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Nuclear Instruments and Methods in Physics Research A 544 (2005) 55–60
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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M.I-12: short pulse laser generated ion beams for fast ignition

M. Geissel[a,b,*], M. Roth[b], M. Allen[c], P. Audebert[d], M. Basko[e], A. Blažević[b], E. Brambrink[b], J. Cobble[f], T.E. Cowan[g], M.E. Cuneo[a], J.C. Fernández[f], J. Fuchs[g], J.-C. Gauthier[d], M. Hegelich[f], S. Karsch[h]

[a]*Sandia National Laboratories, Albuquerque, NM 87185, USA*
[b]*Darmstadt University of Technology, 64289 Darmstadt, Germany*
[c]*University of California, Berkeley, CA 94720, USA*
[d]*Laboratoire pour l'Utilisation des Lasers Intense, 91128 Palaiseau, France*
[e]*Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia*
[f]*Los Alamos National Laboratories, Los Alamos, NM 87545, USA*
[g]*University of Nevada, Reno, NV 89557, USA*
[h]*Rutherford Appleton Laboratory, Chilton, Oxon OX11 0QX, UK*

Available online 19 March 2005

Abstract

This paper reports the results of a series of experiments on laser generated ions using the 100 TW laser at the 'Laboratiore pour l'Utilisation des Lasers Intenses (LULI)' at the École Polythechnique in Palaiseau, France, and the 30 TW 'Trident' facility at Los Alamos National Laboratories in New Mexico, USA. It shows the importance of the 'Target Normal Sheath Acceleration' process (TNSA) for short pulse laser generated ion beams and its connection to the influence of target properties on the ion beam quality. It is shown that TNSA-generated protons form an ion beam with superior beam quality, following versatile spatial beam shaping approaches. These insights are set into perspective for a fast ignitor scenario based on short pulse laser generated protons.

PACS: 41.75.Jv; 52.38.Kd; 52.40.Kh; 52.57.Kk

Keywords: High-power lasers; Laser generated ions; Fast ignition

1. Introduction

As the compression of DT fuel pellets up to the point of igniting fusion is putting enormous requirements on the driver energy and homogeneity, the idea of an energetic, highly intense 'spark',

*Corresponding author. Sandia National Laboratories, P.O. Box 5800, MS 1193, Albuquerque, NM 87185, USA.
E-mail address: mgeisse@sandia.gov (M. Geissel).

0168-9002/$ - see front matter © 2005 Published by Elsevier B.V.
doi:10.1016/j.nima.2005.01.288

that creates fusion conditions in a small region, is a popular scenario. The 'fast ignitor' is usually thought of as an ultra-intense laser pulse that generates a stream of hot electrons. These electrons can reach the hot and dense core of the compressed fuel and heat it to the necessary temperature, whereas the laser pulse itself cannot penetrate into regions denser than the critical density associated with the laser wavelength [1]. However, the propagation of hot electrons into an extremely dense plasma over a distance of several hundred micrometers poses a difficulty in itself. Instabilities, filamentation and scattering are hard to overcome, thus there is an ongoing discussion involving many experiments to prove or disprove the feasibility of a fast ignitor relying on the heating with hot electrons.

Since the discovery of ultra-intense ion beams generated by Petawatt-class lasers at the NOVA Petawatt facility in 1999 [2,3], the idea of a laser driven proton-fast-ignitor has been developed [4]. Due to the mass induced high rigidity of proton beams, the transport into a dense fusion plasma poses an interesting alternative to hot electrons. To better understand and shape the properties and generation mechanisms of laser generated proton beams, many experiments have been carried out at the most powerful laser installations around the world. A series of experiments at the 100 TW laser of LULI and at the Trident laser has been dedicated to explore the nature of short pulse laser generated ion beams. The main objective was to understand the formation of the electron sheath on the rear surface of the target[a], taking into account the material, surface quality, and geometry of the target.

2. Mechanisms

Regardless of the origin of proton beams, the fundamental process for the generation of proton beams is the acceleration of electrons by the interaction of an ultra intense laser pulse with a preformed plasma. A pre-pulse (either a dedicated second pulse or just amplified spontaneous emission) at a lower energy level heats the front surface of the target foil (several tens of micrometers). Once the main laser pulse hits this pre-plasma, the ponderomotive force of the laser pulse pushes hot electrons forward, which leave a positive space charge. This and the extreme light pressure lead to an acceleration of protons located on the front surface [5,6]. It will be shown, that the main process for the acceleration of highly energetic protons happens at the rear surface due to the TNSA process: As the hot electrons easily reach the multi-MeV regime, they can escape out of the target and leave it positively charged. An immense electric field is created, which pulls many of these electrons back. An equilibrium of newly generated hot electrons, back-pulled electrons and intra-target return currents [7] is established and leads to an electron sheath at the rear target surface. This sheath creates a negative space charge next to a positively charged target, and thus induces an electric field on the order of 10^{12} V/m, orthogonal to the conductive cold rear surface. Thus, this process forms a virtual cathode, similar to the concept used in ion sources for light ion accelerators [8]. Consequently, any light contaminants like hydrogen and carbon are accelerated following this field—mainly normal to the rear surface. In fact, due to its uniquely high charge-to-mass ratio, protons will be preferred by this process, partly shielding the heavier ions left behind from the negatively charged electron sheath. A schematic of the acceleration processes is given in Fig. 1. The sheath formation is crucial to this process and depends on several aspects:

1. *Laser intensity*: The sheath thickness is defined through the kinetic energy (temperature) of the hot electrons, which is a function of $(I\lambda^2)$.

2. *Target material*: As the homogeneity and magnitude of the hot electron current through the target can reach its maximum values with return currents, that counterbalance against the Alfvén-limit, the electric conductivity is of a central importance for the generation of an electron sheath [9].

3. *Target rear surface properties*: As the electron sheath will follow the topography of the rear surface, and the field lines will be normal to this

[a]In this paper, we define the front surface of the target to be facing the laser pulse.

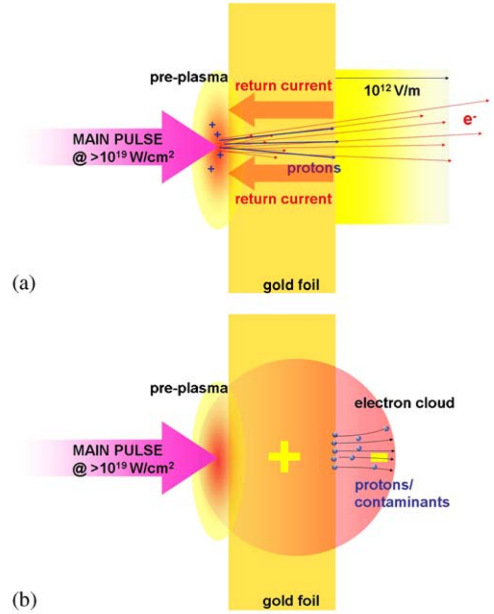

Fig. 1. Schematic of the proton acceleration processes: acceleration of front side protons and generation of high rear side fields (a); established electron cloud (sheath), which accelerates contaminants—mainly protons (b).

surface, the lateral momentum distribution (dispersion) is dependent on the geometry and roughness of the target rear surface.

As the TNSA process is mainly observed at intensities beyond $10^{19}\,W/cm^2$, a variation of intensity was not the main subject of the experiments reported in this paper. The focus of these experiments lies in the investigation of the target influence on the proton beam generation. The strong correlation between variations on the above described relevant factors for TNSA and the response of the ion beam generation will confirm that TNSA is indeed the most relevant process for the generation of highly energetic proton beams.

3. Experiments

All experiments followed a similar pattern, using foils of various materials and thicknesses that are put in focus under normal laser incidence (few experiments were done with tilted targets to examine the relevance of resonance absorption and the dependence of the proton beam direction from the target orientation and the laser incidence direction). The ion beam emerged normal to the rear surface and was analyzed by one or a combination of several of the following diagnostics.

Radiochromic film (RCF): A polymer that images the beam by forming blue color centers when absorbing ionizing radiation.

Ion spectrometers: Charged particles are deflected according to their charge-to-mass ratio in a magnetic field and detected on X-ray sensitive film (DEF). The undeflected γ- and X-rays mark the asymptote for $E_{kin}/m_0c^2 \to \infty$.

Thomson parabolas: Charged particles are deflected in parallel magnetic and electric fields onto separate parabolas for each charge-to-mass ratio. The particles are detected with CR39 nuclear track detectors that have practically no low-energy threshold and are insensitive to γ-radiation. This enables the separation of different ion species.

Interferometer: A laser beam of shorter wavelength (2ω or 3ω) backlights the free-standing foil side-on to investigate the expansion of the plasma plume and the onset of distortion on the rear surface. By interfering with an undisturbed part of the beam, this method is very sensitive to low densities of emerging material.

Further, a second (low energy) short pulse laser was used to probe the TNSA model. A series of experiments with the second laser beam hitting the rear surface at different times, varying in 10 ps-steps, showed that the proton beam stays undisturbed, if the rear surface is not heated during the first 10 ps from the time of the main pulse arrival. If the rear surface is hit before or while the main pulse hits the target, the proton beam is disturbed or even totally suppressed, as there is no possibility to establish an electron sheath next to a well defined target surface. Another clear confirmation of TNSA was the detection of accelerated heavy ions, that had been deposited in a thin layer on the rear surface of a target [10]. To remove all light contaminants, the target had been heated prior to the shot.

Additional experiments with RCF proved efficient in demonstrating the influence of target conductivity, roughness and geometry of the rear surface: plastic foils showed less intense proton beams and strong filamentation, which leads back to the absence of an intra-target return current. Thus, the flow of hot electrons is reduced by the build-up of strong electric fields within the target. Furthermore, the excess of the Alvén limit causes filamentation of the electron flow. These circumstances are reflected in the sheath formation and therefore in the proton beam quality. The sheath is also disturbed by roughening the rear surface of the target, as the RMS roughness is of a similar or larger scale than the sheath itself. Finally, experiments with thin (50 μm) wires proved that the proton beams are emitted normal to the rear surface: the proton beam kept a good collimation along the wire axis (vertical), whereas it spread radially in the plane of curvature (horizontal). The spot-like image of a planar target transforms into a line image, and this line clearly follows the orientation (tilt) of the target wire. Fig. 2(a)–(e) show the RCF imprints of the corresponding experiments.

It was observed that, by structuring the rear surface with a fine line pattern (grid), one introduces lenslets that focus the proton beam and leave a line imprint on the beam profile. By counting the number of lines in the beam imprint, it was possible to determine the source size of the proton emission, which varies with the proton energy between 15 and 60 μm, becoming smaller with increasing energy. The width of the line imprint can be used to measure the transversal beam emittance, which similarly decreased with the proton energy. It could be measured to be smaller than 0.004 mm mrad [11].

The spectral distribution of accelerated protons is continuous and can be approximated with a Maxwellian distribution in the 4–7 MeV regime, with a high energy cut-off up to 25 MeV (varying with different shots and following a $(I\lambda^2)^{0.5}$ scaling [12]). An example of the energy spectra is given in Fig. 3, showing higher energies in the forward direction in comparison to a spectrum recorded under a 13° angle. Although various shots showed peaks in the distribution at 2 and 9 MeV, energetic shaping of the proton beam in order to enhance monochromatic features has not yet been

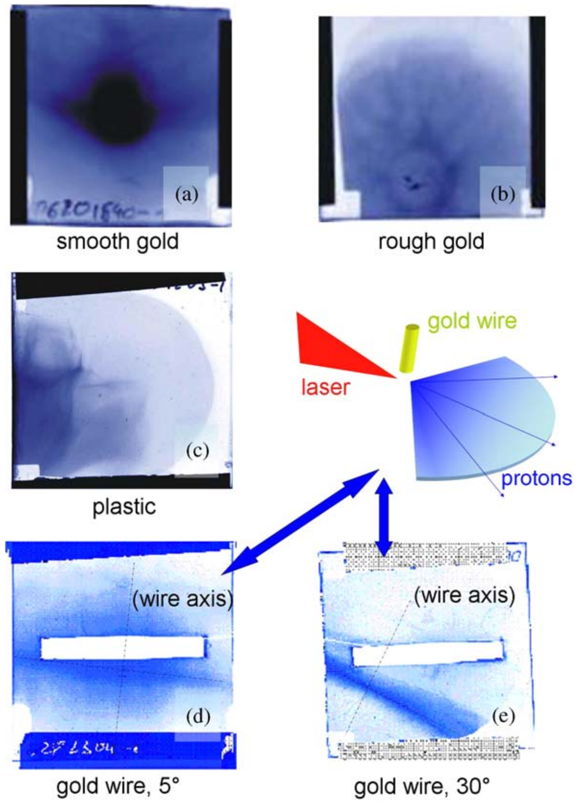

Fig. 2. Radiochromic Film (RCF) imprints for different targets along with a sketch for the wire experiments. The white central area of (e) and (f) is a window for ion spectrometers.

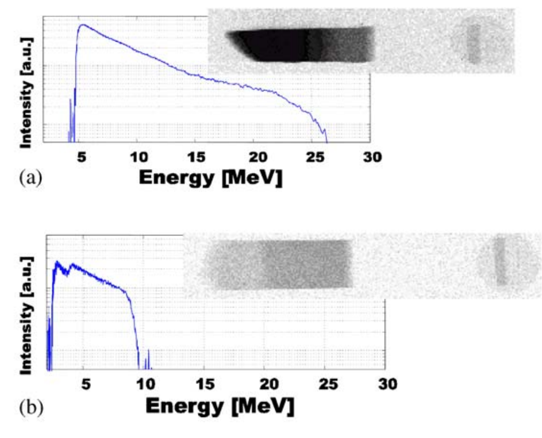

Fig. 3. Example of a proton spectrum recorded at $I \approx 5 \times 10^{19}\,\mathrm{W/cm^2}$ under an observation angle of 0° (a) and 13° (b). The inserted black-and-white pictures show the exposed DEF X-ray film.

achieved. The total amount of protons that have kinetic energies above 4 MeV is approximately 10^{11}, leading to peak currents in the kA range close to the target. The longitudinal distribution thus can be calculated to be less than 10^{-4} eV s [11]. In combination with the above mentioned extremely low-transversal emittance, the beam quality of short pulse laser generated proton beams is superior to conventional accelerators.

4. Fast ignition

With the observation of highly collimated proton beams at the NOVA-Petawatt at Lawrence Livermore National Laboratory first scenarios of a PW-driven proton fast ignitor were developed [4], followed by more detailed studies on the required energy of the proton pulse [13,14]. These studies imply a total ignitor energy of 10–40 kJ, depending on the energy spectra of the proton beam. A promising approach is to choose the proton production target as close as possible (500 μm) to a conical guided fuel pellet and to set the intensity of the laser pulse to achieve a proton beam temperature of ≈ 5 MeV. Thus, approximately 12 kJ of proton energy should be sufficient to ignite the pellet after being pre-compressed in a 210 eV hohlraum [13]. However, the close proximity of the production target to the hohlraum plasma introduces the problem of preserving a cold rear surface and a vacuum acceleration gap. Calculations for a radiation shield in a 160 eV hohlraum arrangement showed that a gold foil of 50 μm thickness will provide sufficient stability (230 μm displacement until moment of ignition) while heating up to 2–3 eV. It may be necessary to add a second thinner foil (10 μm) to protect the proton production target from thermal radiation, which will be emitted by the primary shield. Further studies on this will be done.

Given an efficiency of ≈ 10% for the conversion of laser energy into protons, which has been observed with the NOVA-Petawatt and might be optimized with further development in target studies, a fast ignitor scenario with several beam lines adding up to 100–200 kJ of short pulse energy is demanding yet feasible. A proton production target would have to be shaped like a sphere segment with lenslet-like substructures (pits), thus each proton beam would have optimum collimation and would aim on the same spot. Fig. 4 shows a schematic of a proton fast ignition scenario summarizing the above described requirements. A 50 μm gold foil shields the proton production cavity from the main cavity. Whatever radiation is emitted by this shield is blocked by a 10 μm gold foil, thus the spherical production target with a lenslet for each driver beam remains cold with a vacuum gap on the rear surface.

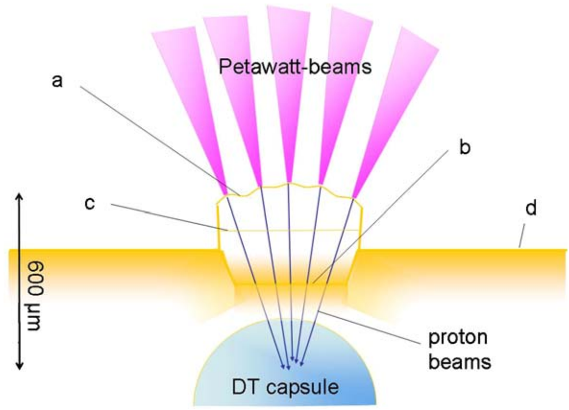

Fig. 4. Schematic for a proton fast ignition scenario with a peripheric cavity consisting of production target (a), main heat shield, 50 μm (b), and secondary heat shield, 10 μm (c) next to the main fusion cavity (d).

5. Summary

It could be shown that laser accelerated protons form a short ion pulse of superior beam quality. The possibility to shape the spatial distribution makes these beams a versatile tool for applications where penetration into dense matter is important. In particular, the use for a fast ignitor in a heavy-ion fusion scenario is a promising approach to overcome problems of the highly demanding driver requirements. A fusion scenario involving multiple Petawatt laser beams for the generation of the ignitor pulse seems demanding but feasible. If progress can be made in tailoring the energy distribution of a proton beam, this scenario will become even more attractive. With the experimental results achieved so far, a proton pulse of a 5 MeV temperature distribution and several 10 kJ of energy shall be sufficient. A double layered gold foil shield will be necessary to protect the proton production target from the high temperatures in the main fusion cavity.

Acknowledgements

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. The experimental program was sponsored by the European Union program HPRI CT 1999-0052 and in addition supported by grant E1127 from Région Ile-de-France, by the "Gesellschaft für Schwerionenforschung mbH (GSI)" in Darmstadt, Germany, by LANL Laboratory Directed Research and Development, and by General Atomics in San Diego.

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