15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG58

RADIATION LEVELS FROM A BEAM GAS CURTAIN INSTRUMENT AT THE LHC AT CERN

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Abstract

A prototype Beam Gas Curtain (BGC) monitor was installed on beam 1 at the Large Hadron Collider (LHC) at CERN to provide 2D images of the transverse beam profile during the ongoing Run 3 (2022 - to date) and in view of the High Luminosity LHC upgrade (HL-LHC). By design, the BGC operation generates collisions between the beam particles and an injected gas jet proportionally to the beam intensity and the gas density, possibly causing radiation-induced issues to the downstream LHC equipment. In this work, the radiation showers from the BGC are characterized using measured data from different LHC radiation monitors during the Run 3 BGC operation, along with Monte Carlo simulations with the FLUKA code. Finally, predictions of the expected radiation showers during operation of the BGC in the HL-LHC era are discussed.

INTRODUCTION

The scope of this paper is to analyse the radiation levels induced by the Beam Gas Curtain (BGC) [1, 2] monitor installed in Interaction Region 4 (IR4) of the Large Hadron Collider (LHC) at CERN [3] in the context of the Radiation to Electronics (R2E) effort [4]; a priori, the radiation levels in the tunnel and on the equipment downstream caused by the secondary products from the beam gas collisions in the BGC could be non-negligible. The radiation levels measured by the Beam Loss Monitors (BLMs) [5] during the LHC Run 3 (2022 - to date) are compared with dedicated FLUKA [6, 7] simulations, and the latter are subsequently used to make predictions for the operation of these devices in the HL-LHC era [8]. Similar work [9] has been carried out to study the radiation levels generated by the operation of the Beam Gas Vertex (BGV) [10] instrument.

RADIATION SOURCE

For the BGC, the intentional injection of Neon gas increases the local gas density used for the 2D beam image reconstruction. This leads as well to radiation showers and thereby higher radiation levels in the tunnel (relevant for equipment and electronics) and heat loads on magnets (for quench protection). The radiation level rates are assumed to be proportional to the interaction rate of inelastic beam-gas collisions:

$$\frac{dR}{dt} \propto N(t) \cdot f \cdot \sigma \cdot \Theta(t; s_a, s_b) \tag{1}$$

which is proportional to the beam intensity $N(t)$, the LHC revolution frequency $f = 11245$ Hz, the inelastic cross section estimated [11] at $\sigma_{p+Ne,inel} = 320$ mb for a beam of 6.8 or 7 TeV protons hitting the gas atoms[1], and the integrated gas density profile $\Theta(t; s_a, s_b)$ along the s-coordinate in the accelerator region $[s_a, s_b]$. The latter can be expressed as:

$$\Theta(t; s_a, s_b) = \rho_{meas} \cdot \int_{s_a}^{s_b} \frac{\rho(s)}{\rho_{meas}} ds \tag{2}$$

where $\rho(s)$ is the density of gas atoms and ρ_{meas} is the measured value of the gas profile at the pressure gauges. From a measurement perspective, just two data points are available at the BGC, via pressure gauges located upstream and downstream of the instrument. The gas density profile used for the BGC demonstrator in FLUKA has been simulated using MOLFLOW+ [12]. The gas profile injected at the BGC location has been different in the two years of operation analysed so far. In 2022, a distributed gas profile (similar to the BGV [9]) has been used, while in 2023 the actual gas curtain has been added on top of it, contributing to about 20% of the integrated gas density $\Theta(s_a, s, b)$.

FLUKA SIMULATION

The FLUKA Monte Carlo code is capable of simulating the radiation shower caused by the beam-gas interactions. The position of the interactions is sampled along a Continuous Distribution Function (CDF) given by the gas density profile in the beam pipe (Eqn. 2), and the interaction secondaries are propagated in the geometry model of the LHC tunnel. Figure 1 displays a top view of the Total Ionizing Dose (TID) at beam height due to the radiation shower caused by the beam-gas collisions, which extends longitudinally over several tens of meters. In addition to the TID, the FLUKA simulation can be used to compute different radiation level quantities in the tunnel that are relevant for R2E applications and beyond, as well as energy deposition and heat loads in the inner layers of the exposed magnets.

MEASURED RADIATION LEVELS

The primary goal of the analysis on measured data was to verify the proportionality between the TID rate measured by the BLMs (explained below) and the product of beam intensity and gas pressure, based on Eqn. 1. This is equivalent to verifying that the BGC is indeed the dominant source of radiation in the portion of the LHC tunnel downstream of the BGC.

The available radiation level measurement data consists of the Total Ionizing Dose (TID) as deposited in the BLMs.

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[1] assumed at rest, as their thermal energy of 0.025 eV at room temperature is negligible

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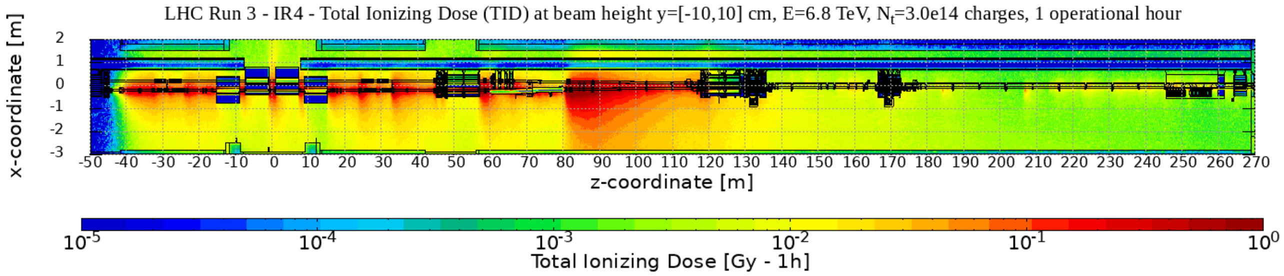

Figure 1: FLUKA simulated radiation shower caused only by the BGC demonstrator on beam 1 (direction: from left to right) for LHC operation, as ZX view, displaying how the shower extends over several tens of meters. The TID is provided at beam height, for a beam at E =6.8 TeV with an intensity of $N_t = 3 \cdot 10^{14}$ charges, and normalized to 1 operational hour.

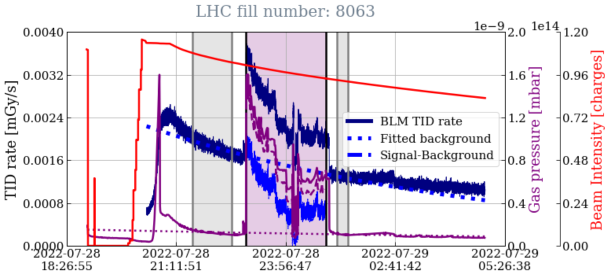

Figure 2: The measured TID rate for the most exposed BLM downstream of the BGC during a reference LHC fill, plotted alongside the beam 1 intensity N_p and the BGC pressure gauge reading p_{BGC}. Both the BLM TID rate and the pressure gauge measurements have been fitted with either exponentially decaying (following the beam intensity evolution) or constant background models.

They are (mostly) Ionization Chambers placed along the accelerator that detect particle showers caused by the beam losses in their active volume of N_2 gas. The BLMs are capable of measuring dose rates with good time resolution down to 40 μs (here, the 1 s running sum has been used). Figure 2 showcases that when gas is injected in the BGC, the BLM TID rate signal increases proportionally to the product of pressure and intensity. However, the background TID levels are not negligible, leading to the need of background modelling (exponentially decaying behaviour over time, following the beam intensity) and subtraction procedures.

One can plot the background subtracted TID normalized by the total number of passing charges as measured by the Beam Current Transformers (BCT) instruments [13] against the background subtracted BGC pressure gauge reading, shown in Fig. 3. The radiation levels downstream of the instrument correlate well with the beam intensity and the gas pressure, indicating that the BGC is indeed the main source of prompt radiation for this BLM. For each monitor downstream of the instrument, the same procedure is repeated, and visible correlations (considered as $R^2 > 0.3$) between the TID per unit intensity and the gauge pressure are observed up to 200 m downstream of the BGC.

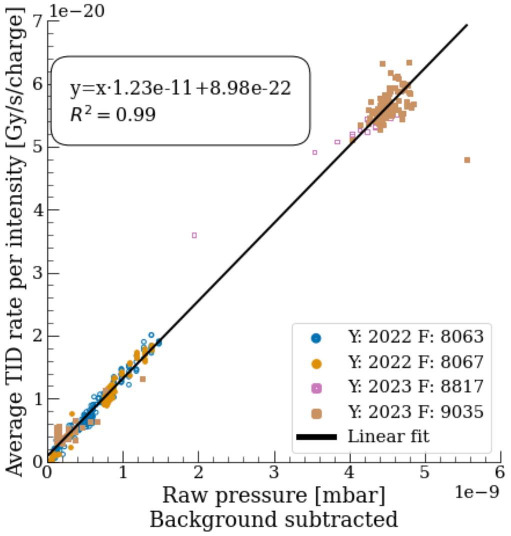

Figure 3: The measured TID of the most exposed BLM divided by the beam intensity N_p plotted against the average BGC pressure gauge reading p_{BGC}.

LHC BGC DEMONSTRATOR BENCHMARK AND HL-LHC SPECIFICATIONS

The radiation levels simulated by FLUKA are compared to the BLM measurements (background subtracted) taken during the operation of the BGC demonstrator in Run 3 (2022-to date) in Figure 4. The shape of the BLM TID profile is well reproduced with a good global agreement within at least a factor of 2 between simulations and measurements, with some outliers at large distance from the radiation source. In other areas of the LHC, such benchmarks have achieved similar levels of agreement [14–16].

Having established its reliability, the same FLUKA simulation (assuming the same operation of the BGC instrument) is then adjusted to replicate the HL-LHC operation, by increasing the beam energy to E=7 TeV, and the computed interaction rate (Eqn. 1) is scaled to HL-LHC beam intensity parameters as well, thus obtaining HL-LHC spec-

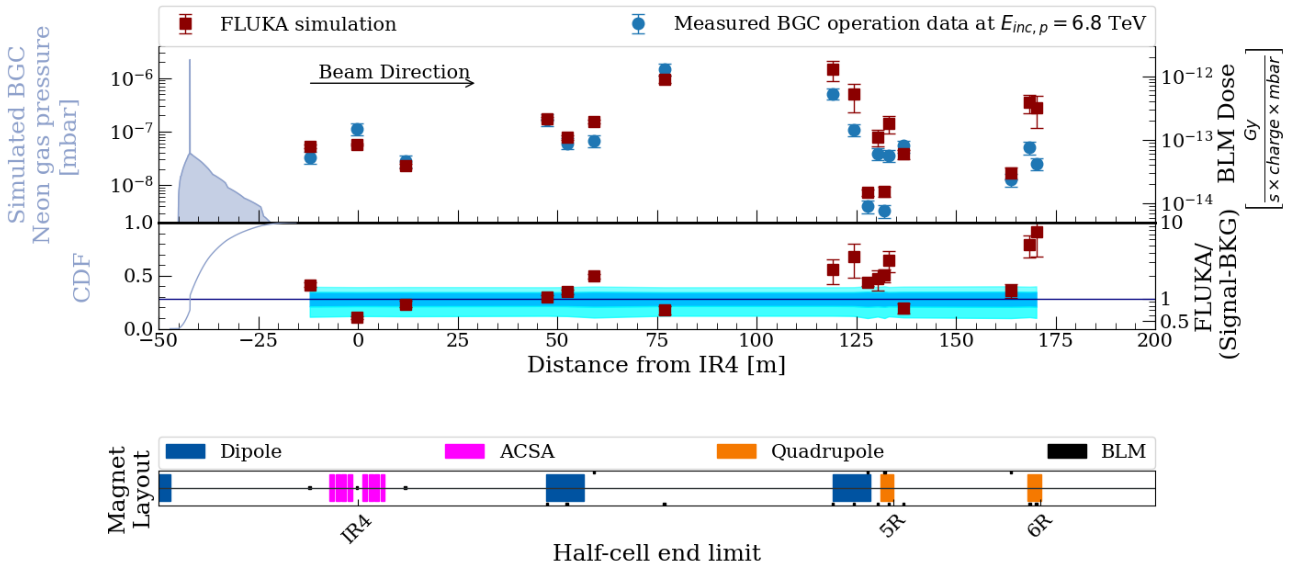

Figure 4: Top panel: The BGC gas density profile used to generate the radiation shower, together with the BLM pattern downstream the BGC placed on beam 1 as measured over the Run 3 proton run (blue points) and as simulated by FLUKA for LHC (red points). Mid panel: The CDF computed from the gas profile, together with the ratio between simulation values and measured data for Run 3, indicating the 1- and 2-σ confidence interval in dark and light blue, respectively. Bottom panel: The machine layout and the BLM locations for the LHC machine.

ifications [17]. The resulting radiation levels are divided into:

1. instantaneous, namely the power deposition on the cryogenic magnets, which are estimated to be at least two orders of magnitude below the quench limits [18]

2. cumulated, as the annual radiation levels depend additionally on the total device operational time, which is estimated at a minimum of 200 h/year during HL-LHC operation, compared to about 100 h/year during Run 3 (2022-to date), for both proton and ion beams [19].

From a machine protection point of view, the simulated radiation levels are not an issue for what concerns the heat loads on the magnets, both as maximum power density or as total power dissipated on the entire magnet. Similarly, the TID levels do not rise any concerns in terms of cumulated damage to the magnets. Further R2E related concerns arise from the fluence of high energy hadrons that could cause Single Event Effects in the electronics, which reveals a levels of above 10^{10} cm^{-2}/year at floor level. From an R2E perspective, TID levels of 1 Gy/year already are a threat in terms of lifetime (assuming a 10 year operation) degradation of electronic systems and the previously mentioned fluences may lead to stochastic electronic failures. Both are significantly (i.e. orders of magnitude) larger than the arc level “baseline”, but lower than the levels near the high luminosity experiments at IP1/5 [20].

CONCLUSIONS

The main result of this study on the radiation levels generated by the BGC instrument is the observed proportionality between the TID measured by the BLMs normalized to the beam intensity, and the measured pressure gauge values. This proportionality is significant, and therefore the BGC is a measureable source of radiation, up to 200 m downstream of the instrument. The comparison between the Run 3 measurements and the FLUKA simulation reveals a good agreement, which is a further confirmation that the origin of the radiation levels is well understood, thereby serving as a reliable basis for predicting the radiation levels for the HL-LHC era. The power deposition on the magnets are estimated to be two orders of magnitude below the quench levels, and neither the TID nor the HEHeq poses critical issues regarding the nominal operation of the accelerator. Nevertheless, the levels are above the typical arc level "baseline" for the LHC, hence the HEH levels could pose SEE related availability issue; however, in this case, it would only affect a small portion of the machine, and hence limited number of units.

ACKNOWLEDGEMENTS

This work has been partly sponsored by the Wolfgang Gentner Programme of the German Federal Ministry of Education and Research (grant no. 13E18CHA).

REFERENCES

[1] H. Zhang *et al.*, "Characterization of a supersonic molecular beam for charged particle beam profile monitor", *Vacuum*, vol. 208, p. 111 701, 2023. `doi:10.1016/j.vacuum.2022.111701`

[2] A. Salehilashkajani *et al.*, "A gas curtain beam profile monitor using beam induced fluorescence for high intensity charged particle beams", *Applied Physics Letters*, vol. 120, no. 17, p. 174 101, 2022. `doi:10.1063/5.0085491`

[3] O. S. Brüning et al., *LHC Design Report*, CERN Yellow Report, 2004. `doi:10.5170/CERN-2004-003-V-1`

[4] *Radiation to Electronics (R2E) at CERN*, Available online: https://r2e.web.cern.ch/ (Accessed on 31 May 2022).

[5] E. B. Holzer *et al.*, "Beam Loss Monitoring System for the LHC", *IEEE Nuclear Science Symposium*, vol. 2, pp. 1052–1056, 2005. `doi:10.1109/NSSMIC.2005.1596433`

[6] *FLUKA website*, Available online: https://fluka.cern (Accessed on 30 August 2023).

[7] C. Ahdida *et al.*, "New capabilities of the fluka multi-purpose code", *Frontiers in Physics*, vol. 9, 2022. `doi:10.3389/fphy.2021.788253`

[8] *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*. CERN, 2020. `doi:10.23731/CYRM-2020-0010`

[9] D. Prelipcean *et al.*, "Radiation levels produced by the operation of the Beam Gas Vertex monitor in the LHC tunnel at IR4", *14th International Particle Accelerator Conference*, vol. IPAC2023, 2023. `doi:10.18429/JACoW-IPAC2023-THPL082`

[10] A. Alexopoulos *et al.*, "Noninvasive LHC transverse beam size measurement using inelastic beam-gas interactions", *Physical Review Accelerators and Beams*, vol. 22, no. 4, p. 042 801, 2019. `doi:10.1103/PhysRevAccelBeams.22.042801`

[11] M. Ferro-Luzzi, "Beam-gas interactions", *CAS - CERN Accelerator School: Vacuum for Particle Accelerators, 6-16 June 2017, Glumslöv, Sweden*, 2020. `doi:10.48550/ARXIV.2006.06490`

[12] R. Kersevan and M. Ady, "Recent Developments of Monte-Carlo Codes Molflow+ and Synrad+", 2019, pp. 1327–1330. `doi:10.18429/JACoW-IPAC2019-TUPMP037`

[13] R. Jones *et al.*, "Introduction to beam instrumentation and diagnostics", *CAS - CERN Accelerator School: Advanced Accelerator Physics*, 2014. `doi:10.5170/CERN-2014-009.23`

[14] A. Lechner *et al.*, "Validation of energy deposition simulations for proton and heavy ion losses in the cern large hadron collider", *Phys. Rev. Accel. Beams*, vol. 22, 7 2019. `doi:10.1103/PhysRevAccelBeams.22.071003`

[15] D. Prelipcean *et al.*, "Comparison Between Run 2 TID Measurements and FLUKA Simulations in the CERN LHC Tunnel of the ATLAS Insertion Region", *13th International Particle Accelerator Conference*, vol. IPAC2022, pp. 732–735, 2022. `doi:10.18429/JACoW-IPAC2022-MOPOMS042`

[16] D. Prelipcean *et al.*, "Comparison between Run 2 SEU measurements and FLUKA simulations in the CERN LHC tunnel and shielded alcoves around IP1/5", *14th International Particle Accelerator Conference*, vol. IPAC2023, 2023. `doi:10.18429/JACoW-IPAC2023-THPL083`

[17] G. Lerner *et al.*, *Radiation level specifications for hl-lhc*. `https://edms.cern.ch/ui/file/2302154/1.0/HLLHC_Specification_Document_v1.0.pdf`

[18] I. Novitski and A. V. Zlobin, "Thermal analysis of sc quadrupoles in accelerator interaction regions", *IEEE Transactions on Applied Superconductivity*, vol. 17, no. 2, pp. 1059–1062, 2007. `doi:10.1109/TASC.2007.898532`

[19] O. Sedlacek, *10th BGC Collaboration Meeting at CERN, Experimental Results in the LHC*. `https://indico.cern.ch/event/1350731/`

[20] D. Prelipcean, *Comparison between measured radiation levels and fluka simulations at charm and in the lhc tunnel of p1-5 within the r2e project in run 2*. 2021. `https://cds.cern.ch/record/2777059`