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RUN 2 PROMPT DOSE DISTRIBUTION AND EVOLUTION AT THE LARGE HADRON COLLIDER AND IMPLICATIONS FOR FUTURE ACCELERATOR OPERATION

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Abstract

During the operation of the Large Hadron Collider (LHC) small fractions of beam particles are lost, creating prompt radiation fields in the accelerator tunnels. Exposed electronics and accelerator components show lifetime degradation and stochastic Single Event Effects (SEEs) which can lead to faults and downtime of the LHC. Close to the experiments the radiation levels scale nicely with the integrated luminosity since the luminosity debris is the major contributor for creating the radiation fields in this area of the LHC. In the collimation regions it was expected that the radiation fields scale with the integrated beam intensities since the beams are continuously cleaned from particles which exceed the accelerator's acceptance. The analysis of radiation data shows that the dose measurements in the collimation regions normalised with the integrated beam intensities for 2016 and 2017 are comparable. Against expectations, the intensity normalised radiation datasets of 2018 in these regions differ significantly from the previous years. Especially in the betatron collimation region the radiation levels are up to a factor 3 higher. The radiation levels in the collimation regions correlate with the levelling of beta-star and the crossing angle in the high luminosity experiments ATLAS and CMS. These increased normalised doses have direct implications on the expected dose levels during future LHC operation, including the High-Luminosity LHC (HL-LHC) upgrade.

THE LHC RADIATION ENVIRONMENT

The LHC is a 26.7 km long circular particle accelerator that contains eight Insertion Regions (IR). These IRs are interconnected by the arc sections which are composed of a regular FODO layout enclosed by dispersion suppressors at the beginning and at the end. In the LHC two proton or ion beams are stored at energies up to 7 TeV for protons and up to 6.3×Z TeV for ions, and circulate in opposite directions. The beams are brought into collisions in four IRs which host the four large experiments, ATLAS (IR1), ALICE (IR2), CMS (IR5) and LHCb (IR8). In IR3 and IR7 dedicated collimation systems are installed to intercept particles which exceed the dynamic aperture of the accelerator. IR4 houses the RF-system with the cavities for accelerating the particles. In IR6 the beam dumping system is installed.

During the accelerator operation small fractions of the stored particles are lost. The continuous losses result in mixed radiation fields whose properties strongly depend on the position along the accelerator. Three major mechanisms can be identified causing continuous losses. The majority of particles are lost due to the particle collisions in the experiments, luminosity burn-off, creating localised radiation levels in the regions of experiments exceeding annual doses of 160 kGys [1]. Dose levels in these regions strongly correlate with the integrated luminosity, which is a direct measure of the particle collision yield. The second largest contributor are the losses in the collimation regions in IR3 and IR7 from particles which exceed the dynamic aperture, resulting in annual dose levels of 70 kGy in IR7 and 1.6 kGy in IR3.

The third mechanism are losses from beam interactions with the residual gas in the accelerator causing annual radiation levels all around the accelerator below 100 mGy [2]. In this paper the focus is on the total ionising dose (TID) levels in the betatron collimation region in IR7.

Impact of Mixed Radiation Fields on the Accelerator Performance

The mixed radiation fields can impact the machine operation by inducing magnet quenches or by causing damage to materials and electronic equipment. A first class of errors induced on the electronic systems is related to their lifetime degradation, which depends on the TID accumulated by the devices or, alternatively, on the Displacement Damage (DD) produced by nuclear interactions in sensitive materials. In parallel, stochastic Single Event Effects (SEEs) can be induced proportionally to the fluence of High Energy Hadrons (HEH) or thermal neutrons, affecting the availability of critical electronic systems during the LHC operation.

MONITORING THE RADIATION FIELDS

In order to monitor the impact of the losses on the sensitive equipment, it is essential to measure the radiation environment in all the relevant areas of the LHC machine.

The TID can be retrieved from the LHC beam loss monitoring system consisting of more than 3500 beam loss monitors distributed along the LHC tunnel, which are ionisation chambers filled with nitrogen gas [3].

A dedicated software framework is employed to calculate the TID levels measured by the BLM system in the LHC tunnel. The time-integrated TID from every BLM detector is calculated individually for every beam present interval, i.e. time interval during which at least one beam is circulating in the LHC. The final uncertainty on the dose calculations is about 10% resulting from the propagated uncertainties of the readout electronics and the BLM calibration factor.

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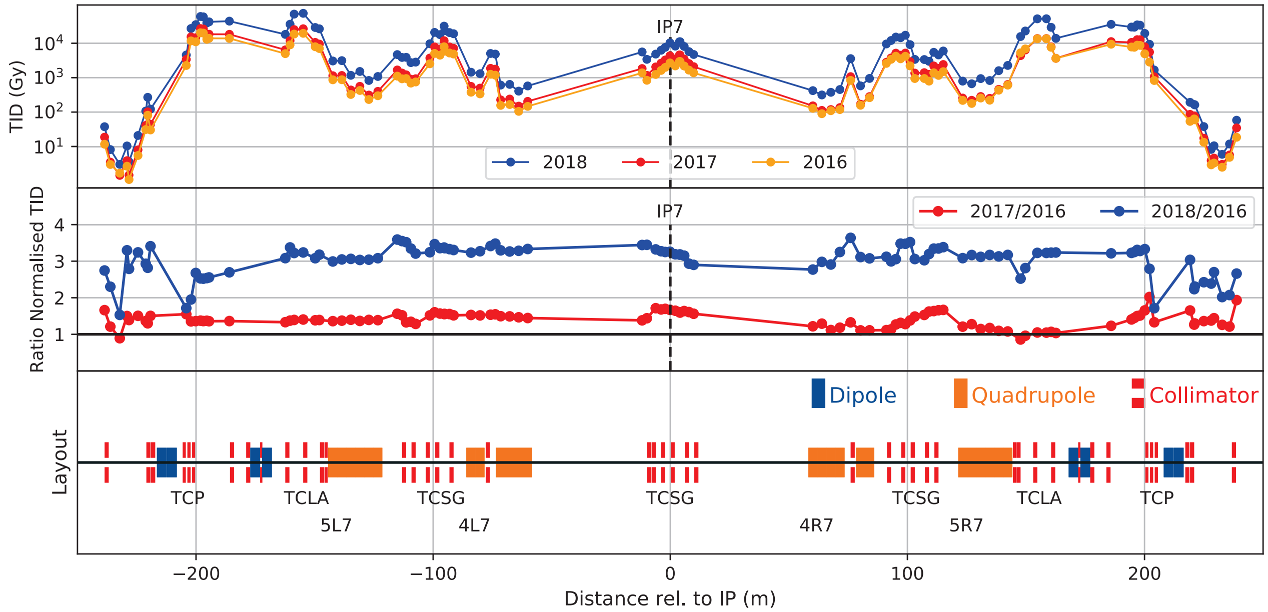

Figure 1: Distributions of absolute TID levels in 2016, 2017 and 2018 (top), 2018/2016 and 2017/2016 ratios of TID normalised with annual integrated beam intensity (middle) and accelerator equipment (bottom) in IR7.

Close to the experiments the TID levels are proportional to the integrated luminosity, while in the collimation and arc sections of the accelerator the levels are expected to scale with the integrated beam intensity [4]. In order to compare the doses from different periods of accelerator operation, these two quantities are hence computed for normalisation purposes. Since the radiation fields are a direct result of particle losses, the number of lost protons from the luminosity production (burn-off) and in the collimation regions are calculated too. Table 1 presents the integrated beam intensities for the sum of beam 1 and beam 2 expressed in proton seconds (ps) and the integrated luminosities of ATLAS and CMS in fb^{-1} in 2016, 2017, 2018 together with the annual expectations for nominal LHC operations in Run 3 and for HL-LHC. The table also includes the number of lost protons in luminosity burn-off and in the collimation regions.

Table 1: Integrated beam intensities ($I_{\mathrm{int.}}$), luminosities ($\mathcal{L}_{\mathrm{int}}$) and number of lost protons due to luminosity production ($N_{\mathrm{lost}}^{\mathrm{lumi}}$) and due to collimation in IR3 and IR7 ($N_{\mathrm{lost}}^{\mathrm{coll}}$). The Run 2 values are measured, while the annual Run 3 and HL-LHC numbers are based on expectations or extrapolations, as described in the text.

	2016	2017	2018	Run 3	HL-LHC
$I_{\mathrm{int.}}$ (10^{21} ps)	2.6	2.5	3.0	4.5	6.0
$\mathcal{L}_{\mathrm{int}}^{\mathrm{ATLAS}}$ (fb^{-1})	38.5	50.6	65.2	100	250
$\mathcal{L}_{\mathrm{int}}^{\mathrm{CMS}}$ (fb^{-1})	41.0	50.0	66.8	100	250
$N_{\mathrm{lost}}^{\mathrm{lumi}}$ (10^{15}p)	12.4	15.6	20.4	34	85
$N_{\mathrm{lost}}^{\mathrm{coll}}$ (10^{15}p)	2.9	3.0	10	15	20

DOSE LEVELS IN THE LHC

The dose distributions along the LHC are calculated for proton-proton and ion operations on annual bases. In Table 2 exemplary normalised TID values are listed. Even though the annual integrated luminosities differ significantly, the normalised dose levels in IR1 and IR5 were relatively constant over the three years of LHC operation with variations smaller than 10%, which is in the range of the uncertainties for the calculated dose values. In the collimation regions the dose levels normalised with the integrated beam intensities were not that constant. In IR3 a decrease of the dose was observed, while the normalised doses in IR7 increased significantly. It should be noted that the dose levels in IR7 are significantly higher compared to IR3. The absolute maximum dose values were consistently recorded close the primary collimators (TCPs). Additionally very high values were observed at the secondary collimators (TCS) and the long absorber collimators (TCLs), see Figure 1.

Table 2: TID measurements close to ATLAS and CMS normalised with the integrated luminosities (Gy/fb^{-1}) and measurements in IR7 normalised with the integrated intensity (Gy/10^{21}ps).

BLM name	IR	2016	2017	2018
BLMQI.03L1	1	180	190	190
BLMQI.01R5	5	250	260	250
BLMTI.06L3	3	320	280	230
BLMTI.06L7	7	4200	5800	11000

TID Distribution in IR7

In Figure 1 the dose distributions in IR7 for the years 2016, 2017 and 2018 are displayed. In addition the ratios of the normalised dose values 2017/2016 and 2018/2016 are shown. It is clearly visible that the increase of the normalised doses is not a local effect but affects the whole collimation region. The normalised dose levels increased by around 50% between 2016 and 2017. Between 2017 and 2018 an additional increase by a factor 2.5 was observed. This increase indicates that the proportionality of the dose levels with the integrated intensity alone in this region of the LHC can be spoiled.

Changes of the accelerator operation can have a direct impact on the losses in the collimation regions and therefore have to be taken into account if the different periods of accelerator operation are compared. Figure 2 shows the loss signal of two representative fills in IR7, one from 2016 and the other from 2018. Both fills have comparable beam intensities and duration and the dose rates were recorded with the same two BLMs, recording beam 1 and beam 2 losses respectively. It is clearly visible that the loss pattern changed, and in 2018 the dose rates were much higher compared to the levels in 2016. In addition, steps can be identified in the 2018 signals which coincide with the reduction of beta star of the main experiments (β^*) from 0.3 m to 0.27 m and subsequently to 0.25 m for this fill, highlighting a correlation between this variable and the IR7 losses. In addition to the lower beta star, a progressive levelling of the crossing angle between the beams in IR1 and IR5 was also performed during the 2018 operation.The increase of TID in IR7 in 2018 showed that the optimisation of the accelerator performance for larger luminosity production can have significant impact on the TID levels along the accelerator. Since the local radiation fields directly correlate with the number of locally lost protons, using the number of lost protons is a more robust measure for scaling the losses in the collimation region in IR3 and IR7. The increase of the number of the lost protons in the collimation regions from 2017 to 2018 coincides with the increased TID values, see Table 1.

IMPLICATIONS FOR FUTURE LHC AND HL-LHC OPERATION

The measurements from 2016, 2017 and 2018 operations can be used as reference for extrapolating the dose levels for LHC Run 3 and HL-LHC operations [5]. The losses and the resulting radiation levels in 2016 and 2017 can be seen as a favourable case for future operation, while in 2018 higher losses were observed. Using the 2018 data for scaling is hence a more conservative approach, which reduces the likelihood of underestimating the radiation levels for future operation.

Based on Table 1, the expected number of lost protons in Run 3 and HL-LHC (for the sum of beam 1 and beam 2) for integrated intensity scaling is approximately $5.4 \cdot 10^{15}$ and $7.2 \cdot 10^{15}$ per year when computed from 2017 data, while it grows to $15 \cdot 10^{15}$ and $20 \cdot 10^{15}$ per year when computed from 2018 data.

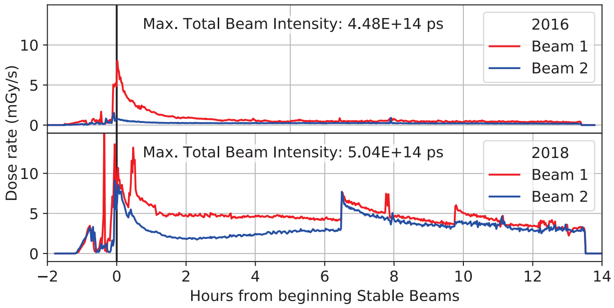

Figure 2: Loss signals in IR7 for two comparable exemplary fills of the LHC from 2016 and 2018.

CONCLUSION

The measured dose levels per unit integrated beam intensity in the IR7 region of the LHC accelerator increased from 2016 to 2017 by approximately 50% and from 2017 to 2018 by an additional factor 2.5, as a result of changes in the beam parameters aimed at increasing the rate of luminosity production in the experiments. A similar scaling was observed in the number of lost protons in the collimators. The estimated total number of lost protons in collimators during the HL-LHC operation is computed under the assumption of integrated beam intensity scaling starting from the Run 2 measurement. If the 2018 operation is used as starting point, the HL-LHC prediction increases by more than a factor 2 compared to the estimate based on 2017 data.

REFERENCES

[1] O. Stein *et al.*, “Identification and Analysis of Prompt Dose Maxima in the Insertion Regions IR1 and IR5 of the Large Hadron Collider”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 2078–2080. `doi:10.18429/JACoW-IPAC2017-TUPVA016`

[2] K. Bilko, O. Stein, K. Malarz, “Detailed analysis of the evolution and distribution of the total ionising dose in the LHC arc sections during the accelerator operation”, CERN, Switzerland, CERN-THESIS-2018-307, 2018. `http://cds.cern.ch/record/2652979`

[3] E. B. Holzer *et al.*, “Commissioning and Optimization of the LHC BLM System”, in *Proc. 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB’10)*, Morschach, Switzerland, Sep.-Oct. 2010, paper WEO1C01, pp. 487–491.

[4] O. Stein *et al.*, “A Systematic Analysis of the Prompt Dose Distribution at the Large Hadron Collider”, in *Proc. 9th Int. Particle Accelerator Conf. (IPAC’18)*, Vancouver, Canada, Apr.-May 2018, pp. 2036–2038. `doi:10.18429/JACoW-IPAC2018-WEPAF082`

[5] R. García Alía *et al.*, “LHC and HL-LHC: Present and Future Radiation Environment in the High-Luminosity Collision Points and RHA Implications”, *IEEE Trans. Nucl. Sci.*, vol. 65, no. 1, p. 448, 2018. `doi:10.1109/TNS.2017.2776107`