Mechanisms for Beam Losses and their Time Constants

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Abstract

The paper introduces several mechanisms that can lead to beam losses, for example a quench of magnets, trips of power converters or the RF system, and discusses the time constants for such losses and how fast the beams need to be dumped.

1 INTRODUCTION

Operating the LHC with high beam intensities requires a tight control of the beam losses in the super-conducting magnets. The quench limit of the main dipole magnets is $N_{quench} = 7 \cdot 10^8$ protons/m/s at injection energy. Compared to the design beam intensity of 0.5 A per beam, this corresponds to a relative beam loss of less than $2.2 \cdot 10^{-6}$ % of the nominal beam intensity. Thus, the machine operation requires large beam lifetimes and/or an efficient collimation system at all stages of the operation (injection, ramp and luminosity operation). The beam lifetime in the LHC depends on the ratio of the mechanical (MA) and dynamical (DA) aperture. The base line design of the LHC collimation system requires a primary collimator position of 7 σ and allows a peak orbit distortion of 4 mm and a β-beat of 20The DA depends on the tune and the multi-pole error distribution of the magnets in the machine and a sufficient large beam lifetime depends on a tight control of the magnet errors, the tune and the orbit of the machine. Table 1 and 2 summarize the allowed tolerances for some key beam parameters which are based on experience with the beam operation in HERA and were discussed in the 1997 Dynamic effects workshop at CERN.

Beam loss monitors (BLM) are installed around the arcs and the in collimation sections of the LHC machine. The signals of the BLM is used by the machine protection system that will trigger a beam abort as soon as the beam losses exceed a given threshold value. The BLM are made out of pin diodes which require an integration time of approximately 5msec (approximately 60 turns in the LHC). A machine protection based on signals from the BLM requires that the losses in the machine do not build up faster than the integration time of the pin-diodes.

The following analysis looks at how fast different equipment failure modes generate beam losses in the machine and whether the machine protection system can rely on the information from the BLM's in the machine for triggering a beam abort.

2 BEAM LOSS CRITERIA

In case of equipment failure one can distinguish two types of beam losses:

2.1 Local losses due to aperture restrictions

Local losses can be caused, for example, by a local orbit excursion that exceeds 4mm or a β-beat that exceeds 20this type of beam loss can occur at any position in the machine. At top energy, where the arc beam size is reduced by a factor of $\sqrt{7000/450}$ this kind of beam loss is only relevant at locations with high β-functions (D1, D2 and the low-β triplet magnets in the luminosity optics). In all cases we assume that a local beam loss starts to develop when either the local orbit or the β-beat in the machine changes by more than half of the allocated aperture budget: 2 mm for the local orbit error and 10the machine.

2.2 Distributed losses due to the loss of beam lifetime

Distributed losses can be caused, for example, by a tune change, a change in chromaticity or the failure of one of the spool piece circuits which correct the multi-pole field errors in the main dipole magnets. Distributed losses are absorbed in the collimation sections of the LHC machine. The β-tron cleaning insertion in IR3 is designed to absorb $1.6 \cdot 10^{16}$ protons per year. Assuming a total of 200 proton fills of nominal intensity per year this corresponds to approximately 25stored in one year. The momentum cleaning section in IR7 is designed to absorb $1.0 \cdot 10^{16}$ protons per year which corresponds under the above assumption to approximately 1843sections. Because of these large allowed losses on the collimation system one can tolerate beam parameter changes which are slightly larger than the values in Table 2 before initiating a beam abort. In the following we assume that a beam abort must be triggered if the tune of the machine changes by more than 0.01 or if the chromaticity in the machine changes by more than 5 units.

$\delta p/p_0$	Closed Orbit	β-beat
$< 10^{-3}$	$< 4\,mm$	$< 20\,\%$

Table 1: *Tolerances for beam parameters relevant for local losses.*

$\delta p/p_0$	δQ	ΔQ	$\delta\xi$
$< 10^{-3}$	$< 3 \cdot 10^{-3}$	$< 10^{-2}$	$1 \leftrightarrow 2$

Table 2: *Tolerances for beam parameters relevant for distributed losses. δQ indicates the tune change and ΔQ the global coupling expressed in the minimum tune separation.*

3 TIME CONSTANTS FOR BEAM LOSSES AFTER EQUIPMENT FAILURE

In case of equipment failure the magnetic field in the magnets decays exponentially

$$\frac{\Delta B}{B_0} = 1 - e^{-t/\tau} \tag{1}$$

where τ is the time constant for the decay.

In the following we will look at the following cold and warm element in the machine:

Cold elements:

- main bending magnets (power converter failure and quench) [$\rightarrow$ local and distributed losses]
- main quadrupoles (power converter failure) [$\rightarrow$ distributed losses]
- single quadrupoles in the long straight sections (power converter failure) [$\rightarrow$ local and distributed losses]
- individual dipole magnets (orbit corrector magnets in the arc and separation/recombination magnets) [$\rightarrow$ local losses]
- spool piece correction circuits (any failure mode) [$\rightarrow$ distributed losses]
- RF system (any failure mode) [$\rightarrow$ particles fill the abort gap $\rightarrow$ local losses]

Warm elements:

- separation/recombination dipoles in IR1 and IR5 [$\rightarrow$ local losses]
- septum magnet [$\rightarrow$ local losses at the septum magnet and in the transfer line to the beam dump]
- insertion quadrupoles [$\rightarrow$ local and distributed losses]
- transverse damper system [$\rightarrow$ local losses]

3.1 Main Bending Magnets

A power converter failure results in a systematic change of the bending field in one or more arcs. A systematic change of the bending field in all main dipoles results in a change of the beam energy (provided the RF system is on) and thus to tune change of

$$\delta Q = \xi_{nat} \cdot \frac{\Delta B}{B_0} \tag{2}$$

where ξ_{nat} is the natural chromaticity of the machine ($\xi_{nat} \approx 80$ for the LHC).

A systematic change in the bending field over one arc only results in a orbit distortion that follows the dispersion orbit in that arc [1]

$$\Delta x = D_x \cdot \frac{\Delta B}{B_0}. \tag{3}$$

Requiring that the tune change in the machine must be smaller than $\delta Q = 0.01$ and that the maximum orbit excursion in the arc must be smaller than $\Delta x = 2\ mm$ one gets from Equation (2)

$$\frac{\Delta B}{B_0} < 8.7 \cdot 10^{-4} \tag{4}$$

and from Equation (3)

$$\frac{\Delta B}{B_0} < 1.3 \cdot 10^{-4} \tag{5}$$

Inserting the limit of Equation (4) into Equation (1) and inserting a time constant of $\tau = 9928$ seconds [2] one obtains

$$\Delta t \approx 1.3 \text{ seconds} \tag{6}$$

for the time interval after which the orbit excursions in the arc exceed the tolerable limit given in Table 1.

A quench in a single bending magnet leads to a local field error at one position of the machine. The orbit response to such an isolated field error is

$$\Delta x_{max} = \frac{\sqrt{\beta_{max} \cdot \beta x}}{2 \cdot \sin(\pi \cdot Q)} \cdot \frac{l \cdot \Delta B}{\rho \cdot B_0}, \tag{7}$$

where l is the length of the bending magnet ($l = 14.3$ meter for one LHC arc dipole), ρ is the bending radius inside the dipole magnet ($\rho \approx 2770$ meter for the LHC), β_x the average β-function in the arc ($\beta_x \approx 100$ meter in the LHC arcs) and β_{max} the maximum β-function in the machine ($\beta_{max} = 180$ meter for the injection optics in the arcs and $\beta_{max} = 4750$ meter for the collision optics inside the triplet quadrupoles). Inserting these values into Equation (7) and requiring that the peak orbit excursion must be smaller than 2 mm one gets for the maximum permissible change in the bending field

$$\frac{\Delta B}{B_0} < 3.3 \cdot 10^{-3} \text{for the injection optics and} \tag{8}$$

$$\frac{\Delta B}{B_0} < 6.5 \cdot 10^{-4} \text{for the collision optics.} \tag{9}$$

The time needed to change the magnetic field by the above amount during a quench is [3]

$$\Delta T = 40 \text{ msec[injection optics] } (\approx 440 \text{ turns}) \tag{10}$$

$$\Delta T = 25 \text{ msec[collision optics] } (\approx 280 \text{ turns}). \tag{11}$$

3.2 Main Quadrupole Magnets

A systematic change of the field in all main quadrupole magnets results in a change of the total tune of the machine (the induced β-beat is negligible) [1]

$$\delta Q \approx 54 \cdot \frac{\Delta B}{B_0}. \tag{12}$$

Requiring that the total tune of the machine must not change by more than $\delta Q = 0.01$ one gets from Equation (12)

$$\frac{\Delta B}{B_0} < 1.9 \cdot 10^{-4} \tag{13}$$

Inserting this limit into Equation (1) and using a time constant of $\tau = 260$ seconds [2] one gets for the maximum amount of time one has to initiate a beam abort

$$\Delta T \approx 0.048 \text{ s} \rightarrow \text{¿ } 500 \text{ turns.} \tag{14}$$

3.3 Individual Dipole Magnets

Using Equation (7) for estimating the maximum orbit response for a single dipole kick Table 3 lists the resulting time constants and maximum time intervals before beam loss for the injection optics. For the injection optics we assume a maximum β-function of 180 meter in the arc.

Name	β [meter]	$\Delta\alpha$ [μrad]	α_{nom} [μrad]	τ [sec]	ΔT [sec]
arc	180	18	81	200	50
MCBH	180	18	81	40	50
MCBL	350	12.8	161	130	10.8
MCBY	200	17	108	250	42.8
Triplet	280	14.8	71	45	10.5
Cleaning	350	2.6	73	0.7	0.025
D1-warm	200	16	1400	1.0	0.011
D1-cold	200	16	1400	43	0.49
D2	180	17	1400	62	0.76

Table 3: *Maximum time intervals before beam loss occurs for the injection optics (maximum β-function of 180 meter in the arcs). The first column specifies the dipole name, the second the β-function at the dipole, the third the maximum permissible change in the deflection angle (calculated via Equation (7)). The fourth column gives the nominal deflection angle, the fifth the time constant for the field decay in the magnet and the sixth column the maximum time interval before beam loss will occur.*

The shortest time intervals occur for the warm dipole magnets where the time constants for the field decay are short. The shortest time interval corresponds to 120 turns and occurs at the warm D1 dipole magnet. Table 3 lists the resulting time constants and maximum time intervals before beam loss for the injection optics.

Table 4 lists the resulting time constants and maximum time intervals before beam loss for the collision optics. For the collision optics we assume a maximum β-function of 4750 meter in the low-β triplet magnets.

For the collision optics a failure of the D1 magnets can not cause any damage for the triplet magnets. The phase advance between the D1 magnet and the triplet magnets on the other side of the IP is approximately 180° ($\rightarrow$ no orbit offset due to the D1 failure in the triplet magnets). The next aperture restriction downstream from D1 is at the collimator jaws in the cleaning insertions. Because of the small beam size at top energy the aperture in the arcs is large and well protected by the collimation sections. Because there is a collimation insertion between the two long straight sections with warm D1 magnets for each beam the miskicked beam can not reach the cold elements in the arc and will allways be absorbed in the collimator jaws of one of the two cleaning insertions.

Name	β [meter]	$\Delta\alpha$ [μrad]	α_{nom} [μrad]	τ [sec]	ΔT [sec]
arc	180	3.5	81	200	8.8
MCBH	180	3.5	81	40	1.8
MCBL	350	2.5	161	130	2.0
MCBY	1500	1.2	108	250	2.8
Triplet	4750	0.7	71	45	0.45
Cleaning	350	0.5	73	0.7	0.005
D1-warm	4000	0.7	1400	1.0	0.0005
D1-cold	4000	0.7	1400	43	0.02
D2	2000	1.0	1400	62	0.04

Table 4: *Maximum time intervals before beam loss occurs for the collision optics (maximum β-function of 4750 meter in the triplet magnets). The first column specifies the dipole name, the second the β-function at the dipole, the third the maximum permissible change in the deflection angle (calculated via Equation (7)). The fourth column gives the nominal deflection angle, the fifth the time constant for the field decay in the magnet and the sixth column the maximum time interval before beam loss will occur.*

The shortest time intervals occur for the warm dipole magnets where the time constants for the field decay are short. The shortest time interval corresponds to only 5 turns and occurs at the warm D1 dipole magnet.

3.4 Individual Cold Quadrupole Magnets

A gradient error in an individual quadrupole magnet results in a tune change and a β-beat. The tune change is given by

$$\Delta Q = \frac{\beta_{max} \cdot l \cdot \Delta k}{4\pi} \tag{15}$$

where l is the length of the quadrupole magnet, β the β-function at the quadrupole magnet and Δk the change in the normalized quadrupole gradient

$$k = 0.3 \cdot B[\text{T/m}]/p[\text{GeV}]. \tag{16}$$

The β-beat in the machine is given by

$$\frac{\Delta\beta}{\beta} \leq \frac{1}{2\sin(2\pi Q)} \cdot \frac{l \cdot \Delta k}{4\pi}. \tag{17}$$

Using Equations (15) and (17) for estimating the maximum tune change and β-beat for a single quadrupole error Table 5 lists the resulting time constants and maximum time intervals before beam loss.

The shortest time interval occurs for the triplet quadrupole magnets where the β-function in the collision optics is large. The shortest time interval corresponds to approximately 1200 turns.

Name	l [m]	β_{max} [m]	Δk [10^{-3}]	k_{nom}	τ [sec]	ΔT [sec]
Q1/Q3	12	4750	0.002	8.5	514	0.12
Q4	3.4	1700	0.02	6.8	170	0.5
Q5	3.4	1000	0.04	6.8	30	0.15
Q6	3.4	350	0.1	8.5	30	0.4
Q7	3.4	180	0.2	8.5	30	0.7
Q8	4.8	180	0.15	8.5	30	0.5
Q9	5.8	180	0.12	8.5	30	0.4
Q10	4.8	180	0.15	8.5	30	0.5
QT11	1.15	180	0.6	4.7	9.4	1.3
QT12	0.32	180	2.2	4.7	1.9	1.2
QT13	0.32	180	2.2	4.7	1.9	1.2

Table 5: *Maximum time intervals before beam loss occurs for a failure of an individual quadrupole magnet. The first column specifies the quadrupole name, the second the magnet length, the third the β-function at the quadrupole, the fourth the maximum permissible change in the normalized quadrupole gradient (calculated via Equation (12)). The fifth column gives the nominal normalized quadrupole gradient, the sixth the time constant for the field decay in the magnet and the seventh column the maximum time interval before beam loss will occur.*

3.5 Individual Warm Quadrupole Magnets

The warm quadrupole magnets in the LHC collimation insertions have short time constants for the field decay ($\tau = 1.1$ seconds). The warm quadrupole in the collimation sections are made out of fife modules each 3.2 meter long, have a normalized gradient of $k = 0.0015$ and a maximum β-function of 350 meter. Inserting these values into Equations (15) and (17) and requiring that the maximum tune change must be smaller than $\Delta Q = 0.01$ and the maximum β-beat smaller than 10Equation (1) a maximum time interval of

$$\Delta T = 1.7 \text{ msec} \tag{18}$$

before beam losses occur (approximately 18 turns).

3.6 Chromaticity Correction Circuits

Each arc is equipped with four families of arc sextupole magnets for a compensation of the natural machine chromaticity. Two circuits for the horizontal and two for the vertical chromaticity. The total natural chromaticity consists of approximately 80 units from the arc quadrupoles plus 80 additional units of chromaticity generated by the triplet quadrupoles (for the collision optics only). Thus, each arc sextupole circuit generates approximately 5 units of chromaticity for the injection and 10 units for the collision optics. For the injection optics, the loss of one circuit changes the chromaticity by the same amount that we considered tolerable before a beam abort is necessary and the time constant for the circuit failure is irrelevant for the machine protection. For the collision optics the chromaticity change is twice as large but still too small to be relevant for the machine protection.

In addition to the arc sextupole magnets each arc has one sextupole spool piece circuit which compensates the chromaticity generated by the main dipole sextupole field errors (approximately 70 units of chromaticity per spool piece circuit at injection energy). The time constant for the field decay in the spool piece circuits is $\tau \approx 13$ seconds. Requiring that the total machine chromaticity must change by less than 5 units one obtains from Equation (1) a maximum time interval of 1.1 seconds.

3.7 RF Failure

Under normal operating conditions the 400 MHz RF system devides the proton beams in the machine into small packages of 0.25 ns (7.5 cm at top energy) and 0.43 ns (13 cm at injection energy) length (rms bunch length $\rightarrow$ 1/4 full bunch length) with a spacing of 25 ns between individual bunches. Additional wholes are maintained for the LHC injection (0.94 μs) and the beam abort (3.17 μs) kickers. Without the RF system the particles in the individual particle packages will debunch and slowly spread around the whole machine circumference. The longitudinal debunching is proportional to the energy spread in the bunches and the longitudinal slippage factor

$$\eta = \frac{1}{\gamma_{tr}^2} - \frac{1}{\gamma^2}, \tag{19}$$

where γ is the relativistic gamma factor and γ_{tr} the relativistic gamma factor at transition energy. For the LHC we have

$$\eta = 3.43 \cdot 10^{-4} \text{ at injection energy} \tag{20}$$

$$\eta = 3.473 \cdot 10^{-4} \text{ at top energy.} \tag{21}$$

Due to the longitudinal debunching the abort gap for the dump kicker will be reduced with a rate of

$$\frac{d\Delta\tau}{dt} = 2 \cdot \eta \cdot \frac{\Delta p}{p_0}. \tag{22}$$

The factor 2 in the above Equation comes from the fact that particles from both sides will spread into the abort gap. The kicker rise time for the abort kicker is $\tau_{dump} = 3$ μs leaving a margin of $\Delta\tau = 0.175\mu$s. Inserting these values into Equation (19) on obtains that after

$$\Delta T = 0.15 \text{ seconds} \tag{23}$$

the first particles will have spread into the gap interval required for the rise of the abort kicker.

If the RF voltage is off but the system remains tuned on resonance the RF control loop will shift the RF phase by $90°$ and rather then putting energy into the beam the cavities will extract energy from the particles in the machine. The particles can loose an energy of [4]

$$\Delta E = 16 \text{ MeV per turn} \tag{24}$$

Name	Operation Mode	Loss Type	Loss Location	ΔT
D1 warm	collision	local	triplet / collimator	5 turns
damper	injection	local	arc / triplet	6 turns
warm quadrupoles	any	distributed	collimator	18 turns
dump septum	any	local	diluter kicker / septum	35 turns
warm orbit corrector	collision	local	triplet / collimator	55 urns
RF ?	any	local	arc / triplet / septum	55 turns
D1 warm	injection	local	arc / triplet / collimators	120 turns
D1 cold	collision	local	triplet / collimator	220 turns
warm orbit corrector	injection	local	arc / triplet / collimator	250 turns
MB quench	collision	local	triplet / collimator	280 turns

Table 6: *Top 10 of the fastest beam losses after equipment failure. The first column specifies the element type, the second the operation mode for which the losses can occur (injection versus collision optics), the third the expected location for the losses, and the fourth column the maximum time interval before beam loss will occur.*

which corresponds to a relative momentum change of

$$\frac{\Delta p}{p_0} = 3.6 \cdot 10^{-5} \text{ per turn.} \qquad (25)$$

Due to the change of the particle energy the peak disperion orbit in the machine changes every turn by

$$\Delta x = D_x \cdot \frac{\Delta p}{p_0} \qquad (26)$$

Assuming a constant rate for the energy change and a peak disperion of $D_x = 2.3$ meter in the arcs of the LHC the maximum orbit distortion has changed by more than 2 mm after

$$\Delta T = 5 \text{ msec} \rightarrow 30 \text{ turns.} \qquad (27)$$

The above mechanism only works if the particles in the machine remain their 400 MHz structure. Thus, the longitudinal debunching which takes place after the RF failure reduces the above energy loss and might even stop the process before the peak orbit excursion exceeds 2 mm.

3.8 Septum Magnet

Before the aborted beams reach the beam dump at the end of the extraction transfer line the beamsizes are blown up by two transverse diluter kickers. In order to avoid particles losses in the transferline the maximum trajectory error in the transferline at the position of the diluter kickers must be smaller than

$$\Delta x = 3\text{mm.} \qquad (28)$$

The diluter kickers are placed 73 meter downstream from the dump septum and the above trajectory restriction can be translated into a tolerance for the deflection angle at the septum magnet

$$\Delta \alpha \leq 4 \cdot 10^{-5}. \qquad (29)$$

The nominal defelction angle of the septum magnet is $\alpha_0 = 2.57$ mrad (corresponding to an integrated field of 60 Tm) and the time constant for the field decay in the septum magnet is $\tau \approx 2$ sec. Inserting these values into Equation (1) one obtains for the maximum time intervall after which the aperture restriction is exceeded

$$\Delta T \approx 0.03 \text{ sec} \rightarrow \text{(35 turns).} \qquad (30)$$

3.9 Transverse Damping System

The transverse damping system has a total length of 6 meter and provides a maximum deflection voltage of

$$V = 7.5 \text{ kV} \qquad (31)$$

For a β-function of $\beta = 182$ meter this corresponds to a maximum transverse deflection angle of

$$\Delta \alpha = 2\ \mu\text{rad.} \qquad (32)$$

At injection energy this allows a damping of injections errors with a initial amplitude of up to 4 mm with a damping time of $\tau = 4.7$ ms. Exciting the beam at injection energy with the wrong phase (amplitude increase) the damping system can increase the particle amplitudes by

$$\Delta x = 0.35 \text{ mm per turn for } \beta = 180 \text{ m} \qquad (33)$$

and the peak orbit excursion exceeds the limit of 2 mm after less than

$$\Delta T \approx 0.5 \text{ msec} \rightarrow \text{less than 6 turns.} \qquad (34)$$

4 SUMMARY

Table 6 lists the 10 elements with the shortest time intervals after which beam losses will occur after eipment failure. All losses which occur more than 200 turns after the eqipment failure can probably be detected by the BLM system. Losses which occur faster than 100 turns after the equipment failure (approximately twice the integration time of the BLM system) are too fast for being detected by the BLM system.

5 REFERENCES

[1] O. Brüning, “Accumulation and Ramping”, Session VI: LHC Operations, Chamonix2000, February 2000.

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