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A SYSTEMATIC ANALYSIS OF THE PROMPT DOSE DISTRIBUTION AT THE LARGE HADRON COLLIDER

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Abstract

During the operation of the Large Hadron Collider (LHC) the continuous particle losses create a mixed particle radiation field in the LHC tunnel and the adjacent caverns. Exposed electronics and accelerator components show dose and fluence dependent accelerated aging effects. In order to achieve an optimal lifetime associated to radiation damage, the position of the equipment is chosen in dependency of the amplitude of the radiation fields. Based on the continuous analysis of the data from more than 3900 beam loss monitors the evolution of the radiation levels is monitored during the accelerator operation. Normalising the radiation fields with either the integrated luminosity or the integrated intensities allows the comparison of the radiation levels from different operation periods. In this paper, the general radiation levels in the arcs and the insertion regions (IRs) at the LHC and their evolution are presented. The changes in the prompt dose distribution along the LHC between the operation in 2016 and 2017 will be discussed. The impact of different accelerator settings on the local dose distribution will be addressed as well.

INTRODUCTION OF THE LHC

The LHC is a 26.7 km long circular particle accelerator/collider. In the LHC two high intensity proton or ion beams are stored at energies of up to 7 TeV. The two in opposite direction circulating beams are brought into collision in the center of the four large experiments, ATLAS, ALICE, CMS and LHCb. Outside the experiments the beams circulate in two beam pipes which are separated by 19.5 cm in the horizontal plane. During the operation of the accelerator small amounts of particles are lost which create a prompt radiation field along the LHC. The prompt radiation causes accelerated aging of the exposed elements, e.g. electronics, which results in a reduced lifetime. Therefore the knowledge of the dose distribution is important for choosing the correct position for the elements in order to optimise their lifespan. In this paper the focus is on the proton operation.

MONITORING THE TOTAL IONISING DOSE AT THE LHC

With more than 3900 installed beam loss monitors (BLMs) the particle losses are monitored during the LHC operation with a very high granularity [1]. These detectors are installed outside the cryostats in the cold sections or close to the beam pipes in the warm section of the LHC, see Fig. 1. Depending on their position in the horizontal plane of the beam, the measurements are dominated by the losses of the beam closer to the monitor, which allows to distinguish the losses from the two beams. From the BLM data sets the total ionising prompt dose (TID) at the position of the BLM can be calculated for every period of the accelerator operation. By filtering TID data by the BLM position with respect to the beams the radiation profile for each beam along the accelerator can be derived.

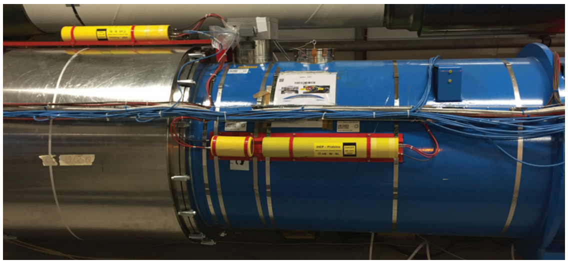

Figure 1: Ionisation chamber BLMs installed outside of a LHC dipole magnet.

SOURCE MECHANSIMS OF THE DOSE LEVELS AND THEIR NORMALISATION

Multiple parameters and accelerator settings influence the profile of the dose distribution along the LHC and the dose levels. In general the local dose levels scale with local losses along the accelerator. Since the collimators deliberately intercept particles from the beam, the openings of the collimators in the accelerators have a strong influence on the radiation profile [2]. Beside the particle losses on the collimators there are two loss mechanisms, which lead to an increase of the dose levels. During the luminosity production collision debris is lost downstream of the experiments causing high radiation levels in the final focusing section, in the matching section and in the dispersion suppressors including the beginning of the arc sections. These levels scale with the integrated luminosity of the experiment. The second mechanism contributing to the dose distribution is the continuous loss of particles along the accelerator due to beam gas interactions with the residual gas molecules in the beam pipe. In this case the dose levels are proportional to the integrated beam intensities in the LHC, as well as to the residual gas pressure. In order to compare the dose levels from different periods of the LHC operation the dose distributions are normalised, depending of the position in the accelerator, either with the integrated luminosity or the integrated beam intensities.

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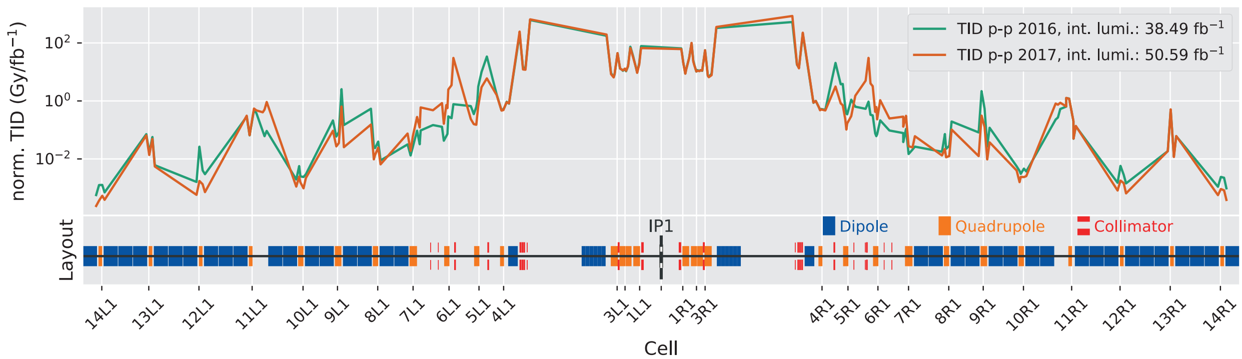

Figure 2: Dose distributions normalised with the integrated luminosity in IR 1 for the years 2016 and 2017.

IONISING DOSE DISTRIBUTION NORMALISED WITH INTEGRATED LUMINOSITY IN IR 1

The insertion region one (IR 1) houses the ATLAS experiment. In its center the two beams of the LHC are collided. The particle collisions cause a change of the transverse and forward momentum of the outgoing particles. These debris particles create secondary showers when they are lost downstream of the interaction point (IP) resulting in mixed field radiation distributions with high levels. The highest dose rates were measured at the absorber blocks and at the collimators where the debris particles with a too large transverse momentum are intercepted in order to protect the down stream accelerator components. Due to the symmetry of the accelerator layout around the IP the resulting dose distribution is very symmetric. The dose in cell 3 and cell 4 reached more than 23.7 kGy in 2016 and even 33.0 kGy in 2017.

Figure 2 displays the normalised dose distribution in IR 1 for the years 2016 and 2017. To compare the data sets of the two years the distributions were normalised with the corresponding integrated luminosity for the proton-proton operation, 2016: 38.49 fb^{-1} and 2017: 50.59 fb^{-1}. Even with the 30% higher luminosity in 2017 the normalised dose levels close to the IP have very comparable values. A difference is visible from cell five to cell nine on both sides of the experiment. The peaks result from different openings of the collimators, TCL5 and TCL6 during the two years. In 2016 the TCL 5 was closed (15 σ) and TCL 6 was open. In 2017 TCL5 was more opened (35 σ) and TCL6 was mainly closed (20 σ), according to the needs of the forward physics experiments [2] [3]. The openings of the collimators have a strong influence on the dose distribution. In the dispersion suppressor region, cell seven until cell eleven, and the adjacent arc section the normalised dose distributions of the two years reached again similar levels. The peaks in this region are caused by debris particles with a forward momentum exceeding the LHC momentum acceptance. These particles are lost due to the increasing dispersion in the dipole magnets. The normalised dose levels stretch fro m60 mGy/fb^{-1} in the dispersion suppressor sections up 650 Gy/fb^{-1} close to the IP.

DOSE DISTRIBUTION IN THE LHC ARC SECTIONS

In the LHC arc sections the dominating loss mechanism is the interactions of the beam with the residual gas creating the prompt dose distribution. Circulating particles scatter with the residual gas molecules which are assumed to be equally distributed in the beam pipe. The particle losses scale with the residual gas pressure and the integrated beam intensities. Figure 3 shows the exemplary dose distribution in the LHC arc section between IR 1 and IR 2. This sector is representative for all the LHC arcs. The first two plots in Fig. 3 show the annual total ionising prompt dose of 2016 and 2017 distinguishing between the two circulating beams in the LHC. In the third plot in Fig. 3, the dose distributions normalised with the corresponding integrated intensities are displayed, which allow the direct comparison between the two years of operation. Deeper in the arc the base line of the dose distribution is at about 80 mGy in 2016 and 40 mGy in 2017. The reduction of the base line from 2016 to 2017 is most probably due to an improvement of the vacuum levels in the arc sections, which results in less beam gas interactions.

Dose Peaks in the LHC Arcs

In addition to the regular loss pattern at the base line levels in the arcs, several dose peaks are visible in Fig. 3. The dose distribution peaks in the cells 12 - 18 result from the dispersive collision debris from ATLAS. They decrease with distance to the IP. At some positions deeper in the arc additional peaks were observed which exceed the base line level by up to two orders of magnitude resulting in local dose levels of up to 10 Gy. In 2016 the data showed a peak in cell 21L2 with 7.7 Gy. However, in 2017 peaks were recorded in the cells 19L2 with 2.3 Gy and in 16L2 with 2.6 Gy. The smaller peaks in the arc exceed the base line level by up to a factor five. The peak distribution is individual in each arc section. There are different loss mechanisms driving these peaks. Some of these peaks correlate with the luminosity production in the experiments some of the peaks are caused by local aperture and intensity limitations. The analysis of the dose evolution over time allows to correlate these peaks with changes of the accelerator settings.

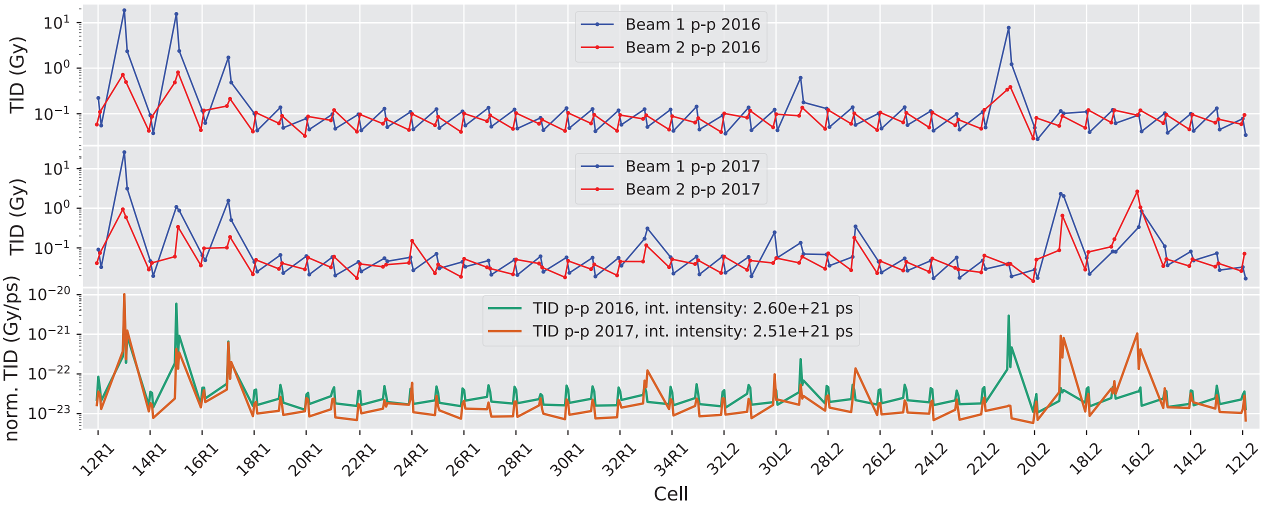

Figure 3: Distributions of the absolute dose and the TID normalised with the integrated intensity in the LHC arc section between IR 1 and IR 2 for the years 2016 and 2017.

Evolution of the Dose Peaks During the LHC Operation in 2017

By comparing the peak locations between 2016 and 2017, the change between the years is clearly visible. In 2017 the peak in the cell 21L2 vanished while two new peaks occur in the cells 19L2 and 16L2. Figure 4 displays the evolution of the TID of the BLMs which recorded the peaks in 19L2 and 16L2. The measurements show that these peaks are very localised. In 2017 some dump events were accompanied by losses in cell 16L2. These losses were most probably caused by condensed rest gas on the beam screen, a remnant from an incorrect evacuation procedure of the beam pipe. In order to reduce the condensed gas the beam screen was flushed with liquid helium in August 2017, indicated by the red line in Fig. 4. The trend of the dose was very steep before the flushing process. Afterwards the trend of the dose changed significantly to lower loss rates during the LHC operation. The dose rate of the peak in 19L2 already increased during the year until the trend of the dose evolution changed drastically in October 2017. The increase of the trend coincides with the reduction of the β^* in the experiments ATLAS and CMS. These measurements proof that deep in the arcs some losses are driven by the luminosity production.

CONCLUSION

The systematic analysis of the BLM data shows that small changes in the accelerator settings can have strong influence on the dose distribution in the LHC. The dose peaks in the arc sections reach values two orders of magnitude larger than the base line. Peaks have a very dynamic evolution so that the amplitude and position can change during the accelerator operation. Therefore a detailed temporal analysis of the dose evolution is necessary to evaluate the impact of the changes in the accelerator settings on the dose distribution. The measured dose distributions give limitations for future installations and indications if the relocation of existing equipment is necessary.

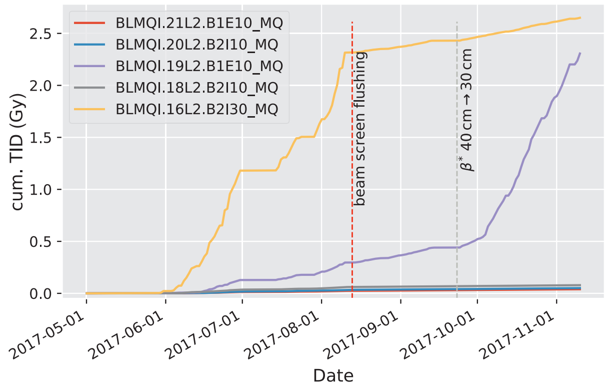

Figure 4: Evolution of total ionising dose measured by selected BLMs in the LHC arc between IR1 and IR2.

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