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First demonstration of collimation and monochromatisation of a laser accelerated proton burst

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Abstract

Laser produced ion beams have a large divergence angle and a wide energy spread. To our knowledge, this is the first demonstration of collimation and monochromatisation of laser accelerated proton beams, using a permanent quadrupole magnet lens system. It acts as a tunable band pass filter by collimating or focusing the protons with the same energy. Because it gathers nearly the whole proton emission, a strong enhancement of the beam density appears. For the collimated beam, an increase of the proton density in the (3.7 $\pm$ 0.3) MeV energy band up to a factor of ~30, from possible 40, relative to the non-collimated beam is demonstrated. With the help of this simple, reliable, and well established technique new perspectives will be opened for science and technology, monoenergetic ion beams can be attained in any lab, where a source of laser accelerated ions exist. This finding enables to apply afterward well known beam steering techniques to the formed ion beam, which are applied in conventional accelerators to manipulate the beam parameters or to transport the beams and make them use in many application.

Keywords: Ion acceleration; Ion beam collimation; Laser plasma; Quadrupole-magnet lens; Spectral tailoring

INTRODUCTION

Recent studies (Clark *et al.*, 2000; Hatchett *et al.*, 2000; Mackinnon *et al.*, 2002; Maksimchuk *et al.*, 2000; Wilks *et al.*, 2001; Spencer *et al.*, 2003) demonstrated that relativistically intense and ultrashort laser pulses are very promising candidates for a new generation of particle accelerators. Highly energetic ions with kinetic energies approaching several tens of MeV per nucleon have been observed. Such energetic particles create new perspectives for ion-matter interaction studies, like radiographic investigations of field structures by proton imaging (Cobble *et al.*, 2002; Borghesi *et al.*, 2001, 2005), or the generation of warm dense matter, and, as a long term prospect, applications in the classical domain of accelerator physics.

The laser-driven acceleration of ions is at least a two-step process. First, the laser energy is transferred to energetic electrons, which acquire energies up to several MeV. Then this energetic electron pulse breaks out of the rear side of a thin target foil, and sets up a strong electric field perpendicular to the back surface at a distance comparable to the plasma Debye length. The ions from the front side of the target are accelerated due to an ambipolar plasma expansion (Gitomer *et al.*, 1986), by an electric field sweeping with the laser (Sentoku, *et al.*, 2003), or a mechanism wherein the ponderomotive pressure of the short laser pulse displaces the background electrons, and the ions are accelerated by the electrostatic field of the propagating double layer (Shorokhov & Pukhov, 2004), while the ions emitted at the rear surface of the target are accelerated by a static electric field. The latter mechanism is called the target normal sheath acceleration (TNSA) (Hatchett *et al.*, 2000; Wilks *et al.*, 2001). Typically produced field strength of several MV/μm has to persist for some 100 fs in order to accelerate the ions to MeV energies.

Actually, proton beams with extremely low transverse and longitudinal emittances have been demonstrated (Cowan *et al.*, 2004; Brambrink *et al.*, 2006*a*, 2006*b*). These ion generators have dimensions of a few mm, and are capable of producing bunches of 10^{10}–10^{12} particles with a repetition rate of a few Hz, where the latter is in principle only limited by the repetition rate of the available lasers. In spite of these unique features, the laser-based ion sources have up to now some imperfections, which gradually impede their application for the above mentioned fields. These are

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the difficulties to generate in a stable way ion beams both of monoenergetic distribution and of a small angular spread. It is worth mentioning that despite of the breakthrough reported in the literature (Hegelich *et al.*, 2006; Schwoerer *et al.*, 2006; Ter-Avetisyan *et al.*, 2006) on the first demonstration of nearly monoenergetic proton and ion bunches, their reproducibility is even low and also the physics of the acceleration process is still under discussion. Another method to produce nearly monoenergetic protons and to allow also a collimation of the diverged proton beam relies on the use of a plasma capillary (Toncian *et al.*, 2006; Willi *et al.*, 2007). Here the authors explain that transient electric fields induced inside a metallic cylinder by laser-driven hot electrons are responsible for the energy-dependent focusing behind the capillary. Such a manipulation is advantageous in contrast to ion beam deflection in conventional accelerators, because the charge neutralization of the laser accelerated plasma beam is kept. Thus the Coulomb interaction between ions is insignificant.

However, even if this method is more simple and applicable nearly independent on the source distribution, it has the disadvantage that the capillary is being damaged at each shot, and therefore hardly useful for a future operation at higher repetition rates. Similar restrictions bear on the ballistic focusing of ion beams with a curved surface of the target rear, which has been demonstrated both numerically (Wilks *et al.*, 2001), and experimentally (Patel *et al.*, 2003).

In the present work, we show that the spatial and spectral characteristics of the laser-produced ion beam can be manipulated with a simple quadrupole-magnet system. From the accelerated ion burst with a broad kinetic energy spectrum, selectively the particles with certain energy are collimated or focused. By tuning the magnetic field strength and the geometry of the magnetic lens system, a particle beam with a necessary energy can be formed. Also, this collimated and quasi-monoenergetic ion beam can be transported over long distances without significant loses. This simple and unique method can be used independent on the source characteristics and also at any repetition rate.

EXPERIMENT

Pulses with a duration of 40 fs from a TW Ti:Sapphire laser system was focused with an $f/2.5$ off-axis parabolic mirror to a maximum intensity of about 2×10^{19} W/cm^2 onto a 5 μm thick Ti target. A proton burst with a broad energy spectrum up to a maximum energy of about 4 MeV was created. The particle energies were measured using a Thomson parabola spectrometer (Ter-Avetisyan *et al.*, 2005) and the protons at either the spectrometer or the quadrupole exit were detected by single particle sensitive multi-channel-plate (MCP) detector coupled to a phosphor screen. A magnetic field of about 0.27 T and electric fields of (2–10) kV/cm have been applied inside the spectrometer.

The emitted proton beam divergence was measured by proton imaging of the mesh with a (50×50) μm^2 cell size and period 58 μm through 12 μm Al filter on the CR39 track detector (Fig. 1). From the geometry one can estimate half emission angle of the protons with energy above 1 MeV about 20°.

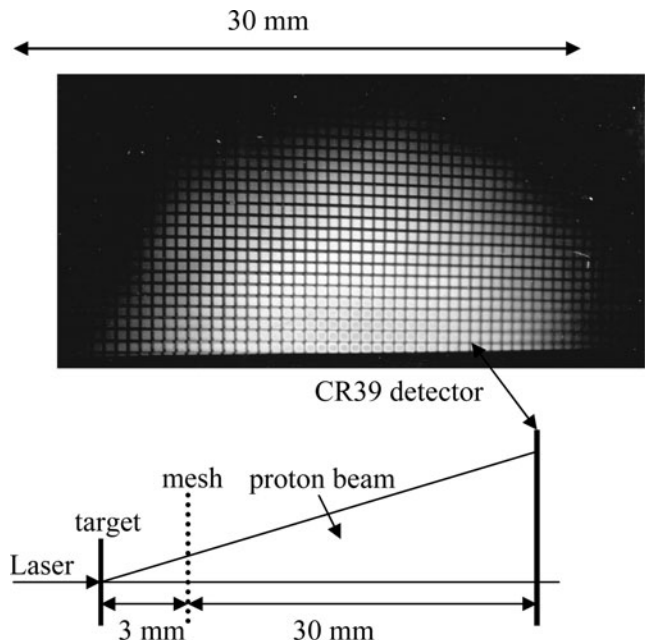

Fig. 1. Proton imaging of the mesh with 50 μm cell size and period 58 μm through 12 μm Al filter on CR39 track detector (on the top) and the used imaging geometry (on the bottom).

QUADRUPOLE MAGNET SYSTEM

The use of different magnet configurations in high-energy accelerators for low current particle beams with un-neutralized charge are well-known, and beam transport through quadrupols is well understood and the theory is straightforward (Basten *et al.*, 1994). For the laser accelerated almost charge neutralized ion beams, it is not *a priori* clear, if such a magnetic lens system will act similarly as for a low density charged beam. The laser driven ion beams are cold plasma "bullets" (Ter-Avetisyan *et al.*, 2004) typically characterized by a divergence of about 15–20 degree (half-angle) and it is under question whether a magnetic system can compensate for this large emission angle. Therefore, we first experimentally tested the ability to focus a laser produced proton beam with a single quadrupole, and than investigated whether a quadrupole-magnet lens system could collimate the strongly divergent proton beam. This collimated beam should have a "monoenergetic" feature.

The collimating system consists of two successive identical quadrupole magnets, where the order of the poles in the second quadrupole is reversed to the first one, and therefore the fields of the two quadruples are rotated by 90° relative to each other. The cross section of the field inside a quadrupole magnet and a field distribution along the axis are shown in Figure 2. The magnitude of the field in any point inside the quadrupole is proportional to the distance from the axis. In

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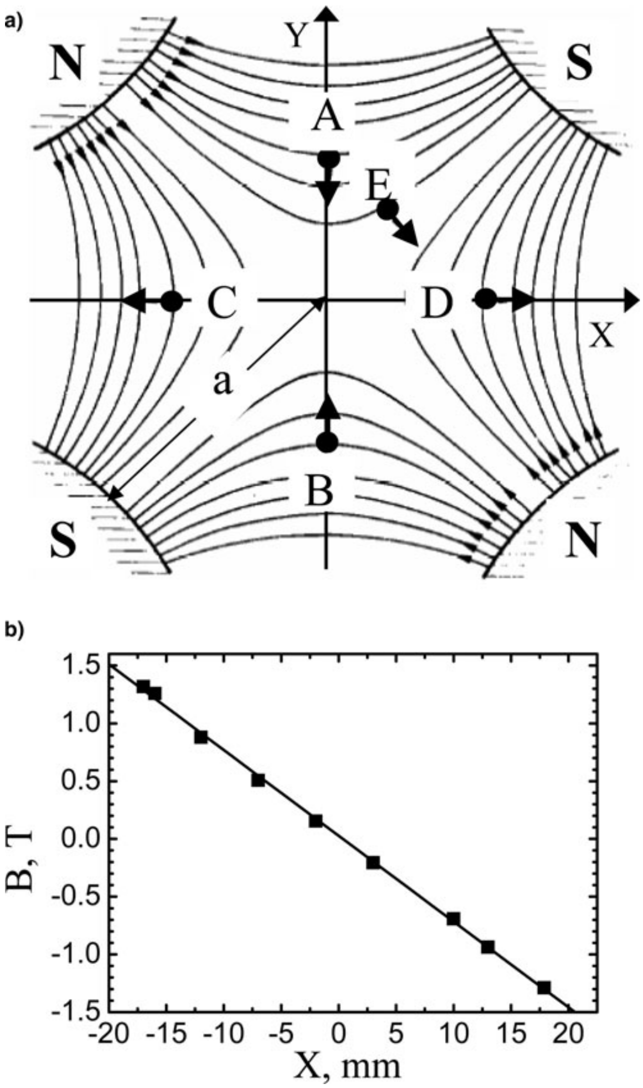

Fig. 2. (**a**) Field lines in the magnetic quadrupole. A, B, C, and D are the direction of force on positively charged protons at different places and (**b**) distribution of the magnetic flux density along the *X* axis of the aperture (distribution is the same along the *Y* axis).

an x, y coordinates system, the magnetic field is ideally given by $B_y = B_0(x/a)$ and $B_x = B_0(y/a)$ (Wollnik, 1987). The B_0/a referred as quadrupole gradient.

Indeed, the magnetic field lines in the XY plane inside the quadrupole are parallel to the X and Y axes, and particles that are propagating in XZ and YZ planes are exactly perpendicular to the magnetic field line. Those, which are not in these planes, have a slightly different angle but still enough small (about few degrees) in order to be neglected. Therefore the particles trajectories can be reasonably well described by the equations written in the paraxial approximation.

For the axisymmetric field configuration if to restrict our consideration neglecting particles transverse velocities ($v_{z0}^2 \approx v_x^2 + v_y^2 + v_z^2$), which is spatially true for high energy protons, the none relativistic equations of motion of the proton through a quadrupole magnetic field in the paraxial approximation gives

$$\frac{\partial^2 x}{\partial t^2} = -\frac{eZ}{m_p} v_z B_y = -\frac{eZ}{m_p} v_{z0} B_0 \frac{x}{a};$$

and

$$\frac{\partial^2 y}{\partial t^2} = \frac{eZ}{m_p} v_z B_x = \frac{eZ}{m_p} v_{z0} B_0 \frac{y}{a}. \quad (1)$$

Replacing $d/dt \rightarrow v_{z0} d/dz$ the proton trajectories in a magnetic quadrupole can be described with:

$$x''(z) + k(z)x = 0 \quad \text{and} \quad y''(z) - k(z)y = 0 \quad (2)$$

where $k(z) = eB_0/m_p a v_{z0}$ is the focusing strength for a magnetic quadrupole, e is the elementary charge, m_p is the proton mass. The solution of Eq. (2) represents converging and diverging motion of the particles given by Rgenstreif (1967). The positively charged particle is moving through two identical quadrupoles having the same focusing strength $k(z)$, a length L, and are separated on a distance d (the drift part is field free and physically has to be $d \geq 0$) as well as rotated by 90° relative to each other. Then, according to the X, Z plane, the particle motion is defocusing-drift-focusing and according to the Y, Z plane focusing-drift-defocusing. The focusing strength of the magnetic quadrupole and its geometry will define the paraxial output of the beam. In other words the focusing quadrupole system is just compensating the original divergence of the beam.

The overall diameter of the used quadrupole-magnet lens was 180 mm with a usable aperture diameter of 2a = 40 mm and a length of L = 50 mm. The magnetic field at the maximal useable diameter was about $B_0 = 1.3$ T (Fig. 2b). The field lines follow hyperbolic paths, which are normal to the beam direction.

The force experienced by the positively charged particles *A* and *B* on the *Y*-axis (Fig. 2a) is directed toward the quadrupole axis, but because of the antisymmetric field geometry, the force along the orthogonal *X*-axis is directed outward from the quadrupole axis (particles *C* and *D*). Therefore, in a single quadrupole, the proton beam converges into a line. A collimation of the proton beam can be achieved with help of two successively placed identical quadrupoles with reversed pole geometry, which will constitute a quadrupole-magnet lens.

EXPERIMENT AND DISCUSSION

In a single quadrupole set up (Fig. 3a) where the proton beam converges into a line, the protons with different energies are focused at different distances from the quadrupole. Therefore, at a certain focus plane their contribution appears as background. For a clear detection of the focus distribution, all protons with energies below 2.8 MeV were blocked with a 70 μm Al filter in front of the detector (Fig. 3a). The action

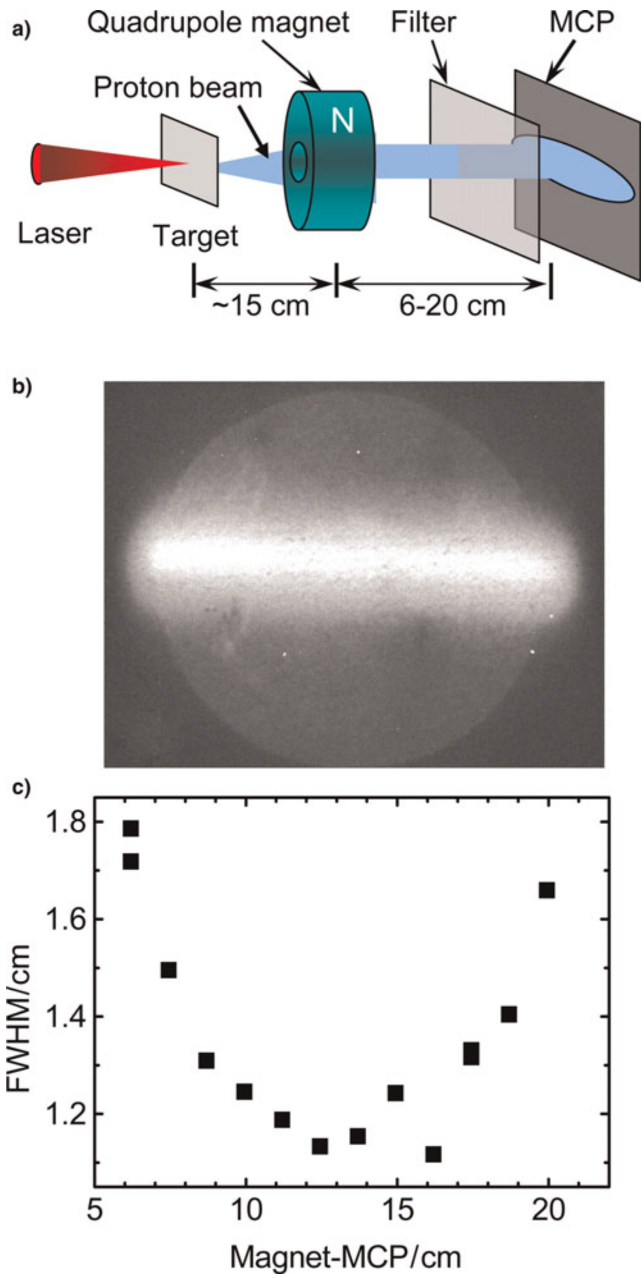

Fig. 3. (**a**) A single quadrupole set-up. (**b**) The single quadrupole focuses the beam in the horizontal plane and spread it in the vertical plane, forming a line image. (b) FWHM of the measured focus distribution of a proton beam with (2.8–4) MeV energies dependence on the distance between magnet and MCP-detector.

of a single quadrupole on a laser accelerated proton beam is shown in Figure 3b where inevitably only protons with energy can be sharply focused at a certain distance from the quadrupole. The proton density distribution (full width half maximum (FWHM)) at different distances from the magnet is shown in Figure 3d. The caustic has a clear minimum, which extends within the movement of the magnet in a relatively long $\sim$50 mm distance (Fig. 3b) when the distance between source and magnet was changed. This is a result of the relatively broad proton energy interval: from 2.8 MeV up to 4 MeV applied in the experiment. This and scattering due to filter propagation broadens the detected focus distribution in comparison to the expected focus size at only one fixed proton energy.

This shows that indeed the quadrupole magnet can compensate the large emission angle of protons as they are accelerated from the target. In the present geometry, the protons with an emission angle of up to 20° have been collected. Additionally, the used geometry bears in the following characteristic: the distance of the quadrupole from the source transforms the laser accelerated proton beam to a "low density." As a result, the almost charge neutralized proton beam is cleaned up at the fringing fields just before entering the magnet without destruction of the beam initial phase space characteristics.

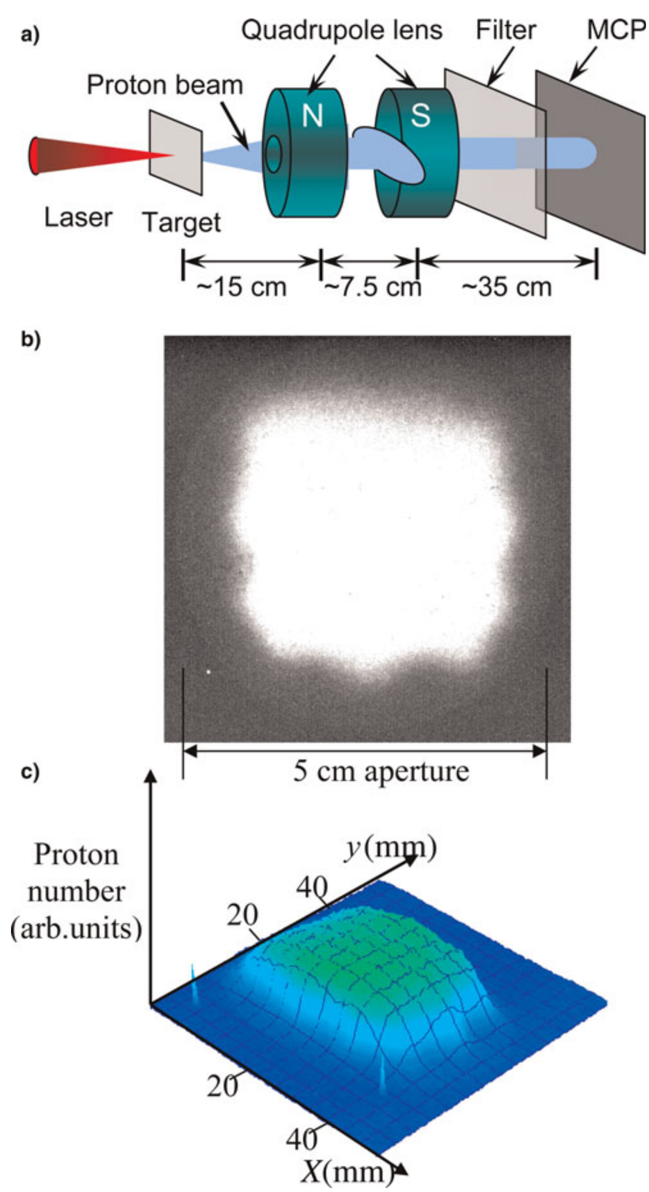

Fig. 4. (**a**) Quadrupole lens set-up. (**b**) Footprint of a collimated laser accelerated proton beam and (**c**) proton beam density distribution measured at a distance of 350 mm from the last quadrupole.

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A collimated proton beam was formed with help of two successively placed identical quadrupoles with reversed pole geometry as shown in Figure 4a, which constitute a quadrupole-magnet lens. In Figures 4b and 4c, the pattern of a collimated proton beam and a particle density distribution profile, correspondingly, are shown, which has due to the selective magnetic field deflection a *quasi*-monoenergetic characteristic. This flat-top, relatively sharp beam density profile with a size of (40×40) mm^2 was measured at a distance of over 350 mm from the last quadrupole. It was obtained at a minimum possible distance between the two quadrupols, which was in our case 25 mm due to shielding plates necessarily placed between the quadrupoles. A collimation is apparent because the beam has still the same diameter as the aperture of the quadrupole. The protons emitted with the divergence angle up to 20° are collimated into a quasi-parallel beam. The rectangular shape of the beam comes from the fact that the magnetic field is zero inside the quadrupole along the $y = x$ line, which corresponds to an $\pi/4$ angle (Fig. 2a). Therefore particle trajectories inside the collimated beam are not "perfect" parallel and also not "perfect" monoenergetic. The parallelism can be improved by applying common techniques as used in accelerators, for instance, with an octupole configuration where the zero field is at $\pi/8$ angle.

The measured proton energy distribution in the free expanding and collimated beams are shown in Figure 5, where a 200 μm entrance pinhole of Thomson spectrometer was positioned at a distance of 350 mm from the last quadrupole. The width of quasi-monoenergetic peak is given by the resolution of the measuring system. The ion energy selection by the quadrupole-lens system shows that in the collimated beam, the density of protons in the narrow energy band of (3.7 ± 0.3) MeV is increased up to a factor of $\sim$30, from possible 40 if all protons with this energy from the non-collimated beam would be collimated (Fig. 5), whereas the low energy part is completely suppressed. In the "monoenergetic" beam, more than $\sim 10^8$ protons with an energy of (3.7 ± 0.3) MeV are collimated.

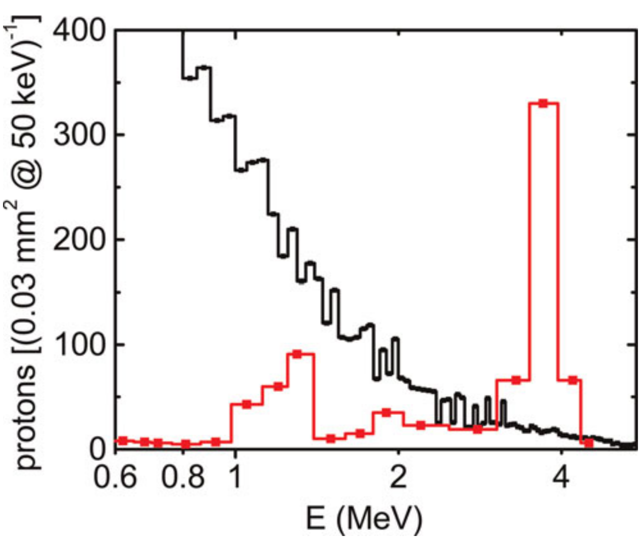

Fig. 5. (Color online) The measured proton spectrum in free expanding (black) and collimated (red) beams. The width of (3.7 ± 0.3) MeV quasi-monoenergetic peak is defined by the resolution of the measuring system.

The angular spread of those protons was rather small and about (20 ± 5) mrad, despite that the collimation condition was not optimal. Additionally, due to removed electrons from the proton beam, the former charge-neutralized beam was experiencing a positive volume charge with a certain current density I (A/cm^2). This in turn could broaden the initial beam radius r (cm) during the propagation along a distance l (cm), which can be estimated according to (Sisoev & Schupachin, 1977)

$$\frac{\Delta r}{r} \approx 1.2 \cdot 10^6 l^2 \left(\frac{m_p}{z}\right)^{1/2} \frac{I}{(E_i/z)^{3/2}}, \tag{3}$$

where m_p is the proton mass in u, E_i is the ion energy in eV, Z is the ion charge. This can be an estimate of the possible maximum current in a quadrupole-magnet system. It is obvious that in our case, due to relative big cross section of the collimated beam its broadening due to positive volume charge is negligible.

SUMMARY

To summarize, we have demonstrated the capability of a conventional quadrupole-magnet lens system to shape the emission of a laser driven proton source, which is normally characterized by a high divergence and a broad energy spectrum, into a collimated proton beam with selected energy. Because it gathers nearly the whole proton emission a strong enhancement of the beam density appears. The increase of density of protons in the narrow energy band of (3.7 ± 0.3) MeV up to a factor of ~30, from possible 40, relative to the non-collimated beam is demonstrated. The method appears to be more feasible and superior to existing schemes to create monoenergetic ion beams. Moreover, benefiting from the broad energy spectrum of laser accelerated protons it allows to tune the energy of the proton beam: by changing the geometry of quadrupols one can selectively collimate the protons with appropriate energy. Such, this method is unique, because it allows not only collimation, spectral tailoring with the possibility of concomitant tuning but is also usable at any repetition rate, which is highly important for future applications of the laser-based ion sources.

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