Structural Health Monitoring of Superconducting Magnets at CERN Using Fiber Bragg Grating Sensors

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ABSTRACT

The use of Fiber Bragg Grating sensors is becoming particularly challenging for monitoring different parameters in extreme operative conditions such as ultra-low temperatures, high electromagnetic fields and strong mechanical stresses. This work reports the use of the FBG for a new generation of accelerator magnets with the goal to develop an adequate sensing technology able to provide complementary or alternative information to the conventional strain gauges through the whole service life of the magnet. The study is focused on the mechanical performances of the magnet structure, which has to preserve the sensitive coils from any damage during the entire magnet fabrication process preventing even microscopic movements of the winding that can eventually initiate a transition from superconducting to normal conducting state of the material used (called in the specific literature as "quench"). The FBGs have been glued on the aluminium structure of two magnets prototypes by using an adhesive suitable for cryogenic temperature. The feasibility of the bonding procedure for bare sensors at 4.2 K leads to the validation of the final integration of the FBGs for the structural monitoring of the magnet during the assembly and cool down at 77 K.

KEYWORDS : *fiber optic sensors, Fiber Bragg Grating, superconducting magnet, strain, dipole*

INTRODUCTION

For the High Luminosity upgrade of the Large Hadron Collider (HL - LHC) a sustained R&D effort is required on the implementation of challenging technologies for the development of a new generation of superconducting magnets, which will handle forces and magnetic fields significantly larger than the present NbTi based LHC dipoles. For this purpose, at the European Organization for Nuclear Research (CERN), a multidisciplinary research program is currently focused on the design, manufacture and test of Nb_3Sn subscale dipoles magnets. Nb_3Sn, for its brittle and strain sensitive characteristics, requires new approaches for magnet design and fabrication. The performance of Nb_3Sn magnets can be strongly affected by the mechanical stresses in the windings during magnet operation. It is therefore mandatory to understand and to monitor the strain in the superconductor envisaging a support structure capable of minimizing the stresses in the coils through the whole service life of the magnet: assembly, cool down and powering [1]. The concept is based on a thick aluminum structure, pre-tensioned a room temperature using the bladders and keys technology [2] , which provides a substantial coil pre-load after cool-down (up to 150 MPa) in order to retain the electromagnetic forces that appear during the powering. Monitoring the mechanical performance of

the magnet helps the mechanical model validation setting a proper pre-stress during the assembly phase, with the aim to prevent the coil from any motion which might lead to magnet quenches during operation. The choice of the instrumentation is strongly influenced by the extreme operative conditions as ultra-low temperatures (down to 1.9 K), strong electromagnetic fields (up to 14 T), and strong mechanical pre-stress (up to 150 MPa). The instrumentation conventionally used to monitor the strain profile of the magnet is based on resistive strain gauges, nevertheless, their magnetic field dependence, the large amount of wires required, the heat-leak into the cryogenic bath add issues which might be overcome by developing a new technology based on Fiber Bragg Grating (FBG) sensors. So far FBGs have been developed to monitor a wide range of environmental parameters like strain, temperature, pressure, humidity, vibrations [3] becoming particularly attracting for Structural Health Monitoring (SHM) of composite structure. The FBGs are small and light in weight therefore they do not affect the properties and the structural integrity of the composite where they are embedded. Moreover their intrinsic electrical insulation, immunity to electromagnetic interferences and the multiplexing capability, make them a good alternative to the resistive strain gauges. In recent years few studies on the use of FBG based sensors for superconducting magnets have been already reported mainly focusing on the measurement of the strain distribution on the coil [4] and the quench detection during the powering [5]. Despite the potential of the FBG in such hard working conditions, the complexity of the new accelerator magnet structure still makes this technology not yet assessed. The challenge in using these sensors for the structural monitoring arises also in the implementation of a bonding procedure suitable for cryogenic temperatures and real operational magnets, which has not been largely investigated so far. Furthermore, the development of low temperature FBG for superconducting magnets represents also a rich source of technological innovations which benefits various applied research disciplines like the aerospace. They offer indeed interesting perspective for the structural health monitoring of vehicles and satellites in the natural cryogenic environment which require adequate instrumentation with lower maintenance cost and higher structural reliability [6].

This contribution will report the results of the structural monitoring of two short scale dipole magnet currently designed, manufactured and tested in the CERN laboratories. First the feasibility study of the use of bare FBGs in the Short Model Coil (SMC) during its operation at 4.2 K will be discussed followed by the further implementation of a strain monitoring system for a bigger magnet, the Racetrack Model Coil (RMC), during its phases of assembly and mechanical model validation.

1   FIBER BRAGG GRATING SENSING PRINCIPLE

An FBG is a periodic modulation of the index of refraction in the core of an 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 working like a narrowband reflecting filter. The Bragg reflection wavelength of an FBG is given as

$$\lambda_B = 2n_{eff}\Lambda \tag{1}$$

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 [7]. The Bragg wavelength shift with strain (ε) and in temperature (T) can be expressed using

$$\Delta\lambda_B = \lambda_B\left[(1-\rho_a)\Delta\varepsilon + (\alpha+\xi)\Delta T\right] \tag{2}$$

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 temperature sensitivity of the FBG has been previously observed to decrease significantly with decreasing temperature, approaching zero below 50 K [8]. For a bare

FBG, the thermal response is dominated by the refractive index change, as the thermal expansion of silica is very low (0.5×10^{-6} at room temperature). Approaching cryogenic temperatures, both the effects reduce, so the temperature sensitivity of a bare FBG dramatically reduces. When the FBG is embedded or bonded, the thermal response is thus dominated by the thermal apparent strain related to the thermal contraction of the host material offering therefore the possibility of temperature-insensitive strain measurement in cryogenic environments [9].

2   MECHANICAL STRUCTURE OF SMC AND RMC MAGNETS

The SMC and RMC magnets are the first two short-scale models of a Nb_3Sn dipole magnet where an FBG based monitoring system has been implemented. The structure of the magnets is shown in figure 1. The SMC consists of a two racetrack-shape coils mounted into the iron yoke which is then assembled in a 20 mm thick aluminum shell- based structure of 500 mm length and 540 mm outer diameter [10]. Between the yoke and the coil pack dedicated gaps are foreseen to incrementally inflate the bladders with pressurized water delivering lateral pre-stress to the structural shell. After the last pressurization, the keys are inserted and the bladders deflated and removed in order to leave the shell in the desired tension. The longitudinal pre-stress is provided by a couple of Al rods.
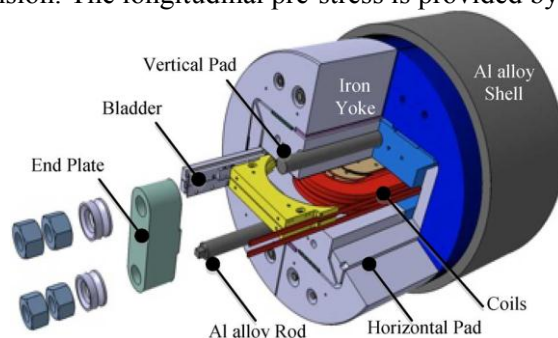


Figure 1. SMC structure and main magnet components

The RMC magnet takes over the same design principles of the SMC with a structure upgrade in order to test bigger Nb_3Sn cables. As in SMC, the racetrack coil pack is mounted into the iron yoke which is then assembled in the 570 mm outer diameter and 39 mm thickness Al shell [11].

3   FIBER INTEGRATION AND SET UP IN SMC AND RMC MAGNETS

For the feasibility study on SMC, four bare FBGs with 10 mm grating inscribed in acrylate coated fiber have been glued on the aluminium structure in the two principal directions: longitudinal and azimuthal. Two opposite points of measurements have been chosen in the middle of the length of the cylindrical structure few centimetres far from the resistive strain gauges. The choice of this location is driven by the fact that the arising azimuthal forces during the powering are directed towards the mid-plane, where the accumulated stress reaches its peak at high field. The same criterion has been followed for the location of the FBGs on the RMC structure. The 4 FBGs were arranged in 2 arrays and read out in a Wavelength Division Multiplexing (WDM) scheme.

No standard procedure is known for gluing fiber optic sensors for cryogenic applications so it was decided to use the same glue and gluing procedure used for the resistive strain gauges. After the preparation of the surface, the FBGs were glued with the HBM® M-BOND 610 epoxy resin suitable for cryogenic applications and then left under applied pressure for curing in an oven at 120 °C for 5 hours. In the case of RMC it was not possible to adapt the bonding process used for SMC because of the size of the magnet which would not enter the oven available for the curing of the glue. Therefore eight FBGs of 10 mm grating inscribed in fully polyimide recoated fibers were glued on the shell with standard araldite (two-part adhesive resin) and left for 24 hours under pressure to complete the bonding process minimizing the glue thickness between the sensor and the host material. The sensors were arranged in 4 arrays placed in transversal and longitudinal

directions on two opposite sides of the magnet, four sensors for each side as showed in Figure 2. The set up was completed with two free FBGs for temperature monitoring and one FBG glued on a rectangular Al sample free from any mechanical stress provided by the magnet structure.
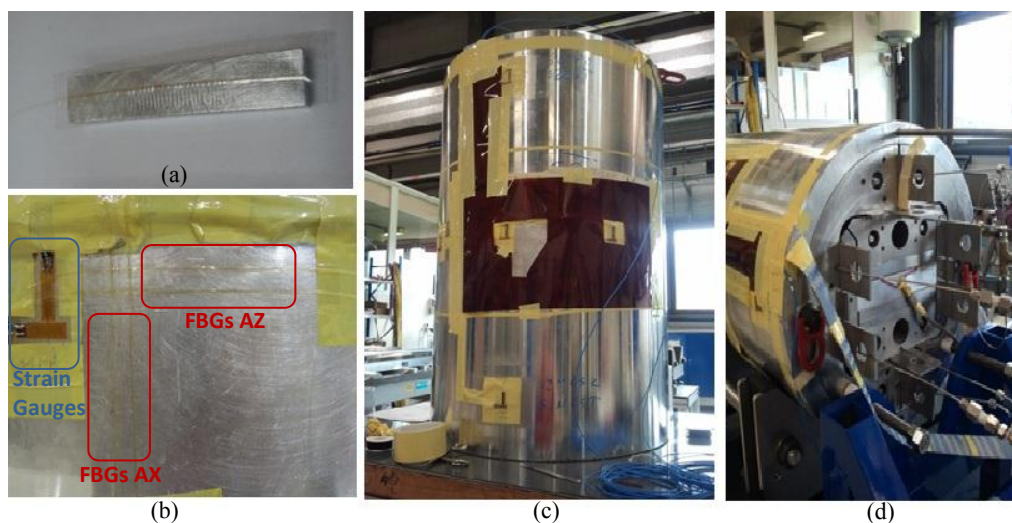
Figure 2. (a) FBG glued on the Al sample; (b) FBGs glued on the shell in the azimuthal and axial directions; (c) RMC magnet; (d) magnet's components during assembly

The magnets were tested in the SM18 test facility at CERN using dedicated vertical cryostats. SMC was tested at 4.2 K liquid Helium temperature. RMC was tested in a 4 meter height cryostat built for liquid Nitrogen cooling 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. This insert allows the connections of all electrical, optic and cryogenic instrumentation to the outside read out systems while supporting the structure inside the cryostat. To allow the continuous monitoring of the cool-down the facility was implemented also with a permanent fiber optic installation able to connect the fiber optic leak - tight feed through placed on the top of the cryostats to the acquisition system at 30 m distance from the test station. The optical fibers were connected to the four channel of the optical interrogator Micron Optics SM125, in the case of RMC it was necessary to use also the Micron Optics SM041 Channel Multiplexer connected to the SM125 in order to read the six arrays.

4   EXPERIMENTAL RESULTS

The feasibility study of the use of FBGs for the structural strain monitoring of SMC aimed to investigate the response of the sensors in a real magnet configuration during operation at cryogenic temperature and to evaluate the needs for a successful implementation of the optical instrumentation in a complex test facility. The encouraging results and the experience gained from SMC lead to the implementation of the FBG based monitoring system on RMC during all the phases of the copper dummy coil assembly including the thermal cycles at 77 K. The results discussed in this section help in the validation of the fiber optic instrumentation to be used for the strain monitoring of the RMC magnet structure during operation in the next tests at 1.9 K.

4.1   Feasibility study on SMC magnet

The FBGs' reflected wavelengths have been continuously acquired during cool down to 4.2 K, current ramp up with various current ramp rates to spontaneous quenches and warm up. The change in wavelength during 60 hours cool down to 4.2 K and the 120 hours warm up is shown in Figure 3a and 3b for the sensors placed in the azimuthal (FBG AZ) and in the axial (FBG AX) directions. As already mentioned in section 1 the responses of the bonded FBGs are dominated by the thermal

apparent strain related to the thermal contraction/expansion of the host material. This clearly explains the blue shift of λ_B during the cool down while the red shift reported during the warm up is evidence of the expansion of the structure with the increase of the temperature.
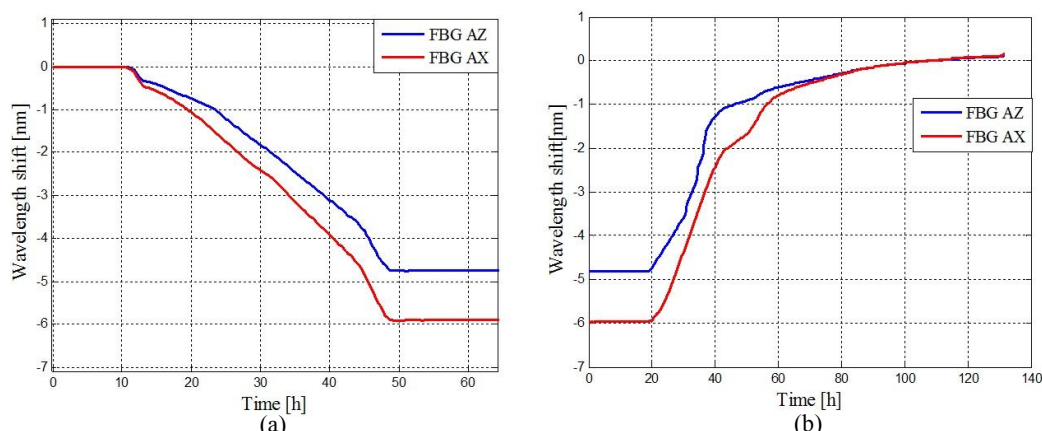
Figure 3. FBGs' responses during the cool down from 300 K to 4.2 K (a) and the warm up (b)

After the cool-down the magnet was powered with current ramped at 10 A/s to the quench current. Figure 4a and 4b show the change in wavelength of the FBGs in the azimuthal and axial directions to a series of current ramps and quenches at 11.15 kA. In response to the powering the coil releases the pre stress achieved after the assembly and the cool down. Under the Lorentz forces the coil expands towards the outer shell, while after each quench, when the current is discharged, the coil returns to the original strain it had before the powering. This explains the increase of the wavelength during the ramp followed by a sharp decrease after the quench.
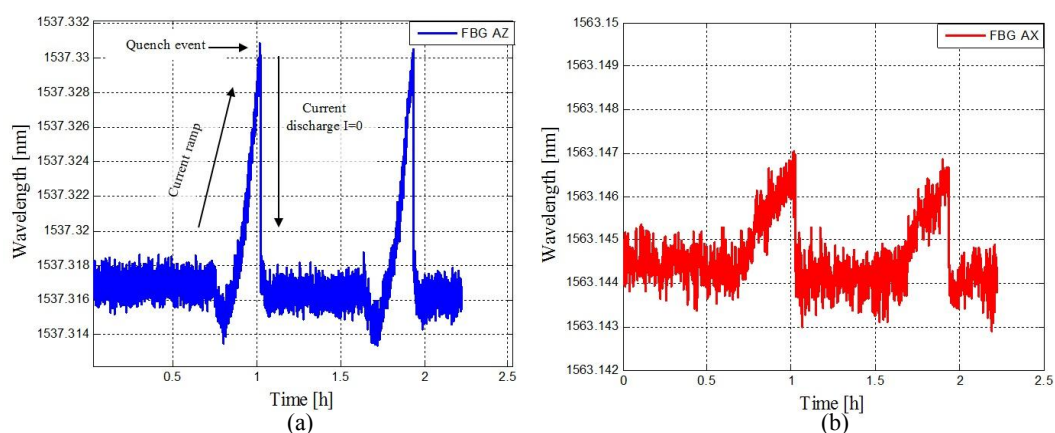
Figure 4. FBGs' responses to a series of quenches in the azimuthal (a) and axial (b) directions

As expected from the mechanics the deformation in the azimuthal direction is larger than the axial deformation in response to the same powering, the strain gauges measured indeed a maximum variation of 90 με and 60 με respectively in the two directions. Monitoring these values represents essential information to understand whether the electromagnetic forces become larger than the retaining forces compromising the integrity of the coil, but, for this purpose, it becomes crucial the synchronization of the FBGs with the strain gauges and the current, adapting the FBGs' data acquisition system to the needs of the test. The capability of the FBGs to monitor the mechanical behavior of the shell at this stage and to detect events related to the quench envisaged the implementation of the FBGs on the structure of RMC since the first assembly of the magnet and the mechanical model validation. Nevertheless, not all the sensors could be read during the whole

duration of the SMC test due to handling issues which brought to choose the more robust fully polyimide recoated fibers for the next implementation.

4.2   Strain monitoring on RMC magnet

The study and the validation of the structural behavior of RMC have been performed through the main life steps of the magnet before its cold powering: two assemblies each of one followed by a cool down to 77 K. Figure 5 shows the change in wavelength with the mechanical deformation of the shell during the first assembly of the dummy coil in both azimuthal and axial direction: after the coil pack has been inserted in the yoke and the surrounded shell, four lateral bladders are slide between the yoke and coil pack. By monitoring the shell strain, the bladders are pressurized gradually forcing the yoke against the shell inner surface up to 20 MPa target defined by the ANSYS model. The final gain is then achieved increasing the size of the interference keys. The expansion in the azimuthal direction explained by the red shift of λ_B in figure 5a is then corresponding to a contraction and the consequently blue shift in the axial direction shown in figure 5b. The small variation in strain as well as in wavelength shift in the axial direction is coherent with the mechanics since the pre load of the coil pack is mainly performed in the azimuthal direction. The data shown in Figure 5a refer to both the sensors located on side 1 in the azimuthal direction while Figure 5b shows the two FBGs in the axial direction on the same side. The same response to the bladder and keys operation is shown also by the azimuthal FBGs on side 2 reporting in this case 20% less in wavelength shift. This is anyway in agreement with the strain gauges measurements, which report 23% strain difference between the two sides. In Figure 6a and 6b is clearly shown the linearity of the azimuthal FBGs responses with the azimuthal strain during the assembly at room temperature.
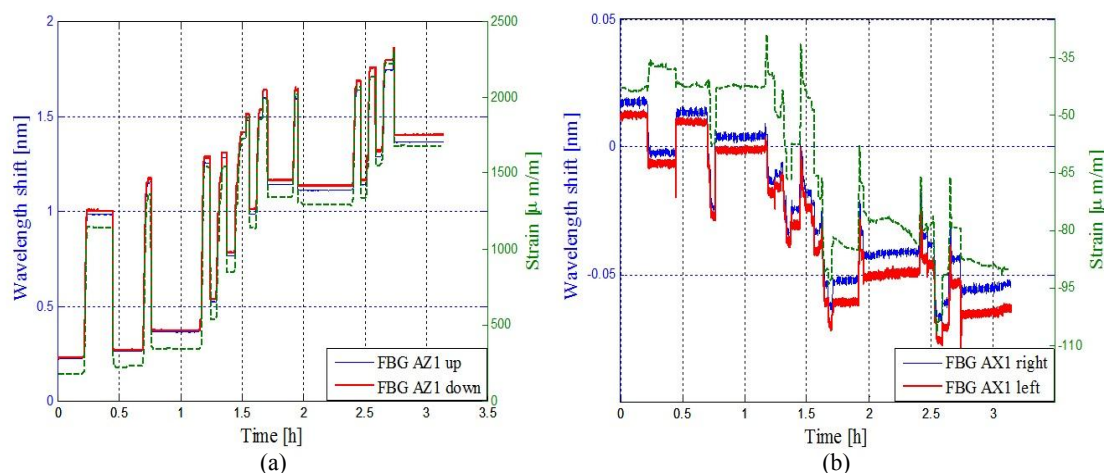

(a)   (b)

Figure 5. Shell deformation during assembly in the azimuthal (a) and axial (b) directions

By deriving the obtained $\lambda-\varepsilon$ curve, the strain sensitivity S_ε is found to be 0.7 pm/$\mu\varepsilon$ for FBG AZ1 up and 0.8 pm/$\mu\varepsilon$ for FBG AZ1 down. The same analysis has been performed for the azimuthal sensors on side 2 bringing to a sensitivity of 0.8 pm/$\mu\varepsilon$ for both the FBGs. Using these values of sensitivity the strain measured by the FBGs can be computed and the results are coherent with the values measured by the strain gauges.

On side 1 the FBGs computed strain variation after the assembly results to be 1839 $\mu\varepsilon$ and 1835 $\mu\varepsilon$ in comparison with 1679 $\mu\varepsilon$ measured by the strain gauges. On side 2 the two FBGs measure 1365 $\mu\varepsilon$ and 1388 $\mu\varepsilon$ in comparison with 1343 $\mu\varepsilon$ 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 FBGs can be also explained as the result of the different locations as well as the effect of the glue substrate.
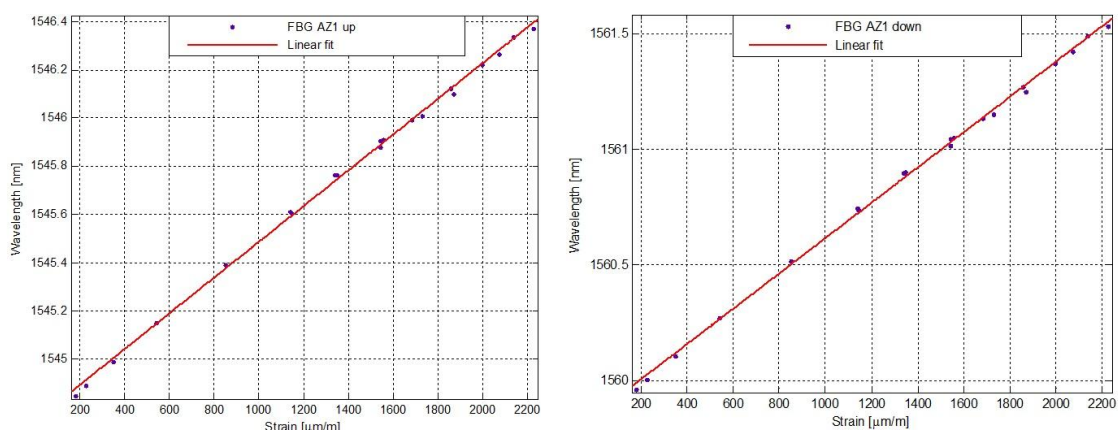
Figure 6. Azimuthal FBGs' wavelengths versus azimuthal strain during assembly

After the first assembly, the cool down to 77 K is performed and the FBGs responses are shown in Figure 7a. Four of the 11 sensors are shown in order to evaluate the different effects of the cool down in the four configurations: FBG glued on the shell in the azimuthal direction (FBG AZ 1 up), FBG glued on the shell in the axial direction on the same side (FBG AX 1 left), FBG free in the liquid Nitrogen bath (FBG T sensor) and FBG glued on the Al sample. For the free FBG without substrate the wavelength shifted only by -1.49 nm for the temperature change from 300 to 77 K. In contrast, the wavelength variation of the bonded FBGs is dominated by the induced strain related to the thermal contraction of the host material.
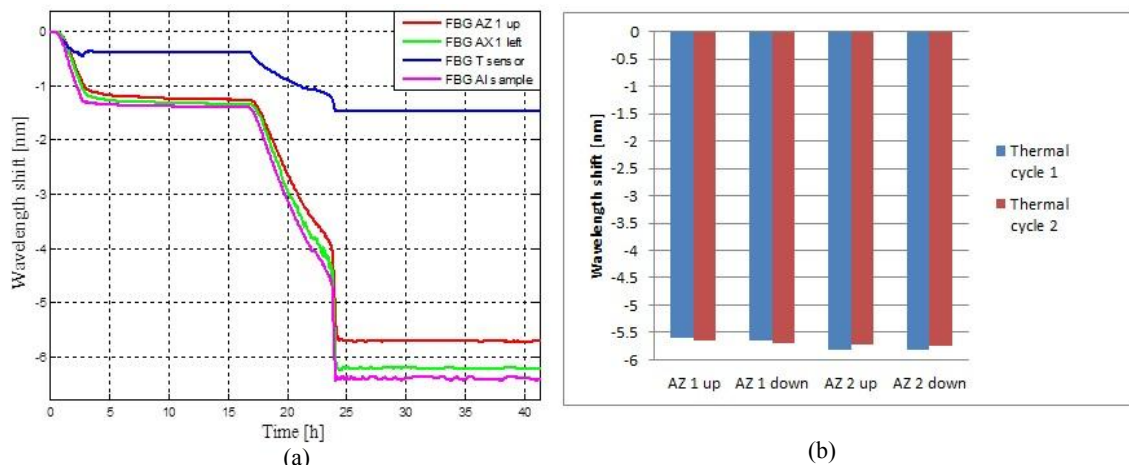

(a)   (b)

Figure 7. (a) Wavelength shifts during cool down from 300 K to 77 K; (a) Azimuthal wavelength shifts during two thermal cycles to 77 K

This is clearly experienced by the FBG glued on the rectangular Al sample which shows the effect of the temperature – induced apparent strain reaching a wavelength shift of - 6.39 nm for the same temperature range. On the other hand, in addition to the thermal apparent strain, the responses of FBGs glued on the magnet structure take into account also the effect of the differential thermal contraction of the aluminum shell and the iron yoke in the enclosed structure which induces a smaller variation in wavelength in both azimuthal and axial directions respectively of - 5.69 nm and -6.20 nm. Figure 7b summarizes the wavelength shift of the FBGs in the azimuthal direction during the two thermal cycles showing the reliability of the fibers and the bonding process. A further investigation is ongoing to evaluate the FBGs' strain measurements correcting them form the thermal apparent strain within the temperature range of interest, in order to experience only the mechanical strain of the magnet structure at 77 K.

Once the optimization of the structure was completed and the mechanical model validated, the final assembly of the Nb_3Sn coil has been performed. The FBG set up will be finally validated after the cold powering at 1.9 K during which the structural monitoring will give crucial information on the goodness of the pre load provided during the assembly described in this work.

CONCLUSION

The integration of FBGs on the structure of new accelerator magnets, 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. The successful implementation of FBG based monitoring systems in high energy physic applications, overcoming the technological difficulties related to the fragility of the optical fiber and responding to the needs of ultra-precision sensing under harsh operative conditions, gives the opportunity to address the study also to the structural health monitoring of aircraft and aerospace structures.

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