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BEAM LOSS DETECTION SYSTEM IN THE ARCS OF THE LHC

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Beam Loss Detection System in the Arcs of the LHC

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Abstract. Over the whole circumference of the LHC, Beam Loss Monitors (BLM) will be needed for a continuous surveillance of fast and slow beam losses. In this paper, the location of the BLMs set outside the magnet cryostats in the arcs is proposed. In order to know the number of protons lost on the beam screen, the sensitivity of each BLM has been computed using the program GEANT 3.21, which generates the shower inside the cryostat. The material and the magnetic fields have been described thoroughly in 3-D and the simulation results show the best locations for 6 BLMs needed around each quadrupole. The number of minimum ionizing particles received for each lost proton serves to define local thresholds to dump the beam when the losses are menacing to quench a magnet.

INTRODUCTION

In the future LHC, superconducting magnets produce the high magnetic fields needed to guide protons. These magnets store an enormous amount of energy and fast and efficient beam loss monitors are required to prevent quenches. Quench levels have been computed for different loss duration [1]. Fast losses will be seen as an ulterior readout of the BLMs system. For a medium range loss (10 ms) the number of top energy protons inducing a quench is of about 10^7. In order to prevent quenches, a loss detection system sensitive to much smaller losses is needed. For monitoring losses we need to correlate the number of lost protons with the detection signal in a BLM.

During the beam lifetime losses are concentrated in the cleaning sections, where most of the halo is caught. Beyond the cleaning sections, there are still some protons, which will be scraped by the beam pipe bottlenecks. Losses will happen where the betatronic functions have a maximum value near focusing quadrupoles. The absolute position of a quadrupole combined with the local amplitude of the closed orbit will define the likely vacuum chamber bottlenecks. There are also some possible misalignments between the end of a quadrupole and the adjacent dipoles. The accuracy of alignment gives a displacement of the beam screens by a maximum of 3 mm peak to peak from one magnetic element to the next. It has been shown [2] that most losses will happen on the first half of the quadrupole and misalignments can produce losses in the upstream dipole or in the downstream one. We have considered these three possible locations of the losses.

The Monte Carlo shower code GEANT 3.21 [3] has been used to simulate the impact of high energy protons (point losses) on the aperture of superconducting magnets in the LHC arcs. These calculations allow to determine the efficiency of beam loss monitors as well as the suitable position and number of these monitors.

We are interested in the detection of losses outside the cryostat. There we have the advantage of easier accessibility and positioning flexibility, as well as, less restriction on the detector size and control electronics. The detection system will be made up of PIN diodes. PIN diodes are sensitive to the passage of Minimum Ionizing Particles (MIPs).

LOSS SIMULATIONS: GEOMETRY AND PROCEDURE

The geometry used in the simulations corresponds to a Short Straight Section (SSS) of the LHC arcs. The layout and the different elements configuration and description is based mainly on [4], as well as the latest modifications when available. The code GEANT calculates the hadronic and electromagnetic cascade produced by a proton hitting the beam screen at a given position. The longitudinal distribution of generated secondaries is obtained outside the vacuum vessel.

LHC arc half-cell model

The SSS of the half-cell consists of a main twin aperture quadrupole (MQ), and the surrounding main bending magnets plus correctors. In the geometry used, we are centered on the MQ, and only the MD (Main Dipole) first neighbors, plus the corrector magnets associated are defined. The values for the bending field in the MD and the focalizing field in the MQ are given from an external file to the main program. The field data is obtained with the program ROXIE [5]. It has been mapped from the beam pipe center up to 60 mm in the magnet transversal plane.

To obtain the number of MIPs going out of the cryostat, two theoretical loss detectors have been placed on both sides all along the longitudinal geometrical configuration. Every one consists of an aluminum foil 0.05 cm thick, 10 cm high and 3600 cm long.

In Fig. 1 is plotted the geometrical configuration for the LHC half-cell. The top figure shows the cross section of the beam pipes and of the cryostat, together with the position of a point loss and the detectors, L, for the left detector and R, for the right detector. In the bottom of the figure, the longitudinal section is plotted, with the magnet configuration and the intermagnet gaps.

The losses in the half-cells are distributed in a few meters in the quadrupole or in the upstream dipole [2]. Loss spread depends on the limitation in aperture, the halo width and the misalignment between the beam screens of the different magnetic elements. We admit a tertiary halo effective width of 1 mm and an incident betatronic angle of 0.25 mrad at the hitting point [2]. In this case, losses happen from –325 to 0 cm in the quadrupole, from –700 to –325 cm in the upstream dipole for a misalignment of more than 1 mm; and at +325 cm in front of the downstream dipole for a misalignment of more than 0.6 mm.

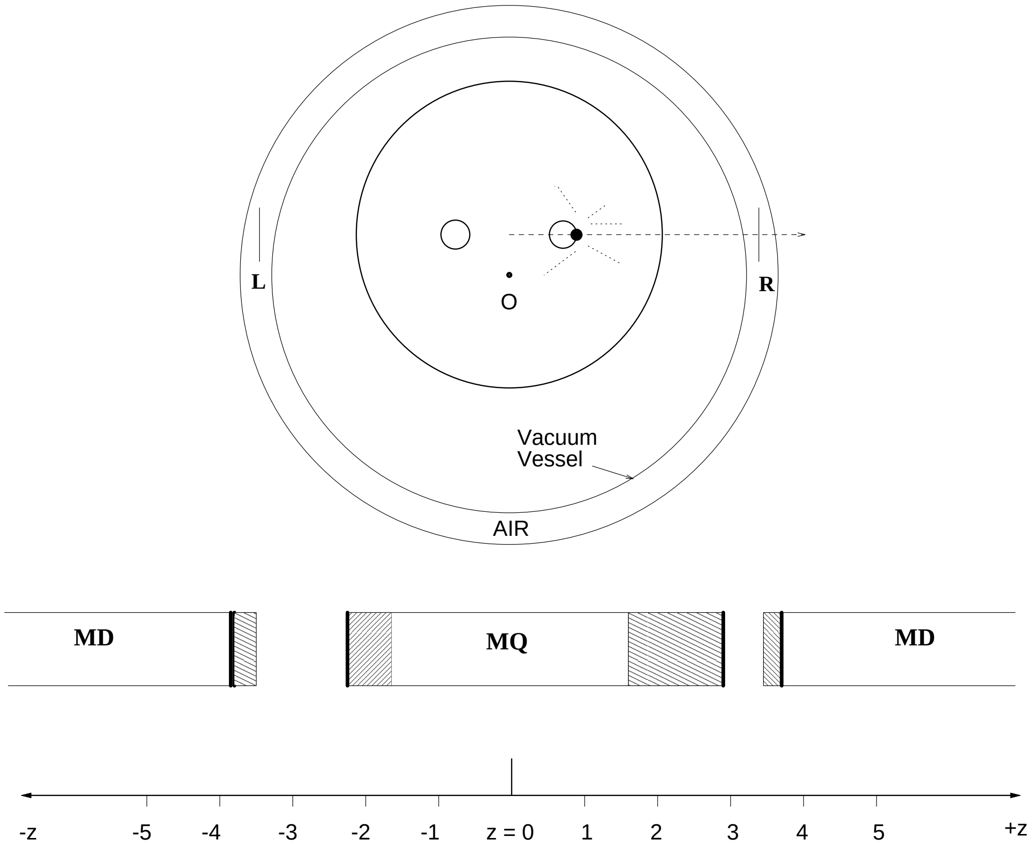

FIGURE 1. Detail of the SSS half-cell geometry simulated. Top: cross-section which shows the beam pipes, cryostat and loss detectors (L, R). Bottom: longitudinal configuration, including the quadrupole (MQ), the dipoles (MD) and correctors (z values are in meters).

Point losses are considered for the positions where the loss distribution has his maximum value. These are the three possible longitudinal positions z = -325 cm, 0 cm and +325 cm. The proton hits the beam screen at a maximum value of the horizontal or vertical coordinate, depending if the MQ focalize horizontally or vertically respectively. It has been observed that the shower presents transversally a maximum value in the plane of the magnet [6]. Therefore, the number of MIPs reaching the detector is count, in any of these cases, in the horizontal plane.

Geometrical Configurations

The configuration shown in Fig. 1 is quite general. Depending on the beam direction in the beam pipes and on the MQ field (focalizing horizontally or vertically), it can be distinguished four different geometrical and magnetic configurations to take into account in the calculations [7]. These are plotted in Fig 2.

For any of these four configurations we have to simulate four types of point loss, two in every beam pipe, for the three longitudinal most likely positions. For statistics, the longitudinal MIPs shower is computed for a hundred protons for the top energy (7 TeV) and for a thousand protons at the injection energy (450 GeV).

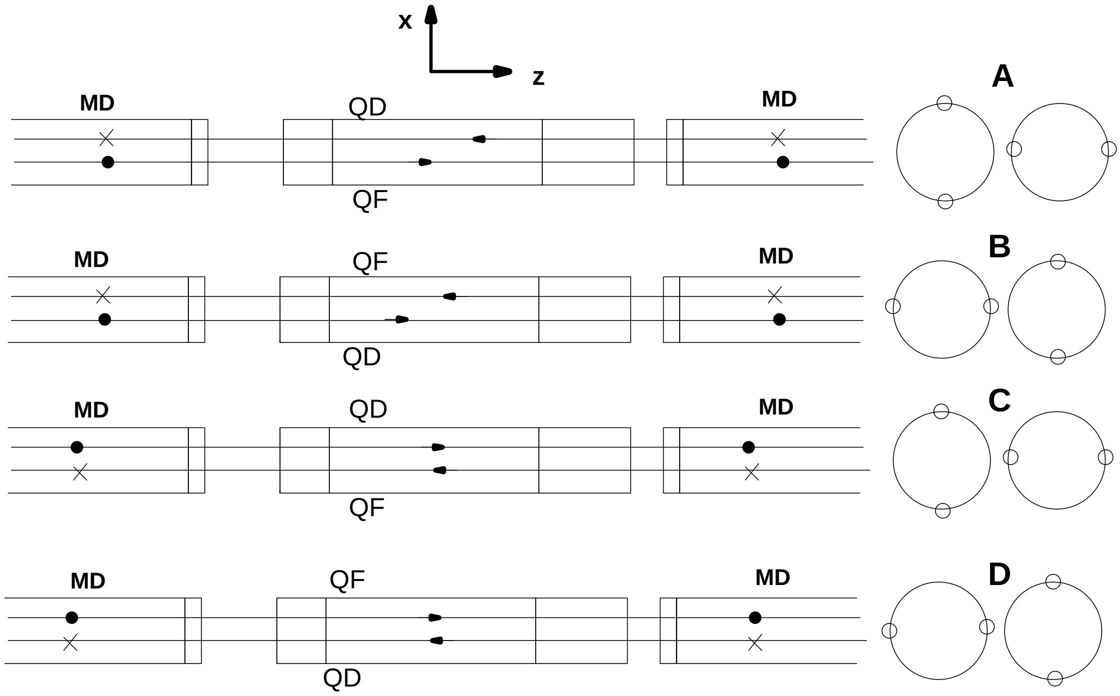

FIGURE 2. Schematic representation of the different configurations for the half-cell. View from the top, the arrows mean the direction of the beams. In the MD, the standard signs indicate the magnetic field. In the MQ, QF means focusing and QD defocusing in the horizontal plane. On the right, the different kinds of point losses are shown for each beam pipe.

RESULTS ANALYSIS

The shower of particles is obtained for a point loss, that is an amount of lost protons in a point or vertex. The program uses some cuts in the energy of the generated particles. These are 0.3 MeV for $e^{\pm}$ and 3.0 MeV for charged hadrons and muons. This limit serves also as a detection limit for the detector.

The result of every point loss is a shower of particles, which gives a longitudinal distribution along the beam direction. For any of both beams, the shower is observed in both detectors. The direct detection is obtained in the closest detector, RD (Right Detector) for the beam at the right and LD (Left Detector) for the beam at the left. The signals observed in the detector situated at the opposite side of the vessel, the so called cross-talk, are usually much smaller.

An example of the cascade for the three longitudinal point losses is shown in Fig. 3. It can be seen how the distribution starts approximately at the interaction point, or point loss position, it goes through a maximum and it decreases softly in the beam direction.

For all the cases the simulations are done with point losses, only in the A configuration distributed losses have been considered. The results can be extrapolated to the other configurations, in view of the results found for point losses.

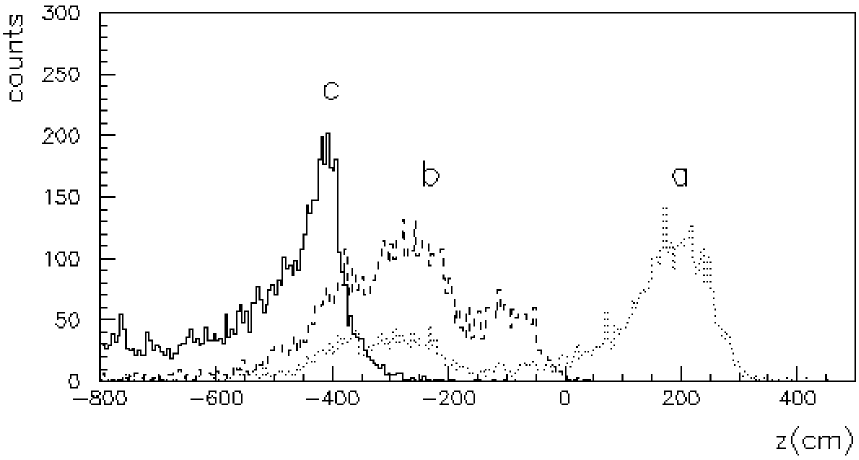

FIGURE 3. Developed shower for a point loss in the innermost side of the beam screen; case C (right beam pipe). a) z_v = 325 cm, b) z_v = 0 cm, c) z_v = -325 cm..

General Features

For the four configurations analyzed we have found similar characteristics and behavior of the losses. For any of the point losses, only slightly differences are observed in the generated showers for the different configurations. The main systematic features are the following.

- The distribution peaks at a position 1-2 meters from the interaction point.
- The highest signal is observed when the loss happens at the end of the upstream dipole beam screen, just in the long intermagnet gap (see Fig. 1). In general, the distribution shape is drastically modulated by the amount of lateral material. As a consequence the distributions present sometimes several secondary maxima.
- The magnetic field in the MD increases remarkably the number of MIPs when the particles have to cross the magnet gap. This effect is due to charged particles which, bend by the field, giving rise to more interactions in the median plane.
- The particles reaching the detector have a wide spectrum of momentum orientation.
- The material distribution and the magnetic field in the main magnets can explain all the differences observed between configurations.
- In the analysis of the losses from injection energy (450 GeV) to top energy (7 TeV), it is found that, the shape and position of the distribution does not present noticeable changes with energy. The maximum signal evolves almost linearly with energy.
- In most cases a point loss is a good approximation for a distributed loss.

Cross-Talk

In order to analyze the cross talk, we look at the signal obtained in the detector assigned to one beam, due to a loss occurring in the other beam. All cros-talk signals are less than 25 % of the proper signals and therefore, the beam which creates losses is clearly identified.

Time of Flight

After the first interaction, generated particles travel through different materials interacting in their turn and creating new secondaries. The arrival time at the detector is recorded, so that the shower time of flight can be determined.

In all the types of point losses, the time taken by the particles to reach the detector ranges from 5 ns to 10 ns. Higher times correspond to the tail of the distribution.

Once the loss detector positions are determined, the time of flight for the shower detected can be determined with a good accuracy in the case of a point loss. For a loss distributed over 4 m, the time of flights are also distributed.

An example of the time of flight and time distribution is shown in Fig. 4. Top figure shows the MIPs distribution, in the middle it is represented the time of flight as a function of the position.

The time distribution for a distributed loss can be estimated computing the time dispersion of the main peak. The results are presented in the bottom figure, showing a distribution width of about 4 ns.

This time is a short time compared with the bunch period, 25 ns. Therefore, with 40 MHz loss detectors, it would be able to measure losses produced in a bunch.

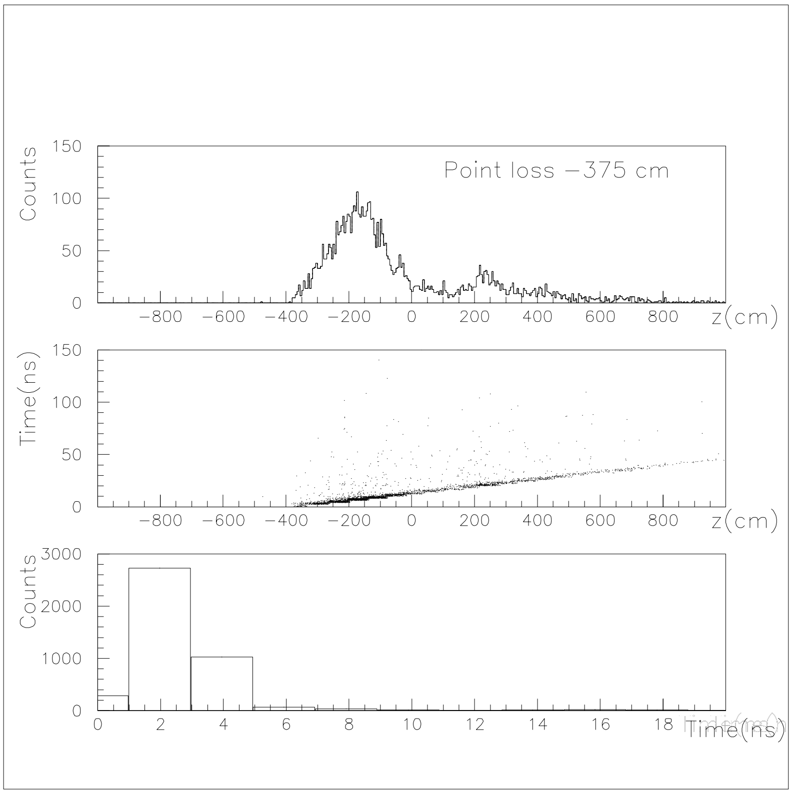

FIGURE 4. Representation of MIPs time of flight. Top figure: shower longitudinal distribution, case BT. Middle: scatter plot showing the time of flight vs. the detector position. Bottom: time dispersion of the main peak.

BEAM LOSS DETECTORS

As stated before, the most likely BLMs to be used in the LHC arcs, are two PIN diodes in coincidence. PIN diodes work in counting mode and can work at very high counting rates. They also have high dynamic range and sensitivity [8].

In base of the results, for any of the cases simulated, the loss can be monitored with a unique loss detector. Therefore we need 3 BLMs per beam per quadrupole. That makes a set of six detectors around every quadrupole outside the cryostat. We call these detectors RD1, RD2, RD3 for the right beam, and LD1, LD2, LD3 for the left beam. The order 1, 2, 3 is given as a function of the longitudinal position in increasing z value.

BLMs Configuration

The position for the BLMs has been chosen taking into account the efficiencies of detection (shower intensity) for the different types of losses for any configuration.

In some cases, there exist several possible signals which, can not be distinguished. It is the case for a horizontal loss between an inner and an outer loss (in a vertical loss, both are similar by symmetry). In these cases, the lower value is chosen as the efficiency level.

TABLE 1. Positions and threshold values for the BLM set. A configuration.

A - DETECTORS	RD1	RD2	RD3	LD1	LD2	LD3
z (cm)	-150	250	450	-450	-250	200
7 TeV Threshold[1]	210	50	60	50	75	120

TABLE 2. Positions and threshold values for the BLM set. B configuration.

B - DETECTORS	RD1	RD2	RD3	LD1	LD2	LD3
z (cm)	-150	220	450	-450	-250	200
7 TeV Threshold[1]	180	70	60	50	120	120

TABLE 3. Positions and threshold values for the BLM set. C configuration.

C - DETECTORS	RD1	RD2	RD3	LD1	LD2	LD3
z (cm)	-450	-250	200	-150	220	450
7 TeV Threshold[1]	60	110	120	180	60	60

TABLE 4. Positions and threshold values for the BLM set. D configuration.

D - DETECTORS	RD1	RD2	RD3	LD1	LD2	LD3
z (cm)	-450	-250	200	-150	250	450
7 TeV Threshold[1]	70	110	100	220	70	50

Tables 1, 2, 3 and 4, show the proposal for the BLMs positions and the threshold obtained at each detector for the different configurations. The figures obtained correspond to the same beam loss (a hundred 7 TeV protons) at the three beam pipe bottlenecks.

The proposed positions for the BLMs in the different configurations are almost the same. It is worth to point out that, right detectors (RD1-RD3) in A and B

[1] $\times$ $2.0\cdot10^{-4}$ MIPs/cm^2 per lost proton on the beam screen

configurations are equivalent to left detectors (LD1-LD3) in the C and D configurations. And vice versa.

Here it is not shown the cross-talk signal in every detector due to a loss of the same intensity occurring in any point of the other beam. There is only one case in which the direct signal and the cross-talk are at the same level. The probability of both losses to happen is of the order of 10^{-4}. So we can consider losses in both beams as independent. With the proposed loss detection system, it can be distinguished where the beam loss is produced and the amount of lost protons.

Intensity Variations

In Tables 1, 2, 3 and 4 are shown the sensitivity for every detector corresponding to the same proton loss (7 TeV). There exists a dispersion in the obtained values for the different detectors.

Moreover, there is already a dispersion between the intensity for an innermost loss and an outermost loss which is not shown in the tables. This inherent unavoidable dispersion reaches sometimes a factor 2.4 between both losses. The differences found for distributed losses are within a 30 % which is not considerable.

The final chosen sensitivity values go from a minimum of 50 up to a maximum of 220.

For PIN diodes, it would be nice to have the same threshold everywhere. A solution to unify the levels could be to shield loss detectors with a plate of 1 mm to 15 mm of tungsten [7]. In this way, we would have a signal level of 50 for all loss detectors, that is 10^{-2} MIPs/cm^2 per lost proton.

As for injection energy, the same amount of lost protons gives a signal about 15 times smaller[2], that is about $6.7\cdot10^{-4}$ MIPs/cm^2 per lost proton.

Quench Alarm

Summarizing, if we consider PIN diodes of 50% efficiency (0.5 counts per MIP) and an active surface of 2 mm^2 the number of MIPs per lost proton reaching a detector is:

- $6.7\cdot10^{-6}$ counts/p^+ at injection energy
- 10^{-4} counts/p^+ at top energy

The quench level for different types of losses is analyzed in references [1,9]. The BLMs in the LHC arcs will monitor transient losses and steady losses. We are interested in medium range transient losses, which have a time constant of about 10 ms. Steady losses have a linear threshold in time, since they imply a continuous evacuation of heat. This kind of losses happens for times of more than 4 s. For transient losses the quench level is:

- $2.7\cdot10^{11}$ p^+/m/s at injection energy
- $4.6\cdot10^{9}$ p^+/m/s at top energy

These figures give a count rate in the loss detectors for a quench of $1.8\cdot10^{6}$ counts/s for injection energy and of $4.6\cdot10^{5}$ counts/s for top energy.

[2] This value has a r.m.s. of 30%.

Let us assume that the threshold for quenching is put at a value 10 times smaller to prevent the quench. This is equivalent to a counting rate of $1.8 \cdot 10^5$ counts/s at 450 GeV and of $4.6 \cdot 10^4$ counts/s at 7 TeV. Therefore, it is needed to decrease the threshold level during ramping.

A monitoring rate of the order of a hundred kHz would be sufficient for quenching control, but detectors will run at 40 MHz in order to limit saturation.

CONCLUSIONS

A beam loss detection system has been proposed with a set of six Beam Loss Monitors around each Main Quadrupole in the LHC arcs. All the possible geometric and magnetic field configurations are considered. The BLM are placed outside the cryostat in the median plane. Three BLMs at each side will measure the beam losses of the respective beam. The exact location in given as well as the threshold level for detection. Quenching control is achieved with a detector count rate 40 MHz.

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