Proton deflectometry measurements of self-generated magnetic fields in laser-produced plasmas

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Introduction

The generation of spontaneous electric and magnetic fields in laser-matter interactions is a phenomenon of fundamental interest since these fields can strongly affect the dynamics of a plasma system. In the case of long pulse and moderate irradiance the main source for the magnetic field **B** is via the non-collinear density and temperature gradients[1,2]. In simple terms, in an expanding plasma the electron pressure force gives rise to a charge-separation electric field ($qn_e\mathbf{E} \sim \nabla P_e$). From Faraday's law ($\partial\mathbf{B}/\partial t=-\nabla x\mathbf{E}$) it follows that:

$$\partial\mathbf{B}/\partial t=-\nabla x(\nabla P_e/qn_e)= (\nabla T_e x\nabla n_e)/qn_e$$

Magnetic fields are relevant to electron energy transport and a detailed knowledge of their distribution and dynamics is important for many fundamental plasma physics processes. These fields can affect the density and temperature distributions enhancing laser-plasma instabilities. The **B** field behaviour inside hohlraums is of interest to the Indirect Drive approach to Inertial Confinement Fusion (ICF)[3].

Traditionally magnetic fields in ICF-relevant laser-produded plasma have been detected by optical polarimetry, i.e. via Faraday rotation of the polarization plane of a transverse optical probe[1,4]. By using this technique, however it is difficult to obtain information about B fields' presence at densities close to the critical density, mainly due to probe deflection caused by plasma density gradients. We present here the first application to the detection of magnetic fields of a proton deflectometry technique[5,6], which is in principle capable of detecting magnetic fields in the near-critical region. The technique has been applied to the measurement of the magnetic fields generated by focusing a long laser pulse on thin Al flat foils.

Experimental arrangement and computational tools

The experiment was carried out at the VULCAN laser facility. The proton beams, originating from hydrocarbon impurities on the rear target surface and accelerated by the Target Normal Sheath Acceleration mechanism[7,8], were produced by irradiating thin Al foils with 50 J, 1-ps laser pulses focused in a 10 μm radius focal spot up to intensities of 5x10^{19} W/cm^2. The dual CPA configuration was used, allowing to obtain simultaneously two proton beams from two separate foils. The two proton beams were used to probe laser produced plasmas along two perpendicular probing directions (see fig.1). Two of the six long pulses (50 J, 1-ns, 1 μm) available in Target Area West were alternatively used for producing these plasmas on either the front or rear surface of a 2 μm thick Al foil. The pulses were focused in a 50 μm radius focal spots to intensities of the order of 10^{14} W/cm^2. In every shot two maps of proton deflections were obtained, of which one was *face-on* (i.e. with the proton probe axis parallel to the plasma axis) and the other one was *side-on* (i.e with proton probe axis parallel to the target surface). In addition, the plasma was probed by the *face-on* proton beam in two different configurations: interaction facing the incoming probing beam (*front interaction*), and interaction placed at the rear surface of the target (*rear interaction*) respectively (see fig.1). As it will be explained in the following, these arrangements were specifically chosen to distinguish magnetic field effects. The proton deflectometry arrangement was used on the proton probe lines. For this purpose 1500 lpi meshes were inserted between the proton source and the plasma, so that parts of the proton beam cross section could be traced in the detector plane and a map of proton deflection easily obtained. The main detectors used in the experiment were radiochromic films[9], of the Gafchromic HD810 and MD55 types[10], placed in a multilayer arrangement inside suitably designed boxes.

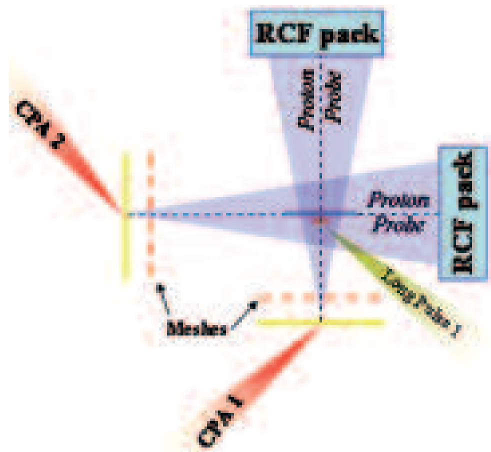

Figure 1. Schematic of experimental set-up. The long pulse was focused in alternate shots either at the front of the target (*front interaction* configuration) or at the rear of the target (*rear interaction* configuration). The direction of the azimuthal B-field produced in the expanding plasma is opposite in the two cases.

The RCF pack was filtered with a 13 µm Al foil. Thanks to the design of the detector and the fact that ions release almost all of their energy at the Bragg peak, data from a RCF pack provides simultaneously information on the energy spectrum of the particle probe and on the temporal evolution of the system probed[11]. The temporal window accessible in a single shot due to time-of-flight dispersion of the detected proton range was of the order of 200-300 ps. Temporal evolutions on longer timescales could be explored by suitably varying the delay of the two CPA pulses.

Simultaneous optical probing (carried out at 45 degrees off-plane by employing a 1 ps, 0.527 µm pulse) allowed the retrieval of the density distribution of the plasma by employing a modified Nomarsky interferometry arrangement.

Experimental results

Comparison between *face-on* and *side-on* deflection maps, and between *front* and *rear interaction* data allows discriminating between the contributions of the electric and magnetic fields present in the plasma to the proton deflection pattern.

In standard laser-produced plasma geometry, the B-field geometry is mainly azimuthal. As a consequence, face-on radiography will be more sensitive to **B** fields than side-on geometry. Furthermore, in face-on probing deflections due to B fields will differ strongly in *front* and *rear interaction* configurations, due the change in direction of the transverse component of the **v**×**B** force. This is seen in fig.2, where typical experimental data taken close to the peak of the ns pulse in the two configurations are displayed. While in front interactions the magnetic field deflects outward the ions, causing the stretching of the mesh elements, in the other case, it causes a compression

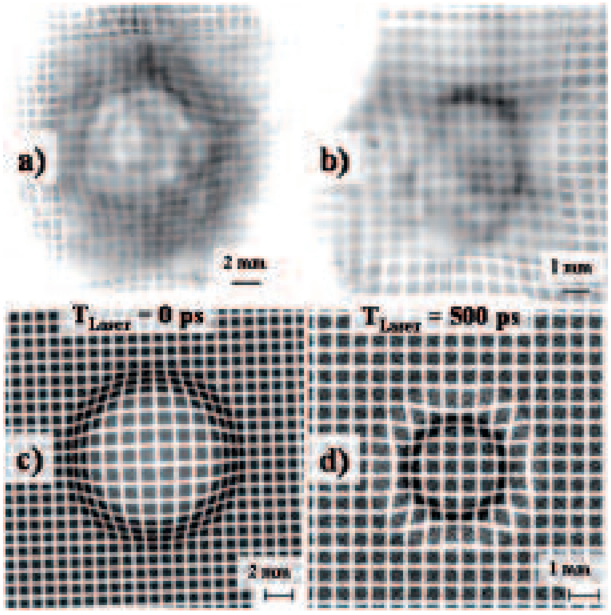

Figure 2. a) typical *face-on* proton defelctogram in the *front interaction* configuration; b) typical *face-on* proton deflectogram in the *rear interaction* configuration, magnification is 33; c) and d) Ptrace simulations in *front and rear configuration* respectively. In these simulations the protons are traced through a toroidal magnetic field, with inner radius 130 µm, outer radius 170 µm, and maximum amplitude 40 T. The field peaks at the centre of the thorus and decays exponentially within it. Rulers indicate dimensions in the detector plane.

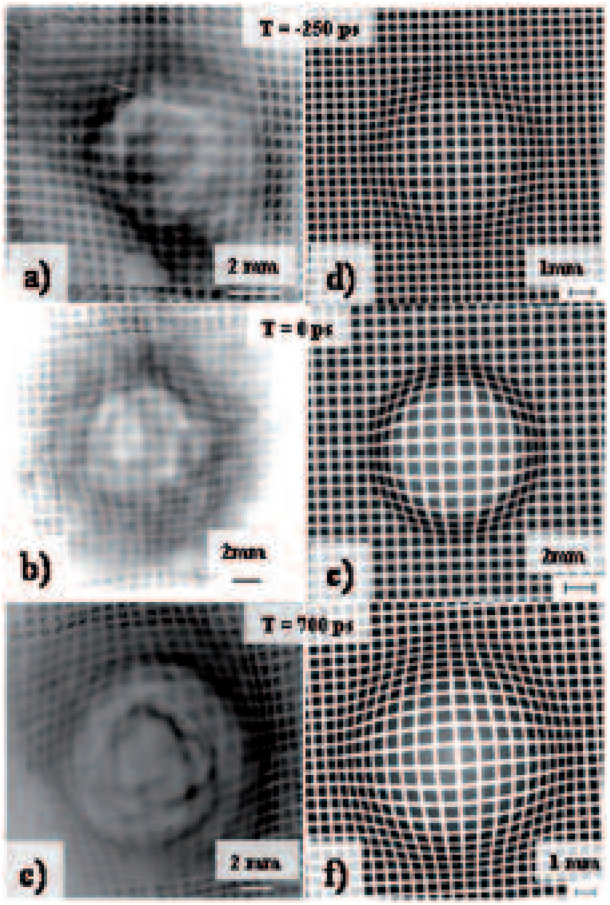

Figure 3. The experimental data in a), c) and e) were all acquired in the face-on, front-interaction configuration using a 1500 lpi mesh, magnification 13, and focusing the 1 ns laser pulse in a 50 µm focal spot radius over 2 µm thick Al foil. Shots intensity were in the range 1-2 10^{14} W/cm^2. Figures d), e) and f) show PTRACE simulations done using thoroidal B fields of amplitudes in the range 40-70 T and average radius in the tange 150-200 µm. In these simulations a radial electric field with peak amplitude of the order of 10^8 V/m varying spatially according to a Gaussian function was added to simulate the effect of the pressure gradient fields in the plasmas. Rulers in the simulations are 1mm. All rulers indicate dimensions in the detector plane.

of the mesh lines in the inner part of the plasma. This effect is a demonstration of the presence of a magnetic field, as inverting the probing direction would not affect the transverse deflection if this was mainly caused by pressure gradients electric fields in the plasma.

Figures 3 a), c) and e) show the face-on images relative to three different shots in which the proton beams arrived respectively ~250 ps before, ~0 ps and ~700 ps after the peak of the interaction pulse. This data was obtained in separate shots maintaining the same target configuration and laser parameters but shifting the temporal window of the probe around the long pulse peak.

Figure 4(a) shows a typical side-on deflectogram, taken simultaneously to fig.4 (d). The deflections are in this case much less pronounced. Figure 4(b) shows the results of a particle tracing simulation carried out with the same field configuration used in Fig. 3 (d), but with the probing direction changed by 90º. The particle tracing results

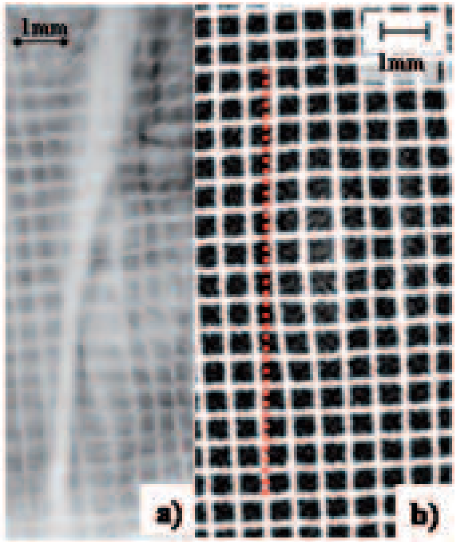

Figure 4. (a) Side-on deflectogram taken at the peak of the pulse. (b) PTRACE simulation.

confirm that, in the conditions of fig.3 (c) no substantial deflections should be expected for *side-on* probing.

Modelling

The interpretation of this data is currently undergoing. As with previous data, this is developing along two directions. A particle tracer (PTRACE)[11,12], using the experimental features of the proton probe and the physical response of the detector, is employed to model the deflections undergone by the protons in a prescribed electric and magnetic field distribution based on the expected geometry and magnitude of the fields. The parameters describing the field distribution can be varied iteratively until the deflection resembles the experimental data. Synthetic deflectograms obtained in this way are shown in fig. 2-4 beside the relevant experimental data. The general features of the face-on data can be reproduced reasonably well by thoroidal B-fields with average radius of the order of 150-200 µm and magnitude in the range 50-100 T. In the simulations of figures 3-4 an E-field was tentatively added with the aim of modelling the additional effect of pressure-gradient fields in the plasma. This did not change the overall structure of the deflection pattern, but modified slightly the mesh deflection at the centre of the plasma. At the same time the evolution of the plasma and of the associated E and B fields can be simulated *ab-initio* by using hydrodynamic or magneto-hydrodynamic codes. Electron density profiles can be compared to the experimental density maps to check that the plasma expansion is modelled properly by the code. The field distributions provided by the hydro codes at different times can then be compared to the field estimates obtained from the particle tracer simulations, or used directly for further tracing. Preliminary results of simulations indicate B fields which are reasonably close in magnitude and extension to the ones suggested by the PTRACE simulations. Further work will be devoted to a more detailed comparison of computational outputs and experimental data, with the aim of identifying the relative contribution of pressure gradient E-fields, $\nabla T_e x \nabla n_e$ B-fields and possibly of other magnetic field source terms[2,13].

Conclusions

Proton deflectometry has been applied for the first time to the detection of magnetic fields in laser-produced plasmas. Distinctive deflection patterns have been observed in a face-on probing configuration, while side-on probing shows much less dramatic deflections. Preliminary interpretation of this data suggests that the deflection patterns are broadly consistent with a sub-MG thoroidal magnetic field peaking at the edge of the plasma. Comparison with hydrocode predictions is currently undergoing. It is expected that a careful observation of the deflection patterns, and the comparison of data obtained in all the different probing configurations tested will yield detailed information on the B-field spatial distribution and temporal evolution.

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