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RADIATION LEVELS PRODUCED BY THE OPERATION OF THE BEAM GAS VERTEX MONITOR IN THE LHC TUNNEL AT IR4

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Abstract

The Large Hadron Collider at CERN is equipped with instruments that exploit collisions between beam particles and gas targets, one of them being the Beam Gas Vertex monitor. By design, its operation generates secondary particle showers used to measure beam properties, that also result in radiation levels in the tunnel proportional to the beam intensity and gas pressure. In this work, the radiation showers are characterised using measured data from LHC Run 2 operation and Monte Carlo simulations with the FLUKA code, and predictions are made for the operation of these devices in the HL-LHC era.

INTRODUCTION

The scope of this paper is to analyse the radiation levels induced by the Beam Gas Vertex (BGV) [1] monitor installed in Interaction Region 4 (IR4) of the Large Hadron Collider (LHC) at CERN [2] in the context of the Radiation to Electronics (R2E) project [3, 4], since the radiation levels in the tunnel and on the equipment downstream caused by the secondary products from the beam gas collisions in the BGV could be non-negligible. The radiation levels measured by the Beam Loss Monitors (BLMs) [5] during the LHC Run 2 (2015-18) are compared with dedicated FLUKA [6–8] simulations, and the latter are subsequently used to make predictions for the operation of these devices in the HL-LHC era.

RADIATION SOURCE

For the BGV, the intentional injection of Neon gas increases the local gas density, which leads 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, which scales with several parameters described below as follows:

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

with the number of charges $N(t)$ passing through the gas, the LHC revolution frequency f = 11245 Hz, the inelastic cross section estimated [9] at $\sigma_{p+Ne,inel}$ = 320 mb, for a beam of 6.5 or 7 TeV protons hitting the gas atoms (assumed at rest, as their thermal energy of 0.025 eV at room temperature is negligible), and the gas with an integrated density profile $\Theta(t; s_a, s_b)$ along the s-coordinate in the accelerator region $[s_a, s_b]$ as:

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

where $\rho(s)$ is the number density of gas atoms and ρ_{max} is the peak value of the profile. From a measurement perspective, just one data point is available at the BGV via a pressure gauge located at the assumed peak ρ_{max}, but no measured information on the distribution width. Nevertheless, the gas density profile used for the BGV demonstrator in FLUKA (see the lower pannel of Fig. 4) has been simulated using MOLFLOW+ [10]. In addition to the main gas target of the BGV which is meant to produce the secondaries for vertex reconstruction, the tails of the gas target and the residual gas profile (estimated to be at most 10^{-9} mbar, but with local peaks reaching even 10^{-7} [11]) contribute as well to the radiation levels downstream of the BGV. The values for LHC Run 2 and the foreseen ones for HL-LHC beam parameters are given in Table 1.

Table 1: Reference Values of the Operational Parameters of the Machine and the BGV Monitor for the Past LHC Run 2 and Maximum Expected for the HL-LHC Operation [12].

	LHC Run 2	**HL-LHC**
total charges N [10^{14}]	3.00	6.35
energy E [TeV]	6.5	7.0
gas pressure p [10^{-7} mbar]	0.79	1.00

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 tunnel (Eqn. 2), and the interaction secondaries are propagated in the geometry model of the LHC tunnel.

Figure 1 displays a top (ZX) 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

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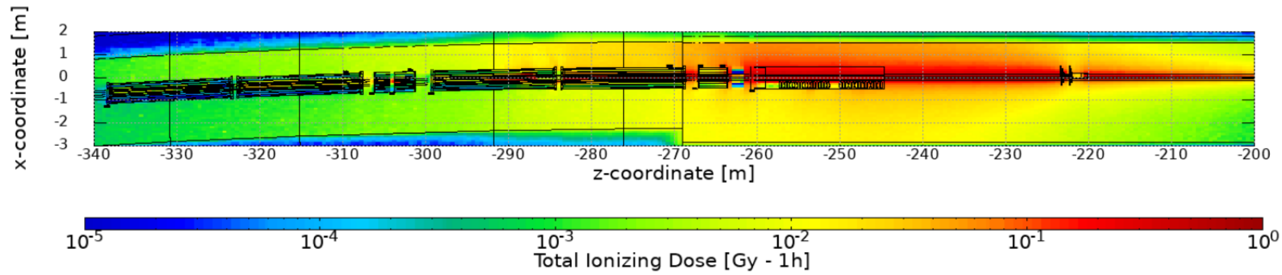

Figure 1: FLUKA simulated radiation shower caused by the BGV demonstrator on beam 2 for LHC operation, as ZX view, displaying how the shower extends over several tens of meters. The TID is provided at beam height, for a beam at $E = 6.5$ TeV with an intensity of $N_t = 3 \cdot 10^{14}$ charges, and normalized for 1 operational hour, for a gas pressure profile peak at $0.73 \cdot 10^{-7}$ mbar, corresponding to the averaged measured maxima.

the BLMs (explained below) and the product of intensity and pressure, based on Eqn. 1. This is equivalent to verifying that the BGV is indeed the dominant source of radiation in the portion of the LHC tunnel downstream of the BGV.

The available radiation level measurement data consists of the Total Ionizing Dose (TID) as deposited in the BLMs, which 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, and the measured data is stored in CERN's Next Generation Accelerator Logging Service (NXCALS) [13] and analyzed within the R2E Monitoring and Calculation Working Group (MCWG) [14]. Figure 2 showcases that when gas is injected in the BGV, the BLM TID rate signal increases proportionally to the product of pressure and intensity. To improve the robustness of the analysis, the typical fill duration of about 10 h was divided into multiple time periods of roughly 1h, such that the gas pressure is rather constant within the time period.

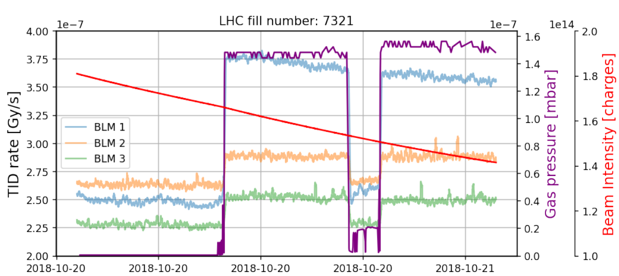

Figure 2: The measured TID rate for the first three BLMs downstream of the BGV within a time period of LHC fill number 7321, showing the beam intensity N_p as measured by the BCT instruments for beam 2 and the BGV pressure gauge reading p_{BGV}.

Considering all such time periods, one can plot the total measured TID normalized by the total number of passing charges as measured by the BCT instruments [15] against the injected BGV pressure gauge reading, shown in Fig. 3. One observes that when there is significant ($p_{BGV} > 2 \cdot 10^{-8}$ mbar) gas injected in the BGV gas chamber, the radiation levels downstream of the instrument correlate very well with the beam intensity and the gas pressure, indicating that the BGV is indeed the main source of prompt radiation in the position where BLM1 is located. For each BLM, we hence defined signal time periods as the windows of operation during which the peak BGV pressure was at least $3 \cdot 10^{-8}$ mbar. In total, 169 hours of operation with an average pressure of $p_{BGV,operation} = 7.89 \cdot 10^{-8}$ have been recorded. Similarly, one can identify background time periods with $p_{BGV} < 1 \cdot 10^{-9}$ mbar, where the measured radiation levels can come from the residual gas along the accelerator or other less relevant sources, and this is designated as the background, summing up to 116 hours.

The LHC accelerator tunnel is divided into cells [2], and by examining all BLMs up to cell 13 in the DS, we found that visible correlations between the TID per unit intensity and the peak pressure in signal time periods can be observed up to cell 9, indicating that the BGV is a dominant (or, at least, non-negligible) source of radiation in the tunnel for more than four half-cells downstream of it.

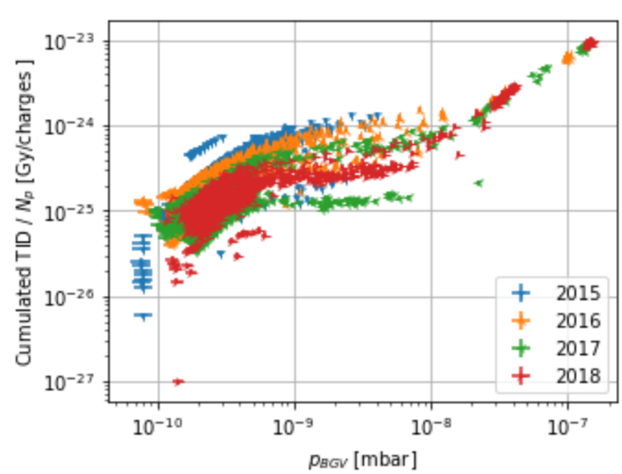

Figure 3: The measured TID of BLM 1 (the most irradiated during Run 2) divided by the number of protons passing through the BGV N_p plotted against the average BGV pressure gauge reading p_{BGV} for all the time periods under consideration, for each year of Run 2 operation.

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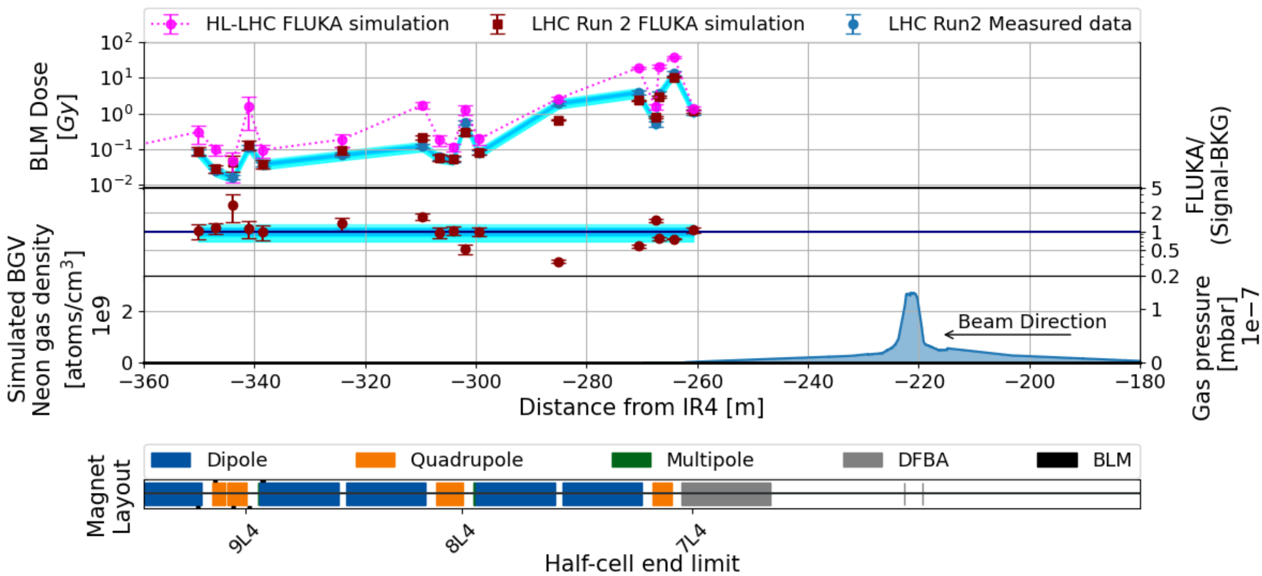

Figure 4: Top panel: BLM pattern downstream the BGV placed on beam 2 as measured over the Run 2 proton runs (blue points) and as simulated by FLUKA for LHC (red points) for 170 h of operation and HL-LHC (magenta points) for 400 h of operation. Mid panel: Ratio between simulation values and measured data for Run 2. Lower panel: BGV gas density profile. Bottom panel: The machine layout and the BLM locations, where we assumed that the BLMs during HL-LHC operation will be in the same position as in Run 2.

LHC BGV DEMONSTRATOR BENCHMARK AND HL-LHC SPECIFICATIONS

The radiation levels as simulated by FLUKA are compared to the radiation monitor measurements taken during the operation of the BGV demonstrator in Run 2 in Fig. 4. The shape of the BLM TID profile is well reproduced with a good global agreement within a factor of 2 between simulations and measurements, with just one outlier. Additionally, Fig. 4 includes the HL-LHC predictions that are based solely on FLUKA simulations. Usually a few ten percent agreement can be achieved in the complex accelerator scenario [16, 17].

Moreover, the BGV was the main contributor for integrated yearly radiation levels in cell 7 and for selected BLMs in the next two cells downstream. The analysis shown here stops at -360 m from the center of IR4 (or 150 m downstream of the BGV on beam 2), because the measured radiation levels induced so far away by the BGV operation generally fall below other sources of radiation.

The annual radiation levels depend on the total operational time, for which it is estimated at a minimum of 400 h per year during HL-LHC operation, compared to approx. 170 h in total during Run 2 (2015-2018) when the gas was injected above $p_{BGV} > 2 \cdot 10^{-8}$ mbar. Together with the larger beam intensity and energy (see Table 1), this could result in the radiation levels shown in Fig. 4.

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 plateau of 10^{10} cm^{-2}/year from the BGV to the second DS dipole. From an R2E perspective, levels of 10 Gy/year are a threat in terms of TID lifetime of electronic systems and fluences of $3 \cdot 10^{10}$ cm^{-2}/year may lead to stochastic electronic failures. Both are significantly (i.e. orders of magnitude) larger than the arc level "baseline" [18], but lower than the levels near the high luminosity experiments at IP1/5 [17].

CONCLUSIONS

The main results of this study are the observed proportionality between the TID measured by the BLMs and the product of pressure and intensity up to half-cell 9 included, signaling that in this portion of tunnel the BGV was indeed the main radiation source. The comparison between the Run 2 measurements and the FLUKA simulation reveals a good agreement, which is a further confirmation that we understand the origin of the radiation levels and trust their prediction powers for the TID and power deposition for HL-LHC. A similar study is expected for the Beam Gas Curtain (BGC) [19] monitor and its planned Run 3 (2022-2025) operation.

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