Development and Qualification of a Fiber Optic Sensor Package for ITk Environmental Monitoring

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Abstract. The High-Luminosity Large Hadron Collider requires precise environmental monitoring in the ATLAS Inner Tracker to prevent water condensation that could damage detector electronics. This study focuses on the development and the performance of Fibre Optic Sensor packages. Each package is made up of a Long Period Grating sensor and two Fibre Bragg Grating sensors for accurate temperature, dose and relative humidity measurements in a harsh radiation environment. Extraction of the relative humidity (and Dew point) involves the decoupling of the effects of the measured temperature and radiation dose which requires compensation to be accurate. The temperature and relative humidity measurements may depend on location in the 2D (temperature, relative humidity) plane, as indicated by some measurements. This could be an effect of the packaging or a systematic physics effect of the FOS sensors. Calibration studies were performed to assess any possible dependency of temperature calibration on relative humidity in order to determine whether it arises from real sensor sensitivity or external factors such as packaging constraints. Calibration protocols were extended, and compensation algorithms refined to improve measurement accuracy. We present the outcome of the made Fibre Optic Sensor package and compensation methodology to ensure stable ATLAS Inner Tracker conditions for the High-Luminosity Large Hadron Collider era.

1 Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) represents the next major upgrade of the LHC at CERN which is aiming to increase the instantaneous luminosity by a higher factor [1]. This larger collision rate will give better chances for precision measurements and the discovery of rare processes. However, it comes with significant challenges for the stability and longevity of the ATLAS detector systems.

A major requirement for the ATLAS Inner Tracker (ITk) is its environmental monitoring to prevent conditions that could lead to water condensation inside the detector volume. Condensation poses a serious risk to sensitive electronics and could result in permanent damage or degraded detector performance [1, 2]. Maintaining stable operating conditions therefore demands accurate, real-time measurements of temperature, relative humidity, and accumulated radiation dose within a complex and harsh radiation environment.

Conventional electronic sensors face limitations in the high-radiation regions of the ITk due to radiation-induced damage and signal degradation [1, 2, 3]. Fibre Optic Sensors (FOS) have emerged as a promising alternative, offering inherent advantages such as immunity to electromagnetic interference, compactness, and radiation resistance[3]. In particular, Long Period Grating (LPG) and Fibre Bragg Grating (FBG) sensors have demonstrated the potential to measure key environmental parameters with high accuracy [3, 4, 5, 6, 7].

However, to assess the dew point by the accurate monitoring and extraction of temperature (T) and relative humidity (RH) from FOS data is a non trivial issue. The measured RH is strongly coupled to both the local T and the radiation dose (D). This demands careful calibration and compensation algorithms to disentangle the above mentioned effects. Additionally, preliminary studies indicate that the response of the sensors may vary with location in the two-dimensional (T, RH) parameter space, either due to genuine sensor physics or packaging-related constraints. Understanding and mitigating these dependencies is essential to ensure reliable environmental monitoring.

Presented in this work at the maximum operating temperature of ATLAS (T = 25^{o}C) is the quality assurance and checks (QA/QC) performed on one of the dedicated Fibre Optic Sensor FOS) packages for the ATLAS ITk. Each FOS package comprises of three grating-based point sensors (one LPG sensor and two FBG sensors per package). We describe the pre-irradiation, irradiation and post-irradiation calibration procedures performed including its extension to assess the possible dependence of temperature calibration on relative humidity. The performance of these sensor packages is evaluated under laboratory conditions representative of the ATLAS as outlined in Table 1 .

The Fibre Optics Sensors (FOS) requirements for RH monitoring	
Parameter	Value
Accuracy	$\Delta_{\text{RH}} < 3.5\%$ (between 0 and 10% RH)
	$\Delta_{\text{RH}} < 10\%$ (above 10% RH)
Precision	$\sigma_{\text{RH}} < 1.7\%$ (between 0 and 10% RH)
	$\sigma_{\text{RH}} < 5$ % (above 10% RH)
Typical operating temperature	-20^{o}C
Maximum operating temperature	25^{o}C

Table 1: The FOS requirements for RH monitoring. Presented is the work done at the maximum operating temperature of 25^{o}C.

2 Fibre Optic Sensor Packages and Measurement Method

To ensure accurate environmental monitoring in the ATLAS Inner Tracker (ITk) during the High-Luminosity Large Hadron Collider era, dedicated Fibre Optic Sensor (FOS) packages were developed and tested under controlled conditions. Each sensor package is designed to provide simultaneous measurements of temperature, relative humidity, and radiation dose in a harsh radiation environment where conventional electronic sensors would be susceptible to damage and signal degradation. The sensor package integrates three grating-based point sensing elements: two Fibre Bragg Grating (FBG) sensors and one Long Period Grating (LPG) sensor.

2.1 FBG working principle

As a grating-based point sensor, its sensing characteristics are based on the periodic perturbation of the refractive index of the optical fibre core over a portion of its length [1, 3]. The typical grating period of an FBG is in sub-microns. An FBG is created where there is a permanent photo-induction of the refractive index of the single mode optical fibre core. When light guided within the fibre core hits on FBG's micro-structure, one specific wavelength gets reflected and the rest wavelength will pass unperturbed [7]. The specific reflected wavelength is called the Bragg wavelength (λ_{B}) which strictly dependent on the fibre effective refractive index n_{eff} and the pitch of the grating Λ (grating period), according to the so-called Bragg condition: $\lambda_{\text{B}} = 2\, n_{\text{eff}}\, \Lambda$.

Both the refractive index and the grating pitch can be affected by strain and temperature. An axial strain (easily occur during packaging) in the grating changes the grating spatial period, as well as the effective refractive index and results in a shift of the Bragg wavelength due to the elastic behavior and elasto-optic effect [3]. On Similar ground, the change of ambient temperature (we appear to experience this in our lab) induces a similar effect on the grating, due to the thermal expansion and the thermo-optic effect. Consequently, the Bragg wavelength shift ($\Delta\lambda_{\text{B}}$) due to the change in strain ($\Delta\epsilon$) and thermal effects (ΔT) can be expressed as follows [3]:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1 - P_e)\epsilon + \big[(1 - P_e)\alpha + \zeta\big]\Delta T \tag{1}$$

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. The FBG responds to both temperature variations and strain which demands the application of proper methods to decouple the effect of temperature and strain from its readings (compensation)[8]. In our case, during the packaging of the sensors, the assembling process was done to achieve a strain-free FBG that is only sensitive to temperature.

2.2 LPG operation principle

The LPG sensor, just like the FBGs, is a grating-based point sensor. This photonic device is created by inducing a periodic index modulation of the core of a single mode optical fiber along a few centimeters of its length[3]. The period of the perturbation is longer than the FBG counterpart: it goes typically from 100 to 500 μm and the length of the grating is usually around 2 or 3 cm. In our case, the length of the grating 3cm (30mm) while that of the FBG is 8mm. This perturbation allows for the power coupling from the fundamental guided core mode to a discrete number of forward propagating cladding modes. Each coupling happens at a distinct wavelength, where the so-called phase matching condition is satisfied [5, 3, 1]:

$$\lambda_{\mathrm{res,i}} = (n_{\mathrm{eff,co}} - n^{i}_{\mathrm{eff,cl}})\Lambda \tag{2}$$

where $n_{\mathrm{eff,co}}$ and $n^{i}_{\mathrm{eff,cl}}$ are the effective refractive indexes of the core and of the i^{th} cladding mode respectively, while Λ is the period of the grating. In case of relative humidity sensors based on LPG technology, an appropriate hygrosensitive material (TiO_2) has to be selected such that the water absorption/desorption of water by the coating itself modifies its refractive index and/or thickness, thus creating a spectral variation and amplitude change in the LPG attenuation band, independently from the adhesion properties of the coating onto the grating itself [9, 3]. In our case, the LPG is pre-strain by an associated force of 0.3 N for it to be more responsive to measurement.

2.3 FOS package

Inside the FOS neoceram package, LPG sensor is sensitive to changes in relative humidity (RH), temperature (T) and radiation dose (D). One of the FBGs (radiation soft) is sensitive to temperature (T) and radiation dose (D) while the second FBG (radiation hard) is made to be only sensitive to temperature (T). By the virtue of decoupling and compensation, the three parameters (T, RH and D) can be separately measured and accounted for from the FOS data that simultaneously have the response effects of these parameter altogether. The combination of these sensors within a single package allows for cross-checking and compensation of environmental cross-sensitivities. The neoceram packaging materials was chosen to ensure it has no impact on the sensor response in term of pre-strain, moisture ingress and thermal coupling. To characterize and calibrate the sensor packages, a dedicated custom-built climatic chamber was used to expose the sensors to controlled ranges of temperature in the range of 25^{o}C to -20^{o}C and relative humidity (0% to 90% RH). The radiation response data were measured by exposing the package to radiation beam in the IRRAD facility at CERN.

3 Discussion and Results

The calibration and characterization of the FOS package was done using data recorded in three stages:pre-irradiation, during irradiation, and post-irradiation.

3.1 Pre-irradiation campaign

The pre-irradiation commences by using our sensors in the FOS package and commercially available sensors (pt10k and HIH-Honeywell) to measure our custom-built climatic chamber conditions. The data collected were then use for the T and RH calibration with characterisation. The standard commercial sensor pt10k responds to T while the HIH-Honeywell sensor responds to RH. The T calibration and RH calibration for FOS:

$$(t, \lambda_{\mathrm{T}})_{\mathrm{FOS}} \;\;\&\;\; (t, \mathrm{T})_{\mathrm{pt10k}} \rightarrow (\mathrm{T}_{\mathrm{FOS}}, \lambda_{\mathrm{FOS}}) \;\;:\;\; (t, \lambda_{\mathrm{RH}})_{\mathrm{FOS}} \;\;\&\;\; (t, \mathrm{RH})_{\mathrm{HIH}} \rightarrow (\mathrm{RH}_{\mathrm{FOS}}, \lambda_{\mathrm{FOS}}) \tag{3}$$

The set-up was made such that it can be used to regulate the T and RH in order to determine their thermo-hygrometric response. For T characterisation: RH was constant (0%) while T was varied. Conversely, for RH characterisation: T was constant (25^{o}C which is the maximum operating temperature) while RH was varied. Using equation (3), the T and RH calibration curves for the LPG is obtained as shown in Figure 1

The Fibre Optics Sensors (FOS) requirements for RH monitoring as stipulated in Table 1, FOS meets the specification in the pre-irradiation as shown in Figure 2.

3.2 FOS Functionality during irradiation campaign

The Irradiation campaign took place at CERN IRRAD facility. The FOS was exposed to 24 GeV/c proton beam which applies cumulative fluence of 7.56×10^{15} protons per cm^2 for 1 week. Sensors still function after 2.06 MGy ionizing dose as shown in Figure 3.

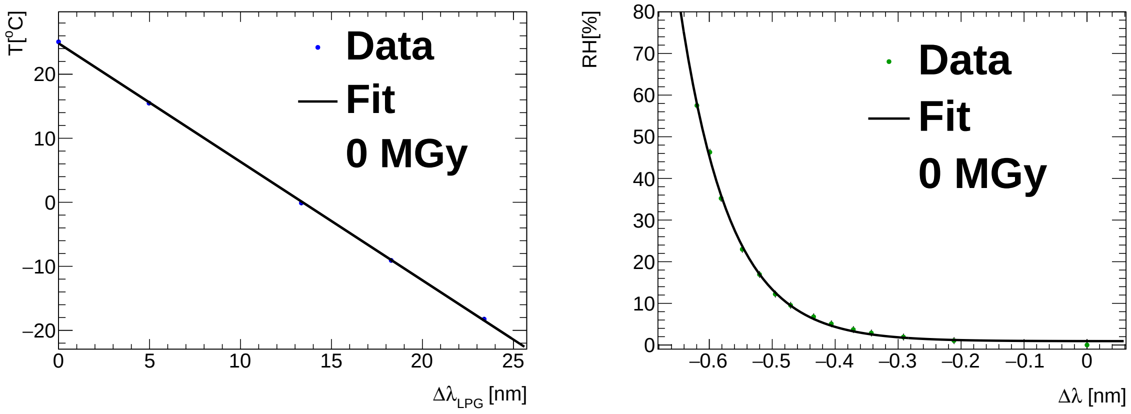

Figure 1: (*left*) Evaluated T calibration curve for the LPG for pre-irradiation campaign (*right*) Evaluated RH calibration curve for the LPG for pre-irradiation campaign. The 0 MGy on the plot indicate that the package is not irradiated (pre-irradiation campaign

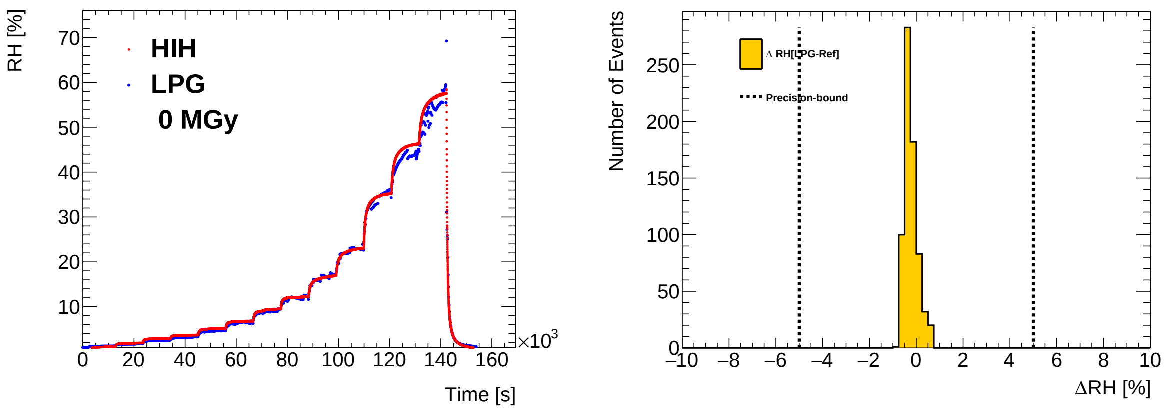

Figure 2: (*left*) RH over time – FOS vs HIH sensor. FOS RH readout comparison to conventional sensor HIH. It almost exactly matches conventional sensor. (*right*) Shown is for RH less than 20%, Variance is within precision bounds as stipulated in Table 1 .

3.3 Post-irradiation campaign

The calibration for the post-irradiation campaign is similar to that of pre-irradiation using equation (3) to acquire the T and RH calibration curves. From the post-irradiation plots in Figure 4, the FOS still almost exactly matches conventional sensor and the FOS readout minus HIH readout shows that the FOS meets the specification.

3.4 RH Calibration curves at different radiation dose and sensitivity

When the FOS packages are finally installed around the ATLAS detector, they would not be physically accessible for a long period of time. This demands more characteristic study in a varying and increasing radiation environment. Our approach for this is to use the data-driven RH calibration curves of the pre-irradiation (O MGy) and post-irradiation (2 MGy) campaign to acquire interpolation and extrapolation functions for different radiation dose as shown in Figure 5. By Differentiating the fit function of the RH calibration curves, you acquire the sensitivity of the respective sensor shown in Figure 5. Despite the reduction of the sensitivity of the sensor due to exposure to high radiation dose, it can still respond to change in RH at very low %RH.

4 Conclusion and future works

Quality assurance and checks (QA/QC) has been done on the FOS package that was assembled for environmental monitoring the condition in the ATLAS Inner tracker. In the work presented, it was in the maximum operating

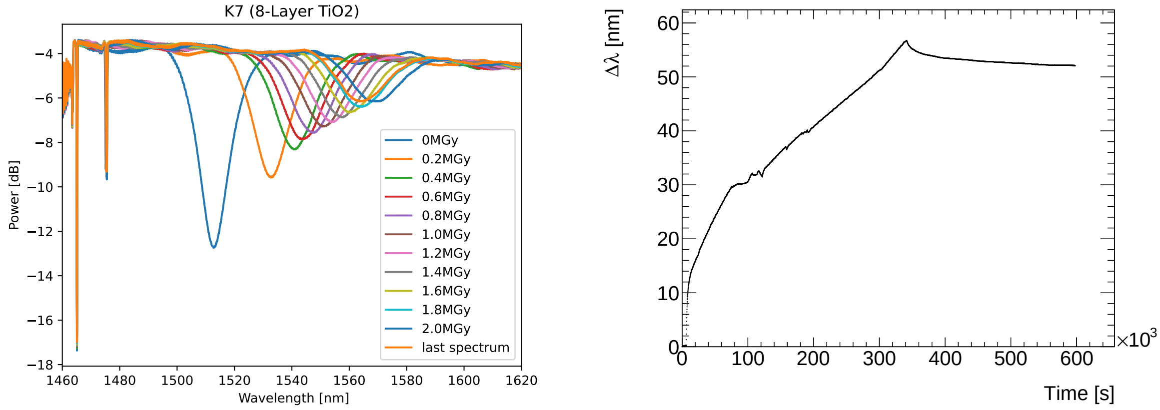

Figure 3: (*left*) Sensor functionality survives radiation. Change in response with increasing radiation dose. (*right*) Wavelength shift with increasing radiation dose.

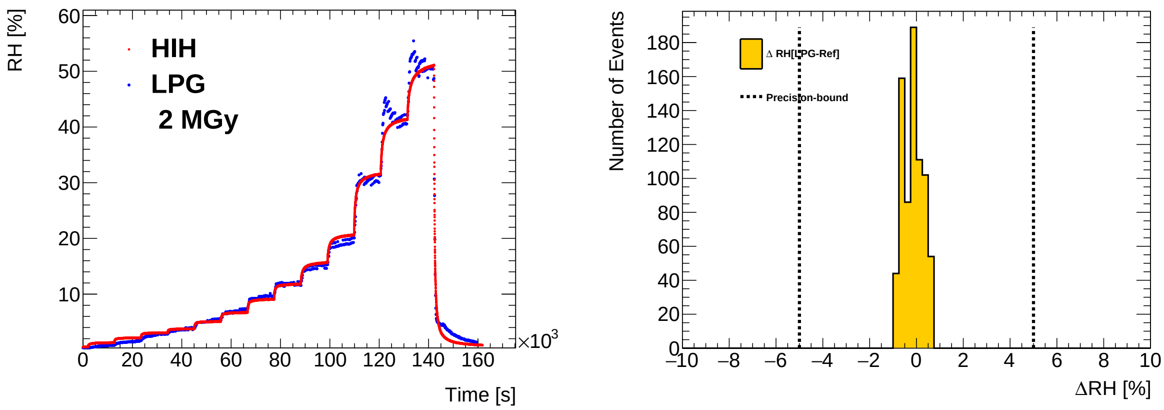

Figure 4: (*left*) For the post-irradiation, RH over time – FOS vs HIH sensor. FOS RH readout comparison to conventional sensor HIH. It still almost exactly matches conventional sensor. (*right*) Shown is for RH less than 20%, variance is within precision bounds as stipulated in Table 1 .

temperature of 25 ^{o} C. For the pre-irradiation and post-irradiation campaign, comparing the FOS RH readout to that of commercial sensor HIH readout indicate that RH variance is below the allowed specification. This implies the FOS package passed the test. Using our written code and algorithm we were able to handle conditions where the LPG was cross sensitive to both RH and T. This was achieve by temperature compensating the RH values we tend to measure. We are currently busy with QA/QC for condition under the normal operating temperature -20^o C of ATLAS iTK environment.

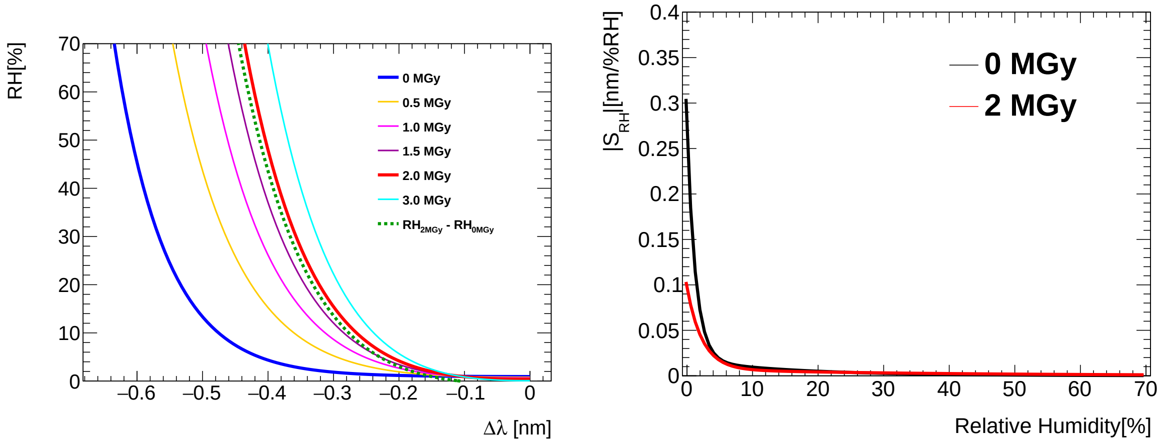

Figure 5: (*left*) Interpolated/extrapolated function at several dose exposure. (*right*) Despite radiation dose exposure which diminished the sensitivity of the LPG sensor, it still works as it shows it can read RH at very low $\%$ RH.

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