Proceedings of the 6th International Conference on Dense Z-Pinches, University of Oxford, UK July 25th- 28th, 2005

Magnetic Field Measurements in Wire-Array Z-Pinches and X Pinches

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Abstract. We are investigating novel techniques to obtain time-dependent magnetic field measurements in wire-array Z-pinches and X-pinches. An ideal method would be emission spectroscopy (Zeeman splitting of lines, for example, in the visible or VUV spectrum), as it would be entirely passive and non-perturbing. However, a spectroscopic method to determine the high magnetic fields present in megampere level wire-array Z-pinches with high spatial resolution has not yet been identified. Determining the Faraday rotation of laser light passing through wire-array Z-pinches suffers from severe difficulties precisely where the measurements are most interesting, namely inside of the array where density gradients are large and the plasma is thought to be magnetohydrodynamically turbulent. We are looking into using "remote sensing" methods whereby a very small sensor material is placed in the plasma and then is investigated to extract useful information. Faraday rotation of polarized laser light traversing a small area through thin film waveguides coupled to a fine optical fiber is a possibility. While these films may not survive for long in a dense z-pinch, they may provide useful information for a significant fraction of the current pulse. Details of these two methods along with preliminary results from one or both of them will be discussed. We will also discuss results of experiments conducted using magnetic CoPt thin films to obtain the maximum magnetic field seen by the film near the end of the load current pulse.

Keywords: Wire-Array Z-Pinches, X Pinches, Magnetic Field Measurements, High Energy Density Matter, Faraday Rotation, Magneto-Optically Active Materials, Verdet Constant, Magnetic CoPt Thin Films, SQUID, Magnetic Hysteresis, Magnetization, Remanence, High Coercivity, X-ray Diffraction.
PACS: 52.58.Lq, 52.59.Qy, 52.70.-m, 52.70.Ds, 52.70.Kz, 32.60.+i, 75.60.-d, 75.60.Ch, 75.60.Ej, 75.60.Jk, 75.60.Nt, 75.70.Ak, 75.50.Vv, 76.60.Es, 76.60.Jx, 75.50.Cc, 85.25.Dq, 07.85.Jy, 61.10.Nz, 68.55.-a, 68.55.Jk, 81.15.Cd

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FARADAY ROTATION THROUGH A MAGNETO-OPTICALLY ACTIVE MATERIAL WAVEGUIDE

Magneto-Optical effects, in the general sense, involve the behavior of light-matter interaction in the presence of a magnetic field. Materials that affect light in the presence of magnetic fields are normally classified as magneto-optically active. When plane-polarized light travels through a medium in the direction parallel to an applied magnetic field, the plane of polarization of light rotates – this is known as the Faraday Effect. The Faraday effect only occurs when the magnetic field intensity (H) or magnetic induction (B, flux density) is parallel to the direction of propagation of light. The Faraday rotation is quantified by Equation (1) when the flux density is constant and by Equation (2) when the flux density is not constant [1]. The proportionality constant, V, is the Verdet constant. It depends on the material and the wavelength of light.

$$\Phi = VBd \tag{1}$$

$$\Phi = V\int \vec{B} \bullet d\vec{l} \tag{2}$$

The experiments herein were conducted on COBRA, the Cornell megampere (MA), 100ns pulsed power generator. For our initial experiments, a cylindrical glass rod (M-18 glass from Kigre, ~70% Terbium-doped, ~2 cm in length and 1 cm in diameter) was used for Faraday rotation of light. A 543.5nm CW 4mW HeNe laser was used as the light source. At this wavelength, M-18 has a Verdet constant of ~0.37 min Oe^{-1} cm^{-1} (~62 ° T^{-1} cm^{-1}). Initially, the M-18 glass rod was tested to see if it fluoresces under hard x-ray radiation (tens of keV). We found that it did not fluoresce. The M-18 rod was then placed in the vicinity of the Z-pinch and linearly polarized light shone through it. An analyzer (polarization beam splitter) was used to resolve the output beam from the rod into two orthogonal, linearly polarized components. We detected the components using fast response photodiodes with 1ns rise time. The signals obtained by one of the photodiodes from two shots on COBRA are shown in Fig. 1 and 2.

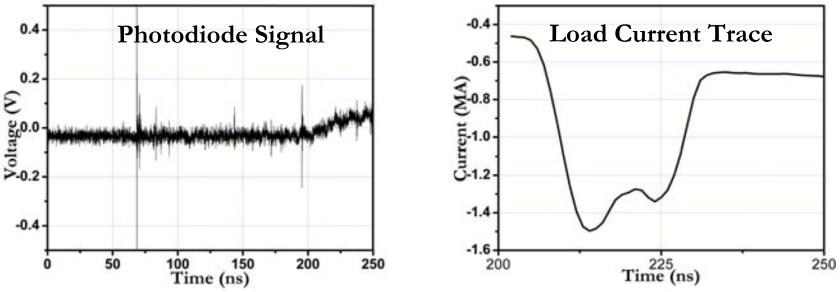

FIGURE 1. An 8 wire x 12.5 µm Al Z-pinch was used (shot 325). Rod was placed ~4.5 cm from z-axis. One can see slight rise in photodiode signal when load current starts. Photodiode was triggered by standard scope trigger generated by the machine control panel (gas switches in self-breaking mode).

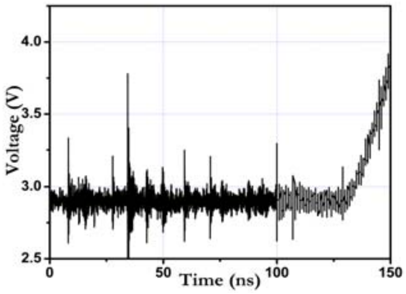

FIGURE 2. Photodiode signal from shot 327. An 8 wire x 17 μm W Z-pinch was used. Rod was placed ~4.5 cm from z-axis. Photodiode was triggered by a photodiode monitoring the laser triggered gas switches. In this particular shot though, timing was off, therefore can't compare with current trace.

The rise in the photodiode signals beyond the noise level indicates potentially meaningful signals. In Fig. 1, the photodiode signal correlates well with the current trace. However, more shots are needed to adequately examine the noise level. We found that the setup needs to be optimized to take into consideration the various parameters and variables involved. The noise needs to be shielded maximally and the photodiode sensivity needs to be increased due to its low responsivity at this particular laser power. Once the setup has been optimized (and results are reproducible), one can use Malus' Law ($I_{out} = I_{in} \cos^2\theta$, where I is the intensity of light) to obtain the amount of rotation undergone by the light. This would then be correlated to the magnetic flux density via Equation (2) (or Equation (1) to first order). Also, preliminary bench testing of the M-18 rod with a magnet, after several shots on COBRA, seemed to indicate a change in its responsivity. This also needs to be investigated further. The crucial issue with this experiment is the penetration time of magnetic field flux lines into the waveguide. We are planning further investigations with other materials such as TGG. We are also in the process of developing thin film waveguides which would be coupled to the light via optical fibers. The thinner waveguides should allow for a shorter penetration time for the magnetic field.

MEASURING SUB-MICROSECOND MAGNETIC FIELDS USING MAGNETIC (COPT) THIN FILMS

This novel technique exploits a well known property of ferromagnetic materials – their magnetic hysteresis. Two sets of CoPt films were developed [2]. Their magnetic hysteresis was examined using a Superconducting Quantum Interference Device (SQUID). The films' microstructure was analyzed using an x-ray system with an area detector (GADDS) as well as a Θ-Θ diffractometer. Using the SQUID, two thin film samples (A &B, each ~5x4 mm) were initialized with remnant magnetization along a specified direction (Fig. 3). The films were placed near the X-pinch plasma column with their magnetizations in opposite directions to each other but aligned parallel to the azimuthal magnetic field produced in the vicinity of the X pinch. We found that the current driven through the X pinch induced a change in magnetization in sample A. The induced change in the magnetization of the films was then determined using the SQUID. Further analysis of the hysteresis loop yielded a lower bound of 1.7 T for the magnitude of the maximum magnetic flux density to which the film was exposed.

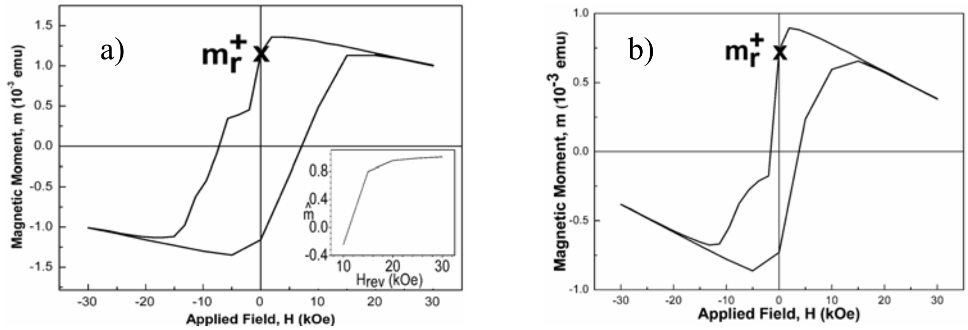

FIGURE 3. a) Hysteresis loops (in-plane) of the CoPt film (Sample A). Inset: Calibration curve of moment after recoil demagnetization as a function of field excursion. b) Hysteresis loops (in-plane) of the CoPt film (Sample B).

This technique also worked with the other set of films developed. To take into account the demagnetizing field (due to cracks in A), a calibration curve for film A (inset of Fig. 3a) was generated to determine the value of the field (1.7 T). The change in magnetization of the films showed that the corresponding current through the X pinch was in a direction opposite to the current during the initial part of the pulse. The current in the last pulse to reach the X-pinch load generates the magnetic field that the thin films record (if this field is larger than the coercivity).

The response of the film magnetization is of the order of tens of ns due to the inherent temporal response time of magnetic domains, thus facilitating the measurement of sub-microsecond magnetic field pulses via this approach. This technique can be readily extended to the measurement of larger magnetic fields by developing magnetic thin films with higher coercivity (e.g. Nd-Fe-B compositions) enabling us to probe closer to the X-pinch plasma column where the field is higher as well as inside a wire-array Z-pinch. This technique can, however, be universally applied to any system where sub-microsecond magnetic fields are to be probed. To our knowledge, this work marks the first time magnetic thin films have been used to measure sub-microsecond magnetic fields.

SPECTROSCOPIC APPROACH

We are investigating Zeeman splitting of lines in visible or VUV spectrum which can provide a way of measuring the magnetic field provided other broadening mechanisms (e.g. Stark broadening) are taken into account. Zeeman splitting of an x-ray line would be too small for typical fields one expects in Z-pinches. Time resolution is crucial otherwise the splitting would be largely indistinguishable from the Doppler and/or Stark broadenings (over a range of B field amplitudes). One approach is to dope wires with a different material and then examine the emission spectra of the Z-pinch for specific lines of the dopant. Another approach could be to have a thin film of a material on the end of a fine optical fiber. This might provide information about the magnetic field through Zeeman spectroscopy when the film turns into plasma.

ACKNOWLEDGMENTS

This research was sponsored by the National Nuclear Security Administration under the SSAA program through DOE Cooperative Agreement #DE-F03-02NA00057. The work on thin films made use of the X-ray Diffraction Facility of the Cornell Center for Materials Research (CCMR) with support from the NSF MRSEC) program (DMR-0079992).

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