LHC Beam Loss Detector Design; Simulation and Measurements

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Abstract

The Beam Loss Monitoring (BLM) system is integrated in the active equipment protection system of the LHC. It determines the number of particles lost from the primary hadron beam by measuring the radiation field of the shower particles outside of the vacuum chamber. The LHC BLM system will use ionization chambers as its standard detectors but in the areas where very high dose rates are expected, the Secondary Emission Monitor (SEM) chambers will be additionally employed because of their high linearity, low sensitivity and fast response.

The sensitivity of the SEM was modeled in Geant4 via the Photo-Absorption Ionization module together with custom parameterization of the very low energy secondary electron production. The prototypes were calibrated by proton beams.

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). The results are validated by comparing the simulations to measurements using protons, neutrons, photons and mixed radiation fields at various energies and intensities.

BLM SYSTEM

The system [1] has to detect dangerous beam losses which could quench superconductive magnets or even damage components of the accelerator. 3700 ionization chambers (BLMI) will be used in LHC as the main beam loss detectors. Additional 280 SEM detectors (BLMS) are needed for the high radiation areas; mainly the collimation zones, injection points, interaction points, beam dump and at other critical aperture limits.

BLMS DETECTOR

The BLMS detector will usually be installed in pair with the BLMI to extend the dynamic range of the system towards higher dose rates without saturation of the detector or electronics. Considering a possible beam lifetime of 1 s during acceleration, the BLMI would have an output of 3 A if no saturation or limitation occurred. The maximum steady state input current for the electronics is 1 mA, therefore a 3×10^3 to a 10^4 times lower sensitivity is needed compared to the BLMI.

MODELING OF BLMS RESPONSE

SEY estimation

In Geant4 [4] is no module for the Secondary Emission (SE) simulation defined. Therefore, a modified semi-empirical formula of Sternglass [5] (the contribution of δ electrons to the true SEY has not been included) was used to calculate the SEY for TiO_2 surface.

$$SEY = 0.01 C_F L_S \frac{dE}{dx}|_{el} \quad L_S = (0.23 N \sigma_g)^{-1}. \quad (1)$$

Where $dE/dx|_{el}$ stands for electronic energy loss, L_S for effective penetration distance of SE, N for number of atoms per unit volume and $\sigma_g = 1.6 Z^{1/3} 10^{-16}\ cm^{-2}$. The calibration factor $C_F = 0.8$ was used in order to match the experimental data for Al_2O_3 [7] and TiO_2 [8]. The maximum measured SEY for the very low energy (i.e. 100 keV) protons hitting the Al target is 1.3 [9] compared to 2 from the parametrization, but particles with such energies have a negligible contribution to the signal as they don't penetrate the chamber walls or they lie below the e^- production cut of the simulation [3].

Geant4 simulations

The geometry of the BLMS prototype was implemented in Geant4 including a thin layer of TiO_2 on the signal electrodes.

When a charged particle passes through the TiO_2 to vacuum interface, the SEY is calculated in the G4UserSteppingAction using the Eq. 1 and a SE electron is recorded with its corresponding probability. The $dE/dx|_{el}$ is calculated by the G4EmCalculator but in the case of primary e^- or e^+ and μ^- or μ^+ the dE/dx from Bremsstrahlung must be subtracted. For e^-/e^+ pair production the $dE/dx|_{el}$ must be subtracted too, as all these processes don't contribute directly to secondary emission. Nevertheless, their products are treated as other particles. The δ electrons are produced by the Photo-Absorption Ionization (PAI) module and are treated as other charged particles. The δ electrons are only recorded as signal if they are able to penetrate the electrodes (i.e. $E_k > 750\ keV$). The Geant4 QGSP_HP [4] module was used for simulating the hadronic interactions. The simulations were performed using a round beam of 0.5 or 1cm radius. The cut

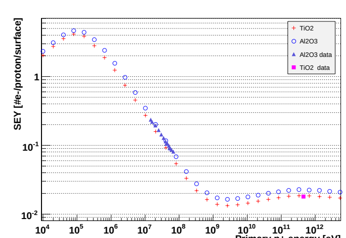

Figure 1: Modified Sternglass formula for true SEY of primary protons for different materials scaled by a factor of 0.8 to fit the reference data[7, 8].

value for electrons was found to influence the results and is the main reason for the 10% error bar of the simulation points. The signal response of the SEM detector for dif-

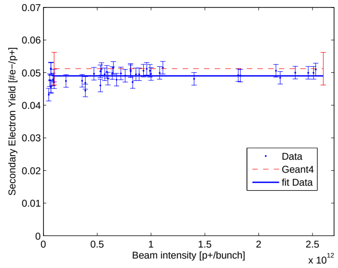

Figure 2: SEY of BLMS as function of proton beam intensity at 1.4 GeV. Simulation error was estimated to 10%.

ferent particle types was simulated using a model in the Geant4.8.1.p01 code. The QGSP_BERT_HP [4] was used as the hadronic Geant4 model. The simulated round beam of σ = 2mm was entering the SEM through a 5mm thick steel plate at the bottom of the detector. The signal is produced by counting the charge balance on the signal electrode and by the "true secondary electrons" created by a custom model proportional to the energy loss in the surface layer of the signal electrode. The protons below 60 MeV do not penetrate the detector, so their contribution to the signal is null. The energy loss of the penetrating protons with energies below 300 MeV is situated on the descending part of the Bethe-Bloch curve. The signal growth for hadrons at high energies is caused by the relativistic rise of the energy deposition and shower development caused by the bottom plate. As it can be seen in figure 3 the negative signal at 8 MeV is caused by the absorption of electrons inside the signal electrode. The neutral particles produce signal only indirectly as only charged particles can give rise to the secondary electrons.

MEASUREMENTS

The simulations were validated by measurements with particle beams of well known parameters. The prototypes have been placed directly in the primary proton beams in the Paul Scherrer Institute (PSI) and in CERN PSB and SPS transfer line.

Calibration with 63 MeV protons

Two prototype versions ("type C" and the newer "type F" [3] which was simulated) were tested in the 62.9 MeV proton Optis line in PSI. Protons were entering through the 5 mm thick steel bottom cover of the detector. The output current was measured by a Keithley electrometer 6517A. The resulting SEY was calculated by dividing the beam current by the detector output. The corresponding simulations were performed with a 1.5 kV electric field and are in a good agreement with measurements ($< 5\%$).

Calibration with 1.4 and 400 GeV protons

The older "prototype C" [3] was installed in the PS Booster dump line and tested with a bunched proton beam.

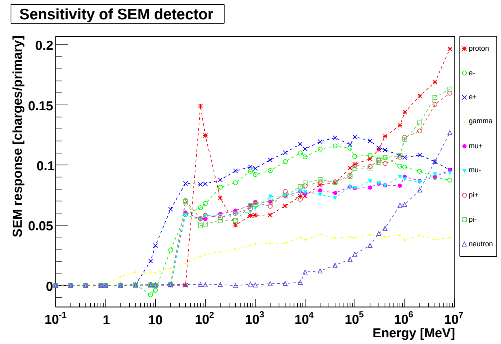

Figure 3: Response of the secondary emission monitor for particle impacting longitudinally.

Figure 2 shows a very good linearity of the BLMS and a reasonable agreement with the simulation, which lies within the statistical error. A reference ACEM (Aluminum Cathode Electron Multiplier tube) detector with fast response time was installed close to the BLMS outside of the beam. A very fast time response without any under-shoot or tail in the signal for a bunch length of about 160ns was observed. The chamber signals were measured with Tektronics oscilloscope and 50 Ω termination. The integration was done offline in Matlab code.

The calibration in the SPS T2 transfer line with a 400 GeV proton beam passing through the center of the bottom plate resulted in a SE yield of 0.09 electrons per proton. The corresponding Geant4 simulations estimate the sensitivity to 0.125 electrons/proton with relatively high contribution of δ electrons.

IONIZATION CHAMBER RESPONSE

Geant4 simulations

The main detector type is an ionization chamber with parallel aluminum electrodes separated by 0.5 cm. 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. 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 [4]) 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. 4 for the response function for transverse impacting particle direction.

Verification Measurements

Mixed Radiation Field Measurements where done at CERF (CERN-EU High Energy Reference Field Facility)

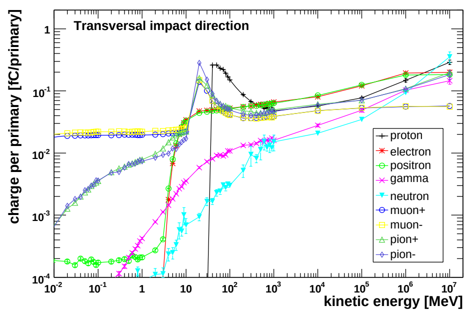

Figure 4: Response of the ionization chamber for particles impacting transversely to the detector axis.

were 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 (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 would be exposed to different radiation fields (varying in particle composition and energy).

FLUKA simulated spectra from [10] were used as input to simulate the detector response in Geant4. A comparison of the Geant4 simulation to the BLMI detector measurement shows a relative difference of about 12%, except at the 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 include the statistical error, a systematic error from uncertainties on the beam intensity measurement (10%) and from misalignment investigations on the detector positions [10]. 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.

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 were used for a further comparison between simulation and measurement with 662 keV gamma rays of a 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 measurements and the simulations agree within 64% with an error of 7%.

Neutron measurements were performed at the Svedberg

Table 1: Overview of Geant4 simulations results, 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

Laboratory, Uppsala University (Sweden) [11]. 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 results are shown in Table 1, assuming an 11.2% gamma contribution, for longitudinal and transversal neutron impact direction on the chamber.

CONCLUSIONS

Measurements at different energies seem to validate the chosen approach of Secondary Electron Emission simulation in Geant4. The largest relative error between measurements and simulations is 28% for the case of 400 GeV protons. More understanding of the model is needed in order to set correctly the production cuts for electrons to find a better agreement at high energies.

The Geant4 detector response simulations are part of the LHC BLM calibration. Various verification measurements were performed. Generally, the simulations and measurements agree very well. The highest deviation is 36% in the gamma source measurement.

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