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Laser-driven proton acceleration: source optimization and radiographic applications

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Abstract

Ion acceleration from solid targets irradiated by high-intensity pulses is a burgeoning area of research, currently attracting large interest worldwide. The properties of laser-driven ion beams (high brightness and laminarity, high-energy cut-off, ultrashort burst duration) are, in several respects, markedly different from those of 'conventional' accelerator beams. In view of these properties, laser-driven ion beams have the potential to be employed in a number of innovative applications in the scientific, technological and medical areas. The scope of this paper is to briefly review the state of the art in this area and discuss in this context some recent results obtained by our group and collaborators, aimed at studying the acceleration mechanism, optimizing the source properties and applying the beams as a diagnostic tool in scientific experiments. An application that has already produced important results is the use of laser-accelerated protons as a particle probe for the detection of electric and magnetic fields in plasmas. Examples of these results will be presented and discussed.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Energetic beams of ions can be produced from thin metallic foils, as a result of their irradiation with relativistically intense, short laser pulses [1, 2]. These beams have unique characteristics

which differ greatly in several respects from beams of comparable energy obtained from conventional accelerators. Since the first observations, a very large amount of experimental and theoretical work has been devoted to the study of these beams' characteristics and production mechanisms. Particular attention has been devoted to the accelerator-like spatial quality of the beams, and current research focuses on their optimization for use in a number of applications. Our group at QUB has been active in this area for a number of years, and the scope of this paper is to briefly review the state of the art in this area and discuss in this context some recent results obtained by our group and collaborators, aimed at studying the acceleration mechanism, optimizing the source properties and applying the beams as a diagnostic tool in scientific experiments.

2. Acceleration mechanism, state of the art and applications

Mechanisms leading to forward-accelerated, high-quality ion beams, operating at currently accessible intensities in laser–matter interactions, are mainly associated with large electric fields set by laser-accelerated electrons at target interfaces. Typically the front surface of a laser-irradiated foil will become ionized ahead of the peak of the irradiating pulse. During the high-intensity laser–plasma interaction taking place at the pulse peak, electrons will be accelerated forward into the target through a number of mechanisms depending on the interaction and target conditions [3]. The typical energies of fast electrons accelerated at the front of the target are such that their mean free path is much larger than the thickness of the targets typically used in experiments (up to tens of micrometres), so that they can easily propagate to the target rear. The fast electrons that are electrostatically confined on the target rear surface set a charge separation field over a Debye length λ_D [4], typically of the order of a micrometre, inducing strong ($\sim$ TV/m) electric fields. Such fields can ionize atoms and rapidly accelerate ions normal to the initially unperturbed surface. The accelerated ions form a dense bunch of short duration that is charge neutralized by co-moving electrons. The extremely short duration of the acceleration and the fact that, at the target rear, it starts from an initially cold surface are essential facts that result in excellent emission properties. After this initial phase, ions stream into vacuum with electrons, preceded by a Debye sheath of hot electrons. This acceleration from the target rear has been described [5, 6] as an extension of the classical case of a plasma expanding into vacuum [7], driven by the ambipolar electric field generated in a narrow layer at the front of the plasma cloud. This mechanism for ion acceleration from the target rear is usually referred to as target normal sheath acceleration (TNSA).

The observation of highly collimated proton beams with multi-MeV energies was first reported independently by three research groups [4, 8, 9] and widely investigated by many groups worldwide following these first measurements [1]. Under standard laboratory conditions, efficient acceleration of protons is observed from any laser-irradiated foil, regardless of its composition. This is due to the presence at the target surfaces of contaminant layers (hydrocarbon or water vapour impurities) containing hydrogen. Heavier ion species are also accelerated [10], and their acceleration efficiency can be greatly enhanced if the impurities are removed with target heating [11, 12] or laser ablation [13] techniques. Typical proton spectra are broadband up to a cut-off energy, where the proton number drops abruptly. The various energy components are emitted from the target with different divergence, typically decreasing as the energy increases. A survey of data as obtained in the various facilities where this phenomenon has been investigated is provided in [1]. Figure 1 summarizes the peak energies obtained in experiments so far, plotted versus laser intensity. The energy of the protons varies with the target thickness and with the laser pulse intensity I , increasing roughly as $I^{0.5}$ for laser pulse duration in the range 300 fs–1 ps, and as I for shorter laser

Figure 1. Maximum proton energy from laser-irradiated metal foils for experiments on different laser systems as a function of the laser pulse irradiance, grouped in three different ranges of pulse durations. References to the relevant experiments can be found in [1], except for the points labelled Saclay [34] and Lund [35].

pulses (40–150 fs). Conversion efficiency into high energy protons varies from less than 1% for the shorter pulses to $\sim 10\%$ for longer pulses and PW power.

The current interest in laser-driven ion sources arises from a number of factors, including ease of beam production and synchronization in scientific experiments, reduction of the facility scale required for acceleration and some unique features of their emission properties, opening up ample opportunities for applications [1]. The ions are accelerated in bursts of duration of the order of a picosecond [14, 15], i.e. orders of magnitude shorter than in conventional accelerators, opening up the possibility of employing them in innovative pump–probe experiments. Furthermore, it has been experimentally shown that for the higher energy end of the proton spectrum, the transverse emittance is extremely low [16, 17]. Emittances as low as 0.004 mm mrad have been reported, i.e. 100-fold better than typical RF accelerators and at a substantially higher ion current (kA range) [17].

A broad range of applications employing these ion beams has been proposed [1]. An application which has already been implemented and is the subject of a separate section of this paper is the use of laser-driven proton beams as a radiography source [14, 18, 19].

Other proposed applications of laser-driven high-energy ions include production of high-energy density matter [20] of interest for astrophysics, high-brightness injectors for accelerators [17], use in cancer therapy [21] or radioisotope production [22] or as a fast trigger for inertial confinement fusion pellets [23]. While the currently available beam characteristics are sufficient for some of these applications to be implemented, others will require highly improved beam specifications.

For example, laser-driven proton sources have been proposed as possible particle probes for diagnosing National Ignition Facility (NIF) implosions [24, 25]. However, proton scattering calculations show that, while 50 MeV protons would be energetic enough to propagate through

a compressed core, 150 MeV protons would be required to provide meaningful information on density or uniformity of the compressed core (for lower proton energies, scattering would degrade the spatial resolution of the radiography to an unacceptable level). Protontherapy for cancer treatment requires beams with energies in the range 50–250 MeV, and a bandwidth of a few per cent of the central energy [26]. While 50 MeV beam production has already been demonstrated, the energies in excess of 200 MeV, required for treating deep seated tumours, are beyond current capabilities. In addition, beams currently produced have broad energy spectra and are divergent; therefore there is a requirement to develop methods to reduce the energy spread to acceptable values and to control the beam divergence.

3. Recent results and current trends in optimization of the beam parameters

Various routes can be envisaged for increasing the peak proton energies. In the first place, a clear understanding of the mechanisms and scaling laws acting at present is necessary to try and unify the many results obtained in a variety of experimental conditions, and to extrapolate the conditions which may lead to energy increase using the TNSA mechanism. In addition, several theoretical works have discussed acceleration driven ponderomotively at the target surface [27] or by shocks launched into the target [28, 29]. In particular, recent particle in cell (PIC) simulations predict much more efficient acceleration (with proton energies scaling as the laser intensity I instead of $I^{0.5}$) as the so-called *radiation pressure dominated* regime is entered ($I > 5 \times 10^{21} \text{ W cm}^{-2}$ for $\lambda = 1 \mu\text{m}$) [30, 31]. The *piston* effect of ultra-intense ($> 10^{23} \text{ W cm}^{-2}$) laser radiation pressure leads to a cocoonlike deformation of ultrathin foils and acceleration of the ions up to relativistic velocities in the forward direction. A transition to the radiation pressure regime at more moderate intensities has recently been identified via multi-parametric PIC simulations [31]. The use of circularly polarized pulses has been proposed as a means to achieving efficient ponderomotive drive at more moderate intensities [27]. The main advantage of circular polarization is that energy coupling to hot electrons is suppressed and this provides better coupling via ponderomotive force to colder electrons and prevents target disassembly during the pulse. A substantial theoretical effort has been recently devoted to the study of this approach [32–34]. By the use of contrast-free pulses coupled to ultrathin targets, this research aims to predict conditions leading to the production of narrow-band high-energy protons and carbon ion beams suitable for medical applications.

Radiation pressure can play a significant role also in linear-polarization interactions at more moderate irradiances than in [30]. Although, in this case, TNSA will be the dominant process leading to high-energy acceleration, radiation pressure will be applied to front-surface ions, at the critical density surface, driving them into the targets. Recently published results by our group suggest that this process can lead to the ejection of well-collimated plasma jets [35], when the accelerated ion bunches break out at the rear surface of thin foils.

Figure 2 shows interferograms obtained at the VULCAN facility at the Rutherford Appleton laboratory, where the target was irradiated at intensities in the range 3×10^{19} – $5 \times 10^{20} \text{ W cm}^{-2}$. While in thin targets ($5 \mu\text{m}$ targets) there is a clearly evident plasma jet expanding from the target, with increasing thickness the plasma profile presents the features of an ordinary thermal plasma expansion. Numerical and analytical considerations suggest that radiation pressure plays an important role in the formation of these jets [35].

Testing of RPA using circularly polarized pulses and ultra-high contrast pulses is currently the aim of several groups worldwide. This will require the implementation of plasma mirror devices in order to reduce the prepulse level below the plasma formation threshold and allow the use of ultrathin targets. Interaction with ultrathin targets (down to a few nanometres) with linearly polarized pulses has already been investigated in a number of experiments [36–38].

Figure 2. Interferograms of laser-irradiated foils showing jet formation at the target rear: (a) $3\ \mu\text{m}$ Al foil irradiated by 1 ps pulse at $3 \times 10^{19}\ \text{W cm}^{-2}$; (b) $5\ \mu\text{m}$ Cu foil irradiated by a 700 fs pulse at $10^{20}\ \text{W cm}^{-2}$. Probing time: (a) +250 ps; (b) +400 ps with respect to the foil peak irradiation.

An important requirement for many proposed applications of laser-accelerated protons is a narrow energy spread $\Delta E/E \ll 1$, while current laser-driven proton beams have a 100% energy spread. While this would be an inherent feature of RPA as proposed in [30, 32–34], several methods have been considered to achieve this goal with TNSA accelerated ions, including radio-frequency based phase-space rotation techniques, combinations of conventional deflecting magnets with selecting apertures or target engineering relying on an ultrathin light-ion layer deposited on the surface of a higher Z material. Recently, narrow band beams have been obtained by employing such target design [11, 39] through mechanisms in which the ions collected in the band experience the same acceleration history.

We developed an alternative scheme, first tested in experiments at the LULI 100 TW facility and more recently applied at the RAL VULCAN facility, which employs laser-driven transient electrostatic fields for controlling both the spectral and the spatial properties of proton (and higher Z ion) beams [40, 41]. The fields are excited at the inner surface of a metal cylinder ($\sim\text{mm}$ diameter and length) irradiated on the outer surface by a high-intensity laser pulse while a laser-driven proton beam transits through it. The fields act on the protons by modifying their divergence leading to a narrow, collimated beamlet. As the fields are transient, typically lasting for ~ 10 ps, they will affect only the component transiting through the cylinder within this time window, i.e. the cylinder can act as an energy filter, affecting only protons within a narrow energy band which can then be easily extracted from the rest of the beam.

Figure 3(a) shows two consecutive RCF layers in a detector stack, corresponding to protons of approximately 7.6 and 6.2 MeV, respectively—recording the proton beam profile after its propagation through a laser-illuminated cylinder in the standard experimental configuration. The CPA₂ laser pulse triggered the cylinder a few picoseconds after the 7.6 MeV protons exited the cylinder. As expected, these protons propagate unaffected with their natural divergence. In the case of the 6.2 MeV protons, the electric field developed while these protons were still inside the cylinder. As a consequence, they are focused by the developing radial fields, and a small spot about $200\ \mu\text{m}$ $\sim\text{FWHM}$ in diameter (with a 15-fold increase in proton flux, compared with the unfocused case) is seen on the RCF at the centre of the cylinder's shadow. The energy selection properties of the technique were highlighted by directing the focused beam onto a magnetic spectrometer. The focused component with divergence matching the angular aperture of the spectrometer leads to a spike in the energy spectrum, as clearly visible in figure 3(b) showing a 0.2 MeV band at ~ 6 MeV. By collimating the selected beam, this technique is also advantageous in terms of beam transport.

Figure 3. (a), (b) Beam profile, as shown by two different RCF layers, in a RCF stack, corresponding respectively to energies of 7.6 MeV and 6.25 MeV; the cylinder is triggered at a time intermediate to the transit time of protons of these two energies through its exit plane. (c) Gray (green online) line: spectrum obtained under the same triggering conditions as in (a) and (b). Black line: typical exponential spectrum obtained when cylinder is not triggered.

A further experiment carried out at VULCAN, RAL has shown that the position of the spectral peak can be controlled by varying the delay between the two laser pulses. In addition, we carried out measurements in which a thin Cu mesh with 2000 lpi was placed 10 mm after the end of the cylinder [42]. In this way the mesh was backlit by the focused protons, and by observing the mesh magnification on RCF, it was possible to infer at what distance from the cylinder the different energy components, detected on different RCF layers, were focussed. As expected, the data showed an energy dependent focal length, resulting in different mesh magnifications for the different energies. This is due to the different focusing history experienced by different energy components dispersed by time-of-flight and propagating in a time-varying focusing field.

An alternative scheme for beam collimation, in which the focusing fields are self-triggered by the ion accelerating pulse has also been recently demonstrated [43].

4. Radiographic applications for transient field detection

The unique properties of protons from high-intensity laser–matter interactions, particularly in terms of spatial quality and temporal duration, have opened up a totally new area of application of proton probing/proton radiography [18, 19]. This application exploits the ultralow emittance and high degree of laminarity of the source to achieve high spatial resolution when probing samples in a point projection backlighting scheme. In such a configuration, the projection can be treated by considering a virtual source size much smaller ($\sim \mu\text{m}$) than the actual dimensions of the area emitting protons ($\sim 100 \mu\text{m}$) [16]. The ultrashort duration of the emitted bursts ensures high temporal resolution when probing dynamic events. Suitable detection arrangements, such as multilayer packs of dosimetric films or thin track detectors, provide a multiframe temporal capability [18, 19]. Proton radiography can be used as a density diagnostic, by exploiting differential stopping or scattering to reveal static or dynamic variations of aerial density in the sample under investigation [24, 44]. However, the most important applications to date of proton probing are related to the unique capability of this technique to detect electrostatic fields in plasmas. Two experimental arrangements are used for this purpose: *proton projection imaging* [19], where proton deflections by the field are detected via proton density variations in the detector planes, and *proton deflectometry* [14], where the distortion of a mesh pattern imprinted in the proton beam cross section provides a direct measurement

of the deflections. We have been active in this area of application over the past few years, and applied this technique successfully to the detection of highly transient fields in a number of experiments [1, 14, 18, 19]. One should note that this is arguably the only application so far in which laser-driven multi-MeV protons have been employed for a practical use and that this is an application working already well with beam parameters currently available. As already mentioned, the broad spectral content of the beams is here an advantage as it can result in a multiframe temporal capability if a stack detector (of RCF or CR39) is employed [14, 18, 19]. Furthermore, the use of a stack detector permits the selection of a narrow band out of the broad spectrum, which in the case of CR39 can be as narrow as ~ 100 keV if etching time is kept to a minimum [45]. This is mandatory in order to minimize track overlap, which would degrade the spatial information in the CR39 image. This energy resolution compares well with monochromatic sources (fusion products from multi-kJ driven implosions) recently proposed for proton radiography [25, 46], while retaining the advantage of multiframing, and of a significantly higher spatial ($\sim \mu\text{m}$) and temporal ($\sim \text{ps}$) resolution, important for the detection of fast evolving, small-scale features.

The technique has been applied to a broad variety of laser-plasma phenomena. As an example of the potential of this diagnostic approach, we present here some recent experimental results. The sensitivity of the diagnostic to electric and magnetic fields has provided a novel opportunity for investigating physical processes for which experimental evidence has so far been limited or scarce.

In a recent experiment we used proton radiography to study the detect laser-excited collisionless shocks in a low density plasma ($n \sim 10^{15} \text{ cm}^{-3}$) and study their propagation [47]. The shocks are generated following the sudden expansion of a dense plasma into a rarefied ionized background [48, 49]. The dense plasma is produced via direct laser ablation of a solid target with a relatively long (470 ps) and intense ($I \sim 10^{15} \text{ W cm}^{-2}$) laser pulse. It is assumed that the ambient plasma, where the shocks are excited and propagate, is created via photoionization of the residual gas in the target chamber, mainly driven by the thermal radiation emitted from the laser-heated target [46, 47]. The shocks have been observed by using a transverse charged particle probe. The electric field at the shock front has been measured and the shock profile has been reconstructed. This has permitted the identification of different shock typologies, which were interpreted within the framework of the weakly non-linear wave description based on the Korteweg-de Vries–Burgers (KdV–B) equations and identified as the typical solutions of these equations, namely, collisionless shock waves, solitons and soliton trains [50, 51].

Figure 4 shows a typical proton projection image obtained during this experiment. The interaction pulse was focused onto a $25 \mu\text{m}$ thick W target, on which it produced an expanding plasma in the surrounding low pressure ionized gas. At a distance of ~ 1 mm from the focal spot, a clear modulation is observed, which has on the whole a semi-annular shape with an average radius of curvature $R \sim 750 \mu\text{m}$ and a thickness $\Delta R \sim 50 \mu\text{m}$. The modulation consists of an annulus of proton depletion delimited by two thin rings of proton accumulation. This pattern reveals an electric field distribution characterized by a first region where the field points in the inward radial direction followed by a region where the field points in the outward direction. Given that the deflection is small, from the proton density modulation it is possible to reconstruct the profile of the E field causing the deflection via a numerical Abel-like inversion process and ultimately the velocity profile across the shock. These profiles are typical of an ion-acoustic soliton in the KdV–B description, and the inferred parameters are in good agreement with theoretical expectations for the experimental conditions [47].

Phenomena also investigated successfully using proton imaging techniques are the formation and dynamics of electromagnetic structures in the wake of ultraintense laser pulses

Figure 4. Proton projection image of the region in front of a $25\ \mu\text{m}$ W foil irradiated by a 500 ps pulse at $10^{15}\ \text{W cm}^{-2}$ intensity. A shock-like feature is seen at a millimetre distance from the interaction point. A detail is highlighted, and the proton density perturbation is shown.

propagating through underdense plasmas [52, 53]. Figure 4 shows a proton projection image taken 15 ps after the propagation of the VULCAN laser pulse through a low density gas jet. Quasi-regular structures (a series of black dots and white circles) appear in the plasma channel formed by the laser pulse, and develop on timescales of several tens of picoseconds. These structures are being interpreted with the help of PIC simulations and particle tracing simulations. Although an e.m. soliton nature [52] of the structures is in principle a possibility, we tentatively trace these ‘bubbles’ back to patterns of slowly varying fields which in the 2D PIC simulations are observed to grow inside the channel, and have been discussed in [54]. The pattern of the slowly varying magnetic field can be described as a sequence of electron vortices, ‘packed’ into the channel. These are localized, magnetized current loops arising from instabilities in the presence of counterpropagating current sheets (e.g. laser-accelerated electrons and return currents drawn from the plasma by space charge forces) [55, 56]. The internal magnetic pressure causes the vortex to expand slowly sustaining a local depression of the density and a quasi-steady radial electrostatic field (see figure 5(b)). Preliminary particle tracing results through a row of such structures in a plasma channel are shown in figure 5(c). The magnetic field shell contained in the structures appears to defocus the protons at the right of the proton beam axis, creating ‘white’ bubbles and to focus them into dark spots in the left side of the beam, a typology observed in the experimental data.

5. Conclusions

A substantial experimental and theoretical effort is currently devoted to the optimization of the properties of laser-driven ion beams in view of applicative use. Laser-accelerated protons can already be used effectively, with current beam characteristics, as a radiographic source for plasmas below solid density. Other applications will however require a marked improvement of the beams’ characteristics, in terms of peak energies, spectral properties and, in some cases, source repetition. Current developments in PW and multi-PW laser systems will lead in the short/medium term to the availability of intensities in the $10^{22}\ \text{W cm}^{-2}$ range, and, according to projected scaling laws, to proton energies in the right range for hadrontherapy applications. In this context, ponderomotive acceleration schemes also appear very suited to the acceleration

Figure 5. (a) Proton projection image of the plasma formed in the wake of an intense laser pulse (1 ps, $10^{19} \text{ W cm}^{-2}$) propagating in a He gas jet. (b) Diagram showing field distribution observed in structures resulting from evolution of electron vortices in 2D PIC simulations; (c) preliminary particle tracing simulations through a row of three of such structures (aiming to reproduce the experimental *bubbles* observed in the channel in (a)).

of carbon ions [32]. Further, planned laser developments (e.g. [57, 58]) may lead in the longer term to the availability of ultra-high intensity, high repetition sources, which could push the ion energies beyond the GeV/nucleon range and allow further applications in the nuclear/particle physics domain [3, 30].

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