Measurements of the Inverse Faraday effect in high intensity laser produced plasmas

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The generation of magnetic fields in laser-produced plasmas has recently been the subject of increasing attention both theoretically and experimentally[1]. One particular phenomenon , the inverse Faraday effect (IFE) , has been a source of some controversy as theoretical predictions are in disagreement[2,3]. IFE is a magneto-optical phenomenon in which the propagation of circularly polarised radiation through a non-linear medium induces an axial magnetic field along the direction of propagation. Relatively small fields generated in this way were measured in solid state materials using lasers at low powers in early experiments[4] and in the early 1970s magnetic fields were induced in plasmas through the use of circularly polarised microwaves[5] . It has been postulated that using circularly polarised light at much higher intensities, time averaged azimuthal currents in near critical density plasmas could be generated which might produce an extremely large axial magnetic field [2,3]. For 1 µm laser radiation at I = 10^{19} Watts/cm^2 and a plasma density of 8 x 10^{20} cm^{-3} recent calculations[3] predict a magnetic field of greater than 10 MG which should be localised in space to the focal region of the intense laser pulse. There have been recent measurements of fields due to this effect at lower intensity (~ 10^{14} W/cm^2)[6] which disagree significantly with theoretical predictions.

In this paper, we report the first time-resolved measurements of multi-MegaGauss magnetic fields generated by the IFE in an underdense plasma by a laser focused at relativistic intensities of ~10^{19} Wcm^{-2}. The experiments were performed using the CPA beam of the Vulcan laser at the Rutherford Appleton Laboratory. The laser pulse was at a wavelength of 1.054 µm and had an energy of 60 J, a duration of 0.9 ps, and had a 3.5 times diffraction limited focal spot. A detailed description of the laser system can be found in Reference 7. In these experiments the laser pulse was focused into a helium gas-jet target using a f/4 off axis parabolic mirror. Several diagnostics were run simultaneously during these experiments in order to measure the laser parameters (i.e., focal spot diameter, pulse length, pulse energy) and the vacuum intensity was found to be about 5x10^{18} Wcm^{-2}. A λ/4 wave plate was placed inside the vacuum chamber (after recompression) to change the laser polarisation from linear to circular for the purpose of the IFE measurements.

A small fraction of the pulse was split from the uncompressed main beam, recompressed using a separate pair of gratings and subsequently frequency doubled to 527 nm for use as a probe beam. The pulse length of the probe could be adjusted by changing the separation of the recompression gratings. The minimum pulse duration was 1.3 ps. For the purpose of the IFE experiments the probe gratings were adjusted to give a pulse length of ~15 ps duration. A Hamamatsu fast streak camera (1ps resolution) was used to measure the pulse duration of the probe beam and to time the probe beam with the main beam. Several other diagnostics were used during the experiments to provide information on laser propagation and plasma dynamics. In particular, Moire deflectometry and measurements of forward Raman scattering shadowgraphy were implemented to observe the laser plasma interaction region and density gradients in the plasma. Moire deflectometry and shadowgraphy

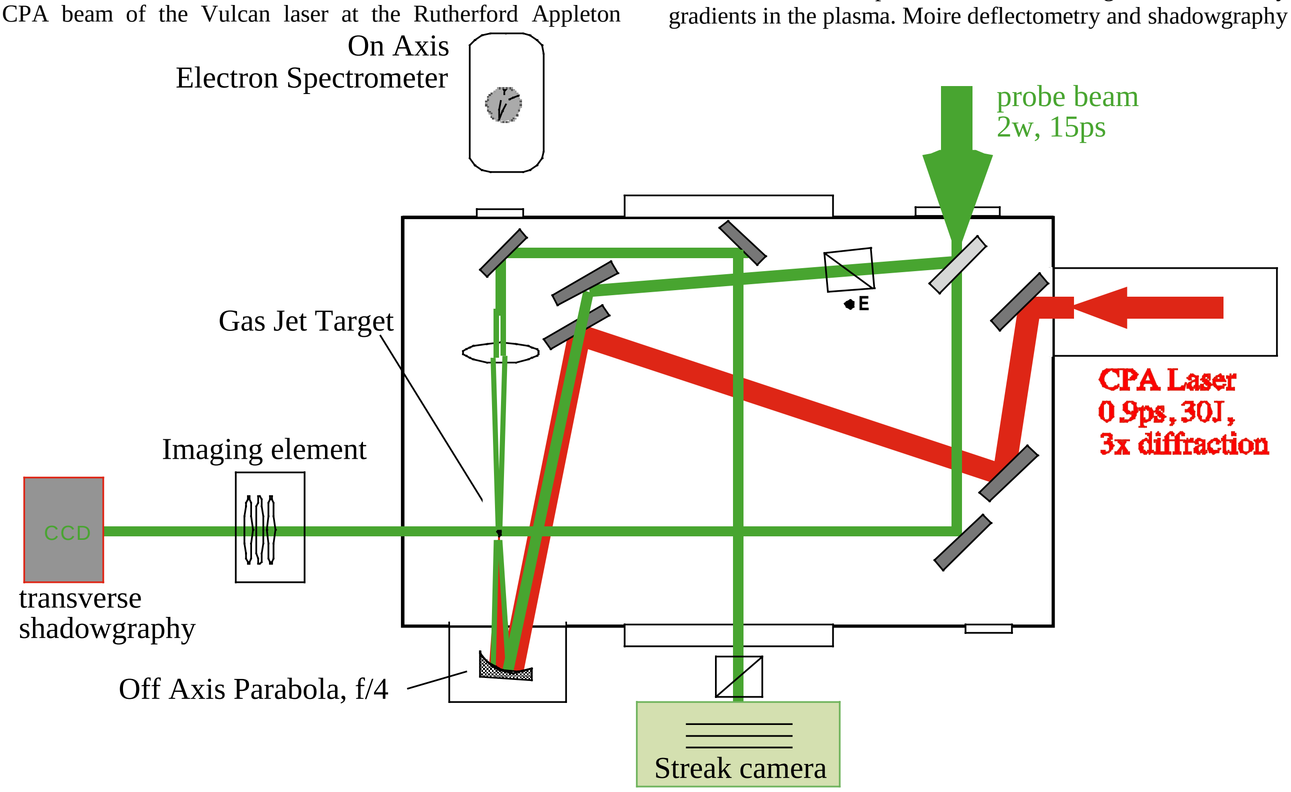

Figure 1. Experimental setup.

were performed using the same probe beam but with the pulse length adjusted to be about 1.5 ps. Furthermore, for these two diagnostics the probe pulse was transversely directed into the plasma. These images were then relayed by a high resolution (~5 µm) optical element onto CCD cameras. When helium gas was used as the target the electron density was found to be about 10^{19} cm^{-3}. The electron density could be adjusted to lower or higher values by changing the backing pressure of the gas jet.

When the probe was used collinearly it was linearly polarised and was directed onto the same parabolic mirror used to focus the interaction beam into the gas jet target (see Figure 1). Far field monitors were used to ensure that the focal regions of the two beams overlapped. The collinear probe was then imaged onto the slit of the Hamamatsu streak camera, which was used as the detector. A polarimetric system (a pair of high extinction ratio polarisers) was responsible for detecting polarisation changes of the probe due to the magnetic field generated in the plasma interaction region by the pump beam. The effect of the rotation of the plane of polarisation of a linear polarised probe propagating into a magnetised plasma (Faraday rotation) can be found in Reference 8. The angle of rotation of the electric field vector is given by;

$$\phi(\mathrm{deg}) = 3.02 \times [\lambda_p(\mu\mathrm{m})]^2 \int \frac{n(\mathrm{cm}^{-3})\ B_z(\mathrm{MG})\ dz(\mu\mathrm{m})}{10^{21}\left(1 - \frac{n}{n_{cr}}\right)^{1/2}}$$

where n and B are the electron density and magnetic field strength respectively and λ_p is the plasma wavelength (= c/ω_p).

Figure 2 presents a typical streak camera signal. The light line (top) shows the measurement when no analyser was used and the streak camera captured the probe light unaffected by the analyser. The duration is 15 ps as expected. The dark line (lower) was the signal obtained when the analyzer was set to transmit only light rotated due to the axial magnetic field light. The signal duration was about 1-3ps – which is about the duration of the high intensity laser pulse (to within the streak camera resolution). In the absence of an axial magnetic field the polarisation of the probe radiation would remain unchanged

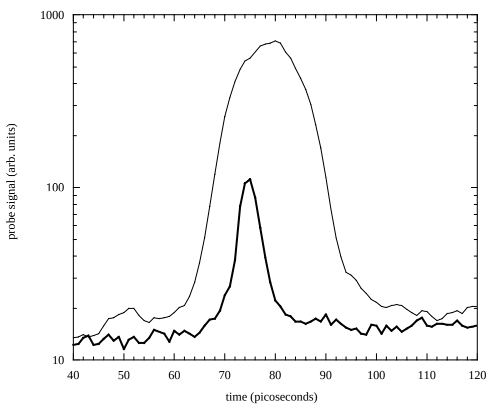

Figure 2. Lineout of the streak camera signal. Light line (top signal) indicates signal without analyser. Dark line (lower signal) indicates Faraday rotated signal (using analyser).

and therefore light would not be transmitted through the analyser. Shots without gas but with probe, or with gas but without probe were taken and only background light at noise level was observed. Furthermore, when linear polarised light was used no rotation of the probe radiation was observed. This clearly demonstrates that the source of the axial magnetic field is the circularly polarised light and is due to the IFE. It should be noted that the direction of the field (± z) was not determined in these experiments.

The magnetic field can be calculated from the intensity ratio between shots with the analyser crossed and those with the analyser parallel to the initial polarisation of the probe (Figure 2). In order to calculate the magnetic field the propagation length of the probe in the plasma is needed and this was measured by the other probe diagnostics (shadowgraphy, Moire deflectometry) as well as by imaging the second harmonic emission from the plasma. The “effective length” (the region in the plasma where the magnetic field is strong enough to significantly rotate the probe) is likely smaller than that seen by the above diagnostics, so this magnetic field measured is the estimated minimum.

The Faraday rotation angle was measured to be 19 ± 5 degrees which gives a magnetic field of ~ 9 ± 3 MG for an electron density of 10^{19} cm^{-3} and a propagation length of 0.5± 0.1 mm.

An important aspect of this measurement is that it shows that magnetic fields due to the inverse Faraday effect have a duration which is only for about that of the intense circularly polarised laser pulse which generates the field. The dissipation/ convection time for this magnetic field is clearly very short and is on the order of a picosecond. Also, there was no definite evidence of very large magnetic fields in the “wake” of the high intensity laser pulse where turbulent fields (vortices) have been predicted to exist[9] . However, from the asymmetry of the signal in Figure 2 there is some indication that much smaller fields (an order of magnitude less than that due to IFE) may exist in this wake.

In conclusion, we have performed the first time-resolved measurements of the Inverse Faraday Effect in which we measure fields of 9 ± 3 MG from interactions at intensities 5×10^{18} W/cm^2. The field was generated by a 0.9 ps duration laser pulse and lasted for a duration of 1-3 ps. These measurements are in reasonable agreement with theory.

Such fields may be useful for applications of laser plasma accelerators in order to reduce propagation instabilities of laser-accelerated electron beams through plasmas and perhaps improve their emittance.

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