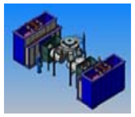
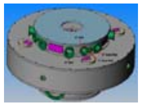


Magnetic Field Measurements in Wire-Array Z-Pinches*



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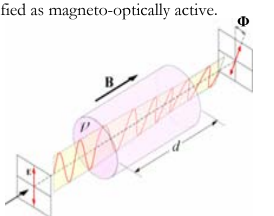
INTRODUCTION

A method to determine the magnetic field in megampere level wire-array Z-pinches with high spatial and temporal resolution has not yet been developed. An ideal method would be passive and non-perturbing, such as Faraday rotation of laser light or emission spectroscopy. However, Faraday rotation measurements in Z-pinches suffer from severe difficulties, because density gradients are large and the plasma is magnetohydrodynamically turbulent inside the Z-pinches. Therefore, we are developing a method based on Faraday rotation through a sensing waveguide placed in the vicinity of, or perhaps in, a wire-array Z-pinch. We will also discuss emission spectroscopy methods based upon the Zeeman effect that are also under investigation. Finally, we will present a technique developed using magnetic CoPt thin films that measures a lower limit for the maximum magnetic field.

FARADAY ROTATION THROUGH A MAGNETO-OPTICALLY ACTIVE MATERIAL WAVEGUIDE

The Faraday Effect

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. It can occur in all materials, both anisotropic and isotropic, though the magnitude is decreased by birefringence. Magneto-optical effects are inherently related to differential transitions within the spin-orbit energy level of a material. 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. When the magnetic field is perpendicular to k, we have another phenomenon occurring known as the Voigt effect.

The Faraday rotation illustrated in the figure is quantified by the following equation:

$$\Phi = VBd \qquad \_\_(1)$$

The proportionality constant, V, is the Verdet constant and depends on the material and the wavelength of light. A positive Verdet constant corresponds to L-rotation (counter-clockwise) when the direction of propagation of light is parallel to the magnetic field, and to R-rotation (clockwise) when the direction of propagation is anti-parallel. If a ray of light is passed through a material and reflected back through it, the rotation doubles.

If the flux density is not constant, then the equation becomes:

$$\Phi = V\int B.dl \qquad \_\_(2)$$

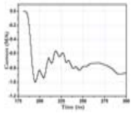
Experimental Setup

The experiments herein were conducted on COBRA, the Cornell megampere (MA), 100ns pulsed power generator. For 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. A 543.5nm CW 4mW HeNe laser was used. At this wavelength, M-18 has a Verdet constant of ~0.37 min Oe^{-1} cm^{-1} (~62° T^{-1} cm^{-1}). The M-18 rod was placed in the vicinity of the Z-pinch and the laser light shone through it.

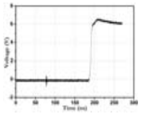
The M-18 glass rod was first tested to see if it fluoresces under hard x-ray radiation (tens of keV). It was placed in an anodized Al container, which in turn was placed outside a port window of the vacuum chamber. An 8 wire Manganin X pinch was loaded (25 µm for shot 320, 50 µm for shot 322). For shot 320, the container was closed off with an Al plate. For shot 322, the plate was removed. In both instances, a photodetector was facing the glass rod on the other side to monitor any radiation given off. For shot 320, there was no signal indicating no fluorescence. As expected, shot 322 gave a signal.

Anodized Al container

Shot 322
Current trace from load Rogowski

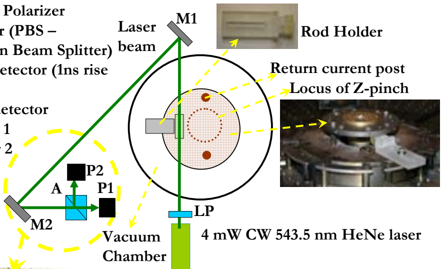


Shot 322
Photodetector signal (no cover plate)



The figure shown below is a plan view of the COBRA chamber along with the experimental setup.

LP: Linear Polarizer
A: Analyzer (PBS – Polarization Beam Splitter)
P1: Photodetector (1ns rise time)
P2: Photodetector
M1: Mirror 1
M2: Mirror 2



These optics (below) were covered with a box before a shot

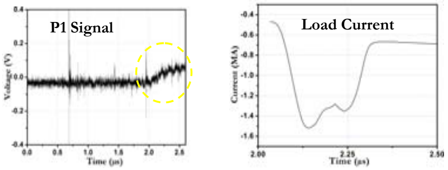
The photo on the left shows the rod positioned near a Z pinch. The laser beam traversing through the rod is also visible in this photo.

The two photos above show different views of the M-18 rod positioned near a Z-pinch. An 8 wire x 12.5 µm Al Z-pinch is shown here. In shot 325, rod was placed ~4.5 cm from the z-axis and in shot 327, ~3.5 cm.

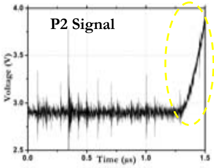
Photo on the right shows a close-up of the M-18 rod surface after a Z-pinch shot. Surface appears to have been ablated by the debris and perhaps a plasma shock wave. Surface required re-polishing after each shot. Surface tomography and atomic force microscopy (AFM) can provide further insights to investigate effects on such materials in HED regimes.

Results

<u>Shot 325</u> 8 wire x 12.5 µm Al Z-pinch



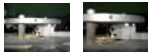
<u>Shot 327</u> 8 wire x 17 µm W Z-pinch



-The time scale corresponds among plots in each shot.
-Highlighted regions indicate potentially meaningful signals. In shot 325, signal correlates well with current trace. Setup needs to be optimized.

Shot 325 - 50Ω termination. Shot 327 - 1 MΩ termination with short shielded coax cables. With 50Ω termination, difficult to obtain signal from P1 & P2 because photodetectors had low responsivity at 543.5nm due to low power (4 mW) of laser. New laser has been ordered. A Diode Pumped Solid State (DPSS) CW 532 nm Green laser (80 mW) will be used in future shots.

Further shots with BTS-18 glass rods (Verdet constant of ~ -0.73 min Oe^{-1} cm^{-1} ~-122° T^{-1} cm^{-1} at 532 nm) needed. BTS-18 is a Terbium doped glass from Sumita Optical Glass, Inc. In shot 382, the BTS-18 (few mm's from Z pinch) fell from its holder so no change in intensity of polarization components was seen.



Shot 382 with BTS-18 rod

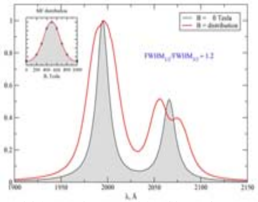
Conclusions

-Optimize setup: Need to shield out noise maximally and increase sensitivity. New DPSS 532 nm CW 80 mW Green laser higher powered.
-Use **Malus' Law: $I_{out} = I_{in} \cos^2\theta$**, where I is the intensity of light and relate rotation obtained to B field via Equation (2) (or Equation (1) to first order).
-Preliminary bench testing of M-18 glass rod with magnet, after several shots on COBRA, seems to indicate change in its responsivity. Interestingly enough, Villaverde et al., in *J. Phys. C: Solid State Phys.,* Vol. 11, 1978, discussed observing some hysteresis in TGG but we need further investigation before drawing any conclusions.
-Penetration time of B field flux lines into waveguide crucial issue.
-Further investigations are planned with other materials, e.g. BTS-18 and TGG. More shots with M-18 glass are also planned.
-Development of thin film waveguides & coupling light using optical fibers. Collaboration with Prof. Michal Lipson, Cornell Nanophotonics.

SPECTROSCOPIC APPROACH

•Zeeman splitting of lines in visible or VUV spectrum. Take into account other broadening mechanisms (e.g. Stark). Zeeman splitting of x-ray line too small for typical fields in Z-pinches. Time resolution crucial else splitting would be largely indistinguishable from Doppler and/or Stark broadenings (over range of B field amplitudes). Use doped wires & examine emission spectra of Z-pinch to look for specific lines of dopant.

•Possibly look at ~2000 Å line (Al XI 3s -> 3p transition). Collaboration with Prof. Yitzhak Maron from Weizmann Institute of Science, Israel.



•Another approach could be to have a thin film of a material on the end of a fine optical fiber. This might provide information on the magnetic field at the film through Zeeman spectroscopy when the film turns into plasma.

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