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Quench Detection and Temperature measurement with Fiber Optic Sensors

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Abstract— **For the EU DEMO conductor testing, a temperature sensor based on Fiber Bragg Grating (FBG) optical fiber is studied at the EPFL Swiss Plasma Center. The SULTAN test facility has been upgraded to use fiber optic sensor for temperature monitoring and quench detection. Up to four optical fibers can be interrogated simultaneously (eight fibers separately). In order to qualify the system and improve fiber integration in complex superconducting structure, one 2.6 m-long REBCO conductor of a SULTAN sample has been instrumented with FBG sensors. Two fibers, each containing 10 FBG sensors along their length and separated by 60 mm, are installed within the conductor. The first fiber is soldered together with the REBCO tapes and thus subjected to the thermal strain of the whole conductor. The second fiber is inserted inside a stainless steel capillary tube that insures strain free condition to the FBG sensor. A 4-FBG sensors fiber is also placed at the outer surface of the stainless steel jacket in correspondence with CERNOX sensors. The procedure for fiber routing and protection is described. In a separated experiment in a small cryostat, different coating materials are studied and used to calibrate the FBGs response from room temperature to 4.5 K over several cycles.**

***Index Terms*— Fiber optic sensors, temperature measurement, Cryogenics, Quench detection, Fusion reactor, FBG, Superconductor.**

I. INTRODUCTION

IN the framework of the European Fusion program, the Superconducting Group of the Swiss Plasma Center (SPC) from the École Polytechnique Fédérale de Lausanne (EPFL) is developing a thermometer for cryogenics temperature based on Fiber Bragg Grating (FBG) technology. The sensor is foreseen to be used as quench detection system for fusion magnet built with REBCO coated conductors.

Voltage quench detection is considered difficult in REBCO magnets because large voltage (hundreds of mV) appears only when the hot spot temperature is already quite high. Instead, temperature quench detection is deemed to be faster, showing an anomalous situation before the voltage detection, when the temperature is still relatively low. Optical fiber for quench detection (Mach-Zender interferometer) was already studied in 1995-97 in the SULTAN facility, in the frame of an international collaboration (QUELL) [1-2]. It was found that inserting the fiber in a capillary nicely protected the fiber and allows to separate mechanical strain from thermal induced strain. In the last twenty years several works have studied optical fiber for quench detection in single tape and small coils using either pointwise FBG [3-5], [6] or distributed Rayleigh scattering technologies [7], [8], [9], [10]. There are only few recent works dealing with large cable and large fusion magnets. Commonwealth Fusion has chosen to use FBG sensor to detect quench in their CS coil (operating at 20 K). The optical fiber are inserted in notched groove and soldered with the tapes and the VIPER copper former. The cable is then jacketed in a steel pipe [11]. The drawback of this method is that mechanically couples the sensor to the conductor. The sensor will then respond to both temperature and strain, making difficult to distinguish one from the other.

Inspired from these works, our laboratory has assembled and tested a SULTAN sample made of REBCO tapes instrumented with Fiber Optic Sensors (FOS). This conductor is developed for the inner layer of the DEMO Central Solenoid magnet. Arrays of 10 FBG per fiber are placed along the conductor in different configurations. The main issue with the use of commercial polyimide or acrylate coated FBGs is their low sensitivity below 10 K that need to be improved. For these reasons new fiber coating materials have been tested in this study similar to what was done in [4] [12].

This paper reports on the issues and success of the FOS integration and discussed the signals obtained during the conductor cool-down, warm-up and powering to quench.

II. OPTICAL EQUIPMENT

The SULTAN test facility [13], have been upgraded with optical equipment to anticipate the growing demand of fiber testing in fusion conductors. It includes: the optical interrogator, two 20 m room temperature optical cables, two vacuum leak-tight push-pull optical feedthrough, two 2 m long cryogenics proof optical cables, and two 0.5 m break-out cables that separately connect each fiber coming from the instrumented sample. Each optical cable contains four fibers so that a total of eight fibers can be tested. The connectors at the

Submitted for review September 19, 2023

This work has been carried out within the framework of the EUROfusion Consortium, via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion) and funded by the Swiss State Secretariat for Education, Research and Innovation (SERI). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union, the European Commission, or SERI. Neither the European Union nor the European Commission nor SERI can be held responsible for them.

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Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org end of the break-out cables are FC-APC (Ferrule Connector, Angle Physical Contact). The connectors at the end of the room temperature cables are Lucent connectors (LC-APC). The aging of the cables will be studied as the test benches will overcome numerous thermal cycles due to the great turnover of samples at SULTAN. The optical cables are from Fischer Company [14].

The interrogator (Luna Inc., Hyperion si255) has only four ports that limits to four the number of fibers that can be interrogated at the same time. Its wavelength range is 1460 to 1620 nm, its accuracy is 1 pm and its frequency of acquisition up to 1 kHz for the peak tracker and 1 Hz for the full spectrum. [15]. Having the full spectra accessible is crucial to understand to soundness of the FBG as spectral distortion occurring when the sensor is not properly installed (Chirping, birefringence effect, peak splitting) or multiaxial strain. The source code for the data monitoring and peak tracking is fully accessible allowing to easily communicate with other Data Acquisition System (DAS). A Labview program that controls the SULTAN DAS has been modified to read the interrogator output signals (Ethernet cable). The optical signal reading is thus synchronized with the current, voltage tap and CERNOX sensor reading.

Fibers instrumented with several FBG sensors have been purchased for our R&D purpose. Those are single mode fiber coated with either polyimide or acrylate and referred to as "Corning's SMF-28 Ultra optical fiber". It features a core diameter of 8.2 µm, a cladding diameter of 125 ± 0.7 µm and a coating diameter of 242 ± 5 µm. Their maximum attenuation is lower than 0.3 dB/km.

The FBGs are inscribed using UV mask by external companies. We have acquired various 5-m long fibers containing 1, 2, 4 or 10 FBG sensors. Each FBG is 10 mm long. The spacing between the ten FBG sensors is chosen so as to cover the SULTAN sample High Field Zone (HFZ), with a minimum distance of 6 cm between two FBGs. Each FBG gets a nominal different Bragg peak. Their values are chosen anticipating the spectral shift induced by the cool down (between 4 and 30 nm depending of the FBG coating material down to 4.2 K) thus preventing any spectrum overlapping and such taking into account to interrogator available wavelength range (1460-1620 nm). A fiber splicing machine and a fiber clever are also part of the optical equipment and are used to make connections, and eventually fix broken fibers.

III. Sensor calibration

Before installation in SULTAN sample, FBG responses of free standing fiber have been measured in terms of Bragg peak wavelength shift function of temperature to calibrate the sensors. The 15 T magnet cryostat is used to perform the FBG signal calibration. The facility allows to measure two fibers at the same times with CERNOX sensors to measure the temperature. Fig. 1 shows the measurements for a thin acrylate layer coated FBG, for a FBG in a PTFE shrinking tube (wall thickness 0.58 mm) and for a 3x3 mm silicon rubber coated FBG. The silicon rubber is Room Temperature Vulcanization 566 (RTV566) sold by Momentive, special low temperature rubber, used in aerospace engineering for its good mechanical properties both low and high temperatures. It maintains elasticity down to 160 K (glass transition point). The results of the RTV566 are very promising with usable signal down to 4.2 K and is four times more sensitive that the acrylate fiber. The PTFE coated FBG is less sensitive than the one coated with RTV566 and is less practical to handle with noticeable bending of the sensors during curing that requires improvement.

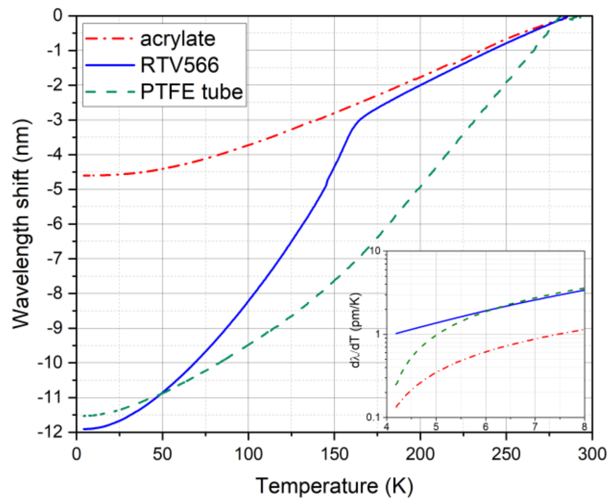

Fig. 1. Sensor calibration curves for the as-received FBG (acrylate), for the silicon rubber RTV566 coated FBG and for PTFE shrinking tube coated FBG. The inset shows the sensor sensitivities (derivative of the main plot) that a response persists down to 4.2 K for the RTV566 and PTFE.

IV. FBG in HTS Conductor

A. Fiber configuration

SPC is currently developing REBCO tape conductors for the DEMO Central Solenoid. Various cable design are investigated [16-17]. In the present study, the SULTAN sample is composed of two legs respectively named ASTRA (Aligned Stacks Transposed in Roebel Arrangement) and Non-Transposed Non-Twisted (NTNT), both connected in series through a bottom joint. Fig. 2 shows the schematics of the samples with the locations of the sensors. The conductor is instrumented with voltage taps, CERNOXs and FBG with a focus on the SULTAN high field zone (2x483 mm). The optical fibers with FBG sensors were installed only on the NTNT conductor. Two NTNT conductors (A and B) have been tested with complete disassembly of the samples between the two runs. Both have the same design, the main difference is in the location of the FBG optical fibers. In conductor A, three fibers have been integrated: one 10-FBG fiber was soldered together with the stack of tapes between the copper channel for helium and the jacket (see Fig 2) and one 10-FBG fiber was inserted into a 0.3 mm steel capillary; the steel capillary is placed in a groove machined in the copper block which surround the REBCO stack. One 4-FBG coated by PTFE adhesive shrinking tube was placed on the external steel jacket of the conductor. An aluminum foil was used to gently press the FBG to the jacket, aiming a good thermal contact without bonding to the jacket.

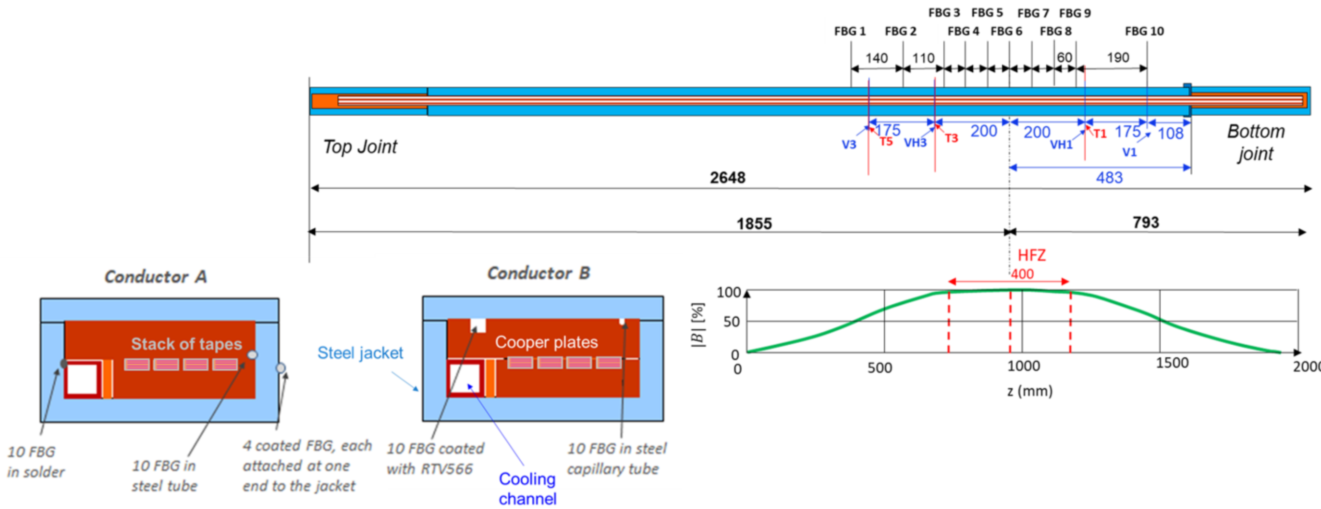

Fig. 2. Schematic of the NTNT conductor instrumented with CERNOX (in red), voltage taps (in blue) and 10-FBG array (in black). The normalized SULTAN background field is indicated with the high field zone. The schematic of the transverse cross-section of both tested configurations (A & B) are represented showing the location of the fibers.

In conductor B, two grooves on the external surface of the copper profile were machined. A steel capillary tube was placed in the first one (Ø 1 mm). In the second groove (3x3 mm of cross section), a fiber with silicone rubber coated FBGs was set in. The coated FBG are free to move axially thanks to PTFE spray coating of the groove done before the fiber setting.

The motivation of having the fiber inside a capillary is twofold: to protect the fiber and to maintain strain free state at the level of the FBGs thus sensing only the temperature.

The fibers exiting from the sample are protected inside 1 mm PTFE tubes up to their connector. The fiber splices are protected by a specific Polyethylene shrinking tube and rigidify by a steel rod (3.0 x 60 mm).

B. Conductor cool-down and Warm-up

Fig. 3 and Fig. 4 shows the temperatures measured by the in-capillary FBGs for the conductor A during cool-down and warmup. The agreement with the CERNOX down to 10 K is remarkable. A gradient of temperature is clearly capture by the FBG array.

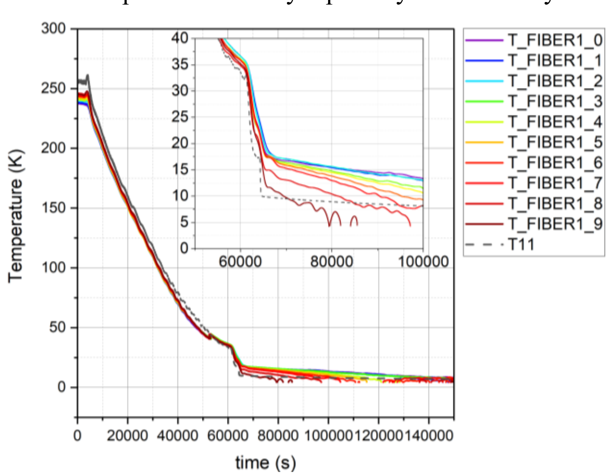

Fig. 3. Cool down of the conductor B seen by the FBG array and the CERNOX (black dash, T11). The change of slope at 35 K and 10 K is due to cryogenics process (mass flow reduction).

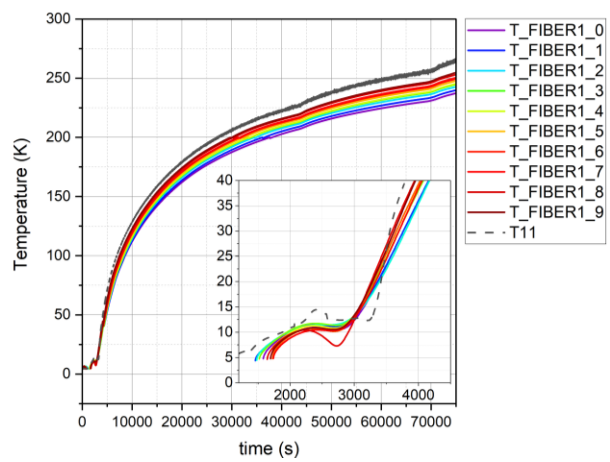

Fig. 4. Warm-up of the conductor B seen by the FBG array and the CERNOX.

C. Integration issues and success

1) The embedded fiber dramatically suffered from the soldering process. The signals from the FBGs show particularly deformed spectra with three severely damaged FBGs after soldering. The deterioration of the FBG seems partly due to the misplacement of the fiber that tends to float above the solder leading to a wavy pattern of the fiber, partly because the acrylate coating thermally decomposes and melts. During the cool-down to 4.5 K, the deformed spectra worsen even more. The automatic peak tracker could not be used due to large power loss (25 dBm) and important spectral deformation. At 4.2 K, only one FBG responded. This fiber is discarded from the rest of the analysis.

2) The FBGs in the PTFE tubes showed highly deformed spectra during cool-down and the monitored shift could not be trusted. The use of PTFE tube should be improved as the tube tends to bend during the 360 °C shrinking process getting worse at low temperature.

3) The nice potential of RTV566 coated FBG could

unfortunately not be tested because of a malfunction of the fiber's splice. A loss greater than 40 dBm was measured during cool-down. A posteriori investigation revealed that the splice protection was severely bent certainly during the SULTAN sample insertion in the SULTAN pit. After replacing the splice, all spectra were intact.

4) The FBG inside the capillary behaved particularly well during the tests. The temperature along the fiber during the welding process could be monitored showing no temperature peak potentially dangerous for the HTS tapes.

Using the stainless steel tube allows good heat transfer to the FBG, decouple the FBG from the monitored structure and offers a protection to the fiber along its length. As discussed in the next paragraph, the fibers in the capillary have been able to detect the quenches during the powering test.

D. Powering test, result from the capillary fiber

This study focuses on the results obtained by the capillary fibers. Fig. 5 shows the Bragg peak variations for ten FBGs during the powering of the conductor A up to quench.

The data shows a clear bell shape distribution of spectrum change from FBG1 to FBG10 located at the HFZ centered on the FBG 7 and FGB 8. At the 40 kA plateau current, the temperature seen by the fiber increases for FBG 7, 8, 9, 10 but decrease for FBG 1, 2, 3, 4 and flat for FBG 5 and 6, showing a local heat up of the conductor not captured by the CERNOX on the jacket. A sudden rise of FBG 9 and FBG 10 five seconds before the quench occurs (at t=459 s) shows a quench location close to the bottom joint. It was later found out that the NTNT conductor was defective at that location.

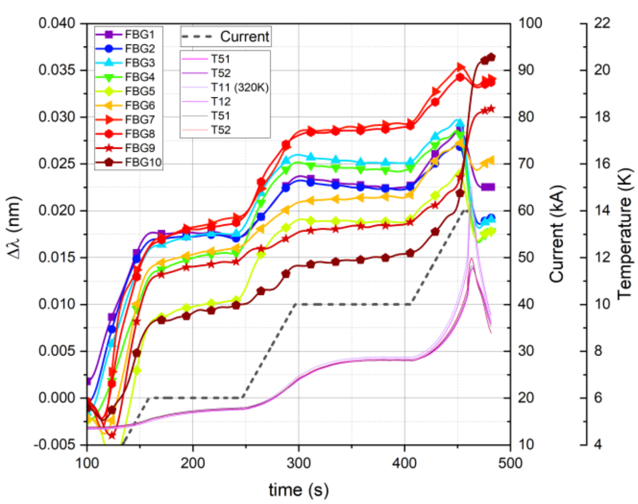

Fig. 5. Powering test at 9 T going to 60 kA with current plateau. Signals from the FBGs (left axis), current (right axis 1) and CERNOX (right axis 2).

Fig. 6 shows a typically quench obtained during the test of conductor B. The conversion from wavelength shift to temperature has been done using the calibration curve (Fig. 1). The quench occurs in the SULTAN high field zone with higher temperature measured by FBG 5 & 6. The longitudinal temperature distribution is here clearly visible. The difference with the CERNOX on the jacket, shows the existence of a thermal gradient across the conductor cross-section and shows the advantage of having FBG near the conductor for quench detection.

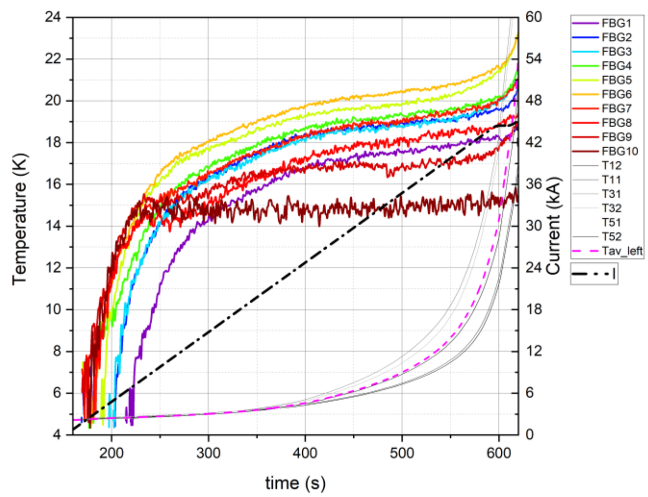

Fig. 6. Temperature evolution during a powering test at 6T up to quench (47.5 kA). Signals shown for the FBGs and CERNOX (left axis), current (right axis).

V. Conclusion

As the demand of testing superconductors for fusion application instrumented with fiber optic sensor is growing, the SULTAN test facility has recently been equipped with optical feed-thru and optical cables that allows to interrogate up to eight fibers independently. The optical signals are monitored and synchronized in the same data acquisition system as the others sensors. Integrations of 10-FBG arrays inserted in a steel capillary in HTS SULTAN sample have been successful with exploitable data coming from the cool down and powering test of the conductors. A temperature map of the conductor could have been retrieved from the FBGs signal. The sensitivity of FBG to temperature is significantly improved using silicon rubber and PTFE as coating material down to 4.2 K. Developments is on-going at the Swiss Plasma Center that aims at finding solution for safe and robust fiber integration in large scale tokamak coils for future temperature monitoring and quench detection systems.

Acknowledgment

The authors are indebted with the SPC workshop and SULTAN operation team for their skilled and dedicated support. They wish to deeply thank CERN for interrogator loan.

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