Plasma current measurement in thermonuclear fusion reactors based on a POTDR setup

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In this paper we investigate the use of a Polarisation Optical Time Domain Reflectometer (POTDR) for the measurement of an electrical current. The measurement is based on the state of polarization (SOP) rotation of the Rayleigh backscattered signal when an optical fiber is coiled around a current (Faraday effect). A POTDR trace provides information about the spatial distribution of the SOP along the fiber. We show that the Faraday polarization rotation and the current can be determined from the POTDR trace when a low-bi fiber is used. We demonstrate this concept for plasma current in nuclear fusion tokamak reactors.

Introduction

Fiber Optical Current Sensor (FOCS) has already been proposed as an alternative to inductive sensors for the measurement of the plasma current in thermonuclear fusion reactor [1]-[3]. Its operation is based on measuring the light polarization state at the output of an optical fibre in transmission or after reflection. Due to the Faraday effect, the state of polarization (SOP) of an incoming light is indeed rotated when the fibre is subject to a non-zero axial magnetic field [4]. By installing a fiber loop around the plasma current to be measured, the polarization rotation is directly related to the magnetic field integral along the loop and the plasma current can then be determined using the Ampere law.

In this paper, we present the theoretical analysis and the experimental demonstration for the measurement of the plasma current using the Rayleigh backscattering in a low birefringence optical fibre surrounding the vacuum vessel. The basic principle of the measurement consists in launching an optical pulse and to measure the polarization state of the Rayleigh backscattered signal as a function of time. The backscattered SOP will change as a function of time with a periodicity directly related to the magnetic field strength induced by the plasma current [5].

The paper is organized as follow. Section I introduces the dependence of birefringence on an externally applied magnetic field (Faraday effect). The proposed measurement setup is then described in section II where the determination of the magnetic field and the plasma current from the measurement trace is also explained. Section III describes experimental results that have been carried out at the thermonuclear fusion reactor Tore Supra situated at CEA Cadarache in France.

I. Faraday effect

The Faraday effect characterizes the interaction between the polarization of a light beam travelling in a transparent medium and an external magnetic field aligned with the light wave propagation vector. The consequence of the magnetic field interaction is the creation of two different refractive indices for left-hand and right-hand polarized light. If we consider a constant magnetic field intensity B over an optical path length l, an input polarized light that propagates parallel to $\vec{B}$ is rotated by an angle $\rho = VBL$ (1) (Fig.1). The proportionality factor V is called the Verdet constant and is equal for standard silica fibers to 0.64 rad/(m.T) at 1550nm. The Faraday rotation is a non-reciprocal effect and is independent on the propagation direction within the optical fiber. A light beam that passes back and forward in the medium where the magnetic field is applied, will experience a double rotation of its plane of polarization.

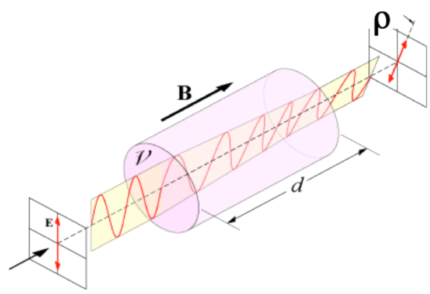

Fig. 1 Rotation of the polarization plane of a linearly polarized light due to Faraday effect [Bob Mellish, http://en.wikipedia.org/wiki/File:Faraday-effect.svg].

If we combine this rotation with the Ampere theorem:

$$\oint_C \frac{\vec{B}}{\mu_0} \cdot d\vec{l} = I \tag{2}$$

where B is the magnetic field and C is a contour surrounding the current. We deduce that the Faraday rotation, along a close path, is proportional to the current flowing through the path section:

$$\rho = v\oint_C \vec{B} \cdot d\vec{l} = v\mu_0 \oint_C \frac{\vec{B}}{\mu_0} \cdot d\vec{l} = v\mu_0 I \tag{3}$$

A basic implementation of a FOCS would consist in the determination of the rotation angle of a linear polarized light traveling in an optical fiber surrounding the current.

II. Principle of measurement

The proposed measurement set-up is a Polarization Optical Time Domain Refletometer (POTDR) (Fig.2a). A laser launches a polarized optical pulse into the fibre via a coupler. The polarization of the input light is fixed by the linear polarizer. When this pulse propagates down the fibre, it is attenuated and continuously scattered in all directions via the Rayleigh scattering process [6]. A part of this scattered signal is captured by the fibre and propagates back towards the source. The backscattered signal is then attenuated when it propagates back, and again goes through the polarizer and the optical coupler before reaching the receiver where it is measured as a function of time. When birefringence (intrinsic or externally-induced birefringence) is present in the fiber, the polarization state varies along its length. As a result, the SOP of backscattered light also varies with the backscattering location of the pulse. Thanks to the presence of the input polarizer, this SOP variation is converted into power fluctuations that contain information about the birefringence distribution along the fibre and therefore about magnetic field. We will consider a system composed of a lead fiber going from the POTDR to the vacuum vessel. The lead fiber is followed by a low birefringence sensing fiber surrounding the vacuum vessel (Fig.2b).

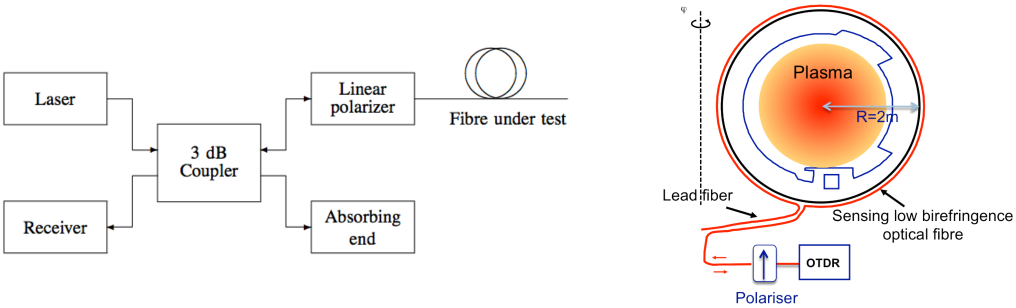

Fig. 2 a) Polarization optical time domain reflectometer b) Set-up on Tore Supra

It was shown in [5] that if we consider that the induced fiber birefringence is only due to the magnetic field (low birefringence fiber), the normalized power *P(z)* measured by the POTDR is expressed by:

$$P(z) \propto \frac{1}{2}\left(1 + \cos 4 \int_0^z \rho(z')dz'\right) \quad (4)$$

where ρ is half the circular birefringence representing the phase difference per unit of length between the two eigenmodes (the right-handed and left-handed circular SOPs). If we consider a constant magnetic field along the fiber, equation (4) becomes:

$$P(z) \propto \frac{1}{2}(1 + \cos 4\rho z) \quad (5)$$

We deduce from Eq.(1) and (5) that the magnetic field *B* and the plasma current *I* can be deduced from the spatial frequency f_s of the POTDR trace:

$$f_s = \frac{2\rho}{\pi} = \frac{2BV}{\pi} = \frac{\mu_0 VI}{\pi^2 r} \quad (6)$$

where r is the radius of the vacuum vessel of Tore Supra and μ_0 the vacuum permeability.

III. Experimental results

The OTDR used for this measurement campaign is a photon counting Luciol instrument. Figure 3 represents the comparison between a reference trace (green curve) with no plasma current and a POTDR trace with a plasma current of 1.5MA (red curve). The spatial resolution of the OTDR is 0.01 meter and we used a moving average of 20 points for a better signal to noise ratio. We inserted a low birefringence lead fiber of ~50m long to avoid a strong reflection in the optical measurement window and a saturation of the POTDR receiver. This low birefringence fiber was still on a spool. The curvature induced linear birefringence that modified the SOP of light and created strong oscillation on the POTDR trace. This characteristic is not detrimental and allows an easy recognition of the optical fiber surrounding Tore Supra. A SMF fiber of 1000m also on a spool was put at the end to avoid a strong Fresnel reflection. The SOP modification linked to the Faraday effect occurs in the sensing fiber placed around the vacuum vessel (12.5m). The circular shape of the Tore Supra vacuum vessel allows us to assume that the magnetic field is constant along the optical fiber and the POTDR trace oscillates with the frequency given by Eq.(6). The magnetic field and the plasma current intensity can then be deduced.

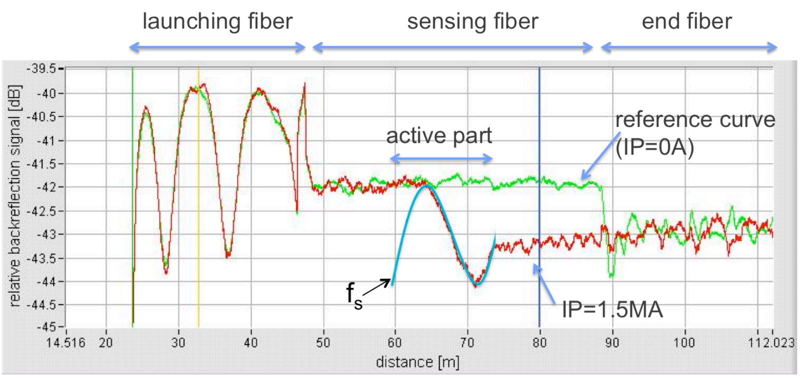

Fig. 3 POTDR trace of a low birefringence fiber with a plasma current =1.5MA

The magnetic field for two values of the plasma current (1.2 and 1.5MA) was estimated and compared to one deduced from the oscillation frequency of the POTDR trace (maximum error of 6.7%) (Tab.1).

Table 1 Comparison between measured and estimated values of the plasma current.

Plasma current	Estimated Magnetic field	Pre-determined spatial period	Measured spatial period	Measured magnetic field	Measured plasma current
1.5MA	0.15T	16.44m	17.05m	0.145T	**1.45MA**
1.2MA	0.12T	20.56m	19.30m	0.128T	**1.28MA**

Conclusions

We demonstrate the first experimental measurement of the plasma current on a thermonuclear fusion reactor with a POTDR setup. The low birefringence optical fiber for this experiment was surrounding the vacuum vessel of Tore Supra. The measurement was done for two values of the plasma current (1.2 and 1.5MA). A good agreement was found between measured and estimated values of the plasma current.

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