

## Laser-driven ion acceleration in long-lived optically shaped gaseous targets enhanced by magnetic vortices

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This work demonstrates high-repetition-rate laser-driven ion acceleration utilizing optically shaped gaseous targets. The optical shaping is achieved via dual, intersecting, counterpropagating laser-generated blast waves that precisely shape the underdense gas into long-lived, controlled, and reproducible near-critical density targets. The compressed target persists for several nanoseconds, time long enough to allow for the excellent synchronization between the target and the main accelerating femtosecond laser beam. Measurements of multi-MeV ion energy spectra are presented. Three-dimensional (3D) hydrodynamic simulations are used to optimize the density profile and assess the influence of the amplified spontaneous emission of the femtosecond accelerating laser pulse. A synthetic optical probing model is applied to directly compare simulations with experimental data. 3D particle-in-cell simulations reveal the formation of multi-kT, azimuthal magnetic fields, strongly suggesting magnetic vortex acceleration as the main acceleration mechanism.

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### I. INTRODUCTION

Laser-driven ion sources are of current interest in a range of applications. Ion-driven fast ignition of inertially confined fusion fuel [1,2] offers several advantages relative to electron-driven fast-ignition schemes. Proton-boron fusion experiments [3,4] in the pitcher-catcher configuration [5,6] are also reliant on our ability to field bright ion sources. Laser-produced ion sources are also being considered for possible application in tumor treatment [7,8]. There are also many current examples of their use as radiographic sources in high-energy-density physics experiments [9,10]. Most breakthroughs have been achieved with overdense targets by using the target normal sheath acceleration [11–13] or radiation pressure acceleration [14–16] mechanisms. Proton energies up to 150 MeV have recently been reported using these foil-based approaches [17,18]. However, conventional solid targets present several limitations. Targets are destroyed after each

shot and require continuous replacement, repositioning, and alignment, restricting their suitability for high-repetition-rate ion sources. Dense plasmas produced from solid targets reflect a large portion of the laser energy, resulting in limited coupling through hot electrons [19]. Additionally, solid targets generate debris that can damage optical components. Recent progress in target fabrication has led to designs incorporating foams [20], nanowires and nanostructures [21,22], or multi-layered foils [23]. These modifications improved laser energy coupling to the plasma and enhanced proton acceleration efficiency. Efforts have also focused on fast, motorized target delivery systems, such as rotating solid tape setups, to address repetition rate limitations [24,25].

Ion acceleration mechanisms in the near-critical density regime offer favorable energy scaling with laser power. The regenerative nature of these targets enables high-repetition-rate operation. The targetry is approached through various methods, including cluster gas jets [26,27], cryogenic targets [28,29], liquid droplets [30], and exploding foils [31], where the main acceleration mechanisms include collisionless-shock acceleration (CSA) [32–34] and Coulomb explosion [26,35]. Efforts have also been made on optical shaping of underdense target density profiles [36–40]; however, challenges in generating long-lived, controlled, and reproducible near-critical density profiles have significantly limited the effectiveness of this approach.

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In the past two decades, ions have been accelerated to multi-keV and multi-MeV energies from near-critical density targets in experiments using the CSA mechanism [33,36,41]. These results were obtained with high-energy, nanosecond or picosecond, long-wavelength laser systems. Such systems operate at lower intensities and are limited to single-shot operation, while reaching the near-critical density regime at lower densities due to their longer wavelengths. Recently, an approach achieved efficient proton acceleration by optical shaping using planar-planar and planar-cylindrical implosion schemes. In this work, authors were able to accelerate protons up to 5 MeV when synchronizing the main pulse with the exact moment of the shock front collision, achieving an  $\sim 50\%$  reproducibility [42] due to the relatively short-lived target compression. In addition, 80 MeV protons were measured from the interaction of a near-critical density cryogenic hydrogen jet with a petawatt Ti:sapphire (Ti:Sa) laser [43].

Particle-in-cell (PIC) simulations predict proton acceleration to energies from hundreds of MeV up to the GeV range via the magnetic vortex acceleration (MVA) mechanism, driven by intense, femtosecond TW-PW laser pulses [44–48]. MVA [44–49] is widely considered to be the most promising acceleration technique in terms of scaling with laser power, but experimental evidence of ion acceleration through MVA remains scarce [50–53], particularly for Ti:Sa laser wavelengths. Simulations indicate that precise control of target density, density-gradient, and thickness is required [48] for this acceleration mechanism to be practicable.

Here, we report, to our knowledge, the first experimental demonstration of high-repetition-rate ion acceleration using a method for optically shaping gas-jet targets. The critical feature in our approach is the use of intersecting laser pulses, rather than parallel ones that provide compression only at the short-lived period of the shock front collision. The initial underdense gas-jet profile is shaped using two blast waves generated by nanosecond duration laser pulses intersecting inside the gas-target. The optimal angle between the nanosecond shaping pulses is determined to be at  $60^\circ$ , based on a systematic parametric hydrodynamic simulation study. This approach enables maintenance of the compressed gas profile for the record duration of more than 15 ns, resulting in a broad synchronization window between the shaping and main acceleration pulses. While  $60^\circ$  was the primary angle used in this configuration, effective gas compression remains achievable within a narrow adjustment range of approximately  $\pm 10^\circ$ . Additionally, the configuration eliminates unwanted long-scale-length preplasma, enabling undisturbed propagation of the main pulse to the steep density gradient. Parametric computational studies indicate a larger compression factor compared to planar colliding blast wave [54,55] geometries under similar laser and target conditions [56,57]. The observations are supported by three-dimensional (3D) hydrodynamic and PIC simulations, which reveal the underlying role of the induced magnetic field vortices in the acceleration mechanism. Accelerated ion spectra with cutoff energies exceeding 11 MeV/u are observed.

## II. METHODS

The experiment was performed using the Zeus 45 TW Ti:Sa laser system located at the Institute of Plasma Physics

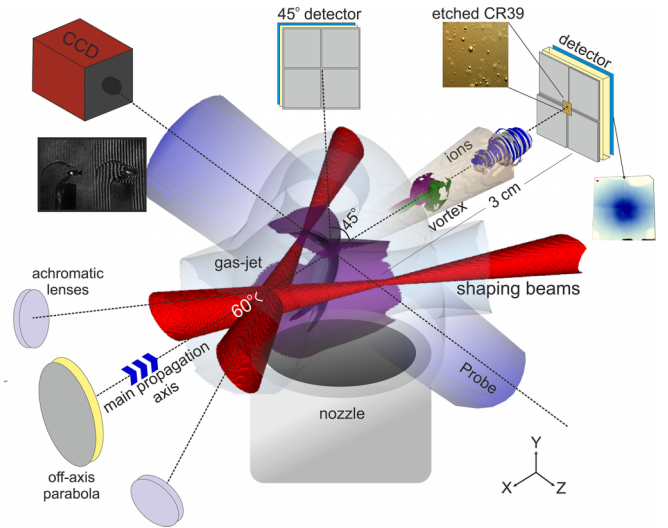


FIG. 1. Schematic layout of the experimental setup. The shaping beams drive dual intersecting blast waves, compressing the gas-jet profile. The black onyx-shaped region indicates peak compression. The delayed main pulse propagates undisturbed through a hollow pathway, penetrating the compressed target and accelerating multi-MeV per nucleon ions. Ion acceleration is supported by the generation of a kT-scale magnetic vortex field. A probe beam records the evolution of the compression on the nanosecond scale and the accelerated plasma structure on the picosecond scale. Shadowgraphy and interferometry images are acquired simultaneously using a Nomarski diagnostic. Passive detectors, CR39, and radiochromic film record the ion and electron signals.

and Lasers (IPPL) [58]. The experimental realization of the conceptional background is illustrated in Fig. 1. An 800 nm, 25 fs FWHM,  $p$ -polarized laser pulse with 1 J energy was focused in a  $3\ \mu\text{m}$  diameter spot, using an  $f/2$  parabolic mirror, resulting in a normalized vector potential amplitude  $a_0 \sim 14$ . An 800  $\mu\text{m}$  diameter cylindrical nozzle delivered an underdense gas-jet composed of a 99% He–1%  $\text{H}_2$  mixture at 55 bar. The measured initial density was  $9 \times 10^{19}\ \text{cm}^{-3}$  corresponding to  $0.05n_{\text{cr}}$ . A 1064 nm, 6 ns FWHM laser pulse with 0.85 J energy was split into two equal parts and focused on both sides of the gas-jet forming two  $\sim 15\ \mu\text{m}$  spots, resulting in intensity of  $2 \times 10^{13}\ \text{W}/\text{cm}^2$  each, to generate the dual blast waves. Furthermore, a 10 mJ, 800 nm probe pulse was used to diagnose the interaction with  $\sim \text{fs}$  timing accuracy, controlled by a motorized delay stage with 30 nm step size. The probe pulses passed through a Wollaston prism generating two beams of different polarization, which partially interfere, resulting in Nomarski interferometry along with shadowgraphy, captured simultaneously by the same charge-coupled device (CCD) camera. As particle diagnostics, the well-established CR39 nuclear track detectors covered by a multilayer aluminum filter mask were used, allowing measurement of different ion stopping powers per mask sector. The CR39 detector was placed 3 cm from target chamber center (TCC). The dose distribution of ions and electrons was acquired using a radiochromic film (RCF), placed behind the CR39.

Additionally, 3D FLASH [59] hydrodynamic simulations were performed to study the temporal evolution of the shaping. The simulations included the effects of the inherent

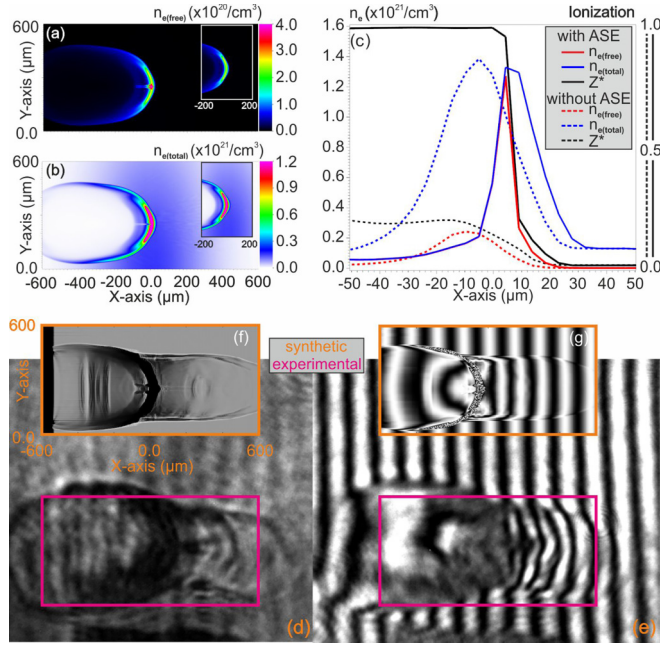


FIG. 2. FLASH simulation results of free electron density [panel (a)] and total electron density [panel (b)] at maximum compression, with and without ASE effects (insets), 5 ns after the arrival of the leading edge of the shaping pulses at the target. Lineouts of electron densities and ionization degree  $Z^*$  [panel (c)], with ASE (solid lines) and without ASE (dashed lines), show the steepening of the density profile. Comparison between experimental shadowgraph [panel (d)] and interferogram [panel (e)] with synthetic ones [panels (f) and (g)] at similar times illustrates an overall good agreement. To capture ASE effects, the laser attenuator was set to 0%, allowing only a few millijoules of the main pulse energy to reach the target. Interferograms show qualitative agreement in fringe shifts. A larger region is obscured by probe absorption.

amplified spontaneous emission (ASE) of the main accelerating pulse. A synthetic diagnostic model has been developed to perform ray tracing within the simulation domain, producing synthetic interferograms and shadowgraphs. This approach enables direct comparison between the measurements and the simulation results, rather than the optical probing results with simulated density profiles. The synthetic diagnostic model accounts for the index of refraction from both electron and neutral species, as well as absorption of the rays [60–62].

### III. RESULTS

Details of the dynamics of gas-shaping ion acceleration conditions are presented in Fig. 2. The nanosecond shaping pulses fully ionize the gas at the focal spot region, while the shock fronts of the generated blast waves remain predominantly neutral [Fig. 2(c), dashed lines] [63]. As a result, the probe pulse encounters the index of refraction associated with the ejected electrons [Figs. 2(a) and 2(c), red lines]. The neutral density of the shock fronts contributes negligibly to the refractive index [37], and therefore, shadowgraphs and interferograms are the result of gradients in the free electron density,  $n_{e(\text{free})}$ , and associated index of refraction. When the femtosecond main accelerating pulse arrives, it interacts with

the shaped near-critical neutral gas density profile ejecting two electrons per helium (He) atom, resulting in the electron density,  $n_{e(\text{total})}$ , shown in Figs. 2(b) and 2(c) (blue lines). The prepulse preceding the main interaction ionizes the neutral shock front [Fig. 2(c), solid lines], and thus, the main femtosecond pulse interacts with a near-critical electron density formed by the prepulse.

A significant advantage of the present gas-jet shaping scheme is that even though intense ASE (intensity contrast  $\sim 10^6$ ) can be destructive for thin foil targets [64,65]; here, it contributes beneficially by steepening the density profile. This can be clearly seen in Figs. 2(a)–2(c) where the profile thickness shifts from 40  $\mu\text{m}$  at  $1/e$  of the peak density without ASE to 23  $\mu\text{m}$  with ASE, with the peak density remaining almost unchanged. The lack of cylindrical symmetry prevents reliable Abel inversion for cubic electron density retrieval. Therefore, direct comparison between synthetic diagnostics and experimental probing is required. Experimental and synthetic shadowgraphs [Figs. 2(d) and 2(f)] and interferograms [Figs. 2(e) and 2(g)] show good overall agreement, which suggests consistency between experimental and numerical results for both electron and neutral densities, thus validating the numerical model. The total electron density reaches  $\sim 1.2 \times 10^{21} \text{cm}^{-3}$  ( $\sim 0.69 n_{\text{cr}}$ ), which according to the MVA matching condition [Eq. (1)] [47,48] corresponds to an optimum channel length of  $\sim 35 \mu\text{m}$  for the specifications of the femtosecond main accelerating pulse.

$$\frac{n_e}{n_{\text{cr}}} = \sqrt{2} K \left( \frac{P_L}{P_c} \right)^{1/2} \left( \frac{L_p}{L_{\text{ch}}} \right)^{3/2}. \quad (1)$$

$K$  is a geometrical factor equal to  $1/10$  in three dimensions,  $P_L$  is the laser power,  $P_c$  is the critical laser power threshold, above which relativistic self-focusing occurs,  $L_p$  the length of the pulse, and  $L_{\text{ch}}$  is the length of the plasma channel. Equation (1) yields an optimal plasma peak density, for a given laser power and pulse length, as a function of the plasma channel length.

During the ion acceleration phase, the shaped target is irradiated by the 45 TW femtosecond laser pulse. The results of the averaged signal from 50 shots, accumulated on the passive diagnostic detectors, are presented in Fig. 3. The red arrow in Fig. 3(a) indicates the propagation direction of the main pulse. The interaction shows intense pointlike self-emission at the laser-shock front interface [Figs. 3(a) and 3(b)], which is a characteristic feature of intense laser, critical-density interactions [42,66,67]. The self-emission remains intense despite the presence of neutral density filters and an 800 nm interference filter. Optical probing diagnostics show that the pulse penetrates the near-critical density region, forming an accelerated plasma structure at the rear of the target, as captured at 2 ps after the interaction (Fig. 3). The approach is insensitive to the jitter between the synchronized laser systems ( $\pm 2$  ns in our experiments). Figures 3(a)–3(h) show shadowgraphs and interferograms of the interaction between the main pulse and the compressed target at 5, 9, 13, and 17 ns, from four separate shots (time zero corresponds to the arrival of the start of the nanosecond shaping pulses at the target). The acceleration interaction remains consistent throughout the compression duration of approximately 15 ns, with optimal synchronization at

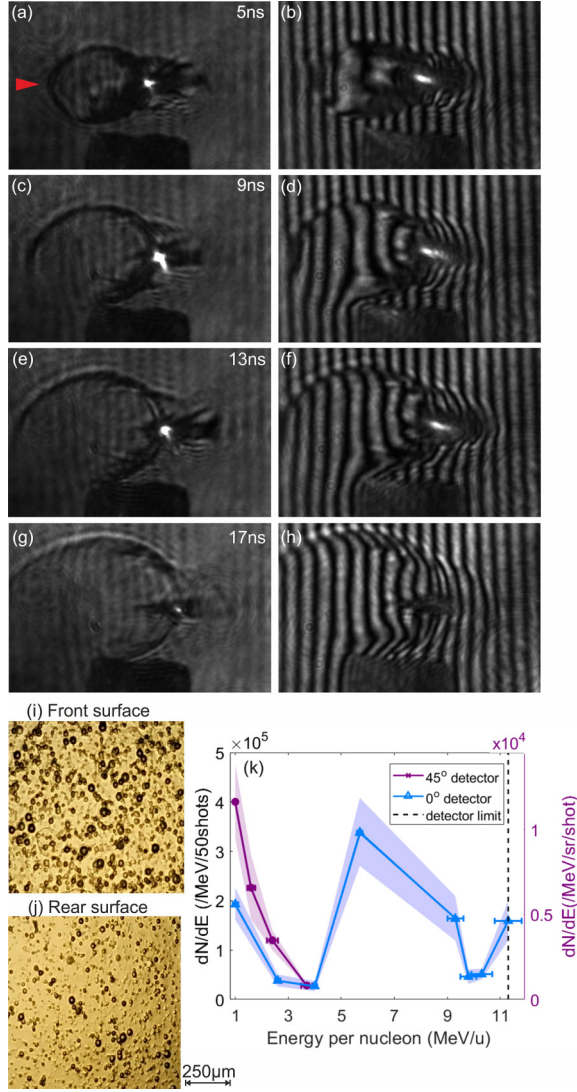


FIG. 3. Shadowgraphs [panels (a), (c), (e), and (g)] and interferograms [panels (b), (d), (f), and (h)] from three separate shots, showing the evolution of the compression at 5, 9, 13, and 17 ns, respectively. The main interaction with the target is observed at 2 ps in all cases. The red arrow indicates the propagation axis of the main pulse. Front [panel (i)] and rear [panel (j)] surfaces of the etched CR39 under transmissive microscopy show pits generated by accelerated ions, at 5.7 and 11.3 MeV/u energy diagnostic sectors, respectively. The ion energy spectrum [panel (k)] is extracted from CR39 by measuring pits corresponding to different Bragg peaks.

$\sim 5$  ns, as indicated by hydrodynamic simulations. At 17 ns, in Figs. 3(g) and 3(h), the compression is largely dissipated, and the self-emission appears faint, while at later times no self-emission is observed. No plasma channel is observed on the left side of the shaped target, both experimentally and in simulations, indicating a hollow pathway for undisturbed propagation of the main pulse. This is crucial for the unperturbed propagation of the intense main femtosecond laser pulse.

The multilayer filter mask of the CR39 detector is segmented into eight sectors. The four front-surface sectors correspond to energies ranging from 1.0 to 5.7 MeV/u, while the four rear sectors cover the 9.3–11.3 MeV/u

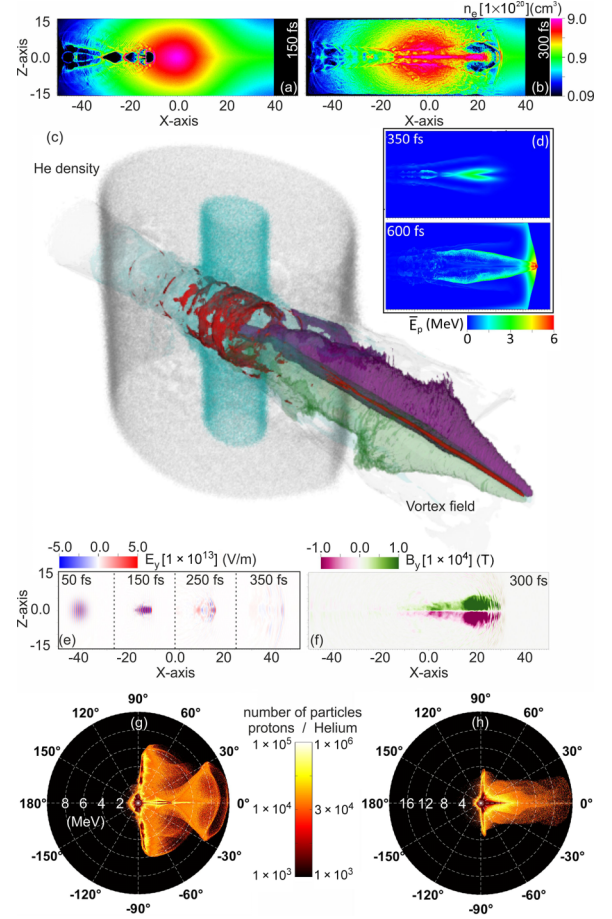


FIG. 4. Electron density at 150 fs [panel (a)] and 300 fs [panel (b)] from PIC simulations, showing the generation of a short-scale wakefield. 3D isosurface plot of He density (in gray, cyan, and red) with magnetic fields (in purple and green) at 600 fs [panel (c)], illustrating near-critical target-laser interaction. Average proton energy at 350 and 600 fs [panel (d)]. Longitudinal electric field of the laser pulse between 50 and 350 fs [panel (e)], demonstrating strong self-focusing and beam absorption. Y component of the magnetic field [panel (f)], which shows the generation of an azimuthal vortex magnetic field. Proton [panel (g)] and He ion [panel (h)] angular energy distributions, demonstrating particle beam directionality with 30° and 20° half-angles, respectively.

range. Ion stopping power is calculated using SRIM Monte Carlo simulations [68] to calibrate the detector. After chemical etching in NaOH solution, pits are counted under transmissive microscopy to extract the ion energy spectra [Figs. 3(i) and 3(j)].

The energy spectrum demonstrates a peak feature around 6 MeV/u and the cutoff ion energy at 11.3 MeV/u (45.2 MeV total energy for He ions) [Fig. 3(k), blue line]. Fewer large pits, associated with higher-Z ions (corresponding to 99% He), are observed on the rear side of the CR39. This indicates a greater number of higher energy-per-nucleon protons (corresponding to 1% H<sub>2</sub>) due to higher charge-to-mass ratios, reaching the rear surface. Integrating along the energy spectrum, a total number of  $4.2 \times 10^6$  ions/shot is obtained. 3D PIC simulations predict  $\sim 10$  MeV/u protons and  $\sim 5$  MeV/u He ions (20 MeV total energy) [Figs. 4(g) and 4(h)]. A

Gaussian-like, high-dose distribution of  $\sim 1.1$  Gy per shot is recorded on the RCF, from both ion and electron signals. However, most of the dose measured on the RCF is attributed to electrons, as most ions are stopped within the CR39 and do not reach the RCF. The ion beam profile on the CR39 presents an oval shape, with the major axis oriented perpendicular to the laser polarization direction. The ions display a broad spatial divergence, with an estimated half-angle of approximately  $\sim 35^\circ$  [53]. The ion energy spectrum measured by the CR39 diagnostic detector at  $45^\circ$  with respect to the laser propagation axis exhibits an exponentially decaying distribution with a cutoff energy of  $\sim 4$  MeV/u [Fig. 3(k), purple line].

As expected, no measurable ion signal appears on the CR39 detectors when one or both of the nanosecond shaping laser beams are switched off. In order to investigate the underlying acceleration mechanism in the current gas-jet shaping conditions, EPOCH [69] 3D PIC simulations were employed [56,57]. The PIC models use initial conditions derived from hydrodynamic simulations, consistent with experimental observations. The initial electron density, with a peak of  $1.2 \times 10^{21} \text{ cm}^{-3}$ , responds rapidly to the propagation of the focusing main femtosecond laser pulse. This interaction generates plasma wakes, forming a short-scale-length laser wakefield acceleration (LWFA) structure [Figs. 4(a) and 4(b)]. Beyond the peak density, at 300 fs, a large electron population is injected into the bubble, producing a high current of energetic electrons ( $>100$  MeV). The bubble elongates significantly after the electron density peak, a process that appears to facilitate electron injection, similar to the down-ramp injection mechanism [70,71]. The pulse undergoes relativistic self-focusing just before reaching the peak electron density [Fig. 4(e)] and is efficiently absorbed by the dense plasma [56]. The high electron current drives a strong azimuthal magnetic vortex [Fig. 4(f)] with a peak value of 100 kT at the time of reaching the peak density region, fast expanding within the plasma waveguide [44,47,49]. The transient magnetic vortex induces longitudinal quasistatic electric fields, which along with charge separation accelerate the protons and He ions. Concurrently, the magnetic field pinches the proton and ion densities toward the propagation axis of the pulse. The longitudinal electric field is on the order of the electric field of the laser pulse [45]. Initially, ions and protons gain energy in two lobelike regions near the magnetic field vortex [Fig. 4(d), top]. As the interaction progresses, the most energetic ions become focused toward the front of the target, while lower-energy particles are accelerated in a sheathlike distribution [Fig. 4(d), bottom]. This strongly indicates that MVA is the dominant underlying ion acceleration mechanism [44–48]. The protons and ions are accelerated in the forward direction in a half-angle of  $30^\circ$  [Fig. 4(g)] and  $20^\circ$  [Fig. 4(h)], respectively, that is in remarkable agreement with the experimental measurements ( $\sim 35^\circ$ ). The cutoff energy acquired by the protons (10 MeV) and He ions is  $\sim 5$  MeV/u, in remarkable agreement with the experiment ( $\sim 11.3$  MeV/u total energy). Our EPOCH 3D PIC simulations with the laser pulse reaching the peak density of the shaped target, generating the vortex field, and collimating the ion density [Fig. 4(c)] bear close resemblance to the experimental results. As a result, our study strongly suggests that in the experiments a strong  $\sim$ kT magnetic vortex drives the acceleration of the ions.

#### IV. DISCUSSION

In conclusion, we present an exciting demonstration of the production of high-repetition-rate ion beams from laser-driven MVA. Efficient compression of underdense gas from an 800  $\mu\text{m}$  diameter cylindrical nozzle, into near-critical, sharp-gradient, density profiles, is employed. The required density profiles persist for  $\sim 15$  ns, which is substantially longer than can be achieved via other means. This eliminates laser synchronization challenges. Our study advances the field toward high-repetition-rate ion acceleration applications, eliminating the drawbacks of single-shot and shots-per-minute methods, present in high-energy low-repetition-rate laser systems and solid-target approaches. The experiments were conducted with 10 s intervals to allow chamber vacuum recovery, enabling a 0.1 Hz repetition rate. A record ion energy, exceeding 11 MeV/u, using gaseous targets is reported for high-repetition-rate multi-TW laser systems. The method is adaptable for use on laser facilities with powers from TW up to PW and for both low- and high-repetition-rate systems. Work is underway to implement differential pumping and pellicle shields to protect compressor gratings, targeting operation at  $\sim$ Hz frequencies.

Near-critical density gaseous targets are challenging to characterize. Accurate measurements are required to optimize shaping and acceleration mechanisms. For this purpose, a synthetic diagnostic ray-tracing model has been developed to match optical probing results with simulations, providing indirect measurements that replicate the experimental density profiles. In addition, electron deflectometry is considered the appropriate method to measure high-resolution density profiles along with the magnetic field topology.

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#### DATA AVAILABILITY

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

#### APPENDIX A: SYNTHETIC DIAGNOSTIC ALGORITHM

The developed synthetic diagnostic algorithm begins by calculating the spatial derivatives of the natural logarithm of the refractive index along the  $x$ ,  $y$ , and  $z$  directions. These derivatives describe how the refractive index varies across the computational grid and are essential for calculating how light rays bend when passing through the density profile. The script computes these derivatives using finite difference methods, approximating the gradients at each point. Using these derivatives, the script performs ray tracing, updating the ray trajectory step by step. As the rays propagate through the plasma, they bend in response to the spatial gradients of the refractive index, while absorption and phase shifts are continuously accumulated along their paths. The direction of each ray is numerically updated, based on the ray-tracing equations given as [60]

$$\begin{aligned} x''(z) &= \frac{1}{\eta}(1 + x'^2 + y'^2) \times \left( \frac{\partial \eta}{\partial x} - x' \frac{\partial \eta}{\partial z} \right), \\ y''(z) &= \frac{1}{\eta}(1 + x'^2 + y'^2) \times \left( \frac{\partial \eta}{\partial y} - y' \frac{\partial \eta}{\partial z} \right), \end{aligned} \quad (\text{A1})$$

where  $\eta$  the refractive index and primes denote differentiation with respect to  $z$ . These equations describe how the ray direction changes due to the refractive index gradients. The updated position of the ray at each step is then calculated as

$$\begin{aligned} x_i x_s &= x_s - x_i = x_e + l x'(z_e), \\ y_i y_s &= y_s - y_i = y_e + l y'(z_e), \end{aligned} \quad (\text{A2})$$

where indices  $i, e, s$  denote coordinates at entry, exit, and screen (observational plane), respectively, and  $l$  is the distance between the target and observational plane [60]. The refractive index of the medium is calculated in the script by [62]

$$n = \sqrt{1 - \frac{n_e}{n_{cr}}} + \frac{1}{4\pi\epsilon_0} 2\alpha_n n_n + \frac{1}{4\pi\epsilon_0} 2\alpha_i n_i. \quad (\text{A3})$$

In this expression, the first term represents the contribution from free electrons, while the second and third terms account

for the contributions of neutral atoms and ions, respectively.  $n_n$  and  $\alpha_i$  are the polarizability of neutral atoms and ions, respectively. The ion contribution to the index of refraction is generally negligible compared to that of the electrons, since the ion and electron densities are typically of the same order [62]. The absorption coefficient is then computed along the ray path using [61]

$$\theta = \left( \frac{C_1 Z^2 g n_e n_i}{T_e^{1/2} v^3} \right) \left( 1 - e^{-\frac{h\nu}{k_B T_e}} \right), \quad (\text{A4})$$

where  $C_1 = 3.69 \times 10^8 \text{ cm}^5 \text{ K}^{1/2} / \text{s}^3$  and  $g$  is a Gaunt factor (with empirical values of  $\sim 3-7$ ). This expression accounts for absorption due to free electrons in the plasma, which attenuates the probe beam as it propagates through the medium. To generate a synthetic interferogram, the script calculates the phase shift accumulated along each ray path and combines it with a reference beam to simulate interference. The reference beam is assumed to be a plane wave propagating without distortion, allowing the resulting interference pattern to represent the optical phase variations introduced by the plasma. These calculations accurately model the interaction of light with the shaped target. This enables the script to generate synthetic shadowgrams and interferograms that can be directly compared with experimental diagnostics.

#### APPENDIX B: SYNCHRONIZATION OF LASER SYSTEMS

The experiments were conducted at the Institute of Plasma Physics and Lasers using the Zeus 45 TW Ti:Sapphire (femtosecond) laser system in conjunction with a Quantel Q-smart Nd:YAG (nanosecond) laser. Synchronizing two independent laser systems is a nontrivial challenge, necessitating precise coordination of multiple timing signals. To achieve this, the Quantel Nd:YAG flashlamps and Q-switch were externally triggered via transistor-transistor logic (TTL) pulses derived from the 10 Hz optical output of the pulse picker after the oscillator of the Zeus laser system. This ensured that both systems operated at a synchronized 10 Hz frequency. A dual (pulse 1 and pulse 2) TTL pulse sequence (400  $\mu\text{s}$  duration per pulse) was employed to trigger the Quantel Q-switch. While the system is capable of 10 Hz operation, a 0.1 Hz repetition rate was used in this study to maintain vacuum stability. Pulse 1 was launched 100 ms prior to the Zeus femtosecond pulse to activate auxiliary equipment, including the gas-jet controller and CCD cameras. Pulse 2 was synchronized precisely with the arrival of the Zeus femtosecond pulse. The requisite delays were managed using a Stanford Research Systems DG535 Delay Generator, allowing for the fine-tuning necessary to align the nanosecond shaping pulse with the main femtosecond pulse. To maximize the Quantel laser's output energy and stability, a constant delay of 265  $\mu\text{s}$  was maintained between its flashlamp and Q-switch triggers. The temporal arrival of both laser pulses at the gas-jet interaction region was monitored using two fast photodiodes (20 ps rise time). All signals were monitored using a four-channel LeCroy oscilloscope with a 2 GHz sampling rate.

[1] S. M. Weng, Z. M. Sheng, M. Murakami, M. Chen, M. Liu, H. C. Wang, T. Yuan, and J. Zhang, Optimization of hole-boring

radiation pressure acceleration of ion beams for fusion ignition, *Matter Radiat. Extremes* **3**, 28 (2018).

- [2] M. Roth, *et al.*, Fast ignition by intense laser-accelerated proton beams, *Phys. Rev. Lett.* **86**, 436 (2001).
- [3] D. Margarone, *et al.*, In-target proton–boron nuclear fusion using a PW-class laser, *Appl. Sci.* **12**, 1444 (2022).
- [4] J. Bonvalet, *et al.*, Energetic  $\alpha$ -particle sources produced through proton–boron reactions by high-energy high-intensity laser beams, *Phys. Rev. E* **103**, 053202 (2021).
- [5] K. Batani, Perspectives on research on laser driven proton–boron fusion and applications, *J. Instrum.* **18**, C09012 (2023).
- [6] D. Margarone, *et al.*, Generation of  $\alpha$ -particle beams with a multi-kJ, peta-watt class laser system, *Front. Phys.* **8**, 343 (2020).
- [7] S. V. Bulanov and V. S. Khoroshkov, Feasibility of using laser ion accelerators in proton therapy, *Plasma Phys. Rep.* **28**, 453 (2002).
- [8] P. R. Bolton, The integrated laser-driven ion accelerator system and the laser-driven ion beam radiotherapy challenge, *Nucl. Instrum. Methods. Phys. Res. A* **809**, 149 (2016).
- [9] A. J. Mackinnon, *et al.*, Proton radiography of a laser-driven implosion, *Phys. Rev. Lett.* **97**, 045001 (2006).
- [10] C. K. Li, *et al.*, Measuring  $E$  and  $B$  fields in laser-produced plasmas with monoenergetic proton radiography, *Phys. Rev. Lett.* **97**, 135003 (2006).
- [11] E. L. Clark, K. Krushelnick, M. Zepf, F. N. Beg, M. Tatarakis, A. Machacek, M. I. K. Santala, I. Watts, P. A. Norreys, and A. E. Dangor, Energetic heavy-ion and proton generation from ultraintense laser-plasma interactions with solids, *Phys. Rev. Lett.* **85**, 1654 (2000).
- [12] R. A. Snavely, *et al.*, Intense high-energy proton beams from petawatt-laser irradiation of solids, *Phys. Rev. Lett.* **85**, 2945 (2000).
- [13] A. Maksimchuk, S. Gu, K. Flippo, D. Umstadter, and V. Yu. Bychenkov, Forward ion acceleration in thin films driven by a high-intensity laser, *Phys. Rev. Lett.* **84**, 4108 (2000).
- [14] 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).
- [15] C. A. J. Palmer, *et al.*, Monoenergetic proton beams accelerated by a radiation pressure driven shock, *Phys. Rev. Lett.* **106**, 014801 (2011).
- [16] I. J. Kim, *et al.*, Radiation pressure acceleration of protons to 93 MeV with circularly polarized petawatt laser pulses, *Phys. Plasmas* **23**, 070701 (2016).
- [17] T. Ziegler, *et al.*, Laser-driven high-energy proton beams from cascaded acceleration regimes, *Nat. Phys.* **20**, 1211 (2024).
- [18] J. Bin, Petawatt pulse pushes protons, *Nat. Phys.* **20**, 1055 (2024).
- [19] I. Tazes, J. F. Ong, O. Tesileanu, K. A. Tanaka, N. A. Papadogiannis, M. Tatarakis, and V. Dimitriou, Target normal sheath acceleration and laser wakefield acceleration particle-in-cell simulations performance on CPU & GPU architectures for high-power laser systems, *Plasma Phys. Control. Fusion* **62**, 094005 (2020).
- [20] I. Prencipe, *et al.*, Development of foam-based layered targets for laser-driven ion beam production, *Plasma Phys. Control. Fusion* **58**, 034019 (2016).
- [21] S. Vallières, *et al.*, Enhanced laser-driven proton acceleration using nanowire targets, *Sci. Rep.* **11**, 2226 (2021).
- [22] X. Li, Y. Chao, D. Liu, S. Zhang, Z. Liu, L. Cao, and C. Zheng, Enhanced proton acceleration from laser interaction with curved surface nanowire targets, *J. Plasma Phys.* **89**, 905890113 (2023).
- [23] S.-F. Tong, Z.-M. Sheng, and M. Y. Yu, Target normal sheath acceleration of protons using triple-layer target with long pre-plasma, *Phys. Rev. Accel. Beams* **21**, 051303 (2018).
- [24] F. P. Condamine, *et al.*, High-repetition rate solid target delivery system for PW-class laser–matter interaction at ELI Beamlines, *Rev. Sci. Instrum.* **92**, 063504 (2021).
- [25] M. Ehret, D. de Luis, J. I. Apiñaniz, J. L. Henares, R. Lera, J. A. Pérez-Hernández, P. Puyuelo-Valdes, L. Volpe, and G. Gatti, Stability and debris-mitigation of a solid tape target delivery system for intense laser-matter interactions towards high-repetition-rate, *Plasma Phys. Control. Fusion* **66**, 045003 (2024).
- [26] T. Ditmire, T. Donnelly, A. M. Rubenchik, R. W. Falcone, and M. D. Perry, Interaction of intense laser pulses with atomic clusters, *Phys. Rev. A* **53**, 3379 (1996).
- [27] T. Ditmire, J. W. G. Tisch, E. Springate, M. B. Mason, N. Hay, R. A. Smith, J. Marangos, and M. H. R. Hutchinson, High-energy ions produced in explosions of superheated atomic clusters, *Nature (London)* **386**, 54 (1997).
- [28] D. Margarone, *et al.*, Proton acceleration driven by a nanosecond laser from a cryogenic thin solid-hydrogen ribbon, *Phys. Rev. X* **6**, 041030 (2016).
- [29] J. Polz, *et al.*, Efficient laser-driven proton acceleration from a cryogenic solid hydrogen target, *Target Sci. Rep.* **9**, 16534 (2019).
- [30] G. A. Becker, *et al.*, Characterization of laser-driven proton acceleration from water microdroplets, *Sci. Rep.* **9**, 17169 (2019).
- [31] M. Gauthier, *et al.*, Investigation of longitudinal proton acceleration in exploded targets irradiated by intense short-pulse laser, *Phys. Plasmas* **21**, 013102 (2014).
- [32] L. O. Silva, M. Marti, J. R. Davies, R. A. Fonseca, C. Ren, F. S. Tsung, and W. B. Mori, Proton shock acceleration in laser-plasma interactions, *Phys. Rev. Lett.* **92**, 015002 (2004).
- [33] D. Haberberger, S. Tochitsky, F. Fiuza, C. Gong, R. A. Fonseca, L. O. Silva, W. B. Mori, and C. Joshi, Collisionless shocks in laser-produced plasma generate monoenergetic high-energy proton beams, *Nat. Phys.* **8**, 95 (2012).
- [34] P. Puyuelo-Valdes, *et al.*, Proton acceleration by collisionless shocks using a supersonic  $H_2$  gas-jet target and high-power infrared laser pulses, *Phys. Plasmas* **26**, 123109 (2019).
- [35] K. Krushelnick, *et al.*, Multi-MeV ion production from high-intensity laser interactions with underdense plasmas, *Phys. Rev. Lett.* **83**, 737 (1999).
- [36] O. Tresca, N. P. Dover, N. Cook, C. Maharjan, M. N. Polyanskiy, Z. Najmudin, P. Shkolnikov, and I. Pogorelsky, Spectral modification of shock accelerated ions using a hydrodynamically shaped gas target, *Phys. Rev. Lett.* **115**, 094802 (2015).
- [37] N. P. Dover, N. Cook, O. Tresca, O. Ettlinger, C. Maharjan, M. N. Polyanskiy, P. Shkolnikov, I. Pogorelsky, and Z. Najmudin, Optical shaping of gas targets for laser–plasma ion sources, *J. Plasma Phys.* **82**, 415820101 (2016).
- [38] S. Passalidis, O. C. Ettlinger, G. S. Hicks, N. P. Dover, Z. Najmudin, E. P. Benis, E. Kaselouris, N. A. Papadogiannis, M. Tatarakis, and V. Dimitriou, Hydrodynamic computational modelling and simulations of collisional shock waves in gas jet targets, *High Power Laser Sci. Eng.* **8**, e7 (2020).

- [39] J.-R. Marquès, *et al.*, Over-critical sharp-gradient plasma slab produced by the collision of laser-induced blast-waves in a gas jet: Application to high-energy proton acceleration, *Phys. Plasmas* **28**, 023103 (2021).
- [40] A. Maitrallain, *et al.*, Proton acceleration from optically tailored high-density gas jet targets, *J. Plasma Phys.* **90**, 965900201 (2024).
- [41] M. S. Wei, *et al.*, Ion acceleration by collisionless shocks in high-intensity-laser-underdense-plasma interaction, *Phys. Rev. Lett.* **93**, 155003 (2004).
- [42] O. Seemann, Y. Wan, S. Tata, E. Kroupp, and V. Malka, Laser proton acceleration from a near-critical imploding gas target, *Phys. Rev. Lett.* **133**, 025001 (2024).
- [43] M. Rehwald, *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).
- [44] A. Sharma and A. Andreev, Effective laser driven proton acceleration from near critical density hydrogen plasma, *Laser Part. Beams* **34**, 219 (2016).
- [45] S. S. Bulanov, E. Esarey, C. B. Schroeder, W. P. Leemans, S. V. Bulanov, D. Margarone, G. Korn, and T. Haberer, Helium-3 and helium-4 acceleration by high power laser pulses for hadron therapy, *Phys. Rev. Spec. Top. Accel. Beams* **18**, 061302 (2015).
- [46] S. S. Bulanov, *et al.*, Generation of GeV protons from 1 PW laser interaction with near critical density targets, *Phys. Plasmas* **17**, 043105 (2010).
- [47] J. Park, *et al.*, Ion acceleration in laser generated megatesla magnetic vortex, *Phys. Plasmas* **26**, 103108 (2019).
- [48] T. Nakamura, S. V. Bulanov, T. Z. Esirkepov, and M. Kando, High-energy ions from near-critical density plasmas via magnetic vortex acceleration, *Phys. Rev. Lett.* **105**, 135002 (2010).
- [49] S. V. Bulanov, Ion acceleration in a dipole vortex in a laser plasma corona, *Plasma Phys. Rep.* **31**, 369 (2005).
- [50] L. Willingale, *Ion Acceleration from High Intensity Laser Plasma Interactions: Measurements and Applications* (Imperial College, London, 2007).
- [51] A. Yogo, *et al.*, Laser ion acceleration via control of the near-critical density target, *Phys. Rev. E* **77**, 016401 (2008).
- [52] Y. Fukuda, *et al.*, Energy increase in multi-MeV ion acceleration in the interaction of a short pulse laser with a cluster-gas target, *Phys. Rev. Lett.* **103**, 165002 (2009).
- [53] M. H. Helle, D. F. Gordon, D. Kaganovich, Y. Chen, J. P. Palastro, and A. Ting, Laser-accelerated ions from a shock-compressed gas foil, *Phys. Rev. Lett.* **117**, 165001 (2016).
- [54] R. A. Smith, J. Lazarus, M. Hohenberger, A. Marocchino, J. S. Robinson, J. P. Chittenden, A. S. Moore, E. T. Gumbrell, and M. Dunne, High resolution imaging of colliding blast waves in cluster media, *Plasma Phys. Control. Fusion* **49**, B117 (2007).
- [55] F. Suzuki-Vidal, *et al.*, Counterpropagating radiative shock experiments on the orion laser, *Phys. Rev. Lett.* **119**, 055001 (2017).
- [56] I. Tazes, S. Passalidis, E. Kaselouris, I. Fitis, M. Bakarezos, N. A. Papadogiannis, M. Tatarakis, and V. Dimitriou, A computational study on the optical shaping of gas targets via blast wave collisions for magnetic vortex acceleration, *High Power Laser Sci. Eng.* **10**, e31 (2022).
- [57] I. Tazes, *et al.*, Efficient magnetic vortex acceleration by femtosecond laser interaction with long living optically shaped gas targets in the near critical density plasma regime, *Sci. Rep.* **14**, 4945 (2024).
- [58] E. L. Clark, *et al.*, High-intensity laser-driven secondary radiation sources using the ZEUS 45 TW laser system at the Institute of Plasma Physics and Lasers of the Hellenic Mediterranean University Research Centre, *High Power Laser Sci. Eng.* **9**, e53 (2021).
- [59] B. Fryxell, K. Olson, P. Ricker, F. X. Timmes, M. Zingale, D. Q. Lamb, P. MacNeice, R. Rosner, J. W. Truran, and H. Tufo, FLASH: An adaptive mesh hydrodynamics code for modeling astrophysical thermonuclear flashes, *Astrophys. J. Suppl. Ser.* **131**, 273 (2000).
- [60] W. Schöpf, J. C. Patterson, and A. M. H. Brooker, Evaluation of the shadowgraph method for the convective flow in a side-heated cavity, *Exp. Fluids* **21**, 331 (1996).
- [61] Yu. G. Kalinin, V. A. Korel'skii, E. V. Kravchenko, and A. Yu. Shashkov, Laser probing of the plasma in the S-300 facility, *Plasma Phys. Rep.* **28**, 790 (2002).
- [62] L. Prevosto, G. Artana, B. Mancinelli, and H. Kelly, Schlieren technique applied to the arc temperature measurement in a high energy density cutting torch, *J. Appl. Phys.* **107**, 023304 (2010).
- [63] H. D. Weymann, Electron diffusion ahead of shock waves in argon, *Phys. Fluids* **3**, 545 (1960).
- [64] M. Kaluza, J. Schreiber, M. I. K. Santala, G. D. Tsakiris, K. Eidmann, J. Meyer-ter-Vehn, and K. J. Witte, Influence of the laser prepulse on proton acceleration in thin-foil experiments, *Phys. Rev. Lett.* **93**, 045003 (2004).
- [65] D. Batani, *et al.*, Effects of laser prepulses on laser-induced proton generation, *New J. Phys.* **12**, 045018 (2010).
- [66] M. Tatarakis, *et al.*, Propagation instabilities of high-intensity laser-produced electron beams, *Phys. Rev. Lett.* **90**, 175001 (2003).
- [67] M. Tatarakis, J. R. Davies, P. Lee, P. A. Norreys, N. G. Kassapakis, F. N. Beg, A. R. Bell, M. G. Haines, and A. E. Dangor, Plasma formation on the front and rear of plastic targets due to high-intensity laser-generated fast electrons, *Phys. Rev. Lett.* **81**, 999 (1998).
- [68] J. F. Ziegler and J. P. Biersack, in *Treatise on Heavy-Ion Science* (Springer, Boston, MA, 1985), pp. 93–129.
- [69] T. D. Arber, *et al.*, Contemporary particle-in-cell approach to laser-plasma modelling, *Plasma Phys. Controlled Fusion* **57**, 113001 (2015).
- [70] H. Suk, N. Barov, J. B. Rosenzweig, and E. Esarey, Plasma electron trapping and acceleration in a plasma wake field using a density transition, *Phys. Rev. Lett.* **86**, 1011 (2001).
- [71] G. Andrianaki, *et al.*, Design, manufacturing, evaluation, and performance of a 3D-printed, custom-made nozzle for laser wakefield acceleration experiments, *Rev. Sci. Instrum.* **94**, 103309 (2023).