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Particle Shower Simulations and Loss Measurements in the LHC Magnet Interconnection Regions

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CERN – Geneva/CH

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PARTICLE SHOWER SIMULATIONS AND LOSS MEASUREMENTS IN THE LHC MAGNET INTERCONNECTION REGIONS

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Particle losses in the LHC arcs are mainly expected in the interconnection region between a dipole and quadrupole magnet. The maximal beam size, the maximal orbit excursion and aperture changes cause the enhancement of losses at this location. Extensive Geant4 simulations have been performed to characterise this particular region to establish beam abort settings for the beam loss monitors in these areas. Data from first LHC beam loss measurements have been used to check and determine the most likely proton impact locations. This input has been used to optimise the simulations used for the definition of thresholds settings. The accuracy of these settings is investigated by comparing the simulations with actual loss measurements.

INTRODUCTION

The maximum energy stored in the LHC beam will be 362 MJ, enough to heat 500 kg of copper from 2 K to the melting point. High field superconducting magnets are used to keep the beams on correct trajectories. Through regular and irregular beam losses, energy is deposited in their superconducting coils. If the limits are exceeded, the transition from the superconducting state to the normal conducting one, called quench, can occur. Such transition leads to a suspension of the accelerator operation for a time between a few minutes up to a few hours in order to recover the superconducting state and recondition the magnets.

The Beam Loss Monitoring (BLM) system measures the energy deposition of secondary particle showers outside of the magnet cryostat. The quench protection for superconducting magnets is achieved by extracting the beam from the ring in case thresholds imposed on measured radiation levels are exceeded. The main detector type is an ionisation chamber and about 4000 are installed around the ring.

Geant4 particle shower simulations enable to make the link between the energy deposition in the coil and the signal in the detectors from beam losses. The quench-protecting threshold is evaluated from the quench limit of the coil, the loss pattern and the particle-shower simulations.

The interconnection between the main dipole magnet (MB) and the main quadrupole magnet (MQ) is a location where the beta and the dispersion function reach their maximum on the focusing plane. Furthermore, changes in the aperture limitations occur and misalignment due to construction imperfections are possible. Six monitors are placed around the interconnection, three for each beam.

QUENCH LIMIT

The superconducting magnets in the LHC arcs are cooled down to 1.9 K. The quench stability margin of the coil for fast transient losses is determined by the enthalpy reserve of the cable ΔH. The calculations of ΔH are done with ROXIE [1, 2, 3]. The obtained enthalpy reserve of the most exposed region for transient losses at injection energy is of 36.5 mJ/cm^3 and 3.44 mJ/cm^3 at 7 TeV.

In the case of continuous beam losses the stability margin is determined by a heat evacuation rate from the superconducting magnets to the cryogenic system (Q_{lim}). The heat flow in the main magnets of the LHC was analysed through the construction of a Network Model [4]. The Steady state quench limit of 23 mW/cm^3 for a Gaussian beam loss profile at 7 TeV has been found for MQ. Together with assumptions from [5], the quench limit for injection energy was found to be around 48 mW/cm^3.

LOSS PATTERNS

SixTrack Simulations

SixTrack [6] is a simulation code used to test beam stability in accelerators. Beam halo particles are tracked, their scattering in collimators is simulated and losses in the aperture are recorded. The loss pattern at injection energy is depicted in Fig. 1. The plot shows in red the aperture limitation given by the beam screen, the beam position monitor and the beam pipe. In black is the proton loss probability. Zero is the center of the MQ coil.

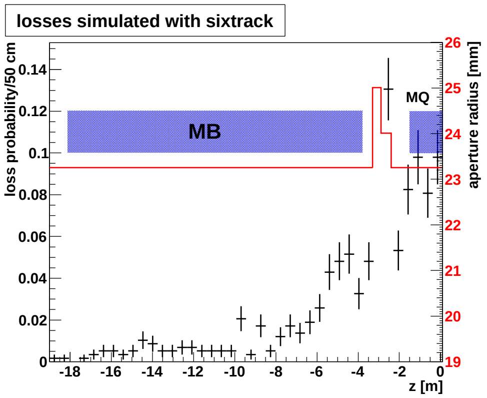

Figure 1: Proton loss probability along the MB-MQ interconnection, from SixTrack simulations at injection energy.

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Twiss Parameter Calculation

Additionally to those simulations proton losses can be estimated analytically from the beam size, the β-function (Twiss parameters) and the aperture dimensions, considering a gaussian shape of the beam tail and no beam repopulation along the MB-MQ magnets.

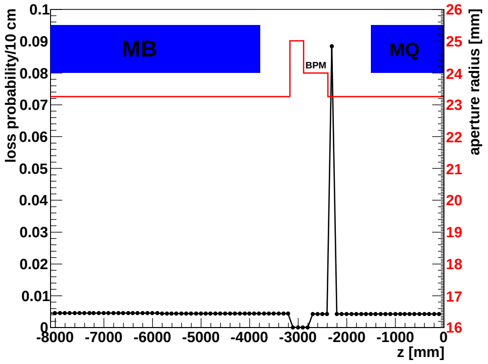

Figure 2: Proton loss probability from Twiss parameters calculations.

The obtained result is plotted in the Fig. 2. Similarly to SixTrack results the maximum of the loss is observed at the beginning of the MQ beam screen. No losses are expected in the region of the largest aperture, which is in the shadow of MB and MQ beam screens.

Both loss scenarios have been used afterwards to set operational thresholds. At injection, when the arc is an aperture bottleneck, the SixTrack pattern has been used. For collision the SixTrack gives very small statistics as the LHC arcs are not a bottleneck anymore. In this case, the loss pattern based on Twiss parameters is used.

SHOWER SIMULATIONS

Method

Because of a large variety of possible loss patterns it has been decided to perform the CPU-costly shower simulations separately for predefined punctual losses and fold the results according to the loss patterns. For every loss location the energy deposition in the coil together with the signals in the ionisation chambers are recorded.

Energy Deposition in the Coil

With the objective of protecting the sensitive elements, one needs to investigate the maximum energy density deposition in the coil. Energy density decreases with radius and its maximum is located on the inner surface of the coil.

Furthermore, a linear interpolation between the simulated loss locations is applied, in order to augment the precision and smoothen out the variations. Together with the loss patterns, the maximum energy density deposition from realistic loss scenarios can be identified.

In Fig. 3 the individual energy density distributions at each loss location for the inner layer and the most exposed azimuth of the coil are shown. The farther away the loss location from the coil, the lower the maximum energy density deposition.

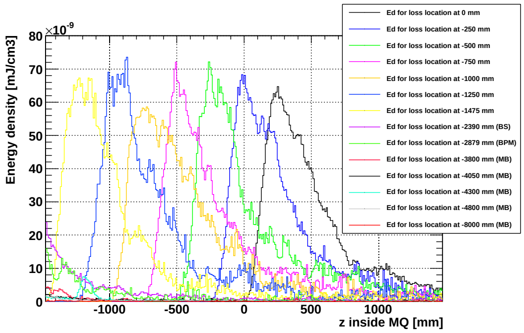

Figure 3: Energy density per proton in the MQ coil inner layer for the most exposed azimuth for different loss locations.

Figure 4 represents the energy density distribution per 450 GeV proton obtained by weighting distributions from Fig. 3 with SixTrack scenario. A second peak, in the middle of the coil, comes from the increase of the loss towards the coil center.

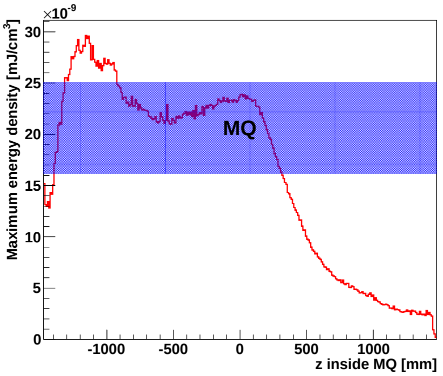

Figure 4: Energy density of the most exposed azimuth per proton after the weighted averaging for the SixTrack loss pattern.

The maximum energy density for the Twiss-like loss reads $2.4 \cdot 10^{-8}$ mJ/cm^3 per 450 GeV proton, while the value for SixTrack reads $3.0 \cdot 10^{-8}$ mJ/cm^3.

For the steady state case the energy deposited by the beam is transported to the cryogenic system. The initial energy deposition profile is modified by the heat transport processes. It is assumed that the temperature equalizes within a cable volume, where the heat transfer is the fastest. Therefore, the adequate parameter is the energy averaged over the volume corresponding to the approximate thermal equilibrium volume (E_{cab}). The estimated values of E_{cab} at the injection energy are $9.1 \cdot 10^{-9}$ mJ/cm^3 for Twiss and $1.2 \cdot 10^{-8}$ mJ/cm^3 for SixTrack loss patterns.

Signal in the BLM

The BLM positions are schematically shown in Fig. 5. The signal in the BLMs is obtained by folding the spectra of the particles entering the chamber with its response functions, studied in [7]. The obtained BLM1 signals (Q_{BLM}) are between 53.3 aC per 450 GeV proton and 1 nC at 7 TeV.

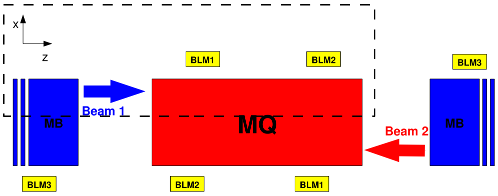

Figure 5: A schematic of the BLM positions around MQ.

QUENCH-PROTECTING THRESHOLD

The threshold defines the limit between safe losses and losses at which the deposited energy induces a quench of the superconductor. The threshold T_{BLM} for each BLM can be determined with the following equations:

$$T^{fast}_{BLM} = \frac{\Delta H}{E_{max}} Q_{BLM}, \quad T^{steady}_{BLM} = \frac{Q_{lim}}{E_{cab}} Q_{BLM} \qquad (1)$$

where ΔH and Q_{lim} are the quench limit of the superconducting coil at the most exposed region.

The threshold setting depends on the loss pattern and on the assumption concerning the zone to be protected. The BLM1 has been placed to protect optimally from losses occurring at the end of the upstream dipole, within the interconnection and at the beginning of MQ, while the BLM2 is well placed to protect from losses inside the coil. For detailed discussion see [8]. The final proposed thresholds for injection energy and 7 TeV collision energy are summarised in Table 1.

Table 1: Proposed Quench Protecting Thresholds

Beam Energy [TeV]	fast transient threshold [μGy]		
	BLM1	BLM2	BLM3
0.45	1521	575	54
7	178	29.4	3.05
	steady state threshold [μGy/s]		
0.45	4960	1876	175
7	3789	805	83.5

MEASUREMENTS

Until May 2010 only the beam-induced quenches of MB magnets at injection and for fast losses have been observed [9]. Therefore, other observables have been investigated in order to validate the simulations. A good example is the ratio of the signals in the chambers being placed in position 2 and in position 1.

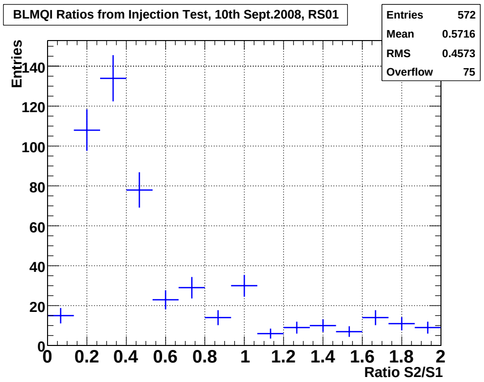

Figure 6: Measurements of the ratio of signals in BLM1 and BLM2.

The measured ratio is shown in Fig. 6. The maximum is at about 0.3, but a long tail of events with signal being larger in BLM2 is observed. The measurments lie between the simulated values for both scenarios presented in Table 2.

Table 2: Ratio of Signals Observed in BLM2 and BLM1

	Signals BLM2/BLM1
Measurements	0.30 ± 0.15
Twiss	0.12 ± 0.05
SixTrack	0.46 ± 0.18

CONCLUSION

Two loss patterns were investigated for the region of the interconnection: one relying on the beam optical parameters and the other on beam halo tracking simulations. The link between energy deposition in the coil and the signal in the BLM was established through particle shower simulations for the two loss scenarios. The quench protecting thresholds, used as initial settings in the BLM system for the 2010 run, is estimated. A comparison with available data is performed.

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