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Fiber Bragg Grating Sensors Based Monitoring System for Superconducting Accelerator Magnets

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Abstract: New generation of accelerator magnets for high energy applications currently designed, manufactured and tested at the European Organization for Nuclear Research (CERN) require the implementation of precise cryogenic sensors with long-term robustness and reliability able to withstand cryogenic temperature and to monitor the mechanical stresses affecting the winding during all the stages of his service life, assembly, cool down and powering. Monitoring the mechanical behavior of the magnet from assembly to operation is a critical task which aims to assure the integrity of the magnet and to safely handle the coils made of new brittle material. This contribution deals with the first successful embedding of Fiber Bragg Grating sensors in a subscale Nb₃Sn 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 new perspectives for the development of a complementary sensing technology based on fiber optic sensors.

Keywords: Superconducting magnet, fiber optic sensor, FBG, dipole, Nb₃Sn, strain, coil

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 Nb₃Sn which has a higher magnetic field capability than the presently used NbTi.

A dedicated magnet, the Short Model Coil (SMC), was designed, manufactured and tested at CERN with the aim to study the applications of Nb₃Sn cable [1]. Since the superconductor is strain sensitive, precise monitoring of the mechanical performance of the magnet from fabrication to operation gives a critical feedback on possible coil motions which may lead to further damages. The sensing system required for this kind of magnet has to be resistant and reliable in extreme conditions like ultra-low temperatures (1.9 K), high magnetic fields (up to 14 T) and strong mechanical pre-stress (up to 150 MPa). To date, resistive strain gauges are the devices most commonly used for measuring the strain in the magnets, but their sensitivity to the magnetic field and the amount of electrical wires needed for their operation add issues that could be efficiently addressed through the use of Fiber Bragg Grating (FBG) sensors. The challenge of using the FBGs is to embed them directly on the superconducting cables since the coils fabricated at CERN have currently only strain gauges glued on the main pole around which the conductor is wound. So far, few studies on the use of FBGs for cryogenic applications and superconducting magnets have been reported in literature [2], [3] and the complex integration in real coils still makes this technology not yet assessed. However encouraging results demonstrate that the strain behavior in the superconducting coils can be well monitored in the small solenoid magnets [4], [5]. This work reports the results of the first FBG integration in the Nb₃Sn coil manufactured at CERN in a dipole configuration with the aim to develop a validated FBG based sensing system for the new generation of accelerator magnets.

2. Fiber Integration and Set - up

SMC is the first short-scale model of a Nb₃Sn dipole magnet where an FBG based monitoring system has been successfully implemented. In its so-called racetrack coil of dimensions 500 x 193.6 x 31.7 mm (length, width, thickness), the Nb₃Sn insulated cable is wound around a central titanium pole in a double-layer configuration. The coil is then mounted in an iron yoke surrounded by an aluminum shell structure with 540 mm outer diameter and 500 mm length. Two 10 mm long FBGs inscribed in 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.

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The FBGs 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 (transition from superconducting to resistive state) is expected during the powering.

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 and then it was impregnated in a vacuum tank using a mix of Epoxy resin and polyetheramine hardener at 120°C [6] (figure 1c). After the assembly the magnet was tested in the SM18 cryogenic test facility at CERN. 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 using a compact optical interrogator (Micron Optics SM125). 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. The evolution of the strain reported in figure 2a and 2b provide important information of the coil thermo-mechanical behavior 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.

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.

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.

After the cool down, 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.

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.

4. Conclusion

FBG sensors have been embedded in the Nb₃Sn 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 monitored in the coil is in agreement with the expected mechanics envisaging the development of a complementary technology to strain gauges for the validation of the mechanical model of the magnet.

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