Laser and Particle Beams (2005), *23*, 291–295. Printed in the USA.

DOI: 10.1017/S0263034605050408

High-intensity laser-plasma interaction studies employing laser-driven proton probes*

M. BORGHESI,[1] P. AUDEBERT,[2] S.V. BULANOV,[3] T. COWAN,[4] J. FUCHS,[2] J.C. GAUTHIER,[5] A.J. MACKINNON,[6] P.K. PATEL,[6] G. PRETZLER,[7] L. ROMAGNANI,[1] A. SCHIAVI,[8] T. TONCIAN,[8] AND O. WILLI[8]

[1]School of Mathematics and Physics, The Queen's University of Belfast, United Kingdom
[2]Laboratoire pour l'Utilisation des Lasers Intenses, Ecole Polytechnique-CNRS, Palaiseau, France
[3]Advanced Photon Research Center, Kansai Research Establishment, JAERI, Kyoto, Japan
[4]Nevada Terawatt Facilities, University of Nevada, Reno
[5]CELIA, Université Bordeaux I Talence, France
[6]Lawrence Livermore National Laboratory, Livermore, California
[7]Institut für Laser- und Plasmaphysik, Heinrich-Heine-Universitaat, Düsseldorf, Germany
[8]Dipartimento di Energetica, Universita' di Roma "La Sapienza", Roma, Italy

(RECEIVED 22 November 2004; ACCEPTED 7 January 2005)

Abstract

Due to their particular properties (low emittance, short duration, and large number density), the beams of multi-MeV protons generated during the interaction of ultraintense ($I > 10^{19}$ W/cm^2) short pulses with thin solid targets are suited for use as a particle probe in laser-plasma experiments. When traversing a sample, the proton density distribution is, in general, affected by collisional stopping, scattering and deflections via electromagnetic fields, and each of these effects can be used for diagnostic purposes. In particular, in the limit of very thin targets, the proton beams represent a valuable diagnostic tool for the detection of quasi-static electromagnetic fields. The proton imaging and deflectometry techniques employ these beams, in a point-projection imaging scheme, as an easily synchronizable diagnostic tool in laser- plasma interactions, with high temporal and spatial resolution. By providing diagnostic access to electro-magnetic field distributions in dense plasmas, this novel diagnostics opens up to investigation a whole new range of unexplored phenomena. Several transient processes were investigated employing this technique, via the detection of the associated electric fields. Examples provided in this paper include the detection of pressure-gradient electric field in extended plasmas, and the study of the electrostatic fields associated to the emission of MeV proton beams in high-intensity laser-foil interactions.

Keywords: Electric field measurements; Laser acceleration of ions; Laser-plasma interactions; Proton probing

1. INTRODUCTION

In a number of experiments, performed in recent years 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 (Clark *et al*., 2000; Snavely *et al*., 2000; Borghesi *et al*., 2002*d*). Since the first observations, an extraordinary amount of experimental and theoretical work was devoted to the study of the beam's characteristics and production mechanisms. This work was motivated by the exceptional accelerator-like spatial quality of the beams (Borghesi *et al*., 2004; Cowan *et al*., 2004; Roth *et al*., 2005), their ease of production and by other unique properties, leading to their possible use in a number of ground breaking applications (Pegoraro *et al*., 2004; Faenov *et al*., 2004; Issac *et al*., 2003; Deutsch, 2003). One of the applications is particle probing of plasmas for detection of electric and magnetic fields with high temporal and spatial resolution, in the proton imaging, and deflectometry arrangements (Borghesi *et al*., 2002*a*, 2002*c*).

The mechanism leading to the acceleration of the multi-MeV proton beams from laser-irradiated foils was object of discussion since the first experimental observations. During the interaction with the front surface plasma, high-intensity laser pulses transfer their energy via a number of processes to a population of forward-directed hot electrons. The space-

Address correspondence and reprint requests to: M. Borghesi, Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast BT7 1NN, United Kingdom. E-mail: m.borghesi@qub.ac.uk
*This paper was presented at the 28th ECLIM conference in Rome, Italy.

charge force caused by the electron displacement can accelerate the target ions (with most of the energy transferred to protons, generally present in every type of target as surface impurities) (Davies, 2002; Shorokhov & Pukhov, 2004). For thin foils, the most effective acceleration is predicted to take place at the target rear surface (Pommier & Lefebvre, 2003), where escaping electrons are retained by target charge-up and create a Debye sheath (Wilks *et al.*, 2001). For intensities in the 10^{19} W/cm^2 regime, peak accelerating electric fields exceeding 10^{12} V/m are predicted to take place. The shape of the sheath will be strongly dependent on the spatial distribution of the electrons reaching the rear of the target. The ion acceleration and expansion process can then be treated as the expansion of a plasma into vacuum (Mora, 2003; Passoni & Lontano, 2004) driven by a population of hot electrons.

We review here investigations of high-intensity laser-plasma interaction carried out by employing the proton probing diagnostics. After a brief description of the experimental method, we will provide examples of its application, including one in which the technique was employed to gather information on the proton acceleration process itself.

2. RADIOGRAPHY AND IMAGING WITH LASER-ACCELERATED PROTONS

The use of ion beams, and particularly proton beams, for radiographic applications was first proposed in the 1960s. Quasi-monochromatic beams of ions from conventional accelerators were used for detecting spatially resolved aerial density variations in samples (Koehler, 1968). Beams of ions from accelerators were also employed on some occasions for electric field measurements in plasmas, via the detection of the ion deflection. In practice, the difficulties and high cost involved in coupling externally produced particle beams of sufficiently high energy to laser-plasma experiments (or indeed magnetic confinement experiments) and the relatively long duration of ion pulses produced from conventional accelerators, limited the application of such diagnostic techniques. The unique properties of protons from high intensity laser-matter interactions, particularly in terms of spatial quality and temporal duration, opened up a totally new area of application of proton probing/proton radiography. Several experiments were carried out in which laser-driven proton beams were employed as a back lighter for static and dynamic target assemblies, in some cases a secondary target irradiated by a separate laser pulse. A general schematic for this type of experiments is presented in Figure 1.

The protons emerging from a laser-irradiated foil can be described as emitted from a virtual, point-like source located in front of the target (Borghesi *et al.*, 2004). A point-projection imaging scheme is therefore automatically achieved. The magnification of the system is determined by $M = 1 + L/h$, with L and h, respectively, the object-to-detector and source-to-object distances. Electric or magnetic fields in the sample region can be revealed by the proton deflection and

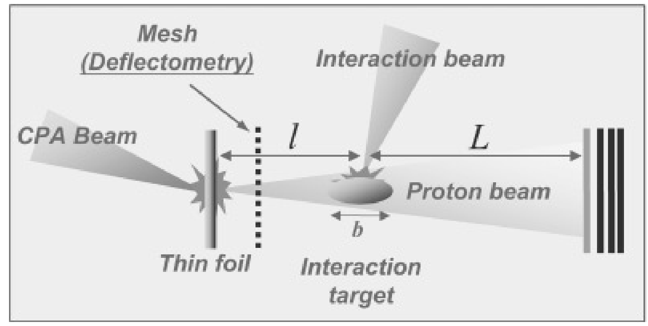

Fig. 1. Set-up for high intensity proton probing experiments.

the associated modifications in the proton density pattern. The detector employed in proton radiography/probing experiments consists mainly of radiochromic films (RCF), often arranged in a multilayer package. The equivalent dose of energetic protons stopped in each layer can be measured from the changes in optical density undergone by the film, yielding information on the number and energy of the protons. Since protons deposit energy mainly in the Bragg peak at the end of their range, and the number of the protons decreases with their energy, the signal on each active layer is mainly due to protons having energies within a narrow range

As mentioned above, back lighting with laser-driven protons has intrinsically high spatial resolution, which in absence of scattering-related degradation, is mainly determined by the size δ of the virtual proton source. The ultimate limit of the temporal resolution is given by the duration of the proton burst τ at the source, which is of the order of the pulse duration for near-ps pulses. However, other effects are also important: the finite energy resolution of the detector layers and the finite transit time of the protons through the region where the fields are present normally limit the resolution to a few ps.

Energy dispersion provides the technique with an intrinsic multi-frame capability (Borghesi *et al.*, 2003). Depending on the experimental conditions, two-dimensional (2D) proton deflection map frames spanning up to 100 ps can be obtained in a single shot.

3. E-FIELD DETECTION

Probably the most important applications to date of proton probing are related to the unique capability of this technique to detect electrostatic fields in plasmas. This has allowed obtaining for the first time direct information on electric fields arising through a number of laser-plasma interaction processes. The high temporal resolution is here fundamental in allowing the detection of highly transient fields following short pulse interaction.

When the protons cross a region with a non-zero electric field they are deflected by the transverse component $E_{\perp}$ of the field. The proton transverse deflection at the proton detector plane is equal to $\Delta \mathbf{r}_\perp \approx eL\int_0^b (\mathbf{E}_\perp/m_p v_p^2)\, dl$ where $m_p v_p^2/2$ is the proton kinetic energy, e its charge, b the distance over which the field is present, and L the distance from the object to the detector. As a consequence of the deflections, the proton beam cross-section profile undergoes variations showing local modulations in the proton density.

Assuming the proton density modulation to be small $\delta n/n_0 \ll 1$, where n_0 and δn are, respectively, the unperturbed proton density and proton density modulation at the detector plane, we obtain $\delta n/n_0 \approx -|div(\Delta \mathbf{r}_\perp)|/M$ where M is the geometrical magnification. The value of the electric field amplitude and spatial scale can then be determined if a given functional dependence of $E_\perp$ can be inferred *a priori*, that is, from theoretical or geometrical considerations. Thin meshes inserted in the beam (between the proton source and the object) are sometimes used as "markers" of the different parts of the proton beam cross sections, in a proper proton deflectometry arrangement particularly suited to reveal relatively large scale fields (Mackinnon *et al*., 2004). The meshes impress a modulation pattern in the beam before propagating through the electric field configuration to be probed. The beam is so effectively divided in a series of beamlets, and their deflection can be obtained directly from the deflection of the impressed pattern. A general analysis method, applicable to both proton imaging and proton deflectometry data, consists in using particle tracing codes to follow the propagation of the protons through a given three-dimensional (3D) field structure, which can be modified iteratively until the computational proton profile reproduces the experimental ones. State-of-the-art tracers allow realistic simulations including experimental proton spectrum and emission geometry, as well as detector response.

4. RECENT EXPERIMENTAL MEASUREMENTS

In this section we will provide some examples of applications of the techniques, carried out in recent experiments. In order to give an idea of the range of applicability of proton probing for electric field detection we will briefly discuss an example of probing of a slowly evolving plasmas created by a long pulse, and an example of field detection in ultrashort pulse laser-plasma interaction. For a more detailed description of already published results, we refer the reader to previous works (Borghesi *et al*., 2002*a*, 2002*b*, 2003).

The first experiment using the mesh deflectometry technique was carried out on the 100 TW LULI laser at the Ecole Polytechnique, France. In this experiment a 300 ps duration interaction beam with 1.054 μm wavelength and 50 J energy was focused at an irradiance of 0.5–1 $\times 10^{16}$ Wcm^{-2} onto the surface of a 125 μm copper wire target.

The fields produced during this interaction were diagnosed by passing a MeV proton through the plasma region at 90° to the interaction beam onto a multi-layer film pack (side-on imaging). The proton beam was produced by focusing a 20 J pulse of duration 300 fs and 1.054 μm wavelength onto a solid tungsten target at an irradiance exceeding 10^{19} Wcm^{-2}. A deflectogram obtained from 10 MeV protons passing through the plasma, at the peak of the interaction pulse is shown in Figure 2. The laser is incident from the right and the position of the plasma is clearly recognizable via the localized perturbation of the mesh pattern.

The electric field configuration causing the deflection was reconstructed by means of 3D particle tracing. The amplitude and spatial distribution of the field appear to be consistent with the pressure gradient field $E = -\nabla p/ne$, where p and n are electron pressure and density (Mackinnon *et al*., 2004).

As mentioned before, the temporal resolution of the technique makes it ideal for the detection of highly transient fields. A recent experiment also carried out at the LULI laboratory, aimed to investigate by means of proton probing, the transient fields driving the acceleration and expansion of MeV protons from thin foils laser-irradiated at high intensity. A first CPA laser pulse was focused onto a 10 μm thick gold foil (proton target) at an intensity exceeding 10^{19} W/cm^2 in order to accelerate a proton beam. The proton beam was used as a back-lighter for the rear surface of a second foil (interaction target, 10 to 40 μm thick aluminum or gold) on which a second CPA pulse was focused at intensity of the order of 10^{18} W/cm^2. The relative delay of the two CPA pulses could be changed from shot to shot and varied with ps precision. The interaction target design was chosen in order to minimize the effect of global charge-up which had been observed in previous experiments with

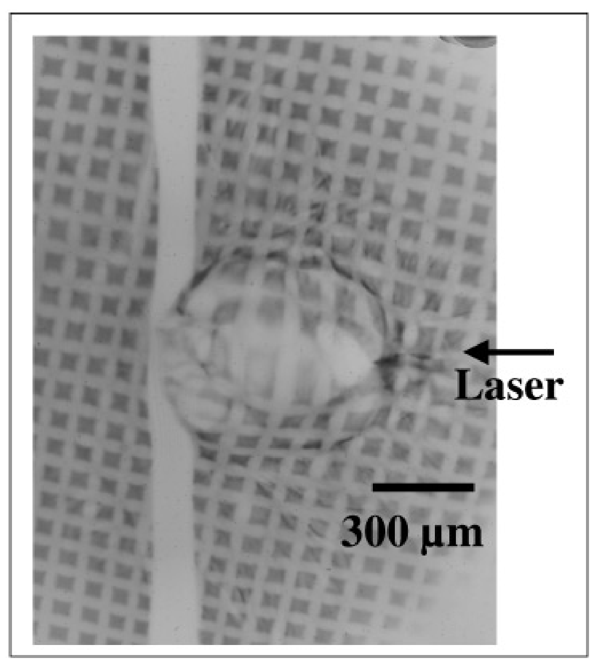

Fig. 2. Proton deflectogram of plasma produced by irradiating a 125 μm Cu wire with a 600 ps, 50 J laser pulse.

https://doi.org/10.1017/S0263034605050408 Published online by Cambridge University Press

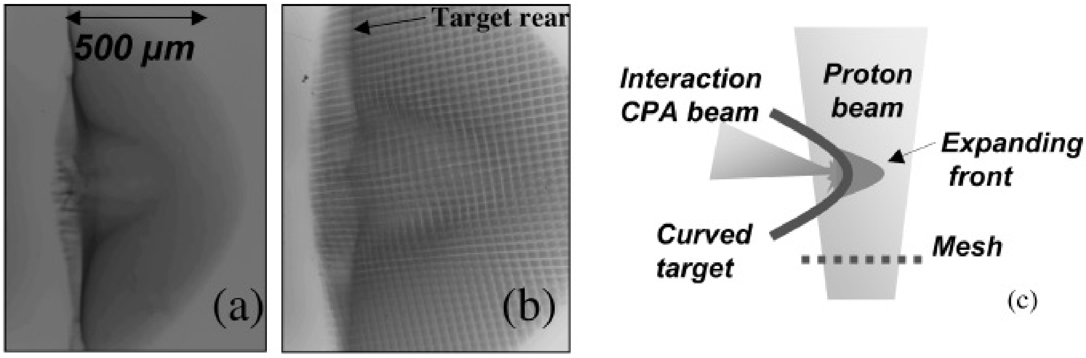

Fig. 3. Proton image (**a**) and deflectogram (**b**) of the region behind a laser-irradiated curved target. The interaction pulse parameters were: 1 μm wavelength, pulse duration 1 ps, intensity $\sim 10^{18}$ W/cm^2. The images (a) and (b) were taken in separate shots, respectively, 7 and 80 ps after the interaction. A schematic of the experiment is given in (**c**).

highly energetic CPA pulses (Borghesi *et al*., 2003) and which would have prevented from probing close to the target surface.

A well defined bell-shaped front, expanding from the rear surface of the interaction target, was observed in proton imaging and deflectometry data (see Fig. 3). By comparing information from the imaging and deflectometry data, one can infer an electric field (of the order of 10^9 V/m) peaking at the front and almost constant behind it, as consistent with existing models (Mora, 2003). In order to reconstruct the exact value and structure of the electric field, recursive 3D particle tracing simulations are currently undergoing.

5. CONCLUSIONS

Probing with laser accelerated MeV proton beams is an emerging technique which exploits the unique emission properties of the beams to achieve electric and magnetic field detection in laser-plasma experiments with extremely high temporal and spatial resolution. This widely expands the diagnostic possibilities of the laser-plasma interaction research area and offers the possibility of studying a range of new physical processes.

ACKNOWLEDGMENTS

The authors acknowledge the support of the EU program HPRI CT 1999-0052, of Grant No. E1127 from Region Ile-de-France, of a Royal Society Study Visit grant, of the British Council-MURST-CRUI British-Italian Partnership program, and of the QUB-IRCEP Fellowship/Professorship scheme.

REFERENCES

Borghesi, M., Campbell, D.H., Schiavi, A., Haines, M.G., Willi, O., Mackinnon, A.J., Patel, P., Gizzi, L.A., Galimberti, M., Clarke, R.J., Pegoraro, F., Ruhl, H. & Bulanov, S.V. (2002*a*). Electric field detection in laser-plasma interaction experiments via the proton imaging technique. *Phys. Plasmas* **9**, 2214–2218.

Borghesi, M., Bulanov, S.V., Campbell, D.H., Clarke, R.J., Esirkepov, T.Zh., Galimberti, M., Gizzi, L.A., Mackinnon A.J., Naumova, N., Pegoraro, F., Ruhl, H., Schiavi, A. & Willi, O. (2002*b*). Macroscopic evidence of soliton formation in multiterawatt laser plasma interaction. *Phys. Rev. Lett.* **88**,135002.

Borghesi, M., Campbell, D.H., Schiavi, A., Willi, O., Mackinnon, A.J., Hicks, D., Patel, P., Gizzi, L.A., Galimberti, M. & Clarke, R.J. (2002*c*). Laser-produced protons and their application as a particle probe. *Laser Part. Beams* **20**, 269–275; Erratum, **20**, 641.

Borghesi, M., Campbell, D.H., Schiavi, A., Willi, O., Galimberti, M., Gizzi, L.A., Mackinnon, A.J., Snavely, R.D., Patel, P., Hatchett, S., Key, M., & Nazarov, W. (2002*d*). Propagation issues and energetic particle production in laser–plasma interactions at intensities exceeding 1019 W/cm^2. *Laser Part. Beams* **20**, 31–38.

Borghesi, M., Romagnani, L., Schiavi, A., Campbell, D.H., Willi, O., Mackinnon, A.J., Galimberti, M., Gizzi, L.A., Clarke, R.J. & Hawkes, S. (2003). Measurement of highly transient electrical charging following high-intensity laser-solid interaction. *App. Phys. Lett.* **82**, 1529–1532.

Borghesi, M., Mackinnon, A.J., Campbell, D.H., Hicks, D.G., Kar, S. Patel, P.K., Price, D., Romagnani, L., Schiavi, A. & Willi, O. (2004). Multi-MeV proton source investigations in ultraintense laser-foil interactions. *Phys. Rev. Lett.* **92**, 055003.

Clark, E.L, Krushelnick, K., Davies, J.R., Zepf, M., Tatarakis, M., Beg, F.N., Machacek, A., Norreys, P.A., Santala, M.I.K., Watts, I. & Dangor, A.E. (2000). Energetic Heavy-Ion and Proton Generation from Ultraintense Laser-Plasma Interactions with Solids. *Phys. Rev. Lett.* **84**, 670–673.

Cowan, T.E. Fuchs, J., Ruhl, H., Kemp, A., Audebert, P., Roth, M., Stephens, R., Barton, I., Blazevic, A., Brambrink, E., Cobble, J., Fernández, J., Gauthier, J.C., Geissel, M., Hegelich, M., Kaae, J., Karsch, S., Le Sage, G.P., Letzring, S., Manclossi, M., Meyroneinc, S., Newkirk, A., Pépin, H. & Renard-Legalloudec, N. (2004). Ultralow Emittance, Multi-MeV Proton Beams from a Laser Virtual-Cathode Plasma Accelerator. *Phys. Rev. Lett*. **92**, 204801.

Davies, J.R. (2002). Proton acceleration by fast electrons in laser–solid interactions. *Laser Part. Beams* **20**, 243–253.

Deutsch, C. (2003). Transport of megaelectron volt protons for fast ignition. *Laser Part. Beams* **21**, 33–35.

Faenov, A., Pikuz, T., Magunov, A., Batani, D., Lucchini, G., Canova, F. & Piselli, M. (2004). Bright X-ray point source based on a commercial potable 40 ps Nd:YAG laser system. *Laser Part. Beams* **22**, 373–379.

Issac, R., Wirthig, J., Brunetti, E., Vieux, G., Ersfeld, B., *et al*. (2003). Bright source of Kα and continuum X-rays by heating Kr clusters using a femtosecond laser. *Laser Part. Beams* **21**, 535–540.

Koehler, A.M. (1968). Proton radiography. *Science* **160**, 303.

Mackinnon, A.J., Patel, P.K., Town, R.J., Edwards, M.J., Phillips, T., Lerner, S.C., Price, D.W., Hicks, D., Key, M.H., Hatchett, S., Wilks, S.C., Borghesi, Kar, S., Romagnani, L., Toncian, T., Pretzler, G., Willi, O., Koenig, M., Martinolli, E., Lepape, S., Benuzzi-Mounaix, A., Audebert, P., Gauthier, J.C., King, J., Snavely, R., Freeman, R.R. & Boehlly, T. (2004). Proton radiography as an electromagnetic field and density perturbation diagnostic. *Rev. Sci. Inst.* **75**, 3531–3536.

Mora, P. (2003). Plasma expansion into a vacuum. *Phys. Rev. Lett.* **90**, 185002.

Passoni, M. & Lontano, M. (2004). One-dimensional model of the electrostatic ion acceleration in the ultraintense laser–solid interaction. *Laser Part. Beams* **22**, 163–169.

Pegoraro, F., Atzeni, S., Borghesi, M., Bulanov, S., Esirkepov, T., Honrubia, J., Kato, Y., Khoroskhov, V., Nishihara, K., Tajima, T., Temporal, M. & Willi, O. (2004). Production of ion beams in high power laser plasma interaction and their application. *Laser Part. Beams* **22**, 19–24.

Pommier, L. & Lefebvre, E. (2003). Simulations of energetic proton emission in laser–plasma interaction. *Laser Part. Beams* **21**, 573–581.

Roth, M., Brambrink, E., Audebert, P., Blazevic, A., Clarke, R., Cobble, J., Cowan, T.E., Fernandez, J., Fuchs, J., Geissel, M., Habs, D., Hegelich, M., Karsch, S., Ledingham, K., Neely, D., Ruhl, H., Schlegel, T. & Schreiber, J. (2005). Laser accelerated ions and electron transport in ultra-intense laser matter interaction. *Laser Part. Beams* **23**, 95–100.

Snavely, R.A., Key, M.H., Hatchett, S.P., Cowan, T.E., Roth, M., Phillips, T.W., Stoyer, M.A., Henry, E.A., Sangster, T.C., Singh, M.S., Wilks, S.C., Mackinnon, A., Offenberger, A., Pennington, D.M., Yasuike, K., Langdon, A.B., Lasinski, B.F., Johnson, J., Perry, M.D. & Campbell, E.M. (2000). Intense high-energy proton beams from petawatt laser irradiation of solids. *Phys. Rev. Lett.* **85**, 2945–2948.

Wilks, S.C., Langdon, A.B., Cowan, T.E., Roth, M., Singh, M., Hatchett, S., Key, M.H., Pennington, D. Mackinnon, A.J. & Snavely, R.A. (2001). Energetic proton generation in ultra-intense laser–solid interactions. *Phys. Plasmas* **8**, 542–546.