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Fiber Optic Cryogenic Sensors for Superconducting Magnets and Superconducting Power Transmission lines at CERN

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ABSTRACT

The design, fabrication and tests of a new generation of superconducting magnets for the upgrade of the LHC require the support of an adequate, robust and reliable sensing technology. The use of Fiber Optic Sensors is becoming particularly challenging for applications in extreme harsh environments such as ultra-low temperatures, high electromagnetic fields and strong mechanical stresses offering perspectives for the development of technological innovations in several applied disciplines.

Keywords: Optical fiber sensors, Fiber Bragg Gratings, superconducting magnet, superconducting power line, cryogenic temperature

1. INTRODUCTION

The Large Hadron Collider (LHC), the largest circular particle accelerator built at the European Organization for Nuclear Research (CERN), is equipped with NbTi based superconducting magnets to achieve a bending field of 8.3 T in the main dipoles. In order to improve the luminosity of the LHC advanced accelerator magnets able to operate in the 11-13 T range need to be developed using a new technology based on Nb₃Sn. Moreover, to avoid radiation damage of the power converters presently located in 100 m deep tunnel, it is planned to bring them in the surface or in radiation-free underground areas feeding the magnets down to the tunnel through High Temperature Superconducting transmission lines (SC - Link) to transfer high currents up to 20 kA [1]. New technologies and devices require a complex development phase and the implementation of new sensing instrumentation becomes crucial to provide useful information from fabrication to operation in extreme conditions as ultra-low temperatures (down to 1.9 K), strong electromagnetic fields (up to 13 T), and strong mechanical stress (up to 150 MPa). The instrumentation presently used in this field is based on resistive sensors. The high number of instrumentation wires during the R&D phase and during operation is limiting the number of instruments which can be embedded within the magnets and the SC- Link. Moreover, their magnetic field dependence and the heat-leak into the cryogenic bath, add issues which might be overcome by developing a new technology based on Fiber Optic Sensors (FOS). Among them, the Fiber Bragg Gratings (FBG), for their characteristics like small size, light in weight, intrinsic electrical insulation, immunity to electromagnetic interferences and multiplexing capability, represent a good alternative to the resistive sensors. Several studies on the use of FBG based sensors for superconducting magnets and cryogenic applications have been already reported mainly limited in providing a proof of principle of the strain and temperature measurement in cryogenic environment [2]-[3], but in spite of the potential of the use of FBG sensors in such hard working conditions, the complex integration in real accelerator magnets and in cryogenic environments still makes this technology not yet assessed. In this work we present the implementation of cryogenic fiber optic sensors for the temperature monitoring in the first SC Link prototype over 20 m distance and the integration in short scale Nb₃Sn dipole magnets currently designed, manufactured and tested in the CERN laboratories for the strain monitoring during their whole service life.

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2. FIBER BRAGG GRATING SENSORS WORKING PRINCIPLE

An FBG is a periodic modulation of the index of refraction in the core of a single mode optical fiber formed by exposing the fiber to a UV laser pattern. When broadband light is emitted to a Bragg grating, it only reflects the specific wavelength component. The Bragg reflection wavelength of an FBG is given as

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

where n_{eff} is the effective refractive index of the core and Λ is the grating period. The FBG is sensitive to both temperature and strain. The strain response arises from both the physical elongation of the sensor and the change in fiber index because of photo elastic effects. The dependence of the Bragg wavelength on temperature arises from the change of the effective index due to thermo-optic effect and the change of the period due to thermal expansion of the glass [4]. The Bragg wavelength shift with strain (ϵ) and in temperature (T) can be expressed using

$$\Delta\lambda_B = \lambda_B [(1 - \rho_a)\Delta\epsilon + (\alpha + \xi)\Delta T] \quad (2)$$

where ρ_a is the photo elastic coefficient of the fiber, α is the thermal expansion coefficient and ξ is the thermo-optic coefficient. The thermal response is dominated by the thermo-optic effect, as the thermal expansion of silica is very low (0.5×10^{-6} at room temperature). At cryogenic temperature both the effects reduce so the sensitivity of a bare FBG decreases significantly with decreasing temperature, approaching zero below 50 K [5]. The sensitivity of the FBG at cryogenic temperature can be improved by embedding or bonding the sensor to a host material such a way the thermal response is dominated by the thermal apparent strain related to the thermal contraction/expansion of the material itself.

3. FBG BASED SENSORS FOR SUPERCONDUCTING POWER TRASMISSION LINES

In the power transmission lines the temperature monitoring is required to keep the temperature of the Helium gas homogeneous all along the line in order to assure operation of the superconducting cable above its critical temperature (transition temperature from resistive to superconducting state). FBGs read in wavelength division multiplexing scheme give attractive perspectives for the instrumentation wire reduction, but the implementation of cryogenic sensors for this application requires the study and the selection of the proper material able to enhance the sensitivity of the FBG in the temperature range of interest.

3.1 Fiber Bragg Grating Sensors integration and set up

Based on preliminary studies carried out at CERN [6] eight FBGs of 10 mm grating recoated with epoxy and PMMA of dimensions 2.5 x 5.0 x 25.0 mm (height x width x length) have been selected and arranged symmetrically in 4 arrays of 20 meters length. The FBGs were placed in proximity of each reference sensor (Cernox) in order to monitor the temperature variation in the same locations distributed over the 20 meters. The set-up of the FBGs is designed with the aim to continuously monitor the cryostat ambient temperature in order to assure safe working conditions during operation. Figure 1 shows the schematic of the 4 locations where the FBGs and the reference sensors have been placed. The distance of each sensor is considered from the optical interrogator placed more than 20 meters far from the gas entrance. To assure the integrity of the fibers during the installation and the operation, they were placed inside a 10 mm inner diameter Kapton tube, conveniently perforated in order to force the flow of Helium gas through. The tube was then fixed to the insulated superconducting cable and pushed together with it inside the 20 meter long horizontal cryostat.

Figure 1. FBGs and Cernox locations over 20 m length in the SC Link

The first 20 m SC- Link prototype was then cooled to 30 K and the temperature kept homogeneous by a forced flow of helium gas coming from a feed box located at the end of the cryostat. Tests at different temperature in the range 15 - 30

K have been also performed powering the cable from 3 to 20 kA before warming the SC - link to room temperature and cool down again. The FBGs were connected to the four channels of the Micron Optics sm125 using a dedicated ultra - vacuum tight feed through at the beginning of the cryostat, 25 meters far from the feed box where the gas is forced to flow all along the cable.

3.2 Experimental results

The FBGs reflected wavelengths were continuously monitored during the cool down and the main test phases. The sensors are named as FBG A and FBG B to indicate the epoxy and the PMMA recoated ones respectively. Figure 2a shows the characteristic curve of one PMMA recoated sensor and the nonlinear behavior of the wavelength with the temperature due to the reduction of the sensor sensitivity with the decreasing temperature, coherently with the expectations already discussed in section 2. The dynamics of each sensor is clearly depending on the distance from the gas injection located at 20 m and this is shown in figure 2b where the FBGs temperature reconstruction during the first cool down is reported. Coherently with the temperature profile monitored by the reference sensors, it is possible to map the temperature along the line. As shown in figure 2c a temperature decrease of 85 K is seen at the entrance of the cold gas at 20 meters after 3 hours while the same temperature is reached at the distance of 7 meters and then at the beginning of the cryostat in more than 5 showing the cooling power of the Helium gas over long distance. Reaching lower temperature, the time needed to each sensor, therefore to each location, to get the same temperature decreases until the line reaches a stable and homogenous temperature at 30 K in about 12 hours. The temperature reconstruction along the 20 meters is reported for 3 of the 4 locations of interest due to a damage occurred to one of the reference sensors during the test.

Figure 2: (a) Characteristic curve $\Delta\lambda$ -T; (b) FBGs' temperature profile during cool down from 300 to 30 K; (c) Temperature mapping over the distance.

The capability of the FBGs to monitor the temperature of the Helium gas along the distance offers the possibility to increase the number of temperature sensors which cannot be easily implemented with the use of resistive sensors due to the limitation introduced by the wiring. This can also assure the implementation of an FBG based monitoring system able to give redundancy of data helpful in case of fiber damages due to the harsh working conditions. Moreover, the precise monitoring of the local temperature variation all along the superconducting transmission line gives complementary information to preserve the safe working condition of the cable by detecting gas leaks which can compromise the homogeneity of the temperature leading to eventual damages.

4. FBG BASED SENSORS FOR SUPERCONDUCTING MAGNETS

The performance of the new generation of accelerator magnets can be strongly affected by the mechanical stresses in the windings during magnet operation due to the brittle and strain sensitive characteristics of Nb_3Sn . It is therefore mandatory to understand and to monitor the strain in the superconductor envisaging a precise sensing system both on the support structure of the magnet and inside the coil. For this purpose FBG sensors have been bonded on the cylindrical Aluminum structure of the magnet and embedded in the epoxy impregnated race-track coil. During its assembly phase the coil pack is preloaded up to 150 MPa through the magnet structure in order to retain the forces that appear during the powering. Monitoring the mechanical behavior of the structure is essential in understanding whether the electromagnetic forces become larger than the retaining forces compromising eventually the integrity of the coil during operation. Additionally, the strain monitoring of the coil gives a critical feedback on possible coil motion which may lead to

unwanted quenches (transitions from superconducting to conducting state of the material used). The challenge of using the FBG in superconducting magnets is to embed them directly on the superconducting cables where the resistive strain gauges integration is very difficult due to their size.

4.1 Fiber Bragg Grating Sensors integration and set up

FBGs of 10 mm grating inscribed in fully polyimide recoated fibers were selected for the integration in the two short-scale models of a Nb₃Sn dipole magnet: the Short Model Coil (SMC) and the Racetrack Model Coil (RMC). The two magnets take over the same design principles with a structure scale - up for RMC where bigger cable can be tested [7]. They are used as test benches for testing the Nb₃Sn cables in the same working conditions of the magnets presently working in the LHC. Figure 3a shows the structure of the magnets and its components during the assembly phase.

Figure 3: (a) Magnet Assembly; (b) FBGs glued on the magnet structure; (c) FBGs and strain gauges location inside the coil before impregnation

Eight FBGs arranged in 4 arrays were glued on the RMC shell with standard araldite (two-part adhesive resin) suitable for cryogenic temperature. The sensors were placed in transversal and longitudinal directions close to the resistive strain gauges as shown in Figure 3b, on two opposite sides of the magnet, where the accumulated stress reaches its peak at high field. In the SMC coil two FBGs were laid on the winding along its axial direction in its straight part, as shown in figure 3c, where the cable is subjected to the maximum stress during assembly and cool down and where the quench location is expected during the powering due to the highest magnetic field in that zone. The coil was then impregnated in a vacuum tank using a mix of epoxy resin and polyetheramine hardener at 120 ° C [8].

The magnets were tested in the SM18 test facility at CERN using dedicated vertical cryostats. SMC was tested at 1.9 K, superfluid Helium temperature. RMC was tested in a 4 meter height cryostat built for liquid Nitrogen cooling at 77 K in order to study the mechanical properties of the magnets components. Before the insertion inside the cryostats, the magnets were installed on vertical inserts used to close the cryostats and to finalize the connections of all electrical, optic and cryogenic instrumentation to the outside read out systems.

The optical fibers were connected through an optic leak - tight feed through at the top of the cryostat to the four channel of the optical interrogator Micron Optics SM125. In the case of RMC it was also used a Micron Optics SM041 Channel Multiplexer connected to the SM125 in order to read the six arrays.

4.2 Experimental results

The structural behavior of RMC has been monitored during the different assembly phases. Figure 4a clearly shows the linear behavior of the azimuthal FBG response with the azimuthal strain during the assembly at room temperature, when, by using the bladders and keys technology [9] the shell is gradually set to different pre-stress values in order to deliver the designed pre compression to the coil pack. The strain sensitivity S_ϵ is found to be 0.7 pm/ $\mu\epsilon$ and 0.8 pm/ $\mu\epsilon$ for the sensors in the azimuthal direction giving coherent strain values measured by the FBGs in respect to the values measured by the resistive strain gauges. On side 1 the FBGs computed strain variation after the assembly results to be 1839 $\mu\epsilon$ and 1835 $\mu\epsilon$ in comparison with 1679 $\mu\epsilon$ measured by the strain gauges. On side 2 the two FBGs measure 1365 $\mu\epsilon$ and 1388 $\mu\epsilon$ in comparison with 1343 $\mu\epsilon$ measured by the strain gauges. The difference between the strain gauges and the FBGs is due to the different locations on the structure of the magnet which results to be indeed not perfectly symmetric.

Moreover the difference between each FBG can be also explained as the result of the different locations as well as the effect of the glue substrate.

The same assembly procedure was followed for SMC that was then tested during four thermal cycles to 1.9 K and 4.2 K and its training quenches when the magnet is powered each time to higher current up to the quench event. Figure 4b shows the change in wavelength during the cool down from 300 to 1.9 K for the two embedded sensors. As mentioned in section 2, the response is dominated by the thermal apparent strain induced by the thermal contraction of the host material which explains the blue shift of λ_B . Despite the complex integration in the coil the fibers survived to four thermal cycles to 1.9 K and 4.2 K showing reproducibility of data and allowing a complete monitoring of the coil mechanical behaviour during its operation. In figure 4c the response of the FBG to a series of current ramps is reported: during the ramp the wavelength increases due to the expansion of the coil in its axial direction up to the quench at 15.5 kA when the current is discharged and the wavelength rapidly decreases to the original value it had before the powering.

Figure 4: (a) Azimuthal strain characteristic curve during RMC assembly; (b) wavelength shift during SMC cool down; (c) embedded FBG response during SMC powering at 1.9 K

The encouraging results obtained, the agreement with the conventional strain gauges and the fiber robustness in such complex environment give perspectives for a promising alternative or a complementary instrumentation to the resistive staring gauges in the field of superconducting Nb_3Sn based magnets, specifically during their R&D phase.

5. CONCLUSIONS

Fiber optic sensors for cryogenic and high energy applications now experimented in the CERN laboratories represent a great potential for both temperature and strain monitoring for power transmission lines based on high temperature superconducting cables and for superconducting magnets. Such technology and its validation in the applied superconductivity field offer advanced development and a rich source for technological innovations which may benefits various applied research disciplines like transmission of electrical power applications and medical applications where superconducting magnet are used.

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