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TITLE CURRENT MEASUREMENTS BY FARADAY ROTATION IN SINGLE-MODE FIBERS

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CURRENT MEASUREMENTS BY FARADAY ROTATION IN SINGLE-MODE FIBERS*

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ABSTRACT

We have measured currents in the several-hundred-kilamp range, with tens-of-nanoseconds risetime, in magnetic fusion devices using simple polarimetric techniques.

INTRODUCTION

The tremendous growth of fiber optics communications technology during the seventies overshadowed the simultaneous development of fiber optic sensors: devices to use optical fibers as transducers to convert, electric or magnetic fields or mechanical strains due to temperature or pressure changes into optical signals. The primary thrust of most current work in this field is toward extreme sensitivity, as in sensors for the detection of very small magnetic fields, rates of rotation or acoustic disturbances; and tends towards the use of single mode fibers, integrated optics, and interferometric techniques. An excellent overview of this rapidly developing field is given by Giallorenzi, et al, in reference 1.

Large magnetic fields can be detected with optical fibers by measuring the Faraday rotation,

$$F = \int \underline{H} \cdot d\underline{l} , \quad (1)$$

of plane polarized light. If the fiber makes a closed loop around a current source, then

$$F = VI , \quad (2)$$

where V = Verdet constant, about 4.68×10^{-6} rad amp $^{-1}$ for silica, and I = current.

*Work performed under the auspices of the USDOE.

A drawback to this technique is the presence in fibers of linear birefringence. The analysis of the evolution of the state of polarization in the presence of linear birefringence and Faraday rotation has been done for a simple but practical case by Smith (2). A computer program written in our group at Los Alamos is capable of analyzing more complex cases by accomplishing the multiplication of vectors and matrices necessary to the use of the Jones calculus. We find that our experiments can be roughly modeled using these theoretical tools, but that we need a much better experimental technique, particularly with respect to stress-and bending-induced birefringence, before we can do quantitative predictive modeling. However accurate current measurements can be accomplished by in-situ current calibration.

EXPERIMENTAL

The High Density Z-Pinch (HDZP) experiment of Hammel, et al, (3) produces a large current in a narrow, laser-ionized path in dense (2 atmospheres) hydrogen gas. The radial extent of the current path is of interest and it was proposed to determine this by looping the current with fibers which pass very close to the supposed current channel, then moving them between shots to see if the amount of current enclosed varies. This technique should provide a means of mapping the current distribution in the region of the channel. We have not yet accomplished the mapping, but we have detected the current.

Figure 1 is a sketch which shows how the fiber is placed in the pressure vessel with respect to the current channel. The fiber passes through the vessel twice so that its position can be accurately controlled by sliding the access plates into which it is glued. Linearly polarized light is incident on the end of the fiber, with its plane of polarization parallel to one of the fiber birefringent axes. The output light is analyzed by a Thompson beam splitter oriented at 45 degrees to the exit face fiber axes, so that the photocurrents of the two detector diodes are equal with no plasma current. The photocurrents are amplified and displayed on a dual-beam oscilloscope. The Rochon prism and quarter-wave plate are necessary to rotate the plane of polarization of the input light. The mode stripper removes laser light from the cladding, and also light which enters the cladding from the plasma. This insures that the detectors are only affected by laser light which propagates in the fiber core.

When current flows within the fiber loop, the Faraday rotation of the plane of polarization unbalances the photocurrents I_1 and I_2 . We record the changes in these currents on the oscilloscope and from them we can calculate the quantity

$$T = \frac{I_1 - I_2}{I_1 + I_2}, \quad (3)$$

the behavior of which is predicted by Smith (2) as a function of Faraday angle and the birefringence of the fiber, and described by equation (4) below.

A copper bar was placed in the position of the current channel for calibration and figures 2 and 3 show the current measured by an inductive probe (scale factor 92 KA per division) and the photocurrents, respectively. We will explain the features of these traces below. Figures 4 and 5 show the same traces for conditions where the current was in the plasma channel briefly, but a sudden arc transferred the current to an insulator, resulting in the detected current, that is the current looped by the fiber, going to zero. The inductive probe continued to measure current with only a small glitch to show where the arc had occurred. Figures 6 and 7 show the effect of a pressure wave striking the fiber; evidently light leaves the fiber core because both traces move in the same direction. We hypothesize that the pressure modulates the indices of refraction at the fiber core-clad interface, destroying its wave-guiding properties. The onset of this drift correlates roughly with the impingement of a pressure wave identifiable by a Schlieren photograph taken at about 700 nsec.

ANALYSIS

The birefringence of the fiber can not be measured unambiguously. The technique we use, following Smith (1), produces a value for $\cos(\delta_1 + \delta_2)$, where δ_1 is the birefringence of the portion of the fiber exposed to the magnetic field, and δ_2 is the birefringence of the portion between there and the detector. Considerable ingenuity is involved in trying to determine which value of birefringence to choose, and how to assign the birefringence to the different legs of the fiber. Figure 8, curves A, B, and C are plots of T versus Faraday angle for three different values of birefringence corresponding to the value of $\cos(\delta_1 + \delta_2)$ measured in this experiment. Faraday angle F is computed from

equation (2) using the Verdet constant for silica, and T is calculated from Smith's formula,

$$T = -2\cos(\delta_2 + \eta)\sin\chi\sin\frac{\phi}{2}(\cos^2(\frac{\phi}{2}) + \cos^2\chi\sin^2(\frac{\phi}{2}))^{\frac{1}{2}}, \quad (4)$$

where

$$\eta = \tan^{-1}(\cos\chi\tan\frac{\phi}{2}), \quad (5)$$

and

$$(\frac{\phi}{2})^2 = (\frac{\delta_1}{2})^2 + F^2, \quad (6)$$

and

$$\tan\chi = \frac{2F}{\delta}. \quad (7)$$

It can be seen that the function is quite different for the different possible values of δ_1 and δ_2 . Curve A is the one which corresponds most closely with the recorded data.

The current in figure 2 peaks at 248 KA, which corresponds to 66.5 degrees of Faraday rotation. From curve A, figure 8,, the value of T should be about 0.97, whereas the value calculated from figure 3 is about 0.8. We attribute some but not all of the discrepancy to the time response of the amplifiers used. There are other indications, however, that curve A may be a fair predictor: when the current was increased in later shots, the slight dip noticeable in the traces on figure 3 became more apparent, suggesting that the function was "turning the corner", that is, tracing the curve past the peak and part way down the other side. This shows that the peak is located at about the right value of F.

CONCLUSIONS

Faraday rotation in optical fibers can be a useful diagnostic for large currents in fusion devices only if there exists a means of either controlling the birefringence of the fiber or calibrating the sensor response. Even in the case where a calibration can be done, the birefringence must be maintained at the value present during the calibration, and this may not be a simple task in most experimental environments. We intend to continue development of this diagnostic, both in the form presented here and in the more sophisticated form of a Sagnac interferometer (4).

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Fig. 1 Experimental setup to monitor dense Z-pinch current.

Fig. 2 Inductive current probe signal.

Fig. 3 Photo currents associated with Figure 2.

Fig. 4 Inductive current probe signal - note glitch.

Fig. 5 Photo currents associated with Figure 4.

Fig. 6 Inductive current probe signal.

Fig. 7 Photo currents associated with Figure 6. Notice positive drift starting about 600 nsec attributed to shock striking fiber.

delta-2 delta-1
 Acc:2
 Acc:37

FIGURE 8 CURVE A (SOLID LINE)

$$\delta_1 = 37^\circ$$

$$\delta = 2^\circ$$

'delta-2 delta-1'
Acc:43
Acc:73

FIGURE 8 CURVE B (SOLID LINE)

$$\delta_1 = 73^\circ$$

$$\delta_2 = 40^\circ$$

'delta-2 delta-1'
Acc:66
Acc:155

FIGURE 8 CURVE C (SOLID LINE)
 $\delta_1 = 155^\circ$
 $S = 1.0$