SECONDARY ELECTRON EMISSION BEAM LOSS MONITOR FOR LHC

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Abstract

Beam Loss Monitoring (BLM) system is a vital part of the active protection of the LHC accelerators' elements. It should provide 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. The LHC BLM system will use ionization chambers as standard detectors but in the areas where very high dose rates are expected, the Secondary Emission Monitor (SEM) chambers will be employed because of their high linearity, low sensitivity and fast response. The SEM needs a high vacuum for proper operation and has to be functional for up to 20 years, therefore all the components were designed according to the UHV requirements and a getter pump was included. The SEM electrodes are made of Ti because of its Secondary Emission Yield (SEY) stability. 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 in CERN PS Booster dump line, SPS transfer line and in PSI Optis line. The results were compared to the simulations.

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. 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.

The ultimate transient loss event of 3×10^{13} p^+ lost in 20 μs in case of an injection kicker fault has to be measurable by the BLMS (i.e. a full injection from the SPS).
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.

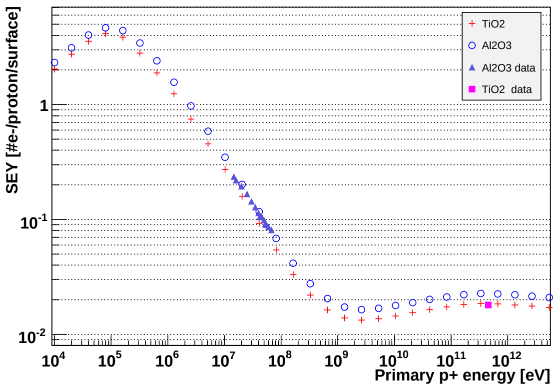

Figure 1: Modified Sternglass formula for true SEY of primary protons for different materials scaled by factor 0.8 to fit reference data[6, 7].

SEM working principle

The BLMS detector is based on the Secondary Electron (SE) emission from solids. When a charged particle passes through the signal electrode, 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. The BLMS can detect neutral particles only indirectly, if they initiate a shower in the steel vessel.

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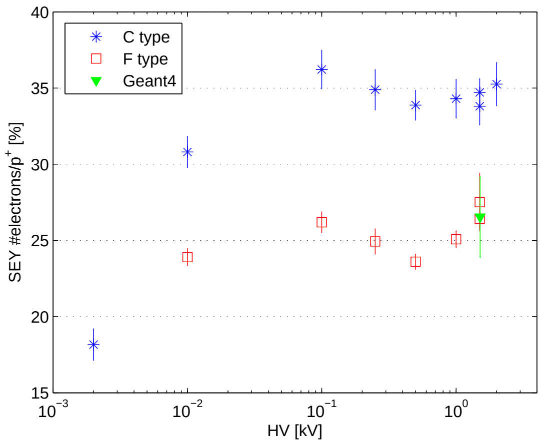

Figure 2: Variation of BLMS normalized response with bias voltage for two prototype detector versions (63 MeV cyclotron proton beam in PSI).

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 active area inside the steel vessel which can adsorb a quantity of H_2 higher than the total surface capacity of the chamber.

MODELING OF BLMS RESPONSE

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.

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

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 [6] and 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] (not plotted) 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 lie below the e^- production cut of the simulation. The resulting functional dependence for different materials can be found in Figure 1.

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. 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. 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 module was used for simulating the hadronic interactions. The simulations were performed using a round beam of 0.5 or 1cm 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.

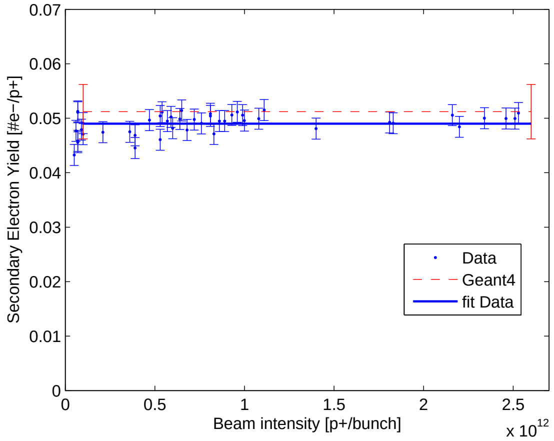

Figure 3: SEY of BLMS as function of proton beam intensity at 1.4 GeV. Simulation error was estimated to 10%.

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 and SPS transfer line.

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 seems to be caused by the low energy δ electrons coming from the HV electrodes. The corresponding simulations were performed with a 1.5 kV electric field and are in a surprising agreement with measurements for the "F type".

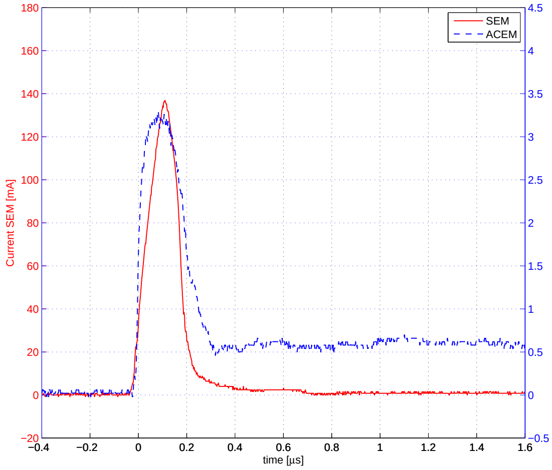

Figure 4: Time response to single bunch compared to reference ACEM detector (160 ns bunch of 2.16×10^{12} p^+ at 1.4 GeV).

Calibration with 1.4 and 400 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, 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. Figure 4 shows a very fast time response without any undershoot or tail in the signal for a bunch length of about 160ns. The chamber signals were measured with Tektronics oscilloscope and 50 Ω termination. The integration was done offline in Matlab code.

The preliminary calibration in the SPS TT2 transfer line at 400 GeV resulted to 0.134 electrons/proton, but the beam profile was not measured. Therefore the measurement will be repeated soon. The corresponding Geant4 simulations estimate the sensitivity to 0.116 electrons/proton with relatively high contribution of δ electrons.

CONCLUSIONS

The BLMS prototype showed no saturation effect and high linearity at the ultimate particle flux as foreseen in the design. Measurements at different energies seem to validate the chosen approach of Secondary Electron Emission simulation in Geant4, which can now be used for determination of thresholds of the LHC BLM system. The largest relative error between measurements and simulations is 14% 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. Further tests in a mixed radiation field on the SPS beam dump and SPS collimation area for proton and ion beams are foreseen or ongoing.

REFERENCES

[1] E.B. Holzer et al., Beam Loss Monitoring System for the LHC, IEEE NSS '05, Puerto Rico, CERN-AB-2006-009 BI.

[2] D. Hasselkamp et al., Particle Induced Electron Emission II, Springer-Verlag, (1992).

[3] GEANT4 simulation toolkit, http://www.cern.ch/geant4.

[4] E.J. Sternglass, Theory of Secondary Electron Emission by High-Speed Ions, Phys. Rev. 108(1957) 1.

[5] G. Ferioli and R. Jung, Evolution of the Secondary Emission Efficiencies of various materials measured in the CERN SPS secondary beam lines, CERN-SL-97-071-BI, (1997).

[6] C.M. Castaneda et al., Secondary electron yields from the bombardment of Al_2O_3 by protons, deuterons, alpha particles and positively charged hydrogen molecules at energies in the range of 10 to 80 MeV, Nuclear Instr. and Meth. B 129(1997) 199-202.

[7] K. Bernier et al., Calibration of secondary emission monitors of absolute proton beam intensity in the CERN SPS North Area, CERN-97-07, (1997).

[8] B. Svensson and G. Holmén, Electron Emission from aluminum and copper under molecular-hydrogen-ion bombardment, Phys. Rev. B 25(1982) 5.

[9] Paul Scherrer Institute, Villigen Switzerland, http://www.psi.ch.