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Plasma Optics for Control of Relativistic Laser Pulses in Laser-Plasma Accelerators

by

Joshua Stackhouse

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering–Nuclear Engineering

in the

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of the

University of California, Berkeley

Committee in charge:

Professor Carl Schroeder, Co-chair

Professor Ellie Tubman, Co-chair

Professor David Attwood

Spring 2026

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Joshua Stackhouse

Abstract

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Professor Carl Schroeder, Co-chair

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Laser-plasma accelerators have the potential to be the foundation for the next generation of compact particle accelerators and radiation sources. These devices produce plasma structures with accelerating fields orders of magnitude greater than those in conventional accelerators. In order to drive laser-plasma accelerators, high-intensity laser pulses are required. The laser pulses are focused down to sub-millimeter spot sizes near the plasma accelerator entrance to reach the required intensities. In these regions located close to the accelerator entrance, the laser intensities exceed the damage threshold of conventional optics. This prevents optics from being placed near the accelerator entrance and limits the ability to manipulate laser pulses in that region. One potential solution is the use of plasma optics, which are already ionized and therefore can operate at the high laser intensities present.

This work discusses experimental development and implementation of various plasma optics—plasma mirrors, plasma channels, and plasma lenses—for control of relativistic laser pulses in laser-plasma accelerators. Plasma mirrors are an overdense plasma generated by the ionization of solid target that reflects an incident laser pulse. Plasma mirrors can be used as the final turning optic to compactly couple the drive laser pulse into a plasma accelerator. Compact coupling is especially relevant for setups that stage together multiple accelerators, each driven by an independent drive laser, to sequentially inject new laser energy to achieve higher energy gain. In this work, plasma mirrors produced by ionization of a tape target are characterized for their performance on a petawatt-class laser. The surface quality and pointing stability were measured and improved to suitable levels in preparation for the commissioning of the second beamline on the BELLA laser at Lawrence Berkeley National Laboratory. Plasma channels are cylindrical plasma structures capable of guiding intense laser pulses over many diffraction lengths. In this work, plasma channels are formed through optical-field ionization and used to guide laser pulses from the BELLA laser. The laser guid-

ing and electron acceleration was studied. A novel gas jet design was used to allow for control over the plasma channel length. This allowed for direct measurements of the laser evolution as it propagated through the channel. Dark-current-free accelerator operation was achieved, and electrons were accelerated up to 10 GeV. Plasma lenses also utilize plasma channels but operate in a mismatched regime where the laser pulses undergoes spot size oscillations as they propagate through the channel. These spot size oscillations have the potential to enable laser spot size control at the entrance of a plasma accelerator. This work examines the effects of short plasma channels on laser propagation and evolution under various channel conditions. Particle-in-cell (PIC) simulations were performed alongside experiments, aiming to improve the understanding of the observed laser evolution.

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Chapter 1

Introduction to laser-plasma accelerators and plasma optics

Laser-plasma accelerators [1, 2, 3] are capable of generating electric fields and acceleration gradients orders of magnitude greater than conventional accelerators, allowing for more compact particle accelerators. Compact accelerators are of interest to the scientific community with applications in free electron lasers [4, 5, 6], Thompson sources [7], and high energy physics colliders [8, 9]. Laser-plasma accelerators create ultra-high electric fields in the form of a plasma wake, where the plasma electrons are resonantly driven to oscillate in plasma waves. The plasma wakes arise from the pondermotive force, i.e., the radiation pressure, produced by an intense laser pulse as it propagates through the plasma. The plasma wake can sustain electric fields up to the cold wavebreaking field [1], which is an estimate for the maximum field strength assuming that all plasma electrons are oscillating in the plasma wake. For a typical plasma density of $n_0 \sim 10^{18} \text{cm}^{-3}$, the cold wavebreaking field is $E_0 \approx 100 \text{GV/m}$. Electrons can be trapped and accelerated by the fields from the plasma wake, and then the total energy gain is approximately the product of the acceleration gradient and acceleration length.

In order to drive laser-plasma accelerators, high-intensity laser pulses are required ($I \geq 10^{18} \text{W/cm}^2$). Lasers systems capable of producing such pulses have been enabled by chirped pulse amplification (CPA) [10] where the laser pulse is stretched spectrally (chirped) before amplification; the laser power in the amplification medium is reduced which minimizes deleterious, nonlinear effects during amplification. These high-intensity laser pulses needed for laser-plasma accelerators pose a challenge to manipulate as the laser intensities exceed the ionization threshold ($I \sim 10^{12} \text{W/cm}^2$) of dielectrics [11], leading to material breakdown and ablation. The process of laser damage is driven by the nonlinear excitation of electrons from the valence band to the conduction band of the optical component, where the electrons are heated rapidly leading to collision ionization. Once a critical electron density is reached, the material becomes strongly absorbent to the laser energy through inverse bremsstrahlung heating which results in the ablation of material and permanent structural damage [12].

To avoid laser-induced damage, conventional optics cannot be used close to the laser

focus, limiting the proximity of optics to the plasma accelerator entrance for laser manipulation. For example, on the petawatt laser system at the Berkeley Lab Laser Accelerator (BELLA) Center [13], the final turning optic is located ~ 10 m from the laser focus and the accelerator entrance. The long focal length is motivated by the requirement of the laser spot size to be on the order of the plasma wavelength—which is dependent on the plasma density—for wake excitation that leads to efficient electron acceleration. If the overall linear length of the accelerator is considered, for a meter-scale laser-plasma accelerator stage, a 10 m coupling distance for the drive laser reduces the average acceleration gradient by a factor of $\sim 10\times$. Reduction of the drive laser coupling distance below 1 m would preserve the high acceleration gradient of the accelerator [8].

A solution for laser-induced damage in optical components is the use of plasma-based optics, which can allow for laser manipulation near the laser focus and accelerator entrance. Plasma-based optics are already ionized and thus are capable of operating at laser intensities above the damage threshold of conventional optics. They have previously been used in a variety of laser applications [14], with early development of plasma optics centered around the use of plasmas as amplifiers via scattering processes [15, 16, 17]. Other types of plasma optics have been proposed and developed including plasma mirrors, plasma channels, and plasma lenses.

Plasma mirrors are created by the ionization of a solid-density target to create an over-dense plasma that reflects the incident laser pulse. Plasma mirrors have been used for the reduction of laser prepulse and production of high contrast pulses [18, 19, 20, 21, 22]. They can also be shaped in an ellipsoidal manner to refocus the reflected pulse and provide an intensity enhancement effect [23, 24]. Due to the ability to operate above the dielectric ionization threshold, plasma mirrors can be located near the laser focus and enable the compact coupling of the drive laser into the plasma accelerator. Furthermore, for a fixed drive laser energy, achieving higher energy electron beams using laser-plasma accelerators requires staging multiple laser-plasma accelerators in series, each powered by an independent laser. Compact coupling of the drive lasers into the plasma targets is particularly important for the staging of multiple laser-plasma accelerators, where the average acceleration gradient can be dominated by the inter-stage coupling distance. Plasma mirrors have been proposed [25] and demonstrated [26] as the final steering optic for compact delivery of laser pulses in laser-plasma accelerator staging experiments. Future work will aim to design laser-plasma accelerator staging experiments with electron beams at the GeV energy level and continue to develop plasma mirrors based on operational requirements set forth by the accelerator community.

Plasma channels can be used for the optical guiding of a high power laser pulse. Optical guiding is a way to overcome diffraction and increase the region of high-intensity laser focus that is required to drive a laser-plasma accelerator. The increased region of high-intensity laser focus extends the length of the accelerator and leads to an increase in the energy gain of the accelerated electron beams, which is approximately equal to the product of the electric field and accelerator length. The optical guiding produced by a plasma channel is based on the refractive guiding created by the radial density profile of the channel. The refractive

index profile, $\eta(r)$, must be peaked on-axis and decrease with radial position, i.e., $\partial\eta/\partial r < 0$. This refractive index profile is similar to that of a gradient-index optical fiber. Because the laser phase velocity is inversely proportional to the refractive index, the refractive index profile of the channel causes the phase velocity of the laser pulse to be slowest on-axis and increase with radial position. This creates curvature in the laser phase front and the laser beam focuses around the propagation axis. The refractive index of a plasma increases with decreasing plasma density, meaning that a plasma channel for optical guiding has a plasma density profile with a minimum on-axis and increases with radial position. For a Gaussian laser beam, a plasma channel with a parabolic density profile with a matched depth [27] produces matched guiding where the effects of diffraction and refractive guiding cancel out, and the laser beam size remains constant during propagation in the channel.

Initial development of plasma channels to guide laser pulses was related to studies on laser-plasma interaction [28, 29], with the goal of achieving laser heating of a plasma by containing a laser pulse in the plasma through refraction. Plasma channels for optical guiding in laser-plasma accelerators are formed through various techniques, including capillary discharge [30, 31, 32, 33, 34, 35] and hydrodynamic expansion of laser-heated plasma [36, 37, 38]. In a capillary discharge setup, the plasma channel is created by an electrical discharge inside of a hollow capillary, creating a cylindrical plasma. The outside edge of the plasma loses heat due to conduction to the capillary walls which leads to a radial pressure. The temperature profile and radial pressure results in a minimum plasma density on-axis and a maximum density at the walls, satisfying the condition for optical guiding through diffraction. In a setup using the hydrodynamic expansion of laser-heating, an initial plasma column is formed by ionizing a gas using an intense laser focused into a line, typically using an axicon. Due to the laser heating, the plasma column expands hydrodynamically and pushes out against the surrounding neutral gas. Once again, the required density profile is created, with a minimum on-axis and maximum density at the edge. Recent developments [39, 40, 41, 42, 43, 44] have used optical field ionization to produce plasma channels with an on-axis density down to $n_e(r=0) \simeq 10^{17} \text{ cm}^{-3}$ and increased the channel depth by ionizing the ring of neutral gas around the expanding plasma channel. These developments allow for optically formed plasma channels to be used in laser-plasma accelerators that produce electron beams at the multi-GeV energy level.

Plasma-based lenses cover a broad range of applications and provide refraction-based beam manipulation such as focusing of high-intensity laser pulses [45], phase control [46], and compression [47]. Due to the varied applications, there are various methods of plasma lens formation. One potential way to create a plasma lens is using a plasma channel where the laser spot size oscillates as it propagates due to a mismatch between the laser spot size and the channel width. The laser pulse can then be extracted from the plasma channel after the desired spot size evolution and injected into the plasma accelerator. The use of plasma channels as a plasma lens before the entrance of a laser-plasma accelerator has been proposed [48] but not demonstrated. The ability to manipulate the high-intensity laser pulses would allow for focusing/defocusing of the drive laser to match the laser transverse spot size to the plasma channel, as required for efficient guiding and acceleration [2]. This

can allow a single laser system to operate efficiently at a variety of different energy levels, broadening the experimental scope of a single system. A plasma lens also enables mode filtering [49] of the drive laser to improve energy coupling into the accelerator, which is an important step in optimizing the energy efficiency of laser-plasma accelerators. In order for laser-plasma accelerators to be viable for potential accelerator applications, they must improve the energy efficiency of the accelerator. Improving the energy coupling of the laser into the plasma accelerator allows for increased energy conversion in terms of laser-to-beam efficiency, which is a step towards improving the overall efficiency and viability of laser-plasma accelerators.

This thesis will describe the use of plasma optics in laser-plasma accelerators. Chapter 2 will present theoretical background on laser-plasma accelerators and introduce the experimental facility used throughout this work. Chapter 3 will present developments on plasma mirrors and preparation for their use in experiments on the staging of laser-plasma accelerators. Chapter 4 will present the use of optically-formed plasma channels for optical guiding in laser-plasma accelerators and the acceleration of electrons up to 10 GeV. Chapter 5 will present an exploration into the use of plasma lenses to control laser pulses for improved coupling efficiency into a laser-plasma accelerator. Chapter 6 will provide an overview of the presented work and place it in context for its scientific impact.

This thesis contains experimental results published in:

- A Picksley, **J Stackhouse**, C Benedetti, K Nakamura, HE Tsai, R Li, B Miao, JE Shrock, E Rockafellow, HM Milchberg, CB Schroeder, J van Tilborg, E Esarey, CGR Geddes, & AJ Gonsalves. Matched guiding and controlled injection in dark-current-free, 10-GeV-class, channel-guided laser-plasma accelerators. *Phys. Rev. Lett.* **133**, 255001 (2024).

Chapter 2

Background on laser-plasma accelerators

In this chapter, the relevant background physics for laser-plasma accelerators are examined. This begins with the laser beams that drive laser-plasma accelerators. Next, relevant plasma physics parameters are discussed. Then, the physics involved with laser-plasma acceleration is covered. Finally, the BELLA PW laser system and diagnostics are described.

2.1 Laser beams

High-intensity laser beams ($I \geq 10^{18} \text{ W/cm}^2$) are required to drive laser-plasma accelerators. Therefore the first step to understanding the physics behind laser-plasma accelerators is to understand the physics of laser propagation. The propagation and diffraction of coherent laser beams in free space can be described using the scalar Helmholtz wave equation. The paraxial solutions to the Helmholtz equation in free space are the modes for the propagating laser beams. By solving for the modes of propagating laser beams, the profiles of the laser pulses that drive laser-plasma accelerators can be found. The drive laser pulse profiles for laser-plasma accelerators are typically assumed to be Gaussian, which is the lowest order mode of the solution to the Helmholtz equation.

Additionally, in solving the equations for laser beam propagation, the beam waist evolution can be found. Given the intensity requirements of a laser-plasma accelerator, the drive laser pulse needs to be tightly focused. The beam waist evolution describes the region of high laser intensity around the laser focus that is suitable for driving a laser-plasma accelerator. The diffraction of laser beams in vacuum also presents a challenge to laser-plasma accelerators that will be further discussed later in this chapter.

To begin solving for the modes of laser beams propagating through free space, and following the derivations from Ref. [50], the scalar Helmholtz wave equation is given by

$$(\nabla^2 + k^2)\tilde{E}(x, y, z) = 0, \quad (2.1)$$

where $\tilde{E}(x, y, z)$ is the complex amplitude of the field and $k = 2\pi/\lambda$ is the laser wavenumber. The complex field amplitude $\tilde{E}(x, y, z)$ can be decomposed such that

$$\tilde{E}(x, y, z) = \tilde{u}(x, y, z) \exp(-ikz), \quad (2.2)$$

where $\tilde{u}(x, y, z)$ is the complex scalar wave amplitude and $\exp(-ikz)$ is the plane wave propagation factor for a wave traveling in the z -direction. Substituting Equation 2.2 in Equation 2.1, the plane wave term $\exp(-ikz)$ can be factored out, resulting in

$$\frac{\partial^2 \tilde{u}}{\partial x^2} + \frac{\partial^2 \tilde{u}}{\partial y^2} + \frac{\partial^2 \tilde{u}}{\partial z^2} - 2ik \frac{\partial \tilde{u}}{\partial z} = 0. \quad (2.3)$$

Given that the z dependence of $\tilde{u}(x, y, z)$ is also entirely due to diffraction effects, the variations in $\tilde{u}(x, y, z)$ along z are slow compared to the optical wavelength,

$$\left| \frac{\partial^2 \tilde{u}}{\partial z^2} \right| \ll \left| 2k \frac{\partial \tilde{u}}{\partial z} \right|, \quad (2.4)$$

so that the paraxial approximation can be applied to Equation 2.3. The simplified equation is the paraxial Helmholtz wave equation

$$\frac{\partial^2 \tilde{u}}{\partial x^2} + \frac{\partial^2 \tilde{u}}{\partial y^2} - 2ik \frac{\partial \tilde{u}}{\partial z} = 0. \quad (2.5)$$

The paraxial Helmholtz wave equation can be rewritten into a more general form

$$\nabla_{\perp}^2 \tilde{u}(\vec{s}, z) - 2ik \frac{\partial \tilde{u}(\vec{s}, z)}{\partial z} = 0, \quad (2.6)$$

where $\vec{s}$ is defined as the transverse coordinates $s \equiv (x, y)$ for Cartesian coordinates or $s \equiv (r, \theta)$ for cylindrical coordinates and $\nabla_{\perp}^2$ is the Laplace operator acting on those transverse coordinates. Given the symmetries that exist in laser-plasma accelerator physics, cylindrical coordinates will be assumed for future derivations.

The solutions to Equation 2.6 are a family of functions that can take the form of Hermite-Gaussian functions for Cartesian coordinates and Laguerre-Gaussian functions for cylindrical coordinates. The Laguerre-Gaussian solutions for the electric field envelope are of the form

$$\begin{aligned}
\tilde{E}(r, z) &= A \left(\frac{\sqrt{2}r}{w(z)} \right)^m L_p^m \left(\frac{2r^2}{w^2(z)} \right) \exp \left(\frac{-r^2}{w^2(z)} \right) \exp \left(-ik \frac{r^2}{2R(z)} \right) \exp(i\Phi), \\
\text{with } w(z) &= w_0 \sqrt{1 + \left(\frac{z}{z_R} \right)^2}, \\
A &= \frac{1}{w(z)} \sqrt{\frac{2p!}{\pi(p+m)!}}, \\
R(z) &= z + \left(\frac{z_R^2}{z} \right), \\
\Phi &= (2p + m + 1) \arctan \left(\frac{z}{z_R} \right), \\
z_R &= \frac{\pi w_0^2}{\lambda},
\end{aligned} \tag{2.7}$$

where L_p^m is the Laguerre polynomial of radial order p and azimuthal order m , w_0 is the beam waist that represents the minimum focal spot that will be reached at some point of propagation, and λ is the laser wavelength. The term for $w(z)$ provides a mathematical definition for the beam waist evolution around the focal plane, which is assumed to be at $z = 0$ in this derivation. The behavior of the beam waist and the beam divergence, $\theta = \arctan[w(z)/z]$, is shown in Figure 2.1. There is a minimum waist w_0 at $z = 0$ that expands as z increases in both directions. At $z \gg z_R$, the beam waist $w(z)$ increases linearly with z and the beam divergence approaches $\theta = \lambda/\pi w_0$. The solution can be adjusted for a focal plane at $z \neq 0$ by substituting the expression $(z - z_0)$ for z where z_0 is the longitudinal z -position of the focal plane.

Another significant term from Equation 2.7 is the term $z_R = \pi w_0^2/\lambda$ which is defined as the Rayleigh range and dictates the longitudinal scale length for the laser beam evolution. The effect of the Rayleigh range can be observed more directly in the lowest order solution to the Laguerre-Gaussian family. The fundamental Gaussian mode ($p = m = 0$) is given by

$$\tilde{E}(r, z) = E_L \frac{w_0}{w(z)} \exp \left[\frac{-r^2}{w^2(z)} - \frac{ikr^2}{2R(z)} + \arctan \left(\frac{z}{z_R} \right) \right], \tag{2.8}$$

where E_L is the peak electric field amplitude of the laser. An example electric field is plotted in Figure 2.2 as a function of the radial position r . The laser focus is assumed to be at $z = 0$ and as z increases by integer steps of z_R , the maximum field amplitude decreases and field envelope width increases. It should be noted that the behavior is symmetrical around both the $r = 0$ and $z = 0$ axes.

The fundamental Gaussian mode at the focal plane can also be expressed in a simplified manner in the same form as a Gaussian distribution, i.e.,

$$E(r, 0) = E_L \exp \left(\frac{-r^2}{w_0^2} \right). \tag{2.9}$$

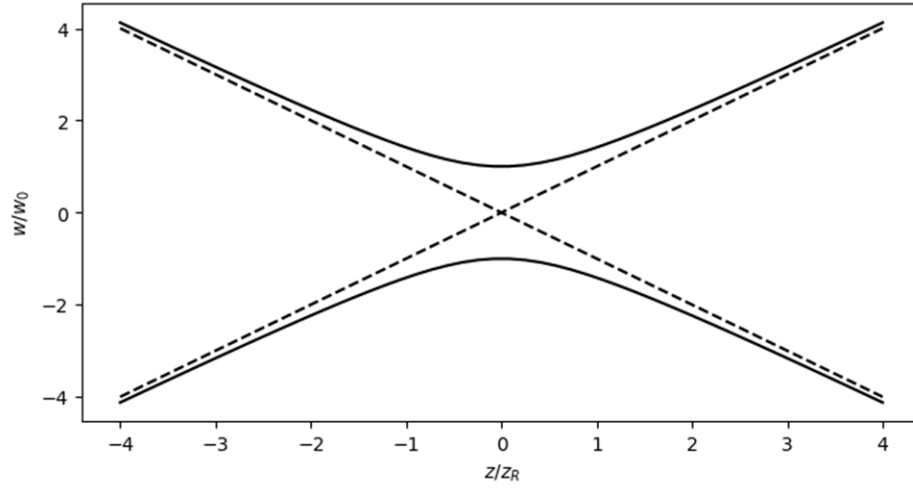


Figure 2.1: Normalized beam waist evolution, w/w_0 , as a function of z (solid). The dashed lines represent the beam divergence, $\theta = \arctan[w(z)/z]$.

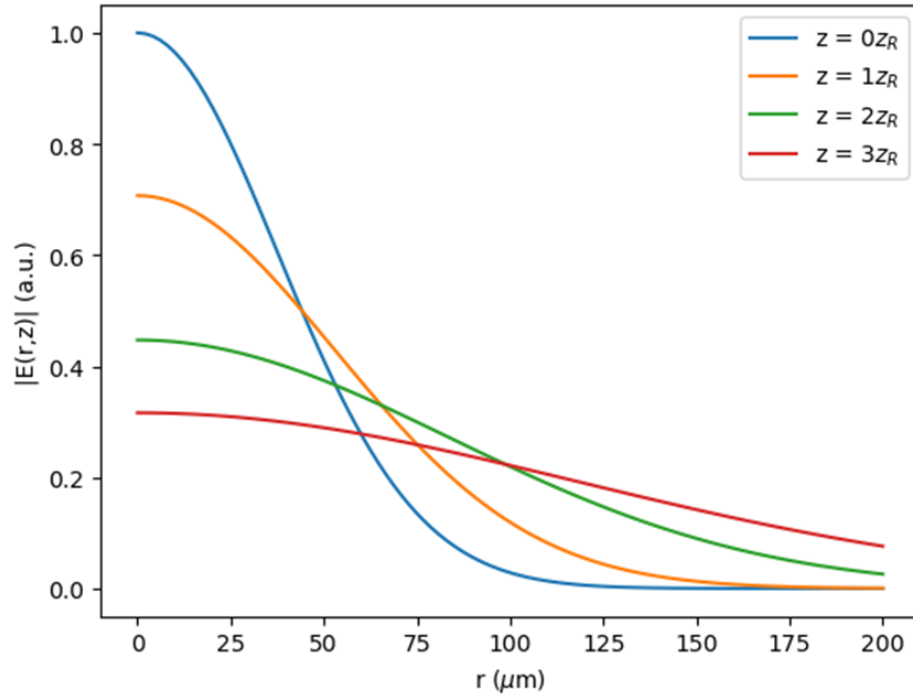


Figure 2.2: Gaussian electric field envelope as a function of r plotted at various z positions for a beam waist $w_0 = 53 \mu\text{m}$ and laser wavelength of 800 nm.

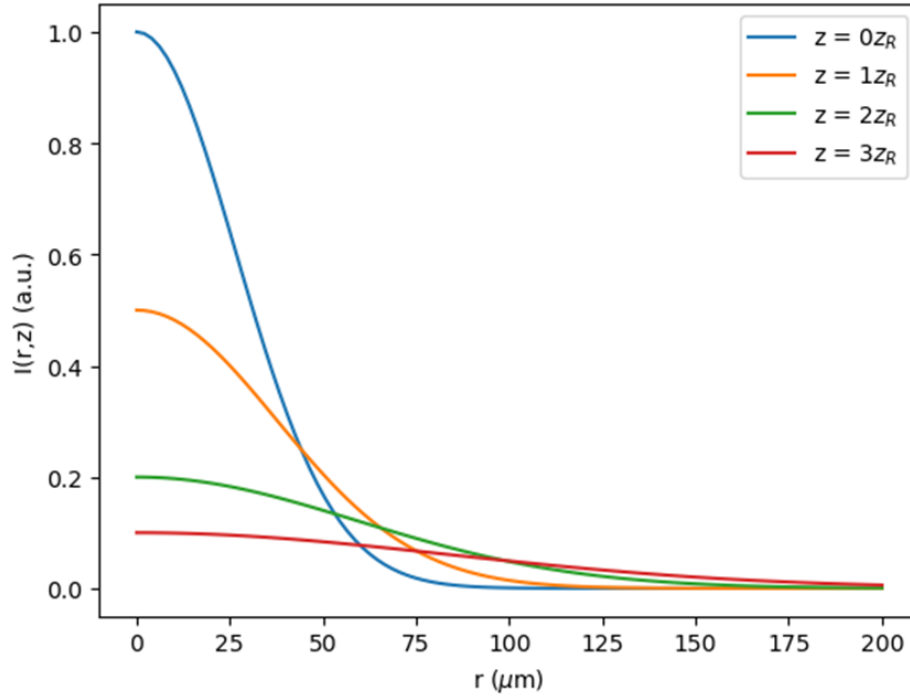


Figure 2.3: Spatial intensity distribution of a Gaussian pulse as a function of r plotted at various z positions for a beam waist of $53\mu\text{m}$ and a laser wavelength of 800 nm .

The fundamental Gaussian mode is often used to model the ideal laser pulse for laser-plasma accelerators. As such, laser pulses can also be modeled with a spatial Gaussian intensity profile. Given that the intensity distribution follows $I \propto |E|^2$, these profiles would follow the form of

$$I(r, 0) = I_0 \exp\left(\frac{-2r^2}{w_0^2}\right). \quad (2.10)$$

The intensity distribution of a Gaussian pulse is shown in Figure 2.3, similar to Figure 2.2. Again, the intensity is plotted as a function of radial position at integer steps of z_R . Due to the relation between field and intensity, Figure 2.3 has a steeper profile that drops off more quickly as the radial position increases. Additionally, the intensity decreases more rapidly as the longitudinal position moves away from the focus at $z = 0$. Given that the beam waist increases by a factor of $\sqrt{2}$ at $z = z_R$, the intensity decreases to $1/2$ the peak intensity at $z = z_R$.

While the Gaussian pulse is often the assumed distribution, high power laser systems typically do not produce Gaussian laser pulses. The optimal pulse distribution for full extraction from laser amplifiers is a flat top distribution, extracting pump energy from the entire amplifier crystal volume. As a result, the spatial pulse distributions produced by high power laser systems are somewhere between a flat top distribution and a Gaussian distribu-

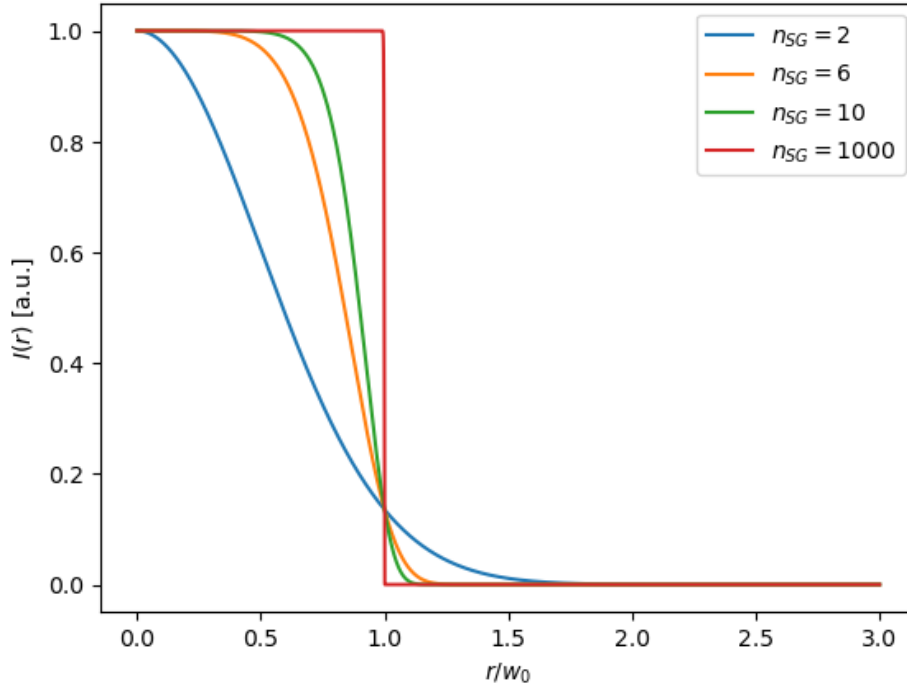


Figure 2.4: Comparison of spatial intensity profiles from supergaussian distributions of order 2, 6, 10, 1000. The supergaussian order $n_{SG} = 2$ distribution matches a Gaussian distribution while the supergaussian order $n_{SG} = 1000$ approaches a flat top distribution.

tion. One such distribution that spans these two profiles is the supergaussian distribution. An intensity profile with a supergaussian distribution has form

$$I(r) = I_0 \exp \left(-2 \left| \frac{r}{w} \right|^{n_{SG}} \right), \quad (2.11)$$

where n_{SG} is the supergaussian order. For $n_{SG} = 2$, the distribution matches a Gaussian distribution. As $n_{SG} \rightarrow \infty$, the distribution approaches a flat top profile. This behavior is shown in the intensity profiles plotted in Figure 2.4 with additional distributions for supergaussian orders $n_{SG} = 6$ and $n_{SG} = 10$. These profiles are typical of the nearfield of the laser system discussed in this work. Often the supergaussian distribution is used to describe the laser profile after amplification and before focusing. Thus, the description is in the near-field or far from focus. Unlike Gaussian or top-hat distributions, the supergaussian does not have a simple analytical solution for propagation or focusing. Therefore, the propagation of supergaussian pulses are typically described numerically or described by approximate solutions.

It is also necessary to consider the laser distribution in the temporal/longitudinal domain. Following [51], a pulse evaluated at a fixed position in space, such as a stationary detector,

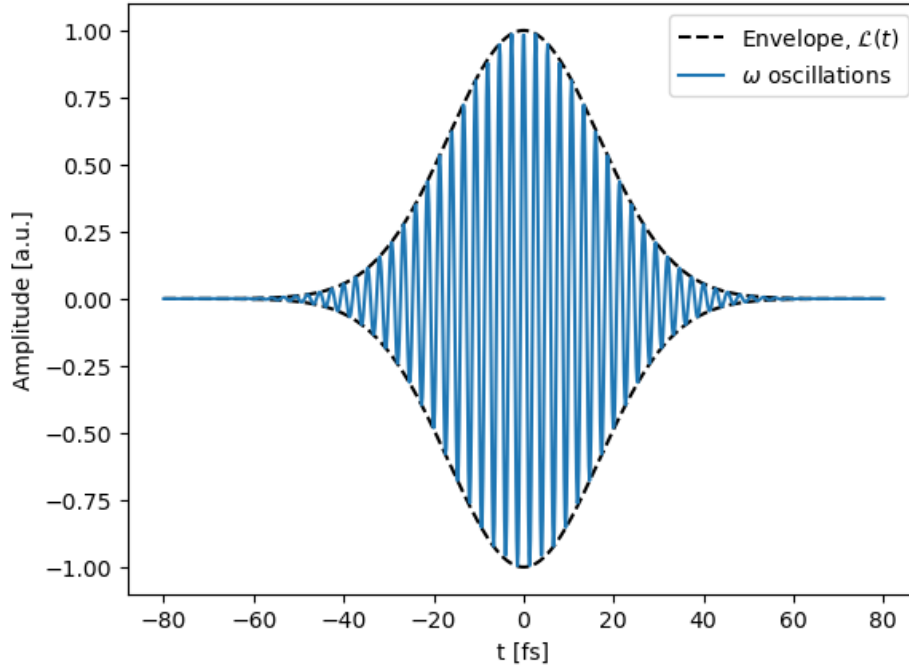


Figure 2.5: Carrier envelope $\mathcal{L}(t)$ and laser frequency ω oscillations as a function of time for a Gaussian pulse with temporal width of $\tau_{FWHM} = 40$ fs and a laser wavelength of 800 nm.

has an electric field strength of

$$E(t) = \mathcal{L}(t) \cos(\omega t - \Phi_0), \quad (2.12)$$

where $E(t)$ is a scalar quantity, $\mathcal{L}(t)$ is the longitudinal envelope, ω is the carrier angular frequency, Φ_0 is the carrier envelope phase. The electric field amplitude for an example pulse is shown in Figure 2.5 with both the envelope and frequency oscillations.

The temporal intensity for such a quantity is given by

$$I(t) = \frac{1}{2c} \mathcal{L}(t)^2, \quad (2.13)$$

where the factor of $1/2$ arises from the time-averaging of the harmonic wave component of the electric field. If the function follows a Gaussian distribution, it can be expressed as

$$I(t) = I_0 \exp \left[-2 \frac{(t - t_0)^2}{\tau^2} \right], \quad (2.14)$$

where t_0 is the time at which the intensity reaches its maximum amplitude and τ is the duration of the laser pulse. Often the pulse duration is expressed in terms of the full width half maximum (FWHM) in which case $\tau = \tau_{FWHM} / \sqrt{2 \ln 2}$. The laser field and intensity profiles are relevant because the laser pulse profile determines the plasma wave excitation.

Additionally, an important quantity for laser-plasma accelerators is the laser strength parameter, a_0 . It is defined as the peak amplitude of the normalized vector potential of the laser field [2]:

$$a_0 = \frac{e\vec{A}}{m_e c^2} \simeq \frac{e\vec{E}_L}{\omega m_e c}, \quad (2.15)$$

where m_e is the electron mass, ω is the laser angular frequency, and $\vec{A}$ is the laser vector potential, which is related to the laser electric field by $\vec{E}_L = -\partial\vec{A}/\partial ct$. The laser strength parameter is related to the peak laser intensity I_0 by

$$I_0 = \left(\frac{\pi c}{2}\right) \left(\frac{m_e c a_0}{e \lambda}\right)^2. \quad (2.16)$$

Equation 2.16 can also be expressed as an engineering formula for a_0 given by

$$a_0 \simeq 8.85 \times 10^{-10} \lambda [\mu\text{m}] \sqrt{I_0 [\text{W/cm}^2]}, \quad (2.17)$$

where a linearly polarized laser field is assumed. The laser strength parameter a_0 defines the physical regime for laser-plasma interaction. For $a_0 \gtrsim 1$, the electron quiver motion is relativistic and the interaction is nonlinear [2]. Relativistic electron motion $a_0 \gtrsim 1$ requires laser intensities $I \gtrsim 10^{18} \text{ W/cm}^2$ for laser wavelengths $\lambda \simeq 1 \mu\text{m}$.

2.2 Plasma physics

In order to discuss the physics involved in laser-plasma accelerators, it is also necessary to establish some basic understanding of plasma behavior. A plasma is an ionized gas where the potential energy of a particle due to its interaction with its neighbors is much less than the particle's kinetic energy [52]. Many of the plasma parameters can be derived by considering test cases with fixed conditions. For example, the plasma frequency can be derived by considering a hypothetical slab of plasma with heavy, immobile ions and an equal density of oppositely charged electrons. If the electron slab is offset from the ion slab, there will be an electric field and a restorative force pulling the electron slab back to overlap the ion slab. This produces oscillatory motion with a frequency determined by the properties of the plasma slab. The frequency of oscillation is the electron plasma frequency and defined as

$$\omega_{pe} = \left(\frac{4\pi n_0 e^2}{m_e}\right)^{1/2}, \quad (2.18)$$

where n_0 is the initial electron density, e is the elementary charge, and m_e is the mass of an electron. By analogy, this can be extended to the ion plasma frequency, setting $n_0 = n_e = Zn_i$, defined as

$$\omega_{pi} = \left(\frac{4\pi n_i Z_i^2 e^2}{m_i}\right)^{1/2}, \quad (2.19)$$

where Z_i is the charge state and m_i is the mass of the ion species. The total plasma frequency ω_p for a two-component plasma is thus

$$\omega_p^2 = \omega_{pe}^2 + \omega_{pi}^2. \quad (2.20)$$

For most plasmas, due to the difference in mass between the electrons and ions, $\omega_{pe} \gg \omega_{pi}$ so $\omega_p^2 \approx \omega_{pe}^2$.

The plasma frequency is an important parameter for describing plasma interactions with electromagnetic waves. The simplest case to begin with is a non-magnetized plasma subjected to an external oscillating electromagnetic field of the form

$$E(\vec{x}, t) = \tilde{E}(\vec{x}) \exp(-i\omega t), \quad (2.21)$$

where the angular frequency of the field, ω , is assumed to be greater than the plasma frequency, ω_p , which allows for the ion motion to be ignored. The motion of the electrons in the plasma fluid equation can be analyzed with Maxwell's equations to derive the electromagnetic dispersion relationship. Following Ref [2], the cold, non-relativistic plasma fluid equations for electrons are given by

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{v}) = 0, \quad (2.22)$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} = -\frac{e}{m} \left[\vec{E} + (\vec{v} \times \vec{B})/c \right], \quad (2.23)$$

where $\vec{v}$ is the electron velocity. Equation 2.22 is the fluid continuity equation that enforces that the plasma fluid quantity in the system is constant. Equation 2.23 is the fluid force (momentum) equation that defines the temporal evolution of the plasma fluid under electromagnetic fields. Together they provide a description of the cold, non-relativistic plasma. Note that if the plasma is not cold, this is not a complete description and an equation of state or closure of the fluid equations is required.

When an external oscillating electromagnetic field is applied, the linearized plasma fluid equations and Maxwell's equation can be analyzed to yield the electromagnetic dispersion relation

$$\omega^2 = \omega_p^2 + k^2 c^2. \quad (2.24)$$

For $\omega > \omega_p$, the wavenumber k remains real and the electromagnetic wave can propagate through the plasma. In such a case, the plasma is considered underdense. However, for $\omega < \omega_p$, k becomes imaginary which corresponds to evanescence. The electromagnetic wave will reflect and attenuate off the plasma, which would be considered overdense. Given that the plasma frequency is dependent on the plasma density, a critical plasma density, n_{crit} , can be derived where this change in behavior occurs. Setting the laser frequency equal to the plasma frequency from Equation 2.18, $\omega = \omega_p$, gives

$$\omega = \left(\frac{4\pi e^2 n_{crit}}{m_e} \right)^{1/2}, \quad (2.25)$$

which can be solved for the critical density. Often, the critical density is expressed in terms of the laser wavelength giving

$$n_{crit} = \left(\frac{2\pi c}{\lambda} \right)^2 \frac{m_e}{4\pi e^2} \approx \frac{1.12 \times 10^{21}}{\lambda[\mu\text{m}]^2} [\text{cm}^{-3}]. \quad (2.26)$$

For a laser wavelength of $\lambda = 800 \text{ nm}$, which is typical for a Ti:Sapphire system, the critical density is approximately $n_{crit} \approx 10^{21} \text{ cm}^{-3}$.

It is also worthwhile to recall that the optical index of refraction is defined as

$$\eta = \frac{ck}{w} \quad (2.27)$$

for light traveling through a medium. From the electromagnetic dispersion relation in Equation 2.24, the plasma index of refraction is found to be

$$\eta_{plasma} = \sqrt{1 - \omega_p^2/\omega^2}. \quad (2.28)$$

Note that in order for light to propagate through a plasma, $\omega > \omega_p$. Therefore, the plasma refractive index is always less than one, $\eta_{plasma} < 1$. These plasma parameters are relevant to this work because they define the laser-plasma interaction. The critical plasma density is the threshold at which a plasma will reflect an incident laser pulse and thus must be exceeded for the formation of a plasma mirror. The refractive index of plasma is dependent on the plasma density and allows for the guiding of laser pulses in tailored plasma channels in a similar manner to a graded-index optical fiber.

2.3 Laser-plasma accelerators

In scenarios with more intense electromagnetic fields, like that of high-intensity laser pulses but with the laser strength parameter still less than one, $a_0 \ll 1$, it becomes necessary to consider second order terms that were previously discarded. Returning to the fluid force equation (2.23), it can be rewritten with the plasma fluid momentum, $\vec{p}$, as

$$\frac{d\vec{p}}{dt} = -e \left[\vec{E} + (\vec{v} \times \vec{B})/c \right], \quad (2.29)$$

where $d/dt = \partial/\partial t + (\vec{v} \cdot \nabla)$. The electric and magnetic fields of the laser can also be rewritten using the vector potential $\vec{A}$ such that $\vec{E} = -\partial\vec{A}/\partial ct$ and $\vec{B} = \nabla \times \vec{A}$. In the linear limit, $a_0 \ll 1$, it can be shown that the leading order electron fluid motion, which results from $\partial\vec{p}_q/\partial t = -e\vec{E}$, is the transverse electron momentum, also known as the quiver momentum:

$$\vec{p}_q = m_e c \vec{a}, \quad (2.30)$$

where $\vec{a} = e\vec{A}/m_e c^2$ is the normalized vector potential. Expanding around the leading order transverse quiver momentum with $\vec{p} = \vec{p}_q + \delta\vec{p}$, the equation for the second-order motion is given by [2]

$$\begin{aligned} d\delta\vec{p}/dt &= -[(\vec{p}_q/m_e) \cdot \nabla]\vec{p}_q - \vec{p}_q \times (c\nabla \times \vec{a}) \\ &= -m_e c^2 \nabla a^2/2 \end{aligned} \quad (2.31)$$

The right hand term is defined as the pondermotive force, $\vec{F}_{pond} = -m_e c^2 \nabla a^2/2$. Equation 2.31 is exact for $a^2 < 1$, where $a^2 = \hat{a}^2(\vec{r}, t) \cos[\omega t - kz]$ and $\hat{a}^2(\vec{r}, t)$ is the laser envelope. The pondermotive force can also be viewed as the radiation pressure from the laser pulse and drives electron waves in the plasma. Using the Poisson equation and the fluid equations, and expanding around the perturbation $n_e = n_0 + \delta n$, the plasma wake generated in cold plasma by a laser pulse ($a_0 \ll 1$) due to the pondermotive force is given by

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2 \right) \frac{\delta n}{n_0} = \frac{c^2}{2} \nabla^2 a^2, \quad (2.32)$$

where δn is the electron density perturbation and produces an electric field given by

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2 \right) \frac{\vec{E}}{E_0} = -\frac{\omega_p c}{2} \nabla a^2, \quad (2.33)$$

where $\vec{E}$ is the resultant electric field and E_0 is the cold wavebreaking field [1]. The resultant electric field is responsible for the acceleration of trapped electrons to high energies. These results from Equations 2.32 and 2.33 are valid for $E \ll E_0$. The cold wavebreaking field, E_0 , is the maximum field strength the plasma waves can sustain with all electrons perturbed (i.e., $\delta n = n_0$) and is given by

$$E_0 = \frac{cm_e \omega_p}{e} \approx 96 \sqrt{n_0 [\text{cm}^{-3}]} \left[\frac{\text{V}}{\text{m}} \right]. \quad (2.34)$$

For readily achievable plasma densities around $n_0 \sim 10^{18} \text{ cm}^{-3}$, the cold wave breaking field, and hence the acceleration gradient, approach $E_0 \sim 100 \text{ GeV/m}$.

The solutions to density perturbation and electric field of the wake are

$$\frac{\delta n}{n_0} = \frac{c^2}{2\omega_p} \int_0^t dt' \sin[\omega_p(t-t')] \nabla^2 a^2(\vec{r}, t'), \quad (2.35)$$

and

$$\frac{\vec{E}}{E_0} = -\frac{c}{2} \int_0^t dt' \sin[\omega_p(t-t')] \nabla a^2(\vec{r}, t'), \quad (2.36)$$

and are plotted in Figure 2.6 for a circularly polarized Gaussian drive laser with $a_0 = 0.5$. For linear polarization, the fast oscillation is averaged: $\langle a^2 \rangle = \hat{a}^2 \langle \cos^2(\omega t - kz) \rangle = \hat{a}^2/2$.

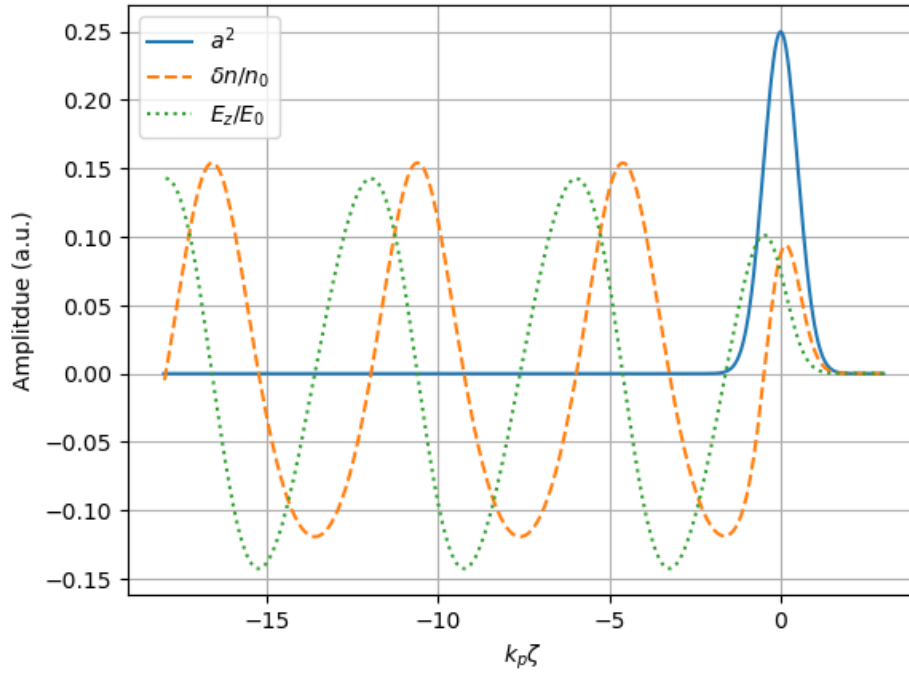


Figure 2.6: Normalized density ($\delta n/n_0$) and electric field (E_z/E_0) perturbations of a plasma wake driven by a Gaussian drive laser with $a_0 = 0.5$ and pulse length $k_p L = 1$.

Note that the sinusoidal oscillations in the normalized axial field, E_z/E_0 , follow the density perturbation, $\delta n/n_0$, with a $\pi/2$ phase shift.

The solutions also provide insight into the design requirements of a laser-plasma accelerator. The axial field amplitude for a wake driven by a Gaussian pulse profile, $a^2 = a_0^2 \exp(-2\zeta^2/L^2)$, is given by [2]

$$\frac{E_z}{E_0} = a_0^2 \sqrt{\pi/2} (k_p L) \exp[-(k_p L)^2/2], \quad (2.37)$$

where L is the laser pulse length, $k_p^{-1} = c/\omega_p$ is the plasma skin depth, and $\zeta = z - ct$ is the comoving coordinate. The result is plotted in Figure 2.7 and demonstrates that the maximum wakefield is achieved when $k_p L = 1$ with $E_{max} \approx 0.76 a_0^2 E_0$. This indicates that the ideal laser pulse length is resonant with the plasma skin depth. If the pulse length is much greater than the plasma skin depth, the drive laser will fail to excite a wake. For an example plasma with a density of $n_e = 10^{18} \text{ cm}^{-3}$, the plasma skin depth is $k_p^{-1} \sim 5 \mu\text{m}$ which dictates a laser pulse length $L \sim 20 \text{ fs}$.

Additionally, the maximum axial field amplitude for a linearly polarized laser with a flat-top profile of optimal duration is given by [2]

$$\frac{E_z}{E_0} = \frac{a_0^2/2}{\sqrt{1 + a_0^2/2}}. \quad (2.38)$$

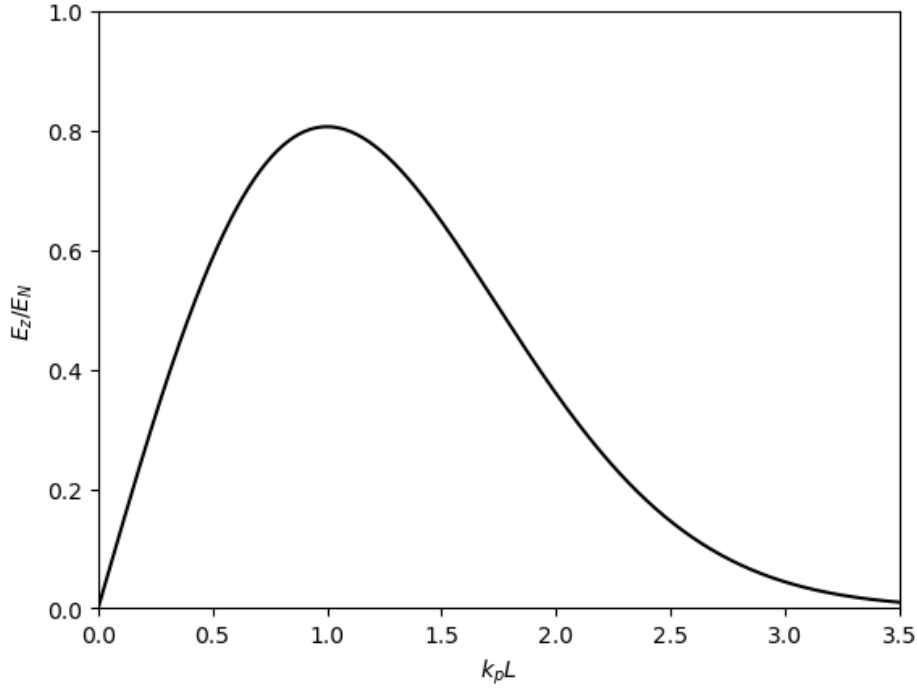


Figure 2.7: Axial field amplitude E_z plotted as a function of laser pulse length $k_p L$ for a Gaussian laser pulse profile $a^2 = a_0^2 \exp(-2\zeta^2/L^2)$. The field is normalized to the maximum amplitude of a flat-top pulse: $E_N = (a_0^2/2)/(1 + a_0^2/2)^{-1/2}$.

In order for the maximal field strength to approach the wavebreaking field, $a_0 \gtrsim 1$ which necessitates drive laser intensities $I \gtrsim 10^{18} \text{ W/cm}^2$.

2.3.1 Limits on laser-plasma accelerators

The energy gain generated by a laser-plasma accelerator is approximately the product of the acceleration gradient and the acceleration length. The primary limit on the energy gain are the limitations on the acceleration length in the accelerator.

In order to drive the accelerator, a high-intensity laser pulse is required and the drive laser pulse must be brought to a tight focus to create the required intensity. However, the region of high-intensity focus is limited by vacuum diffraction. The scale length for the laser focus is the Rayleigh range, z_R . The on-axis laser intensity is given by

$$I(0, z) = \frac{I_0}{1 + (z/z_R)^2}, \quad (2.39)$$

which means that the laser intensity drops by a factor 2 over the distance z_R . For an example PW laser system, the BELLA PW laser system has a Rayleigh range $z_R \approx 10 \text{ mm}$ while the

desired acceleration lengths are on the order of tens of centimeters. The acceleration length can be extended by guiding the laser pulses either through pondermotive self-guiding [53, 54] or guiding in a pre-formed plasma channel [28, 29]. The latter technique is used for experiments in Chapters 4 & 5.

In addition to the diffraction, another effect that limits the acceleration length is dephasing. As the electron bunch is accelerated, it will begin to travel with a group velocity greater than that of the laser pulse driving the wake in the plasma. As a result, the bunch will begin to advance out of an accelerating region of the plasma wake and towards a decelerating region. The distance for the accelerating bunch to slip out of phase with the accelerating field is the dephasing length and given by $L_d = \lambda_p^3 / 2\lambda_L^2$, where λ_p is the plasma wavelength and λ_L is the laser wavelength. As a result, the dephasing length scales with plasma density is $L_d \propto n_0^{-3/2}$ [2]. Dephasing can be mitigated by tailoring the longitudinal plasma density [55, 56] or implementing dephasingless schemes driven by spatio-temporally structured laser pulses [57].

One final limit on the acceleration length is the depletion of laser energy to the plasma wake. Comparing laser energy to wake energy gives $E_z^2 L_{pd} \sim E_L^2 L$ which can be rearranged to $L_{pd} \sim \lambda_p^3 / a_0^2 \lambda^2$. Once again, the scaling relation with density is $L_{pd} \propto n_0^{-3/2}$, the same as for dephasing. As a result, the laser-plasma interaction length scales $L_{acc} \propto n_0^{-3/2}$. The accelerating gradient scales $E \propto \sqrt{n_0}$ and as a result the energy gain scales $W \propto 1/n_0$ [2].

These scaling relations dictate that in order to produce higher energy gain, the laser-plasma accelerator must operate at a lower plasma density. However, lower density decreases the acceleration gradient, reducing one of the key advantages of laser-plasma accelerators. In order to maintain a reasonable acceleration gradient while still achieving high energy gain, a laser-plasma accelerator needs to be staged with multiple accelerator sections. In each accelerator section, a new drive laser is coupled in to address laser depletion. The staging of laser-plasma accelerators is discussed in Chapter 3.

2.4 Layout and specifications of BELLA PW laser facility

The plasma optic experiments performed and described in Chapters 3 – 5 used the high-power, short-pulsed laser facility at Lawrence Berkeley National Laboratory. In this section, the Berkeley Lab Laser Accelerator (BELLA) laser facility, including the laser system and diagnostics, are described.

2.4.1 Laser system

The petawatt (PW) laser system at the BELLA Center is a Ti:Sapphire-based laser system capable of delivering 1 PW laser pulses at a repetition rate of 1 Hz [13]. The laser pulses can contain up to 46 J on target focused by a 13.5 m focal length off-axis parabola

(OAP) to a laser focal waist of $r_0 = 53 \mu\text{m}$. At focus, approximately 75% of the energy is contained within the first minimum of the diffraction pattern ($r = 67 \mu\text{m}$). The laser pulses are compressed to $\tau = 33 \text{ fs}$ in full width at half maximum (FWHM). This results in a peak power of 1.2 PW and a peak intensity of $17 \times 10^{18} \text{ W/cm}^2$.

BELLA PW is a dual-chirped pulse amplification (CPA) [10] architecture laser system with a cross-polarized wave generator (XPW) [58] between amplifier stages for enhanced pulse contrast. The first amplifier section consists of an oscillator, stretcher, regenerative amplifier, and optical compressor. The first amplifier produces pulses with a bandwidth of 40 nm FWHM and 700 μJ of energy per pulse at 1 kHz. The bandwidth is tuned to be 30 nm FWHM so that the XPW output beam bandwidth matches the bandwidth of the second amplifier stage. This minimizes pulse contrast degradation [59], resulting in 45 fs FWHM pulses. The energy is also attenuated to 150 μJ per pulse to avoid white light generation inside the XPW.

The XPW contains two BaF_2 crystals [60] that are wedged to avoid multiple reflections. The output from the XPW are pulses with an energy of 25 μJ and a bandwidth of 50 nm FWHM. The XPW has an energy efficiency of 17% and a spectral broadening of 1.7 times which indicates that the temporal mode of the input pulse from the first amplifier stage is nearly optimized [61].

After the XPW, laser pulses pass through the stretcher and an acousto-optic programmable dispersive filter (DAZZLER HR800) to control spectral phase. A pockel cell is also used to reduce the repetition rate to 1 Hz before the pulses enter the second amplifier stage which consists of 4 multi-pass Ti:Sapphire amplifiers that bring the laser pulse energy up to 60 J. The pump energy for the final two amplifiers, Amp2 and Amp3, can be varied to achieve the desired on-target energy. The pump energy is supplied by 12 GAIA pump lasers, 4 pump lasers in Amp2 and 8 pump lasers in Amp3 as shown in Figure 2.8.

After amplification, the laser pulses pass through a beamsplitter that splits the laser energy between the two beamlines on BELLA PW, also shown in Figure 2.8. The second beamline was installed as part of an upgrade to BELLA PW that was completed in 2022 that significantly expands the scientific reach of the laser system by enabling experiments such as guiding in optically formed channels, study of multi-stage laser-plasma accelerators, optical injection, and QED experiments [62]. Each beamline is capable of handling the full laser energy so experiments can be conducted with the full energy in the first beamline, full energy in the second beamline, or any split in-between the two. The typical beamsplitters used on the system include 50/50, 80/20, 90/10, and 96/4 where the first number indicates the percentage of energy sent to the first beamline and the second number indicates the percentage of energy sent to the second beamline.

After the beam splitter, the laser pulses are transported to the experimental chamber through the first and second beamlines. Each individual beamline has its own separate compressor and deformable mirror. This allows for independent control over pulse duration and pulse wavefront. Additionally, there is a 1 m double-pass delay stage in the first beamline that provides on-shot control of about 7 ns over the timing between the two beamlines. Other changes to timing can be made through semi-permanent beamline adjustments and bypasses.

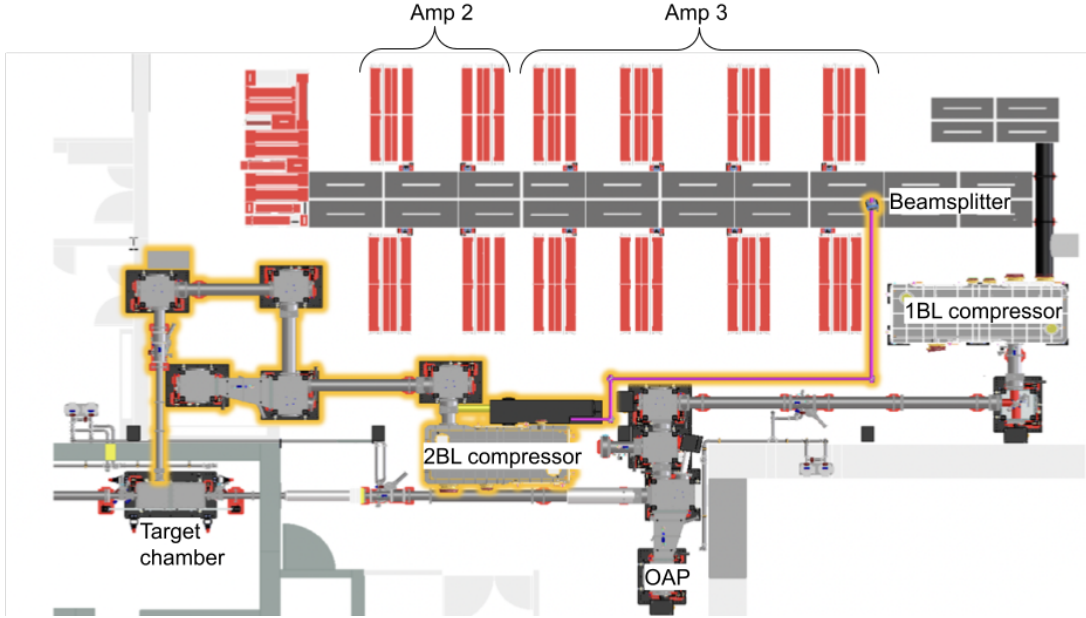


Figure 2.8: Schematic layout of the BELLA PW amplifiers, beamlines, and target chamber. Each beamline has a separate compressor located after the beamsplitter for individual control over pulse length, labeled 1BL and 2BL compressor. The second beamline upgrade is highlighted in yellow.

The first beamline, which transports the primary drive laser, has a fixed focal geometry with a 13.5 m focal length OAP that brings the laser pulses to a focus in the target chamber. The second beamline has a variable focal geometry allowing for flexibility in experimental setup. It can be set up with the same 13.5 m focal length OAP as the first beamline for setups requiring a second long focal length beam such as staging with two laser-plasma accelerators. It can also be configured to deliver a collimated beam to the experimental chamber. This setup is used in single stage laser-plasma accelerator experiments such as optical plasma channel formation [63] and optical injection [64].

2.4.2 Diagnostics

After the laser-plasma interaction point, the laser pulses and electron beams travel towards the high-power diagnostics of BELLA PW. The diagnostic setup is illustrated in Figure 2.9. The electron beams, if generated during the interaction, travel approximately 10 m from the interaction point through to the magnetic spectrometer. Along the way, the electron beams pass through a set of integrating charge transformers (ICTs) that provide a measurement for charge in the beam. As the beams approach the magnetic spectrometer, they pass through a 25.6 mm hole in a wedged optic—that is part of the laser transport line—towards the high-power diagnostic area. Due to the geometry of the hole and the propagation

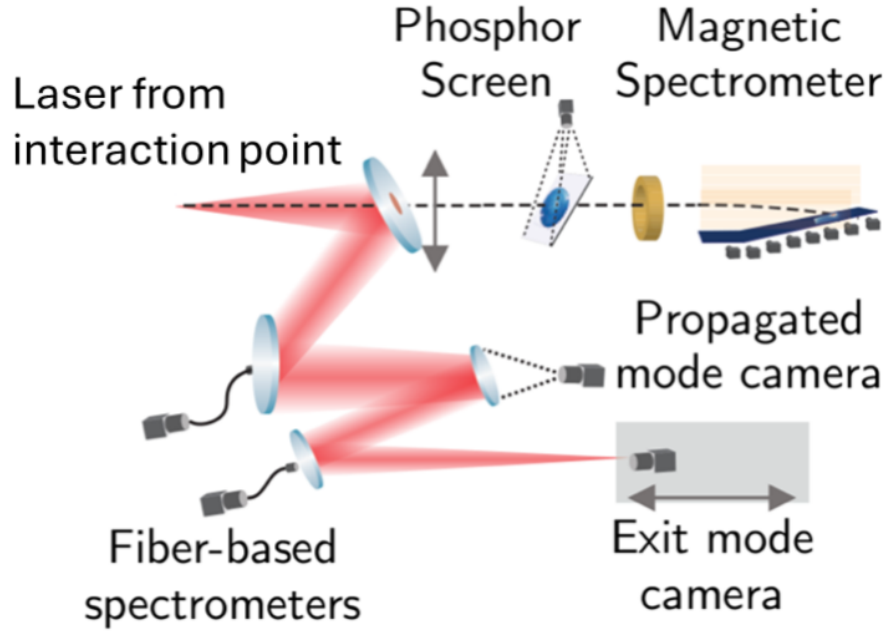


Figure 2.9: Diagram of the high power diagnostic setup of BELLA PW for the laser pulse and electron beam after the interaction point. The electron beam passes straight through an optic with a hole and into the phosphor screen and magnetic spectrometer. The laser pulse is reflected off a set of wedged optics with a pair of fiber-based spectrometers and a propagated mode camera. Afterwards, the laser pulse reaches the exit mode camera that is re-imaging the interaction point inside the target chamber.

distance from the interaction point, the angular acceptance of the electron spectrometer is around 0.5 mrad . The wedged optic with a hole allows for the simultaneous collection of on-shot electron and laser data.

After the 25.6 mm hole, the electron beams are incident on a phosphor screen at the entrance to the magnetic spectrometer. The phosphor screen fluoresces due to the incident electrons, and the fluorescence is captured by a camera to provide a measurement of the transverse spatial profile of the beam. The screen also provides another measurement for charge, based on a calibrated measurement of the total fluorescence from the screen. When the electrons reach the 2.5-m -long magnetic spectrometer, they are bent downwards by the magnetic fields and the spectrum is imaged onto an array of cameras. The array of 12 CCD cameras allows the spectrometer to collect spectra for electron beams from $< 1 \text{ GeV}$ to $\gtrsim 10 \text{ GeV}$ with few percent-level resolution [65]. Furthermore, the magnetic field within the spectrometer is produced by an electromagnet which allows for the field strength to be tuned to the electron bunch energy and optimize the energy resolution across the spectrometer.

After exiting the experimental chamber, the post-interaction laser pulses are reflected and attenuated by a series of wedges and through an all-reflective aberration-free telescope

to be re-imaged on the high-power diagnostic table. As mentioned above, the first wedge has a 25.6 mm hole that allows electron beams to pass through unperturbed. During laser tuning and guiding studies, the wedge can be driven by a translation stage such that the hole in the optic is moved out of the beamline to improve the imaging quality of the laser beam at the high-power diagnostics area. Spatial profiles of the post-interaction laser are collected at the wedges, located approximately 10 m downstream of the interaction point, which provides a quasi-nearfield measurement of the post-interaction laser pulse. There is also a calorimeter-type energy meter to record pulse energy, located after one of the wedged optics.

After the wedges, the attenuated laser pulse is sent to a variety of diagnostics, further described in Ref. [13, 66]. There is a mode imager camera on a 60 cm translation stage. The mode imager is configured with the aberration-free telescope to re-image the laser focus and interaction point inside the target chamber. The translation stage allows for scanning of the image plane. This is either done to complete focal scans of the laser pulse in vacuum or to adjust the focal plane to the exit of plasma channels.

There is a wavefront sensor [67] located near the exit mode camera (not shown in Figure 2.9) that images the surface of the deformable mirror. This wavefront sensor is used to control the deformable mirror and tune the wavefront of the laser pulse. It allows for correction of aberrations introduced into the laser beam from optics and propagation. It also enables data collection of the post-interaction wavefronts.

Finally, there are a set of fiber-based optical spectrometers that cover a broad range of wavelengths from around ~ 400 nm to ~ 2000 nm. The optical spectra obtained by the spectrometers are an important tool for diagnosing the laser-plasma interaction. The data can show signs of spectral modulation and spectral shift. A blue-shift from the original wavelength can be an indicator of laser ionization in the plasma [68], while a red-shift from the original wavelength can be an indicator of laser energy transfer to the plasma and wake generation [69].

Chapter 3

Plasma mirrors for staging of laser-plasma accelerators

3.1 Background

As stated in Section 2.3.1, the laser-plasma accelerator scaling laws dictate that higher energy gain requires lower plasma density, for the energy gain scales like $W \propto 1/\sqrt{n_0}$. At a lower plasma density, the acceleration gradient is lower and the accelerator stages are longer. In order to achieve high energy gain while maintaining the acceleration gradient, multiple high acceleration gradient accelerators can be staged together. In a setup with multiple accelerator stages, the beam from the previous accelerator is injected into the following one and the beam is further accelerated; this process is repeated until the desired energy gain is achieved. The staging of multiple laser-plasma accelerators allows for high energy gain operation while preserving the compact nature of laser-plasma accelerators.

In a staging setup, it is important to minimize the space between the accelerators to maintain a high average acceleration gradient across the entire setup. With regards to laser-plasma accelerators, one spatial constraint is the coupling of the drive laser into the plasma accelerator. The laser must be focused to produce the required intensities by an upstream optic, and then reflected towards the accelerator by a final steering optic. One way to compactly couple the drive laser is to place the final steering optic close to the laser focus and accelerator entrance. This is challenging due to the high laser intensities $I \geq 10^{12} \text{ W/cm}^2$, which exceed the damage threshold of conventional optics [11], that are present in that region.

A solution to the issue of optical damage is the use of plasma mirrors. Plasma mirrors are formed by ionizing a solid target to form an overdense plasma that reflects the incident laser pulse. Since the plasma is already ionized, a plasma mirror can operate at laser intensities where damage to conventional optics occurs. Therefore, a plasma mirror can be located close to the laser focus and operate as a compact final steering optic for the second accelerator stage in a multi-stage laser-plasma accelerator, as shown in Figure 3.1 and labeled “Plasma

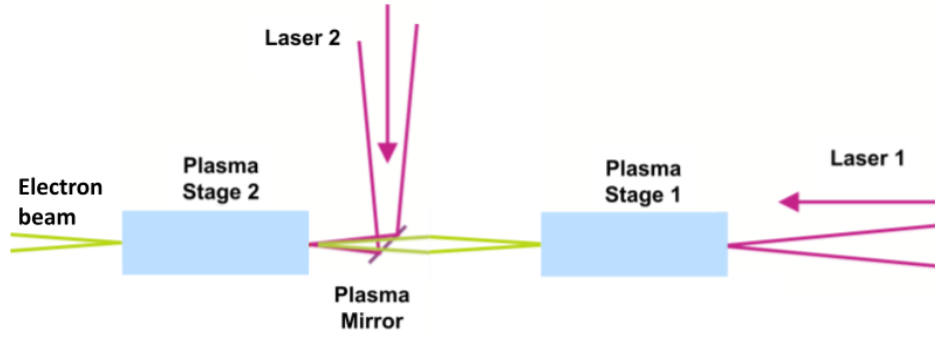


Figure 3.1: Basic schematic for staging of two laser-plasma accelerators for electron acceleration with a plasma mirror to compactly couple the second laser into the second plasma stage.

Stage 2". On the BELLA PW laser system, the final turning optic is located ~ 10 m from the laser focus to avoid laser-induced damage [13]. A plasma mirror can be located a few centimeters from the laser focus, with the minimum distance to the laser focus determined by a maximum operational intensity $I \approx 4 \times 10^{17} \text{ W/cm}^2$ [70].

3.2 General tape drive design

For high repetition rate operation, a plasma mirror device may be based on a tape drive design, where a solid target tape is used as the plasma source and is continually refreshed to provide new target substrate for each laser shot. A photograph of the device is shown in Figure 3.2.

In this design, the tape is wound between two spools, as shown in Figure 3.3, that keep the tape under tension. The feed spool holds the new target material and unwinds with each laser shot. The collection spool collects the used target material after each shot and rewinds it for compact storage. An important element of the tape spools is the spacing between the top and bottom discs that house the roll of tape. It is set to only be slightly taller than the width of the tape to minimize vertical drift of the tape as it is unspooled.

Both ends of the tape are held by motors connected to each tape spool and oriented in opposite directions so that the target substrate is held under tension. When new target substrate is needed, power to the motor on the feed spool is reduced and the motor on the collection spool drives both spools to rotate and the new target substrate is moved to the laser interaction point. In order to sustain this operation under vacuum, the tape drive motors are cooled using thermally-conductive jackets connected to a chiller system.

Near the central target area of the tape where the laser interaction occurs, there is also a set of tension pins that the tape runs across. The tension pins in the central target area allow for the spools to be placed further from the interaction area and provide clearance from

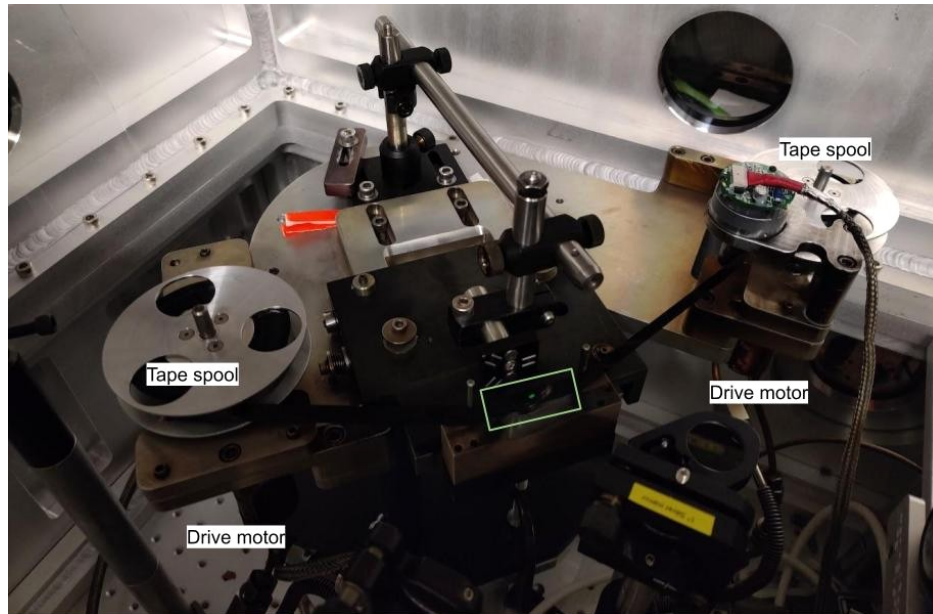


Figure 3.2: Photograph of the tape drive where the tape is held under tension between two spools mounted above drive motors oriented in opposing directions. The target area of the tape (highlighted by the green rectangle) is supported by tension pins in the middle and illuminated by a green probe beam.

the incident laser pulses. The tension pins also properly position the tape and improve the surface quality by providing structure to the tape near the interaction point and reducing the length of unsupported tape.

Previous iterations of the design had an encoder that contacted the tape through a roller. The encoder would allow the control system to monitor how much the tape moved when the tape was stepped to a new target. This feature was removed during the most recent round of development for various reasons. First, the encoder introduced additional complexity to the tape drive, requiring an additional data acquisition (DAQ) system in the control system. Second, the encoder was highly susceptible to the electromagnetic pulses (EMP) produced during laser-plasma interaction, posing an operational risk when at high laser power. Finally, the encoder was not necessary for plasma mirror operation because accurate indexing of the tape position on a shot-to-shot basis is not required. Simpler optical methods can be used to determine successful refreshing of the target substrate.

The tape drive is located downstream of the nominal focus of the first beamline on BELLA PW and at the longitudinal position where the second beamline enters the experimental chamber, as shown in Figure 3.4. In this configuration, the tape drive plasma mirror is the final turning optic for the second beamline that reflects laser pulses from the second beamline to be collinear with those from the first beamline. The tape drive is also positioned such that the focal position of laser pulses from the second beamline is downstream of the plasma

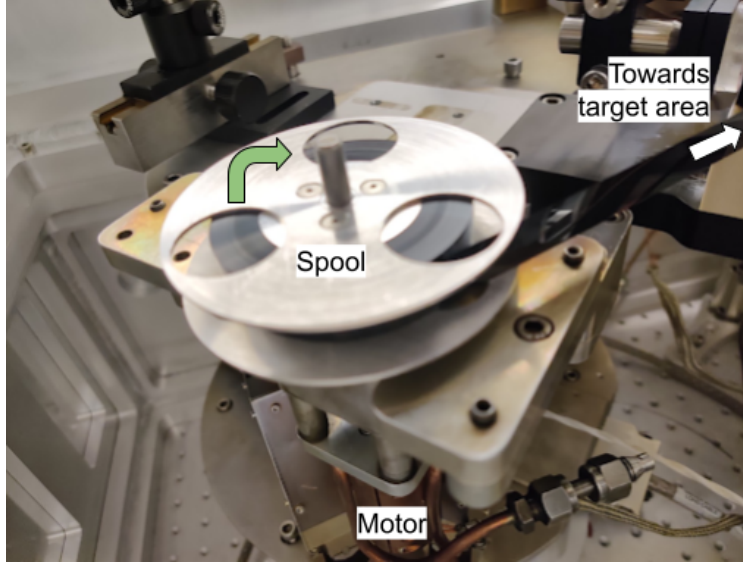


Figure 3.3: One of the spools for winding and unwinding tape substrate in the tape drive, driven by the motor located below the spool. The green arrow indicates the direction of rotation of the motor to provide tension to the tape. The white arrow points towards the target area of the tape that is located in the center of the tape drive and beyond the edge of the photograph.

mirror surface. The laser pulses from the second beamline are reflected by the plasma mirror and then propagate to the high-power diagnostic setup on BELLA PW.

3.2.1 Previous work

The development [25, 70] and application in staging [26] of the tape drive-based plasma mirror has been previously demonstrated at BELLA. Previous work has optimized the tape material and maximum intensity for reflectivity. The optimal target for reflectivity was found to be video home system (VHS) magnetic tape. The optimal laser intensity where reflectance was maximized was found to be $4 \times 10^{17} \text{ W/cm}^2$ [70], with a sharp decrease in reflectance for intensities exceeding the optimal intensity. This determines the location of the plasma mirror relative to the desired laser focus and second plasma accelerator by setting a maximum laser intensity for optimal plasma mirror operation.

In the previous experiments [26, 71], the staging of two laser-plasma accelerators was demonstrated, with charge from the first laser-plasma accelerator captured and accelerated in the second laser-plasma accelerator. A total energy gain of $\sim 200 \text{ MeV}$ using 40 TW of laser power was achieved, with an energy gain in the second stage of 100 MeV . The accelerated beams had a 85 % energy spread, low divergence (5.0 ± 0.3) mrad, and a pointing stability of 0.3 mrad . The transport between the first and second stage was aided by an active

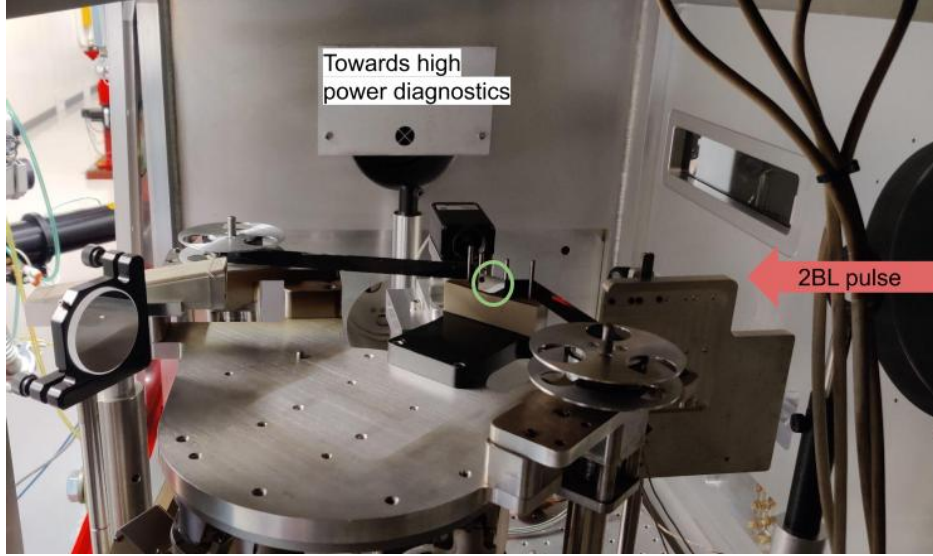


Figure 3.4: Photograph of tape drive plasma mirror in the BELLA PW target chamber for commissioning of the second beamline (2BL). The second beamline pulse enters from the right (red arrow) and is reflected towards the high power diagnostics by the plasma mirror. The target area on the tape is highlighted by a green circle. The beamline towards the high power diagnostics is covered by a target for alignment purposes.

plasma lens that focused the accelerated beam from the first plasma stage into the second plasma stage with a trapping efficiency of 3.5 %. Future staging experiments aim to increase the energy gain to the GeV range while also reducing the energy spread and improving the charge capture efficiency. A reduced energy spread from the first plasma stage improves the transport and charge capture efficiency between stages due to the energy dependence of trajectories from the active plasma lens.

3.2.2 Requirements for PW class systems

The transition of the tape drive to a PW-class system presented two specific challenges that needed to be addressed. Laser pulse energies up to 20 J will be incident on the tape drive, a significant increase over the 450 mJ used in previous staging experiments [26, 71]. It has been demonstrated that the reflectivity of the tape drive decreases at intensities beyond $4 \times 10^{17} \text{ W/cm}^2$ [70]. Therefore, the tape drive must be located further from the entrance of the second plasma accelerator.

As a result, the spot size of the laser on the tape drive increases from $160 \mu\text{m}$ to the millimeter scale. In order to maintain the laser pulse quality, the surface flatness of the tape drive must be sufficiently uniform—on the order of the laser pulse wavefront error—across the target area. Due to the larger area on the tape drive used for plasma mirror formation,

improved surface flatness across the tape is required.

Additionally, the increased distance between the tape drive and the accelerator entrance increases the laser pulse propagation distance after reflecting off the plasma mirror from ~ 15 mm to ~ 10 cm. Therefore, the positioning of the laser pulse at the accelerator entrance is more sensitive to pointing fluctuations from the tape drive. The laser pulse must be positioned within the acceptance of the plasma entrance, imposing a maximum pointing error from the tape drive of $100 \mu\text{rad}$ with a desired pointing error of $\sim 15 \mu\text{rad}$. In order to reach this level of pointing stability, pointing correction for the tape drive was required. Work was undertaken to address both of these challenges related to implementing the tape drive plasma mirror on BELLA PW.

3.3 System improvements

In preparation for the implementation of the tape drive on BELLA PW, the tape drive was first characterized on a low-energy test stand, as shown in Figure 3.5. The probe laser, illustrated in Figure 3.6 used in the test stand was a low-power, continuous-wave, 532 nm diode laser. The laser beam was then expanded and spatially filtered using an optical telescope. After beam expansion, the laser beam was focused onto the tape drive. The focusing geometry was set to closely match the focusing of BELLA PW, which has an $F/\# \approx 65$. The laser focus was also set to be downstream of the tape surface to match BELLA PW. After reflecting off the tape drive, the laser beam was sent to diagnostics for characterizing the tape drive performance.

To measure surface quality, the probe laser was imaged onto a wavefront sensor [67] measuring the wavefront error introduced by the tape surface quality. To measure the pointing deflection, the probe beam was propagated to a camera and the location of the beam centroid was tracked.

In addition to the tape drive, there was also a reference mirror that was positioned directly behind the tape drive. This allowed for reference wavefronts to be taken by removing the tape and measuring the beam reflected from the reference mirror, which was located in the same plane. The reference measurements were subtracted from the measured wavefront error of the tape drive to remove the wavefront error introduced by the probe beamline. The reference subtraction allowed for a more accurate measurement of the wavefront error due specifically to the tape surface.

The tape drive was also mounted on top of a hexapod in the same way it would be for experiments on BELLA PW. The hexapod provided translation along three orthogonal axes and rotation around those three axes, enabling precision positioning with 6 degrees-of-freedom. The hexapod also provided the motion for the pointing correction system that was developed for the tape drive.

It is important to note that on this test stand, characterization was only made on the reflection from the tape; no plasma was created. The tape drive would not undergo ionization

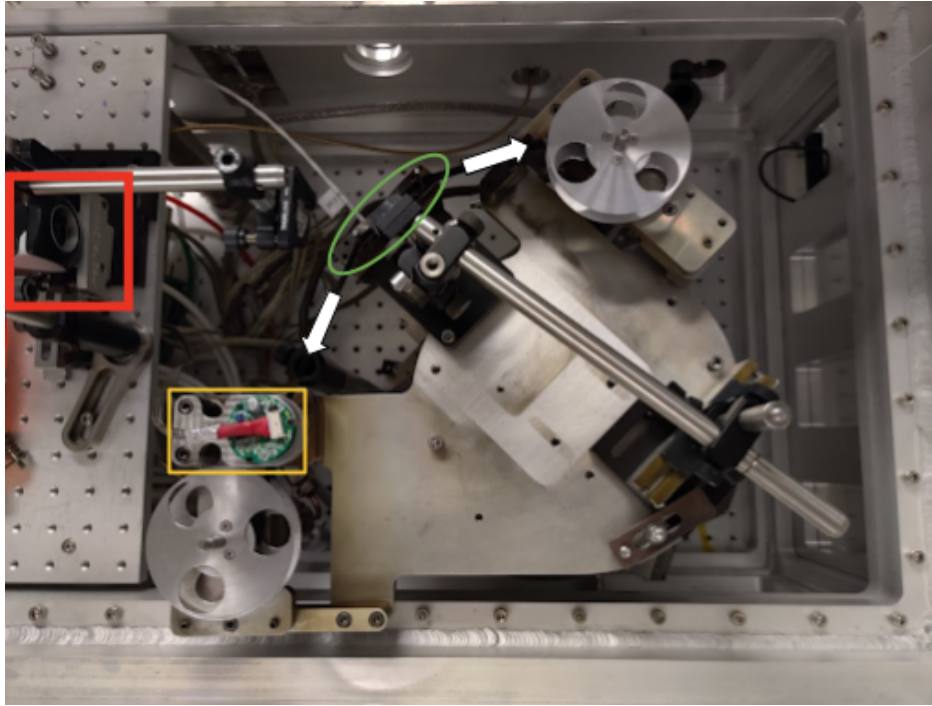


Figure 3.5: Test stand setup for tape drive testing with the central target area circled in green. The white arrows indicate the tension being applied to the tape by the motors of the tape drive. In this configuration, the wavefront sensor (highlighted by the red square) is being used to image the surface flatness of the tape. The yellow box highlights an encoder that was removed in newer designs.

to form a plasma mirror until high power commissioning on BELLA PW as part of the commissioning process for the second beamline.

3.3.1 Surface flatness characterization and optimization

The increase in laser energy associated with BELLA PW increases the laser spot size on the tape surface from $160\text{ }\mu\text{m}$ to the mm scale. As described in Section 3.3, a wavefront sensor was used to measure the surface quality across the entire area of the tape within the laser spot. The test stand had the ability to adjust the focusing geometry of the probe beamline to vary the laser spot size on the tape, and measurements were taken at a variety of beam sizes to characterize the relationship between area and surface flatness. The main metric for quantifying surface flatness was the root-mean-squared (RMS) wavefront error of the reflected wavefront from the probe beam as measured by the wavefront sensor. Twenty measurements of the RMS wavefront error were taken with each beam size configuration and the median RMS wavefront errors were compared, as shown in Figure 3.7.

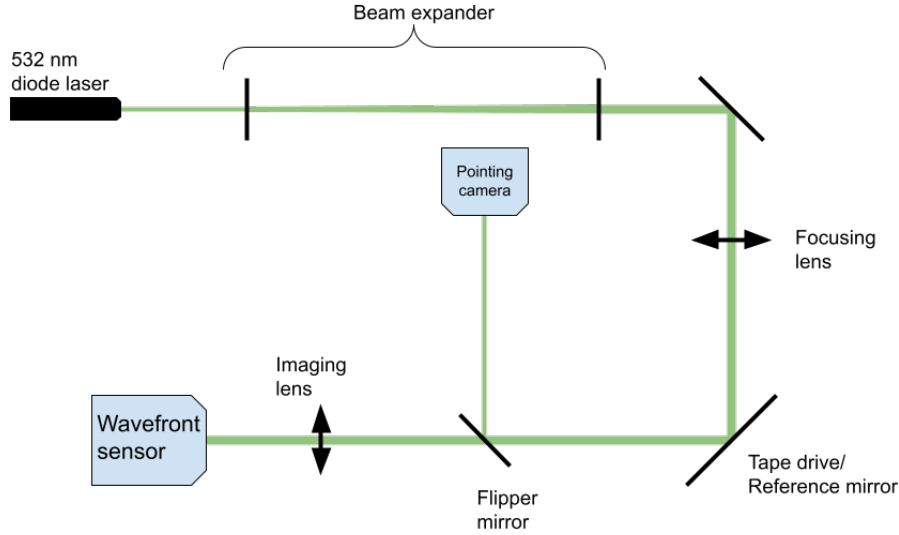


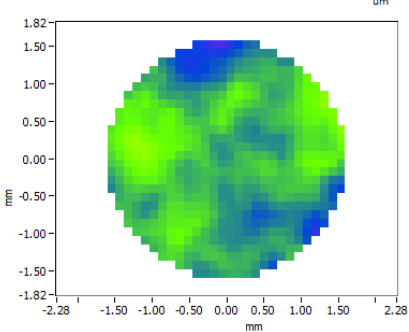
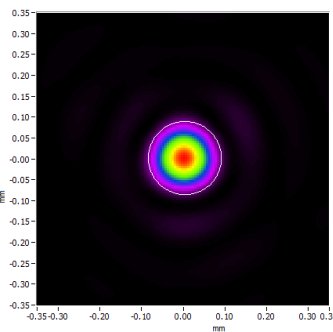
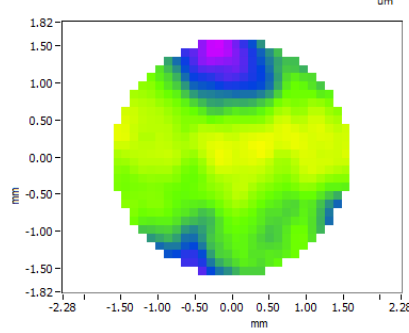
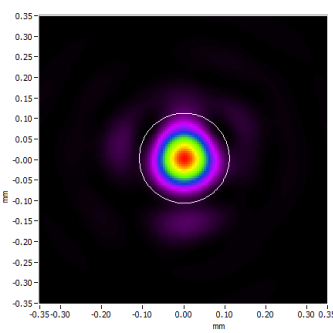
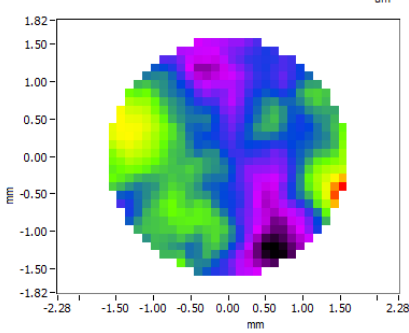
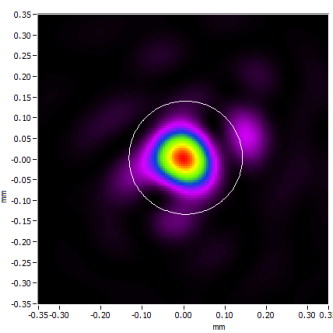
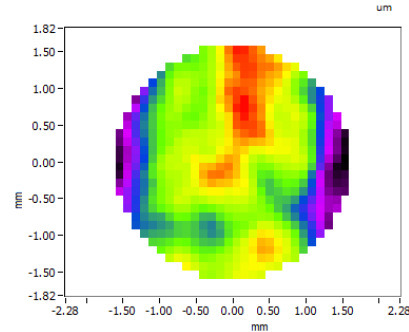
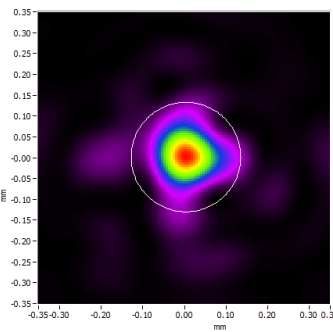
Figure 3.6: Schematic of the probe beam setup on the tape drive test stand where the focused probe beam is reflected off the tape surface. Two diagnostic setups are shown, with the wavefront sensor for flatness characterization and the pointing camera for pointing correction. A flipper mirror was used to switch between the two setups.

A sample of wavefront measurements with their associated point spread functions and RMS wavefront error are shown in Table 3.1 to contextualize the measured wavefront errors in terms of focal beam quality. The point spread functions are the optical focusing response and represent the expected focal quality for each wavefront. The RMS wavefront errors, which provide a quantifiable measurement of the beam quality, were calculated by taking the root-mean-square of the wavefront error across the entire probe beam. The typical RMS wavefront error on BELLA PW is around 40 nm, and this was the targeted threshold for surface flatness optimization.

The spot size was selected to balance the competing effects of area and surface flatness. A larger area is beneficial because it reduces the intensity on the plasma mirror substrate and allows for a higher maximum laser energy before reflectivity decreases, as shown in [70]. However, there is less uniform flatness over the larger target area. From Figure 3.7, all beam sizes below 1.5 mm had the lowest RMS wavefront error were comparable within the error bars. A 1.2 mm spot size was selected as this beam size aligned well with the geometric design considerations for implementation on BELLA PW.

With a spot size selected, optimization of the surface flatness could proceed. One of the components investigated, while optimizing surface flatness, was the shape and design of the tension pins that held the tape near the interaction point. The tension pins were varied in terms of their shape, size, and number. The experiments tested variations with 2 and 4 tension pins. In the 2 pin configuration, the tape ran straight between the tension pins.

Table 3.1: Sample of wavefront measurements and point spread functions of the probe beam reflected off the tape drive. The wavefront error is shown by the color scale (in μm) and quantified by the RMS wavefront error. The point spread function is the optical focusing response for a given wavefront.

Wavefront Measurement	Point Spread Function	RMS Wavefront Error
		20 nm
		40 nm
		60 nm
		85 nm

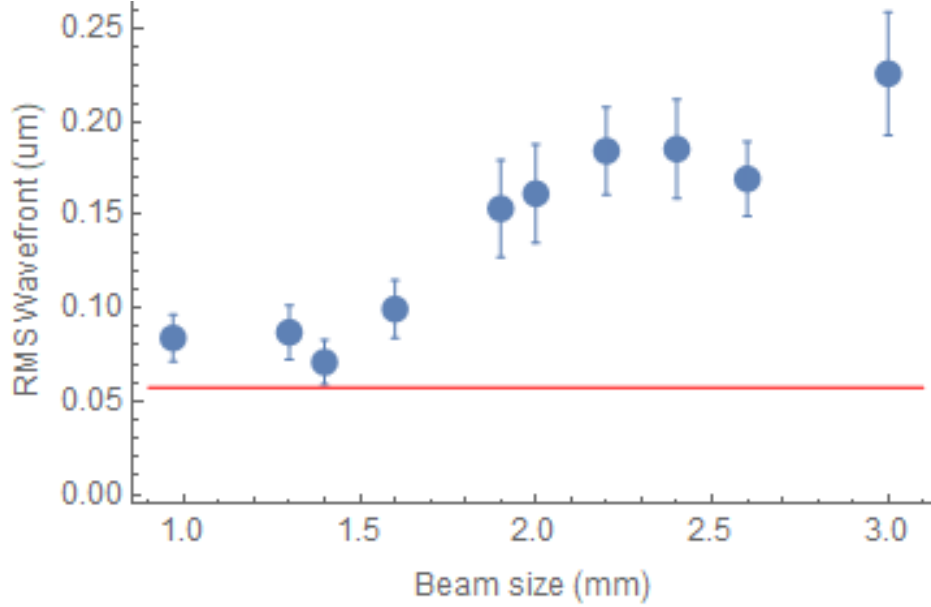


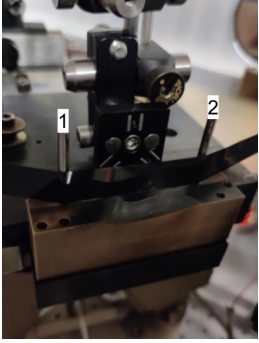
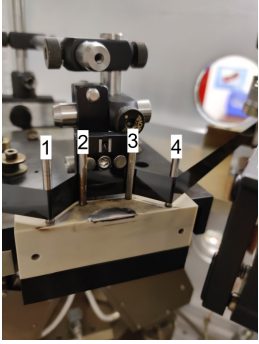
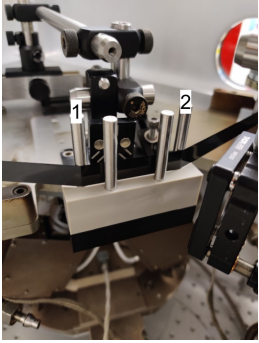
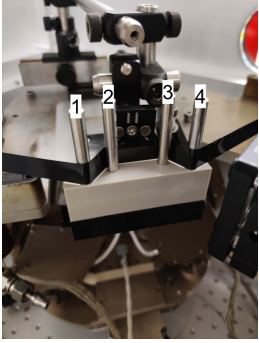
Figure 3.7: Median RMS wavefront error measurements from variable probe beam spot sizes on the tape surface with error bars indicating the median absolute deviation of the measured wavefront error due to shot-to-shot fluctuations. The red line indicates the RMS wavefront error in the probe beam with the reference mirror inserted instead of the tape. The shot-to-shot fluctuations of the reference mirror are significantly less than that of the tape and are not appreciable when compared to the other measurements.

In the 4 pin configuration, the tape ran in a W-shaped pattern across all of the tension pins. Variations with 1/8" and 1/4" pins were also tested. The variations in the tension pin configuration are shown in Table 3.2.

When a new set of tension pins was installed, the wavefront sensor was used to record the wavefront error of the reflected probe beam. Then, the tape drive was activated and the device stepped to a new position on the target tape and the new position was measured. This process was repeated to collect 50 shots for each configuration and compare the average RMS wavefront error to determine the ideal setup.

The results for the tension pin testing determined that for both the pin sizes, the 4 pin setups (Table 3.2: Test Numbers 2 & 4) had reduced wavefront error compared to the 2 pin setups (Table 3.2: Test Numbers 1 & 3). It is hypothesized that in the 4 pin setups, the W-shaped pattern of the pins provided additional support for the tape by forcing the tape to bend twice before reaching the central interaction point (illustrated in Figure 3.8), limiting surface deflections in the target region of the tape and improving the surface flatness as measured by the wavefront error of the reflected probe beam. Between the 1/4" and 1/8" pins, no significant difference was observed so the smaller pins (Table 3.2: Test Number 2) were selected to provide more clearance near the interaction point.

Table 3.2: Tension pin configurations tested for improved surface flatness of the tape drive. Each configuration varies the number and diameter of pins holding the tape under tension, with the resulting RMS wavefront error measured for each case.

Test #	Configuration	Number of Pins	Pin Diameter	Wavefront Error (nm)
1		2	1/8"	53 ± 7
2		4	1/8"	50 ± 7
3		2	1/4"	58 ± 8
4		4	1/4"	49 ± 6

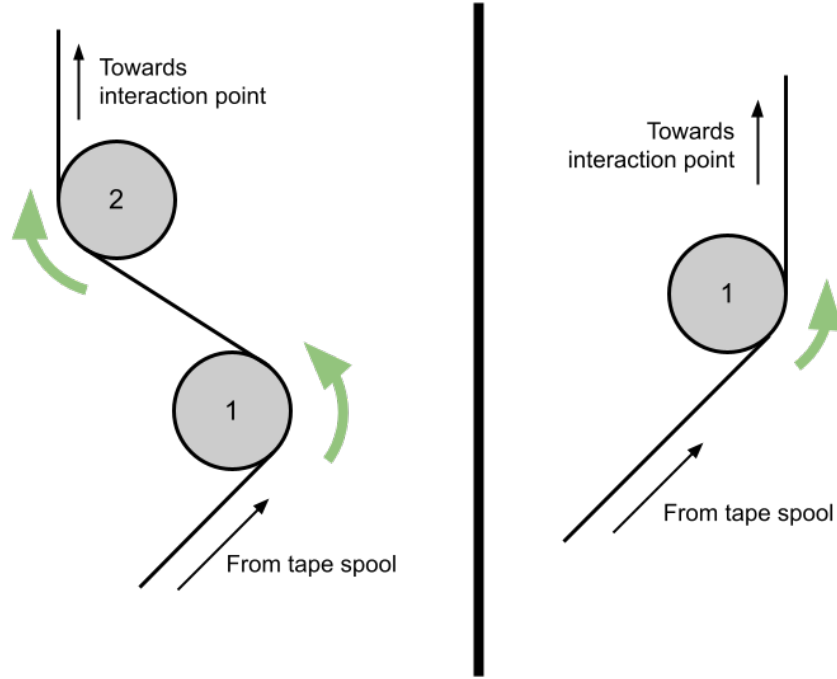


Figure 3.8: Illustrated tape paths (from one direction) for the 4 pin (left) and 2 pin (right) setups. Green arrows indicate bends in the tape due to the tension pins, which are numbered. Black arrows indicate the direction of travel for the tape, from the tape spool to the interaction point in the middle of the tape drive.

The next variable on the tape drive that was optimized was the motor velocity. Through the control system, there is a velocity value that the user can set that determines the power supplied by the motor controller to the tape drive motors. The tape drive motors are DC motors and have a linear torque response to the supplied input power. Thus, the input power supplied to the motor is proportional to the tension that is applied to the tape by the motor when it is being held statically. Unfortunately, due to the abstraction of the motor controller, the velocity value cannot be converted into physical units without secondary measurements. Direct measurements of the force applied to the tape would be ideal, but measurements of the power supplied to the tape drive motors would also be sufficient in the future.

In a similar manner to the tension pin optimization, wavefront error data from the probe beam reflection off the surface of the tape was collected using a wavefront sensor. Data was collected for each motor velocity over 50 shots then the average RMS wavefront errors were compared to determine the optimal motor velocity for operation. The results are shown in Figure 3.9. The motor velocity was optimized with respect to the minimization of the RMS wavefront error. (Operationally a motor velocity of 6 arb. units was used.)

Finally, tests were conducted to determine if a backing plate for the tape to run across would improve the target flatness. It was hypothesized that using an optically smooth sur-

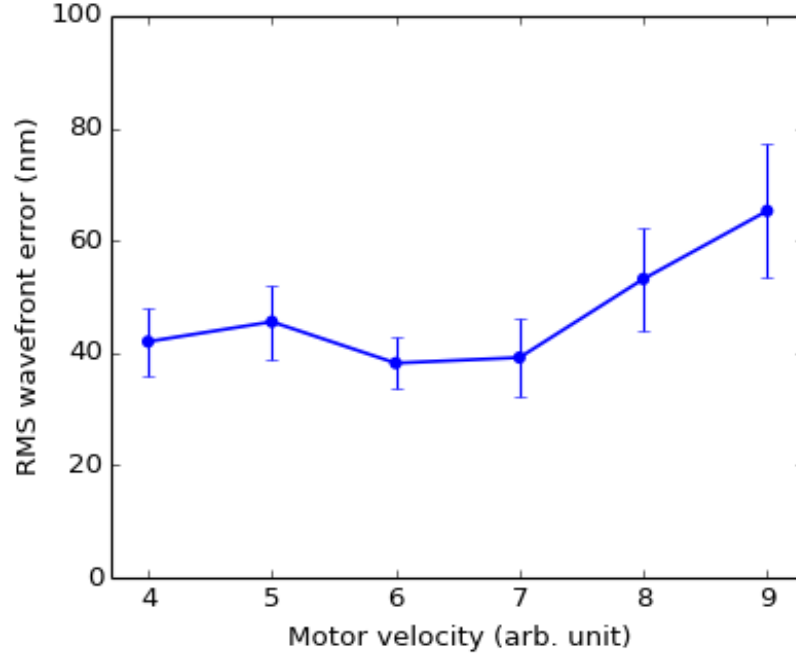


Figure 3.9: RMS wavefront error measurement from a motor velocity scan. Plotted values are the median RMS wavefront error at each velocity with error bars for the standard deviation of the measurements at each motor velocity.

face, like a mirror, to press against the back of the tape would allow the flexible tape to conform to the smooth surface and improve the surface flatness. During testing, the implementation was challenging as it was difficult to precisely locate the backing plate. Additionally, the amount of pressure from the backing plate onto the tape was often inconsistent, leading to large fluctuations in the reflected probe beam. Finally, this technique was deemed to be not worth the risk associated with placing a solid object near the laser focus. Laser safety best practices require minimizing accidental laser interaction with solid objects, which could lead to unapproved radiation generation. This risk factor outweighed any potential flatness improvement so no further backing plate development was pursued.

Overall, the RMS wavefront error of the probe beam reflected off the tape surface was improved from 86 ± 14 nm to 43 ± 9 nm. The improved wavefront errors are on the same order as the typical wavefront error from the BELLA PW system.

3.3.2 Pointing stability and correction

Compared to the previous staging experiment [26], the distance from the plasma mirror to the plasma accelerator entrance on BELLA PW will be increased from ~ 1 cm to ~ 10 cm.

As a result of the increased distance, pointing fluctuations from the plasma mirror that result in laser centroid shifts at the entrance to the accelerator would be $\sim 10\times$ greater than on previous experiments. The acceptable offset at the plasma entrance is a fraction of the laser spot size and was set at $15\text{ }\mu\text{m}$. For this offset at the entrance to the plasma accelerator, the acceptable laser pointing is $\leq 100\text{ }\mu\text{rad}$. This is the upper limit for pointing fluctuations, and the desired value for more consistent accelerator performance was $\lesssim 15\text{ }\mu\text{rad}$.

Given the pointing requirement for the plasma mirror, characterization of the pointing fluctuations of the tape drive is required. The test stand setup was configured to monitor the pointing fluctuations of the probe beam reflected off the surface of the tape. A CCD camera was installed and imaged the focal position of the probe beam. The beam centroid on the pointing camera was recorded after stepping to a new location of the tape and then the pointing fluctuation could be calculated using

$$\theta_{x_i} = \arctan [(\bar{x} - x_i) / z], \quad (3.1)$$

where θ_{x_i} is the horizontal pointing fluctuation for shot number i , $\bar{x}$ is the average horizontal position of the laser centroid, x_i is horizontal position of the laser centroid for shot number i , and z is the distance from the surface of the tape to the CCD camera. The same process is repeated to calculate the vertical pointing fluctuation using the vertical position of the laser centroid. The root mean square (RMS) fluctuations were calculated for the horizontal and vertical directions to quantify the typical fluctuation that contains 68% of the expected shots:

$$\sigma_{\theta_x} = \sqrt{\sum_i^N \frac{(\theta_{x_i})^2}{N}}, \quad (3.2)$$

where σ_{θ_x} is the RMS fluctuation in the horizontal direction and N is the total number of shots. The same process is repeated for the vertical direction. Note that the pointing fluctuations are already zero centered, i.e., $\bar{\theta}_x = \bar{\theta}_y = 0$. The RMS pointing fluctuations were found to be $60\text{ }\mu\text{rad}$ and $290\text{ }\mu\text{rad}$ in the horizontal and vertical directions, respectively. These quantities were in excess of the acceptable pointing fluctuations so correction was needed.

To install pointing correction on the tape drive that returns the laser pointing to the center of the plasma accelerator entrance, the hexapod that the tape drive was mounted on was used. The hexapod is normally used for adjustment of the tape drive position and reflection angle and can be used for the fine adjustment for pointing correction. The pointing correction that was implemented was a passive stabilization loop that operates after every step of the tape drive and before every laser shot. The logic is illustrated in Figure 3.10.

During setup, there are two calibration steps. The first step moves the hexapod through a series of angles causing the pointing of the tape to change and the camera records the location of the probe beam centroid. The second step uses linear regression between the hexapod angles and the measured centroid beam locations to calculate a first-order calibration of the hexapod angles to beam pointing. This calibration is used to convert the desired pointing corrections, which arise after each step of the tape drive, to hexapod angle changes.

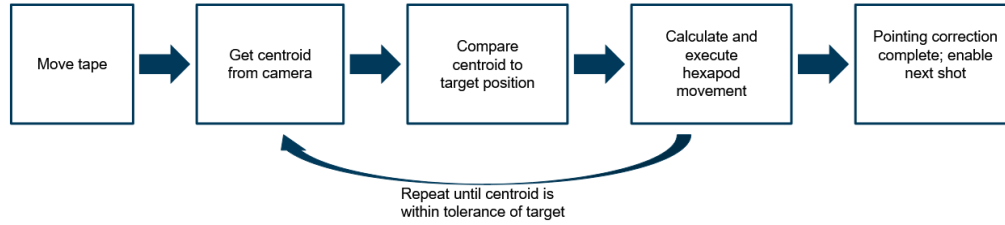


Figure 3.10: Logic diagram for pointing stabilization system.

Next, the hexapod is manually adjusted so the tape drive is pointed at the desired target and probe beam location on the pointing camera is recorded. This is the target location that the correction system brings the probe beam back to after each step of the tape drive. In the test stand, the target was the center of the pointing camera, and in experiments on BELLA PW the target was the high power diagnostic camera downstream of the experimental chamber.

During use, the pointing stabilization will record the probe beam centroid after each step of the tape drive and calculate the offset to the target. It will then use the calibrated hexapod-to-beam pointing conversion to determine how to move the hexapod in order to bring the probe beam centroid back to the target. Due to shot-to-shot variation in the laser pointing, the pointing correction will not bring the pointing exactly to the target, and multiple corrections are required. Therefore, there is a damping factor that the predicted move is scaled by before passing the command to the hexapod. This factor is user-defined and has a default value of 0.9. This creates a system that underestimates the move and reduces the likelihood of overshoot as the correction approaches the target. A higher damping value would result in a more aggressive stabilization approach that attempts to correct the pointing error in fewer steps but with a higher likelihood of overshooting the target and vice versa for a lower damping value.

After each move of the hexapod, the beam centroid and the difference to the target centroid position is recalculated. If the difference is greater than the user-defined accuracy limit, then another correction loop occurs. If the difference is less than the accuracy limit, then the pointing correction is considered complete and the next laser shot is allowed to fire.

It is important to note that this pointing stabilization system is fully integrated with the control system on BELLA PW. This means that while the correction loop is running, the shot control shutters that allow amplified laser pulses into the compressors and through the beamline remain closed. This prevents the possibility of a high-intensity pulse being delivered through the system while the beamline is not completely stationary and aligned, limiting the possibility of misfires and stray laser beams.

The pointing correction system was first implemented on the test stand before being tested on BELLA PW. When the stabilization was turned on, the pointing fluctuations were reduced from 60 μrad to 12 μrad and from 290 μrad to 12 μrad in the horizontal and vertical directions, respectively. The results are shown in Figure 3.11. This is below the target value

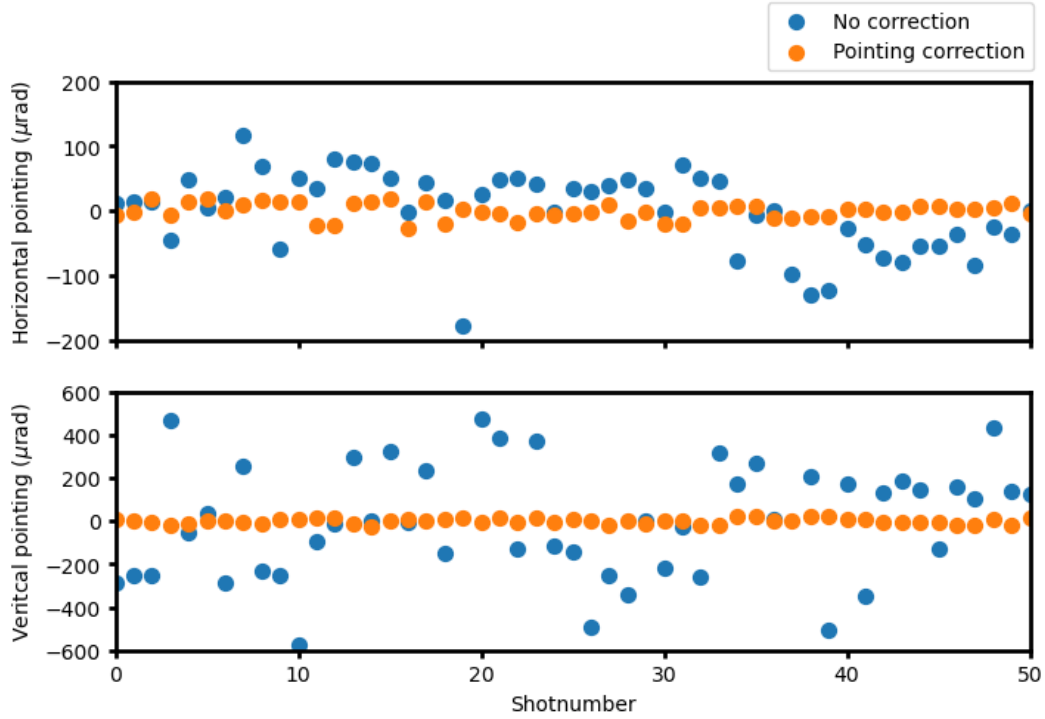


Figure 3.11: Pointing fluctuations before (blue) and after (orange) the stabilization system was enabled. The top plot shows the horizontal pointing fluctuations and the bottom plot shows the vertical pointing fluctuations.

defined previously and sufficient to implement on the PW laser system.

3.4 Commissioning results on the BELLA PW second beamline

After development on the test stand, the tape drive was deployed onto the BELLA PW laser system as part of the commissioning of the second beamline that was installed in 2022. The goal of the commissioning was to prepare the new beamline for high power operation. This is a necessary step before proceeding with high power experiments with the second beamline. The beamline was aligned with the low power pilot laser and unamplified pulsed laser. The beamline was then optimized for transport to the target chamber, with specific interest on the beam compression, wavefront, and focus. The laser energy was then slowly increased along with diagnostic attenuation until full laser power was reached. This would correspond to the full 40 J of laser energy from the amplifier with a 50/50 beamsplitter, meaning 20 J of laser energy in the second beamline.

This also marked the first experiments where a high-intensity, pulsed laser would be incident upon the tape drive and plasma mirrors would form. As a result, the diagnostic probe beam used in the pointing stabilization system had to be moved to the back surface of the tape. This change did not affect the operation of the pointing stabilization.

With the tape drive in the beam line, the pointing stability of the entire system was evaluated. This was first done with the PW pilot beam which is a CW 800 nm diode laser with similar beam size characteristics to the main amplified beam. With the tape held statically, the ambient pointing fluctuations from the entire system were measured by a camera positioned at the focal position of the second beamline. The RMS pointing fluctuations were measured to be $17\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$ in the horizontal and vertical directions, respectively.

Next, the pointing fluctuations were measured with the tape drive moving between each camera acquisition as it would during high power operation. Without pointing correction, the RMS fluctuations increased to $18\text{ }\mu\text{m}$ and $47\text{ }\mu\text{m}$ in the horizontal and vertical directions due to the tape drive moving between shots. With pointing correction, the RMS fluctuations were reduced to be $17\text{ }\mu\text{m}$ and $20\text{ }\mu\text{m}$ in the horizontal and vertical directions. These are on the same level of pointing fluctuation for the static tape and are within the specified limit, making the setup acceptable for future experiments.

It should be noted that one consequence of the tape drive pointing correction is the decrease in repetition rate due to the time it takes for the hexapod to correct for the beam pointing. BELLA PW and the tape drive are capable of firing on fresh substrate at a 1 Hz repetition rate. When the pointing stabilization is turned on, the repetition rate drops to 0.5 Hz.

After the pointing stability was confirmed with the pilot beam, the amplified pulsed beam could be sent to the tape drive and evaluation of plasma mirror performance could begin. In order to generate a plasma mirror, the amplified laser energy was slowly increased up to 10 J ($\sim 250\text{ TW}$). At each increase in energy, the laser focal position was scanned to optimize the quality of the reflected beam from the plasma mirror. The primary goal was to produce reflected beams with spatial profiles close to a Gaussian focal spot and minimize laser energy outside of the central focal region.

During these tests, large shot-to-shot variation in the laser mode quality reflected off the plasma mirror was observed, as shown in Figure 3.12. These variations were not observed during the reflected wavefront characterization of the tape drive. It was found that by moving the tape drive vertically, perpendicular to the plane of the laser pulses, sections of the tape were located that yielded improved laser mode quality in the reflected pulse. Similar trends were observed in the probe beam, where the laser mode quality of the back-reflection probe beam had large shot-to-shot variation that correlated with the reflected pulses. With the vertical rastering, vertical positions of the tape could be found where the reflected beam modes were improved, also shown in Figure 3.12 at hexapod heights of 4.0 mm and 5.0 mm. It is suspected the variation in reflected beam quality is due to non-uniform deformation of the tape that occurs while it is moved through the tape drive. The device was inspected for any signs of unnecessary contact with the tape due to misalignment but none was found.

Overall, the commissioning of the second beamline was a successful campaign. High

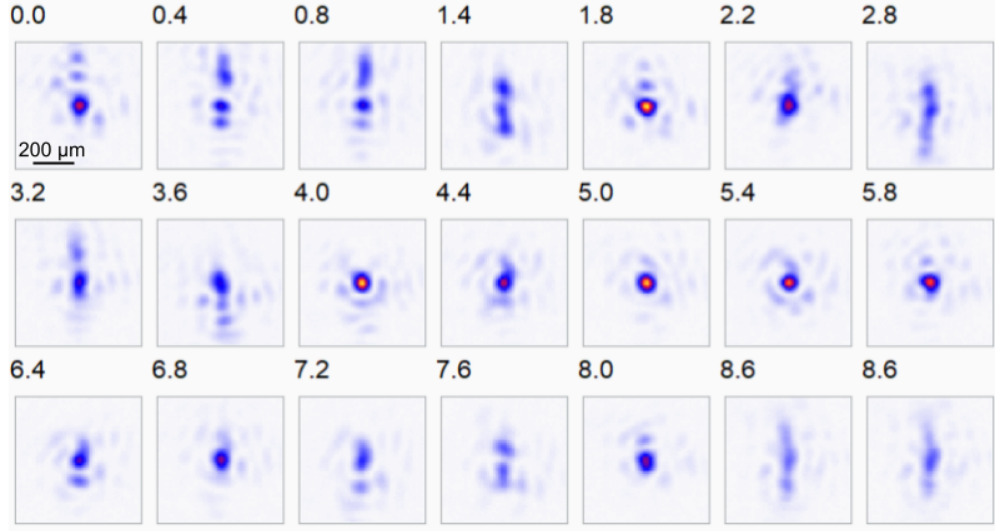


Figure 3.12: Variation in laser modes reflected off the plasma mirror depending on the vertical location of the beam on the tape drive, which was varied using the hexapod height. The parameter listed top left above each image is the hexapod height and was scanned from 0 mm to 8.6mm.

power laser propagation down the beam transport and reflection off the plasma mirror to the high power diagnostics were both demonstrated. Attempts to increase the laser to the full energy (~ 1 PW) resulted in issues with damage to attenuating foils in the experimental chamber. Despite not reaching full power, the commissioning demonstrated that the second beamline and the plasma mirror are ready for future staging experiments.

3.5 Conclusion

To prepare for staging experiments at the GeV energy level that will be performed on a PW-class laser system, upgrades to the tape drive plasma mirror were needed. The higher laser energy necessitated that the plasma mirror be located further from the laser focus and accelerator entrance. This leads to a larger beam size on the tape requiring a sufficiently flat surface and increased displacement at the accelerator entrance due to pointing fluctuations from the tape drive.

A wavefront sensor was used to measure the wavefront error of a probe beam reflected from the tape drive as a measurement of the flatness of the sampled area on the tape drive. This was used to select a beam size of approximately 1.2cm on the tape that balanced surface flatness and geometric constraints. From there, improvements to the tape drive setup involving the motor velocity and tension pins were made that improved the RMS wavefront error to (43 ± 9) nm, which is sufficiently close to the typical wavefront error on

the BELLA PW laser system.

Also, a pointing correction system was developed and implemented to reduce the pointing fluctuations that occur after each step of the tape drive. The system monitored the centroid position of the probe beam on a camera and used a hexapod to correct the pointing fluctuations. During normal operation of the tape drive, pointing errors of $60\text{ }\mu\text{rad}$ and $290\text{ }\mu\text{rad}$ were observed in the horizontal and vertical direction, respectively. When the pointing correction system was turned on, the pointing errors were reduced to $12\text{ }\mu\text{rad}$ in both directions. The pointing errors with correction were within the acceptable tolerance of $15\text{ }\mu\text{rad}$.

Finally, the tape drive was used to commission the second beamline on the BELLA PW laser system. Laser energy up to 10 J ($\sim 250\text{ TW}$) was used to generate plasma mirrors that reflected the high power laser pulses to the diagnostic area. The commissioning also revealed variations in the reflected laser mode that were dependent on the vertical location of the beam on the tape drive. It is suspected that the variation was caused by non-uniform deformation of the tape as it was spooled through the tape drive. The commissioning experiment was a successful demonstration of plasma mirror operation on the BELLA PW laser system and is the first step towards staging of laser-plasma accelerators, which is essential for high energy applications.

Chapter 4

Electron acceleration to 10 GeV in optically formed plasma channels

4.1 Background

4.1.1 Necessity for guiding in GeV-class laser-plasma accelerators

Laser-plasma accelerators require a high-intensity laser pulse to drive the accelerator. The drive laser must be focused down to achieve the necessary intensities. When a laser is focused, vacuum diffraction limits the region of high-intensity focus, characterized by the Rayleigh range, z_R . For PW class laser systems, the Rayleigh range is typically on the order of tens of millimeters and for BELLA PW, $z_R \approx 11$ mm.

The laser-plasma accelerator scaling laws for energy gain and accelerator length (Section 2.3.1) dictate that higher energy gain with fixed laser energy requires lower plasma electron density and longer accelerator lengths. For 10 GeV-level electron energy gain, this requires a laser-plasma accelerator that is tens of centimeters long with on-axis plasma electron densities on the order of 10^{17} cm^{-3} . An accelerator length that is tens of centimeters long is an order of magnitude greater than the laser Rayleigh range, so techniques are needed to extend the region of high-intensity focus. Two of these techniques are self-focusing through relativistic and pondermotive effects and guiding in preformed plasma waveguides. For a given laser energy, guiding in a preformed plasma channel produces greater energy gain and is the primary approach for laser-plasma acceleration at BELLA PW.

4.1.2 Plasma waveguides

Preformed plasma channels can guide a focused laser pulse due to the refractive index of the plasma channel, similar to a gradient-index optical fiber. The laser spot size evolution while propagating through a parabolic plasma channel with channel depth $\Delta n = n(w_0) - n_0$,

in the low power limit, is given by [2]

$$\frac{d^2 R}{dz^2} = \frac{1}{Z_R^2 R^3} \left(1 - \frac{\Delta n}{\Delta n_c} R^4 \right), \quad (4.1)$$

where $R = r/w_0$ is the normalized laser spot size with w_0 as the minimum laser spot size in vacuum, Z_R is the vacuum Rayleigh range, $\Delta n_c = (\pi r_e w_0^2)^{-1}$ is the critical channel depth with $r_e = e^2/m_e c^2$ as the classical electron radius. By tailoring the plasma density such that $n(r) = n_0 + \Delta n r^2/w_0^2$, a constant laser spot size can be achieved and the high-intensity laser focal region can be extended over the acceleration length. For a laser pulse with a Gaussian transverse profile, a plasma channel with a parabolic transverse profile produces a constant laser spot size.

It is important to note that the width of the parabolic plasma channel must be properly matched to the spot size of the laser. For a Gaussian laser pulse, the matched channel profile is given by

$$n = n_0 + \Delta n \left(\frac{r^2}{w_0^2} \right) = n_0 \left(1 + \frac{r^2}{r_{ch}^2} \right) \quad (4.2)$$

where Δn is the channel depth at the laser spot size and r_{ch} is the channel radius.

When matched, the Gaussian laser maintains a constant spot size as it propagates through the parabolic plasma channel. If the channel and laser are mismatched, the laser will undergo spot size oscillations as it propagates. In the linear regime, the oscillations follow the form,

$$w(z)^2 = \frac{w_0^2}{2} \left[1 + \frac{w_m^4}{w_0^4} + \left(1 - \frac{w_m^4}{w_0^4} \right) \cos \left(\frac{2\pi z}{\lambda_{osc}} \right) \right], \quad (4.3)$$

where w_0 is the initial laser spot size, w_m is the matched radius of the channel, and λ_{osc} is the oscillation length given by $\lambda_{osc} = \pi^2 w_m^2 / \lambda_L = \pi z_R (\Delta n_c / \Delta n)^{1/2}$. The matched spot size is related to the channel radius by $w_m = \sqrt{2 r_{ch} / k_p}$.

Previous experiments at BELLA PW used capillary discharge [30, 31] to generate the plasma channels. For reference, the BELLA PW laser has a focal spot size of $w_0 \approx 53 \mu\text{m}$. In 2014, beams up to 4 GeV were produced using a plasma channel with an on-axis density of $n_{e0} \approx 7 \times 10^{17} \text{cm}^{-3}$ and a matched spot size of $w_m \approx 93 \mu\text{m}$ [72]. In 2017, electron energy gain was improved by adding laser heating with a nanosecond laser pulse, producing beams up to 8 GeV. Through inverse bremsstrahlung heating, the heater laser pulse formed a deeper channel in a cold capillary discharge plasma, leading to a lower matched spot size of $w_m \approx 61 \mu\text{m}$ with an on-axis density of $n_{e0} \approx 2.7 \times 10^{17} \text{cm}^{-3}$ [66].

These results were able to extend the maximum energy gain from a laser-plasma accelerator, but there was an underlying challenge. Using a capillary discharge, even with additional laser heating, matched guiding at optimal density around 10^{17}cm^{-3} was not possible due to the density dependency of the nanosecond laser heating.

4.1.3 Hydrodynamic optical-field-ionized channels

An alternative approach to plasma channel formation is through the hydrodynamic expansion of optically formed channels. For these optically formed channels, an initial hot (few eV) plasma column is formed by an ionizing laser pulse. The heated plasma column expands over the nanosecond-timescale and drives a shock into the cold, unionized gas. This forms the desired plasma density profile that increases with radial position, and leads to a refractive index profile that is peaked on-axis and can guide a laser pulse.

Initial experiments with optically formed plasma channels were heated by laser-driven electron-ion collisions (i.e., inverse bremsstrahlung heating) with plasma densities of $n_0 > 10^{18} \text{ cm}^{-3}$ [36, 38, 73], too high for optimal acceleration at the 10 GeV-level. Additional work was performed that allowed channel formation at lower densities in the range of $n_0 \sim 10^{17} \text{ cm}^{-3}$ [39, 41], which are suitable for 10 GeV-level laser-plasma accelerators. The formation of low density channels was achieved through the use of optical field ionization, where the plasma is formed by ionization and heated by the high-intensity optical fields. The applied optical field strength must be comparable to the atomic fields that bind the valence electrons in the target gas. Consequently, optical field ionization is an atomic heating process that is independent of density and requires laser intensity $I \gtrsim 10^{14} \text{ W/cm}^2$.

Further development on optically formed channels increased the channel depth and reduced leakage by ionizing the surrounding neutral gas collar that is formed as the central plasma column expands [40, 42, 44, 74]. The ionized neutral gas collar creates significantly denser plasma channel walls, which increases the guiding strength (depth) of the channel. These channels have demonstrated guiding of high-intensity laser pulses over the centimeter-scale [43, 75] and electron acceleration to the GeV-level [76, 77, 78].

Due to the heating mechanism being independent of density, hydrodynamic optical-field-ionized (HOFI) channels can reach the densities required for 10-GeV class laser-plasma accelerators. Additionally, the channel width is determined by the expansion time of the channel, allowing for tailoring of the channel width to achieve matched guiding.

4.2 Experiment design on BELLA PW

For the HOFI channel campaign on BELLA PW, illustrated in Figure 4.1, an axicon lens was used in the channel forming beamline. The axicon lens is a lens that focuses different radial rings at the lens to different longitudinal locations at the focus, producing a mapping between near-field radius and far-field longitudinal positions. The axicon produced a line focus over a hydrogen gas jet target that was ionized to create the initial plasma column. The plasma column that formed was 30 cm in length with a density of $n_0 \approx 10^{17} \text{ cm}^{-3}$.

The expansion time, and thus the plasma channel radius, was determined by the delay between the channel forming beam and the main drive beam. The delay, which was typically in the 5-7 ns range, was set to produce channels with a target width that was closely matched to the main drive pulse. Driver laser energies of $U_L \approx (19.6 \pm 0.4) \text{ J}$ ($a_0 \approx 2.2$) and $U_L \approx$

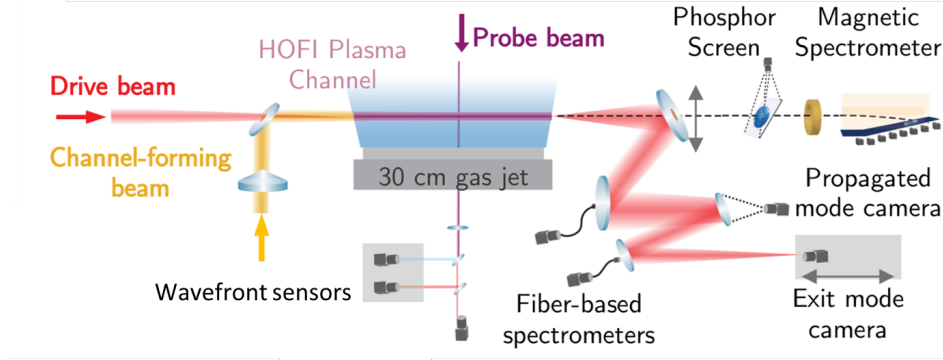


Figure 4.1: Schematic of experimental layout for HOFI channel experiments on BELLA PW.

$(6.0 \pm 0.1) \text{ J}$ ($a_0 \approx 1.3$) were used, with the energy in the channel forming beam remaining constant at $U_L \approx (1.3 \pm 0.3) \text{ J}$ to produce consistent plasma channels.

One of the significant controls in the experiment was the ability to vary the jet length and therefore the plasma length. This allowed for direct observation of the laser as it propagated through the plasma channel and provided insight into the laser evolution as a function of propagation distance. The length control was achieved by using a linear stage to insert a blade over the gas jet and eliminate gas flow over longitudinal regions of the jet. A stair-stepped blade design with increments of $\Delta L_{\text{ch}} = 4.5 \text{ mm}$, i.e., the first step is 4.5 mm long, the second step is 9 mm long, etc. This blade was inserted from the side of the jet to minimize the travel required by the stage.

4.3 Experimental results

4.3.1 Laser guiding in HOFI channels

Using the control over jet length, new insight into the laser evolution could be gained. One of the first observations was the laser mode conversion of the main drive pulse over the full $L_{\text{ch}} = 30 \text{ cm}$ propagation length. This can be seen by comparing the input laser mode, i.e., the vacuum focal spot, to the re-imaged exit modes with variable channel length, as shown in Figure 4.2. Here, the laser mode evolves from the vacuum focus into a near-Gaussian mode at the exit of the plasma channel. During this evolution, large fluctuations in the guided mode size are not observed. Additionally, there is minimal laser mode evolution beyond $L_{\text{ch}} = 12 \text{ cm}$, with all exit modes exhibiting well-confined, near-Gaussian modes. The lack of mode evolution beyond this point indicates that matched guiding between the laser and the plasma channel has been achieved (via mode filtering, as described below).

Further evidence of the laser evolution before $L_{\text{ch}} = 12 \text{ cm}$ can be seen in the propagated exit modes, which are captured at $z \approx 10 \text{ m}$ downstream of the plasma channel, shown in Figure 4.3. The measured input mode is a supergaussian (Equation 2.11) of order $n_{SG} \approx 6$,

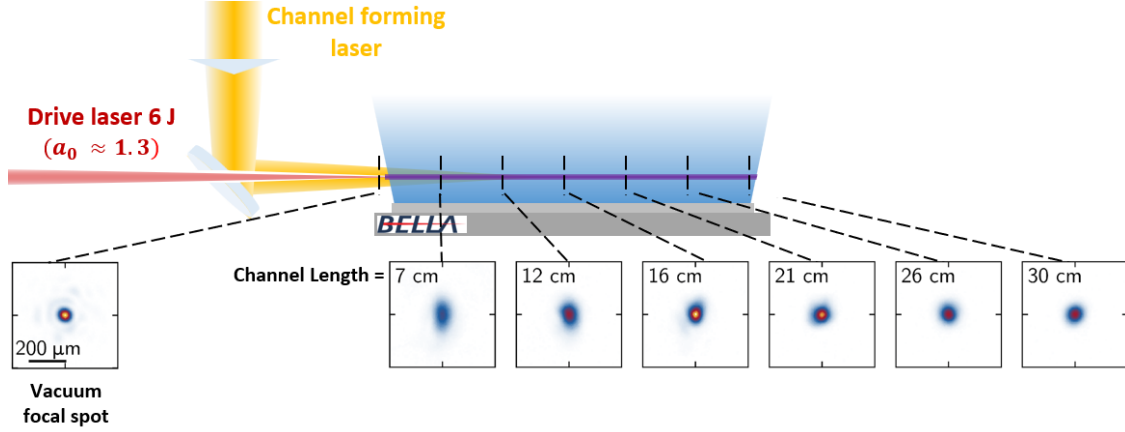


Figure 4.2: Exit laser modes measured at various channel lengths overlayed on a schematic of the experimental setup with both the drive laser ($U_L \approx 6$ J, $a_0 \approx 1.3$) and channel forming laser. The vacuum focal spot is shown in the cutout on the bottom left and is the profile for the input laser pulse. Each cutout under the gas jet shows the exit mode measured for the channel length listed in the top left of each image, with the same spatial scale at the vacuum focal spot.

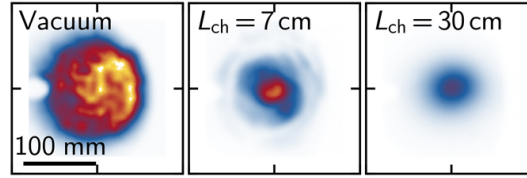


Figure 4.3: Propagated modes measured at approximately 10 cm downstream of waveguide exit. The left image is the propagated vacuum mode when no plasma channel is present. The middle image is the propagated mode with a plasma channel length of 7 cm. The right image is the propagated mode with a plasma channel length of 30 cm. All images have the same spatial scale as the vacuum mode.

and for $L_{\text{ch}} = 7$ cm, the propagated mode supergaussian fit (via nonlinear least squares) is reduced to $n_{SG} \approx 2$, which is near-Gaussian. This is maintained through the full plasma channel length of $L_{\text{ch}} = 30$ cm. The significant mode evolution at the early lengths of the plasma channel followed by minimal evolution indicates that the guiding is not matched at the input, but matched guiding and stable propagation is eventually reached through mode filtering.

More direct observation of mode filtering can be observed by examining the propagation at the start of the plasma channel. This was done using a shortened version of the gas jet

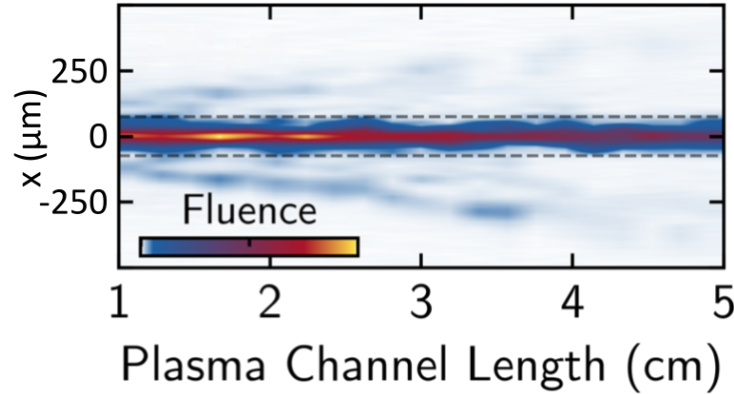


Figure 4.4: Waterfall plot of transverse fluence lineouts of the exit modes from the 5 cm gas jet, plotted sequentially based on plasma channel length. The dashed lines indicate the measured peak of the channel density profile.

with a length of $L_{\text{ch}} = 5$ cm. The blade to control jet length was changed to be inserted from the rear of the gas jet. Therefore, the jet length was set by the length of the blade that was inserted over the gas jet. This allowed for finer control over plasma channel lengths and a channel length step size of $\Delta L_{\text{ch}} = 2$ mm. In this new configuration, there was finer resolution to observe mode leakage at the start of the plasma channel.

In Figure 4.4, transverse fluence lineouts are plotted sequentially based on plasma channel length in a waterfall plot, showing exit modes as a function of plasma channel length. Each fluence lineout of the exit mode is plotted vertically against the plasma channel length on the x-axis, showing the evolution of the lineouts as the plasma channel length is varied. Because the plasma is opaque, controlling and scanning through the plasma channel length is a novel technique for direct observation of the laser evolution as it propagates through the channel. Throughout the entire channel length, there is a central fluence peak of the laser mode that is surrounded by higher order modes that are not bound. The leakage of the higher order modes, shown as fluence diverging outside the black, dashed lines as the plasma channel length increases, is due to the finite transverse extent of the HOFI channel. The finite channel only supports a limited number of laser modes that will remain confined by the channel as they propagate. The higher order modes leak out of the plasma channel, and the laser energy contained in the higher order modes does not contribute to wake generation or electron acceleration in the laser-plasma acceleration.

The energy lost through mode leakage represents an area for potential improvement. If a drive pulse could be generated without excess energy in the wings (i.e., with less higher-order mode content), more laser energy would be coupled into the laser-plasma accelerator and the accelerator efficiency would be increased. Investigation into laser coupling is explored in Chapter 5.

When the drive laser energy is increased to $U_L \approx (19.6 \pm 0.4)$ J ($a_0 \approx 2.2$), similar

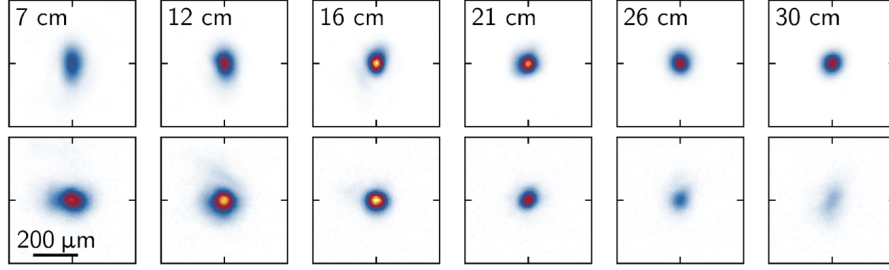


Figure 4.5: Comparison between exit modes for various channel lengths at 6 J (top) and 20 J (bottom) of drive laser energy.

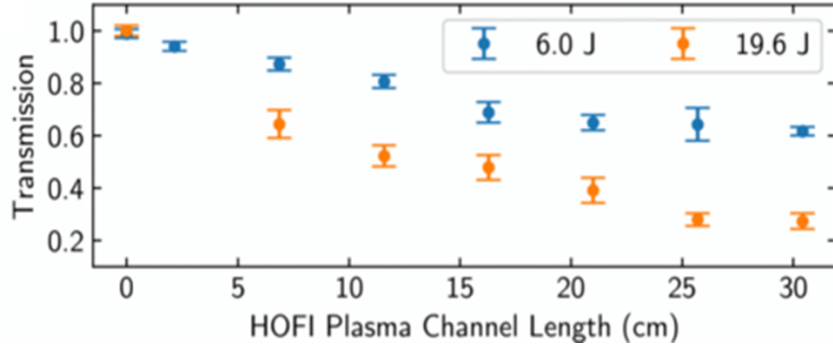


Figure 4.6: Measured energy transmission for 6 J (blue) and 20 J (orange) drive laser energies, averaged over 20 shots.

guiding behavior is observed compared to the lower energy 6 J case, as shown in Figure 4.5. At increased drive laser energy, the exit modes exhibit minimal evolution after $L_{\text{ch}} = 12$ cm and no significant changes in spot size are observed, again indicating that matched guiding is reached after initial mismatch at the start of the plasma channel. There is a decrease in laser energy transmission compared to the 6 J case, as shown in Figure 4.6 by the decrease in intensity, as more energy is being transferred to the wake due to increased wake generation.

The optical spectrum from the transmitted laser exhibits a gradual increase in redshift as the channel length is increased, as shown in Figure 4.7 on the left, indicating that laser energy is continually being transferred to the wake. These results are also supported by simulations from the PIC code INF&RNO [79] shown in Figure 4.7 on the right. The 5% signal cutoff, denoted by λ_R and shown in black, closely matches between the experiment and simulation. From the simulations, the calculated laser energy loss was 32% and the calculated average field was $E_z \approx 30 \text{ GVm}^{-1}$.

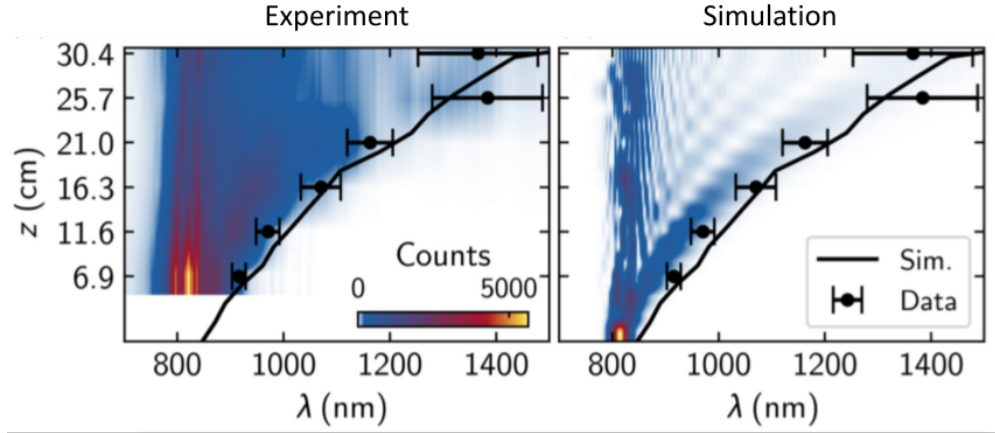


Figure 4.7: Measured (left) and simulated (right) optical spectra versus propagation distance for 20 J drive laser. Measured (averaged over 20 shots) and calculated λ_R is overlaid in black.

4.3.2 Electron acceleration up to 10 GeV

With increased drive laser energy (20 J, $a_0 \approx 2.2$), such that driver energy depletion and wake generation occurred, no electrons were observed at the magnetic spectrometer, as shown in Figure 4.8(a). The lack of accelerated electrons demonstrated dark-current-free operation where no electrons from the background plasma are trapped and accelerated. This was enabled by the HOFI plasma channels that formed at lower plasma densities to suppress self-trapping of background electrons. Dark-current-free operation is vital to future applications and staged laser-plasma accelerator studies because it enables control over charge injection through targeted injection techniques.

Starting with a dark-current-free accelerating structure, a 1% N_2 dopant was then introduced throughout the full 30 cm gas jet and ionization injection was triggered. This produced beams with a broad energy spread where most of the charge was below 5 GeV and some charge exceeded 10 GeV, shown in Figure 4.8(b). Beams with charge up to ~ 1 nC were observed. The broad energy spread was a result of injection being triggered at several points along the jet. Charge that is injected earlier will undergo more acceleration and reach a higher energy.

The dopant region was then restricted to a subset of valves at the start of the jet to isolate the high energy components of the accelerated bunches. With the dopant gas between 0 and 6 cm, no beams were observed. For dopant gas between 0 and 12 cm in the gas jet, beams were produced with single, quasimonoenergetic peaks up to 10 GeV, shown in Figure 4.8(c). The difference in beam generation based on dopant locations indicates that trapping must occur within the 6–12 cm region of the jet. These results are in good agreement with INF&RNO simulations (Figure 4.8(e)) where trapping of electrons was limited to the 8.6–12 cm region of the jet and produced beams up to 9.3 GeV.

Finally, the dopant concentration was increased to 5% N_2 . The higher dopant concentra-

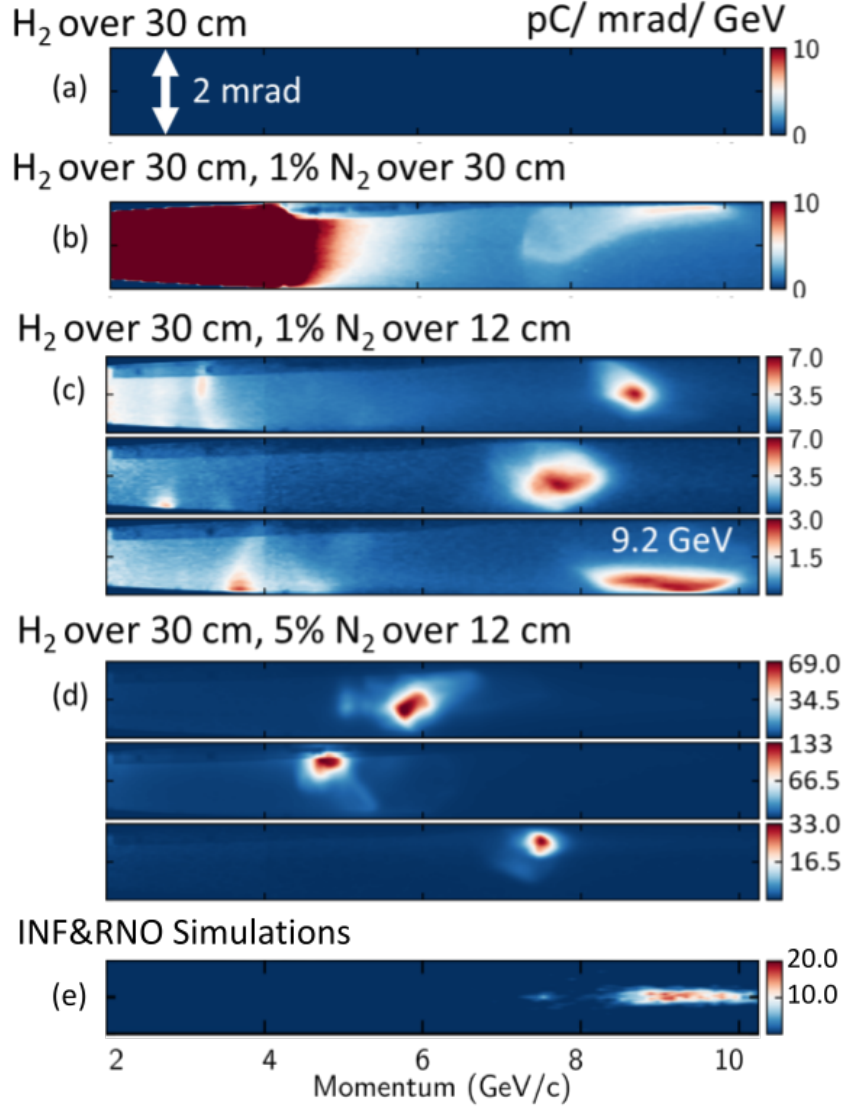


Figure 4.8: Electron beam spectra from 30 cm HOFI channels and 20 J drive laser energy: (a) $\tau = 6$ ns, H_2 only. (b) $\tau = 7$ ns, 1% N_2 in full jet. (c) $\tau = 5$ ns, 1% N_2 in first 12 cm of jet. (d) $\tau = 6$ ns, 5% N_2 in first 12 cm of jet. (e) INF&RNO simulations with the same conditions as (c). Each panel shows a 2 mrad window on the vertical axis, and τ is the delay between the channel forming laser and driver laser.

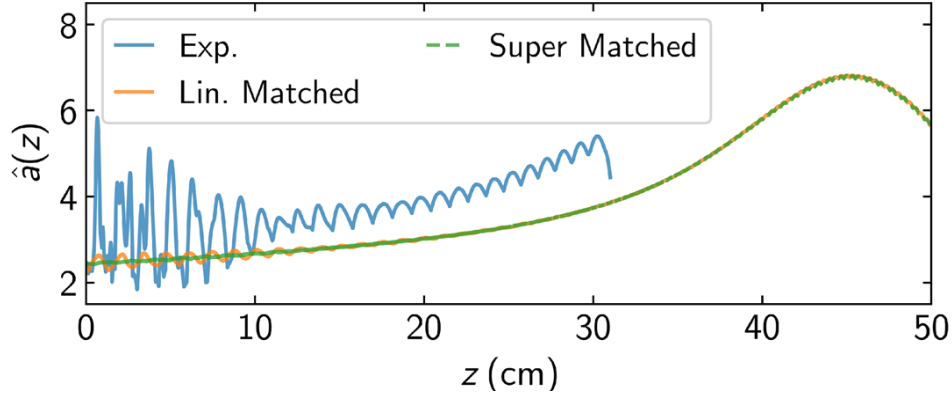


Figure 4.9: Calculated normalized peak laser intensity $\hat{a}$ as a function of propagation distance for the experimental input (blue), linearly matched (orange), and supermatched laser profiles (green).

tion produced beams with increased beam charge up to 100 pC and reduced energy spread as low as 3%, shown in Figure 4.8(d). Additionally, the maximum beam energy was reduced to 7.44 GeV. These effects are consistent with beam loading, where the high charge beam reduces the wake amplitude.

Simulations can be used to gain more insight into the processes that occur during the experiment. PIC simulations using INF&RNO and measured experimental parameters, the laser-plasma accelerator stage can be modeled. The normalized peak intensity is plotted in blue in Figure 4.9. The simulations show laser mode beating that causes intensity oscillations in the first few centimeters of propagation. These oscillations prevent the acceleration of charge that is injected in the first 6 cm of the jet, which matches what was observed in the experiment.

The simulations provide a pathway towards improving laser-to-bunch efficiency. If the laser can be linearly matched to the channel profile such that $w_0 = w_m$ (i.e., $\Delta n = \Delta n_c$), as shown in orange in Figure 4.9, mode beating can be reduced and the wakefield will maintain charge that is injected near the start of the accelerator. For the same laser energy and channel, this would increase the beam energy to 13.0 GeV and the bunch charge to 65 pC and increase the energy transfer to the wake to 46%.

Further tailoring of the laser pulse can achieve supermatching [80], where each longitudinal slice of the laser is matched to the pondermotively perturbed channel. This eliminates mode beating and intensity oscillations altogether, which is shown in green in Figure 4.9, resulting in further improved beam parameters of 13.1 GeV for the beam energy and 105 pC for the bunch charge.

4.4 Applications to muography

Electron beams generated from HOFI channels have also been demonstrated to produce muons with the potential for imaging applications [81]. Muons have considerable penetration power allowing for imaging of solid objects that are tens to hundreds of meters thick, which could provide an imaging capability for science and security applications beyond typical imaging techniques. Currently, the primary source of muons are cosmic rays that interact with the Earth's atmosphere and generate showers of charged particles. The resulting muon flux is low ($\approx 70 \cos^2 \theta \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$) [82], where θ is the angle from the zenith, so the imaging exposure times are on the span of months. The ability to generate a higher flux directional muon beam can drastically reduce the required exposure time.

Muons were produced from the multi-GeV electrons beams generated by the BELLA PW laser system. The accelerated electron beams interact with the high-Z material in the beam dump, where the high-energy electrons are deflected by the atomic nuclei in the beam dump and emit Bremsstrahlung photons. The emitted photons can then interact with the atomic nuclei and be converted into charged particle pairs through the Bethe-Heitler process. Additionally, the electrons can interact with the atomic nuclei and produce pions which subsequently decay into muons. The combined sources contribute to the total muon flux.

A pair of scintillator detectors were installed behind the beam dump to measure particle events. Muons with an energy range $0 \leq E \lesssim 20 \text{ MeV}$ could be stopped by the layers of plastic scintillator where they would undergo decay into an electron and two neutrinos. Stopped muons were identified by their decay times measured by the delay between events recorded in the two detectors, with the event decay times fitted by an exponential lifetime of $(2.24 \pm 0.50) \mu\text{s}$ that is comparable to the decay time of stopped muons, $2.2 \mu\text{s}$. The produced muon beams had measured counts $\gtrsim 10^2 \text{ shot}^{-1}$ compared to counts from cosmic rays of $\leq 1 \text{ s}^{-1}$. Since the detectors can only detect stopped muon beams, simulations were used to construct the total muon flux. The experiment was simulated using Geant4 [83, 84, 85], where agreement was found for the stopped muon counts [81]. The simulated muon fluxes were predicted to be on the order $\gtrsim 10 \text{ m}^{-2} \text{ shot}^{-1}$. Assuming laser-plasma accelerator operation at 1 Hz, the directional muon flux could be $40\times$ greater than cosmic ray muons. The improved flux, specifically along the direction of the produced beams, could significantly reduce exposure times required for imaging applications involving muons.

4.5 Conclusion

Optically formed plasma channels were used to guide laser pulses in laser-plasma accelerators with energy gain up to 10 GeV. The plasma channels guided the drive laser pulse and extended the accelerator length to 30 cm. The hydrodynamic expansion of optical-field-ionized plasmas allowed for channel formation at lower plasma densities in the range of $n_0 \sim 10^{17} \text{ cm}^{-3}$, which are optimal for laser-plasma accelerator operation.

Within these plasma channels, a novel control mechanism was implemented that allowed for variation in the plasma channel length. This was used to systematically scan the plasma channel length to uncover the laser evolution as it propagated through the plasma. At lower laser energy (~ 6 J), it was observed that a majority of the laser evolution occurred in the first 12 cm of the plasma channel, after which there was minimal laser evolution, indicating that matched guiding had been achieved. This was evident in both the exit modes and the propagated modes. At increased laser energy (~ 20 J), similar results in terms of guiding and laser evolution were observed. There was a decrease in the laser energy transmission as more laser energy was transferred to the wake. Notably, no electrons were trapped and accelerated while driving the wake, indicating that the accelerator was dark-current-free.

Electrons were injected and accelerated by adding a N_2 dopant gas. With a 1% dopant, beams with a board energy spread exceeding 10 GeV were observed. By restricting the dopant to the first 12 cm of the plasma channel, injection was localized and quasimonoenergetic beams with peaks up to 10 GeV were observed. Finally, the dopant concentration was increased to 5%, which lead to beams with increased charge up to 100 pC, reduced energy spread as low as 3%, and reduced maximum energy of 7.4 GeV. These results were consistent with beam loading effects.

The multi-GeV electron beams were also used to generate muons using the high-Z material in the BELLA PW beam dump. Through pair production and meson decay, directional muons were produced and measured by scintillator detectors behind the beam dump. The detectors measured low energy $0 \leq E \lesssim 20$ MeV muons that stopped in the scintillator, decaying into an electron that was subsequently recorded. Muons were identified by the delay time between recorded events. The decay times were fitted by an exponential lifetime of (2.24 ± 0.50) μ s that is comparable with the decay time of stopped muons, 2.2 μ s. Simulations were conducted in Geant4 to construct the full muon flux from the stopped muons that were measured. The simulations showed that for laser-plasma accelerator operation at 1 Hz, the directional muon flux could be $40\times$ greater than cosmic ray muons, which could allow for significantly reduced exposure time for muography.

Chapter 5

Plasma lensing in plasma channels

5.1 Motivation for enhanced laser control in laser-plasma accelerators

In addition to increasing the energy gain of laser-plasma accelerators, it is also important to optimize the efficiency of the accelerator. One way this can be achieved is through the coupling of laser energy to the plasma wake by improving the matching between the laser pulse and the plasma channel. Given an ideal plasma channel with parabolic transverse plasma density profile given by Equation 4.2, the matched transverse laser profile for such a channel is a Gaussian pulse [2]. For plasma channels created through the hydrodynamic expansion of a plasma column, the transverse profile is approximately parabolic and finite in the radial extent. The supported laser modes of the plasma channel can be found by solving the Helmholtz wave equation for propagation in the channel and are the quasibound modes of the channel. The lowest order of the quasibound modes is the fundamental mode and is approximately Gaussian.

Due to the amplification process in solid-state lasers, the transverse profile of the drive laser is typically non-Gaussian. Far from focus, the near field profile is close to a flat-top beam and can be described by a supergaussian distribution given by Equation 2.11. For supergaussian order $n_{SG} = 2$, the distribution is Gaussian and as $n_{SG} \rightarrow \infty$, the distribution approaches a flat top profile. The supergaussian order of the experimental profile can be found by fitting measurements of the near-field laser profile. On BELLA PW, the near-field laser profile is typically fit by a supergaussian order between $n_{SG} = 6$ and $n_{SG} = 10$. The variation in supergaussian order can be attributed to differences in beam profile at various levels of amplification.

Since the near-field laser profile is not Gaussian, the far-field profile near the laser focal plane is also not Gaussian. The difference between the non-Gaussian laser focus and the approximately Gaussian fundamental mode of the plasma channel will lead to a mode mismatch [49, 86, 87, 88]. The fundamental mode is the primary driver of the desired plasma wake [89]. As such, closer matching of the laser profile to the fundamental mode would increase

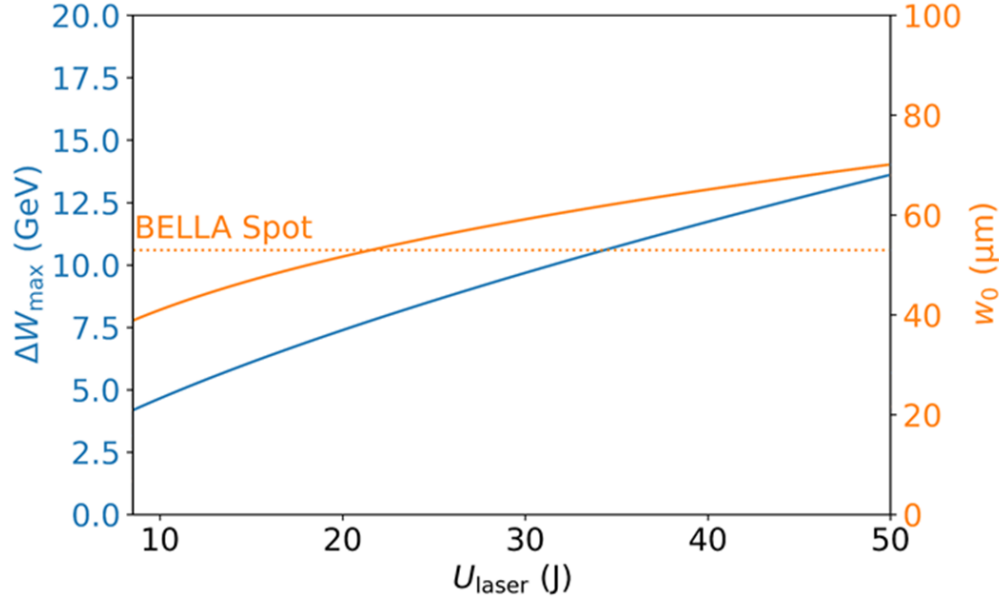


Figure 5.1: Scaling relationship between drive laser energy and accelerator energy gain (shown in blue with the corresponding axis on the left) and laser spot size (shown in orange with the corresponding axis on the right). The nominal spot size for BELLA PW is the dotted orange line.

the energy transfer to the wake and improve the efficiency of the laser-plasma accelerator.

Furthermore, beating among the quasi-bound lower order modes occurs as the laser propagates through the plasma channel and leads to oscillations in the laser intensity. As a result of the intensity oscillations, the wake experiences changes in its structure which can cause it to become unsuitable for the transport of electrons. The oscillations eventually subside owing to laser mode leakage and at that point the wake becomes suitable for the transport and acceleration of injected electrons. Mode beating reduces the effective acceleration length of the laser-plasma accelerator. If the laser mode is matched to the fundamental mode of the channel, termed as linearly matched, intensity oscillations due to mode beating are reduced and electrons injected at the start of the accelerator can be accelerated. Since the total energy gain is approximately the product of the acceleration gradient and the accelerator length, electrons injected earlier will have a higher energy gain, allowing for improved laser-to-beam efficiency in terms of energy gain for a given input laser energy.

Additionally, scaling laws dictate that for varying drive laser energies, the laser spot size should also be varied. The laser spot size should approximately be the plasma wavelength, $w_0 \sim \lambda_p$. Given that the plasma wavelength cubed is proportional to the laser spot energy for efficient excitation of plasma wakefields, $\lambda_p^3 \propto U_L$, the scaling between laser spot size and drive energy is $w_0 \propto U_L^{1/3}$. The relationship between drive laser energy and laser spot size is illustrated in Figure 5.1.

Achieving variable laser spot size is a challenge for current laser systems. The focal spot size on the plasma target is determined by the final focusing optic in the laser system, and most laser systems are designed around a specific focal length and spot size. For high-power laser systems, optics are large and expensive, making additional optics difficult to procure. Furthermore, swapping of large, in-vacuum optics is a time consuming task that reduces laser up-time. Hence, the laser focusing and laser spot size are typically fixed. Even if the focusing optic can be changed, control over the laser spot size does not exist on a shot-to-shot basis.

A plasma lens in the form of a plasma channel located near the accelerator has the potential to solve the aforementioned challenges. With regards to the laser spot size, if the channel radius is mismatched with initial laser spot size, the laser spot will undergo oscillations as it propagates through the plasma channel, as shown in Figure 5.2 and given by Equation 4.3. The maximum change in spot size can be found by setting the cosine term in Equation 4.3 equal to -1 , which gives a final output spot size of $w(z) = w_m^2/w_0$. Therefore, there is a channel width w_m that can produce output beams with the desired spot size w for a given input laser spot size w_0 , which is determined by the final focusing optic of the laser system. In order to extract the oscillating laser pulse at the desired spot size, the length of the plasma lens must be controlled. When the plasma lens length is at integer values of $\lambda_{osc}/2$, the laser pulse wavefront has zero curvature which is ideal for injection into a laser-plasma accelerator.

A plasma lens can also affect the laser profile by acting as a modal filter [90]. The plasma channel used in the lens is finite in the radial extent and subsequently is leaky; only a subset of the laser modes will be quasibound. As a result, higher-order modes will leak out of the channel [90] and will not be transported to the laser-plasma accelerator entrance. Additionally, there will be longitudinal separation between the fundamental mode and other low-order modes which can reduce the length of mode beating inside of a laser-plasma accelerator. The length of the plasma lens would have to be tailored to balance the effects of mode filtering, which increase with length, against laser energy deposited and lost into the plasma. A properly designed plasma lens could allow for laser spot size control and mode filtering of the main drive laser before it enters the primary plasma channel and drives the accelerator, leading to increased efficiency of energy transfer.

5.2 Experimental setup

Plasma lensing experiments took place on the BELLA PW laser system using a similar setup to the experiments described in Chapter 4 and illustrated in Figure 5.3. The laser system was configured with an 80:20 beamsplitter that split 80% of the laser energy to the drive laser beamline and 20% of the laser energy to the channel forming beamline. After the beamsplitter, the drive laser was focused with a 13.5 m off-axis parabola to a laser focus beam waist of approximately 53 μm . The drive laser beam had energies of $U_L = (5.5 \pm 0.1)$ J on target which corresponds to a laser strength parameter of $a_0 \approx 1.2$. The laser energy was

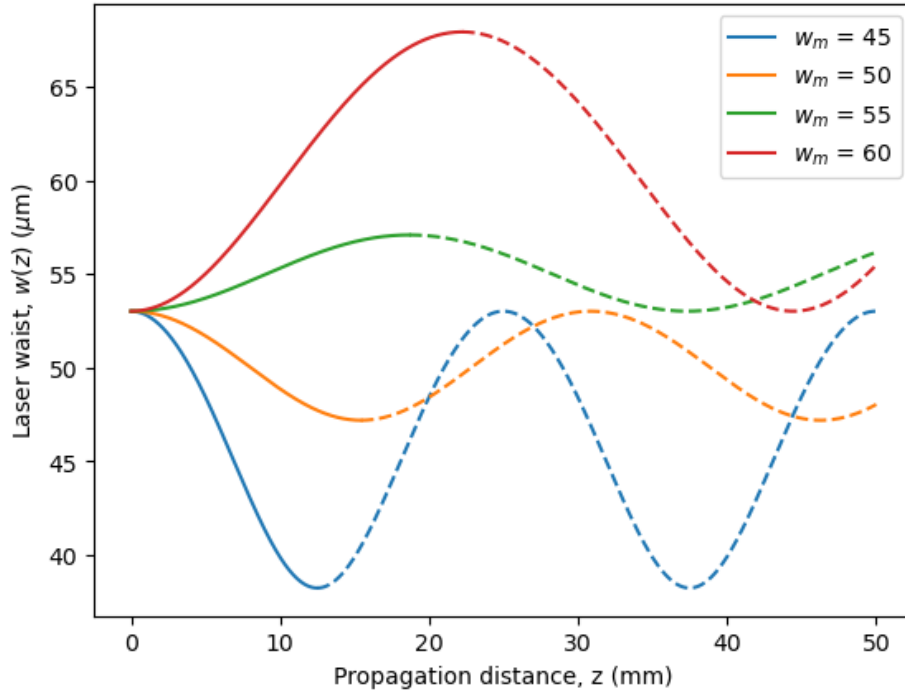


Figure 5.2: Spot size oscillations for Gaussian pulse with a beam waist $w_0 = 53 \mu\text{m}$ in parabolic channels with a matched radius, w_m . The solid portions of the curve are for laser propagation up to $\lambda_{osc}/2$ where the spot size exhibits maximum change from the input spot size. The dashed portion shows the continued oscillation out to the full channel length, $z = 5 \text{ cm}$.

limited to avoid driving a wake and minimize nonlinear effects.

The second beamline delivered a collimated channel forming pulse, containing approximately 1.1 J of laser energy, to the target chamber. In the chamber, the channel forming beam was focused using an axicon lens into a bessel beam. The bessel beam creates an extended laser focus that is used to ionize a hydrogen plasma column that evolves into a plasma channel through hydrodynamic expansion. The laser focal region extended beyond 60 cm, but the maximum plasma channel length was determined by the length of the gas jet target. The gas jet for channel formation was a 5 cm jet comprised of a converging-diverging nozzle driven by two gas jet valves. The jet length was selected to be on order of a spot size oscillation length which would be around tens of millimeters, $\lambda_{osc} \approx 30 \text{ mm}$, for a channel radius of approximately $w_m \approx 50 \mu\text{m}$. Additionally, the plasma channel length could be varied on-shot by translating a horizontal blade over the gas jet and blocking a portion of the jet. The variable plasma channel length allowed for investigation into the laser evolution in these short plasma channels. The blade allowed for length control of the 5 cm plasma channel with a 2 mm step size.

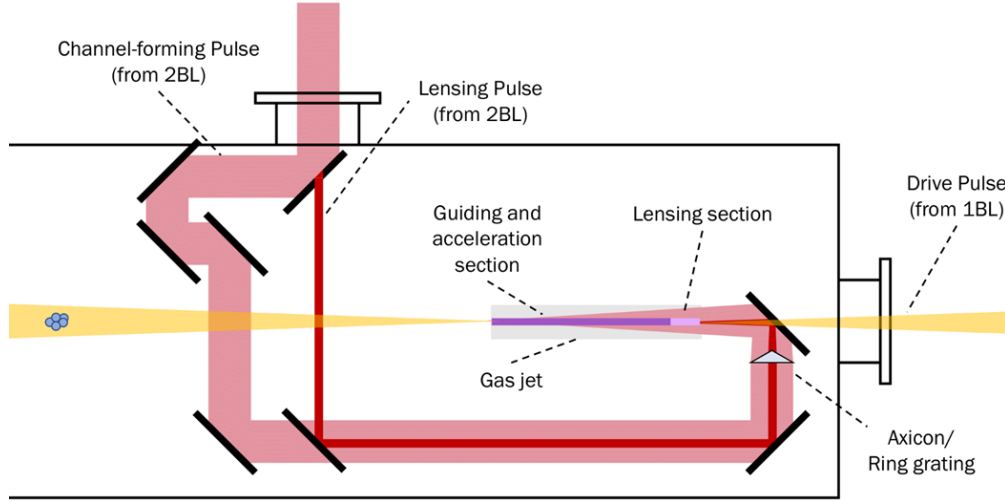


Figure 5.3: Layout of plasma lensing setup on BELLA PW, with the plasma lensing section in light purple. For initial experiments, no guiding and acceleration section is included. The drive laser pulse is delivered through the main beamline (1BL) while the channel forming pulse is delivered in the second beamline (2BL).

The drive laser pulse arrived after the channel forming pulse with a delay between 4 ns and 9 ns. The delay of the drive laser pulse to the channel forming pulse provided control over the expansion time of the plasma channel, and therefore control over the plasma channel width.

Two-color interferometry [91, 92] was used to measure the transverse plasma channel profile. The probe beam for interferometry was picked off from the main channel forming beam after compression. The probe beamline contained a delay stage to allow for scanning of the probe beam delay relative to the channel forming beamline. Interferometry data from the plasma channel expansion was captured out to expansion times of 7.3 ns after initial ionization. The probe beamline also contained a doubling crystal for second harmonic generation at 400 nm. The second harmonic allowed for two-color interferometry to enable measurement of both the electrons and the neutral gas in the plasma. After passing through the plasma, the probe beam was separated based on wavelength by a dichroic mirror into the fundamental and second harmonic. The separate beams were imaged onto two different wavefront sensors that measured the phase imparted onto the probe beam by the plasma channel.

After interacting with the plasma channel in the experimental chamber, the post-interaction laser propagated approximately 10 m to a set of wedges that reduce the beam power before being imaged on the high-powered diagnostics. A camera was used to image the surface of the first wedge and provide an image of the quasi-near field of the post-interaction laser

pulse. The quasi-near field image is also calibrated to the vacuum laser pulse and can then be used to provide an approximate measurement for the laser energy transmission during interaction. The accuracy of the energy transmission measurement is limited by the field of view of the camera. Higher divergence beams, such as those with smaller spot sizes, can exceed the field of view.

After the wedges, the post-interaction laser arrives at the high-power diagnostic area of BELLA PW. There is a mode imager camera on a 60 cm stage that images the focal plane of the drive laser in the target chamber. The stage allows for the imaging plane of the camera to be scanned around the laser focus to create a focal scan for focus quality and position. The stage also allows for the imaging plane to be moved to the exit of a plasma channel when the channel is in operation. This allows for measurement of the laser exit mode after propagation through the channel. This can be combined with the control over channel length to collect exit mode measurements at different channel lengths, providing direct measurements of the laser evolution.

The high-power diagnostic area also contains a wavefront sensor used to correct aberrations in the beam and improve the drive laser focus. There is also a set of fiber-based optical spectrometers that can be used to measure the post-interaction laser for spectrum shifts. These laser wavelength shifts are useful tools for diagnosing the laser-plasma interaction. The red-shift is a measure of the laser energy deposited into the plasma via plasma wake excitation, and the blue-shift is a measure of the amount of laser ionization, i.e., laser interaction with neutral gas.

5.3 Experimental results

Experimental data was collected across a range of conditions. The primary variables that were scanned are the channel expansion time which controls plasma channel width, the backing pressure which controls plasma density, and the plasma channel length. The primary diagnostics were the exit mode imager and the quasi-near field imager. With the exit mode imager, spot size, transmitted fluence, and higher-order mode leakage were measured. With the quasi-near field, the spatial profile and transmitted energy were measured.

One of the primary forms of data collected were scans of the plasma channel length due to the length being the easiest variable to change on a shot-to-shot basis. During the scans of the plasma channel length, all other parameters were held constant. The plasma channel length scans allowed for the extraction of the laser at varying propagation lengths, which allowed for measurements of the laser evolution as the plasma channel length varied.

During the data collection, the plasma lens performance was highly sensitive to the position of the incoming drive laser. This was one of the primary sources of shot-to-shot fluctuations.

Sets of jet length scans showing spot size evolution are shown in Figure 5.4. The measured spot sizes are averaged over 20 shots at each plasma length with error bars for the standard deviation due to shot-to-shot variation. As the expansion time increases, the exit beam

size from a Gaussian fit tends to increase. This is most clearly illustrated between Figures 5.4b and 5.4e, measured with expansion times of 6 ns and 9 ns, respectively, with exit mode beam sizes between 40 μm and 50 μm with 6 ns plasma channels and beam sizes exceeding 60 μm at 9 ns plasma channels. Note this trend does not hold for measurements at the 5 ns expansion time. It is hypothesized that at the lowest expansion time, the plasma channel is not sufficiently wide to support the full laser pulse and not all of the laser is coupled into the channel, leading to larger exit beam sizes.

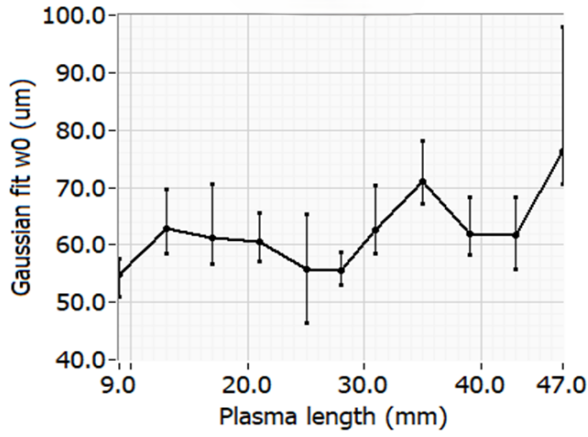
In addition to the exit mode beam size, radially-averaged lineouts of the exit mode can be plotted against plasma channel length in a waterfall plot to provide a more complete image of the beam profile. Sets of jet length scans showing the evolution of higher-order mode leakage are shown in Figure 5.5. The mode leakage is most clearly observed in Figure 5.5b with a ring of laser intensity outside of the central spot diverging in a diagonal direction while the central spot is guided through the full plasma length. There is also a decrease in the amount of laser intensity outside the central spot for expansion times ≥ 7 ns. Beyond $z \approx 30$ mm, there is minimal signal from the unbound higher-order mode leakage compared to shorter expansion times. The decrease in mode leakage suggests the increased coupling of the drive laser for larger plasma channels.

Scans of backing pressure were also performed while collecting exit mode data. Waterfall plots at various backing pressures are shown in Figures 5.6 and 5.7. The variation in gas jet backing pressure changes the plasma density which affects the plasma channel depth and subsequently the laser coupling into the channel. One of the observed effects of pressure variation is the change in the intensity of the leakage outside of the plasma channel. At lower backing pressure of 100 psi, the plasma density is lower and the intensity of leakage outside of the plasma channel, located centrally along the vertical axis, is increased. As the backing pressure and plasma density increase, there is a reduction in leakage. This trend is present across multiple expansion times.

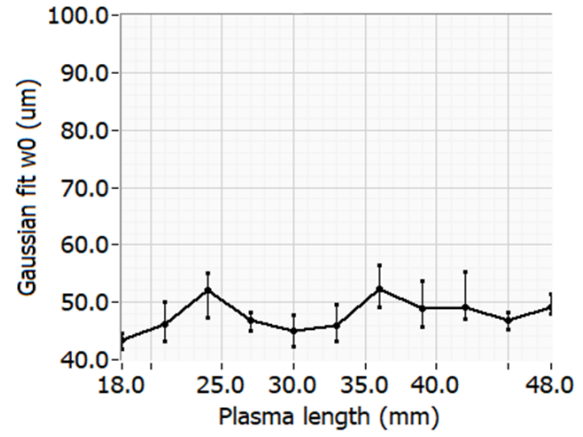
Individual exit modes taken at regular increments of 1 cm are examined in Table 5.1 for expansion delays of 5, 7, and 9 ns. It is difficult to observe any significant variations in the modal composition of the central spot. Leakage of higher-order modes is visible but does not provide any additional insight compared to the waterfall plots in Figure 5.5. The individual modes also highlight the reduced coupling for the 5 ns plasma channel with the most laser intensity outside the central spot after propagation through a 1 cm channel.

To extract more information about the mode evolution as the laser pulse propagates through the plasma lens, the quasi-near field can be used. The laser propagates approximately 10 m to where the quasi-near field data is collected. Table 5.2 presents the propagated modes that were measured at the same parameters as the exit modes from Table 5.1.

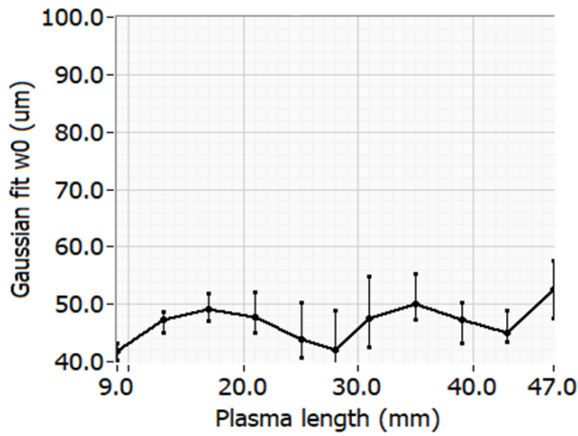
Significant variation in the laser mode is revealed through the propagated modes. Over the range of 5 cm, the propagated modes undergo significant change before transforming into approximately Gaussian profiles. There are ring structures present in the propagated mode as well as beams with highly-peaked spots of laser intensity. It is clear that the laser pulse is undergoing significant evolution in the early stages of the plasma lens. There does not appear to be a significant trend within the propagated modes that is dependent on the



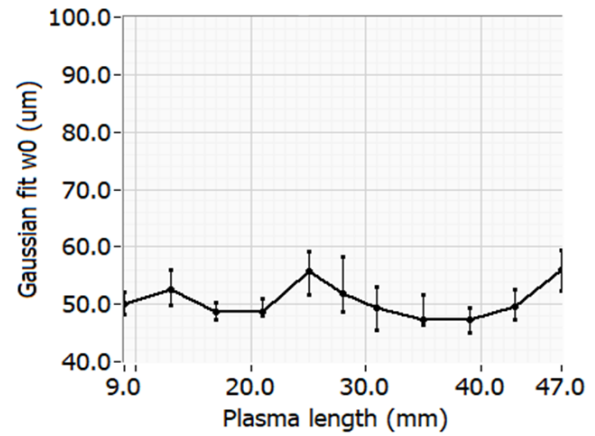
(a) Gaussian fit of exit modes at 5 ns.



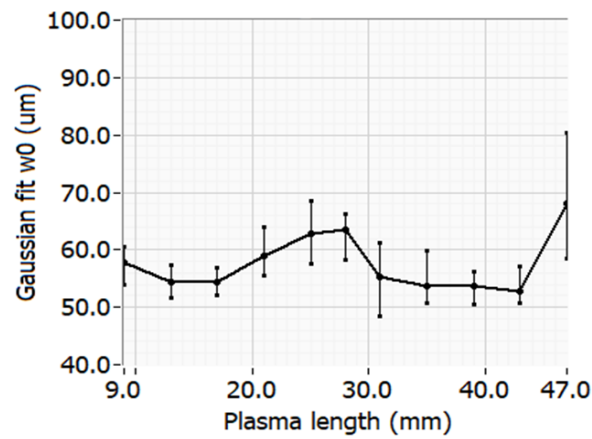
(b) Gaussian fit of exit modes at 6 ns.



(c) Gaussian fit of exit modes at 7 ns.



(d) Gaussian fit of exit modes at 8 ns.



(e) Gaussian fit of exit modes at 9 ns.

Figure 5.4: Plots of Gaussian fit beam sizes from exit modes for plasma channel expansion times from 5 ns to 9 ns.

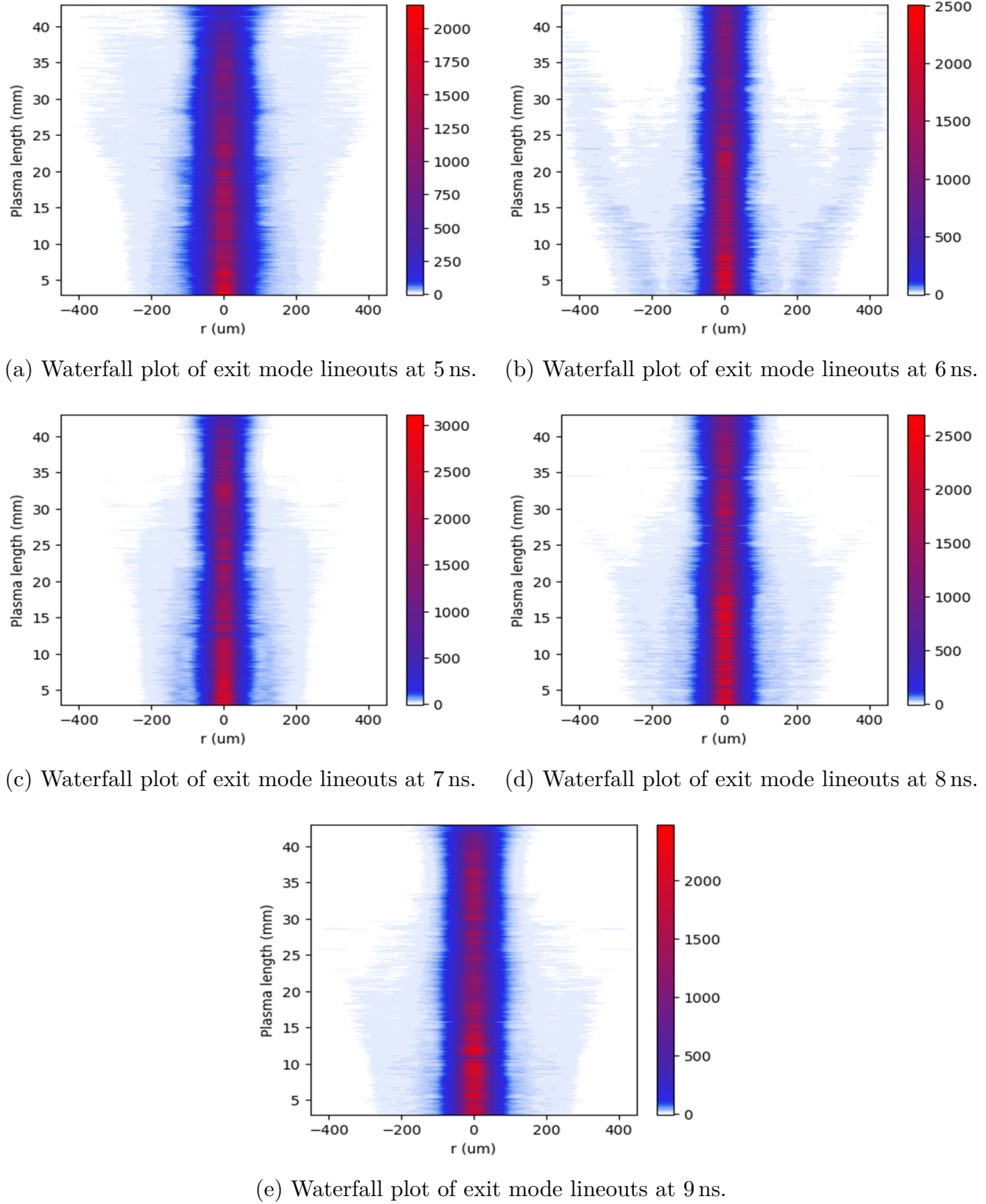
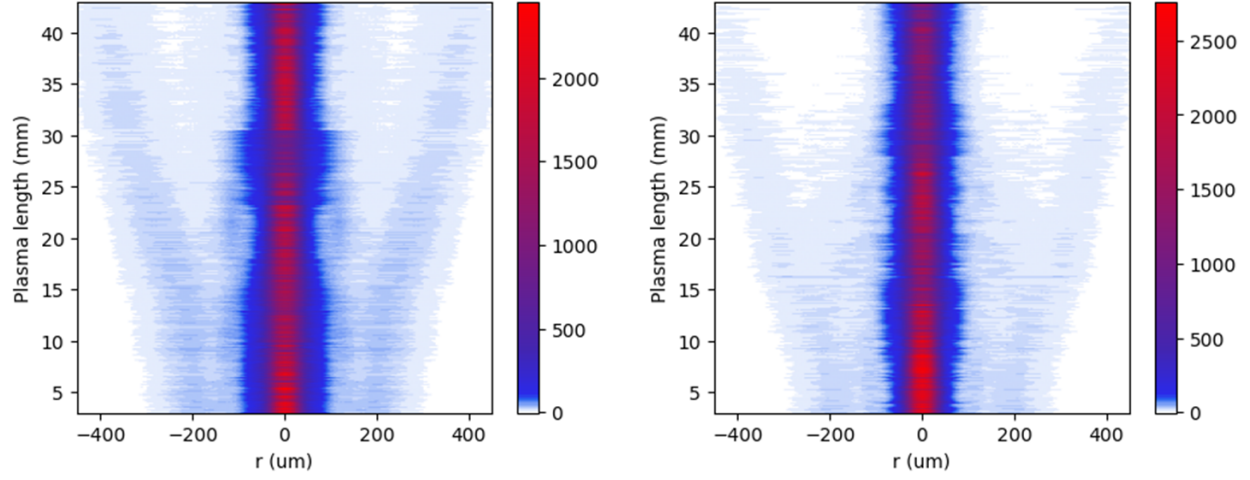
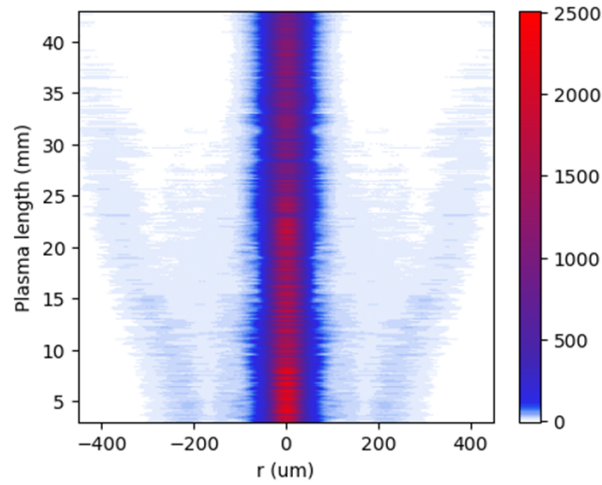


Figure 5.5: Waterfall plots of radially-averaged exit mode lineouts plotted against plasma length for plasma channel expansion times from 5 ns to 9 ns. The colorbar for all plots is the lineout intensity with arbitrary units.

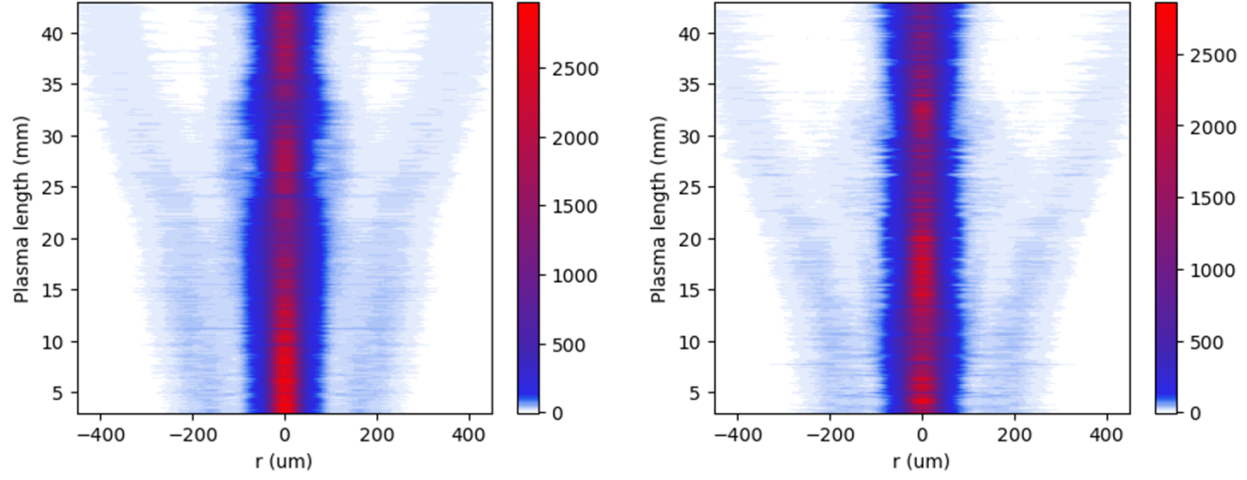


(a) Waterfall plot of exit mode lineouts at 6 ns with a gas jet backing pressure of 100 psi. (b) Waterfall plot of exit mode lineouts at 6 ns with a gas jet backing pressure of 200 psi.

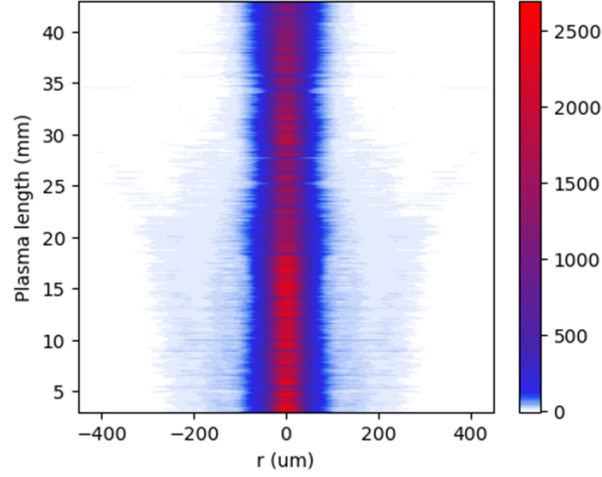


(c) Waterfall plot of exit mode lineouts at 6 ns with a gas jet backing pressure of 300 psi.

Figure 5.6: Waterfall plots of exit mode lineouts at a plasma channel expansion time of 6 ns for gas jet backing pressures from 100 psi to 300 psi. The colorbar for all plots is the lineout intensity with arbitrary units.



(a) Waterfall plot of exit mode lineouts at 8 ns with a gas jet backing pressure of 100 psi. (b) Waterfall plot of exit mode lineouts at 8 ns with a gas jet backing pressure of 200 psi.



(c) Waterfall plot of exit mode lineouts at 8 ns with a gas jet backing pressure of 300 psi.

Figure 5.7: Waterfall plots of exit mode lineouts at a plasma channel expansion time of 8 ns for gas jet backing pressures from 100 psi to 300 psi. The colorbar for all plots is the lineout intensity with arbitrary units.

Table 5.1: Table of exit mode images for plasma lengths of $L_{ch} = 1, 2, 3, 4, 5$ cm with plasma channel expansion times of 5, 7, 9 ns.

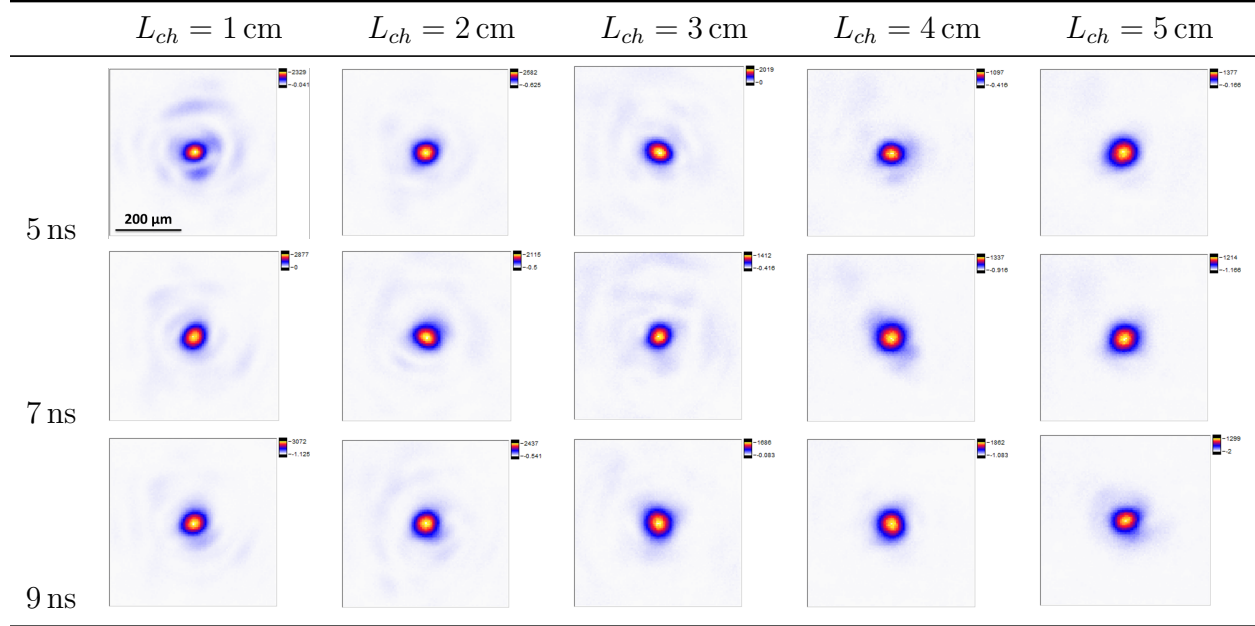


Table 5.2: Table of propagated mode images at 10 m for plasma lengths of $L_{ch} = 1, 2, 3, 4, 5$ cm with plasma channel expansion times of 5, 7, 9 ns.

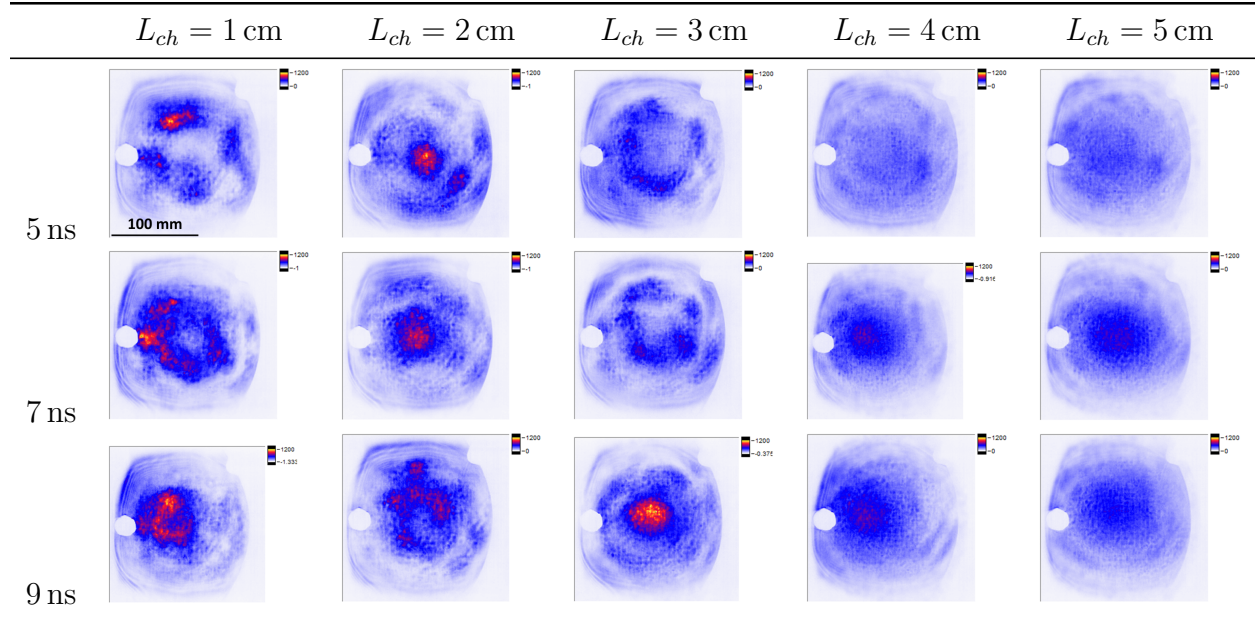
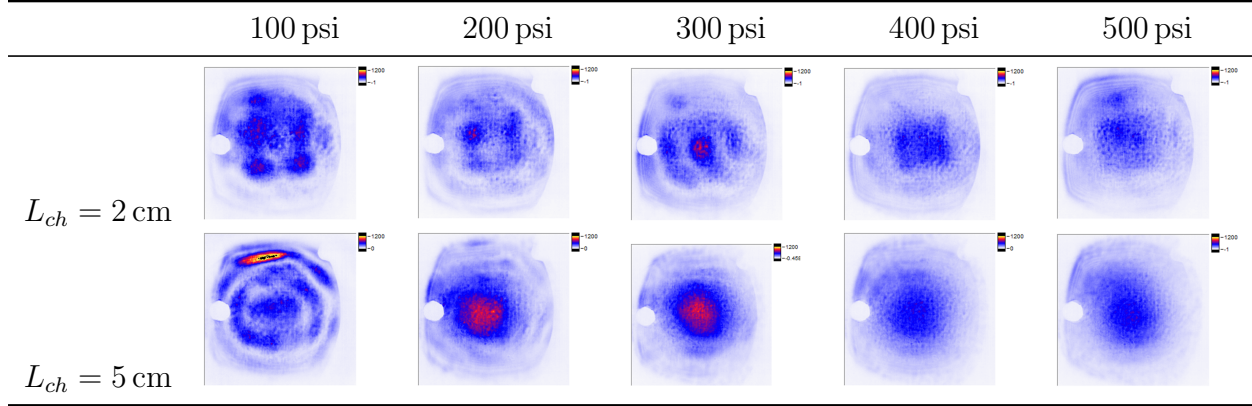


Table 5.3: Table of propagated mode images as a function of gas jet pressure with a channel expansion time of 9 ns for channel lengths of 2 cm and 5 cm.

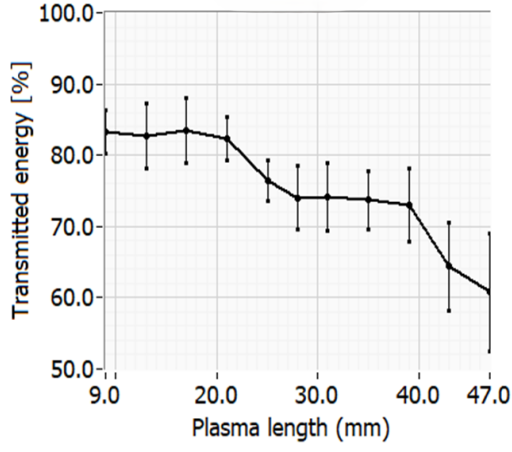


channel expansion time.

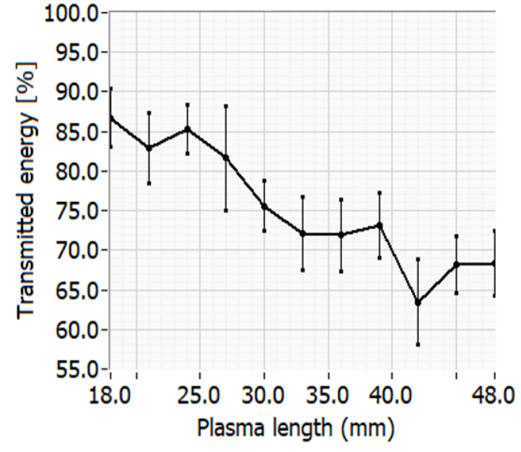
Propagated mode data was also collected during scan of the gas jet pressure. The results are shown in Table 5.3. Data was collected at two different plasma channel lengths: 2 cm and 5 cm. In the 2 cm channel, the conversion to a Gaussian mode can only be observed for gas pressures at 400 psi and above. Below this pressure, the propagated mode remains highly variable and evolving with propagation. In the longer 5 cm plasma channel, the conversion to a Gaussian mode happens at a gas jet pressure of 200 psi and above. As the pressure increases beyond 200 psi, the mode remains fairly constant while the energy transmission decreases. Below 200 psi, there is a significant ring structure.

The propagated modes can also be used to calculate energy transmission through the plasma lens as a function of plasma channel length, as shown in Figure 5.8. The energy transmission measurements are averaged over 20 shots at each plasma length with error bars for the standard deviation due to shot-to-shot variation. As expected, energy transmission decreases with plasma length. While there is slight variation for different expansion times, there is not a clear trend for the energy transmission. The transmission losses can be broken into two main components, coupling losses and propagation losses. The plateau that is observed over the first approximately 20 mm of propagation is a result of the losses from the initial coupling of energy into the plasma channel which range from 10% to 20%. After the initial plateau, there is a fairly linear decrease in the transmitted energy as a result of losses during propagation through the plasma channel.

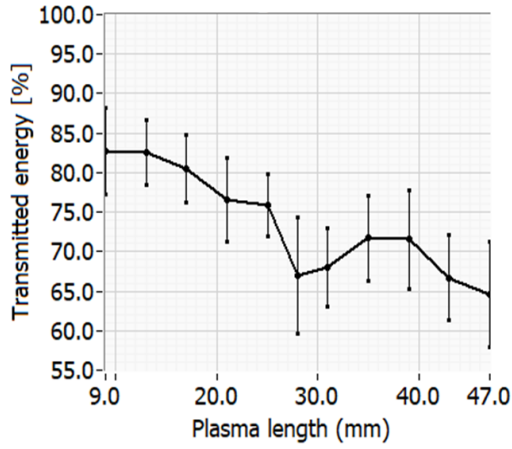
The lack of agreement in the exit spot sizes between the linear theory shown in Figure 5.2 and the experimental measurements in Figure 5.4 suggests a more complicated relationship between the exit spot size and the laser-plasma parameters. This can likely be attributed to nonlinear laser-plasma interactions that arise for laser strength $a_0 > 1$, which are modeled with PIC simulations.



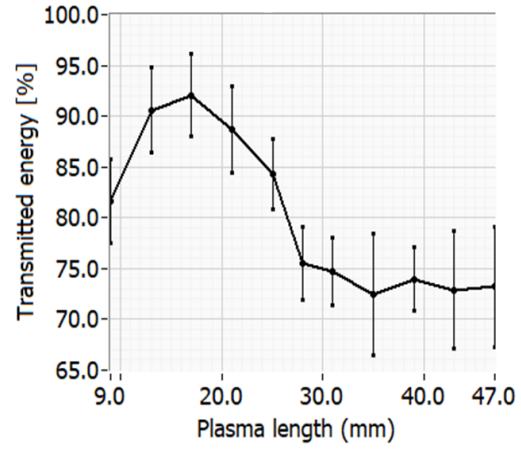
(a) Energy transmission plot at 5 ns.



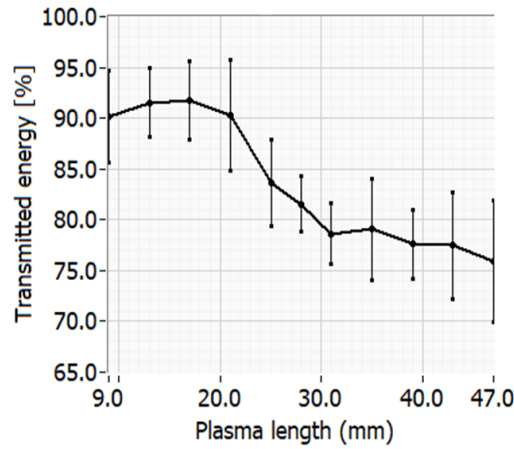
(b) Energy transmission plot at 6 ns.



(c) Energy transmission plot at 7 ns.



(d) Energy transmission plot at 8 ns.



(e) Energy transmission plot at 9 ns.

Figure 5.8: Plots of energy transmission as calculated from the integrated counts over the quasi-near field for plasma channel expansion times from 5 ns to 9 ns.

5.4 Plasma lensing simulations

To better understand the physics of laser evolution in the short plasma channels, simulations were performed with the goal of matching the experimental results. Given the amount of variables and the uncertainty from some measurements, the primary goal is to find qualitative agreements between the experimental data and the simulation results. The simulations of the laser-plasma interaction were run using a Fourier-Bessel particle-in-cell code, FBPIC [93, 94, 95, 96, 97]. One of features of this code is the use of spectral cylindrical representation which makes the code fast and accurate for cylindrically symmetric problems and well-suited for this application. The primary inputs into the simulation are the laser pulse profile and the plasma channel profile. Measurements of the laser profile and the channel were collected, but the relatively large uncertainty in the measurement meant that there was some freedom in the choice of input parameters used in the simulation. Hence, matching simulations and experiments required exploration of the simulation input parameters within the uncertainty of their measurements.

Initial simulations were run to confirm the validity of the simulation setup. The first goal was to match linear theory demonstrating matched and mismatched guiding of laser pulses in plasma channels. For both tests, a Gaussian pulse with a parabolic channel was used. The laser pulse had a laser waist of $w_0 = 53 \mu\text{m}$ to match the laser waist measured on BELLA PW. The laser energy was reduced to give a laser strength parameter of $a_0 = 0.1$, setting the laser-plasma interaction in the linear regime where $a_0^2 \ll 1$. The linear regime would allow for direct comparison between the simulation results and the linear theory.

The parabolic channel was not infinite but did extend to the full extent of the simulation box. The matching condition was controlled by the channel width, r_{ch} , with a transverse plasma density profile of $n(r) = n_0(1 + r^2/r_{ch}^2)$. For matched guiding, the channel width was set to satisfy $w_m = w_0$, with the relation between the matched spot size and channel radius given by $r_{ch} = \frac{1}{2}k_p w_m^2$. In the mismatched case, oscillations were expected following the form of Equation 4.3. Mismatch of both larger and smaller channel widths were tested to ensure there was no bias in mismatch behavior within the simulation setup and the results were compared to the linear theory.

5.4.1 Laser pulse modeling

The laser pulses used in the PIC simulations using FBPIC are based on measured pulses, but the measurements are not able to capture the full physical description of the laser used in the experiments. This is most evident by comparing vacuum propagation of the modeled laser pulse around focus to an experimental focal scan. The modeled laser pulse can be specified in order to match the laser on one side of focus but not the other. This mismatch suggests the presence of spatio-temporal coupling in the pulse that is not being captured in the mode imager. Additional measurements [98] would be required to include these laser effects in simulations.

Given the challenges in fully modeling the experimental laser pulse, laser pulses that are analytically well-defined, such as the Gaussian and jinc profiles, were used. The advantage of using such pulse profiles is that there is significant built-in compatibility for these profiles in the FBPIC simulations. This allows for simplified control over parameters such as the laser strength parameter, laser focal position, and initial position of the laser centroid. The control over these parameters allows for more rapid iteration and scanning of parameters where input parameter space scans are performed.

The most basic laser profiles used in the simulations are Gaussian laser pulses which are the ideal profile for driving a laser-plasma accelerator. The electric field near focus, where the pulse is initialized, is given by [51]

$$E(\mathbf{x}, t) = a_0 \times E_L \exp \left[-\frac{r^2}{w_0^2} - \frac{(z - z_0 - ct)^2}{c^2 \tau^2} \right] \cos[k_0(z - z_0 - ct) - \phi_{cep}], \quad (5.1)$$

where $k_0 = 2\pi/\lambda$ is the laser wavevector and $E_L = m_e c^2 k_0 / e$ is the field amplitude for $a_0 = 1$. The laser beam waist w_0 defines the transverse extent of the laser envelope while the laser duration τ defines the envelope in the longitudinal extent. The initial laser position can be modified by the term z_0 . The oscillatory component is given by the cosine term with the inclusion of the carrier envelope phase term ϕ_{cep} . For all simulations, this phase term was set to zero, i.e., $\phi_{cep} = 0$.

Another laser pulse profile commonly used in the simulations is the jinc profile, described by the function $2J_1(x)/x$, where J_1 is the Bessel function of the first kind of order 1. The jinc profile is the far-field distribution at the focal plane for a beam that has a flat-top profile in the near-field. It is also the function for the Airy pattern that arises from Fraunhofer diffraction of a circular aperture. The amplification process in solid-state lasers is more efficient for flat-top beams due to the more uniform extraction of laser energy from the amplification medium. As a result, the laser near-field tends to be close to a flat-top distribution. When a flat-top beam is focused, the resulting distribution at the focal plane is a jinc profile, with the transverse laser envelope described as

$$E(r) = E_L \times 2 \frac{J_1(r/R)}{(r/R)}. \quad (5.2)$$

Note that in this form, R is not the same as the beam waist in a Gaussian distribution and must be adjusted to give the distribution the proper width. Typically the width R is modified such that the jinc profile has the same full-width half-maximum of intensity as a comparable Gaussian beam, where the intensity is of the form $I \propto |E|^2$, as shown in Figure 5.9. The scale factor must be calculated numerically and results in $R = w_0 \times \sqrt{2 \ln 2} / 3.23$.

The Gaussian and jinc profiles can be the bounds between which the experimental pulse exists and serve as the extreme cases for the input beam profile. The real experimental pulse can be thought of as existing between these two bounding profiles. One such way to describe the near-field would be using a supergaussian profile, as given by Equation 2.11. The supergaussian profile can also be fit to the experimentally measured data of the near-field to provide an analytic expression for the laser profile.

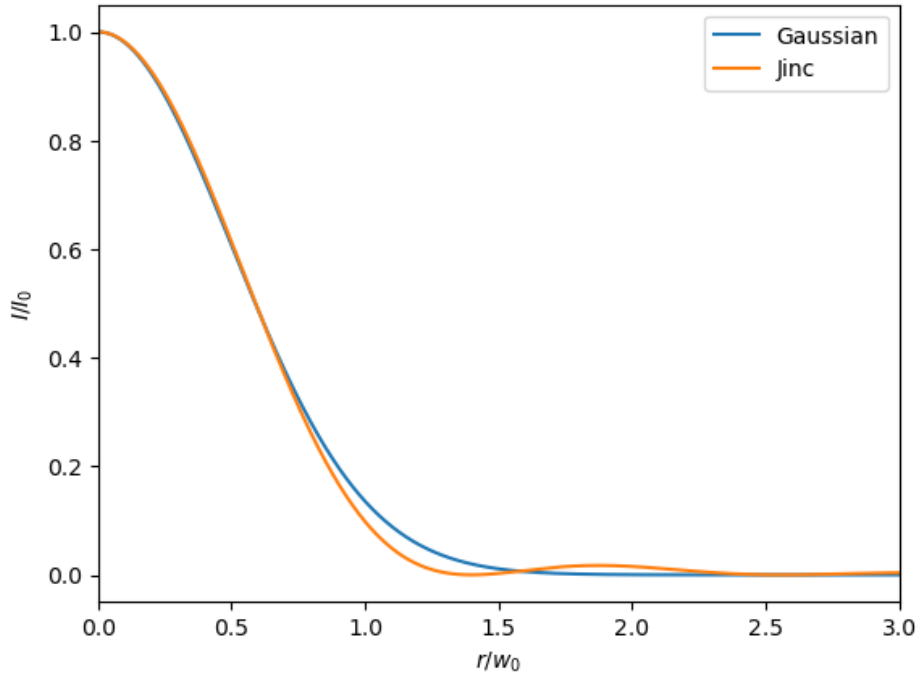


Figure 5.9: Intensity profiles for a Gaussian (blue) and a jinc (orange) laser pulse. The jinc pulse width matches the full-width half-maximum of the Gaussian pulse.

The supergaussian distribution can provide a good description of the transverse profile of the beam far away from focus, e.g., after the laser amplifiers and before focusing. However, there is not an analytic expression for a focused supergaussian pulse at the focal plane. The only way to create a far-field profile would be to numerically propagate the pulse to focus. Fortunately, there is a family of functions called the flattened Gaussian [99] that can give an analytic expression for a transverse laser profile at the focal plane and far away from focus. At the focal plane, the expression for a flattened Gaussian is

$$E(r) = E_L \times \exp \left[-\frac{r^2}{(N_{FG} + 1)w_0^2} \right] \sum_{n=0}^{N_{FG}} c'_n L_n^0 \left(\frac{2r^2}{(N_{FG} + 1)w_0^2} \right), \quad (5.3)$$

with L_n^0 being the Laguerre polynomials and

$$c'_n = \sum_{m=n}^{N_{FG}} \frac{1}{2^m} \binom{m}{n}.$$

The parameter N_{FG} determines the “flatness” of the profile. For $N_{FG} = 0$, the profile is Gaussian and for $N_{FG} \rightarrow \infty$, the profile is a jinc, as shown in Figure 5.10. Note that the beam waist w_0 needs to be adjusted to maintain the same full-width half-maximum of

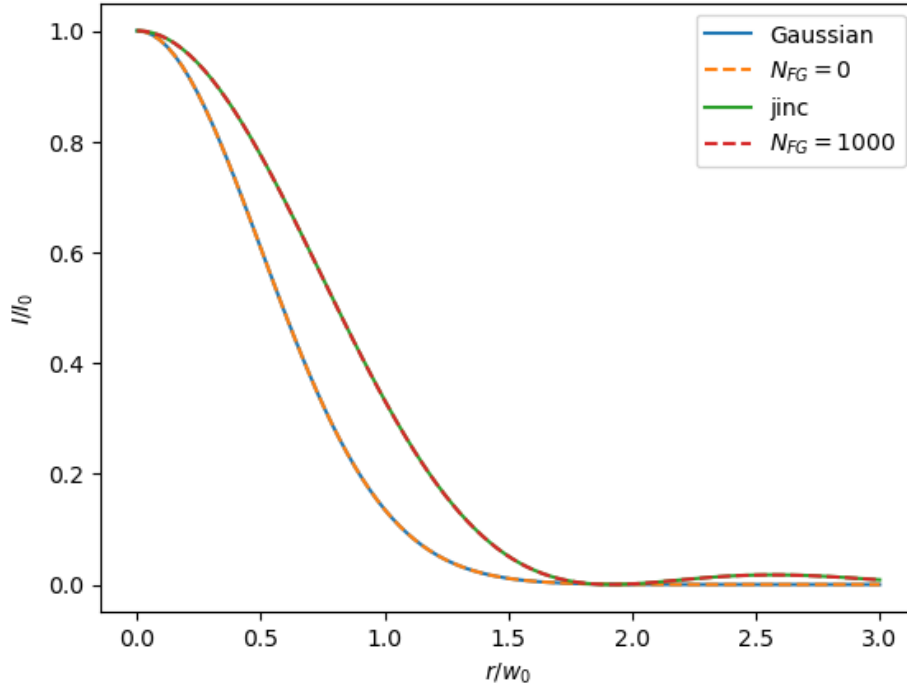


Figure 5.10: Overlay of a flattened Gaussian intensity distributions against a Gaussian (blue) and a jinc (green) intensity distributions demonstrating behavior at $N_{FG} = 0$ and as $N_{FG} \rightarrow \infty$. Due to numerical limitations, $N_{FG} = 10^4$ was the “flattest” profile that could be generated. Note that the beam widths have not been adjusted to equalize the full-width half-maxima between the distributions.

intensity as a comparable Gaussian pulse with a beam waist w_0 . The scale factor for the flattened Gaussian waist can be found numerically, similar to the width parameter R for a jinc profile.

In the near-field, far from the focal plane, the expression for a flattened Gaussian is

$$E(r) = E_L \times \exp \left[-\frac{(N_{FG} + 1)r^2}{w(z)^2} \right] \sum_{n=0}^{N_{FG}} \frac{1}{n!} \left(\frac{(N_{FG} + 1)r^2}{w(z)^2} \right)^n, \quad (5.4)$$

with the paraxial expression for the beam size at location z from the focal plane z_{foc} given by

$$w(z) = \frac{\lambda_0}{\pi w_0} |z - z_{foc}|.$$

Once again, the parameter N_{FG} determines the flatness of the profile. For $N_{FG} = 0$, the profile is Gaussian and for $N_{FG} \rightarrow \infty$, the profile is a flat-top. The near-field and far-field profiles match the expected result from Fourier optics at the $N_{FG} = 0$ and $N_{FG} \rightarrow \infty$

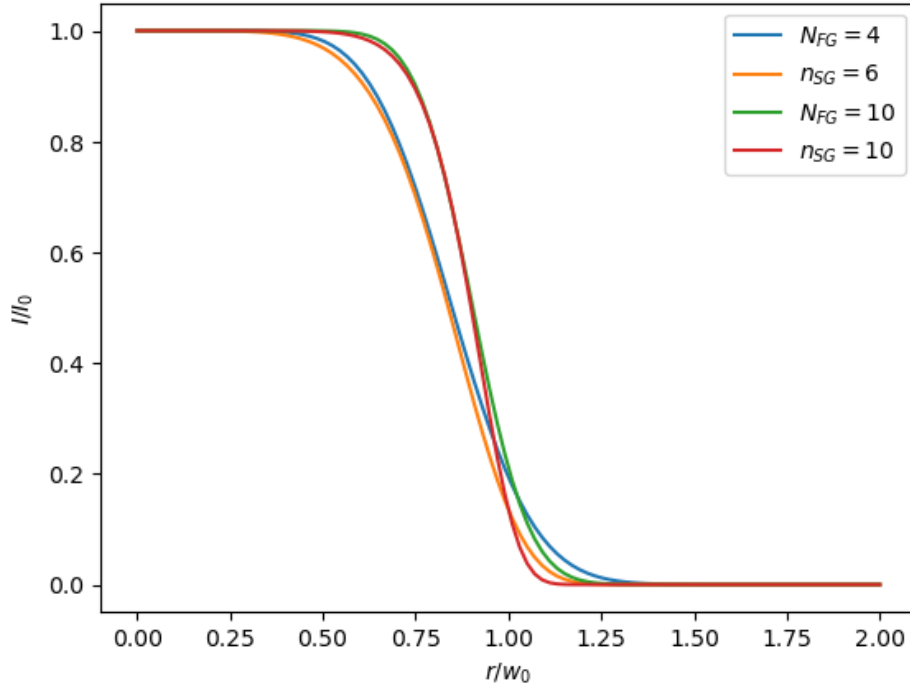


Figure 5.11: Plots of intensity distributions for flattened Gaussian and supergaussian beams. A flatness of $N_{FG} = 4$ (blue) corresponds to an order of $n_{SG} = 6$ (orange) while a flatness of $N_{FG} = 10$ (green) corresponds to an order of $n_{SG} = 10$ (red).

limits. Using the measured laser near-field profile, the flatness parameter N_{FG} could be found by performing a fit using the flattened Gaussian profile and the N_{FG} parameter could be compared to the supergaussian order fits as well. There was slight variation in the experimentally measured near-field beam profile depending on amplification. The beam profile ranged from a flatness of $N_{FG} = 4$ and supergaussian order $n_{SG} = 6$ to a “flatness” of $N_{FG} = 10$ and supergaussian order $n_{SG} = 10$, illustrated in Figure 5.11.

For most simulations, a flattened Gaussian profile of flatness $N_{FG} = 4$ was used. In order to match the full-width half-maximum of intensity for a comparable Gaussian pulse with beam waist w_0 , the flattened Gaussian had a modified waist of $w_0/1.25$.

5.4.2 Plasma channel modeling

The plasma channel profiles were reconstructed from measurements retrieved from two-color interferometry, where the use of a dual-wavelength probe allowed for the separation of the plasma contribution and the neutral contribution to the phase shift [92]. The channel reconstruction used a combination of measured plasma density and the measured neutral density. The measured plasma density was used to reconstruct the density on-axis and out

to a radial position of $r = 30 \mu\text{m}$. Beyond $r = 30 \mu\text{m}$, the reconstructed density was the sum of the plasma density and neutral density. Finally, the reconstructed density profile was fitted with a 4th order polynomial that was used to “cure” the final profile by creating a piecewise function of the reconstructed density and polynomial fit. The entire density reconstruction process can be described by the following:

$$\begin{aligned} n_{\text{plasma_raw}} &= n_{\text{plasma}} \text{ for } r < 30 \mu\text{m}, \\ n_{\text{plasma_raw}} &= n_{\text{neutrals}} + n_{\text{plasma}} \text{ for } r > 30 \mu\text{m}, \\ n_{\text{plasma_cured}} &= n_{\text{poly_fit}} \text{ for } r < 50 \mu\text{m}, \\ n_{\text{plasma_cured}} &= (1 - w) \times n_{\text{poly_fit}} + w \times n_{\text{plasma_raw}} \text{ for } 50 \mu\text{m} < r < r_{\text{max}}, \\ n_{\text{plasma_cured}} &= n_{\text{plasma_raw}} \text{ for } r > r_{\text{max}}, \end{aligned}$$

where $n_{\text{poly_fit}}$ is a fourth order polynomial fit using the function $n(r) = a + br^4$ of the raw reconstructed density profile $n_{\text{plasma_raw}}$ for $r < r_{\text{max}}$, r_{max} is the radial position where $n_{\text{plasma_raw}}$ reaches its maximum, and $w = (r - 50 \mu\text{m}) / (r_{\text{max}} - 50 \mu\text{m})$. This process is illustrated in Figure 5.12. The density profiles were reconstructed for the following delays: 4.5 ns, 5.5 ns, 6.0 ns, 6.5 ns, and 7.3 ns. This set of profiles is shown in Figure 5.13. This is the same process that was used for the density profiles in simulations from Ref. [63].

While the density profile measurements spanned delays between the channel-forming beam and the drive beam of 4.5 ns to 7.3 ns, the experimental data collected was taken with expansion delays ranging from 4 ns to 9 ns. In order to generate density profiles at these delays, the density profiles would need to be extrapolated. The hydrodynamic expansion of an optically-formed channel is the blast wave expansion of the initial plasma column [39] and can be modeled using the Sedov-Taylor blast wave equation for a cylindrical line:

$$r(t) = (\gamma + 1)^{1/2} \left(\frac{ZE_k}{m_{\text{ion}}} \right)^{1/4} [r_0(t + \tau_0)]^{1/2}, \quad (5.5)$$

where gamma is the adiabatic index that is 5/3 for a fully ionized medium, E_k is the electron kinetic energy, r_0 is the radius of the initial plasma column, and τ_0 is the idealized time when $r(t) = 0$.

When applied to the reconstructed profiles, a fit of the form

$$r(t) = a(t + b)^{1/2} \quad (5.6)$$

can be found. The results of the fit for blast wave expansion are plotted on the left in Figure 5.14. This allows for the construction of density profiles within the 4 ns and 9 ns range where data was collected, as shown on the right in Figure 5.14. Using the fitted channel widths, channel profiles can be generated using a quartic model of the form

$$n(r) = n_0(1 + r^4/R_{\text{ch}}^4), \quad (5.7)$$

where R_{ch} is the quartic channel width. Note that this fitted parameter R_{ch} is different from the parabolic channel width r_{ch} described in Section 5.4, and the relation for the quartic channel width to the matched spot size is $R_{\text{ch}}^4 = k_p^2 w_m^6 / 2$.

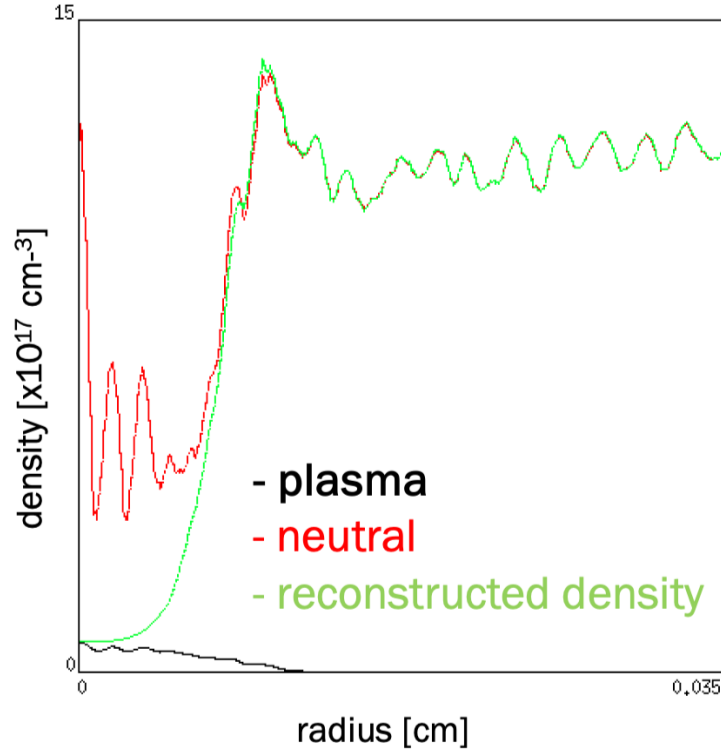


Figure 5.12: Reconstructed density profile, shown in green. The reconstruction is composed of the plasma density data (black) and the neutral gas density data (red). Near the axis, there is poor signal hence large uncertainty in the neutral gas data, so the data in that region is ignored in the reconstruction.

It is then necessary to factor in the finite nature of the optically formed channels. The full plasma channel does not form until the arrival of the main drive pulse which is not captured in the interferometry. The full radial extent of the neutral gas density is not completely ionized. To account for this, the maximum radial width of the density profile must be truncated.

The radial position at which the plasma density profile should be truncated can be found by examining the radial intensity profile of the drive pulse compared to the intensity threshold required to ionize the hydrogen gas neutrals. The laser intensity ionization threshold for hydrogen is on the order of 10^{14} W/cm². Using an energy calibrated intensity profile of the laser, the intensity dropped below the ionization threshold at a radial position of approximately $r \approx 100$ μ m. Using this value, an approximate truncation of the plasma density can be found.

It should be noted that there is still significant uncertainty in the density measurements and plasma profiles and this uncertainty likely dominates along with the laser profile as compared to other parameters such as laser position, laser energy, and plasma length. Fur-

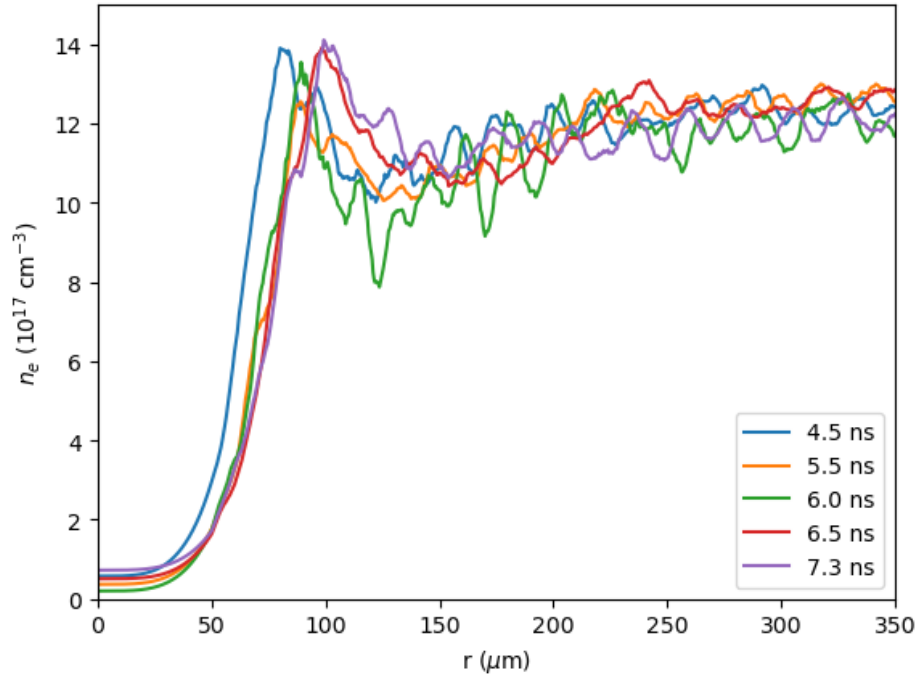


Figure 5.13: Reconstructed plasma channel density profiles at expansion times ranging from 4.5 ns to 7.3 ns.

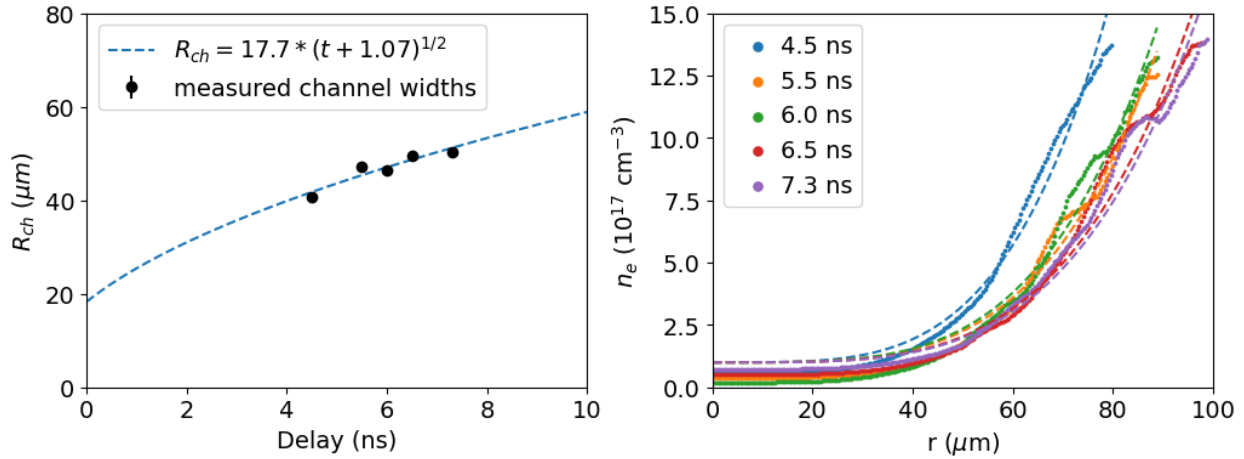


Figure 5.14: Left: Fit of Sedov-Taylor blast wave expansion equation to the measured channel widths. Right: Plot of 4th order fitted polynomials for channel density profiles (dashed line) against reconstructed density profiles (dotted line).

thermore, the uncertainty in density measurements and laser profile as outlined in Section 5.4.1 limit the ability to simulate the direct ionization in order to create the plasma channel. Therefore, simplified models of the plasma channels allow for more rapid iteration of possible channel shapes while providing a reasonable approximation given the uncertainty in the measurements.

All plasma channels also had their quasi-matched radius calculated to enable comparison between channels despite different profiles. The quasi-matched radius of a plasma channel can be found by solving the nonlinear integral equation [100] for quasi-matched propagation of a Gaussian laser pulse in channel given by:

$$\int_0^\infty \rho(r) \left(\frac{2r^2}{w_{qm}^2} - 1 \right) \exp \left(\frac{-2r^2}{w_{qm}^2} \right) r dr = \frac{1}{2}, \quad (5.8)$$

where $\rho(r)$ is the density profile, and w_{qm} is the quasi-matched spot size that satisfies the integral equation. For a parabolic channel, the quasi-matched radius is the same as the matched radius but for non-parabolic profiles, the quasi-matched radius provides a useful metric of comparison.

5.4.3 Propagation simulations

As the simulations are run in FBPIC, the laser profiles at each step are saved. The laser profiles at each step represent the exit modes if the plasma channel were to be truncated at that simulation step. The simulated exit modes can be compared to the experimental exit modes, specifically looking at size and intensity distribution. However, due to the constraints of the imaging within the experimental setup, the resolution of the exit mode imager was around 40 μm . Given that this is close to the laser waist of $w_0 = 53 \mu\text{m}$, for any reduction in laser spot size, the measurements would be close to the resolution limit of the system. As a result, it is difficult to distinguish any changes in the modal composition and profile of the exit mode outside of the unbound modes that are clearly separate from the central spot. In order to examine the beam profile of post-interaction laser pulses more closely, the quasi-near field camera could be used. After propagating approximately 10 m, the expanded beam size provides higher resolution of the beam profile.

In order to collect the same data from simulations, the results from FBPIC simulations needed to be propagated to the longitudinal position of the quasi-near field diagnostic. This could be done in the same PIC-code simulation as the plasma interaction but the computational load would be excessive due to the spatial resolution and temporal step size for laser-plasma simulation that is unnecessary for vacuum propagation. Therefore, an alternative laser code, LASY (LAsEr manipulations made eaSY) [101], was used.

The LASY simulations imported the output laser data files from FBPIC and created laser objects in the code. The laser objects could be manipulated as needed, propagated to the desired longitudinal position, then the propagated laser pulse was saved. In order to propagate the FBPIC exit modes, the default Hankel transform propagator needed to be

replaced by the paraxial propagator. With the paraxial propagator in use, the initial grid step size and domain needed to be tuned. If the initial grid step size was too small, the final propagated beam would lack the correct resolution. If the initial domain was too small, the final propagated beam would be improperly truncated in the radial direction. The vacuum propagation also used the ability in LASY to apply a new grid to the propagated beam which allowed for the correct spatial resolution at both the exit mode and quasi-near field despite the large difference in spatial scale. With vacuum propagation using LASY, both exit modes and quasi-near field modes can be compared between experimental data and simulations.

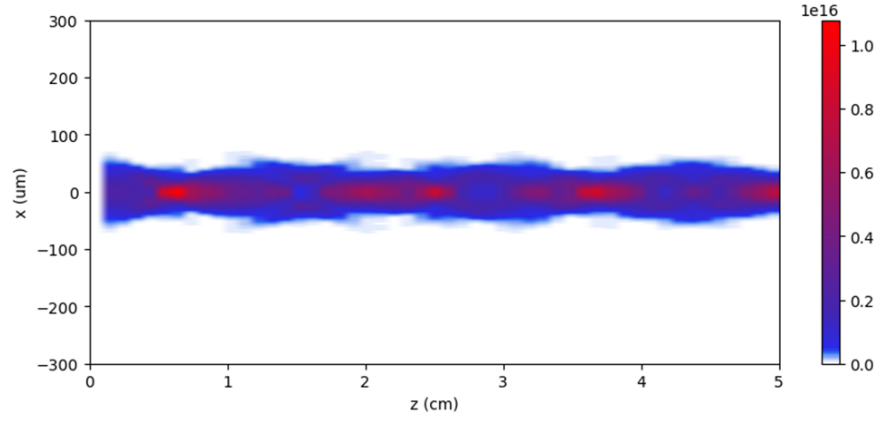
5.4.4 Simulation results

The primary results of the simulations for plasma lensing looked for agreement with the experimental data. First, simulations had to be iterated to ensure the simulation environment was properly configured by comparing results to linear theory. Then the simulation complexity was increased as the results tried to be brought closer to the experimental data.

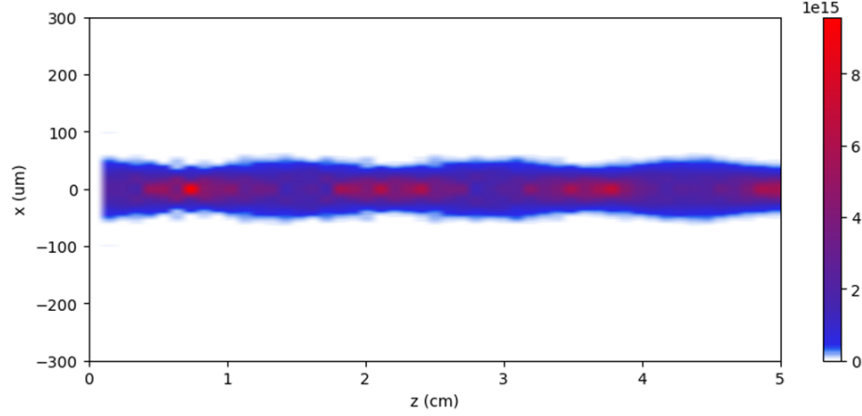
Simulations were performed with variable laser pulse profiles to examine the effects of the laser pulse profile. The results were also propagated 10 m to produce the quasi-near field. The results are shown in Figure 5.15 and Table 5.4. Figure 5.15 (a), (b), and (c) exhibit similar behavior for all three laser pulse profiles. There are oscillations as the laser propagates through the length of the plasma channel. In the propagated modes shown in Table 5.4, there is significant variation between the pulses. The Gaussian pulse modes with multiple ring structures were not exhibited in the experimental data. By the end of the plasma channel, the jinc and flattened Gaussian pulses are undergoing transitions towards a Gaussian profile, which is similar to the experimental results. For all future simulations, the flattened Gaussian profile was used.

After performing simulations to compare laser pulse, variations in the plasma channel profiles were examined. A parabolic, quartic, and the 7.3 ns reconstructed profile were used. All channels had the same on-axis density and quasi-matched radius as calculated from Equation 5.8. The simulation results are shown in waterfall plots in Figure 5.16 and the propagated modes are shown in Table 5.5. The waterfall plots exhibit signs of spot size oscillation as the laser propagates across all channel profiles. There is also no observable leakage outside the channels, indicating the channel depth needs to be adjusted. With the propagated modes, the results are similar. There is slight variation as to the longitudinal position where the laser intensity is focused and maximized as shown in the column for $L_{ch} = 3$ cm. Despite the variations in intensity, all beams have similar modal structure at each measurement location. The conversion of the pulse profile towards Gaussian is reduced.

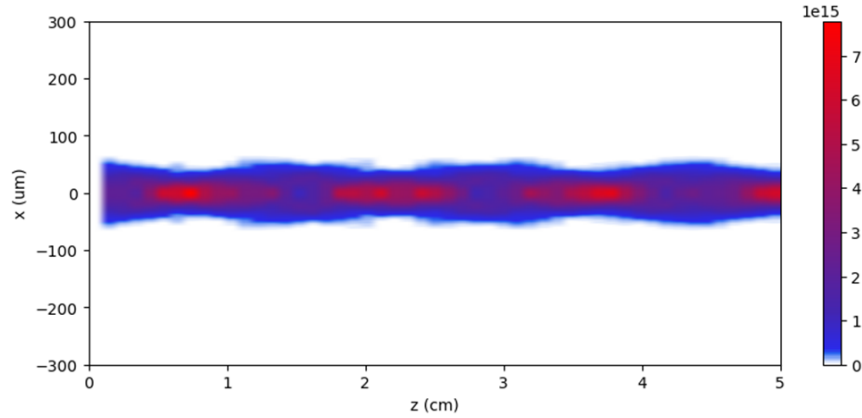
In order to increase the leakage outside the channel to match experimental data, channel truncation due to drive laser ionization was implemented. As specified in Section 5.4.2, the radial ionization threshold was found to be between 80 μm and 100 μm . Simulations with the plasma density threshold truncated in this range were conducted. The results are present in Figure 5.17 and Table 5.6. The results for the wall truncated at 100 μm are almost identical to the results from the full channel in Figure 5.16a, which suggests that channel wall



(a) Waterfall plot of longitudinally averaged intensity for a Gaussian laser pulse.



(b) Waterfall plot of longitudinally averaged intensity for a Jinc laser pulse.



(c) Waterfall plot of longitudinally averaged intensity for a $N_{FG} = 4$ flattened Gaussian laser pulse.

Figure 5.15: Waterfall plots comparing a Gaussian, jinc, and flattened Gaussian profiles propagating in a plasma lens. The colorbars are for the lineout intensity with arbitrary units.

Table 5.4: Table of propagated mode images from simulations using Gaussian, jinc and flattened Gaussian laser profiles.

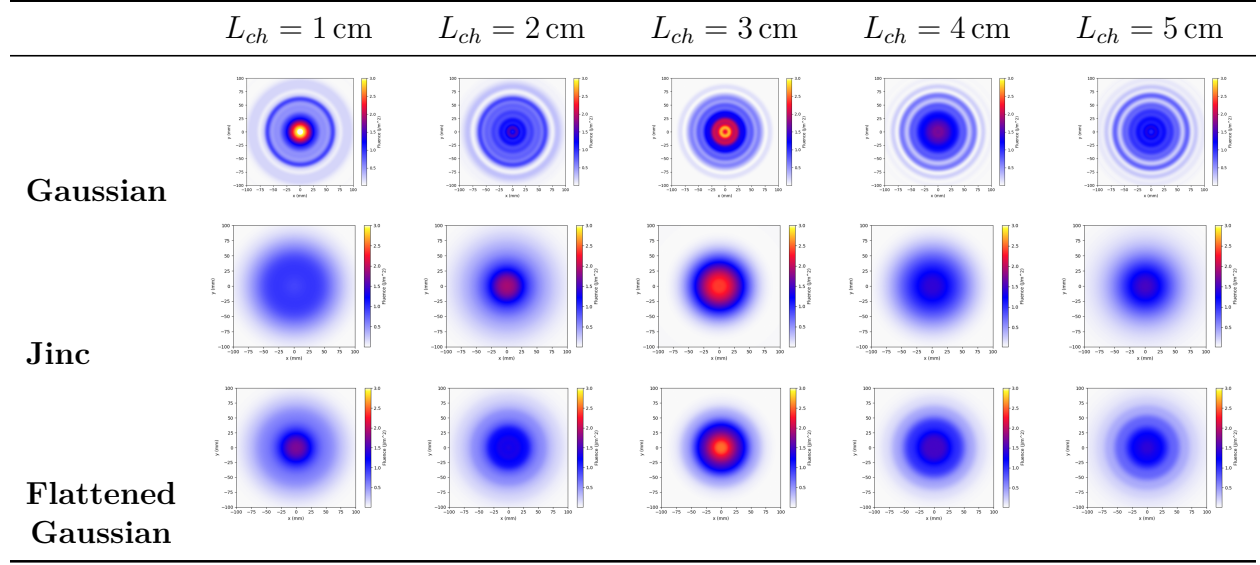
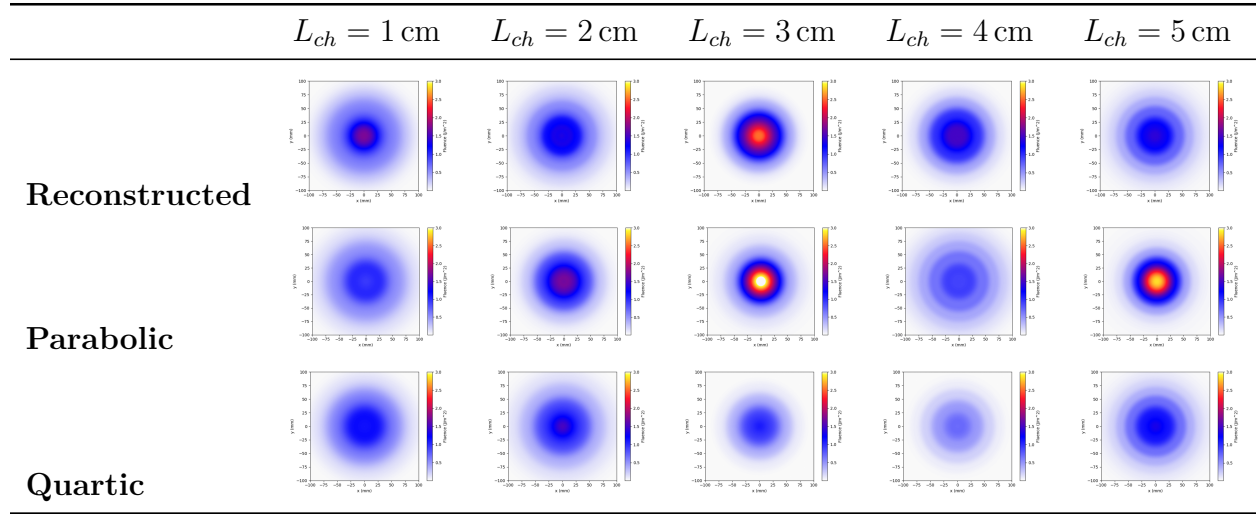
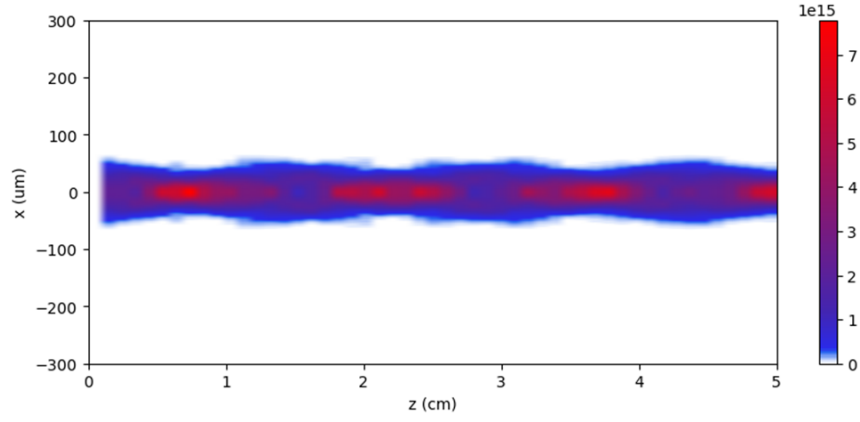
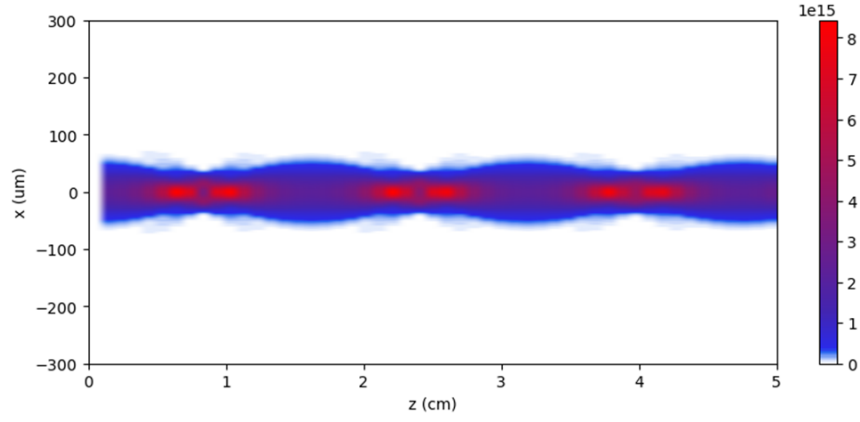


Table 5.5: Table of propagated mode images from simulations using reconstructed, parabolic, and quartic plasma channels.

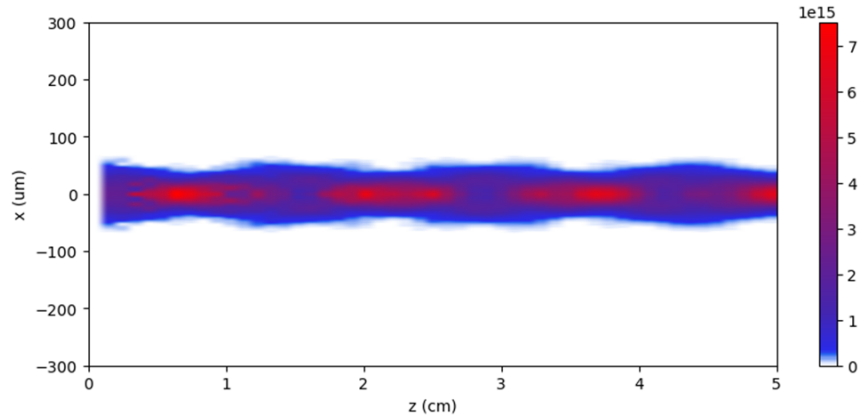




(a) Waterfall plot of longitudinally averaged intensity for propagation in the 7.3 ns reconstructed profile.



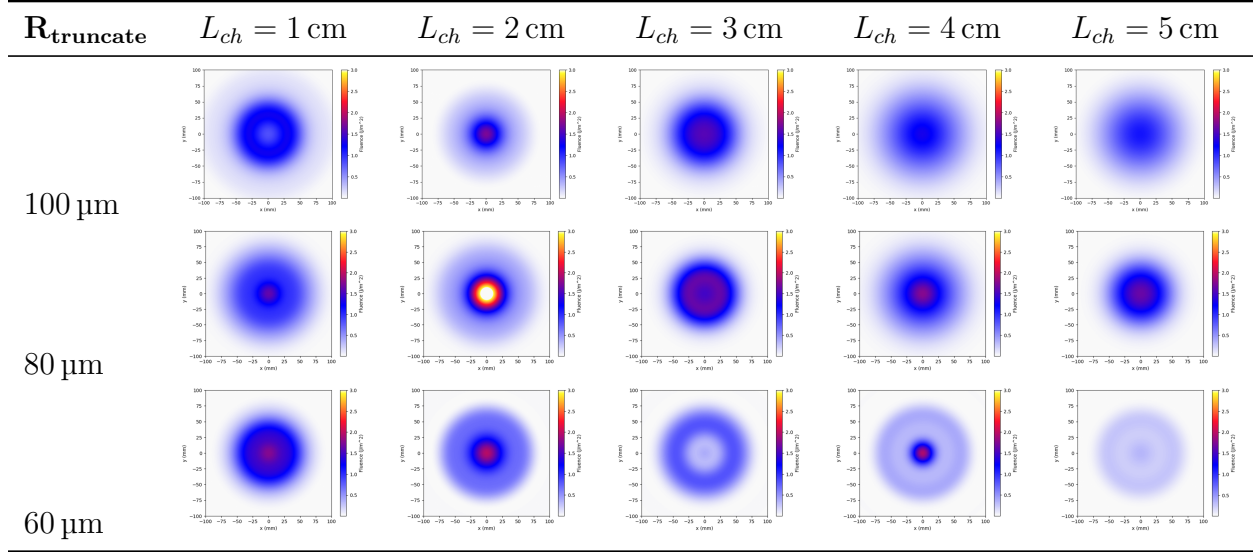
(b) Waterfall plot of longitudinally averaged intensity for propagation in a parabolic channel.



(c) Waterfall plot of longitudinally averaged intensity for propagation in a quartic channel.

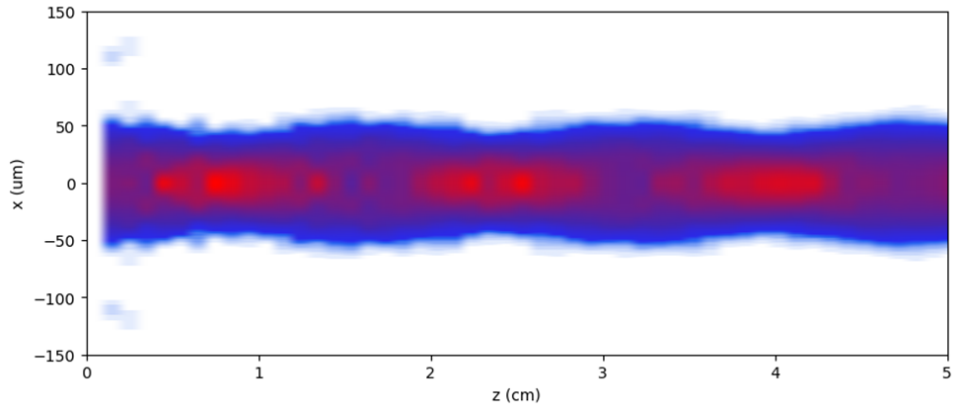
Figure 5.16: Waterfall plots comparing reconstructed, parabolic, and quartic plasma channels. The colorbars are for the lineout intensity with arbitrary units.

Table 5.6: Table of propagated mode images from simulations using a plasma channel with truncated walls between 100 μm and 60 μm .

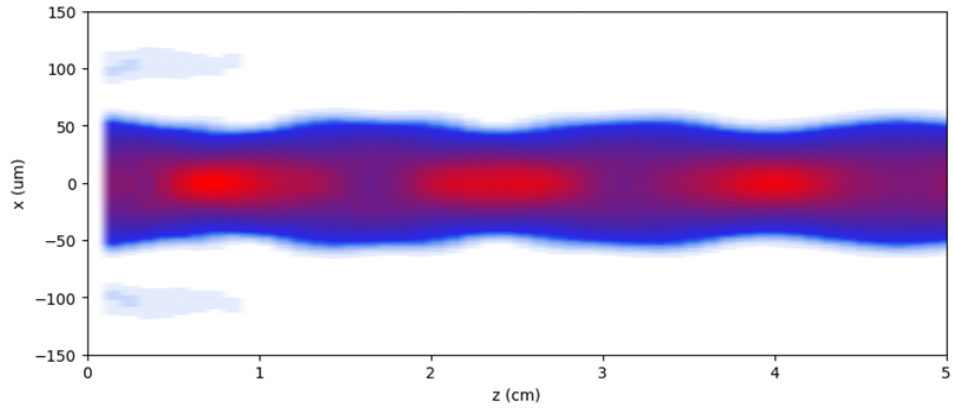


truncation at this location has minimal effect on the mode leakage. As the truncation radius R_{truncate} decreases, the amount of mode leakage outside the channel increases. Additionally, the spot size oscillations decrease as the truncation radius decreases. The setup with the truncation radius at 60 μm shows large losses to leakage, especially evident through the reduced intensity of the propagated modes in Table 5.6. Figure 5.17c shows leakage occurring almost continuously throughout the whole channel, indicating that the channel is too shallow to fully guide the laser pulse. Truncation at 80 μm appears to be the most similar to the experimental results. It does not have the same amount of mode leakage as the experimental data but the transition in the propagated mode towards a Gaussian profile is in-line with the data.

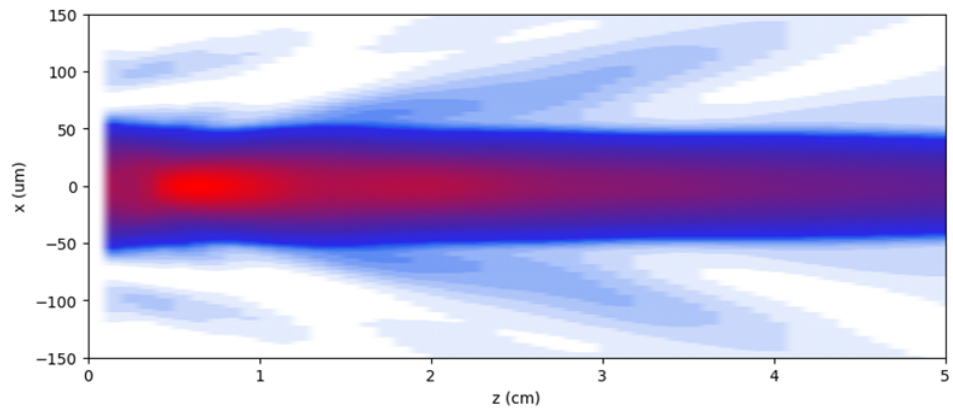
In addition to a sharp cutoff due to truncation, a downramp at the plasma channel truncation was examined. The results are shown in Table 5.7. The addition of the downramp was a relatively small change to the over plasma profile, shown in Figure 5.18 yet there were significant changes in the propagated modes shown in Table 5.7. The sensitivity of the propagated modes to small variations in the plasma density profile pose a challenge in trying to match simulation results to experimental data, especially given the high uncertainty associated with the plasma density profile. Consequently, further investigation is required to establish simulation accuracy compared to the experimental results.



(a) Waterfall plot of longitudinally averaged intensity for a plasma channel with walls truncated at $100\text{ }\mu\text{m}$.



(b) Waterfall plot of longitudinally averaged intensity for a plasma channel with walls truncated at $80\text{ }\mu\text{m}$.



(c) Waterfall plot of longitudinally averaged intensity for a plasma channel with walls truncated at $60\text{ }\mu\text{m}$.

Figure 5.17: Waterfall plots comparing plasma channels with truncated walls between $100\text{ }\mu\text{m}$ and $60\text{ }\mu\text{m}$. The colorbars are for the lineout intensity with arbitrary units.

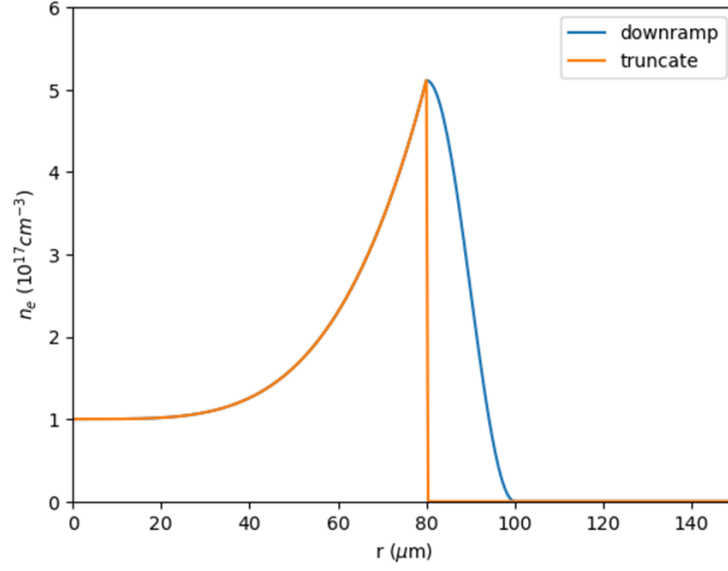


Figure 5.18: Plasma density profile with a truncation at 80 μm (orange) and with a cosine-shaped downramp (blue).

Table 5.7: Table of propagated mode images from simulations using a plasma channel with and without a downramp after the wall truncation.

	$L_{ch} = 1 \text{ cm}$	$L_{ch} = 2 \text{ cm}$	$L_{ch} = 3 \text{ cm}$	$L_{ch} = 4 \text{ cm}$	$L_{ch} = 5 \text{ cm}$
No downramp					
Downramp					

5.5 Conclusion

Plasma lenses have the potential to provide both laser spot size control and mode filtering for laser-plasma accelerators. The laser spot size control can be achieved by leveraging the spot size oscillations that occur during mismatched guiding in a plasma channel. The mode filtering can occur if the plasma channel is leaky due to its finite radial extent. Optically formed plasma channels can provide both functions, with the expansion time of the plasma channel used to control the channel width.

Plasma lensing experiments were conducted with a 5 cm plasma channel with a translatable blade to control the plasma channel length. The variable plasma channel length allowed for observation of the laser evolution as it propagated through the plasma channel. A diagnostic camera was configured to capture the laser mode at the exit of the plasma channel and another diagnostic camera monitored the propagated mode. Exit mode imager was used to calculate the laser spot size evolution at the channel exit while the propagated mode imager was used to calculate laser energy transmission. The measured exit modes differed from the expectations based on linear theory, likely due to nonlinear laser evolution.

To understand the nonlinear laser propagation effects, simulations were performed using a PIC code. Measurements of the drive laser pulse were used in combination with interferometry data on the plasma channels as the basis for inputs to the PIC code. In addition to the measured parameters, the mode leakage and the evolution of the propagated pulse were compared to the experimental measurements. Due to the uncertainties in the measured inputs, a search of the input parameter space around the experimentally measured input conditions was required to work towards agreement with experimental results. It was observed that the simulation results were highly sensitive to small variations in the plasma density profiles, posing a challenge in the comparison of simulation results with experimental data. Further investigation is required to strengthen the connection between simulation and experimental results, which can then be used to optimize the plasma lens design for improved coupling in laser-plasma accelerators.

Chapter 6

Conclusion

This work presents research and developments in plasma optics for enhanced laser control in laser-plasma accelerators. Three forms of plasma optics—plasma mirrors, plasma channel, and plasma lenses—were examined.

Chapter 3 details plasma mirrors that can enable the compact coupling of laser-plasma accelerators in a multi-stage design. The staging of multiple accelerator sections is essential for the development of plasma-based accelerators for high energy gain in the tens to hundreds of GeV and towards TeV-class colliders for high energy physics. By using multiple stages to accelerate particles up to the target energy, the stages can be more compact and require less drive laser energy which improves the overall feasibility of such a design. For the staging of plasma-based accelerators to maintain its compact design, the distance between the stages must also be compact. This requires the compact coupling of the driver for each acceleration section. Compared to particle beams, another possible driver for plasma-based accelerators, lasers can be manipulated on much shorter length scales. Specifically, lasers can be reflected in a 90° angle by a mirror with a turning radius of zero, while the turning radius of particle beams is limited by magnetic field strength and radiation losses. This allows new drive lasers to compactly be injected into a series of accelerators. However, the drive laser for a plasma-based accelerator must be brought to a tight focus to create sufficient intensity required to drive the laser-plasma accelerator. At the centimeter-scale distances to the accelerator, the laser intensity would damage conventional optics. A plasma mirror provides the ability to operate at intensities above the damage threshold of conventional optics and can therefore be located much closer to the accelerator, allowing for compact staging between accelerator sections.

Previous laser-plasma accelerator staging experiments have been performed on the 100-MeV energy level with 40 TW of laser power [26]. Staging experiments at the GeV energy level will be performed on a PW-class laser system. The increase in drive laser power requires changes to the operating conditions of the plasma mirror. There is a maximum intensity beyond which the reflectivity of the plasma mirror starts to decrease [70]. Therefore, the plasma mirror must be further away from the entrance of the accelerator to allow for a larger spot size and therefore a lower intensity on the mirror. This requires a larger area

with sufficiently flat surface quality and improved pointing stability due to the increased deflection from pointing errors.

Using a low-power test stand, improvements to a tape drive-based plasma mirror were made. The surface flatness was characterized by the RMS wavefront error of a probe beam reflected off the tape surface. By optimizing the tape drive setup, the surface flatness across the increased surface area was improved to a RMS wavefront error of (43 ± 9) nm which is sufficiently close to the typical wavefront error on the BELLA PW laser system, around 30 nm. The test stand was also used to develop a pointing correction system that used the reflection of the probe beam to maintain the pointing stability of the tape drive between moves of the target substrate. Measurements showed significant pointing error in the vertical axis of 290 μ rad that were reduced to 12 μ rad. Pointing error in the horizontal axis was also reduced from 60 μ rad to 12 μ rad. The pointing errors with correction enabled were within the system tolerances of ≤ 15 μ rad. These improvements to the tape drive allow for compact laser coupling in future staging experiments.

Staging experiments on BELLA PW are planned and currently ongoing. The first round of staging experiments are targeting a 1 GeV + 1 GeV configuration: The first laser-plasma accelerator stage will include an injector section optimized for stable generation of electron beams and acceleration up to the GeV-level. The first stage is followed by an active plasma lens for electron beam transport to the second stage. The plasma mirror will be used to couple the second drive laser into the second stage where the accelerated electron beam energy will be increased to the few GeV-level. Compared to previous staging experiments, the goal is to demonstrate high charge capture efficiency in the second stage. After demonstration of GeV-level staging, the experimental setup will shift towards a 5 GeV + 5 GeV configuration.

Plasma mirrors must preserve the pulse quality of the drive laser being coupled into each accelerator to maintain accelerator performance. The challenges posed to plasma mirror operation continue to scale as laser power increases due to the intensity limits for plasma mirror reflectivity. As new laser facilities are constructed with greater laser power, further development on plasma mirrors will be required. The demonstration of operation on a PW-class laser system is an important step towards plasma mirror operation at future multi-PW laser power facilities.

Chapter 4 details the use of plasma channels for guiding laser pulses in laser-plasma accelerators with energy gains up to 10 GeV. The use of a preformed plasma channel with a plasma density minimum on-axis allows for guiding of the drive laser pulse similar to a gradient-index optical fiber. Guiding of the drive laser pulse extends the acceleration length beyond the vacuum diffraction length and enables acceleration at lower plasma densities for higher energy gain. The laser guiding experiments used hydrogen plasma channels 30 cm in length at a plasma density $n_0 \sim 10^{17} \text{ cm}^{-3}$. The plasma channels were created through optical-field-ionization, allowing for formation at lower densities ($n_0 \sim 10^{17} \text{ cm}^{-3}$) due to the density-independent heating. The experiment was set up with the ability to change the length of the plasma channel, allowing for examination into the laser evolution as it propagated through the plasma channel.

Laser pulses of $U_L \approx (19.6 \pm 0.4) \text{ J}$ ($a_0 \approx 2.2$) and $U_L \approx (6.0 \pm 0.1) \text{ J}$ ($a_0 \approx 1.3$) were used

to demonstrate guiding in the channels. Guiding at the lower drive laser energy had reduced energy loss to the wake, and provided insight into the evolution of the guided laser mode and the leakage of higher-order laser modes. For the experimental parameters, it was observed that the majority of the mode evolution occurred for channel lengths $L_{ch} \leq 12$ cm after which there was minimal evolution of the guided mode. This was observed in both the exit modes and the propagated modes ~ 10 m downstream of the plasma channel exit. Guiding at the higher drive laser energy produced similar results with regards to laser evolution; however, there was a decrease in the energy transmission as more laser energy was transferred to the wake. Energy transfer to wake was also observed in the gradual red-shifting of the optical spectrum as a function of plasma channel length. These results were supported by PIC simulations. Importantly for the accelerator application, no electrons were trapped or accelerated while driving a wake, meaning the accelerator was dark-current-free.

Electrons were injected and accelerated by adding a N_2 dopant gas. With a 1% dopant, beams with a broad energy spectrum exceeding 10 GeV were observed. By restricting the dopant region to the first 12 cm of the plasma channel, injection was localized and quasimonoenergetic beams with peaks up to 10 GeV were observed. Finally, the dopant concentration was increased to 5%, which produced beams with increased charge up to 100 pC, reduced energy spread as low as 3%, and reduced maximum energy of 7.4 GeV. These results were consistent with beam loading effects. Simulations showed intensity oscillations in the first few centimeters of propagation caused by laser mode beating. The intensity oscillations prevented the acceleration of charge that was injected in the first 6 cm of the accelerator, reducing the maximum energy gain. The simulations also showed that, if the laser transverse profile could be linearly matched to the plasma channel profile, the mode beating and intensity oscillations would be reduced. This would allow for the acceleration of charge injected early in the accelerator and lead to an increase in energy gain 13.0 GeV with a bunch charge of 65 pC for the same drive laser energy. Matching of the laser to the plasma channel profile can be achieved by varying the laser spot size at the entrance of the plasma channel.

The laser guiding and electron acceleration in optically formed plasma channels in this work represent an important development for laser-plasma accelerators. The optically formed channels allow for a lower density plasma channel to suppress self-trapping of background electrons and enable dark-current-free accelerator operation. Dark-current-free operation provides a foundation upon which electron beams can be tailored and accelerated depending on the needs of the application. One application that was advanced as part of this work was the use of multi-GeV electron beams to generate directional muons through pair production and meson decay in a high-Z material target. For laser-plasma accelerator operation at 1 Hz, the directional muon flux is 40 times greater than cosmic ray muons, enabling muography with significantly reduced exposure time.

Chapter 5 details the use of plasma channels as plasma lenses to improve matching and laser coupling efficiency into channel-guided laser-plasma accelerators. A channel-based plasma lens can provide laser spot size control by using the spot size oscillations that occur from mismatched guiding in a plasma channel. Laser systems typically have a fixed laser spot size that is determined by the focusing optic and beamline geometry. As such, changing

components is difficult and expensive due to the size and quality of optics in high-power laser systems. Using a plasma lens close to the laser focus would enable laser spot size control at the location of the laser-plasma accelerator. During mismatched guiding in the linear regime, the laser spot size varies between w_0 and w_m^2/w_0 , where w_0 is the laser waist and w_m is the matched channel radius. By tailoring the channel profile (matched radius) and length (oscillation phase at the exit of the channel), laser spot size control can be achieved and used to match the laser into a channel-guided plasma accelerator for improved laser coupling.

In addition to laser spot size control, a channel-based plasma lens can provide higher-order mode filtering to the drive laser. Higher-order modes that exist in non-Gaussian pulses can be filtered out due to mode leakage that occurs in optically formed channels, which are leaky due to finite in the radial extent. Additionally, separation of the quasi-bound modes will occur due to group velocity dispersion, isolating the fundamental mode of the channel, resulting in a near-Gaussian laser mode. Following the plasma lens, the mode-filtered laser pulse can then be injected into a channel-guided laser-plasma acceleration. Because of the mode filtering that occurred in the plasma lens, mode beating in the laser-plasma accelerator will be minimized. This reduction in mode beating allows charged particles, such as electrons, that are injected into the plasma wake at the start of the plasma channel to remain trapped and be accelerated, increasing the effective acceleration length and the total energy gain.

Experiments were conducted using a 5 cm plasma channel with a translatable blade that provided control over the plasma length. This was coupled with an exit mode imager that was also on a stage to maintain the imaging location at the plasma exit as the length was varied. This experimental configuration allowed for measurements of the laser as it propagated through the channel that gave insight into the laser evolution. Additionally, there was a propagated mode diagnostic located approximately 10 m downstream of the plasma channel. The propagated mode diagnostic allowed for measurements with significantly more data on the spatial composition of the post-interaction beam. Specifically, it provided data on the transition of the laser mode content towards a Gaussian profile. The propagated mode diagnostic was also calibrated to provide an approximate measure of the laser energy that was transmitted through the plasma lens. Nonlinear laser evolution in these experiments resulted in the measured exit modes differing from expectations based on linear laser propagation theory.

To understand the nonlinear laser propagation effects, simulations of the plasma lens were performed using a PIC code and the laser fields were numerically propagated to the quasi-near field for comparison with experimental measurements. Data collected on the drive laser pulse and interferometry of the plasma channel were used to generate models of the laser profile and plasma channel profile as inputs to the PIC code. Mode leakage and the evolution of the propagated pulse were studied and compared to measurements. Further work can be done to optimize the plasma lens design for coupling into a channel-guided laser-plasma accelerator, with energy transmission and the final output beam profile as key metrics.

The research described in this dissertation aims to develop plasma-based optics to improve the ability to control high-power laser pulses for laser-plasma accelerator applications.

Plasma-based optics allow for control of high intensity laser pulses beyond what is possible with conventional optics. As the field of laser-plasma accelerators evolves and matures, accelerator performance requirements will become more specific to each application, requiring enhanced control over the lasers that drive these accelerators.

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