AIP Review of Scientific Instruments

Detection of plasma equilibrium shifts with fiber-optic sensing of image currents

P. R. Forman, F. C. Jahoda, and G. Miller

Citation: Review of Scientific Instruments 59, 1500 (1988); doi: 10.1063/1.1140176
View online: http://dx.doi.org/10.1063/1.1140176
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/59/8?ver=pdfcov
Published by the AIP Publishing

Detection of plasma equilibrium shifts with fiber-optic sensing of image currents

P. R. Forman, F. C. Jahoda, and G. Miller

Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, New Mexico 87545

(Presented on 14 March 1988)

Plasma shifts generate opposite-polarity net shell image currents at diametrically opposed shell locations. In theory these image currents can be detected by Faraday rotation fiber-optic current sensors wound around the shell sections. In practice the validity of the measurement depends on the extent of suppression of the linear birefringence induced by the fiber coil bending and lateral pressure. Circular birefringence bias twist of 60 turns/m of 125-μm o.d. single-mode fiber is sufficient for 2-in. radii of curvature bends, in agreement with theory, while 100 turns/m of 80-μm o.d. fiber have not been successful with 1-in. radii of curvature, contrary to calculations. Different means for further suppression of linear birefringence are discussed.

INTRODUCTION

The radial equilibrium position of reverse field pinch experiments is determined by the $j\times B$ force on the plasma. One component of the field is due to induced image currents in the close-fitting conducting shell which encircles the plasma. These currents vary in time due to the finite L/R time of the conducting shell. It is the object of this article to investigate the possibility of measuring these shell currents with fiber-optic sensors and provide a real-time analog correction signal to the equilibrium feedback circuit.

Assuming a steady plasma current I_p, the magnitude of the induced shell image currents is related to the equilibrium plasma shift by the equation[1]

$$\frac{dI_{\text{shell}}}{d\theta}=\mu_0\frac{\Delta}{\eta\pi}I_p\dot{\xi}\cos\theta\,, \tag{1}$$

where Δ is the shell thickness, η the shell resistivity, $\dot{\xi}$ the time derivative of the horizontal plasma equilibrium shift, and θ the poloidal angle.

The anticipated fiber configuration to measure this current is illustrated in Fig. 1. Holes are drilled through the metallic shell and two fiber coils are wound through the shell. The measurement is a differential one between the inside and the outside coils. The instrumentation to measure the net shell currents is similar to that used in Ref. 2.

Fiber-optic Faraday rotation sensors offer several advantages over conventional Rogowski coils for such a measurement. If Rogowski coils were to be employed, great care would be required to orient the coil turns. For times short compared to the L/R time of the shell, there will be almost complete exclusion of the magnetic field from the shell. This means that there will be almost equal and opposite currents running on the inside and on the outside of the shell. The magnitude of each of these currents will approximate that of the toroidal plasma current. For the ZT-P experiment,[3] these currents will be about 50 kA while the difference current which we are trying to measure is on the order of 100 A. Rogowski coils, one inside and one outside the shell, would be subtracting two large numbers so that accurate orientation and uniform winding of the sensor coils would be extremely critical.

A fiber sensor for either the inside or outside coil is also differencing the surface currents but the nature of the fiber sensor avoids many construction problems. The actual positioning of the fiber is not important as the signal is proportional to the total current which passes through the fiber loop.

Fiber current sensors are subject, however, to their own set of problems. Bending of the fiber and pressure on the fiber will induce unwanted linear birefringence which can destroy the measurement or, at least, cause errors.[4] Twisting of the fiber mitigates these effects. Three different twisted fibers have been produced by EOTec.[5] EOTec's original fiber has an outside diameter of 125 μm and a twist rate of 15 turns/m. This firm has recently produced two other new fibers: one of 125-μm o.d. with 60 turns/m and a smaller, 80-μm o.d. fiber with 100 turns/m. We have tested all three fibers by repeating the ZT-40M experiment.[2] All gave equivalent results, requiring about a 5% change in the Verdet constant of the silica to keep the agreement between fiber sensor and Rogowski coil/Pearson transformer always within 1%.

The linear birefringence introduced by bending has been calculated,[6] as has the induced circular birefringence produced by twisting the fiber.[7] The important parameter to be kept small in order to make an accurate measurement of the current[4] is $\delta/2T$ (the ratio of unwanted linear birefringence to twice the circular birefringence induced by twisting the fiber):

$$\delta/2T\sim\rho^2/\tau R^2\,, \tag{2}$$

where ρ is the radius of the fiber, τ is the twist of the fiber, and R is the radius of the bend the fiber makes. This shows that the smaller-diameter, more highly twisted fiber should yield

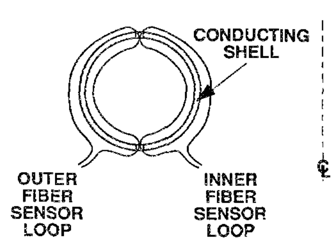

FIG. 1. Schematic drawing showing the inner and outer fiber coils on the shell of a toroidal experiment.

better measurements. The constraints of the Los Alamos ZT-P machine dictate a maximum fiber bend radius of 1.3 cm.

I. EXPERIMENTAL TESTS

To test whether this would permit a reasonably good measurement, the following model was taken for the fiber sensor. The fiber is assumed to be a racetrack form consisting of straight sections of fiber which have length $l_1 = 17$ cm and half-circle ends of radius 1.3 and $l_2 = 4.08$ cm. Assuming a uniform magnetic field along the fiber, the Jones matrix[8] representation of a half-turn of this sensor is then the product of two matrices:

$$M = \begin{pmatrix} \cos[(T+F)l_1] & -\sin[(T+F)l_1] \\ \sin[(T+F)l_1] & \cos[(T+F)l_1] \end{pmatrix} \times \begin{pmatrix} \cos(\phi/2) + i\sin(\phi/2)\cos\chi & -\sin(\phi/2)\sin\chi \\ \sin(\phi/2)\sin\chi & \cos(\phi/2) - i\sin(\phi/2)\cos\chi \end{pmatrix}, \tag{3}$$

where

$$\phi = \sqrt{\delta^2 + 4(F+T)^2}\, l_2, \quad \tan\chi = 2(F+T)/\delta .$$

δ is obtained from the bending formula and $2F$ is the Faraday rotation due to the magnetic field of the current. A full turn of the sensor is then M^2 and the sensor is described as M^{2N}, where N is the number of turns in the sensor. Numerical calculations were performed using calculated values for $\delta/2T$ for the various fibers.

In particular the results vary with the length of the straight section of the racetrack, and there are relatively sharply defined limits on $\delta/2T$, above which there is practically no sensitivity to current.

Figure 2 shows the calculated Faraday rotation change for unit current relative to the ideal case of no linear birefringence as a function of the straight-section length for the 100-turns/m fiber of 80-μm o.d. with 1.27-cm radius of curvature semicircles on a 50-turn coil. For certain discrete lengths there is a lack of sensitivity but overall the response is good.

To test this model experimentally, a fiber sensor was constructed using the 80-μm fiber. Forty-seven turns were placed on a coil form which approximated the theoretical model. The fibers were lightly constrained by foam rubber so that pressure birefringence[4] would be minimized. As a further precaution the curved end sections of the form were constructed in such a manner that they could be removed during operation so that there could only be bending birefringence in the end sections. The best results obtained with this sensor were of marginal quality and showed unacceptable distortion in the current time history. For example the second peak of the damped sine-wave current was smaller than the third peak by about 10%. These results were for uniform windings and optimum orientation of the analyzer polarizer.[4] The coils were then distorted in their coil form to simulate the nonuniformities in the radii of curvature which would be present in the winding of a practical sensor coil on an actual experiment. Under these conditions no orientation of the polarizer produced reasonable-looking Lissajous figures.

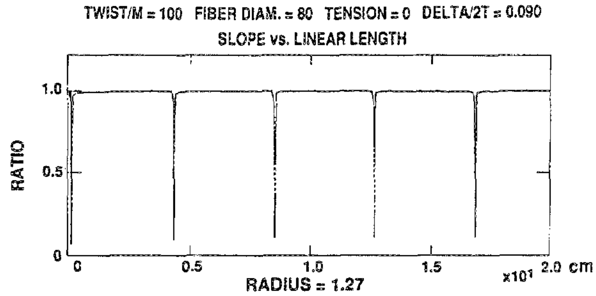

FIG. 2. Calculated dependence of the 80-μm, 100-turns/m fiber on a straight-section length, for 1.3-cm-radius end sections. Plotted is the Faraday rotation change per unit current relative to the case of no birefringence.

The results of these tests are not encouraging. The bends of the fiber end sections seem to be too severe to make a practical measurement on ZT-P. The same fiber was next rewound on a similar form, but with an end-section radius of 2.5 cm. The number of turns in this case was 39. As can be seen from Figs. 3(a) and 3(b), this sensor is also not totally free from birefringence effects, but a polarizer orientation was easily determined where accurate measurements of the current could be made. With the return current routed inside the sensor to give zero net current (but the return leg close to the bends, where birefringence effects are maximized), the

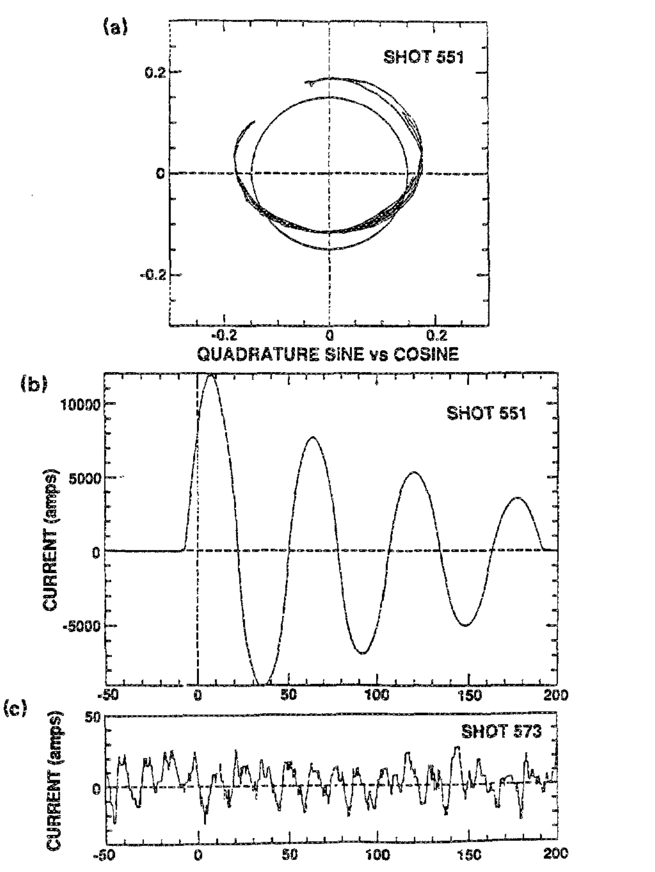

FIG. 3. Current trace (b) when the 80-μm fiber was wound on a 2.5-cm-radius coil form. In (a) is the corresponding Lissajous figure. In (c) is the residual when the current wire was returned through the fiber loop close to the curved ends, showing good cancellation.

cancellation was one part in 10^3. Figure 3(c) shows the measured current. There is clearly an instrumental oscillation at about 40 kHz. If this can be eliminated the measurement will exhibit a cancellation in the 10^{-4} range. This would be adequate for a 10% measurement if the shell surface currents differ by 100 A out of 100 kA. All data of Fig. 3 were taken with an optimum orientation of the analyzer polarizer. (Imperfect cancellation results when the worst orientation for the analyzer is chosen. In this case about 60 A registers when 12 kA is flowing.) With this sensor of larger bending radius and optimal analyzer orientation, a measurement could be practical.

The 125-μm, 60-turns/m fiber was also tested. Thirty-two turns were placed on the smaller, 1.3-cm-radius form. Surprisingly, in contradiction to the calculations, the results of this test were almost as good as that of the previous fiber on the 2.5-cm form. In this case an optimum polarizer orientation was easily established. Good measurements of the current were possible, and when the return current was passed back through the coil close to the curved end, the cancellation was 60 A out of 12 kA. This result is almost but not quite good enough for a measurement on ZT-P. It suggests that something peculiar is occurring with the 80-μm fiber.

An obvious solution to the problems presented above is to deploy the fiber sensor on a larger experiment which would permit more gentle bending of the fiber. To this end a sensor was tested on a spare piece of the ZT-40M conducting shell. The minor diameter of the torus is 40 cm. Because the shell is split in the main plane of the torus, both the inner and outer sensors will need to be split at this midplane as well. The four sensor coil sections will then be put in series either optically or electrically after installation. Ten turns of the 125-μm, 60-turns/m fiber were wound on the shell and taped to it. The fibers make a gentle turn so as to become almost parallel to the horizontal midplane slot. The radius of curvature of the fiber is still greater than 5 cm at the tightest point. In this way the birefringence effects are rather small. The same 12-kA test current was passed through the fiber loop at the point outside the shell where the bends were sharpest. With this arrangement excellent measurements of the current were obtained. The installation of fiber sensors on ZT-40M would, however, require the removal and reinstallation of several shell sections (a major operation).

An alternative approach to the fabrication of Faraday fiber sensors that is claimed to be much more tolerant to tighter bends is being developed by York Technology Inc. in England.[9] It achieves a highly elliptical birefringence fiber by extreme twisting during the drawing operation of an intentionally high linear birefringence fiber. The large temperature dependence of the high birefringence is compensated by averaging over many wavelengths, each of different birefringence, with a broadband diode laser light source. Furthermore the light is reflected from the far end back through the fiber to the entrance end. The Faraday rotation doubles while the reciprocal distortions, such as linear birefringence, tend to cancel. The cancellation would be complete if Faraday rotation did not change the polarization azimuth of the light encountering the distortions on the return path relative to the azimuth in the forward direction. To maximize the cancellation the total Faraday rotation should be kept small. This puts a premium on very high sensitivity in order to retain reasonable dynamic range.

We propose to test this method with a phase conjugator replacing the reflector. Besides providing higher reflectivity, this might open the possibility of a multimode fiber replacing the wavelength averaging achieved by the diode laser source and thereby also allow the much simpler input coupling of a multimode fiber.

II. CONCLUSIONS

The physical constraints on the ZT-P experiment make the desired measurements marginal with the present fiber available from EOTec. Something is wrong with the 80-μm fiber; possibly it does not really have the twist birefringence that was expected. On a physically larger device which allows large bending radii, a shell current measurement would seem possible. The novel design of the York twisted high-birefringent fiber offers hope that such a measurement is also practical on the smaller ZT-P experiment.

[1] V. S. Mukhovatov and V. D. Shafranov, Nucl. Fusion **11**, 605 (1971).
[2] G. I. Chandler, P. R. Forman, F. C. Jahoda, and K. A. Klare, Appl. Opt. **25**, 1770 (1986).
[3] K. Schoenberg *et al.*, Report No. LA-10593-MS, 1986.
[4] P. R. Forman and F. C. Jahoda, Appl. Opt. (in press).
[5] EOTec, Inc., 420 Frontage Road, West Haven, CT 06516.
[6] S. C. Rashleigh, J. Lightwave Technol. **LT-1**, 312 (1983).
[7] R. Ulrich and A. Simon, Appl. Opt. **18**, 2241 (1979).
[8] R. C. Jones, J. Opt. Soc. Am. **31**, 488 (1941).
[9] Private communications; R. I. Laming, D. N. Payne, and L. Li, SPIE **798**, Fiber Optics Sensors II, 283 (1987).