

Magnetic field generation from a foil-coil target using kJ-ns class lasers

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Introduction:

The generation of Mega-Gauss level magnetic fields has numerous applications in laser plasma physics, especially in the fields of laboratory astrophysics, charged particle lensing and fast ignition [1]. The magnetic field for such applications can be created by the interaction of a kJ-ns class laser with a capacitor-coil target [2-6]. This paper presents the results from a recent experiment on the generation of magnetic fields inside a wire loop connected to a flat foil, by exploiting the self-capacitance of the foil target irradiated by the Iodine Laser of the Prague Asterix Laser System (PALS). The spatial distribution and temporal evolution of the magnetic field was measured by Faraday rotation at two wavelengths using an ultrashort Ti:Sa probe beam and an approximately 350 ps long probe beam at 2ω . The data from in situ measurement demonstrates the generation of strong magnetic field from foil-coil target.

Experimental Setup:

The experiment was conducted employing the Iodine Laser (energy on target ~ 600 J, pulse duration ~ 350 ps) of Prague Asterix Laser System (PALS), Prague. The focal spot diameter of the laser on the target was ~ 80 μm , providing a peak irradiance ($I\lambda^2$) of 10^{16} - 10^{17} $\text{W/cm}^2\mu\text{m}^2$. The interaction target was a Cu foil of dimensions 4 mm x 28 mm and thickness of 50 μm . A Al wire loop of 1.1 mm diameter and 100 μm thickness was attached on one end to the interaction foil and to the ground on its other end (see Fig. 1), providing a single path for the neutralizing current to flow from the interaction target to ground. This geometry allows to optimize the current in the wire loop, hence magnetic field generation at the center of the coil. Schematic of the experimental setup is shown in Fig. 1. The two probe beams of different wavelengths were made collinear using a beam splitter before probing the coil, in order to facilitate a direct comparison between the data obtained from the two different probes. A Terbium Gallium Garnet (TGG) crystal of thickness 500 μm was placed behind the coil. The

distance between the TGG and the coil was varied from shot to shot between 300 and 1300 μm . The TGG crystal rotates the polarization of the probe beams in proportion to the magnetic field generated by the coil. A broadband Wollaston prism with high extinction ratio ($\sim 10^6$) was used to split the beams into quadrature components. Downstream of the Wollaston prism, dichroic mirrors were used to split the probe beams for polarimetry imaging (using the Ti:Sa probe) and streak camera measurement (using the 2ω probe). The polarimetry imaging using the Ti:Sa beam had a magnification of 2 using a system developed by institute of plasma physics and laser micro fusion, Warsaw, Poland [7]. B-dot probes were used as a complementary diagnostic measuring the time varying magnetic field in order to reconstruct the magnetic field at the center of the loop. The B-dot probe (RS-H 50-1, dia.=10 mm) having frequency bandwidth of 30 MHz – 2 GHz was placed at distance 28 mm from the coil center [8]. Due to the absence of an absolute calibration, the B-dot probes measured the most dominant frequencies from the coil.

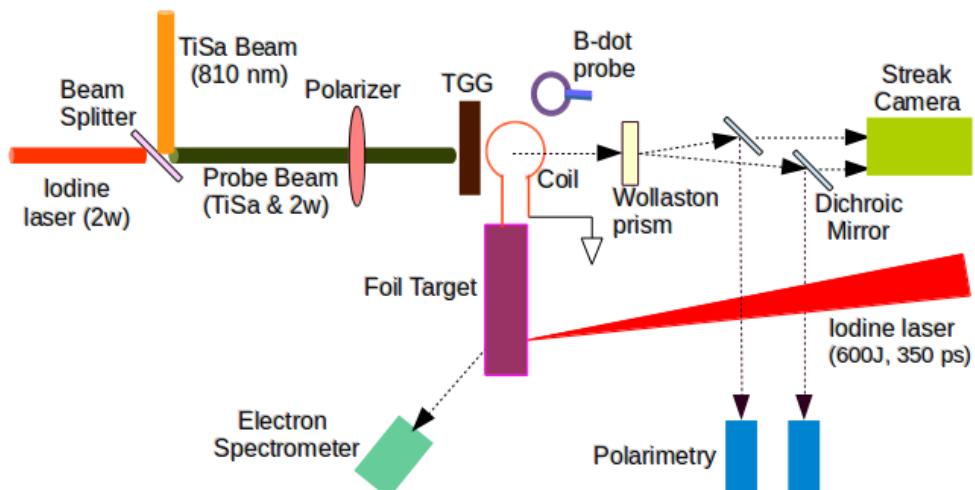


Figure 1:
The schematic of
experimental set-up
and diagnostics

An electron spectrometer with side a view configuration to minimize noise from incident X-ray photons [9] was specifically developed for the experiment. The electron spectrometer was installed 28 cm from the focus and had a collection opening angle of 2.46×10^{-5} sr.

Experimental Results:

In this article we present typical measurements obtained from the TiSa polarimetry imaging system and the electron spectrometer. The magnetic field at the TGG was calculated by measuring the Faraday rotation of the TiSa probe beam. The angle of Faraday rotation (θ) is linearly dependent on magnetic field (B) i.e. $\theta = V \times B \times L$, where V (3800 degree. $\text{T}^{-1}\text{m}^{-1}$) is Verdet constant of TGG medium and L (0.5 mm) is the length of optical path in the medium. Figure 2 shows a typical raw measurement of the polarization rotation angle. The boundary of

the coil and the TGG crystal are clearly visible [see Fig. 2 (a)]. The small aperture of the Wollaston prism resulted the imaging systems to have a small f-number of $\sim f/30$. Consequently the shadow of the coil caused diffraction patterns as shown in Fig 2(a). Thus, meaningful data can be obtained at the center of the coil, where the region is devoid of diffraction artifacts.

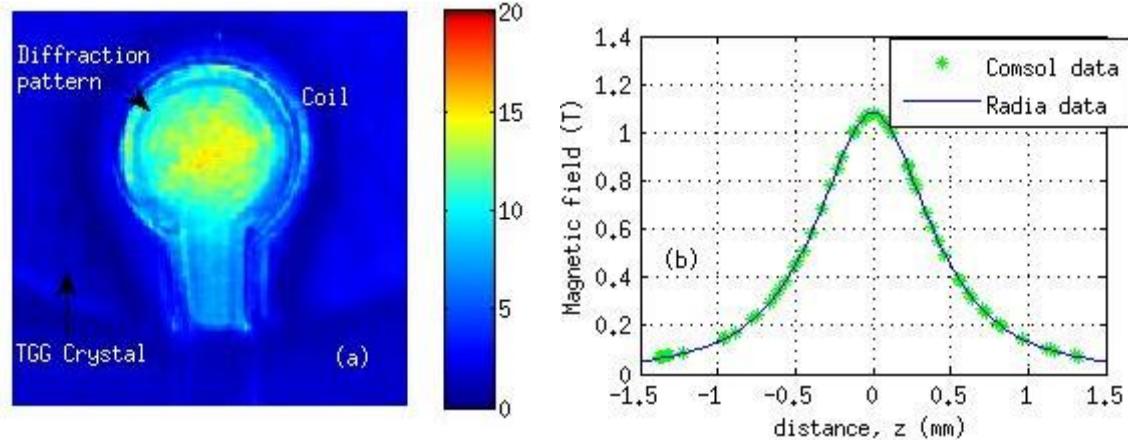


Figure 2: (a) The figure shows the experimental demonstration of Faraday rotation angle measured in degree (see color bar) using TGG crystal and TiSa beam. (b) Comparison of simulation results between radia and comsol software for magnetic field along the axis of coil ($x=y=0$) when 1kA current passing through it.

In order to scale the magnetic field measured at the location of TGG to the plane of the coil, magneto-static solvers COMSOL and RADIA [10] were used to model the field created by the coil. Figure 2b shows the spatial variation of the axial field along the center of the coil. For example, the rotation angle shown in fig 2a corresponds to a magnetic field of about 20 T at the center of the coil and a current of about 19 kA. By varying the delay of the Ti:Sa probe beam with respect to the arrival of the interaction laser on the target, we were able to measure the evolution of the current in the coil as a function of time. The data shows that the current pulse in the coil lasted for about 4 ns, thus we can estimate the total initial charge on the target to be around 80 μ C.

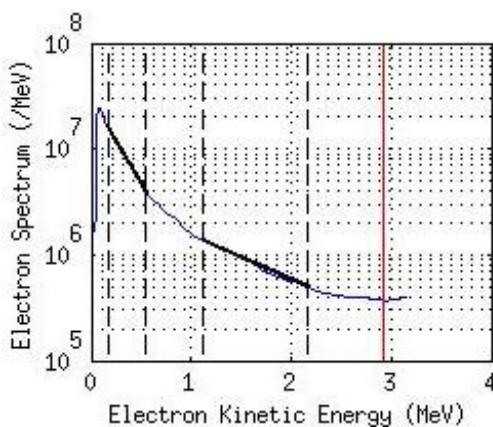


Fig. 3 shows the typical result obtained from the electron spectrometer. Since the hot electron temperature is expected to be around 100 keV [11], the spectrometer was designed to cover electron energy in the range 100 keV to 4 MeV. The typical hot electron temperature measured in our experiments was of the order of 100 keV and electron cut off energy of about 2.5-3 MeV.

Figure 3: The experimental observations of electron spectrum vs kinetic energy.

Conclusion:

In conclusion, we reported generation of strong magnetic fields (~ 20 T) inside a wire loop connected to a flat foil target irradiated by the Iodine Laser of the PALS. This paper presented results from polarimetry and electron spectrometer. Moreover, B-dot probe and streak camera are also used to determine the time evolution of magnetic field profile. The experimental results from other targets and diagnostics are currently under analysis and will be reported elsewhere. Such kind of laboratory generation of large magnetic fields provides an experimental test bed to explore various unresolved physics problems in basic and astrophysical plasma such as magnetic reconnection and collisionless shocks.

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References

- [1] Report on B-fields at NIF workshop held at LLNL October 12-14 (2015).
- [2] S. Fujioka et al., *Scientific Reports*, **3** (2013).
- [3] C. Courtois et al., *Journal of Applied Physics* **98.5**, 054913 (2005).
- [4] H. Daido et al., *Phys. Rev. Lett.* **56** (8 1986), pp. 846–849.
- [5] J. J. Santos et al., *New J. Phys.* **17** 083051 (2015).
- [6] X. X. Pei et al., *Phys. Plasma* **23**, 032125 (2016).
- [7] T. Pisarczyk et. al., *Phys. Plasma* **21**, 012708 (2014).
- [8] https://www.rohde-schwarz.com/cz/home_48230.html
- [9] O. V. Gotchev, P. Brijesh, P. M. Nilson et al., *Review of Scientific Instruments* **79**, 053505 (2008).
- [10] <http://www.esrf.eu/Accelerators/Groups/InsertionDevices/Software/Radia>
- [11] D. V. Giovanielli et. al. *Journal of Applied Physics* **47.7**, pp. 2907-2910 (1976).