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Assessment of the environmental effects on the ITER FOCS operating in reflective scheme with Faraday mirror

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Plasma current measurements will play an important role in ITER to provide real-time plasma control and machine protection. Performance of standard electromagnetic sensors may be not sufficient to fulfill this task due to a combined effect of steady-state operation and the presence of strong nuclear radiation. The Fiber Optics Current Sensor (FOCS) is a back-up systems included in the ITER design. Faraday mirror (FM) is an important part of the FOCS, which allows to improve the system performance, provided it has exactly 90° polarization rotation angle with acceptable deviations below 0.3°. We have experimentally investigated the effect of thermal perturbations and radiation on the rotation angle of commercial FMs. The FM rotation thermal sensitivity was found to be ~0.12°/°C. Gamma-irradiation resulted in a 1.2° change, saturated after a 12.5 kGy dose. Based on these results we conclude that the Faraday mirror has to be located in the cubical area despite that implies placing additional link fibers to reach the ITER vacuum vessel.

Keywords: ITER; radiation effects; magnetic diagnostics; plasma current measurements; fiber optics current sensor; Faraday mirror.

1. Introduction

Plasma current measurements is a part of the ITER real-time plasma control and machine protection systems. This task will be performed using standard electromagnetic sensors. However, there are indications that the accuracy of such sensors may degrade due to a combined effect of steady-state operation and the presence of strong nuclear radiation. Therefore, back-up solutions for plasma current measurements are considered. Fiber Optics Current Sensor (FOCS) is one of such back-up systems which is already included in the ITER design [1].

ITER FOCS consist of 3 redundant sensing fibers installed on the external surface of the vacuum vessel (VV), the data acquisition system installed in a cubical area, and the connecting fiber (see Fig. 1). FOCS operation is based on the Faraday effect, which corresponds to a polarization rotation of light proportional to the magnetic field component aligned with the propagation axis [2]. If a light beam propagates in an optical fiber enclosing a current, the rotation angle is directly proportional to the current through the loop. This makes FOCS more suitable for the ITER steady-state operation as compared to today's standard electromagnetic sensors, where the signal (voltage) is proportional to the time derivative of the magnetic flux through the sensor loop.

FOCS fiber will be exposed to severe nuclear environment. Polarization-based operation of the FOCS makes it less sensitive to the most common radiation effect, namely radiation induced absorption. However, it also means that the intrinsic and extrinsic linear birefringence may significantly degrade the sensor performance. It was proposed that using FOCS reflective scheme with a Faraday mirror (FM) can resolve the problem [2, 3]. It may be noted that in the presence of magnetic field the FM does not provide the full compensation of the induced birefringence [4]. Nevertheless, as it was demonstrated via numerical simulations, operating ITER-relevant FOCS with an ideal FM, i.e. the rotation angle is exactly 90°, can significantly improve the measurement accuracy [5]. It has also been recently demonstrated that a FM detuning above 0.3° gives unacceptable error at the low current range (<1 MA) [6]. Therefore, the FM requires additional attention before installation to guarantee the correct rotation angle.

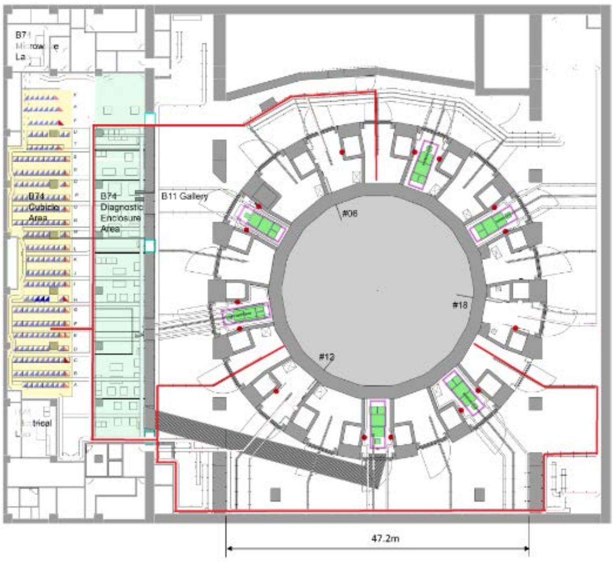

Fig. 1 Routing (in red) of the 3 FOCS fibers from the cryostat to the cubicle area. The lengths are 50, 100, and 150 m.

There are several potential locations for the FM. One is the cubical area, where the other components of the data acquisition system are located. That would require long

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connecting fibers, which induce polarization variations. On that path, no strong magnetic fields are expected so that there will be no significant non-reciprocal circular birefringence [7] and an ideal FM should exactly compensate the polarization variations. However, for a FM rotation angle different than 90 deg, the compensation is not fully achieved. A solution to this issue consisting of taking into account the FM detuning angle in the demodulation process is proposed in [6]. Alternatively, the FM can be placed close or directly on the VV. The advantage of this solution is the removal of the additional connecting fibers, which reduces the installation works and associated costs. However, the FM will be subject to thermal and radiation fields.

The goal of the present work is to address how the rotation angle of a FM is influenced by ionizing radiation and temperature variations and to make a conclusion on the component location in the ITER FOCS.

2. Temperature effects on FMs

We used the Optical Vector Analyzer (OVA-5000) from Luna technologies to measure the thermal sensitivity of several FMs, using the method described in [8]. Two measurements need to be performed. First, P_1, the polarization mode dispersion (PMD, [7]) of a polarization maintaining fiber (PMF), terminated by a conventional mirror (M) is measured, see. Fig. 2.

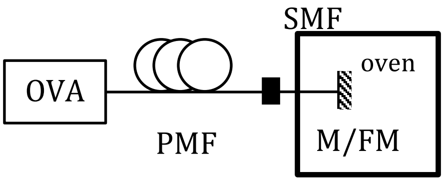

Fig. 2 Setup for FM characterization using OVA. PMF – a 13 m long polarization-maintaining fiber with a 5 mm beat length, SMF – a single-mode pig-tail of a conventional (M) or a Faraday mirror, and the black box corresponds to a FC/APC connector.

The mirror is then replaced with a FM and the corresponding PMD P_2 is measured. To address the temperature effect, the FM is placed in an oven, which controls temperature with an accuracy of ~0.1°C. A typical example of P_2 measurements for a FM from AFM Technology is shown in Fig. 3. The minimum of each V-curve corresponds to 90 deg rotation and the dispersion effect of the PMF is compensated. The 90°C rotation angle is defined by both the temperature and the wavelength. The detuning angle ε of the FM from 90 deg is calculated from P_2 and P_2 by [8]: $\sin(\varepsilon)=\left(P_2/P_1\right)$.

We have characterized FMs from several manufacturers, see Table 1. Our results show that the thermal/wavelength sensitivities of commercially available FMs are ~0.12 deg/°C and ~0.12 deg/nm. It was already mentioned that an acceptable angle deviation from the nominal 90° is <0.3°. The standard FM rotation angle tolerance is therefore not satisfactory. Thermal stabilization better than ±2.5°C and wavelength stability better than ±2.5 nm are required to satisfy the ITER requirements. Before installation the assessment of the actual rotation angle must be performed. The optimal angle can be obtained by adjusting the measurement wavelength or operational temperature [6].

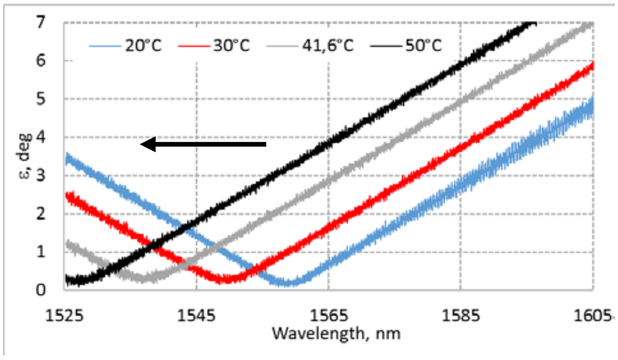

Fig. 3 Detuning angle as a wavelength function at several temperatures for a FM from Provider #3. The arrow indicated the direction of the minimum shift with temperature increase.

Table 1 Specifications of tested FMs

Provider	Band, nm	FM angle tolerance, °	Temp. range, °C
#1	34	±1.0	NS
#2	50	±0.5	0 - 70
#3	30	±3.0	-5 - 70
#4	40	NS	NS
#5	30	±0.5	-5 - 70

3. Radiation effects on FM

To assess radiation influence, a FM from Provider #5 was irradiated during 7 days in the underwater Co^{60} RITA irradiator at SCK•CEN at a dose rate of 520 Gy/h. The total accumulated dose was 90 kGy. The reference dosimetry was done using Harwell Amber 3042 dosimeters, traceable to the UK standard of absorbed dose at the National Physical Laboratory. The OVA set-up was not available to measure radiation effect on the FMs. We used an alternative set-up, which is shown in Fig. 4.

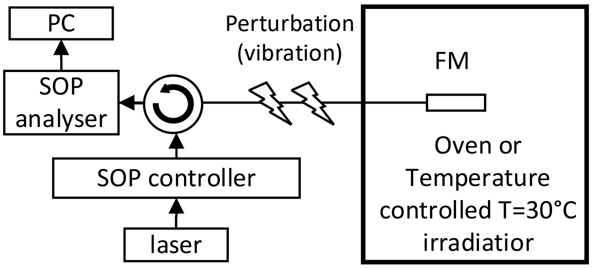

Fig. 4 Setup for FM characterization under irradiation.

A 1550 nm fiber laser was used as the light source. The controller (Thorlabs DPC5500) sends light with a controlled state of polarization (SOP). The length of the fiber link between the circulator and the FM is 12 m, which is required to provide connection with the irradiation chamber located 7 m under water. The mechanical perturbation is applied on ~50 cm of the link fiber and the rest of the fiber is subject to an industrial environment. The stability of the SOP at the link fiber input is ensured by the SOP controller An ideal FM with 90 deg rotation would fully compensate the perturbations applied on the link fiber. A detuning of the FM form 90 deg results in polarization instability caused by the perturbation. The amplitude of the polarization fluctuations depends on the FM detuning.

This approach was first tested in a thermal experiment. A fiber shaker was installed between the circulator and the FM to have a repeatable perturbation. The output Stokes parameters S1, S2, and S3, were measured (1000 samples; sample rate 100 Hz) by the SOP analyzer at nine different temperature from 10 to 50 °C. The temperature was always stabilized for at least 15 minutes. These measurement are visualized in Fig. 5. The spread of the measurement points around the average value is a measure of the sensitivity of the set-up to the vibrations and consequently a measure of the Faraday rotation detuning. On the Poincaré sphere [6]. The minimum is observed at ~30°C, which corresponds to the 90 deg rotation (optimal operation of the FM) at 1550 nm.

The irradiation experiment used the same approach as the temperature test and the same hardware. During the irradiation the temperature was stabilized at 30°C which is close to the condition of the 90° Faraday rotation. Any increase of the noise band should in principle be caused by radiation. The results of the irradiation test are shown Fig. 6. Spurious peaks in spreading of the Stokes parameters coincide with moments when control of the data acquisition was performed and are attributed to changes of the position of the fibers between the circulator and the SOP analyzer as such perturbations are not compensated by the FM. The standard deviation calculated on 100 samples is used as a measure for the noise band. During the first day the noise band increased and then stabilized. The effect under irradiation is similar to the FM detuning obtained for a temperature change of ~10°C, corresponding to 1.2 deg according the thermal test data.

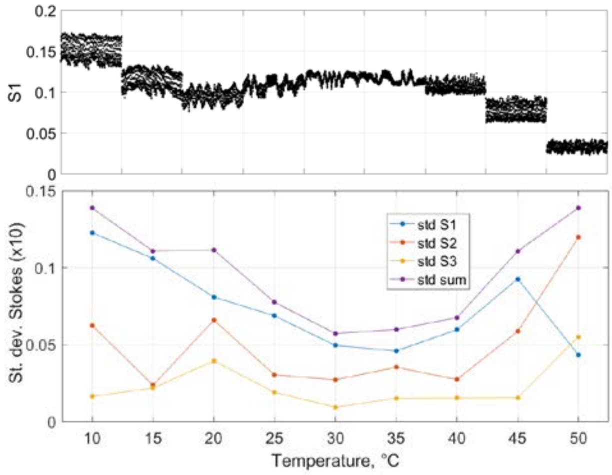

Fig. 5 Normalized Stokes S1 parameter and standard deviations (std) of the three stokes parameters during the temperature test. Std sum is the square root of the sum of the squared standard deviation of the three Stokes parameters.

With a constant input light power, the output power dropped by 0.2 dB at the end of irradiation. This decrease is the sum of the radiation-induced absorption in the ~1 m of the FM pigtail and the FM itself. This is a low value compared to radiation induced losses acceptable for FOCS [1].

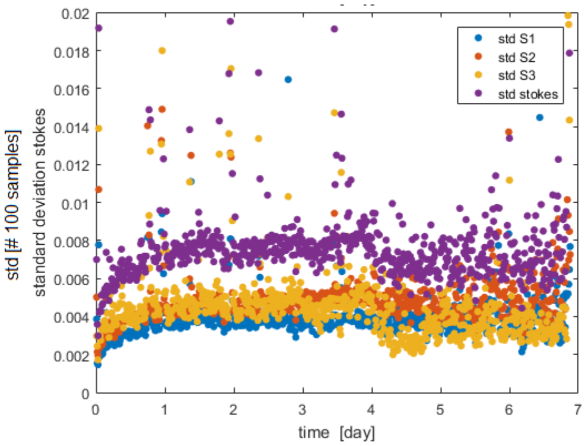

Fig. 6 Standard deviations of the stokes parameters during the irradiation test.

3. Discussion

Our results show that the commercially available FMs are sensitive to both temperature and radiation. The design of the FM is shown in Fig. 7. Epoxy can be used to keep the optical components together. In our case, the FMs from different providers are very likely based on the same magneto-active material, Bismuth-Iron Garnet (BIG).

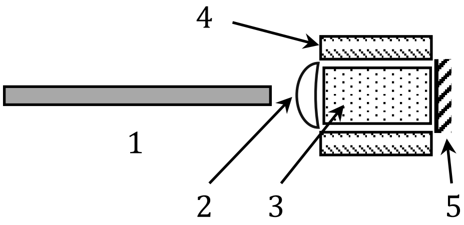

Fig. 7 Design of the FM. 1 – optical fiber, 2 – lens; 3 – magneto-active material; 4 – permanent magnet; 5 – mirror.

Temperature effects on the lens, permanent magnet, and the mirror can be neglected. A study of the Faraday rotation in BIG films indeed shows that there is a strong dependence of the Verdet constant on temperature [9]. In the temperature range 0 - 60°C and for three tested experimental films with different Bismuth concentration, the polarization rotation temperature sensitivity varies from 0.023 deg/µm/°C to 0.039 deg/µm/°C [9]. For the 90 deg FM, this corresponds to a thermal sensitivity from 1.4 to 2.4 mrad/°C or 0.08 to 0.14 deg/°C. The results of [9] were obtained at a wavelength of 548 nm. However, as explained below, it is possible to demonstrate that the thermal sensitivity of a FM operating at 548 nm or 1.55 µm is the same. Based on the data of [9], we can represent the thermal and the wavelength sensitivity of a FM rotation angle in the temperature interval 10-50°C as:

$$\begin{aligned}\varphi(\lambda_0, \Delta T) &= L_0 B V_0 (1 + b\Delta T) \\ &= L_0 (A + C\Delta T). \qquad (1)\end{aligned}$$

where L_0, is the BIG element length, B is the magnetic field applied in the FM, V_0 is the Verdet constant at λ_0 =

548 nm; b is the wavelength-independent temperature sensitivity parameter. The BIG length L_0 is defined to provide 90 deg rotation φ at λ_0 and an optimal temperature (when $\Delta T = 0$), i.e. $L_0 A = 90$ deg. In the infrared range the Verdet constant depends on the wavelength as $V(\lambda) = V_0(\lambda_0^2/\lambda^2)$ [3] so that for a wavelength λ,Eq. (1) becomes:

$$\begin{aligned}\varphi(\lambda, \Delta T) &= LBV_0(\lambda_0^2/\lambda^2)(1 + b\Delta T) \\ &= L(\lambda_0^2/\lambda^2)(A + C\Delta T) \qquad (2)\end{aligned}$$

For a FM operating at λ the BIG element length L is defined by the condition that $L(\lambda_0^2/\lambda^2)A = 90$ deg. This means that $L = L_0(\lambda^2/\lambda_0^2)$, and therefore $\varphi(\lambda, \Delta T) = L_0(A + C\Delta T)$, i.e. the temperature sensitivity of an optimized FM is wavelength independent and our results are directly comparable with [9].

The effect of gamma-radiation is related with changes in the optical fiber, the lens, and the BIG. Ionizing radiation is known to influence the refractive index of optical materials and therefore may influence the Verdet constant. However, for pure silica fibers no changes in the Verdet constant could be detected at much higher MGy dose level [10]. Moreover, only the BIG is subject to magnetic field and therefore observed rotation angle change could only be explained as a modification in the BIG. To the best of our knowledge, only one publication report on gamma-radiation induced modification of the Verdet constant. For a Cu-doped glass fiber a 46%, increase was reported after a 1.2 kGy gamma-dose [11]. The effect was attributed to generation of Cu metal particles which were reduced from Cu^{2+} ions by the irradiation. The observed FM detuning of ~1.5% could also be attributed to Verdet constant changes related to charge-exchange transformations in BIG. Unfortunately, no additional information on radiation-induced changes in BIG could be found in literature.

Fig. 6 shows that the radiation-induced detuning is limited and saturates after one day of irradiation at a dose of 12.5 kGy. Therefore, this detrimental effect can be compensated by adjusting the FM temperature by ~10°C.

3. Conclusion

We have investigated thermal and radiation effects on the performance of commercial fiber-coupled Faraday mirrors. This investigation was necessary to evaluate possible locations of the Faraday mirror in the future FOCS installation at ITER. The temperature-induced detuning of the tested commercial the Faraday mirrors was found to be ~0.12° for a 1°C temperature change, in agreement with published data on the thermal sensitivity of BIG, material which is often used to fabricate the FMs. This means that, according our numerical modelling results [6], to satisfy the FOCS performance requirements, the temperature of the mirror during ITER operation must remain stable within ±2.5°C, assuming perfect initial alignment.

Irradiation of a FM up to 90 kGy dose results in a rotation change saturated at 1.2° after 12.5 kGy. The radiation-induced absorption was ~0.2 dB at the end of the irradiation.

Comparison of the thermal sensitivity of the FMs with the acceptable detuning results in a conclusion that this component must be temperature stabilized. Temperature also allows to compensate the effect of radiation on polarization rotation angle. Placing of such a temperature controlling system close to the ITER VV is a complicated task. Therefore, it may be concluded that the cubical area is the preferable place where the FM should be located, despite the fact that it implies placing additional fiber links.

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