Micronscale spatially resolved and femtosecond time resolved megagauss magnetic pulse in hot, dense plasmas

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Abstract. We report the measurement of spatially and temporally resolved evolution of the self generated magnetic field in laser generated solid density plasma on Al coated glass target. In a two pulse experiment we capture the magnetic field generated by the main pulse in the change in ellipticity of polarisation of the probe pulse, which is incident at various time delays. The observed multi megagauss magnetic field has a rise time which is very short. The decay of the field occurs over a much longer time scale.

1. Introduction
MeV hot electrons are generated in laser matter interaction at super-Coulombic (> 10¹⁶ W cm⁻²) light intensities. These are of extreme importance in basic science and technology [1]. The fast ignition (FI) scheme of inertial fusion depends critically on the generation, transport and eventual stopping of these hot electrons in the overdense plasma [2]. The time evolution [3] and morphology of the associated self generated magnetic fields contain essential information on these issues. Recent simulation by Robinson and Norreys [4] has shown that self generated spontaneous azimuthal magnetic field can be used to offer superior collimation of hot electron jet in their propagation through hot dense plasma. The spatial and temporal characterisation of laser generated magnetic field thus becomes of immediate interest in view of all these phenomena.

2. Experiment
The experiments are performed at TIFR using a Ti: Sapphire chirped pulse amplified laser (Thales Laser, Alpha 10) emitting 55 fs pulses centered at 800 nm wavelength at 10 Hz repetition rate. The P polarised laser is focused at oblique incidence with a f/4 off axis parabolic mirror on targets housed in a vacuum chamber at 10⁻⁴ torr. The maximum pulse energy used in the present set of experiments, gives a peak intensity of about 2 ×10¹⁷ Wcm⁻² at a 20 μm focal spot. In all our experiments we used optically polished (roughness≈ λ/5) Al coated BK7 glass targets where the thickness of the Al coating is >> the laser skin depth for 800 nm implying that the glass background has no effect on the experiments. The target is constantly translated in the focal plane in order to avoid multiple laser hits at the same spot. Our technique relies on two pulse pump-probe experiments. The pump here is typically at an intensity of 1–2×10¹⁷ Wcm⁻² at 800nm wavelength and is incident at 27° with p-polarization. A probe beam at second harmonic wavelength (400nm), is a factor of 10³ to 10⁴ weaker than the pump and is normally incident on the target interaction region (Fig.1) so that it can sample the overdense regions where large hot electron densities and high magnetic fields are expected to occur (Fig1c ). The reflected probe beam is collected after the polarimetric set up using a PMT and a highly
sensitive triggerable CCD which takes snapshots at regular intervals synchronised to the incident pump beam (Fig.1). The zero time reference for two-pulse experiments involves the spatial and temporal matching of two the laser pulses on the target. The sharp dip in the reflectivity of the probe pulse when the pump pulse forms plasma on the metal surface defines the zero of time delay between the two pulses. The self-generated magnetic field \( B \) has azimuthal geometry due to the fact that its main source i.e. hot electron jets penetrate normally into the target. The measurement of all stokes parameters of the reflected probe yields the magnetic field induced ellipticity [5]. The probe wave vector \( 'k' \) is thus perpendicular to quasi-static magnetic field ‘B’. In this configuration, probe traveling through magnetized plasma acquires ellipticity due to difference in refractive indices of two characteristic modes, O-wave and the X-wave [5,6]. The reflected probe is split in two parts - the first arm has a calibrated photodiode to measure reflectivity (establishes the zero of time delay) and, the other has a combination of quarter wave plate and polarizer in front of photodiode to measure ellipticity. The measurement of all Stokes parameters is done with polarizer alone at 0°, 45°, 90° and then with quarter wave plate at 0° and polarizer at 45°.

The analysis of polarization of the reflected probe beam yield information about the integrated effect of the magnetic field along the path of propagation [6]. The CCD image pixel values render the measurement of spatial profile of the azimuthal magnetic field.

Figure 1. (a) Schematic showing the experimental set up. (b) Interaction region and the magnetic field geometry. (c) Schematic showing that the probe reaches the overdense region of interest

The hard x-ray bremsstrahlung (25 KeV - 250 KeV) emission under high intensity laser irradiation is measured using a properly calibrated NaI(Tl) scintillating detector looking normally into the target. Background noise and pile up problems are eliminated by using (i) time gated data acquisition (30 µs collection time window opened in synchronization with the incident laser pulse) and (ii) keeping hard x-ray count rate below one per second, i.e. 0.1 per laser shot by adjusting the solid angle subtended into the detector.

3. Results and discussions
The hard X-ray spectrum yields a hot electron temperature of 40±1 keV (Fig. 2 left). The magnetically induced ellipticity is obtained as a function of the time delay (Fig. 2 right) between pump and probe pulses by measuring the Stokes parameter of probe pulse. The evolution of stokes vector \( s \) inside the magnetized plasma is determined by \( ds/dz = \Omega(z) \times s(z) \). Here \( \Omega = (\omega/c)(\mu_o - \mu_x) \) is proportional to difference between refractive indices \( \mu_o \) and \( \mu_x \) of O and X-waves, which depends on strength of the magnetic field [3,6]. The ellipticity is induced due to two different processes- the different refractive indices of O- and X- wave and different turning points or cut-off’s for O- and X-wave. In order to deduce the magnetic field from measured ellipticity, we numerically integrate the
polarization evolution equation $ds/dz = \Omega(z) \times s(z)$, with well-defined initial polarization of input laser [6]. At each delay we integrate this equation numerically inside the plasma and the value of magnetic field required to generate experimentally observed ellipticity is deduced (Fig. 3 left).

**Figure 2.** Left: Bremsstrahlung spectra. Right: Ellipticity Vs. time delay

Fig. 3 left shows the time dynamics of the azimuthal magnetic field created by the combination of forward going hot electron current and return shielding current in the plasma. Note that the magnetic field shows a very sharp rise time (< 2 ps) and a comparatively slow decay time (~ 25 ps). Fig. 3 right shows the spatial profile of ellipticity (top) which is deduced after subtracting the background inherent ellipticity of the laser pulse itself. The pixel values where the background ellipticity is more than the magnetic field induced ellipticity are eliminated from the figure to get rid of noise. The figure

**Figure 3.** Left: The evolution of the magnetic field in time. Right: Background subtracted polarigram at 1.3 ps (top) and spontaneous laser generated magnetic field profile at 1.3 ps (bottom)
below it shows the azimuthal magnetic field distribution at a delay time of 1.3 ps. The direction of magnetic field lines is anticlockwise with respect to the figure. The polarigram shows a complicated magnetic field structure with a spatial maximum of ~65 MG.

4. Summary
In summary experimentally we have measured the spatial profile of laser generated magnetic field in the over dense region of solid density plasma by using a second harmonic probe which penetrates beyond the critical density layer of the pump pulse where the hot electrons are generated. In a two pulse experiment we captured the azimuthal magnetic field at different times and quantified its evolution. The azimuthal magnetic field distribution shows a complicated structure and embedded in it holds signature of hot spots which are cites of high magnetic field values. Temporally the magnetic field rises sharply within a few ps and decays in 10s of ps.

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