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High energy implementation of coil-target scheme for guided re-acceleration of laser-driven protons

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Developing compact ion accelerators using intense lasers is a very active area of research, motivated by a strong applicative potential in science, industry and healthcare. However, proposed applications in medical therapy, as well as in nuclear and particle physics demand a strict control of ion energy, as well as of the angular and spectral distribution of ion beam, beyond the intrinsic limitations of the several acceleration mechanisms explored so far. Here we report on the production of highly collimated (∼ 0.2° half angle divergence), high-charge (10s of pC) and quasi-monoenergetic proton beams up to ∼ 50 MeV, using a recently developed method based on helical coil targetry. In this concept, ions accelerated from a laser-irradiated foil are post-accelerated and conditioned in a helical structure positioned at the rear of the foil. The pencil beam of protons was produced by guided post-acceleration at a rate of ∼ 2 GeV/m, without sacrificing the excellent beam emittance of the laser-driven proton beams. 3D particle tracing simulations indicate the possibility of sustaining high acceleration gradients over extended helical coil lengths, thus maximising the gain from such miniature accelerating modules.

Current interest in laser-driven ion accelerators, as a radically different, compact alternative to RF accelerators, stems from remarkable properties such as large particle flux, short pulse duration and exceptional beam emittance1. However, the large angular and spectral spread of the ion beams which are intrinsic to laser-driven acceleration mechanisms, pose significant technical challenges to their applicative use. For instance, application in cancer therapy would require the delivery of high energy protons (60–250 MeV)2–4 with narrow energy spread and sufficient particle flux at significant distances from the interaction targets, so that the extraneous radiation produced during the intense laser interaction can be shielded adequately. There has been recent significant progress in increasing the maximum proton energies delivered through laser-driven processes, with recent reports of the acceleration of near 100 MeV protons5,6, albeit with a broad spectral content and large angular spread, with an half cone divergence of 5° – 10° at the highest energies.

Control of the beam divergence and of its energy spectrum have been key research objectives over the past decade, and a number of approaches using magnetic systems, target or plasma engineering7–13 have been explored for this purpose. The recently developed scheme based on helical coil (HC) target14 offers, in this context, a miniature and versatile setup that, in addition to reducing the divergence and energy spread of the beams, has been shown to post-accelerate the guided protons at a rate of the order of GV/m. In this scheme, the electromagnetic (EM) pulse generated due to transient charging of an intense-laser irradiated foil14–18 is directed to travel...
along the helical path defined by an HC. The characteristics of the EM pulse are governed by the generation of hot electrons and their dynamics during the laser interaction and hence depend on a number of laser and target parameters. While traveling along the windings of the HC, the EM pulse generates a strong electric field pattern which travels along the coil with a speed depending on the coil radius and pitch. Through a suitable choice of these parameters, it can be made to match the speed at which 10s of MeV protons travel. Deploying the coil at the rear side of the laser irradiated foil, protons within a narrow energy range are allowed to co-propagate with the travelling field pattern, enabling the synchronised proton bunch to be guided and post-accelerated simultaneously under the effect of the radial and longitudinal components of the electric field.

In this article, we demonstrate the generation of highly directional beams (half-angle divergence ∼ 0.2°) of protons with energies up to ∼ 50 MeV and narrow energy spread (∼ 10% FWHM), by employing HC targets at petawatt-class laser systems. The proton flux in the pencil beam at the spectral peak (∼ 45 MeV) is of the order of 10^{12}/MeV/sr, which is orders of magnitude higher than the fluxes typically generated by the TNSA mechanism at the high energy end of the spectrum. Particle tracing simulations corroborate the experimental results, showing synchronous focusing and post-acceleration of transiting protons at a rate of ∼ 2 GeV/m, about four times larger than reported in the first demonstration of the HC technique and well beyond the capabilities of conventional RF accelerators. The scaling for Ti:Sa systems have been discussed in the ref. 14, which shows that acceleration gradients of multi-GeV/m can be achieved with ultra-short, petawatt class lasers. A current limitation of the scheme will be discussed, together with a possible scheme to overcome it towards the production of beamlets at energies of therapeutic interest.

**Results**

The data presented in this paper were collected from two experimental campaigns employing similar laser parameters, (see “Materials and methods” section for details). Fig. 1a shows a schematic of the HC target employed in the experiments, where the HC was placed at a few millimetres away from the interaction foil, and connected to the interaction foil by a metallic wire (the ‘delay line’). This configuration enabled precise control of the arrival time at the HC of the EM pulse relative to the arrival of the protons from the foil by either varying the length of
the delay line, or the distance between the HC and the foil. Fig. 1b,c show results relating to the production of pencil beams of protons with a narrow energy bandwidth peaking at \( \sim 45 \) MeV. As can be seen in Fig. 1b,c, the experimental data shows a highly collimated beamlet with energies up to \( \sim 49 \) MeV, well beyond the maximum proton energies observed from reference flat foil shots taken during the campaign. The diameter of the central bright spot (containing more than 75% of the total flux) at the detector (Radiochromic film (RCF)) plane, 60 mm away from the target, is less than the internal diameter of the HC (shown by the black dashed circles in the zoomed-in views of the RCF images in Fig.1b,c). The spectral profile of the guided beam produced by the HC was reconstructed from the RCF data, as shown in Fig. 1d. Compared to the exponentially decaying spectra obtained from the reference flat foil shot, as typically expected from the TNSA mechanism, the on-axis proton spectra from the HC targets showed a pronounced, narrow spectral peak at \( \sim 45 \) MeV with a full width at half maximum (FWHM) energy spread of less than 10% and peak prominence better than an order of magnitude. The number of protons at the spectral peak was of the order of \( 10^8 \) (proton flux of the order of \( 10^{12} \) /MeV/sr), which one could filter out (for instance, by using conventional accelerator optics\(^{23,24}\)) from the rest of the spectrum to deliver narrow-band, collimated proton beams for applications.

The pencil beam of high energy protons results from the unique capability of chromatic guiding and post-acceleration offered by the HC targets. For a given HC radius and pitch, the strong focussing and accelerating fields move longitudinally along the HC axis with a fixed speed, which for the case shown in Fig. 1 was close to that of 30 MeV protons. At a given time the field pattern spans over a few windings of the HC as described in ref.\(^{14}\). While the maximum focusing field exists over the plane defined by the location the peak of the EM pulse, the accelerating field is optimum at a small distance (a few hundreds of microns depending on the HC radius and pitch) ahead of this position\(^{14}\). The delay line design of the HC targets, as used in the experiment, aids injecting the appropriate energy protons slightly ahead of the EM pulse peak, so that the protons clutch to the leading part of the field pattern and experience the optimum accelerating field.

Figure 2 illustrates the dynamics of transiting protons through the HC target, as reconstructed through particle tracing simulations employing the PTRACE code (see “Materials and methods” section). In Fig. 2a, the HC is seen accelerating efficiently the leading bunch of protons (28 ± 1 MeV) entering the HC, whereas the lower energy protons entering later in time, i.e. after the arrival of the EM pulse peak, are decelerated due to the reversal of the longitudinal field, which points towards the proton source in the trailing part of the field pattern. Furthermore, as shown in Fig. 2b, within the accelerated bunch, the fastest protons which are sufficiently ahead of the EM pulse peak do not experience a strong focussing field and exit the HC without significant divergence reduction. Therefore, it is protons from a narrow slice of the input spectrum which emerge with an extremely low divergence and a significant energy gain—this simultaneous effect of energy-selection, focussing and post-acceleration is a capability unique to the HC targets. As indicated in Fig. 2, the HC target used for the shots shown...
delivering a pencil beam of $\sim 0.35 \text{ mm}$, indicating that the exceptional transverse emittance of TNSA = 0.1 mm.$^{\text{7}}$ The particle internal was maintained within this range. At 60 $^{\text{+}}$ pitch were recorded at different distances from the targets. Fig. 3b–d show beam at 200 mm, corresponds to a nominal half-angle at half-maximum divergence of $\beta \sim 0.2$,$^{\text{+0.015 mm}}$ and 0.3 mm, expanded to 0.7 mm diameter and the beam) can be estimated as $0.1 \text{ mm}^2$. Taking the 0.7 mm diameter exit aperture of the HC as an upper estimate for the source size of the pencil beam, an upper limit for the beam’s normalised transverse emittance ($\epsilon_T$) is the energy gain per unit $G$ is the energy gain per unit $E_p(z) = \gamma_p(z) m_p c^2 = m_p c^2 + T_{kin} + G z$, where $G$ is the proton rest mass, $c$ is the speed of light in vacuum, $T_{kin}$ is the kinetic energy of the protons entering the HC and $G$ is the energy gain per unit

Figure 3. (a) Experimental setup (not to scale) used for characterizing the degree of beam collimation achieved by HC targets. Irradiating identical HC targets at similar laser conditions, proton beams were diagnosed by placing the RCF stack at different distances from the interaction foil. The HC targets used in this case were made of 0.125 mm thick Stainless steel wire of internal diameter, pitch and length of 0.7 $\pm$ 0.015 mm, 0.35 $\pm$ 0.015 mm and 10 $\pm$ 0.1 mm respectively, designed to synchronise optimally with $\sim 9$ MeV protons and post-accelerate them to $\sim 30$ MeV. (b–d) show spatial profiles of $\sim 30$ MeV proton beams captured by the RCF stack placed at 60 $\pm$ 1 mm, 100 $\pm$ 1 mm and 200 $\pm$ 1 mm respectively. (e) shows the 3D dose profile of the proton beam shown in (c).
length inside the HC, need to remain at a fixed distance in front of the peak of the EM pulse, which requires the electric field pattern to travel with the same velocity as the protons at any given z. The velocity of the travelling field can be varied by changing either the radius or the pitch of the HC. For the purpose of this calculation we consider the pitch variation only as these are easier to implement in practice. The longitudinal velocity of the field pattern inside the HC can be expressed as

\[
v_z(z) = \frac{c}{\beta_{EM}(z)} \sqrt{\frac{1}{2\pi r(z)^2 + p(z)^2}}
\]

where \( r \) and \( p \) are the diameter and pitch of the HC respectively and \( \beta_{EM} = v_{EM}/c \), where \( v_{EM} \) is the velocity of the EM pulse along a straight wire, which was measured experimentally as \( \sim 0.98 \pm 0.02 \) \( c \) \( 14,16,17 \). Equating the velocity of the travelling field to the proton velocity, one can find an expression for varying pitch to maintain a constant acceleration over an extended length.

**Materials and methods**

**Experiment.** Experiments were conducted at two different facilities, namely the Titan laser system at Lawrence Livermore National Laboratory (LLNL, USA) and the VULCAN Petawatt (VPW) system at Rutherford Appleton Laboratory (RAL, UK). They are both Nd:Glass based laser systems operating at central wavelength of
1.053 μm. In the Titan experiment, CPA pulses of duration 600 ± 100 fs and energy 150 ± 25 J were focused on target by an f/3 off-axis parabola to a spot of \(7 \pm 0.5 \mu m\) FWHM delivering peak intensity \((2\pm 1) \times 10^{20} \text{W/cm}^2\).

In the second experiment, VPW delivered laser pulses of 1 ± 0.1 ps duration with energy 300 ± 50 J. The laser pulses were focused by an f/3 off-axis parabola to a spot of \(5.5 \pm 0.5 \mu m\) FWHM, resulting in peak intensity \((3.5\pm 1) \times 10^{20} \text{W/cm}^2\). In both experiments, 10 μm thick gold foils were used for proton generation. HCs were made of 0.125 mm stainless steel wire and the laser was incident at 20° to the target normal. The spatial and spectral distribution of the proton beams was characterised by deploying a stack of dosimetrically calibrated Radiochromic films (RCF)\(^{22}\). The proton spectra were reconstructed by backdeconvolution of the dose deposited in the RCF layers\(^{27}\), by using an iterative algorithm similar to the procedures used in refs.\(^{22,28}\). Starting from the last RCF layer in the stack, the final spectrum is produced by calculating spectra between Bragg peak energies of consecutive RCF layers, while considering the energy response of the RCF layers (simulated by SRIM\(^{29}\)) in the stack and subtracting the dose contribution in a given layer by the protons stopping deeper in the stack.

Simulations. The particle tracing simulations presented in this paper were performed using the PTRACE code\(^{30}\), which simulates the propagation in 3D of protons from source to detector through the region where e.m. fields are present in this case the field pattern produced by the EM pulse travelling along a HC target. The protons transit through the HC together with the co-propagating electric field associated to the travelling EM pulse. The protons are traced by computing relativistic equations of motion using a Runge-Kutta fourth-order algorithm coupled with an adaptive step size monitoring routine. The HC was modelled in PTRACE using a cylindrical co-ordinate system and the physical dimensions as used in the experiment. An EM pulse of peak linear charge density \(50 \mu C/m\), 5 ps half-maximum rise and 15 ps half-maximum decay, similar to that measured experimentally in both the campaigns using the technique of self-probing (described in the ref\(^{14}\)), was set to travel along the HC wire. In the delay line configuration, the proton source was modelled as a point source located on the axis of the HC at a given distance from the entrance plane of the HC, emitting protons towards the HC with a given energy spectrum and divergence, mimicking the proton beam produced by the reference flat foil target.

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Author contributions
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Competing interests
The authors declare no competing interests.

Additional information

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