Proton acceleration via the TNSA mechanism using a smoothed laser focus

Cite as: AIP Advances 10, 035023 (2020); https://doi.org/10.1063/1.5117236
Submitted: 22 January 2020 . Accepted: 25 February 2020 . Published Online: 19 March 2020

M. Afshari , J. Hornung , A. Kleinschmidt, P. Neumayer, D. Bertini , and V. Bagnoud

AVS Quantum Science

Co-Published by

RECEIVE THE LATEST UPDATES

© 2020 Author(s).
Proton acceleration via the TNSA mechanism using a smoothed laser focus

Cite as: AIP Advances 10, 035023 (2020); doi: 10.1063/1.5117236
Submitted: 22 January 2020 • Accepted: 25 February 2020 • Published Online: 19 March 2020

M. Afshari,1,a) J. Hornung,1,2,3 A. Kleinschmidt,1,2 P. Neumayer,1 D. Bertini,1 and V. Bagnoud1,2

AFFILIATIONS
1 GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany
2 Helmholtz Institute Jena, Fröbelstieg 3, 07743 Jena, Germany
3 Friedrich Schiller University Jena, Fürstengraben 1, 07743 Jena, Germany

a) Author to whom correspondence should be addressed: m.afshari@gsi.de

ABSTRACT

In this work, we present the results of an experiment aiming at proton acceleration using a focus with a homogeneous intensity distribution, called smoothed focus. To achieve this goal, we implemented a phase plate before the pre-amplifier of the Petawatt High-Energy Laser for Heavy Ion EXperiments laser facility. The phase plate was used for the first time at a high-power short-pulse laser. Demonstrating a low divergent ion beam was the main goal of this work. Numerical simulations using the particle-in-cell code Extendable PIC Open Collaboration estimated a 2–5 times reduction in the angular divergence of the proton beam using a phase plate due to a smoother sheath at the rear side of the target. However, the reduction in the angular divergence was not sensible according to the experimental data. A positive point is that the spectrum of protons that are generated with the smoothed beam is shifted toward lower energies, provided that the laser absorption is kept in check, compared to the Gaussian proton spectrum. Moreover, the number of protons that are generated with the smoothed beam is higher than the ones generated with the Gaussian beam.

© 2020 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5117236

I. INTRODUCTION

Laser-driven ion acceleration1,2 attracts much attention due to its diverse applications, such as fast ignition,3 injection into conventional accelerator structures,4 isochoric heating of samples to warm-dense-matter states,5 and hadron therapy for cancer treatment.6 A key feature for some of these applications is a mono-energetic and collimated ion beam for efficient energy transfer.

The most extensively studied mechanism for the laser-driven ion acceleration is Target Normal Sheath Acceleration (TNSA).2,7 According to the TNSA model, the interaction of an ultra-intense short-pulse laser with a target ionizes the target and consequently generates energetic electrons at the front side of the target, which propagate through it and accumulate at its rear side. The excess of charges at the rear side of the target creates a strong quasi-static electric field, which accelerates ions up to several MeV in the direction normal to the target. The spatial extension of the electron sheath at the backside of the target strongly depends on the laser intensity profile at the target front side and electron dynamics on the backside. Accordingly, a transversal Gaussian electron distribution in the range of 30–100 μm is typically observed in TNSA with strong spatial density gradients.8

Though the ion beam shows a very low emittance, its angular divergence typically reaches 20°–60°, which imposes severe restrictions on the particle transport and subsequent applications. For instance, for experiments using an ion beam for warm-dense-matter studies, the secondary target must be located within 100’s of micrometers from the proton source to keep a desirable ion flux. This closely located primary ion source generates a high background (x rays and electrons) that strongly alters the precision of the measurements.

Initial studies have shown that using a larger intensity distribution at the laser focus can positively influence the proton divergence. This can be achieved, for instance, when a very long focal length focusing element is used, but it is not experimentally feasible in many facilities due to the spatial restrictions. Using a phase plate is another possibility that does not require much space. In this context, we explore the use of a phase plate at laser intensities beyond
I = 10^{18} \text{W/cm}^2 to produce a homogeneous intensity distribution at the focus, which creates a speckle-like intensity distribution over an area 1600 times the diffraction limit. Following this approach, we investigate the proton acceleration in the TNSA regime with a smoothed focus, which can generate a uniform sheath at the rear side of the target and, probably, accelerate a more collimated ion beam.

II. NUMERICAL SIMULATIONS

We ran several simulations to check the applicability of using a phase plate for generating a smoothed laser beam with subsequent lower divergent proton beam production. For this purpose, we used the particle-in-cell (PIC) code Extendable PIC Open Collaboration (EPOCH). Simulations have been done in two dimensions and ran on the Green IT cube of the GSI Helmholtz center using the KRONOS cluster with 1024 cores per simulation.

The simulation box for the Gaussian laser intensity \( I = 10^{19} \text{W/cm}^2 \) has the dimensions \((-10, 120) \text{ mm}\) and \((-60, 60) \text{ mm}\) in the \( x \) and \( y \) directions, respectively. For intensity \( I = 10^{20} \text{W/cm}^2 \), the dimensions in \( y \) are the same but the dimensions in \( x \) are \((-10, 190) \text{ mm}\). The simulation box for the smoothed laser focus, \( I = 10^{19} \text{W/cm}^2 \), has the dimensions \((-10, 80) \text{ mm}\) and \((-150, 150) \text{ mm}\) in the \( x \) and \( y \) directions, respectively. The left boundary radiates the laser beam, while the right and lateral boundaries (up and down) allow the particles to be removed from the simulation when they reach the boundaries.

The resolution in the \( x \) and \( y \) directions was 10 nm, and the number of particles per cell was 260. We ran several simulations with no laser for 2 ps to check the level of the numerical heating. All simulations show a very low numerical heating, which causes proton energies in the range of 0.2–0.5 MeV.

To follow the experimental conditions, we used two types of plastic targets in the simulations: polystyrene (C_9H_8)_n, commonly known as CH, with density \( n_{\text{CH}} = 1 \text{ g/cm}^3 \), and polyethylene (C_2H_4)_n, denoted as CH_2, with density \( n_{\text{CH}_2} = 0.9 \text{ g/cm}^3 \). Due to the technical limitations for manufacturing the targets, we used CH plastics for thin targets, with 1 \( \mu \text{m} \) thickness, and CH_2 plastic for thick targets beyond 1 \( \mu \text{m} \). Three species were used in the simulations: electrons, protons, and carbon ions. The initial temperature of the electrons was assumed to be 100 eV. Since the PIC simulations with the lower target densities may result in unrealistically higher proton energies, we considered only the real solid densities. In our simulations, the electron and proton densities were \(2.3 \times 10^{23} \text{ cm}^{-3}\) and \(4.6 \times 10^{22} \text{ cm}^{-3}\), respectively. The ionization of the carbon ions was supposed to be 4 to account for the preheating of the target due to the rising edge of the laser pulse. An exponential density profile with a density scale length of 3 \( \mu \text{m} \) in front of the target has been considered to include the preplasma effect. No collisions have been included in the simulations since their effects are negligible.

In all simulations, the laser beam propagated normal to the target, in the positive \( x \) direction, and had a wavelength of 1.053 \( \mu \text{m} \). The laser pulse with a duration of \( \Delta t_{\text{short}} = 500 \text{ fs} \) started at time \( t = 0 \) and terminated at \( t = 1000 \text{ fs} \). The beam entered the simulation box from the left side at position \( x = -10 \mu \text{m} \) and the peak intensity reached the target surface, at location \( x = 0 \), after \( t = 530 \text{ fs} \). Depending on the simulation, the peak laser intensity varied in the range of \(I = 10^{19}–10^{20} \text{W/cm}^2\). The waist of the Gaussian beam was \( \omega = 5 \mu \text{m} \), and the polarization of the laser pulse was in the \( y \) direction.

A. Gaussian beam profile

As many experiments have been done with Gaussian beams in the past and reliable experimental data are available, we benchmark our simulation results with Gaussian beams.

Figure 1 shows the amplitude of the total quasi-static electric field \( E = \sqrt{E_x^2 + E_y^2} \) generated at the rear side of a target due to the interaction of a Gaussian beam, \( I = 10^{20} \text{W/cm}^2 \), with a 10 \( \mu \text{m} \) CH target at solid density. The sheath with maximum strength in the range of teravolt per meter \( (10^{12} \text{ V/m}) \) is reached 200–300 fs after the arrival of the peak intensity and annihilates after 2 ps.

Following the Mora model, the classical kinetic energy of protons follows the temporal evolution of the proton velocity,

\[
v = 2c_i \ln[(\tau - \tau_0) + \sqrt{(\tau - \tau_0)^2 + 1}],
\]

where \(\tau_0\) is an offset and \(\tau = \omega_p t/\sqrt{2c}\) is a dimensionless parameter, where \( t \) is the time and \( \omega_p \) is the plasma frequency, which is \( \omega_p = 6.6 \times 10^{14} \text{ rad s}^{-1} \). \( c_i \) is the ion-acoustic velocity,

\[
c_i = \sqrt{\frac{k_BT_e}{m_p}},
\]

where \( m_p \) is the proton mass, \( k_B \) is the Boltzmann constant, and \( T_e \) is the electron temperature.

The evolution of the kinetic energy of the accelerated protons as a function of time is shown in Fig. 2. As the evolution of the kinetic energy of the protons is more understandable vs time (than \( \tau \)), we plotted the time in the horizontal direction of Fig. 2. It can be seen that after 2 ps, the protons are reaching their maximum energy.

Knowing the kinetic energy of the protons, given by the PIC simulations, we can calculate the proton velocity, \( v \) at Eq. (1). By plotting the proton velocity vs \( \tau \) and fitting the data with Eq. (1), we can estimate \( c_i \) at Eq. (1). Substituting \( c_i \) in Eq. (2) gives the electron temperature, \( T_e \). Following all the steps, the Mora model for the...
Figure 2 shows the corresponding angular divergence of the accelerated protons, above ≥1 MeV, for that simulation at time t = 2000 fs.

Considering all simulations with the same laser intensity and the target thickness, the cutoff energy of the protons is $E_{\text{max}} = 41.9$ MeV at time $t = 2500$ fs and their angular divergence is $\Delta \theta = (-9^\circ, 9^\circ)$. The results of the new simulation with the longer temporal window are in agreement with the previous simulation results considering the error bars. Moreover, $E_{\text{max}}$, estimated with the EPOCH code, follows the experimental data. Anomalous double peaks can be seen in the angular divergence of the protons. While a full description of this physical effect, which is also observed in some experiments and our simulations confirm, is the subject of another work, we briefly mention that it is due to the deflection of the accelerated protons due to the electric and magnetic fields.

B. Smoothed beam

The novel idea of this scheme is the generation of a uniform electron sheath. The sheath is created by a speckle-like laser intensity distribution with the dimensions large enough to neglect the effects of the electrons moving away from the laser focus. Hence, we need a beam of several tens of micrometers in diameter. In addition, the speckle grains must remain small, compared to the target thickness, to initiate the local electron-density smoothing effect, resulting from the electron emission cone and their propagation in the target.

To simulate the effect of a phase plate, a periodic laser intensity distribution is focused onto a target front surface at position $x = 0$ and propagated along the positive x direction. It follows a cosine function with a period of 10 μm over a spot of 120 μm (12 periods) to account for the speckle-like structure created by the phase plate,

$$E(y) \propto \cos\left(\frac{2\pi y}{T}\right), \quad T = 10 \mu m. \quad (3)$$

To reach the desired intensity distribution at position $x = 0$, we back-propagated the electric field to the left of the simulation box using a standard Fresnel diffraction calculation to generate the input field in phase and amplitude. We then fed these data as a binary file into the EPOCH code and verified that the intensity at $x = 0$ follows Eq. (3) when no target is used.

Figure 4 shows the total electric field at the rear side of a target due to the interaction of a smoothed beam, $I = 10^{20}$ W/cm², with a 10 μm CH target.

The interaction of a smoothed beam with a CH target yields a reduced electrostatic field strength due to the lower laser intensity, but the resulting electric field distribution is more favorable as it creates a uniform sheath, which is mostly 1D and accelerates protons in the x direction. For the Gaussian beams, the sheath exhibits a strong component in the transversal direction, Fig. 1.

Figure 5 shows the angular divergence of the accelerated protons for the smoothed beam simulation at $t = 2000$ fs.

While the reduction of the sheath strength causes a lower proton cutoff energy, $E_{\text{max}} \approx 17 \pm 0.4$ MeV, the most important point is that the angular divergence of protons, $\Delta \theta = (-1^\circ, 1^\circ) \pm 0.5^\circ$, is much

Figure 3 shows the angular divergence of the accelerated protons due to the interaction of a smoothed beam, $I = 10^{20}$ W/cm², with a 10 μm CH target.
more peaked around the normal direction compared to the Gaussian beam results shown in Fig. 3. Following the simulation results, the reason for such a peaked proton distribution could be that the sheath of the smoothed beam is mostly one dimensional, unlike the Gaussian one, which causes a lower angular divergence. For the Gaussian beam, Fig. 1, we can see that the sheath is developing in 2D, which causes a higher angular divergence. Hence, the simulation results show the advantage of using a phase plate for proton acceleration.

Though the Mora model should be used for the Gaussian beam analysis, for a direct comparison, we repeat the analysis for the smoothed beam. The analysis shows \( \tau_0 = 200 \) and \( c_s \approx 4351.6 \text{ km/s} \), which correspond to an electron temperature of \( T_e \approx 201.2 \text{ keV} \).

## C. Parametric studies

In this section, we investigate the effects of the target thickness, \( L_{tar} \), and the laser intensity on the cutoff energy and the angular divergence of protons.

### 1. Target thickness effect

One of the central points when using a phase plate is that one relies on a smoothing effect of the single speckle points through the electron motion within the target. For this reason, the influence of the target thickness on the proton beam should be studied. Therefore, we have simulated the laser interaction with targets of thicknesses 1 \( \mu \text{m} \), 4 \( \mu \text{m} \), and 10 \( \mu \text{m} \).

Table 1 shows \( E_{\text{max}} \) and the angular divergence of the protons for the Gaussian and smoothed beams at laser intensity \( I = 10^{19} \text{ W/cm}^2 \). Targets with 4–10 \( \mu \text{m} \) thicknesses are made of CH2, while for 1 \( \mu \text{m} \) targets, we considered CH to match the experimental conditions.

Our numerical results for the Gaussian beam with intensity \( I = 10^{19} \text{ W/cm}^2 \) at solid intensity are similar to the previous numerical estimations. The simulations show an increase in the maximum proton energy when the target thickness is decreased as should be expected. This happens, however, at the cost of a larger divergence angle. The reason for the increase of proton \( E_{\text{max}} \) could be that the energetic electrons, which are created at the front side of the target, can reach the rear side sooner and also they can recirculate more. Both reasons strengthen the sheath at the rear side of the target and generate more energetic protons.

### 2. Laser intensity effect

Scaling the results with the laser intensity is important to get an impression of the performance with different parameters that can be achieved with the high-energy lasers. As the sheath strength directly depends on the laser intensity, we ran several simulations to investigate the effect of different laser intensities on the maximum proton energy and divergence. We have to mention, since in all simulations, for both the smoothed and Gaussian focuses, the laser pulse duration and the focal spot are kept fixed, the intensity is scaled with the energy.

| \( L_{tar} (\mu\text{m}) \) | \( E_{\text{max}} \) (MeV) | \( \Delta \theta \) (deg) |
|---|---|---|
| 10 | 7.6 | (−3, 3) |
| 4 | 9.7 | (−4, 4) |
| 1 | 14.8 | (−8, 7) |
| 10 | 17.4 | (−1, 1) |
| 4 | 20.2 | (−2, 2) |
| 1 | 26.6 | (−2, 2) |
TABLE II. \(E_{\text{max}}\) and \(\Delta \theta\) of protons due to the interaction of a Gaussian (a) and a smoothed (b) beam with intensities in the range of \(I = 10^{19} - 10^{20}\) W/cm\(^2\) with 10 \(\mu\)m CH targets. \(I_{19}\) represents the laser intensity \(I = 10^{19}\) W/cm\(^2\).

| \(I_{19}\) | \(E_{\text{max}}\) (MeV) | \(\Delta \theta\) (deg) |
|-------|-----------------|--------------------|
| (a) Gaussian beam | | |
| 1 | 7.6 | (−3, 3) |
| 5 | 24.5 | (−7, 6.5) |
| 10 | 39.5 | (−8, 8) |
| (b) Smoothed beam | | |
| 0.3 | 7 | (−1.5, 1.5) |
| 1 | 17.4 | (−1, 1) |

Table II presents \(E_{\text{max}}\) and \(\Delta \theta\) of protons for simulations with the Gaussian and smoothed beams with intensities in the range of \(I = 10^{19} - 10^{20}\) W/cm\(^2\), with 10 \(\mu\)m CH targets.

As expected, by increasing the laser intensity, \(E_{\text{max}}\) and \(\Delta \theta\) of protons are increased. The experimental results \(^1\) for \(I = 10^{19}\) W/cm\(^2\) show \(E_{\text{max}} \approx 5-20\) MeV and \(\Delta \theta \approx 20^\circ - 60^\circ\).\(^{11,13}\) While our estimated proton energies stand in this range, \(\Delta \theta\) is still far from the reality. A reason could be that the angular divergence is a 3D effect, while our simulations are in 2D.

Moreover, while for the higher Gaussian beam intensities, the increase of the divergence is much more, such a trend cannot be seen for the smoothed beams, since as shown in Fig. 4, protons are accelerated mostly in the \(x\) direction.

By looking at Table II, one can see an increased proton energy for the smoothed focus compared to the Gaussian focus for laser intensity \(I = 10^{19}\) W/cm\(^2\). Since the intensity and the pulse duration are kept constant in all simulations, the pulse energy for the smoothed focus increased by a factor of 8 to maintain the same intensity. This leads to increased proton energy.

As there is no experimental evidence in the literature for \(E_{\text{max}}\) and \(\Delta \theta\) of protons using a phase plate and since PIC codes cannot estimate correctly the angular divergence of the accelerated protons, we can only scale the simulation results to see any difference between the Gaussian and smoothed beams. Overall, scaling all parametric studies shows a reduction about 2–5 times in the angular divergence of protons using a smoothed beam, which is in favor of the phase plate scheme.

III. EXPERIMENT

We conducted an experiment at the Petawatt High-Energy Laser for Heavy Ion EXperiments (PHELIX) laser facility\(^2\) to compare the behavior of TNSA with a small Gaussian beam and a large modulated smoothed beam. The setup of the experiment is shown in Fig. 6.

The \(S\) polarized beam enters the chamber and is focused onto the target using an off-axis parabola with an angle of 45\(^\circ\) normal to the target. We used stacks of radiochromic film (RCF) as the main diagnostic for proton dosimetry and cutoff energy of protons, which were located 5 cm behind the targets in the normal direction. Two kinds of targets were used in the experiment: gold with thicknesses of 1 \(\mu\)m, 4 \(\mu\)m, 10 \(\mu\)m, and 25 \(\mu\)m and plastic: CH\(_2\) (4 \(\mu\)m and 10 \(\mu\)m) and CH (1 \(\mu\)m). The plastic targets were used as a direct comparison with the simulations but better results are expected for the metal targets because of the smoother transportation of the electrons in the metal.

A smoothed electron-density distribution at the rear of the target can be achieved by using a phase plate, which creates a high-spatial-frequency speckle pattern over the desired spot size. While the use of a phase plate is a well-established technique to reach quasi-monodimensional interaction geometries for the nanosecond pulses at the PHELIX laser, it has been used for the first time with high-intensity short-pulses. However, the high intensity of the beam prevents from using the phase plate at its standard location, before the last focusing optics. Instead, the phase plate was installed in front of the preamplifier and the beam monitored throughout its amplification, and after compression. Our observations indicate that the beam shape remains very stable from shot to shot because thermal beam distortions remain much smaller than the phase modulation introduced by the phase plate. It enabled increasing the repetition rate of the experiment by a factor of 3, only limited by the RCF and target exchange rate. In addition, we designed the phase plate to have a minimum impact (less than 7\%) on the pulse duration, and we verified this experimentally. A complete description of the phase plate implementation and thereby generation of a smoothed beam falls beyond the scope of this paper and is discussed comprehensively by Bagnoud et al.\(^3\).

Figure 7 shows a Gaussian focus obtained with a F1.3 focusing off-axis parabola vs a smoothed beam generated with the phase plate. Note that the scales are normalized for better comparison.

While the waist of the Gaussian beam is 5 \(\mu\)m, the radius of the smoothed beam is about 35 \(\mu\)m, which causes a lower intensity for the smoothed beam compared to the Gaussian one, injecting the same laser energy.

Though the main idea of having a homogeneous intensity distribution over a focal spot has been achieved, several hot spots can be
seen in the smoothed beam, which have intensities one order of magnitude higher than the mean intensity of the beam. As the phase plate filters the high spatial frequencies, it produces the spatial discontinuities in the beam, which are converted into a speckle pattern in the near field image of the smoothed beam. Such speckles are presented as the hot spots in the far field images. The number and the size of the hot spots varied shot to shot and we could not see a fixed pattern for them for different shots. As will be shown, such hot spots can affect the interaction of the smoothed beams with the solid targets and, consequently, the proton acceleration.

IV. EXPERIMENTAL RESULTS

In this section, we present the experimental results. For the Gaussian beam, the intensity of different shots varied in the range of $I_{\text{gauss}} = (0.4–3) \times 10^{20}$ W/cm$^2$. For the smoothed beam, the mean intensity of different shots was $I_{\text{smo,mean}} = (2.3–2.8) \times 10^{18}$ W/cm$^2$, keeping the same laser energy.

Figure 8 shows the cutoff energy of protons vs the laser intensity for both the Gaussian and smoothed beams. For the Gaussian beams, we could change the laser energy easily to reach higher intensities, so a large range of $E_{\text{max}}$ of protons could be achieved. The average cutoff energy of the protons for the Gaussian beam is $22 \pm 7$ MeV, while the one for the smoothed beam is $9 \pm 1.4$ MeV.

Figure 9 shows the RCF stacks, which were irradiated with protons accelerated with a Gaussian and a smoothed beam, respectively. By looking at the RCF films, the angular divergence of protons for the Gaussian and smoothed beams seems to be the same.

Figure 10 confirms this issue, where the angular divergence of protons is plotted as a function of proton energy for the Gaussian and smoothed beams. A similar trend can be seen in both cases.

For the smoothed beams, we selected two shots with the same mean intensities, $I = 2.4 \times 10^{18}$ W/cm$^2$, and the same target thicknesses, 10 $\mu$m gold. In the case of the Gaussian beam, we used the shot with the highest peak intensity since we observed the most energetic protons for this shot and considered it as an upper limit for the Gaussian beam. For this shot, the target was 4 $\mu$m gold. As the intensity of the Gaussian beams was about two orders of magnitude higher than the mean intensity of the smoothed beams, $E_{\text{max}}$ protons accelerated with the Gaussian beams were higher than the ones accelerated with the smoothed beams. To have an analogous $E_{\text{max}}$ for both cases for a direct divergence comparison, we used two Gaussian beams with lower intensities. The first shot with intensity $I = 10^{20}$ W/cm$^2$ was focused onto a 10 $\mu$m gold target, while the second shot with intensity $I = 0.4 \times 10^{20}$ W/cm$^2$ was focused onto a 4 $\mu$m gold.

For the Gaussian shot with the highest laser intensity, the RCF stack started from 12 MeV, while for the lower laser intensities of the Gaussian shots and all the smoothed shots, the RCF stacks started from 1 MeV.

Figure 10 clearly shows the angular divergence variation for the lowest and the highest Gaussian laser intensity and at the same time
the differences between the angular divergences of the smoothed and Gaussian beams.

All numerical simulations show a lower angular divergence for the accelerated protons using a smoothed beam compared to the Gaussian beam, but such a trend cannot be seen following the experimental results.

The reason for such discrepancies could be due to the experimental conditions or the numerical estimations. From the experimental point of view, as we discussed earlier, the phase plate delivers a smoothed beam but with several hot spots, so the beam is not fully smoothed. Such hot spots can act as point sources for proton generation and acceleration. This effect can be clearly seen in Fig. 8, where $E_{\text{max}}$ values for the smoothed beams are plotted twice: first, vs the mean intensities of the beam, which show the average laser intensities across the focus, $I_{\text{mean}}$, and second, for the maximum intensity present in the hot spots, $I_{\text{max}}$. It can be seen that the smoothed beams fit the scaling of the proton energy, if we consider the maximum intensity present in the hot spots, instead of the mean intensity of the whole beam. It has an important consequence: the proton acceleration is mostly governed via the hot spots present in the beam. Moreover, the beam generated with the phase plate does not have a well-defined shape, Fig. 7, right, and has tails in the outward directions. Such tails could have enough energy to ionize the target and produce a non-homogeneity in the sheath borders and probably affect the proton divergence. Accordingly, further modifications are required for better performance.

From the numerical point of view, the simulations have been done in 2D, while the angular divergence is a 3D issue. This point is under investigation and 3D simulations will be done in the near future. Another possible reason is that the experimental sheath is not as smooth as predicted in the simulations. In fact, PIC codes consider a high initial temperature of electrons, while the target is still cold. It causes ambiguities in the accuracy of the hot electron transport through the target, which is reforming from a cold solid to a very hot dense plasma. This can cause an underestimation of the hot spot effects in the experiment. It becomes more complicated when we take into consideration the magnetic field generations, which depend on the hot electron current inside the target and their probable influence on ion acceleration.

A positive point of the phase plate, as shown in Fig. 11, is that the number of protons, which are generated with the smoothed beams, is higher than the number of protons generated with the Gaussian beam when $E_{\text{max}}$ is comparable.

We have to mention that most of the experiment was done with the pulses of very high temporal contrast. For these shots, the high-energy Gaussian focus delivered more particles. We expect that the
smoothed shots with low intensities were suffered from poor light absorption. The absorption of the laser light into the target plays an important role in the comparison. The absorption of a target depends on many different factors. In general, a higher intensity, for instance, at $10^{20}$ W/cm², has a much higher absorption than a lower one for a high-contrast pulse. When one goes from a high intensity Gaussian pulse to a smoothed beam, not only the electron temperature is reduced, but also the coupling efficiency from the laser light into the electrons and subsequently the number of particles are reduced as well. One way around is to have an increased pre-plasma as the absorption mechanisms in the pre-plasma are different and the coupling of the laser into electrons is less sensitive to the laser intensity. For this reason, we conducted a few smoothed shots at a nanosecond temporal contrast of $10^{-6}$ that created a preplasma and increased the laser absorption at low intensity. For the low contrast shots, the RCFs were saturated, showing that the number of particles was much higher than the ones with the high contrast.

V. CONCLUSION

We implemented a phase plate in front of the pre-amplifier of the PHELIX laser to achieve a large focus of a uniform intensity distribution. The phase plate was used for the first time for such high-power short-pulse lasers at such a configuration. While numerical simulations estimated a 2–5 times reduction in the angular divergence of the accelerated proton beam, the experimental data showed no reduction. Our interpretation is that the sheath smoothing effect is not happening in the current conditions, either because the smoothed beam is not homogeneous or because the sheath smoothing effect has been overestimated by the numerical simulations.

Nevertheless, the use of a phase plate can lead to a large number of low energy protons, up to 10–15 MeV when the absorption efficiency is improved. Another advantage of the phase plate is less sensitivity of the focus quality on the optical aberration and tolerating the thermal loading as for the Gaussian beams, a good beam wavefront quality is needed. It causes higher shot rates for the phase plate. It means while the number of Gaussian shots per day was about 5, for the phase plate, we could conduct 10–15 shots per day, three times more. In conclusion, this scheme is favorable for applications where low energy protons are needed at higher repetition rates.

ACKNOWLEDGMENTS

This work was carried out within the framework of the EUROfusion Consortium and received funding from the Euratom Research and Training Programme 2014–2018 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The data that support the findings of this study are openly available in GSI-Helmholtzzentrum für Schwerionenforschung at https://doi.org/10.15120/GSI-2020-00409, reference number [GSI-2020-00409], under the License CCBY4 https://creativecommons.org/licenses/by/4.0/.

REFERENCES

1. A. Maksimchuk, S. Gu, K. Flippo, D. Umstadter, and V. Y. Bychenkov, "Forward ion acceleration in thin films driven by a high-intensity laser," Phys. Rev. Lett. 84, 4108–4111 (2000).
2. R. A. Snavely, M. H. Key, S. P. Hatchett, T. E. Cowan, M. Roth, T. W. Phillips, M. A. Stoyer, E. A. Henry, T. C. Sangster, M. S. Singh, S. C. Wilks, A. MacKinnon, A. Offenberger, D. M. Pennington, K. Yasuike, A. B. Langdon, B. F. Lasinski, J. Johnson, M. D. Perry, and E. M. Campbell, "Intense high-energy proton beams from petawatt-laser irradiation of solids," Phys. Rev. Lett. 85, 2945–2948 (2000).
3. M. Roth, T. E. Cowan, M. H. Key, S. P. Hatchett, C. Brown, W. Fountain, J. Johnson, D. M. Pennington, R. A. Snavely, S. C. Wilks, K. Yasuike, H. Ruhl, F. Pegoraro, S. V. Bulanov, E. M. Campbell, M. D. Perry, and H. Powell, "Fast ignition by intense laser-accelerated proton beams," Phys. Rev. Lett. 86, 436–439 (2001).
4. S. Busold, D. Schumacher, C. Brabetz, D. Jahn, F. Kroll, O. Deppert, U. Schramm, T. E. Cowan, A. Blazević, V. Bagnoud et al., "Towards highest peak intensities for ultra-short MeV-range ion bunches," Sci. Rep. 5, 12459 (2015).
5. P. Pella, G. Gregori, D. O. Gercke, J. Vorberger, S. H. Glasner, M. M. Günther, K. Harres, R. Heathcote, A. L. Kritcher, N. L. Kugland, B. Li, M. Makita, J. Mithen, D. Neely, C. Niemann, A. Otten, D. Riley, G. Schumacher, L. Schollmeier, A. Tauschwitz, and M. Roth, "Ultrafast melting of carbon induced by intense proton beams," Phys. Rev. Lett. 105, 265701 (2010).
6. K. Zieg, M. Baumann, E. Beyreuther, T. Burris-Mog, T. E. Cowan, W. Enghardt, L. Karsch, S. D. Krait, L. Laschinsky, J. Metzkes, D. Naumburger, M. Oppelt, C. Richter, R. Sauerbrey, M. Schmitz, U. Schramm, and J. Pawelke, "Dosage-controlled irradiation of cancer cells with laser-accelerated proton pulses," Appl. Phys. B 110, 437–444 (2013).
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, 542–549 (2001).
8. M. Schollmeier, M. Roth, A. Blazević, E. Brambring, J. Cobble, J. Fernandez, K. Flippo, D. Gauthier, D. Habs, K. Harres, B. Hegelich, T. Heßling, D. Hoffmann, S. Letzring, F. Nürnberg, G. Schumacher, J. Schreiber, and K. Witte, "Laser ion acceleration with micro-grooved targets," Nucl. Instrum. Methods Phys. Res., Sect. A 577, 186–190 (2007), proceedings of the 16th International Symposium on Heavy Ion Inertial Fusion.
9. J. Fuchs, T. E. Cowan, P. Axubert, H. Ruhl, L. Gremillet, A. Kemp, M. Allen, A. Blazevic, J.-C. Gauthier, M. Geissel, M. Hegelich, S. Karsch, P. Parks, M. Roth, Y. Sentok, R. Stephens, and E. M. Campbell, "Spatial uniformity of laser-accelerated ultrahigh-current MeV electron propagation in metals and insulators," Phys. Rev. Lett. 91, 235002 (2003).
T. D. Arber, K. Bennett, C. S. Brady, A. Lawrence-Douglas, M. G. Ramsay, N. J. Sircombe, P. Gillies, R. G. Evans, H. Schmitz, A. R. Bell, and C. P. Ridgers, “Contemporary particle-in-cell approach to laser-plasma modelling,” Plasma Phys. Controlled Fusion 57, 113001 (2015).

H. Padda, M. King, R. J. Gray, H. W. Powell, B. Gonzalez-Izquierdo, L. C. Stockhausen, R. Wilson, D. C. Carroll, R. J. Dance, D. A. MacLellan, X. H. Yuan, N. M. H. Butler, R. Capdessus, M. Borghesi, D. Neely, and P. McKenna, “Intrapulse transition between ion acceleration mechanisms in intense laser-foil interactions,” Phys. Plasmas 23, 063105 (2016).

P. Mora, “Plasma expansion into a vacuum,” Phys. Rev. Lett. 90, 185002 (2003).

C. Brabetz, S. Busold, T. Cowan, O. Deppert, D. Jahn, O. Kester, M. Roth, D. Schumacher, and V. Bagnoud, “Laser-driven ion acceleration with hollow laser beams,” Phys. Plasmas 22, 013105 (2015).

A. Pukhov, “Three-dimensional simulations of ion acceleration from a foil irradiated by a short-pulse laser,” Phys. Rev. Lett. 86, 3562 (2001).

D. Neely, P. Foster, A. Robinson, F. Lindau, O. Lundh, A. Persson, C.-G. Wahlström, and P. McKenna, “Enhanced proton beams from ultrathin targets driven by high contrast laser pulses,” Appl. Phys. Lett. 89, 021502 (2006).

A. J. Mackinnon, Y. Sentoku, P. K. Patel, D. W. Price, S. Hatchett, M. H. Key, C. Andersen, R. Snavely, and R. R. Freeman, “Enhancement of proton acceleration by hot-electron recirculation in thin foils irradiated by ultraintense laser pulses,” Phys. Rev. Lett. 88, 215006 (2002).

C. McGuffey, A. Raymond, T. Batson, R. Hua, G. M. Petrov, J. Kim, C. M. Krauland, A. Maksimchuk, A. G. R. Thomas, V. Yanovsky, K. Krushelnick, and F. N. Beg, “Acceleration of high charge-state target ions in high-intensity laser interactions with sub-micron targets,” New J. Phys. 18, 113032 (2016).

Y. Sentoku, T. E. Cowan, A. Kemp, and H. Ruhl, “High energy proton acceleration in interaction of short laser pulse with dense plasma target,” Phys. Plasmas 10, 2009–2015 (2003).

M. Zepf, E. Clark, F. Beg, R. Clarke, A. Dangor, A. Gopal, K. Krushelnick, P. Norreys, M. Tatarakis, U. Wagner et al., “Proton acceleration from high-intensity laser interactions with thin foil targets,” Phys. Rev. Lett. 90, 064801 (2003).

V. Bagnoud, B. Aurand, A. Blazevic, S. Borneis, C. Bruske, B. Ecker, U. Eisenbarth, J. Fils, A. Frank, E. Gaul, S. Goette, C. Haeffner, T. Hahn, K. Harres, H.-M. Heuck, D. Hochhaus, D. H. H. Hoffmann, D. Javorková, H.-J. Kluge, T. Kuehl, S. Kunzer, M. Kreutz, T. Merz-Mantwill, P. Neumayer, E. Onkels, D. Reemts, O. Rosmej, M. Roth, T. Stoehlker, A. Tauschwitz, B. Zielbauer, D. Zimmer, and K. Witte, “Commissioning and early experiments of the PHELIX facility,” Appl. Phys. B 100, 137–150 (2010).

V. Bagnoud, J. Hornung, M. Afshari, U. Eisenbarth, C. Brabetz, Z. Major, and B. Zielbauer, “Implementation of a phase plate for the generation of homogeneous focal-spot intensity distributions at the high-energy short-pulse laser facility PHELIX” (unpublished) (2019).

J. Davies, A. Bell, M. Haines, and S. Guerin, “Short-pulse high-intensity laser-generated fast electron transport into thick solid targets,” Phys. Rev. E 56, 7193 (1997).

E. d’Humières, E. Lefebvre, and L. Gremillet, “Proton acceleration mechanisms in high-intensity laser interaction with thin foils,” Phys. Plasmas 12, 062704 (2005).