PROTECTION LEVEL DURING EXTRACTION, TRANSFER AND INJECTION INTO THE LHC

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Abstract

Failures during the LHC transfer and injection process cannot be excluded and beam loss with the foreseen intensities and energies will cause serious equipment damage. Consequences of equipment failures such as kicker erratics, power converter faults, etc. are investigated by means of a Monte Carlo based on MAD-X tracking with a full aperture model of the transfer line and the injection region. Geometrical and optical mismatch, orbit tolerances, mechanical tolerances for settings of protection elements, power converter ripples, misalignment of elements, etc. are all taken into account. The required performance of the protection system is discussed. The overall protection level for the LHC and the transfer lines during injection is presented.

INTRODUCTION

The LHC is filled from the SPS via the 3 km long transfer lines TI 2 and TI 8. The stored energy of the 450 GeV beam extracted from the SPS is 2.3 MJ. The energy deposition limit for damage to equipment is around 100 J/cc [1], corresponding to $\sim 2.2 \cdot 10^{12}$ protons, or 5% of an injected batch ($4.7 \cdot 10^{13}$ protons) at ultimate intensity.

The aperture in the transfer line is very tight; at many locations it is smaller than 7 σ [2], where σ is the R.M.S. beamsize. The available aperture in the LHC ring at 450 GeV is 7.5 σ [3].

Many failures have been identified which can lead in a very short time to damaging amplitudes. A trip of the power converter of the MSE, the extraction septum in the SPS, can move the trajectory by 40 σ in 1 ms. This failure has already caused severe damage to the transfer line [4]. Kicker failures (erratics etc.) can lead to damaging amplitudes even faster, of the order of μs.

The different types of failures are divided into three classes, depending on the time required to change the trajectory by about 10 σ:

- *slow:* $> \sim$3 ms;
- *fast:* $\sim$0.1 to $\sim$3 ms;
- *ultra-fast or single-turn:* $< \sim$0.1 ms.

Machine Protection for Injection

To prevent damage from failures which can occur during the injection process, a machine protection system is needed comprising both active and passive protection. Active protection is based on surveillance of the equipment state before extraction (beam surveillance can only be used for analysis after the beam passage). Examples of active systems are the power converter surveillance (PCS), with a reaction time of $>$ 3 ms, or the Fast Magnet Current Change Monitor (FMCCM) to detect sub-ms changes of the magnet current. The core of the active protection is a "beam interlocking system", which collects the equipment status information and inhibits extraction or injection in case of faults [5]. Passive protection systems such as collimators and absorbers must be correctly placed to intercept mis-steered beams, and absorb or dilute the beam energy.

Slow failures can be fully covered with active protection; fast failures require a combination of active and passive protection; for ultra-fast failures only passive protection devices can prevent damage.

The protection level of the overall system for the LHC injection has been derived from tracking simulations of the effects of the various failures on the beam.

PASSIVE PROTECTION SYSTEMS

Transfer Line Collimation

The transfer line collimators, TCDI, have two 1.2 m long graphite jaws, and protect the LHC and MSI injection septum aperture. Three collimators are used per plane with 60° betatron phase advance between adjacent collimators, to guarantee full phase space coverage and thus to protect against any failure occurring upstream [6].

The required setting of the TCDI jaws is 4.5 σ from the beam axis. Maximum amplitudes of 6.9 σ into the LHC are ensured taking machine imperfections such as mismatch from the SPS, beta-beating, misalignment of the elements, etc. into account, see Fig. 1.

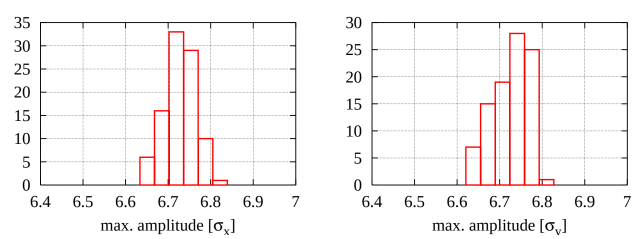

Figure 1: Results of a Monte-Carlo for the protection level of the TCDI system. The LHC is protected at 6.9 σ.

Passive Protection for the Injection Region

The injected beam is vertically deflected onto the LHC orbit by the MKI injection kicker. A dedicated vertical passive protection system protects the LHC against MKI failures. This system consists of the 4.185 m long TDI injection stopper at 90 degrees downstream of the kicker, with two jaws made of hBN, Al and Cu, and the two auxiliary collimators, TCLI, at 180±20 degrees from the TDI.

The required setting of these devices was obtained with particle tracking simulations of MKI failures including machine imperfections and setting tolerances [7]. The TDI and TCLI jaws must be set to 6.8 σ to guarantee that not more than 5 % of the injected batch (corresponding to the damage level) reach an amplitude of more than 7.5 σ, the LHC aperture.

SIMULATIONS OF THE OVERALL PROTECTION LEVEL

The overall protection level for the present layout of the protection systems was checked in a Monte-Carlo combined with a particle tracking. The whole injection process was simulated - connecting the SPS extraction region, the transfer line and the injection region in the LHC. The Monte-Carlo was used to sample different possible states of the extraction, the line and injection region. The tracking was done with the MAD-X tracking module for LHC beam 2: the particles were extracted from the SPS, were transferred through the transfer line TI 8 and injected into the LHC in IR 8. The last element included in the tracking is the LHC quadrupole Q6 downstream of the second TCLI on the other side of the insertion. The criterion for safe injection was that losses on the aperture had to be below the 5% damage limit during the whole process.

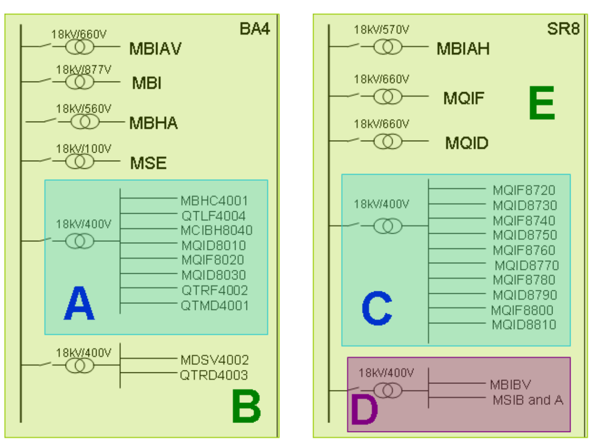

Figure 2: Powering scheme for the magnet families of the injection process via TI 8.

Mismatch between SPS and transfer line and transfer line and LHC was randomly chosen between ±20%, anti-correlating vertical and horizontal plane. Random effects for power converter ripples, misalignments and tilts of accelerator equipment, beam jitter, etc. were included. For every seed the orbit of the transfer line was corrected to give a realistic trajectory. All passive protection elements were taken into account and set to the required protection setting plus maximum tolerance. A full aperture model for the transfer line and the injection region was used [2]. Single failures and group failures were studied. Power converter faults lead to a switch-off of the magnet family which is supplied by this power converter. These failures are referred to as single failures; only one magnet family is affected. Single failures for all dipole families playing a role in the injection process have been investigated.

Table 1: Results of Monte-Carlo for single failure tracking.

Family	**Tolerable error** $[\Delta k/k_0]$	**Required reaction time** [ms]	**LHC**	**TL**
			covered by	
MPLH	0.185	201.0	TCDI	PCS
MKE	0.125	-	TCDI	-
MSE	0.005	0.1	TCDI	FMCCM
MBHC	0.005	5.1	TCDI	FMCCM
MBHA	0.012	31.5	TCDI	PCS
MBI	0.003	2.7	TCDI	FMCCM
MCIBH	0.630	389.0	TCDI	PCS
MBIAH	0.003	7.9	PCS	FMCCM
MBIBV	0.003	43.4	PCS	PCS
3MCIAV	0.183	98.43	PCS	TCDI
MSI	0.0035	3.5	FMCCM	n/a

Different power converters can be connected to the same transformer. A fault at the level of the transformer can lead to a trip of all families connected to the transformer. These failures are called group failures.

Fig. 2 shows the powering scheme of the magnet families involved in the injection process via TI 8. The group failures studied are marked with the letters A, B, C, D and E. For example, case B corresponds to a failure scenario where all magnet families connected to transformers in the building BA4 are accidentally switched off.

Each case, single or group failures, was studied with 1000 different seeds and 1000 particles per run (since only %-level statistics are required to check for damage). For each run, loss patterns along the line and injection region were calculated and after the last element of the tracking the number of particles outside the LHC aperture of 7.5 σ in phase-space was evaluated. Post-processing routines finally determined for each magnet family the maximum tolerable error in bending angle and the required reaction time for interlocking the power converter surveillance in the case of single failures, see Table 1, or the maximum allowable time after the switch-off in the case of group failures, see Table 2. The last two columns of Table 1 and 2 show whether the transfer line or the LHC are protected and by which protection system. Fig. 3 shows the result for the Monte-Carlo of single failures of the injection septum MSI.

The calculation of the required reaction times for single and group failures is based on the conservative assumption of an exponential decay of the current after the switch-off with the time constant $\tau = L/R$ (not applicable for kickers). The additional output filtering at the power converter, which slows down the decay of the current, is not taken into account. The obtained numbers contain thus an additional safety margin.

Discussion of Results

An FMCCM is required as the required reaction time for several families in Table 1 is either below the reaction time

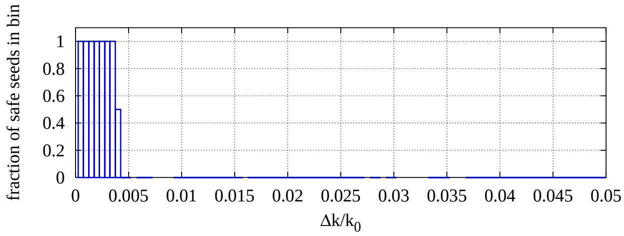

Figure 3: Histogramm of fraction of safe seeds versus relative error for single failure tracking of the MSI.

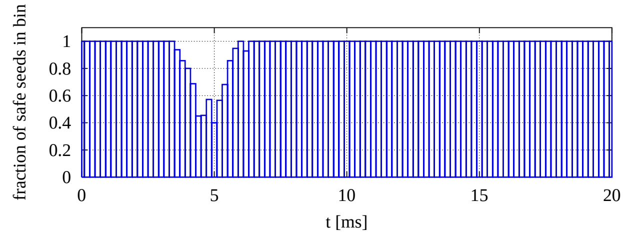

Figure 4: Result for case D.

of the PCS or at the limit. This is especially true for the case of the extraction septum MSE with its required reaction time of only 100 μs. The main bending magnets of the transfer lines, the MBI, and dipole families at the beginning of the line, the MBHC, and at the end of the line, the MBIAH, also need to be equipped with an FMCCM. The injection region does not have any passive protection in the horizontal plane. An undetected failure of the horizontally deflecting injection septum, the MSI, could directly lead to LHC damage. The required reaction time of the MSI is short, 3.5 ms, and an FMCCM is proposed there as well.

Table 2: Monte-Carlo results for group failures.

Group	**Tolerable time after switch-off** [ms]	**LHC**	**TL**
		covered by	
A	1.3	TCDI	FMCCM on MBHC
B	0.1	TCDI	FMCCM on MSE
C	15.8	TCDI	PCS
D	3.5-6.4, >20	FMCCM on MSI	TCDI/PCS
E	4.2-11.8, >20	FMCCM on MBIAH, MSI	FMCCM on MBIAH

Provided that the MSI will be equipped with an FMCCM, the protection of the LHC from injection failures can be guaranteed. The transfer line collimators give full protection from any upstream failures.

At present transfer line damage cannot be fully excluded. A failure of the extraction kicker MKE could lead to damaging amplitudes in the transfer line. Solutions are being investigated. Consequences of single quadrupole failures have been studied analytically in [8] and are less severe.

The group failure cases containing the extraction septum MSE are dominated by the effect of the septum with its very short time constant of only 23 ms (case B in Table 2). Other group failures, such as group D and E consisting of families at the end of the line - either in the collimation section or even after such as the MSI, show the effect of the transfer line collimators leading to time windows which could cause damage, whereas after this time the collimators intercept the mis-steered beam before it impacts downstream, see Fig. 4.

Table 2 shows that the protection system required to protect against single failures also protects against group failures. No additional FMCCMs are required. However, group failures can be 5 times faster than single failures (compare group A in Table 2 and MBHC in Table 1). Hence covering group failures needs an improved performance of the protection system.

The specification for an FMCCM resulting from the study is to detect a current change of $\Delta I/I = 0.1\%$ with a reaction time of 50 μs. Recent tests of a possible device have shown the feasibility of these requirements [9].

CONCLUSION

Comprehensive tracking simulations were used to define protection systems and to check the protection level. Results of these simulations show that the LHC is fully protected with the foreseen protection system, provided a Fast Magnet Current Change Monitor is implemented for the injection septum MSI (specification: detection of 0.1% current change with a reaction time of 50 μs). With the present protection system failures of the extraction kicker MKE can still cause transfer line damage. An alternative solution is being worked on.

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