CLASSIFICATION OF THE LHC BLM IONIZATION CHAMBER

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Abstract

The LHC beam loss monitoring (BLM) system must prevent the super conducting magnets from quenching and protect the machine components from damage. The main monitor type is an ionization chamber. About 4000 of them will be installed around the ring. The lost beam particles initiate hadronic showers through the magnets and other machine components. These shower particles are measured by the monitors installed on the outside of the accelerator equipment. For the calibration of the BLM system the signal response of the ionization chamber is simulated in GEANT4 for all relevant particle types and energies (keV to TeV range). For validation, the simulations are compared to measurements using protons, neutrons, photons and mixed radiation fields at various energies and intensities. This paper will focus on the signal response of the ionization chamber to various particle types and energies including space charge effects at high ionization densities.

INTRODUCTION

Figure 1: The LHC beam loss monitors (yellow insulation, mounted on a red support) are mounted on the outside of the cryostats, horizontally aligned to the beam pipe.

An unprecedented amount of energy will be stored in the circulating beams of the LHC (up to 360 MJ per beam) and in the magnet system (10 GJ). The loss of even a very small fraction of this beam may induce a quench of the superconducting magnets or cause physical damage to machine components. The BLM system [1] detects and quantifies the amount of lost beam particles. It generates a beam abort trigger when the losses exceed predetermined threshold values. About 4000 detectors will be installed, mostly around the quadrupole magnets (Fig. 1). The detectors probe the transverse tails of the hadronic showers through the cryostats which are induced by lost beam particles. The start-up calibration of the BLM system is required to be within a factor of five in accuracy, and the final accuracy within a factor of two. For the calibration and threshold determination a number of simulations are combined: Beam particles are tracked to find the most probable loss locations. At these locations hadronic showers through the machine components are simulated to get the particle spectra at the detector locations. A further simulation yields the detector response. The quench levels of the superconducting magnets, according to loss duration and beam energy, are simulated separately. Whenever possible, crosschecks with measurements have been performed or are planned before the start-up of the LHC. This paper will focus on the detector response simulation, which is part of the system calibration, and on the uncertainty estimation of transverse hadronic shower tail simulations, which contributes to the system calibration error.

IONIZATION CHAMBER RESPONSE

Simulations

The main detector type is an ionization chamber with parallel aluminum electrodes separated by 0.5 cm (Fig. 2). The detectors are about 50 cm long with a diameter of 9 cm and a sensitive volume of 1.5 liter. The chambers are filled with N_2 at 100 mbar overpressure and operated at 1.5 kV.

Figure 2: Inside structure of the LHC BLM ionization chamber.

Depending on the loss location the detectors will be exposed to different radiation fields. The energy of the particles is spread over a large range from keV to TeV. GEANT4 (version 4.8.1.p01 QGSP BERT HP [2]) simulations of the ionization chambers were performed to determine the signal response for different particle types at various kinetic energies in the range of 10 keV to 10 TeV. The sensitive volume was determined by simulation of the electric field configuration. It is 4% bigger than the volume covered by the electrodes (2 mm larger diameter). The cut off value of the ionization chambers is below about 2 MeV for photons and electrons and below about 30 MeV for neutrons and protons. See Fig. 3 for the response function for transverse impacting particle direction.

Verification Measurements

Mixed Radiation Field Measurements: At CERF (CERN-EU High Energy Reference Field Facility) a copper target (length 50 cm, diameter 7 cm) was placed in a secondary beam of 120 GeV/c hadrons. The main beam particles were pions (60.7%), protons (34.8%) and kaons

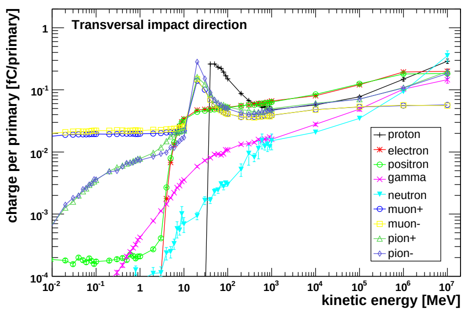

Figure 3: Response of the ionization chamber for particles impacting transversely to the detector axis.

(4.5%) with intensities up to $9.5 \cdot 10^7$ hadrons per 4.8 seconds. Five ionization chambers were positioned around the copper target so that they were exposed to different radiation fields (varying in particle composition and energy). FLUKA simulated spectra from [3] were used as input to simulate the detector response with GEANT4. A comparison of the GEANT4 simulation to the BLM detector measurement shows a relative difference of about 12%, except at detector position 1 (Table 1). There, a relative difference of 21% can be seen. The detector specific energy cut-off and the shift of the particle spectrum to lower energies (below 1 GeV) lead to low statistics in the number of particles that contribute to the detector signal. The error on the measurement includes the statistical error and a systematic error from uncertainties on the beam intensity measurement (10%) and from misalignment investigations on the detector positions [3]. The error on the simulation includes only the statistical error of the signal simulation, it does not include the uncertainties in the spectrum. All detectors showed a linear behavior at measurements over one order of magnitude in beam intensity.

Table 1: Result of GEANT4 simulations, beam measurements and their comparisons for mixed radiation fields, proton, gamma and neutron measurements.

	Simulation		Measurement		sim./meas.	
	BLM	err.	BLM	err.	ratio	err.
pos.	CERF experiment [pC per $9.2 \cdot 10^7$ hadrons]					
1	91.13	0.35	115.33	11.66	0.79	0.08
2	281	6	—	—	—	—
3	1656	18	1578	163	1.05	0.11
4	2387	22	2122	231	1.12	0.12
5	3944	23	3532	370	1.12	0.12
6	6496	18	7091	1097	0.92	0.14
	proton experiment [C/(p·cm)]					
	125	25	110	0.06	1.13	0.23
	gamma experiment [aC/γ]					
	0.27	0.02	0.42	0.01	0.64	0.05
	neutron experiment [aC/n]					
long.	12.94	0.16	15.23	0.09	0.85	0.01
trans.	6.74	0.09	9.57	0.06	0.70	0.01

Proton Measurements with 400 GeV/c protons at an SPS extraction line (T2) were compared to the simulation. The beam size was estimated to 1 cm horizontally and 0.5 cm vertically (4σ). The intensity was $(30.0 \pm 0.1) \cdot 10^{11}$ protons per 4.8 seconds. A vertical scan of the beam position was simulated and compared to the measurement. The unknown beam position (vertically) relative to the inner structure (parallel electrodes) led to a systematic uncertainty of 23%. Measurement and simulation agree within errors.

Gamma Ray Measurements: A further comparison between simulation and measurement was done with 662 keV gamma rays at the TIS-RP Calibration Laboratory for Radiation Protection Instruments (CERN) with Cs137 sources at various activities and distances. The detector showed once more a linear behavior over two orders of magnitude in dose rate (30 μSv/h to 3 mSv/h). The response simulation results for 600 keV and 700 keV gamma rays were interpolated and compared to the measured results. The measurement and the simulation agree within 64% with an error of 7%.

Neutron Measurements were performed at the Svedberg Laboratory, Uppsala University (Sweden) [4]. The neutrons had a peak energy of 174 MeV and an intensity from $0.7 \cdot 10^6$ to $4.6 \cdot 10^6$ per second. They were produced by an incident proton beam of 179 MeV and a maximum beam current of 0.4 μA on a 23.5 mm thick lithium target. The contribution of gamma rays to the measured signal was estimated to between 11.2% and 16%. The results are shown in Table 1, assuming an 11.2% gamma contribution, for longitudinal and transversal neutron impact direction on the chamber. For an 11.2% gamma contribution, the agreement is 85% and 70% for longitudianl and transversal impact respectively. For a 16% gamma contribution, the agreement is 90% and 74% for longitudinal and transversal impact.

SHOWER TAIL MEASUREMENTS AT HERA

The HERA internal proton beam dump served as a test bed for the LHC BLM system. The proton energy at collision is about twice the LHC injection energy. The particle spectrum outside the dump is comparable to the one outside of an LHC magnet. It is dominated by low energy (below 10-100 MeV) neutrons and photons. The HERA machine was running nearly continuously since the installation of the experiment in 2005, allowing for a long term test of the complete LHC BLM system. Six ionization chambers are placed on top of the dump, with a longitudinal spacing of about 1 m. They measure the tails of the hadronic showers induced by the impacting protons. The proton energy is 39 GeV at injection and 920 GeV at collision. The beam intensity is in the range of $1.3 \cdot 10^{11}$ to $1.3 \cdot 10^{13}$ protons per 21 μs. The measurements have been corrected for space charge effects according to a formula derived in [5]. Above a critical ionization density a dead zone of thickness $d - x_0$ (d being the electrode spacing) forms next to the cathode:

$$x_0 = \left[\frac{\epsilon_0}{q}\frac{4\mu V^2}{\phi}\right]^{1/4}$$

μ is the ion mobility, ϕ is the ionization per volume and time, V is the chamber voltage and q is the elementary charge. The magnitude of this correction is shown in Table 2. At the standard LHC operation range of the ionization chambers, the ionization density is lower and the dead zone will not form. It will only be reached at special beam tests. At HERA, on the contrary, it gives a correction of up to a factor of 8.7.

Table 2: Range of correction factors due to space charge for all detectors depending on proton beam energy and current.

Det.	39 GeV		920 GeV	
	I_{min} 1 mA	I_{max} 90 mA	I_{min} 1 mA	I_{max} 100 mA
1	1.	2.95	1.17	6.70
2	1.	3.80	2.00	8.71
3	1.	3.27	1.97	8.61
4	1.	2.60	1.71	7.95
5	1.	1.76	1.16	6.34
6	1.	1.35	1.	5.03

Fig. 4, left, shows the case of the highest correction, the signal of detector 2 (charge per proton) at 920 GeV as a function of beam current before and after space charge correction. On the right side all 6 detector signals at 920 GeV after correction are shown with a linear fit through zero. Most of the nonlinearity in the signals is corrected for by the simple model of space charge.

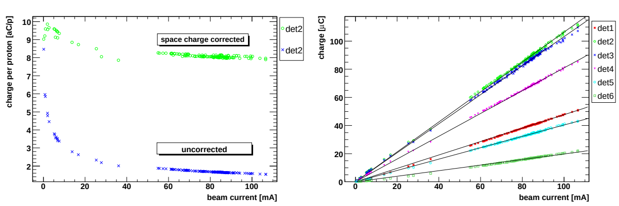

Figure 4: Signal as function of beam current at 920 GeV beam energy before (left) and after (right and left) space charge correction.

The showers through the beam dump have been simulated with GEANT 4.8.2 and two different physics models, QGSP BERT HP and FTFP. A FLUKA simulation of the dump was also done for comparison. Fig. 5 gives the preliminary results of the simulations and the measurements. The measurements have been corrected for space charge effects. The predicted signal strongly depends on the choice of simulation code and physics model. All models significantly underestimate the transverse shower tails. The GEANT4 QGSP BERT HP is closest to the data, within less than a factor of 2 in the detector 2, which is close to the shower peak. Longitudinally as well, the models underestimate the extent of the shower in both directions, backward (detector 1) and forward (detectors 4, 5 and 6).

CONCLUSION

The GEANT4 detector response simulations are part of the LHC BLM calibration. Various verification measurements were performed. Generally, the simulations and

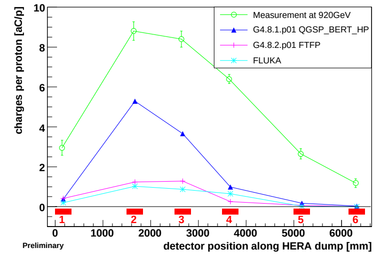

Figure 5: Preliminary simulated and measured signals versus detector position on the HERA proton beam dump. Detector positions (in scale) indicated at the bottom.

measurements agree very well. The highest deviation is 36% in the gamma source measurement.

A rather simple model of space charge can explain most nonlinearities encountered in the detector responses in the HERA measurements. However, this space charge regime will not be reached during normal LHC operation of the ionization chambers. A final verification of the HERA results is pending (including a completely independent simulation). If confirmed, the LHC threshold calibration will take into account the significant deviation of the measured shower tails from the simulated ones. The simulated threshold values will have to be corrected accordingly.

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