

Geometric scaling of laser-driven proton focusing from hemispherical foils

J. Griff-McMahon^{1,2,*}, X. Vaisseau³, W. Fox^{1,2,4}, K. Lezhnin⁵, K. Bhutwala⁶, R. Nedbailo⁵,
V. Ospina-Bohórquez³, T. Karpowski⁶, P. K. Patel³, and S. Malko²

¹Department of Astrophysical Sciences, Princeton University, Princeton, New Jersey 08544, USA

²Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA

³Focused Energy Inc., Redwood City, California 94063, USA

⁴Department of Physics, University of Maryland, College Park, Maryland 20742, USA

⁵Department of Physics, University of Texas, Austin, Texas 78701, USA

⁶Focused Energy GmbH, 64293 Darmstadt, Germany



(Received 20 October 2025; accepted 20 January 2026; published 19 February 2026)

We systematically characterize the focusing behavior of laser-driven proton beams from hemispherical targets of various diameters using mesh radiography. The proton focal location is inferred to be near the geometrical center for the smallest tested hemisphere ($\Psi = D_{\text{hemi}}/D_{\text{Laser}} = 6.1$). However, larger hemispheres ($\Psi = 14.6$) degrade the focusing behavior and behave more like flat foils with focal location significantly inside the hemisphere. We also infer a tight virtual focus of $9 \pm 3 \mu\text{m}$ through a mesh transition analysis.

DOI: 10.1103/3cs1-8r6s

I. INTRODUCTION

Tightly focused beams of multi-MeV protons are a powerful tool for creating and probing matter in extreme states. They can isochorically heat solid-density materials to the warm dense matter regime [1,2] and are central to the advanced inertial confinement fusion scheme of proton fast ignition (PFI) [3]. Unlike central hot spot ignition, PFI separates the compression and heating stages in inertial confinement fusion, offering potential improvements over central hot spot ignition through higher target gains and relaxed symmetry requirements. Long-pulse lasers precompress the fuel to a relatively cold and dense state, whereby a high-fluence proton beam isochorically heats and ignites the assembly. From several design studies, ignition requires a proton beam with $\sim 20 \text{ kJ}$ of energy in a temperature from 4 to 8 MeV, delivered within a beam radius of $\sim 20 \mu\text{m}$ and in less than 20 ps before the fuel disassembles [3–6].

To achieve these requirements, high-intensity lasers irradiate a curved, hemispherical foil or “hemi” to generate a focused proton beam. This scheme uses the well-known target normal sheath acceleration (TNSA) mechanism [7] in which relativistic electrons are energized from the laser interaction and create a strong electrostatic sheath field on the rear side of the target, capable of accelerating protons to MeV energies. Since protons are predominantly accelerated in the target-normal direction on the rear of the target, using a curved target geometrically focuses protons toward a common focal spot. In

the final PFI design, the hemi is placed inside a hollow cone, primarily to protect the hemi, but ultimately plays a role in proton focusing [6,8–10]. In the context of PFI, the beam focal spot size and the focal location are critical.

Design studies [6] identify an optimal beam radius of $15\text{--}20 \mu\text{m}$ at 300 g/cm^3 fuel density, which balances two competing effects. Smaller beams produce a stronger hydrodynamic response and suffer from range lengthening by rapidly heating and rarefying the deposition channel so that protons arriving at later times deposit their energy deeper into the fuel assembly. However, larger beams distribute the energy over a greater volume, lowering the achieved temperature. Likewise, the axial location of the beam focus should ideally coincide with the densest part of the fuel assembly to minimize the ignition energy required in the proton beam. The axial location also balances two competing requirements: The hemi target must be placed sufficiently far from the fusion capsule to prevent the imploding target from disrupting the protective cone structure used in fast-ignition designs, yet close enough to limit temporal dispersion from a polyenergetic beam.

Many prior experiments have shown that curved targets lead to improved proton focusing and heating of a secondary sample, as compared to flat targets [1,8,11–15]. Two important parameters in these experiments are the laser intensity that roughly controls the electron temperature (and therefore the TNSA electric fields since $E_{\text{TNSA}} \propto T_e \propto \sqrt{I_L}$) and the dimensionless focusing geometry defined as the ratio of the hemi diameter to the laser spot diameter ($\Psi = D_{\text{hemi}}/D_{\text{Laser}}$) [16]. Figure 1 shows prior focusing experiments plotted in this parameter space.

Patel *et al.* [1] first demonstrated heating of a secondary sample from a hemi, resulting in a heating area $16\times$ smaller than from a flat target. Later, Snavely *et al.* [12] performed an experiment at higher energy and showed that optimal heating of a secondary sample occurs when the sample is

*Contact author: jgriffmc@pppl.gov

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.

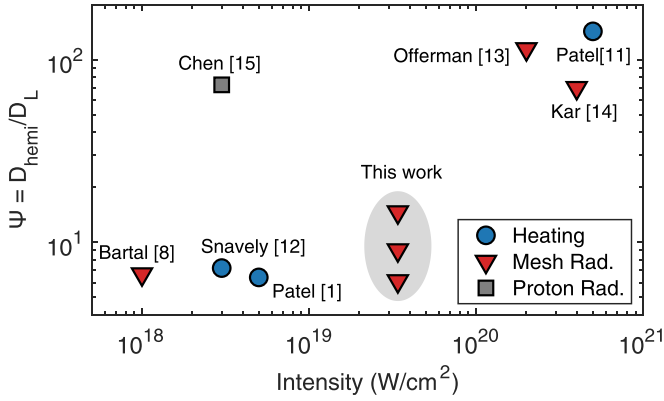


FIG. 1. Experimental parameter space of dimensionless focusing geometry $\Psi = D_{\text{hemi}}/D_L$ and laser intensity from Refs. [1,8,11–15] and this work. References [14,15] used semicylinders. The markers illustrate the different experimental characterization techniques of heating a secondary sample, mesh radiography, and side-on proton radiography.

placed roughly 1 radius downstream of the hemi geometrical center. Several other experiments characterized the focusing dynamics using mesh radiography and inferred that proton trajectories were curved and bent outward around the focus from radial electric fields [8,13]. The experiments established proton focusing as a powerful tool; however, there are several open questions surrounding its robustness, scalability, and the key parameters for optimization. For one, these experiments inferred their conclusions from a small number of shots (often <5), which are susceptible to shot-to-shot variations of laser parameters and pointing stability between the hemi center and laser focal spot. Obtaining statistical measurements in these systems is vital to understanding the hemi focusing dynamics. Second, many of these works [11,13–15] performed experiments with large values of $\Psi > 70$ that may have different focusing behavior than small Ψ . Recent simulation studies have identified small Ψ ($\lesssim 15$) as a key for optimized focusing [17] and showed that best focusing occurs at $\Psi = 6\text{--}8.5$ for a 40 fs, 18 J, 4×10^{19} W/cm² drive [16]. Furthermore, while PFI requires proton beams from multi-kJ ultrashort lasers, such drivers do not yet exist, preventing direct experimental validation of ignition-scale focusing. Instead, medium-scale, high-repetition-rate facilities offer a path forward; they enable collection of the large datasets needed to characterize variability and focusing dynamics in the lower-energy regime, and provide crucial benchmarks for particle-in-cell (PIC) codes. These codes, once validated, can then be used to reliably extrapolate to ignition-relevant conditions. Beyond fast ignition, systematic optimization and characterization of proton focusing are equally critical for generating well-controlled warm dense matter samples, enabling improved understanding of fundamental material properties like proton transport [18] and equation of state [19].

In this work, we performed a parametric study of hemisphere diameter on proton focusing characteristics at the ALEPH laser at Colorado State University. Enhanced shot rate targetry and small hemispheres were fielded to diagnose the proton beam dynamics over 70 shots. $\Psi = D_{\text{hemi}}/D_L$ was varied between 6 and 15. Mesh radiography characterized the

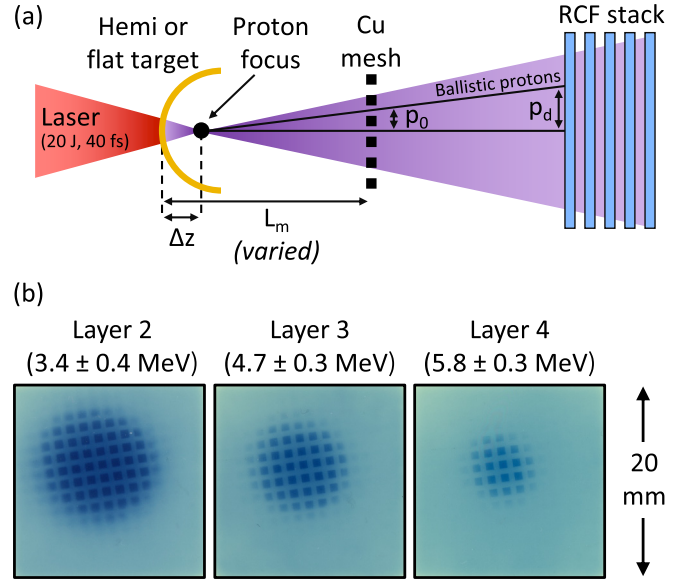


FIG. 2. (a) Mesh radiography setup used to characterize the proton focusing. p_0 is the mesh pitch and p_d is the magnified pitch on the detector. The laser focus is fixed and the target is moved into the focus. (b) RCF images from a single shot showing different layers and energy resolution.

focal location at several mesh distances to inform both the virtual and physical focal locations. The smallest hemisphere ($\Psi = 6.1$) focused protons near the geometrical center, while the largest hemisphere ($\Psi = 14.6$) focused deeper inside the target. The proton virtual focal spot size was inferred to be ~ 9 μm through a mesh transition analysis. In addition, the proton beam pointing was more erratic for smaller hemispheres as laser pointing stability had a stronger effect.

Section II introduces the experimental setup. Sections III and IV characterize the focal location and focal spot size using a mesh radiography analysis. Section V studies the beam pointing and divergence behavior and Sec. VI provides a discussion and comparison to previous experiments.

II. EXPERIMENTAL SETUP

The experiment was performed at the ALEPH laser at Colorado State University and the setup is shown in Fig. 2(a). A short-pulse laser irradiates a 10- μm -thick Au target, which is either a hemi or flat foil, to produce a beam of TNSA protons on the rear side of the target. The hemi diameter was varied between 220, 325, and 525 μm . An enhanced shot rate target assembly housed the targets in a grid and enabled many shots within a single vacuum cycle [20]. The precision of the target-positioning system was a central requirement of this experiment. Each hemispherical target was precharacterized and automatically aligned with three axes linear stages to the laser focal spot with positioning uncertainty of ± 5 μm in both the transverse and laser-propagation directions. The laser was characterized by 19.9 ± 0.9 J of energy, 40 fs FWHM (full width at half maximum) pulse duration, 800 nm wavelength, and laser contrast of 10^{-8} . It was focused using an $f/25$ parabolic mirror to a spot size of 36 ± 4 μm FWHM and peak intensity of $(3.4 \pm 0.8) \times 10^{19}$ W/cm² on target. A

TABLE I. Mesh distances from the hemi apex L_m for each target type.

Target type	$L_{m,1}$ (μm)	$L_{m,2}$ (μm)	$L_{m,3}$ (μm)
Flat	340	—	960
Hemi 525 μm	—	710	960
Hemi 325 μm	340	650	960
Hemi 220 μm	280	600	960

25- μm -thick Cu mesh is placed behind the target to imprint a shadow into the proton beam. The distance between the target and the mesh L_m is varied for each target configuration between 280 and 960 μm to gain insight into the proton beam dynamics. Meshes placed closer to the target had a pitch of 400 lines per inch, while meshes further away had a finer pitch of 600 lines per inch. The L_m distances are given in Table I and characterized to within 30 μm . The proton beam fluence is measured with a radiochromic film (RCF) stack positioned 20 mm away from the target. The stack consisted of 12.5- μm -thick Al foil and five layers of HD-V2 RCF film and provided energy resolution into five proton energy bins with central energies of 1.3, 3.4, 4.7, 5.8, and 6.7 MeV and bandwidths of 0.3–0.6 MeV. Figure 2(b) shows typical RCF images from three different layers in a single shot. A clear mesh imprint is visible and enables high-quality data extraction. Over 70 radiography shots were performed during five days of data collection due to the enhanced shot rate. RCF stacks were mounted in a 4 $\times$ 5 frame allowing acquisition of 20 shots without breaking vacuum. This starkly contrasts with prior experiments of proton focusing that were limited to around one shot per hour at large laser facilities.

III. FOCAL LOCATION

The mesh is used to infer the longitudinal position of the proton focus based on the observed magnification of the mesh in the RCF image. We assume straight-line trajectories of the proton beam from a source location through the mesh holes onto the detector. Due to this assumption, mesh radiography implicitly measures the location of the virtual proton focus inferred from the secant line between the mesh image on the detector and the physical mesh [21]. This may differ from the actual focus if the proton trajectories are curved. The virtual focus location Δz is defined relative to the hemi apex in Fig. 2(a) and given by

$$\Delta z = L_m - L_d \frac{p_0}{p_d - p_0}. \quad (1)$$

Here, L_m is the distance from the hemi apex to the mesh, $L_d = 20 \text{ mm} - L_m$ is the distance from the mesh to the detector, p_0 is the mesh pitch, and p_d is the magnified pitch measured on the detector. p_d is found by hand for each shot and layer by locating the mesh crossbars in the RCF images and calculating the average spacing. The mesh location L_m is varied to two or three positions for each target, given in Table I.

Figure 3 shows the virtual focus location for different target types as the mesh distance is varied. Each data point corresponds to the inferred virtual focus location for a single layer

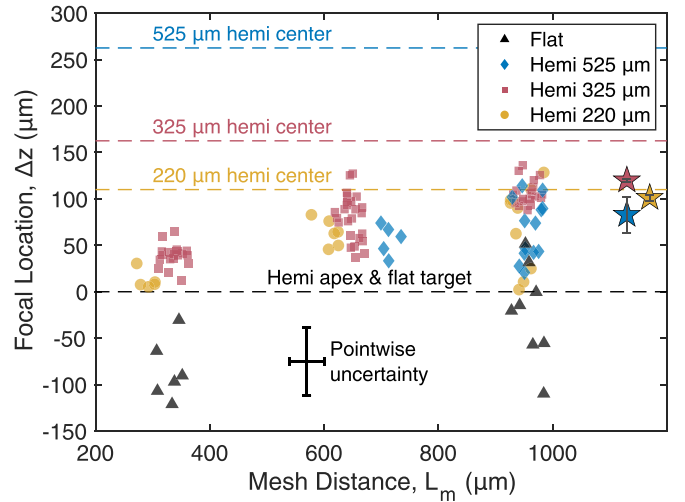


FIG. 3. Virtual focal location Δz as the mesh distance L_m is varied. For reference, $\Delta z = 0$ corresponds to the front surface of the target where the laser hits (hemi apex or flat foil) as shown in Fig. 2(a). The flat target is shown in black triangles, while the hemis of diameter 525, 325, and 220 μm are shown in blue diamond, red square, and yellow circle, respectively. RCF layers 2, 3, and 4 are shown. The dashed lines correspond to the geometric center of each hemi target. The stars on the right side are the inferred physical focus from fitting hyperbolic trajectories to the data with error bars indicating the fit uncertainty. A small amount of horizontal spreading is applied to the data points for visibility.

in one shot. The black data are from flat targets, while the blue, red, and yellow data refer to hemis with diameters of 525, 325, and 220 μm , respectively. The black dashed line denotes $\Delta z = 0$, which is the apex of the hemisphere targets where the laser hits and the location of the flat targets. The different colored dashed lines refer to the geometric center (i.e., radius) of the different sized hemis. The uncertainty in each data point is dominated by uncertainty in the mesh position L_m , which was precharacterized to within roughly 30 μm .

For nearly all shots, we observe that the virtual focal location is less than the hemi radius, corresponding to the region inside the hemi. Surprisingly, we also find that the virtual focal location from the hemi apex is nearly the same for all tested hemi sizes. The flat target produces a virtual focus that is behind the target due to laminar expansion, as demonstrated in previous work [21].

In addition, there is a clear trend in virtual focus location moving downstream (away from the target) as the mesh is moved further away. This trend was also observed in Ref. [13] and can be explained by an evolving proton trajectory that passes through the mesh plane before the beam becomes ballistic. Prior work has shown that protons focused from hemis may not travel in straight lines through the geometric center but are rather curved away from the axis due to the hot electron pressure [8,13,22,23]. The electron pressure sets up a radial electric field $E_r \approx -\nabla P_e / (en_e)$ that first focuses protons inward and then switches sign to defocus and curve protons outward. There are several models for proton focusing including that explored in Ref. [23] and the isothermal model presented in Ref. [13]. However, in this work we

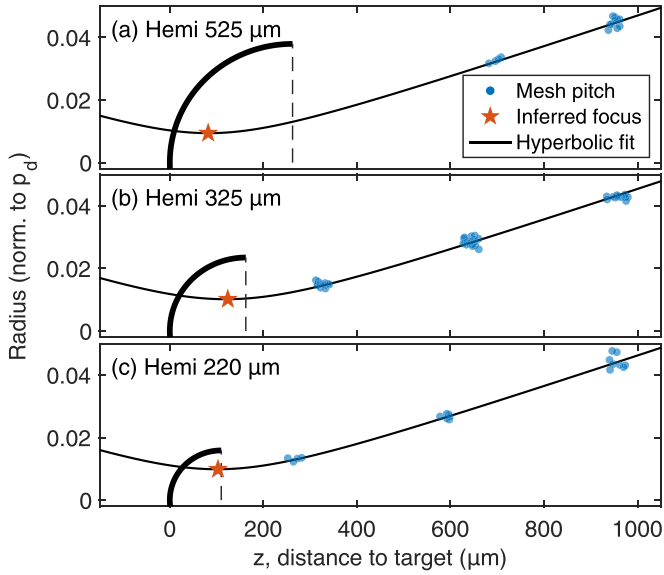


FIG. 4. Sample proton trajectories for each target type. The blue dots show the mesh pitch normalized to the measured detector pitch (p_0/p_d) at different mesh positions L_m . The data are plotted this way to compare self-similar proton trajectories. A hyperbolic fit is given for each target type (solid line). The red star is the physical focal position based on the minimum of the hyperbolic trajectory. A small amount of horizontal spreading is applied to the data for visibility. Note that the hemis are depicted with a circular aspect ratio but should actually be stretched in the radial direction from the normalization.

assume a hyperbolic trajectory for simplicity that showed good agreement to the isothermal model in Ref. [13] and replicates the main characteristics of curved trajectories near the focus and asymptotic evolution away from the focus.

Figure 4 shows evolving hyperbolic proton trajectory through the mesh data for each target. The radial coordinate is normalized to the measured detector pitch p_d so that data from different mesh locations can be compared on the same footing on self-similar trajectories. This leads to a spread in mesh pitch datapoints p_0/p_d and a data point at the RCF plane at ($z = 20$ mm, $p_d/p_d = 1$). The fitted trajectory assumes the following hyperbolic form:

$$R(z) = m\sqrt{(z - \Delta z_{\text{phys}})^2 + r_0^2}, \quad (2)$$

with asymptotic slope m , physical focal location Δz_{phys} , and minimum proton beam radius mr_0 . If r_0 and Δz are kept constant, then all trajectories have the same asymptotic virtual focus location, regardless of the value of m . Experimentally, this manifests as having the same detector pitch everywhere on the image so that different radii trace back to the same focal location within the small angle (paraxial) approximation.

The minimum of each hyperbolic fit is used to infer the proton focal location and is plotted as a star on the right side of Fig. 3. These locations are equivalent to the virtual focus if the mesh were placed infinitely far away. All three hemi diameters have similar asymptotic focal locations of $\Delta z_{\text{phys}} \approx 100$ μm from the hemi apex. The 220 and 325 μm hemis have small uncertainties in the focal location of less than 4 μm , while the 525 μm hemi has 20 μm uncertainty

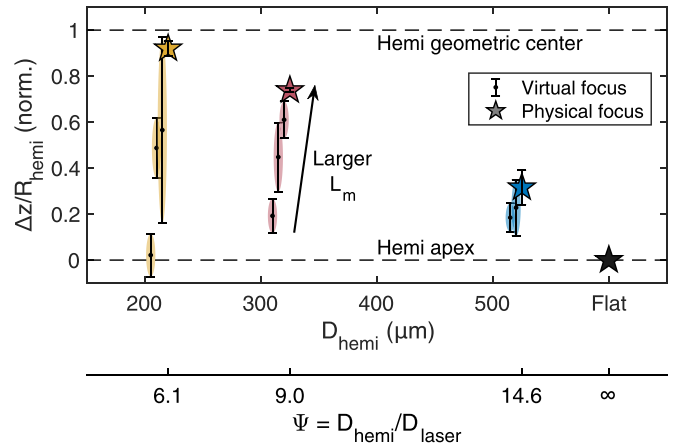


FIG. 5. Normalized focal location $\Delta z/R_{\text{hemi}}$ for different hemi diameters. Virtual focal locations are shown by shaded ellipses and error bars containing one standard deviation. The virtual focii have slight horizontal offsets corresponding to different mesh distances L_m and culminating in a star referring to the inferred physical focal, or equivalently the virtual focus as $L_m \rightarrow \infty$. The $\Psi = D_{\text{hemi}}/D_{\text{Laser}}$ value for each target is given in the secondary x axis.

because there are only two mesh positions for this target type. Through this hyperbolic fit, we may connect the virtual and physical sources and observe why the virtual source changes with mesh distance. The ratio of the first to second terms in Eq. (2) controls when the trajectory becomes ballistic. Protons are ballistic when they reach the mesh if $L_m - \Delta z_{\text{phys}} \gg r_0$. In this case, the virtual focus location will coincide with the physical location. In contrast, if $L_m - \Delta z_{\text{phys}} \lesssim r_0$, then the beam is still evolving when it passes through the mesh and the virtual focus will be upstream of the physical source. The hyperbolic fits found r_0 to be between 200 and 300 μm . However, if the proton trajectory is nonhyperbolic, then it is less clear how the physical and virtual focuses are connected. For example, Ref. [16] observed extended channeling of the focused protons into a collimated beam with small transverse waist and significant longitudinal extent. This configuration would lead to virtual focusing near the end of the channel despite the physical focus occurring further upstream.

Figure 5 plots the focal location normalized to the hemi radius $\Delta z/R_{\text{hemi}}$ for different hemi sizes. A value of $\Delta z/R_{\text{hemi}} = 1$ corresponds to a focus at the hemi geometric center, while a value of $\Delta z/R_{\text{hemi}} = 0$ is a focus at the hemi apex. The virtual focal locations at intermediate mesh distances L_m are plotted as shaded ellipses and the physical focal location is denoted by a star. Interestingly, a clear trend emerges where the smallest hemi focuses near the geometric center with $\Delta z_{\text{phys}}/R_h = 0.92$ and the larger hemis focus to points deeper inside the hemisphere with $\Delta z_{\text{phys}}/R_h = 0.74$ and 0.32 for the 325 and 525 μm hemis. The focusing from larger hemis (i.e., larger Ψ) behaves more like a flat foil, with the focal location moving inside the hemisphere (i.e., degraded focusing) as observed in Ref. [16].

In order to see trends with proton energy, Fig. 6 shows the virtual focal location shift relative to layer 2 for different RCF layers. This quantity removes the ± 30 μm variation in Δz that arises from uncertainties in the mesh distance characterization

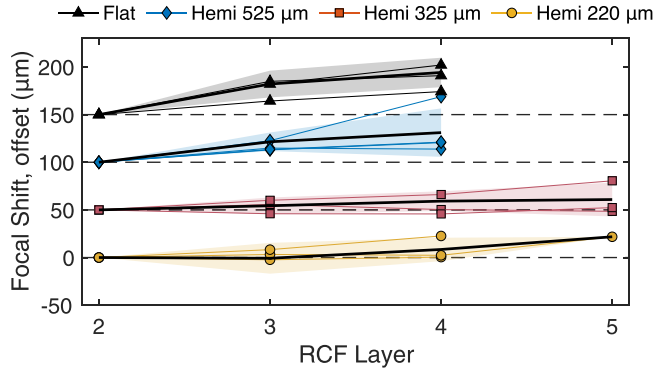


FIG. 6. Focal location shift relative to layer 2 for different RCF layers. Different colors correspond to different target types and the plot is offset for each target. The thick black line is the mean value and the shaded region shows ± 1 standard deviation. Selected shots are shown as markers where thin lines connect data from a single shot.

and isolates trends from a single shot. The virtual focus tends to move downstream for greater RCF layers and is more pronounced for hemis with larger diameter and for the flat foil.

IV. FOCAL SPOT SIZE

The transverse proton focal spot size is relevant for proton fast ignition to efficiently heat the target and ensure adequate proton fluence to ignite the compressed fuel [4,6]. We measure the virtual focus size using a mesh transition analysis shown in Fig. 7 and first discussed in Ref. [21]. The sharpness of the mesh transition is directly related to the size of the focus; a larger focus leads to a more blurred image. To extract the focus size, we model the transverse profile $w_s(x)$ as a Gaussian with width a . With this assumption, the signal on the detector $I_d(x)$ transitions across a mesh cell according to an error function with spatial scale Ma , where M is the mesh magnification in the detector plane.

$$w_s(x) \propto \exp\left(-\frac{x^2}{a^2}\right), \quad (3)$$

$$I_d(x) \propto 1 + \operatorname{erf}\left(\frac{x}{Ma}\right). \quad (4)$$

Twenty-five different shots were analyzed across layers 2–4, with 18 transitions fit per image, totaling over 1000 different

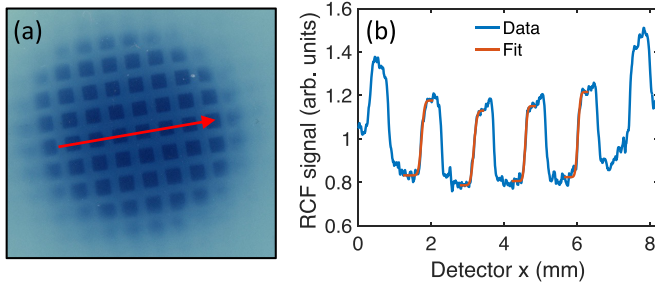


FIG. 7. (a) Mesh radiograph with lineout location. (b) Lineout with several error function fits around the mesh transition to infer virtual spot size.

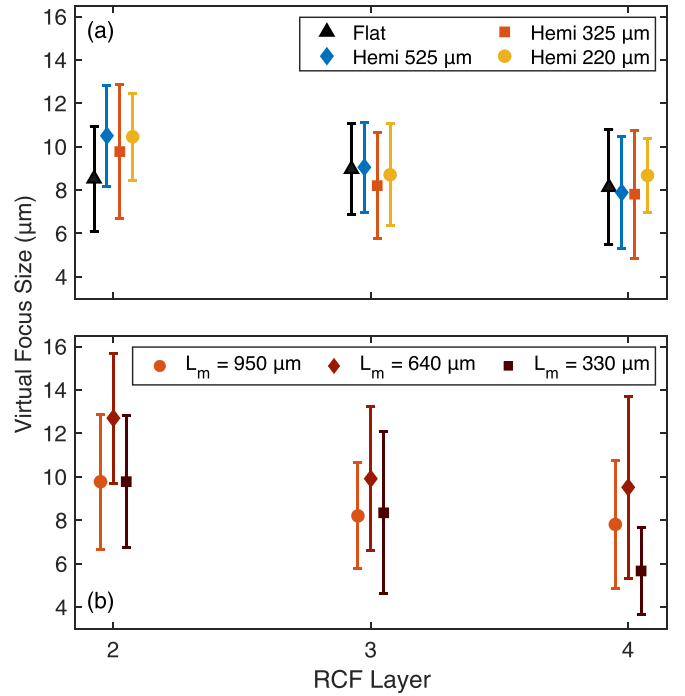


FIG. 8. (a) Virtual focus size FWHM vs layer (energy) for each target type at a fixed mesh distance of 960 μm . (b) Virtual focus size vs layer for the 325 μm hemi, showing different mesh distances, L_m .

transitions to characterize the proton focal spot size. Across all the different target types and layers, the mean virtual focal spot FWHM is $9.3 \pm 3 \mu\text{m}$. Figure 8(a) shows the virtual focal size as a function of the RCF layer for each target type, at constant mesh distance $L_m = 960 \mu\text{m}$. The proton beam focal spot size decreases slightly for higher RCF layer as expected; the mean size for RCF layer 2 is $9.9 \pm 2.6 \mu\text{m}$, compared to $8.0 \pm 2.6 \mu\text{m}$ for layer 4. Higher energies are less divergent and therefore exhibit a tighter focus. There is no clear trend between the target types. Figure 8(b) shows measurements of the focal size for the 325 μm diameter hemi at different mesh distances, L_m . There is no clear trend in the focal size with mesh distance, suggesting that mesh distance does not impact the virtual focal size to the same degree as it does the virtual focal location. With this being said, the virtual focus size is a lower bound to the physical focus size and the physical focus may be larger.

One important note is that the magnification is given by the ratio between the source-to-detector distance and the source-to-mesh distance, $M = (L_d + L_m - \Delta z)/(L_m - \Delta z)$, which includes the focal location Δz in the calculation. For simplicity in this analysis, we have assumed $\Delta z = 0$ so that the source location is at the front surface of the target at the hemi apex, which would produce an estimated magnification $M_{\text{est}} = (L_d + L_m)/L_m$. Since hemis focus protons downstream of the apex, M_{est} underestimates the true magnification and therefore overestimates the virtual focus size for a measured transition size $M_{\text{est}}a$. Inserting the inferred focal location of $\Delta z \approx 100 \mu\text{m}$ decreases the spot size by 11%, 16%, and 30% for mesh distances of 950, 640, and 330 μm , respectively. However, the fact that there is no trend in virtual focal size

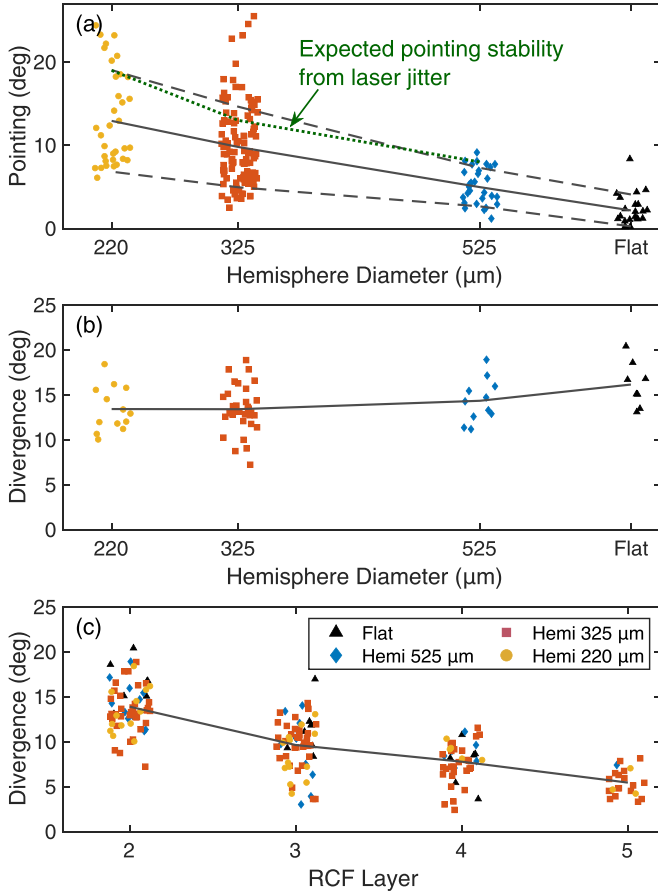


FIG. 9. (a) Beam pointing relative to the center of the RCF image for different hemi diameters with the mean value in solid line and $\pm$ standard deviation in dashed lines. The dotted green line shows the expected proton beam pointing from laser jitter, assuming a laser mispoint of one spot size and target normal proton beam propagation. (b) Beam divergence HWHM (half width at half maximum) for RCF layer 2. (c) Beam divergence HWHM for different RCF layers. A small amount of horizontal spreading is applied to all of the data for visibility.

with mesh distance [Fig. 8(b)] suggests that our estimate for $\Delta z = 0$ is adequate.

V. BEAM POINTING AND DIVERGENCE

The proton beam pointing and divergence are important properties in the context of proton fast ignition. In contrast to TNSA from a flat foil, the structured nature of a hemispherical target is relatively sensitive to laser mispointings, especially for small Ψ values. From simulations, laser mispointings leads to a focused proton beam that propagates mainly in the direction normal to where the laser hits, resulting in a beam pointing that is mirrored across the hemi axis [15,24].

Here, we quantify the proton beam pointing and divergence across 66 shots and 4 layers. Figure 9(a) shows the beam pointing relative to the proton beam centroid from the flat target (close to the center of the RCF). The proton beam is centered on the RCF more frequently as the hemi diameter is increased. This is consistent with laser mispointings becoming less important for the larger hemis. If we take a simple

estimate of the laser jitter to be $36 \mu\text{m}$ (equivalent to one spot size) with geometrically focused protons, then a ballistically focused proton beam would be directed at 19° , 13° , and 8° from the center of the RCF for the 220, 325, and $525 \mu\text{m}$ hemis, respectively. These values are roughly consistent with one standard deviation above the mean of the pointing data, shown as dotted lines.

Figure 9(b) shows the beam divergence HWHM for RCF layer 2 for different hemi diameters. The divergence is roughly constant at $\sim 15^\circ$ with a small upward trend of a few degrees from the $220 \mu\text{m}$ target to the flat target. The divergence measures the asymptotic behavior of the proton beam downstream of the proton focus. If the assumption of a hyperbolic trajectory holds near the proton focus, the beam divergence can be combined with the hyperbolic fit to recover an estimate of the physical proton focal spot size using Eq. (2). For a divergence of 15° , the minimum proton beam radius mr_0 is estimated to be $50\text{--}80 \mu\text{m}$ for all targets. This is $3\text{--}4\times$ larger than the laser spot which has a FWHM of $36 \mu\text{m}$. Although it is unclear whether the hyperbolic model is valid close to the focus, this result suggests that the virtual proton beam size may underestimate the physical size.

Figure 9(c) shows the beam divergence decreasing as a function of RCF layer. Qualitatively, protons emitted normal at the location where the laser hits are accelerated for longer distances and reach higher energies.

VI. DISCUSSION AND CONCLUSION

A central thrust of this experiment was characterizing the proton beam focal location using mesh radiography. However, this diagnostic only accesses the virtual source properties inferred by projecting straight line trajectories from the RCF image back through the mesh plane. To circumvent this limitation, we assumed that the protons travel in a hyperbolic trajectory and leveraged how the virtual focus position changes with mesh distance L_m to infer a physical source (Figs. 3 and 4). However, an alternative explanation of the changing virtual focus with mesh distance is that the mesh became charged from fast electrons and x-rays ahead of the proton beam; meshes placed closer to the interaction could become charged to a higher degree and would have less time to discharge before protons arrived, resulting in a stronger proton deflection.

However, the role of mesh charging was investigated and found to be minimal in this experiment due to the small degree of charging and fast discharge rate. Through auxiliary PIC simulations, we estimate $\sim 50 \text{ pC}$ of uncompensated electron charge preceding the main proton beam that could charge the mesh negative. Previous experiments and theory have shown that the electrical discharge speed is close to the speed of light and would discharge the mesh exponentially [25,26]. The characteristic discharge time is estimated as $\tau = R_{\text{mesh}}/c = 1.5 \text{ ps}$, where $R_{\text{mesh}} \approx 500 \mu\text{m}$ is the radius of the mesh that the proton interacts with. For the worst-case scenario, the closest mesh is located at $L_m = 280 \mu\text{m}$, which has an 8 ps time of flight for 5 MeV protons, associated with layer 3 in the mesh. This mesh discharges from 50 to 0.2 pC in this time duration. However, to reproduce the observed trend in virtual source, we estimate the mesh must be charged to $\sim 5 \text{ pC}$ and

TABLE II. Comparison of hemisphere focusing experiments. We emphasize the variability in both characterization technique and proton energy of interest for a direct quantitative comparison.

Source	Laser parameters				Target parameters		Focusing behavior			Technique
	E (J)	τ (fs)	D_L (μm)	I (10^{19} W/cm 2)	D_h (μm) ^a	$\Psi = D_h/D_L$	Δz (μm)	R_f (μm) ^b	$\Delta z/R_h$ ^c	
Patel [1]	10	100	50	0.5	320	6.4	160	23	1.00	Heating
Patel [11]	400	400	7	50	1000	143	500	47	1.00	Heating
Snively [12]	170	700	50	0.3	360	7.2	350	103	1.94	Heating
Offerman [13]	80	600	7	20	800	114	657	189	1.64	Mesh rad.
Kar ^d [14]	350	750	10	40	700	70	800	25–90	2.29	Mesh rad.
Bartal [8]	75	550	90	0.1	600	6.7	75	15–30	0.25	Mesh rad.
Chen ^d [15]	1	320	11	0.3	800	73	370	15	0.93	Proton rad.
					220	6.1	101	9.4	0.92	
This work	20	40	36	3.4	325	9.0	120	8.6	0.74	Mesh rad.
					525	14.6	83	9.3	0.32	

^aHemisphere diameter.

^bProton beam focal radius.

^cFocal location normalized to hemi radius. A value greater than unity measures a focus outside of the hemi.

^dThese experiments used a semicylinder instead of a hemi target. Reference [14] used a 250- μm -thick target.

it is therefore unlikely that the mesh charging influenced the proton trajectories at the diagnosed energies of ~ 5 MeV.

Another indication that the mesh charging does not impact our measurements is the observed energy dependence of the virtual focus. If the mesh were significantly charged, it would alter the virtual focus in a way that depends on both the mesh distance and the proton energy. A mesh placed close to the interaction would acquire more charge and thus produce a stronger energy dependence on the virtual focus since the electric deflection is inversely proportional to the proton energy, $d_E \propto E_p^{-1}$. In contrast, a farther mesh would become less charged and have a weaker dependence on proton energy. Instead, we observe that the variation in virtual source with proton energy is constant for both close and far meshes, suggesting that the mesh does not impact the proton beam dynamics.

In this experiment, we find that the normalized focal location $\Delta z_{\text{phys}}/R_h < 1$ and decreases with increasing hemisphere size, moving the focus deeper inside the hemisphere (Fig. 5). Larger hemis (i.e., larger Ψ values) behave more like flat foils and have degraded focusing, with the focus approaching the target surface as $\Delta z_{\text{phys}}/R_h \rightarrow 0$. In our measurements, $\Delta z_{\text{phys}}/R_h = 0.92$ for the 220 μm hemi ($\Psi = 6.1$) and decreases down to $\Delta z_{\text{phys}}/R_h = 0.32$ for the 525 μm hemi ($\Psi = 14.6$). While smaller hemis were not tested due to manufacturing limits, a smaller target may produce further improved focusing with $\Delta z_{\text{phys}}/R_h > 1$ under these experimental conditions. However, there is a clear trade-off between Ψ and pointing stability, as shown in Fig. 9(a). It is unclear if the proton beam pointing is correlated with a transverse shift in the physical proton focal location, as discussed in simulations in Ref. [15].

We also find that statistics enabled by an enhanced shot rate are important to reliably detect trends in the data. With over 70 shots, we could establish systematic trends across the experimental variables, rather than relying on a few shots like prior works. This is the first experiment to measure proton focusing from hemispheres at an enhanced shot rate. The large

sample size is critical to informing scaling laws to the higher driver energies required for proton fast ignition.

Table II compares our results with prior hemisphere and semicylinder experiments that diagnosed the focusing behavior with secondary heating of a sample, mesh radiography, or side-on proton radiography. Due to the variability in laser parameters, target geometries, and diagnostic methods, direct quantitative comparison is difficult. Nevertheless, reducing the parameter space to laser intensity, dimensionless focusing geometry $\Psi = D_{\text{hemi}}/D_L$, and dimensionless focal location $\Delta z/R_h$ offers interesting points of comparison. First, we infer $\Delta z/R_h$ between 0.32 and 0.92, which spans from inside the hemi to near the geometric center. Several other experiments also report focusing at or inside the geometric center [1,8,11,15]. These experiments vary across a wide range of intensities and Ψ values but are generally at lower intensities $I < 10^{19}$ W/cm 2 and smaller $\Psi < 10$. These contrast with the experiments that predict a focus downstream of the hemi center [12–14] and generally have larger intensities $I > 10^{20}$ W/cm 2 and larger $\Psi > 70$. Physically, the intensity roughly controls the electron temperature, while Ψ shapes the electron sheath and focusing fields. The focus behavior presented here is qualitatively consistent with the simulation results from Ospina-Bohórquez *et al.* [16], which showed optimal focusing for $\Psi = 6$ to 8.5 under similar conditions and degraded focusing for $\Psi = 13.5$. However, that study predicted proton channeling and a focus outside of the hemisphere at optimal Ψ value. Target thickness also plays a role, as in Kar's experiment where the 250- μm -thick target likely reduced electron temperature and Ψ value since the electron beam diverges inside the solid, effectively increasing the equivalent laser spot size. The reported energy-dependent trends of downstream-shifted focal locations and slightly smaller virtual focal size are consistent with previous work [8,14].

In conclusion, we performed the first systematic study of proton focusing from laser-irradiated hemispherical targets of different diameters. A detailed mesh radiography analysis was performed over 70 shots, due to advances in enhanced

shot rate targetry. Mesh radiography measurements at several distances allowed us to constrain both the virtual and physical focusing properties. We find that the physical focus is near the geometric center for the smallest diameter hemi ($\Psi = 6.1$), but shifts deeper inside the hemisphere for larger diameter targets ($\Psi = 14.6$). A mesh transition analysis measures the virtual focal spot size to be $9 \pm 3 \mu\text{m}$ for all hemisphere sizes. Finally, the proton beam pointing was characterized and found to be more erratic for small hemispheres as laser pointing stability became more impactful. These results provide critical benchmarks for scaling proton focusing toward the high driver energies demanded by proton fast ignition.

ACKNOWLEDGMENTS

The authors thank the Colorado State University Advanced Beam Laboratory laser facility staff for their help in conducting these experiments as well as the targetry team at Focused Energy for providing the targets and developing the enhanced rep-rate hemisphere alignment system. The research described in this paper was funded under the INFUSE program—a DOE SC FES public-private partnership—under CRADA No. 2725 between Princeton Plasma Physics Laboratory and Focused Energy Inc. company under its U.S. Department of Energy Contract No. DE-AC02-09CH11466.

The experimental work was supported by the U.S. Department of Energy's (DOE) Office of Science (SC) Fusion Energy Sciences (FES) program under DE-SC0021246: the LaserNetUS initiative at the Advanced Beam Laboratory. The PPPL team's experimental activities, numerical modeling, and calculations supporting the experimental results were conducted under the Laboratory Directed Research and Development (LDRD) Program at Princeton Plasma Physics Laboratory, a national laboratory operated by Princeton University for the U.S. Department of Energy under Prime Contract No. DE-AC02-09CH11466.

The United States Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

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.

-
- [1] P. K. Patel, A. J. Mackinnon, M. H. Key, T. E. Cowan, M. E. Foord, M. Allen, D. F. Price, H. Ruhl, P. T. Springer, and R. Stephens, Isochoric heating of solid-density matter with an ultrafast proton beam, *Phys. Rev. Lett.* **91**, 125004 (2003).
 - [2] M. Bailly-Grandvaux, S. Bolaños, J. Kim, J. Saret, C. McGuffey, K. Bhutwala, P. M. Nilson, T. Filkins, W. Theobald, A. Haid, S. Ivancic, and F. N. Beg, Creation and characterization of warm dense matter isochorically heated by an intense laser-driven proton beam to temperatures exceeding 100 eV, *Commun. Phys.* **8**, 285 (2025).
 - [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. Yasuie, 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. Atzeni, M. Temporal, and J. J. Honrubia, A first analysis of fast ignition of precompressed ICF fuel by laser-accelerated protons, *Nucl. Fusion* **42**, L1 (2002).
 - [5] M. Tabak, D. Hinkel, S. Atzeni, M. Campbell, and K. A. Tanaka, Fast ignition: Overview and background, *Fusion Sci. Technol.* **49**, 254 (2006).
 - [6] J. J. Honrubia and M. Murakami, Ion beam requirements for fast ignition of inertial fusion targets, *Phys. Plasmas* **22**, 012703 (2015).
 - [7] S. C. Wilks, A. B. Langdon, T. E. Cowan, M. Roth, M. Singh, S. Hatchett, M. H. Key, D. Pennington, A. MacKinnon, and R. A. Snavely, Energetic proton generation in ultra-intense laser–solid interactions, *Phys. Plasmas* **8**, 542 (2001).
 - [8] T. Bartal, M. E. Foord, C. Bellei, M. H. Key, K. A. Flippo, S. A. Gaillard, D. T. Offermann, P. K. Patel, L. C. Jarrott, D. P. Higginson, M. Roth, A. Otten, D. Kraus, R. B. Stephens, H. S. McLean, E. M. Giraldez, M. S. Wei, D. C. Gautier, and F. N. Beg, Focusing of short-pulse high-intensity laser-accelerated proton beams, *Nat. Phys.* **8**, 139 (2012).
 - [9] B. Qiao, M. E. Foord, M. S. Wei, R. B. Stephens, M. H. Key, H. McLean, P. K. Patel, and F. N. Beg, Dynamics of high-energy proton beam acceleration and focusing from hemisphere-cone targets by high-intensity lasers, *Phys. Rev. E* **87**, 013108 (2013).
 - [10] C. McGuffey, J. Kim, M. S. Wei, P. M. Nilson, S. N. Chen, J. Fuchs, P. Fitzsimmons, M. E. Foord, D. Mariscal, H. S. McLean, P. K. Patel, R. B. Stephens, and F. N. Beg, Focussing protons from a kilojoule laser for intense beam heating using proximal target structures, *Sci. Rep.* **10**, 9415 (2020).
 - [11] P. K. Patel, M. H. Key, A. J. Mackinnon, R. Berry, M. Borghesi, D. M. Chambers, H. Chen, R. Clarke, C. Damian, R. Eagleton, R. Freeman, S. Glenzer, G. Gregori, R. Heathcote, D. Hey, N. Izumi, S. Kar, J. King, A. Nikroo, A. Niles, *et al.*, Integrated laser–target interaction experiments on the RAL petawatt laser, *Plasma Phys. Controlled Fusion* **47**, B833 (2005).
 - [12] R. A. Snavely, B. Zhang, K. Akli, Z. Chen, R. R. Freeman, P. Gu, S. P. Hatchett, D. Hey, J. Hill, M. H. Key, *et al.*, Laser generated proton beam focusing and high temperature isochoric heating of solid matter, *Phys. Plasmas* **14**, 092703 (2007).
 - [13] D. T. Offermann, K. A. Flippo, J. Cobble, M. J. Schmitt, S. A. Gaillard, T. Bartal, D. V. Rose, D. R. Welch, M. Geissel, and M. Schollmeier, Characterization and focusing of light ion beams generated by ultra-intensely irradiated thin foils at the kilojoule scale, *Phys. Plasmas* **18**, 056713 (2011).
 - [14] S. Kar, K. Markey, M. Borghesi, D. C. Carroll, P. McKenna, D. Neely, M. N. Quinn, and M. Zepf, Ballistic focusing of polyenergetic protons driven by petawatt laser pulses, *Phys. Rev. Lett.* **106**, 225003 (2011).

- [15] S. N. Chen, E. d'Humières, E. Lefebvre, L. Romagnani, T. Toncian, P. Antici, P. Audebert, E. Brambrink, C. A. Cecchetti, T. Kudyakov, A. Pipahl, Y. Sentoku, M. Borghesi, O. Willi, and J. Fuchs, Focusing dynamics of high-energy density, laser-driven ion beams, *Phys. Rev. Lett.* **108**, 055001 (2012).
- [16] V. Ospina-Bohórquez and X. Vaisseau, Scaling and performance analysis of Smilei in hemispherical foil target simulations for inertial fusion energy, *Proc. Comput. Sci.* **255**, 112 (2025).
- [17] A. J. Kemp, S. C. Wilks, and M. Tabak, Laser-to-proton conversion efficiency studies for proton fast ignition, *Phys. Plasmas* **31**, 042709 (2024).
- [18] S. Malko, W. Cayzac, V. Ospina-Bohórquez, K. Bhutwala, M. Bailly-Grandvaux, C. McGuffey, R. Fedosejevs, X. Vaisseau, A. Tauschwitz, J. I. Apiñaniz, *et al.*, Proton stopping measurements at low velocity in warm dense carbon, *Nat. Commun.* **13**, 2893 (2022).
- [19] D. J. Hoarty, T. Guymer, S. F. James, E. Gumbrell, C. R. D. Brown, M. Hill, J. Morton, and H. Doyle, Equation of state studies of warm dense matter samples heated by laser produced proton beams, *High Energy Density Phys.* **8**, 50 (2012).
- [20] T. S. Bauer, Development, characterization, alignment and experimental validation of partial sphere target arrays for advanced proton acceleration studies, Ph.D. thesis, TU Darmstadt, 2025.
- [21] M. Borghesi, A. J. Mackinnon, D. H. Campbell, D. G. Hicks, S. Kar, P. K. Patel, D. Price, L. Romagnani, A. Schiavi, and O. Willi, Multi-MeV proton source investigations in ultraintense laser-foil interactions, *Phys. Rev. Lett.* **92**, 055003 (2004).
- [22] M. E. Foord, T. Bartal, C. Bellei, M. Key, K. Flippo, R. B. Stephens, P. K. Patel, H. S. McLean, L. C. Jarrott, M. S. Wei, and F. N. Beg, Proton trajectories and electric fields in a laser-accelerated focused proton beam, *Phys. Plasmas* **19**, 056702 (2012).
- [23] C. Bellei, M. E. Foord, T. Bartal, M. H. Key, H. S. McLean, P. K. Patel, R. B. Stephens, and F. N. Beg, Electron and ion dynamics during the expansion of a laser-heated plasma under vacuum, *Phys. Plasmas* **19**, 033109 (2012).
- [24] K. Lezhnin, V. O. Bohorquez, K. A. Bhutwala, J. Griff-McMahon, X. Vaisseau, T. Bauer, W. Fox, and S. Malko, Laser ion acceleration from concave targets: Focusing, scaling, and robustness studies, *Talk at the 66th Annual Meeting of the APS Division of Plasma Physics, Mini-Conference: Proton Transport in HED II: Proton Focusing* (Session CM10.4) (2024).
- [25] H. Ahmed, S. Kar, G. Cantono, G. Nersisyan, S. Brauckmann, D. Doria, D. Gwynne, A. Macchi, K. Naughton, O. Willi, C. Lewis, and M. Borghesi, Investigations of ultrafast charge dynamics in laser-irradiated targets by a self probing technique employing laser driven protons, *Nucl. Instrum. Methods Phys. Res. Sect. A* **829**, 172 (2016).
- [26] A. Poyé, J.-L. Dubois, F. Lubrano-Lavaderci, E. D'Humières, M. Bardon, S. Hulin, M. Bailly-Grandvaux, J. Ribolzi, D. Raffestin, J. J. Santos, P. Nicolai, and V. Tikhonchuk, Dynamic model of target charging by short laser pulse interactions, *Phys. Rev. E* **92**, 043107 (2015).