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PROTECTION OF SUPERCONDUCTING MAGNETS IN CASE OF ACCIDENTAL BEAM LOSSES DURING HL-LHC INJECTION*

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Abstract

The LHC injection regions accommodate a system of beam-intercepting devices which protect superconducting magnets and other accelerator components in case of missteered injected beam or accidentally kicked stored beam, e.g. due to injection kicker or timing malfunctions. The brightness and intensity increase required by the High Luminosity (HL) upgrade of the LHC necessitates a redesign of some devices to improve their robustness and to reduce the leakage of secondary particle showers to downstream magnets. In this paper, we review possible failure scenarios and we quantify the energy deposition in superconducting coils by means of FLUKA shower calculations. Conceptual design studies for the new protection system are presented, with the main focus on the primary injection protection absorber (TDI) and the adjacent mask (TCDD).

INTRODUCTION

The transfer lines from the SPS join the LHC in the ALICE and LHCb experimental insertions (IR2 and IR8) where four kicker magnets (MKIs) apply the final vertical deflection (0.85 mrad) on injected bunch trains [1]. To protect machine components in case of MKI malfunctions and timing errors, the injection regions accommodate a system of beam-intercepting devices and masks. The main element of the protection system is the TDI, a movable two-sided absorber installed at a phase advance of 75–95° from the MKIs. The TDI is located between a pair of superconducting dipoles (D1 and D2), which reduce the beam separation and bring the counter-rotating beams onto colliding orbits. In case of beam impact on the TDI, the single-bore D1 downstream of the TDI is the most exposed magnet and is protected by a mask (TCDD) which intercepts secondary particle showers leaking from the TDI. The TDI and TCDD are complemented by further collimators and masks downstream in the insertion regions, which provide some additional protection in case of phase errors.

The High Luminosity (HL) upgrade of the LHC requires an increase of the bunch intensity at LHC injection from 1.15×10^{11}/1.7×10^{11} (nominal/ultimate LHC) to 2.3×10^{11} protons. Together with a smaller beam emittance, this yields a significantly higher brightness than existing injection protection devices were designed for. These beam parameters not only pose a challenge for the robustness of absorber materials, but put new demands on the protection of superconducting magnets, particularly the D1 magnet.

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Following a review of possible failure scenarios, this paper evaluates the protection provided by the existing TDI and TCDD and proposes potential solutions to reduce the energy density in the D1 coils. Other relevant aspects related to the upgrade of LHC injection protection devices, particularly the material robustness, are presented in another paper [2].

FAILURE SCENARIOS

In order to sufficiently protect the LHC during injection but also allow for some operational margin, the TDI jaws are maintained at a half gap of $6.8\sigma_n$ [3], where σ_n corresponds to the nominal LHC emittance (ε_n=3.5 μm·rad). With a β-function of ~43 m, this yields a jaw opening of approximately 7.6 mm. It is assumed that the same settings can be retained for HL-LHC operation since no significant optics changes are foreseen in the injection regions. A malfunction of the MKIs can affect either the injected or stored beam, but also both beams in the same event for specific kicker timing errors. As can be seen in the Table 1, different failure modes can affect a maximum of either 159 or 288 bunches (plus some bunches which are swept) and can give rise to different kick strengths, which in turn lead to different impact positions on the TDI jaws.

In case no kick is applied to the injected bunch train or in case circulating bunches are deflected with 100% of the MKI kick strength (timing error), beams typically impact on the TDI some 30–35 mm from the absorber block edge. The energy deposition in downstream magnets is however significantly higher if bunches impact close to the edge or if they graze along the jaws since secondary particle showers can escape through the TDI gap. Such events occur if the injected beam is deflected by approximately 90% or 110% (impact on the upper or lower jaw, respectively), or if the

Table 1: Overview of possible injection failure scenarios. Combination of different failures are not considered. The expected kick strength is expressed as a percent fraction of the nominal kick strength. Swept bunches are not included in the table.

Failure case	**Bunches**	**Kick strength**
Charging failure	288 (inj.)	99–101%
Main switch erratic	159 (inj. or circ.)	≤100%
Main switch missing	288 (inj.)	75%
Magnet breakdown	≤288 (inj.)	75–125%
Timing error	≤288 (inj.)	0%
	≤288 (circ.)	100%

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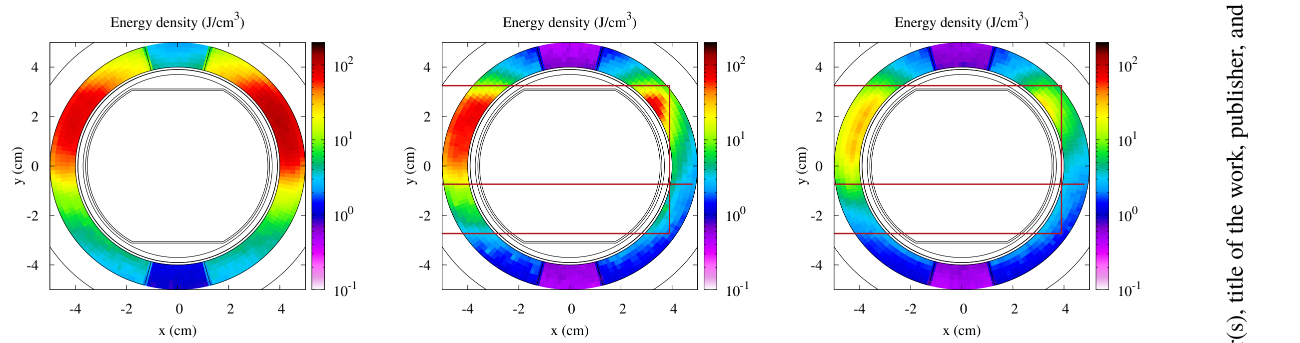

Figure 1: Transverse energy density profile in D1 coils due to secondary particle showers leaking from the TDI. Results correspond to an injection failure where 288 bunches with an intensity of 2.3×10^{11} impact on the TDI close to the absorber block edge. The three figures derive from simulations without (left) and with TCDD (center), as well as from simulations which include in addition a realistic description of the vacuum layout between TCDD and D1 (right). The red lines represent a geometrical projection of the TCDD and TDI opening on the D1 front face.

circulating beam is kicked with ~10% of the nominal MKI strength (impact on the lower jaw). This may happen during an MKI main switch erratic or a kicker magnet breakdown. A few instances of such failure cases have been observed in 2011 and 2012, leading to the quench of several superconducting magnets due to particle showers escaping the TDI and TCDD [4].

EFFICACY OF THE EXISTING PROTECTION SYSTEM

The jaws of the TDIs presently installed in the LHC are 4.185 m long and accommodate blocks of hexagonal boron nitride (18×15.7 cm), aluminium (1×60 cm) and copper (1×70 cm). The two latter blocks are retracted by 2 mm with respect to the boron nitride in order to avoid direct beam impact on these materials which could lead to an extensive heating of these blocks. The TCDD, which is located 7 m downstream of the TDI, is made of copper and has a length of 1 m. It has a rectangular opening (70×42 mm^2), which is smaller than the inner diameter of the D1 coils (80 mm). The drift space between the TCDD and the D1 front face amounts to almost 3 m and is occupied by room temperature vacuum equipment (valves, pumps etc.), a beam position monitor, as well as a 50 cm long cold-to-warm transition inside the magnet cryostat which connects the magnet cryo-assembly to the room temperature vacuum system.

In order to determine if the efficacy of the present TDI and TCDD needs to be improved for the HL-LHC era, FLUKA [5, 6] shower calculations were carried out based on a realistic simulation model of the injection region. The simulations extend previous studies reported in Ref. [4]. Fig. 1 shows the transverse energy density in D1 coils for one of the worst failure scenarios expected during LHC injection, i.e. where 288 bunches impact close to the absorber block edge of the TDI (1σ impact parameter). The transverse normalized emittance was assumed to be 1.37 μm·rad. Results are normalized to the nominal HL-LHC bunch intensity at SPS extraction (2.3×10^{11} protons). The displayed energy density profiles correspond to an accidental kick of the clock-wise rotating beam (injected in IR2), but are comparable for the other beam (IR8).

To determine the effectiveness of the TCDD and to evaluate the shielding effect of the vacuum equipment, simulation studies were carried out for a) a setup without TCDD, b) a setup with TCDD, and c) a setup which includes in addition a realistic description of the vacuum layout between TCDD and D1. As illustrated in Fig. 1, the mask provides an asymmetric protection of the D1 coils since it is centered around the machine axis while particle showers give rise to an asymmetric load on the D1 front face due to the horizontal beam separation. The simulation results also suggest that the vacuum chamber upstream of the D1 has a significant shielding effect since it absorbs grazing shower particles leaking through the mask. This is further illustrated in Fig. 2, which shows the longitudinal peak energy density profile in D1 coils for the three cases presented in Fig. 1. Without vacuum chambers, the simulations predict a maximum energy density of about 70 J/cm^3, while this reduces to about 30 J/cm^3 if the vacuum chambers are included in the simulation model.

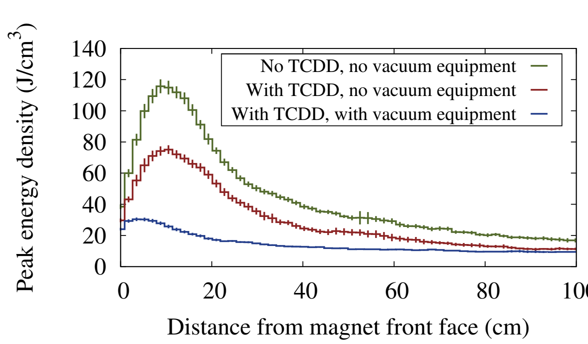

Figure 2: Longitudinal peak energy density profile in D1 coils. Only the first 100 cm of the magnet are shown. See also Fig. 1 for more details.

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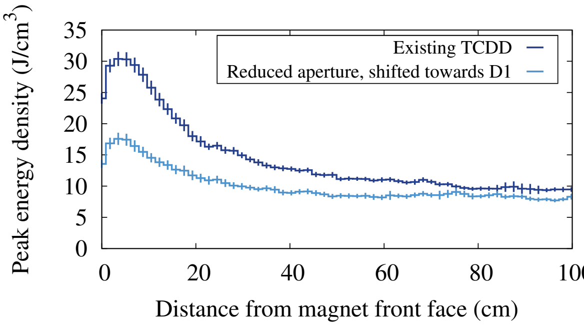

Figure 3: Effect of a modified and displaced TCDD on the peak energy density in D1 coils. The opening was reduced from 70×44 mm^2 to 55×42 mm^2, and the TCDD was moved by 50 cm towards the D1. Same injection failure scenario as in Figs. 1 and 2 is assumed.

During the design phase of the present TDI and TCDD [7, 8], the damage limit of D1 coils in case of fast beam losses was assumed to be 87 J/cm^3 [9]. This value is however currently being revised [10]. Considering the present understanding of the damage limit and accounting for a suitable safety margin (factor 3) due to inevitable approximations in the simulation model, it can presently not be excluded that the damage limit is exceeded for a failure case as the one described above. Conceptual design studies how to improve the existing system for the HL-LHC era are presented in the following section. The present design goal is to reduce the peak energy density in the D1 coils by a factor two.

CONCEPTUAL DESIGN STUDIES FOR THE HL-LHC

By increasing the TDI length, one can only achieve a limited gain in protecting the D1 in case any mis-steered beam grazes along the TDI jaws. For such failure scenarios, a sufficient reduction of the energy deposition in the D1 can only be ensured by improving the shielding of secondary showers leaking from the TDI. Two alternative concepts have been studied which are described in this section. One is based on a redesign of the existing TCDD, while the other one relies on a complementary mask inside the D1 cryostat.

Modification and Displacement of the TCDD

The effectiveness of the TCDD in shielding shower particles can only be sufficiently improved if a) its opening is reduced and b) it is moved closer to the D1. Owing to the stringent aperture requirements for the circulating beams the mask dimensions can only be reduced by a few millimeters on each side. The minimum acceptable dimensions differ between IR2 and IR8 due to different crossing and separation schemes. The maximum distance the TCDD can be moved towards the D1 is about 50 cm and requires the displacement of a beam position monitor. Fig. 3 illustrates the reduction of the energy deposition in the D1 coils if the TCDD has a 15 mm smaller horizontal opening and is located 50 cm closer to the magnet. With these modifications, the maximum energy density decreases by more than 40%.

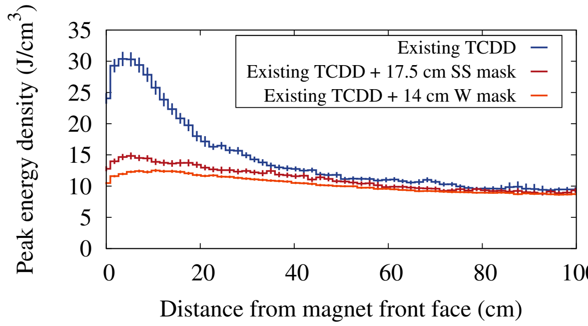

Figure 4: Effect of a complementary stainless steel or tungsten mask on the peak energy density in D1 coils. Same injection failure scenario as in Figs. 1 and 2 is assumed.

Complementary Mask Inside D1 Cryostat

As an alternative solution, we studied the option of complementing the existing TCDD with another mask-like protection element inside the insulation vacuum of the D1 cryostat. This solution offers the advantage of intercepting shower particles closer to the magnet and would not affect the present machine aperture. Made of a heavy material to optimize its protection efficiency (e.g. tungsten or steel), such a mask could be placed upstream of the cold mass end-cap, tightly enclosing the cold bore which protrudes from the D1 cold mass assembly. A radial thickness of 1 cm would be sufficient to effectively shield the coil cross section. The length of this mask could be between 14 cm and 17.5 cm depending on the detailed integration [11]. Figure 4 demonstrates the effect of a 17.5 cm long steel mask and a 14 cm long tungsten mask placed inside the cryostat. As can be seen in the Figure, either mask reduces the peak energy density by a factor two or more compared to the existing protection layout.

SUMMARY AND CONCLUSIONS

This paper evaluated the efficacy of existing LHC injection protection devices (TDI and TCDD) and presented conceptual design studies for the HL-LHC upgrade. In particular, it was shown how the shielding of secondary showers impacting on the downstream superconducting separation dipole can be improved. The two solutions proposed in this paper both have the potential to meet the presently assumed design goal, which not only reflects the present knowledge of the coil damage limit, but also includes an adequate safety margin due to simulation uncertainties.

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