Polarization-sensitive reflectometer for distributed magnetic field measurement in tokamaks: impact of reflectometer’s dynamic range

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In this paper, we investigate a fully passive polarization-sensitive reflectometry-based optical fibre sensor for measuring the spatial distribution of magnetic field in tokamaks. The measurement principle exploits the Faraday magneto-optic effect occurring in the optical fibres in the presence of magnetic field. Experimental data from the Tore Supra (now WEST) reactor is presented. Based on the analysed experimental data, a discussion on the impact of the reflectometer's dynamic range on the magnetic field measurement accuracy is presented.

Magnetic diagnostics play an indispensable role in the safe operation of tokamak-based thermonuclear reactors like ITER [1]. Nonetheless, in the future tokamaks like ITER and DEMO, the measurement accuracy of the conventional electromagnetic sensors may be compromised due to the combined effect of quasi steady-state operation and nuclear radiation. Optical fibres, thanks to their advantages over conventional methods like relative immunity to temperature and radiation effects, are a potential solution for measuring the magnetic field in the future burning plasma installations. This paper discusses a method for measuring the spatial distribution of magnetic field in tokamaks using the state of polarization (SOP) evolution of the Rayleigh backscattered light in the sensing optical fibre installed around a section of the tokamak’s Vacuum Vessel (VV).

It is well known that a Polarization-Sensitive Reflectometer (PSR) can provide information about the spatial distribution of a measurand which can change the SOP of the light propagating in an optical fibre. In the presence of the magnetic field, the SOP of a linearly polarized light is rotated proportional to the axial magnetic field strength, thanks to the *Faraday effect.* The principle of the PSR consists in converting the Rayleigh backscattered SOP evolution into the light power fluctuations, thanks to the polarizer. When the influence of the perturbing effects is insignificant compared to the Faraday magneto-optic effect, the normalized backscattered power recorded at the PSR such as POTDR (Polarization Optical Time-domain reflectometer) or POFDR (Polarization Optical Frequency-domain reflectometer) is given by:

$$P_B(z) = \left(\cos\left(2\int_0^z \rho(l)dl\right)\right)^2 \tag{1}$$

where z is the distance along the fibre and $\rho(l) = VH(l)\,cos(\theta(l))$ is the local Faraday rotation per unit length. V is the Verdet constant ($\sim 6.8\times 10^{-7}$rad/A in silica fibres operating at 1550 nm [2]), $H(l)$ is the local magnetic field strength and $\theta(l)$ is the angle between the magnetic field and the fibre axis. The above equation can be exploited to measure the plasma current in a tokamak even in the presence of perturbing effects [3]. However, by slightly modifying the equation it can also be used for distributed magnetic field measurement:

$$P_B(z) = (\cos(2\,\rho(z)dz \, + \, \varphi(z)))^2 \tag{2}$$

where $\varphi(z) \; = \; 2\int_0^{z+dz}\rho(l)dl$ and dz is the length of the local section of the fibre along which the magnetic field can be considered constant. By locally fitting the normalized measured trace, of length dz, with the analytical equation, i.e. Eq. (2), one can measure the local $\rho(z)$ which indeed gives the local axial magnetic field strength along the fibre axis, $H(z)\,cos(\theta(z))$. The best local fit is decided based on the Least Mean Square Error, by sweeping ρ and φ over the chosen range. It is worth stressing here that as the analytical equation, i.e. Eq. (2), is a cosine function and therefore insensitive to the sign of ρ, which changes according to the direction of magnetic field w.r.t the fibre axis, consequently, the technique is insensitive to the direction of the magnetic field. Note that in general φ is swept over 0 to 2π and the sweep step $\Delta\varphi$ should be chosen small enough such that the required magnetic field accuracy is achieved. The results reported in this paper are based on $\Delta\varphi$ = 0.001 rad. The range of ρ should be higher than the ρ corresponding to the highest magnetic field to be measured. The sweep step used in this paper is $\Delta\rho$ = 0.001 rad, which translates to $\Delta H \; \approx$ 1.5 kA/m (ΔB ~1.9 mT).

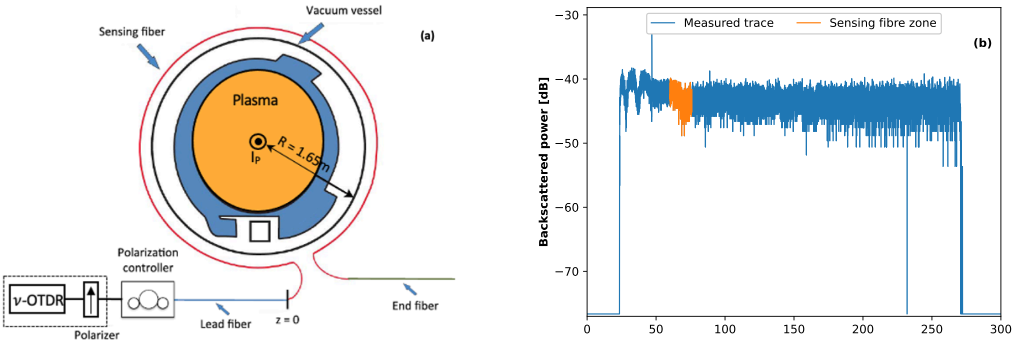

Fig.1 (a) Schematic of the experimental arrangement of the ν-POTDR setup at Tore Supra tokamak; (b) Measured ν-POTDR trace for a 1.5 MA plasma current.

Fig. 1(a) depicts a graphic representation of the experimental arrangement of the photon counting POTDR (ν-POTDR) based setup for the magnetic field measurement at the Tore Supra tokamak. A lo-bi sensing fibre, with a beat length of 420m, is installed on the VV thermal shield with a radius R ≈ 1.65 m. More details on the experiment can be found in [4, 5]. Fig. 1(b) shows the measured ν-POTDR trace for a 1.5 MA plasma current circulating in the Tore Supra tokamak. Note that the bending induced linear birefringence, for a bending radius of 1.65 m is too small compared to the intrinsic birefringence of the lo-bi fibre, which is itself more than 5 times smaller than the non-reciprocal circular birefringence resulting from the magnetic field generated by the 1.5 MA plasma current. The ν-POTDR used for the experiment has a 4 dB dynamic range (DR) and the measured data has a spatial resolution of ~ 1.3 cm. Nevertheless, Savitzky-Golay (SG) filtering is used to improve the SNR of the experimental data. The results presented in this paper are based on an SG filter of order 2 with a filtering window of ~ 9 cm. In the rest of the paper, SG filter implies an SG filter with the aforementioned parameters.

Fig. 2(a) shows the impact of repeatedly filtering the sensing fibre zone of the measured trace with the SG filter. Repeated filtering is done in the following way: each filtered signal is input to the next filtering iteration until the end, except in the beginning where the noisy measured signal is the input to the filter. It can be noticed that the higher the number of times SG filtering is repeated the smoother is the trace. For repeatedly filtering 15 million times, SNR of the signal in the sensing fibre zone has a significant improvement. Note that by further increasing the number of times filtering is performed, beyond 15 million times, there is no significant improvement in the SNR on one hand but on the other hand this over filtering will affect the local frequency of the trace which in turn affects the magnetic field measurement accuracy.

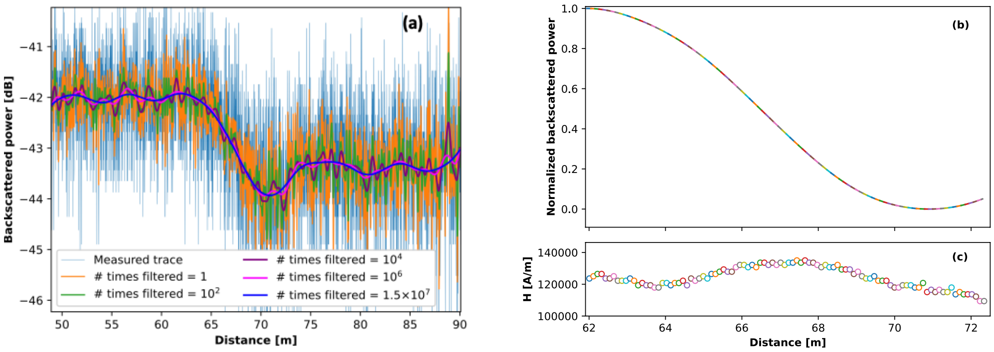

Fig. 2(a) Impact of repeated filtering of the interesting zone of the measured trace with a 2nd order SG filter of 9 cm filtering window; (b) Fitting of the normalized backscattered trace of the measurement from the sensing fibre after applying SG filtering (of order 2 and 9 cm filtering window) for 1.5×10^7 times; (c) Distributed magnetic field measurement

Fig. 2(b) shows the result of fitting (using Eq. (2)) the normalized trace of the fibre in the sensing region, after filtering 15 million times. Note that the fitting is performed over 9 cm (which corresponds to the SG filtering window length) and the best fitting curve of each of the 9 cm section of the trace is plotted in a different colour than its neighbouring section to facilitate identification of successive sections. Fig. 2 (c) shows the magnetic field measured (with 9 cm spatial resolution) from the (local) frequency $\rho(z)$ of the local best fittings shown in Fig. 2(b). Recall that the (local) frequency $\rho(z)$ of the local best fitting is obtained by sweeping $\rho(z)$ in Eq. (2) over the chosen range. In this case the range is (0, 0.16) where the maximum value of ρ, i.e. 0.16 rad, corresponds to twice the magnetic field calculated (H_E) considering the plasma current (1.5 MA) as a point source located in the centre of the VV. Thus, according to Amperes law, the magnetic field can be estimated as $H_E = \frac{I_P}{2\pi R}$, where I_P is the plasma current, and R is the radius of the VV thermal shield over which the sensing fibre is installed. Let us note that in practice, the actual magnetic field is not just induced by the plasma current but also by the eddy currents circulating in the VV shell and the currents circulated in various coils installed in the tokamak. The accuracy of the measured magnetic distribution profile cannot be reported yet due to the lack of a reference measurement. It is a perspective of this work to compare the obtained measurement data with that of the conventional magnetic field sensors installed on the tokamak. Nevertheless, the preliminary analysis of the experimental data from the Tore

Supra tokamak indicates a potential solution for the distributed magnetic field measurement.

To understand the influence of the PSR's DR on the magnetic field measurement accuracy, simulation approach is considered. The details of the approach are as following: a simulation model for PSR, based on the Jones formalism, is developed considering the intrinsic and bending induced birefringence of the fibre besides the Faraday magneto-optic effect resulting from the 1.5 MA plasma current. Note that the magnetic field used in the simulations is obtained by considering plasma current as a point current source in the centre of the 1.65 m circular VV section. A detailed discussion on the development of the PSR simulation model can be found elsewhere [3,4]. Assuming the noise of the PSR has a gaussian distribution, the DR of the device can be used to get the standard deviation of the random noise $\sigma = \left(\frac{10^{\frac{DR}{5}}}{P_{Max}}\right)^{-1}$, where P_{Max} is the maximum power in the linear scale, which for a normalized trace is 1. Thus, the effect of the DR on the normalized trace is included by adding gaussian noise with zero mean and the standard deviation σ. Also, note that the spatial resolution of the simulation data matches the ν-OTDR used in the experiment.

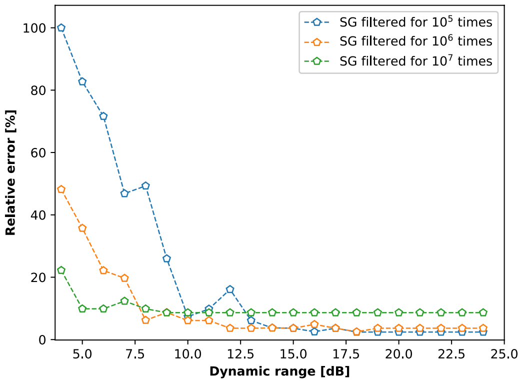

Fig. 3 Impact of dynamic range on the relative error in magnetic field measurement; SG: Savitzky-Golay.

Fig. 3 shows the maximum relative error ($\varepsilon_r = \frac{|H_M - H_E|}{H_E} \times 100$) made in the magnetic field measurement (H_M) from the simulated traces at different dynamic ranges (while all the other simulation parameters are constant), for SG filtering repeated at 3 different number of times. Note that the SG filter used in the simulations is same as the one used for the experimental data. The figure clearly depicts that the relative error in magnetic field measurement decreases as the dynamic range increase. For example, in the case of filtering 10^5 times at 4 dB DR we make 100% error, but with a DR of 10 dB the error drops to less than 10% which is a significant improvement. At 15 dB the ε_r drops to less than 5% and after that there is no significant improvement seen in the relative error. Besides, the results also indicate that over filtering will compromise the accuracy of the measurement in the high DR range, while this is also true for low DR range, but the effect is not relatively as pronounced as it is in the high DR range. In practice, it is quite common to have 10-15 dB DR PSR devices over a distance range of 200 m, which is normally sufficient for the magnetic field measurement in tokamaks. In addition to this, most of the PSR with DR in this range has better spatial resolution which eventually leads to an improved spatial resolution in the measurement. In particular, the low spatial resolution will be of great help in tokamaks where the magnetic field shows strong local variations. Thus, the simulation results infer that a high DR, i.e. 10-15 dB, PSR is desirable for the magnetic field measurement in tokamaks.

In conclusion, a fully passive distributed magnetic field sensor in the form of a PSR-based optical fibre sensor is investigated. Preliminary results of the measurement from the Tore Supra tokamak taken with a 4 dB dynamic range ϑ-POTDR has provided magnetic field measurement with a 9 cm spatial resolution, thus, showing the feasibility of the approach. The simulation results demonstrate that the measurement technique can provide magnetic field measurement with good accuracy when using commercially available PSR's with DR around 10-15 dB.

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[1] Moreau, Ph, et al. "Development of a magnetic diagnostic suitable for the ITER radiation environment." *1st Inter. Conf. on Advancements in Nuclear Instrumentation, Measurement Methods and their App*. IEEE, 2009.

[2] Cruz, J. L., M. V. Andres, and M. A. Hernandez. "Faraday effect in standard optical fibers: dispersion of the effective Verdet constant." Applied optics 35.6 (1996): 922-927.

[3] Dandu, Prasad, et al. "Plasma current measurement in ITER with a polarization-OTDR: impact of fiber bending and twisting on the measurement accuracy." Applied Optics 61.9 (2022): 2406-2416.

[4] Wuilpart, Marc, et al. "Plasma current measurement in thermonuclear fusion reactors using a photon-counting POTDR." IEEE Photonics Technology Letters 29.6 (2017): 547-550.

[5] Moreau, Ph, et al. "Test of fiber optic based current sensors on the Tore Supra tokamak." *Fusion engineering and design* 86.6-8 (2011): 1222-1226.