EQUIPMENT FAILURE AND BEAM LOSSES IN THE LHC

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Abstract

The LHC has been designed to operate at an energy of 7 TeV with a luminosity of $10^{34}\, cm^{-2} s^{-1}$. This requires two beams with 2808 bunches, each bunch with 10^{11} protons. The energy stored in each beam is about 350 MJ, sufficient to heat and melt 500 kg of copper. At 7 TeV, a loss fraction of about 10^{-8} could quench a superconducting magnet. Protection systems to prevent uncontrolled beam loss include the beam dump system, the collimation system, the beam loss monitors and the interlock system. For optimizing the parameters of the machine protection systems, the effect of various failure scenarios on the circulating beams is discussed. The most likely failures are magnet quenches and power converter faults. Taking into account the time constants for the decay of the magnetic field, the impact on the orbit and the beam loss at the collimators is derived.

1 INTRODUCTION

The proton energy of 7 TeV is a factor of seven above present machines, the energy per beam is two to three orders of magnitude higher. An uncontrolled release could seriously damage equipment.

The beams must be handled in an environment with superconducting magnets that would quench in case of sudden localized beam loss of about 10^6 protons when operating at 7 TeV. The complexity of the LHC is unprecedented, with about 8000 superconducting magnets powered in 1700 electrical circuits. A quench in a magnet or a failure in the powering system could cause the beam to be lost. Three insertions are for machine protection: two insertions for beam cleaning, and one for extracting the beams towards the beam absorber blocks (see figure 1). The LHC also requires collimators to define the mechanical aperture through the entire cycle. The collimators are adjusted to about 5-9 σ (σ: rms of Gaussian transverse beam distribution) absorbing the beam halo with a required suppression of about 10^{-4}, in order to avoid protons impacting in the cold magnets [1]. In case of equipment failures, collimators will be the first elements to intercept the perturbed beam and must absorb part of the energy until the beams are extracted.

1.1 Collimators and Machine Protection

In one of the insertions reserved for beam cleaning with non-zero dispersion, collimators catch particles with a too large momentum deviation, for example non-captured protons at the start of the energy ramp. In a second insertion a series of collimators are installed to capture protons with large betatron amplitudes. Downstream of a primary collimator that is closest to the beam, four secondary collimators catch the protons scattered by the primary collimator. Ionization chambers installed close to the collimators and other aperture limitations, such as the quadrupoles in the low-beta insertions, monitor the flux of secondary particles continuously [2]. In case of equipment failure, beam losses could then be detected within one turn, and the beam could be dumped within about three turns.

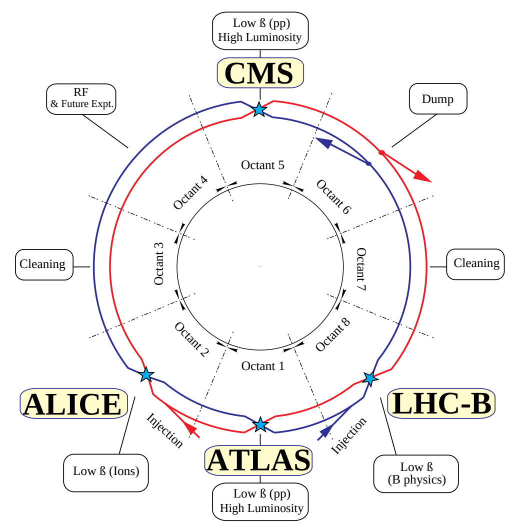

Figure 1: Layout of the LHC

1.2 Equipment Failures

A number of failure scenarios has been considered, such as magnet quenches or failures of power converters leading to beam losses. In case of a failure, enough time must be available to safely detect the failure, to take the decision that a beam dump is required, to inform the extraction kickers and to send the beam to the beam absorbers.

The effect of a failure on the beam was simulated in a program for linear particle tracking. The displacements of the particles were calculated at the collimation section in IR7, with the primary collimators at 6 σ and the secondary collimators at 7σ. The tracking was done for one beam (beam 1) with bunches of a Gaussian transverse particle distribution, at an energy of 7 TeV, with LHC optics version 6.2 and nominal emittance $0.5nm$. It was assumed that a proton hitting a collimator jaw is absorbed.

2 THE MAGNETIC FIELD DURING EQUIPMENT FAILURES

A failure such as a magnet quench or a power converter fault leads to a decaying magnetic field and to an error field ΔB.

- Failure of the Power Converter or Power Abort

$$\Delta B(t) = \Delta B_0 \cdot \left(1 - e^{-\frac{t}{\tau}}\right) \qquad (1)$$

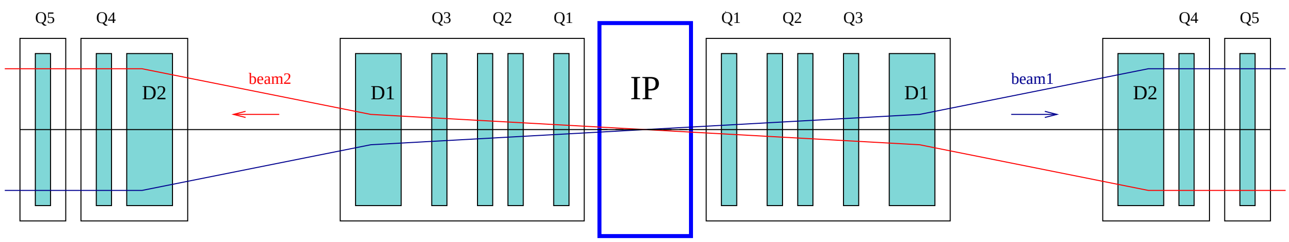

Figure 2: Illustration of the magnet placing at the interaction point

- Magnet Quenches

$$\Delta B(t) = \Delta B_0 \cdot \left(1 - e^{-\frac{t^2}{2\sigma^2}}\right) \qquad (2)$$

The time constant τ in equation (1) is determined by the inductance L and the resistance R, $\tau = L/R$.
The typical time constant σ for a quench is $\sigma \approx 0.2\,s$ [4].

2.1 Failures of Dipole Magnets

Dipole magnet failures cause orbit distortions. The deflection angle Θ due to the field deviation ΔB is (l =length of the magnet, p =particle momentum)

$$\Theta = \frac{e}{p} \cdot l \cdot \Delta B \qquad (3)$$

Equation (4) gives the horizontal closed orbit distortion at a position s_C in case of a failure at position s_Q for large time constants in equation (1) or (2).

$$x_{closed}(k) = \frac{\Theta}{2} \sqrt{\beta_Q \beta_C} \frac{cos(\pi Q - \Delta\psi)}{sin(\pi Q)} \qquad (4)$$

β is the beta function, Q the tune of the accelerator and $\Delta\psi$ the betatron phase advance between position s_Q and s_C.
A more accurate equation for the particle trajectory for time dependent dipole fields is obtained by using the well-known transfer matrices, see equation (5). The horizontal displacement x of a particle in bunch n at a position s_C with initial displacement x_0 and angle x'_0 after k turns in an accelerator with failures of N dipole magnets is:

$$x(n,k) = \sqrt{\frac{\beta_C}{\beta_{q=1}}}(cos(2\pi Q\,k \,+\, \Delta\psi_{1\to C})$$
$$+\alpha_{q=1} sin(2\pi Q\,k \,+\, \Delta\psi_{1\to C}))\,x_0$$
$$+\sqrt{\beta_C \beta_{q=1}}\,sin(2\pi Q\,k \,+\, \Delta\psi_{1\to C})\,x'_0$$
$$+\sum_{l=0}^{k}\sum_{q=1}^{N}\sqrt{\beta_q \beta_C}\,\sin(2\pi Q\,(k-l) \,+\, \Delta\psi)\Theta(l,q,n) \qquad (5)$$

3 CRITICAL DIPOLE MAGNET FAILURES IN THE LHC

3.1 Failure of the D1 Dipole Magnets

The D1 magnets are single aperture separating dipoles and will be installed next to the quadrupole magnets at the

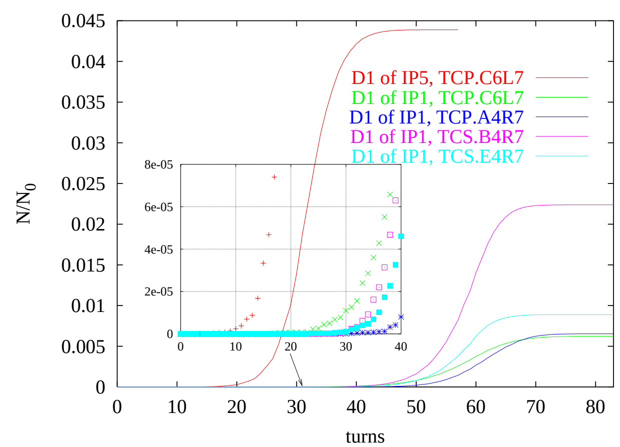

Figure 3: Number of particles hitting the collimators in IR7 relative to the initial number N_0 for a powering failure of the D1 magnets. Particles in the core of the bunch were not tracked.

interaction point (see figure 2). The warm D1 magnets at IP5 and IP1[1] consist of 6 magnets on each side of the interaction point, with a nominal field of $1.38\,T$ and a length of $3.4\,m$. All 12 magnets are connected in series to one power converter, the time constant is $\tau = 2.53\,s$.

A power converter failure for the D1 magnets in IP5 or IP1 leads to particle impact at the primary horizontal collimator TCP.C6L7.B1 in IR7 (for the naming convention of the collimators see [3]).
Since the phase advance between magnets and collimators for the D1 magnets in IR1 and IR5 is different, the time before the first particles impact on the collimator changes, see figure 3. While it takes 29 turns for a failure at the IP1 magnets, it takes 12 turns for the IP5 magnets until the displacement of a fraction of 10^{-5} of the initial number of particles has exceeded $6\,\sigma$ at TCP.C6L7.B1.
In order to avoid any damage of a collimator, the beam should be extracted before, say, 10^{11} protons have hit the collimator. This limit is shown as a straight line in figure 4 for the IP5 magnets. According to these results it takes 12 turns for the first $3 \cdot 10^9$ particles to exceed $6\,\sigma$ at TCP.C6L7.B1 during a power converter failure at IP5 and additional 7 turns to reach the limit.

[1] At IP2 and IP8 superconducting D1 magnets will be used, one on each side of the interaction point.

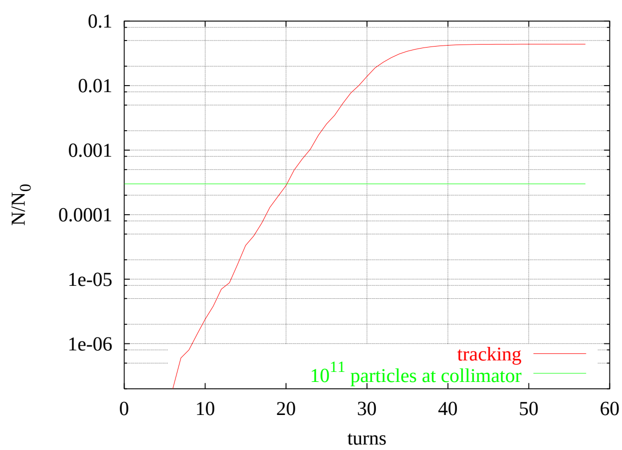

Figure 4: Power converter failure at the D1 magnets in IP5. Particles in the core of the bunch were not tracked.

3.2 *Failures of the Main Dipole Magnets*

The LHC is divided in 8 sectors (see figure 1), each arc consists of 23 FODO cells with 6 superconducting main dipole magnets per cell. In total there are 154 main dipole magnets in one arc which are connected in series to one power converter. The length of one magnet is $14.3\,m$ providing a magnetic field of $8.3\,T$ at collision energy (7 TeV). For each arc the following failure scenarios were examined

- Quench of 154 main dipole magnets at 7 TeV (case 1)
- Quench of one main dipole magnet followed by a power abort (case 2)

The results are summarized in table 1. The probability for a quench of all dipole magnets in one arc is very low, whereas a quench of one magnet followed by a power abort is a realistic failure scenario. The most critical case is therefore a quench of one magnet in arc IR2-IR3. It takes about 10 turns between first impact and reaching the limit of 10^{11} particles at the collimator.

Arc	**case 1**			**case 2**		
	TC-	Δt	Δt^*	TC-	Δt	Δt^*
IP1-IP2	P.C6L	85	102	P.C6L	133	171
IP2-IP3	P.C6L	18	23	P.C6L	20	31
IP3-IP4	P.C6L	25	30	P.C6L	37	56
IP4-IP5	P.C6L	84	113	P.C6L	85	114
IP5-IP6	S.B4R	132	149	S.C6L	173	199
IP6-IP7	P.C6L	94	121	P.C6L	79	95
IP7-IP8	P.C6L	81	100	P.C6L	159	207*
IP8-IP1	P.C6L	80	103	S.B4R	120	137

Table 1: Quenches or power converter fault for the main dipole magnets. First column: name of the collimator hit first; second column: number of turns before $3 \cdot 10^9$ particles have hit the collimator; third column: number of turns before 10^{11} particles have hit the collimator.

*: case 2: first impact is at TCP.C6L7.B1, but TCS.C6L7.B1. has absorbed 10^{11} particles first

4 FAILURE SCENARIOS WITH QUADRUPOLE MAGNETS

Decaying quadrupole fields lead to tune shifts and for initially off-center orbits to orbit distortions. A particle with coordinates x_n and z_n passing a quadrupole error field of a magnet with length L_n at position s_n receives kicks $\Delta x'_n$ and $\Delta z'_n$ in both transverse planes according to its displacement, see equation (6). The error field gradient is Δg_n, $\Delta k_n = e/p \cdot \Delta g_n$.

$$\begin{pmatrix} \Delta x'_n \\ \Delta z'_n \end{pmatrix} = \Delta k_n L_n \begin{pmatrix} x_n \\ z_n \end{pmatrix} \qquad (6)$$

The superconducting single aperture quadrupole magnets Q1, Q2 and Q3 next to the interaction points (see figure 2) have a nominal field gradient of $205\,T/m$. The magnetic length of Q1 and Q3 is $6.37\,m$, for Q2 $2 \cdot 5.5\,m$. Q1, Q2 and Q3 are serially connected to one power converter; there is additional powering for Q2. The simulations were done for IP1 (vertical crossing) and IP5 (horizontal crossing).
The main effect considered so far is the orbit distortion, no sextupole corrector magnets were taken into account. For quenches at the quadrupoles on the left or right of IP5 the particles start hitting the horizontal primary collimator after about 145 turns, for the quadrupoles at IP1 the vertical primary collimator is hit after approximately 160 turns. This approximation gives about 30 turns between first impact and 10^{11} particles at the collimator for IP1 and 40 turns for IP5.

5 CONCLUSION

A program has been developed that calculates particles losses after a failure of any combination of magnets in the LHC. Several failure scenarios were analysed. As already pointed out in [5], failures of the D1 magnets are most critical, but many other failures lead to fast particles losses. After such failure, massive beam losses will be observed by monitors close to the collimators in IR7. The signal from the beam loss monitors will be used to trigger the beam dump. Hardware interlock from the equipment is considered as a redundant method to generate a beam dump. Future studies will consider beam distributions different from Gaussian. Nonlinearities of magnets and beam-beam effects could be included.

6 REFERENCES

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