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Fiber Bragg Grating Sensor as Valuable Technological Platform for New Generation of Superconducting Magnets

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ABSTRACT

New generation of superconducting magnets for high energy applications designed, manufactured and tested at the European Organization for Nuclear Research (CERN) require the implementation of reliable sensors able to monitor the mechanical stresses affecting the winding from fabrication to operation in magnetic field of 13 T. This work deals with the embedding of Fiber Bragg Grating sensors in a short model Nb_3Sn dipole magnet in order to monitor the strain developed in the coil during the cool down to 1.9 K, the powering up to 15.8 kA and the warm up, offering perspectives for the replacement of standard strain gauges.

Keywords: Superconducting coil, fiber optic sensor, FBG, dipole, Nb_3Sn, strain

1. INTRODUCTION

The development of a new generation of magnets for the High Luminosity upgrade of the Large Hadron Collider (HL-LHC) at the European Organization for Nuclear Research (CERN) requires the use of the more challenging superconductor Nb_3Sn which has a higher magnetic field capability than the presently used NbTi. The goal is to allow a larger bore of the insertion magnets of the LHC within the same allowed space, leading to larger forces and larger magnetic fields in the magnets.

A dedicated magnet, the Short Model Coil (SMC), was designed, manufactured and tested at CERN with the aim to study the applications of Nb_3Sn cable suitable for high field accelerator magnets. Nb_3Sn, for its brittle and strain sensitive characteristics, requires new approaches for magnet design and fabrication. In order to retain the forces that appear during the powering, high pre-stress is applied on the coils trough a mechanical structure. Since the superconductor is strain sensitive, it is important that the pre-stress level is optimized at cryogenic temperatures [1]. Precise monitoring of the mechanical performance of the magnet during all the stages of fabrication and operation gives critical feedback on possible coil motion which may lead to unwanted quenches and the consequently destruction of the superconductor due to the overheating at the transition from superconducting to resistive state. Therefore it is necessary to develop an adequate instrumentation able to operate in extreme conditions like ultra-low temperatures (1.9 K), high magnetic fields (up to 14 T) in order to monitor the large forces on the conductors. It was decided to embed all the instrumentation needed for this purpose into the coil before its filling with epoxy. The complex thermo mechanical sensing system required for this kind of magnets has to be resistant and reliable during the thermal transient between room temperature and 120°C, corresponding to the curing of the coil in the epoxy resin, and from 300 K to 1.9 K for its operation. It should sustain applied compressive forces during the assembly and during cool down, when the pre stress on the coil increases to 150 MPa and provide accurate reading of the coil unloading during the powering. To date, resistive strain gauges remain the devices most commonly used for measuring the strain in the superconducting magnets, but their sensitivity to the magnetic field and the amount of electrical wires needed for their operation (4 for each sensor) are the main limitations for their efficient implementation. Moreover, in the case of coils currently fabricated at CERN, issues related to intrusion and to the minimum cross section required, make their installation more affective and simple if

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they are glued on the main pole around which the conductor is wound rather than directly on the coil winding.

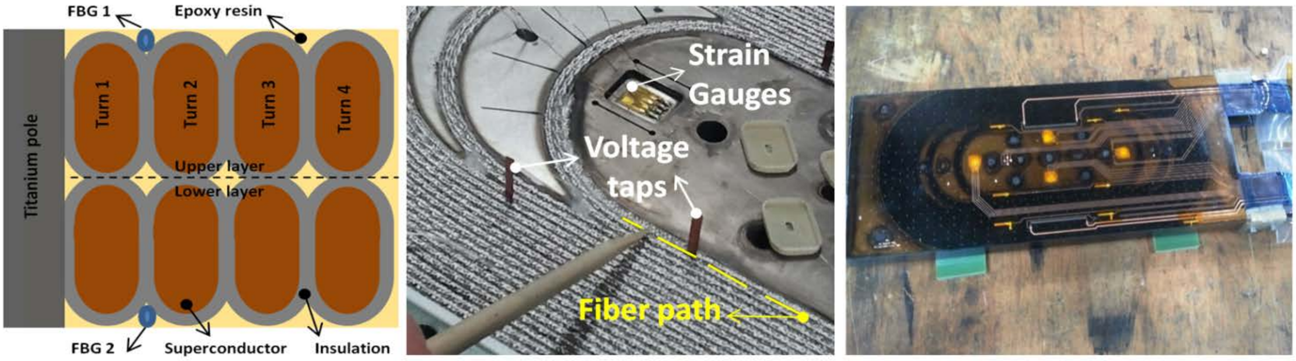
These issues could be usefully and efficiently addressed through the use of fiber optic sensors (FOS) for their attractive characteristics like small size, immunity to the electromagnetic interferences, multiplexing capability. In the last 20 years few studies on the use of Fiber Bragg Grating (FBG) sensors for cryogenic applications and superconducting magnets have been reported in literature mainly limited in providing a proof of principle of the strain and temperature measurement in cryogenic environment [2], [3]. The challenge of using the FBG in superconducting magnets is to embed them directly on the superconducting cables. The complex integration in real coils still makes this technology not yet assessed. However encouraging results reported in this field demonstrate that the strain behavior in the superconducting coils can be well monitored and the quench detection is in principle possible in the small solenoid magnets [4], [5].

This paper reports the results of the first FBG integration in the Nb_3Sn coil manufactured at CERN in a dipole configuration with the aim to develop a validated fiber optic sensing system for the new LTS magnets. So far, no application of FBG for strain measurements has been reported in accelerator type dipole magnets.

2. FIBER INTEGRATION AND SET UP

SMC is the first short-scale model of a Nb_3Sn dipole magnet where an FBG based monitoring system has been successfully implemented. In its so-called racetrack coil the Nb_3Sn insulated cable is wound around a central titanium pole in a double-layer configuration to form one "coil pack" of dimensions 500 x 193.6 x 31.7 mm (length, width, thickness). The coil is then mounted in an iron yoke surrounded by an aluminum shell structure with 540 mm outer diameter and 500 mm length [6].

Two 10 mm long FBGs inscribed in two fully polyimide recoated fibers were laid between the first and the second turn of the winding close to the Ti pole, one for each layer, in a symmetric configuration as shown in figure 1a. Particular care has been taken to ensure that the sensors were located along the axial direction of the coil in the middle of the 160 mm straight section, where the cable is subjected to the maximum stress during the assembly and the cool down and where the quench location is expected during the powering (highest magnetic field zone).



(a) (b) (c)

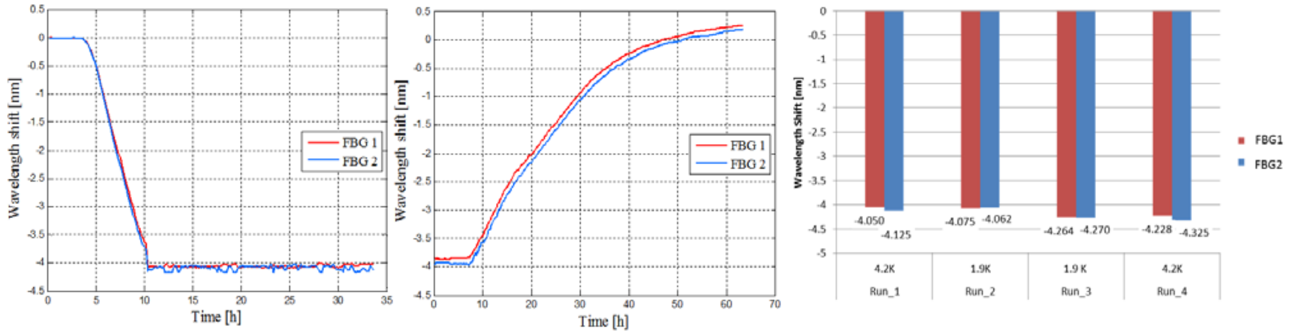
Figure 1. (a) Coil transvers cross section (view from the inside) and FBGs location between the first and the second turn of winding on the upper and lower layer; (b) Location of strain gauges, voltage taps, and fiber; (c) Coil after the impregnation.

The coil was also instrumented with voltage taps and resistive strain gauges as shown in figure 1b. In particular for the strain gauges dedicated cavities have been machined in the Ti pole in order to prevent any damages during assembly of the magnet. From the picture the fiber location between the first two turns of the winding is also visible. The fabrication of the coil was completed with the impregnation in a vacuum tank using a mix of Epoxy resin and polyetheramine hardener at 120 ° C. A photograph of the coil is shown in figure 1c.

The magnet assembly was then completed by mounting the coil pack inside the yoke and the shell and applying lateral and vertical compression. The magnet was tested in the SM18 test facility at CERN using a vertical cryostat filled with liquid Helium and further cooled down to superfluid Helium. Before the insertion inside the cryostat, the magnet was installed on a vertical insert used to close the magnet and to finalize the electrical, optic and cryogenic instrumentation. The optical fibers were connected to a compact optical interrogator (Micron Optics SM125) using a dedicated feed through placed on the top of the cryostat. Tests have been performed during four runs in each of which the magnet was cooled to 1.9 K and/or 4.2 K, powered with various current ramp rates to spontaneous quenches and then warmed up.

3. EXPERIMENTAL RESULTS

FBGs data has been acquired continuously during each cool down, current ramp up and warm up. The change in wavelength during 10 hours cool down from 300 to 1.9 K is shown in figure 2a for both the sensor FBG 1 and FBG 2. For a bare FBG, the thermal response is dominated by the refractive index change, as the thermal expansion of silica is low. Approaching cryogenic temperatures, both the effects reduce, so the temperature sensitivity of a bare FBG dramatically reduces. In the case of embedded or bonded FBG, the thermal response is thus dominated by the thermal apparent strain related to the thermal expansion/contraction of the host material. In our case, the observed thermal behavior, especially at low temperatures, is dominated by the resin expansion/contraction. In addition, the Al shell provides additional pre-stress to the coil thanks to the differential thermal contraction with the inner Fe yoke.

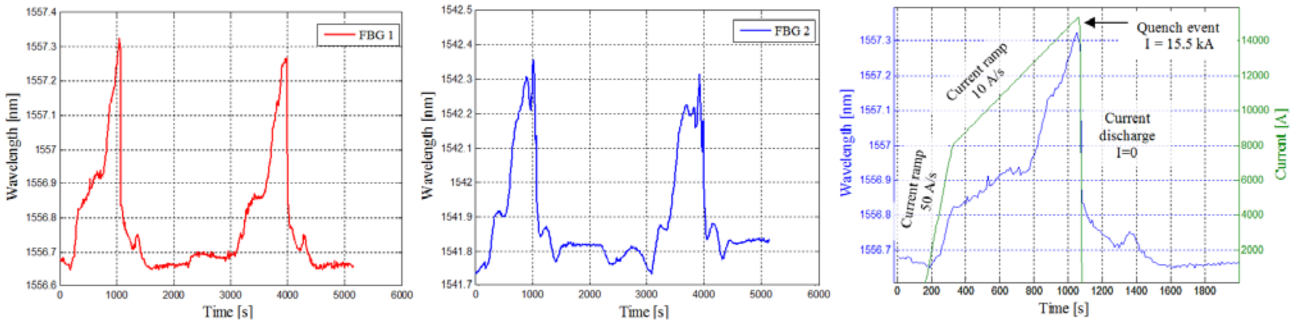


(a) (b) (c)

Figure 2. (a) Wavelength shift during cool down from 300 K to 1.9 K; (b) Wavelength shift during warm up from 1.9 K to room temperature; (c) Wavelength shift during the four cool down of the four runs.

This means that the data reported in figure 2a and 2b could provide important information of the coil thermo–mechanical behavior following the evolution of its strain during one entire run. In fact, the wavelength shift in figure 2b differs of 250 pm from the values at the same temperatures in figure 2a, showing the change in strain due to an overall relaxation of the coil after tests made at 1.9 K and a complete thermal cycle between 300 and 1.9 K. As expected from the magnet mechanics, motions of the wires, friction and cracks in the resin due to the powering and the stress release during the warm up, can set the coil to a different strain from the original one. In the bar chart of figure 2c the computed wavelength shift for both sensors at each cool down is reported, showing the reproducibility of the data during the four runs and the reliability of the fibers during the whole test campaign. No reference data from strain gauges can be reported in this paper since they resulted to be lost after the first cool down to 4.2 K.

For its training (a number of quenches performed in the same run, in which ideally the quenches occur each time at higher current thanks to a mechanical settling of the magnet), the magnet was powered with current ramped at 50 A/s to 8 kA and then at 10 A/s to the quench current. Figure 3a and 3b show the change in wavelength of the two FBGs to a series of current ramps and quenches at 15.5 kA. In response to the powering, the coil releases the pre stress achieved after the assembly and the cool down expanding in its axial direction, while after each quench, when the current is discharged, the coil returns to the original strain it had before the powering.



(a) (b) (c)

Figure 3. (a) - (b) Wavelength responses of FBG 1 and FBG 2 during a series of current ramps and quenches at 15.5 kA; (c) Magnification of the first quench of (a) with the current profile.

This is illustrated in more details in figure 3c for the first quench of the series of FBG 1 where the current profile is also plotted, showing the increase of the wavelength during the ramp followed by a sharp decrease after the quench. As consequence of the quench, apart from stress changes, there is also a temperature variation. In fact, due to the Joule heating in the zone of the quench initiation, the temperature increases, explaining why the wavelength doesn't go back to the original value it had before the powering as fast as the current drops to zero. Source of slight difference between the two sensors may be their different location as well as the misalignment of the FBG along its measuring axis, the resin thickness surrounding and the movement of the cables.

Lastly, considering the constant temperature during the magnet ramp up, the maximum FBG wavelength shift reached at the end of the current ramp could be translated into strain using the theoretical sensitivity of 1.2 pm/με. These values have been compared with the expected values of the SMC Finite Element Model: for a current of 14.3 kA the measured values of FBG 1 and FBG 2 were respectively 460 με and 420 με in respect of the expected theoretical value of 638 με.

4. CONCLUSIONS

FBG sensors have been embedded in the Nb_3Sn coil manufactured at CERN for a subscale dipole magnet and have survived the integration process, the assembly and the cold powering for several thermal cycles. The strain behavior of the coil in the high pre-stress and magnetic field zone has been monitored in agreement with the expected mechanics. The measurements show the reliability of the FBG as a complementary technology to strain gauges for the validation of the mechanical model of the magnet.

With the better understanding gained from this test an improved sensor configuration has been made and will be used in a new model magnet.

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