Simulations and Measurements of Secondary Electron Emission Beam Loss Monitors for LHC

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Secondary Emission Monitor (SEM) is a part of the LHC Beam Loss Monitoring system, which is providing the number of particles lost from the primary hadron beam by measuring the radiation field induced by their interaction with matter surrounding the beam pipe. SEM detectors will be used in the high dose rate environments of LHC because of their low sensitivity and excellent linearity. The design of SEM consists of two bias electrodes separating the produced secondary electrons from the Ti signal electrode placed in a vacuum steel cylinder. The response of the chamber was tested with bunched and continuous proton beams and compared with a reference detector and GEANT4 simulations.

1. BLM system

The Beam Loss Monitoring system [1] is a vital part of the active protection of the LHC. It has to detect dangerous beam losses which could quench superconductive magnets or even damage components of the accelerator. 3800 ionization chambers (BLMI) will be used in LHC as the main beam loss detectors.
Additional 360 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.

2. 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. The ultimate transient loss event the BLMS has to be able to measure is a full SPS injection of $3\,10^{13}$ p^+ lost in 20 μs in case of a kicker fault. The lifetime of the detector should be 20 years as the exchange will be impossible in some locations due to high radiation levels. The expected radiation dose at some locations is several ten MGy per year.

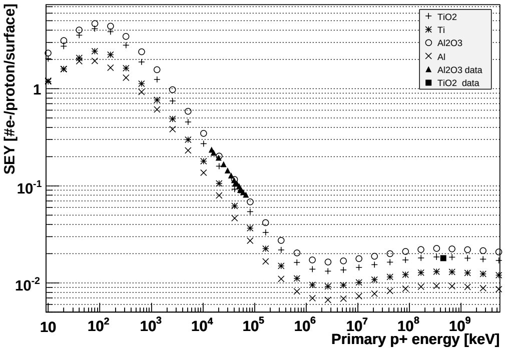

Figure 1. Modified Sternglass formula for true SEY of primary protons for different materials compared with reference data[6,7].

2.1. SEM working principle

The BLMS detector is based on the Secondary Electron (SE) emission from solids. When a charged particle passes through the signal elec-

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trode, it can excite conduction band or inner shell electrons. These so called "True Secondary Electrons" can diffuse only several nm as they usually have energies lower than 50 eV independent of the primary particle's energy and type [2] in contrary to the "knock-on" δ electrons. The material escaping SE come only from a thin surface layer of the traversed material and are 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 resulting current between the signal and bias electrodes (and also between the signal electrode and mass) is measured.

The high energy δ electrons leaving the Ti electrode do not produce a signal, because their contribution is canceled by the δ electrons arriving from the bias electrodes but only if they don't have enough energy to penetrate the electrode plates.

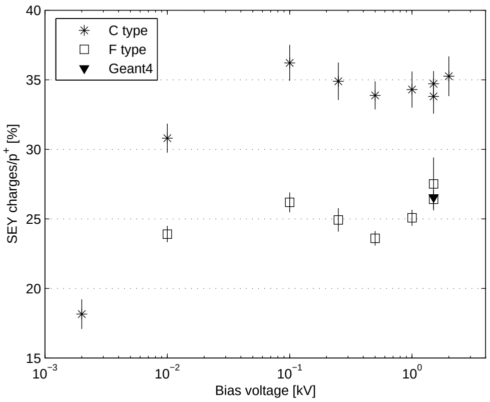

Figure 2. Variation of BLMS normalized response with bias voltage for two prototype detector versions (63 MeV proton beam in PSI).

2.2. Prototype design

The signal electrode is made of 0.5mm thick Ti, because its SEY was found to be constant up to 10^{20} p^+/cm^2 integrated dose [5]. The bias electrodes are made of Al. The detector has to operate in high vacuum of at least 10^{-4} $mbar$, because the contribution of the gas ionization to the signal has to be kept below 1% of the secondary emission to prevent a nonlinear response. All the steel components undergo the standard CERN UHV cleaning procedure and are vacuum fired at $950°C$ for several hours. A careful insulation of the signal path outside of the detector was found to be very important to prevent a signal contribution from the ionization in air.

For the final version, all the electrodes will be made of 0.25mm thick Ti. It will also contain a NEG ST707 foil of 170 cm^2 inside the steel vessel to sustain the vacuum for the lifetime of the BLMS.

3. Modeling of BLMS response

3.1. SEY estimation

It is not straightforward to simulate the SE in Geant4 [3] as it has no corresponding process defined. A modified semiempirical formula of Sternglass [4] (the contribution of δ electrons to the true SEY was not included) was used to calculate the SEY for TiO_2 surface.

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

Where $dE/dx|_{el}$ stands for electromagnetic 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 [6], TiO_2 [7]. The maximum measured SEY for the very low energy (i.e. 100 keV) protons hitting the Al target is 1.3 [8] compared to 2 from the parametrization, but particles with such energies have a negligible contribution to the signal for this application. The resulting parametrization for different materials can be found in Figure 1.

3.2. 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. 3.1 and a SE is recorded with the corresponding probability. The $dE/dx|_{el}$ is calculated by the G4EmCalculator but in case of primary e^- or e^+, the dE/dx from Bremsstrahlung must be subtracted and for mu^- or mu^+ also the e^-/e^+ pair production, as these processes don't contribute directly to secondary emission.

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 module was used for simulating the hadronic interactions. The simulations were performed using a round beam of 1cm radius.

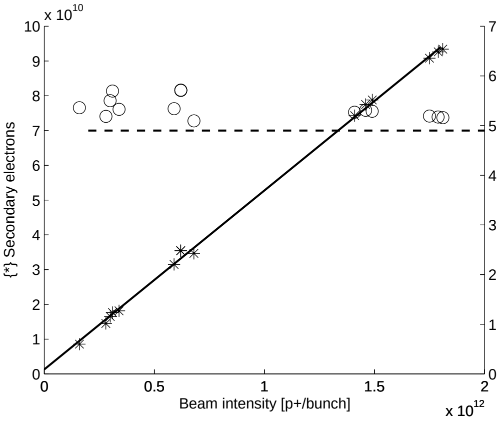

Figure 3. SEY of BLMS as function of proton beam intensity at 1.4 GeV (left axis: stars, solid line: fit to data; right axis: circles, dashed line: Geant4 simulation).

4. Measurements

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

4.1. Calibration with 63 MeV protons

Two prototype versions ("type C" and the newer "type F" which was simulated) were tested in the 62.9 MeV proton Optis line in PSI [9]. 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 bias high voltage was varied from 2 V to 1.5 kV and the resulting SEY was calculated by dividing the beam current by the detector output. Figure 2 shows a systematic pattern which has yet to be understood. The corresponding simulations were performed with a 1.5 kV electric field and are in agreement with measurements for the "F type".

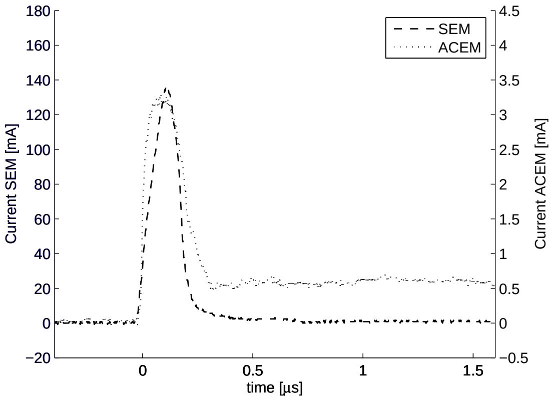

Figure 4. Time response compared to reference ACEM detector (160 ns bunch of 10^{19} p^+/s at 1.4 GeV).

4.2. Calibration with 1.4 GeV protons

The older "prototype C" was installed in the PS Booster dump line and tested with a bunched proton beam. Figure 3 shows a very good linearity of the BLMS and a reasonable agreement with the simulation. A reference ACEM (Aluminum Cathode Electron Multiplier tube) detector with fast response time was installed close to the BLMS outside of the beam. Figure 4 shows a very fast time response without any under-shoot or tail in the signal for a bunch length of about 160ns.

5. Conclusions

The BLMS prototype showed no saturation effect and high linearity at the ultimate particle flux as foreseen in the design. Measurements at two different energies partially validated the chosen approach of Secondary Electron Emission simulation in Geant4, which can now be used for determination of thresholds of the LHC BLM system. Further tests in a mixed radiation field and with a 400 GeV proton beam are planned as well as a high sensitivity outgassing test.

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