Using Faraday Rotation to Study Z-Pinch Plasmas

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1. Introduction

Z-pinches have several practical applications, including: creation of both x-rays and blackbody radiation, generation of magnetic fields, and possibly controlled thermonuclear fusion[1]. Specifically, wire array Z-pinches are recognized as a leading source of generation soft x-ray radiation[2]. Recent advances pulsed power technology and diagnostics instrumentation have furthered our understanding of Z-pinches[1]. These advances have led to more research in the field of wire array Z-pinches, especially for use in inertial confinement fusion.

Research on wire array Z-pinches is being done in several facilities around the globe. At Imperial College, the MAGPIE (mega-ampere generator for plasma implosion experiments) generator was built to further understanding of wire arrays Z-pinches. The MAGPIE generator was designed to run at high voltages, with a maximum charging voltage of 2.4 MV, a target current of 1.8 MA, and an impedence of around 1.25 Ω. The current is delivered to high inductance Z-pinch loads with a rise time (10-90%) of around 150 ns[3]. These specifications satisfy the conditions necessary to create implosions in wire array Z pinches[1,4].

Experiments on wire arrays around the world have resulted in numerous advances. At Imperial College, recent experiments on wire arrays have included research on the physics of wire array Z-pinches[4,5], and radial wire array Z-pinches[6]. The goal of these experiments is to increase the x-ray power generated from the Z-pinches.

But the physics of wire arrays Z-pinches are not fully understood. In particular, the current distribution in Z pinches is very complicated, and requires further studies. Before the array implodes, most of the current remains near the wires. But not much is known about the current distribution during and after implosion[7].

In order to study the current distribution, we have developed a non-invasive diagnostic system to measure Faraday rotation angles and plasma density. One can measure the magnetic field through polarimetry, by shining a laser through plasma and using the laser's polarization angles[8,9]. And one can measure the plasma density through interferometry, by using a reference beam.

2. Faraday Rotation

When an electromagnetic wave – in our case, a probing laser beam – interacts with a magnetic field, its plane of polarization will be rotated by a certain angle. This angle largely depends on the magnetic field and the electron density. For example, assume the beam passes through a plasma with cylindrical symmetry – as is the case for the arrays we studied over the summer – and refraction is negligible. Then the Faraday rotation angle can be derived by the following formula:[10]

$$\phi = \frac{e^3\lambda^2}{8\pi^2\varepsilon_0 m_e{}^2 c^3}\int n_e \mathbf{B}\cdot\mathbf{dl}\,. \qquad (1)$$

Here $\frac{e^3}{8\pi^2\varepsilon_0 m_e{}^2 c^3}$ is a constant, λ is the wavelength of the beam, **B** is the magnetic field, and **dl** is an element of length traveled by the electromagnetic wave. Previous

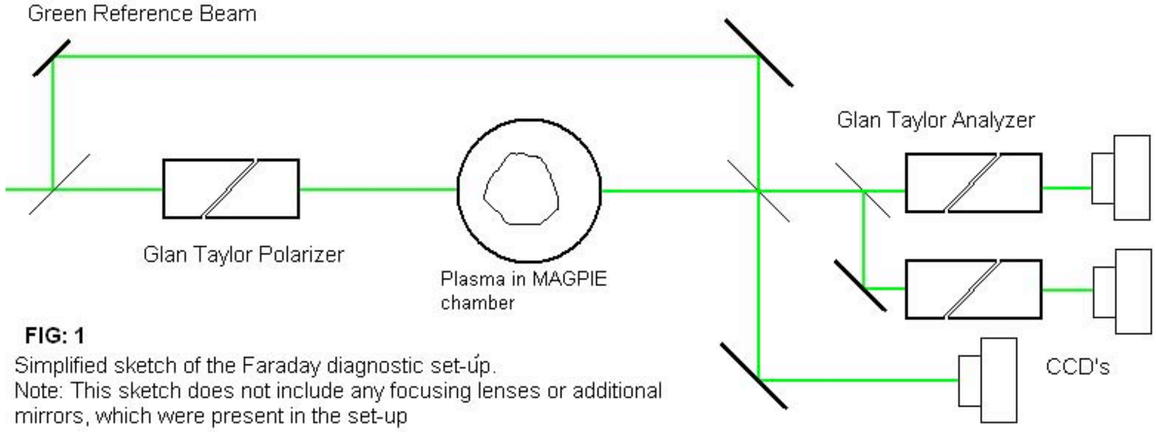

FIG: 1
Simplified sketch of the Faraday diagnostic set-up.
Note: This sketch does not include any focusing lenses or additional mirrors, which were present in the set-up

calculations and attempts at measuring Faraday rotation angles at Imperial College have shown that the expected Faraday rotation angles are approximately $3 \cdot 10^{-3}$ rad[7].

For our experiments, we constructed a system (figure 1) to measure the Faraday rotation angles. In our system, we used an Nd:YAG green (wavelength = 532nm) laser pulse, which delivered 0.5 J in 0.7 ns to provide the input beam. This beam first traveled through a calcite, air spaced Glan-Taylor polarizer. The Glan-Taylor polarizer breaks the beam into an ordinary ray (o ray) and an extraordinary ray (e ray) (figure 2a). The ordinary ray's polarization is perpendicular to the axis of the crystal, and the extraordinary ray's polarization is parallel. The beam then traveled through two focusing lenses (not shown in figure 1) into the MAGPIE chamber, where it passed through the plasma and the wire array. After the beam exited the MAGPIE chamber, it passed through more focusing lenses (not shown) and through a non-polarizing beam splitter.

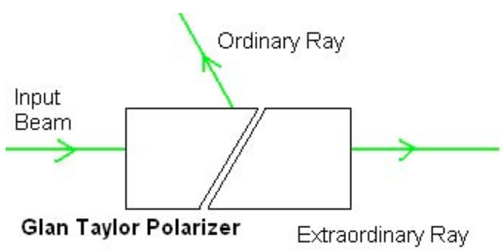

FIG: 2a
The Glan Taylor Polarizer breaks the input beam into two beams with different polarizations

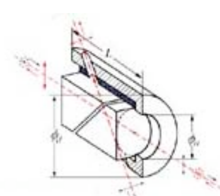

Fig: 2b
A sketch of the Glan Taylor polarizer that we used. Here, φa = 20 mm, φd = 38 mm, and L = 48.9 ± .1 mm.

One beam traveled through more focusing lenses (not shown) and into a charge-coupled device (CCD) camera for interferometry. This is done to measure the plasma density and the Faraday rotation angles along the same beam path[10]. The other beam traveled through a second beam splitter, and both beams traveled through two analyzers. For the analyzers, we used the same Glan-Taylor polarizers. The analyzers provided us with $\sim 10^6$ extinction. Finally, both beams passed through focusing lenses (not shown), and into CCD cameras for polarimetry. All CCD's used were 1024 x 1024 8 bit CCD cameras.

During our experiments the CCD's were timed to capture an image of the wire array before and after explosion. This provides us with a background image. The analyzers were adjusted to extinction, and then rotated by a small angle $\pm\theta_A$ (one analyzer was rotated by an angle $+\theta_A$ and the other by $-\theta_A$) to allow some light to reach the CCD's. Since the current is expected to flow through the plasma, we expect the plasma to have a bright side and a dark side, compared to the background images. Assuming axial symmetry, according to Malus's law, the intensities for the bright and dark side of the plasma are[7]:

$$I_{bright} = I_0 \cos^2(\theta_A - \phi) \;\&\; I_{dark} = I_0 \cos^2(\theta_A + \phi) \tag{2}$$

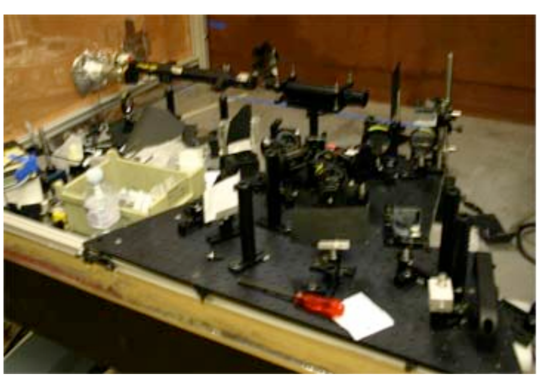

FIG 3
The Faraday imaging system. Both CCD's aren't shown in the picture. The system had to be constructed on this small black platform, in order to fit on the MAGPIE and measure Faraday rotation angles occurring in the plasma.

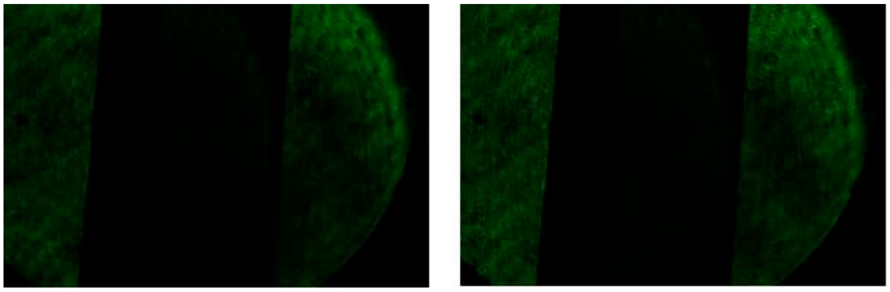

FIG: 4
CCD images (before and after) measuring Faraday rotation of a cylindrical tube. Since there is no external current, no change in the images is expected.

3. Results & Discussion

After the Faraday imaging system was constructed (figure 3), we measured exploding wire arrays. As stated previously, the CCD's were timed to capture a background image before the pulse arrived, and a second image a few nanoseconds after the pulse arrived. One day, instead of an array, a cylindrical tube was inserted into the MAGPIE chamber. As expected, there was no change in the images (figure 4). (These images both seem to have a "double image" – which will be discussed later).

We mainly used the Faraday imaging system to measure exploding wire arrays. Figure 5 shows a polarized image from an exploding array with coiled wires, before and after pulse. This coiled exploding wire array had 4 x 25µm Al wires, placed on a diameter of 17.8 mm. Each wire had a length of 85mm, and had 14 turns in the coil. From the images, one can see small streams of plasma ablating off the core wires. Also, the intensity on one side of the wires is much higher than the intensity on the other side of the wires. This could possibly confirm that Faraday rotation has taken place inside the array. Unfortunately, this image was taken with only one analyzer active, so Faraday

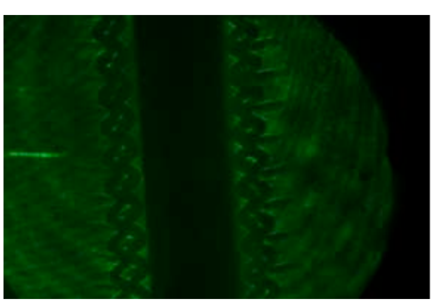

FIG: 5
Here is an image of an exploding coiled wire array, taken after pulse. Plasma is ablating off the wires. This image shows 4 x 25µm coiled Al wires. All four wires are present in the picture - two are on the right side, and two are on the left side. Notice how one side of the wires appears much brighter than the other side. This suggests that Faraday rotation possibly occurred in the wire array.

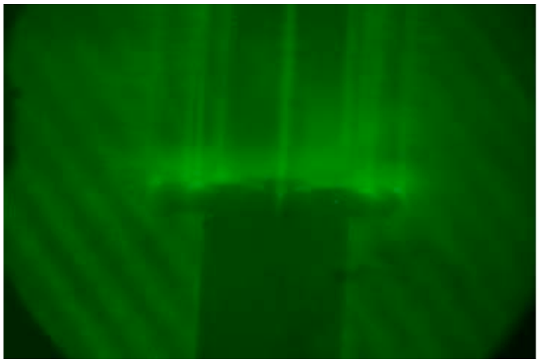

Fig: 6
CCD image of an exploder array. This array had 8 x 25μm straight wires. For this image, we believe that not enough light passed through the plasma and into the CCD's.

rotation might not have caused the differences in intensities. (For example, the differences in intensities can be due to refraction).

Currently, both analyzers in the Faraday imaging system are active. The Faraday imaging system has been used to measure exploding wire arrays with both straight and coiled wires. However, for the few times when both analyzers were active, we ran into several difficulties. For some images, stray light entered the system. For some images, not enough light passed through the polarizer and analyzers into the CCD's, causing a very high noise to signal ratio (figure 6). Some images (figure 4) had the aforementioned double image. Some images had a combination of problems. Nevertheless, most problems in the Faraday imaging system have been resolved. Changing the orientation of the polarizer and analyzers, allowed more light to enter the CCD's, which resulted in a much lower noise to signal ratio. And we found out that the double image problem was caused by back reflections off the analyzers into the CCD's. These back reflections were reduced by placing small apertures at the focal points of the beam, to block out secondary images (figure 7).

Although the Faraday imaging system was only in use for a few weeks, we have made great progress in our measurements. In the coming months, the Faraday imaging system will be perfected, and we will gather more data using the Faraday imaging

Fig: 7
This image shows a focusing lens and an aperture. The aperture was positioned to block any secondary images from reaching the CCD (not shown).

system. As stated previously, the interferometer (figure 1) will use the same beam path to measure plasma density. These improvements in the Faraday imaging system should

4. Acknowledgements

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