TRACKING TOOLS TO ESTIMATE THE QUENCH TIME CONSTANTS FOR MAGNET FAILURES IN LHC

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Abstract

At LHC, beam losses, with about 360 MJ of stored energy per beam at nominal collision operation, are potentially dangerous for the accelerator equipment and can also affect the operational efficiency by inducing quenches in superconducting magnets. Magnet failures may affect the beam leading to proton losses primarily in collimators and secondarily in superconducting magnets due to scattering of protons from collimator jaws. The evolution of the beam during magnet failures has been simulated using MAD-X with a variable magnetic field. The impacts of particles in the collimators have been recorded as a function of time. A second program, CollTrack, has been used to determine the loss patterns of scattered particles from each collimator as a function of the initial impact parameter. The magnets that are likely to quench are identified and an estimation of the time between the beginning of a failure and a quench is obtained by combining the results from the simulations. The time to a start of a quench is a relevant parameter to determine the dump threshold of beam loss monitors in order to optimize protection redundancy and operation smoothness for LHC.

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, with a total stored energy of about 360 MJ per beam. 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. The LHC Machine Protection Systems (MPS) [2] ensure that the beam is safely extracted in time before any damage is produced.

Knowledge about the evolution and location of the losses in case of operational failures is of great interest to optimize the LHC MPS. To properly simulate the energy deposition of lost particles in the accelerator elements a simulation code would be needed, able to:

- Track particles using an arbitrarily changing magnetic field (the change is induced by the failure)
- For lost particles, simulate the interactions inside the collimators and keep tracking the particles that have not been absorbed but scattered back into the beam.
- Record the losses at different locations.

At CERN, two main simulation codes are used: MADX [3] and SixTrack [4]. Tracking with an arbitrary variable magnetic field is feasible using MADX. However, in MADX, a particle that hits a collimator is considered lost, while in reality it will be most probably scattered back into the beam. CollTrack [5] is an adaptation of Sixtrack that simulates the particle interactions inside collimators and continues tracking scattered particles, but it does not allow tracking with an arbitrarily changing magnetic field.

So far, an integration of these two features has not been done for any simulation code at CERN. In order to estimate the distribution of the losses in case of magnet failures at LHC, a combination of data from MADX and CollTrack has been used.

IMPACT DISTRIBUTIONS AT COLLIMATORS

The impact distribution in a collimator can be recorded for a given failure scenario using MADX. The distribution is exponential-like and can be reconstructed accurately enough from only three parameters using the function

$$f(x,t) = A_f e^{-\frac{x^2}{2\sigma^2(t)} - \frac{x}{\tau(t)}} \qquad (1)$$

In the case of LHC, the average impact parameter ranges from 7 μm to 620 μm depending on the failing magnet and mode of operation [6].

Figure 1 shows the evolution of the losses with time at a primary collimator (TCP.C6L7.B1) after a powering failure of the dipole circuit RD1.LR1 when operating at 7 TeV. The profile has been reconstructed using equation 1 with A_f, σ and τ calculated from simulated data. In this case, significant losses start appearing about 50 turns (4.45 ms) after the beginning of the failure and fully develop in only 10 turns (0.89 ms). On the collimator, they produce an impact distribution with $\sigma \approx 50$ μm.

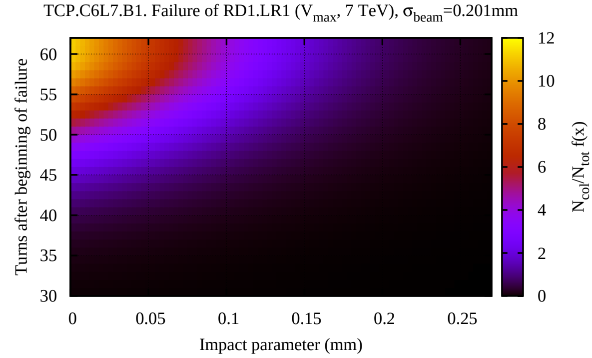

Figure 1: Impact distribution as a function of time for a powering failure at RD1.LR1 recorded at the primary collimator TCP.C6L7.B1 at 7TeV

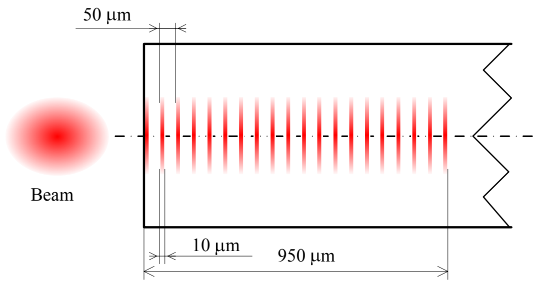

Figure 2: Configuration of the initial distributions of particles generated before each collimator. The collimator representation does not correspond to the collimator real shape and is not to scale.

DISTRIBUTION OF LOSSES ALONG LHC

The loss patterns[1] of steady losses in LHC have been studied in [1] using CollTrack. Particles lost during normal operational conditions always hit first a primary collimator with a small impact parameter (less than 5.07 μm). This is not the case for losses produced by magnet failures, as evidenced in figure 1. Therefore, the loss patterns in case of a magnet failure have to be determined as a function of the collimator where particles hit (type and location) and of the impact parameter in this collimator.

For this purpose, benchmark simulations have been run using CollTrack. A sheet beam has been generated before each LHC phase 1 collimator, parallel to the collimator edge and at different offsets as shown in figure 2. For each sheet beam the particles scattered out of the collimator have been tracked for a maximum of 15 more turns and the loss patterns have been recorded. These benchmark simulations have been performed with nominal optics. The results may not be accurate when the scattered particles pass through the failing magnet, which is not the case for most failures, where the scattered particles are lost closely after the initial impact.

It has been observed that the amount and distribution of the post-impact losses in the LHC elements (excluding collimators) is strongly dependent on the following factors:

- *Energy of the beam*: More losses are recorded outside collimators at 450 GeV than 7 TeV
- *Impact parameter*: In most cases, smaller impact parameters in the collimators produce higher losses in the LHC elements
- *Location of the collimator*: Impacts on collimator outside or at the end of the cleaning insertions produce more losses in the cold aperture

Figure 3 shows the amount of losses that are deposited in the super-conducting magnets after an initial impact at different collimators. These values have been averaged over the whole simulated range of initial impact parameters (1 mm depth). In case of very narrow impacts the losses in the cold aperture can be a factor of 3 higher than the average, particularly for impacts in TCSG.6R7.B1 and TCSG.4R6.B1, at the end or outside of the cleaning insertion (see figure 4). Both the total fraction of losses in the cold aperture as well as the fraction of losses at the most affected SC magnet are represented. The ratio of these two values for each case gives an idea of the distribution of the post-impact losses. It is interesting to note how the greater losses are produced by impacts at the collimators outside or in the end of the cleaning insertions (as expected), and also how in these cases the losses at 450 GeV are significantly higher than at 7 TeV, unlike in the case where initial impacts happen in the collimators inside IR7.

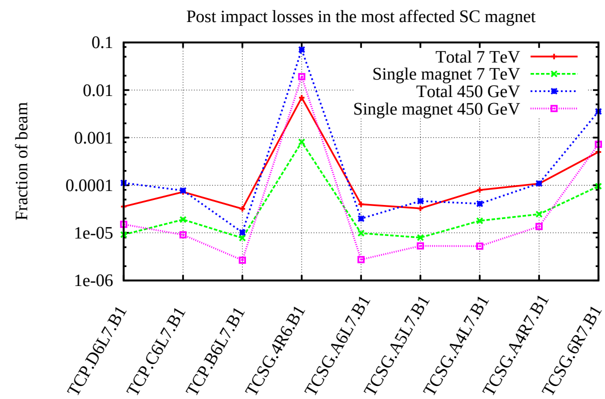

Figure 3: Fraction of the beam lost in the super-conducting magnets after an initial impact in different collimators. The values have been averaged for initial impact parameters in the collimators up to 950 μm. For each collimator the plots display the total fraction of losses in the cold aperture as well as the fraction of losses at the most affected SC magnet in each case.

Table 1 lists the superconducting elements where most of the scattered particles are eventually deposited for initial impacts in different collimators. At 7 TeV the most affected magnets are located shortly after the collimator where the initial impact happens. This is not the case for losses happening at 450 GeV.

Table 1: Most affected SC elements by particles scattered from initial impacts on different collimators

Collimator	Element (7 TeV)	Element (450 GeV)
TCSG.4R6.B1	MB.B10R6.B1	MQY.5R6.B1
TCP.C6L7.B1	MB.B9R7.B1	DFBAL.5R6.B1
TCSG.A5L7.B1	MQ.11R7.B1	MQM.A7R2.B1
TCSG.A4R7.B1	MQ.11R7.B1	MCBCV.A5R2.B1
TCSG.6R7.B1	MB.B9R7.B1	MQML.6R8.B1

The amount of losses deposited in the cold aperture as a function of the initial impact parameter is represented in figure 4. For collimators outside or at the end of the cleaning insertions these losses do not depend much on the impact parameter, except for very small impact parameters where the absorption of particles by the collimator is lower and the losses in the cold aperture can be up to a factor of 3 higher. If the initial impact happens in collimators inside the cleaning insertions the amount of losses recorded in SC

[1] *Loss pattern* refers to the longitudinal distribution of the losses in different LHC elements, while *impact distribution* is used to denote the transverse distribution of lost particles in a single collimator

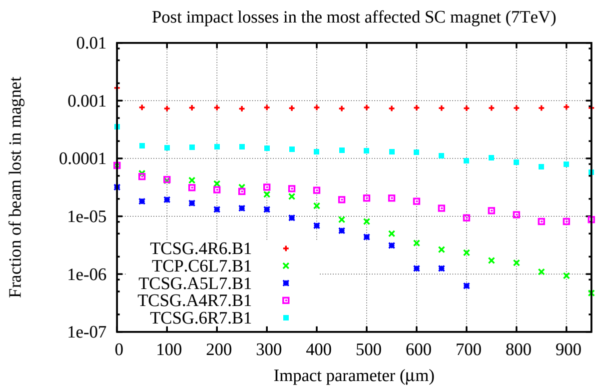

Figure 4: Fraction of the beam lost in the most affected superconducting magnet after an initial impact in different collimators as a function of the impact parameter.

elements quickly decrease with the impact parameter.

Figure 5 shows the losses in the most affectd SC magnets after an impact at TCP.C6L7.B1 (primary collimator at the beginning of the cleaning insertion). All the magnets shown in the plot correspond to the first SC magnets downstream from the cleaning insertion IR7, as expected.

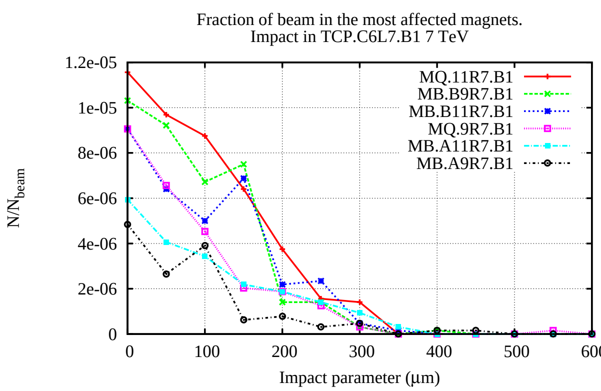

Figure 5: Fraction of the beam lost in the most affected superconducting magnets after an initial impact in TCP.C6L7.B1 as a function of the impact parameter.

ESTIMATING QUENCH TIME CONSTANTS FOR MAGNET FAILURES IN THE LHC

By combining the results presented in the previous sections, we can estimate the fraction of losses deposited in a superconducting element as a function of time, as expressed in equation 2,

$$N_{sc}(t) = N_{col}(t) \sum_{i=0}^{19} f(\alpha_i, t) n(\alpha_i) \Delta\alpha \qquad (2)$$

where α_i represents the impact parameter from each benchmark simulation, N_{col} the fraction of the beam lost in the collimator, $f(\alpha_i, t)$ the distribution of the losses in the collimator (equation 1), $\Delta\alpha$ = 50 μm and $n(\alpha_i)$ the fraction of scattered particles that reach the superconducting element. $f(\alpha_i, t)$ and N_{col} are derived from the MADX tracking, while $n(\alpha_i)$ is obtained from the benchmark simulations.

The result of this calculation for an initial impact at TCP.C6L7.B1 after a powering failure of RD1.LR1 is shown in figure 6. We can see the evolution of the losses at the collimator and the initial amount of losses. As we can see in figure 1, most of the losses in this failure concentrate in the 100 μm closest to the collimator edge, and the losses in the magnets follow the evolution of the losses in the collimator a factor of about 10^{-5} lower. The quench limit has been estimated at 10^{-8} of the beam [2]. In this case, a quench would be generated at MQ.11R7 26 turns after the failure starts developing.

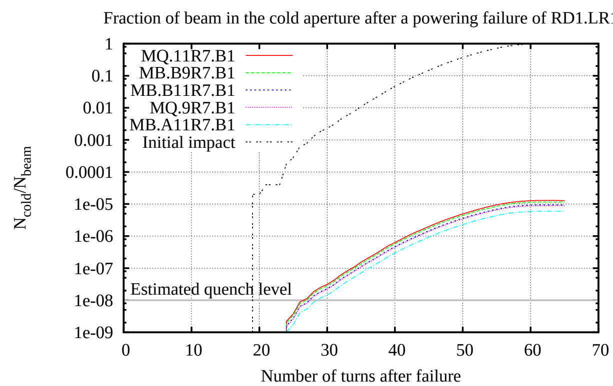

Figure 6: Fraction of the beam lost in the most affected superconducting magnet after an initial impact in different collimators as a function of the impact parameter.Powering failure at RD1.LR1 (D1 dipole in IR1)

CONCLUSIONS

The combination of results from simulations using MADX (tracking with variable magnetic field) and Coll-Track (post-impact tracking of scattered particles from collimators) allows estimating the quench time constant after fast multiturn failures in LHC. The distribution of scattered particles after impacts in the main collimators at LHC has been studied for impact parameters up to 950 μm. A procedure to estimate the quench time constant has been developed and is presented for a powering failure at RD1.LR1.

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