LHC Beam Loss Detector Design; Simulation and Measurements

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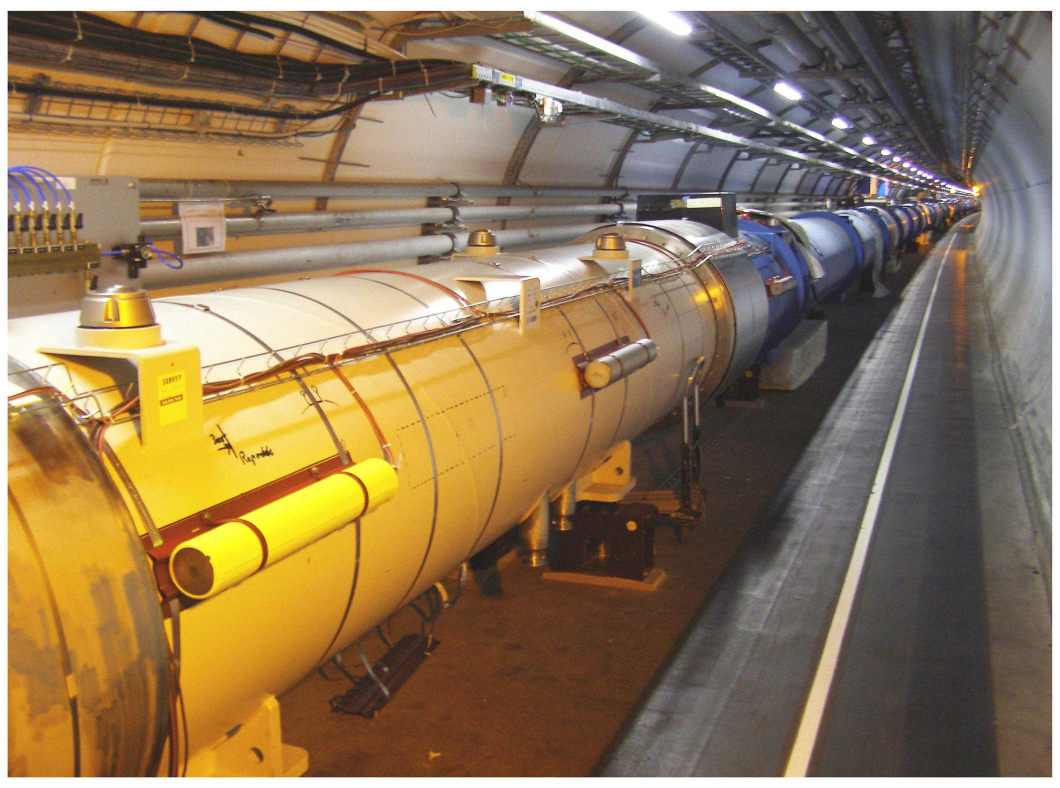
Abstract: *The Beam Loss Monitoring (BLM) system is integrated in the active equipment protection system of the LHC. It determines the number of particles lost from the primary hadron beam by measuring the radiation field of the shower particles outside of the vacuum chamber. The LHC BLM system will use ionisation 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 Ionisation 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



- detect dangerous beam losses
- avoid quench or damage
- 3700 ionisation chambers (BLMI)
- 280 SEM detectors (BLMS) (high radiation areas)
- ionisation chamber and SEM to extend the dynamic range

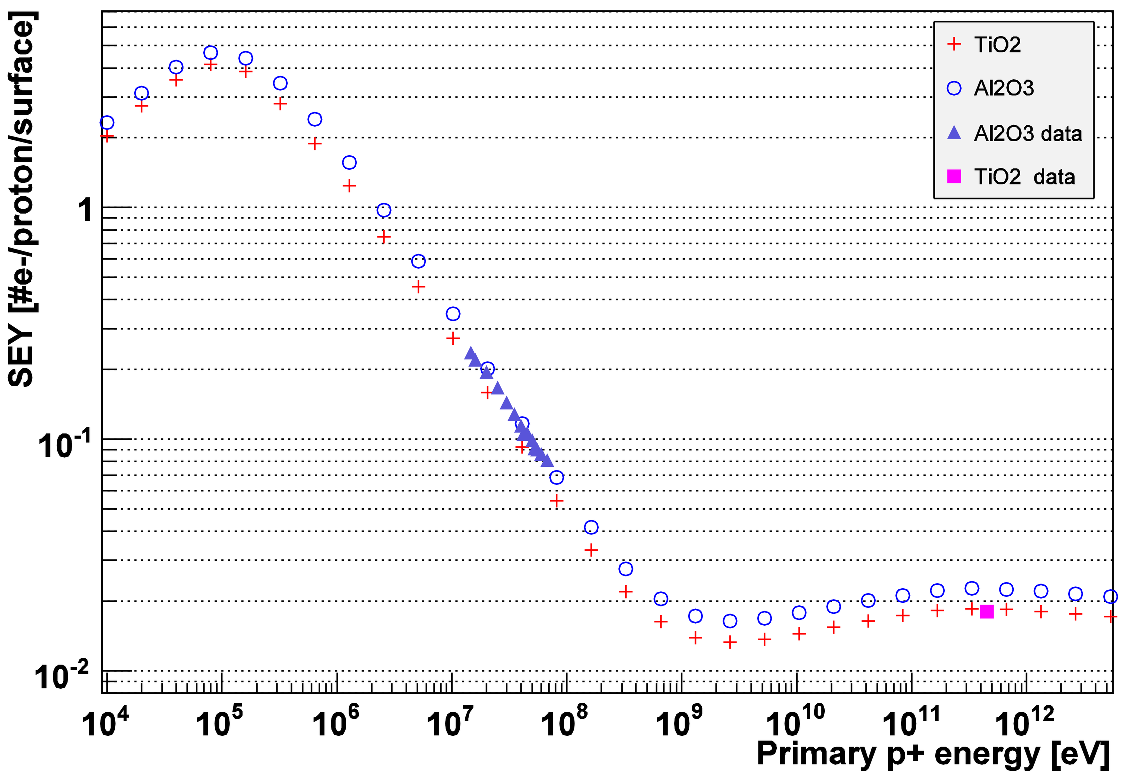
- BLMs located outside of the cryostat at the plane of the vacuum chambers
- Two detectors are on the quadrupole magnets (white) and one on the adjacent bending magnet (blue).

Basics of Secondary Electron Emission

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

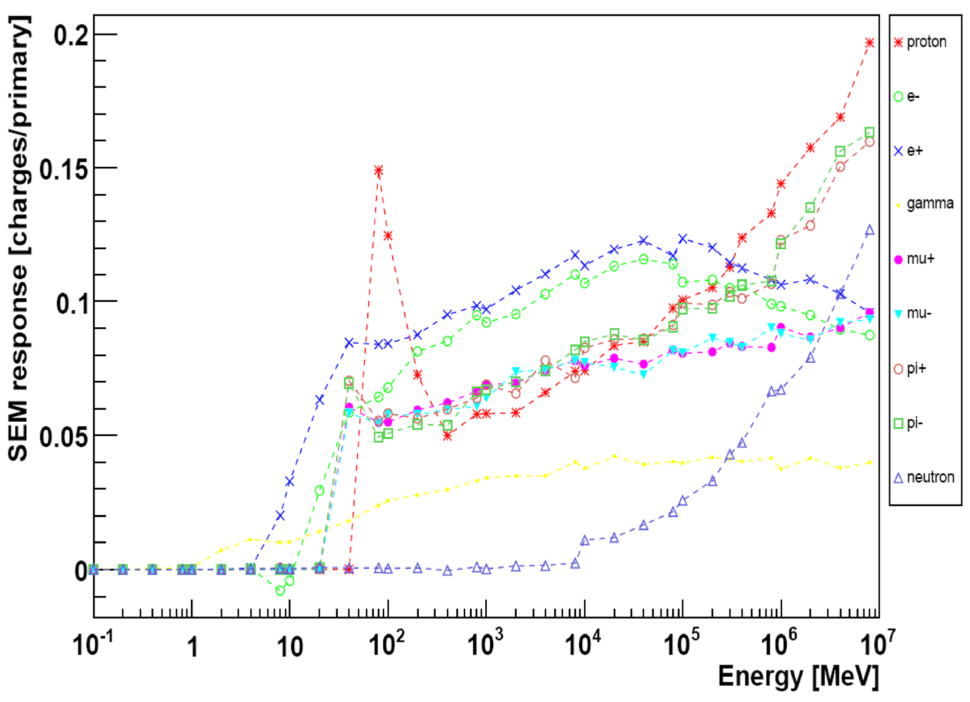
Secondary Emission Yield depends on the electronic energy loss of the projectile inside the surface layer (i.e. TiO_2 for Ti electrode) and effective penetration distance (L_s) of SE .

- **Secondary Electrons** have energies < 50 eV
- Diffuse from few nm of surface layers
- Are produced by excitation of conduction band or inner shell electrons
- Are influenced by the work function of the material
- Are produced only by charged particles
- Energy spectrum independent of projectile energy



Secondary Emission Monitor Response Simulation

- Geant4.8.1.p01 hadronic module QGSP_BERT_HP
- no Geant4 module for SEM
- Sternglass formula (semiempirical)
- Signal: charge balance on the signal electrode plus "true secondary e⁻" from custom model
- round beam (σ = 2 mm)
- no signal from particles below 10MeV, stopped in detector walls
- hadron signal increased due to relativistic rise
- negative signal of e⁻ due to absorption in signal electrode



Ionisation Chamber Response Simulation

Characterisation of the LHC BLM detector

Detector response can be folded with spectra → Detector signal

Verification of simulation by analytic calculations for muons with Bethe-Bloch formula

Agreement:

- 1 GeV mu^+: 95%
- 35 MeV mu^+: 75%

2 mm thick detector wall of stainless steel leads to an **energy cut-off**: (particle above this level start to deposit energy in the detector)

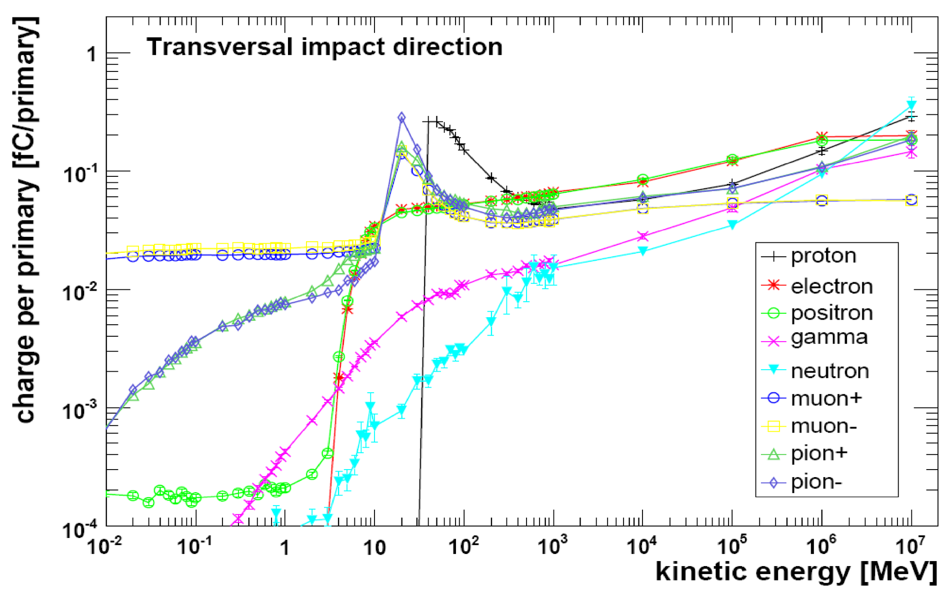
- Protons, neutrons ~ 30 MeV
- Electrons, photons ~ 2 MeV

Deposited energy is converted with the w-value to produced charges (Nitrogen: 35 eV per electron-ion pair, ICRU report 31)

Detailed detector simulation with

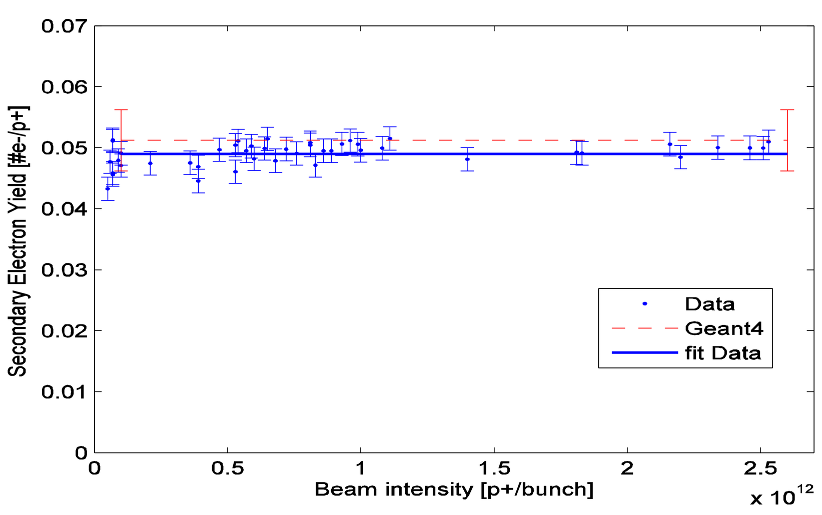
Geant4 (4.8.1.p01 QGSP_BERT_HP):

- 9 different particle types
- kinetic energy range: 10 keV – 10 TeV
- transverse and longitudinal irradiation

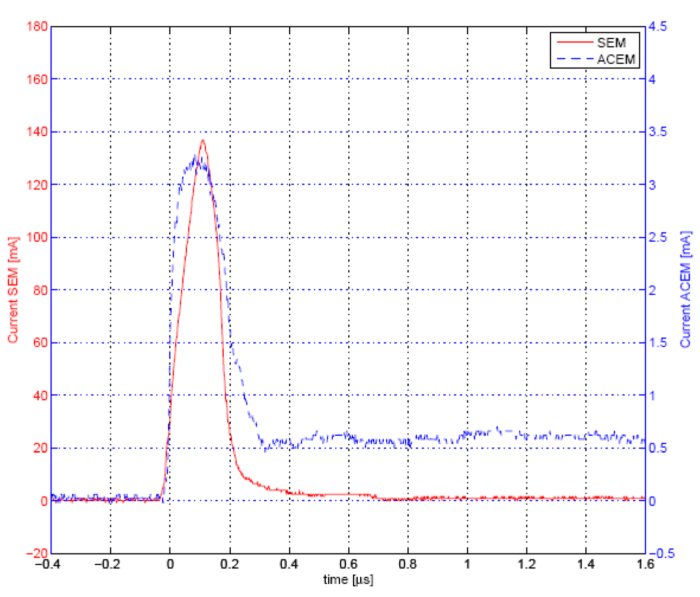


SEM Measurements with Proton Beams

- The older "prototype C" installed in the PS Booster dump line and tested with a single bunch proton beam of 1.4 GeV
- Very good linearity of the BLMS and a reasonable agreement with the simulation, (within the statistical error)



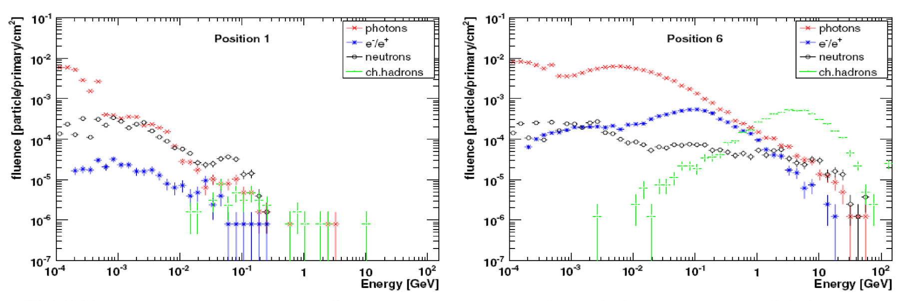
Linearity test with single bunched proton beam of 1.4GeV in front of PSB Dump



- SEM and ACEM (Aluminum Cathode Electron Multiplier tube) response time measurement
- SEM response without any undershoot or tail

BLMI Verification Measurements

1 Mixed radiation field measurements at CERF target area (CERN-EU High Energy Reference Field Facility), 5 positions: different particle composition and mean energy, simulation agrees with measurement, except position 1 (lower energy spectra, 21%). Linearity of the detector verified over 1 order of magnitude



FLUKA spectra: up-stream (lower mean energy) and down-stream (higher mean energy) position (H. Vincke)

2 Protons at 400 GeV/c: SPS extraction line at CERN, systematic error of 23%, due to beam position uncertainty

3 Gamma Calibration at TIS-RP Calibration Laboratory for Radiation Protection Instruments (CERN) with Cs137 sources (662 keV)

4 Neutrons at 174 MeV: Svedberg Laboratory, Uppsala University (Sweden), intensity:(0.7 to 4.6) 10^6 neutron per second, assuming 11.2% gamma contribution to signal

	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

Conclusion

- 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.