IMPACT OF AND PROTECTION AGAINST FAILURES OF THE LHC INJECTION KICKERS

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Abstract

The LHC injection systems consist of horizontally deflecting steel septum magnets and vertically deflecting kickers. A mobile beam stopper is placed downstream of the kickers for setting up with single bunches and to protect the superconducting machine elements during normal injection in the event of a malfunctioning of the kickers. The effects of various potential kicker failures and their impact on the machine have been investigated. The injection parameters, the design principles of the stopper and additional protection measures are discussed.

1 INTRODUCTION

Two new beam transfer lines with a combined length of 5.6 km and using over 700 room-temperature magnets, TI 2 and TI 8, are being built at CERN to transport 450 GeV/c protons from SPS to LHC [1]. An overview of these lines is given in [2].

TI 2 leads to the injection into LHC ring 1 near intersection 2 (IP2), TI 8 to the injection into ring 2 near intersection 8 (IP8). Civil engineering for both lines has started in 1998. First injection tests are foreseen for autumn 2003 (TI 8) and mid 2005 (TI 2).

A schematic plan view of an injection region is given in

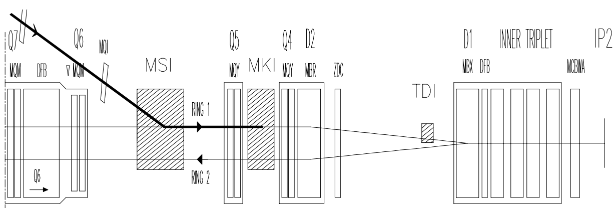

Figure 1: Schematic plan view of IP2 injection

Fig. 1. The beam to be injected passes through 5 horizontally deflecting steel septum magnets (MSI) with a total deflection of 12 mrad and a vertically deflecting kicker (MKI), consisting of 4 modules, with a nominal total kick strength of 0.85 mrad [3]. A mobile beam stopper (TDI), consisting of 2 absorber blocks positioned a few mm above and below the nominal LHC orbit, will be placed some 70 m downstream of the MKI, at a phase distance of $\Delta\mu_y = 90°$. Its main role is to protect the immediately following (cold) separation dipole D1 against miskicked bunches and to receive intentionally beam during commissioning and verification/re-adjustment of the injection before each fill.

The main beam and kicker parameters are given in Table 1. The destructive power of the beam imposes high precision and very good protection when injecting beam into the small aperture, superconducting LHC. The quench limit (through instantaneous energy deposition in a coil) is assumed to 38 mJ/cm^3 [4], the damage limit to 87 J/cm^3 [5].

Table 1: Beam and kicker parameters at injection

Beam (proton) momentum	450 GeV/c
Nominal single bunch intensity	$1.1{*}10^{11}$ p
Nom. batch intensity (3*81 bunches)	$2.67{*}10^{13}$ p
Ultim. batch intensity (3*81 bunches)	$4.13{*}10^{13}$ p
Bunch distance	25 ns
Nom. norm'd transverse emittance	3.5 μm rad
Nominal kick strength	0.85 mrad
Kicker rise time	0.9 μs
Kicker flat top length	6.6 μs
Kicker fall time	3 μs

In the following the various modes of using the MKI/TDI ensemble, either intentionally or accidentally, will be described. Then, results of simulations are presented leading to a preliminary design of an appropriate TDI. Finally, the impact of particles escaping the TDI on the LHC is looked at, discussing the benefit from supplementary protection elements.

2 OPERATIONAL AND FAILURE MODES

Various circumstances of using the MKI/TDI ensemble have been investigated and listed in Table 2, grouped into "cases" with the same total kick strength seen by the beam, in order of decreasing expected occurrence. Operational (intentional) uses (marked shaded) imply normally the use of single bunches, accidental or emergency uses have to proceed from the assumption of full batch intensity.

Case 2 (sweep) occurs when the passage of beam to be injected or circulating beam coincides with the rise or fall slope of the kicker pulse. The latter case results in close to 100 bunches put on various places of the TDI and close to 20 bunches escaping the TDI (assuming linear kick slope). One of the reasons for a beam sweep is a possible

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prefire of one of the kicker modules. Special precautions are foreseen to make this very unlikely, or to reduce its consequences, e.g. applying the high voltage only very shortly before the trigger pulse to the thyratron switches or firing rapidly the other three kicker modules if one produces a prefire.

Table 2: Operational (shaded) and failure modes of the MKI/TDI ensemble

Case	Kick [%]	Reason(s) [expected rate]
1	0	Setting-up [during commissioning] Verification/re-adjustment [before each fill] SPS extraction launched but LHC not ready [occasional] Trigger missing (MKI internal or external) [rare]
2	0-100	Beam sweep: Wrong timing (MKI internal or external) [occasional] Prefire of one MKI module, followed by firing the other 3 [rare]
3	75	One MKI module full fault [rare]
4	75-125	One MKI module flashover or equiv. [extremely rare] (grazing case ≈ 86 %)

Fig. 2 shows a simplified side view (left) of the injection region (not to scale), with an enlarged front view (right) of the upper TDI block, showing schematically the beam impacts for the different cases.

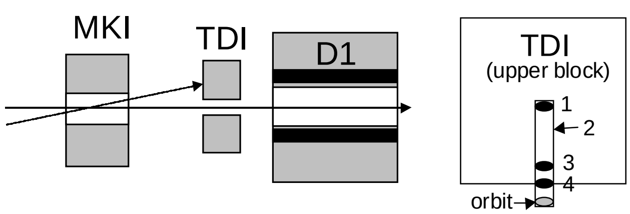

Figure 2: Schematic side view (left) of injection area (case 1 shown); enlarged beam view (right) of upper TDI block with schematic beam impacts for various cases (case 4 shown for grazing impact).

Case 1 corresponds to an impact distance from the bottom edge of about 30 mm, case 3 to about 3.5 mm. The lower TDI block (not shown) is foreseen to receive miskicked circulating beam in mirrored positions. At injection the TDI blocks are supposed to be ± 8.5 σ (tangential to the machine aperture) or less distant from the LHC orbit (corresponding to about ± 4.3 mm).

3 TDI/D1 SIMULATION RESULTS

The TDI/D1 ensemble has been simulated using FLUKA [6]. For the most frequent case 1 the length and the composition of the TDI was varied. The results are shown in Fig. 3, plotted as maximum energy deposition in the D1 coil against the number of interaction lengths of the TDI. The transverse dimensions were kept fixed at 8*8 cm. Even though the counter-rotating beam imposes a space limitation in the horizontal plane, these dimensions reveal to be sufficient with a contribution from lateral leaking of only ≈5*10^{-7} GeV/cm^{3}p.

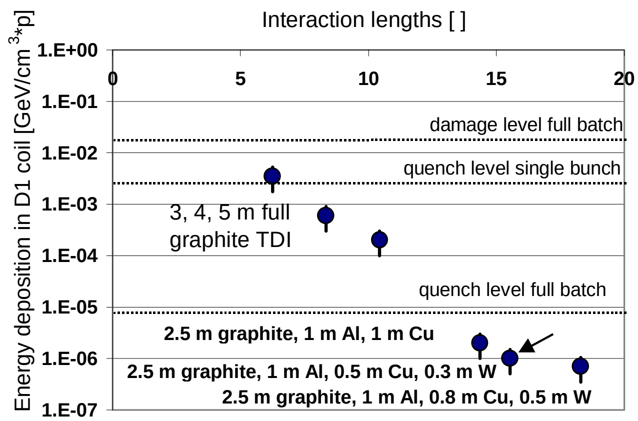

Figure 3: Energy deposition in D1 coil as a function of the number of interaction lengths of the TDI (case 1).

Sandwich constructs of appropriate materials have the benefit over full graphite to stay below the quench limit even for full batches, at a comparable length. A sequence of 2.5 m graphite, 1 m aluminium, 0.5 m copper and 0.3 m tungsten (marked with arrow) has been chosen as "reference TDI". In a next step it has been investigated what protection this TDI procures to D1 in the various cases. The results are given in table 3.

Table 3: Energy deposition in D1 coil (preliminary) for various cases (reference TDI)

Case	Error	Energy deposition in D1 coil [J/cm^3]		
	[%]	1.1*10^{11} p	2.67*10^{13} p	4.13*10^{13} p
1	50	1.8*10^{-5}	4.3*10^{-3}	6.7*10^{-3}
2	50		6.8	10.5
3	50	2.3*10^{-2}	5.6	8.7
4	25	0.25	60.3	93.3

Case 1 leads to no quench, even with highest intensities. Full batches in cases 2 and 3 will, without additional measures, quench D1. Case 4 (values given for grazing impact) approaches the damage limit for a nominal full batch and surpasses it slightly for the ultimate intensity. To test the effect from additional shielding a copper cylinder (25 ≤ r ≤ 140 mm, 1m long) has been introduced in the simulation 3 m in front of D1. This reduced the energy deposition by about a factor 120, thus excluding damage to D1 under all circumstances. Whereas such a shield would only be mandatory for case 4 with highest intensity, it is also beneficial in the other cases. The figure for the sweep case at nominal batch intensity is then close to the quench level. Some further shield optimisation will probably allow to fall short of the quench level for this case.

A perspective sketch of the preliminary design of the reference TDI is given in Fig. 4. Each TDI block has 2 servo motors allowing a vertical adjustment with a precision of better than 0.1 mm. The enlargement in Fig. 4 (upper left corner) shows the front face of the TDI in more detail. The main absorber material is shrink-mounted into an aluminium frame, attached to an iron beam which in turn is moved by the motors. The required vertical movement is relatively small in IP8 but in IP2 it must take into account the opening requirements of the ALICE Zero Degree Calorimeter [7].

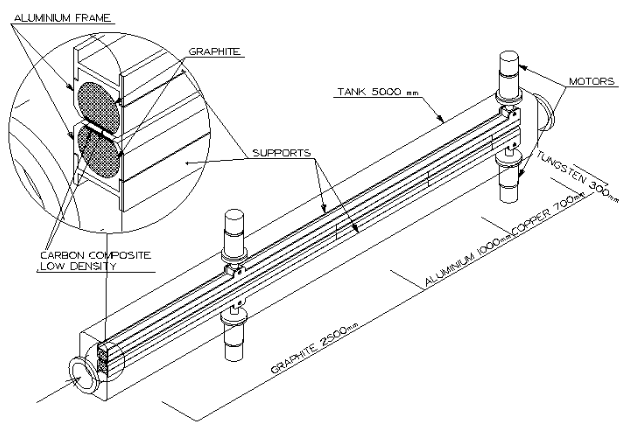

Figure 4: Perspective sketch of the TDI assembly (preliminary).

4 OTHER IMPACTS THAN ON D1

4.1 Triplets / Dispersion Suppressors / Arcs

The effect of injected bunches missing the TDI on other parts of the LHC than D1 has also been looked at. Two worst cases are considered:

Firstly, the case 2 where close to 20 bunches could be swept between the orbit and the TDI edge, starting to oscillate around the orbit. The mean particle density is about $2*10^{10}$ p / 0.1 σ. The damage level is estimated to be 10^{12} p lost per m, the quench level 10^{9} p lost per m. Damage seems therefore excluded, but to avoid a quench the TDI must be set such that it covers entirely the machine aperture of 8.5 σ.

Secondly, the case 4 with a full batch just missing the TDI edge. Here the worst case particle density is about $1.6*10^{12}$ p / 0.1 σ (peak). Excluding machine damage with certainty would again require a sufficient closure of the TDI.

Two additional collimators, positioned at a phase advance $\Delta\mu \approx \pm 20°$ from the TDI (at around Q6/Q7 on the other side of the injection insertions), with the same aperture, would provide the same protection as the TDI in the presence of phase errors.

4.2 Cleaning Sections

Badly injected particles oscillating around the LHC orbit between 8.5 σ (TDI) and 7 σ (primary cleaning collimators) will end up in the LHC cleaning sections. This does not cause problems for a few bunches, but if a full batch is lost in this area, the collimators are likely to be damaged.

4.3 Experiments

Since the aperture of the experimental vacuum chambers is large compared to the machine aperture, it seems excluded that parts of the detectors can be hit directly by misinjected bunches. However particles leaking out of the TDI or supplementary protection elements or scattered particles may reach the experiments in IP2 and IP8. Their impact is however at present estimated to be insignificant compared to the radiation from normal operation. More detailed studies are required to confirm this assumption.

5 CONCLUSIONS

The destructive beam power and the LHC characteristics as superconducting, small-aperture machine require highest care at injection. Mishaps can have severe consequences. Although the injection kickers are being built for utmost reliability, failures are not entirely excluded. Simulations of these failures reveal that a beam stopper with supplementary shielding and collimators can, appropriate setting assumed, provide sufficient protection, except in very rare cases where the warm aperture limiting cleaning collimators can be affected.

6 ACKNOWLEDGEMENTS

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