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iPIPE: AN INNOVATIVE FIBER OPTIC MONITORING SYSTEM FOR BEAM INDUCED HEATING ON ACCELERATOR PIPES

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Abstract

The iPipe project consists in the development of a monitoring instrumentation, with Fiber Bragg Grating (FBG) sensors, of the beam pipe of for the Compact Muon Solenoid (CMS) experiment, which is part of the Large Hadron Collider (LHC). This fiber optic temperature and strain monitoring system, was designed, developed and installed by our research group on different sectors of the beam pipe of the CMS experiment. It secures the measurement of any deformation induced on the central beam pipe by any motion in the CMS detector due to element displacement or to magnetic field induced deformations. The iPipe FBG temperature sensors represent a unique solution to monitor the beam pipe thermal behavior during the various operational and maintenance phases. This contribution reports the use of the iPipe to measure the beam induced heating on the CMS beam pipe.

INTRODUCTION

Being spectrally encoded, the FBG sensors are insensible to optoelectronic noise, intensity modulation of the optical carrier and broadband-radiation- induced losses. All these characteristics allow to manufacture extended distance sensing systems, capable to operate in harsh environments like the underground experimental facilities at CERN (European Organization for Nuclear Research). Radiation hardness represents the most important specification required to a monitoring system operating in a High Energy Physics (HEP) environment. Other needs are: no EM interference with particle detectors, low complexity layout, multiplexing and multi-parameters measurement capabilities. Nuclear radiation effects on optical materials and photonic devices have been studied since several decades [1]. Ionizing radiation, mainly, produces wavelength dependent radiation-induced attenuation in optical fibers. FBG based monitoring systems were installed in the underground site of CERN CMS experiment [2] 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 [4]. In particular we installed a new FBGs strain and temperature monitoring system (also called iPipe) on the new Central Beam Pipe of the CMS experiment to monitor on-line unpredictable mechanical deformations.

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, 6]. These sensors are characterized by a reflected wavelength defined as the Bragg wavelength λ_B. Puntual-distributed sensing systems based on FBGs can be easily manufactured by using a Wavelength-Division Multiplexing (WDM) approach. It permits to use FBG arrays to arrange a simple sensing system with a high number of detecting points per single Optical Fiber, distributed along a wide area. The extremely low loss level allows multipoint sensing systems distributed in a large area [7]. The advantages of small size, light weight, electromagnetic immunity, radiation hardness make FBG sensors the ideal devices for a large variety of applications and, in particular, for HEP large size apparatus. As well known by the literature, for an FBG, the center wavelength of reflected light strongly depends on external fields, temperature and strain. For this reason these gratings have been proposed and widely used as a sensing mechanism. The center wavelength of reflected light from FBG is given by the Bragg equation:

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

where n_{eff}, Λ and λ_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.

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

where the term $k \cdot \varepsilon$ describes the strain impact caused by force ε_M and to the thermal expansion ε_T , the term $\alpha_\delta \cdot \Delta T$ describe the change of the glass refraction index caused only by temperature, while λ_0 is the reference wavelength value.

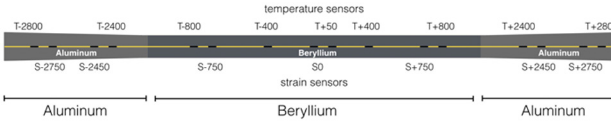

Figure 1: Longitudinal layout of the fiber optic monitoring system installed on the CMS central beam pipe. The quotes refer to the distance of the temperature and strain sensors from the center of the vacuum chamber.

CMS BEAM PIPE MONITORING SYSTEM

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. In December 2016, a new Pixel detector with 4 silicon layers has been installed. It allowed to record particle track points closer to proton interaction point. It will be placed at only 1,5mm from central beam pipe external face. To allow the new Pixel detector installation a new central Beam Pipe was installed in CMS during LHC LS1 period. The new central beam 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 manufactured 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 1. 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 220°C), necessary to "remove" from the inner surfaces of the vacuum chamber unwanted polluting particles. From the iPipe system supplied detailed measurements of the temperature distribution along the CMS beam pipe during maintenance and operation phases. The monitoring capability of this system has been widely demonstrated in the last two year of data taking [8, 9]. The iPipe FBG temperature sensors represent a unique solution to monitor the beam pipe thermal behavior during the various operational and maintenance phases. In particular, with the iPipe monitoring system it is possible to directly measure the RF beam induced heating [10] during the LHC operations.

BEAM INDUCED HEATING MEASUREMENTS

The iPipe monitoring system FBG sensors are placed on the outer surface of the CMS central beam pipe, in direct contact with the metallic surface. This peculiar, and unique, sensing position allow to measure for any thermal dynamic that took place on the vacuum chamber structure. Moreover, the system has been designed to take data 24/7 at 0.1Hz. The thermal behavior of the CMS central beam pipe during a typical LHC fill, as recorded by the iPipe monitoring system is shown in Figure 2.

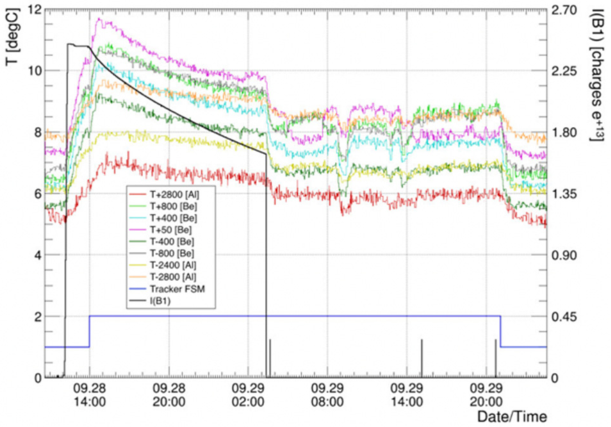

Figure 2: Thermal dynamic on the CMS central beam pipe.

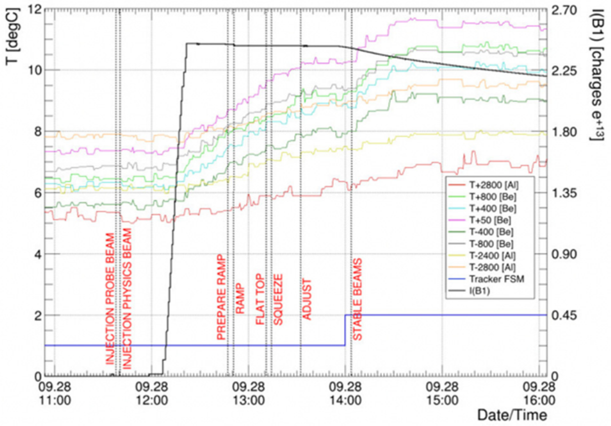

Figure 3: Highlight of the temperature increase during the LHC Fill 5345 happened in September 2016.

Focusing on the left part of the plot in Figure 2 it can be seen that the temperature increase is factorable in two parts. As the beam intensity starts to increase there is a temperature increase on the pipe between the injection of the physics beam and the declaration of the stable one. A further temperature increase is recorded by the iPipe sensors after the stable beam declaration. As evidenced in Figure 3, the first pipe temperature rise is clearly related to the presence of the beam and can be associated to RF beam induced heating phenomenon. Indeed, other sources of beam induced heating than wake fields could be present, but they can be excluded in the case under test:

- synchrotron radiation, can be excluded because the CMS central beam pipe is a straight section of the LHC ring and no synchrotron radiation is foreseen;
- direct beam losses, are not included because the measure has been performed during the period before collisions;

- electron cloud, the presence of the CMS magnetic field inhibit the electrons of the cloud from interacting with the vacuum chamber walls.

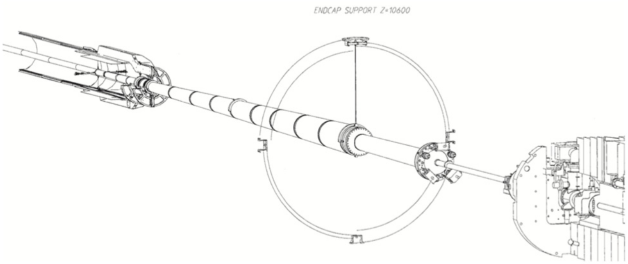

Figure 4: Technical drawing of the half section CMS beam pipe. The Endcap support is highlighted.

Moreover, the central beam pipe is located in the tracker volume, which is a thermal and humidity controlled environment. Following the excellent results achieved in the direct measurement of the beam RF induced heating on the CMS central beam pipe, the CMS Collaboration decided that the iPipe monitoring system has to be installed also on the sectors at z = ±10 m, with respect to the impact point, located in the CMS Endcap pipe zones, referring to the technical drawing in Figure 4. Indeed, the presence of a mode trapped at the end of the End-cap pipe, about ±10m from the interaction point, has been highlighted from calculation [11] resulting in a potential power loss up to 250W [12]. This scenario poses the need for a continuous and reliable monitoring of these sections of the CMS beam pipe. With the support of the CMS Central Technical Coordination, we have designed and installed an upgrade of the iPipe system.

CONCLUSIONS

The iPipe monitoring system, turned out to be a solid and reliable solution for challenging monitoring tasks, in particular for the measurement of local thermal gradients on the accelerator sectors. The iPipe data can be seen as the first direct measure of the beam RF induced heating on the CMS central beam pipe, made possible by the uniqueness of the iPipe monitoring system. Indeed, the CMS central beam pipe is the first, successful, example of direct measurements of the temperature dynamic of a particle accelerator in the sector where particles collide. The iPipe system is unique and innovative and opens new perspectives in the manufacturing of solid and reliable structural health monitoring system in this domain.

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