

Improved electron beam stability in laser wakefield acceleration through control of laser angular chirp and wavefront stability

Zhan Jin^{1,2,*} Yan-Jun Gu^{1,2} Shingo Sato¹ Nobuhiko Nakanii^{2,3} Kai Huang^{2,3} Izuru Daito³ Toshiya Muto,¹ Yoshio Mizuta,¹ Szuba Wojciech² Masaki Kando^{1,2,3} and Tomonao Hosokai^{1,2}

¹SANKEN, *The University of Osaka*, Mihogaoka 8-1, Ibaraki, Osaka 567-0047, Japan

²Laser Accelerator R&D, Innovative Light Sources Division, *RIKEN SPring-8 Center*, Kouto 1-1-1, Sayo-cho, Sayo-gun, Hyogo 679-5148, Japan

³*Kansai Institute for Photon Science (KPSI), National Institutes for Quantum Science and Technology (QST), 8-1-7 Umemidai, Kizugawa, Kyoto 619-0215, Japan*



(Received 30 April 2026; accepted 2 October 2026; published 23 October 2026)

Stable operation of laser wakefield acceleration (LWFA) is essential for future applications of compact radiation sources and advanced accelerators. In this work, we investigate stabilization of LWFA electron beams through control of laser angular chirp and wavefront stability. We show that angular chirp strongly affects beam pointing stability and identify an instability-transfer chain that links laser-pointing fluctuations to group-delay dispersion, pulse-front tilt, and electron beam pointing jitter. Stabilization of the laser transport environment, including vacuum beam transport and thermal control, reduces wavefront fluctuations and improves beam stability in energy, charge, and pointing by factors of 2–4, enabling improved control of beam quality.

DOI: [10.1103/rsvg-r3bg](https://doi.org/10.1103/rsvg-r3bg)

I. INTRODUCTION

High-energy particle accelerators have played a central role in experimental physics by enabling detailed investigations of the fundamental structure of matter. Conventional accelerator technologies, including radio-frequency linear accelerators and synchrotrons, have achieved outstanding performance but require large-scale facilities due to their limited accelerating gradients, leading to substantial cost and infrastructure demands. Laser wakefield acceleration (LWFA) has emerged as a promising alternative approach, offering ultrahigh accelerating gradients that enable more compact accelerator systems [1–6]. In recent years, LWFA experiments have demonstrated electron energies extending into the multi-GeV regime [3–5]. Beyond particle acceleration itself, LWFA-driven beams have been used to demonstrate free-electron lasing [7–12], and additional applications, including muon production [13] and nuclear-related studies [14], have been proposed.

However, the stability of LWFA electron beams remains a major challenge for practical applications. Previous studies have investigated the origins of beam instability using statistical analyses, including data mining and machine learning approaches [6], which have identified several contributing

factors such as beam loading and the wavefront quality of the driving laser [15–18].

Previous studies have demonstrated electron beam steering through controlled angular chirp or pulse-front tilt (PFT) [19,20] and have established the sensitivity of LWFA performance to laser wavefront quality [15,16]. In contrast, the present work focuses on the stability problem: how shot-to-shot fluctuations in these laser properties arise and are transferred to electron beam fluctuations in an operational LWFA system. In particular, we identify and quantitatively examine an instability-transfer chain linking laser-pointing fluctuations, group-delay dispersion (GDD) variations, PFT, and electron beam pointing jitter. We further identify practical sources of wavefront instability, including air flow and thermal perturbations in the laser system, and quantitatively connect the measured wavefront fluctuations to the resulting electron beam stability. Thus, rather than demonstrating the already established influence of angular chirp and wavefront quality on LWFA beam properties, this work focuses on how fluctuations in these laser characteristics determine the shot-to-shot reproducibility of LWFA electron beams.

With these improvements, electron beams with a mean central energy of approximately 370 MeV were obtained over an acceleration length of 3 mm, with an RMS energy fluctuation of 5.2 MeV, a mean energy spread of 0.8% (RMS fluctuation of 0.13%), a mean charge of 18.5 pC (RMS fluctuation of 3 pC), and a pointing stability of 0.12 mrad in RMS.

II. EXPERIMENTAL SETUP

The experiments were carried out at the Laser Acceleration Platform LAPLACIAN (Laser Acceleration Platform as a

*Contact author: jin@sanken.osaka-u.ac.jp

Published by the American Physical Society under the terms of the *Creative Commons Attribution 4.0 International* license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

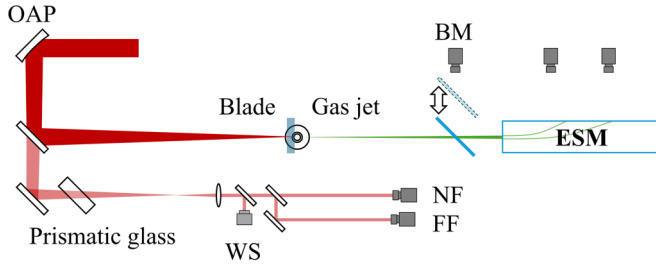


FIG. 1. Schematic layout of the experimental setup. The driving laser is focused onto a supersonic gas jet using an OAP. The accelerated electron beams are diagnosed using a beam profile monitor (BM) and an electron spectrometer (ESM). A fraction of the leakage beam from the final turning mirror is used for real-time laser diagnostics, including wavefront sensing (WS) and near- and far-field (NF, FF) monitoring.

Coordinated Innovative Anchor), located at the RIKEN SPring-8 Center and dedicated to laser wakefield acceleration studies. The facility is equipped with a custom-built Ti:sapphire femtosecond laser system (Amplitude Laser) that provides three synchronized beamlines (beamlines 1–3) with independently adjustable parameters.

For the beam stability studies, beamline 2 was employed as the driver laser, delivering pulses with an energy of 0.8 J and a minimum duration of 21 fs after compression. The temporal contrast was measured to be 10^{-11} at 50 ps prior to the main pulse. The Strehl ratio after the final amplifier was approximately 0.95. The laser beam was focused onto the gas target using a gold-coated off-axis parabola (OAP) with a slant focal length of 1500 mm. The measured focal spot size was approximately $22 \mu\text{m}$ (FWHM), with an energy concentration of approximately 70%. The peak laser intensity was estimated to be $5.0 \times 10^{18} \text{ W/cm}^2$, corresponding to a normalized vector potential of $a_0 = 1.5$. A schematic overview of the experimental configuration is shown in Fig. 1.

The transverse distribution of the electron beam was measured using a movable phosphor screen (BM; Mitsubishi Chemical Co., Ltd., DRZ-High) positioned 1 m downstream from the source. The electron energy spectrum was measured using a movable ESM consisting of a 0.55 T dipole magnet with a magnetic length of 900 mm, corresponding to a maximum measurable energy of approximately 2 GeV. The ESM was located 2.5 m from the source and employed the same type of phosphor screen (DRZ-High). The scintillation images were recorded using intensified charge-coupled device cameras (Princeton Instruments, ProEM-HS:1024BX3).

Precise control of electron injection is essential for achieving stable and high-quality LWFA beams. In this work, a shock-induced injection scheme [21,22] was employed using a supersonic gas jet with a Mach number of 3. A knife edge was positioned 3 mm above the nozzle exit to generate a sharp density transition. When the supersonic gas flow interacts with the knife edge, a shock front is formed, producing a localized high-density region followed by a thin density down-ramp.

Electron injection process is confined within this localized density down-ramp region, which leads to electron beams with energy spread below 1%. In addition, the injected charge can be controlled by adjusting the shock strength,

corresponding to the density difference between the peak and plateau regions. Further details of the injection scheme and density profile are provided in Ref. [12].

To investigate the correlation between electron beam properties and laser parameters, a real-time laser diagnostic system was implemented using leakage light from the final turning mirror downstream of the OAP, as illustrated in Fig. 1. Because the converging beam passes through the mirror at an incidence angle of 45° , a prismatic glass element was introduced to compensate for the aberrations induced by this transmission process [23]. The transmitted beam was subsequently collimated using a lens with a focal length of $f = 200 \text{ mm}$ and directed to a wavefront sensor (SID-4 HR, Phasics). In addition, two cameras (a2A3840-45umBAS and a2A5320-23umPRO, Basler) were installed to monitor the near-field and far-field intensity distributions of the laser beam in real time.

III. ELECTRON BEAM POINTING STABILITY

Beam pointing stability is a critical parameter not only for practical applications but also for reliable beam diagnostics. Our previous studies demonstrated that improving the hydrodynamic stability of the gas target can significantly enhance electron beam pointing stability [24–26]. However, in subsequent experiments, we observed that variations in laser conditions also lead to substantial differences in LWFA beam pointing performance. Further analysis indicates that minimizing the angular chirp of the driving laser is a key factor for achieving improved beam pointing stability.

The influence of laser angular chirp on LWFA electron beam pointing has been reported by several groups [19,20], including the use of angular chirp or PFT for controlled electron beam steering. The optical origin and characterization of PFT associated with spatiotemporal coupling have also been extensively studied [27,28]. While these studies established the steering effect of angular chirp and PFT, the present work focuses on a different aspect: How fluctuations in the laser system are transferred through angular chirp and PFT into shot-to-shot electron beam pointing instability.

Angular chirp is commonly introduced by dispersive optical elements such as prisms or diffraction gratings. In chirped-pulse amplification laser systems, angular chirp is most often caused by a slight nonparallel alignment of the grating pair inside the pulse compressor, denoted as ψ_g in Fig. 2(a). Such misalignment leads to wavelength-dependent variations in both propagation angle and arrival time, thereby introducing PFT into the laser pulse [27,28].

During focusing, the PFT is effectively amplified, as illustrated in Fig. 2(b), resulting in an asymmetric laser-driven wakefield. Consequently, the propagation axis of the accelerated electron beam becomes tilted relative to the nominal optical axis.

To clarify the underlying physical mechanism, we performed particle-in-cell (PIC) simulations by imposing a PFT along the laser polarization direction (x direction). Figure 3(a) shows that, for a representative PFT of 0.3 mrad, the injected electron bunch is displaced from the nominal propagation axis, indicating off-axis electron injection. Figure 3(b) further

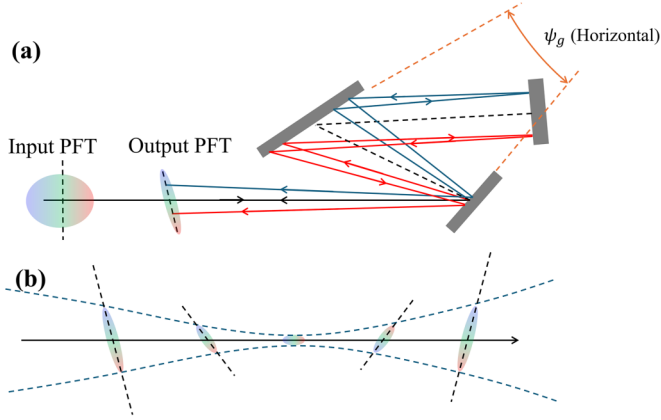


FIG. 2. (a) Schematic illustration of PFT introduced by nonparallel alignment of the compressor grating pair, characterized by the misalignment angle ψ_g . (b) Amplification of the PFT effect during laser focusing, leading to increased transverse displacement near the focal plane.

shows that the transverse wakefield becomes asymmetric, resulting in a displaced transverse focusing structure.

Physically, the imposed PFT introduces a transverse arrival-time difference of the laser pulse across the laser polarization direction. Consequently, the plasma wake is excited at different times across the transverse direction, producing an asymmetric plasma response and wakefield structure. As a result, the transverse focusing field becomes asymmetric, causing electrons to experience different transverse forces during injection and acceleration. This asymmetric transverse momentum ultimately produces a systematic electron beam pointing deviation along the pulse-front-tilt direction. The PIC simulations thus directly support the downstream physical mechanism from PFT to asymmetric wake excitation, off-axis electron injection, and electron beam pointing deviation. The upstream origin of the PFT fluctuations is examined separately below using ray-tracing calculations and experimental GDD scans.

Previous studies have shown that the electron beam pointing direction can be controlled by adjusting the angular chirp or the GDD of the driving laser. In addition to this steering effect, our results indicate that the grating misalignment parameter ψ_g also has a strong influence on the stability of the electron beam pointing, consistent with earlier reports [19].

To verify this effect, the grating misalignment parameter ψ_g was scanned by adjusting the relative angle of the compressor grating, while the beam path of the central wavelength was maintained using a roof mirror to preserve the nominal optical alignment. It should be noted that grating misalignment can involve three degrees of freedom (rotation, tilt, and yaw), with the latter two primarily responsible for introducing vertical angular chirp. To simplify the study, only the rotation of the grating was adjusted, so that angular chirp was introduced primarily in the horizontal direction. Such adjustment also modifies the temporal dispersion of the pulse and therefore affects the pulse duration at focus. The GDD was subsequently optimized using a Dazzler (acousto-optic programmable dispersive filter, Fastlite) to minimize the pulse duration at focus.

TABLE I. Standard deviations of LWFA electron beam pointing in the horizontal (x) and vertical (y) directions for different values of the grating misalignment angle ψ_g .

ψ_g (mrad)	Angular chirp ($\mu\text{rad}/\text{nm}$)	STD _{x} (mrad)	STD _{y} (mrad)
−0.1	−0.21	0.91	0.27
−0.05	−0.11	0.39	0.29
0	0	0.11	0.12
0.025	0.05	0.37	0.18
0.05	0.11	0.52	0.41

With the introduction of angular chirp, however, the pulse could not be compressed to its minimum duration (approximately 21 fs in the absence of angular chirp), resulting in a reduction of the injected charge. To compensate for this effect and maintain comparable experimental conditions, the shock strength was slightly increased, allowing the beam charge to be kept at approximately 20 pC.

Figure 4 shows the measured electron beam pointing stability, represented as RMS ellipses, for different values of ψ_g . The corresponding standard deviations (STD) in the horizontal (x) and vertical (y) directions are summarized in Table I. It can be clearly seen that the electron beam exhibits significantly larger fluctuations in the horizontal direction when horizontal angular chirp is introduced. Under conditions of minimal angular chirp, the best pointing stability reaches approximately 0.1 mrad, as indicated by the black solid ellipse in Fig. 4. For direct comparison with Ref. [19], the corresponding angular chirp values ($\mu\text{rad}/\text{nm}$), converted from the grating misalignment parameter ψ_g , are also listed in Table I. The conversion from the grating misalignment angle to the corresponding angular chirp is described in detail in Appendix A.

Nevertheless, the beam distribution retains an elliptical shape even at the minimum angular chirp, indicating the presence of residual angular chirp in both directions, likely limited by the positioning accuracy of the motorized rotation stage. This residual misalignment also explains why the RMS ellipses appear both elongated and rotated as ψ_g increases. In addition, a slight degradation of pointing stability is observed in the vertical direction, as reflected by the increase in STD _{y} values listed in Table I. This behavior can be attributed to imperfect alignment between the rotation axis of the stage and the grating surface, where small angular mismatches introduce both horizontal and vertical angular chirp during stage rotation.

Having established with the PIC simulations how PFT can modify the wakefield and electron beam pointing, we next investigate the upstream origin of the PFT-related pointing fluctuations. Further experiments and ray-tracing calculations indicate that an important contribution arises from laser-pointing fluctuations at the compressor entrance. In our system, the laser-pointing instability was measured to be 1.17 μrad , which results in a GDD variation of $\Delta\text{GDD} = 29.3 \text{ fs}^2$ after compression, as estimated using geometrical-optics ray-tracing calculations described in Appendix A. In the presence of angular chirp, laser-pointing fluctuations induce GDD variations, which in turn modify the PFT during focusing, leading to fluctuations in the electron beam pointing direction.

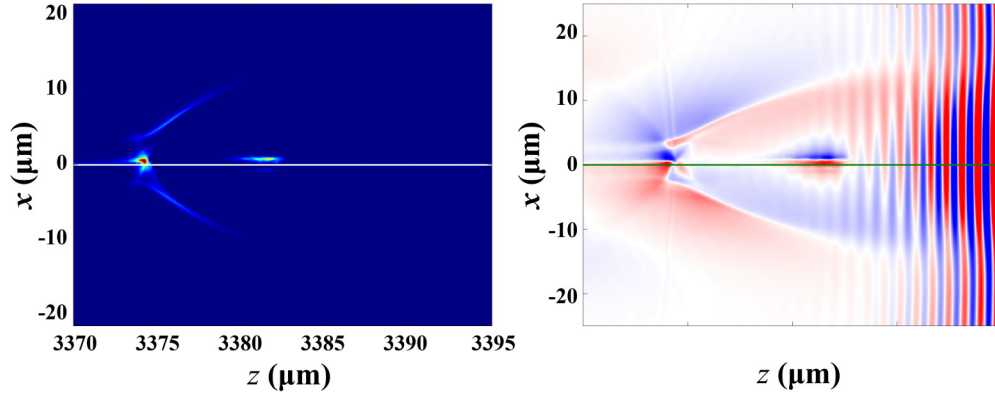


FIG. 3. PIC simulation illustrating the physical mechanism of electron beam pointing induced by PFT. (a) Electron-density distribution showing off-axis electron injection. (b) Corresponding transverse wakefield distribution showing the asymmetric transverse focusing structure produced by an imposed PFT of 0.3 mrad.

To further investigate the correlation between GDD and electron beam pointing, experimental scans of the GDD were performed with ψ_g fixed at 0.1 mrad. The results show that the horizontal pointing position of the electron beam can be systematically tuned by varying the GDD using the Dazzler, as shown in Fig. 5. In contrast, the central position in the vertical direction remains nearly unchanged, and the overall shape of the RMS ellipse shows little variation. A linear fit to the data yields the empirical relation

$$x_{\text{center}} \text{ (mrad)} = (0.025 \pm 0.006) \times \text{GDD (fs}^2\text{)}, \quad (1)$$

which quantifies the sensitivity of horizontal pointing to GDD variations. According to Eq. (1), a GDD fluctuation of $\Delta\text{GDD} = 29.3 \text{ fs}^2$ results in an expected pointing fluctuation

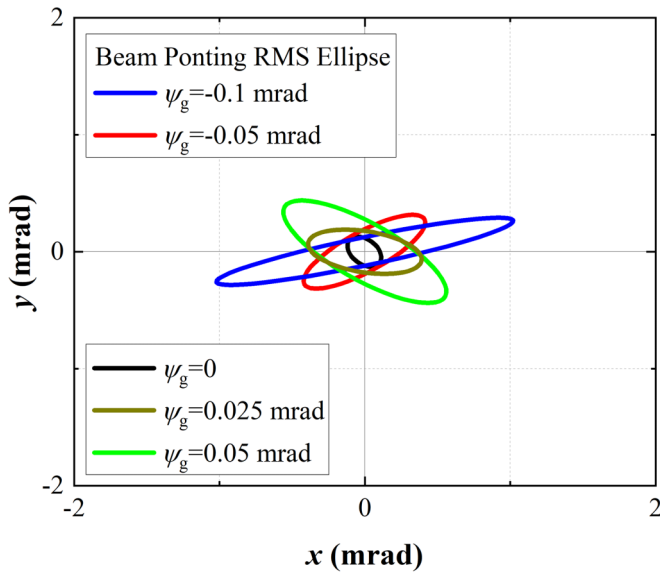


FIG. 4. RMS pointing ellipses of LWFA electron beams for different values of the grating misalignment angle ψ_g . The beam pointing stability degrades with increasing $|\psi_g|$, indicating the strong influence of angular chirp on electron beam pointing stability. Each RMS pointing ellipse is calculated from 20 consecutive electron beam shots.

of $\text{STD}_{x,\text{cal}} = 0.73 \pm 0.18 \text{ mrad}$, which is in good agreement with the experimentally measured value of 0.91 mrad.

Together, the ray-tracing calculation and the experimental GDD scan support the upstream instability-transfer pathway from laser-pointing fluctuations to GDD variations and the resulting PFT-dependent electron beam pointing response. Combined with the PIC simulations, which establish the downstream mechanism from PFT to asymmetric wake excitation and off-axis electron injection, these results provide

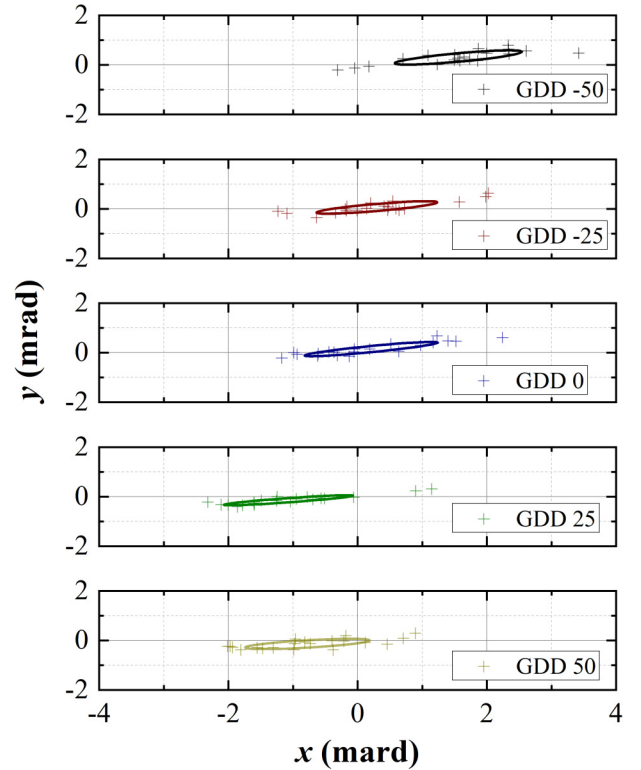


FIG. 5. Deviation of the LWFA electron beam pointing center as a function of GDD with fixed $\psi_g = 0.1 \text{ mrad}$. The horizontal shift of the beam pointing center demonstrates the correlation between GDD and electron beam pointing.

TABLE II. Comparison of the electron beam stability before and after stabilization. The values are given as mean $\pm$ shot-to-shot STD. The numbers of analyzed shots are indicated in the table headers.

Parameter	Before stabilization [12] ($N = 20$)	After stabilization ($N = 50$)	Stability improvement factor
Energy (MeV)	376 ± 15.5	367 ± 5.2	2.98
Energy spread (%)	1.50 ± 0.50	0.84 ± 0.13	3.85
Beam charge (pC)	25.3 ± 7.4	18.5 ± 3.1	2.43

a consistent physical picture of the overall instability-transfer process.

IV. ELECTRON BEAM ENERGY STABILITY

Previous studies have demonstrated that laser wavefront quality can strongly influence electron beam generation and properties in LWFA [15,16]. Here, we focus specifically on the shot-to-shot wavefront fluctuations present during routine operation, their practical sources in the laser system, and their impact on electron beam stability. This effect is particularly important for shock injection, where the laser intensity at the shock location strongly influences the injected charge. Excessive injection leads to reduced energy gain and increased energy spread due to beam-loading effects [16].

In our previous work [12], a beam mask [29] was introduced into the laser system to suppress wavefront fluctuations, resulting in an approximately 50% reduction in wavefront instability. Combined with an improved gas-nozzle design, this approach enabled the generation of quasimonoenergetic electron beams with a central energy of 376 MeV (RMS fluctuation of 15.5 MeV), a mean energy spread of 1.5% (RMS

fluctuation of 0.5%), and a mean charge of 25.3 pC (RMS fluctuation of 7.4 pC), as summarized in Table II.

Further improvement of laser wavefront stability often requires extensive modifications to the overall laser system, and the implementation priorities may vary depending on the specific design of each facility. Among the possible improvements, control of thermal sources and air flow along the optical path represents one of the most practical and effective approaches.

In our system, a laser transport line approximately 10 m in length was required between the final amplifier and the compressor due to building layout constraints. Enclosed beam pipes were installed to suppress air flow along this path. However, thermal sources located nearby, specifically two scroll pumps, generated residual air movement that affected the stability of the laser beam even within the enclosed transport line.

To verify this effect, the beam transport line was converted from air-filled pipes to vacuum beam pipes. Figure 6 compares the measured laser wavefront stability under air and vacuum conditions. A clear reduction in the fluctuations of the Zernike modes Tilt X and Coma Y is observed, with decreases of approximately 20% and 10%, respectively, while the other Zernike coefficients remain largely unchanged.

These results suggest that refractive-index fluctuations in the vertical direction contribute significantly to the observed Tilt X instability, consistent with the presence of heat sources located beneath the beam transport line. In addition, residual air convection within the transport path is likely responsible for the observed Coma Y fluctuations.

Another significant heat source within the laser system originates from the diagnostic cameras. In total, 15 cameras are installed inside the laser enclosures, spanning from the stretcher to the final amplifier, to monitor laser profiles and pointing stability. Temperature measurements using thermal sensors indicate that the camera bodies can reach temperatures of 40–50 °C during operation. Since the ambient room

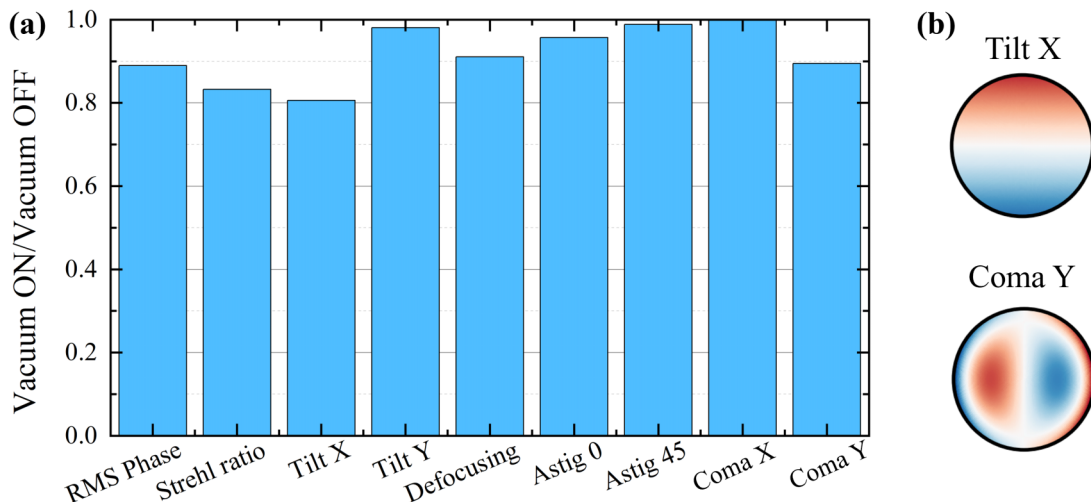


FIG. 6. (a) Ratio of the standard deviations of Zernike coefficients measured under vacuum and air transport conditions (vacuum on/vacuum off), obtained from 600 measurements. Values smaller than unity indicate improved stability under vacuum conditions. Significant reductions are observed in the Tilt X and Coma Y terms. The corresponding Zernike mode shapes are illustrated in panel (b). The coordinate axes differ from the conventional definition due to a 90° rotation of the beam by a periscope before entering the compressor.

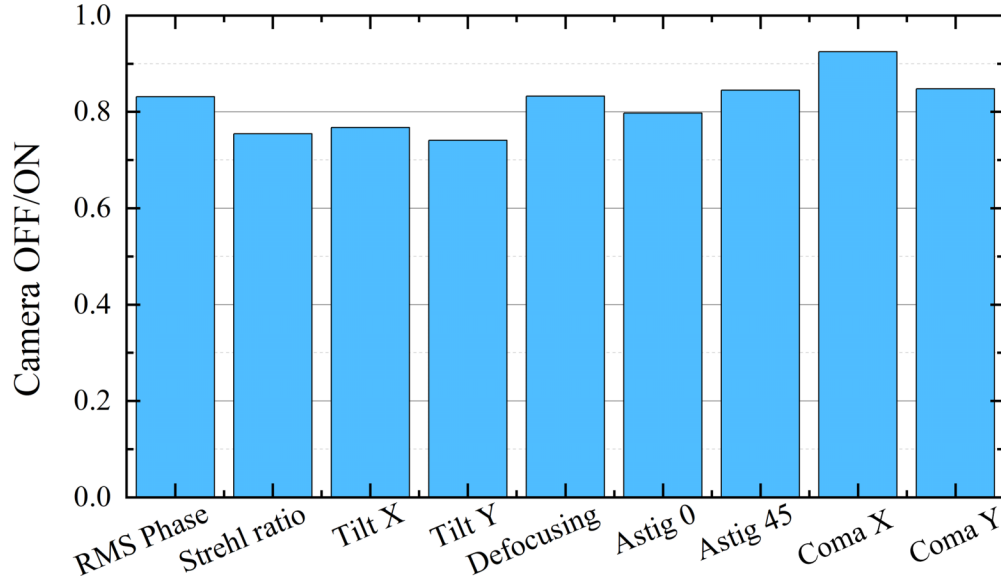


FIG. 7. Ratio of the standard deviations of Zernike coefficients measured with most cameras inside the laser system powered off and on (camera off/camera on), obtained from 600 measurements. The measurements were performed under vacuum beam transport conditions. Values smaller than unity indicate improved wavefront stability when the cameras are powered off. An overall reduction of approximately 20% is observed across most Zernike terms.

temperature is maintained at approximately 21 °C, this large temperature gradient can induce air convection inside the laser enclosures.

To evaluate this effect, most of the cameras in the laser system (14 out of 15) were temporarily powered off, and the system was allowed to thermally stabilize for approximately 120 min. Subsequent wavefront measurements show that the standard deviations of most Zernike coefficients were reduced by approximately 20%, as shown in Fig. 7. Because the laser beam propagates through a complex optical path within these enclosures, such a global improvement across multiple Zernike modes is expected, rather than selective improvement in individual modes.

For completeness, the corresponding absolute shot-to-shot standard deviations of all measured Zernike coefficients are listed in Appendix B.

Figure 8 presents the measured LWFA electron energy spectra before and after improvement of the laser wavefront stability. Figures 8(a) and 8(c) show the corresponding raw scintillation images recorded by the ESM, while Figs. 8(b) and 8(d) display the reconstructed energy spectra accumulated over multiple shots. A clear reduction in the shot-to-shot fluctuation and spectral width can be observed after stabilization, indicating improved reproducibility of the electron beam generation.

The corresponding shot-to-shot variations of central energy, beam charge, and energy spread are summarized in Fig. 9. Figures 9(a)–9(c) show the central energy, charge, and energy spread, respectively, before wavefront stabilization, while Figs. 9(d)–9(f) present the corresponding results after stabilization.

Quantitative statistical results are summarized in Table II. The standard deviation of the central energy is reduced from 15.5 to 5.2 MeV, corresponding to an improvement factor of approximately 3. Meanwhile, the energy spread is reduced

from $1.5\% \pm 0.5\%$ to $0.84\% \pm 0.13\%$, and the charge stability is improved from 7.4 to 3.1 pC, corresponding to improvement factors of approximately 3.9 and 2.4, respectively. These results demonstrate that stabilization of the laser wavefront significantly enhances the overall stability of LWFA beam parameters. This improvement is particularly important for shock-front injection, where the injected charge is highly sensitive to the laser intensity at the density transition. Improved stability of the defocus term can therefore significantly reduce the shot-to-shot fluctuation of the injected charge and consequently improve the energy stability [16]. A quantitative analysis based on the experimentally measured defocus fluctuation and supporting PIC simulations is presented in Appendix C.

The improved stability also enables more precise tuning of the injected charge, which is essential for optimizing the beam-loading effect. With reduced shot-to-shot fluctuations, the injected charge can be controlled within a narrower range, allowing improved control of the beam-loading effect and consequently better control of the final energy spread.

The effects of beam loading can be more clearly resolved under improved stability conditions. Figure 10(a) shows the correlation between beam charge and central energy, demonstrating a reduction in energy gain at higher charge due to overinjection, in good agreement with previously reported results [12,16].

Figure 10(b) shows the correlation between beam charge and energy spread. An increase in energy spread is observed at both low- and high-charge levels, forming a characteristic U-shaped dependence of energy spread on charge. At low charge, the increased spread is attributed to overphase rotation during acceleration, whereas at high charge, it results from beam-loading effects. These observations are also consistent with previous reports [12].

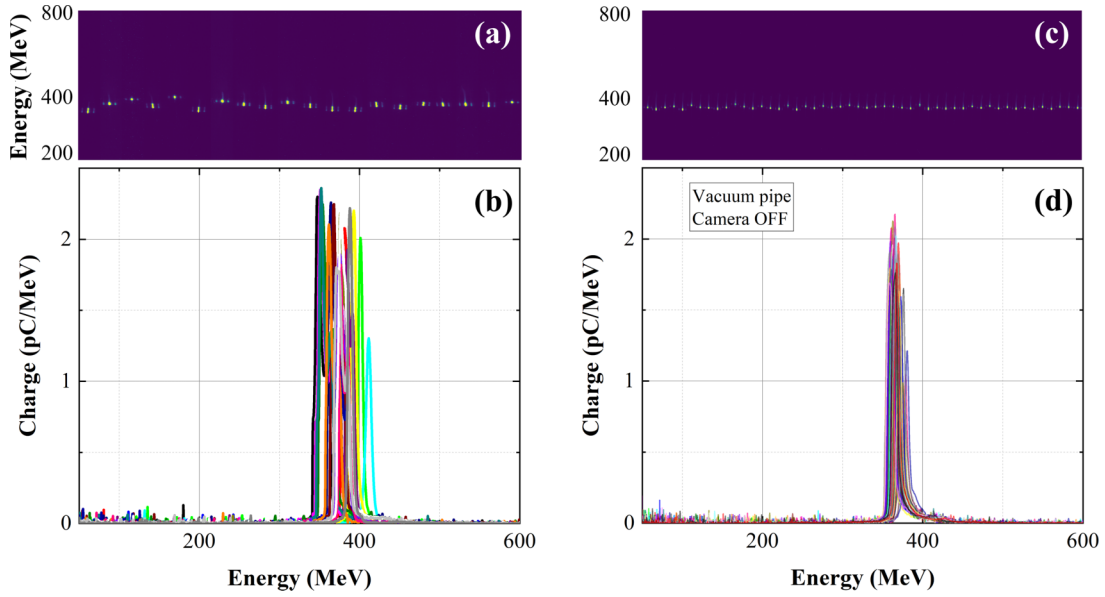


FIG. 8. Measured LWFA electron energy spectra before [panels (a) and (b)] and after [panels (c) and (d)] improvement of the laser wavefront stability. Panels (a) and (c) show the raw scintillation images recorded by the ESM, while panels (b) and (d) present the corresponding reconstructed energy spectra. Quantitative statistical results are summarized in Table II.

To further examine the influence of the operating charge on the observed beam stability, additional measurements were performed under the stabilized laser condition with a higher mean charge of approximately 24 pC, close to the value before stabilization. The results, summarized in Appendix D, show that the charge fluctuation remains nearly unchanged (3.1 pC at 18.5 pC versus 3.4 pC at 23.6 pC), whereas the higher charge results in a lower beam energy and a

larger energy spread, consistent with the beam-loading effect. These observations indicate that, within the investigated charge range (approximately 18–25 pC), the improvement in beam stability originates primarily from the enhanced laser stability rather than from the reduced mean charge. The improved stability further enables operation near the optimum beam-loading condition for minimizing the energy spread.

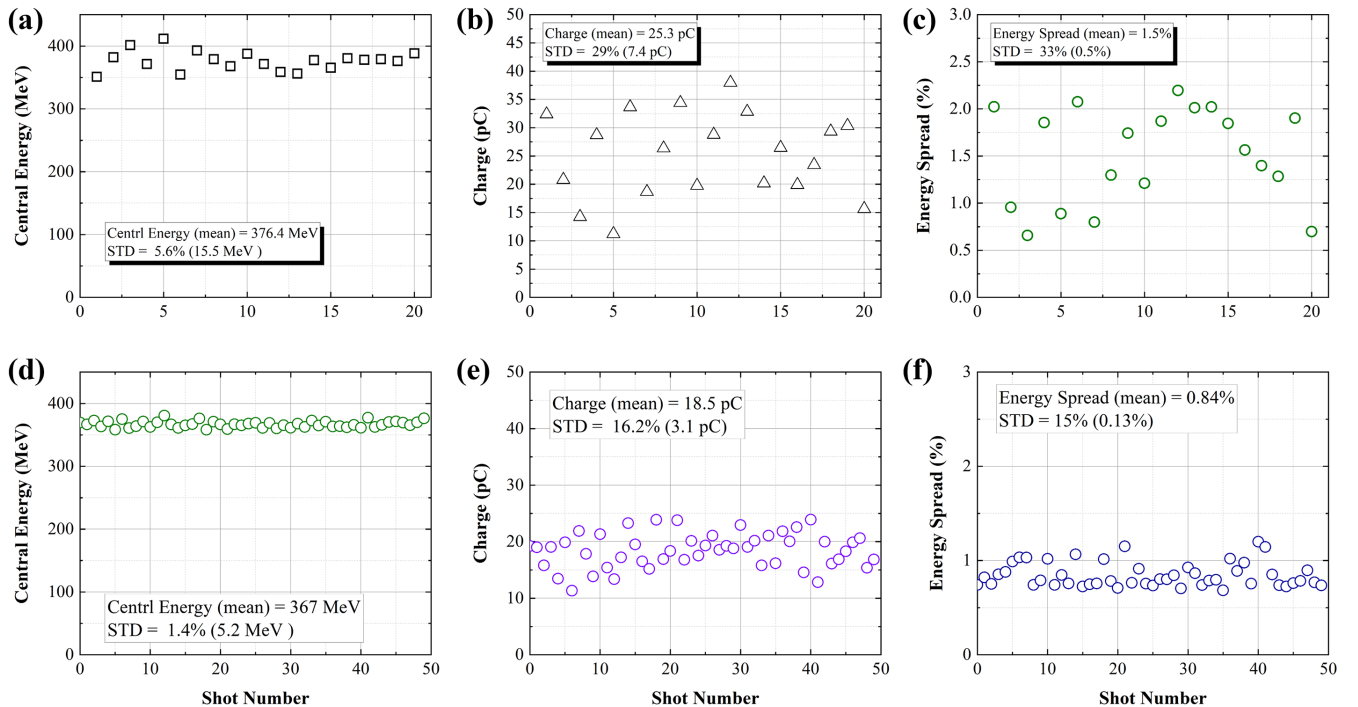


FIG. 9. Shot-to-shot variations of the LWFA electron beam parameters. (a)–(c) Central energy, beam charge, and energy spread before improvement of the laser wavefront stability. (d)–(f) Corresponding parameters after stabilization.

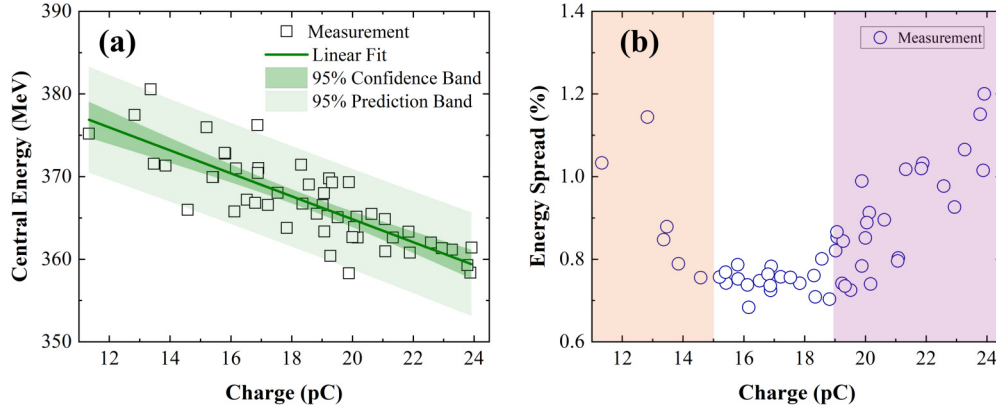


FIG. 10. (a) Correlation between the LWFA electron beam energy and injected charge. The green solid line represents a linear fit to the data. The light-green region indicates the 95% prediction band, while the dark-green region represents the 95% confidence band of the fit. (b) Correlation between the electron beam energy spread and injected charge. The low-charge region (orange-shaded area) and the high-charge region (purple-shaded area) exhibit increased energy spread, forming a characteristic U-shaped dependence on beam charge.

Figure 11 presents the Pearson correlation coefficients among the wavefront RMS phase, defocus, beam charge, and central energy. The remaining Zernike coefficients exhibit only weak correlations (absolute Pearson coefficients below 0.3) and are therefore omitted for clarity. A strong negative correlation ($r = -0.82$) is observed between beam charge and central energy, consistent with the trend shown in Fig. 10(a). In addition, the defocus term exhibits a noticeable correlation with the beam energy ($r = -0.55$); the corresponding shot-resolved data are shown in Fig. 18.

To further examine the combined statistical dependence of the beam energy on charge and defocus, a multiple linear regression analysis was performed. The fitted model yields $R^2 = 0.808$, indicating that approximately 80.8% of the measured energy variance is represented by the charge and defocus terms and their covariance within the linear model.

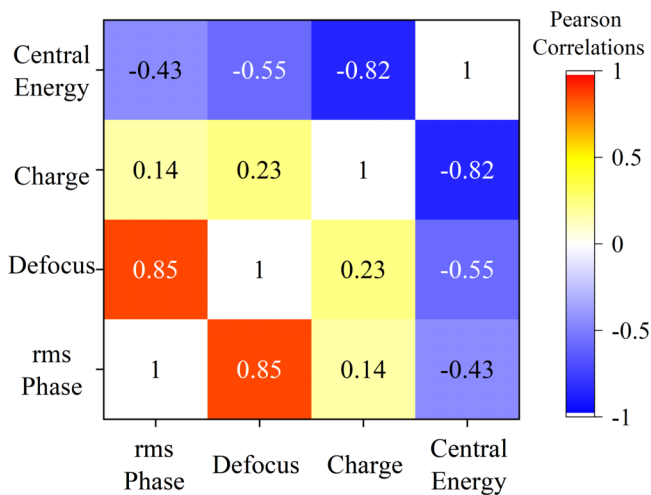


FIG. 11. Pearson correlation matrix among the wavefront RMS phase, defocus, beam charge, and central energy of the LWFA electron beam. The color scale represents the magnitude and sign of the correlation coefficients, with values ranging from -1 to 1 . Numerical values inside each cell indicate the corresponding Pearson coefficients.

A variance decomposition gives contributions of 53.6% from the charge term, 14.3% from the defocus term, and 12.8% from their covariance term. These percentages describe statistical variance contributions within the fitted model and should not be interpreted as independent causal contributions. The regression procedure and detailed variance decomposition are provided in Appendix E.

In contrast, only weak correlations are observed between the wavefront parameters and beam charge, which is contrary to expectations. Previous studies have demonstrated that the injected charge is highly sensitive to the laser wavefront, especially to the focal position [15,16]. The reduced correlation observed here suggests that, after stabilization of the laser wavefront, the remaining fluctuations in the injected charge are likely influenced by factors that were not monitored in the present experiment. One possible source is the residual instability of the gas target, including fluctuations of the shock-front position or density profile, as suggested by our previous studies [24,25]. However, other laser-related parameters that were not measured simultaneously, such as spectral phase fluctuations and the resulting pulse-duration variations, may also contribute. Further simultaneous diagnostics will therefore be required to identify the dominant source of the remaining charge fluctuations.

Our previous studies demonstrated that improving the shock-position stability using an optimized converging-diverging nozzle significantly enhanced beam stability [24,25]. Therefore, further improvements in gas-target stability remain a promising direction, although additional measurements will be necessary to quantify its relative contribution.

V. CONCLUSIONS

Stabilization of LWFA beam parameters requires improvements across multiple subsystems. Previous studies have demonstrated that angular chirp and pulse-front tilt can influence electron beam pointing and can be used for controlled beam steering. Beyond these established steering effects, the present work focuses on their role in electron beam pointing stability and shows that compressor misalignment can

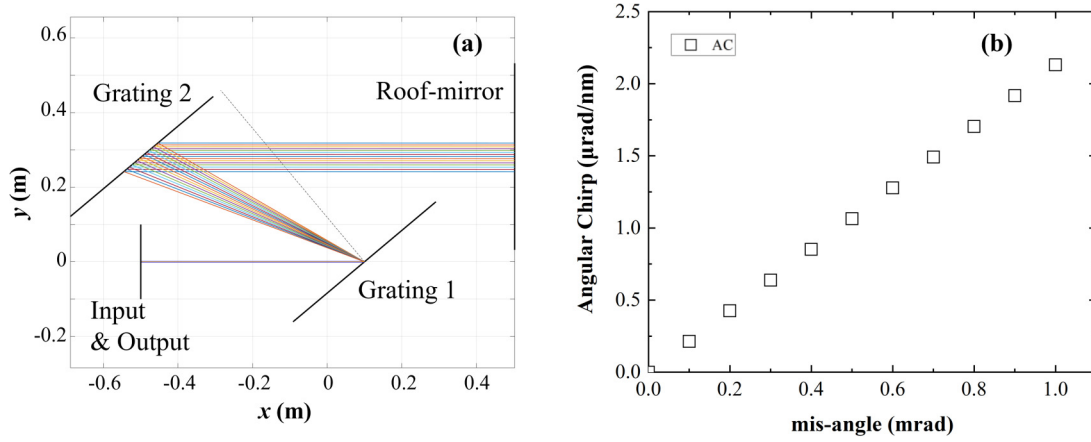


FIG. 12. (a) Optical layout used for the geometrical-optics ray-tracing calculation. (b) Calculated angular chirp as a function of the grating misalignment angle, ψ_g .

enhance the transfer of laser fluctuations to electron beam pointing jitter through PFT. The results establish a quantitative instability-transfer chain linking laser-pointing fluctuations, GDD variations, PFT, and electron beam pointing jitter.

Laser wavefront quality is also known to play an important role in LWFA electron beam generation. In this work, we focus specifically on the shot-to-shot wavefront variations encountered during routine operation and identify their practical sources in the laser system. Suppression of thermal sources and air-flow-induced refractive-index fluctuations improves laser wavefront stability, leading to enhanced stability of beam charge and energy. The measured reduction in defocus fluctuations, together with the PIC simulations, further supports a quantitative connection between improved wavefront stability and reduced electron beam charge fluctuations. The improved stability also enables more reliable tuning of the injected charge and clearer observation of beam-loading effects.

It is also worth noting that laboratory temperature stability plays an important role. Our experiments show that an increase of 0.5°C in room temperature results in a degradation of the pointing stability from 0.1 to 0.3 mrad. The corresponding measurements are summarized in Appendix F. This degradation is likely associated with thermally induced

changes in the residual angular chirp caused by thermal expansion of the compressor optics. These observations highlight the importance of long-term thermal stability for reliable operation of LWFA systems.

Although many of the approaches presented here are technical in nature, the results provide practical guidelines and physical insight for further optimization of LWFA beam quality. In particular, after stabilization of the laser wavefront, gas-flow and shock-structure stability remain possible sources of residual charge fluctuations, indicating that further improvements in gas-target design represent an important next step. These results contribute to the development of stable, high-quality LWFA beams, which are essential for future applications such as compact radiation sources and advanced accelerator systems.

ACKNOWLEDGMENTS

This work was supported by the JST-MIRAI Program (Grant No. JPMJMI17A1). We acknowledge SMARTSHELL Co., Ltd. for valuable discussions and technical assistance. Additionally, we extend our sincere gratitude to Prof. Y. Sano, Program Manager of the JST-MIRAI Program;

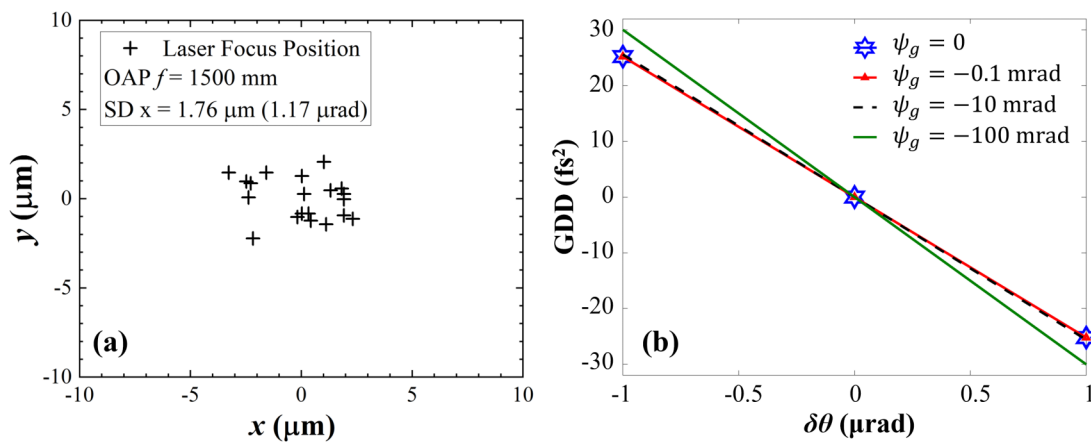


FIG. 13. (a) Measured laser-pointing stability at the compressor entrance. (b) Calculated GDD variation as a function of the laser-pointing fluctuation for different grating misalignment angles ψ_g .

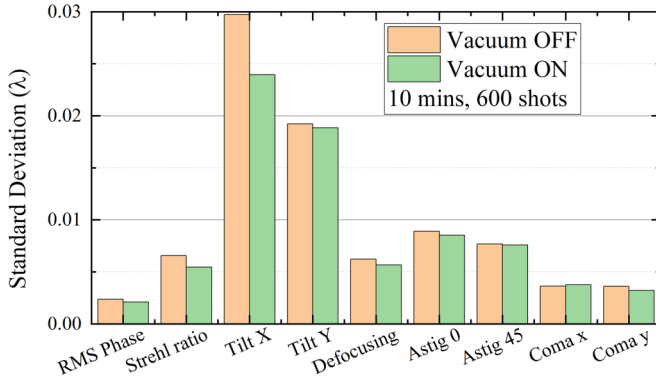


FIG. 14. Shot-to-shot standard deviations of the measured Zernike coefficients with the laser transported through air (vacuum off) and through vacuum (vacuum on). Each value was calculated from 600 consecutive wavefront measurements acquired over a 10-min period.

Prof. R. Kodama from the Institute of Laser Engineering (ILE) at Osaka University; Dr. T. Ishikawa, Director of the RIKEN SPring-8 Center; and Dr. T. Otsuka from Utsunomiya University for their substantial contributions to establishing the LAPLACIAN facility under the ImpACT program of the Council for Science, Technology, and Innovation, Cabinet Office, Government of Japan.

DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

APPENDIX A: CALCULATION OF ANGULAR CHIRP AND GDD VARIATION

The angular chirp and the corresponding GDD variation were calculated using a geometrical-optics ray-tracing model. Figure 12(a) illustrates the optical layout of the pulse compressor used in our laser system. The compressor consists of a pair of diffraction gratings with a groove density of

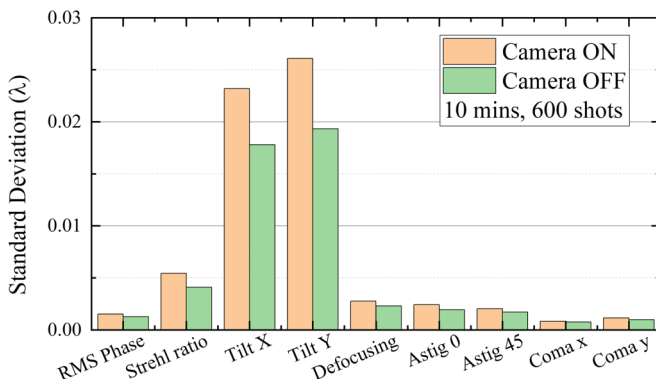


FIG. 15. Shot-to-shot standard deviations of the measured Zernike coefficients with the internal cameras switched on (camera on) and off (camera off). Each value was calculated from 600 consecutive wavefront measurements acquired over a 10-min period.

1480 lines/mm. The incident angle on the first grating is 50° , the perpendicular separation between the two gratings is 600 mm, and the distance between the second grating and the roof mirror is 1000 mm. The ray-tracing calculation follows the propagation of rays with different wavelengths through the compressor optics. The angular chirp is obtained from the wavelength dependence of the output beam angle, $AC = d\theta/d\lambda$.

Using these parameters, the angular chirp introduced by the grating misalignment was calculated as a function of ψ_g , as shown in Fig. 12(b). For the experimentally estimated grating misalignment of $\psi_g = 0.1$ mrad, the corresponding angular chirp is calculated to be $0.21 \mu\text{rad}/\text{nm}$, as listed in Table I.

The horizontal laser-pointing stability at the compressor entrance was measured to be $1.17 \mu\text{rad}$ (RMS), as shown in Fig. 13(a). Based on the ray-tracing calculation presented in Fig. 13(b), this pointing fluctuation corresponds to a GDD variation of $\Delta\text{GDD} = 29.3 \text{ fs}^2$ for the experimentally estimated grating misalignment angle of $\psi_g = 0.1$ mrad.

APPENDIX B: ABSOLUTE SHOT-TO-SHOT STANDARD DEVIATIONS OF THE MEASURED ZERNIKE COEFFICIENTS

The main text presents the stabilization performance in terms of the ratios of the shot-to-shot standard deviations of the measured Zernike coefficients. For completeness, this Appendix provides the corresponding absolute values before and after each stabilization procedure. The bar charts (Figs. 14 and 15) are retained to facilitate direct comparison with the main text, while the complete numerical values are summarized in Table III. Since the vacuum on/off and camera on/off measurements were performed on different experimental days, the absolute values should not be directly compared between the two experiments; instead, the corresponding ratios provide the appropriate metric for evaluating the effectiveness of each stabilization method.

APPENDIX C: CORRELATION BETWEEN THE DEFOCUS COEFFICIENT AND INJECTED CHARGE

Among the measured Zernike modes, the defocus term exhibits the strongest correlation with the injected charge and beam energy. We therefore use the measured defocus fluctuation as a representative example to quantitatively evaluate how the experimentally observed improvement in wavefront stability influences the LWFA beam stability.

The measured standard deviation of the defocus coefficient is reduced from $6.2 \times 10^{-3} \lambda$ before stabilization to $2.3 \times 10^{-3} \lambda$ after stabilization. These values correspond to focus-position fluctuations of approximately 55 and 20 μm , respectively, calculated using

$$\Delta z = 16\sqrt{3}\lambda a(F/\#)^2, \quad (\text{C1})$$

where a is the defocusing coefficient, $\lambda = 800 \text{ nm}$ is the wavelength, and $F/\# = 20$ is the f number of the focusing optics.

PIC simulations were then performed using these experimentally measured focus-position fluctuations. The simulation results (Fig. 16 and Table IV) show that improving the

TABLE III. Shot-to-shot standard deviations of the measured Zernike coefficients before and after the vacuum and camera stabilization procedures. The corresponding ratios are defined as the standard deviation after stabilization divided by that before stabilization. Since the vacuum on/off and camera on/off measurements were performed on different experimental days, the absolute values are presented for completeness, while the ratios provide the primary metric for evaluating the stabilization performance.

Zernike mode	Vacuum off	Vacuum on	Ratio	Camera on	Camera off	Ratio
RMS Phase (λ)	0.002 37	0.002 11	0.890	0.001 53	0.001 27	0.831
Strehl ratio	0.006 57	0.005 46	0.832	0.005 45	0.004 11	0.755
Tilt X (λ)	0.029 72	0.023 95	0.806	0.023 18	0.017 79	0.767
Tilt Y (λ)	0.019 22	0.018 85	0.981	0.026 09	0.019 33	0.741
Defocus (λ)	0.006 22	0.005 66	0.910	0.002 76	0.0023	0.832
Astig 0 (λ)	0.008 91	0.008 52	0.957	0.002 42	0.001 93	0.797
Astig 45 (λ)	0.007 68	0.007 59	0.988	0.002 03	0.001 71	0.845
Coma x (λ)	0.003 62	0.003 77	1.039	8.27×10^{-04}	7.65×10^{-04}	0.925
Coma y (λ)	0.0036	0.003 23	0.895	0.001 16	9.81×10^{-04}	0.848

focus-position stability from 55 to 20 μm reduces the injected-charge fluctuation from 6.5 to 2.4 pC, in good agreement with the experimental observations. Although the simulation considers only the experimentally measured defocus fluctuation and does not include other wavefront modes or gas-target instabilities, it quantitatively reproduces the experimentally observed reduction in charge fluctuation. This agreement provides direct evidence that the measured improvement in wavefront stability is sufficient to account for a substantial fraction of the observed improvement in electron beam stability.

APPENDIX D: ELECTRON BEAM PARAMETERS STABILITY AT HIGHER CHARGE

In Sec. IV, the operating beam charge after stabilization was intentionally chosen to be approximately 18 pC because this charge corresponds to the bottom of the U-shaped dependence between beam charge and energy spread shown in Fig. 10(b). At this operating point, the beam-loading effect is close to optimal, resulting in the minimum energy spread. The improved charge stability achieved after wavefront stabilization makes it possible to maintain the accelerator near this optimum operating point with good reproducibility.

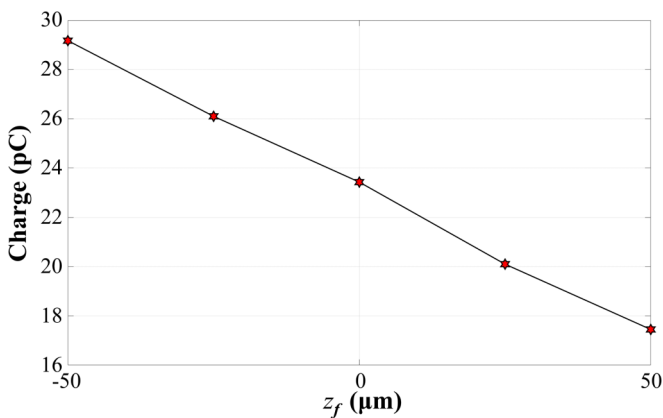


FIG. 16. Injected charge as a function of the laser focus position obtained from PIC simulations.

To examine the influence of the operating charge on the measured beam stability, we additionally measured the beam stability under a higher mean charge of approximately 24 pC while maintaining the stabilized laser condition. The corresponding results are presented in the newly added Fig. 17 and Table V.

The measured beam charge is 23.6 ± 3.4 pC, which is close to the value before stabilization (25.3 ± 7.4 pC), while the charge fluctuation remains nearly unchanged compared with the optimized operating point after stabilization (18.5 ± 3.1 pC). As expected from the beam-loading effect, the higher mean charge leads to a lower beam energy and a larger energy spread. These results indicate that, within the investigated charge range (approximately 18–25 pC), the improvement in charge stability is not simply a consequence of operating at a lower mean charge. Instead, the improved wavefront stability enables more reproducible injection, allowing the mean charge to be controlled more precisely and the operating point to be optimized for minimum energy spread.

APPENDIX E: STATISTICAL ANALYSIS OF ENERGY FLUCTUATIONS

To further examine the statistical relationships among the electron beam energy, charge, and laser defocus, shot-resolved correlation and multiple linear regression analyses were performed using the 50 consecutive shots acquired under the stabilized condition. Figure 18 shows the central electron energy as a function of the defocus coefficient for individual shots. The two quantities exhibit a moderate negative correlation, with a Pearson correlation coefficient of -0.55 . The

TABLE IV. Defocusing coefficient instability and corresponding focus-position fluctuations before and after the wavefront stabilization. The injected-charge fluctuations were obtained from the PIC simulations.

	Before stabilization	After stabilization
Defocus STD (λ)	6.2×10^{-3}	2.3×10^{-3}
Focus position STD (μm)	55	20
Charge fluctuation (pC)	6.5	2.4

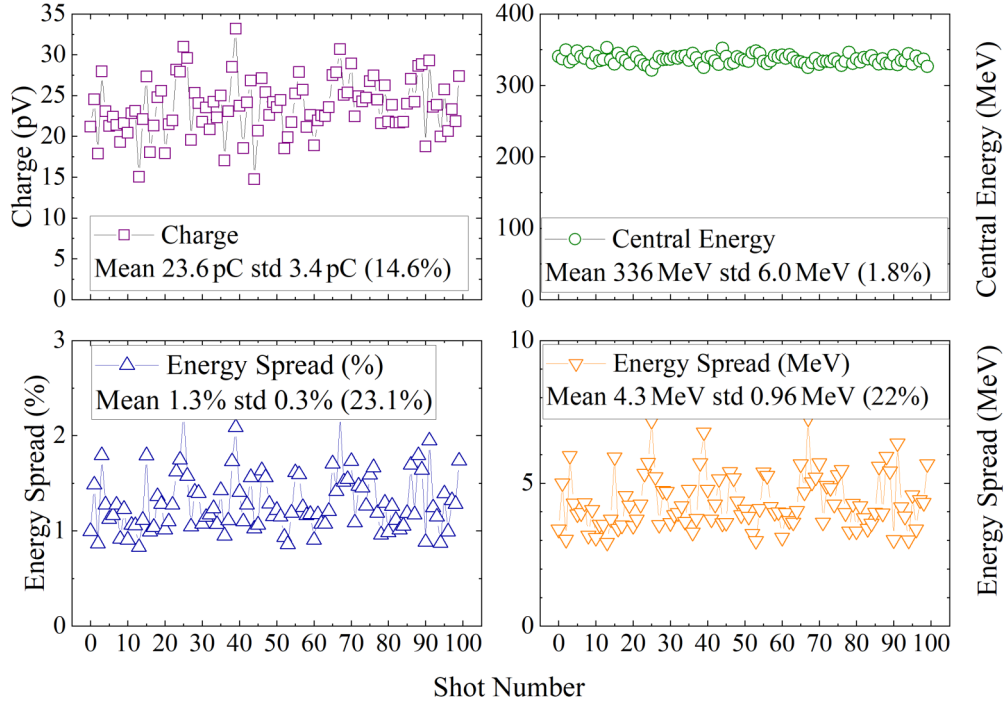


FIG. 17. Shot-to-shot variations of the LWFA electron beam parameters with higher mean charge (23.6 pC) after improvement of the laser wavefront stability.

corresponding shot-resolved charge-energy data are shown in Fig. 10(a), where a stronger negative correlation is observed (Pearson coefficient = -0.82).

To evaluate the combined statistical dependence of the electron beam energy on charge and defocus, the experimental data were fitted using the multiple linear regression model

$$E = \beta_0 + \beta_Q Q + \beta_D D, \quad (\text{E1})$$

where E is the central electron energy, Q is the beam charge, and D is the defocus coefficient. The fit yields

$$E = 409.12 - 1.241Q - 1135.3D, \quad (\text{E2})$$

where E , Q , and D are expressed in MeV, pC, and λ , respectively. The coefficient of determination is $R^2 = 0.808$, indicating that the fitted two-parameter linear model represents approximately 80.8% of the measured energy variance.

The measured standard deviations are

$$\begin{aligned} \sigma_E &= 5.175 \text{ MeV}, \quad \sigma_Q = 3.054 \text{ pC}, \\ \sigma_D &= 1.725 \times 10^{-3} \lambda. \end{aligned} \quad (\text{E3})$$

TABLE V. Mean values and standard deviations of the LWFA electron beam energy, energy spread, and charge after improvement of the laser wavefront stability, with different mean charge.

	After stabilization Case I	After stabilization Case II
Beam charge (pC)	18.5 ± 3.1	23.6 ± 3.4
Beam energy (MeV)	367 ± 5.2	336 ± 6.0
Energy spread (%)	0.84 ± 0.13	1.3 ± 0.3

Because charge and defocus are not completely independent ($r_{QD} = 0.231$), their covariance is retained in the variance analysis. The variance of the fitted energy is

$$\text{Var}(\hat{E}) = \beta_Q^2 \sigma_Q^2 + \beta_D^2 \sigma_D^2 + 2\beta_Q \beta_D \text{Cov}(Q, D), \quad (\text{E4})$$

where

$$\text{Cov}(Q, D) = r_{QD} \sigma_Q \sigma_D. \quad (\text{E5})$$

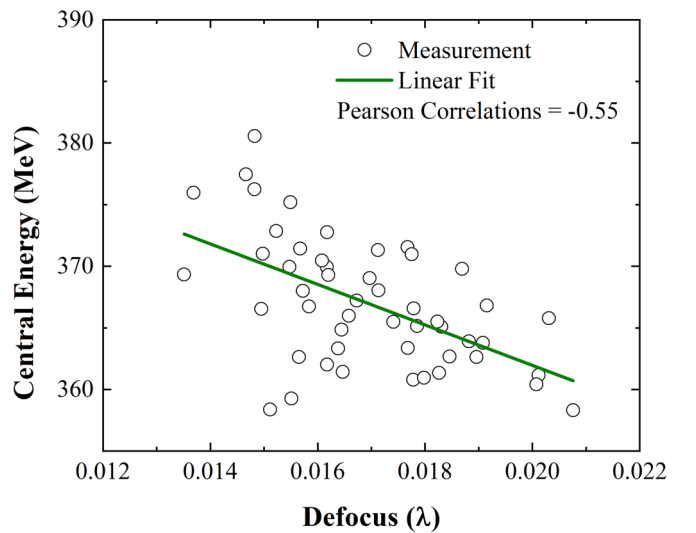


FIG. 18. Shot-resolved central electron energy as a function of the laser defocus coefficient for 50 consecutive shots under the stabilized condition. The solid line represents a linear fit to the experimental data. The Pearson correlation coefficient is -0.55 .

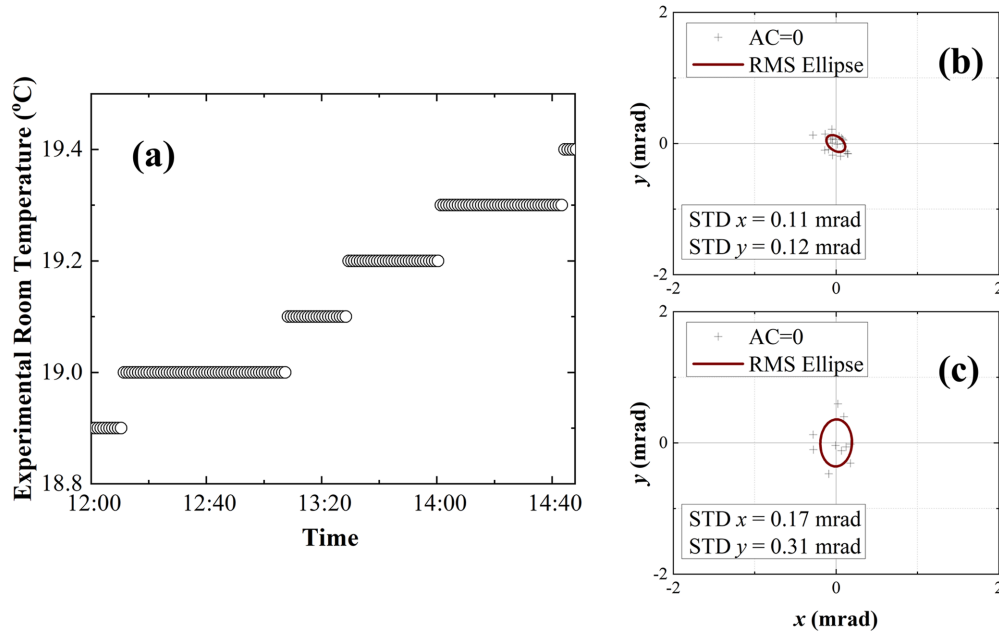


FIG. 19. Effect of the experimental-room temperature on the electron beam pointing stability. (a) Measured room temperature during a typical experiment. (b) Electron beam pointing distribution before the room temperature increased. (c) Electron beam pointing distribution after the room temperature increased by approximately 0.5 °C.

Using $r_{QD} = 0.231$, the covariance is

$$\begin{aligned} \text{Cov}(Q,D) &= 0.231 \times 3.054 \times 1.725 \times 10^{-3} \\ &\approx 1.22 \times 10^{-3} \text{ pC } \lambda. \end{aligned} \quad (\text{E6})$$

The three terms in Eq. (E4) are therefore

$$\beta_Q^2 \sigma_Q^2 = (-1.241 \times 3.054)^2 \approx 14.36 \text{ MeV}^2, \quad (\text{E7})$$

$$\beta_D^2 \sigma_D^2 = (-1135.3 \times 1.725 \times 10^{-3})^2 \approx 3.84 \text{ MeV}^2, \quad (\text{E8})$$

and

$$\begin{aligned} 2\beta_Q\beta_D\text{Cov}(Q,D) &= 2(-1.241)(-1135.3)(1.22 \times 10^{-3}) \\ &\approx 3.43 \text{ MeV}^2. \end{aligned} \quad (\text{E9})$$

The measured total energy variance is

$$\sigma_E^2 = (5.175)^2 \approx 26.78 \text{ MeV}^2. \quad (\text{E10})$$

Relative to the measured total energy variance, the charge term, defocus term, and charge-defocus covariance term in the fitted model correspond to approximately 53.6%, 14.3%, and 12.8%, respectively,

$$\frac{\beta_Q^2 \sigma_Q^2}{\sigma_E^2} \approx 53.6\%, \quad \frac{\beta_D^2 \sigma_D^2}{\sigma_E^2} \approx 14.3\% \quad (\text{E11})$$

and

$$\frac{2\beta_Q\beta_D\text{Cov}(Q,D)}{\sigma_E^2} \approx 12.8\%. \quad (\text{E12})$$

The sum of these terms is approximately 80.8%, consistent with the R^2 value of the multiple linear regression. The remaining approximately 19.2% of the measured energy

variance is not represented by the present two-parameter linear model.

These percentages represent a statistical decomposition of the variance within the fitted linear model and should not be interpreted as independent causal contributions of charge and defocus to the electron beam energy fluctuations. In particular, the covariance term represents the shared statistical variation of charge and defocus and cannot be uniquely assigned to either parameter.

APPENDIX F: EFFECT OF EXPERIMENTAL-ROOM TEMPERATURE ON ELECTRON BEAM POINTING STABILITY

The ambient temperature in the laser room is controlled with a stability of approximately ± 0.1 °C. However, no active temperature control is currently implemented for the experimental area, including the compressor and target chamber. As a result, heat generated by the experimental equipment, particularly the vacuum pumps, gradually increases the room temperature during operation.

Figure 19(a) shows the measured room temperature during a typical experiment, recorded using a temperature sensor (TR-72nw-S, T&D). The room temperature gradually increases by approximately 0.5 °C over the course of the experiment.

The corresponding electron beam pointing distributions are shown in Figs. 19(b) and 19(c). The RMS pointing stability degrades from (0.11, 0.12) mrad to (0.17, 0.31) mrad in the horizontal and vertical directions, respectively. The degradation is more pronounced in the vertical direction, resulting in a noticeably enlarged RMS ellipse.

These measurements provide experimental evidence supporting the statement in the main text that room-temperature

variations can significantly degrade the electron beam pointing stability.

-
- [1] T. Tajima and J. M. Dawson, Laser electron accelerator, *Phys. Rev. Lett.* **43**, 267 (1979).
- [2] D. Strickland and G. Mourou, Compression of amplified chirped optical pulses, *Opt. Commun.* **56**, 219 (1985).
- [3] W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Tóth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, GeV electron beams from a centimetre-scale accelerator, *Nat. Phys.* **2**, 696 (2006).
- [4] W. P. Leemans, A. J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, C. Tóth, J. Daniels, D. E. Mittelberger, S. S. Bulanov, J.-L. Vay, C. G. R. Geddes, and E. Esarey, Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime, *Phys. Rev. Lett.* **113**, 245002 (2014).
- [5] A. J. Gonsalves, K. Nakamura, J. Daniels, C. Benedetti, C. Pieronek, T. C. H. de Raadt, S. Steinke, J. H. Bin, S. S. Bulanov, J. van Tilborg, C. G. R. Geddes, C. B. Schroeder, C. Tóth, E. Esarey, K. Swanson, L. Fan-Chiang, G. Bagdasarov, N. Bobrova, V. Gasilov, G. Korn, P. Sasorov, and W. P. Leemans, Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide, *Phys. Rev. Lett.* **122**, 084801 (2019).
- [6] A. R. Maier, N. Delbos, T. Eichner, L. Hubner, S. Jalas, L. Jappe, S. W. Jolly, M. Kirchen, V. Leroux, P. Messner, M. Schnepf, M. Trunk, P. A. Walker, C. Werle, and P. Winkler, Decoding sources of energy variability in a laser-plasma accelerator, *Phys. Rev. X* **10**, 031039 (2020).
- [7] C. Emma, J. Van Tilborg, R. Assmann, S. Barber, A. Cianchi, S. Corde, M. E. Couprie, R. D'Arcy, M. Ferrario, A. F. Habib, B. Hidding, M. J. Hogan, C. B. Schroeder, A. Marinelli, M. Labat, R. Li, J. Liu, A. Loulergue, J. Osterhoff, A. R. Maier, B. W. J. McNeil, and W. Wang, Free electron lasers driven by plasma accelerators: Status and near-term prospects, *High Power Laser Sci. Eng.* **9**, e57 (2021).
- [8] W. Wang, K. e Feng, L. Ke, C. Yu, Y. i Xu, R. Qi, Y. u Chen, Z. Qin, Z. Zhang, M. Fang, J. Liu, K. Jiang, H. Wang, C. Wang, X. Yang, F. Wu, Y. Leng, J. Liu, R. Li, and Z. Xu, Free-electron lasing at 27 nanometres based on a laser wakefield accelerator, *Nature (London)* **595**, 516 (2021).
- [9] M. Labat, J. C. Cabadağ, A. Ghaith, A. Irman, A. Berlioux, P. Berteaud, F. Blache, S. Bock, F. Bouvet, F. Briquez, *et al.*, Seeded free-electron laser driven by a compact laser plasma accelerator, *Nat. Photon.* **17**, 150 (2023).
- [10] S. K. Barber, F. Kohrell, C. E. Doss, K. Jensen, C. Berger, F. Isono, Z. Eisentraut, S. Schröder, A. J. Gonsalves, K. Nakamura, G. R. Plateau, R. A. van Mourik, M. Gracia-Linares, L. Labun, B. M. Hegelich, S. V. Milton, C. G. R. Geddes, J. Osterhoff, C. B. Schroeder, E. H. Esarey, and J. van Tilborg, Greater than 1000-fold gain in a free-electron laser driven by a laser-plasma accelerator with high reliability, *Phys. Rev. Lett.* **135**, 055001 (2025).
- [11] T. André, I. A. Andriyash, A. Loulergue, M. Labat, E. Roussel, A. Ghaith, M. Khojoyan, C. Thauray, M. Valléau, F. Briquez, *et al.*, Control of laser plasma accelerated electrons for light sources, *Nat. Commun.* **9**, 1334 (2018).
- [12] Z. Jin, M. Kando, Y.-J. Gu, K. Huang, N. Nakanii, I. Daito, Z. Lei, S. Sato, H. Sano, T. Muto, S. Yamamoto, and T. Hosokai, Optimized laser wakefield acceleration: Generating stable, high-energy, monoenergetic electron beams and demonstrating extreme-ultraviolet free-electron lasers, *Phys. Rev. Res.* **8**, 013207 (2026).
- [13] J. D. Ludwig, S. C. Wilks, A. J. Kemp, G. J. Williams, N. Lemos, E. Rockafellow, B. Miao, J. E. Shrock, H. M. Milchberg, J.-L. Vay, A. Huebl, R. Lehe, A. Cimmino, R. Versaci, S. V. Bulanov, P. Valenta, V. Tang, and B. A. Reagan, Laser based 100 GeV electron acceleration scheme for muon production, *Sci. Rep.* **15**, 25902 (2025).
- [14] L. Chen, J. Feng, W. Yan, H. Xu, Y. Li, W. Wang, X. Ge, X. Huang, and J. Zhang, Ultra-high charge electron acceleration for nuclear applications, *Fundam. Plasma Phys.* **12**, 100071 (2024).
- [15] M. Kirchen, S. Jalas, P. Messner, P. Winkler, T. Eichner, L. Hübner, T. Hülsenbusch, L. Jappe, T. Parikh, M. Schnepf, and A. R. Maier, Optimal beam loading in a laser-plasma accelerator, *Phys. Rev. Lett.* **126**, 174801 (2021).
- [16] J. Götzfried, A. Döpp, M. F. Gilljohann, F. M. Foerster, H. Ding, S. Schindler, G. Schilling, A. Buck, L. Veisz, and S. Karsch, Physics of high-charge electron beams in laser-plasma wakefields, *Phys. Rev. X* **10**, 041015 (2020).
- [17] H. Jiang, K. Feng, R. Hu, Q. Zhan, W. Wang, and R. Li, Robustness optimization for compact free-electron laser driven by laser wakefield accelerators, *Phys. Rev. Res.* **8**, 013204 (2026).
- [18] F. Kohrell, S. K. Barber, C. E. Doss, K. Jensen, S. Schröder, C. Berger, Z. Eisentraut, K. Nakamura, A. J. Gonsalves, F. Isono, *et al.*, Over 8 hours of continuous operation of a free-electron laser driven by a laser-plasma accelerator, *Phys. Rev. Accel. Beams* **29**, 041301 (2026).
- [19] A. Popp, J. Vieira, J. Osterhoff, Z. s. Major, R. Hörlein, M. Fuchs, R. Weingartner, T. P. Rowlands-Rees, M. Marti, R. A. Fonseca, S. F. Martins, L. O. Silva, S. M. Hooker, F. Krausz, F. Grüner, and S. Karsch, All-optical steering of laser-wakefield-accelerated electron beams, *Phys. Rev. Lett.* **105**, 215001 (2010).
- [20] C. Zhu, J. Wang, Y. Li, J. Feng, D. Li, Y. He, J. Tan, J. Ma, X. Lu, Y. Li, and L. Chen, Optical steering of electron beam in laser plasma accelerators, *Opt. Express* **28**, 11609 (2020).
- [21] H. Ekerfelt, M. Hansson, I. Gallardo González, X. Davoine, and O. Lundh, A tunable electron beam source using trapping of electrons in a density down-ramp in laser wakefield acceleration, *Sci. Rep.* **7**, 12229 (2017).
- [22] H.-E. Tsai, K. K. Swanson, S. K. Barber, R. Lehe, H.-S. Mao, D. E. Mittelberger, S. Steinke, K. Nakamura, J. van Tilborg, C. Schroeder, E. Esarey, C. G. R. Geddes, and W. Leemans, Control of quasi-monoenergetic electron beams from laser-plasma accelerators with adjustable shock density profile, *Phys. Plasmas* **25**, 043107 (2018).

- [23] A. Rondepierre, D. O. Espinós, Z. Jin, and T. Hosokai, Implementation of a single-shot metrology system for a TW-class laser in a particle accelerator facility, *Opt. Laser Technol.* **180**, 111523 (2025).
- [24] Z. Lei, Y. Gu, Z. Jin, S. Sato, A. Zhidkov, A. Rondepierre, K. Huang, N. Nakanii, I. Daito, M. Kando, and T. Hosokai, Supersonic gas jet stabilization in laser-plasma acceleration, *High Power Laser Sci. Eng.* **11**, e91 (2023).
- [25] Z. Lei, Z. Jin, Y.-J. Gu, S. Sato, A. Zhidkov, A. Rondepierre, K. Huang, N. Nakanii, I. Daito, M. Kando, and T. Hosokai, Modular supersonic nozzle for the stable laser-driven electron acceleration, *Rev. Sci. Instrum.* **95**, 015111 (2024).
- [26] Y. Gu, Z. Jin, Z. Lei, S. Sato, K. Huang, N. Nakanii, I. Daito, M. Kando, and T. Hosokai, Generation of highly stable electron beam via the control of hydrodynamic instability, *Sci. Rep.* **14**, 31162 (2024).
- [27] S. Akturk, X. Gu, E. Zeek, and R. Trebino, Pulse-front tilt caused by spatial and temporal chirp, *Opt. Express* **12**, 4399 (2004).
- [28] K. Nakamura, H. Mao, A. Gonsalves, H. Vincenti, D. Mittelberger, J. Daniels, A. Magana, C. Toth, and W. Leemans, Diagnostics, control and performance parameters for the BELLA High repetition rate petawatt class laser, *IEEE J. Quantum Electron.* **53**, 1 (2017).
- [29] N. Nakanii, K. Huang, K. Kondo, H. Kiriya, and M. Kando, Precise pointing control of high-energy electron beam from laser wakefield acceleration using an aperture, *Appl. Phys. Express* **16**, 026001 (2023).