Accuracy of LHC proton loss rate determination by the BLM system

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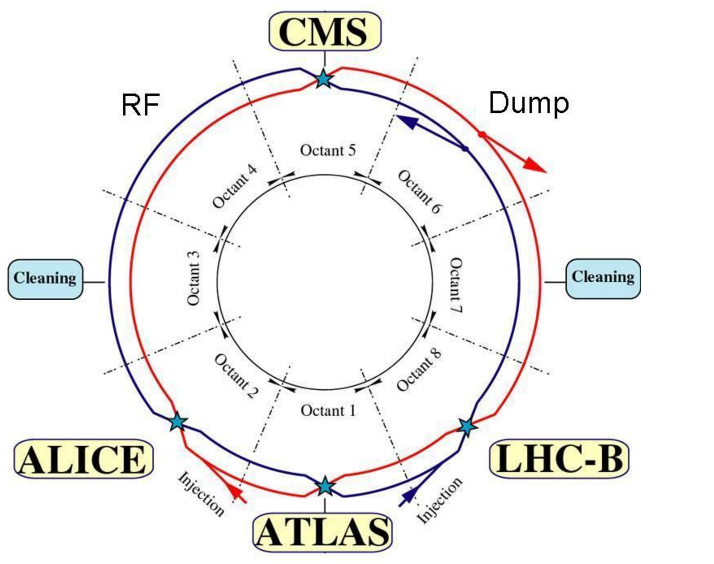
Abstract: *Most of the monitors of the LHC beam loss monitoring (BLM) system are installed on the outside of the magnet cryostats, around the quadrupole magnets. Their aim is to prevent quenches and to protect the super conducting magnets from damage. The lost beam particles initiate hadronic showers through the magnets and deposit energy in the coils. The gas filled BLM ionization chambers probe the very far transverse tail of the showers. The BLM system relies on GEANT simulations to determine the relation between the chamber signal, the number of lost beam particles and the deposited energy in the magnet coil. The specification of the BLM system includes a factor of two absolute precision on the prediction of the quench levels. As the shower tails are not necessarily well represented by particle simulation codes, it is crucial to experimentally determine the accuracy of these simulations.*

An LHC type BLM system was installed at the internal beam dump of HERA at DESY since 2005. The hadronic showers created by the impacting 39 GeV and 920 GeV protons have been simulated with GEANT4. The far transverse tails of the showers on the outside of the dump have been measured by ionization chambers. This paper will present the comparison of simulation to measurement and the conclusions drawn for the LHC BLM system.

LHC and its 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:
- BLMI mounted outside of cryostat (transverse tail of hadronic showers), six around each quadrupole, special locations (high dose rates) BLMS

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

Calibration of the BLM System

Proton loss locations
Hadronic showers
Detector Response

Number of locally lost beam particles

↓ *Hadronic showers*

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

BLM signal

Precision Factor 2–5

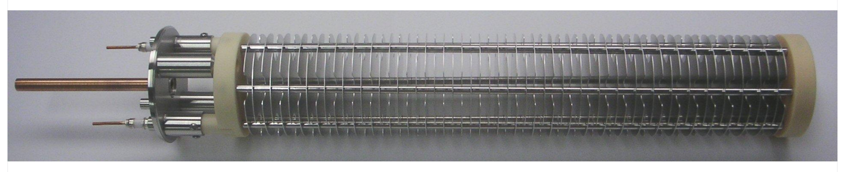
Dump at 30% of damage level

→ *Simulations performed*

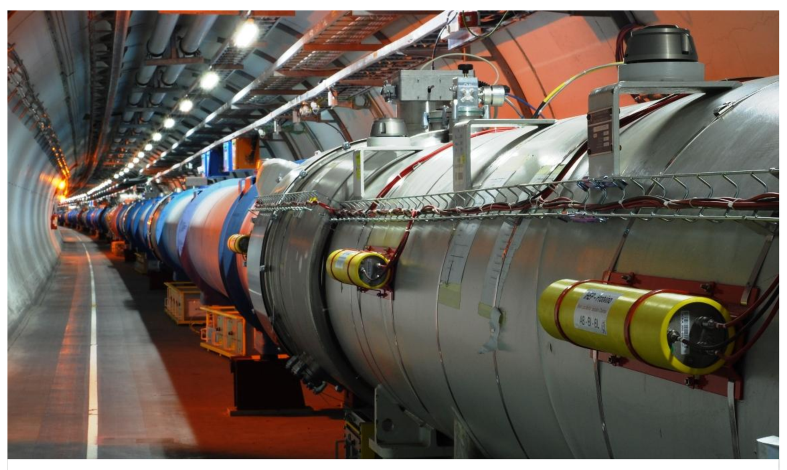
Dump threshold values depend on:
- Machine component
- Loss location
- Detector position
- Beam energy
- Loss duration

Precision required:
- Factor 5 initially
- Factor 2 finally

Ionization chamber design:
Diameter = 8.9 cm; Length: 60 cm; Volume: 1.5 litre; 61 Al disks of 0.5 mm; Gas: N_2 (1.1 bar); Bias voltage: 1500 V



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



Ionization Chamber Response Simulation

Characterization of the LHC BLM detector

Detector response can be folded with spectra → Detector signal

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)

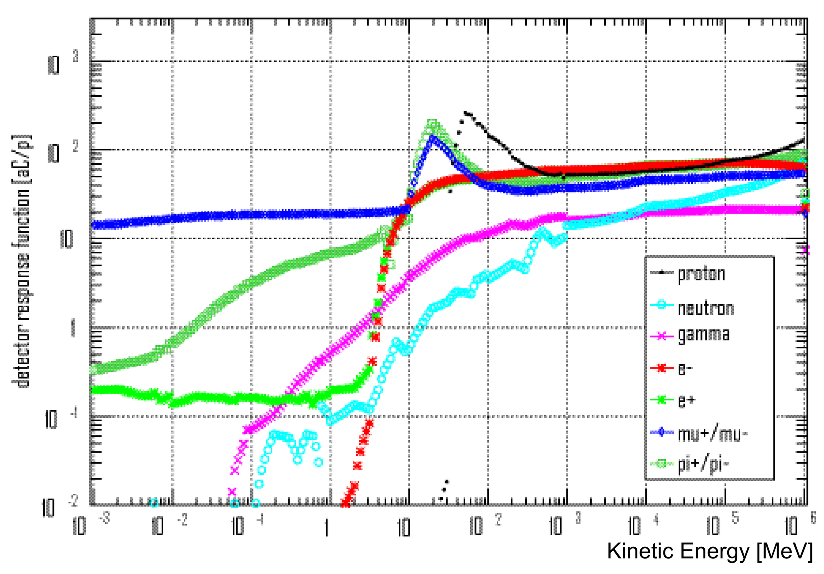
- Protons ~ 30 MeV
- Electrons, pions ~ 2 MeV
- Deposited energy is converted with the w-value to produced charges (Nitrogen: 35 eV per electron-ion pair, ICRU report 31)

Verification of simulation by analytic calculations and measurements of proton, neutron, gamma and mixed radiation fields

Uncertainty of 17%derived as the systematic error of the detector response functions in the LHC

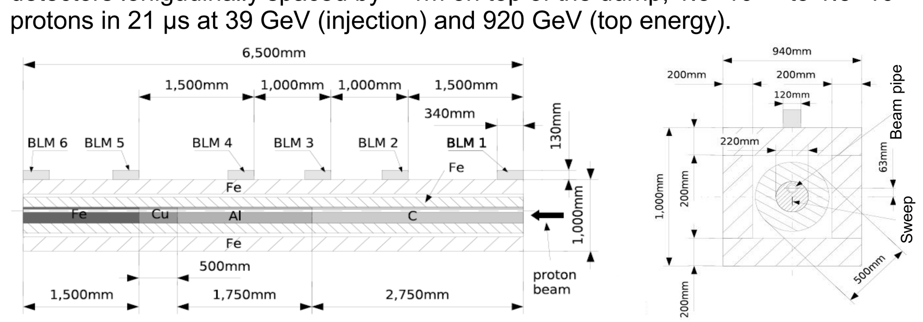
Detailed detector simulation with Geant4 (4.8.1.p01 QGSP_BERT_HP):

- 9 different particle types
- kinetic energy range: 10 keV – 10 TeV
- 60 deg impact angle relative to detector axis is used for LHC threshold calculations

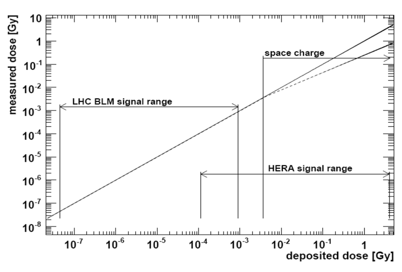


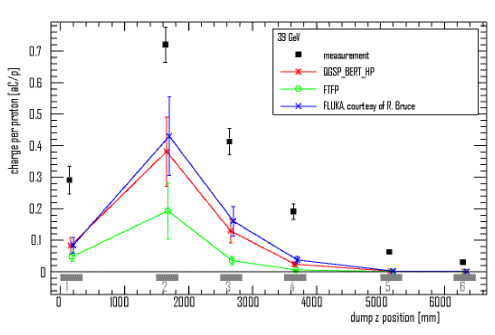
Hadronic Shower Measurements at HERA

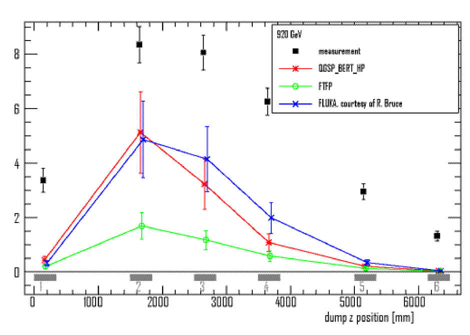
HERA/DESY internal proton beam dump equipped with LHC type BLM system; 6 detectors lonigudinally spaced by ~ 1m on top of the dump; 1.3×10^{11} to 1.3×10^{13} protons in 21 µs at 39 GeV (injection) and 920 GeV (top energy).



Space charge correction applied to HERA measurements (factor 1 to 5). Above a critical ionization density a dead zone forms next to the cathode (R.M. Zwaska, PhD thesis, University of Texas at Austin, December 2005)





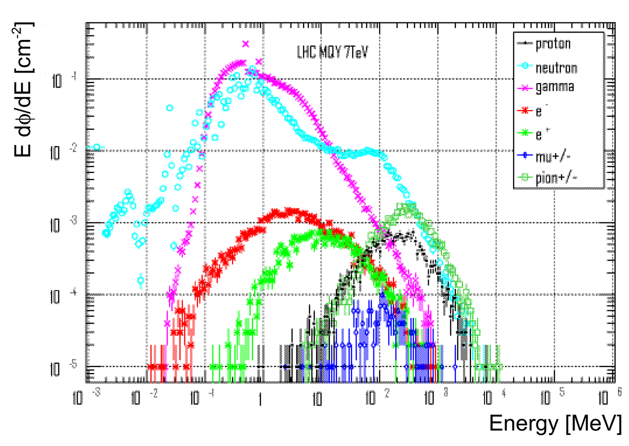


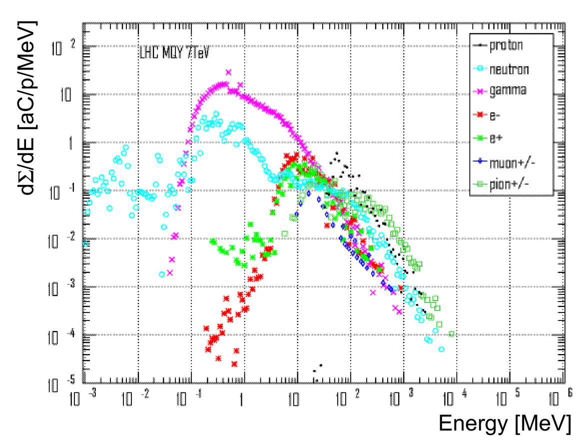
Part of the error estimation of the LHC BLM system calibration with Geant4:

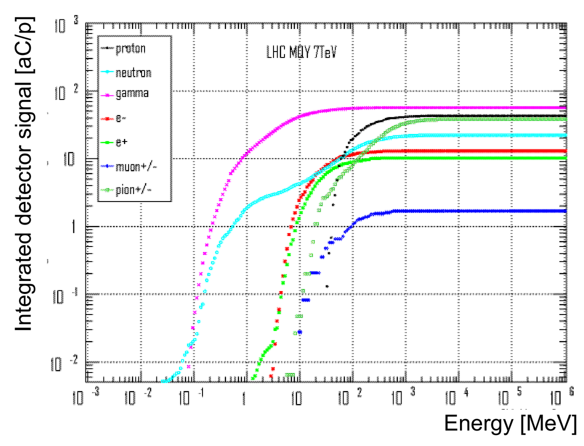
- Verification of far transverse hadronic shower tail simulations
- High flux of low energy neutrons and gammas
- Strong dependence on simulation code and physics modes, QGSP_BERT_HP and FLUKA closest to data (less than factor 2 in the peak)
- Significant difference in absolute height and longitudinal shape between measurement and simulation.
- Successful longterm test of the complete LHC BLM System in real accelerator environment

LHC BLM Detector Thresholds

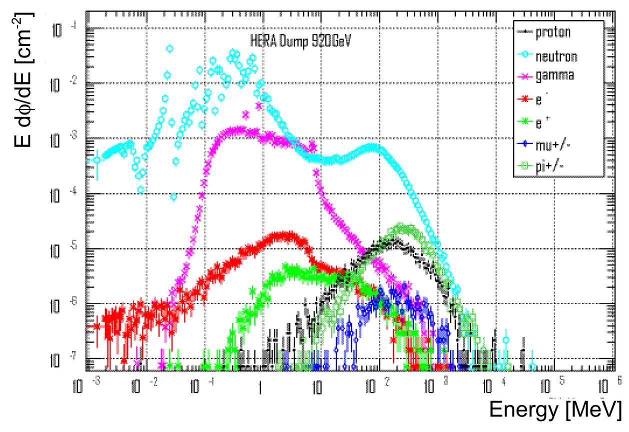
MQY LHC quadrupole magnet 7TeV

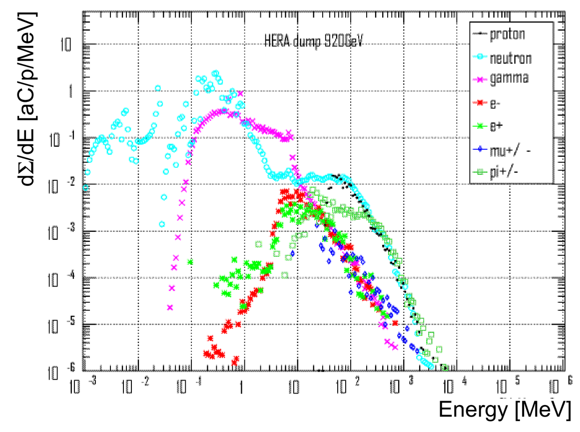


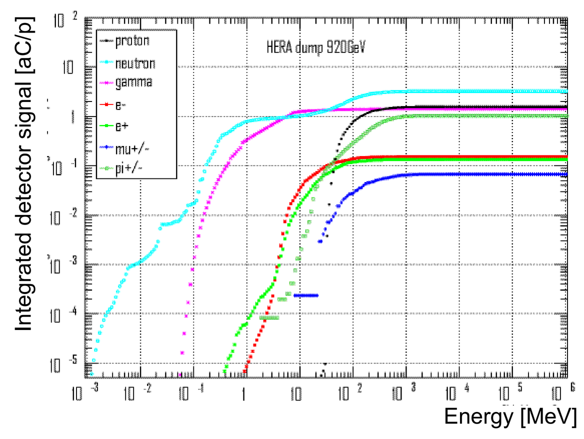




HERA proton beam dump 920 GeV







Secondary particle fluence spectrum on the outside recoded in a 3.4 m long stripe, lethargy representation.

Detector signal, Σ, (particle fluence folded with detector response) at 1.5m from the proton impact

Integrated detector signal

Interpolation between the HERA beam dump measurement (70% uncertainty at 16 λ_0) and the mixed radiation field measurement (20% uncertainty at 3 λ_0) yields an **estimated uncertainty on the LHC threshold simulations of 50%** from 0.5 to 3.5 m after impact.

Loss duration dependent quench limits for the MQY magnet. Previously calculated minimum and maximum BLM signals for LHC arc magnet in comparison.

loss duration	quench limit	detector current [A]			
		min	max	this work	error
<100 µs	5 mJ/cm^3	3.05e-07	1.83e-05	6.89e-05	3.65e-05
100 s<	5.29 mW/cm^3	4.17e-10	2.50e-08	2.92e-09	1.55e-09

	LHC MQY	HERA dump
e+/-	12.6%	3.8%
gamma	30.7%	18.5%
mu+/-	0.9%	0.9%
neutron	12.1%	42.6%
pi+/-	20.6%	13.6%
proton	23.1%	20.6%
total signal [aC/p]	184.14	7.61

Contribution from the different particle types to the signal. Compared are the signals for an LHC MQY BLM detector and detector 2 at the HERA dump experiment.

Comparison of a superconducting LHC magnet to the HERA proton beam dump in terms of radiation length (X_0) and nuclear interaction length (λ_0)

distance		HERA dump		distance	MQY LHC	
long. [m]	lateral [m]	[X_0]	[λ_0]	lateral [m]	[X_0]	[λ_0]
0	0.5	21.02	2.28	0.33	11.59	1.17
1.5	0.5	64.44	6.98	0.33	51.08	5.17
2.5	0.5	103.42	11.18	0.33	83.83	8.49
3.5	0.5	144.57	15.62	0.33	116.86	11.83
5	0.5	202.54	21.88	0.33	—	—
6	0.5	246.47	26.64	0.33	—	—