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TRANSVERSE IMPACT DISTRIBUTION OF THE BEAM LOSSES AT THE LHC COLLIMATORS IN CASE OF MAGNET FAILURES

A. Gomez Alonso
CERN, Geneva, Switzerland

Abstract

During LHC operation, magnet failures may affect the beam optics leading to proton losses in the collimators. These losses, with about 360MJ of stored energy per beam at nominal collision operation, are potentially dangerous for the accelerator equipment. The LHC Machine Protection Systems ensure that the beam is extracted safely before these losses can produce any damage. As a magnet failure develops, so does the distribution of the lost particles, longitudinally along the ring as well as transversally at each collimator. The transversal impact distributions of lost particles at the most affected collimators and their evolution with time have been studied for representative magnet failures in the LHC. It has been found that the impact distribution at a given collimator can be approximated by an exponential function with time-dependent parameters. The average impact parameter ranges from about 7 to 620 μm for the cases studied.

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CERN,
CH-1211 Geneva 23
Switzerland

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During LHC operation, magnet failures may affect the beam optics leading to proton losses in the collimators. These losses, with about 360MJ of stored energy per beam at nominal collision operation, are potentially dangerous for the accelerator equipment. The LHC Machine Protection Systems ensure that the beam is extracted safely before these losses can produce any damage. As a magnet failure develops, so does the distribution of the lost particles, longitudinally along the ring as well as transversally at each collimator. The transversal impact distributions of lost particles at the most affected collimators and their evolution with time have been studied for representative magnet failures in the LHC. It has been found that the impact distribution at a given collimator can be approximated by an exponential function with time-dependent parameters. The average impact parameter ranges from about 7 to 620 μm for the cases studied.

INTRODUCTION

The Large Hadron Collider (LHC) at CERN will be the highest energy particle accelerator ever built. At its nominal mode of operation it will accelerate protons up to an energy of 7 TeV, a factor of seven higher than the most powerful existing accelerators, while the stored energy per beam will be a factor of 100 higher.

The total energy stored in each proton beam at the LHC is about 360 MJ and the main electrical circuits store more than 10 GJ. Estimations calculated so far indicate that localized losses of about 1% of the beam at 450 GeV and 0.01% at 7 TeV could damage the LHC components.

At LHC, primary losses happen always at the collimators, being the most restrictive aperture limitations. The LHC Collimation System has been designed to provide a good cleaning efficiency with normal operating conditions. In this case only particles far from the beam axis hit the collimator and the average impact parameter is small (from 0.3 to 5.07 μm [1]). Also, particles are intercepted first by a primary collimator. However, in case of magnet failure, these conditions do not apply:

- All particles can reach the aperture limit if the beam is not extracted in time.
- The average impact parameter can reach up to 620 μm.
- Particles may also hit a secondary collimator first, thus reducing dramatically the cleaning efficiency of the collimation system.

Therefore, the efficiency of the passive protection provided by the collimation system in case of failure depends on two factors that do not need to be taken into account when considering beam losses in normal operating conditions: the impact parameter of a collimated particle as well as the type of collimator that it hits first.

CRITICAL MAGNET FAILURES

An estimation of the criticality of magnet failures has been presented in [2]. The transversal distribution of the losses in a collimator is related to the time constant of the losses produced by a magnet failure as well as to the type and position of the failing magnet. Particle tracking has been done with several failure cases in the LHC. These failure scenarios are listed in table 1, together with the most affected collimator in each case, for which the impact distribution has been studied.

Table 1: Simulated circuits, failures and most affected collimator in each case. 0 V and V_{max} represent the voltage set by the failing power converter.

Circuit/Magnet	Failure	Mode	Collimator
RD1.LR1	0 V	Collision	TCP.C6L7.B1
RD1.LR1	V_{max}	Injection	TCSG.6R7.B1
RQ5.LR7	0V	Injection	TCP.B6L7.B1
RQ5.LR7	V_{max}	Injection	TCSG.A5L7.B1
RQX.R1	Quench	Collision	TCSG.A4R7.B1
MB.A25R3	Quench	Collision	TCSG.6R7.B1

SIMULATION PROCEDURE

The tracking has been performed with MADX introducing a turn-by-turn variable magnetic field. The particles are tracked for a single turn and the lattice values are changed before traking the next one. The time resolution is therefore limited to 1 turn (89 μs), which is enough for the failures considered where the fastest time constants are at least 70 turns (typically, they exceed several hundred turns) [2].

The change in the magnetic field is governed by the change in the current in the magnet. For the simulations, it has been approximated by analytical formulas as described in [2].

The number of turns while the failure develops can be high, therefore the number of particles that can be simulated in a reasonable time is limited to values between 10^4 and 10^5. In order to obtain a good resolution for the very first losses, two particle distributions have been tracked for each failure case: a full Gaussian beam distribution and a Gaussian tail distribution with only the outer 0.1% of the

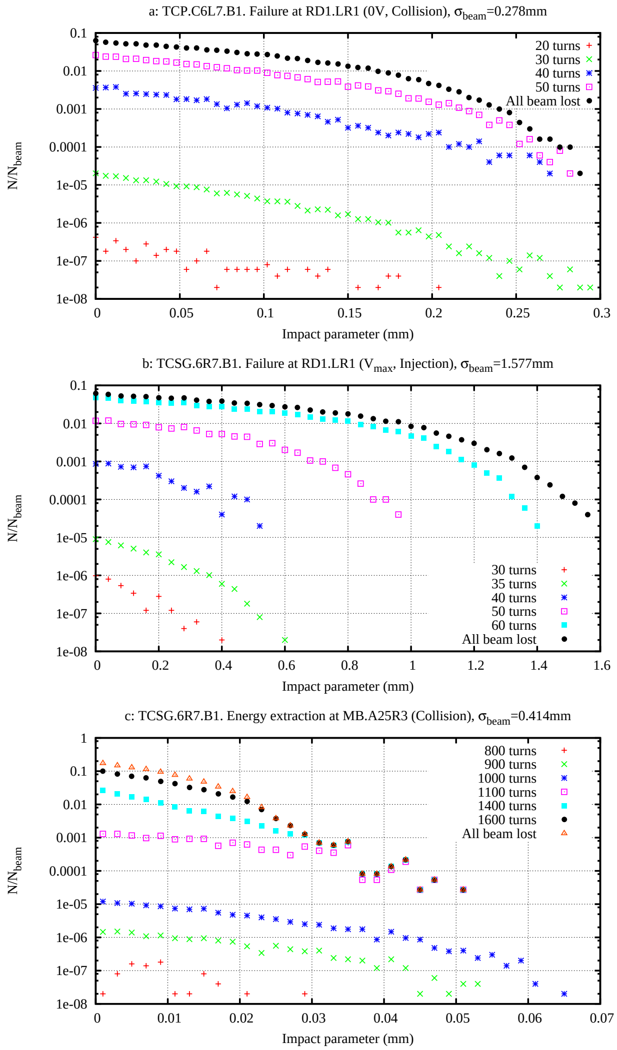

Figure 1: Impact distributions after different numbers of turns for each dipole failure. The size of the beam in the axis of the collimator is given for comparison with the width of the impact distribution.

beam. Thus, the obtained resolution for the first lost particles reaches 10^{-7} for 10000 simulated particles, which yields acceptable statistics for the first beam losses produced by the failure. The full distribution is useful to obtain a better understanding of the evolution of the losses in case of failure.

The coordinates of the lost particles and the turn are recorded at the location where each particle is lost. Only primary losses are recorded. When a particle hits a collimator it can be scattered back into the beam. This fact is not taken into account and the particles hitting a collimator are considered lost. Studies of further tracking of the scattered particles are presented in [3].

IMPACT DISTRIBUTIONS FOR THE SIMULATED FAILURES

The impact parameter (α) represents the transversal offset of a lost particle in a collimator referred to the edge of the collimator [1]. The distribution of the impact parameter of all lost particles in a collimator is named hereafter as the *impact distribution* for a given failure and collimator.

Figure 1 shows the impact distribution for the dipole failure cases that were simulated, recorded at the most affected collimators in each case. The width of the impact distribution is strongly dependent on the failure case. Faster failures (Figure 1a and 1b) produce losses with a larger impact distribution than slower ones (Figure 1c). For comparison, the width of the impact distribution has to be referred to the size of the beam in the axis the location of the collimator where the losses are recorded.

Figure 2 shows the impact distribution for the quadrupole failure cases that were simulated, recorded at the most affected collimators in each case. A comparison with figure 1 suggests that the shape of the impact distribution in the case of a quadrupole failure is similar than for losses produced by a dipole failure. The amount of losses recorded on the most affected collimator, however, is smaller in the case of quadrupole failures. This is mainly due to two reasons:

- Quadrupole failures produce losses distributed over a larger number of collimators than dipole failures.
- The main disturbance on the beam produced by a quadrupole failure is transverse defocusing, which in the absence of other effects leads to symmetric losses in the collimators. Therefore the impact in a jaw is half than in the case of a dipole failure, where all the losses are concentrated in one of the two collimator jaws.

A GENERAL FIT FOR IMPACT DISTRIBUTIONS

The data presented in the above figures show linear and parabolic trends (in logarithmic scale). The functions $e(x)$, $g(x)$ and $f(x)$ (equation 1) have been evaluated as approximations of the probability density functions (pdf) of the impact distributions, in three cases showing distributions with different shapes.

$$\begin{aligned} e(x) &= A_e e^{-\frac{x}{\tau_e}} \\ g(x) &= A_g e^{-\frac{x^2}{2\sigma_g{}^2}} \\ f(x) &= A_f e^{-\frac{x^2}{2\sigma^2}-\frac{x}{\tau}} \end{aligned} \qquad (1)$$

The parameters A_g, σ_g, A_e and τ_e from $e(x)$ and $g(x)$ have been obtained directly from the impact parameter of each lost particle using the method of moments. For $f(x)$ a variation of this method has been applied. Indeed, a better fit is obtained by setting

$$A_f = \frac{A_e + A_g}{2}$$

and then applying the method of moments to obtain σ and τ. Table 2 summarizes the accuracy of the fits for each function in three failure cases studied with loss distributions of different shapes.

Table 2: Accuracy of the fit for each case of failure studied.

Failure case 1			
Function	$e(x)$	$g(x)$	$f(x)$
$\frac{\text{RMS of }\Delta_y}{f(0)}$	3.26×10^{-2}	5.49×10^{-2}	1.40×10^{-2}

Failure case 2			
Function	$e(x)$	$g(x)$	$f(x)$
$\frac{\text{RMS of }\Delta_y}{f(0)}$	6.04×10^{-2}	3.90×10^{-2}	3.72×10^{-2}

Failure case 3			
Function	$e(x)$	$g(x)$	$f(x)$
$\frac{\text{RMS of }\Delta_y}{f(0)}$	2.37×10^{-2}	6.92×10^{-2}	3.47×10^{-2}

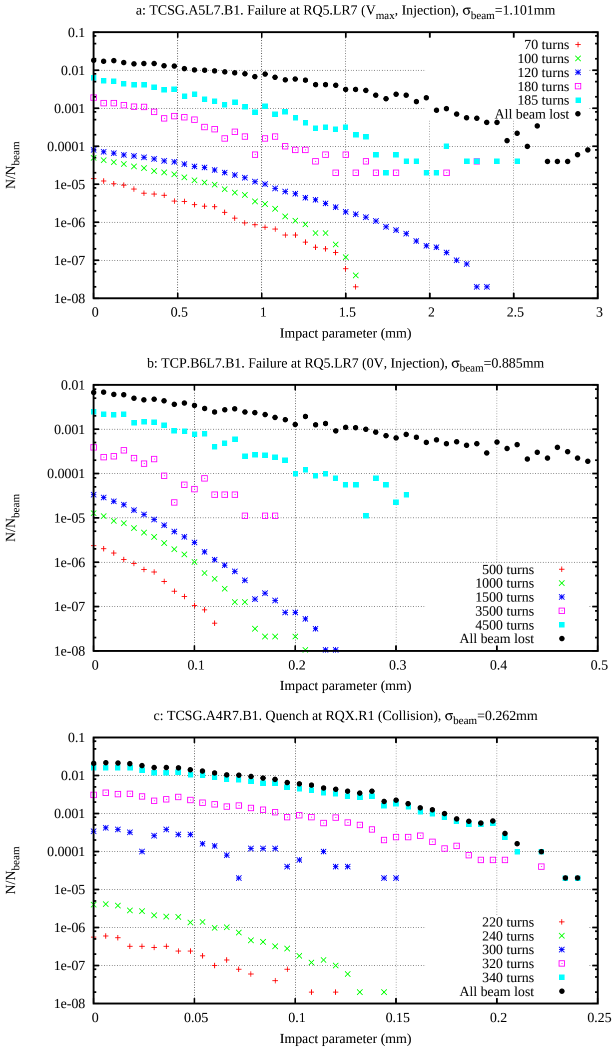

Figure 2: Impact distributions after different numbers of turns for each considered quadrupole failure.

Figure 3 shows the evolution of the parameters A_f, σ and τ with time in the case of a powering failure at RD1.LR1 (V_{max}, injection) recorded at TCP.C6L7.B1. Similar data are obtained for each failure case and collimator, allowing an approximate reconstruction of the impact distribution at any time from only these three parameters.

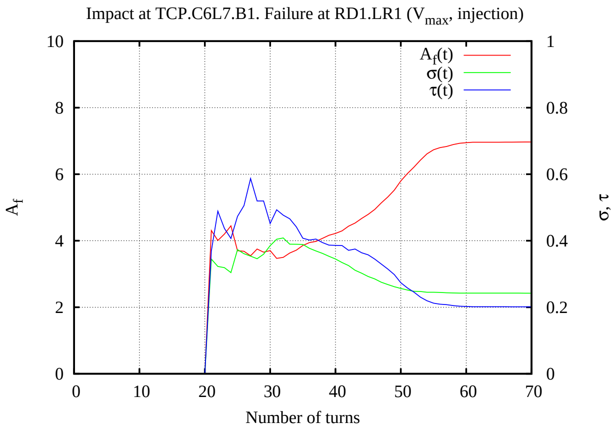

Figure 3: Evolution of the parameters of the fit function with time for a powering failure of RD1.LR1 (V_{max}, injection) recorded at TCP.C6L7.B1.

CONCLUSIONS

In case of failure during the LHC operation, particles are lost in the collimators as the failure develops. The evolution with time of the transverse distribution of these losses in the collimators has been studied through tracking simulations with variable magnetic field using MADX.

The simulations show that in most cases the shape of the impact distribution does not vary significantly with time, and the main change is its amplitude increase (number of lost particles). The impact distribution is smooth in all cases and can be approximated accurately with an exponential function. It has been found that slow failures produces losses that are more concentrated in the edge of the collimator, while faster failures produce larger impact distributions in the collimators.

A general fitting function whose parameters can be obtained directly from the impact parameter of the lost particles has been found. The evolution of the parameters of this function can be stored at each turn and the shape of the impact distribution reconstructed at any given time only from these three parameters.

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