Optimizing ITER-Fibre Optic Current Sensor performance

P. Dandu,[1] A. Gusarov,[2] and M. Wuilpart[1]

[1] University of Mons, Dept. of Electromagnetism & Telecommunications, Blvd. Dolez 31, 7000 Mons, Belgium.

[2] Belgian Nuclear Research Centre SCK-CEN, Boeretang 200, 2400 Mol, Belgium.

Polarimetric-Fibre Optic Current Sensor (FOCS) is one of the plasma current sensors considered for ITER. The sensor operates by exploiting the Faraday effect in optical fibres in the presence of plasma current. To maximize the signal to noise ratio of the measurement, particularly at small currents, it is essential to have a linear State of Polarization (SOP) at the beginning of the sensing fibre. However, the lead fibre between the sensing fibre and the interrogation unit changes the SOP launched into it. To address this, we propose a Bayesian optimization-based method to optimize the input SOP at the source. Considering the practical difficulties in accessing the ITER site, experimental validation of the approach is made through a hybrid method: simulating Faraday rotation on the data collected from ITER-FOCS-like interrogation unit.

Introduction

Optical fibre-based current sensors have been extensively investigated and are now well commercialized. Owing to their versatility, these sensors are gaining interest in measuring plasma current in tokamas. Particularly in the context of ITER, polarimetric-FOCS is being engineered to meet the plasma current measurement accuracy requirements. The operation of the sensor relies on the Faraday effect-induced circular birefringence in the sensing fibre: the plane of the light's state of polarization (SOP) rotates by an angle θ, known as the Faraday rotation angle, which is proportional to the current (I) to be measured. When visualized on the Poincaré sphere (PS), the resulting SOP evolution describes an arc along a circle, with the centre of the circle located at a point where the plane containing the arc intersects the line perpendicular to the plane and passing through the centre of the PS. The angle between the tip of the Stokes vectors, representing the SOP of the light on the PS, without and with current, $\vec{S}_{ref}$ and $\vec{S}_P$, respectively, w.r.t. the centre of the SOP evolution circle will be proportional to θ [1]. It is worth stressing that this approach of finding the current requires finding the plane that best fits the SOP evolution arc, which becomes particularly challenging at low currents as the resulting arc length will be small. The accuracy of θ measurement is influenced by how well the plane fits the SOP evolution arc.

From a magnetooptic sensitivity point of view, the sensor's response represented by the arc length, depends on both the material of the sensing fibre and SOP of the light launched into it. The former is defined in terms of the material proportionality constant, known as the Verdet constant, $V = \frac{\theta}{I}$. For the latter, the closer the SOP is to a linear state, the greater the change observed in the SOP evolution on the PS, resulting in a larger arc length. In the context of ITER, Verdet constant improvement is not a viable solution. Therefore, to enhance the sensor's response, it is crucial to launch a linearly polarized light at the beginning of the sensing fibre. Furthermore, optimizing the sensor's response is also vital for ITER-FOCS Verdet constant calibration, which involves precise measurement of the Faraday rotation angle for known currents to determine the Verdet constant.

In practice at ITER, as the interrogation unit must be placed far from the sensing region, an extra piece of fibre (lead fibre) will be used to connect the sensing fibre to the interrogation unit. Due to the intrinsic linear birefringence of the lead fibre, a linear SOP launched into it generally emerges as an elliptical SOP at the entry of the sensing part. Therefore, it is essential to develop an optimization procedure to obtain a linear SOP at the sensing fibre input. To achieve this, a Bayesian optimization method is proposed.

Bayesian Optimization-based FOCS input SOP optimization: approach

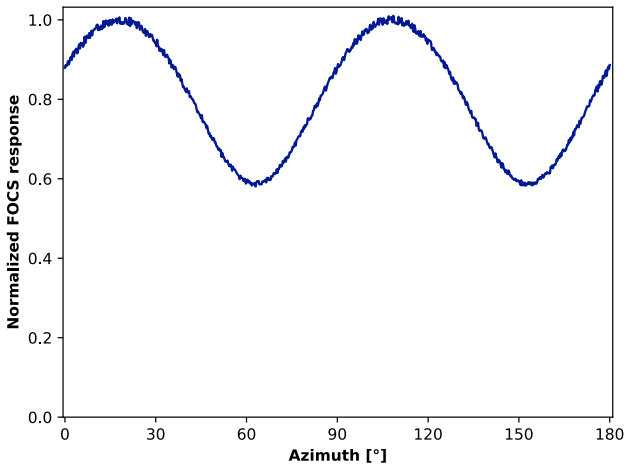

Fig.1 Simulated normalized ITER-FOCS response as a function input linear SOP azimuth at the source

To understand how the sensor's response changes with the input SOP at the source, the ITER-FOCS setup was modelled, as detailed in [2], with the following considerations. As the lead fibre could be subjected to some unwanted external effects, it is treated as an elliptically birefringent element with random retardance, rotation and principal axes orientation. The sensing fibre is only subjected to Faraday effect, which is a reasonable for a spun sensing fibre with a large enough beat length-to-spun period ratio [3]. Furthermore, the noise resulting from the 1% DOP uncertainty of the polarimeter on the measured Stokes parameters is also taken into consideration. Fig.1 shows the simulated normalized FOCS response as a function of the SOP azimuth of the linear SOP fixed at the lead fibre input. Note that to obtain the figure, the retardance, rotation and principal axes orientation of the lead fibre were randomly set to 27°, 51° and 18° for forward propagation and 34°, 19°, 41° for backward propagation, respectively. The FOCS response is calculated as the great circle distance between $\vec{S}_{ref}$ and $\vec{S}_P$, and is normalized by dividing with the true Faraday rotation angle. The FOCS response is maximized when the SOP launched into the sensing fibre is linear and decreases as it deviates from the linear state.

Observing Fig.1 suggests that the problem of finding an optimal input SOP azimuth at the source, such that a linear SOP is launched at the sensing fiber input, can be reduced to finding the azimuth that maximizes the FOCS response function. However, sweeping through all possible input SOP azimuths at the source is impractical, so it is essential to find the optimal input SOP in as few attempts as possible. Furthermore, FOCS response measurements will be noisy due to polarimeter noise, making this a classic Bayesian Optimization (BO) problem [4].

BO works by sequentially building a surrogate—a probabilistic model of the objective function (in our case, the FOCS response function, as shown in Fig.1), often using a

Gaussian Process (GP). This surrogate model, based on the existing observations of different input SOP azimuths and their corresponding FOCS responses, predicts the FOCS response across the search space, i.e., azimuth values from 0-180°. For each point, the model provides an expected value and associated uncertainty. The next point to evaluate is selected by the Acquisiton function, which aims to maximize a criterion such as Expected Improvement (EI)—prioritizes points that are likely to improve upon the current best result, either where the surrogate's mean is high (indicating likely improvement) or where the variance is high (suggesting potential for large improvement due to uncertainty). Each call or evaluation updates the model based on all the prior measurements, continually refining the prediction of the optimal FOCS response. The stopping criterion is usually a predefined number of calls or a convergence condition.

Experimental validation of the optimization algorithm

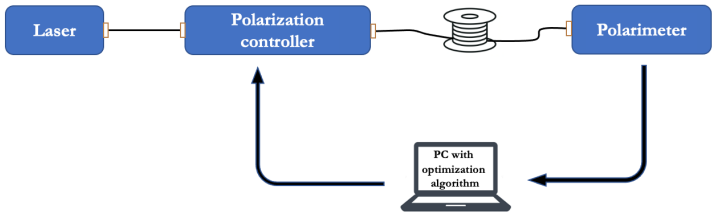

Fig.2 Schematic of the setup used for the optimization algorithm validation via hybrid approach

Since ITER is under construction, a hybrid approach, as shown in Fig. 2, has been adopted for the experimental validation. In this approach, an ITER-FOCS-like interrogation unit is used, but the Faraday rotation resulting from the plasma current is simulated on to the data collected from the interrogation unit. The details of the approach are as follows. Similar to the ITER-FOCS source, where it is designed to launch a linear SOP into the lead fibre (~100 m long), the hybrid approach setup is arranged, see Fig. 2, such that a linear SOP is launched into a fibre spool of about 150 m long. The light launched by the laser passes through the polarization controller, which is set to output a linearly polarized light with the ability to adjust the azimuth of the linear SOP. The light coming from the other end of the fibre spool is connected to the polarimeter. Conceptually speaking, the only difference between the hybrid approach and actual arrangement that will be tested at ITER, is how the Faraday effect is generated. At ITER, it will result from the plasma current, whereas in the hybrid approach, the Faraday effect is simulated on the data (Stokes vector) collected by the polarimeter. Simply put, if n Stokes vectors are recorded during a measurement, the first $n/2$ form the reference data cluster, representing SOPs recorded without current, whose mean is the reference Stokes vector $\vec{S}_{ref}$. The remaining $n/2$ Stokes vectors are modified using a rotation Mueller matrix to simulate the Faraday rotation angle, creating the SOPs recorded with current, the mean of which represents $\vec{S}_p$.

The optimization process starts by running the optimization algorithm on the PC, where it suggests an input SOP azimuth to be set at the polarization controller and the corresponding data is recorded by the polarimeter. As described earlier, $\vec{S}_p$ is then calculated by simulating a 5° Faraday rotation angle (which is close to the angle that would be generated by ITER calibration current). The FOCS response is then calculated as the great circle distance between $\vec{S}_{ref}$ and $\vec{S}_p$. This process is repeated until the stopping criterion is satisfied, after which the algorithm identifies the optimized input.

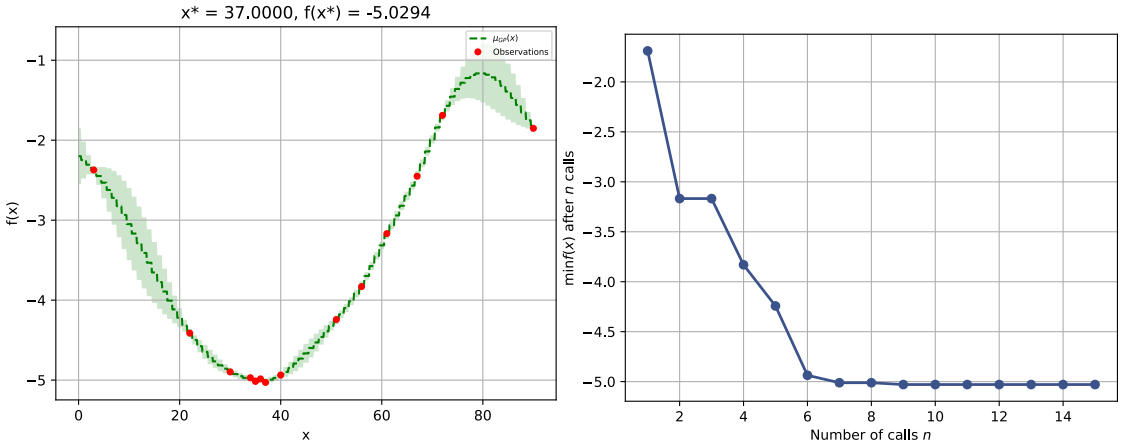

Fig.3 Result of the Optimization algorithm with hybrid approach: a) surrogate model constructed from the observations, b) convergence plot. Note: f(x) is the negated FOCS response and x is the input SOP azimuth angle

Fig. 3 shows the results of the BO algorithm using the *gp_minimize* function from the Python *scikit-optimize* library, with EI acquisition function, stopping criterion set to 15 calls and [0, 90°] integer search space. The search space is restricted to 0-90°, as Fig. 1 shows at least one maximum exists within this range. Note that to find the maximum FOCS response, the evaluated FOCS responses were negated, essentially making it into a minimization problem. Here *f(x)* represents the negated FOCS response with *x* being the input SOP azimuth angle. The red dots represent the evaluated FOCS responses, while the green line shows the surrogate model's predicted function. The shaded area indicates uncertainty in the predictions, with wider regions showing more uncertainty. From Fig. 3(a), we can see that the maximum arc length of the FOCS response function, 5.0294, closely matches the set 5° rotation angle, within the polarimeter's uncertainty of 0.34°, thus validating the approach. The corresponding azimuth angle, 37°, is the input SOP azimuth angle, which when set at the polarization controller, results in a linear SOP emerging from the other end of the fibre spool. Fig. 3(b) shows the convergence of the optimization process. The plot indicates that the input SOP optimization can be achieved in under 10 iterations, and it is acceptable in the case of ITER-FOCS.

Conclusion

Bayesian optimization algorithm is studied for input SOP optimization of ITER-FOCS to achieve maximized FOCS response. The method is experimentally demonstrated using a hybrid approach. The results showed the potential of the approach for ITER-FOCS optimization in less than 10 iterations.

References

[1] 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.

[2] Kim, Sung-Moon, et al. "Assessment of the structural vibration effect on plasma current measurement using a fiber optic current sensor in ITER." *Sensors* 23.3 (2023): 1460.

[3] Aerseens, Matthieu, et al. "Influence of the optical fiber type on the performance of fibre-optics current sensor dedicated to plasma current measurement in ITER." *Applied optics* 54.19 (2015):5983-5991.

[4] Agnihotri, Apoorv, and Nipun Batra. "Exploring Bayesian Optimization." *Distill* 5.5 (2020): e26.