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DISTRIBUTED OPTICAL FIBER RADIATION SENSING AT CERN*

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Abstract

CERN's accelerator tunnels are very complex mixed field radiation environments, in which many electronic components and systems are installed. The radiation generated by the circulating beam degrades all electronic equipment and impacts directly its lifetime. In the worst case, it may also cause failures that contribute to increase the machine downtime periods. Consequently, both active and passive dosimetry technologies are used to monitor the radiation levels. These point radiation sensors are installed in thousands of specific locations in the machine tunnels, and the nearby caverns, in order to provide either online or post-irradiation radiation dose measurements. In this contribution, we present a new radiation monitoring technology implemented at CERN called Distributed Optical Fiber Radiation Sensor (DOFRS). The first operational prototype of this system was installed in 2017 in the Proton Synchrotron Booster (PSB), the first and smallest circular accelerator of the injection chain of LHC. The most interesting capability of the DOFRS, with respect to other currently installed dosimetry systems, is to provide one dimensional maps of radiation dose levels all along the sensing Optical Fiber (OF). Such characteristic makes it very well-adapted for radiation detection and dosimetry in large facilities and accelerators. In particular, it allows the online monitoring of the cumulated radiation dose over hundreds of meters with a spatial resolution down to one meter. By combining these measurements with simulation studies, it is also possible to draw conclusions on the radiation dose levels at locations closer to the beam line. Below, we report the results and performances of the DOFRS in the PSB after its first year of operation. The measurements are compared to several point passive dosimeters that were installed in regions of interest in close proximity to the OF sensor. Furthermore, the system under implementation at CERN provide distributed temperature measurement capabilities specifically adapted for radiation environment.

OF RADIATION SENSOR

In the last three decades, several authors have investigated the potentiality of OFs to be employed as dose sensors in a wide range of radiation environments: nuclear power plants, high-energy physic facilities, medicine and space. OFs are very appealing technology because of many well-known characteristic: small size and mass, immunity to electromagnetic fields, resistance to humidity, possibility to be conveniently replaced via cable blowing.

In general, OFs' base material, doped silica (SiO_2), is especially sensitive to ionizing radiation [1-3]. This latter causes three main macroscopic phenomena: Radiation Induced Attenuation (RIA), mainly due to the absorption bands of radiation induced point defects; Radiation Induced Emission (RIE), due to the Cherenkov emission, luminescence from excited states of point defects, electron-hole pair recombination; refractive index change due to the appearance of absorption bands via the Kramers-Kronig relations. Very high radiation doses and neutron fluences can also cause material compaction which also leads to refractive index change.

The opto-geometric properties of OFs are achieved by radially doping the SiO_2 matrix and creating a refractive index difference between the so called core and cladding of the OF. Since several elements can be used as dopants, the extended research of the past has clearly shown that the chemical composition plays a major role in determining the response of an OF to radiation.

The RIA is the physical phenomenon which is actually used by DOFRS system to perform distributed dose measurements. By studying the response of the OFs under irradiation it is possible to calibrate the RIA as a function of deposited dose [1-3]. To this aim, it is important to verify that the sensor response is dose-rate independent, temperature independent (within the temperature range of the envisaged application), it does not suffer from fading effects after the irradiation. In the first implementation of the DOFRS at CERN, the sensor of choice was a Phosphorus-doped Multimode graded index OF [4]. In order to estimate the deposited radiation dose along the sensor, the OF sensor was preliminarily calibrated under ^{60}Co γ-rays and also qualified for employment in mixed filed in the CHARM facility (CERN High energy Accelerator Mixed field facilities) at CERN [4].

DOFRS IMPLMENTED IN PSB

The DOFRS system developed at CERN is composed of two main elements: a calibrated radiation sensitive OF (discussed in the previous section and in [4]); a commercial Optical Time Domain Reflectometer (OTDR), capable of measuring the optical attenuation along the OF with one meter spatial resolution.

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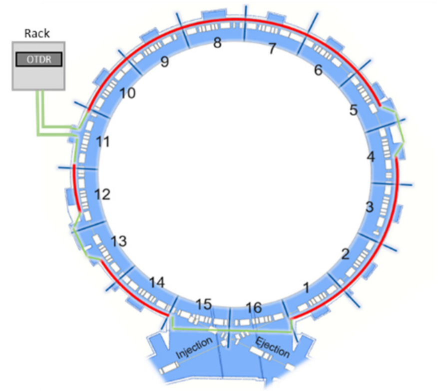

Figure 1: Layout of the PSB with the 16 periods in evidence. The red line shows the section of the machine where the OF cable lies on the cable tray.

After demonstrating the working principle of DOFRS [4], an operational prototype was installed in the Proton Synchrotron Booster (PSB) tunnel during 2016/17 end of the year technical stop [5]. The PSB has a total length of 157 m and is made of 16 almost identical periods. It is composed by four superimposed synchrotron rings that receive 50 MeV protons from LINAC2 and accelerate them up to 1.4 GeV before extraction.

In Figure 1, we show a schematic representation of the OF cable path in PSB, with the two fiber ends reaching the rack on ground level. The red line represents the sections of the machine where the OF cable lies on the cable tray at fixed distance from the beamline, on circumference arcs. All deviations from the circular path are due to the tunnel architecture and are represented in green. The longest deviation is in the injection-extraction zone, which corresponds to periods 15 and 16, as can be seen from Figure 1.

In this area the fiber gets closer to the ceiling and passes above the injection/extraction beamlines.

In Figure 2, we show a cross section of PSB tunnel to highlight the relative positions of the four superimposed rings and the cable duct containing the OF sensor, located on the outer wall of the tunnel. The OF cable runs at a distance of 1.5 m from the topmost of the four synchrotron rings for most of its path. Previous Monte Carlo simulations, based on high level dosimetry measurements, showed an average reduction factor of the dose from the beamlines to the outer wall of about 5 [6].

The rack containing the interrogator unit is located in a non-hazardous and radiation free area, which is accessible at any time. From the rack, the OF sensor can be interrogated in both directions since both OF extremities are available. A control unit in the rack is used to carry out data acquisition cycle in continuous mode and store the measurements. It is worth to mention that because of the way the OF cable is deployed, the recorded traces are longer than the actual length of the accelerator.

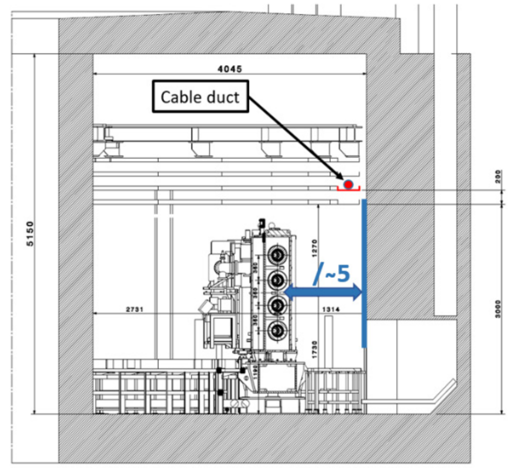

Figure 2: The PSB tunnel cross section. The OF cable position, at ~1.5 m of distance from the topmost of the four synchrotron rings, is highlighted in red. In blue the dose average reduction factor from the beamlines to the tunnel outer wall [6].

Therefore, in order to retrieve the correct correspondence between points in the measured radiation map and locations in the tunnel, it was necessary to carefully study the cable deployment. Another possibility would be to perform a cable marking, in some locations of choice, by means of portable radioactive source.

In addition to providing online and distributed measurement of the dose along the OF sensor, the DOFRS has other interesting characteristics: a depleted OF sensor can be replaced via cable-blowing technique, which eliminates the necessity to access the tunnel; a single OF cable can contain several optical fibers that allow to address very different radiation environments at the same time and measure the temperature and its variation with a sensitivity a few degrees.

AUXILIARY PASSIVE DOSIMETRY

As already mentioned, several active point dosimeters are installed in the machine tunnel. However, these are always positioned at very specific locations near the beamlines and cannot be used to make direct comparison with DOFRS data. For this reason, before the start of 2017 operations, we installed several passive dosimeters in close proximity to the OF sensor. We used two types of passive dosimeters: Radio Photo-Luminescence (RPL) dosimeters [7], which are glasses that develop a phosphorescence when exposed to radiation; and Radiation-sensing FET (RadFET) that are p-channel MOS transistors that experience a charge build-up in the insulating SiO_2 layer under radiation [8]. Both dosimeter technologies were calibrated at ^{60}Co γ-rays and qualified in CHARM. When used in the mixed field an absolute uncertainty of 25% is usually considered. However, because of the coherent calibration procedure, the relative uncertainty among dosimeters should be lower.

In the aim of benchmarking DOFRS measurements with other sensors, RPL where attached to the OF sensor in period 1 and beginning of 2, 8 and 14, whereas the RadFETs

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were attached only in period 1 and in beginning of period 2. It is worth to mention that the RPL and RadFET in periods 1 and 2 have been positioned at the same locations. Therefore, they have been exposed to the same radiation field. All passive dosimeters were collected at the end of 2017 operation and measured. The choice of the three regions for the benchmarking was based on the results of some previous studies on radiation levels [6].

RESULTS AND DISCUSSIONS

The prototype of DOFSR installed in PSB acquired data during the whole operational year 2017. Some preliminary results (until about half of last year operations) were reported in ref. 5.

In Figure 3, we show the cumulated radiation doses measured along the OF sensor at the end of the operations, about 250 days from the beginning of data acquisition.

It is possible to distinguish two large regions where there are measurable radiation levels. The first one, between 70-110 m, corresponds to injection-extraction zone of the PSB. It concerns mainly periods 1, 14, 15 and 16. The second one, between 175 to 210 m, corresponds to periods from 8 to 11.

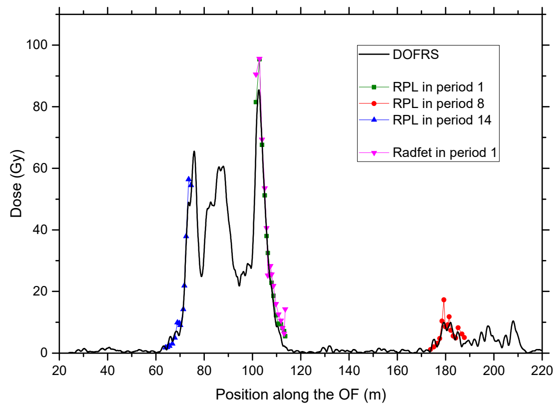

Figure 3: Comparison between the cumulated radiation doses measured by the DOFRS in PSB at the end of 2017, and the passive dosimeters installed at the OF cable location.

The highest dose peak corresponds to the beginning of period 1, whereas we can link the first peak of area between 70-110 m with the end of period 14. Unlike the injection/extraction zone, in periods 8, 9 and 10 the OF cable lies on the cable tray at fixed distance from the beamline. Here, the total radiation doses are clearly much lower. As it can be seen in Fig. 3, if we consider a radiation sensitivity of 3 mdB m^{-1} Gy^{-1} we have a good agreement between the doses measured by the DOFRS and the passive dosimeters. The considered radiation sensitivity is compatible with the fiber calibration curve reported in ref. 4. However, we should notice that this value corresponds to the lowest radiation sensitivity within the spread of calibration curves of Figure 2 of ref. 4. Beside the crosscheck with the measured radiation dose values, the comparison between DOFRS traces and passive dosimeters enable us to verifying the correct spatial registration of the traces with respect to the machine.

Both spatial and temporal dependencies of the radiation levels in PSB can be represented in a single three-dimensional colour map, as shown in Figure 4. During the year the radiation dose traces almost preserved its shape, indicating a rather stable radiation field pattern [5]. The lowest detection limit for our dosimeter was assessed at ~3Gy, whereas the maximum measured dose was ~80 Gy (30% associated uncertainty). The interrogator optical budget was sufficient to monitor radiation levels during the whole year without difficulty and using the highest spatial resolution.

CONCLUSION

In this work, we described the implementation of the first DORFS prototype installed at CERN in the PSB accelerator in 2017. After one year of online data acquisition, we were able to generate a spatial/temporal radiation map of 2017 in PSB tunnel, demonstrating the system capabilities to monitor the cumulated radiation dose along the sensing cable. Moreover, we performed a comparison with passive dosimeters installed at the OF cable location. The comparison with passive dosimeters and DOFRS radiation traces is good and compatible with the uncertainty associated to dose measurement.

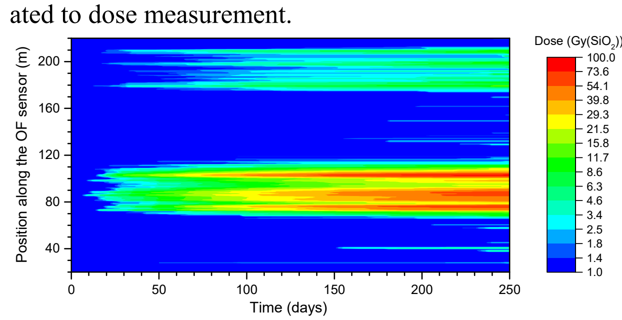

Figure 4: Spatial/temporal color map of radiation dose levels in the PSB during 2017.

The promising results that were obtained led to the new installation of the DOFRS system in Proton Synchrotron (PS) (628 m) at the beginning of 2018 and stimulated further development and additional deployment in larger machines at CERN. During the long shut down 2, we foresee to install it in the whole SPS (~7 km), and in six regions of LHC (dispersion suppressor regions).

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