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Laser-accelerated high-energy ions: state of-the-art and applications

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Abstract. The acceleration of high-energy ion beams (up to several tens of MeV per nucleon) following the interaction of short (t < 1ps) and intense ($I\lambda^2 > 10^{18}$ W cm^{-2} μm^{-2}) laser pulses with solid targets has been one of the most important results of recent laser-plasma research. The acceleration is driven by relativistic electrons, which acquire energy directly from the laser pulse and set up extremely large (~TV/m) space charge fields at the target interfaces. In view of a number of advantageous properties, laser-driven ion beams can be employed in a number of innovative applications in the scientific, technological and medical areas. Among these, their possible use in hadrontherapy, with potential reduction of facility costs, has been proposed recently. This paper will briefly review the current state-of-the-art in laser-driven proton/ion source development, and will discuss the progress needed in order to implement some of the above applications. Recent results relating to the optimization of beam energy, spectrum and collimation will be presented.

1. Introduction

One of the most important results recently obtained in laser-plasma interaction experiments is the observation of very energetic beams of ions produced from thin metallic foils [1]. In a number of experiments, performed some years ago with different laser systems and in different interaction conditions, protons with energies up to several tens of MeV were detected behind thin foils irradiated with high intensity pulses [2-4]. These high energy proton beams have fundamentally different properties from lower energy protons observed in earlier work at lower laser intensity with laser pulses in the nanosecond and tens of picosecond regime [5,6], which were accelerated from the coronal plasma and emitted into a large solid angle. Beams produced during these longer interactions exhibited strong trajectory crossing and a broad energy spectrum with typical ion temperatures of ~100 keV/nucleon. These unspectacular characteristics prevented major applications. On the contrary, beams accelerated by ultra-intense laser pulses exhibit a remarkable degree of beam collimation and laminarity, high cut-off energy and emission along the normal to the un-irradiated rear surface of the target. Since the first observations, an extraordinary 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 exceptional accelerator-like spatial quality of the beams, and current research focuses on their optimization for use in a number of groundbreaking applications [1]. The scope of this paper is to report on the state of the art in this area of research, and on the ongoing development and perspectives for future use of these sources.

2. Ion acceleration mechanism

Ion acceleration mechanisms in high-intensity laser-matter interactions are mainly due to 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 laser pulse, and during the high-intensity laser-plasma interaction at the peak of the pulse, electrons will be accelerated forward inside the target through a variety of mechanisms that depend on the interaction and target conditions [7, 8]. These electrons follow typically a relativistic Maxwellian distribution with an effective temperature of the order of the ponderomotive potential of the laser pulse (about 1 MeV for an intensity of 10^{19} W/cm^2 and wavelength of 1 μm) [9].
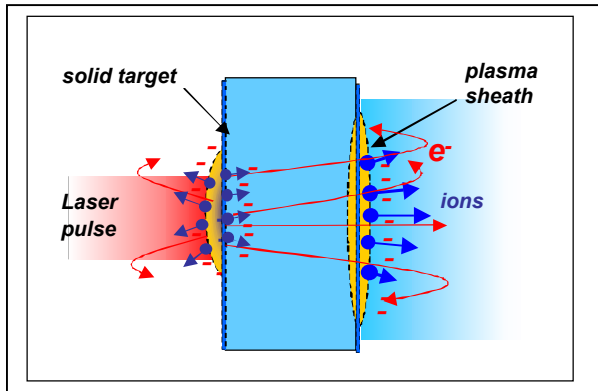

Figure 1. Schematic of ion acceleration process during high-intensity laser foil interaction

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 μm), so that they can easily propagate to the target rear. The target capacitance however allows only a small fraction of electrons to escape before the target is sufficiently charged that escape is near impossible. The fast electrons that are electrostatically confined on the target rear-surface therefore set a charge-separation field over a Debye length [9]. Typically the Debye length is of the order a micron, inducing strong (~TV/m) electric fields. Such fields can ionize atoms and rapidly accelerates 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 it starts from an initially cold surface are essential facts that result in the unique characteristics of the ion beam, as will be detailed in the following sections. After this initial phase, ions stream into vacuum with electrons, preceded by a Debye sheath of hot electrons, as schematically illustrated in figure 1. The charge separation structure at the expansion front results in a peak of the accelerating electric field at the ion front [10]. The most energetic electrons always extend further out into vacuum, maintaining the accelerating field as long as the electron temperature is high. This acceleration from the target rear has been described by several authors [10, 11] as an extension of the classical case of a plasma expanding into vacuum [12], driven by the ambipolar electric field generated in a narrow layer at the front of the plasma cloud. Ion acceleration from the target rear (usually referred to as Target Normal Sheath Acceleration, TNSA) has been studied by many groups both analytically and numerically (mainly by Particle In Cell simulations [1], which are also used as a predictive tool for interaction regimes not yet accessible experimentally [13] and innovative target schemes [14]). Acceleration by an electron-driven ambipolar field can also take place at the front of the target [15], and in the target bulk [16], however at present intensities these phenomena give rise to beams with less interesting characteristics, therefore experimental attention has been mainly focused on forward directed TNSA accelerated beams.

3. Characteristics of laser-driven ion beams

In principle ions of any species can be accelerated via the mechanism described above, by simply changing the bulk component of the target. However in standard experimental conditions (e.g., evacuated vacuum chamber to pressures of 10^{-3}-10^{-4} mbar), a layer of impurities (either hydro-carbon or water-vapour contaminants) is always present at the target surface [5]. The acceleration of protons is more efficient due to the higher charge-mass ratio; therefore most of the hot electron energy is transferred into protons. This is one of the reasons why laser-driven proton acceleration has been studied much more broadly than higher-Z ion acceleration. However, heating [17] or ablation [18] of the target prior to the high-intensity irradiation can be used to eliminate the hydrogen, enhancing the acceleration of heavier ions.

The observation of highly collimated proton beams with multi-MeV energies was first reported independently by three research groups [2 – 4]. In each of these experiments a well-defined proton beam was observed with a roughly exponential spectrum, mean energy in the MeV range and a high-energy cut off in the 10- 55 MeV range. The beam was generally emitted with a low divergence angle, with the most energetic protons having the lowest divergence angle, along the normal to the rear target surface. Following these first measurements, laser-driven ion acceleration has been investigated by many experimental teams under very different physical conditions, and using laser systems with different characteristics. Among published data, the highest proton energies have been achieved using the Nova PetaWatt laser facility at the Lawrence Livermore National Laboratory. A well-collimated, forward-directed ps bunch of 3 x10^{13} protons with energies up to ~60 MeV, and with an energy content up to 48 J, or 12 % of the laser energy, was generated as a result of the interaction of 400 joules, in 1 μm, 0.5 ps laser pulses, focused in a 8 - 9 μm focal spot, producing an intensity up to 3 x 10^{20} W/cm^2, with a 100-μm-thick CH target [3].

Typical proton spectra extend up to a cut-off energy, where the proton number drops abruptly to zero. The various energy components are emitted from the target with different divergence, decreasing as the energy increases [19]. A survey of data as obtained in the various facilities where this phenomenon has been investigated is provided in [1]. 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, as I for shorter laser pulses (40-150 fs). Conversion efficiency into high energy protons varies from less than 1% for the shorter pulses [20] to ~10% for longer pulses and PW power [3, 21]. As mentioned previously, by treating the target surface prior to the high-intensity irradiation, experimenters have demonstrated heavy ion acceleration up to more than 5 MeV/u, i.e. reaching ion energies usually available at the end of conventional accelerators of hundreds of meters in length [17].

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 ps [22], 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 protons of up to 10 MeV, the transverse emittance is as low as 0.004 mm.mrad, i.e. 100-fold better than typical RF accelerators and at a substantially higher ion current (kA range) [23].

4. Proposed applications and requirements

A broad range of applications employing these ion beams has been proposed [1]. An application which has already obtained important results is the use of laser-driven proton beams as a radiography source [24]. 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 configuration, the projection can be treated by considering a virtual source size much smaller (~ μm) than the actual dimensions of the area emitting protons (~ 100 μm) [25] The ultrashort duration of the emitted bursts ensures high temporal resolution when probing dynamic events [22]. Suitable detection arrangements provide a multiframe temporal capability [22, 24]. 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 [26, 27]. 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 [24, 28]. Two experimental arrangements are used for this purpose: *proton imaging* [24], where proton deflections by the field are detected via proton density variations in the detector planes, and *proton deflectometry* [29], where the distortion of a mesh pattern imprinted in the proton beam cross section provides a direct measurement of the deflections. The use of this technique has made possible obtaining for the first time direct information on electric fields arising through a number of laser-plasma interaction processes [22, 24, 30-32]. The technique has been applied to obtain information on the ion acceleration process itself, by detecting the fields causing the acceleration, visualizing the ion front expansion via the associated electric field [32] and validating existing theories on TNSA acceleration [10, 11]. Data from this experiment is shown in figure 2.

Other proposed applications of laser-driven high-energy ions include production of high energy density matter [33] of interest for astrophysics, high-brightness injectors for accelerators [23], use in cancer therapy [34] or radioisotope production [35], or as a fast trigger for Inertial Confinement Fusion pellets [36]. While the currently available beam characteristics are sufficient for some of these applications to be implemented, others will require highly improved beam specifications.
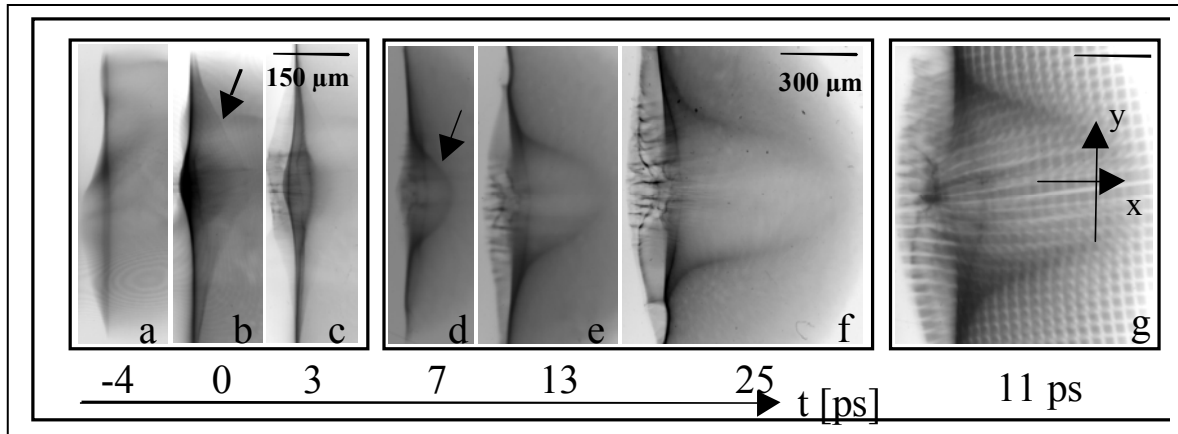

Figure 2. (a-f) Proton projection images and (g) Deflectogram of the rear of a bent foil irradiated at the front by an high-intensity laser pulse. Time delays of the snapshots relative to the peak of the interaction pulses are indicated below the frames. Frames (a) and (f) are collected during the same shot, and show the multiframe capability of this diagnostic.

For example, laser-driven proton sources have been proposed as possible particle probes for diagnosing National Ignition Facility (NIF) implosions [26]. 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 % of the central energy [37]. While 50 MeV beam production has already been demonstrated, the energies in excess of 200 MeV, required for treating deep seated tumours are well beyond current capabilities. In addition, beams currently produced have broad energy spectra and are divergent, therefore methods to reduce the energy spread to acceptable values and to control the beam divergence will need to be developed.

5. Perspective for ion beam optimization

Various routes can be envisaged for increasing the peak proton energies to the values required by some of the applications above. 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. Work suggesting suitable parameter ranges for reaching 200 MeV protons energies via TNSA acceleration has recently been published [38]. In addition, recent Particle in Cell simulations predict much more efficient acceleration (with proton energies scaling as the laser intensity I instead of $I^{0.5}$) as the radiation pressure dominated regime is entered ($I > 5 \times 10^{21}$ W/cm^2 for λ=1 μm) [14]. A different path to higher energy acceleration may be provided by the relativistic transparency regime [39] where simulations predict extremely efficient proton acceleration. In this scheme, the laser pulse interacts with the whole volume of a very thin, dense target and this can accelerate the whole electron population efficiently. This however requires ultra thin targets and therefore ultra-high contrast pulses, so that the peak of the pulse interacts with an unperturbed target. Preliminary experiments accessing such interaction regimes have been carried out using laser pulses with contrast improved by the use of two consecutive plasma mirrors [40]. This has allowed employing targets as thin as 30 nm with no significant reduction of proton energies, despite of a laser energy loss on the plasma mirrors, showing significant promise for this scheme once plasma mirror operation will be optimized.

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. Several methods have been considered to achieve this goal, including radio-frequency based phase-space rotation techniques, combinations of conventional deflecting magnets with selecting apertures, target engineering relying on a ultra-thin light-ion layer deposited on the surface of an higher Z material. Recently, narrow band beams have been obtained by employing such target design [18,41], in which the light-ion layer is depleted before the accelerating field decreases, so all the ions of the layer experience the same acceleration history.

An alternative scheme, recently tested at the LULI 100 TW facility, employs laser-driven transient electrostatic fields for controlling the spectral and spatial properties of proton (and higher Z ion) beams [42]. The fields are excited at the inner surface of a metal cylinder ($\sim$ mm diameter and length) irradiated on the outer surface by a high-intensity laser pulse while a laser-driven proton beam transit 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 $\sim$ 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. Energy selection within a 0.2 MeV band at $\sim$ 6 MeV has so far been demonstrated with this technique, which, by collimating the selected beam, is also advantageous in terms of beam transport.

All these recent achievements testify to the momentum of current research in this area which, if one takes into account the ongoing development in laser technology [8], bodes well for the future applicability of these sources in medical and technological fields.

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