

Precision alignment and tolerance of a plasma wakefield accelerator in a laser-ionized plasma source

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We present a novel method to align a laser-ionized plasma source with ultrarelativistic electron beams in a plasma wakefield accelerator. The technique relies on analyzing plasma afterglow light at two longitudinal positions as the plasma column is scanned across the beam axis. Using this method, we aligned an 85-cm plasma source to a 10-GeV, 1.6-nC electron beam with better than 10- μ m transverse offset and 10- μ rad angular error. The alignment was validated by measuring the drive beam energy loss, beam-to-wake energy transfer efficiency, and witness beam energy gain as functions of intentional misalignment. From these measurements, we determined the alignment tolerances required between the laser-ionized plasma source and the electron beams, an essential parameter for the design of plasma-based colliders and advanced light sources.

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I. INTRODUCTION

Plasma wakefield accelerators (PWFA) have shown orders of magnitude higher accelerating gradients compared to conventional radiofrequency (rf) accelerators, making them a lower-cost, more compact solution for future colliders [1–4]. In an electron beam-driven PWFA, a “drive” bunch of electrons expels plasma electrons from the beam axis as it travels through plasma, creating a plasma wake behind it. The much heavier ions remain stationary and attract the expelled electrons back to the axis, forming an ion bubble surrounded by a sheath of electron current. This structure simultaneously provides a transverse focusing force and a longitudinal accelerating field for a second “witness” electron bunch.

PWFA has been demonstrated using beam-ionized alkali vapor ovens [5,6], beam-ionized noble gases [7], discharge plasma sources [8–10], and laser-ionized plasma sources [11]. Beam-ionized alkali plasma sources based on heat pipe ovens offer the advantage of being self-aligning to the electron beam but suffer from head erosion of the drive

beam [12] and overheating from excess deposition of beam energy, making them unsuitable for high repetition rates. Preionized discharge plasma sources avoid head erosion and have been used to demonstrate energy spread [8] and emittance [9] preservation with relatively low-energy electron beams. However, both discharge plasma sources and an alkali vapor ovens present challenges in shaping the plasma density profile and offer limited optical access for optical diagnostics [13] and laser injection schemes [14].

Laser-ionized plasma sources can create plasmas with controlled longitudinal density profiles, required for emittance preservation [15–17], and controlled diameter, necessary for advanced PWFA applications such as positron acceleration [18,19] and the ion channel laser [20]. A major challenge of this scheme is to align the plasma column to the electron beam with sufficient precision. This challenge is exacerbated with high-current electron beams, as it is difficult to accurately determine the electron beam vector at the waist using optical-transition-radiation-based (OTR) beam diagnostics due to the presence of camera-blinding coherent transition radiation (COTR). Using traditional OTR-based alignment, we achieve a plasma-to-beam (laser-to-beam) alignment of 200 μ m.

For our application, at the Facility for Advanced Accelerator Experimental Tests II (FACET-II) at the SLAC National Accelerator Laboratory [21], an 85-cm-long, 200- μ m-diameter laser-ionized plasma is formed in a 1.35-torr hydrogen gas (plasma density of 4.5×10^{16} cm⁻³).

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The diameter of the wake is approximately $\lambda_p = 150 \mu\text{m}$, necessitating a plasma-to-beam (laser-to-beam) alignment of better than $50 \mu\text{m}$ along the length of the plasma.

In this paper, we describe the experimental setup in Sec. II and introduce a novel alignment technique based on plasma afterglow light, that is suitable for the high-current FACET-II beams, in Sec. III. This technique enables us to align the plasma to the electron beam with a precision of $10 \mu\text{rad}$ in tilt and $10 \mu\text{m}$ in offset. Following the alignment, we explore the plasma-to-beam alignment tolerance for this experimental setup in Sec. IV.

II. EXPERIMENT

At FACET-II, the plasma is formed by a 200-mJ, 50-fs laser pulse that passes through a pair of diffractive optics, denoted Lens A and Lens B in Fig. 1, forming an 85-cm long Bessel focus with a focal spot diameter of $120 \mu\text{m}$ beginning 1.45 m downstream of lens B. When the beamline is filled with a $4.5 \times 10^{16} \text{ cm}^{-3}$ hydrogen gas, the laser is modestly refracted by the partially ionized plasma formed at the head of the pulse, resulting in a 200- μm -wide plasma column [22]. The plasma column vector follows the ionization laser's trajectory. In between lens B and the start of the Bessel focus, the laser reflects off two mirrors (M1 and M2) that are used to adjust the alignment of the laser relative to the electron beam. In addition to mirrors M1 and M2, both lens A and lens B are located on two-axis translation stages, allowing the plasma to be translated in the transverse plane independent of the trajectory angle. The leakage light from M1 is viewed by the RAIL camera to collect shot-to-shot laser position at focus.

The FACET-II linac delivers 10-GeV electron beams, in a single-bunch configuration, at 10 Hz, with a total charge of 1.6 nC, transverse root-mean-square (rms) spot sizes of $20 \times 20 \mu\text{m}$, a bunch length of $20 \mu\text{m}$, resulting in a peak current of $> 30 \text{ kA}$, and a normalized emittance in both transverse dimensions of approximately 10 mm mrad [21]. A two-bunch configuration is achieved by inserting a collimator into the center of the beam in a dispersive region [23], creating a drive beam of 0.9 nC and a witness beam of 0.1 nC.

The electron beam travels from left to right in Fig. 1, focused by a set of three quadrupoles to produce a waist with adjustable beta function of 10–50 cm and an adjustable waist location around the entrance of the laser-ionized plasma column at the interaction point (IP). The electron beam is timed to arrive 2 ps behind the laser pulse. At the IP, four viewing ports are equipped with cameras (OTR0, OTR1, OTR2, and OTR3). Metal foils can be inserted into the beamline at 45° to the beam axis to serve as OTR-based beam position diagnostics at OTR0, OTR1, OTR2, and OTR3. At the middle two ports (OTR1 and OTR2), mirrors can also be inserted at 45° to reflect the laser beam to the camera in order to diagnose its position at these locations. When neither the mirror nor the metal foil is inserted, OTR1 and OTR2 can also directly view the laser-ionized plasma.

Upstream of the IP, a low-power HeNe laser assists in marking the electron beam vector acquired by OTR-based beam vector measurement via OTR0 and OTR3. Downstream of the IP, an electron imaging spectrometer, consisting of three quadrupoles and a dipole, transports and disperses the beam to image the plasma exit plane onto a

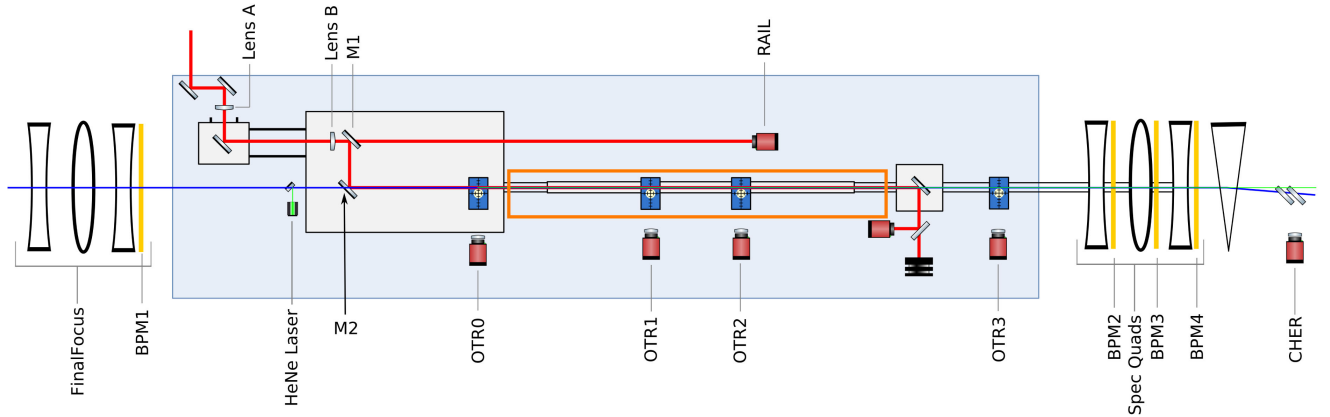


FIG. 1. Experimental setup around the interaction point (IP area) at FACET-II. The electron beams travel from left to right (blue line) and are focused by the Final Focus, which is composed of three quadrupoles. Along the electron beam path, there are four insertable OTR screens, monitored by cameras: OTR0, OTR1, OTR2, and OTR3, respectively. The distance between OTR1 and OTR2 is 40 cm. The compressed laser beam (red line) enters the IP area from the top of the figure and passes through the tandem lens pair (lenses A and B). The laser beam is then reflected off mirrors M1 and M2, which are used to align the laser beam to the electron beam vector. The laser intensity incident on M2 has a donut-shaped profile, and because M2 is a hole mirror, the electron beam passes through its center without interfering. The laser focus appears within the orange area. Mirrors can be inserted at a 45° angle at OTR1 and OTR2 to view the laser focus. An alignment laser (green line) is used to mark the electron beam vector in the IP area. Finally, the electron beams are imaged by the spec quads to a Cherenkov-based detector (CHER). Four beam position monitors (BPMs) are marked yellow behind quadrupoles.

Cherenkov-based detector screen (CHER). Beam position monitors (BPMs) are located before and after the IP to measure the shot-to-shot beam position before and after the beam-plasma interaction. Further details of the experimental area and the available diagnostics at FACET-II are provided in Ref. [7].

III. PLASMA AFTERGLOW-BASED ALIGNMENT TECHNIQUE

In this section, we introduce a novel alignment technique to align an 85-cm plasma to the electron beam based on the plasma afterglow light emitted by the plasma, suitable for achieving the alignment requirement demonstrated in Sec. IV. In the absence of the electron beam, a thin, laser-ionized plasma source emits the afterglow light [13]. When an electron beam drives a wake in the plasma, the brightness of the plasma light scales linearly with the amount of energy deposited into the plasma [24,25]. Further, the amount of energy deposited—and thus light emission—is reduced, but not eliminated, when the beam narrowly misses the plasma [26]. This beam-driven light emission is an order of magnitude larger than the light from the laser-ionized plasma alone. Because of this feature, plasma afterglow light can be used for transverse alignment and synchronization [27,28]. Figures 2(c) and 2(d) provide examples of plasma light images, with and without an electron-driven wake.

To perform the alignment of the 85-cm plasma to the electron beam, the plasma afterglow light was recorded on OTR1 and OTR2 while scanning the transverse position of the plasma column across the electron beam vector, as illustrated in Fig. 2. The plasma position is controlled by

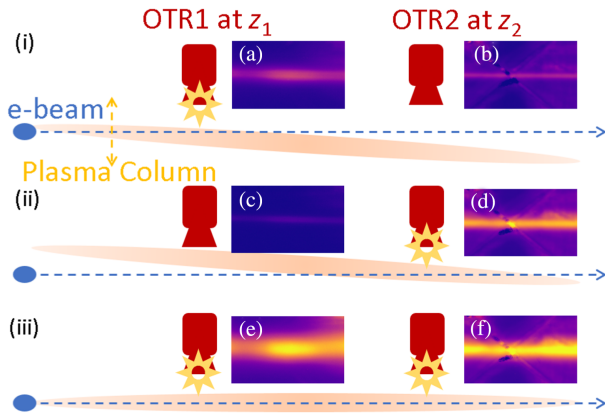


FIG. 2. Alignment method. The electron beam vector is shown as a blue dashed line moving from left to right. The plasma column is scanned transversely across the beam vector. When the plasma column is tilted relative to the electron beam vector, OTR1 (a) initially observes more light than OTR2 (b). As the plasma moves past the electron beam, the light on OTR1 is reduced (c), while the light on OTR2 increases (d). When the plasma is aligned to the electron beam, both cameras observe bright plasma at the same time (e) and (f).

translating lens A and B via micrometer-precision stepper motors. Because the ionizing laser has a flattop profile and overfills lens A, simultaneous transverse translation of lens A and B produces a pure lateral shift of the plasma column without altering the focus.

When the plasma column is misaligned with respect to the electron beam vector, the plasma afterglow brightness reaches its maximum at different plasma column positions on OTR1 and OTR2 [Figs. 3(a)–3(d)]. We can then calculate the misalignment angle and position and align the plasma column accordingly by adjusting M2 (for the angle) and translating lens A and B (for the position) until the plasma afterglow light is maximized simultaneously at both cameras [Figs. 3(e) and 3(f)]. This method offers a significant advantage over conventional OTR-based alignment, as it directly measures the vector misalignment through the interaction between the electron beam and the plasma, providing a more accurate and reliable signal.

The results of a two-dimensional scan of the laser (plasma) position are shown in Fig. 3. Acquiring the full 20×20 -step transverse scan, with ten shots per step as shown in Fig. 3, takes over an hour due to the network-related bottleneck when saving data. As long as the initial alignment is within 0.5 mm, iterative one-dimensional scans can be used in the vertical and horizontal axes to achieve the best possible degree of alignment in

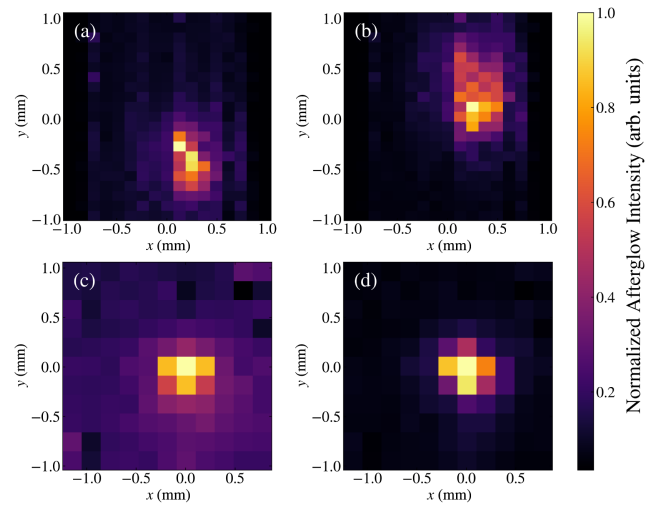


FIG. 3. Raster scan results. The color map indicates the normalized plasma afterglow intensity. (a) Plasma afterglow intensity as a function of the plasma column position relative to a defined beam axis at OTR1 and (b) plasma afterglow intensity at OTR2. When the plasma column is misaligned with the electron beam vector, the plasma afterglow intensity is maximized at different relative positions for each camera. In contrast, in an aligned case, the plasma afterglow intensity is maximized simultaneously at OTR1 (c) and OTR2 (d). The transverse coordinate origin ($x = 0$, $y = 0$) is arbitrary because the alignment is performed relative to the electron beam trajectory rather than to a fixed absolute reference.

significantly less time than a high-resolution two-dimensional scan.

Although, in theory, this alignment procedure only needs to be performed once after the misalignment is measured, in practice, an iterative process with a feedback gain of 0.5 is used for two reasons. First, it better mitigates measurement noise. For example, if the electron beam possesses current spikes [7] and ionizes the plasma, the resulting afterglow measurement may not accurately reflect the alignment; the iterative process ensures the alignment is achieved once the scan has converged. Second, the tip-tilt of M2 is controlled by piezo linear actuators (picomotors), which have repeatable linearity only for small steps. The calibration between angle and picomotor steps becomes less accurate for large moves; therefore, a 200- μm misalignment cannot be corrected accurately in a single step.

At FACET-II, we have implemented an automated procedure to perform this alignment. First, with the laser blocked, we insert metal foils at OTR0 and OTR3 to record the electron beam trajectory using points far from the waist (to minimize the impacts of COTR). Next, we use the same two screens to align the HeNe alignment laser to the electron beam vector (see Fig. 1). To obtain a coarse initial alignment of the ionization laser with the beam vector marked by the HeNe alignment laser, we insert mirrors at OTR1 and OTR2 to view the laser beam position and use mirrors M1 and M2 for a two-point alignment. Typical measurements of plasma interaction strength after OTR-based alignment are shown in Figs. 4(a) and 4(b), showing a misalignment as large as 200 μm and 80 μrad .

Finally, we proceed with an automated 1D plasma afterglow-based alignment, iteratively measuring the angular misalignment by the afterglow signal in x and y and adjusting M1 and M2 to correct the misalignment until alignment is achieved in both directions. The results after the full alignment procedure are shown in Figs. 4(c) and 4(d). The residual peak separation from the Gaussian fits demonstrates alignment better than 10 μrad in tilt and 10 μm in offset.

IV. ALIGNMENT TOLERANCE STUDY

The geometric position and angular tolerance of a PWFA in a laser-ionized plasma source can be estimated as

$$dr + L\sin(d\theta) \leq 2(R_p - r_b) \quad (1)$$

where R_p is the radius of the plasma column, r_b is the blowout radius, L is the length of the plasma, dr is the transverse offset from the center at the start of the plasma column, and $d\theta \ll 1$ is the angular misalignment. With $2R_p = 200 \mu\text{m}$, $2r_b \approx \lambda_p = 157 \mu\text{m}$ (λ_p is the plasma wavelength), and $L = 85 \text{ cm}$, we can predict that $dr \leq 43 \mu\text{m}$ when $d\theta = 0$, and $d\theta \leq 50.6 \mu\text{rad}$ when $dr = 0$. This calculation seems straightforward. Previous studies have shown that a misaligned drive beam can be attracted

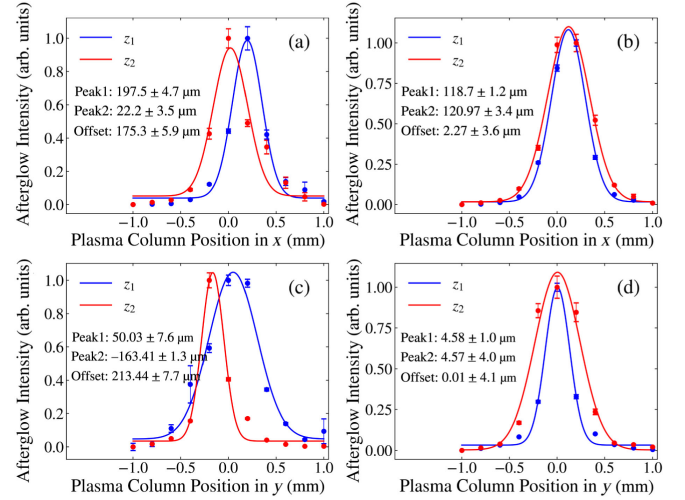


FIG. 4. One-dimensional scan results for plasma column alignment in x (a),(b) and y (c),(d) directions. The plots show the normalized plasma afterglow intensity as a function of the plasma column position. The markers represent the experimental data points with error bars, and the curves are the Gaussian fit results. (a) OTR-based alignment (coarse alignment) result for the x direction measured at two different longitudinal positions: OTR1 (z_1) (blue) and OTR2 (z_2) (red); the peaks are separated by 175.3 μm . (b) Plasma afterglow-based alignment (fine alignment) result for the x direction. As the alignment improves from coarse to fine, the peaks of the afterglow intensity curves at OTR1 and OTR2 converge to 2.27 μm in x , indicating successful alignment of the plasma column with the electron beam. Similarly, (c) and (d) show the coarse and fine alignment results in the y direction. The peak separation improves from 213.4 to 0.01 μm .

into the plasma column [26,29], which suggests that the alignment tolerance may be greater than that predicted by the simple geometric argument of Eq. (1), implying that slight misalignments can be “corrected” by the attractive force, thereby increasing the effective tolerance.

To study the alignment tolerance of the PWFA, we scanned the plasma transversely across the electron beam vector, similarly to the alignment method introduced in Sec. III. The shot-to-shot plasma-to-beam misalignment is measured using the laser far-field camera and the RAIL camera (to determine the shot-to-shot laser vector) and the two BPMs downstream of the IP (to determine the shot-to-shot beam vector) [30]. The energy spectra are analyzed, and the minimum energy of the decelerated electrons ($E_{\min}$), the beam-to-wake energy transfer efficiency ($\eta_{\max}$) extracted from the spectra assuming the missing charge has the minimum energy visible on the screen [11], and the witness beam energy gain (E_{gain}), as functions of misalignment in both transverse directions, are plotted in Fig. 5.

The $E_{\min}$ and $\eta_{\max}$ distributions show a tolerance of $\approx 150 \mu\text{m}$, while a tolerance of $\approx 40 \mu\text{m}$ is necessary to maintain a consistent value of E_{gain} . Although previous studies suggested that a misaligned drive beam may be

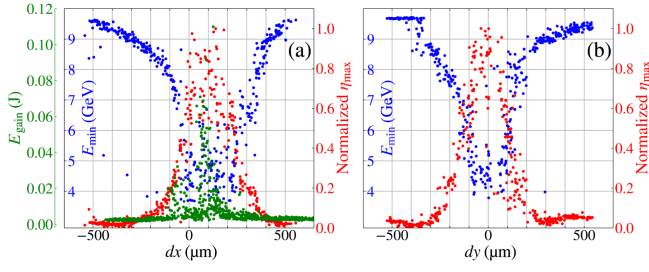


FIG. 5. PWFA performance as a function of beam-to-plasma misalignment in x (a) and y (b). The markers represent the experimental data points of the minimum energy of the decelerated electrons (E_{min} , blue), the normalized upper bound of beam-to-wake energy transfer efficiency (η_{max} , red), and the energy gained after the PWFA (E_{gain} , green). The E_{gain} result shows that the transverse misalignment must be less than $40 \mu\text{m}$. The tolerance is measured by the extent of the flattop region of the peak, with the boundaries determined by fitting decay functions to the left and right edges and taking their intersection with the plateau level. Due to limited beam time and subsequent accelerator downtime, witness energy gain was measured only for horizontal beam-plasma offsets. No qualitative difference is expected for the conclusions presented here for vertical offsets.

pulled into the plasma column [26], the driven wake is noticeably weaker in this case, because the sheath electron current is smaller at the misaligned edge. Moreover, there is likely an offset between the drive and witness beams, which reduces the size of the transverse acceptance window relative to the drive. This effect is evident from the more limited tolerance observed in E_{gain} . This finding indicates that E_{min} may overestimate the alignment tolerance of a PWFA in a laser-ionized plasma source. Instead, acceleration metrics such as E_{gain} provides a more reliable indication. The results show that the transverse offset for the parallel plasma column must be less than $40 \mu\text{m} = 0.93 \times 2(R_p - r_b)$ to maintain an E_{gain} consistent within 97% of the peak achievable value.

Figure 6 shows the beam-to-wake energy transfer efficiency (η_{max}) as a function of transverse and angular misalignment. At each step of the angular misalignment scan, the transverse position was scanned. The results show that the angular misalignment tolerance to maintain a consistent η_{max} within 85% of the peak achievable value is less than $48 \mu\text{rad}$. When normalized to the plasma length, L , this corresponds to an angular offset tolerance of $48 \mu\text{rad} = 0.95 \times 2(R_p - r_b)/L$.

Both the transverse and angular tolerances are consistent with the geometric calculation, indicating that geometric estimates are a reliable metric for determining alignment tolerance in a laser-ionized PWFA. The vertical spread of the data points in Figs. 5 and 6 is largely driven by the sensitivity of the PWFA interaction to jittering electron beam parameters, such as the bunch charge and compression. At FACET-II, with a laser rms pointing jitter of $10 \mu\text{rad}$ and an electron beam position jitter of up to $30 \mu\text{m}$

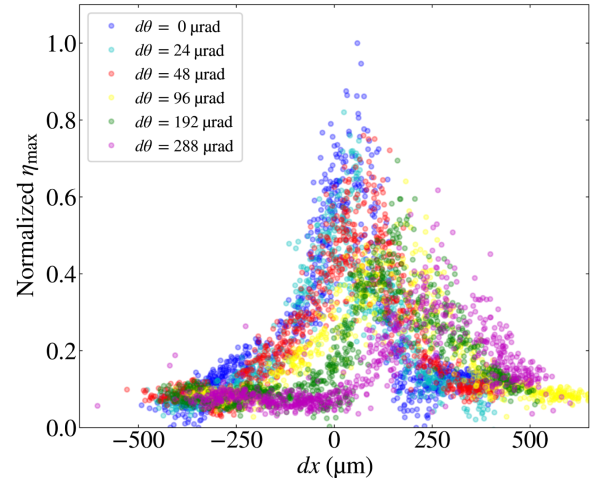


FIG. 6. PWFA performance as a function of beam-to-plasma misalignment with different angular misalignment. The markers represent the experimental data points of the normalized upper bound of beam-to-wake energy transfer efficiency (η_{max}). The results indicate that the angular misalignment tolerance lies between 24 and $48 \mu\text{rad}$: at $24 \mu\text{rad}$ (light blue), the outcome is consistent with the aligned case (dark blue), whereas at $48 \mu\text{rad}$ (red), the amplitude of the peak begins to decrease.

at its waist, stable PWFA operation is successfully demonstrated in a laser-ionized plasma source [11].

V. CONCLUSIONS

We have presented a novel alignment technique developed at FACET-II to precisely align a meter-scale laser-ionized plasma source with a 10-GeV , 1.6-nC high-current electron beam. This method automates two-point alignment based on plasma afterglow diagnostics. By performing 1D scans along the x and y axes, we measured and corrected misalignments, achieving alignment precision within a $10\text{-}\mu\text{m}$ offset and $10\text{-}\mu\text{rad}$ tilt. The entire alignment could be achieved in 1 h while operating at 10 Hz , limited primarily by data transfer and storage rates.

One limitation of this method is the dependency of plasma afterglow brightness on the wake strength driven by the beam, which can be influenced by beam ionization rather than by alignment accuracy to the laser-ionized plasma column. This issue can be mitigated by reducing the beam current through adjustments to beam compression, ensuring reliable alignment diagnostics, or by utilizing a high ionization threshold gas, such as helium.

Following successful plasma-to-beam alignment, we measured the alignment tolerance of the PWFA interaction by analyzing the minimum energy of the decelerated drive-beam particles (E_{min}), the drive beam-to-wake energy transfer efficiency (η_{max}), and the energy gain of the witness beam (E_{gain}). Measurements of the drive beam performance via E_{min} and η_{max} showed a more relaxed alignment tolerance than that of the witness beam acceleration,

E_{gain} , due to the attractive force exerted by the plasma column. Meanwhile, the geometric model predicted the tolerance of the witness beam acceleration via E_{gain} very well. At FACET-II, the required level of precision has been achieved, enabling stable PWFA operation in a laser-ionized plasma source.

This study is critical for future plasma-based collider designs, particularly for staged plasma accelerator modules and narrow plasma channels for positron acceleration [18]. The alignment method and tolerance characterization demonstrated here provide a practical pathway for meeting these stringent requirements in high-repetition-rate collider environments.

In conclusion, this novel alignment method significantly enhances the precision and reliability of plasma column alignment in PWFA experiments. These advancements position laser-ionized plasma sources as a promising next-generation technology for future plasma wakefield accelerators.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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