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Fibre optic sensors structural health monitoring of the central beam pipe in the CMS experiment at the CERN laboratories

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Abstract

In this paper, we show the new structural monitoring project of the central beam pipe of the Compact Muon Solenoid Experiment (CMS) at CERN. The measurements are carried out by means of a system of Fibre Bragg Grating (FBG) sensor arrays glued on the central Beam Pipe of CMS. The system consisting of FBG sensors represents the ideal solution to manufacture a reliable and accurate sensing system to be used 24/7 in the harsh environment in CMS. The mechanical complexity of the structure is described and the first strain (temperature compensated) measurements data recorded during the LHC operation throughout 2015 are discussed.

Keywords: Fibre Bragg Grating, High Energy Physics, beam pipe, monitoring system, temperature, strain.

1. INTRODUCTION

We designed and installed a new fibre optic sensors (FOS) structural monitoring system on the new central beam pipe of the CMS experiment to monitor on-line unpredictable mechanical deformations. The CMS central beam pipe is part of the LHC ring and it is the place where the high energy proton-proton collisions take place into the heart of CMS. Any monitoring system to be installed on the beam pipe must not interfere with the particle detectors that wrap around the pipe. Radiation immunity represents the most important specification required to a monitoring system operating in a High Energy Physics (HEP) environment. Other needs are: low complexity layout, multiplexing and multi-parameters measurement capabilities. Based on these technical specifications, a structural system based on Fibre Bragg Grating (FBG) sensors was designed and developed by our research group.

Being spectrally encoded, the FBG sensors are insensible to optoelectronic noise, intensity modulation of the optical carrier and broadband-radiation-induced losses. Nuclear radiation effects on optical materials and photonic devices have been studied since several decades [1,2]: ionizing radiation, mainly, produces wavelength dependent radiation-induced attenuation in optical fibres. All these characteristics allow to realize extended distance sensing systems, capable to operate in harsh environments like the underground experimental facilities at CERN (European Organization for Nuclear Research).

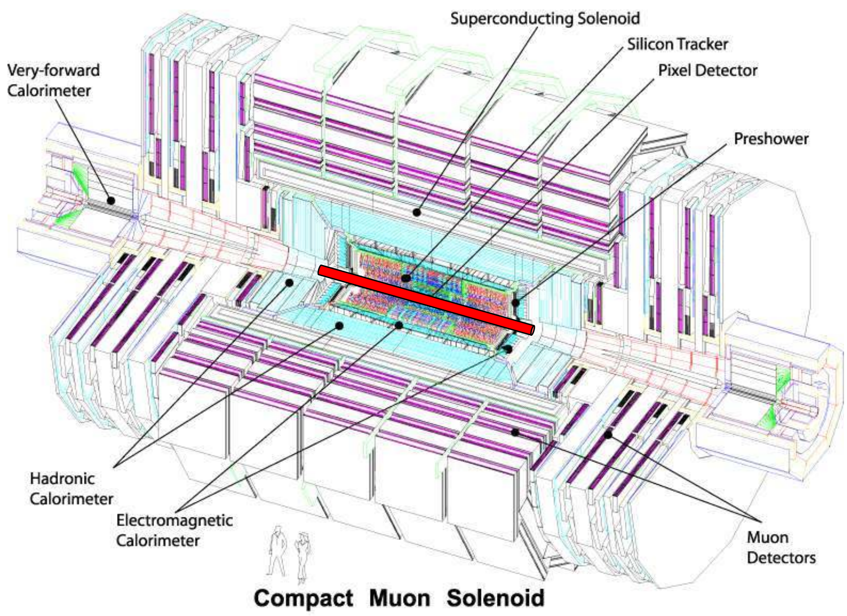


Figure 1: CMS detector technical view. All the subdecteor are labelled: pixel, silicon tracker, ECAL, HCAL, superconductiong solenoid, iron return yoke with muon chambers. The monitored Pipe is the LHC section located into CMS, here colored in red.

2. THE NEED FOR FOS BASED MONITORING SYSTEM AT CERN

The CERN is the largest laboratory in the word for the HEP studies. Since 2008 is active at the CERN the most powerful particle accelerator: LHC. CMS Experiment is one of the experiments active at the CERN, which was designed to found the Higgs's boson and any new elementary particle in the new energy range allowed by LHC collisions.

The CMS Experiment [4] is a very complex and large detector made of a large superconductive magnetic solenoid, which is able to produce a magnetic field up to 4T, and several particles sub-detectors. The CMS experiment is 21 m long, 15 m wide and 15 m high, and sits in a cavern. It is divided into sections: the main body (barrel) is composed by five disks, while the ends (endcaps) are composed by four disks. As described in the schematic shown in Figure 1, detectors consist of layers of material that exploit the different properties of particles to catch and measure the energy and momentum of each one.

The CMS operation in very complex environmental conditions requires a constant monitoring of temperature, structural deformation, relative humidity, and magnetic field. Nowadays, all the CMS area is under constant monitoring with the main scope of having information about of the working condition of all the subsystems. The monitoring became crucial for all the equipment that are temperature dependent and/or have to work under particular thermal conditions. The already significant number of detectors and electrical wiring installed at the CMS, does not facilitate further installation of additional monitoring systems. Moreover, during the operation of LHC, the high level of radiation and magnetic field is often not compatible with a good functioning of conventional electronic sensing devices.

Monitoring systems based on the FBGs technology were installed, by our group, in the underground site of CERN CMS experiment since 2009. They were gradually increased up to 200 temperature and strain sensors, running 24/7 for 3 years during LHC collisions, without any interference with CMS operating conditions [3]. Since February 2013 until March 2015 the LHC has been stopped in order to allow technical interventions and upgrade of the machine and experiments, Long Shut-Down (LS1). During this period, we expanded our FBG monitoring system. Now we have nearly one thousand FBG sensors installed and operational, covering the CMS experiment from the outer to the most inner part. The central beam pipe structural monitoring system is part of the CMS-FBG monitoring system and it is taking data, continuously, from the beginning of 2015.

3. FIBER BRAGG GRATING FOR HIGH ENERGY PHYSICS

The general aspects of the fiber optic sensors technology based on FBGs have been widely demonstrated during the last decade [5]. These sensors are characterized by a reflected wavelength defined as the Bragg wavelength λ_B. Punctual-distributed sensing systems based on FBGs can be easily achieved by using a Wavelength-Division Multiplexing (WDM) approach [6]. It permits to use FBG arrays to arrange a simple sensing system with a high number of sensing points per single Optical Fiber, distributed along a wide area. The extremely low loss level allows multi-point sensing systems distributed in a large area [7]. The advantages of small size, light weight, electromagnetic immunity [8], radiation hardness [9 - 10], make FBG sensors the ideal devices for a large variety of applications [11] and, in particular, for HEP large size experiments. As well known by the literature, in the Fiber Bragg Gratings external fields, temperature and strain will change the center wavelength of reflected light, which has been proposed and widely used as a sensing mechanism. The center wavelength of reflected light from FBG is given by the Bragg equation:

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

where n_{eff} , Λ and $\lambda_B$are the effective refractive index, period of grating and center wavelength of FBG respectively, and depend on temperature and strain. The strain influences λ_B due to grating's period change and elastic-optic effect, while the temperature influences λ_B due to thermal expansion and thermo-optic effect:

$$\frac{\Delta\lambda}{\lambda_0} = k \cdot \varepsilon + \alpha_\delta \cdot \Delta T \tag{2}$$

where the term $k \cdot \varepsilon$ describes the strain impact caused by force ε_m and to the thermal expansion ε_T while the term $\alpha_\delta \cdot \Delta T$ describe the change of the glass refraction index caused only by temperature.

Since temperature as a very strong impact on the FBGs signals, precise strain measuring results can be achieved only with a proper temperature compensation. In our structural monitoring system this is done using additional temperature-measuring FBGs and the signal of the strain-measuring FBGs is corrected by calculations. Moreover, thanks to the presence of the temperature sensors, of our monitoring system is able to provide detailed information about the thermal profile of the structure.

4. CMS BEAM PIPE MONITORING SYSTEM

The new central Beam Pipe was installed in CMS during LHC LS1 period. The pipe is made of a beryllium tube section (3m long with a central diameter of 45mm and only 0,8mm thickness wall), sealed on the two extremities with two conical aluminum sections, each 1.5m long. Our monitoring system consists of four “naked” glass 28SMF fibers (200um diameter: core-cladding-buffer) placed along the cardinal longitudinal positions on beam pipe cross section. 16 FBG sensors have been manufacted on each fiber, 7 of them are solidary glued on the pipe to measure the local strain and the remaining 9 are left unglued but in contact with beam pipe in order to work as local thermometers and as strain temperature compensators for the adjacent strain sensors. A schematic representation of the FBG distribution around the beam pipe is depicted in Figure 2. The system has been designed to stand the high radiation dose in this region during LHC operation and to survive the bake-out treatment of beam pipe at high T (up to 220C), necessary to “remove” from Pipe inner surfaces unwanted polluting particles.

4.1. Description of the beam pipe structure

The CMS central beam pipe in part of the CMS beam pipe shown in Figure 3. It is supported by two collars positioned symmetrically with respect to the impact point (IP) and distanced of 3260 mm and two end flanges. The total length of the central beam pipe, including the two end flanges, is 6240 mm. Between the central beam pipe and the subsequent endcap beam pipe there is, on both side, a “double bellow” in order to reduce any mechanical interaction between the two sector and to secure the stability of the central beam pipe. A permanent support for the central beam pipe and bellows is attached to the tracker bulkhead. It is shown in Figure 4(a). This support, called tracker support, consists of three separate supports:

- Ax-y support for the central pipe at Z=1.632m through wires engaged into pulleys and attached to the nose (or “fishing rod”) structure for tensioning and regulation, Figure 4(b),
- A x-y support for the central pipe at Z=3.1m through a system of sticks and carriages integrated into the nose structure, Figure 4(c),
- A x-y-z support for the endcap pipe at Z=3.5m through a system of sticks integrated into the nose structure, Figure 4(c).

The Z=3.1m support holds the central pipe at the connection flange to the endcap pipe, just before the double bellow section, while the Z=3.5m support holds the endcap pipe through a full translation-constrained point. Between the endcap beam pipe and the HF beam pipe there is another permanent support, inside YE3: it hangs from above and is stabilized from sides and bottom. The top hanger has x, y and z adjustment. Finally, there is a support installed in the base for the CASTOR, between the HF and the CT2 sector of the beam pipe. It is a lever mechanism used to reduce the deflection of the beam pipe. It will be activated from below when the two halves of the base are closed below the beam pipe. When the magnetic field, up to 3.8T, is switched on the CMS structure the structure shrinks toward the center of few millimetres resulting in mechanical forces acting on the bellows, that may induce stress on the central beryllium beam pipe. The same happens when the solenoid rumps down, but in opposite direction. The supports involved in the movement are the endcap and the HF ones, while the other subsequent sectors of the beam pipe do not introduce any mechanical stress on the central beam pipe when the solenoid magnet rumps.

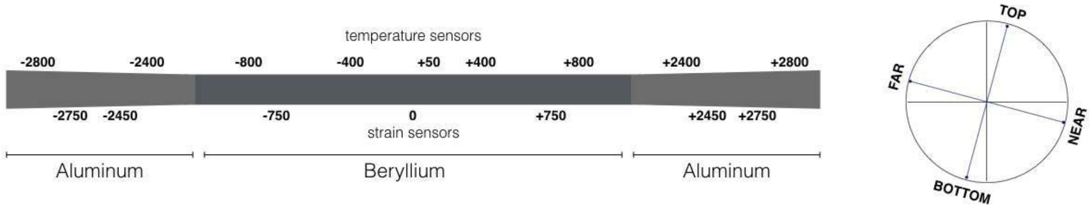


Figure 2: Layout of the fiber optic monitoring system installed on the CMS central beam pipe. 4 FBGs array are installed and on each array there are 16 FBGs: 7 configured as strain and 9 as temperature sensors.

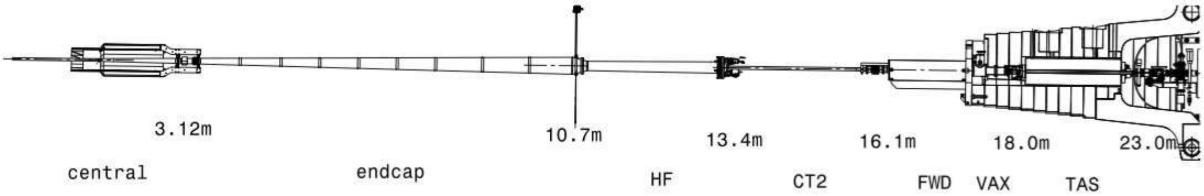
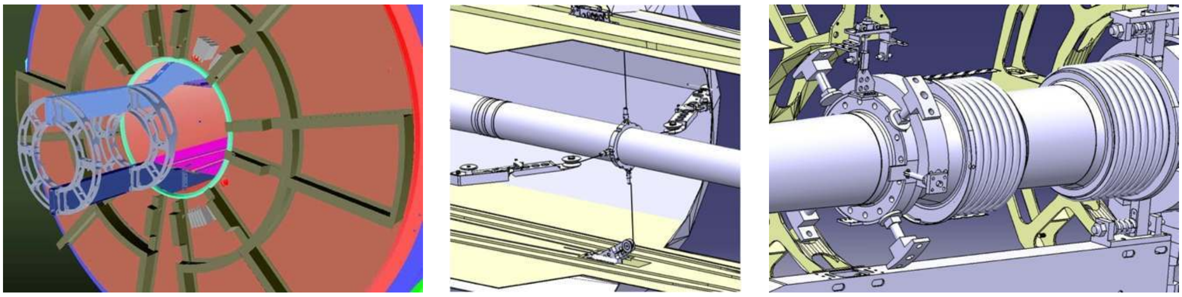


Figure 3: Drawing of one side, with respect to the impact point, of CMS beam pipe. Different sectors are shown.



(a) (b) (c)

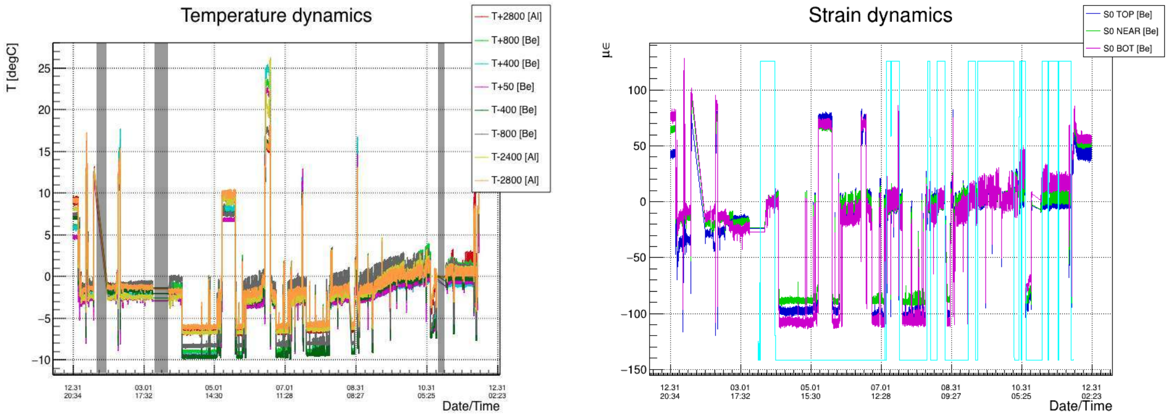
Figure 4: Technical drawing of: the permanent supports for the central beam pipe and bellows attached to the tracker bulkhead, (a); the x-y support for the central pipe for tensioning and regulation, (b); the bellows between the central and the endcap beam pipe sectors, (c).

4.2. Preliminary studies on the glue

The strain sensors have been glued using the epoxy encapsulat Stycast 2850 FT with catalyzer Catalyst 24 LV. This encapsulat is widely used for cryogenic and vacuum applications, such as in aerospace industry (NASA) and is well known for its resistance to radiation. A key issue was to find a glue capable to fulfill the required condition (curing at room temperature, low viscosity, radiation resistance...) and not aggressive on the beam pipe materials with and without radiations. Secure the beam pipe absolutely unaffected by the encapsulate is of the highest importance, as any corrosive action would possibly affect the vacuum level and consequently the operation of the entire LHC machine. To secure the long term FBG gluing and eliminate any risk of damaging the beam pipe it was decided to study the interaction of the Stycast 2850 FT Catalyst 24 LV with Be, Al 2219 in various and representative conditions of CMS beam pipe operation in the underground site. Three heat treatments were set up:

- room temperature for one week, 50% Relative-Humidity;
- 100°C for one week, in order to activate any diffusion process and in closed jars in order to secure stable humidity level;
- 3 times 280°C for 2 days in order to simulate a severe bake-out.

Part of the samples was also sent to IONISOS firm (Lyon, France) for gamma irradiation up to 200 kGy dose. Under these conditions, the SEM and optical observations of the upper and cross-section of the samples showed no evident mark of interactions between the encapsulate and the metallic surfaces of the beam pipe. A dedicated report on these studies has been prepared from the TE Department of CERN, [11].



(a) (b)

Figure 5: Temperature profile of the beam pipe (a) and behaviour of the strain acting on the beam pipe during different phases of switching on and off of the magnetic field recorded during different magnet test periods (b), during the CMS operation throughout 2015. The cyan line represents the B-field variation from 0 to 3.8 Tesla.

4.3. Installation

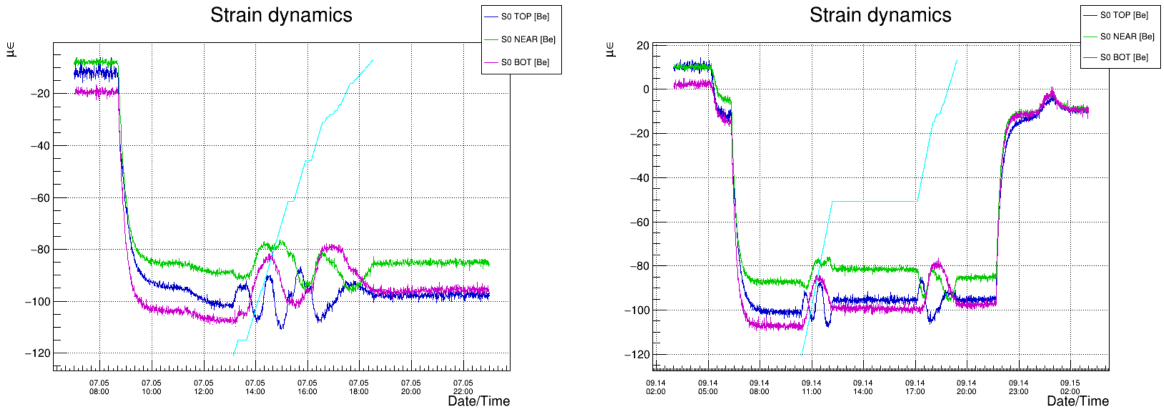
The installation of the arrays on the beam pipe was performed in May 2014, while the beam pipe was in a surface laboratory at CERN. It was a very delicate operation: each array has been carefully put in position over the beam pipe length, each strain sensor had to be glued on the entire FBG length and the glue was left curing for 24h at room temperature. The remaining free fiber was secured with additional glue dots in order to secure a sagitta less than 200 microns, to avoid any contact with present and future Pixel detector during insertion and operation phases. After completion of 1 array gluing, the beam pipe was rotated by 90° in order to install the next array and the operations were repeated for all the four array positions. After four days we successfully completed the installation, and the pipe was ready to be installed in the underground cavern of the CMS experiment. The new beam pipe was installed in June 2014. Its installation was followed immediately by vacuum pumping, combined with heating to more than 200 ºC, to expel gas molecules attached to the chamber walls, this operation is called bake-out. As a consequence of the beam pipe thermal expansion during the bake-out and the fixed glued points along each fiber, the arrays have been subjected to an abnormal mechanical tension which lead to the breaking of the fibers. The reparations were challenging and not always possible. In the final working configuration the monitoring system has 40 reliable FBG sensors out of the 64 installed.

5. RESULTS

This section reports some experimental preliminary results collected during all the CMS testing period and also during the first LHC fine-tuning operation phases.

5.1. Temperature monitoring

After the array installation on the beam pipe, the λ_0 of all the sensors has been re-calibrated in order to take into account the installation induced shift, with respect to the firm calibration parameters. Moreover, the extreme stressing conditions suffered during the bake-out made necessary a further re-calibrations of the sensors in order to take into account any effect on the λ_0 and sensitivity. Those actions have been performed while the beam pipe was still accessible making use of different local electronic sensors as references.



(a) (b)

Figure 6: Strain behaviour on the central part of the pipe during the B-field rump performed on July, 7th 2015 (a) and on September, 14th 2015 (b). The cyan line represents the B-field variation from 0 to 3.8 Tesla.

In Figure 5(a) it is shown the temperature profile of the beam pipe during the CMS operation throughout 2015. Three main temperature intervals can be identified that correspond to different configuration of the CMS detector:

- room temperature, when the detector is opened;
- ten degrees, when the detector is closed, the electronic boards and cooling system are off;
- between zero and minus ten degrees, when the detector is closed and operational and the cooling is on;
- minus ten degrees, when the detector is closed but not operational and the cooling is on.

From Figure 5(a), it is clearly visible the temperature gradient between the beryllium and the aluminium sectors of the central beam pipe. The beryllium part, *i.e.* the sensor from T+800 to T-800, is at -9±1°C when the detector is closed but not operational and the cooling is on, while the aluminium parts are 3°C colder.

5.2. Strain monitoring

To correctly evaluate the strain, it is necessary to separate strain and temperature effect in order to compensate the thermal apparent strain effect. Since in the CMS central beam pipe fibre optic monitoring system the temperature sensors are not bonded on the beam pipe, they can be considered strain-free and used as compensators.

In Figure 5(b), are shown the strain deformations acting on the FBG sensors in the position S0, *i.e.* the centre of the beam pipe, during different phases of switching on and off of the magnetic field recorded during different magnet test periods, from January 1st to December 31th. The reference condition, *i.e.* zero strain, is set when the detector is closed and operational. In particular, it was set on March 24th, when the CMS detector was closed at the end of the upgrade operations of the LS1. The compressions and expansions are in agreement with the thermal model of the beam pipe [12].

Figure 6(a) shows the strain deformation acting on the FBG sensors in the position S0 during a rump-up of the magnetic field, from 0T to 3.8T, happened on August 7th. Figure 6(b) is a demonstration of the reproducibility of this behaviour even during multistep rump-up; the data reported in this plot refer to the magnetic field rump-up happened on September 14th. It is

evident that, while the field is rumping, the beam pipe is subjected to mechanical deformations of the order of 30 με. The CMS structure, during the rumps of the magnetic field, is subjected to forces that cause a movement toward the centre of a few millimetres of the structures around the endcap and HF pipes. We can state that the strain recorded on the central beam pipe by our monitoring system results from magnetic induced forces acting on the bellows during the variations of the magnetic field. Moreover, these results prove the extreme high sensitivity of our FBG strain sensors and validate their level of reproducibility.
In next December 2016 a new PIXEL detector with 4 silicon layers will be installed. It will allow to record particle track points closer to proton interaction point. It will be placed at only 1,5mm from central beam pipe external face. The mechanical stability of the central beam pipe is a crucial parameter to be monitored since an abnormal oscillation could be very dangerous for the surrounding detectors.

6. CONCLUSION

An innovative FBG based monitoring system has been successfully installed on the CMS new central beam pipe. It will be a milestone for any future beam pipe monitoring in High Energy Physics domain. This system will secure the measurement of T distribution along the CMS central beam pipe during maintenance and operation phases. In addition, it will provide detailed measurements for any deformation induced on central beam pipe by any motion in the CMS detector due to element displacement or to magnetic field effects. Preliminary data collected so far showed the high level of sensitivity and reliability of this system. It will help to improve the safe operation of future CMS opening/closing activities and beam pipe manipulations.

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