THE NEW HL-LHC INJECTION AND TRANSPORT PROTECTION SYSTEM

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Abstract

The High-Luminosity LHC (HL-LHC) upgrade represents a challenge for the full chain of its injectors. The aim is to provide beams with a brightness a factor of two higher than the present maximum achieved. The 450 GeV beams injected into the LHC are directly provided by the Super Proton Synchrotron (SPS) via two transfer lines (TL), TI2 and TI8. Such transfer lines are both equipped with a passive protection system to protect the LHC aperture against ultra-fast failures of the extraction and transport systems. In the LHC instead, the injection protection system protects the cold apertures against possible failures of the injection kicker, MKI. Due to the increase of the beam brightness, these passive systems need to be upgraded. In this paper, the foreseen and ongoing modifications of the LHC injection protection system and the TL collimators are presented. Simulations of the protection guaranteed by the new systems in case of failures are described, together with benchmark with measurements for the current systems.

INTRODUCTION

The high brightness of the HL-LHC beams represent an unprecedented challenge for the full set of the passive protection devices of the LHC injection and transport system. An upgrade of the main injection absorber, TDI, is foreseen in order to maintain the necessary protection of the LHC cold aperture. Also, the SPS-to-LHC transfer line collimators will be replaced with more suitable devices for the aimed beam brightness.

The LHC injection system is composed by: injection septum MSI, injection kicker MKI, injection dump TDI and two auxiliary absorbers TCLIA and TCLIB; all acting on the vertical plane. The HL-LHC injection system will not be too different from the present one. The main modification is represented by the new TDI, i.e. the segmented TDI (TDI-S).

The TDI-S will be composed by three separated blocks: the first two blocks will be 1.425 m, made of Graphite (R4550 or similar), the last one instead will be made of higher Z material (60 cm of Aluminium and 70 cm of Copper). Every block will be separated from each other by 125 cm and the last block is also 2 mm further away from the circulating beam than the others to avoid direct impact of the beam. This is the design baseline at the moment of writing this paper.

Among the other modifications, it is worth to mention also the slightly different crossing and separation schemes as well as the upgrade of the transfer line collimators (TCDI). The TCDIs upgrade represents a key upgrade because the aperture of the LHC (especially the horizontal one) during the transport from the SPS is directly protected only by these collimators. They are designed to protect the LHC and the MSI from any kind of failures of the SPS extraction and TL elements.

The protection against fast losses relies on prompt detection of the change in field of the magnet under observation. The MSI (its time constant is about 1 s) is constantly monitored from different systems (Fast Extraction Interlock and Fast Magnet Current Monitor), which guarantee an adequate protection and redundancy. For ultrafast failures of the SPS extraction kickers, the TCDIs represent the last resort to protect the MSI and the LHC arc aperture.

In case of ultrafast failure of the LHC injection kicker instead, the LHC (HL-LHC) injection protection devices are the one responsible to for the protection of the vertical LHC aperture. The TDI (TDI-S) is the main protection against MKI failures - it is installed about 90° vertical phase-advance from the MKI to maximise the protection guaranteed. The TCLIA and TCLIB protect against possible phase-advance errors between MKI and TDI; they are placed at $\Delta\mu_y \approx 180° + 20°$ and $\Delta\mu_y \approx 360° - 20°$ from the TDI respectively.

In this paper the following notation will be used:

$$\sigma_{LHC} \equiv \sqrt{\beta(s)\ 3.5\,\mathrm{mm\,mrad}/(\beta\gamma)} \quad (1)$$

$$\sigma_{HLLHC} \equiv \sqrt{\beta(s)\ 2.5\,\mathrm{mm\,mrad}/(\beta\gamma)}, \quad (2)$$

where $\beta(s)$ is the beta-function at an s location and $(\beta\gamma)$ is the product of the relativistic factors.

TRANSFER LINE COLLIMATORS

The main aim of the TL collimators is to ensure adequate protection of the LHC cold apertures. From the LHC Design Report [1], the minimum available aperture in the arc is $7\,\sigma_{LHC}$, hence this represents the target protection for the TL collimation system.

In order to define the collimator jaws aperture needed to guarantee the above cited protection, all possible sources of error have to be taken into account. All the considered errors are listed in Table 1; summing these contributions linearly, considering a typical beam size of 0.5 mm, the total error is $\approx 1.4\,\sigma_{LHC}$ [2]. The maximum escaping amplitude in a "three-phase" collimation system is given by pure geometrical considerations, i.e. $A_{max} = A_{jaw}/\cos(\pi/6)$; where A_{jaw} is the required jaw position, including errors. For the

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LHC $A_{max} = 7\,\sigma_{LHC}$, so the collimator half-gap should be $A_{jaw} = 4.5\,\sigma_{LHC}$. Due to the very conservative tolerances used in the definition of the LHC minimum aperture, the TL collimators have been operated at 5 σ during LHC Run 2. In view of the HL-LHC upgrade, such collimators will be updated in order to guarantee the required protection of the LHC arc aperture. As detailed described in [3], their active length will be increased to deal with the higher brightness. As a consequence, some of them had to be moved from their current location and hence a optics rematch was done to maintain $\beta_x \times \beta_y > 3600\,\mathrm{m}^2$, that is the brightness limitation. The phase-space coverage is unchanged, even if some mechanical tolerances are increased due to the longer jaws.

Table 1: Errors for the TL Collimator Jaws [2].

Error type	**Unit**	**Value**
Inter-jaw parallelism	μm	50
Jaw axis wrt tank	μm	100
Tank axis wrt beam size	μm	180
Surface flatness	μm	100
Knowledge of bema position	μm	44
Beam size errors	σ	0.5

MKI FAILURE MODE ANALYSIS

The beam coming from the SPS through the two transfer lines is horizontally deflected by the injection septum and vertically by the injection kicker, MKI. Once the injected beam trajectory is equal to the vertical closed orbit at the kicker longitudinal location, $y_{inj}(s_{MKI}) = y_{CO}(s_{MKI})$, the MKI provides the necessary deflection, $\theta_{MKI} \approx 850\,\mu\mathrm{rad}$, to adjust the beam vertical transverse momentum.

The injection kicker is composed by four tanks per ring. To provide the required deflection, a total integrated field of 1.2 T m is needed. Such dipole field is required for a maximum of about 8 µs, which is the maximum possible beam length for LHC injection. Due to the LHC box stacking injection, the rise and fall time of the MKI magnetic field has to be very short, 0.9 µs and 3.0 µs respectively.The reason of such tight requirements on fall and rise time is because this defines the minimum possible space between LHC batches and hence the maximum number of bunches usable for LHC physics. To preserve the beam emittance during the injection process, the MKI flat top ripples amplitude must be below ±0.5 % the nominal field [1].

Each MKI tank is equipped with its own Pulse-Forming Network (PFN). Two resonant charging power supply (RCPS) per system are used to charge the PFNs and a main and dump switch are required at both ends of the PFN to be able to control the pulse duration. To satisfy the challenging requirements, a well matched high bandwidth system is required. This is achieved with a multi-cell PFN and a multi-cell travelling wave kicker magnet, both connected via a transmission line terminated by a matched resistor [4].

Assuming that the beam energy tracking system (BETS) and the re-triggering system always work, and that the MKI pulse length is 8.2 µs, in case of failure only a limited number of bunches can escape the injection region with a dangerous amplitude. This is true only for the following possible MKI failures: charging failure, erratic triggering of the kickers, missing triggering of one switch and timing error.

As a consequence of these failures, the circulating or the injected beam could be swept on the TDI front-face or completely dumped onto the TDI. This could happen any time during the PFN charging process, hence the resulting MKI waveform could have a shorter flat-top (4.1 µs) at any field value up to the maximum. This yields to a maximum of 186 bunches (considering 225 ns batch spacing) that can be deflected at any angle. The flashover inside a magnet needs also to be included among the possible failures. Depending on the longitudinal location of the breakdown, the field seen by the beam can be reduced or amplified. This can affect the whole injected beam (maximum of 288 bunches for 25 ns operation) as well as the circulating one. A short circuit is created and the pulse is reflected - if this happens right at the beginning of the magnet, the current in that magnet will be zero; if it happens at the end instead, the current is doubled and so the field. In case of flashover in more than one magnet simultaneously, the system can provide up to a maximum of twice the design field, 200 %. For both circulating and injected beam, a kick of about 20 % the nominal one corresponds to an impact parameter on the TDI larger than 5 σ.

TRACKING STUDIES OF THE MOST CRITICAL MKI FAILURE FOR HL-LHC INJECTION SYSTEM

A flashover into the MKI magnets can translate in an alteration of the MKI nominal kick, between 0 and 125 %, depending on its longitudinal position. Due to the nature of the LHC box stacking injection, the MKI is ready to kick an upcoming injected SPS batch while another is already circulating in the machine. In case of asynchronous triggering of the MKI, the circulating beam can be deflected by 0 to 0.85 mrad. Of course any combination of the just described failures has a non-zero probability, although very small, hence they are considered beyond design.

In these possible failures, the interesting part for machine protection is represented by the range of kicks $[-20, 20]$%. Above these, the impact parameter on to the TDI is above $5\,\sigma_{LHC}$ and hence almost the whole beam will be lost directly there. This situation can be seen equivalently for the injected and for the circulating beam, where these range of kicks can be originated by a flashover in the MKI at particular longitudinal position. In this range, the scenario that leads to the highest number of particle with the biggest amplitude is represented by the grazing impact on the TDI (i.e. when $y(s_{TDI}) = 8.1\,\sigma_{HLLHC}$). This is the case because the

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TDI-S, due to its design, let only the 0.2 % of the particles that hit it survive, hence this scenario maximises the particles at high amplitudes. The highest number of bunches that can be deflected coherently is 288.

In order to evaluate the maximum amplitude with intensity above the safe beam flag, the survival function S:

$$S(x) \equiv 1 - F(x) = \int_x^\infty f(t)dt \qquad (3)$$

normalised to the beam intensity (6.62×10^{13} p$^+$)) of the tracked particles, in the cases of the above described failures, has been calculated at the exit of the injection protection system.

The amplitude at the exit of the injection system is calculated taking into account also angles (normalising the vertical action to the betatron beam size), that is:

$$Y = \sqrt{y^2 + (\beta_y y' + \alpha_y y)^2}. \qquad (4)$$

When $S(Y) = 5 \times 10^{11}$ p$^+$, represents the maximum amplitude above the safe beam flag. To be noticed, this is a quite pessimistic way of assessing the minimum protected aperture because the implicit assumption made is that all particles with a larger normalized amplitude will be lost at exactly the same longitudinal location.

The simulations of MKI failures, as just described, have been carried out for both B1 and B2 and for different protection device configurations : i) nominal settings, i.e. TDI-S, TCLIA and TCLIB at 8.0 σ_{HLLHC} half-gap; ii) TDI-S at 9.2 σ_{HLLHC} and TCLIA/B at 8.0 σ_{HLLHC}; iii) TDI-S and TCLIs at 9.2 σ_{HLLHC}; iv) TDI-S with maximum error, 2.5 σ_{HLLHC}, and nominal settings for TCLIs; v) injection protection maximum error, i.e. all injection protection devices misaligned of 2.5 σ_{HLLHC}. The maximum error on the injection protection devices takes into account injection precision delivery [5], local orbit, optics discrepancy with the nominal during setting-up and mechanical errors (Table 2). Other possible optics errors that could lead to a beta-beat of maximum 10 % [6], translates in a phase-advance error between the MKI and the TDI smaller than 10°, hence they can be neglected because of the design strategy of the injection protection system. The error on the local orbit is assumed to be maximum 1.1 σ_{HLLHC} due to the two sided collimator nature of the injection protection devices. A bigger error will translate in high losses and a consecutive trigger of the dump. The errors assumed to check the protection guaranteed by the LHC injection protection system have been added linearly and took the most extreme cases in order to be as conservative as possible.

The simulations are done for a 450 GeV beam with normalized emittance of $\epsilon^N_{x,y} = 1.37\,\pi$ mm mrad. The tracking inside active accelerator elements is performed with MAD-X and instead the tracking inside the collimator jaws is done with `pycollimate`. The simulated loss patterns for the three different protection device configurations are shown in Fig. 1 for B1 as example. The losses distribution for B2 is equivalent. It is interesting to highlight the evolution of the losses in IR7 as function of the injection protection elements settings - the losses increase by about an order of magnitude for only 1.2 σ_{HLLHC} error at the TDI. Evaluating then the survival function at the exit of the injection protection system (Fig. 2), the worst case is represented by the scenario with all protection devices misaligned by 2.5 σ_{HLLHC} for B2. This gives the maximum amplitude of the halo with intensity equal to the setup beam flag, that is 10.3 σ_{HLLHC}, hence the maximum dangerous amplitude of the halo originated by SPS extraction, transport and injection process shall be considered to be 10.3 σ_{HLLHC}, which corresponds to 8.7 σ_{LHC}. These studies, and their implication, are discussed in details in [6].

Figure 1: Losses distribution on the HL-LHC elements in case of failure of the MKI for three different protection devices configurations. Left, for Beam 1 and right for Beam 2.

Table 2: Maximum errors, at the TDI and TCLIs, assumed to evaluate the amplitude of the halo escaping the injection protection system, calculated assuming an emittance of 2.5 mm mrad.

Parameter set	**Value** ($\sigma_{\mathbf{HLLHC}}$)
Injection precision	0.35
Mechanical tolerances	0.35
Setting-up optics	0.71
Local orbit	1.1
Total	2.5

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Figure 2: Survival function of the tracked particle distribution at the exit of the HL-LHC injection protection system for B1 (Top) and B2 (Bottom) for the cases: i, iv and v.

EXPERIMENTAL DATA FROM THE PRESENT LHC INJECTION PROTECTION SYSTEM

In order to benchmark the simulations presented in this paper, experimental data have been taken on the present LHC injection protection system. The aim of these measurements was to validate with beam the chosen settings of the TDI. All injection protection devices were set to 6.8 σ_{LHC} and centred around the established machine closed-orbit. Pilot beams (one bunch of $\approx 1 \times 10^{10}$ protons) are then injected and sent directly to the dump without completing a full revolution. Two superconductive correctors, positioned between the MSI and the TDI, are used to steer the beam on to the TDI, simulating an MKI kick. Such correctors are set in a way that there is a direct control of the beam displacement at the TDI. Varying the corrector strengths and recording losses at the TDI, TCLIA and TCLIB, the actual aperture of the TDI can be retrieved. In Fig. 4, the measurements taken during Run 2 commissioning are plotted (blue dots). Here the closest BLM, and with the longest integration time, at each protection device was used. Their readings were normalised by the extracted intensity from the SPS. The losses trend, at the TCLIA and TCLIB, is reverted between 6.5 and 7 σ_{LHC} (half nominal sigma was the resolution of the measurements), confirming the theoretical half-gap of the TDI of 6.8 σ_{LHC}.

Figure 3: (Top) Measured normalised losses at the TDI in IP2 (red dots) as function of the theoretical beam displacement the the TDI. The solid blue line is a least square fit of the measurement point with a double Gaussian CDF. (Bottom) Reconstructed vertical beam profile distribution (for B1 and B2) with the data shown in Fig. 4 at the IP1. These are compared with the ideal Gaussian distribution (red) at the same location.

From these data, the beam profile at the TDI can be also inferred. At the time of the measurements, the beam was not scraped in the SPS. As suggested in literature [7], the beam delivered in this way to the LHC is more likely to have a double Gaussian profile than being normally distributed. In fact, the TDI BLM data can be fitted with the function (Fig.3–top):

$$f(x) = c_1(1 - c_2)\mathcal{N}[\mu_0, \sigma_1](x) + c_2 c_1 \mathcal{N}[\mu_0, \sigma_2](x), \quad (5)$$

where the same average, μ_0, is used for both Gaussian distributions due to the assumption of symmetric beam; c_1 and c_2 are scaling factors and σ_1, σ_2 the standard deviations of the two Gaussian distributions. The same procedure was repeated for both B1 and B2. The resulting distribution is plotted in Fig. 3–bottom and compared with the ideal Gaussian distribution at the chosen location. The observable difference between the fit results for B1 and B2 is thought to be originated from the impossibility to measure losses with high impact parameter in IP8 (B2). This was due the interlock triggering at the experiments and the consequent interruption of commissioning procedure.

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Figure 4: Comparison of measurements (blue dots) and simulations (dashed lines) of losses induced by different MKI kick at the three injection collimators. In red are plotted the results from particle tracking starting with a Gaussian transversally distributed beam, in green the same tracking has been performed but using the beam vertical profile obtained from Fig. 3.

To be able to compare simulations and measurements, a conversion from proton undergone inelastic scattering in the collimators and BLM signal has to be done. Previous studies [8] show the complexity in obtain reliable calibration factors for the injection collimator BLM data, hence the comparison done is based on the ratio among different BLMs. The proximity of the protection devices to each other makes the losses at the previous device interfere with the readings of the following one via particle shower development. In Fig. 4, the measurements form 2016 commissioning have been compared with two beam configurations: ideal Gaussian (red dashed line) and double Gaussian (green dashed line) distributed beam. As expected, the main difference between the types of transverse beam distribution is visible for small beam displacements at the TDI. At the TCLIA, the discrepancy with simulations reaches the maximum for $9\,\sigma_{LHC}$ deflection of about an order of magnitude. The main source of disagreement between BLM readings and simulations is originated from the fact that the simulations only account for primary and secondary protons lost at the different devices and not for any another kind of particles. Also, the simulations are done considering an ideal machine configuration, which is obviously not the case. The agreement at the TCLIB is smaller than a factor 2 overall. A better agreement could be achieved taking into account possible errors and particle shower developments, although for the propose of these studies this was not necessary. It can be concluded that the agreement between simulations and measurements is satisfactory, especially considering the uncertainty on beam position at the different devices and particle shower contribution.

CONCLUSIONS

Failures of the MKI are a serious machine protection concern. The increase in brightness will only translate in an increased danger if no countermeasures are put in place. The TDI upgrade will permit to properly protect the downstream elements (mainly the D1 and the triplet) and to survive a direct impact of the full SPS train.
A model for the HL-LHC injection system has been developed and possible failure cases studied in detail. An estimation of the maximum amplitude with intensity equal to the setup beam flag has been given.
A very good agreement between BLM readings and particle tracking has been shown. Due to the similarities with the model developed for HL-LHC and LHC, the prediction presented in this chapter for the new injection protection system can be considered validated.

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