Measurements of magnetic field generation at ionization fronts from laser wakefield acceleration experiments

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Abstract. Laser wakefield acceleration experiments were performed using a 30 fs, 1 J laser pulse interacting with an underdense helium plasma. Temporally resolved polarimetry measurements demonstrate the presence of magnetic fields at the ionization front within the plasma which had a peak strength of \( \sim 2.8 \) MG and a radial extent of approximately 200 \( \mu \)m. The field was seen to vary in strength over picosecond time-scales. The field is likely generated by return current generated in the plasma at the interface between plasma and neutral gas and which is caused by hot electrons produced in the wakefield during formation of a plasma ‘bubble’ and prior to the time of wave-breaking (beam injection). These effects are confirmed using particle-in-cell simulations. Such measurements can be useful as a diagnostic of bubble formation in laser wakefield accelerators.

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The generation of large amplitude relativistic plasma waves through the interaction of an intense laser pulse and a low density plasma offers the promise for low-cost, compact sources of high-energy electrons and radiation [1]. This process is called Laser Wakefield Acceleration and occurs when a short pulse laser (having a duration less than about 50 fs) propagates through a very underdense plasma (i.e. where $n_e$ is typically less than $10^{20} \text{cm}^{-3}$). A large amplitude relativistic plasma wave can form in the wake of the laser pulse if the pulse duration is less than the wavelength of relativistic plasma waves at that particular plasma density (i.e. $\lambda_p = \frac{2\pi c}{\omega_{pe}}$ where $\omega_{pe}^2 = \frac{n_e e^2}{\epsilon_0 m_e}$ is the electron plasma frequency). If the amplitude of the plasma wave is large the wave can ‘break’ thus injecting electrons into the electric field of the wave [2]. These electrons can subsequently be accelerated to relativistic energies. It has been shown in recent experiments that the three dimensional structure of such nonlinear plasma waves has a ‘bubble’ shape and can accelerate electron beams to 1 GeV [3] and beyond, with relatively low energy spread and excellent emittance [4]. Such beams are initially generated from underdense plasmas that have typically been field-ionized by the leading edge of the short pulse laser. The process of ionization has also recently been shown to be an alternative mechanism for trapping of electrons into the plasma wave for subsequent acceleration [5].

It has been shown in simulations that as a strongly nonlinear wakefield is formed, a ‘bow-shock’ of energetic electrons is generated as a precursor to electron trapping in the bubble [6]. The electrons in such bow-shocks are not trapped but are accelerated transversely to the direction of the laser propagation. The subsequent trapping of electrons for acceleration only occurs when the relativistic plasma wave experiences transverse wake-breaking [2] or ‘self-injection’ after which it is able to transfer much of its energy to the beam of relativistic electrons.

Laser wakefield experiments using femtosecond pulses have produced beams carrying in excess of a nC of charge ($\sim 10^{10}$ electrons) [7] and consequently, if the electron bunch duration is estimated to be similar to the laser pulse length, the corresponding peak current in the forward direction can be more than 1 kA. Note that the electron beam current inside the plasma itself is larger than that reaching a detector outside, as the charge leaving the plasma sets up an electric field which retards many of the lower energy electrons. Consequently there is also a longer duration, lower energy ‘dark current’ component to the forward going electron population as well. The magnetic field associated with this current, if confined to the width of the laser spot size, can therefore be several tens of megagauss in magnitude. Measurements of the magnetic field associated with the highly relativistic electron beams driven by laser wakefield accelerators have been used to diagnose the properties of such intense laser plasma interactions [8].

In this paper, we describe a set of experiments in which we have used a short pulse probe laser beam to measure a new source of magnetic fields in the plasma of a laser wakefield accelerator. In these experiments, the very large and highly transient magnetic fields in the ‘plasma bubble’ itself were not probed, rather a new source of magnetic fields appearing at the edge of the ionization front of the plasma was discovered and was found to be due to the population of hot electrons from the ‘bow-shock’ propagating transversely to the direction of the laser beams which are produced by the formation of the highly nonlinear wakefield. These fields are not due to the wavebreaking or electron injection but rather appear at the formation time of the ‘nonlinear plasma wave’—i.e., the bubble which precedes the injection of electrons. The fields have the opposite polarity to those in the plasma bubble and can be enhanced by ‘return currents’ driven in the plasma. These fields are straightforward to detect, require less stringent control of the probe laser properties and can also provide important information concerning the
electron acceleration process in the plasma, in particular for diagnosing wakefield generation, bubble–formation and wave-breaking.

The relatively large scale magnetic fields measured in these experiments occurred only at the edge of the ionization region of the plasma that was produced by the laser. From particle-in-cell simulations these fields were seen to be caused by the current of electrons emitted transversely to the direction of laser propagation during the process of ‘bubble or wakefield formation’ in the plasma. As these electrons cross the ionization boundary they generate a return current that is opposite to the direction of that due to the relativistic electron beam in the laser propagation direction and which can be consequently observed as a large scale magnetic field in our diagnostics. This was confirmed using particle in cell simulations of the interaction.

In general a transient magnetic field in a transparent medium may be detected through the use of an optical probe beam via the Faraday effect. The direction of polarization of an electromagnetic wave travelling through a magnetized plasma and which has its \( \mathbf{k} \)-vector parallel to the direction of the magnetic field will be rotated by an angle \( \phi = \frac{e}{2\pi m_e c} \int n_e \mathbf{B} \cdot d\mathbf{l} \). The field strength inside the plasma may therefore be measured through simultaneous polarimetry and interferometry measurements, whereby a plane-polarized probe beam is passed through the plasma and then the difference in polarization between the input and the output beam is determined. The interferometry measurement is typically required to provide the plasma electron density.

In this experiment, a relativistic electron beam was generated during the nonlinear evolution of the plasma wave produced via a high intensity laser wake-field interaction. For the experiment a 30 fs, 1 J pulse, was produced by the Salle Jaune laser at LOA (Laboratoire d’Optique Appliquée) [9]. The lasing medium of the Salle Jaune laser system is Ti:sapphire and the central operating wavelength is 800 nm. The pulse was focused using an f/18 parabolic mirror onto the edge of a helium gas jet from a 2 mm supersonic nozzle which has an electron density of about \( 7 \times 10^{19} \) cm\(^{-3} \). The plasma density scalelength was about 0.5 mm on the outside of the gas jet and the vertical density scalelength was more than 1 mm. This arrangement gives a focused laser intensity of approximately \( 4.2 \times 10^{18} \) W cm\(^{-2} \) and \( a_0 = 1.4 \) (where \( a_0 \) is the normalized vector potential of the laser pulse, i.e. \( a_0 = (1.38 \times 10^{18} \text{ W cm}^{-2} \mu \text{m}^{-1})^{1/2} \), with a focal spot size of 21 \( \mu \)m (full-width at half-maximum). An electron spectrometer was used to measure the average energy of the electron beam produced by the interaction, which was found to be 10 \( \pm \) 1 MeV. The electron beam typically has a broad Maxwellian energy spectrum at these plasma densities. Relatively high density was used in these experiments in order to facilitate these proof-of-principle Faraday rotation measurements however with slight improvements in the experiment setup similar measurements could be made over a much wider density range.

In the experiment a measurement of the charge emerging from the plasma was made using an integrating current transformer, giving a total charge of up to 5 nC within a cone angle of about 30°. Note that this measured all of the integrated charge emitted from the plasma which was much greater than just that in the electron beam as obtained from the electron spectrometer. A portion of the laser was also used as a collimated probe which was passed through the jet along a path perpendicular to the main beam axis (see figure 1). The plasma generated during the main interaction refracted the probe to produce a ‘shadowgraph’ which was imaged onto a 16-bit Andor CCD camera. A Polarcor sheet polarizer was placed before the camera to monitor the rotation of the probe polarization. The plasma density in the interaction region was measured by deoptimizing the compression gratings in the laser system, thereby stretching the pulse and reducing the intensity of the focused laser beam. This changed the interaction conditions to
allow Raman forward scattering to occur which produced side-bands in the laser spectrum separated by the electron plasma frequency—which are dependent on the plasma density.

Experiments were then performed using the compressed pulses focused into a plasma of density approximately $7.0 \pm 0.4 \times 10^{19} \text{ cm}^{-3}$, with the polarizer orientation altered by $15^\circ$ between shots (see figure 2). The plasma produced by the laser pulse refracts the probe, focusing the rays that pass through the electron density gradient at the edge of the plasma so that the image of that part of the probe beam is more intense. Thus the ‘horse-shoe’ shape seen in the images in figure 2 describes the edge of the plasma. The probe intensity $I_0$ at the camera is attenuated by the polarizer at an angle $\theta$ to $I_1 = I_0 \alpha \left[ 1 - \beta \sin^2 \theta \right]$ where $\alpha$ and $\beta$ are the angles for maximum transmission and extinction respectively, and $\theta$ is the polarizer angle relative to the probe. If the polarization direction of the probe varies across the beam, the plasma shadow image will be non-uniformly attenuated. Figure 2 shows that this is indeed the case. The value of $\theta$, and therefore $\phi$, at each point on the image may be recovered by superimposing the camera images produced by two shots with a difference in polarizer angle of $\Delta$ and taking the value of $R = \frac{I_1}{I_0}$. For $\Delta = \frac{\pi}{4}$, $\theta = \sin^{-1} \sqrt{(1 - R)(1 - \beta)} / (\beta(R + 1))$. In this way a map of polarization rotation (polarogram) of the probe by the plasma may be constructed. Figure 3 shows such a map. It can be seen that the rotation is consistent with Faraday rotation of the probe by an azimuthal magnetic field structure approximately $200 \mu\text{m}$ across with a slightly longer length along the laser propagation axis direction. Using this map the magnetic field distribution may be calculated by assuming cylindrical symmetry around the laser axis and inverting the value of $\phi$ through an Abel transformation. The electron density as measured by the Raman scattering is assumed to be constant within the plasma which is a reasonable approximation given the long density scalelengths in the glass jet. To minimize noise in the probe, the map of $\phi$ was averaged along the axis between points $a$ and $b$ in figure 3 to produce a one-dimensional trace which was then inverted using the formula $f(r) = -\frac{1}{\pi} \int_r^R (r^2 - y^2)^{-1/2} \frac{d}{dy} \left( \phi(y)/y \right) dy$ [10] where

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{The arrangement of optics for the polarimetry measurements. The vertically polarized probe beam (wave-vector $k$) passes through the magnetized plasma and the direction of polarization is rotated through an angle $\theta$. The rotation sense is right-handed for $k$ parallel to $B$ and left-handed for $k$ anti-parallel to $B$. The probe passes through the lens, causing the plasma image to be inverted, and then through a sheet polarizer at an angle $\phi$ to the original probe polarization. The camera then re-inverts the image focused onto the CCD chip.}
\end{figure}
Figure 2. Polarimetry images of the plasma. The numbers in the top right corner of each image denote the angle of the polarizer $\theta$ relative to the unrotated probe beam.

$f(r) = \frac{e}{2m_e c n_e(r)B(r)}$. Here $y$ refers to the distance from the laser axis in a two-dimensional (2D) projection of the plasma (e.g. figure 3), and $r$ is the distance from the axis in the reconstructed cylindrical plasma.

It can be seen in figure 4(a) that the data is noisy, and so to obtain a reasonable estimate of the field strength a polynomial curve was fitted to the rotation distribution and an Abel transform was subsequently taken. The upper and lower error limits were found by considering the uncertainties in the curve fitting as well as in the process of producing the polarogram. This gives a peak field strength of $2.8^{+1.3}_{-0.4} \text{ MG}$ on one side of the plasma and $2.7^{+0.9}_{-0.6} \text{ MG}$ on the other.

If the assumption is made that the field was generated by a beam of electrons then an estimate of the beam current may be made. Assuming further that the beam is approximately a skin current on edge of the ionization front, from Ampere’s law $B(r) = \frac{\mu_0 I}{2\pi r}$ the current $I = 10 \text{ kA}$. The apparent axial extent is approximately $350 \mu\text{m}$ (see figure 2), implying a beam duration of about $1.1 \text{ ps}$. This is in reasonable when compared to the measured charge in the forward direction since the return current would be composed of many non-relativistic electrons and therefore the current would have much longer duration. It is likely that the electrons producing the observed field are travelling along the edge of the ionized region and that they are
Figure 3. A calculation of the rotation angle of the probe beam at each point on plasma images at $-35^\circ$ and $55^\circ$.

Figure 4. (a) The line-out generated by averaging the rotation along the laser axis from point $a$ to point $b$ in figure 2. (b) The Abel-inverted line-out, along with the inversion of the curve fit to the line-out.

considerably lower in energy (10’s to 100’s of keV) than the relativistic forward going electron beam generated from the wakefield—however it is also clear that the generation of the return current and subsequent $B$-fields produced is inextricably linked to the forward acceleration of relativistic electrons in this experiment through the necessary formation of a highly nonlinear three-dimensional (3D) structure. Such a scenario would be consistent with the return current in the plasma being the source of the measured magnetic field.

Information on the variability of the field over time was found by taking a series of shots while changing the delay between the probe beam and the main beam. Figure 5 shows polarimetry images of the plasma with the analyser at an angle of $55^\circ$ to the probe polarization. It can be seen that there is an asymmetry between the intensity of the top and the bottom of the plasma shadow in each image, as there was in figure 2. By assuming that this asymmetry
Figure 5. A series of plasma shadowgrams with the analyser at 55° to the probe polarization taken at various delays between the probe beam and the main beam. The magnetic field is measured over time in regions of the field that are (a) static and (b) co-moving with the ionization front.

is due only to the effect of Faraday rotation, the field strength in the plasma may be estimated. This is done by extracting the image of the plasma and inverting it about the main beam axis. This inverted image is then superimposed onto the original. A polarogram was then generated using $\Delta = 110° = 2° \times 55°$. As before, to minimize noise the polarogram was averaged along the laser axis and the magnetic field extracted using the Abel transform. This was done for each image at two positions along the laser axis: one at a constant position relative to the laboratory frame and one co-moving with the apparent position of the front of the plasma. The regions over which the averaging was done are shown in figure 5.

The peak values of the magnetic field at the static position and co-moving with the laser are shown in figure 6. It can be seen that both measurements peak sharply; that they peak at the same time is because they were chosen to coincide at the maximum value. The fields do not appear to last long in these measurements—which suggests that they are related to plasma wave generation and electron injection—both of which are very dynamic processes in the interaction. A particularly remarkable aspect of the field measured in this experiment is the spatial extent, both radial and axial. A plasma has the ability to ‘neutralize’ time-varying magnetic fields by inducing return currents either around or within the beam current. This process tends to limit the
Figure 6. The maximum value of the magnetic field measured at different interaction times, for a constant position in the plasma (squares) and a position moving with the ionization front (circles).

size of time-dependent magnetic fields to the plasma skin-depth, $c/\omega_p$. The plasma used here has a density of $n_e = 7.3 \times 10^{19}$ cm$^{-3}$, giving a skin depth of 0.6 $\mu$m. Therefore, if the field was produced by a beam of accelerated electrons driven by a wakefield generated near the path of laser pulse propagation, it would have been surprising that it could be detected using this method since we did not have sufficient spatial resolution in the diagnostics—however if the source of magnetic field is the extended region supplying return current to the plasma at the edge of the ionization region, its extent would be much larger, as there is a separation between the current due to a near forward directed hot electron cloud propagating outside the ionized region and the return current drawn from within the plasma.

In order to investigate further the processes that may be occurring within the plasma a 2D particle-in-cell simulation was carried out using the OSIRIS 2.0 code [11] in a moving simulation box of spatial size $230 \mu$m $\times$ $300 \mu$m on a grid of size $6000 \times 2400$ cells, with a single species with eight particles-per-cell representing electrons with uniform number density $n_e = 1.3 \times 10^{19}$ cm$^{-3}$ with an initial 130 $\mu$m linear ramp. A Gaussian laser pulse was initiated in the simulation box with waist $w_0 = 20 \mu$m, duration $t_0 = 34$ fs, polarized perpendicular to the simulation plane with normalized field strength $a_0 = 1.4$. This code contains field ionization physics so it is able to model the dynamics of fields appearing at the ionization front in our experiments. We used a smoothed barrier suppression ionization model [4], but with a higher than realistic ionization potential of 200 eV for the hydrogen like neutral species. This was chosen to limit the transverse extent of the ionization region, which due to the limited simulation box size and 2D laser focusing would otherwise reach the boundary too rapidly. Simulations with a realistic (13.6 eV) ionization potential showed similar dynamics for early times.

Some of the results may be seen in figure 7. The simulated laser pulse undergoes self-focusing and stimulates the growth of a large amplitude plasma wave, which breaks to produce a current of high-energy electrons. The magnetic field in this simulation is restricted to the size of the laser pulse and reaches a strength of 60 MG in the region near the laser pulse. However there are lower strength magnetic fields correlated to plasma wave formation and subsequent electron acceleration that are localized at the side of the interaction near the ionization front.

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Figure 7. Data from the particle-in-cell simulation showing (a) the forward momentum of the electrons (normalized to $m_e c$) and (b) the integrated maximum magnetic energy density (in arbitrary units—see text) both as a function of time, and (c) and (d) the magnetic field Abel transformed at times (c) 1700 fs and (d) 2000 fs.

and which have opposite polarity to the magnetic fields produced by the current of accelerated electrons. These fields grow dramatically as electrons are accelerated in a bow shock by the laser pulse during the formation of highly nonlinear 3D plasma wave structures. After the laser pulse has passed, electrons are pulled back to the axis of propagation by space charge forces and many of the higher energy electrons ‘overshoot’ and escape the plasma wave region to travel across the ionization boundary. These electrons—accelerated by the formation of the plasma bubble in a near forward direction—travel at the surface of the ionization front surface and generate a return current within the plasma. For the magnetic field distributions in figure 7 we have assumed that the Cartesian coordinate system approximates the radial distribution. Then, to get data similar to the experimental Faraday rotation measurement, we used an Abel transform of the field in the radial direction so that it replicated the projection of the cylindrical data onto two dimensions, consequently eliminating the large ‘on-axis’ bubble fields. For the magnetic energy as a function of time, we assumed the field was approximately cylindrical and integrated $B^2$ with respect to the longitudinal coordinate and then plotted the maximum of $B^2 r dr$, which is the magnetic field integrated over a cylindrical shell of thickness $dr$. The region indicated in grey cannot be determined from these simulations because, for times after the ionization front

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spreads out to reach the sides of the simulation box, it is inappropriate to track the maximum $B$ field. However one can see that the field is decreasing at this point, as in the experiment. This is likely to be because the total field energy is approximately constant (to first approximation), but then as the ionization front expands the strength of the magnetic field drops as $1/r^2$.

The dynamics of field formation can be clearly observed in movies generated from the particle-in-cell simulations. Movie 1 (see the supplementary material, available from stacks.iop.org/NJP/15/025034/mmedia) shows the dynamics of the electric charge and movie 2 shows the dynamics and formation of the magnetic fields around the ionization front. These simulations agree well with the experimental data obtained, which shows a field that spreads over a diameter of around 250 $\mu$m with a maximum strength of approximately 3 MG. The temporal and spatial scales from the simulations are also in good qualitative agreement with the experimental results. It is clear from the simulations that the growth of the magnetic field at the ionization front of the plasma occurs simultaneously with the current of electrons streaming out of the laser wakefield region and crossing the edge of the ionization front. This population of electrons is produced by the ‘bowshock’ of lower energy electrons (which can be 10’s to 100’s of keV) as the non-linear wakefield is formed which immediately precedes transverse wavebreaking and electron injection into the plasma wave. The temporal duration of these fields can be longer than the laser pulse since the ‘return current’ generated in this way is composed of relatively low energy electrons which travel more slowly than the relativistic electron beam in the forward direction.

In conclusion we have observed during laser wakefield acceleration experiments the formation of an extended region of magnetic field at the ionization boundary of the plasma. These fields are indicative of the dynamics of return current generation due to the acceleration of an electron beam by the generation of highly nonlinear, 3D relativistic plasma wave structures. These magnetic fields have dynamics on sub-picosecond timescales and it is possible to use measurements of the evolution of these fields to quantify mechanisms involved in plasma wave generation and electron trapping in plasma driver electron accelerators. In particular, we may identify the point at which plasma waves transition from a primarily longitudinal plasma wave to a plasma ‘bubble’ as a precursor to electron self-trapping and acceleration.

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