CHARACTERIZATION OF METER-SCALE BESSEL BEAMS FOR PLASMA FORMATION IN A PLASMA WAKEFIELD ACCELERATOR

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Abstract

A large challenge with Plasma Wakefield Acceleration lies in creating a plasma with a profile and length that properly match the electron beam. Using a laser-ionized plasma source provides control in creating an appropriate plasma density ramp. Additionally, using a laser-ionized plasma allows for an accelerator to run at a higher repetition rate. At the Facility for Advanced Accelerator Experimental Tests, at SLAC National Accelerator Laboratory, we ionize hydrogen gas with a 225 mJ, 50 fs, 800 nm laser pulse that passes through an axicon lens, imparting a conical phase on the pulse that produces a focal spot with an intensity distribution described radially by a Bessel function. This paper overviews the diagnostic tests used to characterize and optimize the focal spot along the meter-long focus. In particular, we observe how wavefront aberrations in the laser pulse impact the peak intensity of the focal spot. Furthermore, we discuss the impact of nonlinear effects caused by a 6 mm, CaF_2 vacuum window in the laser beam line.

INTRODUCTION

Particle accelerators are among the grandest machines of the twentieth century because of their contributions to medicine, materials development, renewable energy, and the many fields of high-energy physics and life sciences, with roughly a third of all Nobel Prizes in physics being related to the use or advancements of particle accelerators. However, conventional accelerators are costly due to the size required to accelerate electrons to high energy. Dielectric breakdown in the RF cavities of conventional linear accelerators limits the accelerating gradient to $E_z < 50\,\mathrm{MeV/m}$ [1]. Circular accelerators also face major drawbacks for accelerating electrons, since energy loss due to synchrotron radiation scales with the relativistic factor to the fourth power (γ_b^4). Both limitations are overcome by increasing the size of the machine to reach higher energies. Plasma wakefield acceleration (PWFA) possesses much higher accelerating gradients with some experiments demonstrating $E_z > 100\,\mathrm{GeV/m}$ [2, 3]. This suggests that PWFA can decrease the size of accelerators from the kilometer scale to the meter scale.

Plasma wakefield accelerators must be able to replicate the performance of large particle accelerators to be viable for applications in colliders and light sources. Both applications require high-quality electron beams with low emittance. The incoming electron beam possesses a divergence in the transverse direction inversely proportional to the β^* of the final focus. Conversely, the plasma will create a focusing force with strength determined by the plasma density; however, if the scales of these two effects are not properly matched, the energy spread of the electron beam will drive emittance growth. Unfortunately, the focusing force in a fully ionized plasma column is sufficiently strong that focusing the beam to the transverse size required for matching is not feasible with conventional magnetic optics. It has been shown theoretically and experimentally that introducing a plasma density ramp can properly match the electron beam and preserve emittance [4–9].

At the Facility for Advanced Accelerator Experimental Tests (FACET-II), we preionize hydrogen gas using a laser with a tailored longitudinal intensity profile, creating a plasma density ramp of customizable length. Laser-ionizing plasma has a few distinct advantages over the beam-ionized lithium-vapor oven used in previous FACET-II experiments. The heating of the lithium oven due to the energy deposited by the drive beam will change the plasma density profile, limiting the maximum repetition rate. Moreover, beam-ionized sources suffer from head erosion while this issue is avoided with preionized sources. Most importantly, the density ramps created by the lithium vapor are set in length and are too short to properly match the β^* from the final focus of the beam-line, causing emittance growth. Laser-ionized sources can create nearly any plasma density ramp desired by using the proper focusing optic.

EXPERIMENTAL DESIGN

At FACET-II, we create our plasma by passing a 225 mJ, 50 fs FWHM, 800 nm laser pulse through an axicon or axicon-like optic imparting a conical phase on the pulse that produces a focal spot with an intensity distribution described radially by a Bessel function. The oscillator, pulse stretcher, and amplifiers are located in a laboratory above ground. The laser then travels to the underground beamline via a 30 m evacuated transport line that relay images the laser from the main amplifier to the compressor. This long transport line induces aberrations in the pulse. To correct this, the pulse reflects off a deformable mirror in the laser room, altering the wavefront to cancel aberrations from the transport and amplifiers. After compression, the laser is focused by the axicon-like optic and injected colinear with the electron beam into a $5 \times 10^{16}\,\mathrm{cm^{-3}}$ hydrogen gas where the Bessel beam has a meter-scale region of high-intensity. For more details of the experimental area see Ref. [10]. It is this intensity distribution that creates the plasma density ramp through partial ionization. We measure the laser intensity

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along the length of the focus; leakage light from the first mirror after the focusing optic is incident on a camera mounted on a 1.524 m travel stage where images are taken at set distance intervals. By examining these images, we diagnose various aspects of the pulse quality including collimation, astigmatism, and other forms of aberration, and measure the longitudinal intensity profile of the Bessel beam. We also image the laser at the position of the focusing optic to use as an input for Fourier optics simulations that calculate the intensity in the focal region [11].

AXICON LENS

An axicon is a conical-prism that creates an intensity profile that ramps over a meter-scale region of high intensity. We pass the full 225 mJ of laser through an 0.7° base angle axicon lens with a 20mm ID, 30mm OD annular mask and record ten images every 50 mm. These images are processed with a no-laser background subtraction, and the intensity is fit to a squared zeroth order Bessel function of the first kind. The amplitude of this fit allows us to determine the peak laser intensity as a function of propagation distance, as illustrated in Fig. 1 with error bars determined by the standard deviation of the mean from the ten images at each position. To determine beam collimation, we observe the width of the Bessel spot, that is, the distance between the central maximum and the first Bessel zero. A well-collimated beam has a Bessel width that is constant as a function of longitudinal position. As shown in Fig. 1, the measured beam has an intensity profile in good agreement with the simulated results, implying that our laser is performing as predicted. While we observe a sharp laser-intensity ramp, the ramp shape is determined by diffraction off the ID of the mask and is not adjustable. We mask the axicon, allowing us to delay the position or increase the length of the high-intensity region, but this leaves the ramp shape unchanged.

TANDEM LENS

As the name implies, this optical system is composed of a pair of lenses. The first lens is placed upstream of the second lens and shapes the intensity on the second lens so that it matches the target intensity. The second lens removes the residual phase left by the first lens and adds the target phase. Similar to an axicon lens, the tandem lens also imparts a conical phase on a flat wavefront resulting in a transverse intensity profile described by a zeroth-order Bessel function of the first kind. Unlike the axicon, where the ramps are formed by diffraction off the aperture, the tandem lens is designed to produce a target intensity ramp profile in the longitudinal direction. For more details on the tandem lens optics see Ref. [12]. We measure the intensity profile via the same camera system, however, images were taken at 10 mm intervals. Fig. 2 compares the measured intensity to the intensity predicted by our simulation. Once again, we see quite good agreement between simulation and measurement demonstrating that the tandem lens is capable of producing the target intensity profile.

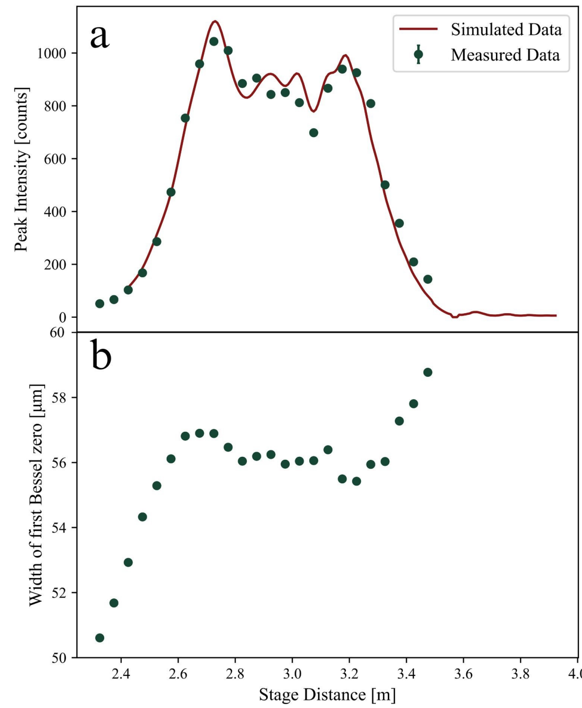

Figure 1: The longitudinal peak laser intensity profile using an axicon lens at full laser power. **a)** Measured peak intensity compared to the simulated intensity. **b)** Measured Bessel width.

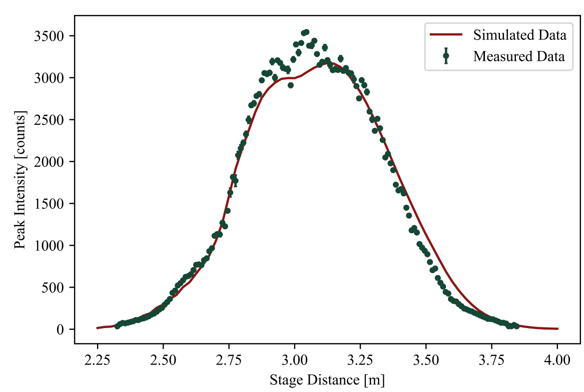

Figure 2: The longitudinal peak laser intensity profile using the tandem lens at low power compared to the simulated intensity.

ABERRATIONS AND NONLINEAR EFFECTS

There are several factors that can prevent the formation of the intended plasma profile. When the laser meets the optic with a flat wavefront, axicons produce perfect Bessel beams. Phase aberration can result in patterns such as those shown in Fig. 3(b) that are saddle-shaped or trefoil-shaped. To diagnose phase issues, we take a series of one-dimensional lineouts at various angles through the center of the Bessel rings. A deformable mirror is used to correct distortions in the wavefront, resulting in a high quality focus as shown in Fig. 3(a). The deformable mirror has proved essential in producing on axis intensity profiles that agree with simulation.

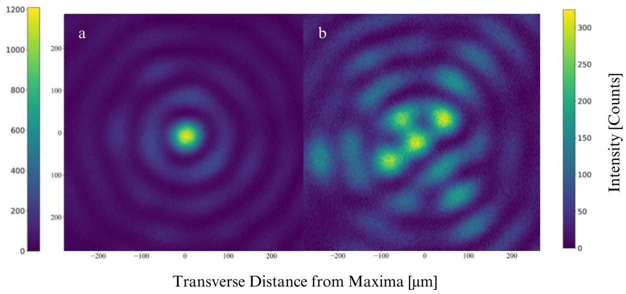

Figure 3: Example intensity profiles from a well and a poorly tuned wavefront. **a)** A flat wavefront produces a symmetric Bessel beam. **b)** A wavefront with aberration produces a distorted asymmetric beam.

Un-correctable aberrations are introduced when our high-powered laser passes through the 6 mm, CaF_2 window separating the compressor from the hydrogen gas. The B-integral in the window distorts the laser as shown in Fig. 4. The two images of the same laser were taken at different compressor grating positions. The peak intensity has been reduced by >50% due to the phase aberration imparted by the window. The aberrations can be removed by removing the window when both sides are under vacuum, confirming that the window is the source of the B-integral.

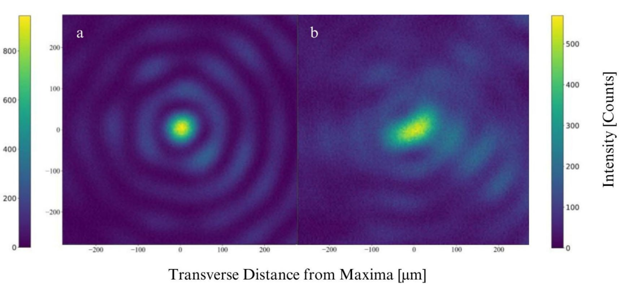

Figure 4: The Bessel focus with two different compressor grating separations. **a)** Under compressed beam. **b)** Fully compressed beam.

The window is necessary in order to contain the ionized hydrogen gas. Due to the difficulty of simulating the effects of this window, we measured the effects on the longitudinal intensity profile directly. It can be seen from Fig. 5 that this distortion alters the peak intensity and shape of the laser intensity ramp for the axicon lens. Note that the errorbars for the plot are significantly larger due to difficulty in fitting a Bessel function to the focal spot at longitudinal positions where the pulse is significantly distorted. Figure 6 shows the effect of the nonlinear distortion from the window when using the tandem lens pair to focus the laser.

CONCLUSION

The significance of this study lies in its departure from previous experiments conducted at FACET, where only limited measurements of the laser were undertaken, predominantly

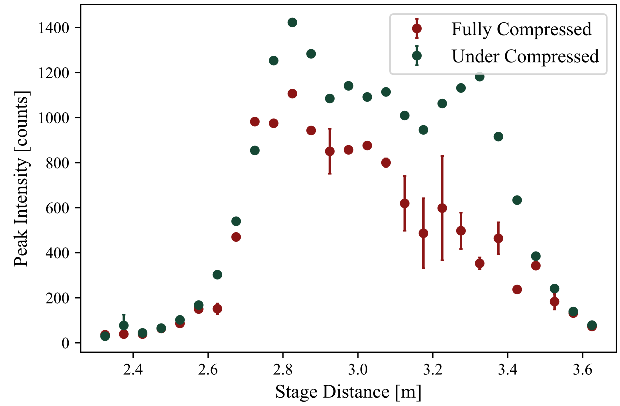

Figure 5: Longitudinal peak laser intensity profiles of identical beams under different levels of compression.

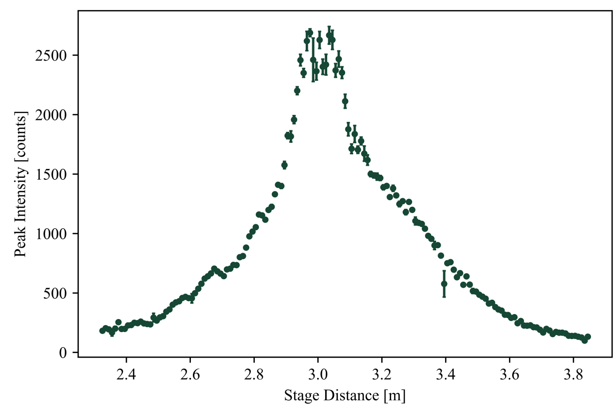

Figure 6: Longitudinal laser intensity profile using the tandem lens at high power with the glass window inserted. Note the difference in shape from the low-power laser shown in Fig. 2.

at low power and at few positions along the beam path, without using a deformable mirror for phase correction. By contrast, we have measured the intensity of the full power laser through the full focal volume, demonstrating the impacts of the transmissive window located after the compressor. Furthermore, our ability to accurately match the measured laser intensity profile with simulation, for both axicon and tandem lens, highlights the importance of phase correction with the deformable mirror. Understanding the evolution of the laser is essential for understanding the formation of the plasma source and thus creating a plasma suitable for demonstrating emittance preservation.

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