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Superconducting magnets and devices**

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Advances in Fiber Optic Sensors technology development for temperature and strain measurements in superconducting magnets and devices

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Abstract— The luminosity upgrade of the Large Hadron Collider (HL-LHC) requires the development of a new generation of superconducting magnets based on Nb₃Sn technology. In order to monitor the magnet thermo-mechanical behaviour during its service life, from the coil fabrication to the magnet operation, reliable sensing systems need to be implemented. In the framework of the FP7 European project EUCARD, Nb₃Sn racetrack coils are developed as test beds for the fabrication validation, the cable characterization and the instrumentation development.

Fiber optic sensors (FOS) based on Fiber Bragg Grating (FBG) technology have been embedded in the coils of the Short Model Coil (SMC) magnet. The FBG sensitivity to both temperature and strain required the development of a solution able to separate the mechanical and temperature effects. This work presents the feasibility study of the implementation of embedded FBG sensors for the temperature and strain monitoring of the 11 T type conductor. We aim to monitor and register these effects during the coil fabrication and cool down in a standalone configuration.

Index Terms— Fiber optic sensors, Fiber Bragg Grating, racetrack coil, Nb₃Sn

I. INTRODUCTION

In the framework of the High Luminosity upgrade of the Large Hadron Collider (HL LHC) at CERN, a new generation of superconducting magnets based on the Nb₃Sn conductors is under development. The brittle and strain sensitive nature of this material requires a precise characterization of the thermo-mechanical state of the conductor at the different phases of its service life, from coil manufacture to magnet operating conditions. The axial and transverse strains applied to the conductor partly determine the performance of the magnet. Besides, the temperature reached by the conductor during a quench is an important information for the magnet protection in terms of hot spot temperature. For both parameters, too high values can eventually lead to conductor damage.

So far, the cable local temperature and strain cannot be directly measured with thermometers or strain gauge because of issues in accessing close contact with the conductor with resistive type sensors. They are integrated on the Ti pole around which the conductor is wound. So, in parallel to the integration of the well-assessed resistive sensors, yet suffering from the number of wires and complex compensation of the

Fig. 1. (Left) Picture of the racetrack coil instrumented with fiber optic sensors on the winding and strain gauges on the Ti Pole; (Right) sketch of the FBGs installation on the winding and picture of the set up completed with spot heater in the high field zone and the instrumentation trace.

magnetic and thermal effects, CERN is developing a new sensing technology based on FOS for superconducting magnet. In fact, in addition to being electrically neutral, FOS offer appealing advantages in terms of smaller size, less intrusive nature and interesting multiplexing capability thus making their integration possible directly on the winding. However, their implementation in complex superconducting magnet structures is not straightforward. Technological development is still required to assess the integration procedure after the coil heat treatment. Several fiber optic technologies have been investigated for their use in magnets or other devices with distributed [1] or multi point sensing scheme [2]. Among them, FBG based sensors seem one of the most promising technology for cryogenic temperatures monitoring [3-6] along with Rayleigh scattering based sensors.

This paper reports on the feasibility of the use of FBG sensors, in embedded configuration, for the cable local temperature and strain monitoring, when integrated for the first time inside impregnated Nb₃Sn coil in a subscale dipole magnet called SMC (Short Model Coil) fabricated at CERN. After a brief introduction of FBG sensing working principle, the procedure for fiber integration is presented. It will then be seen that the coil impregnation and curing process can be followed by the fiber output signal. The last part presents the measurements results of the FBG obtained during two thermal cycles, down to 4.2 K that have been performed for coils in a standalone configuration. The different fibers implemented have survived the different phases of the test allowing validating the sensor integration procedure. Further tests may

help for the qualification of high current density conductor behavior or of the “bladders and keys” assembly procedure [7].

II. FIBER BRAGG GRATING WORKING PRINCIPLE

FBG sensors are sensing elements, which can be photo-inscribed into a silica fiber exposing it to a UV laser pattern. This exposure induces a local periodic modulation of the refractive index of the fiber core over a certain length. When broadband light is emitted to a Bragg grating, it only reflects the specific wavelength component λ_B [8]. The reflected Bragg peak wavelength is given by:

$$\lambda_B = 2 n_{eff} \Lambda \quad (1)$$

where n_{eff} [-] is the effective refractive index of the core and Λ [nm] is the grating period. The FBG is sensitive to both temperature (T) and strain (ϵ). A change in these parameters leads to a shift of λ_B due to their induced effects on both the n_{eff} and Λ [9]. The normalized Bragg wavelength shift from a strain or temperature variation can be expressed as:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - \rho_e)\Delta\epsilon + (\alpha + \xi)\Delta T \quad (2)$$

with ρ_e , α and ξ respectively, the photo-elastic, the thermal expansion and the thermo-optic coefficients. Typical strain and temperature sensitivities with λ_B of 1550 nm are in the range of 1.2 pm/ $\mu\epsilon$ and 12 pm/K at room temperature [10].

The FBG thermal response is dominated by the thermo-optic effect, rather than the thermal expansion coefficient of the fiber material. Approaching cryogenic temperatures both effects reduce and the bare FBG temperature sensitivity significantly decreases dropping to < 0.1 pm/K below 50 K and no possible measurement near 4.2 K [11]. On the contrary, the FBG strain sensitivity has been found to be independent of temperature [12]. It results that the response of bonded or embedded FBG sensors is dominated by the axial strain induced by the host material to the fiber by differential thermal contraction effects [13]. One issue is to distinguish the mechanical effects from the thermal effects for the different phases of the magnet service life. Such effects arise from the coil fabrication, the magnet assembly, the thermal cycle to cryogenic temperatures, the Lorentz force during magnet powering and the Joule heating in the quenched conductor area, the hot spot temperature, so far based on theoretical calculations using semi-analytical models [14]. A specific set-up is proposed using single ended sensors: a bare FBG and a FBG inserted in a capillary Al tube (to obtain fiber strain-free condition) placed in contact with the conductor and impregnated together with the coil (embedded configuration). Fig. 1 displays this set-up where the Al tube and the free fiber are placed at the expected quench location. This configuration would lead to local axial strain and hot spot temperature measurements after it is first validated in the coil standalone configuration as described in the following sections and once the coils are assembled in the magnet.

III. FIBER BRAGG GRATING INTEGRATION PROCEDURE

This part presents the procedure for the FBG integration in the coils of the SMC_11T magnets. FBGs of 5 mm long grating inscribed in single mode (125 μm diameter) fibers recoated in polyimide (15 μm thickness) were selected to be embedded

inside two different coils.

A. Sensors characterization to 4.2 K

Before the sensors are integrated in the magnet, their thermal behavior is characterized in the range 300 - 4.2 K over several thermal cycles. This is done at CERN in a closed cycle refrigerator system composed of a pulse tube and a cryogen free cryostat dedicated to fiber testing. Fig. 2 shows the non-linear response of the wavelength shift with the temperature. In the range 300 - 4.2 K the total wavelength shift results to be 1.61 nm for a minimum sensitivity $d\lambda/dT$ of 1 pm/K at 50 K.

Fig. 2. Polyimide coated FBG characteristic curve in the range 300 – 4 K in the cryo-cooler before the sensors integration in the superconducting coil.

This is the strain-free sensor reference behaviour that is identified as part of the calibration method.

B. Sensor integration in the Al tube

The temperature sensor to be embedded has been realized by integrating the FBG in an Al tube of 20 mm length, 0.3 mm inner and 0.6 mm outer diameter. The geometries of the Al tube are chosen in order to respect the coil design parameters and to avoid damaging the brittle cable. In order to avoid any resin capillarity during the impregnation process and to assure the FBG to be free from any mechanical load, the Al tube has been closed to one extremity and the fiber has been glued at the other extremity with the adhesive Stycast™.

C. Sensors integration in the Nb₃Sn race track coils

Two reacted coils of dimensions 500 x 193.6 x 31.7 mm have been used for the integration of six embedded FBGs. The temperature sensors inside the Al tube were laid between the first and the second turn of the winding close to the Ti pole as shown in Fig. 1. The strain sensors is placed parallel to the Al tube between the second and the third turn in direct contact with the winding. The sensors are placed in the middle of the 150 mm straight part, along the axial direction of the coil, where the cable is subjected to the maximum axial strain and where the quench is expected to occur. As shown in Fig. 1, the instrumentation of the spot heater powering and voltage measurement placed before the coil impregnation is also visible.

For the fiber protection at the sharp edge of the coil, dedicated grooves have been machined into the coil support structure to keep the fiber straight, preventing breakage during the coil handling. Moreover, a 1-mm diameter Teflon® tube hosts the fiber inside and protects them all along. The fibers length can be adapted by splicing extra fiber length by means of the Fujikura Fusion Splicer FSM-70s.

IV. FEASIBILITY OF FBG USE DURING IMPREGNATION

The feasibility study of the use of embedded FBG for strain and temperature monitoring is carried out checking if the sensors “survive” the coil impregnation process.

A. Experimental set-up

For the coil fabrication, the FBG sensors behaviour can be continuously monitored during both the CTD-101K epoxy resin injection in the vacuum chamber and during the curing cycle in the dedicated oven. For the injection monitoring an optical vacuum tight feed-through is used. For the curing, the fibers are small enough for the oven's door to be closed upon them. The sensors are connected to the four channels of a compact optical interrogator (Micron Optics SM125) and acquired at 1 Hz frequency in all the tests presented. K-Type thermocouples are also placed at the top and at the bottom of the Al mould for temperature survey.

B. Results and discussion

The resin injection takes place under vacuum conditions once the mould has reached a stable temperature of 60 °C. After the mold is filled with the resin, the set-up is moved to the oven for the curing process. Fig. 3 shows the wavelength variation during curing cycle consisting of 5 h temperature variation from 60 °C to 110 °C with a post curing of 16 h at 125 °C completing the hardening process of the resin.

FBG named: 1T and 2T, inside the Al tube reach both 0.76 nm for the temperature range of 60 - 125 °C while the strain FBG named 3ε and 4ε embedded in the composite material in direct contact with the resin reach 1.38 and 1.22 nm. The wavelength shift of the strain sensors is indeed dominated by the hosting structure thermal expansion which is clearly not affecting the sensors in the Al tube.

At the beginning of the process, the induced strain transferred to the embedded sensor increases as much as the bonding between the polymer and the fiber becomes more effective owing to the increasing stiffness developed by the resin.

At the end of the process the strain sensors are affected by the residual strain accumulated between the fiber and the host material. It represents a total wavelength shift of -0.47 nm and -0.13 nm with respect to the beginning of the process. It yield a compressive strain of -390 and -110 µε using the standard sensitivity of 1.2 pm/µε. The difference between the two sensors can be due to the different locations and the different amount of resin between the sensor and the cable or an axial misalignment. It is also observed a discontinuous behavior of FBG 1T that could also be a sign of fiber settlement.

Fig. 4 shows the Bragg spectra of two sensors before the impregnation and after the demolding at room temperature,

Fig. 3. Embedded FBG wavelength shift during the racetrack coil impregnation process in the oven. On the double axis the temperature of the mould from the thermocouple installed inside the mould is reported.

when the impregnation process was completed. The spectra do not show any birefringent effect. A slight distortion of the spectra nonetheless appears for the ε-FBG that might be due to the load release after de-moulding. The observed blue shift is likely due to the compressive residual stresses applied to the sensor by the resin. On the contrary the T-FBG inside the Al tube does not experience any shift in wavelength confirming the goodness of the strain-free.

Fig. 4. FBG reflection spectra before and after the coil impregnation. The data refer to the T FBG integrated in the Al tube for temperature monitoring (left) and the sensor directly in contact with the epoxy resin ε FBG (right).

This experiment validates our methods of FBG sensor integration in Nb₃Sn impregnated coils. Besides, fiber-based feedback on the thermomechanical behavior of the system at the step of coil fabrication seems now possible.

V. FEASIBILITY OF FBG USE DURING COOL DOWN

A. Experimental set-up

In order to validate the use of FBG at cryogenics conditions, two cool-downs to 4.2 K have been performed on both fiber-instrumented SMC coils, together but in standalone configuration (not in the magnet structure). This experiment has been done in one cryostat of the CERN-SM18 vertical bench. A part from the CERNOX™ sensors that equip the test facility, one free FBG sensor was placed in the cryostat for ambient

Fig. 5. FBG wavelength shift during the first cool down of the 2 SMC coils from 294 K to 4.2 K. On the double axis the temperature of the cryostat from the CERNOX is reported.

temperature monitoring. With both coils, a total of seven fibers have been connected to the interrogator using Y-optical 1 x 2 couplers and optical feed through.

B. Survival of the FBGs with thermal cycles

Fig. 5 shows the shift of the Bragg wavelength for the strain and temperature FBGs during the cool down to 4.2 K. The temperature read by the CERNOXTM is also plot with the right axis. Fig. 6 shows the coils warm-up.

During the cool-down the splice protection sleeve of the FBG 3 ϵ was damaged, thus introducing losses which prevented the complete cool down and warm up measurements and the reflection spectra comparison at 4.2 K of the same sensor reported in Fig. 4. In the case of FBG 4 ϵ , the splice simply broke. Nevertheless, the possibility to easily re-splice the fibers will allow the monitoring of further tests. Differently, FBG 5T inside the Al tube integrated in the first coil appeared already distorted at the moment of the installation and the wavelength peak could not be detected after the first cool down. The integrity of the Al tube, thus the strain-free condition of FBG T1 and T2 can be confirmed if compared to the -1.55 nm shift of the free FBG T located in the cryostat for the same temperature variation 294 - 4.2 K. Furthermore the thermal cycle does not affect the response of the FBGs which restore the initial condition had at the beginning of the cool down. At the end of the warm up in fact, a total 0.5 nm difference between the FBG-T and FBG- ϵ is reported owing to the induced strain effect of the material on the FBG- ϵ only.

This test is validating the fiber integration and the feasibility of the use of a dedicated Al capillary at cryogenic temperatures.

C. Temperature and strain effect assessment

The response of the strain FBGs during the cool down is dominated by the thermal contraction of the resin which clearly does not affect the FBG-T inside the Al tube. The maximum shift of -4 nm at 4.2 K is reached by FBG 6 ϵ while the wavelength shift of the FBG-T reach maximum values of -1.6 nm for FBG 1T and 2T located in the same coil and -1.55 nm for FBG 5T in the other coil. The different dynamics clearly depend on the different location of the sensors, being the embedded sensors subjected to a different thermal load. This may explain also a slight difference in wavelength shift. For the

Fig. 6. FBG wavelength shift during the second warm up of the 2 SMC coils from 4.2 K to 294 K. On the double axis the temperature of the cryostat from the CERNOX is reported

same reason, the embedded FBG T cannot measure the gas temperature variation which occurs in the cryostat after 1.5 h. This 15 K temperature variation of 10 min could be not enough to be propagated to the embedded sensors for the thermal inertia of the coil and the temperature gradient of 100 K maintained along the coil length. Using the calibration previously discussed, the minimum temperature measured inside the coil corresponds to 50 K. Despite the dataset of the other ϵ -FBGs is not complete the strain sensors are in agreement in terms of behavior and dynamics. The wavelength variation during the second warm up in Fig. 6 shows the effect of the thermal cycling on the ϵ -FBGs. A red shift of 0.5 nm corresponding to about 400 $\mu\epsilon$ can be appreciated at the end of the warm up for the ϵ -FBGs owing to the relaxation of the coil in its axial direction.

The experiment confirms the reliability of the sensors and the use of the FBG as viable solution for temperature monitoring in embedded configuration.

VI. CONCLUSION

The first feasibility study of the use of FBG for strain and temperature monitoring in embedded configuration for superconducting magnets has been presented. The sensors can withstand the conditions of the integration in Nb₃Sn racetrack coils fabricated at CERN. It is shown in this paper that the impregnation and the cool-down to 4.2 K can be continuously monitored. The presented experiments thus offer encouraging perspectives for axial strain and temperature measurement of the coil during its service life after the coil heat treatment. In that sense, further measurement campaigns are planned for the coming SMC assemblies and powering tests of the coils instrumented with FBG sensors.

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REFERENCES

- [1] J. Schwartz et al., "Multi-purpose fiber optic sensors for HTS magnets," in 11th European Particle Accelerator Conference, Genova, Italy, 2008.
- [2] A. Chiuchio et al., "Cryogenic-temperature profiling of high-power superconducting lines using local and distributed optical fiber sensors," *Optics Letters*, vol. 40, no. 19, pp. 4424-4427, 2015.
- [3] A. Chiuchio et al., "Fiber Bragg Grating Cryosensors for Superconducting Accelerator Magnets," *Photonics Journal, IEEE*, vol. 6, no. 6, pp. 1-10, 2014.
- [4] X. Wang et al., "Strain-based quench detection for a solenoid superconducting magnet." *Superconductor Science and Technology*, 25, 095009, 2012.
- [5] R.K. Ramalingam et al., "Fiber Bragg Grating Sensors for Strain Measurement at Multiple Points in an NbTi Superconducting Sample Coil," *Sensors Journal, IEEE*, vol.14, no.3, pp.873-881, 2014.
- [6] A. Chiuchio et al., "Structural Health Monitoring of Superconducting Magnets using Fiber Bragg Grating Sensors," in EWSHM - 7th European Workshop on Structural Health Monitoring, 2014.
- [7] S. Caspi et al., "The use of pressurized bladders for stress control of superconducting magnets," *IEEE Transaction on Applied Superconductivity*, vol. 11, no. 1, pp. 2272-2275, 2001.
- [8] K. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *J. Lightwave Technology*, vol. 15, p. 1263-1276, 1997.
- [9] A. D. Kersey, "Review of Recent Developments in Fiber Optic Sensor Technology," *Optical Fiber Technology*, , vol. 2, pp. 291- 317, 1996.
- [10] R. Yun-Jiang, "In-fibre Bragg grating sensors," *Measurement science and technology*, vol. 8, no. 4, p. 355, 1997.
- [11] H. Zhang et al., "Development of Strain Measurement in Superconducting Magnet through Fiber Bragg Grating," *IEEE Transaction on Applied Superconductivity*, vol. 18, no. 2, pp. 1419-1422, 2008.
- [12] S. James et al., "Strain response of fibre Bragg grating sensors at cryogenic temperatures," *Meas. Sci. Technol.*, vol.13, no. 1535, 2002.
- [13] M. Giordano et al., "Monitoring by a single fiber Bragg grating of the process induced chemo-physical transformations of a model thermoset," *Sensors and Actuators A: Physical*, vol. 113, no. 2, 2004.
- [14] H. Bajas et al., "Quench Analysis of High Current Density Nb3Sn Conductors in Racetrack Coil Configuration," *IEEE Transaction on Applied Superconductivity*, vol. 25, no. 3, pp. 1,5, 2015.