THE EXPECTED PERFORMANCE OF THE LHC INJECTION PROTECTION SYSTEM

V. Kain, O. Brüning, L. Ducimetière, B. Goddard, M. Lamont, V. Mertens
CERN, Geneva, Switzerland

Abstract

The passive protection devices TDI, TCDD and TCLI are required to prevent damage to the LHC in case of serious injection failures, in particular of the MKI injection kicker. A detailed particle tracking, taking realistic mechanical, positioning, injection, closed orbit and local optical errors into account, has been used to determine the required settings of the absorber elements to guarantee protection against different MKI failure modes. The expected protection level of the combination of TDI with TCLI, with the new TCLI layout, is presented. Conclusions are drawn concerning the expected damage risk level.

INTRODUCTION

The transfer lines TI 2 and TI 8 transport the LHC beams from the SPS to the LHC at 450 GeV. TI 2 guides the protons into Ring 1 with injection in IR 2, and TI 8 into Ring 2 with injection in IR 8. Five horizontally deflecting septum magnets MSI and 4 vertically deflecting kicker modules MKI put the injected beams on the LHC orbits. A movable 2-sided 4 m long vertical absorber, the TDI [1], is located at 90° phase advance after the MKI to protect the LHC against kicker failures. The TDI is placed 70 m downstream of the MKI and 10 m upstream of the superconducting separation dipole D1, which is protected by an additional shielding element TCDD against scattered and shower particles from the TDI.

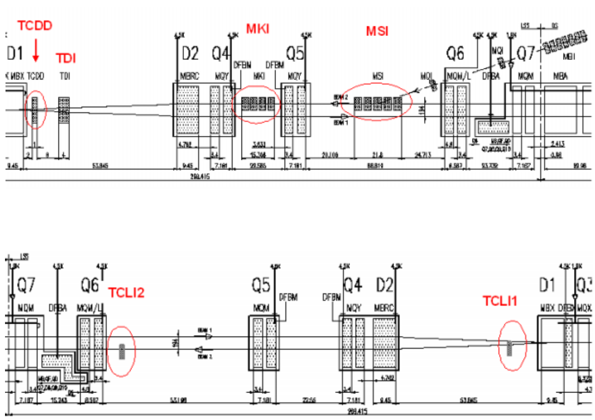

Figure 1: Overview of the injection region of IR8

Two double-jaw auxiliary collimators, TCLI, complete the protection system in case the phase difference between the MKI and the TDI is not exactly 90°. To accommodate a $\pm 20^\circ$ difference, TCLI locations were assigned at $n \times 180^\circ \pm 20^\circ$ from the TDI, (Fig. 1). One of the TCLIs is close to the insertion quadrupole Q6 at $\mu_y = 360 - 20^\circ$ from the TDI, the other one is at the downstream end of the cold separation dipole D1 on the other side of the insertion at $\mu_y = 180 + 20^\circ$.

In the following, the simulations used to define the protection setting for the combined system TDI and TCLI are described. The simulations were performed for the most dangerous case only, a flash-over of the MKI with the full beam grazing the TDI. The input parameters and assumptions are given, and protection levels for a given minimum cold-bore aperture and damage risk are derived. A proposal for a TCLI layout and preliminary collimator design requirements are presented.

SIMULATION METHODOLOGY

The protection level during a MKI flash-over is defined by the number of particles having an amplitude downstream of the chain of protection devices greater than the cold-bore aperture, as a function of the aperture of the system TDI-TCLI. This number is obtained with MAD, with particle tracking through the transfer line and the injection region in the LHC. The simulations were done for the latest LHC optics version V6.5.

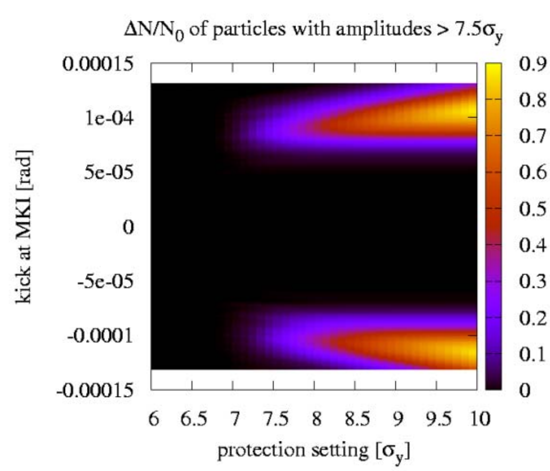

Figure 2: Number of particles getting into the LHC with amplitudes greater than 7.5 σ as a function of the protection setting of TDI and TCLI and of the MKI kick.

A "typical" state of the transfer line was defined with a Monte-Carlo for the random errors of power converter ripples, line drifts and SPS extraction error. These values were scaled to give a 95% confidence level for the injection error at the injection point in the LHC.

The MKI are traveling wave kicker magnets. Depending on the location of a flash-over in the magnet, the kick of a single MKI module can have any value in the range $\pm 100\%$ of its nominal deflection. In the simulation a kick range from -0.15 to 0.15 mrad was scanned, with the maximum kick strengths of the range reaching about $10\,\sigma_y$ (σ_y: vertical RMS beamsize) at the TDI. At the same time a scan of the settings of the TDI and TCLI from $6\,\sigma_y$ to $10\,\sigma_y$ was done. The number of particles above the cold-bore aperture compared to the damage level in the LHC at injection energy defines the required setting of the protection devices. Fig. 2 shows the results for such a scan with a effective (see details below) cold-bore aperture of 7.5 σ.

The load on the protection devices was also derived. Simulations were done for all protection devices having the same aperture setting, as well as for the TDI retracted by $1\,\sigma_y$ or $2\,\sigma_y$ compared to the TCLI.

Parameters and Assumptions

The initial parameters for the simulation are summarized in Table 1. Only the injection region of IR8 was studied. For IR2 no major differences are expected.

The injection error was taken as twice the RMS-value of the expected vertical delivery offset [2]. The orbit precision is given at the locations of the protection devices. The cold-bore aperture is the minimum aperture including a set of tolerances (4mm orbit error, dispersion error,...) available in the machine at injection. The damage limit corresponds to 5% of an ultimate batch ($288 \times 1.7 \cdot 10^{11}$ particles injected in one batch). The phase difference was obtained by changing the strength of Q4, the only quadrupole between MKI and TDI, by $\pm 20\%$.

Table 1: Input parameters

Injection error (y)	$\pm$0.45mm
TDI mechanical	$\pm$ 0.2mm
TCLI mechanical	$\pm$0.075mm
Orbit precision	$\pm$0.05mm
Cold-bore aperture	$7.5\,\sigma_y$
Damage limit	$2.4 \cdot 10^{12} p^+$
MKI-TDI phase error	$\pm 20°$

Issues not included in the simulation

The simulations were done without any aperture model in the transfer line nor in the injection region of the LHC, apart from the protection devices themselves (a preliminary investigation showed that the aperture of elements other than protection devices around IP8 is bigger than $9\,\sigma$).

The sweep effect of the MKI waveform was not taken into account. This effect will distribute the bunches within one batch around a certain amplitude; our assumptions are slightly conservative in this respect. Other additional failures like power converter faults in the transfer line have also been neglected so far.

RESULTS

Fig. 3 shows the maximum number of particles for the simulated kick range and for a certain protection setting getting into the LHC with amplitudes larger than the cold-bore aperture of 7.5σ. The horizontal line in the plot indicates the damage level in the LHC (5% of an ultimate batch). The simulations were done for $0°$ and $\pm 20°$ MKI-TDI phase change as well as for positive and negative sign injection error. Table 2 summarises the required settings for different cold-bore apertures, to stay below the 5% damage level for any MKI flash-over.

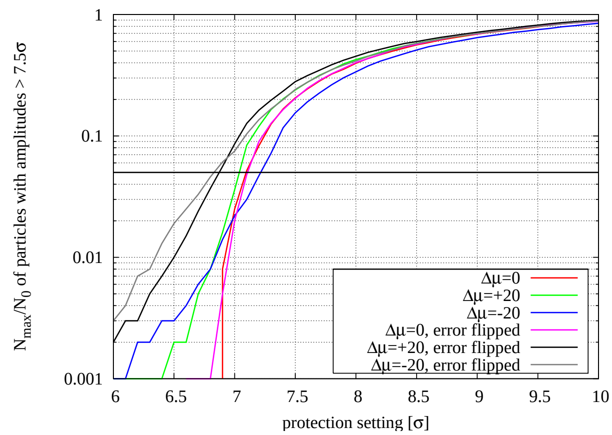

Figure 3: Maximum number of particles getting into the LHC with amplitudes greater than 7.5 σ as a function of the protection setting.

Table 2: Required settings of injection protection system

LHC cold-bore σ	**phase shift**		
	0°	**+20°**	**-20°**
8.2	7.8	7.7	7.6
7.8	7.4	7.2	7.2
7.5	7.0	6.8	6.8

Risk quantification for damaging MKI kick

Under the assumption that the results obtained for IR8 also hold for IR2, and only considering flash-overs, the risk for a damaging MKI kick was quantified. Fig. 4 shows the results for a flash-over probability of 1 MKI flash-over per 8 magnets per year. Results for cold-bore apertures 7.5 σ and $8.2\,\sigma$ are plotted for $0°$,$\pm 20°$ phase change between MKI and TDI. For a cold-bore aperture of $7.5\,\sigma$ and risk level of one damaging kick in 20 years, a protection setting of $\leq 7\,\sigma$ is required.

TDI further retracted

The results shown above indicate that the system TDI-TCLI has to be moved very close to the beam ($< 7\sigma$) to guarantee sufficient protection. This may result in an unacceptable load from the secondary halo for the uncooled TDI and hence require its retraction compared to the TCLIs. The consequences for the load on the TCLIs were investigated. In Fig. 5 the load on one of the TCLIs is plotted.

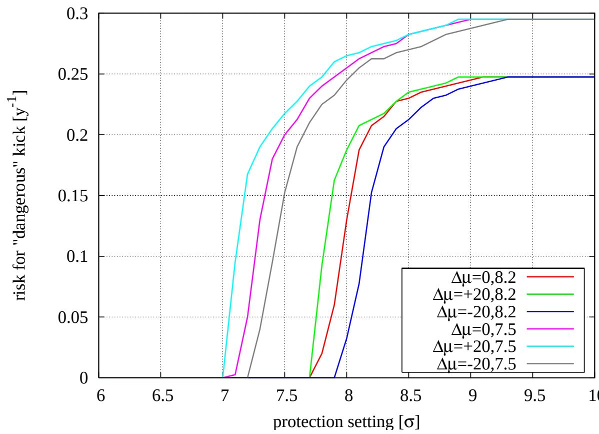

Figure 4: The probability for a damaging kick of the MKI during a flash-over per year for cold-bore aperture 7.5 σ and 8.2 σ as a function of the protection setting.

Without any MKI-TDI phase error and with the same setting for TDI and TCLI more than 10% of the total batch can end up on the TCLI. With a phase advance of $90 \pm 20°$ between MKI and TDI the load reaches more than 40%. If the TDI is retracted by 1 σ the load goes up to 70%, for 2 σ retraction to more than 80%.

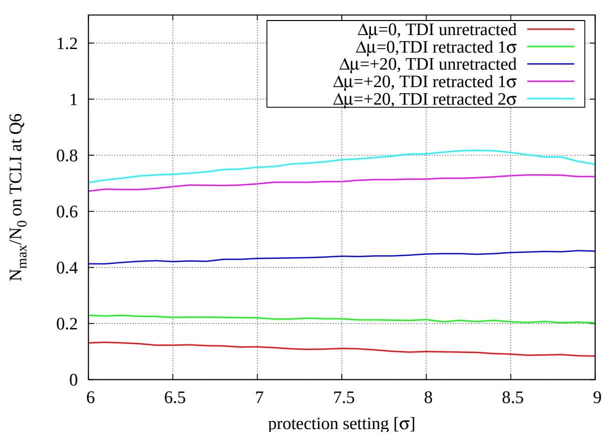

Figure 5: Load on TCLI at Q6 for same protection setting of TCLI and TDI as well as TDI further retracted.

TCLI LAYOUT

The simulations showed that large fractions of the injected batch can end up on the TCLIs in case of failures. The jaws must therefore be robust and will be made of low-Z material such as graphite. Studies for beam impact on low-Z material have shown that due to attenuation combined with emittance blow-up, 1m long low-Z jaws dilute a 450 GeV proton beam sufficiently well, [3]. It will be investigated whether additional shielding outside the vacuum chamber is required to protect downstream equipment from scattering products, as needed for the transfer line collimators, [4]. The TCLIs will have 1m long jaws, fully movable, water cooled and with tapering.

For the TCLI close to Q6, the LHC secondary collimator (TCS) design can be used. The TCLI close to D1 will need a more dedicated design, as at this location both beams share a common beam pipe with a inter-beam separation of about 20mm. A special "half-jaw" design will be applied, making sure that only one beam, namely Beam 1 in IR2 or Beam 2 in IR8, is collimated without disturbing the other beam, see Fig. 6. The final design will consider impedance issues, RF heating, etc.

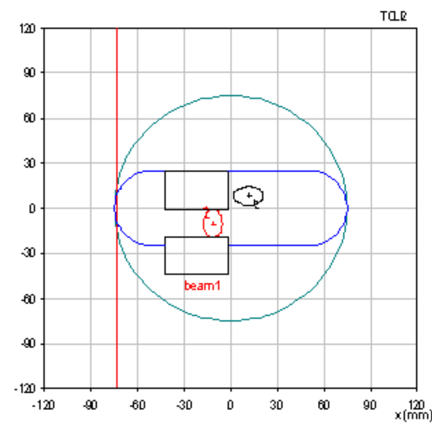

Figure 6: TCLI-cross-section at the D1 location for IR2. Both beams share one beam pipe, and are drawn with a 8.4 σ ellipse at the maximum possible excursion, corresponding to the maximum secondary halo extent. Protection does not interfere with the other beam.

CONCLUSION

The simulations showed that the TDI-TCLI system can give sufficient injection protection for the LHC. With the TDI and two additional TCLIs and protection settings of 6.8 σ, a risk probability of 1 damaging MKI kick in 20 years for any phase error between MKI and TDI and an effective LHC cold-bore aperture of 7.5 σ can be guaranteed. Robust TCLI collimators are required to cope with the beam load which can be more than 40% for identical TDI and TCLI settings, and even more if the TDI needs to be retracted by 1 or 2 σ wrt TCLIs. A preliminary design for the TCLI close to D1 has been worked out satisfying both protection efficiency and local constraints. For the TCLI close to Q6, the LHC secondary collimator design will be used.

REFERENCES

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