# IDENTIFICATION AND ANALYSIS OF PROMPT DOSE MAXIMA IN THE INSERTION REGIONS IR1 AND IR5 OF THE LARGE HADRON COLLIDER

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*Abstract*

During the operation of the LHC the continuous particle losses create a radiation field in the LHC tunnel and the adjacent caverns. Exposed electronics and accelerator components show dose dependent accelerated aging effects and stochastic Single Event Effects (SEEs) which can lead to faults and downtime of the LHC. In order to achieve an optimal life duration, the position of the equipment is chosen in dependency of the amplitude of the radiation fields. Therefore, it is crucial to monitor the prompt dose distributions along the whole LHC. By using the LHC beam loss monitor and RadMon systems, the prompt dose during the accelerator operation is continuously monitored. Measurements in the long straight sections, the adjacent dispersion suppressors and the beginning of the arcs in IR1 (ATLAS) and in IR5 (CMS) have shown that the radiation levels have localised maxima which exceed the baseline by 1 to 2 orders of magnitude. In this paper the analysis of these radiation peaks will be presented and the underlying loss mechanisms will be discussed. The results will help to identify areas not suitable for radiation sensitive electronics. Implications on the expected radiation levels for High-Luminosity LHC (HL-LHC) are also discussed.

## 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. In this paper the focus is on the proton operation.

## THE RADIATION MONITORING SYSTEM AT THE LHC

For measuring the radiation levels different monitor systems are installed at the LHC. The active monitors, e.g. the beam loss monitors (BLMs), the radiation monitors (RadMons) are connected to the CERN network [1] [2]. Their data is stored continuously in the CERN logging data base. Passive monitors, e.g. standalone radiation sensitive field effect transistors (RadFETs) and the radio-photoluminescenct glas dosimeter (RPLs) need to be read out manually on regular bases. These passive monitors are installed in regions of special interest. The beam loss monitoring system with more than 3900 installed ionization chamber BLMs allow monitoring the losses with a high granularity. The BLMs are installed outside the cryostats and the beam pipes of the LHC, see Fig. 1. Depending on their position, outside in the horizontal plane of the beam the measurements are dominated by the losses of the beam closer to the monitor. By filtering the beam loss monitors by their position in respect to the beams the loss profile of each beam along the accelerator can be derived. By integrating the beam loss induced prompt dose, the total ionizing dose (TID) is calculated[1]. The active logging of the loss data allows the calculation of the TIDs for different accelerator operation intervals.

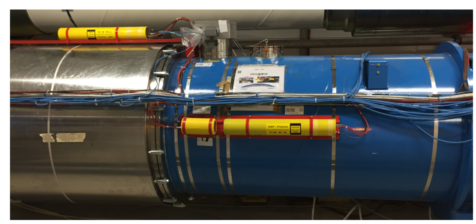

Figure 1: Ionization chamber BLMs installed outside of a LHC dipole magnet.

### *Luminosity Normalized Radiation Measurements*

The radiation levels along the accelerator depend strongly on the LHC availability and the accelerator settings. Close to the collision points, in the long straight sections, the radiation levels are dominated by the losses due to luminosity production. In order to compare radiation levels during different periods of LHC operation the TID is normalized with the total integrated luminosity resulting in grays /fb$^{-1}$. For 2016 the TID for the proton operation was calculated on weekly basis starting with the recommissioning phase in April 2016 until the end of the proton run in November 2016. In average 40 fb$^{-1}$ were delivered.

## PROMPT DOSE MEASUREMENTS IN IR1 AND IR5

The layout of the insertion regions IR1 (ATLAS) and IR5 (CMS) are very similar. In the arcs the magnet lattice has FODO structure with three bending dipoles between the quadrupole magnets. At the end of the arcs the beams pass

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[1] BLMs are filled with nitrogen gas, dose in grays in $N_2$.

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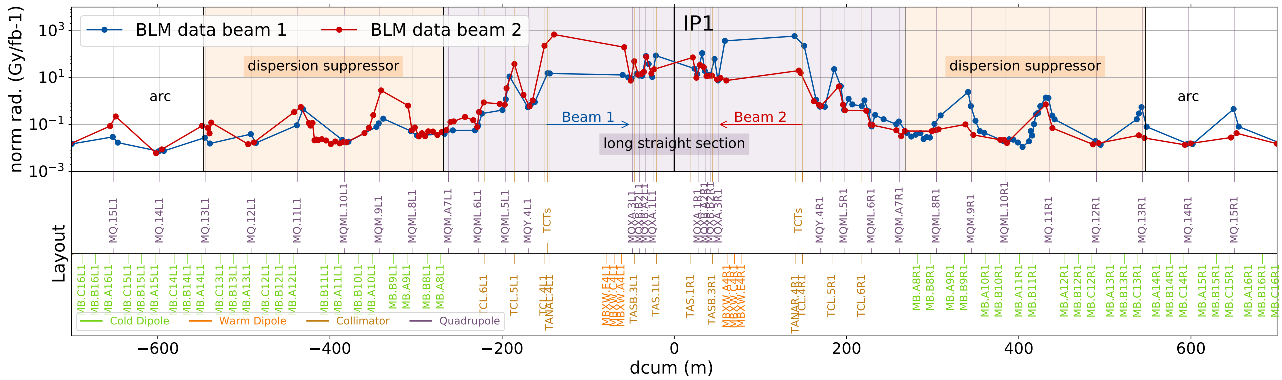


Figure 2: Dose measurements normalized with the integrated luminosity for beam 1 and beam 2 in IR1 of the LHC. Beneath the dose plot the magnet layout with the TCL collimators are shown.

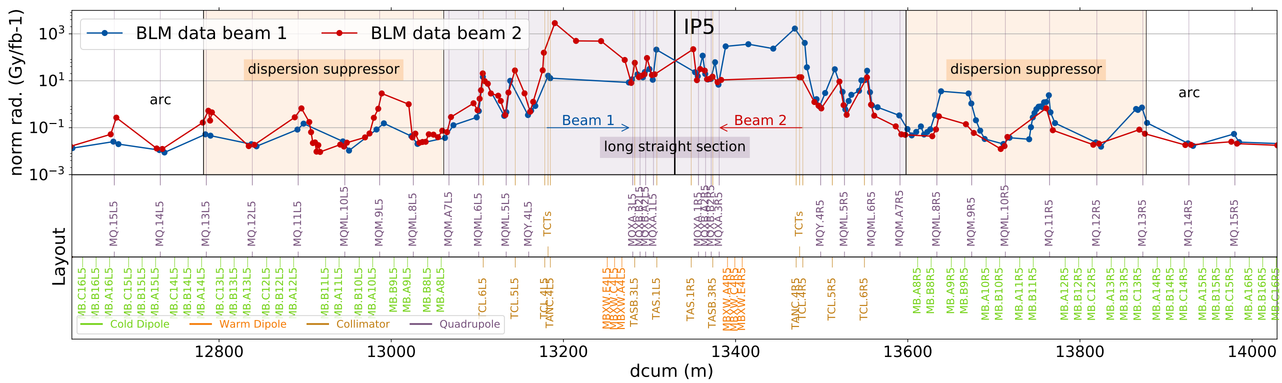


Figure 3: Dose measurements normalized with the integrated luminosity for beam 1 and beam 2 in IR5 of the LHC. Beneath the dose plot the magnet layout with the TCL collimators are shown.

through the dispersion suppressor (DS). At the end of the DS, quadrupoles match the optical function to the long straight section. Special warm dipoles join the two beams into one beam pipe. The final focusing warm quadrupole triplet minimizes the beam size in the collision point. A sequence of collimators protect the radiation sensitive superconducting magnets downstream of the experiment from debris of the particle interactions in the collision points.

### *Measurements of the Radiation Levels*

The measurements of the integrated dose in IR1 and IR5 in 2016 normalized with the luminosity for beam 1 and beam 2 are displayed in Fig. 2 and in Fig. 3. In IR5 the dose level range from $10^{-2}$ Gy/fb$^{-1}$ to $4\times10^3$ Gy/fb$^{-1}$. The regular pattern of focusing and defocusing quadrupoles at the end of the arc section and the beginning of the dispersion suppressor is clearly visible. The dose levels rise in the dispersion suppressor regions. Close to the vertical and horizontal tertiary collimators (TCTs) the dose levels reach a maximum. Taking the integrated luminosity into account the total dose in these regions for the LHC operations in 2016 were calculated. In IR1 the maximum of 25 kGy were measured at TCTs and 100 kGy in IR5 respectively. Additional local maxima are observed close to the long collimators (TCLs). In order to protect the downstream accelerator elements, the collimators form the local aperture bottleneck in the IRs. Losses downstream of the collimators result from dispersive particles due to the rising dispersion functions. The particle interactions in the collision points increase the momentum spread of the outgoing particles. Due to these off-momentum particles the contribution of the outgoing beam to the dose levels is up to two orders of magnitudes higher then the contribution from the incoming beam.

### *Symmetry of the Prompt Dose*

The radiation levels created per beam in IR1 and IR5 during proton-proton operation are symmetric around the collision points. The overall ratio of the two beams is $1.2\pm0.63$ for IR1 and $1.0\pm0.95$ for IR5. These symmetries result from the symmetric settings of the accelerator components of both beams around the collision point of the IRs.

## COLLIMATOR SETTING DEPENDENT RADIATION LEVELS IN IR5

The TCL collimators consist of two movable jaws made of copper for absorbing the high energetic particles. During the periods of colliding beams in 2016 different settings for the collimator gaps of the TCL5 and TCL6 in IR5 were used while the settings for TCL4 were kept constant. In

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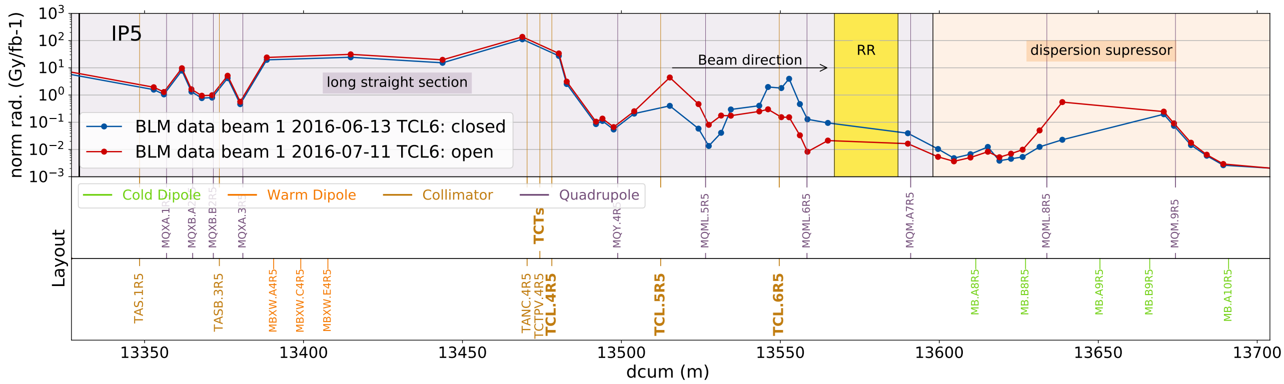


Figure 4: Dose measurements normalized with the integrated luminosity for the right side of the collision point in IR5 (CMS). The changes in the collimator settings lead to significant changes is the radiation levels downstream of the collimators.

Table 1 two periods with two different settings of the TCLs are listed. When the TCL5 was closed TCL6 was open and vice versa. In Fig. 4 the luminosity normalized dose levels for two periods with the different TCL settings on the right side of IR5 are shown. The analysis of the dose levels during the periods with different settings revealed a strong influence of the collimator settings on the radiation levels downstream (outgoing beam) of the collimators. In the first period with TCL5 open and TCL6 closed a local maximum of the dose level was observed direct at the collimator. By changing the collimator settings to TCL5 closed and TCL6 open the dose maximum was moved to TCL5. This reduced the dose at TCL6 by a factor 50 but lead to an increase of the dose levels at TCL5 by a factor 8 and in the dispersion suppressor by a factor 9. In Table 1 the total integrated doses at the TCL5, TCL6, RR, and the dispersion suppressor (DS) are given. The dose levels on the left side of the collision point were comparable.

Table 1: Openings of the Collimators and Total Integrated Doses for Two Different Settings of the TCL5/6 on the Right Side of IR5

| | **13.06. - 20.06.2016** | **11.07. - 18.07.2016** |
|---|---|---|
| TCL5 gap | 22.8 mm | 10.1 mm |
| TCL6 gap | 3.4 mm | 50.0 mm |
| TCL5 | 11.7 Gy | 103.4 Gy |
| TCL6 | 143.3 Gy | 3.1 Gy |
| RR | 3.6 Gy | 0.6 Gy |
| DS | 0.4 Gy | 3.6 Gy |

### *Radiation Level Changes in the RR*

In the service alcove (RR) downstream of the TCL6, electronic systems are installed for controlling accelerator components in this region of the LHC. The exposure of the electronics to the ionizing radiation fields accelerate the dose induced aging effects and can cause single event effects in the electronic components. This can lead to failures in the hardware which then can lead to unwanted downtime of the LHC. To reduce the radiation induced failures, the dose levels have to be as low as possible in RR. Comparing the dose levels of the two different TCL settings, a reduction of the dose level by a factor seven can be achieved by closing TCL5 and opening TCL6. The analysis of dedicated dosimeters at the position of the electronics in the RR will complete the study in the near future.

## CONCLUSION

The LHC BLM system allows monitoring of the radiation levels along the LHC with a high granularity. By normalizing the measured dose with the luminosity allows the comparison of different periods of LHC operation. The dose levels vary over 5 orders of magnitude along the IRs. In 2016, the maximum TIDs were measured at the tertiary collimators with 25 kGy in IR1 and 100 kGy in IR5. The dose levels induced by beam 1 and beam 2 are symmetric around the collision points in IR1 and IR5. Changing the collimator settings of the TCLs in IR5 lead to a favorable reduction of the dose levels in the RR, an alcove with accelerator control electronics.

### *Implications for Future LHC Operation*

The luminosity normalized dose levels at the LHC give dose per $fb^{-1}$ for the accelerator settings in 2016. These values can be used for extrapolating the dose levels for operating the LHC in the coming years. However the changes of the accelerator settings can influence the dose levels significantly. Hence the extrapolated does levels based on 2016 data is only valid if similar accelerator settings are assumed.

## REFERENCES

[1] G. Spiezia et al., "The LHC Radiation Monitoring System - RadMon", Proceedings of Science, vol. RD11, pp. 24, 2011.

[2] E.B. Holzer et al., "Commissioning and Optimization of the LHC BLM System", Proc. of HB'10, paper WEO1C01, p. 487.

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