

Proton jet formation with focused symmetric spatially chirped beams

Eric C. Nelson^{✉,*}, Kyle J. Charbonnet[✉], Trevor Reutershan[✉], Haytham H. Effarah[✉], and C. P. J. Barty[✉]

Department of Physics and Astronomy, University of California, Irvine, Irvine California 92697, USA



(Received 28 July 2025; accepted 31 October 2025; published 3 December 2025)

Three-dimensional particle-in-cell simulations are used to demonstrate the generation of highly collimated, dense proton jets from planar hydrogen targets using shaped, petawatt-class, laser pulses formed via simultaneous spatial and temporal focusing (SSTF). Simulations assume a 30 J, 30 fs laser pulse that is engineered with a radial spatial chirp and then focused into a conical space-time structure. An idealized conical structure that might be produced using a pair of circular diffraction gratings is first modeled and then compared to an approximate implementation using a multibeam combination of four 7.5 J pulses that are produced using conventional single-pass grating pairs. Tightly collimated, 5 μm diameter proton jets with peak energies up to 60 MeV are produced in both instances. Unlike target-shaping schemes that require precise manufacturing and alignment, this shaped-pulse approach can enable high-repetition rate, collimated proton beams using existing thin hydrogen sheet technology.

DOI: [10.1103/z26d-ljfc](https://doi.org/10.1103/z26d-ljfc)

I. INTRODUCTION

Highly collimated, dense proton jets are essential for fast ignition [1–3], cancer therapy [4–6], and nuclear and particle physics [7]. There are many ion acceleration schemes that rely on shaped targets to increase the maximum energy and enhance the axial confinement of accelerated protons [8–15] but require precise manufacturing and shot-to-shot alignment, limiting the ability for high repetition rates [16]. Enabling high repetition rate operation increases the effectiveness of data-driven diagnostics [17], the availability of data for machine-learning models [18], and the rate of discovery [19,20]. A solution to the practical limitation of shaped targets is to instead shape the pulse to influence ion acceleration dynamics while using planar hydrogen sheets as targets. One approach is to use Laguerre-Gaussian (LG) pulses, which have been shown to collimate electrons and protons [21–23]. Laboratory experimentation with LG beams is difficult at petawatt (PW) powers due to optical damage of crucial components used to shape the beam [23]. Plasma-based components (e.g., spiral phase plates) can theoretically be used to generate the appropriate structure [24], but also require precise control of the plasma, limiting experimental viability and throughput. In this manuscript, it is shown that collimated proton jets can be created using lasers with conical pulse fronts interacting with planar hydrogen sheets. Through an axisymmetric extension of simultaneous spatial and temporal focusing, a radial spatial chirp [25] can be generated, resulting in a conical pulse front as the laser pulse passes

through a focus. While the generation of an idealized conical pulse structure is limited by the availability of high-efficiency and high damage threshold optics, an approximate conical pulse front can be readily constructed using four tiled spatially chirped beams [26], as shown in Fig. 2. Many different types of structured light offer promising advancements in laser-plasma interactions, but suffer from detrimental challenges in their generation due to the complexity and efficiency of required specialty optical components [27]. Many practical limitations can be circumvented over other structured light technologies by using four tiled spatially chirped beams, which require only existing petawatt-class optics to generate, enabling the practical implementation of high repetition rate, collimated proton jets at PW laser facilities.

II. THEORETICAL MODELING

Motivated by conical shaped charges, which direct accelerated material on axis [28], a pulse with a conical space-time structure is used to accelerate protons on axis. This schematic is illustrated in Fig. 1, where the pulse interacts with the foil and the protons are accelerated preferentially toward the direction normal to the pulse front tilt (PFT), which steers them toward the propagation axis. Once the protons and electrons are collected on axis, the magnetic field generated from a slight longitudinal charge separation additionally confines the charged particles. For high-intensity circularly polarized light, the deformable mirror model [8,21] has been shown to accurately predict the laser-matter interaction in particle-in-cell (PIC) simulations. The high-intensity light accelerates the ions and electrons together as a whole in a radiation pressure acceleration (RPA) regime [29–31], where the foil acts as a nearly perfect reflecting mirror [32]. However, the pulse discussed is radially polarized which is a spatially oriented linear polarization. Linear polarization requires a higher laser intensity to achieve this RPA regime compared to circular polarization due to increases in electron heating [30]; there-

*Contact author: ecnelson@uci.edu

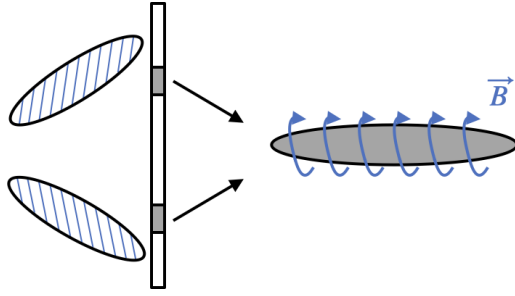


FIG. 1. Schematic of the longitudinal cross section of the interaction window showing protons accelerating (gray) from a conical pulse interacting with a hydrogen foil. The shaped laser pulse (with phase fronts denoted as light blue) accelerates segments of the foil toward the propagation axis (black arrows) where the ions and electrons collect and form a collimating, confining magnetic field.

fore, the deformable mirror model is only able to accurately model the early time steps of the laser-plasma interaction before the increased heating drastically changes the result, which is validated using a three-dimensional (3D) PIC simulation in Figs. 3(a)–3(c). When the conical pulse front interacts with the foil, the initial acceleration of protons follows the deformable mirror equation of motion [8],

$$\frac{\partial \vec{p}}{\partial t} = -\kappa \left[\frac{P}{m_p c} \cos \alpha \right] \frac{\beta \cos \phi - \cos \alpha}{1 - \beta^2 \cos^2 \phi} \frac{\delta S}{\delta N} \vec{n}, \quad (1)$$

where P is the radiation pressure, m_p is the ion mass, α is the angle between the incident laser and the normal of the foil surface, ϕ is the angle between the foil velocity and the surface normal, $\kappa = (\cos \alpha - \beta \cos \phi) / \cos \alpha$, $\beta = v/c$ is the velocity, v , relative to the speed of light, c , and $\vec{p} = \vec{\beta} / \sqrt{1 - \beta^2}$ is the dimensionless momentum. For a ring element of radius δr of the foil, $\delta S = 2\pi r(r_0, t)(r'(r_0, t)^2 + x'(r_0, t)^2)^{\frac{1}{2}} \delta r_0$ is the area where r_0 is the initial radial position of the element at time $t = 0$, r is the radial position as a function of r_0 and t , and x is the longitudinal position as a function of r_0 and t . The prime symbol represents the derivative with respect to r_0 . $\delta N = 2\pi n_0 d_0 r_0 \delta r$ is the number of ions within the element, where n_0 is the foil density and d_0 is the foil thickness at time $t = 0$. Finally, $\vec{n}$ is the unit normal vector of the element's surface, defined by [8]

$$\vec{n} = \frac{r'(r_0, t) \cdot \vec{e}_x - x'(r_0, t) \cdot \vec{e}_r}{(r'(r_0, t)^2 + x'(r_0, t)^2)^{\frac{1}{2}}}. \quad (2)$$

In the deformable mirror model for high-intensity circularly polarized light, $P = 2I/c$, where I is the intensity of the laser light [33–35]. However, for linearly polarized light, more energy is lost to electron heating [36], so the RPA regime requires a larger intensity. This limits the model's applicability to early time steps of the interaction but is still helpful in predicting the initial conical shape of the ions that later forms into a jet. Additionally, an accurate model of the space-time profile of the conical pulse is crucial, so the laser field was computationally generated at the foil surface as a function of r and t using the ALFP code package [37].

The intensity distribution of the conical space-time structure at the foil surface causes a radially inward pressure for a

region of the foil within the conical structure. This results in a converging acceleration, where both electrons and protons in this section of the foil are accelerated toward the axis.

III. SIMULATION RESULTS

The interaction and jet formation is modeled first in an idealized configuration as a radially symmetric pulse. The simulated pulse is characterized by a 40 cm $1/e^2$ intensity beam diameter, 30 fs full-width-at-half-maximum Gaussian temporal profile centered around 800 nm, 30 J of energy, and radial polarization. The peak intensity region of each laser enters the simulation at 80 fs at the left window, where $x = 0$. Before focusing, this beam has an annular structure, shown as the Input Plane inset of Fig. 2(a) that has an annular radius, defined as the distance of the central frequency from the optical axis, of 61.45 cm. The pulse has a positive radial spatial chirp (larger frequencies are positioned at larger radial distances from the optical axis) where the effective beam diameter is increased to 54.0 cm. The pulse is then propagated through an ideal focusing lens and the integrated spatial profile of the pulse incident on the foil is shown in Fig. 2(b). The foil is placed 28.75 μm before the focus, such that the pulse has an open cone structure. At this position, the pulse has a normalized peak vector potential $a_0 = 14.87$. The full spatiotemporal pulse front structure at the foil surface is shown in Fig. 2(c), where the conical structure is presented.

The radial spatial chirp configuration shows the ideal symmetric structure for jet formation. However, the specialized components required to generate this pulse structure make it not only difficult to construct at low intensities, but also increasingly impractical at PW powers. To simplify implementation, an approximation of the radial spatial chirp is modeled through the tiling of four individual, spatially chirped beams. This approach importantly requires only standard optical components that have already been optimized for petawatt-class laser operation. This configuration is shown in Figs. 2(d)–2(f) where the insets again show the four beams at the input plane before focusing, and the foil plane at the interaction point. Each beam is spatially chirped in one dimension, modeled as the output of a single pass grating pair and is positioned 61.45 cm from the optical axis. The unchirped dimension of the beam is expanded by a factor of 0.695, resulting in a beam diameter of 27.8 cm and the chirped dimension maintains the same 54.0 cm effective diameter as the radial pulse. The beams are p -polarized, along the direction of the spatial chirp, and each have an energy of 7.5 J to match the total energy of the radially chirped beam. When they are arranged in the cross pattern as in the Input Plane inset of Fig. 2(b), there is an effective radial polarization across the input plane. At the foil, the pulse front structure appears to be quasiconical, with an overall squareness on the shape due to the Cartesian symmetry and $a_0 = 15.53$. All parameters are set such that the four-beam configuration creates a discretized version of the radial pulse.

The foil is modeled after recent laboratory demonstrations [38] as a hydrogen sheet 600 nm thick, and with square transverse extents of 28.16 μm , placed 28.75 μm in front of the geometric focus. The foil is a collection of fully ionized hydrogen ions and electrons, both with a density $n_0 = 30n_c$,

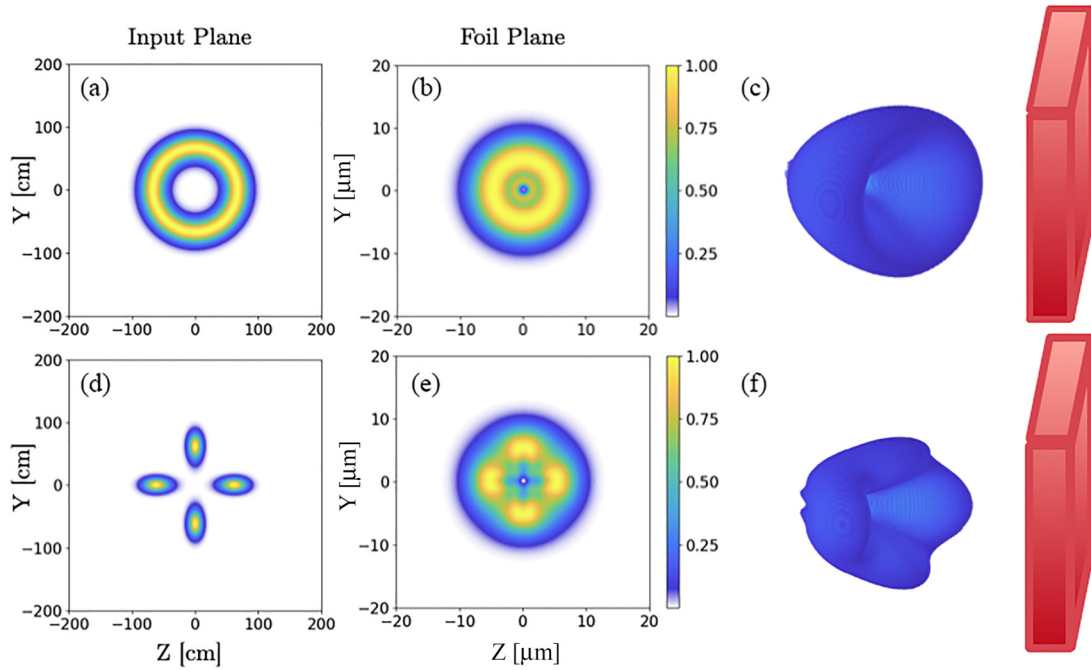


FIG. 2. (a), (b) The transverse profile of radial spatially chirped beam at the focusing optic plane and at the foil plane, respectively. Both profiles are integrated over time. (c) The schematic of the radial spatially chirped beam with a conical pulse front just before interacting with the foil (in red). (d)–(f) The same plots but for four one-dimensional (1D) spatially chirped beams arranged to create an approximate conical pulse front before interacting with a foil.

where $n_c = \epsilon_0 m_e \omega_0 / e^2$ is the plasma critical density. The laser-plasma interactions are simulated using the particle-in-cell code SMILEI [39]. To accurately model the complex space-time structure of the focused laser field, ALFP was used, which Fourier propagates a field to an arbitrary plane and passes it to the PIC simulation. The ALFP and simulation grid parameters are shown in Table I. The optimal parameters for the radial and four-beam approximations were determined through a Bayesian scan of grating separation, annular radius, foil position, and unchirped beam expansion factor to determine the parameters that result in the arrangement with the largest number density and best collimation of protons that reach the edge of the PIC simulation window within a $5 \mu\text{m}$ diameter spot over the duration of the simulation. The Bayesian optimization quickly finds a solution over a multiple parameter phase space, reducing the computational cost.

TABLE I. Grid parameters for the laser input, laser output, and PIC grids.

Parameters	Input grid	Output grid	PIC grid
y step size	0.391 cm	0.117 μm	0.04 μm
z step size	0.391 cm	0.117 μm	0.04 μm
x step size	N/A	N/A	0.02 μm
t step size	0.122 fs	0.122 fs	0.0365 fs
y window size	400 cm	60 μm	28.16 μm
z window size	400 cm	60 μm	28.16 μm
x window size	N/A	N/A	48 μm
t duration	2000 fs	2000 fs	1000 fs

Shown in Figs. 3(a)–3(c), the deformable mirror model closely predicts the early time steps of the 3D PIC simulation for the radially chirped pulse. The initial proton acceleration is influenced by the annular shape of the spatial profile from the laser pulse. Protons within the open angle of the conical structure get accelerated toward the central propagation axis, steered by the PFT [37]. Figure 3(d) illustrates the sheath field strength and direction in an X–Y plane at $t = 147$ fs. The direction of the sheath field is forward and radially inward if within the initial cone of the laser field. This pulls the ions toward the optical axis, forming a jetlike structure. The deformable mirror model breaks down once the protons collect on axis, and the complex behavior is unable to be accurately described with this simple model. The electrons and protons collect on axis, and due to a charge separation from the electrons, which are accelerated to higher energies, a kT-scale toroidal magnetic field is formed. The field moves counterclockwise from the negative longitudinal current in the jet. For the electrons, this field imparts a Lorentz force, $\vec{F} = q\vec{v} \times \vec{B}$, that points inward toward the axis, collimating the population of electrons. This mechanism of collimation has been previously demonstrated in PIC simulations and is sometimes referred to as a magnetic tunnel [21,40]. The magnetic field component, B_z , generated by the jet from the radially chirped beam is displayed in Fig. 3(e) in the X–Y plane and reaches a peak value of 5.1 kT at a radius of $1.8 \mu\text{m}$. These electrons generate a sheath field that pulls the heavier protons with them in a similar fashion, forward and radially inward.

The proton jet formation is shown for both the radial and four-beam cases in Fig. 4, along with the protons accelerated by a linearly polarized Gaussian laser pulse for comparison.

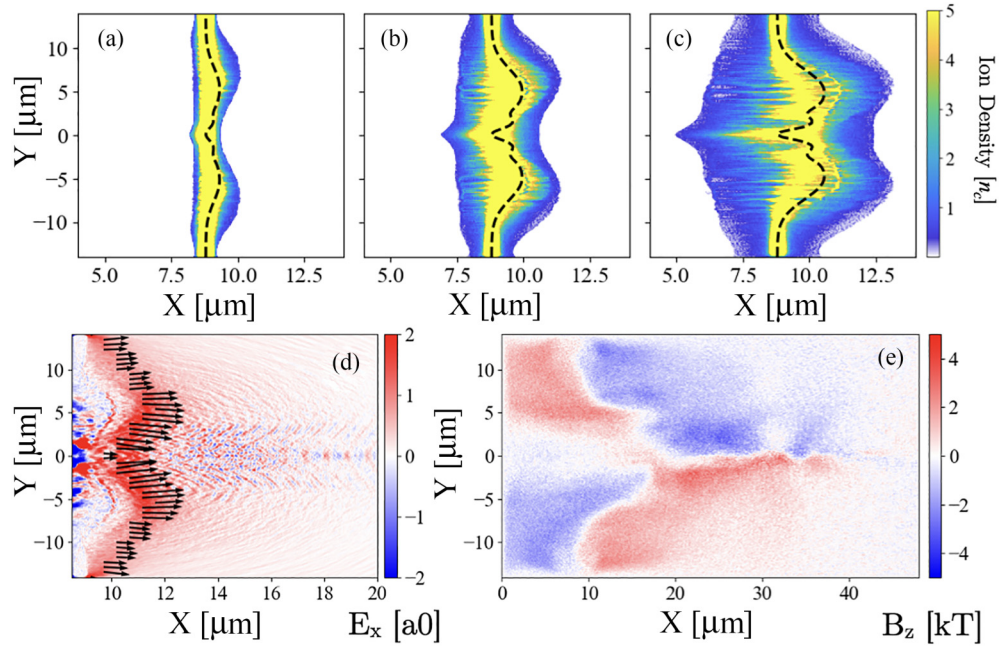


FIG. 3. (a)–(c) The modified deformable mirror model (black dashed line) compared to the PIC simulation of the laser foil interaction at times $t = 120$, 147 , and 173 fs. (d) The sheath field in an X – Y plane at $t = 147$ fs. The colormap shows the longitudinal sheath field E_x . The vectors show $\langle E_x, E_y \rangle$, along the sheath field. (e) The B_z field at $t = 547$ fs generated during acceleration that collimates the electrons.

The Gaussian pulse is set to fill the same effective $1/e^2$ aperture as the radial case, which sets the beam diameter to 176.86 cm and $a_0 = 39.57$. This beam diameter is unrealistically large, but enables a comparison of the best-case scenario

for the Gaussian beam of an equivalent aperture by keeping the f number of the focusing system consistent. A realistic Gaussian pulse of diameter 40 cm and $a_0 = 21.2$, attainable with current PW class optics, is shown in the Supplemental

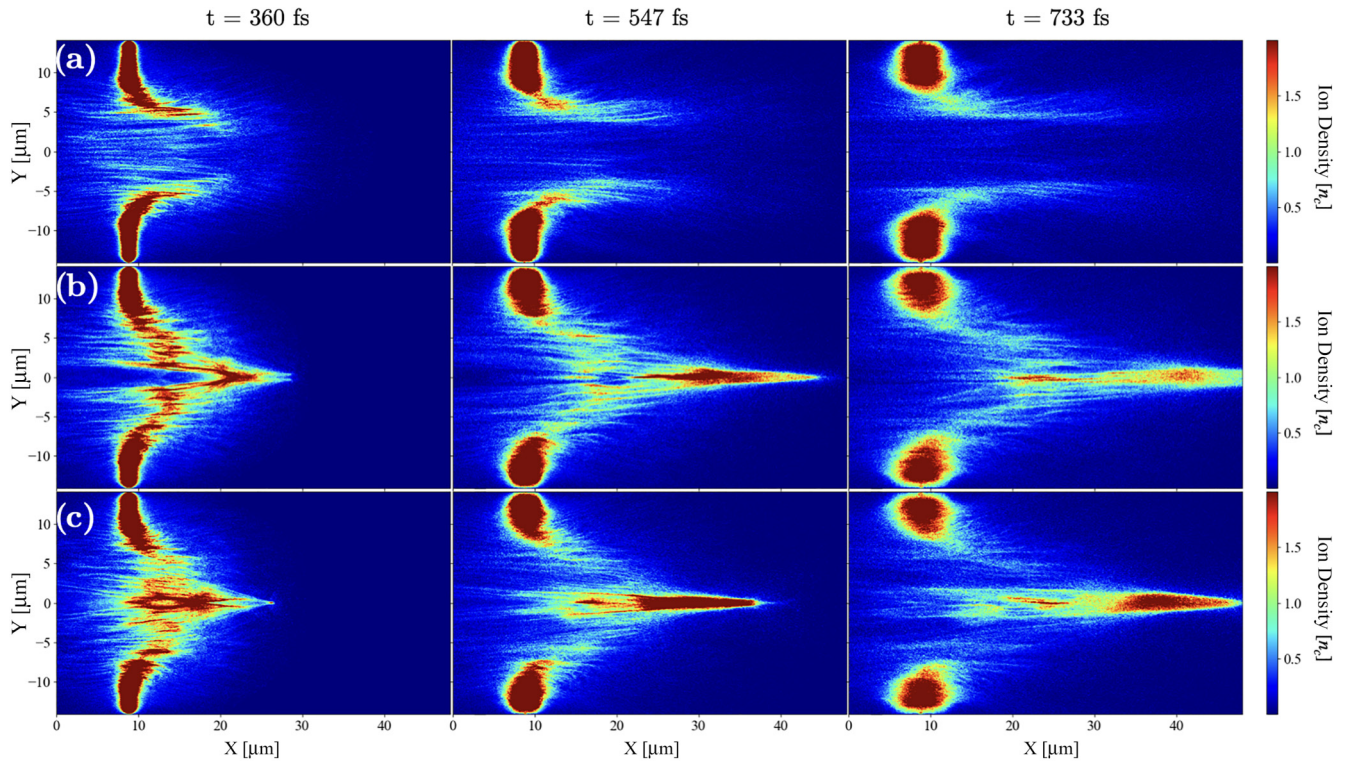


FIG. 4. The proton jet formation for the (a) Gaussian beam, (b) radial beam, and (c) four-beam combination. The ion number density in the X – Y plane is plotted for three different timestamps of the simulation: 360 , 547 , and 733 fs.

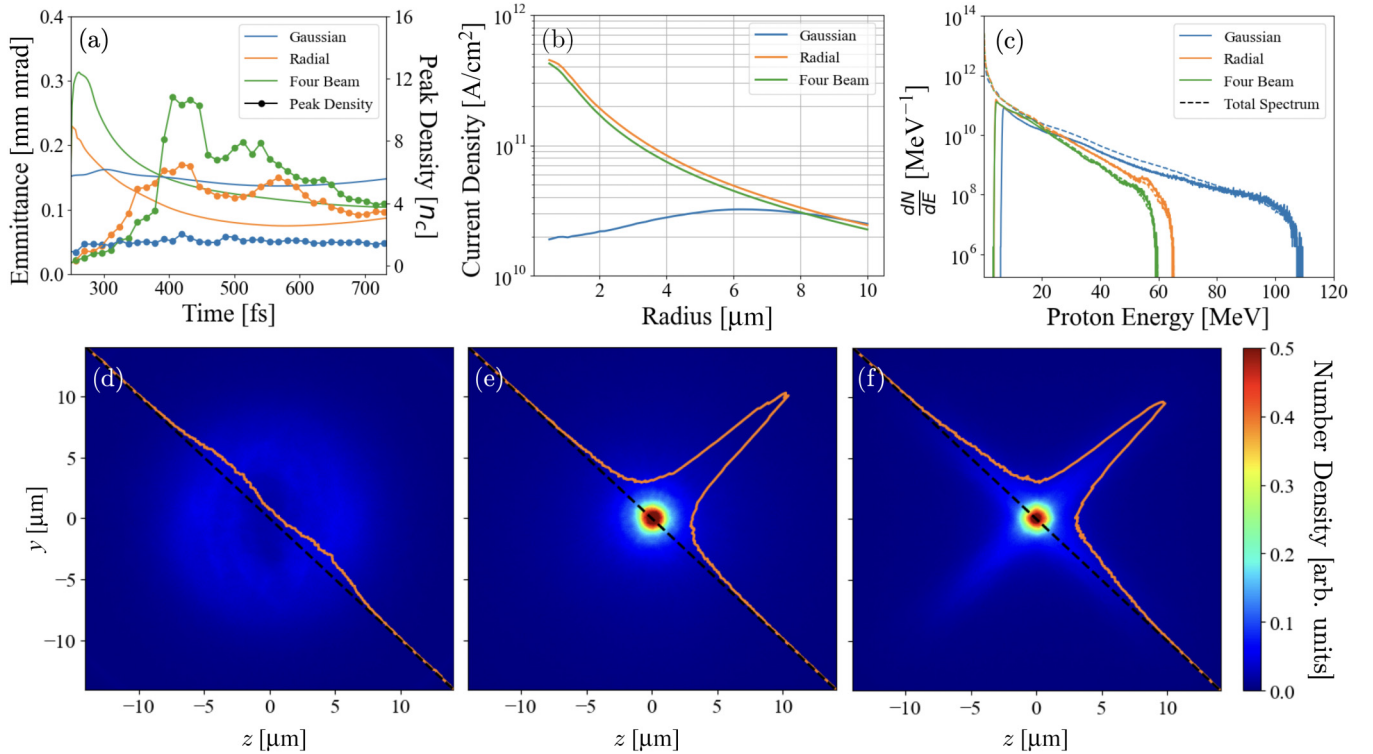


FIG. 5. (a) The transverse rms emittance (left axis) and peak density (right axis) of the proton jet at various times in the simulation. These data were calculated for a cylinder on the longitudinal axis from $x = 20 \mu m$ to $x = 48 \mu m$, and of transverse radius $r = 5 \mu m$. (b) The current density that crosses an on-axis circle on the transverse plane at $x = 40 \mu m$ as a function of circle radius. The current density is calculated as $j = \frac{Q}{\tau \pi r^2}$, where τ is the simulation duration of 1 ps, r is the circle radius, and Q is the charge passing through the circle. (c) The proton energy spectrum within the cylinder (solid lines) and the energy spectrum for the whole simulation (dashed line) shown at the timestamp that peak proton energy was observed for the three cases shown in the manuscript. Peak proton energy was observed at $t = 528 fs$ for the radial beam and four-beam cases. The peak proton energy was observed at $t = 426 fs$ for the Gaussian beam. (d)–(f) The transverse plane of the time-integrated sum of ions over the duration of the simulation that cross the plane $x = 40 \mu m$ for the Gaussian beam, radial beam, and four-beam arrangement, respectively. The orange lines show the number density values along the diagonal (black dashed line) in arbitrary units. The $1/e^2$ diameters of the diagonals for (d)–(f) are 25.14, 4.66, and 5.65 μm , respectively.

Material [41] to have worse emittance and peak density than the equivalently apertured Gaussian. The first column of Fig. 4 shows the early onset of the protons collecting on axis, and the later times display the core jet as it propagates within the simulation. Both spatially chirped pulse shapes create well-defined, approximately 5 μm diameter proton jets, while the Gaussian beam results in very few on-axis protons. The rms emittance [42] and peak number density at various time steps throughout the simulation are visualized in Fig. 5(a) to quantify the quality of the proton jet. The emittance of the proton jet throughout the simulation is tracked by calculating the phase space distribution of the position and angles of each macroparticle within a 10 μm diameter cylinder centered around the propagation axis from $x = 20 \mu m$ to the edge of the simulation window at $x = 48 \mu m$. The emittance is not conserved throughout the simulation and also reaches a minimum of 0.08 and 0.1 mm-mrad for the radial and four-beam cases, respectively. In the absence of external fields, nonconserved emittance indicates space charge effects or influences from the electron beam. The radial and four-beam configurations show a peak density that is several times higher than that produced by the Gaussian pulse. The absolute peak value of density depends strongly on spatial variations of the

accelerated protons and can fluctuate from instabilities originating from the initial laser-plasma interaction. The four beam case experiences higher modulations in the peak density, which results in instantaneous values that are greater than the radial, but at later times in the simulation the value begins to converge to that of the radial pulse. Figure 5(b) shows the current density as a function of radius for the three cases. Both the radial and four-beam simulations result in peak current densities that are an order of magnitude larger than the Gaussian case, with a majority of the current contained within a small area. The spectrum of the jet within the 10 μm cylinder along with the spectrum of all particles is shown in Fig. 5(c). A majority of the high-energy protons are on axis and contained within this cylinder for both the jets and Gaussian cases. Most of the low-energy protons stay close to the initial position of the foil at positions $x < 20 \mu m$. A transverse cross section at 40 μm shows the integrated spatial profile of the accelerated protons for the three cases in Figs. 5(d)–5(f). Compared to the Gaussian case in Fig. 5(d), the spatially shaped pulses result in a well-defined collection of protons near the optical axis. The four-beam arrangement results in some leakage of protons along the diagonal axes where there was no significant beam energy, which is shown in Fig. 5(f). The orange inset shows

the relative number density compared to the peak, which is much higher on axis for the shaped pulses in comparison to the Gaussian. The transverse momentum of the protons slowly increases in magnitude as they propagate, which eventually leads to an increase in the jet diameter. Additionally, due to the polychromatic energy distribution of protons and electrons seen in Fig. 5(c), the longitudinal extent of the jet will spread as the higher energy particles continually advance beyond the lower energy particles.

IV. DISCUSSION AND OUTLOOK

The four-beam approach offers several practical advantages while maintaining similar jet formation compared to the radial case. The radial chirp, while offering an ideal reference case to model, requires optics that are not yet optimized or available for petawatt operation. The radial spatial chirp was modeled from the output of a single-pass, two-grating compressor consisting of two concentric ring gratings [43] with a groove density of 1480 lines/mm with a separation of 102 cm, and 22.8° angle of incidence. The natural output of the gratings results in a negative spatial chirp, as the grating pair diffracts the higher wavelengths to larger angles, and an annular radius of 134.36 cm. To have the proper conical structure when interacting with the foil [26], the radial chirp is inverted around the center frequency before focusing, such that the low-wavelength portion of the beam is on the outside edge, and the annular radius is set to 61.45 cm. The modification of the input beam in this way would require a pair of large aperture reflective axicons, in addition to high damage threshold concentric ring gratings [43]. Additionally, radial polarizers are transmissive optics, offering another technological hurdle due to low damage thresholds. Many high-power laser facilities are moving toward multiple beamlines [44–46], which could be arranged in the configuration presented here. The four-beam approach can also be achieved with a single beamline that is split into four copies with a beam splitter arrangement. Moreover, the four-beam configuration easily enables the ability to control the polarization into a radial configuration. The natural output from high-efficiency gold gratings used in high-power laser systems [47–49] are linearly polarized along the direction of the spatial chirp. When arranged into the cross pattern of the Input Plane inset in Fig. 2(d), the effective polarization will be radial across the aperture. Beam steering optics can be used to properly orient the 1D spatially chirped beams such that the low-wavelength portion is on the outside of the beam, giving the proper space-time profile as it focuses. The four beams must be cophased together through careful alignment of off-axis, reflective parabolic optics. The alignment of large-aperture, tiled optics can readily be achieved with high precision [50–52]. The method of using four beams to form a dense jet of protons is relatively robust. Much of the directed

ponderomotive force comes from the angle of the propagation vector from the off-axis focusing of the beams. Different PFT angles for a given annular radius result in a collection of protons on axis and a noticeable improvement over a Gaussian beam acceleration. The angle of the PFT enables a fine-tuning of the initial proton acceleration, offering improved number density within the core of the jet and is shown in the Supplemental Material [41]. The jet formation from the spatially chirped beams also works for various foil thicknesses. Values of 400, 600, and 1000 nm were simulated and are presented in the Supplemental Material [41], all resulting in a distinct proton jet. Lower-energy pulses may also be used to form the jets. 19 J and 9 J, 30 fs pulses have also been modeled and shown to accelerate the protons in a similar fashion. Pulses with 30 J at 60 fs and 10 J at 100 fs were also determined to provide appreciable jet formation. These additional cases are discussed in the Supplemental Material [41]. As high-power lasers push into multihertz operation, targets also need to be aligned into the interaction region at high repetition rates. While ion focusing schemes based on shaped foils yield low emittance and collimated protons, liquid and solid tape drive targets provide a route for high-repetition rate interactions. Through shaping the laser pulse, these types of targets can be used to generate proton jets at multiple shots per second with current petawatt-class optics.

The hydrogen foil was modeled as a step interface into vacuum, and the temporal structure of the laser pulse was assumed to be a perfect Gaussian profile. Realistically, PW lasers have a prepulse that will affect the structure of the hydrogen foil. The prepulse interacts before the main pulse creating a density gradient [53] that will change the dynamics of the proton acceleration. Efforts are being made to increase the contrast of high-power laser pulses, where temporal contrasts of 10^{12} have already been achieved through second-harmonic generation [54] and double plasma mirrors [55]. A detailed analysis of the effects a prepulse has on the jet formation is outside the scope of this work.

The radially chirped beam enables effective jet formation from laser-accelerated protons. The jet is a highly collimated, low emittance, large current density stream of protons and electrons. The generation of the radially symmetric laser pulse shape is difficult for ultrahigh-intensity laser systems often used in laser-ion acceleration due to the required optics being difficult to manufacture for petawatt-scale energies. A discrete approximation to the radially chirped beam is provided, using four beamlines that are coherently combined. This offers a practical implementation for the creation of the simulated proton jets, utilizing conventional optics that are presently optimized for petawatt operation.

DATA AVAILABILITY

The data that support the findings of this article are openly available [56].

[1] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason,

Ignition and high gain with ultrapowerful lasers, *Phys. Plasmas* **1**, 1626 (1994).

- [2] V. Y. Bychenkov, Fast ignitor concept with light ions, *Plasma Phys. Rep.* **27**, 1017 (2001).
- [3] M. Roth, T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R. A. Snavely, S. C. Wilks, K. Yasuike, H. Ruhl, F. Pegoraro, S. V. Bulanov, E. M. Campbell, M. D. Perry, and H. Powell, Fast ignition by intense laser-accelerated proton beams, *Phys. Rev. Lett.* **86**, 436 (2001).
- [4] S. V. Bulanov, T. Z. Esirkepov, V. S. Khoroshkov, A. V. Kuznetsov, and F. Pegoraro, Oncological hadrontherapy with laser ion accelerators, *Phys. Lett. A* **299**, 240 (2002).
- [5] F. Hannachi, M. M. Aléonard, M. Gerbaux, F. Gobet, G. Malka, C. Plaisir, J. N. Scheurer, M. Tarisien, P. Audebert, E. Brambrink, V. Méot, P. Morel, P. Nicolaï, and V. Tikhonchuk, Prospects for nuclear physics with lasers, *Plasma Phys. Control. Fusion* **49**, B79 (2007).
- [6] F. Kroll, F.-E. Brack, C. Bernert, S. Bock, E. Bodenstein, K. Brückner, T. E. Cowan, L. Gaus, R. Gebhardt, U. Helbig *et al.*, Tumour irradiation in mice with a laser-accelerated proton beam, *Nat. Phys.* **18**, 316 (2022).
- [7] A. Yogo, K. Sato, M. Nishikino, M. Mori, T. Teshima, H. Numasaki, M. Murakami, Y. Demizu, S. Akagi, S. Nagayama *et al.*, Application of laser-accelerated protons to the demonstration of DNA double-strand breaks in human cancer cells, *Appl. Phys. Lett.* **94**, 181502 (2009).
- [8] T. Wang, V. Khudik, and G. Shvets, Laser-ion lens and accelerator, *Phys. Rev. Lett.* **126**, 024801 (2021).
- [9] M. Chen, A. Pukhov, T. P. Yu, and Z. M. Sheng, Enhanced collimated GeV monoenergetic ion acceleration from a shaped foil target irradiated by a circularly polarized laser pulse, *Phys. Rev. Lett.* **103**, 024801 (2009).
- [10] D. Khaghani, M. Lobet, B. Borm, L. Burr, F. Gartner, L. Gremillet, L. Movsesyan, O. Rosmej, M. E. Toimil-Molares, F. Wagner, and P. Neumayer, Enhancing laser-driven proton acceleration by using micro-pillar arrays at high drive energy, *Sci. Rep.* **7**, 11366 (2017).
- [11] I. Khan and V. Saxena, Enhanced target normal sheath acceleration with a grooved hydrocarbon target, *Phys. Plasmas* **30**, 063102 (2023).
- [12] G. Cantono, A. Permogorov, J. Ferri, E. Smetanina, A. Dmitriev, A. Persson, T. Fulop, and C. G. Wahlstrom, Laser-driven proton acceleration from ultrathin foils with nanoholes, *Sci. Rep.* **11**, 5006 (2021).
- [13] J. Choudhury, A. Bhagawati, J. Sarma, and N. Das, Ion acceleration from a multispecies nanostructured target using a high-intensity laser: A simulation study, *Plasma Phys. Control. Fusion* **65**, 085007 (2023).
- [14] X. Shen, Z. Gong, K. Z. Hatsagortsyan, and C. H. Keitel, Highly polarized energetic electrons via intense laser-irradiated tailored targets, *Phys. Rev. Res.* **6**, L032075 (2024).
- [15] M. Tosca, A. Morace, M. Schollmeier, S. Steinke, V. Shirvanyan, Y. Arikawa, L. Giuffrida, D. Margarone, P. Pleskunov, A. Choukourov, R. R. Whitney, L. R. Scammell, and G. Korn, Enhanced laser absorption and ion acceleration by boron nitride nanotube targets and high-energy PW laser pulses, *Phys. Rev. Res.* **6**, 023326 (2024).
- [16] L. Roso, High repetition rate petawatt lasers, *EPJ Web Conf.* **167**, 01001 (2018).
- [17] C. J. G. McQueen, R. Wilson, T. P. Frazer, M. King, M. Alderton, E. F. J. Bacon, E. J. Dolier, T. Dzelzainis, J. K. Patel, M. P. Peat, B. C. Torrance, R. J. Gray, and P. McKenna, A neural network-based synthetic diagnostic of laser-accelerated proton energy spectra, *Commun. Phys.* **8**, 66 (2025).
- [18] P. W. Hatfield, J. A. Gaffney, G. J. Anderson, S. Ali, L. Antonelli, S. Başgömez du Pree, J. Citrin, M. Fajardo, P. Knapp, B. Kettle *et al.*, The data-driven future of high-energy-density physics, *Nature (London)* **593**, 351 (2021).
- [19] E. Sistrunk, T. Spinka, A. Bayramian, S. Betts, R. Bopp, S. Buck, K. Charron, J. Cupal, R. Deri, M. Drouin *et al.*, All diode-pumped, high-repetition-rate advanced petawatt laser system (HAPLS), in *Conference on Lasers and Electro-Optics* (Optica Publishing Group, San Jose, CA, 2017), p. STh1L.2.
- [20] T. Ma, D. Mariscal, R. Anirudh, T. Bremer, B. Z. Djordjevic, T. Galvin, E. Grace, S. Herriot, S. Jacobs, B. Kailkhura *et al.*, Accelerating the rate of discovery: toward high-repetition-rate HED science, *Plasma Phys. Control. Fusion* **63**, 104003 (2021).
- [21] H. Dong, W. P. Wang, J. Z. He, Z. Y. Shi, Y. X. Leng, R. X. Li, and Z. Z. Xu, Self-generated magnetic collimation mechanism driven by ultra-intense LG laser, *Phys. Plasmas* **30**, 083101 (2023).
- [22] C. Brabetz, S. Busold, T. Cowan, O. Deppert, D. Jahn, O. Kester, M. Roth, D. Schumacher, and V. Bagnoud, Laser-driven ion acceleration with hollow laser beams, *Phys. Plasmas* **22**, 013105 (2015).
- [23] W. P. Wang, C. Jiang, H. Dong, X. M. Lu, J. F. Li, R. J. Xu, Y. J. Sun, L. H. Yu, Z. Guo, X. Y. Liang, Y. X. Leng, R. X. Li, and Z. Z. Xu, Hollow plasma acceleration driven by a relativistic reflected hollow laser, *Phys. Rev. Lett.* **125**, 034801 (2020).
- [24] J. Li, X. Wang, Z. Wang, and Z. Wei, Orbital-angular-momentum-controlled laser pulses with near-relativistic intensity, *Phys. Rev. A* **111**, 023506 (2025).
- [25] M. Clerici, D. Faccio, E. Rubino, A. Lotti, A. Couairon, and P. Di Trapani, Space-time focusing of Bessel-like pulses, *Opt. Lett.* **35**, 3267 (2010).
- [26] E. C. Nelson, K. J. Charbonnet, H. H. Effarah, T. Reutershan, K. D. Chesnut, and C. P. J. Barty, Focused axisymmetric spatially chirped beams, *Opt. Express* **33**, 34487 (2025).
- [27] M. Piccardo, M. O. Cernaianu, J. P. Palastro, A. Arefiev, C. Thauray, J. Vieira, D. H. Froula, and V. Malka, Trends in relativistic laser-matter interaction: The promises of structured light, *Optica* **12**, 732 (2025).
- [28] H. Mehmannavaz, A practical review study on shaped charge in the last two decades (2000–2020), *Int. J. Prot. Struct.* **12**, 665 (2021).
- [29] T. Esirkepov, M. Borghesi, S. V. Bulanov, G. Mourou, and T. Tajima, Highly efficient relativistic-ion generation in the laser-piston regime, *Phys. Rev. Lett.* **92**, 175003 (2004).
- [30] A. Macchi, F. Cattani, T. V. Liseykina, and F. Cornolti, Laser acceleration of ion bunches at the front surface of overdense plasmas, *Phys. Rev. Lett.* **94**, 165003 (2005).
- [31] F. Dollar, C. Zwick, A. Raymond, V. Chvykov, L. Willingale, V. Yanovsky, A. Maksimchuk, A. G. R. Thomas, and K. Krushelnick, Enhanced laser absorption from radiation pressure in intense laser plasma interactions, *New J. Phys.* **19**, 063014 (2017).
- [32] A. Macchi, S. Veghini, and F. Pegoraro, “Light sail” acceleration reexamined, *Phys. Rev. Lett.* **103**, 085003 (2009).
- [33] V. Khudik, S. A. Yi, C. Siemon, and G. Shvets, The analytic model of a laser-accelerated plasma target and its stability, *Phys. Plasmas* **21**, 013110 (2014).

- [34] S. V. Bulanov, E. Y. Echkina, T. Esirkepov, I. N. Inovenkov, M. Kando, F. Pegoraro, and G. Korn, Unlimited ion acceleration by radiation pressure, *Phys. Rev. Lett.* **104**, 135003 (2010).
- [35] X. Q. Yan, C. Lin, Z. M. Sheng, Z. Y. Guo, B. C. Liu, Y. R. Lu, J. X. Fang, and J. E. Chen, Generating high-current monoenergetic proton beams by a circularly polarized laser pulse in the phase-stable acceleration regime, *Phys. Rev. Lett.* **100**, 135003 (2008).
- [36] B. Qiao, S. Kar, M. Geissler, P. Gibbon, M. Zepf, and M. Borghesi, Dominance of radiation pressure in ion acceleration with linearly polarized pulses at intensities of 10^{21} W cm $^{-2}$, *Phys. Rev. Lett.* **108**, 115002 (2012).
- [37] K. J. Charbonnet, E. C. Nelson, T. Reutershan, and C. P. J. Barty, Computational methods for focused arbitrary laser fields in plasma simulations, *Phys. Plasmas* **32**, 043901 (2025).
- [38] C. Bernert, S. Assenbaum, S. Bock, F.-E. Brack, T. E. Cowan, C. B. Curry, M. Garten, L. Gaus, M. Gauthier, R. Gebhardt *et al.*, Transient laser-induced breakdown of dielectrics in ultra-relativistic laser-solid interactions, *Phys. Rev. Appl.* **19**, 014070 (2023).
- [39] J. Derouillat, A. Beck, F. Pérez, T. Vinci, M. Chiamello, A. Grassi, M. Flé, G. Bouchard, I. Plotnikov, N. Aunai, J. Dargent, C. Riconda, and M. Grech, SMILEI: A collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation, *Comput. Phys. Commun.* **222**, 351 (2018).
- [40] A. P. Robinson, M. Sherlock, and P. A. Norreys, Artificial collimation of fast-electron beams with two laser pulses, *Phys. Rev. Lett.* **100**, 025002 (2008).
- [41] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/z26d-ljfc> for additional figures with varied laser and target parameters, which includes Refs. [45,57–65].
- [42] M. Reiser, *Theory and Design of Charged Particle Beams*, 2nd ed. (Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, 2008), p. 52.
- [43] J. Dyson, Circular and spiral diffraction gratings, *Proc. R. Soc. London A* **248**, 93 (1958).
- [44] M. Aléonard, M. Altarelli, P. Antici, A. Apolonskiy, P. Audebert, A. Bartnik, C. Barty, A. Bernstein, J. Biegert, P. Böni, N. Booth, D. Bote, S. Bulanov, R. Butkus, L. Cardoso, J. P. Chambaret, D. Charambilidis, G. Cheriaux, R. Clarke, and M. Zepf, *WHITEBOOK ELI–Extreme Light Infrastructure; Science and Technology with Ultra-Intense Lasers* (Thoss Media GmbH, Berlin, 2011).
- [45] J. Bromage, S. W. Bahk, M. Bedzyk, I. A. Begishev, S. Bucht, C. Dorrer, C. Feng, C. Jeon, C. Mileham, R. G. Roides, K. Shaughnessy, M. J. Shoup, M. Spilatro, B. Webb, D. Weiner, and J. D. Zuegel, MTW-OPAL: A technology development platform for ultra-intense optical parametric chirped-pulse amplification systems, *High Power Laser Sci. Eng.* **9**, e63 (2021).
- [46] L. Willingale, A. Maksimchuk, J. Nees, F. Bayer, M. Burger, P. T. Campbell, B. Hou, I. Jovanovic, G. Kalinchenko, C. C. Kuranz, Y. Ma, A. McKelvey, A. G. R. Thomas, L. Weinberg, Q. Zhang, and K. M. Krushelnick, Status of the ZEUS laser user facility, in *CLEO 2023*, Technical Digest Series (Optica Publishing Group, San Jose, CA, 2023), p. SM1D.7.
- [47] Y. Han, Z. Li, Y. Zhang, F. Kong, H. Cao, Y. Jin, Y. Leng, R. Li, and J. Shao, 400 nm ultra-broadband gratings for near-single-cycle 100 petawatt lasers, *Nat. Commun.* **14**, 3632 (2023).
- [48] F. Lureau, G. Matras, O. Chalus, C. Derycke, T. Morbieu, C. Radier, O. Casagrande, S. Laux, S. Ricaud, G. Rey *et al.*, High-energy hybrid femtosecond laser system demonstrating 2×10 PW capability, *High Power Laser Sci. Eng.* **8**, e43 (2020).
- [49] C. M. Werle, C. Braun, T. Eichner, T. Hulsbusch, G. Palmer, and A. R. Maier, Out-of-plane multilayer-dielectric-grating compressor for ultrafast Ti:Sapphire pulses, *Opt. Express* **31**, 37437 (2023).
- [50] G. Chanan, M. Troy, and E. Sirko, Phase discontinuity sensing: A method for phasing segmented mirrors in the infrared, *Appl. Opt.* **38**, 704 (1999).
- [51] G. Chanan, M. Troy, I. Surdej, G. Gutt, and J. L. C. Roberts, Fresnel phasing of segmented mirror telescopes, *Appl. Opt.* **50**, 6283 (2011).
- [52] A. C. Cheetham, P. G. Tuthill, A. Sivaramakrishnan, and J. P. Lloyd, Fizeau interferometric cophasing of segmented mirrors, *Opt. Express* **20**, 29457 (2012).
- [53] M. Rehwald, S. Assenbaum, C. Bernert, F. E. Brack, M. Bussmann, T. E. Cowan, C. B. Curry, F. Fiuza, M. Garten, L. Gaus *et al.*, Ultra-short pulse laser acceleration of protons to 80 MeV from cryogenic hydrogen jets tailored to near-critical density, *Nat. Commun.* **14**, 4009 (2023).
- [54] Y. Wang, S. Wang, A. Rockwood, B. M. Luther, R. Hollinger, A. Curtis, C. Calvi, C. S. Menoni, and J. J. Rocca, 0.85 PW laser operation at 3.3 Hz and high-contrast ultrahigh-intensity $\lambda = 400$ nm second-harmonic beamline, *Opt. Lett.* **42**, 3828 (2017).
- [55] I. W. Choi, C. Jeon, S. G. Lee, S. Y. Kim, T. Y. Kim, I. J. Kim, H. W. Lee, J. W. Yoon, J. H. Sung, S. K. Lee, and C. H. Nam, Highly efficient double plasma mirror producing ultrahigh-contrast multi-petawatt laser pulses, *Opt. Lett.* **45**, 6342 (2020).
- [56] E. C. Nelson, K. J. Charbonnet, T. Reutershan, H. H. Effarah, and C. P. J. Barty, Proton jet formation with focused symmetric spatially chirped beams, Zenodo (2025), <https://doi.org/10.5281/zenodo.16431879>.
- [57] A. M. Wilhelm, Tilted snowplow electron acceleration with simultaneously spatially and temporally focused laser pulses, Ph.D. thesis, Colorado School of Mines, 2021.
- [58] U. Schramm, M. Bussmann, A. Irman, M. Siebold, K. Zeil, D. Albach, C. Bernert, S. Bock, F. Brack, J. Branco *et al.*, First results with the novel petawatt laser acceleration facility in Dresden, *J. Phys.: Conf. Ser.* **874**, 012028 (2017).
- [59] L. Volpe, R. Fedosejevs, G. Gatti, J. A. Pérez-Hernández, C. Méndez, J. Apiñaniz, X. Vaisseau, C. Salgado, M. Huault, S. Malko *et al.*, Generation of high energy laser-driven electron and proton sources with the 200 TW system VEGA 2 at the Centro de Laseres Pulsados, *High Power Laser Sci. Eng.* **7**, e25 (2019).
- [60] H. Kiriya, M. Nishiuchi, A. S. Pirozhkov, Y. Fukuda, H. Sakaki, A. Sagisaka, N. P. Dover, K. Kondo, K. Nishitani, K. Ogura *et al.*, J-KAREN-P laser facility at QST: High contrast, high intensity petawatt OPCPA/Ti:Sapphire hybrid laser system, in *2017 Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC)* (Institute of Electrical and Electronics Engineers (IEEE), Munich, 2017), p. 1.
- [61] K. Nakamura, H.-S. Mao, A. J. Gonsalves, H. Vincenti, D. E. Mittelberger, J. Daniels, A. Magana, C. Toth, and W. P. Leemans, Diagnostics, control and performance parameters for the BELLA high repetition rate petawatt class laser, *IEEE J. Quantum Electron.* **53**, 1 (2017).

- [62] J. W. Yoon, Y. G. Kim, I. W. Choi, J. H. Sung, H. W. Lee, S. K. Lee, and C. H. Nam, Realization of laser intensity over 10^{23} W/cm², [Optica](#) **8**, 630 (2021).
- [63] J. Novák, P. Szotkowski, E. S. Link, J. J. McLoughlin, L. S. Kiani, T. C. Galvin, K. M. Velas, J. Černý, J. Sedmidubská, M. Cuhra, L. Jarboe, B. Lopushanska, T. Spinka, and B. Rus, Towards the petawatt capability of the L3 HAPLS laser system, in *Research Using Extreme Light Infrastructures: New Frontiers with Petawatt-Level Lasers VI*, edited by B. Rus, D. Margarone, and V. Malka, (SPIE, Prague, Czech Republic, 2025), Vol. PC13535, p. PC1353504.
- [64] L. Willingale, A. Maksimchuk, J. Nees, F. Bayer, M. Burger, P. T. Campbell, B. Hou, I. Jovanovic, G. Kalinchenko, C. C. Kuranz, Y. Ma, A. McKelvey, A. G. R. Thomas, L. Weinberg, Q. Zhang, and K. M. Krushelnick, *Status of the ZEUS Laser User Facility*, *CLEO 2023* (Optica Publishing Group), p.SM1D.7.
- [65] C. N. Danson, C. Haefner, J. Bromage, T. Butcher, J.-C. F. Chanteloup, E. A. Chowdhury, A. Galvanauskas, L. A. Gizzi, J. Hein, D. I. Hillier *et al.*, Petawatt and exawatt class lasers worldwide, [High Power Laser Sci. Eng.](#) **7**, e54 (2019).