TRACKING STUDIES WITH VARIABLE MAGNETIC FIELD TO CHARACTERIZE QUADRUPOLE FAILURES IN LHC

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Abstract

During LHC operation, an energy of up to 360 MJ will be stored in each proton beam. A magnet failure can lead to important equipment damage if the beam is not extracted in time. The machine protection systems should detect such failures and trigger the beam extraction system. In order to characterize the beam response after magnet failures, tracking simulations have been performed with MAD-X. The magnetic field was set to change with time according to realistic current changes in the electrical circuits with the magnets after a powering failure. The effect on the beam of powering failures in the normal conducting quadrupoles has been studied. For fast failures (beam lost in less than 100 ms) the linear changes in the optics define the losses and the nonlinear effects are negligible. For slower failures, higher order resonances may lead to beam losses of up to 8% of the beam.

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. The beam intensity that can lead to equipment damage in the case of fast losses depends on different factors such as the distribution of the losses or the equipment hit by the beam. 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 Protection Systems have been developed to provide reliable protection of the accelerator components [1]. In order to properly set the operation parameters of the Protection Systems, a good understanding of the beam loss mechanisms is needed.

QUADRUPOLE FAILURES

Magnet Failures in LHC

Quenches and power converter failures are expected to affect the operation of the LHC magnets. Both effects produce a change of the current in one or more magnets. In the case of super-conducting (SC) magnets only quenches lead to fast beam losses. The high electrical time constants of SC circutis (tens to thousands of seconds) allow only very slow current decays in the case of power converter failures. For normal-conducting magnets, quenches are not an issue while power converter failures can lead to fast losses due to the lower electrical time constants (hundreds of milliseconds to several seconds). A detailed study of these failures and an estimation of the time constants of their effects on the beam is presented in [2]. Other failures have been studied in [3].

To determine the current evolution with time in the case of powering failures, we consider in first approximation the magnet circuit as a simple RL circuit. This model leads to an exponential behavior of the current. The current change is given by equation 1, where V_{nom} is the voltage before the failure, V_{fail} is the voltage set by the failure and τ is the natural time constant of the circuit.

$$i(t) = I_{nom}\left(e^{-\frac{t}{\tau}} + \frac{V_{fail}}{V_{nom}}\left(1 - e^{-\frac{t}{\tau}}\right)\right) \qquad (1)$$

The relative change in the magnetic field of the magnets in the affected circuit follows the same evolution.

Effects of Quadrupole Failures

Quadrupole failures produce two linear effects in the beam: beta beating and tune shift. When the current $i(t)$ in the affected circuit changes, these effects are characterized by equations 2 and 3 respectively.

$$\frac{\Delta\beta_s}{\beta_s} = \frac{k_0 l \sum_{j=1}^{n} \beta_j \cos(\psi(s) - \psi_j + \pi Q)}{2\sin(2\pi Q)}\left(\frac{i(t)}{I_{nom}} - 1\right) \qquad (2)$$

$$\Delta Q = \frac{k_0 l \sum_{j=1}^{n} \beta_j}{4\pi}\left(\frac{i(t)}{I_{nom}} - 1\right) \qquad (3)$$

where k_0 is quadrupole strength before the failure, l the magnetic length of the quadrupole, β and ψ the betatron amplitude and phase and Q the tune of the machine. The subscript j stands for each failing magnet. The beta beating leads to a defocusing of the beam. The tune shift can lead to beam instabilities if the tune approaches resonant values. Both effects can produce beam losses depending on the characteristics of the failure.

SIMULATION OF POWERING FAILURES IN NORMAL CONDUCTING MAGNETS

Settings and Simulated Scenarios

Tracking with a variable magnetic field has been performed with MAD-X using an error free LHC sequence

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(V6.500) and nominal injection optics (450 GeV). More than 25000 particles were tracked for each failure scenario (up to 100000 particles for the two fastest failures). The strength of the quadrupoles in the affected circuits was considered proportional to the current in the circuit, for which equation 1 was used. Among quadrupole failures at injection, those affecting the normal conducting quadrupoles at IR3 and IR7 produce the fastest losses [2]. The following failures have been simulated in circuits with these quadrupoles at both insertions (RQ5.IR3 and RQ5.IR7):

- The failure voltage is set to 0V. Most probable powering failure.
- The failure voltage is set to the maximum voltage deliverable by the power converter. At injection, this type of powering failure produces the fastest losses [2].
- The failure voltage is set to twice the nominal value. The evolution of the current in the circuit is symmetric to the first case.

Table 1 summarizes the electrical parameters of these circuits during operation with nominal injection settings.

Table 1: Electrical parameters of the circuits affected by the simulated failures

Parameter	RQ5.IR3	RQ5.IR7
Number of magnets	10	10
Nominal voltage (V)	23.2	19.4
Nominal current (I)	45.6	45.6
Maximum voltage (V)	495	495
τ (ms)	627	657

Results

Figure 1 shows the evolution of the beam losses with time as the failure develops. The fastest losses are due to a failure voltage set to the maximum value of the power converter. The time constant of these losses is an order of magnitude smaller than the two other cases studied. The high speed of these losses is due to the approach of the tune to a half integer value, which leads to an explosion of the beam size (equation 2).

For the two slower failures the speed of the change in the current is the same, only the direction of this change differs (decreasing or increasing). However, figure 1 shows significant differences between their loss patterns. In the case of a voltage failure set to $0V$, the time constant of the losses is larger for both circuits and the losses happen progressively. For a voltage failure set to $2V_n$ the losses are faster and we notice two important loss steps around 85 ms and 115 ms after the beginning of the failure. These losses may reach up to 7.9% and 1.5% of the beam for failures in RQ5.LR7 and RQ5.LR3 respectively. This difference is not due to differences in the change of the current in both circuits (table 2) but rather to the optical parameters at the location of the affected magnets. In the case of a failure

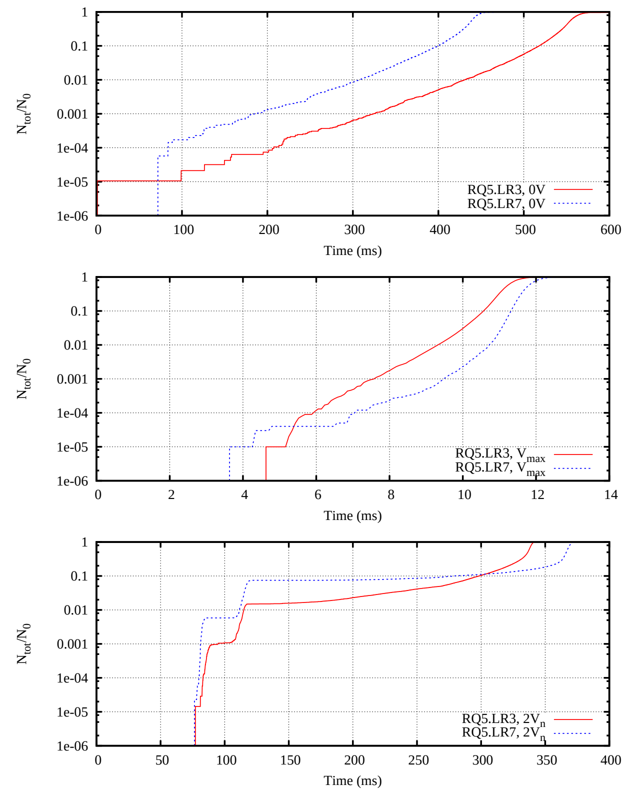

Figure 1: Beam losses as a function of time for the three cases of study: failure voltage set to $0V$ (top), V_{max} (middle) and $2V_n$ (bottom).

voltage set to V_{max} in RQ5.LR7 a set of losses of 0.0045% of the beam happen 4.5 ms after the failure.

In order to understand these unexpected loss patterns, the failure case for circuit RQ5.LR7 has been studied in detail. Figure 2 shows the evolution with time of the distribution of the losses in some of the most affected collimators. The losses corresponding to the two steps do not happen in the same collimators. The secondary collimator TCSG.A5L7.B1 receives a significant amount of losses in both cases.

Table 2: Times and percentage of the losses at the loss steps shown in figure 1 when the failure voltage is set to $2V_n$. Each group of two rows summarizes one step of losses. The third column represents the relative change in the current across the cir cuit

RQ5.LR7		
Losses	Time (ms)	$\Delta I/I_0$
0.00%	<81.34	0.110
0.56%	89.97	0.129
0.56%	<110.89	0.149
7.92%	126.38	0.168
RQ5.LR3		
Losses	Time (ms)	$\Delta I/I_0$
0.00%	<82.41	0.123
0.12%	94.78	0.132
0.14%	<105.82	0.155
1.56%	117.83	0.171

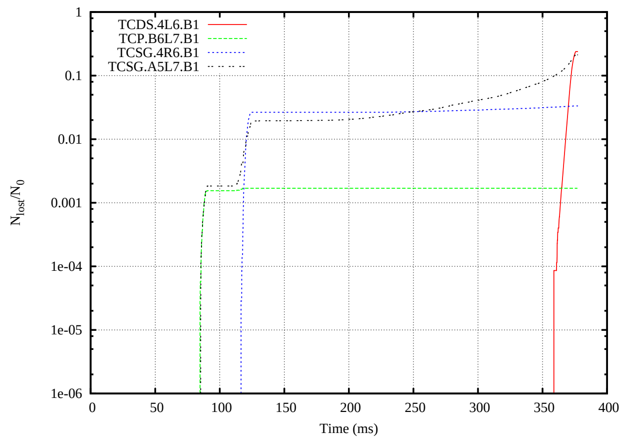

Figure 2: Distribution of the beam losses in different collimators after a powering failure setting the voltage to $2V_n$ in RQ5.LR7.

The size of the beam at this collimator is plotted in figure 3. It undergoes oscillations exactly at the times when the loss steps happen, corresponding to values of the tunes such that 90 ms after the failure Q_x+Q_y = 2/3 and 116 ms after Q_x = 1/3. The coupling resonance at 90 ms induces oscillations in both the horizontal and vertical planes. The horizontal third order resonance at 116 ms induces oscillations only in the horizontal plane, but the decrease of the beam size due to the losses appears also in the vertical plane. This is due to the configuration of TCSG.A5L7.B1 (skew collimator rotated by 40.7°).

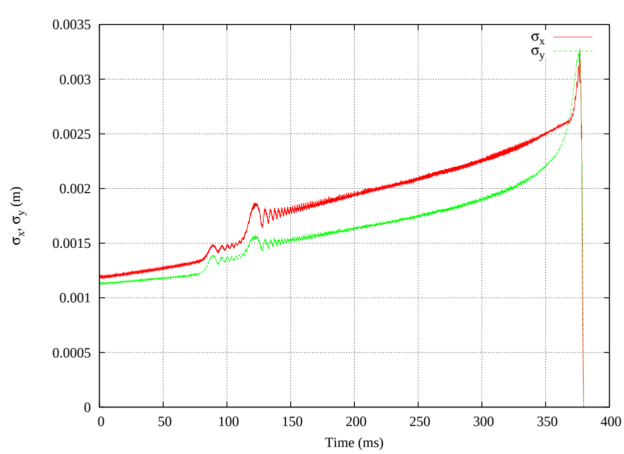

Figure 3: Evolution of the beam size at TCSG.A5L7.B1 after a powering failure setting the voltage to $2V_n$ in RQ5.LR7.

In the case of the failure voltage set to V_{max}, the horizontal third order resonance is reached 4.18 ms after the failure, corresponding to the first step of losses for this fast failure (figure 1). For a failure voltage set to $0V$ the change of the tune is such that third order resonances are not crossed. In this case, losses happen progressively due to the linear effects defined by equations 2 and 3.

A comparative plot of the distribution of the lost particles at the collimator TCSG.A5L7.B1 for failure voltages of $2V_n$ and V_{max} is shown in figure 4. The fastest failure (V_{max}) produces more distributed losses.

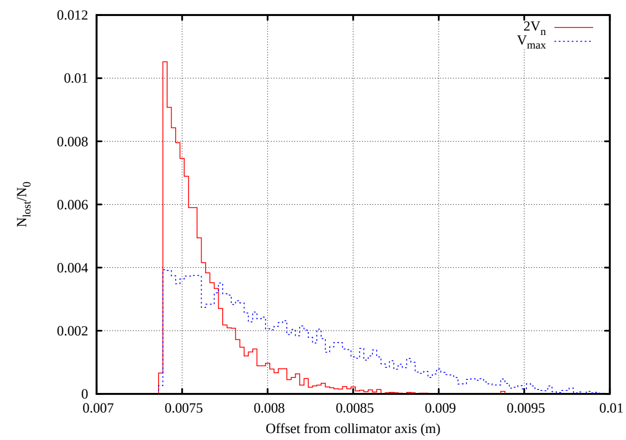

Figure 4: Distribution of the losses at TCSG.A5L7.B1 (right jaw) after powering failures setting the voltages to $2V_n$ and V_{max} in RQ5.LR7. The half-gap of this collimator is 7.37 mm

DISCUSSION AND CONCLUSIONS

Tracking with a variable magnetic field allows to characterize the effect of quadrupole failures in the beam. Simulations of these failures in the normal conducting circuits RQ5.LR3 and RQ5.LR7 have been used to study the mechanisms leading to beam losses after a quadrupole failure in LHC.

Beam losses are governed by the change in the tune induced by the failure. The fastest losses happen when the power converter sets its voltage to its maximum value and the operating point of the machine approaches a half integer resonance. Third order resonances can also generate losses. However, these are significant only for slow failures.

The amount of losses due to third order resonances depends strongly on the position of the magnets affected by the failure. At 450 GeV, for a failure voltage of $2V_n$ in RQ5.LR7 the losses due to resonances reach 7.9% of the beam. For the same failure in RQ5.LR3 they represent only 1.5% of the beam. These losses are enough to produce equipment damage, but in any case their time constant is sufficiently high (8 ms or more for 0.5% of the beam lost) and they can be handled redundantly by the LHC protection systems [1].

REFERENCES

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