Impulsive electric fields driven by high-intensity laser matter interactions

M. BORGHESI,1 S. KAR,1 L. ROMAGNANI,1,3 T. TONCIAN,3 P. ANTICI,3 P. AUDEBERT,3 E. BRAMBRINK,3 F. CECCHERINI,4 C.A. CECCHETTI,1 J. FUCHS,3 M. GALIMBERTI,5 L.A. GIZZI,5 T. GRISMAYER,6 T. LYESEKINA,4 R. JUNG,2 A. MACCHI,5 P. MORA,6 J. OSTERHOLTZ,2 A. SCHIAVI,7 and O. WILLI2

1School of Mathematics and Physics, The Queen’s University of Belfast, Belfast, United Kingdom
2Heinrich Heine Universität Düsseldorf, Düsseldorf, Germany
3Laboratoire pour l’Utilisation des Lasers Intenses, UMR 7605 CNRS-CEA-Ecole Polytechnique-University Paris VI, Palaiseau, France
4Istituto Nazionale per la Fisica della Materia (INFM), Dipartimento di Fisica “E. Fermi,” Universita’ di Pisa, Pisa, Italy
5Istituto per i Processi Chimico Fisici-Consiglio Nazionale delle Ricerche, Pisa, Italy
6Centre de Physique Theorique, UMR 7644, CNRS-Ecole Polytechnique, Palaiseau, France
7Dipartimento di Energetica, Universita’ di Roma 1 “La Sapienza,” Roma, Italy

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Abstract

The interaction of high-intensity laser pulses with matter releases instantaneously ultra-large currents of highly energetic electrons, leading to the generation of highly-transient, large-amplitude electric and magnetic fields. We report results of recent experiments in which such charge dynamics have been studied by using proton probing techniques able to provide maps of the electrostatic fields with high spatial and temporal resolution. The dynamics of ponderomotive channeling in underdense plasmas have been studied in this way, as also the processes of Debye sheath formation and MeV ion front expansion at the rear of laser-irradiated thin metallic foils. Laser-driven impulsive fields at the surface of solid targets can be applied for energy-selective ion beam focusing.

Keywords: High-intensity laser-matter interaction; Hot electron dynamics; Ion acceleration; Ion focusing; Proton probing

1. INTRODUCTION

During the interaction of high-intensity laser pulses with matter highly-transient, large-amplitude electric and magnetic fields are generated either by space-charge separation or by the flow of large currents of relativistic electrons. These fields play a role of fundamental importance in many laser-plasma processes. Electric fields due to charge separation can drive the expansion of the ions of the plasmas, leading to production of ion beams in interaction with thin foils (Borghesi et al., 2006; Roth et al., 2005), or to Coulomb explosion of plasma channels in interaction with underdense plasmas (Borghesi et al., 1998). A major step forward in the detection of such fields has been marked by the development of the proton imaging and deflectometry techniques (Borghesi et al., 2002a, 2002c; Mackinnon et al., 2004), which employing laser-driven protons as a particle probe (Borghesi et al., 2004), have proven to be an exceptionally useful tool for the investigation of ultrafast plasma dynamics. In this paper, after a brief discussion of the principles of the technique, we will present results from some recent experiments in which proton probes have been used to investigate the electron and ion dynamics initiated by high-intensity interaction. An application of transient, laser-initiated fields for control of the angular, and spectral properties of a proton beams will also be discussed.

2. PROTON PROBING TECHNIQUES

The unique properties of protons from high intensity laser-matter interactions, particularly in terms of spatial quality and temporal duration (Borghesi et al., 2006), have opened up a totally new area of application of proton probing/proton radiography. Several experiments have been carried

Address correspondence and reprint requests to: M. Borghesi, Department of Physics and Astronomy, The Queen’s University of Belfast, Belfast BT7 1NN, United Kingdom. E-mail: m.borghesi@qub.ac.uk
out in which laser-driven proton beams have been employed as a backlighter for static and dynamic target assemblies, in some cases, a secondary target irradiated by a separate laser pulse. The proton beams emitted from a laser-irradiated foil are highly laminar (Cowan et al., 2004), and for projection purposes, can be described as emitted from a virtual, point-like source located in front of the target (Borghesi et al., 2004; Brambrink et al., 2006; Ruhl et al., 2006). A point-projection imaging scheme is therefore automatically achieved. The unique capability of this technique to detect electrostatic fields in plasmas has allowed for the first time the retrieval of direct information on electric fields arising through a number of laser-plasma interaction processes. The high temporal resolution, related to the ps duration of the proton burst at the source, is here fundamental in allowing the detection of highly transient fields following short pulse interaction.

Thin meshes inserted in the beam (e.g., between the proton source and the object) are sometimes used as “markers” for the different parts of the proton beam cross sections, in a proper proton deflectometry arrangement (Mackinnon et al., 2004; Borghesi et al., 2005). Alternatively, in the proton projection imaging arrangement, the modulations in proton density across the probe cross section or caustics due to trajectory intersection can be related to the field distribution by particle tracing codes, which follow the propagation of the protons through a given three-dimensional field structure. This can be modified iteratively until the computational proton profile reproduces the experimental one.

3. SPACE-CHARGE FIELDS AND CHANNEL FORMATION IN UNDERDENSE PLASMA INTERACTIONS

Using the proton imaging technique, we have recently investigated the interaction of a high intensity ($\approx 10^{19}$ W/cm$^2$) laser pulse with underdense plasma. The experiment was performed using the 100 TW VULCAN laser at the Rutherford Appleton Laboratory (Danson et al., 1998). The dual Chirped Pulse Amplification mode (CPA) configuration was employed, providing two CPA pulses with adjustable relative delays at ps precision. Each of the output beams delivered approximately 50 J in 1.2 ps (full width at half maximum; FWHM) duration. By using off-axis parabolas, the beams were focused down, on different targets, to spots of 10 $\mu$m FWHM, with peak intensity exceeding $10^{19}$ W/cm$^2$. One of the beams interacted with the He gas from a supersonic nozzle driven at 50 bar pressure. The other CPA beam was employed to generate the probe proton beams by irradiating it onto a foil (a 10 $\mu$m thick Au foil was typically used). Proton beams were observed having a quasi-Maxwell–Boltzmann energy spectrum with temperature and cut-off energy of 3 MeV and 18 MeV, respectively. The detector was a multilayered Radio-chromic film (RCF) detector, placed at a distance of 2–3 cm from the gas jet. In the condition of the experiment, this provided a multi-frame temporal scan of the interaction for up to 50 ps in a single shot (Borghesi et al., 2002a).

The propagation of the laser pulse through the plasma and the subsequent plasma evolution were observed via time-resolved proton-projection images (Fig. 1). In the images, the coordinates $x$ and $y$ refer to the object (interaction) plane, which intersects the probe axis at $x = 0$ and $y = 0$. Each frame detects protons of a given energy $E$ and is labeled according to the arrival time $t_0(E)$ at the object plane of the protons traveling along the probe axis, relative to a reference time $t = 0$ that corresponds to the estimated arrival of the peak of the pulse. Within a layer, the probing time varies as a function of $x$ due to the divergence of the proton beam and the different times of flight (source to object plane) of the probe protons reaching different $x$ positions. Figure 2 shows different frames from the same shot (obtained at an intensity of $4.0 \times 10^{18}$ Wcm$^{-2}$). The laser pulse propagates from left to right. A “white” channel with “dark” boundary and a “bullet” shaped leading edge is clearly visible in Figures 2a and 2b. The channel appears to move along the axis, and if one considers the above timing corrections, its propagation velocity can be estimated to be in the order of $c$.

In the trail of the channel the proton flux distribution around the axis changes qualitatively (see Fig. 1c), showing a dark line along the axis, which is observed up to tens of ps after the pulse peak transit. Figure 2d shows another proton image, obtained in a different shot at higher intensity ($1.5 \times 10^{19}$ Wcm$^{-2}$). The features observed in Figure 2c are even more pronounced and clearly visible.

While the “white” channel (as well as the “bullet” shaped leading part) feature indicates the presence of an electric field which points outward, along the radial direction, the central dark line observed at later times in the channel, suggests that at a second stage the radial electric field must change its sign at some radial position (in other words, the radial field points inward in the vicinity of the axis and outward at larger distances from it), focusing the probe protons toward the axis. This happens as the ion starts moving under the effect of the space-charge field and a cylindrical ion front expands around the laser axis.

At even later times, typically in the order of 6–8 ps, the development of quasi-periodic modulations inside the channel was observed. These structures evolved into circular structures which were observed to decay in hydrodynamic time scales. These structures are tentatively being interpreted as being related to the growth of solitons inside the channel. Solitons form in high-intensity interactions due to trapping of the red shifted electromagnetic radiation by the ambient plasma, which behaves as overdense for them (Bulanov et al., 1999; Lontano et al., 2003). Due to the ponderomotive force, they expel the electrons from the core producing a positively charged sphere, which deflects protons, and are imprinted over the RCF as a “white” region (Borghesi et al., 2002b).

The main features of the observed channel in the experimental data are qualitatively reproduced in 2D electro-
magnetic particle-in-cell (EM PIC) simulations in planar geometry, for a regime of parameters close to the experiment. In the simulation shown in Figure 3, the laser pulse has a Gaussian intensity profile both in space and time, with radius $r_0 = 4\lambda$ and duration $t_0 = 150\lambda/c$ (both FWHM). The laser strength parameter was $a_0 = 2$. The plasma density grows linearly along the axis from zero to the peak value $n_0 = 0.1n_e$ (where $n_e = 10^{21}\text{ cm}^{-3}$ is the critical density for the laser wavelength, $\lambda$) over a length of 400 $\mu$m, and then remains uniform for 200 $\mu$m. In the figures, the laser pulse propagates from left to right along the x-axis. The numerical grid had 6500 points in x and 1200 in y, the spatial resolution was $\delta x = \delta y = \lambda/10$ and 16 particles per cell were used for both electrons and ions.

Figure 2 shows the ion density ($n_i$) and the components $E_y$ and $E_z$ of the electric field at the time $t = 575\lambda/c \sim 1.8$ ps. In this simulation, the laser pulse is $s$-polarized, i.e., the polarization is along the z axis, perpendicular to the simulation plane. In the experiment, CPA$_1$ was polarized along the axis of the proton probe. Thus, $E_z$ in Figure 2 is representative of the amplitude of the propagating EM pulse, while $E_y$ is generated by the space-charge displacement.

The simulation clearly shows the formation of an electron-depleted channel under the effect of the ponderomotive...
force (PF) of the leading part of the laser pulse. This force generates the radial space-charge electric field, which points away from the laser propagation axis. In the region behind the peak of the pulse, one observes two narrow ambipolar fronts (one on either side of the laser propagation axis), slowly moving away from the axis. Such a radial electric field profile can, in principle, produce a pattern in the proton dose profile similar to the feature (III) in Figure 1, observed in the experimental data.

At later times, pulse propagation through the denser plasma region showed in the PIC simulation occurrence of beam hosing, and appearance of soliton-like structures. The geometry and distribution of the solitons in the simulations have a close resemblance to the pattern observed in the proton imaging data at late times.

4. DEBYE SHEATH FORMATION AND ION EXPANSION FROM LASER-IRRADIATED SOLID TARGETS

An experiment investigating the electric fields associated with Debye sheath formation and ion front expansion via the target normal sheath acceleration (TNSA) mechanism was carried out at the Laboratoire pour l’Utilisation des Lasers Intenses (LULI), Ecole Polytechnique.

The experiment was performed employing the LULI 100 TW system operating in the Chirped Pulse Amplification mode (CPA). Two laser pulses (CPA1 and CPA2) were focused onto two separate targets leading to the acceleration of a proton beam from each target. CPA1 was focused onto 10 to 40 μm thick Al and Au foils (interaction target) at
an intensity of \( \sim 3.5 \times 10^{18} \text{ W/cm}^2 \). CPA \(_2\) was focused onto a \( \sim 10 \mu\text{m} \) thick Au foil (proton target) at an intensity of \( \sim 2 \times 10^{19} \text{ W/cm}^2 \). The proton beam from the proton target was employed as a transverse charged particle probe for the accelerating electric fields at the back of the interaction target. The time delay between CPA \(_1\) and CPA \(_2\), and therefore the proton probing time, could be optically adjusted with ps precision. The proton beams from the two targets were detected employing stacks of several layers of RCFs.

Two qualitatively different structures are observed in proton imaging data (Romagnani \textit{et al.}, 2005). Around the peak of the interaction of CPA \(_1\) with the bent foil \((t = 0)\) a transient, pronounced deflection of the probe protons is observed. The probe protons are deflected away from the rear surface of the foil and are re-distributed over a bell-shaped extended region (dark region indicated by the arrow in Fig. 3a).

This deflection vanishes after a few ps, as can be seen from Figure 3c, when a front expanding from the rear of the foil starts to appear. The front is delimited by a region of accumulation of the probe protons (dark bell-shaped line indicated by arrow in Fig. 3b), which gets fainter at late probing times. Behind the front the probe proton density is not significantly perturbed, with the exception of longitudinal modulations associated with filamentary structures.

In proton deflectometry data, the bell-shaped expanding front observed at late probing times is marked by a clear and sudden shift of the mesh imprint lines (Fig. 3d). In particular, the vertical mesh lines appear to be displaced by a larger amount in proximity of the expanding front, while remaining nearly straight behind it. The mesh lines shift decreases in time both in correspondence with the expanding front or at a fixed point behind it. The experimentally measured final velocity of the expanding front is \(3–4 \times 10^7\) m/s, which is consistent with the detected high energy spectral cut-off of \(\sim 6–7\) MeV of the proton beam emitted from the interaction target.

Proton deflectometry data reveals an electric field which peaks at the expanding front and is uniform and substantially smaller behind it, in agreement with theoretical predictions. The experimental results were compared with 1D fluid and particle in cell (PIC) simulations of the expansion of electron–proton plasma of finite width into a vacuum. The initial electron sheath field and the peaked structure of the field at the ion front were observed in the simulations, with peak field intensity in good agreement with the experimental findings.

A detailed understanding of the accelerating field structure was obtained by comparison of the experimental results with numerical simulations of the propagation of a probe proton beam through a given time-dependent electric field structure. Both proton imaging and proton deflectometry data, and both the initial transient deflection and the expanding front at later times, were simulated. The broad spectral content of the probe proton beam was taken into account. Field patterns with cylindrical symmetry were assumed, as it was verified that the bent geometry of the target has negligible effect. Results of these simulations are shown in Figure 4. Details of this comparison are provided in Romagnani \textit{et al.} (2005).

5. USE OF IMPULSIVE ELECTRIC FIELDS FOR ION BEAM TAILORING

The transient electrostatic fields described in the previous section offer novel opportunities as a tool for controlling the properties of proton beams. In particular, while probing ion front expansion from hemi-cylindrical targets, it was seen that not only the ion front accelerated from the hemi-cylinder went through a focus but also that, under certain conditions, the transient fields at the rear of the target caused the protons of the probe beam to form a caustic at the center of the hemi-cylinder. This suggested the idea of using a laser-irradiated hollow cylinder as a tool for varying the angular properties of a proton beam. Indeed the arrangement proved to work effectively as a laser driven micro-lens able to focus controllably laser-accelerated proton beams (Toncian \textit{et al.}, 2006; Willi \textit{et al.}, 2007). Its operation was demonstrated in an experiment also carried out at the LULI Laboratory, employing the 100 TW laser operating in the CPA. One of the two pulses (irradiance \(I = 3 \times 10^{19} \text{ W/cm}^2\)) was used to accelerate a high-current, diverging beam of up to 15 MeV protons from a 10 \(\mu\text{m}\) thick Au foil target. The other pulse \((I = 3 \times 10^{18} \text{ W/cm}^2)\) was focused onto the side of a hollow cylinder. The proton beam from the first foil was directed through the cylinder and detected with a stack of RCF, which was shielded with an 11 \(\mu\text{m}\) Al foil allowing protons with energies above 1.5 MeV to be recorded. Various experimental parameters including the length, diameter and material of the cylinders were varied to study the focusing characteristics of the proton beam under different conditions. At a source-cylinder distance of 1 mm the proton flux increase due to focusing by the micro-lens was so strong that saturation of the film occurred. Quantitative data could only be obtained when the cylinder was moved to 5 mm from the proton foil, in order to collect a smaller part of the diverging proton beam. Under these conditions a small spot (less than 200 \(\mu\text{m}\) diameter) was recorded on the detector (placed at several cm from the source), providing strong evidence of beam focusing and proton flux concentration. Due to the transient nature of the fields, the focusing was energy selective, as only protons passing through the cylinder while the fields were active were focused. Spectral measurements carried out under these conditions show a monochromatic spike in the spectrum (Toncian \textit{et al.}, 2006). These preliminary, proof-of-principle tests indicate that this is an extremely promising approach for focusing an intense proton beam, while at the same time selecting a desired energy range. The range can be tuned by varying parameters such as the relative delay of the laser pulses, and the relative distance of the targets employed. This technique could be of interest for many of...
the proposed applications of laser-driven proton beams (Borghesi et al., 2006), and for application as an ultrafast focusing/switching device for ion beams from conventional accelerators.

6. CONCLUSIONS

We have discussed in this paper results pertaining to the detection and possible use of electric transient fields initiated by high-intensity laser-interaction with matter. The use of laser-driven proton probes as a diagnostic tool has proven crucial in obtaining time and space resolved information on the structure and development of these fields, and consequently on the charge dynamics following high intensity laser-plasma interaction with underdense plasmas and solid targets. By this technique, important, previously unavailable information on the ion acceleration process via the TNSA mechanism has also been obtained. Understanding how these fields develop permits to envisage applications where they are controlled and employed to modify the properties of particle beams. Preliminary results relating to the focusing of laser-accelerated proton beams by using a laser-driven micro-lens appear extremely promising for obtaining the enhanced flux concentration and narrow energy band required by many proposed applications.

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REFERENCES

Borghesi, M., Audebert, P., Bulanov, S.V., Cowan, T., Fuchs, J., Gauthier, J.C., Mackinnon, A.J., Patel, P.K., Pretzler, G., Romagnani, L., Schiavi, A., Toncian, T. & Willi, O. (2005). High intensity laser plasma interaction studies employing laser-driven proton probes. Laser Part. Beams 23, 291–297.

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

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

Borghesi, M., Campbell, D.H., Schiavi, A., Willi, O., Mackinnon, A.J., Hicks, D., Patel, P., Gizza, L.A., Galimberti, M. & Clarke, R.J. (2002c). Laser-produced protons and their application as a particle probe. Laser Part. Beams 20, 269–275, 6411.

Borghesi, M., Fuchs, J., Bulanov, S.V., Mackinnon, A.J., Patel, P.K. & Roth, M. (2006). Fast ion generation by high-intensity laser irradiation of solid targets and applications. Fusion Sci. Techn. 49, 412–439.

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.

Borghesi, M., Mackinnon, A.J., Gaillard, R., Willi, O., Pukhov, A. & Meyer-Ter-Vehn, J. (1998). Large, quasi-static magnetic fields generated by a relativistically intense laser pulse propagating in a preformed plasma. Phys. Rev. Lett. 80, 5137–5140.

Brambrink, E., Roth, M., Blazevic, A. & Schlegel, T. (2006). Modeling of the electrostatic sheath shape on the rear target surface in short-pulse laser-driven proton acceleration. Laser Part. Beams 2, 163–168.

Bulanov, S.V., Esirkepov, T.Zh., Naumova, N.M., Pegoraro, F. & Vshikvov, V.A. (1999). Solitonlike electromagnetic waves behind a superintense laser pulse in a plasma. Phys. Rev. Lett. 88, 3440–3443.

Cowan, T.E., Fuchs, J., Ruhl, H., Kemp, A., Audebert, P., Roth, M., Stephens, R., Barton, I., Blazevic, A., Brambrink, E., Cobble, J., Fernandez, J., Gauthier, J.C., Geissel, M., Hegelich, M., Kaae, J., Karsch, S., Le Sage, G.P., Letzring, S., Manclossi, M., Meyroneinc, S., Newkirk, A., Pepin, H. & Renard-Legalloudec, N. (2004). Ultralow emittance, multi-mev proton beams from a laser virtual-cathode plasma accelerator. Phys. Rev. Lett. 92, 204801.

Danson, C.N., Collier, J., Neely, D., Barzanti, L.J., Damerell, A., Edwards, C.B., Hutchinson, M.H.R., Key, M.H., Norreys, P.A., Pepler, D.A., Ross, I.N., Taday, P.F., Toner, W.T., Trentelman, M., Walsh, F.N., Winstone, T.B. & Wyatt, R.W.W. (1998). Well characterized 1015Wcm2 operation of vulcan—an ultra-high power nd:glass laser. J. Mod. Opt. 45, 1653–1669.

Lontano, M., Borghesi, M., Bulanov, S.V., Esirkepov, T.Zh., Farina, D., Naumova, N., Nishihara, K., Passoni, M., Pegoraro, F., Ruhl, H., Sakharov, A.S. & Willi, O. (2003). Nondrifting relativistic electromagnetic solitons in plasmas. Laser Part. Beams 21, 541–544.

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, M., Kar, S., Romagnani, L., Toncian, T., Pretzler, G., Willi, O., Koenig, M., Martinelli, E., Lepape, S., Benuzzi-Mounaix, A., Audebert, P., Gauthier, J.C., King, J., Snavely, R., Freeman, R.R. & Boehly, T. (2004). Proton radiography as an electromagnetic field and density perturbation diagnostic. Rev. Sci. Instr. 75, 3531–3536.

Romagnani, L., Fuchs, J., Borghesi, M., Antici, P., Audebert, P., Ceccherini, F., Cowan, T., Grismayer, T., Kar, S., Macchi, A., Mora, P., Pretzler, G., Schiavi, A., Toncian, T. & Willi, O. (2005). Dynamics of electric fields driving the laser acceleration of multi-mev protons. Phys. Rev. Lett. 95, 195001.

Roth, M., Brambrink, E., Audebert, P., Blazevic, A., Clarke, R., Cobble, J., Cowan, T.E., Fernandez, J., Fuchs, J., Geis-
SEL, 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.

RUHL, H., COWAN, T. & PEGORARO, F. (2006). The generation of images of surface structures by laser-accelerated protons. *Laser Part. Beams* **24**, 181–184.

TONCIAN, T., BORGHERSI, M., FUCHS, J., DHUMIERES, E., ANTICI, P., AUDEBERT, P., BRAMBRINK, E., CECCHETTI, C.A., PIPAHL, A., ROMAGNANI, L. & WILLI, O. (2006). Ultrafast laser-driven microlens to focus and energy-select mega-electron volt protons. *Science* **312**, 410–413.

WILLI, O., TONCIAN, T., BORGHERSI, M., FUCHS, J., DHUMIERES, E., ANTICI, P., AUDEBERT, P., BRAMBRINK, E., CECCHETTI, C., PIPAHL, A. & ROMAGNANI, L. (2007). Laser triggered microlens for focusing and energy selection of Mev protons. *Laser Part. Beams* **25**.