Classification of the LHC BLM Ionization Chamber

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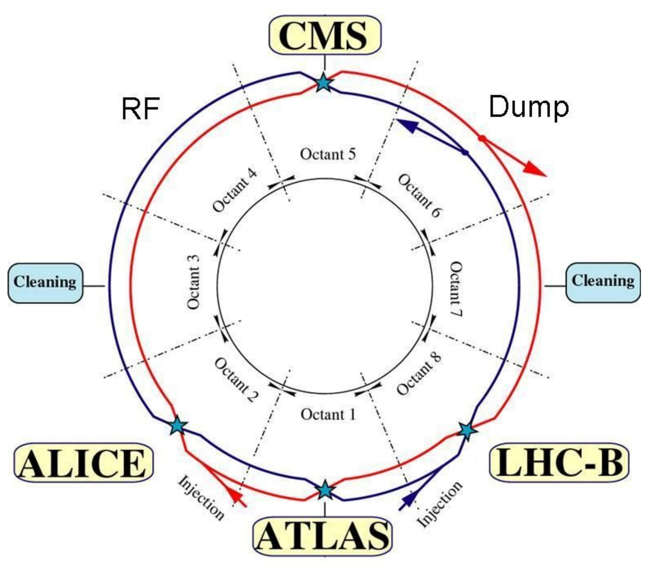
Abstract: *The LHC beam loss monitoring (BLM) system must prevent the super conducting magnets from quenching and protect the machine components from damage. The main monitor type is an ionization chamber. About 4000 of them will be installed around the ring. The lost beam particles initiate hadronic showers through the magnets and other machine components. These shower particles are measured by the monitors installed on the outside of the accelerator equipment. 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). For validation, the simulations are compared to measurements using protons, neutrons, photons and mixed radiation fields at various energies and intensities. This paper will focus on the signal response of the ionization chamber to various particle types and energies including recombination effects in the chamber gas at high ionization densities.*

LHC and it's BLM System



- **Circumference:** 26.7 km
- **Injection energy:** 450 GeV
- **Top energy:** 7 TeV in two counter rotating beams
- **~ 350 MJ** stored energy per beam (can melt 500 kg of copper)
- **~ 11 GJ** stored energy in the magnet system
- **~ $3x10^{14}$** protons per beam
- Superconducting magnets
- Magnetic field **8.3 T** (**1.9 K**)
- Factor 4 − 20 more sensitive to beam losses compared to existing hadron machines

Quench Risk → **BLM System**

Purpose:
- Machine protection against damage of equipment and magnet quench
- Localization of beam losses and identification of loss mechanism
- Machine setup and studies

Location:
- BLM mounted outside of cryostat (transverse tail of hadronic showers), six around each quadrupole

Challenges:
- Reliability (tolerable failure rate 10^{-7} per hour per channel)
- Large dynamic range (10^8, pA - mA)

Calibration of the BLM System

Proton loss location

Hadronic showers
Detector response

Number of locally lost beam particles

→ *Simulations performed*
▭ *Presented in this poster*

Hadronic showers

BLM signal

Precision Factor 2–5

Dump at 30% of damage level

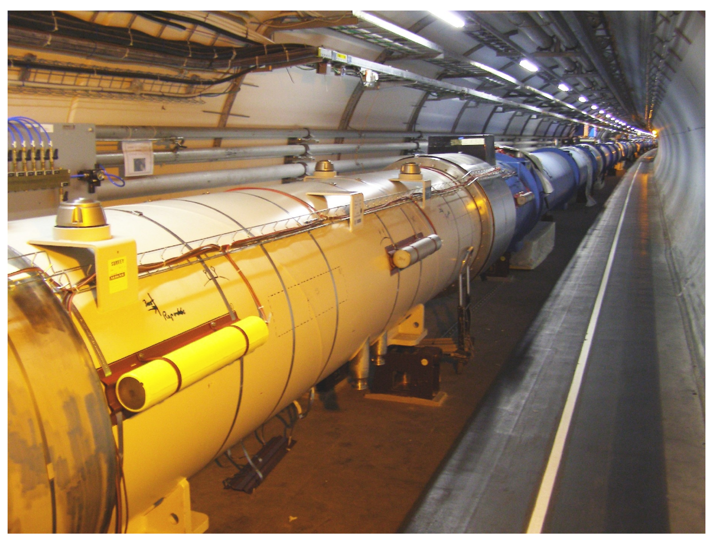
Deposited energy in the machine component

Quench and damage levels as function of loss duration (heat flow in machine component)

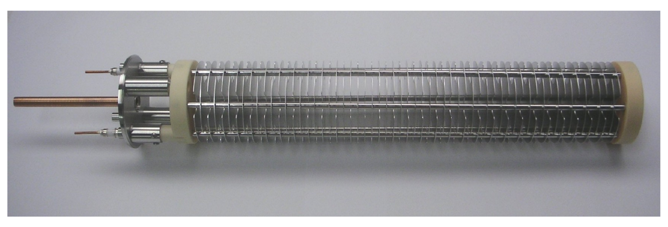
Fraction of quench and damage level of the machine component

Dump threshold values
- Machine component
- Loss location
- Detector position
- Beam energy
- Loss duration

BLM Tunnel installation:
4000 detectors outside of the cryostat in the horizontal plane of the beam



Ionization chamber design:
Diameter = 8.9 cm
Length: 60 cm
Volume: 1.5 litre
60 Al disks, 0.5 mm
Gas: N_2 (1.1 bar)
Bias voltage: 1500 V



Ionization Chamber Response Simulation

Characterization of the LHC BLM detector

Detector response can be folded with spectra → Detector signal

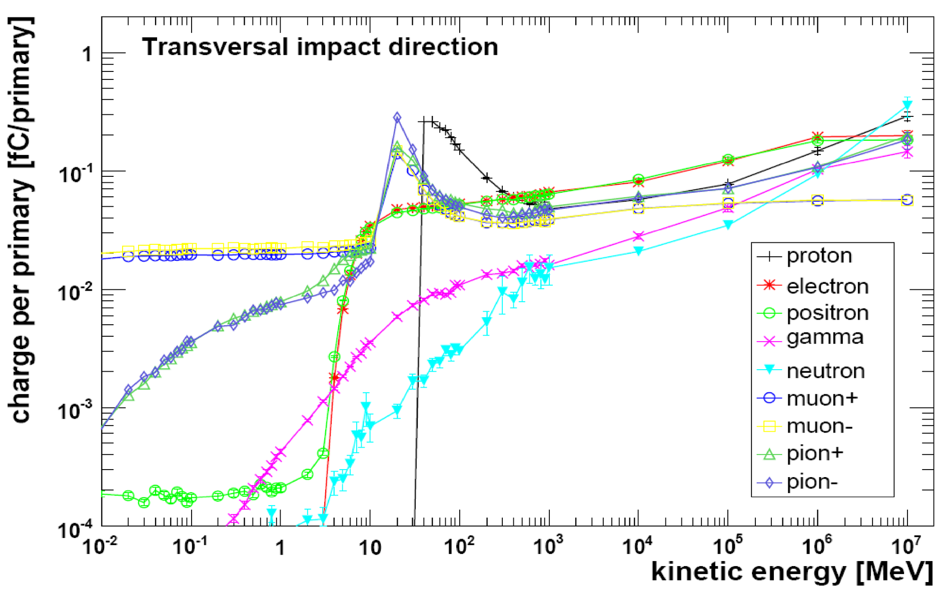
Verification of simulation by analytic calculations for muons with Bethe-Bloch formula

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

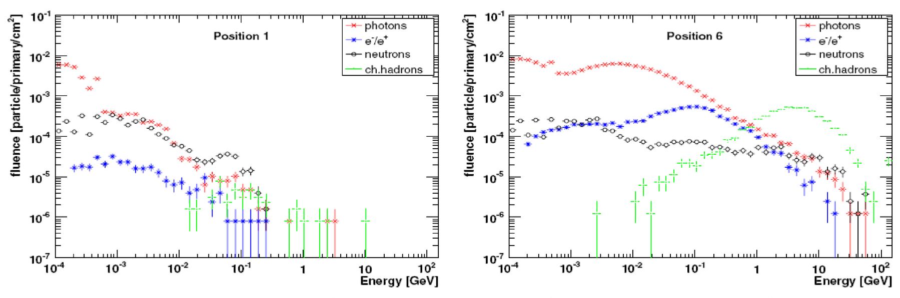
Deposited energy is converted with the w-value to produced charges (Nitrogen: 35 eV per electron-ion pair, ICRU report 31)

Detailed detector simulation with Geant4 (4.8.1 QGSP_BERT_HP):
- 9 different particle types
- kinetic energy range: 10 keV – 10 TeV
- transverse and longitudinal irradiation



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 per second, assuming 11.2% gamma contribution to signal

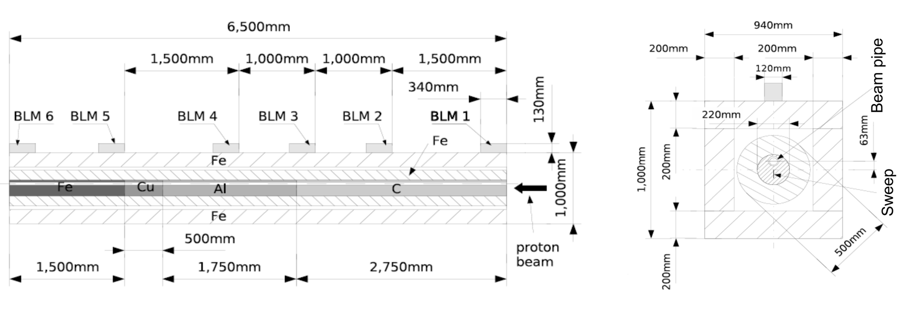
	Simulation		Measurement		sim./meas.	
	BLM	**err.**	**BLM**	**err.**	**ratio**	**err.**
pos.	**CERF experiment [pC per $9.2 \cdot 10^7$ hadrons]**					
1	91.13	0.35	115.33	11.66	0.79	0.08
2	281	6	—	—	—	—
3	1656	18	1578	163	1.05	0.11
4	2387	22	2122	231	1.12	0.12
5	3944	23	3532	370	1.12	0.12
6	6496	18	7091	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

Hadronic Shower Measurements at HERA

Part of the error estimation of the LHC BLM system calibration with Geant4: Verification of far transverse hadronic shower tail simulations.

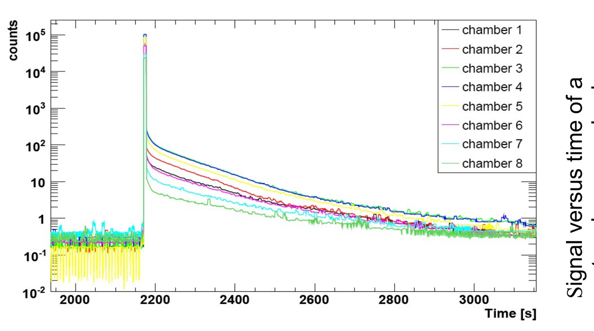
Dump simulation in two steps:
- Simulation of spectra at detector position
- Simulation of detector signal

Simulation codes:
- Geant4.8.1 QGSP_BERT_HP
- Geant4.8.2 FTFP
- FLUKA

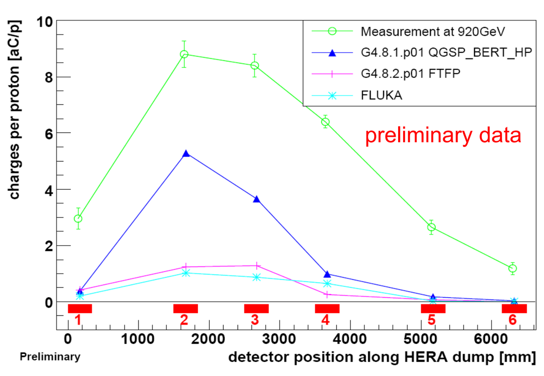


HERA/DESY internal proton beam dump equipped with LHC type BLM system, 6 detectors longidunially spaced by ~ 1m on top of the dump.

$1.3{\times}10^{11}$ to $1.3{\times}10^{13}$ protons in 21 μs at 39 GeV (injection) and 920 GeV (top energy)



Signal versus time of a proton dump, peak: shower measurement, tail: activation



Preliminary simulated and measured signals versus detector position on the HERA proton beam dump. Detector positions (in scale) indicated at the bottom.

Difficulties:
- ionization chambers probe far tails of shower distribution (simulation uncertainties)
- high flux of low energy neutrons and gammas

Preliminary Results:
- strong dependence on simulation code and physics modes, QGSP_BERT_HP closest to data (less than factor 2 in the peak)
- significant difference in absolute height and longitudinal shape between measurement and simulation. Backward and forward tails in the data are not represented in the simulations.

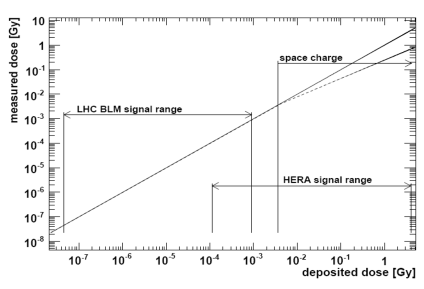
Successful longterm test of the complete LHC BLM System in real accelerator environment

Space Charge Effect in Ionization Chamber

Above a critical ionization density a dead zone of thickness d−x_0 (d being the electrode spacing) forms next to the cathode (R.M. Zwaska, PhD thesis, University of Texas at Austin, December 2005)

$$x_0 = \left[\frac{\epsilon_0}{q}\frac{4\mu V^2}{\phi}\right]^{1/4}$$

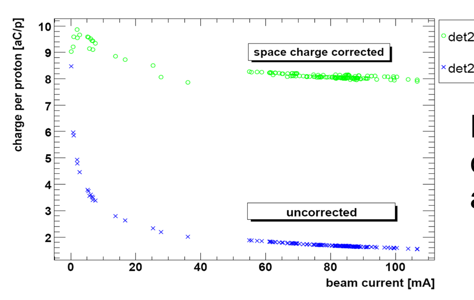
μ: ion mobility, φ: ionization per volume and time, V: chamber voltage, q: elementary charge.



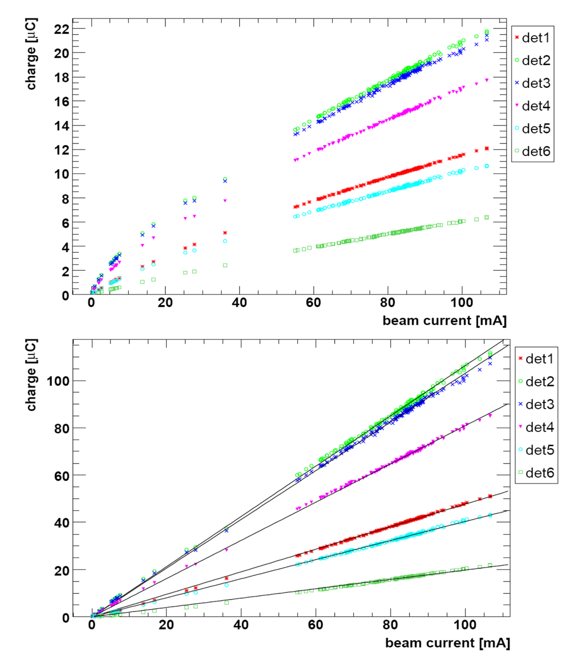
Application of the formula to the LHC BLM ionization chamber: Comparison of a linear detector response to the space charge model. At the standard LHC operation range the ionization density is below the critical value: a dead zone due to space charge will not form.

Det.	39 GeV		920 GeV	
	$\mathbf{I}_{min}$ **1 mA**	$\mathbf{I}_{max}$ **90 mA**	$\mathbf{I}_{min}$ **1 mA**	$\mathbf{I}_{max}$ **100 mA**
1	1.	2.95	1.17	6.70
2	1.	3.80	2.00	8.71
3	1.	3.27	1.97	8.61
4	1.	2.60	1.71	7.95
5	1.	1.76	1.16	6.34
6	1.	1.35	1.	5.03

Range of correction factors at the HERA experiment



Highest correction case (detector 2 at 920 GeV)



All 6 HERA detector signals at 920 GeV as a function of beam current before (above) and after (below) space charge correction. Most of the nonlinearity of the signals has been corrected by the rather simple theoretical model above.

Results

BLM detector response simulation with Geant4 and verification by measurements:

→ Part of the BLM system calibration

- mixed radiation field (CERF) → ratio simulation / measurement within uncertainties, (except upstream position 21%)
- 400 GeV protons → comparison within 13%, determined by systematic uncertainty (23%) in beam position
- gamma calibration → within 4%
- 174 MeV neutrons → below 30% (uncertainty in the magnitude of gamma contribution)

Simulation and measurement of far transverse hadronic shower tails at HERA proton beam dump (preliminary results):
- significant dependence on simulation codes and physics models (final verification pending!)
- simulation does not well represent data in magnitude and longitudinal shape (underestimates transverse and longitudinal tails)
- simple space charge model corrects most of the signal nonlinearities

→ Part of the uncertainty estimation of the LHC BLM system calibration (factor of 5 accuracy requested for LHC startup end of 2007)

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