

Conical coil focusing of laser-plasma accelerated proton beams for applications

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Laser-driven ion beams offer significant advantages over radio-frequency accelerated beams, making them particularly promising for biomedical applications. Key features include their ultrashort pulse duration, on the order of picoseconds, and high peak fluxes ranging from 10^{11} to 10^{13} particles per shot. These characteristics enable the delivery of ultrahigh dose rates, potentially reaching the FLASH therapy regime. The future implementation of laser-driven ion beams in clinical settings relies on the development of advanced focusing and beam transport systems capable of precisely controlling parameters such as energy range, beam focus, and dose distribution to meet stringent therapeutic requirements. However, the integration of ultrashort laser-driven ion beams into medical treatments presents challenges, particularly due to their broad energy spectrum and high angular divergence. We present 3D simulation-based studies investigating the focusing effects of different high-current solenoid configurations on laser-plasma-accelerated proton beams. To identify the optimal focusing solution, we designed, analyzed, and compared high-current solenoids of varying dimensions and shapes, both as stand-alone magnetic elements and as part of two-solenoid focusing systems. Our analysis focuses on magnetic fields between 6 and 9 T, generated by the high-current solenoids. The study considers a proton beam with an energy range from a few MeV to 20 MeV and an initial divergence of 21° . Results are evaluated in terms of collection efficiency, beam focusing position, and beam profile. The optimized beamline configuration was then used to assess the dose distribution in a cylindrical water target with a volume of 78 mm^3 by calculating the absorbed dose and dose delivery rates, demonstrating the potential of laser-plasma-accelerated proton beams for radiotherapy applications.

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I. INTRODUCTION

Employing high-intensity ultrashort laser pulses to generate accelerated charged particle beams has been a hot topic of research over the last two decades [1–3]. The major advances in laser technologies have raised expectations for further progress across numerous applications. Laser-plasma accelerated (LPA) proton beams cover a wide variety of applications, such as proton radiography [4], warm dense matter studies [5], biomedical studies [6], neutron generation [7], and proton fast ignition [8].

One of the many interesting applications of LPA beams is the development of laser-based solutions for proton beam therapy [9]. This type of radiation-based treatment has been proven to have numerous advantages over conventional x-ray radiotherapy. The greater mass of protons assures less scattering and a preplanned in-depth delivery range, as determined from the Bragg peak analysis, allowing for a very precise exposure of the tumoral volume.

Proton beam therapy is an established cancer treatment that currently relies on conventional radio-frequency accelerators such as LINACs, synchrotrons, and cyclotrons. A few representative facilities include the Heidelberg Ion Beam Therapy Center in Germany [10], MedAustron in Austria [11], the Trento Proton Therapy facility in Italy [12], TRIUMF in Canada [13], the Shanghai Proton and Heavy Ion Center in China [14], the Aizawa Proton Therapy Center in Japan, the Dwoskin Proton Therapy Center in the United States. In clinical treatments, proton

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beam energies typically range from a few MeV up to approximately 250 MeV, with sub-MeV precision. These beams offer millimeter-level focusing capabilities and submillimeter spatial accuracy, as seen in pencil beam scanning. Particle fluxes vary between 10^6 and 10^{10} particles s^{-1} , depending on the prescribed dose [11–13].

In contrast, laser-based accelerator systems produce beams with distinct characteristics that offer both opportunities and challenges for biomedical applications. Among their advantages, laser-driven beams feature ultrashort pulse durations as short as tens of picoseconds and high fluxes, with peak values ranging from 10^{11} to 10^{13} particles per shot. These properties enable the potential delivery of ultrahigh dose rates far exceeding 40 Gy/s, the threshold for FLASH therapy. The FLASH effect has gained attention for its ability to effectively target tumor cells while minimizing damage to healthy tissues. Although its underlying mechanisms remain only partially understood [15], this groundbreaking approach holds significant promise for advancing cancer treatment [6,16–18].

The challenges associated with laser-plasma-accelerated particle beams stem from their broadband energy spectrum, characterized by an exponential profile and a high cutoff energy, as well as their large beam divergence. The advancement of biomedical applications that utilize these beams, particularly those capable of reaching the FLASH therapy regime, depends on the development of specialized beam transport and focusing systems. These systems must precisely control beam delivery according to predefined parameters similar to complex gantry systems in radiation therapy [19], ensuring dose confinement to the target volume while minimizing the risk of radiation-induced side effects.

This paper presents 3D simulation-based studies that investigate the focusing effects of different high-current solenoid configurations on laser-plasma-accelerated proton beams [20]. Additionally, it includes a dose distribution analysis to assess the feasibility of achieving the FLASH therapy regime when irradiating a predefined target volume modeled after a superficial tumor.

II. SIMULATION OF THE FOCUSING PROCESS FOR LPA PROTON BEAMS

The defining characteristics of current laser-driven proton beams include a broad energy spectrum, ranging from a few MeV to over 100 MeV [21], and a high angular divergence, with a full spread of up to 40° – 60° [22]. These features necessitate specialized transport systems utilizing strong magnetic fields to control and tailor the beam, ensuring its suitability for clinical applications. Common LPA beam focusing systems are based on high magnetic fields generated by solenoids, dipoles, quadrupoles or various combinations between these elements [1,6,9,23]. Solenoids induce a stronger focusing effect on the lower energetic particles, as described by the focal length equation of a solenoid:

$$\frac{1}{f} = \frac{B^2 l_{\text{coil}}}{4(p/q)^2}, \quad (1)$$

where B is axial magnetic field, l_{coil} is the total length of the coil, while p and q represent the momentum and the charge of the particles, respectively. Dipoles generate uniform magnetic fields that are typically used for steering the beams either in vertical or horizontal direction. Quadrupoles produce magnetic fields with linear gradients that induce a focusing effect on one direction while simultaneously defocusing the beam on the other one. Because of this feature, the quadrupoles usually come in the form of doublets or triplets. Alternate approaches could be the use of an electron plasma lens [24–26], in which case the focusing would be induced by the electrostatic fields generated by the plasma.

Our proposed configuration dedicated to focusing LPA proton beams is based on strong magnetic fields in the several Tesla range generated by high-current solenoids. These magnetic elements are an excellent fit for this study's objectives due to the stronger focusing effect induced on the lower energetic particles, making them suitable for capturing the highly divergent particles of the LPA beams.

A. Simulation setup and proton beam parameters

A particular type of solenoid that we introduce here is a conical coil [27]. Conical coils are employed alongside plasma jets in advanced plasma physics experiments and engineering applications, exploiting their unique geometry to produce customized magnetic fields. These fields are crucial for guiding, confining, or stabilizing plasma jets. This capability is essential for directing charged particles along magnetic field lines in applications such as space plasma thrusters, materials research, high-energy plasma experiments, and fusion research [28–30]. The conical shape ensures a spatial variation in magnetic-field strength, allowing for the compression or expansion of the plasma jet. Similarly, conical coils can manipulate proton trajectories and energies by tapering the magnetic field, compressing the proton beam into a smaller cross section and enhancing beam density and focus, akin to the function of a lens focusing light.

We examined how various solenoid configurations affect the trajectory of a charged proton beam, with the intention of focusing it into a millimeter-scale spot. A proton source emitting from a spot with a $2 \mu\text{m}$ radius was considered. A spectrum with exponential decay, spanning an energy range of 4 to 20 MeV and a divergence of 21.25° , was analyzed based on experiments involving LPA protons [31]. The proton beam described here was generated with a discrete spectrum, having a 0.5 MeV energy step and an exponential distribution $N(E) = 1.4 \times 10^4 \cdot e^{-0.375E}$. Figure 1(a) illustrates the energy spectrum of the beam, while Fig. 1(b) displays simultaneously the energy and angular distribution of the protons, both at the source.

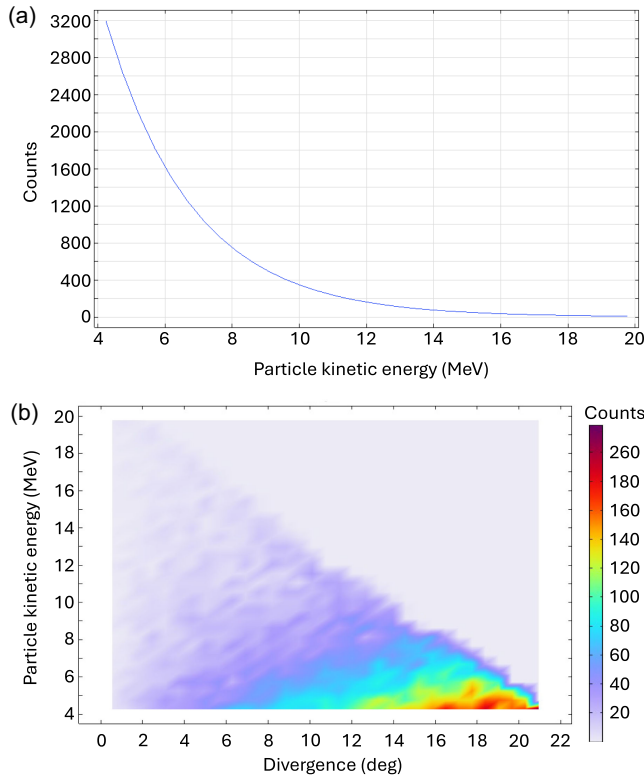


FIG. 1. Energy spectrum (a) and angular distribution (b) of the designed proton beam source used in the simulations and based on results given in [31].

The simulation was implemented using COMSOL Multiphysics [32], a powerful, multipurpose software platform specialized in creating models of the real world and predicting their behavior under various conditions by solving complex mathematical equations that describe physical phenomena. To evaluate the interaction between the laser-driven proton beam and the magnetic field generated by the solenoids, we used the capabilities of the multiphysics platform to simulate magnetic fields and to solve for the charged particle trajectories. The simulation was divided into two interconnected studies: a stationary study to calculate the spatial distribution of the magnetic field generated by the solenoids and a time-dependent study to track the trajectories of individual particles emitted by the source as they interact with the predetermined magnetic field.

We tested out the performance of multiple solenoid configurations by varying their geometric parameters such as the radius of the solenoid and wire, the axial and radial pitch, and the number of turns. The generated magnetic field is variable and controlled by the input value of the coil current. The change in the trajectory of the particles upon interaction with the magnetic field was examined in vacuum for a number of 1.8×10^4 individually simulated protons, with a one-to-one correspondence to the beam charge. The total number of simulated particles was

reduced by roughly 4–6 orders of magnitude compared with the actual beam statistics, due to the high computational demands associated with modeling the full beam.

In this study, we propose a high-current and high-voltage biased focusing system based on two copper solenoids. Although we consider steady magnetic fields of up to 10 T, challenging to achieve in practical experimental setups, we emphasize that our approach remains valid as long as the fields remain steady for durations longer than the beam's transit time through the coil system, which is on the order of a few nanoseconds. In such cases, pulsed coils capable of generating strong magnetic fields for these short durations have been successfully implemented and could potentially incorporate superconductors [33–37]; however, conical coils have not yet been proposed or employed. The cited studies report cylindrical solenoids operating with currents ranging from just under 1 kA up to 40 kA and achieving magnetic fields with peak values from 10 to 23 T. We also mention here that a different class of solenoids, mounted directly on the target support, has been experimentally tested and shown to effectively focus LPA-generated proton beams [38]. However, these solenoids are uniquely self-powered by the currents induced in the target support, which arise from charge imbalances caused by the ponderomotive expulsion of electrons during laser irradiation.

The first solenoid, positioned 1 mm downstream of the source, has a conical shape and consists of 70 turns, with an initial radius of 1.5 cm, a wire radius of 1 mm, an axial pitch of 2.5 mm, and a radial pitch of 0.4 mm. A current of 20 kA was applied to it, generating a peak magnetic field of 9 T. The second solenoid was designed with a cylindrical shape, 50 turns, an outer radius of 4 cm, a wire radius of 1 mm, an axial pitch of 2.5 mm, and had a 16 kA current applied to it, resulting in a peak magnetic field of 6 T.

The total lengths of the wires needed to construct the solenoids previously described are 12.67 and 12.56 m, respectively. The peak power consumption, calculated using Ohm's law, would be approximately 28 MW for the conical solenoid and 17.7 MW for the cylindrical one. While such high peak power levels are challenging in experimental setups, their impact can be reduced by using pulsed solenoids with tens of nanoseconds pulse durations. For such short pulses, the total energy dissipated as heat would be in the millijoule range, which would significantly reduce thermal stress, allowing for practical implementation. Figure 2 shows the spatial magnetic field distribution of the two-solenoid system in the vertical plane while the protons are launched along the z axis. Note the fringe field around both solenoids in Fig. 2.

B. Focusing of proton beam: Results

As mentioned previously, the focusing effect of a solenoid is energy-dependent, causing protons of different energies to be focused at distinct positions along the propagation axis. The first solenoid exerts a stronger

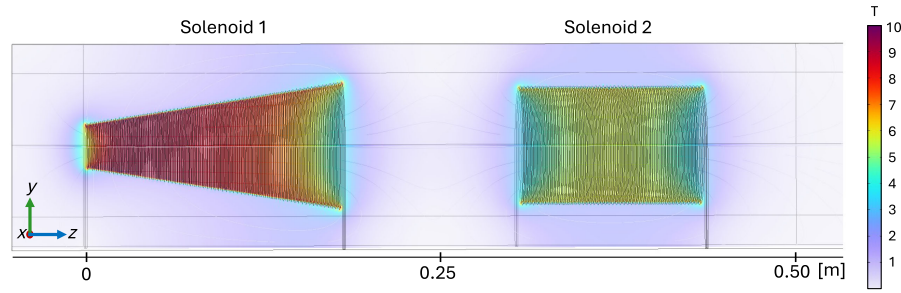


FIG. 2. 2D projection on the vertical plane yz of the mapped magnetic field generated by the two-solenoid focusing configuration for current values of 20 kA applied to the first solenoid and 16 kA to the second one. The source of protons is placed at $z = 0$.

influence on particles of lower energy, as indicated by Eq. (1). This effect, along with the magnetic forces induced by the second solenoid, effectively focuses the protons with energies of under 7 MeV before they can reach the exit of the focusing system. Protons with higher energies, being less affected by the magnetic field, are collimated as they pass through the first solenoid and are later focused by the second one. This distinct behavior is illustrated in Fig. 3 for 6 to 8 MeV protons, showing that lower-energy particles are focused within the second solenoid, while higher-energy protons are focused after fully passing through the magnetic elements.

To assess the focusing capabilities of the configuration, we examine the focal spot position beyond the solenoid system for individual proton energies ranging from 7 to 20 MeV. The resulting focal distances, measured from the source, span from 0.5 to 1.9 m. The radius of the focus spot, defined as the region enclosing over 86% of the total beam charge, was determined to range from 4 to 15 mm. The highest values for both position and size of the focus spot correspond to protons with energies between 16 and 20 MeV. To shorten the focal distance and reduce the size of the focus spot, we extended the spatial distribution of the magnetic field responsible for focusing the higher energetic particles. This was achieved through a modified configuration, based on a trade-off optimization principle,

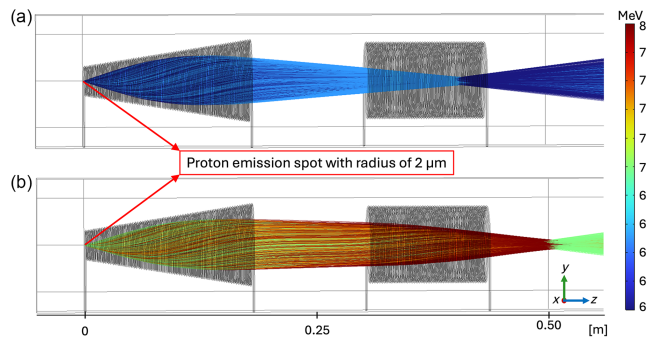


FIG. 3. 2D projection on yz plane of the proton trajectories after passing through the two-solenoid focusing configuration represented for energies of: (a) 6 and 6.5 MeV and (b) 7, 7.5, and 8 MeV.

in which 20 additional turns were added to the second solenoid, increasing the overall system length by 5 cm. Adding turns strengthens the focusing of higher-energy protons and shifts the focal plane closer to the target. However, it also causes lower-energy particles to focus prematurely, leading to strong divergence before reaching the intended interaction region. The configuration with 20 additional turns provided a good compromise between maximizing particle capture at the target and limiting the premature focusing of lower-energy particles.

The extra length of the configuration caused all the protons with energies under 8 MeV to be focused before exiting the second solenoid. Both configurations were tested, and their performances were compared. The analysis was performed on specific energy intervals for protons ranging from 8 to 20 MeV. Figures 4(a) and 4(b) illustrate a comparative analysis between the results obtained with the initial configuration, represented in blue, and the one with the additional 20 turns, illustrated with orange. The first plot shows the radius of the focus spot, along with the corresponding capturing efficiencies, while the second graph presents its position on the propagation axis with respect to five specific energy intervals. By looking at the two datasets from Fig. 4(a), we can notice an overall reduction in the focus spot size achieved with the solenoid having 20 extra turns. The shrinking in size of the focus spot is especially accentuated for the 16 to 20 MeV protons, where we have a downsize of 10.5 mm. Not only does the radius of the focus spot decrease when using the optimized configuration, but the number of particles captured within the analysis area increases across all energy intervals under 16 MeV, with percentages between 1% and 10%.

The position along the propagation axis where protons are focused was also affected by elongating the second solenoid, as illustrated in Fig. 4(b). The difference in performance between the two configurations becomes more pronounced with increasing proton energy. The plot demonstrates that the optimized configuration could focus the highest energy protons nearly 1 m closer to the source compared to the initial design. Figure 4(c) presents the focus positions as a function of particle energy and shows that both datasets follow polynomial laws described by the

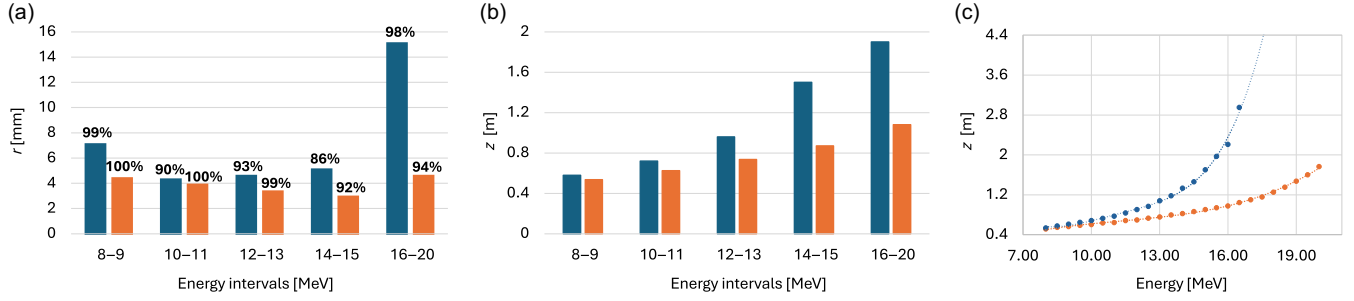


FIG. 4. Comparative analysis between the performance of the original two-solenoid system (shown in blue) and the optimized configuration (shown in orange), which includes an extension of the second coil by an additional 20 turns, across specific energy intervals: (a) radius of the focus spot, along with the percentage of particles contained in the analyzed area in the xy plane. (b) The position z of the focus point on the propagation axis. (c) Plot of focus spot positions z obtained with both initial (blue) and optimized (orange) systems, as a function of energy, fitted with polynomial laws.

fitting equations for the initial and optimized solenoid systems, respectively:

$$z_{\text{initial}} = 0.0015E^4 - 0.065E^3 + 1.073E^2 - 7.75E + z_1, \quad (2)$$

$$z_{\text{optimized}} = 0.0011E^3 - 0.036E^2 + 0.45E - z_2, \quad (3)$$

where $z_1 = 21.15$ m and $z_2 = 1.336$ m. The data points corresponding to higher energy particles (above 16.5 MeV) that were focused by the initial configuration are not shown in the current figure, as their focal points lie outside the defined interaction volume and, consequently, beyond the spatial boundaries relevant to our application.

The effect of the optimized configuration on the particles with energies of under 8 MeV varies significantly. Protons of 6 and 7 MeV are focused inside the second solenoid, resulting in highly divergent beams once exiting the setup. At the same time, protons having energies of 4 and 5 MeV experience different effects induced by the combined influence of the two solenoids. Lower-energy protons have enough time to be focused twice, as illustrated in Fig. 5(a). The first focus point is located at 22.5 cm along the propagation axis and has a radius of 1.7 mm, while the

second focus point is positioned at 56.5 cm having a 4.5 mm radius. The trajectories of the 5 MeV protons are represented in Fig. 5(b), showing a focus point, of 2.1 mm radius positioned in close proximity to the entrance of the second solenoid, at 28.7 cm on the z axis. As the particles travel through the second solenoid, the beam is transformed into a quasiparallel one, reaching a radius of 16.5 mm at approximately 22 cm from the exit of the configuration.

Previous studies on laser-driven ion beam focusing using a pulsed power solenoid [39] have reported similar results, including the focusing of 7 MeV protons and the collimation of 14 MeV protons using peak magnetic fields of 8.5 T. Further research on a more advanced focusing and transport line has been reported [40,41], demonstrating the selection and collimation of 7.8 and 9.6 MeV protons using a pulsed high-field solenoid in combination with an rf cavity and quadrupole magnets for beam bunching, transport, and characterization. While these single solenoid approaches have proven effective, the dual solenoid configuration investigated in this work offers additional advantages, such as improved focusing control and the ability to tailor the magnetic field gradient for enhanced beam confinement across a broader energy range.

Beam modulation analysis also requires an evaluation of the transverse emittance, which describes beam quality in terms of spatial and angular spread. Protons are emitted from various points in the source, having different energies and orientations of the velocity vector. The transverse emittance is defined as the area of the smallest ellipse that encloses the particle distribution in phase space. In this study, the emission was statistically calculated using the root mean square method (rms), expressed by the equation:

$$\epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}, \quad (4)$$

where $\langle x^2 \rangle$ is the mean square deviation of the transverse positions, $\langle x'^2 \rangle$ is the mean squared deviation of the transverse angles, and $\langle xx' \rangle^2$ is the covariance between

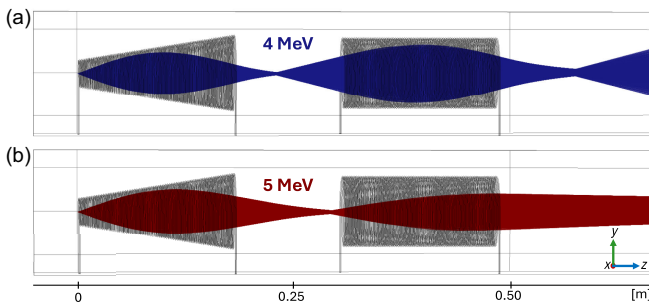


FIG. 5. 2D projection on yz plane of the proton trajectories after passing through the optimized two-solenoid focusing configuration, represented for proton energies of (a) 4 MeV and (b) 5 MeV.

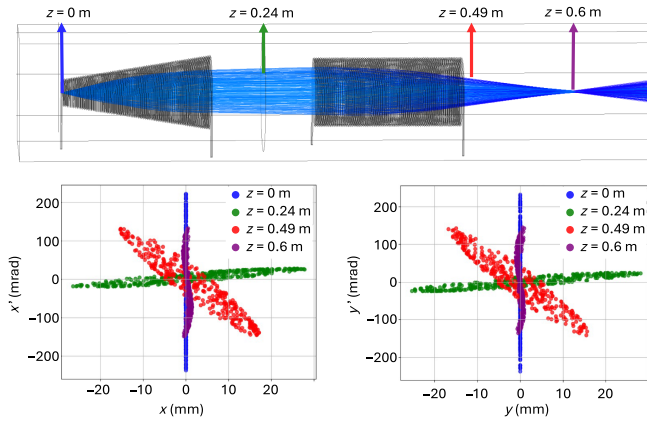


FIG. 6. Phase space monitoring of a 10 MeV simulated proton beam at four positions along the propagation axis: at the source (blue), in between the two solenoids (green), at the exit of the second solenoid (red), and at the focus point (purple).

the transverse positions and angles. Figure 6 illustrates the phase-space evolution of 10 MeV protons as they are focused using the optimized two-solenoid configuration. The proton beam was analyzed at four key longitudinal positions: at the source (blue), at the midpoint between the solenoids (green), at the end of the configuration (red), and at the focus point (purple). Initially, the 10 MeV protons are emitted from a $2\text{ }\mu\text{m}$ radius source having a divergence angle of 13° . As they pass through the first solenoid, the magnetic field transforms the beam into a quasiparallel one, inducing a considerable increase in its size along with a significant reduction in divergence (green dots). As the protons are moving forward through the second solenoid, the beam starts converging, as represented by the red dots. At 60 cm from the source, the protons are focused into a less than 4 mm radius spot. The phase-space distribution at the focal point, shown by the purple dots in Fig. 6, exhibits an S-shaped distortion that can be attributed to spherical aberrations, as protons farther from the solenoid axis experience a stronger focusing effect than those closer to the center [42,43]. The values obtained for the emittance at the focus point for both horizontal and vertical evaluations are $\epsilon_x = 32.79\text{ mm mrad}$ and $\epsilon_y = 29.85\text{ mm mrad}$, respectively, not exceeding the maximum emittance of $30\pi\text{ mm mrad}$ encountered through the beamline at usual cyclotron-based proton beam facilities [44,45].

III. APPLICATION TO SAMPLE IRRADIATION

The simulation was expanded to include a dose monitoring study by evaluating the influence of a 16 to 20 MeV LPA proton beam upon a predefined target volume. For this purpose, a 4 mm long and 5 mm diameter cylinder was defined, resembling a superficial tumor [6]. The cylinder's composition was set to water, as it closely replicates the interaction of ionizing radiation with soft tissues, including energy absorption and scattering properties. The sample

was positioned at 1.08 m from the source, corresponding to the focus point of protons within the energy range of interest in the optimized two-solenoid configuration, as illustrated in Fig. 4(b).

To better evaluate the effects of exposing the target volume to a more realistic particle flux, we increased the number of particles emitted in the energy range of 16 to 20 MeV from less than 300 as in the initial simulations to 1.18×10^6 . Due to the high computational demands associated with the real-time dose monitoring, the total number of particles simulated had to be limited to a value significantly lower than that of a real LPA proton spectrum, which would typically be at least 3 orders of magnitude higher, for the considered energy range. For the same reasons, particles with energies outside the selected range were excluded from the computations. In this way, we simulate the irradiation of a superficial tumor, using a focused laser plasma-accelerated proton beam with energies between 16 and 20 MeV, considering approximately 1.18×10^6 individually generated protons.

The study monitoring particle trajectories and their interactions with matter was carried out over a time frame of up to $2 \times 10^{-8}\text{ s}$, using a time step of $3 \times 10^{-11}\text{ s}$. The parameters were carefully selected to ensure that all protons reached the sample and deposited energy within it. Figure 7(a) compares the number of protons initially generated (represented in blue) with the number of particles that interacted with the sample (shown in orange), as a function of energy, while Fig. 7(b) presents the fraction of total protons that contributed to the irradiation of the sample for the selected range of energies. Protons with energies of 16.5 and 17 MeV exhibit a utilization rate of 100%, while higher energy particles show reduced utilization rates, ranging from 25% to 32%. Overall, up to 63% of the generated spectrum contributes to the irradiation of the sample, whose 5 mm diameter is smaller than the beam's transverse size at the same z position. The remaining 37% of protons have trajectories that do not intersect the target and could contribute to unwanted dose accumulations outside the intended treatment area.

Figure 8 illustrates the percentage of particles captured by circular apertures of various diameters placed at the sample position. As shown in the figure, an aperture matching the sample size would capture over 60% of the beam, while the entire beam could be enclosed within a 13-mm diameter aperture. Therefore, in practical implementations, the use of a physical aperture would be essential to reduce irradiation of surrounding healthy tissue and ensure spatial confinement of the beam.

To analyze the energy distribution within the sample, the interaction volume was divided into eight identical layers, each of 0.5 mm thickness. The energy deposition inferred for each layer is illustrated in Fig. 9(a), while Fig. 9(b) shows the relative dose depth distribution for each energy.

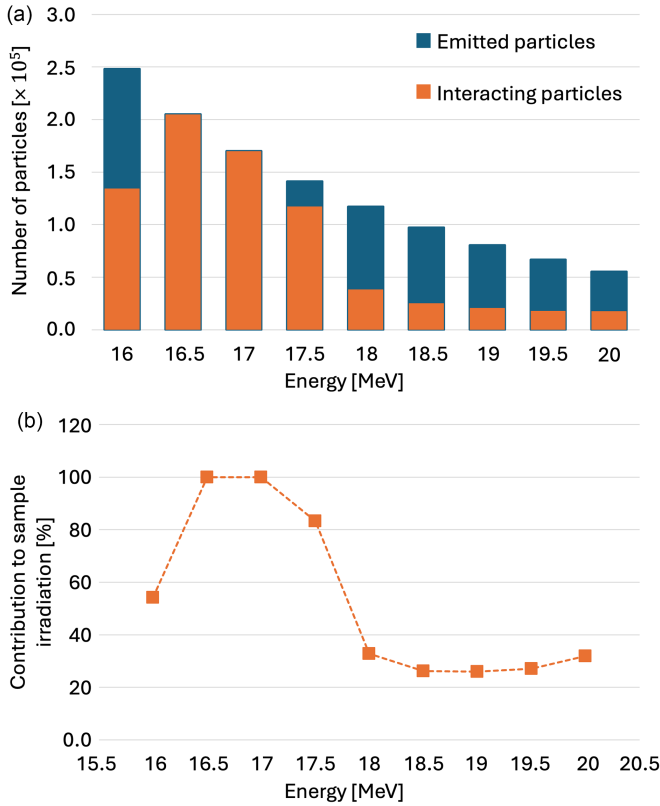


FIG. 7. (a) Comparative analysis between the number of protons initially emitted at the source (blue bars) and the number of protons that reached the cylindrical target volume (orange bars). (b) Percentage of protons contributing to sample irradiation.

The stopping power of the proton beam was provided by the SRIM code [46] while the Bragg-Kleeman rule [47] has been employed to approximate the curve with the following fit parameters:

$$-\frac{dE}{dx} = 28.16 E^{-0.78}, \quad (5)$$

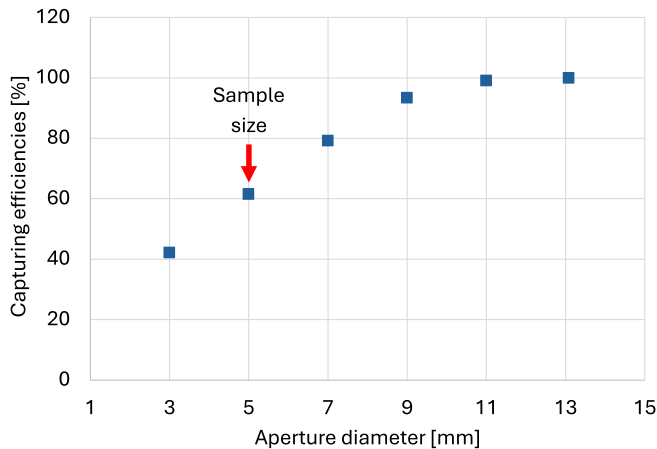


FIG. 8. Particle capture efficiency for various aperture diameters placed at the focal plane ($z = 1.08$ m).

where dE/dx has units of MeV cm^{-1} and E is given in MeV. A peak in the density of the deposited energy is observed in the sixth layer, located at a depth of 2.5 to 3 mm inside the sample. The peak is caused by the absorption of lower-energy protons, 16 and 16.5 MeV as indicated by the Bragg curves illustrated in Fig. 9(b). These lower energy protons are also more abundant and exhibit high utilization rates, as shown in Fig. 7(b), leading to higher energy deposition.

In contrast, the eighth layer, occupying the final 0.5 mm of the sample, shows a significant reduction in the density of the absorbed energy. This layer is primarily reached by protons with energies higher than 18 MeV, as shown in Fig. 9(b), which are emitted in a smaller number and have lower utilization rates, resulting in reduced energy deposition. Additionally, the sample length is insufficient to allow the 20 MeV protons to undergo enough interactions

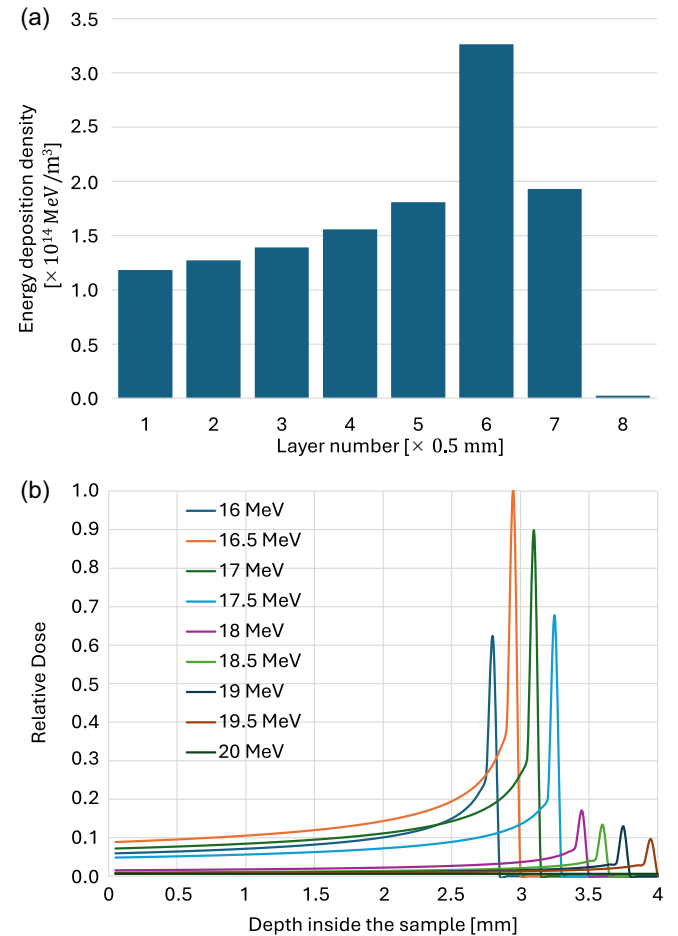


FIG. 9. (a) Absorbed energy density within the sample monitored across eight layers along the z axis, each with a thickness of 0.5 mm. (b) Relative dose depth distribution for individual energies in the 16–20 MeV energy range showing the corresponding Bragg peak curves, except for the one at 20 MeV, which falls beyond the 4 mm long sample.

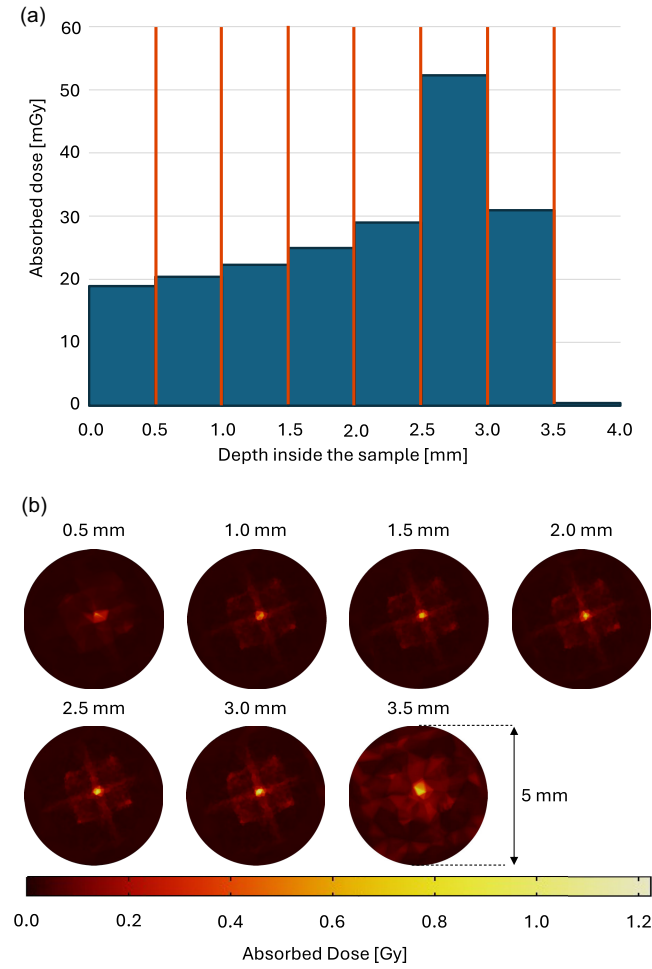


FIG. 10. (a) Dose-depth profiles over eight half-millimeter layers inside the sample. (b) Spatial distribution of the absorbed dose in the transverse plane at different depths z inside the cylindrical target volume.

to reach the characteristic sharp peak of total energy deposition seen in a typical Bragg curve.

Based on the number of particles that interacted with the object, a separate calculation of the absorbed dose in each of the previously defined layers was performed by dividing the total energy deposited in each layer by the corresponding mass. The resulting values are illustrated in Fig. 10(a), where the horizontal axis represents the depth inside the sample in the longitudinal direction. Due to the lower statistics considered in this study, the recorded dose deposition is on the milligray (mGy) scale. Among the analyzed regions, the sixth and eighth layers exhibit the highest and lowest values of the absorbed dose, respectively. Across the remaining regions of the sample, the dose varies within a 12 mGy range, with values spanning from 19 to 31 mGy.

Achieving a uniform dose distribution across the 1–4 mm depth of the water target requires exploiting a broader segment of the laser-driven proton spectrum than

the relatively narrow 16–20 MeV interval shown in Fig. 7. A spread-out Bragg peak can be generated, in principle, by superimposing Bragg peaks from protons in the 8–20 MeV energy range, with carefully optimized spectral weightings, to produce a more homogeneous longitudinal dose profile within the sample. However, implementing this solely by adjusting the currents in the solenoid magnets is highly challenging due to the intrinsically exponential decay of the laser-driven proton-energy spectrum. Directly focusing lower-energy components into the target substantially modifies the system’s focusing properties, perturbing both the range and number density of higher-energy protons.

For example, extending the incident proton-energy range to 10–20 MeV increases the dose in the first five layers of the target by approximately 28%–40%, while the dose in the deeper layers remains nearly unchanged relative to the initial coil-current settings. For the same proton-energy interval, reducing the current in the second solenoid from 16 to 14 kA (while leaving the first solenoid unchanged) results in a two to threefold increase in dose within the first five layers, while the dose in the subsequent three layers exhibits a pronounced decrease.

Further reducing the current in the second solenoid to 12 kA results in a pronounced redistribution of the dose, with the values in the first four layers increasing by approximately 1.5–2 times relative to the previous configuration. In contrast, the dose in the deeper layers decreases by nearly an order of magnitude, indicating a strong forward shift of the energy deposition region. Lowering the currents in both solenoids—specifically to 18 kA in the first and 14 kA in the second—results in a decrease by roughly 40%–55% of the dose in the first three layers compared to the previous setup, though it remains about 2 to 3 times higher than the dose obtained with the initial coil-current settings. The dose in the fourth layer remains nearly unchanged compared to the previous configuration, while a pronounced increase, by more than an order of magnitude, occurs in the fifth layer, indicating a partial shift of the energy deposition region toward greater depths. The dose in the last three layers remains low, with only minor variations. It is noteworthy that in all these modified configurations, the dose in layer 8 remains low, likely due to the fixed 20 MeV cutoff energy of the incident proton spectrum.

A more effective approach to mitigating these nonuniformities is to employ multiple consecutive irradiation shots, each with solenoid currents specifically tuned to optimize transmission for distinct energy intervals. The cumulative effect of such successive irradiation sessions could yield a uniform longitudinal dose distribution throughout the full 4 mm thickness of the water target.

Figure 10(b) shows the spatial distribution of the absorbed dose in the transverse plane at selected positions z within the sample, corresponding to the vertical regions highlighted in Fig. 10(a). In this case, however, the dose is

computed in much thinner layers, just 0.1 mm thick, to match the size and resolution of the mesh grid used in the domain partitioning of the simulation. Note the highly localized dose in the thinner layers of the simulation, compared to the averaged values computed in the thicker transverse layers shown in Fig. 10(a).

The proton beam footprint within the sample layers can be identified through its absorption profile, represented by the color scale. In the 2D dose distribution maps, energy-dependent distinctive patterns are also noticeable. At the low end of the energy spectrum, i.e., 16 to 17.5 MeV, the beam exhibits more complex shapes resembling stars or diamonds, whereas at higher energies it becomes progressively more circular and symmetric. Although the beam profile extends beyond the sample diameter, most of the absorbed dose is confined to a much smaller cross-sectional area. This localized concentration and patterned appearance result from a combination of the simulation mesh, the statistical distribution of the proton spectrum, and the energy-dependent variation in spot size, indicating a pronounced local nonuniformity in the dose distribution.

Previous studies on the experimental implementation of a focusing system based on two identical pulsed solenoids have proposed the use of a micrometer-thick scattering foil in the beam line to improve the homogeneity of the lateral dose distribution within a water sample [48]. This approach could represent a promising solution for the system investigated in this work, and its performance will be the subject of future analysis.

The total absorbed dose within the entire target volume was determined to be 2.54×10^{-2} Gy. Although this dose is lower than the standard therapeutic dose, typically well above 1 Gy in clinical cancer treatments, it was delivered using a lower number of protons. Considering a linear increase in the dose with the number of particles, we can reach the 1 Gy threshold per single shot and even surpass it, given that 10^9 particles are delivered within this energy range. The dose rate was calculated by dividing the absorbed dose, obtained from the simulation, by the duration of the proton beam pulse, which was defined as the time interval between the entry of 20 MeV protons into the cylindrical target and the exit of 16 MeV protons from it. From this calculation, the resulting dose rate was found to be 1.2×10^7 Gy/s, thus confirming the accessibility to the FLASH regime, characterized by ultrahigh dose rates (> 40 Gy/s) that have the potential to enhance therapeutic effectiveness while minimizing damage to healthy tissues.

The scalability of our two-coil conical focusing system to proton energies approaching 200 MeV, typically required for clinical radiotherapy and roughly an order of magnitude above the energies considered in this work, represents a key direction for future research. At present, TNSA-based laser-plasma accelerators are constrained by both laser intensity and target design and thus cannot yet deliver proton energies in the 200 MeV range. Alternative

acceleration mechanisms, such as radiation pressure acceleration (RPA) or hybrid TNSA–RPA schemes, hold the potential to achieve these higher energies at multi-petawatt laser facilities such as ELI-NP [49,50].

However, proton beams produced by these acceleration mechanisms differ fundamentally from TNSA beams: they exhibit quasi-monoenergetic energy spectra and significantly reduced angular divergence [51]. As a result, scaling the current two-coil system to focus such beams would require not only higher magnetic fields but also a reoptimization of coil geometries, spacing, and current profiles to match the modified beam phase-space properties. The reduced divergence, in particular, could ease some of the stringent focusing requirements.

IV. CONCLUSIONS

This paper presents a 3D simulation-based study investigating the focusing effects of high-current solenoid-generated magnetic fields on LPA proton beams. The study investigates the feasibility of employing compact magnetic systems to manage a laser-driven proton beam by taking into account its energy spread, from 4 to 20 MeV, and its divergence of up to 21° , for clinical applications in proton beam therapy. Two dual-solenoid configurations were simulated and analyzed, both consisting of a conical coil, oriented with its narrow opening facing the LPA proton beam, followed by a cylindrical coil. The solenoids generate peak axial magnetic fields of 9 and 6 T, respectively. The two-solenoid system was compared in terms of focused beam size and position, as well as capturing efficiency. The optimal setup captured 94% of the protons with energies of over 16 MeV into a focus spot of 9 mm diameter, located at 1 m from the source. In addition, the dose deposited within a predefined cylindrical volume, designed to resemble a superficial tumor, was evaluated to demonstrate the accessibility to the FLASH therapy regime. The sample was exposed to the 16–20 MeV focused proton beam and received a 25 mGy dose with a rate of 1.2×10^7 Gy/s, potentially reaching the FLASH therapy regime.

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DATA AVAILABILITY

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

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