospheric expansion. A series of experiments using different unique target geometries was conducted.

To estimate the energy required to generate a shockwave in air, Sedov-Taylor scaling is used [57]. This relates the radius $R$ of the shockwave to the energy $E$ required to create it through

$$R = \lambda \left( \frac{E}{\rho} \right)^{\frac{3}{2+\beta}} t^{\frac{3}{2+\beta}}$$

where $\lambda$ is a dimensionless factor close to 1, $\rho$ is the density of the air, $t$ is the time at which the radius is measured, and $\beta$ is the dimensionality of the propagation. For planar expansion $\beta = 1$; for cylindrical $\beta = 2$; and for spherical $\beta = 3$. Setting $\beta = 3$, and solving for $E$,

$$E = \rho \frac{R^5}{\lambda^5 t^2}$$

is the equation showing the initial energy required to produce a given air shockwave.

In order to estimate the conservation of energy in the filament interaction, the plasma energy, the transmitted light into the material, and the shockwave energy must be balanced with the known filament energy. To determine the amount of energy transmitted through the material, a single thin piece of glass is shot on edge. An illustration of the setup is shown in Figure 81. The glass plate is the same type used for the previous experiments. The plate was scribed using a diamond cutter and cleaved along the scribe. Due to the thickness of the material, the smallest
A piece that could be cleaved measured approximately $2 \times 0.1 \times 5$ mm. This piece was affixed to a copper sample holder that was mounted in the main testing fixture.

![Figure 81. Thin glass target geometry.](image)

The probe beam illuminated the target from the top along the 2 mm axis. Due to the nature of the cleaving process in glass, the edge is non-uniform and produces scattering, which is observed in the image plane. For this experiment the filament contained 8 mJ of energy in 120 fs, and the image was taken 40 ns after the filament. The result is shown in Figure 82. The air shockwave is readily visible as a spherically expanding wave in the right half of the image. The dark region in the middle of the image is the plate of glass and the lines to the left and right are diffraction off the edges of the plate due to the thickness. There is a darkened region barely visible in the center of the glass where the light propagated through. On the side opposite the filament incident point, there are two smaller air shockwaves with different diameters. These are the exit points for the energy that filamented through the glass. The difference in size is due to the difference in energy that each glass filament contained.
The radius of the air shockwave on the right is 320 µm, and the radii of the back surface shockwaves are 90 µm and 65 µm. The total energy of the system can then be defined by

\[ E_{\text{total}} = E_{fp} + E_{mat} + E_{bp} + E_t \]

where \( E_{fp} \) is the energy of the front air plasma; \( E_{mat} \) is the energy transferred to the shockwave and to the material in the form of damage; \( E_{bp} \) is the energy in the back surface air plasma; and \( E_t \) is the energy that was transmitted. Using the Sedov-Taylor approximation, both \( E_{fp} \) and \( E_{bp} \) can be calculated.

\[ E_{fp} = \rho \frac{R^5}{\lambda t^2} = \left(1.2 \text{ kg/m}^3\right) \left(\frac{320 \mu m}{40 \text{ ns}}\right)^5 \approx 2.5 \text{ mJ} \]

Then the back-side plasma can be found from
The amounts of energy in the back plasma and the shockwave are quite small, but they are significant over such a small area. The transmitted energy was measured (using an energy meter) to be ~1 mJ. This measurement was approximate as this energy level is near the noise floor of the detector. Then the energy deposited into the target material can be found by simply taking the difference:

\[ E_{\text{mat}} = E_{\text{total}} - E_{\text{bp}} - E_{\text{fp}} - E_l \approx 4.5 \text{mJ} \]

This is a significant amount of energy deposition into the target. Unfortunately, there is no simple way to differentiate between the shockwave energy and energy deposited in the form of optical damage. However, it was noted that for the second shot on the same surface the amount of transmitted light was decreased by roughly half (again, the noise in the detector prevents more accurate measurements) implying that with increased surface roughness the coupling to the target material increases.

To further explore the amount of energy that propagates beyond the second surface, a custom target was created. The target was made from high-quality borosilicate glass ~120 µm thick that was machined to have a hole 250 µm behind the surface as shown in Figure 83.
Figure 83. Custom hole drilled through the thin glass plate. Black marks around hole are debris from ablation.

The idea behind the design is that the energy that propagates through the thin surface will exit and re-enter the material. This additional interface should show significant signs of energy deposition. In addition, by creating the target from a flat object, the distortion noticed in Figure 82 should be eliminated. However, for these preliminary tests the sample was burned in the process of machining. This obscures part of the surface area around the hole, but information can still be gained. Future targets will be debris-free. Again, the probe beam illuminated the target from the top and the incident filament had 8 mJ of energy in 120 fs. The probe is 10 ns after the filament.
Figure 84. Image of filament incident on custom target.

The result is what was predicted; the filament strikes the surface, burns a path through the thin strip of glass, exits the glass and re-enters. The shockwave from the first surface is clearly visible just beyond the interface. At each material interface there is an atmospheric plasma. As before, applying the Sedov-Taylor approximation, the energies can be found. The front surface plasma required 3.1 mJ to create, the second surface plasma 1 mJ, and the third surface 20 µJ. There is likely some energy that propagated through the third surface and into the material, but there was no way to measure this quantity. The remaining 4 mJ of energy was deposited into the glass in the form of the shockwaves and the material ablation. At the second surface there is a significant amount of ablation, which likely required a large fraction of this energy. The energy loss due to spontaneous emission is included with the material absorption energy.
7.2.8. Thermal waves

In the images there are observed other small waves propagating into the glass after the filament. These waves are not shockwaves of any magnitude and were thought to be only effects in the surrounding air. However, it is possible that localized heating of the material (induced by the plasma) could affect the refractive index, resulting in such features. According to MEDUSA models of the filament-produced plasma, the average plasma temperature is 2 eV, or ~23,000 degrees Kelvin.

The propagation of heat through the glass depends on the heat diffusion coefficient, which relates how fast heat can propagate through an area as a function of time. For glass the diffusion coefficient is $43 \times 10^{-8}$ m$^2$/s [34]. The distance which the heat propagates is then found using the characteristic diffusion depth,

$$L = 2\sqrt{Dt}$$  \hspace{1cm} (7-9)

where $D$ is the diffusion coefficient and $t$ the time. At a time of 10 ns after the laser pulse, the diffusion depth is found to be ~130 nm. This distance is not resolvable in the imaging system. Using the longest delay time for a recorded image, 260 ns, the diffusion distance is only 670 nm, or roughly one pixel on the CCD. Thus on these time scales, and due to the low thermal conductivity, localized heating of the sample and the associated material changes can be ignored.

7.3. Fourier reconstruction of refractive index distribution

The refractive index change to the glass slides is the result of the intense laser light. This change in refractive index effectively makes the target a time-varying phase plate at the focus of
the imaging system. Changing the phase of light at the focus of an imaging system results in a non-imaging condition, which is the reason why it is not possible to focus on the light-induced artifacts. One way to reconstruct from the images the refractive index change in the glass is to use a Fourier-optics approach. Some of the expressions used are directly from Goodman [29], and are given without derivation.

![Figure 85. Illustration of imaging system coordinates for Fourier processing.](image)

The imaging system used for collecting data can be simplified to a single-lens system for this analysis and is illustrated in Figure 85. The analysis operates from the CCD plane to the target plane. The target plane, being the sample irradiated by the filamented laser beam, is defined in coordinates of \((u,v)\). This plane is imaged through the lens onto the CCD image plane, having coordinates of \((x,y)\). The distances between the lens and the CCD and target planes are \(z_1\) and \(z_2\), respectively. The initial CCD amplitude distribution is defined as \(U_i(x,y)\). In order to analyze the system, it is easier to work in the spatial-frequency domain. This allows
multiplication of terms rather than convolution. Thus the Fourier transform of the CCD amplitude is

\[ U_i(\zeta, \eta) = \iint_{\infty} U_i(x,y) e^{-j2\pi(\zeta x + \eta y)} dxdy \]  

7-10

where \( \zeta \) and \( \eta \) are the spatial-frequency terms. To propagate \( U_i(\zeta, \eta) \) through the imaging system onto the target plane, the product of \( U_i(\zeta, \eta) \) and the impulse response of the imaging system must be integrated over all space.

\[ U_o(u, v) = \iint_{\infty} h(u,v;\zeta, \eta) U_i(\zeta, \eta) d\zeta d\eta \]  

7-11

Here, \( h(u,v;\zeta, \eta) \) is the impulse response of a single lens in an imaging condition and is defined by

\[ h(u,v;\zeta, \eta) = \frac{1}{\lambda^2 z_1 z_2} \iint_{\infty} P(x,y) e^{-j2\pi\left[\frac{\zeta}{z_1} u + \frac{\eta}{z_1} v\right]} dxdy \]  

7-12

where \( P(x,y) \) is the amplitude transmittance function in the lens plane (in spatial coordinates).

This is assumed to be equal to unity for all space. The target plane must now be defined in separate layers as illustrated in Figure 86. The layers are considered to be the interfaces of the sample, and represent the input \( U_i \) and output \( U_o \) waves of the sample. The target is considered to act as a phase plate, and generates a contribution of \( L(u,v) \).
It is then possible to make the relation that the transmitted field $U_o$ is equal to the product of the input field distribution $U_i$, the amplitude transmittance $P$, and the phase of the target $L$.

\[ U_o(u,v) = U_i(u,v)P(u,v)L(u,v) \]  

7-13

It is assumed that the input field is a plane wave of the form

\[ U_i(u,v) = e^{\frac{-j2\pi(u+v)}{\lambda}} \]  

7-14

and that the phase in the target can be expressed by

\[ L(u,v) = e^{-j\delta} \]  

7-15

for

\[ \delta = \frac{2\pi}{\lambda} n(u,v)\Delta x \]  

7-16

where $\Delta x$ is the thickness of the target, and $n$ is the refractive index as a function of position.

Solving equation 7-13 for $L(u,v)$ and equating to equation 7-15,
\[ L(u,v) = e^{-j\frac{2\pi}{\lambda} n(u,v) \Delta x} = \frac{U_o(u,v)}{U_f(u,v)P(u,v)} \]  

Taking the natural logarithm of both sides and rearranging gives

\[ n(u,v) = \frac{j\lambda}{2\pi \Delta x} \ln \left[ \frac{U_o(u,v)}{U_f(u,v)P(u,v)} \right] \]

which is the solution for the refractive index of the target.

The result seems to be relatively simple, but in practice is extremely difficult to calculate. There are six integrals which must be calculated for every step (pixel) in the image resulting in an enormous amount of computations. Considering that the images recorded are 1280×1024 in dimension, and using a conservative step size for numerical integration, the six integrals result in 1717986918400000000 iterations. Limiting the input size significantly decreases the number of iterations, but increases generation of noise in the impulse response function. Some analytical approximations have been made to the integrals to eliminate a significant portion of the problem; however, this is also seen to generate noise in the frequency domain.

### 7.4. Summary

Self-channeled femtosecond laser pulses were propagated 30 meters down the test range and irradiated various configurations of targets. All the targets used were optically transparent to both the laser and probe wavelengths, optically flat, and thin in the imaging dimension. Many firsts were observed in these experiments; optical detection of filament acoustics, interface shape governing shock front, and optical coupling of light into the target sample.
Acoustical waves generated by propagating filaments had been known prior to these experiments, however, these filament acoustics had never before been visually imaged. Resulting from the heat dissipation from the ionization of the nitrogen molecules in the air, the radial expansion is equivalent to that of the speed of sound in air. Upon striking the target, the filament generates hot, dense plasma and creates a momentary point pressure source on the surface. The high pressure leads to generation of shockwaves into both the glass target and the surrounding atmosphere. Comparing the expansion rate in air with the predictions of MEDUSA, the difference between model and experiment is less than 6%. The shockwaves in the glass were modeled using a newly created non-linear acoustic code. Given the parameters from MEDUSA for the plasma interaction and using results from experiments, the model accurately simulates the shape of the shockwaves in time. Changing the angle of incidence between the filament and target illustrated that the shockwaves always propagate normal to the interface and generally exhibit the shape of the interface under irradiation. For these experiments it was observed that the temporary black streaks generated in the glass slides refracted according to Snell’s law, implying optical coupling to the target from the self-channeled laser pulse. The light coupled into the material contained sufficient energy to self-focus and create optical damage. When the energy was below the damage threshold, stable propagation in the glass was observed over several millimeters. Upon exiting the material, these glass propagating filaments generated optical damage and air shockwaves. Using the Sedov-Taylor approximation, basic energy calculations were performed.
CHAPTER 8. CONCLUSIONS

The use of directed energy in the form of femtosecond self-channeled laser pulses can be applied to many diverse technologies from lasers to microwaves, and even to sound waves, with many different possible applications. Among these technologies, directed self-channeled laser pulses are proving their increasing usefulness in many different areas of research. This thesis explores some of the possible applications and lays the groundwork for further investigations using directed energy as a means to generate specific effects. To our knowledge, this is the first thorough investigation of these effects, the results of which have led to new avenues of research and provided a better understanding of the associated physical processes.

Before undertaking this research, as with many such explorations, a significant amount of preparation was necessary. The laser system slated for use with these experiments was not capable of operating in the needed conditions. The system required significant redesign in terms of its electrical configuration and of the optical beam line. All of these changes were custom-designed, built, and tested to ensure proper operation with the existing components. The creation of an entirely new laboratory was another necessary undertaking. A secured lab for propagating femtosecond beams was critical, as use of the hallways was problematic; in particular, it was impossible to install permanent apparatus outside the lab. The adjacent service chase, containing most of the support subsystems for the Terawatt laser system, was converted into a secured testing range in which to perform these experiments. This required the movement and removal of previous equipment, and the addition of a new diagnostic facility at the end of the service chase. The addition of the facility involved many mounting challenges (optical breadboards are not
generally mounted on the walls of labs), running many diagnostic lines from the laser control system, and building unique diagnostic equipment. This work was critical for the successful observation of directed-energy-induced effects.

All of the effects studied in this thesis are related though the processes occurring on the surface of the target. In the previous chapter, some basic estimates were made regarding the conservation of energy in the interaction region. Once the energy reaches the target, which for these experiments the target was usually glass, two main things happen: part of the energy creates a surface plasma, and part of the energy is transmitted into the target. This separation of energy is significant due to the large amount of peripheral energy present with filamented laser pulses. In comparison, a standard focused laser beam would have little to no peripheral energy and the split of energy would be a small percentage. The plasma created by the laser pulse is the source for EMP emission, shockwaves in the glass and air, and ablation of the target surface. The energy that propagates into the medium was found to form solitons and resulted in optical damage within the volume of the target material and at exit surfaces. The division of energy is estimated to be 44% to the air shockwaves; 12% transmitted through; and 44% divided between the electromagnetic emission, shockwaves, and the creation of optical damage.

The one loss mechanism not included above is the energy loss per distance as a consequence of the filamentation process [23]. As a byproduct of the imaging configuration, this energy, deposited into the air, was visually observed to form what we term filament acoustics. These sound waves are the result of the heating of the air, which is caused when the laser pulse ionizes the atmospheric nitrogen molecules. The existence of filament acoustics was previously known from experiments using ultra-sensitive microphones, but to our knowledge our experiments provide the first visual documentation.
Ablation of material is of great importance for laser cutting and other manufacturing processes. The ablation rate is a critical factor in laser machining, where speed and quality are essential. Using the Terawatt laser, a parametric study was performed across many different elemental materials using conventional laser-focusing techniques, with the goal of improving ablation rates through the use of novel approaches. Using bursts of pulses, where the sum total of the burst contained the same energy as a single pulse, it was found that the ablation rate could be significantly increased once past an irradiance threshold. As a result of burst mode, the ablation quality was markedly better as well. These gains can be attributed to more efficient use of the laser energy. With one pulse, the peak power focused on target was higher than the dielectric breakdown threshold for air; this resulted in some of the energy heating the air rather than ablating the target, and also severely affected the surface quality. But dividing the main pulse into many separate smaller pulses led to lower peak powers, below the air ionization threshold, with the same sum total of energy (the material integrates the energy). Therefore the energy deposition was more efficient. Some basic experiments involving burst-mode ablation were performed at distance using filamented pulses on various targets. Filamented pulses are ideal for burst-mode ablation due to their inherent peak-power being just below the air breakdown. These experiments, however, did not measure the gains made using filamented burst mode, as the ablation mechanisms involved are inherently the same as with conventional focusing techniques. The net result discovered from performing the ablation experiments is that ablation at distance can and should be performed using bursts of pulses for improved speed and surface quality.

The emission of GHz electromagnetic radiation from plasmas is a well-known phenomenon and has been studied in the past by ourselves and others [1, 71]. However, the experiments performed here are believed to be the first measurements of EMP emission for
directed energy configurations. Initial tests of the emission from femtosecond laser-produced plasmas were conducted in the Terawatt target chamber under vacuum using thin metal targets. The targets were mounted 30 cm from an inverse superheterodyne system used for spectral measurements. The signals obtained in vacuum conditions for upwards of 12 mJ per pulse provided electric field strengths in excess of 400 V/m per wavelength. Once the system was calibrated, it was relocated to the diagnostic station at the end of the test range. There the EMP in both polarizations was measured for various materials using filamented laser pulses with 8 mJ of energy. The resulting field strengths were lower than the vacuum tests as is expected due to the atmospheric damping, but still significant. The differences observed between the metals and non-metals proved to be quite interesting. The discrete nature of the non-metal emission spectra implies discrete vibrational modes in these materials. Further investigation is required. This emission region is not completely measured, and the results presented in this thesis are thought to be the first to show these different features. The research showed that self-channeling laser pulses are capable of producing substantial RF emission in the GHz region.

The extreme pressures generated by the filament-produced surface plasma resulted in two shockwaves: one expanding radially into the surrounding atmosphere and the other a planar shockwave in the transparent medium. The gas expansion into the surrounding atmosphere was found to consume upwards of 40% of the total laser energy in the pulse, which also accounts for the extremely high initial velocities (80 km/s) observed in shadowgrams taken with delays below 1 ns. The pressure exerted by the plasma on the surface of the target material results in strong shockwaves propagating inside the material. It is noted that the propagation of the shockwave is always normal to the target interface, as would be expected from a high-pressure impulse. The shockwave takes the shape of the initial pressure distribution, which is here set by the shape of
the interface. This was also noted in modeling the shockwave propagation using the acoustic code. The velocities of the disturbances measured in glass are faster than the calculated speed of sound in the material, thus verifying that they are in fact shockwaves (remembering that a shockwave is defined as when the group velocity is faster than the speed of sound). Verification that the shockwave always propagates normal to the interface was performed by rotating the target such that the incidence angle was 45 degrees. The shockwaves in the glass were still observed to propagate normal to the interface. This experiment led to another interesting result: the observation of optical coupling into the material. It was observed in earlier experiments that there were dark streaks in the glass which persisted for upwards of 40 ns after the filamented laser pulse. In the oblique experiment, these streaks were observed to refract according to Snell’s law, and in some cases resulted in optical damage within the material. This optical coupling and reformation of the filament was actually first observed in experiments testing obscurations in the filament path. It was noted that, even though the filament was blocked, the filament would re-form from its remaining peripheral energy. This is the same scenario as with the angled target: the plasma forms and blocks the filamented pulse, yet the peripheral energy propagates around the plasma and re-generates a filamented pulse. Observations of optical coupling into the target media by femtosecond self-channeled pulses has never been published prior to this work.

There are many effects generated at distance through the use of femtosecond self-channeled laser pulses in directed-energy applications. This thesis serves as a compendium of these interaction mechanisms and their effects. The work detailed herein will undoubtedly improve current understanding of femtosecond ablation and channeling, and generated many novel observations. All of these experiments will require further investigations to optimize the growing uses of this unique technology and bring its applications into everyday use.
APPENDIX: RECONSTRUCTION OF EMP SIGNAL
During each separate time step of the experiment, the time-domain signal, spectral magnitude, and phase information are recorded to comma-separated-value files. The oscilloscope is configured to perform the Discrete Fourier Transform (DFT) internally and plot the data on the screen during the experiment, which helps in aligning the system. The operations performed in the oscilloscope for the DFT (i.e., which algorithms are utilized and how the windowing is configured) are well-documented and can be reversed. The Tektronix scope utilizes a mixed radix implementation of the DFT along with a rectangular window. A background measurement is also acquired for each time step to remove ambient signals.

To handle the processing of data, a MATLAB routine was written. Each separate experiment was stored in separate folders with consistent file names, thereby allowing one script to import any experiment for processing. The code imports each time step of the experiment individually, referring to which window of spectrum was being down-sampled, processes the data, and stores the processed data in the output array in the corresponding spectrum position. The output array is then the total spectrum.

To process the data, each data set is Fourier-transformed from the time-domain signal. When the oscilloscope is set to sample at its maximum sampling speed of 20Gs/s, it internally interpolates the data to 5 GHz of bandwidth; however, it has only 4 GHz of true analog bandwidth, so the remaining spectrum must be removed from the data set. A rectangular low-pass filter after the DFT removes these spectral components. The extra empty data points are removed. Since the gain/loss of the receiver is known, this is divided by the signal in the frequency domain to correct for the system attenuation. In addition, the distance between the receiver and the horn antenna changes the amplitude of the gain, which must be taken into account. Then the known-magnitude signal source data is used to adjust for any offset.
The data processing is repeated for all of the time steps and then stitched together in the spectral domain. This is then plotted in terms of electric field strength (V/m) as a function of frequency. The original time signal can be recovered by performing the inverse DFT on the total set, with careful attention to the different sample length. This provides the total electric field measured in V/m as a function of time in the plasma.
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