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INJECTION PROTECTION UPGRADE FOR THE HL-LHC

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Abstract

The injector complex of the LHC is undergoing important changes in the light of the LIU project to provide brighter beams to the LHC. For this reason and as part of the High Luminosity LHC project the injection protection system of the LHC will be upgraded in the Long Shutdown 2 (2018 - 2019) to be able to protect downstream elements against injection failures with the high brightness, high intensity HL-LHC beams. The upgraded LHC injection protection system will consist of a segmented injection protection absorber TDIS and auxiliary collimators and masks. The layout modifications are described, and the machine element protection and absorber jaw robustness studies are presented for the new systems.

INTRODUCTION

The injection protection system of the LHC is being upgraded as part of the HL-LHC project [1]. The upgrade of the injector complex to prepare the higher intensity proton beam for the HL-LHC is taking place under the LIU project [2] and is foreseen to be finished in the LHC Long Shutdown 2 (2018 – 2019). This means that also the upgrade of the injection protection system as described in this paper should be finished by 2019.

The LHC injection protection system consists of a number of absorbers, part of them movable, to intercept the beam in case of failures of the LHC injection kicker magnets. The different elements are described in [3]. The different kicker failure modes and the TCDD absorber protecting the D1 separation dipole are described in [4].

INJECTION ABSORBER TDIS

Absorber Material Considerations

The injection absorber TDIS is the primary protection of the LHC against injection failures and must be able to withstand the impact of a full injection train consisting of 288 bunches in the case of injection kicker (MKI) failures [3]. Different candidate materials for the absorber blocks are presently being considered, including different grades of boron nitride, graphite and carbon-reinforced-carbon, all having a low density, a low coefficient of thermal expansion, a high strength and a low Young's modulus. Graphite R4550 (SGL) is so far the preferred candidate, as is it seems to be a good compromise in terms of availability of shapes, machinability, costs and performance.

To study the energy deposition and stress wave propagation in the absorber blocks during beam impact, simulation studies based on FLUKA [5, 6] and ANSYS [7] were carried out. Table 1 shows the obtained Mohr-Coulomb Safety factor for Graphite R4550 for different HL-LHC beam parameters. The results correspond to the worst case scenario, where 288 bunches impact close to the jaw edge. The Mohr-Coulomb Safety factor, which is explained in detail in [3], must be greater than 1 in order to guarantee the absorber survival. As can be seen in the table, this is just the case for Standard HL-LHC beam parameters, while in the case of the smaller BCMS type beams and a bunch intensity of 2.0e11 protons, the number of injected bunches will need to be reduced to 240 bunches per injection.

It should be noted that the material limits used for this analysis are rather conservative. Currently a test bench is under preparation to expose blocks of the above candidate materials to proton beams with equivalent brightness in order to observe their behaviour (HiRadMat experiment to be carried out at CERN in 2016).

Table 1: HL-LHC Beam Parameters at Injection with Resulting Mohr-Coulomb (MC) Safety Factor for TDIS Jaw Made of Graphite R4550

Beam	Emit, x,y [μm]	Nb [p/bunch]	# bunches	MC Safety Factor
Standard	2.0	2.3e11	288	1.01
BCMS	1.3	2.0e11	288	0.90
BCMS	1.3	2.0e11	240	1.43

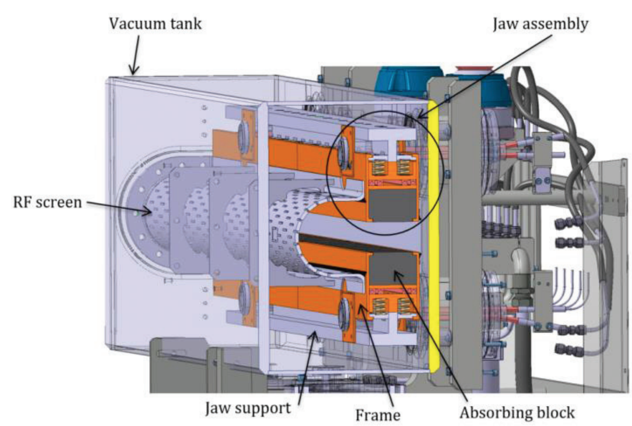

Figure 1: Preliminary design of one TDIS module.

Design Considerations

The preliminary TDIS design consists of three modules of equal length, containing different absorber materials. The first two modules consist of low-Z absorber blocks for which the above mentioned Graphite R4550 is assumed. The third module consists of higher Z materials.

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Candidate materials are aluminium and copper alloys. Figure 1 shows the present design of one module.

Table 2 summarises the transverse dimensions of absorber blocks and specifies the length of a single module with and without tapering. The transverse dimensions of the absorber blocks depend on temperature and stresses in the frame, for which further numerical simulations are needed. The dimensions of the tapering, to be applied on either side, depend on further impedance calculations, as mentioned below. The required flatness of a single module is 100 μm, including any possible deformation due to beam induced heating.

Table 2: Dimensions of TDIS Absorber

Parameter	Value	
Absorber block height	54	mm
Absorber block width	58	mm
Active absorber length	1500	mm
Tapering length	100	mm
Tapering angle	10	°
Total absorber length	1700	mm

Considering the operation of the nearby ALICE ZDC detectors, the jaws should be able to retract up to 55 mm from the beam axis. Conversely, for alignment and calibration of the equipment, each jaw must be able to move up to 5 mm beyond the beam axis. The horizontal aperture required for the spectator protons of the ZDC detector, should be greater than 138 mm.

The jaw movement should be able to move in steps as small as 10 μm, with a positioning repeatability of 20 μm. The maximum applicable jaw angle is 5 mrad, which will allow the alignment of the TDIS with beam. An electronic control system will not allow tilting the jaw at a greater angle.

The accuracy of the jaw position with respect to the TDIS tank must be better than ±25 μm. Likewise, the alignment accuracy of the TDIS tank with respect to the machine axis is required to be better than ±100 μm.

Impedance Considerations

The two TDIs presently installed in the LHC were measured to significantly contribute to both longitudinal and transverse LHC impedances before Run 1 [8, 9]. In addition, beam induced heating was observed during run 1, causing high vacuum pressures that affected the background of the experiments and is also believed to have caused beam screen damage during Run 1 when the jaws were not fully retracted after injection [10].

As a consequence, special care needs to be taken in the design stage to minimize these impedance related issues for the higher intensities planned for Run 3 and HL-LHC operation. Optimizing the impedance requires reducing both geometric and resistive contributions at both injection and top energy gaps. At constant gap, the resistive contribution can be reduced by increasing the conductivity of the absorber materials and minimised by applying an additional metallic coating (e.g. copper). With the constraints linked to the need for clearance between and around the segmented absorber blocks, the low impedance solutions used for the primary collimators cannot be readily used. However, with respect to the current TDI design, simulations predict that a significant reduction of the resonant modes could be obtained by closing the gap around the absorber blocks with RF fingers. Among other detailed studies, the optimal length between the absorber blocks and optimal tapers are being studied in detail to guide the design towards the best compromise for the performance of the LHC.

AUXILARY ABSORBERS TCLIA/B

The auxiliary absorbers TCLIA and TCLIB are placed ± 20° in betatron phase from the TDIS to protect the machine aperture from miskicked beam escaping the TDIS. In order to estimate the behaviour of these elements in case of unavoidable injection kicker (MKI) failures [4], a series of simulations has been carried out: MADX error studies to define worst cases followed by particle tracking studies which in turn provided input for FLUKA calculations of the energy deposition in the absorber elements and downstream superconducting magnets. All the simulations have been performed for the HL-LHC BCMS beam parameters.

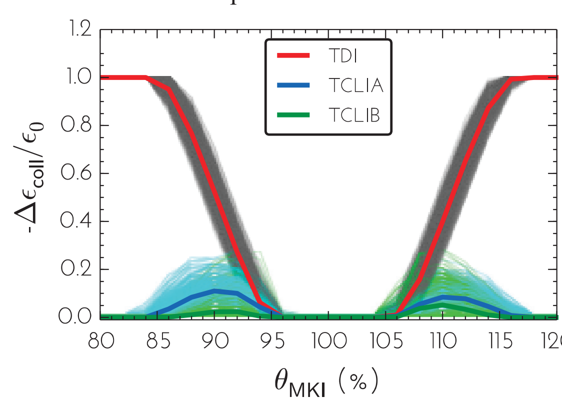

Figure 2: Single particle 5σ emittance cut at the three injection protection devices as function of MKI kick for 500 different machine configurations. The solid thick lines represent the average value for the different machine configurations.

MADX Error Studies

The first set of simulations was performed using MADX. The aim was to evaluate the effect of the machine imperfections [11] to the single particle emittance cut as function of MKI errors [4]. The results, for Beam 1, are shown in Fig. 2. The maximum emittance cut recorded for TCLIA and TCLIB was about 25%. The worst cases for both TCLIA and B were identified and used to quantify the maximum expected load onto these absorbers. The same Monte Carlo simulation was repeated for Beam 2. As expected, the results were very similar.

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Particle Tracking Studies

This first estimate was translated into actual particle losses by performing particle tracking of the injection in the LHC for given worst case MKI failures. MADX-PTC combined with the Pycollimate scattering routine [12] was used to perform such a tracking. The simulated loss map for the worst case, in terms of particles losses at the TCLIB, is shown in Fig. 3.

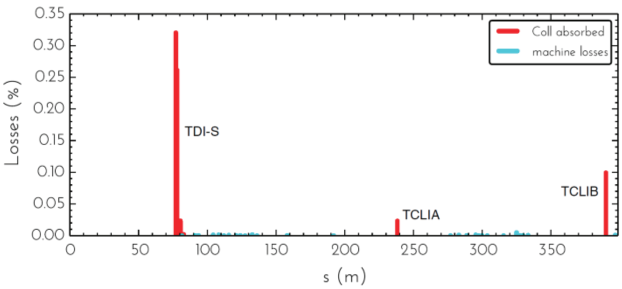

Figure 3: Simulated loss map of Beam 1 in case of MKI kick error of ~11% (grazing impact on TDI in case of ideal machine) considering the machine configuration where the highest losses were seen on the TCLIB.

Energy Density in D2

The results of the tracking simulations mentioned above have been use to estimate the impact of the beam on the TCLIA/B and the secondary showers on the superconducting machine elements.

The TCLIA is made of Graphite R4550 (1.8 g/cm^3) and has an active jaw length of 1 m. The superconducting D2 separation dipole is placed 47.25 m downstream of TCLIA and is shielded by the latter from direct primary proton impact in case of events related to injection kicker failures. The long distance between TCLIA and D2 implicitly offers some protection by diluting the shower. Figure 4 shows the longitudinal energy density in D2 coils for the case where maximum impact of protons on TCLIA is predicted by the tracking studies.

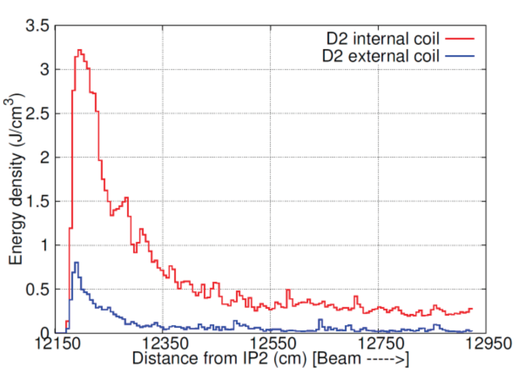

Figure 4: Longitudinal peak energy density in D2 coils.

The maximum energy density is just above 3 J/cm^3 in the internal side of the coil. Given that the damage limit is at least a few tens of J/cm^3, the risk of the D2 being damaged during injection kicker failures is not seen as significant.

Energy Density in Q6 and Q7

TCLIB and TCLIM are the elements designed to protect the Q6 and Q7 superconducting quadrupoles. The TCLIB is 1 m long and made of carbon-reinforced-carbon (AC150, 1.67 g/cm^3) while the TCLIM is 1 m long and made of stainless steel (SS304L). Figure 5 shows longitudinal peak energy density in the inner coils of Q6/7 for the case where maximum impact of protons on TCLIB is predicted by the tracking studies. Note that in Fig. 5 the direction of the beam is reversed in comparison to the previous figure.

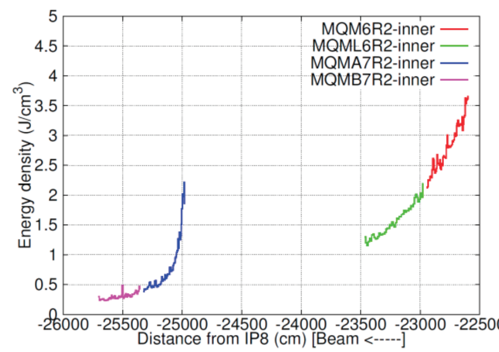

Figure 5: Longitudinal peak energy density in the inner coils of the quadrupoles Q6 and Q7.

The maximum energy density is about 3.5 J/cm3 in the inner coil of the quadrupole magnets. The elements downstream of the Q6/7 score comparatively lower energy densities. Like before, the magnets are not expected to be damaged in case of injection kicker failures. The results presented here are still preliminary but suggest that the present injection protection collimators TCLIA, TCLIB and the mask are efficient enough to protect the magnets from damaging. However, a quench cannot be excluded in any of the cases.

CONCLUSIONS

The design and impedance considerations of the new TDIS absorber are presented. The choice of absorber material is challenging for the small BCMS type beams.

Particle tracking results for worst injection kicker failure scenarios combined with FLUKA simulations show that the existing auxiliary injection protection collimators TCLIA/B will also properly protect the downstream superconducting elements for HL-LHC beam parameters and do not need to be replaced.

The FLUKA simulations of the beam impact on the TCLIA and TCLIB show that there is no concern for the jaw survival of these absorbers in the case of the expected worst case beam impact on these elements.

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