

One year of FBG-based thermo-hygrometers in operation in the CMS experiment at CERN

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One year of FBG-based thermo-hygrometers in operation in the CMS experiment at CERN

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ABSTRACT: In this contribution we present results concerning the very first application of fiber optic sensors (FOSs) for relative humidity (RH) monitoring in high radiations environments. After a few years of investigations at CERN in Geneva, since December 2013 our multidisciplinary research group has successfully installed 72 thermo-hygrometers based on Fiber Bragg Grating (FBG) technology, organized in multi-points arrays, in cold areas of the Tracker Bulkhead of the Compact Muon Solenoid (CMS) experiment, where hundreds of electrical connectors are housed and thousands of services, including many cold pipes, cross the volumes through them. In such a complicated environment, a constant hygrometric monitoring is vital, in order to avoid dangerous phenomena of condensation. The collected results in the last year of operation of the proposed sensors are effective and reliable, with temperature, relative humidity and dew point temperature measurements from the FBG-based devices in full agreement with the readings of conventional sensors, temporarily present in the detector. However, experience in operation has shown some limitations of this technology, which are fully detailed in the last section of the paper.

KEYWORDS: Detector design and construction technologies and materials; Interaction of radiation with matter; Detector cooling and thermo-stabilization

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1 Introduction

Relative humidity (RH) monitoring has a significant impact in various application fields and many sensing schemes and solutions have been proposed according to the specific applications [1]. Here we concentrate our attention on the use of relative humidity fiber optic sensors (FOSs) recently developed by our research group for the application in the Compact Muon Solenoid (CMS) experiment at CERN.

Any humidity sensor to be introduced in the vicinity of a Particle Tracking Detector at the Large Hadron Collider (LHC) of CERN must comply with different requirements in terms of radiation resistance (up to 1 MGy for regions close to the Interaction Point¹), insensitivity to strong magnetic field (up to 4 Tesla for the CMS experiment), accuracy of $\pm 3\%$ RH and operation at temperatures below 0°C, small dimensions, low mass, reliable readings across long distances and reduced number of wires for operation. In this scenario, fiber optic sensors appear as a good alternative to the conventional instruments. Indeed, the fiber itself, if properly selected, can tolerate

¹ The region at the centre of the experiment, where the particle beams accelerated in the LHC are brought into collision is conventionally called “Interaction Point”.

a very high level of radiation [2], optical fiber transmission is insensitive to magnetic field and electromagnetic noise and it is perfectly suited for read-out over very long distances.

In 2011, our multidisciplinary research group has been involved in the development of a new generation of relative humidity sensors for experiments running at CERN. In the wide family of fiber optic-based devices, we decided to focus our attention on the so-called Fiber Bragg Grating (FBG) technology [3], which is playing an important role in a wide range of measurement fields, offering several advantages — such as the possibility of multiple parameter sensing, embedding into structures and multiplexing in a single mode fiber to form an all-fiber sensor network — of which the electronic sensors counterpart lacks.

In particular, following the approach found in literature [4]–[5], consisting in the development of FBG-based relative humidity sensors by coating the grating with a hygroscopic polymeric material, we have demonstrated for the first time to the best of our knowledge that polyimide-coated FBGs can correctly work at low temperatures (down to -20°C) and have a good radiation tolerance characteristic [6]–[8]. As a matter of fact, we found that, except for a radiation-induced shift which has to be taken in account, they survive after the exposure to strong γ -ionizing radiation doses (tested up to 210 kGy) and their sensing performance is not affected by radiation [7]–[8]. In particular we found that a pre-irradiation step at doses higher than 150 kGy, before the installation in high radiation environment, greatly reduces their sensitivity to further irradiation [7]–[8]. Based on the very promising results, 72 FBG-based thermo-hygrometers, organized in multi-sensors arrays, have been installed in the CMS experiment since 2013 and they are currently providing constant monitoring of temperature and humidity in the critical area where power, read-out and cooling services are distributed to the Tracker detector.

In this paper we present one year of data results from this innovative class of sensors in operation in CMS: FOSs data and readout system stability and reliability are demonstrated, with continuous data taking under such severe and complex conditions. However experience in operation has shown some limitations of the proposed technology, which will be discussed in the last section of the paper.

2 Fiber Bragg Grating technology

A Fiber Bragg Grating [3] is formed by a photoinduced modulation of the refractive index in the core of a single mode optical fiber. The structure formed within the fiber behaves as a wavelength selective filter, which reflects the light signal at a certain wavelength, named as Bragg wavelength (λ_{BRAGG}). This means that if broadband light travels in the core of an optical fiber, the incident energy at such a resonant wavelength will be reflected back to the optical fiber, with the remaining optical spectra unaffected, as illustrated in figure 1 (a).

The Bragg wavelength is strictly dependent on the fiber effective refractive index (n_{eff}) and the pitch of the grating (Λ), according to the so-called Bragg condition:

$$\lambda_{\text{BRAGG}} = 2n_{\text{eff}}\Lambda \quad (2.1)$$

Both the refractive index and the grating pitch can be affected by strain and temperature, thus making FBGs very popular for strain and temperature sensing applications [9]–[11]. Consequently, the Bragg wavelength shift ($\Delta\lambda_{\text{BRAGG}}$) due to the change in strain ($\Delta\varepsilon$) and thermal effects (ΔT)

can be expressed as follows:

$$\frac{\Delta\lambda_{\text{BRAGG}}}{\lambda_{\text{BRAGG}}} = (1 - P_e) \varepsilon + [(1 - P_e) \alpha + \zeta] \Delta T \quad (2.2)$$

where P_e is the photo-elastic constant, ε is the strain induced on the fiber, α and ζ are the thermal-expansion and thermo-optic coefficients of the fiber, respectively.

In other words, the first addendum of the second term in eq. (2.2) represents the longitudinal strain effect on the FBG, while the second addendum corresponds to the thermal effect, which comprises a convolution of the thermal expansion of the material and the thermal-optic effect.

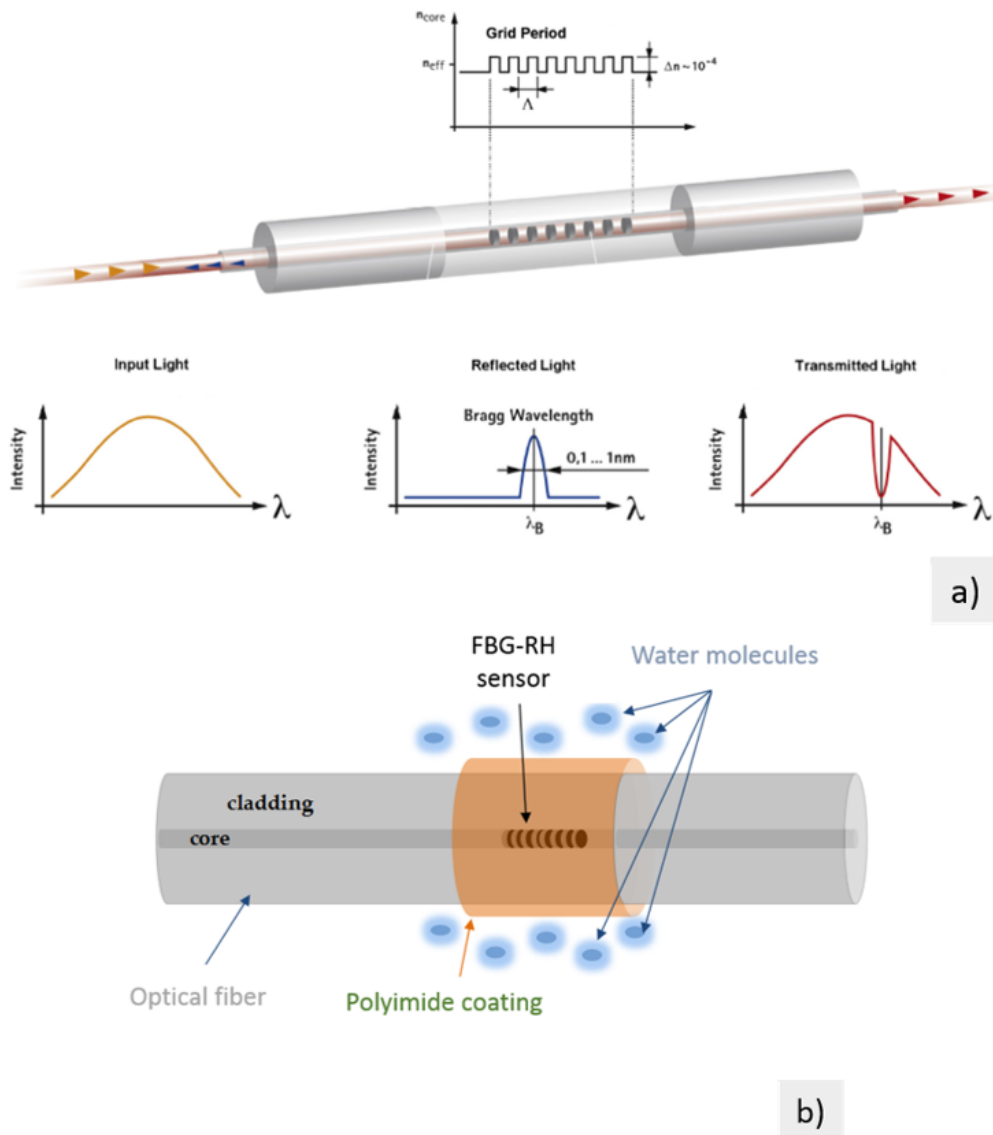


Figure 1. (a) Fiber Bragg Grating structure; (b) Schematization of FBG-coated relative humidity sensor.

2.1 FBGs for relative humidity sensing applications

The standard telecommunication silica fiber SMF28, already in use for the optical read-out of the particle signals from the CMS Tracker, was selected. Therefore, silica fibers were also selected for the fabrication of the Fiber Bragg Gratings.

Bare silica fibers are insensitive to relative humidity. Nevertheless it is possible to develop a FBG-based relative humidity sensor by coating the grating itself with an appropriate hygroscopic material [4]–[5]. When exposed to the surrounding relative humidity change, the volume expansion of the moisture sensitive polymer due to absorption or desorption of water molecules, induces a strain effect on the grating (the so-called swelling effect), this resulting in a shift of the Bragg wavelength. Similarly a Bragg wavelength shift occurs in presence of temperature variations, due to the intrinsic dependence of λ_{BRAGG} to temperature, as explained in the previous section.

A simple schematization of a FBG-coated relative humidity sensor is given in figure 1 (b).

It was demonstrated in literature [4]–[5] that the response behaviour of a polymer-coated FBG is a linear superposition of relative humidity and temperature effects. This means that, in presence of temperature and relative humidity variations, the Bragg wavelength shift can be expressed in linear assumption as:

$$\frac{\Delta\lambda_{\text{BRAGG}}}{\lambda_{\text{BRAGG}}} = S_T \Delta T + S_{\text{RH}} * \Delta\text{RH} \quad (2.3)$$

where S_{RH} and S_T are the relative humidity and temperature sensitivities of the coated FBG, respectively.

It should be noticed that as coated-FBGs are intrinsically sensitive to T and RH variations, the application of proper methods to decouple the effect of temperature and humidity on the sensor readings needs to be foreseen in order to get precise relative humidity measurements. This is what is referred to as temperature compensation, generally requiring an independent temperature reading as close as possible to the humidity sensor position [9].

In particular, for our application, we have proposed an optical thermo-hygrometer made of two coupled FBGs [7]–[8]: the first one, coated with a polyimide (PI) overlay, is sensitive to both RH and T; the second one, a bare one, is only sensitive to T variations.

The resulting FBG-based thermo-hygrometer is shown in figure 2.

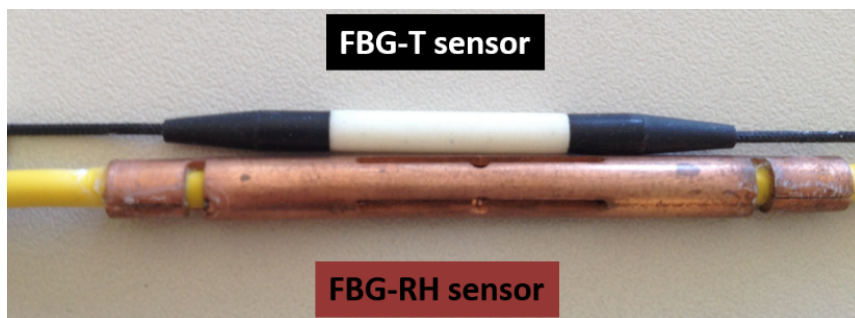


Figure 2. Picture of the final design of FBG-based thermo-hygrometer developed for the CMS experiment.

3 FBG-based thermo-hygrometers for the CMS experiment

The CMS Tracker approved in 2012 the design, procurement and installation of optical thermo-hygrometers based on FBG technology with the aim to have a complete mapping of temperature, humidity and dew point temperature in the CMS tracker Bulkheads, corresponding to the end flanges closing the Tracker volume and separating its cold volume from the external environment at room temperature.

The final integration of the network of FBG-based sensors in the CMS experiment took place in two interventions, in December 2013 and in January 2015, during a two years period of shutdown of the LHC and of its experiments for maintenance and upgrade.

In this section details about the installation of the optical thermo-hygrometers inside the detector as well as examples of their operation are provided.

3.1 Sensors selection and sensors characterization

In order to fulfil the tight schedule requested by CMS concerning the installation of a network of 72 thermo-hygrometers around the cold services in front of the Tracker volume of the experiment, it was decided to rely as much as possible on commercial suppliers.

For the thermometers, the choice was oriented towards reliable and very stable FBGs, mounted in a strain-free ceramic package, developed and produced by Micron Optics (model os4310). For the polyimide-coated sensors, the gratings were produced and coated by the company Welltech, with a requested nominal thickness of the PI sensitive layer of $10\ \mu\text{m} \pm 2\ \mu\text{m}$ [7]. Ad-hoc designed small metallic packages were produced and in-house installed for these sensors.

During the quality check performed after the delivery of the sensors, measurements of the thickness of the polymeric coating were taken over a sample of $\sim 20\%$ of the procured gratings. The results obtained, reported in figure 3, demonstrated a non-homogeneity of the PI thickness deposited onto the gratings larger than specified (with even $5\ \mu\text{m}$ of difference respect to the nominal requested thickness, as in the case of sample 4). Due to the strict timing of the preparation process in order to match the installation window, this non conformity was accepted, thus predicting differences in the response of the sensors in terms of sensitivity to relative humidity changes [5, 7].

Once organized in arrays, the thermo-hygrometers have been fully characterized in the CERN lab in respect to temperature and relative humidity variations, following the general methodology described in [7]–[8]. This allowed for discarding eventually the ones which were not providing good results in terms of linearity and sensitivity in comparison to all the others.

Prior to the installation in the experiment, the selected sensors were pre-irradiated at 210 kGy, in order to reduce their sensitivity to additional γ -ionizing radiation doses [7]–[8]. In particular for each sensors, we evaluated the wavelength shift due to irradiation comparing the data acquired in the experiment in stationary conditions with the data accumulated in the laboratory. Afterwards we applied the mathematical model described in equation (2.3) to translate the wavelength readings provided by the optical thermo-hygrometers in relative humidity values, taking into account the measured radiation-induced shifts.

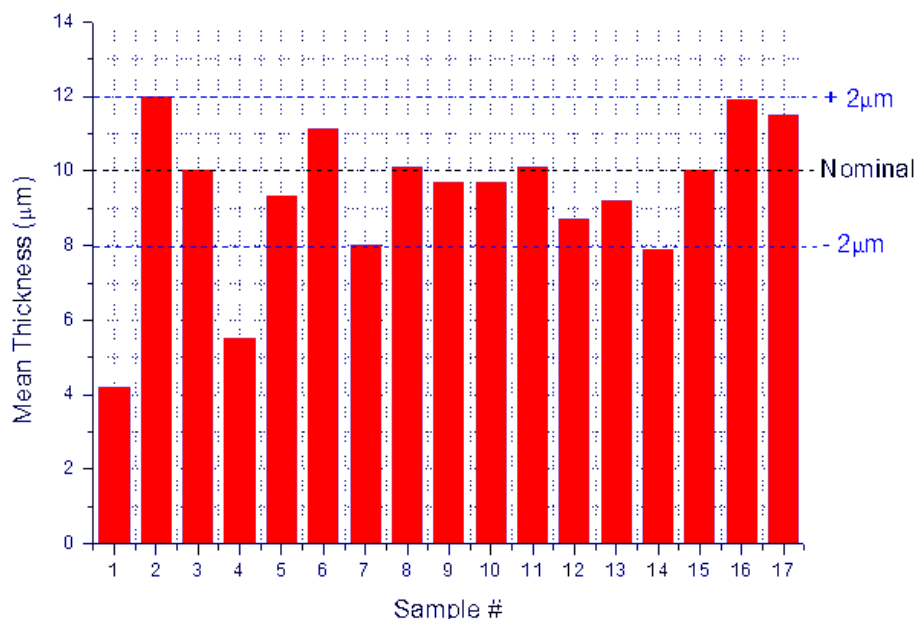


Figure 3. Measurements of the thickness of the PI-coating of a sample of 17 coated FBGs. For each sample, three measurements of the thickness of the polyimide layer were conducted and the mean thickness values are reported in the histogram.

3.2 Installation in the CMS experiment

The final installed monitoring system in the CMS detector includes a total number of 144 FBG-based sensors, 72 coated with PI — providing the humidity measurements — plus other uncoated 72 gratings — providing the temperature readings.

The assembly of the arrays consisted in performing a series of junctions FBG-SMF28 with a fusion splicer. Due to the bending of the fibers distributed over the volume of the experiment as well as due to the presence of several splicing points along the fibers themselves, we found a progressive attenuation of the reflected power towards the end of the arrays. Therefore we decided to assure a minimum peak amplitude of 15 dBm, in order to avoid troubles with the application of the peak detection algorithm. In this regard, a number of 12 gratings per fiber seemed to be a reasonable compromise, well matching the planned sensor pattern. In figure 4 the reflected spectrum of one of the fibers installed in the experiment is shown: the 12 peaks corresponds to the 12 FBGs inscribed on the same optical fiber.

Figure 4 is also a good example of wavelength division multiplexing applied in practical applications.

The fibers prepared for CMS were finally organized as described in table 1.

The details of the positions of each FBG-based thermo-hygrometer in the detector as well as the routing of the fibers in the volume are reported in figure 5, with the fibers with temperature and humidity sensors following exactly the same patterns. For simplicity, the routing of the arrays with both T and RH sensors is reported using one single colour.

The installation of the first 56 FBG-based thermo-hygrometers (56 RH-FBGs and 56 T-FBGs) on the inner face of the Tracker Bulkhead started in December 2013 and it took around ten working

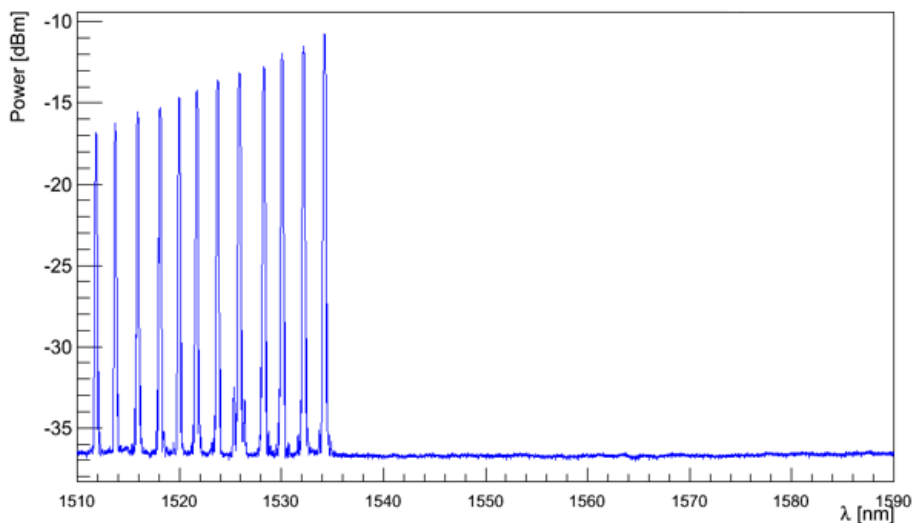


Figure 4. Reflected spectrum of one of the fibers installed in the CMS Tracker: the 12 peaks correspond to the 12 FBG-based sensors inscribed on the same fiber.

days to complete it on both sides of the detector. The remaining 16 thermo-hygrometers (16 RH-FBGs and 16 T-FBGs) were installed on the outer face of the Bulkhead at the end of January 2015.

Table 1. Summary of the arrays of T and RH FBG-based sensors for CMS.

Location in CMS	#Fibers	#FBG-based Sensors
Bulkhead Inside Positive Side	3 fibers for RH	28 RH-FBGs (12+12+4)
	3 fibers for T	28 T-FBGs (12+12+4)
Bulkhead Inside Negative Side	3 fibers for RH	28 RH-FBGs (12+12+4)
	3 fibers for T	28 T-FBGs (12+12+4)
Bulkhead Outside Positive Side	1 fiber for RH	8 RH-FBGs
	1 fiber for T	8 T-FBGs
Bulkhead Outside Negative Side	1 fiber for RH	8 RH-FBGs
	1 fiber for T	8 T-FBGs

In the inner face of the Tracker Bulkhead, during the installation, we coupled, wherever possible, our sensors to standard electronic thermo-hygrometers (Honeywell HIH-4030 capacitive sensor plus Dallas DS2438 digital semiconductor thermometer for humidity and temperature measurements, respectively), read out with Arduino microcontrollers, as shown in figure 6 (a). These sensors have been introduced in CMS during the shutdown period to get a more fine-grained understanding of the humidity situation in the various volumes of the experiment during the maintenance time window. They are not radiation-hard and will not survive for a long time to the radiations produced by the particles collisions. However their presence in the same installation points as the optical thermo-hygrometers gave us the possibility to prove the performance of our optoelectronic monitoring system. Indeed, as they provide temperature, humidity and dew point measurements, we used them to benchmark the optical sensors performance.

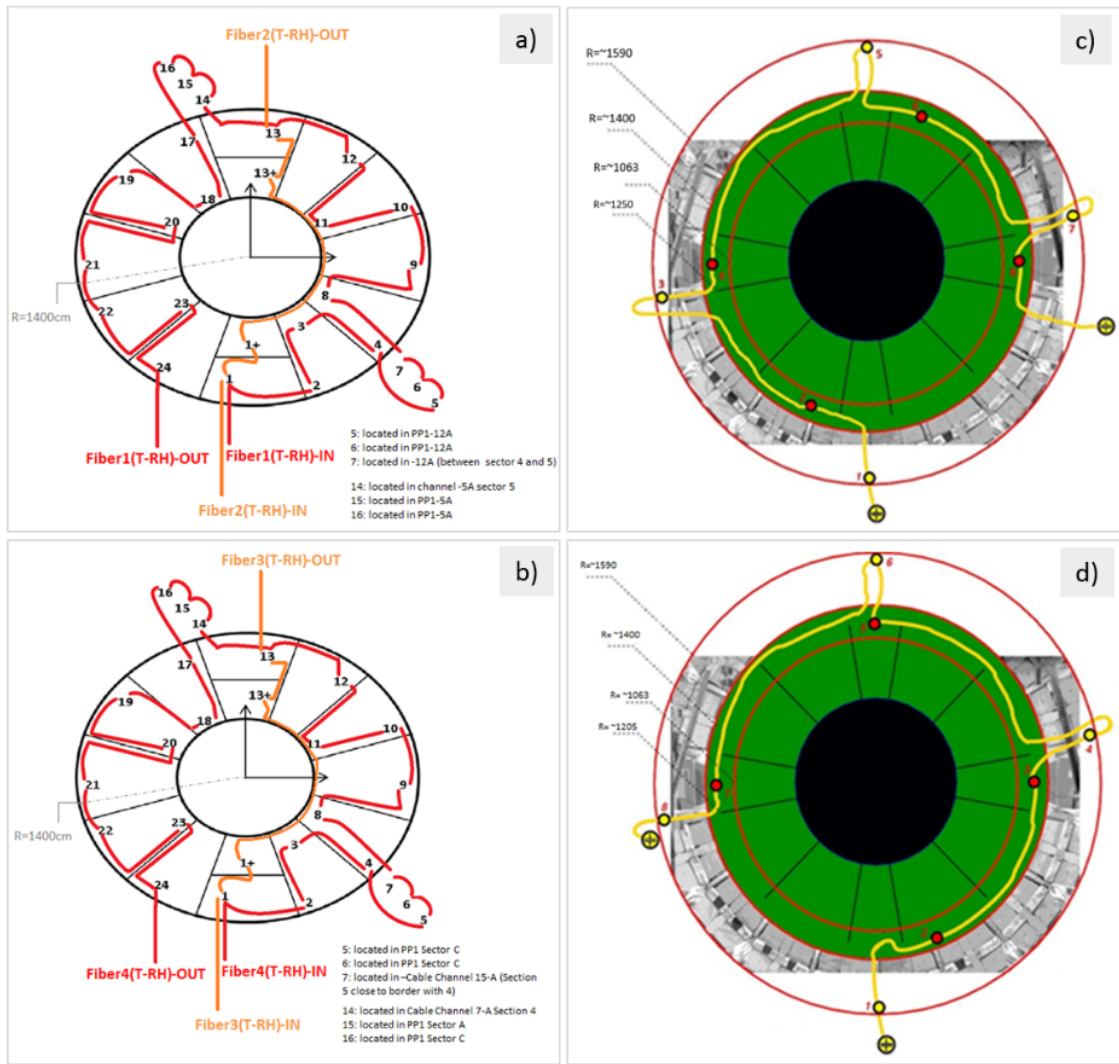


Figure 5. Schematics of the FBG-based thermo-hygrometers installed (a-b) on the inner and (c-d) outer face of the Tracker Bulkhead on both sides of the CMS experiment.

Additionally, in few points of the inner part of the Bulkhead volume — e.g. positions 1 and 13 in figure 5 (a) and (b) — sniffer pipes extracting air samples from the volume and transferring them to the underground service cavern for the hygrometric analysis (through industrial Vaisala DMT242 dew point transmitters) are also available for comparisons. In these cases, we coupled the FBG-based sensors to both the standard electronic sensors and the sniffing pipe, as shown in figure 6 (b).

In the outer face of the Tracker Bulkhead, there is only one point per side where both standard electronic sensors and sniffer are available in the same position as the optical sensors. This corresponds to position 2 in both figure 5 (c) and (d). Apart from these two installation points, the optical fiber sensors are the only devices available which provide the temperature and humidity measurements.

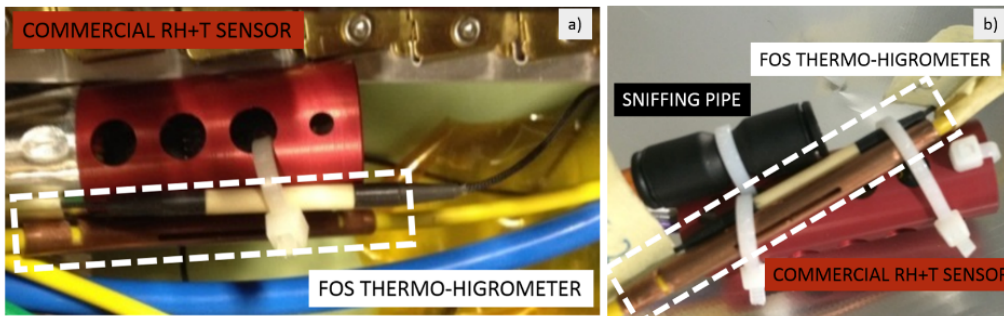


Figure 6. FBG-based thermo-hygrometer installed in the CMS Tracker, coupled to (a) standard electronic sensors and (b) to both standard electronic sensors and sniffing pipe.

3.3 FOS acquisition system at CMS

In order to reach the optical interrogator, the arrays of both T and RH FBG-based sensors have been directed to the so-called Underground Service Cavern which is one of the twin caverns of the experiment, isolated by means of thick concrete walls from the experimental one that houses the detector itself and always accessible, even during the operations of the accelerator.

Here the sensors are read out by a Micron Optics sm125 interrogator equipped with a sm041 optical channel extender. The interrogator has an on-board Ethernet interface and therefore it is accessible through a proprietary TCP/IP protocol. In order to reduce network traffic on the interrogator, it is connected to a mini private network created by the readout computer. This computer has another network interface installed as well, that allows the integration and sharing of the FOS system data with the CMS Detector Control System. Moreover the read out software, which communicates directly with the Micron Optics interrogator, has been written in Java language by our group. It downloads peak definition parameters and reads out both peak information and the spectrum of each optical fiber. After an additional false peak reduction phase, this software creates the final measurement values from the raw peak data using the predetermined calibration constants. Furthermore, this software has a raw data stream too, that allows further refinement of the calibration constants.

Extra details about the acquisition system are provided in [12].

4 Results of one-year operation of FBG-based thermo-hygrometers in CMS

In this section examples of FBG-based thermo-hygrometers in operation in the CMS experiment are provided.

In order to facilitate the dissertation and to appreciate the performance of the proposed sensors, the temperature, humidity and dew point temperature reconstructions provided by the fiber optic-based devices are presented in different subsections, each referring to the following situations:

- FBG-based thermo-hygrometers coupled only to standard electronic sensors;
- FBG-based thermo-hygrometers to both standard electronic sensors and sniffing pipe;
- FBG-based thermo-hygrometers installed in the outer face of the Tracker Bulkhead.

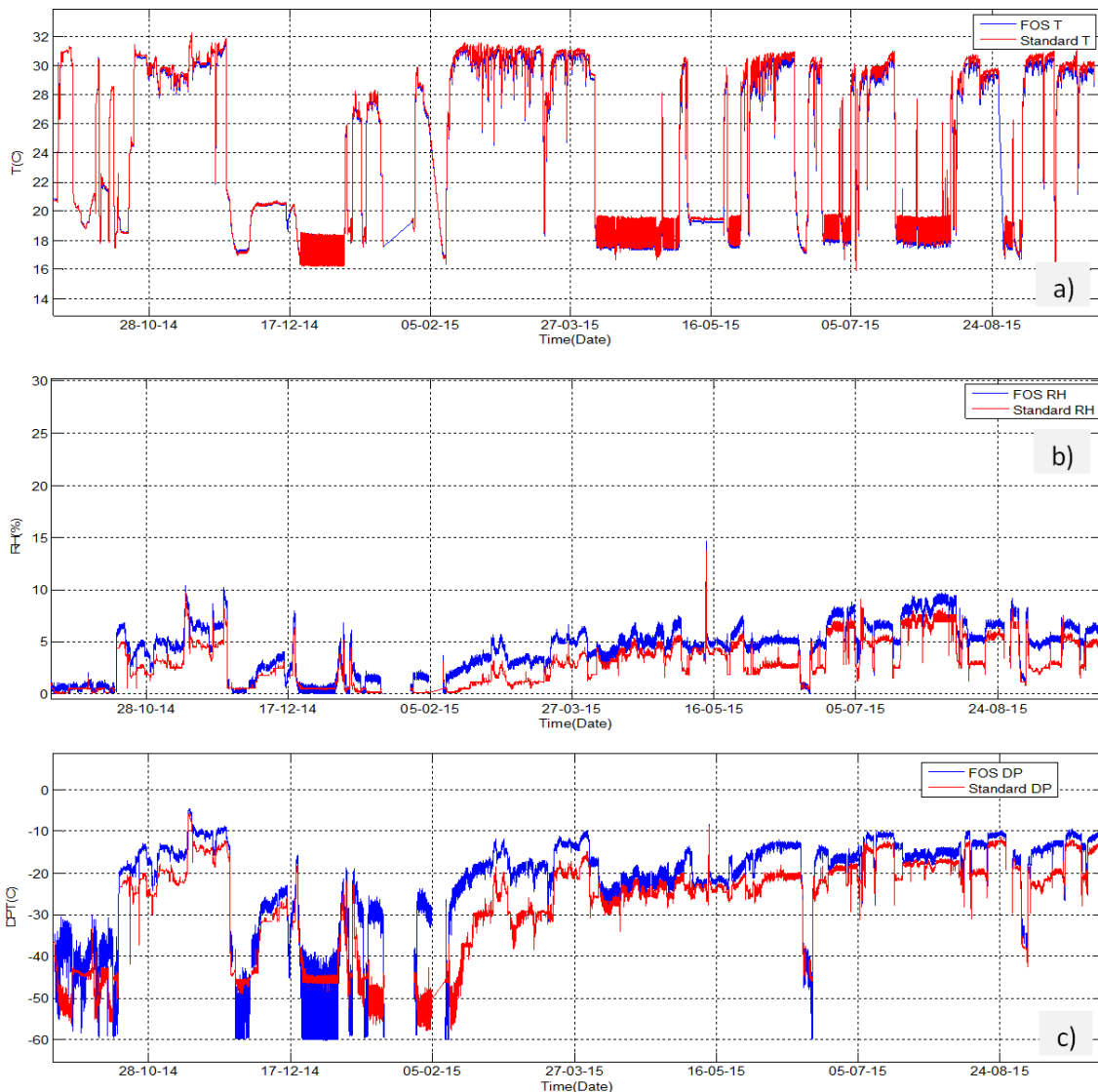


Figure 7. (a) Temperature, (b) relative humidity and (c) dew point reconstructions from the FBG-based thermo-hygrometer installed in position 15 of the schematic in figure 5 (a). For comparison, the readings from the standard hygrometer installed in the same position are reported in red.

4.1 FBG-based thermo-hygrometers coupled only to standard electronic sensors

Figure 7 reports, the temperature (a), relative humidity (b) and dew point temperature (c) reconstructions from the FBG-based thermo-hygrometer installed in position 15 of the schematic in figure 5 (a). In the same installation point, in addition to the fiber optic-based device, a standard thermo-hygrometer is available for comparison.

Reported data are related to twelve months of operation (from September 2014 to September 2015). Comparing the FOS reconstructions (blue line) with the signals provided by the standard electronic sensors (red line), good correlation between the two data sets is observed, therefore validating the FBG-based technology. As a matter of fact, the difference between the temperature

measured by both FBG-based and standard thermometers, reported in figure 7 (a), is below $\pm 0.2^\circ\text{C}$, while, considering the humidity reconstructions in figure 7 (b), the deviation is around $\pm 3\%\text{RH}$, fully within the declared accuracy of the HIH-4030 capacitive sensors and in complete respect of the set of requirements from the CMS experiment, as described in the first section of this paper.

Moreover, it is interesting to notice that a small deviation in the relative humidity measurements between the FOS and the standard hygrometer has a direct effect on the dew point reconstructions — as results from figure 7 (c) — mostly when dry conditions of the air are detected in the volume. In such situations, both the sensors are working outside of the “recommended” operating range: in presence of very low humidity values, we are not able to say which one between the dew point temperature measurements is the most accurate one and we can only conclude that both the sensors are detecting dry conditions of the air in the volume.

4.2 FBG-based thermo-hygrometers coupled to both standard electronic sensors and sniffing pipe

Figure 8 reports another example of FBG-based hygrometer in operation in CMS, during a particular moment of the life of the experiment, represented by the event of magnet powering: the magnet is powered up to a current of 18 kA to reach a 4 Tesla magnetic field and then powered down again, as evidenced in figure 8 (d).

The fiber optic-based thermo-hygrometer under analysis is installed in position 13 of the schematic in figure 5 (b). This configuration differs from the previous one as, in this case, the FOS is coupled to both standard T+RH sensor and sniffing pipe.

Again, the FOS readings are in perfect agreement with the measurements of the standard sensors, this confirming that the FBG-based sensors are not sensitive to magnetic field. On the other hand, it is important to remark that the powering of the magnet, which basically leaves unchanged the temperature level (figure 8 (a)), has an effect on the response of the relative humidity sensors (figure 8 (b)). As a matter of fact, as soon as the magnet is powered on, both optical and capacitive hygrometers register an increase of the level of humidity. This is consistent with previous observations performed in CMS suggesting that the movements of the large iron structures under the effect of the strong magnetic fields cause an inflow of humid air from the outside region towards the innermost volume of the detector. Nevertheless, when the current is lowered down, they take some time to reach the same relative humidity value as before the powering.

4.3 Measurements on the outer face of the Tracker Bulkhead

In this sub-section we report the case of the 8 FBG-based thermo-hygrometers installed in the outer face of the Tracker Bulkhead of the CMS experiment on the Negative side, as shown in figure 5 (d). In particular, figure 9 reports a ten-day period monitoring of temperature (a) and dew point (b), respectively, recorded by these sensors.

During most of the time window reported, the Tracker is operated with cold fluid at -15°C and the external heating foils on the surface of the Bulkhead are active to avoid local condensation problems. For this reason, during operation, the local temperature distribution on the external surface of the Bulkhead shows important spatial variations, depending on the presence of cold pipes in specific regions of the inner surface. On the right side of the temperature plot of figure 9 (a), it

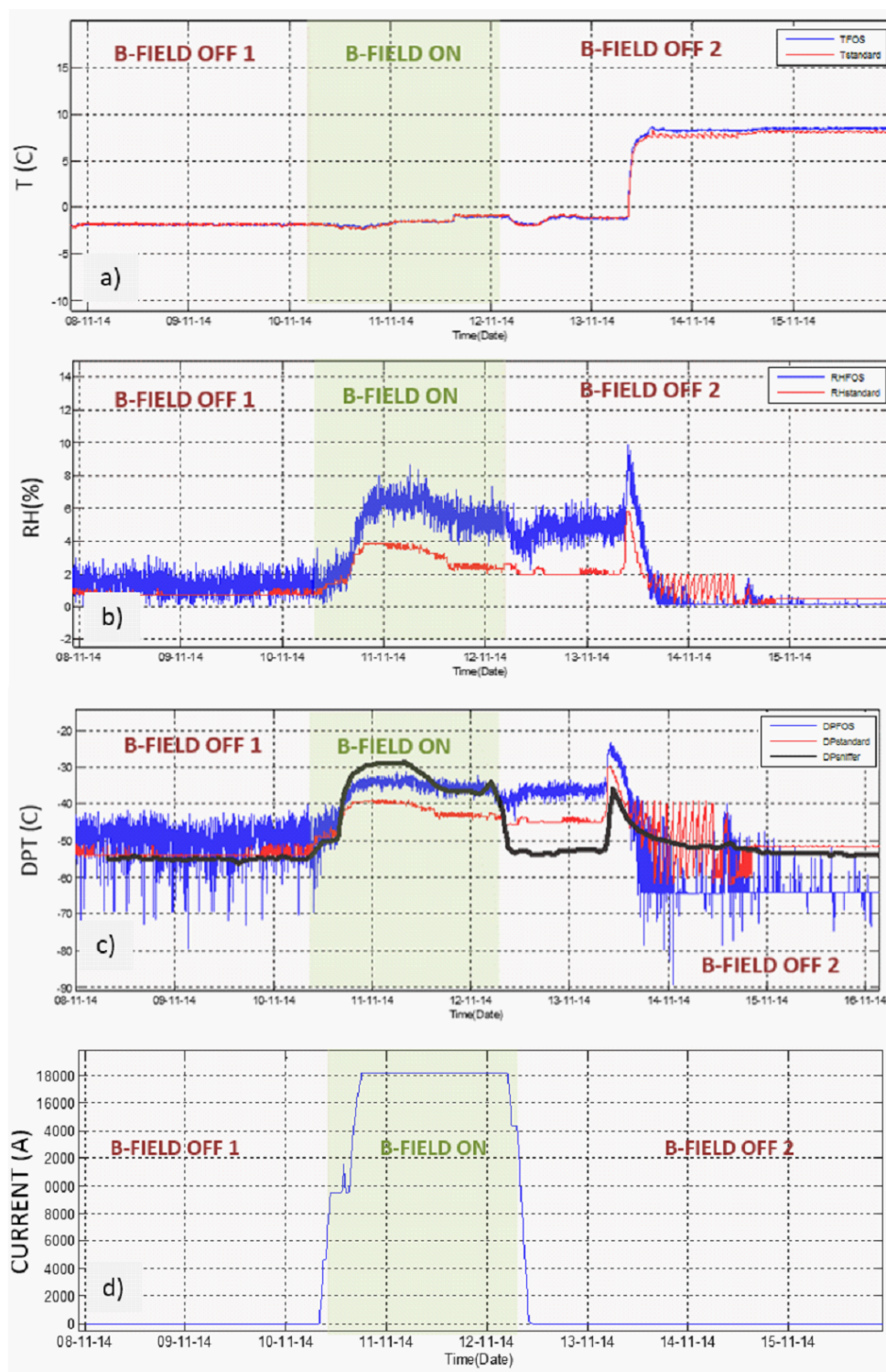


Figure 8. (a) Temperature, (b) relative humidity and (c) dew point reconstructions from a FBG-based thermo-hygrometer during the (d) ramp up and rump down of the magnet. For comparison, the readings from the standard electronic sensor and the sniffer installed in the same position are reported in red and black, respectively.

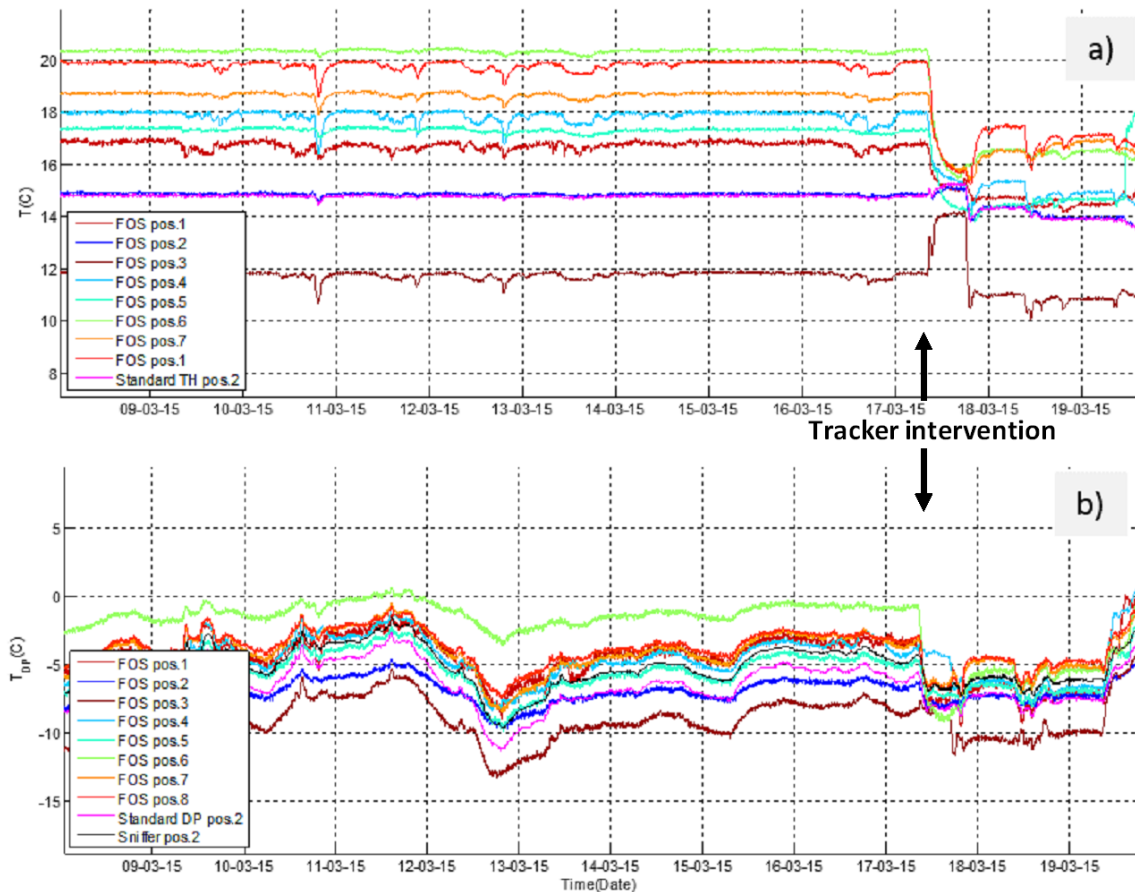


Figure 9. (a) Temperature and (b) dew point temperature readings from eight FBG-based thermo-hygrometers installed in the outer face of the Tracker Bulkhead of the CMS experiment (Negative Side).

is very well visible the effect of an intervention requiring the Tracker cooling fluid to be brought at room temperature and the heating foils to be switched off. This causes all the local temperature differences to gradually disappear and temperature on the Bulkhead surface becomes more uniform. Consistently, all the FBG-based temperature sensors tend to converge to a very similar reading. The black signal visible in the dew point plot in figure 9 (b), comes from the only sniffing pipe available in the volume, while the magenta line refers to the readings of a very close T+RH standard sensor. For their geometrical position in the volume, these two curves should be compared with the dark blue line, corresponding to the measurements from FBG-based device available in the same point.

Finally, considering the dew point temperature reconstruction plot reported in figure 8 (c), it can be observed that the optical sensor shows very similar dynamics to the sniffer, and the reconstructed values are in a very good agreement, even more than the ones measured by the standard sensor.

5 Long-term hygrometric monitoring and mapping with FBG-based sensors

Figure 10 reports the dew point temperature reconstruction from the FBG-based thermo-hygrometer installed in position 2 of the schematic in figure 5 (c), compared to the readings provided by the

sniffer available in the same installation point. The plot refers to 9 months of operation of the sensor in the experiment (from March to December 2015) and confirms the reliability of this sensing platform. As a matter of fact, a very good agreement, in both shape and amplitude, between the two reported curves can be appreciated within the full time window, with a maximum deviation of 2°C , in complete respect of the set of requirements from the CMS experiment.

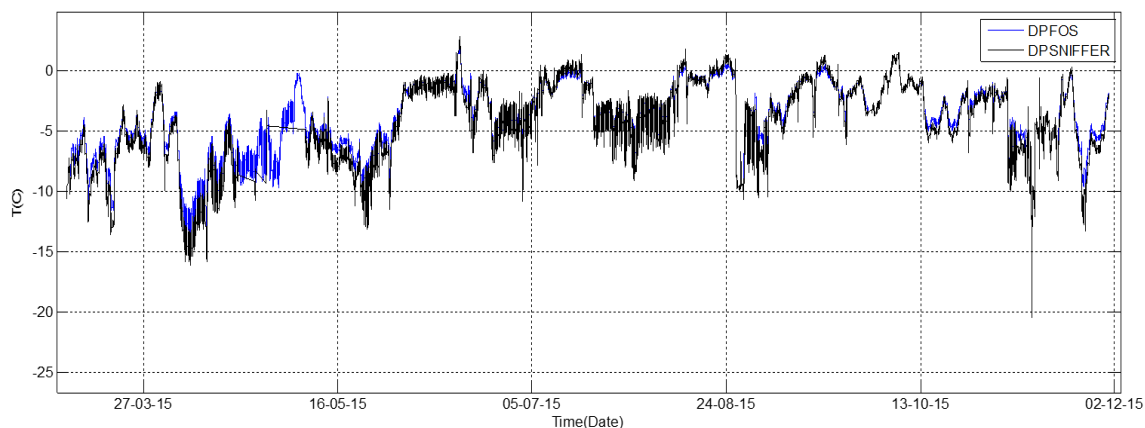


Figure 10. Dew point reconstructions from the FBG-based thermo-hygrometer installed in position 2 of the schematic in figure 5 (d). For comparison, the readings from the sniffer pipe installed in the same position are reported in black.

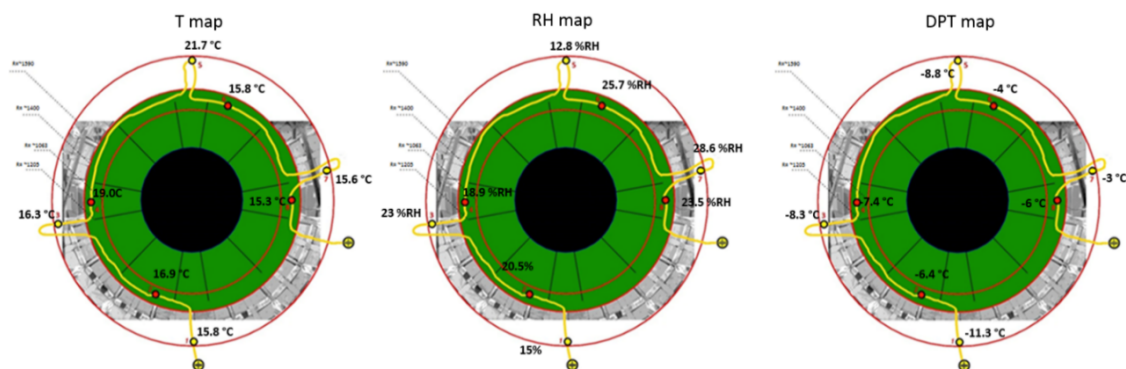


Figure 11. Example of temperature, relative humidity and dew point temperature mapping with FBG-based thermo-hygrometers installed on the outer face of the Tracker Bulkhead, on the Positive side of the experiment.

After more than one year of operation, characterized by extreme working conditions such as severe cooling cycles, magnet powering, and with the accelerator working at the full luminosity, we have not registered any phenomenon of instability or degradation of the performance of the proposed sensors (e.g. due to the aging of polymeric material, as discussed in the next section). However continuous monitoring has to be constantly performed, for a better understanding of the behaviour of this innovative class sensors in real environments.

Finally, to give an idea of the power of the proposed technology, we report in figure 11, a good example of mapping which FBG-based thermo-hygrometers are able to provide. These maps refer to a stationary condition reached in the experiment in March 2015 and they are linked to the eight optical sensors installed on the outer face of the Tracker Bulkhead of the experiment. Such kind of plots are extremely useful as they provide information about the distribution of temperature, relative humidity and dew point temperature in the experiment, helping to localize eventual critical spots in the volume.

6 Issues related to coated-FBGs for humidity monitoring

The correct operation of the FBG-based thermo-hygrometers in the CMS experiment have confirmed the strong potentiality of this technology for applications of relative humidity monitoring in real harsh environments. Nevertheless, after four years of research activity dedicated to the exploration of this innovative technology in humidity sensing applications, we found that it is not completely immune from some limitations.

The main issue is linked to the cross-sensitivity of coated-FBGs to both temperature and relative humidity. As a matter of fact, the typical S_T value of such devices is of the order of $10 \text{ pm}/^\circ\text{C}$ while, for a grating coated with a $10 \mu\text{m}$ thick polyimide layer, S_{RH} is usually of the order of $1 \div 1.5 \text{ pm}/\%RH$ [6]. This translates into a T/RH sensitivities ratio of around $10\%RH/^\circ\text{C}$. Here comes the need to decouple the effect of temperature and relative humidity from the sensors readings through the application of appropriate T-compensation techniques, generally consisting in coupling the coated-FBG to a thermometer with a good accuracy (better than $\pm 1^\circ\text{C}$). Indeed an error of $\pm 1^\circ\text{C}$ in the temperature reading would typically produce a not acceptable error of $10\%RH$ in the humidity reading [8].

Another factor which has to be taken in account when working with coated-FBGs is the influence of the adhesion of the polymeric material on the sensing performance of these devices. Indeed, if the deposited layer is not homogeneous along the region of the fiber where the grating is inscribed, the longitudinal strain transmitted to the grating itself may be not homogeneous as well, thus inducing non-linear responses or even not stable and repeatable measurements. As a matter of fact, from our work experience, we can surely assert that custom coated FBG-based sensors, produced in-house with a well-known and well-controlled process of the coating deposition, are high-performing in terms of linearity, repeatability and stability, compared to the standard sensors produced in batch and in less controlled conditions.

Moreover, while the hygroscopic nature of the polyimide allows to use it as moisture sensing element for the development RH sensors, at the same time, the presence of water absorbed and desorbed by the polymeric coating can lead to long-term reliability problems and chemical instability (aging phenomenon) [13], which have to be taken in account when working with this kind of technology.

Finally it is important to point out that the design and engineering of a small, lightweight and strain-free packaging for the coated FBG-based sensors is another critical task when working with this technology, as the FBGs are intrinsically sensitive to strain. For this reason, the design of the casing for the FBG-based sensors, which has also to protect the sensor during its operation, has to provide insensitivity of the light transmission to the fiber bending or strain close to the sensor

itself. For the same reason, during the installation of the thermo-hygrometers in CMS, great care was taken in order to place the arrays in a free stress configuration.

7 Conclusions

A full network of 72 optical fiber-based thermo-hygrometers, each one formed by a PI-coated FBG and one uncoated FBG, has been installed since the end of 2013 in critical areas of the CMS Tracker end-flange for constant distributed hygrometric monitoring.

During the last LHC shutdown (LS1), the readings of the fiber optic-based sensors have been constantly compared with the information provided by conventional non-radiation-resistant sensors and also with some punctual dew point measurements provided by a few sniffers, available on the volume. This had allowed for the validation of the FBGs measurements in terms of both temperature and relative humidity values, in a region where the concentration of power cables and cooling pipes creates strong local gradients. After the CMS closing and even the restarting of the LHC operations in April 2015, the full network of FBG-based thermo-hygrometers installed in the experiment, has been continuing to correctly work, providing distributed monitoring of the environmental conditions in the detector and preventing the risk of local condensation and ice formation.

After four years of work experience accumulated, we gained confidence on the application of the technology for humidity monitoring, developing an unprecedented wealth of detailed information about the properties, behaviour and limits of this innovative class of sensors.

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