DEVELOPMENT, CHARACTERIZATION AND PERFORMANCE OF THE LHC BEAM LOSS MONITORING SYSTEM

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Abstract

The LHC Beam Loss Monitoring (BLM) system should prevent the superconducting magnets from quenching and protect the machines elements from damage. The main monitor types are an Ionization Chamber (IC) and a Secondary Emission Monitor (SEM) (about 4000 monitors in total). Lost beam particles initiate hadronic showers in the machines components which are then measured by the monitors installed on the outside of the equipment. For the calibration of the BLM system the signal response of the IC and the SEM was simulated using GEANT4, GEANT3 and FLUKA for all relevant particle types and energies (keV to TeV range). For validation, the simulations were compared to measurements using protons, neutrons, photons and mixed field radiation fields at various energies and intensities.

INTRODUCTION

An unprecedented amount of energy will be stored in the circulating LHC beams (up to 360MJ per beam) and in the magnet system (10GJ). The loss of even a small fraction of this beam may induce a quench of the superconducting magnets. Therefore a fast signal detection and robustness against aging were the main design criteria for the BLM monitors. Depending on the loss location the monitors are exposed to different radiation fields and in order to ensure stable operation within a high dynamic range, an ionization chamber and a secondary emission monitor were chosen. The system detects and quantifies the amount of lost particles and triggers a beam abort when the losses exceed predetermined threshold values. The start up calibration of the BLM system was required to be initially within a factor of five in accuracy and finally within a factor of two in accuracy.. For the calibration and threshold determination a number of simulations were combined: beam particles were tracked to find the most probable loss locations. At these locations hadronic showers in the machines components were simulated to get the particle spectra at the detectors locations. A further simulation was done to determine the detector response. The quench levels of the superconducting magnets, according to loss duration and beam energy were simulated separately. Whenever possible, crosschecks with measurements have been performed before the start up of the LHC.

IONIZATION CHAMBER (IC) RESPONSE

The main detector type is an ionization chamber (~3700 ICs). It consists of 61 aluminium electrodes that are arranged in parallel and equally spaced with 0.5 cm. The IC is ~50 cm long (diameter 9 cm) with a sensitive volume of 1.5 litres. The chambers are filled with N_2 at 100 mbar overpressure and operated at 1.5 kV. The collection time of the electrons and ions is of the order of 300 ns and 120 μsec (simulated: 40 -80 μsec, measured 80 -120 μsec, depending on signal cable length).

GEANT4 Simulations

GEANT4 simulations of the ionization chamber have been performed to determine the signal response for different particle types at various kinetic energies in the range from 10 keV to 10 TeV (see Fig. 1). Also the effects of longitudinal and transverse impacting directions with respect to the detector axis were simulated. The longer path for a longitudinal direction increases the response approximately by a factor of two. Less wall material has to be passed in the transverse direction leading to a lower energy cut-off. The deposited energy in the sensitive volume was converted with the so called W-value to the number of produced charges. The W-value for N_2 is 35 eV per electron-ion pair. Different parameters were varied in order to identify the contributions to the systematic error of the simulation. The detector response is different for different impacting angles: at high energies up to a factor of 100 for protons. Changing the production range cut from 1 mm (standard value in GEANT4) to 10 μm increased the response by 12%. 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). NIST data were used to cross check the simulation: The energy cut-off for protons, electrons and gamma rays was estimated. Protons of about 65 MeV start producing a signal, electrons at 9 MeV and gammas at 150 keV. The energy deposition for a positive muon was calculated with the Bethe-Bloch formula and compared to the simulation (agreement at 1 GeV: 95% and at 35 MeV: 75%) [1].

Verification Measurements

Mixed Radiation Field Measurements:
A mixed radiation field experiment at the CERF target area (CERN-EU High Energy Reference Field Facility) was compared to the simulations results. 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 were exposed to different radiation fields, (varying in particle composition and energy). The
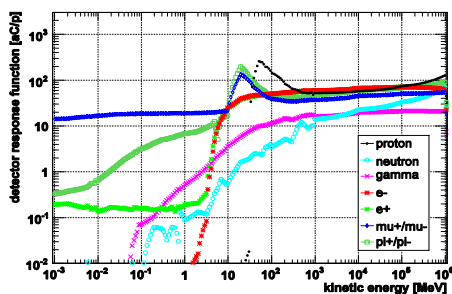
Figure 1: IC response functions for various particle types entering the detector. Impact angle of the particles relative to the detectors axis is 60 degrees.

CERF team had performed a similar experiment with PMI (air filled plastic ionization chamber) detectors and verified it by FLUKA simulations. Their FLUKA spectra 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 for one position (21%). The error on the measurement includes the statistical error and a systematic error from uncertainties on the beam intensity measurement (10%) and from misalignment of the detector positions. 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 behaviour at measurements over one order of magnitude in beam intensity (up to $9 \cdot 10^7$ hadrons onto the copper target) [1]. The CERF facility was used in May 2009 for sensitivity tests the of the IC signal to the radiation field by using a 1mm thick Cd layer wrapped around the detector, as well as by changing the orientation of the IC. The SPS provided a positively charged hadrons beam. The FLUKA Monte Carlo code was used to evaluate the detector response concerning energy deposition and particles spectra. The ICs were put either with the cables upstream or with the cables downstream. The difference in the IC signal was not significant, around 10% depending on the location of the detector around the target, at all positions well reproduced by the corresponding FLUKA calculations, confirming that the horizontal chamber orientation is not important when comparing measurements with simulations at the LHC. Verifying the contribution of low energy neutrons to the signal both measurements and simulations showed no significant difference in the signal with or without the Cd layer (3% to 4% difference). Without the Cd layer, the contribution of low energy neutrons is 6%. The measurements were directly compared with the FLUKA simulations for most of the positions around the target. The comparison shows a good agreement and it is also the case for the measurements performed with the Cd. Differences between simulations and measurements of 22% for one position can be partly explained by positioning uncertainties especially in the most downstream part where the alignment of the beam-line is not guaranteed. Further uncertainties concern the

calibration of the ionization chamber (PIC), the beam shape and alignment. In order to analyze in detail the observed signal and study its dependency on particle energy and type additional FLUKA simulations were performed to determine the main contributions to the signal, and to study the difference in using the Cd layer not only based on integral values, but as a function of particle type and energy. For the case where the chamber is wrapped in Cd a loss of 6% to 7% in the total neutron contribution is observed which is compensated by the gain of 8% to 9% in the photons contribution. At the upstream position, the photons (53%), neutrons (17%) and protons (8%) are more dominant. At the downstream position, the signal is mainly due to the photons (42%), pions (14% from positive, 12% from negative), positrons and electrons (12%) [2].

Proton Measurements:
Another experiment with 400 GeV/c protons at a SPS extraction line (T2) was made and compared to the simulations results. The beam intensity was $(30.0 \pm 0.1) \cdot 10^{11}$ protons per 4.8 seconds with an estimated beam size of 1 cm horizontally and 0.5 cm vertically. 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 [1].

Gamma Ray Measurements:
A comparison between simulation and measurement was done for 662 keV gamma rays at the TIS-RP Calibration Laboratory for Radiation Protection Instruments (CERN) with Cs137 sources at various activities and distances. The IC showed a linear response over two orders of magnitude in dose rate (3 mSv/h-30 mSv/h). The response simulation results for 600 keV and 700 keV gamma rays were interpolated and compared to the measured data. The measurement and the simulation agree within 64% with an error of 7% [1].

Neutron Measurements:
Further verification and calibration measurements were performed in November 2006 at the Svedberg Laboratory, Uppsala University (Sweden) with neutrons (with 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 A on a 23.5 mm thick lithium target. The contribution of gamma rays to the measured signal was estimated to be between 11.2% and 16%. For an 11.2% gamma contribution, the agreement is 85% and 70% for longitudinal and transversal impact respectively. For a 16% gamma contribution, the agreement is 90% and 74% for longitudinal and transversal impact [1].

Shower tail measurements at HERA:
The LHC BLM system was also tested in the HERA internal proton beam dump. 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. Due to the

fact that the HERA machine was running nearly continuously since the installation of the experiment in 2005, it allowed a long term test of the complete LHC BLM system. Six ionization chambers were placed on top of the dump (longitudinal spacing of about 1 m), measuring the tails of the hadronic showers induced by impacting protons. At HERA the proton energy was 39 GeV at injection and 920 GeV at collision. The beam intensity was in the range of $1.3 \cdot 10^{11}$ to $1.3 \cdot 10^{13}$ protons per 21 µs. Most of the nonlinearity in the signals is corrected for by the simple model of space charge. The estimated error on the transverse hadronic shower tail simulations is part of the BLM system calibration error. The simulation was split into two parts. First, the primary proton beam onto the dump was simulated and all particles arriving at the top of the dump were scored. In the second part, these secondary particles were launched for each detector position to get the detector signal. Two vertically separated impacting points on the dump were chosen to simulate the sweeping of the protons. The simulation and measurement are in good agreement [1]. A comparison of a superconducting LHC magnet to the HERA proton beam dump in terms of the detector signal and the detector signal integrated over the particle energy is shown in Figs. 2 and 3 [1].
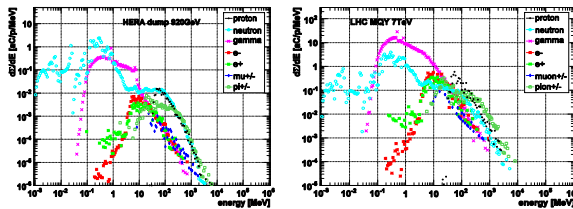

Figure 2: Detector signal generated by convolving the particle fluence spectra with detector response functions. The detector is placed 1.5 m after the proton impacting point. Left: HERA dump, 920 GeV, Right: MQY magnet at 7 TeV.
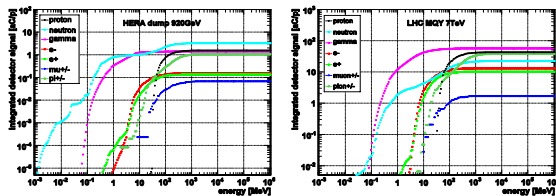

Figure 3: Shown is the detector signal integrated over the particle energy for a detector placed 1.5 m from the impacting point of the protons. Left: HERA dump at 920 GeV. Right: MQY magnet at 7 TeV.

SECONDARY EMISSION MONITOR

In addition to the 3700 ICs, around 300 SEMs are installed in high radiation areas: mainly in the collimation zones, injection and interaction points, beam dump line and at other critical aperture limits. The SEM is usually installed in pair with an IC in order to extend the dynamic range of the system towards higher dose rates without saturation of the detectors or electronics. The detector has to keep a linear response for very high particle fluxes, so it has to have a high saturation limit. Also high stability of the radiation tolerance is needed, because large fluencies up to 70 MGy/year can be integrated during the nominal LHC operation. In some locations it will be nearly impossible to exchange SEMs (like under the core of the beam dumps) therefore the lifetime should be 20 years. The SEM was characterized using Monte Carlo tools and calibrated in various radiation environments.

Working Principle

The SEM detector is based on the Secondary Electron (SE) emission from metallic surfaces. The material escaping SE come only from a thin surface layer of the traversed material and is subsequently drifted away by a bias electric field. The Secondary electron Emission Yield (SEY) is proportional to the electronic energy loss of the particle in the surface layer of the signal electrode. The current created by the drifting electrons is measured between the signal and the bias electrodes. The "high" energy δ electrons are produced mostly in forward direction (same as the primary particle). If they are emitted from the signal electrode, their contribution is in average cancelled by the δ electrons arriving from the bias electrode. The SEM can detect neutral particles only indirectly. The neutral particles have to interact with any part of the detector and create charged secondaries. Also charged particles can produce a signal if their path lengths in the two bias field gaps are not equal [3].

Development

The development of the SEM was conducted according to the ultra high vacuum requirements in order to ensure sufficiently low residual pressure and to keep the ionisation signal negligible. The vacuum and baking cycle was defined and tested at CERN before the use in the series production. All electrodes were made of titanium because to achieve a small SEY stability and vacuum properties, which were confirmed by an out gassing test performed at CERN. The signal feed through has an additional contact shielding on the signal wire to avoid collecting the ionisation signal from surrounding air what would lead to a nonlinear behaviour at high dose rates [3].

Modelling of the SEM Response

Since there is no module for the SE simulation in GEANT4 defined, a modified semi empirical formula of Sternglass (the contribution of δ electrons to the true SEY has not been included) was used to calculate the SEY for a TiO_2 surface and implemented in the Monte-Carlo particle simulation code GEANT4. The resulting formula was compared to published data, and the systematic difference was compensated by applying a correction factor of 0.8. The geometry of the SEM 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 and a SE electron is recorded with its corresponding probability. 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. The GEANT4 QGSP HP module was used to simulate the hadronic interactions. The simulations were performed using a round beam of 0.5 or 1 cm radius. The cut 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 different particle types was simulated using a model in the Geant4.8.1.p01 code. 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. The SEM response curves for the main particle types and the expected energy range were simulated to allow a signal current determination using the particle fluence reaching the detector [3].

Calibration and Verification Measurements

The absolute calibration of the SEM relating the dose to the output charge was performed using the results of a dedicated high energy fixed target experiment and the corresponding simulations. The dose was obtained by measuring and simulating the energy deposition in a SEM filled by air. The output charge of the SEM under the same irradiation conditions was simulated and the two results were combined. The calibration of the SEM used by the LHC BLM system is then:

$$C_{SEM} = (764 \pm 84) \text{ pC/Gray.}$$

The dynamic range of the SEM limited by the analog front-end used in the LHC BLM system is spanning from 13 mGy/s to 1.7 MGy/s. For comparison the IC measures with the same front-end electronics in the range from 0.19 µGy/s to 23 Gy/s. The simulations were validated by various measurements with particle beams of well known parameters. The detector was tested in the range of dose rates from 0.5 mGy/s to 400 MGy/s.

Two prototypes were tested in the 62.9 MeV proton Optis line in PSI. The protons were entering through the 5 mm steel bottom cover of the detector and the output current was measured whereas the bias high voltage was varied from 2 V to 1.5 kV, so that the SEY could be calculated by dividing the beam current by detector output. Simulations and measurements were in good agreement for one of the two tested prototypes.

The detector setup from the LHC collimation areas was reproduced in the SPS accelerator, where it was used for the studies of the complete LHC BLM system. The tests showed a very good linearity of the SEMs and a

reasonable agreement with the simulations. Other tests were made in the PSB with a 1.4 GeV bunched proton beam. A reference ACEM detector (Aluminium Cathode Electron Multiplier tube) with a very fast response time was installed next to the SEM outside of the beam. The performance of the SEM shows a very fast response without under-shoot or tail in the signal for a bunch length of about 160 ns (see Fig. 4).
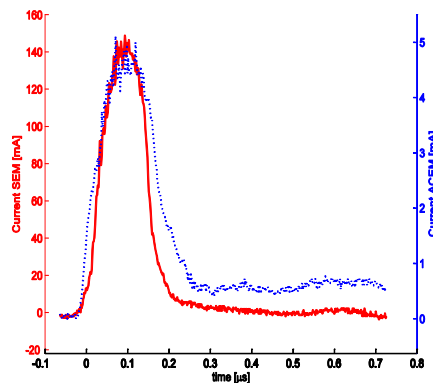
Figure 4: Time response compared to reference ACEM detector (160 ns bunch of 10^{19} p$^+$/s at 1.4 GeV). The maximum current corresponds to 180 MGy/ sec.

During these tests the SEM was also directly compared to the IC. The signal of the IC was corrected for the space charge saturation effect (see Fig. 5).
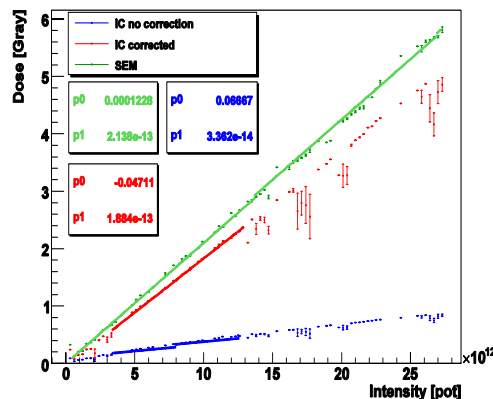
Figure 5: Comparison of the SEM response, the IC corrected for the space charge saturation effect and the IC uncorrected. The curves are fitted with linear functions.

Several preproduction prototypes and series SEMs were tested in different proton and muon beams and mixed radiation fields including a high energy beam scan across the detector to cover the full energy range of the LHC radiation field (see Fig. 6). The results showed a very high linearity and speed of the detector response (see Table 1). In total 370 SEM detectors were tested in a high energy fixed target experiment, which was producing a mixed radiation field similar to the one expected in the LHC. The experiment served for discovering potential nonconformities from the production. It was concluded,

that all the measured detectors had the inner vacuum pressure better than ~0.21 mbar and seven chambers were rejected because of too high dark current. The experiment allowed another comparison between simulation and measurements [3].
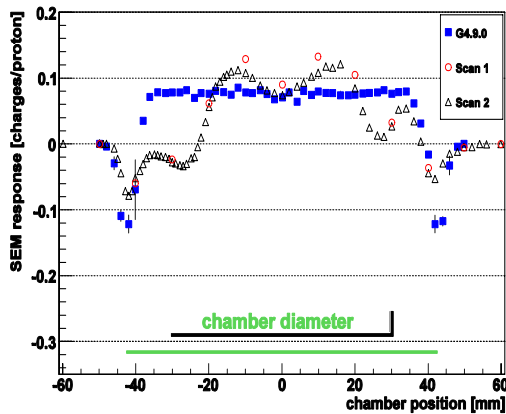

Figure 6: Simulation and measurement of the SEM response while moved stepwise through a 400 GeV proton beam. Each measurement point represents one slow extraction (4.7 seconds) passing through the bottom of the detector transverse to the surface of the electrodes.

Table 1: Summary for SEM Verification Measurements

Beam Type	Measure-ment	Simulation	(Meas-Sim) / Sim
63MeV p+ PSI	0.27±0.01	0.267±0.004	+1%
1.4 GeV p+ PSB	0.04±0.001	0.042±0.005	+19%
400 GeV p+ TT20	0.04±0.004	0.05±0.005	-29%
160 GeV muons	0.06±0.016	0.08±0.008	+26%
300 GeV mixed	3.43±0.75	3.95±0.19	+14%
26 GeV mixed L	(2.74 ±0.08) 10^{-3}	(4.58±0.14) 10^{-3}	+40%
26 GeV mixed R	(2.04±0.02) 10^{-3}	(3.56±0.08) 10^{-3}	+43%
Beam Type	SEM Meas	IC Meas	SEM-IC/SEM
450 GeV mixed	(9.79±0.02) 10^{-4}	(8.98±1.0) 10^{-4}	+8%

CONCLUSIONS

The final calibration of the BLM system was required to be within a factor two in accuracy. To achieve this final accuracy different simulations have been carried out. These simulations include the detector response function simulations and the hadronic shower simulations.

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 for the IC. 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. The SEM simulations agree also very well with the corresponding measurements performed in a wide intensity, energy range and for different radiation fields. The largest disagreement between the GEANT4 simulations and the SEM measurements was -29% obtained for the challenging high energy beam scan. The FLUKA simulations combined with the GEANT4 model resulted in a maximum disagreement of +43%, which complies with the required accuracy of the SEM detector of 40%. The dynamic range and response time for the IC and the SEM are summarized in Table 2.

Table 2: Dynamic Range IC and SEM

Type	Dyn. Range	Response Time	Calibration
IC	0.19μGy/s-23Gy/s	300ns-120μs	(54±10) μC/Gy
SEM	13mGy/s-1.7MG/s	160ns-160μs	(764±84)pC/Gy

REFERENCES

[1] M. Stockner, "Beam Loss Calibration Studies for High Energy Proton Accelerators", CERN-THESIS-2008-099 (2008).

[2] E. Lebbos, M. Brugger, B. Dehning; E. Effinger, A. Ferrari, D. Kramer, A. Nordt, K. Roeed, S. Roesler, M. Sapinski, V. Vlachoudis, "Measurements and Simulations of the BLM Response to a Radiation Field inside the CERF Target Area", CERN-ATS-Note-2010-045 TECH (2010).

[3] Daniel Kramer, "Design and Implementation of a Detector for High Flux Mixed Radiation Fields", CERN-THESIS-2008-090 (2008).