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Cryogenic test facility instrumentation with fiber optic and fiber optic sensors for testing superconducting accelerator magnets

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Abstract. The magnets for the next steps in accelerator physics, such as the High Luminosity upgrade of the LHC (HL- LHC) and the Future Circular Collider (FCC), require the development of new technologies for manufacturing and monitoring. To meet the HL-LHC new requirements, a large upgrade of the CERN SM18 cryogenic test facilities is ongoing with the implementation of new cryostats and cryogenic instrumentation. The paper deals with the advances in the development and the calibration of fiber optic sensors in the range 300 - 4 K using a dedicated closed-cycle refrigerator system composed of a pulse tube and a cryogen-free cryostat. The calibrated fiber optic sensors (FOS) have been installed in three vertical cryostats used for testing superconducting magnets down to 1.9 K or 4.2 K and in the variable temperature test bench (100 - 4.2 K). Some examples of FOS measurements of cryostat temperature evolution are presented as well as measurements of strain performed on a subscale of High Temperature Superconducting magnet during its powering tests.

1. Introduction

Within the High Luminosity LHC (HL-LHC) project and in view of the Future Circular Collider (FCC), several technological innovations are taking place in the laboratories of the European Organization for the Nuclear Research (CERN). The development is addressed to the study of materials, design approaches and fabrication techniques for the new generation of superconducting magnets.

The innovation has also involved the instrumentation for monitoring temperature, strain, magnetic field, acoustic emission, vibrations as complementary tool to the existing instrumentation to validate the design and to qualify the fabrication process. In the instrumentation development the study has been also addressed to temperature and strain fiber optic sensors (FOS) based on the Fiber Bragg Grating (FBG) technology. The use of FBG for cryogenic applications, like monitoring superconducting magnets and cryogenic devices, has been explored in the last years revealing the advantages of using this kind of sensors in the real scale applications [1]. The main advantage to use fiber optic sensors in cryogenic environment is the possibility to have multiple sensing points (wavelength division multiplexing WDM) on a single fiber reducing the wiring load, avoiding heat leak in the cryogenic bath and insulation problems. Nevertheless, the use of distributed FBG configuration for cryogenic temperature requires specific sensors design and layout.

Recently the technology based on Rayleigh scattering distributed fiber optic sensors has been also taken into account for further implementation.

For testing the future Nb_3Sn magnets for the HL-LHC and the HTS magnets for FCC, the SM18 test facility has been upgraded with new vertical test benches able to house larger size of magnets [2]. Today four vertical cryostats are dedicated for testing magnets of different lengths at 4.2 K and 1.9 K (Long, Siegtal, HFM, Cluster D) [3] up to 30 kA, one test station has been built for LN_2 cooling of heavy magnets for testing the mechanical properties of the magnet structures [4], one variable temperature bench is used for testing diodes, current leads and HTS magnets. The upgrade of the facility included also the construction of a horizontal cryostat feed with He gas (4.5 – 80 K) for testing the MgB_2 power transmission lines up to 60 m length.

In the section 2 the paper describes the FBGs characterization and calibration in the range 300 - 4 K using a dedicated cryo cooler. Section 3 is dedicated to the upgrade of the test facility with the description of the facility – FOS interfaces needed for using fiber optic sensors as temperature and strain monitoring systems. The last section is giving examples of measurements of the different cryostats temperature evolution during cooldown to different temperatures and an example of strain monitoring during the powering tests of the subscale of HTS and NbS_3n magnets.

2. Fiber optic sensors for cryogenic applications

2.1. Coated FBGs for cryogenic temperatures

Commercial FBG, bare or written in polyimide recoated fiber of 150 µm diameter, are mainly used in embedded and bonded configuration for mechanical strain measurements, but they are not a valuable solution for monitoring cryogenic temperatures down to 1.9 K because of their low intrinsic temperature sensitivity below 40 K (< 0.1 pm/K [5]). A coating material is needed to improve the FBG temperature sensitivity and the material selection for the coating relies on the effect of the Coefficient of Thermal Contraction (CTE) to induce thermal strain to the grating when the pure thermal effect of the silica becomes negligible [6, 7]. An intensive study has been addressed at CERN in the last 6 years for selecting polymer coating materials able to improve the FBG sensitivity [8, 9]. The sensor optimization focuses on the coating material selection, fabrication process validation, optimization of the geometries and Bragg peak wavelength definition according to the application. The thermal behavior of the coated sensors is characterized down to 4 K by the mean of a dedicated refrigerator system based on the cryo-cooler technology allowing to calibrate the sensor in terms of wavelength shift versus temperature before installation in the cryogenic systems.

2.2. FOS characterization in the range 300 – 4 K

2.2.1. Dedicated cryo-cooler. For the characterization of the thermal behavior of the coated FBG in the range 300-4 K a dedicated cryogen free system (Cryogenic Ltd.^{TM}) has been specifically designed for testing fiber optic sensors. It is installed in the SM18 test facility and consists of a two stages closed cycle refrigerator system with a cryogen free cryostat, a Pulse Tuber (PT) of 1 W cooling power at 4.2 K and a variable temperature insert (VTI) in a top loading configuration. This configuration allows cooling down separately, in two stages, the cryostat and the insert, to slide the samples from the top via a 1.5 m long rod, in a static He gas column. The VTI temperature, controlled by using heaters and monitored by a temperature sensor located at the bottom of the column, meets the demanding specifications of ± 0.5 K temperature homogeneity in an isothermal region of 50 mm outer diameter and 100 mm height. In this region the samples to be tested are placed vertically. The rod used to insert the sensors is equipped at its end with a gold – coated copper platform (24 mm width and 132 mm length) as sample holder for mounting and dismounting the set up. The FBG, typically tested in single ended configuration, are laid down, free of any stress, on the platform at the same locations of 2 reference resistive sensors (CERNOX^{TM} Lake Shore) installed inside the platform at 100 mm from each other. The fibers are connected to four optical vacuum thigh feed-through at the top of the rod in order to realize the external connection to the interrogation system. The reflection wavelength of each FBG sensor is acquired by mean of the compact optical sensor interrogation modules Micron Optics sm125, sm130 or si255. All the modules are provided with four channels to be acquired simultaneously from the minimum frequency of 1 Hz to 1 kHz. The reference sensors of the platform and the one of the VTI are connected to the Lake Shore 350 temperature controller together with the heaters, while the temperature sensors of the cryostat which monitor the status of the PT 1st stage and 2nd stage, are connected to the 218 Lake Shore temperature monitor. Different software are used for the data acquisition of the optical and the resistive sensors respectively the Micron Optics' software ENLIGHT and a customized software provided by Cryogenic Ltd. The PID controller can be set in order to test the sensors in dynamic or static conditions, to change the cooling down and the warming up rates in order to respond to specific tests requirements.

2.2.2. Example of characterization. The characterization and calibration of the FBG coated sensors is performed in dynamic conditions along several thermal cycles, cool down and the warm up, at the same ramp rate (typically 0.9 K/min). The goal of the tests is to validate the sensor design and to verify the reliability of the fabrication process. Figure 1a shows the wavelength shift vs. temperature curves of 16 cool down performed of an FBG of 2 mm Epoxy 1 thickness coating. The measurements show good repeatability of the data: at 10 K the averaged wavelength shift is $\Delta\lambda$= -11.7 nm with a standard deviation of 15 pm corresponding at 7.5 K considering a sensitivity of 2 pm/K at the same temperature. After the characterization, the temperature vs. wavelength curves of the FBG sensors are fitted with three exponential functions over three separate temperature ranges for their temperature calibration.

2.3. FOS optimization for temperature monitoring

2.3.1. Material study to improve sensitivity. The realization of a cryogenic sensor based on FBG requires the selection of the appropriate material able to increase the FBG temperature sensitivity combined to the choice of a reliable fabrication process to guarantee a good strain transfer to the grating and a uniform applied coating [8]. At CERN tests have been carried out on sensors coated using reactive casting as fabrication process, experimenting different materials thickness (5-3-2-1 mm) and different grating lengths (10-5-2 mm) according to the geometries design. It has been proved that shorter gratings reduce the effect of the non-uniform strain transfer from the material to the FBG. Consecutively thinner coatings shows a better stability of the measurements after the thermal cycling without impacting the sensitivity of the sensors. In figure 1b the sensitivity $\delta\lambda/dT$ improvement using different coating materials compared with the bare and the commercial polyimide recoated FBG (155 µm diameter) is shown. FBG of 2 mm grating length have been coated with 1 mm thickness of Polystyrene, PMMA (Polymethyl methacrylate), different kind of epoxy characterised by different glass transition temperature 120°C (Epoxy 1) and 50°C (Epoxy 2), PEGDMA (Polyethylene glycol dimethacrylate). The sensitivity, decreasing with the temperature, is below 1 pm/K at 5 K for most of the materials but the PMMA. In this temperature range, small variations become difficult to be detected as long as the resolution of our optical interrogator is 1 pm/K. The results obtained with the PMMA are comparable with the latest studies reported using the PTFE (Polytetrafluoroethylene) as coating [9], although the sensors fabricated with epoxy are so far the easiest to fabricate and the most suitable to be used in the He gas temperature range [11]. Further improvements in the sensitivity enhancement are required for the range 1.9 - 5 K.

2.3.2. Sensors multiplexing. The number of sensors on a single fiber is strictly depending on the specific application, thus on the temperature range to be monitored, on the material used as coating, as on this relies the total wavelength shift measured, and on the bandwidth of the Optical Interrogator. Presently the test facility is equipped with the Micron Optics si255 (1 kHz on 4 channels simultaneously) with 160 nm wavelength range which would allow a multiplexing capability of 10 epoxy coated FBG on a single channel considering a maximum shift of around -12 nm. However the precise FBG layout need to be carefully designed and fabricated in line with the measurements expectations.

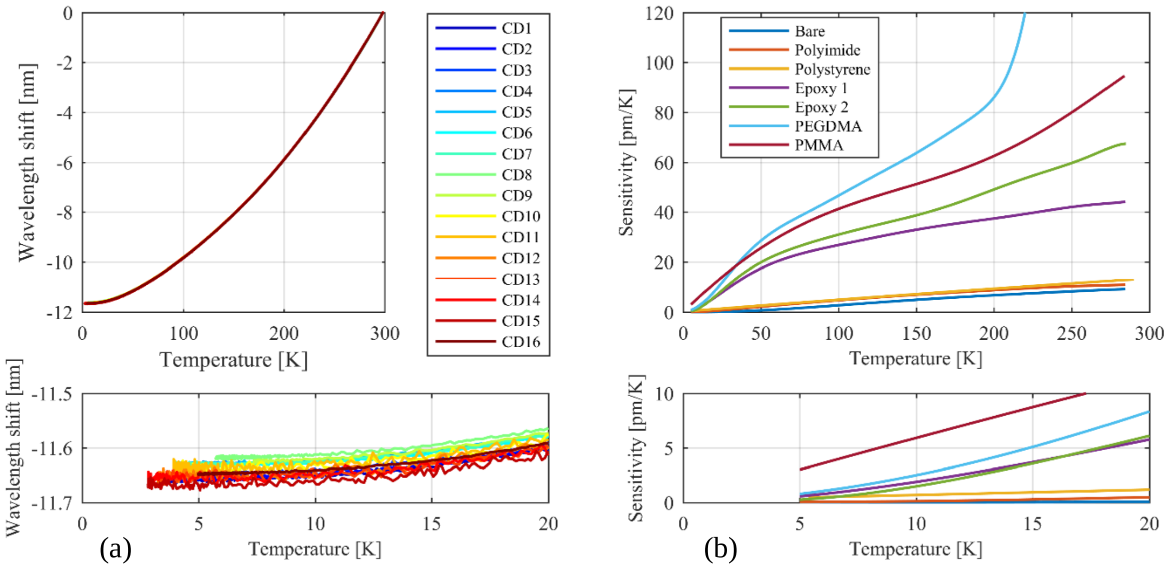

Figure 1. (a) Bragg wavelength shift vs. temperature along 16 thermal cycles; (b) Sensitivity curves for different coating materials.

3. Test benches upgrade for FOS integration

3.1. Cryostat needs and requirements

The vertical cryostats used for testing magnets are provided with the insert used to support the magnet and to connect the cryogenic lines, the power supply and all the instrumentation needed to monitor both the cryostat and the magnets. In this case all the connections of resistive and optical wires need to be done through the top plate (at room temperature), used to ensure leak-tight closing of the cryostat and then through a lower plate (lambda plate) used to separate the helium vessel in the two bath temperatures, 4.2 K on the top, and 1.9 K in the bottom. For this purpose dedicated flanges and feedthrough are installed on the plates. For the correct operation of the cryostat, the connectors need to be leak tight and pressure tight (up to 5 bar relative) both at the top plate and at the lambda plate. For the big amount of wires present inside the cryostat, the cabling and the connectors must be robust to the mechanical handling of the magnet and suitable for cryogenic temperatures. Moreover, long distances are required for the cabling outside the cryostat, linking the bench and the electronics of the different data acquisition systems. In order to guarantee safe working conditions of the cryostat and good operation of the magnets, it would be needed to increase the number of measuring points inside the cryostat (for measuring temperature, level, pressure) and inside the magnet (to measure voltage, strain, temperature, magnetic field, vibrations). Nevertheless the number of voltage taps and resistive sensors like CERNOX, PT100, strain gauges cannot be easily increased due to the limitation introduced by the wires (from 4 to 6 for each measuring points) and the number of connectors and flanges needed. With FOS this limitation can be overcome thanks to the sensors multiplexing, reducing the number of wires. Moreover using dedicated connectors it is also possible to reduce the number of flanges required on the plates.

(a) (b) (c)

Figure 2. (a) Vertical cryostat insert of the HFM cryostat holding the MQXFS magnet. (b) Fiber Optic connectors view on the top plate. (c) Fiber optic connectors view below the lambda plate. Key: 1) Top plate. 2) Lambda plate. 3) Magnet instrumentation plate. 4) MQXFS 5 magnet. 5) Push-pull fiber optic connector on the top plate. 6) Push-pull fiber optic connector below the lambda plate. 7) FC/APC connectors connected to the magnet instrumentation plate.

3.2. FOS-facility interfaces

For the instrumentation update of the test facility, in order to be able to monitor both the cryostat temperature and the magnets instrumented with the fibers, the interfaces between the FOS and the facility have been optimized responding to the requirements described in the section 3.1. The solution used mainly relies in providing each cryostat with fixed single mode fiber optic connections between the interrogator unit and the top plate (item 1 in figure 2), between top plate and the lambda plate (item 2 in figure 2) and lastly between the lambda plate and the magnet instrumentation plate (item 3 in figure 2). This fixed configuration can prevent the fibers from any breakage or unwanted bending at the moment of the magnet installation and other instrumentation cabling. The solution adopted for the upgrade of the facility is to use commercial push - pull fiber optic connectors provided by Fischer Connectors® with 4 fibers. On each of the plates of the insert dedicated flanges are adapted to connect the panel rear receptacles and the relative cable plugs. Therefore, the insert provided with lambda plate are instrumented with 3 cables layout (4 connections points including the interrogator and the magnet) while for the variable temperature cryostat and the horizontal cryostat a 2 cables layout is enough (3 connections). The connections to the interrogator unit and to the magnet is made via FC/APC connectors and adapters. As shown in figure 2c the FC/APC connectors of the facility (item 7) are directly connected to the instrumentation plate of the magnet (item 3). Figure 2b shows the flange mounted on the top plate of the insert with 3 connectors (12 fibers). In figure 2c the connection below the lambda plate is shown. Tests carried out at CERN have shown a good reliability of the connectors at cryogenic temperatures validating their use down to 1.9 K. As reported in [12], insertion losses of 0.1 dB for each 'cold' connection have been measured during a cooldown to 1.9 K. The data acquisition system for the FBG is based on the three type of Optical interrogator described already in section 2.2.1.

4. Operational FOS

4.1. Example of cryostat temperature monitoring

Calibrated FBG sensors as presented in section 2.2.2 have been previously installed in the five vertical cryostats for their validation and are now used as complementary temperature monitoring system to the existing resistive sensors.

As example, the cooldown of the Feather-M04 magnet performed in the variable temperature cryostat is reported in figure 3a [13]. The HTS magnet has been cooled down to 50 K in about 8 hours to be then tested in the temperature range 10-100 K. Epoxy coated FBG sensors have been used as they assure a precision of less than 2 K above 15 K. The temperature variation versus time measured by the 3 FBGs sensors is shown in Figure 3a in comparison with the CERNOX. In this experiment, the temperature sensors have been placed in critical locations like magnet joints, at the top of the magnet, and inside the bore of the bottom of magnet where resistive sensors can hardly access. The temperature profiles are consistent with fact that the cold gas is injected from the bottom of the cryostat and the variable mass flow is delivered with stable temperature control until thermal stabilization. The measurements show a remarkable agreement between the optical and resistive sensors with a difference of less than 1 K at the end of the cool down.

Figure 3b shows the temperature variation measured by the FBG installed in four test benches during different cool down: the Long and Siegtal vertical benches during 25 and 16 hours cooldown to 4.2 K of RMC FRESCA and RMC QXF magnets, the Diode and the SC Link benches during 5 and 8 hours cool down to 20 and 30 K respectively of the HTS Feather M2 magnet and the MgB_2 cable. In the cool down of the Long and Siegtal benches, below 6 K, due to the low sensitivity of the FBG which approaches 1 pm/K, the curves report oscillations equivalent to 2.5 K variation, confirming the need to still improve the sensors' sensitivity closer to the liquid He temperature.

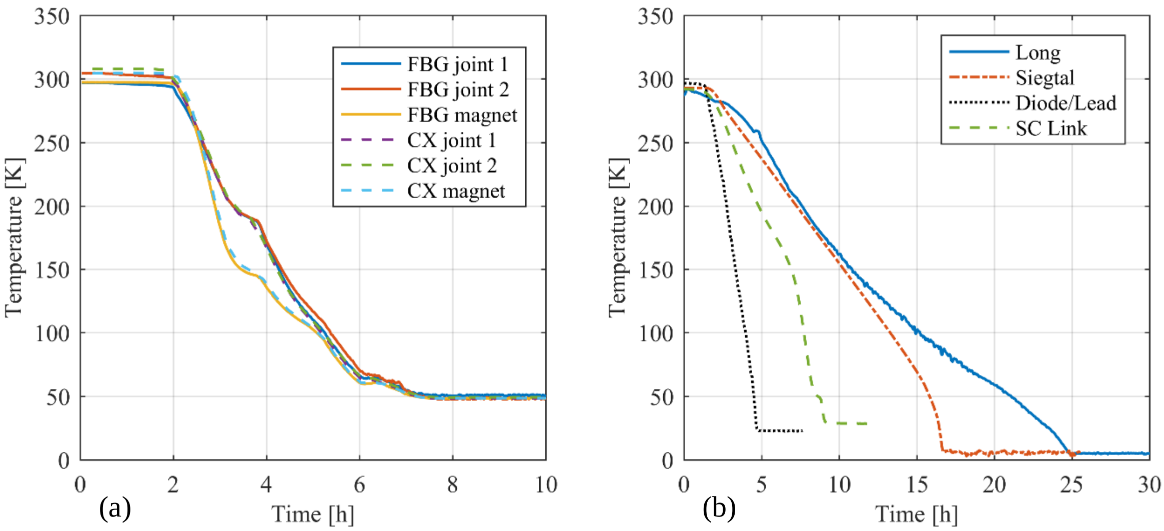

Figure 3. (a) Temperature variation versus time measured by the FBG and the CERNOX in the variable temperature cryostat during HTS magnet cooldown; (b) Cool down temperature profiles measured by the FBGs in four different test benches.

4.2. Example of magnet mechanics monitoring

Beyond temperature measurements, the instrumentation of the test facility also allows to perform mechanical measurements with FBG sensors during the magnet cold powering. For this purpose FBG sensors are bonded or embedded in the coil or on the magnet structure.

Figure 4 shows an example of strain measurements performed by using FBG sensors written in 150 µm diameter fully polyimide recoated fiber glued on the axial direction of the Feather-M04 coil. The plot shows a current stair-step cycle up to 6 kA (right y-axis) in isothermal conditions at 26.6 K (left y axis) during which the reflected wavelength of the glued FBG is measured giving a corresponding strain variation up to 60 micro strain (second y right axis) considering a standard strain sensitivity of 1 pm/strain.

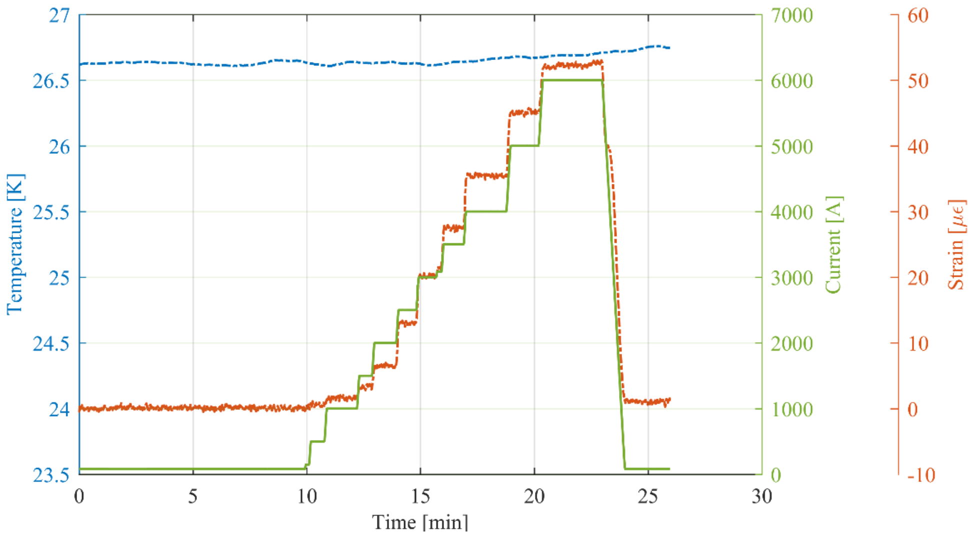

Figure 4. FBG strain measurements during current ramp to 6 kA at constant temperature.

Taking the advantage of the FBG multiplexing capability, the last improvements in the FBG integration has been achieved by using multiple sensing points in one single fiber, optimizing the sensors layout and the connections. Figure 5 shows and example of WDM performed on the MQXFS_5 magnet for coils and shell mechanical strain monitoring. Six FBGs, arranged in three fibers of 2 sensors each, have been connected to one of the 4 channels of the optical interrogator. In the figure, the spectra at 300 K are reported in blue while the spectra of the same sensors after the cool down to 1.9 K are reported in red. The shift toward lowest wavelengths is the effect of the compressive strain induced by the thermo-mechanical behaviour of the magnet structure and coil. In this magnet, a total of 22 sensors can be read using 11 fibers (3 Fischer connectors as shown in figure 2b) and 4 read out channels. The validation of this set up and the sensors layout will bring to a further increase of measuring points on the single fiber (up to 6 sensors for a single fiber) and the consecutive reduction of fibers and thus connectors on the cryostats.

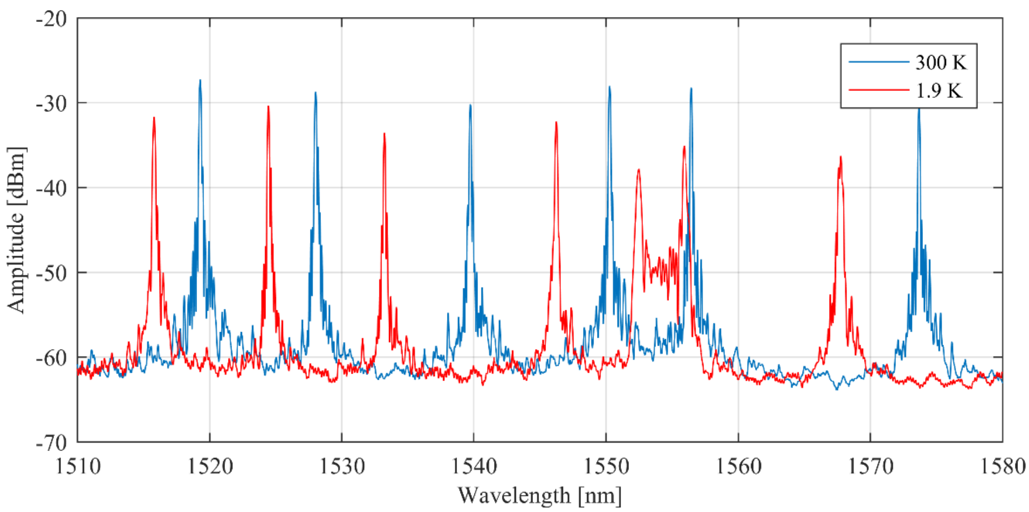

Figure 5. Reflected spectra of 6 FBGs used on one single read out channel for monitoring the mechanical strain of the MQXFS_5 magnet at 300 and 1.9 K

5. Conclusions

Fiber optic sensors are used for monitoring temperature in the test benches of the cryogenic test facility SM18. After the material selection, coated FBG sensors are produced and calibrated using a dedicated cryo cooler in the range 300- 4 K before being installed in the cryostats. Sensors tested so far give promising results especially for monitoring He gas temperature range above 10 K. For using fiber optic sensor, within the upgrade of the test facility, new robust and reliable solutions have been adopted to make the connection between the sensors inside the cryostats and the data acquisition system outside. The same FOS-cryostat interfaces are used to connect the fiber optic sensors integrated inside the magnets in order to monitor the mechanical strain during their powering tests.

Future studies are addressed in producing and calibrated coated sensors in array configurations, multiple points on a single fiber and in developing protection packaging for easy handle and installation.

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