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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 and controll measurements to determine the relation between the chamber signal, the number of lost beam particles and the energy deposited in the magnet coil. The specification of the BLM system includes a factor of two in absolute precision on the final 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 39GeV and 920GeV 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.

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Accuracy of LHC proton loss rate determination by the BLM system

Eva Barbara Holzer, Bernd Dehning, Christian W. Fabjan, Daniel Kramer, Mariusz Sapinski, and Markus Stockner

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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.

***Index Terms*—LHC BLM, beam loss monitoring, Geant4, hadronic shower simulation**

I. INTRODUCTION

AN unprecedented amount of energy will be stored in the circulating beams of the LHC (up to 360 MJ per beam - enough to heat 500 kg of Cu from 2 K to the melting point and melt it) and in the magnet system (10 GJ). The proton energy is 450 GeV at injection and 7 TeV at collision. The loss of even a very small fraction of this beam may induce a quench in the super-conducting magnets or cause physical damage to machine components. The BLM system detects and quantifies the amount of lost beam particles. It generates a beam abort trigger when the losses exceed predetermined threshold values to protect the equipment from damage and the magnets from quenching. The main detector type is an ionization chamber. About 4000 will be installed, mostly around the quadrupole magnets. Fig. 1 shows ionization chambers (yellow cylinders) mounted on the outside of an LHC quadrupole magnet at the same height as the circulating beams. The detectors probe the transverse tails of the hadronic showers through the cryostats. The start-up calibration of the BLM system is required to be within a factor of five in accuracy; and the final accuracy should be a factor of two. For the calibration and threshold determination a number of simulations are combined. Beam particles are tracked to find the most probable loss locations. At these locations hadronic showers through the machine components are simulated to get the particle spectra at the detector locations. A further simulation yields the detector response. The quench levels of the superconducting magnets, according to loss duration and beam energy, are simulated separately. Whenever possible, crosschecks of the threshold calibration simulations by measurements have been performed or are planned before the start-up of the LHC.

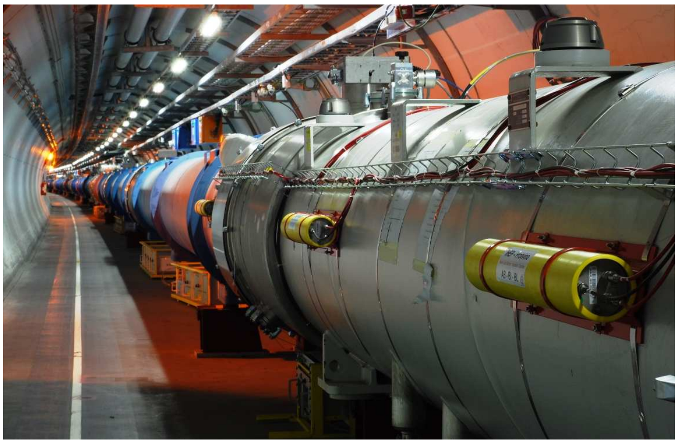

Fig. 1. LHC tunnel. Beam loss detectors (yellow cylinders) are mounted on the outside of a quadrupole cryostat.

This paper will focus on the uncertainty of the estimation of the transverse hadronic shower tail simulations, which is part of the system calibration error. Measurements at HERA/DESY are compared to simulations and conclusions are drawn for the LHC BLM system.

II. CALIBRATION OF THE BLM SYSTEM

The BLM system calibration is based on simulations and backed up by measurements. The simulated detector response functions (see section III) were validated with protons, gammas, neutron, muons and in mixed radiation fields. The quench limit simulations are validated with magnet quench tests at CERN.

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magnets are simulated and the deposited energy in the magnets coil is recorded. The maximum energy deposition is compared to the quench level of the magnet, and the number of lost beam particles which will lead to a magnet quench is derived. In the hadronic shower simulation the particle fluence spectra are recored at the outside of the magnet. From these spectra the detector signal is generated and scaled with the number of beam particles. This gives the detector signal, at which the magnet will quench (the quench level). A specified fraction of this signal will be set as the limit at which a safe beam extraction will be triggered (the beam abort threshold).

III. IONIZATION CHAMBER RESPONSE SIMULATION

The main detector type is an ionization chamber with parallel aluminum electrodes separated by 0.5 cm (Fig. 2). The detectors are about 50 cm long with a diameter of 9 cm and a sensitive volume of 1.5 liter. The chambers are filled with N_2 at 100 mbar overpressure and operate at 1.5 kV.

Fig. 2. LHC BLM ionization chamber.

Depending on the loss location the detectors will be exposed to different radiation fields. The energy of the particles is spread over a large range from keV to TeV. GEANT4 (version 4.8.1.p01 QGSP-BERT-HP [1][2][3]) simulations of the ionization chambers were performed to determine the signal response for different particle types at various kinetic energies in the range of 10 keV to 1 TeV. The cut-off value of the ionization chambers is below 2 MeV for photons and electrons and below about 30 MeV for neutrons and protons. The response functions for particle impacting at 60° in respect to the detector axis are presented in Fig. 3.

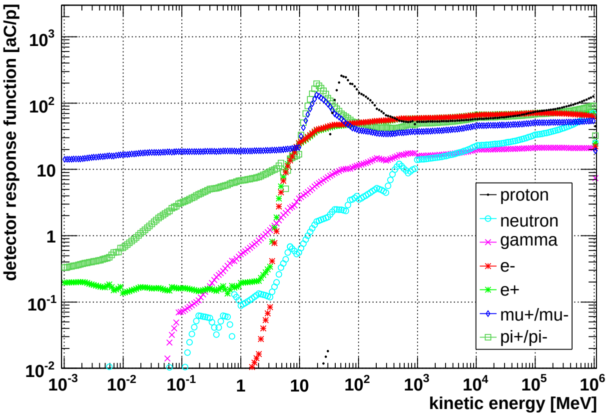

Fig. 3. GEANT4 simulated LHC BLM detector response functions for particle impact direction of 60°.

IV. HADRONIC SHOWER MEASUREMENTS AT HERA

The HERA internal proton beam dump served as a test bed for the LHC BLM system. The proton energy at collision is about twice the LHC injection energy. The particle spectrum outside the dump is comparable to the one outside of an LHC magnet. It is dominated by low energy (below 10-100 MeV) neutrons and photons. The HERA machine was running nearly continuously since the installation of the experiment in 2005, allowing for a long term test of the complete LHC BLM system. Six ionization chambers are placed on top of the dump, with a longitudinal spacing of about 1 m (see Fig. 4 and Fig. 5).

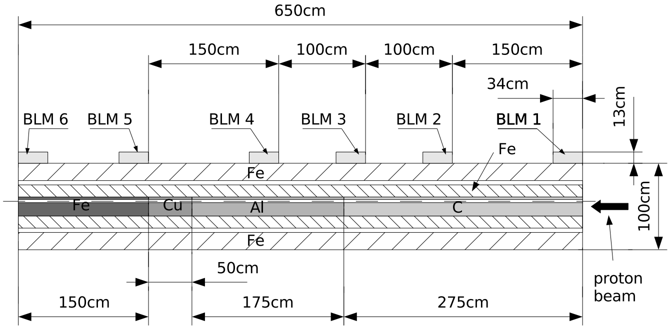

Fig. 4. Schematic of the HERA proton beam dump. Indicated are the ionization chambers.

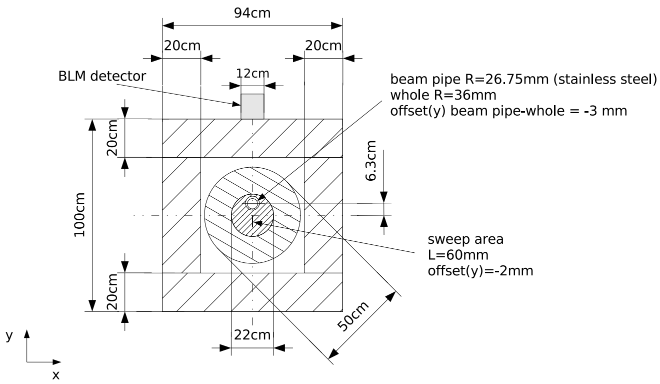

Fig. 5. Schematic of the HERA proton beam dump in beam direction.

They measure the tails of the hadronic showers induced by the impacting protons. The proton energy is 39 GeV at injection and 920 GeV at collision. The beam intensity is in the range of $1.3{\cdot}10^{11}$ to $1.3{\cdot}10^{13}$ protons per 21 μs.

The measurements have been corrected for space charge effects according to a formula derived in [4]. Above a critical ionization density a dead zone of thickness $d - x_0$ (d being the electrode spacing) forms next to the cathode:

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

μ is the ion mobility, ϕ is the ionization per volume and time, V is the chamber voltage and q is the elementary charge. At the standard LHC operation range of the ionization chambers, the ionization density is lower and the dead zone will not form. It will only be reached at special beam tests. At

HERA, on the contrary, it gives a correction of up to a factor of 5 (Fig. 6).

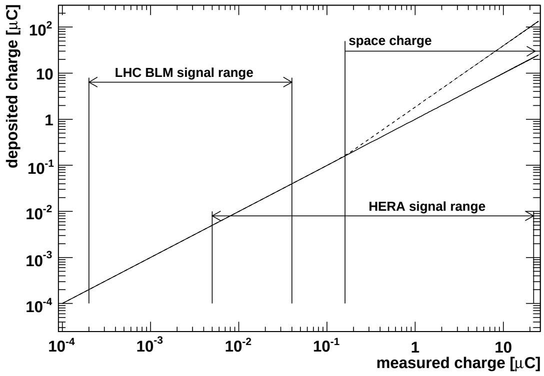

Fig. 6. Acquisition ranges and space charge effect range.

The showers through the beam dump have been simulated with GEANT 4.8.1 and two different physics models, QGSP-BERT-HP and FTFP. A FLUKA simulation of the dump was done for comparison. Fig. 7 shows the results of the simulations and the measurements. The measurements have been corrected for space charge effects.

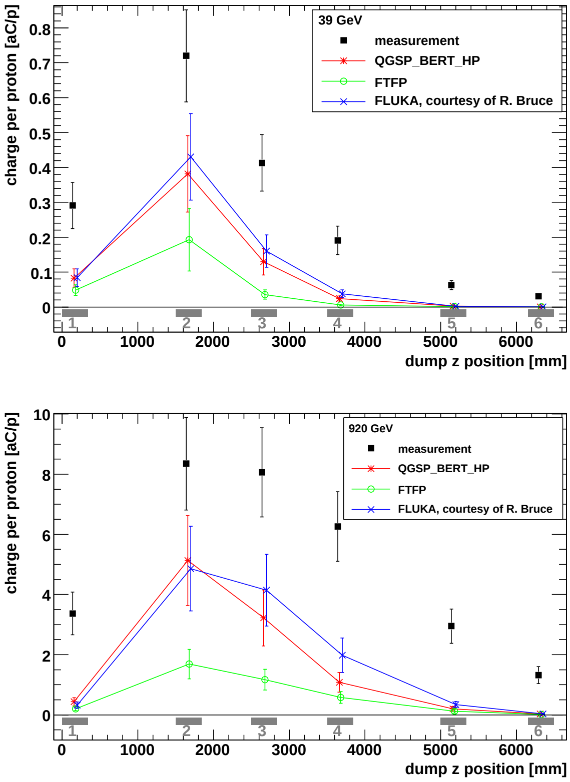

Fig. 7. Measurements and simulations for the HERA proton beam dump. Top: 39 GeV; bottom: 920 GeV.

The predicted signal strongly depends on the choice of simulation code and physics model. All models significantly underestimate the transverse shower tails. The GEANT4 QGSP-BERT-HP and FLUKA are closest to the data, within less than a factor of 2 at the detector 2, which is close to the shower peak. Longitudinally as well, the models underestimate the extent of the shower in both directions, backward (detector 1) and forward (detectors 4, 5 and 6).

Fig. 8. Installation of beam loss detectors on top of the HERA proton beam dump.

From the uncertainties derived from the validation of the detector response functions and the uncertainties determined in the comparison of the hadronic shower tail simulations and measurements at the HERA proton beam dump, a systematic uncertainty of a generated detector signal of 70% has been found. This error estimate is valid for a detector placed in the range of z=0.5 m to z=3.5 m after the impact point of the protons.

V. LHC BLM DETECTOR THRESHOLDS

Table I gives the 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). The interpolation between the HERA beam dump simulation (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.

TABLE I
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) [5].

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	—	—

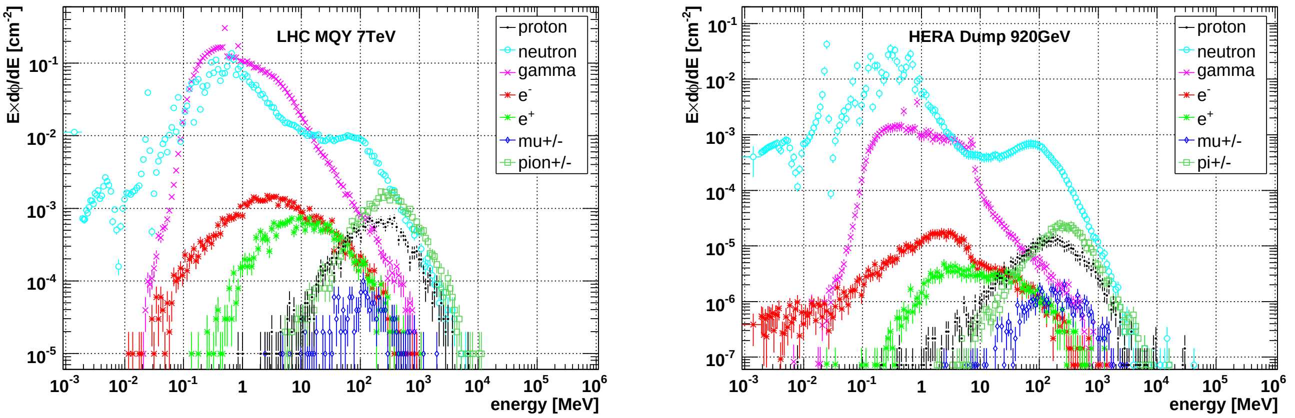

Fig. 9. Secondary particle fluence spectrum on the outside recorded in a 3.4 m long stripe, lethargy representation. Left: MQY magnet, protons with 7 TeV impacting on the beam screen. Right: HERA dump, proton energy 920 GeV.

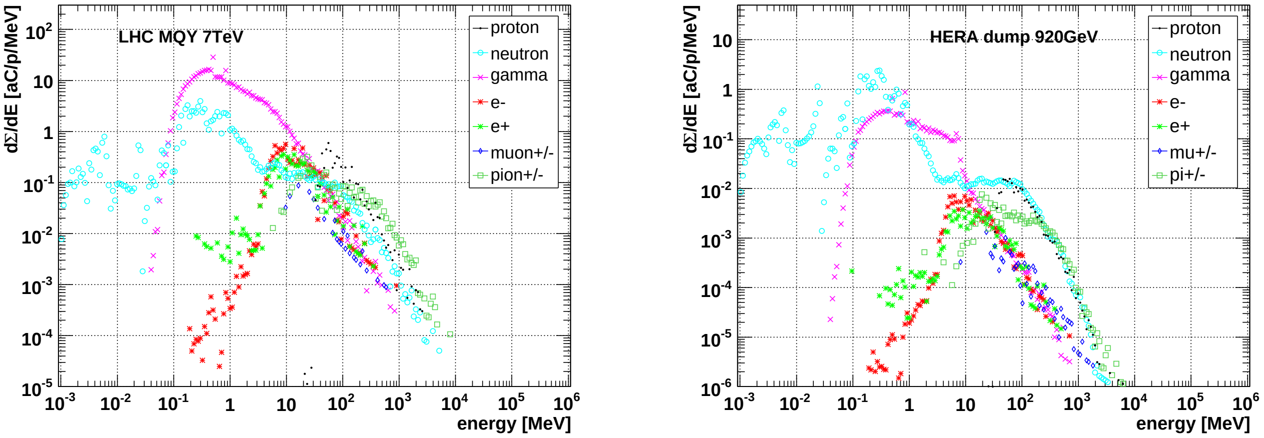

Fig. 10. Detector signal, Σ, (particle fluence folded with detector response) at 1.5 m from the proton impact. Left: MQY magnet, 7 TeV; Right: HERA dump, 920 GeV.

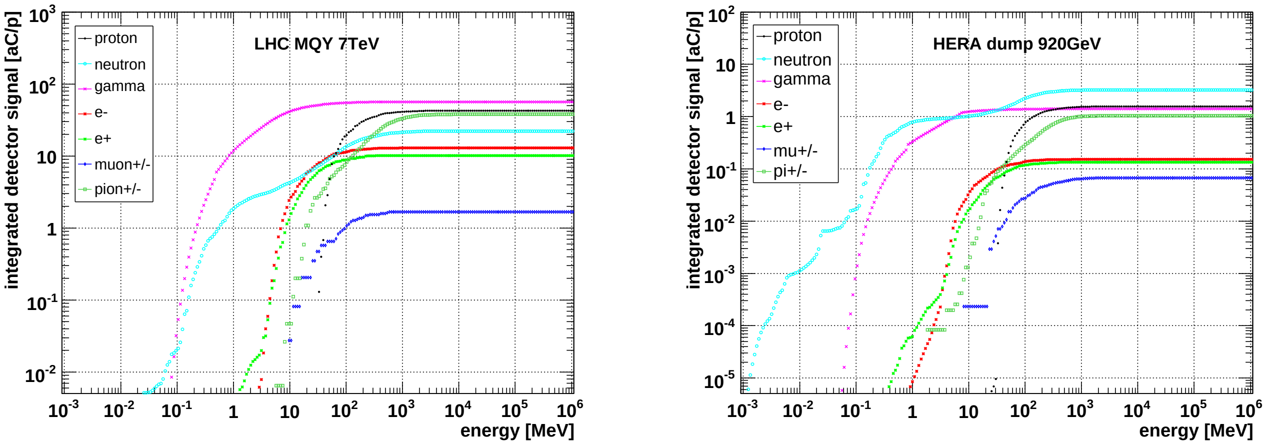

Fig. 11. Integrated detector signal. Left: MQY magnet, 7 TeV; Right: HERA dump, 920 GeV.

LHC BLM detector thresholds for steady state and transient losses were calculated for a long straight section quadrupole magnet, MQY, see Table II. The quench limits have been determined and the hadronic shower through the magnet was simulated. The particles fluence spectrum outside the magnet was convoluted with the detector response function to derive the detector signals. For the design of the dynamic range of the LHC BLM system, detector thresholds had been previously estimated for arc dipole magnets. The newly calculated threshold for steady state losses on an MQY magnet is within the minimum and maximum threshold estimate for the LHC reference arc magnets. The new threshold for transient losses exceeds the previous estimate by a factor of 3.8, but it is still within the design parameters of the LHC BLM electronics.

TABLE II
LOSS DURATION DEPENDENT QUENCH LIMITS FOR THE MQY MAGNET [6]. PREVIOUSLY CALCULATED MINIMUM AND MAXIMUM BLM SIGNALS [7][8] FOR LHC ARC MAGNETS IN COMPARISON TO THE ESTIMATED BLM DETECTOR SIGNAL DERIVED WITHIN THIS WORK.

loss duration	quench limit	detector current [A]			
		min	max	this work	error
$<100\,\mu$s	5 mJ/cm^3	3.1e-07	1.8e-05	6.9e-05	3.7e-05
100 s$<$	5.3 mW/cm^3	4.2e-10	2.5e-08	2.9e-09	1.6e-09

Fig. 9 gives the secondary particle fluence spectra on the outside of an LHC MQY magnet for 7 TeV protons and on the outside of the HERA proton beam dump for 920 GeV protons. The differences in the spectra yield from the difference in nuclear interaction length from proton impact to measurement position and from the different energies. In Fig. 10 the fluence spectra are folded with the detector response (Fig. 3 to give the detector signal at 1.5 m from the proton impact position. And finally, in Fig. 11 the detector signals for each particle type is integrated. Table III gives the contributions from different particle types to the signal of an LHC MQY BLM detector and to detector 2 at the HERA dump experiment. At HERA the largest contribution is from gammas (31%), while at the LHC MQY magnet neutrons give the most significant contribution (43%).

TABLE III
CONTRIBUTION FROM THE DIFFERENT PARTICLE TYPES TO THE SIGNAL. COMPARED ARE THE SIGNALS FOR A LHC MQY BLM DETECTOR AND DETECTOR 2 AT THE HERA DUMP EXPERIMENT.

	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

VI. CONCLUSIONS

The first LHC BLM quench threshold levels have been calculated, which use the full chain of the threshold simulations. They partly deviate from previous estimates, but are well covered by the dynamic range of the BLM system. The uncertainty of the BLM threshold simulation was determined to 50% by comparison to measurements. This uncertainty will be taken into account when setting the save beam abort thresholds. It should not pose anny difficulty for the system, given that an initial accuracy of a factor of 5 is required for the start-up of the LHC.

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