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Report

Energy Deposition Studies for Fast Losses during LHC Injection Failures

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Several instances of injection kicker magnet (MKI) failures have occurred in the first years of LHC operation, leading to misinjections or to accidental kicks of circulating bunches. In a few cases, MKI modules imparted a partial or an increased beam deflection, resulting in grazing bunch impact on beam-intercepting devices and consequently leading to significant secondary showers to downstream accelerator elements. In this study, we investigate different failure occurrences where miskicked bunches were incident on the injection beam stopper (TDI) and on one of the auxiliary injection collimators (TCLIB), respectively.
FLUKA shower calculations were performed to quantify the energy deposition in superconducting magnets. Different sections of the LHC insertion regions 2 and 8 were studied, including separation dipole and inner triplet downstream of the TDI as well as matching section and dispersion suppressor adjacent to the TCLIB. The obtained results are evaluated in view of quench and damage limits.

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ENERGY DEPOSITION STUDIES FOR FAST LOSSES DURING LHC INJECTION FAILURES

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Abstract

Several instances of injection kicker magnet (MKI) failures have occurred in the first years of LHC operation, leading to misinjections or to accidental kicks of circulating bunches. In a few cases, MKI modules imparted a partial or an increased beam deflection, resulting in grazing bunch impact on beam-intercepting devices and consequently leading to significant secondary showers to downstream accelerator elements. In this study, we investigate different failure occurrences where miskicked bunches were incident on the injection beam stopper (TDI) and on one of the auxiliary injection collimators (TCLIB), respectively. FLUKA shower calculations were performed to quantify the energy deposition in superconducting magnets. Different sections of the LHC insertion regions 2 and 8 were studied, including separation dipole and inner triplet downstream of the TDI as well as matching section and dispersion suppressor adjacent to the TCLIB. The obtained results are evaluated in view of quench and damage limits.

INTRODUCTION

The counter-rotating beams of the LHC are injected in different long straight sections accommodating the ALICE and LHCb experiments, respectively. Fast-pulsed kicker magnets (MKIs) impart a final vertical deflection of 0.85 mrad on injected bunches to force them on the circulating beam orbit [1]. Misinjections or accidental kicks due to MKI failures are accounted for by a system of beam-intercepting devices comprising an injection beam stopper (TDI) at 90° phase advance from the MKI, and auxiliary collimators (TCLIA/TCLIB) at 180°±20° phase advance from the TDI [1, 2]. Additional masks (TCDD/M and TCLIM), with a similar aperture as adjacent superconducting magnets, are installed downstream of the TDI and TCLIB. An illustration of the layout of injection protection devices and magnets in the LHC Insertion Regions (IRs) 2 and 8 is shown in Fig. 1.

Secondary particle showers from the TDI and TCLIs, in particular during grazing beam impact, can lead to a considerable energy deposition in neighbouring superconducting magnets. Table 1 summarizes injection kicker malfunctions in the first years of LHC operation which resulted in beam impact on protection devices. Most of the failures concerned the injected beam, while only in one case the circulating beam was deflected. As by design, bunches were fully intercepted by the TDI in cases where no kick was exerted on them during injection. However, magnet quenches occurred in all incidents where bunches were deflected with a non-nominal kick strength (sweep and grazing impact on protection devices).

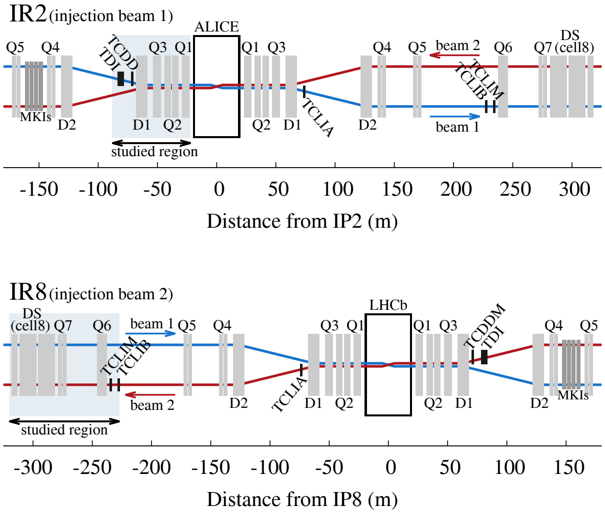

Figure 1: Illustration of IR2 and IR8 layouts.

Table 1: LHC Injection Failures (2010–2012) with Beam Impact (Protons) on Protection Devices [3]

Date	Beam	MKI failure	Applied kick (% nominal)	Lost bunches
2010				
23/10	1/inj.	not firing	0%	32
2011				
18/04	2/inj.	flashover	∼110–125%	36
23/04	1/inj.	not firing	0%	36
27/04	2/inj.	not firing	0%	72
28/07	1/inj.	erratic	0%	144
28/07	1/circ.	erratic	≤12.5%	176
2012				
26/03	2/inj.	erratic	0%	1
15/04	2/inj.	flashover	∼110–126%	108

In this paper, we present FLUKA [4] shower calculations for two failure cases (proton injection at 450 GeV), one concerning grazing bunch impact on the TDI and the second involving losses on the TCLIB. FLUKA has already been used in the design phase of the TDI and TCDD to optimize their protection efficiency for different operational and failure modes [5, 6]. The studies presented here are

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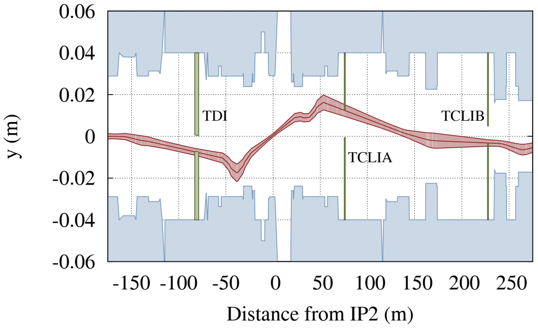

Figure 2: Vertical aperture between MKI and Q7 right of IP2, as well as 3σ beam envelope of a beam deflected at the MKI with 12.5% of the nominal kick strength.

motivated by real failure occurrences encountered so far in operation and are intended to provide an estimate of the energy deposition in magnet coils in view of quench and damage limits. The first study (impact on TDI) aims in analysing a past event, while the scope of the second study (impact on TCLIB) is the estimation of the damage potential for possible future failures. The concerned regions are indicated in Fig. 1.

GRAZING BEAM IMPACT ON TDI

On July 28th 2011, a MKI erratic in IR2 caused a deflection of circulating bunches with up to 12.5% of the nominal kick strength [3]. As a consequence, $\sim$176 bunches with a total intensity of $\sim 2.15\times10^{13}$ were lost in the machine, approximately 14 of them being swept over the aperture during the kicker rise time ($0.7\pm0.1\,\mu$s). The remaining 162 bunches were grazing on the lower TDI jaw after encountering a kick of $\sim$0.11 mrad at the pulse flat top ($8.1\pm0.1\,\mu$s). Particles leaking from the TDI induced a quench in the downstream separation dipole (D1) and the triplet quadrupoles. Three circuits in the most upstream triplet corrector (MCSOX) were found open after the event. Particle showers from the TDI also affected ALICE, inducing permanent damage to the Silicon Drift Detector and leading to high-voltage trips of electronics boards. On the right side of IP2, the D2 dipole downstream of the TCLIA quenched, which can likely be attributed to secondary showers escaping the TCLIA. Figure 2 illustrates the IR2 vertical aperture together with the beam envelope of bunches kicked with 12.5% of the nominal MKI strength.

TDI Impact Distribution

The TDI has two vertical jaws each accommodating six 47.5 cm boron nitride blocks (1.92 g/cm^3), supplemented by higher-Z blocks (60 cm aluminium and 70 cm copper) at the downstream extremity. The jaws are aligned parallel to the circulating beam orbit, with a nominal half gap of $6.8\sigma_n$ where σ_n is the beam size corresponding to a $3.5\,\mu$m rad normalized emittance [7]. At the time of the incident, the external crossing angle bump implied a vertical orbit angle of $-60\,\mu$rad and a vertical orbit offset of -3.34 mm at the position of the TDI. Typically, the TDI angular alignment is affected by an uncertainty of $\pm100\,\mu$rad while the orbit position is obtained with an accuracy of $\pm150\,\mu$m [7]. Besides this, drifts of jaw positions have been observed due to thermal effects. Considering these uncertainties, the impact distribution for grazing impact scenarios such as the one addressed here can only be determined approximately.

The normalized emittance as measured with the beam wire scanner before the incident was 1.2 and $1.4\,\mu$m rad in the horizontal and vertical plane, yielding a beam size ($1\sigma^2$) of $\sim 510\times350\,\mu\text{m}^2$ at the TDI front face. Assuming a TDI half gap of 3.90 mm ($=6.8\sigma_n$) and a perfect parallel alignment with the circulating beam orbit, one obtains (for bunches kicked with 12.5% of the nominal MKI strength) a TDI impact parameter of 1.4σ as well as an impact angle of $\sim 40\,\mu$rad with respect to the jaw axis. In this case, $\sim$76% of the incident particles would hit the tapered jaw front face, $\sim$9% would graze on the jaw surface which is parallel to the circulating beam orbit and $\sim$15% would miss the TDI. However, considering an angular misalignment and a vertical offset within above specified uncertainties, the fraction of particles grazing could be as high as 42%. By design, in none of the cases particles can hit directly the aluminum and copper blocks as they have an offset of 2 mm with respect to the boron nitride.

Energy Deposition in D1 and Inner Triplet

FLUKA shower calculations were carried out to estimate the energy deposition in D1 and triplet quadrupoles during the incident. Simulations were based on a realistic geometry description of TDI, TCTVB, TCDD and magnets (using tools described in [8, 9]), combined with an accurate implementation of beam optics including separation and crossing angle bumps. Figure 3 shows the obtained peak energy density in magnet coils corresponding to 162 bunches (with a bunch intensity of 1.2×10^{11}) impacting on the lower TDI jaw after being deflected with 12.5% of the nominal MKI strength. A nominal TDI half gap and a perfect alignment with the circulating beam orbit was assumed.

The energy density pattern is dominated by distinct peaks at the upstream faces of D1 and Q3. The peak in

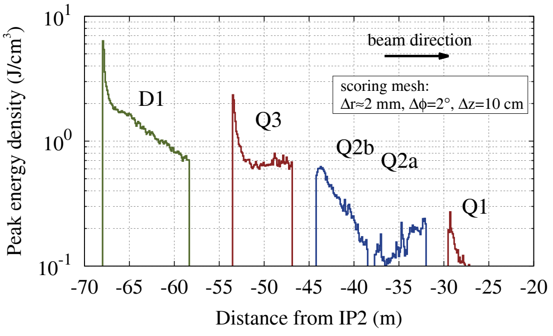

Figure 3: Peak energy density in coils of D1, Q1, Q2 and Q3 due to 162 proton bunches grazing on the TDI jaw.

the D1 is caused by particle showers from the TDI passing through the TCDD aperture ($70\times45.4\,\text{mm}^2$) and directly impacting on the D1 steel front plate. Conversely, the peak in Q3 coils primarily stems from charged particles leaking from the TDI with an angular distribution and a magnetic rigidity which allows them to pass through the D1 before being lost on the aperture between D1 and Q3. The energy density pattern in quadrupole coils beyond the Q3 peak is determined by charged particles lost due to the strong triplet field which features a horizontal focusing-defocusing-focusing layout for the incoming beam.

Studying the effect of different TDI impact distributions due to a jaw misalignment within above specified uncertainties, it is found that the D1 peak can vary roughly by ±10%. Besides this, the presented results neglect the contribution of bunches impacting on the TDI during the initial sweep. The time profile of the MKI pulse waveform suggests that out of the 14 swept bunches approximately 2 were hitting the TDI. It is hence assumed that the energy deposition is dominated by the much larger number of bunches kicked at flat top. In general, the obtained results indicate that the maximum energy density in coils during the incident was safely below the assumed damage limit of 87 J/cm^3 [10]. On the other hand, in all magnets, the calculated energy density is, at least, a few factors higher than the assumed quench limit of several tens of mJ/cm^3 [11].

BEAM IMPACT ON TCLIB

In another incident (April 18th 2011), injection kickers in IR8 suffered a flashover and deflected 36 bunches with $\sim$110-125% nominal kick strength, causing some of them to impact on the TCLIB (1 m graphite jaw, set at $6.8\sigma_n$) and resulting in the quench of 11 magnets [3, 12]. Similar failure cases could potentially pose a risk to magnets if more bunches were involved, particularly in view of planned operation with 25 ns bunch spacing (where the number of bunches per injection doubles to 288).

Impact Scenario

The calculations presented in this section are intended to provide a general account of beam impact on the TCLIB without reproducing the exact conditions of a past event. As impact scenario, a proton beam with nominal emittance was assumed to hit the upper TCLIB jaw, considering a half gap of $6.8\sigma_n$ and an impact parameter of $1\sigma_n$.

Energy Deposition in Q6, Q7 and DS Magnets

The geometry model used in the shower calculations included the TCLIB and TCLIM, followed by Q6, Q7 and magnets of the first Dispersion Suppressor (DS) cell (cell 8). Figure 4 shows the obtained peak energy density per nominal bunch (1.15×10^{11}) impacting on the TCLIB under above described assumptions. The highest value can be observed at the upstream face of the Q6, determined by particles escaping from TCLIB, leaking through the mask and being lost at the aperture close to the Q6 front. Following a long drift chamber, a second peak can be observed at the upstream face of Q7, while the energy density is lower in DS magnet coils. Scaling the results up to 288 bunches, the simulation predictions suggest that the damage limit for coils cannot be reached.

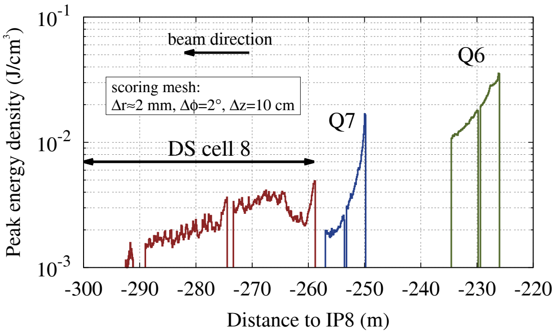

Figure 4: Peak energy density in coils of Q6, Q7 and DS magnets per nominal bunch impacting on the TCLIB.

CONCLUSION

Several injection kicker failures occurring in the first years of LHC operation resulted in magnet quenches due to grazing bunch impact on beam-intercepting devices. For one of the worst cases, with $\sim$162 bunches grazing on the TDI, it was demonstrated that the energy density induced in adjacent magnets was safely below the damage limit, but evidently compatible with observed quenches. Magnet damage is also not expected for primary proton impact on the TCLIB, even for a full batch of 288 bunches.

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