Measurements of Energetic Proton Transport through Magnetized Plasma from Intense Laser Interactions with Solids

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Protons with energies up to 18 MeV have been measured from high density laser-plasma interactions at incident laser intensities of 5×10^{19} W/cm^2. Up to 10^{12} protons with energies greater than 2 MeV were observed to propagate through a 125 μm thick aluminum target and measurements of their angular deflection were made. It is likely that the protons originate from the front surface of the target and are bent by large magnetic fields which exist in the target interior. To agree with our measurements these fields would be in excess of 30 MG and would be generated by the beam of fast electrons which is also observed.

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Recent developments in laser technology have allowed experimentalists to explore the properties of ultrahigh intensity ($I > 10^{19}$ W/cm^2) laser-produced plasmas as well as potential applications for fusion energy research, particle acceleration, and x-ray source development [1]. These high intensity lasers can produce exotic plasmas having multi-MeV electron and ion temperatures and in which multi-megagauss magnetic fields can exist. The effect of such large magnetic fields on the transport of energy in these plasmas is particularly important for evaluating the potential use of intense lasers for igniting compressed deuterium-tritium pellets in inertial confinement fusion experiments [2].

In this paper, we report the first direct measurements of high energy proton generation (up to 18 MeV) and propagation into a solid target during such intense laser plasma interactions. Our measurements of the deflection of these energetic protons imply that magnetic fields exist inside the target which are in excess of 30 MG. The structure of these fields is consistent with those produced by a beam of hot electrons which has also been measured in our experiments. Such observations are the first evidence of the large magnetic fields which have been predicted to occur during such interactions in dense plasma [3].

Magnetic fields have been observed during laser-plasma experiments for the past 30 years [4] in the underdense region ($n_e < n_{\mathrm{crit}}$) where fields can be generated by currents produced from perpendicular density and temperature gradients in the ablated plasma. The diagnostics used in almost all of those experiments were Faraday rotation measurements of a transversely propagating probe laser beam—a technique which cannot be used in high density regions of plasma where the largest magnetic fields should exist [3]. The difficulty of such measurements is accentuated by the short temporal ($\sim$1 psec) and spatial scales ($\sim$10 μm) involved.

The results reported here were obtained during experiments at the Rutherford Appleton Laboratory using the CPA beam of the VULCAN laser [5]. This system produces laser pulses up to 50 J at a wavelength 1.053 μm and with a pulse duration of 0.9–1.2 ps. The beam was p polarized and was focused using an $f/4$ off axis parabolic mirror onto a thin (125 μm) aluminum target positioned at 45° to the axis of laser propagation. The intensity on target was up to 5×10^{19} W/cm^2 and was determined by simultaneous measurements of the laser pulse energy, duration, and focal spot size. Behind the target, at a distance of 25 mm, and aligned with the normal to the target we placed a "sandwich" of several pieces of radiochromic film (RCF) and CR39 plastic track detectors.

RCF is a transparent material (typically nylon) which is coated with an organic dye. Upon exposure to ionizing radiation the film undergoes a color change. The optical density of the film is then measured so that the equivalent dose from energetic protons can be calculated. Consequently, the total number of protons passing through the film at each point can be determined [6].

CR39 [7] is a plastic nuclear track detector which is sensitive only to ions with energies greater than 100 keV/nucleon. In this experiment, these detectors recorded only signal due to protons since the first piece of RCF (110 μm thick) in the sandwich will transmit protons having energies greater than 2.8 MeV, but will stop all energetic aluminum and carbon ions. The stopping range of protons in CR39 and radiochromic film is easily calculated and, consequently, this allows a direct determination of the energy range for those protons which produce a particular series of tracks on the CR39 surface. CR39/RCF sandwich detectors can therefore provide both

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spatial and spectral information of protons emitted during the interaction.

Figure 1(a) shows a scanned image from the front piece of RCF in the sandwich detector from a typical shot at $I \sim 5 \times 10^{19}$ W/cm^2. The film contains signal only within a well-defined radius from the central hot-spot. The angle subtended by the perimeter of this circle covers a cone half angle of 30°, and the mark at the center of the film indicates a region where the film has been saturated. Figures 1(b)–1(e) shows the emission pattern observed on the CR39 from this shot for various energy ranges of ions (i.e., different pieces in the sandwich). RCF is also sensitive to both electrons and x rays which are generated during the interaction [8,9]; however, it is clear from the images shown in Figs. 1(b)–1(e) that the signal on the RCF coincides with that on the CR39—which is sensitive only to ions. Therefore, it is likely that the signal on the front piece of film is predominantly due to energetic ion emission. Using this assumption the total number of protons emitted with energies greater than 2 MeV can be estimated and was found to be approximately 10^{12} per shot.

The ion signal on the CR39 exhibits a ring pattern with decreasing diameter for increasing ion energy up to a maximum energy of 17.6 MeV. The central position of each ring is coincident with the direction of the target normal. The "ion ring" structure on the CR39 was observed consistently from a series of shots at an intensity of $\sim 5 \times 10^{19}$ W/cm^2. The central hot spot on the RCF is correlated with the position of the highest energy ions on the CR39 which exhibit collimated propagation, and the outer extreme of the RCF displays an abrupt decrease in signal level which corresponds to a sharp low energy cutoff below which much fewer protons are observed.

It is likely that this relationship between the energy of the emitted protons and the angle at which they are emitted is caused by large azimuthal magnetic fields within the solid target material that develop and persist during the first few picoseconds after the laser pulse. The protons are consequently deflected like charged particles in a magnetic spectrometer. It is clear that such magnetic fields must be generated by an electron current—which would tend to focus a beam of electrons—but defocus or scatter ions. Such large fields have been predicted [10] and have been shown to contribute to the focusing of electrons at the rear of such targets resulting in plasma formation [11].

The source of energetic protons is either from hydrocarbon contamination of the front and rear target surfaces (which has been observed in previous experiments [12]). It is, however, highly unlikely that the protons in the observed ring structure are from the back of the target. A simple estimate shows that unrealistic field strengths of $>1 \times 10^9$ G are required to achieve the observed proton deflections over a distance of a few microns (which is the size of the rear surface plasma). It is more probable that the energetic protons are generated at the front surface and are subsequently transported through the target. The existence of a "beam" of high energy ions traveling into the target is also consistent with previous measurements of beam-plasma fusion reactions from high intensity laser interactions with CD_2 targets [13].

An energy of 4 MeV or greater is required for a proton to pass through a 125 μm thick piece of aluminum, but protons with energies less than 4 MeV are clearly measured. This can be explained by considering Fig. 2 which shows the relationship between the energy of a proton entering a 125 μm thick aluminum target to that which they retain when leaving. The proton either escapes the target with a minimum of about 2 MeV or is stopped within the target. This calculation shows a lower energy cutoff of about 2 MeV which is consistent with the ion energy measurements using the CR39 as well as the radiochromic film data. Those protons generated at the front surface, which travel through the target and subsequently escape from the rear, would therefore have a minimum energy which produces a sharply defined image on the RCF.

Simultaneously, measurements of the gamma ray spectrum were made using a gamma ray spectrometer (scintillators/photomultipliers) as well as by using nuclear activation techniques [14]. The hot electron temperature implied by these measurements was found to be in the range of 1 to 2 MeV. The spectrum of high energy electrons propagating through the 125 μm targets was also measured, and it was found to extend to energies greater than 20 MeV. This provides further evidence that the source of the measured magnetic fields can be found in the hot electrons produced during these interactions. It is likely that part of the return current requirement

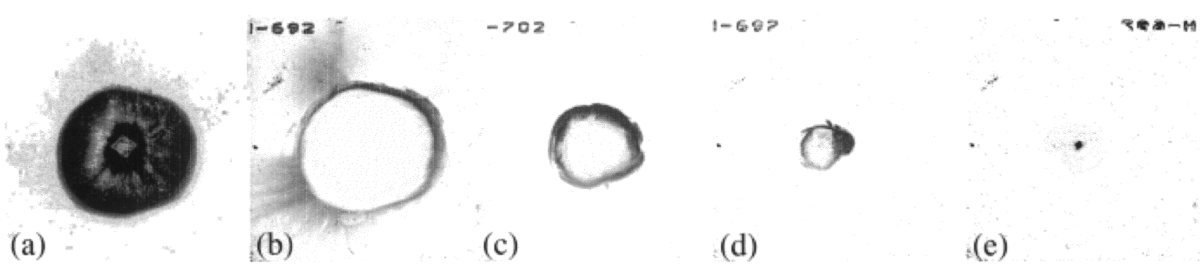

FIG. 1. Ring structure observed on RCF/CR39 "sandwich" track detectors: (a) radiochromic film (front surface); (b) tracks on CR39 from 3 MeV protons; (c) 8.9 MeV, (d) 11.6 MeV, (e) 17.6 MeV protons (track detectors were 5 cm × 5 cm × 0.75 mm thick).

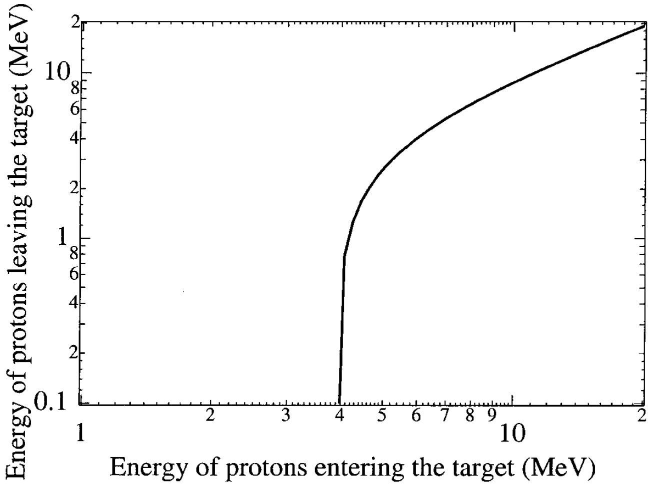

FIG. 2. Energy of incident protons vs energy which they retain after traversing 125 μm thick Al foils.

for propagation of the hot electrons through the target material is provided by protons from the front surface plasma which are pulled along with the electrons as they move through the plasma.

To obtain an estimate for the magnetic field strength required to deflect the protons as measured with the CR39, a charged particle tracking code was developed to simulate the transport of a 12 μm radius proton beam into the target. The magnetic field for these simulations was cylindrically symmetric and constant in the z direction through the target (125 μm). It had a profile in the r direction which was zero at $r = 0$ μm, rose to 30 MG at $r = 10$ μm and then fell off as $1/r^2$. This radial dependence for the magnetic field is similar to that observed in previous detailed numerical simulations [10]. In this case, incident protons with an energy of 10 MeV are used to simulate the experimentally observed ring pattern produced by 8.9 MeV protons—since energy losses within the target will result in these protons leaving the target with an energy of 8.9 MeV. Figure 3(a) shows the measured data which is replicated remarkably well by the simulation [Fig. 3(b)].

It is also possible to make a simple estimate of the magnetic field generated by these high intensity laser-produced electrons [10]. The electric field generated during the interaction can be represented by $\mathbf{E} = \eta \mathbf{j}_b$ where $\mathbf{j}_b$ is the background current density (return current) and η is the resistivity. If the total current is given by $\mathbf{j} = \mathbf{j}_b + \mathbf{j}_{\text{fast}}$ where $\mathbf{j}_{\text{fast}}$ is that due to the hot electrons then, using Ampere's law, $\mathbf{E} = -\eta \mathbf{j}_{\text{fast}} + \frac{\eta}{\mu_0} \nabla \times \mathbf{B}$—where the displacement current has been neglected. If this expression is inserted into Faraday's law the first term can be interpreted as the source term (due to the fast electrons) for the growth of a magnetic field while the second term is a resistive diffusion term. If the Spitzer expression for plasma resistivity is used, we can then estimate the magnitude of the magnetic field generated in these experiments. The averaged magnetic field derived from the data approximately agrees with such simple estimates using reasonable values for plasma and laser parameters.

Detailed calculations have also been performed and compared to the experimental results. The transport of high energy electrons through the target was simulated by solving the Fokker-Planck equation for the fast electrons in a situation similar to the experimental geometry [10]. Figure 4 shows the magnetic fields generated from a simulation at an incident laser intensity of 5×10^{19} W/cm^2, 50 J laser energy, 30% laser conversion into a fast electron population with a temperature of 1.5 MeV, 6 μm laser spot radius at a time 1 ps after the peak of the laser pulse. The number of electrons and the fast electron temperature were determined from previous experimental measurements [8]. It was observed that line-averaged fields of 15 to 20 MG (Fig. 4) are produced and that peak fields up to 30 MG are possible.

Using a qualitatively similar magnetic field distribution (although increased by a factor of 3), we simulated 10 MeV protons entering the target in a 9 μm spot. The resulting proton distribution at the detector plane was then calculated [Fig. 3(c)]. This deflection pattern was observed to be very similar to that observed in the experiment. The measured deflection of lower energy protons can also be reproduced using this field configuration. However, higher energy protons are typically deflected too much by

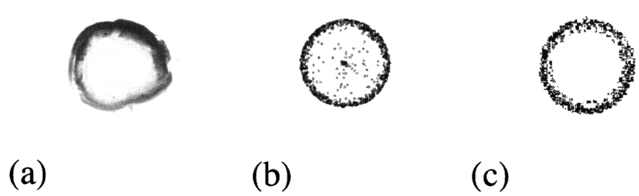

FIG. 3. (a) Experimental ion ring ($E = 10$ MeV); (b) simulated ring structure from best fit magnetic field (30 MG); (c) ion ring from field structure calculated from electron propagation simulations.

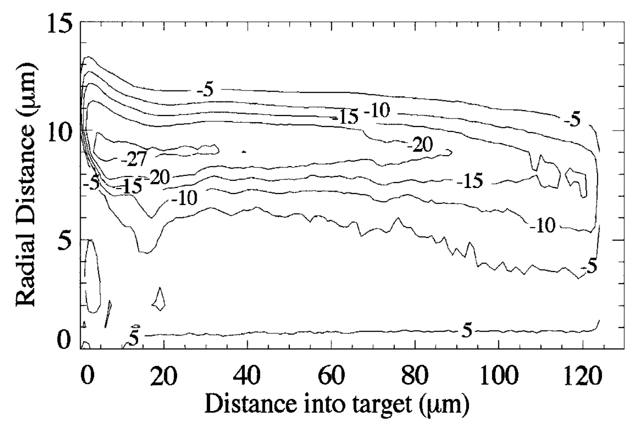

FIG. 4. Simulated magnetic field structure inside solid density target (contours are in MG) from Fokker-Planck calculation at time 1 psec after peak of laser pulse. Electrons are incident from left.

these fields to agree with the experimental observations. This is perhaps because the highest energy protons are able to penetrate far into the target before the magnetic fields have reached their peak value, and are consequently deflected less.

Results from this code also indicate that the magnetic field saturates as the current density is increased. The saturation is caused by the increased temperature of the background plasma resulting from the increased electron current. This in turn, according to the standard Spitzer scaling, decreases the plasma resistivity and consequently causes the magnetic field to saturate. The saturation level occurs at a somewhat lower average magnetic field than the field required to produce the observed deflection which suggests that the Spitzer expression for the plasma resistivity is perhaps no longer valid under these conditions and that an "anomalous" resistivity [15] should be considered to obtain complete agreement between experiment and simulation.

The deflection of fast protons through the existence of radial electric fields in the target is also possible. However, the integrated radial electric field calculated in these simulations was found to be an order of magnitude too low to produce the observed proton deflection and would also not produce the same deflection pattern. It should also be noted that the electric fields produced in the simulation through the target (z direction) are about an order of magnitude too low to produce the observed ion energies. This implies that although the energetic protons can be accelerated somewhat as they traverse the target, they gain most of their energy near the front surface interaction region. These high energy ions may be produced near the critical surface via ponderomotive forces associated with focused laser light and intense plasma wave generation [16].

The experiments described in this paper are the first direct measurements of high energy ion propagation into solid targets and thus give evidence that the mechanism for the observed fusion reactions in previous experiments (up to 10^9 neutrons/shot) [13] is indeed due to beam-plasma effects. These ion measurements also show no evidence of a Weibel-like instability [17] (electron beam filamentation) which may affect the propagation of the electron beam and consequently the magnetic field structure—although it is possible that diffusion of the magnetic field within the target could smooth out nonuniformities before the protons traverse the magnetized region. Such electron beam instabilities may also exist over only a comparatively small region.

In conclusion, these results constitute the highest measured proton energies (up to 18 MeV) from a laser-plasma interaction with about 10^{12} protons greater than 2 MeV produced per shot. From these measurements we have been able to infer the structure and magnitude of the magnetic field generated within a solid target during an ultrahigh intensity laser interaction. These experiments also suggest that the plasma exhibits an anomalous resistivity at the very high current densities which are produced from these interactions. It is possible that further refinements in the use of this diagnostic technique will provide actual "measurements" of the magnetic field structure during these interactions.

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