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THE NEW TRANSFER LINE COLLIMATION SYSTEM FOR THE LHC HIGH LUMINOSITY ERA

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Abstract

A set of passive absorbers is located at the end of each of the 3 km long injection lines to protect the LHC in case of failures during the extraction process from the LHC's last pre-injector or in the beam transfer itself. In case of an erroneous extraction, the absorbers have to attenuate the beam to a safe level and be robust enough themselves to survive the impact. These requirements are difficult to fulfill with the very bright and intense beams produced by the LHC injectors for the high luminosity era. This paper revisits the requirements for the LHC transfer line collimation system and the adapted strategy to fulfill these for the LHC high luminosity era. A possible solution for the new transfer line collimation system is presented.

INTRODUCTION

The LHC is filled from the SPS via two 3 km long transfer lines, TI 8 and TI 2. The LHC injection energy is 450 GeV. The intensity of a full SPS nominal batch is more than an order of magnitude above the damage limit of accelerator components. The beam parameters for the nominal and ultimate LHC injection intensities are given in Table 1. A sophisticated machine protection system has therefore been put in place to protect the transfer lines and especially the LHC from damage in case of erroneous transfer.

Table 1: Number of protons per bunch, normalized transverse emittance and number of bunches per SPS batch for the LHC nominal and ultimate intensity.

	$p^+/bunch$	ϵ	$N_{bunches}$
Nominal	1.15×10^{11}	$3.5 \mu m$	288
Ultimate	1.7×10^{11}	$3.5\ \mu m$	288

The details of the different layers of the LHC injection protection system can be found in [1]. For the very fast failures and also as redundant protection system, a passive protection system in the form of transfer line collimators has been installed at the end of each transfer line. Their first priority is to protect the LHC. The second priority is to protect the transfer line aperture bottleneck in the vertical plane which is at the entrance of the LHC injection septum.

The LHC Transfer Line Collimation System

The LHC transfer line collimation system was designed according to the following criteria:

1. Generic passive protection system: provide full phase space coverage to protect against any failure from extraction or transfer upstream of the collimation system;
2. Attenuate the impacting intensity to a safe level for accelerator components. The safe intensity at 450 GeV is 2×10^{12} protons [2]. This corresponds to an attenuation of a factor of 20 from ultimate intensity;
3. Be robust enough to survive beam impact.

In the LHC transfer line collimation (TCDI) system the full phase space coverage is obtained via three collimators per plane each with left and right jaw, with 60 $+n \times 180$ phase advance between two neighboring collimators. For robustness reasons the jaws are made of graphite R4550 with a density of 1.83 g/cm^3. The required attenuation of a factor of 20 could be obtained by making each graphite collimator 1.2 m long. The collimators are complemented by 50 cm stainless steel masks in front of the entrance face of the downstream magnets to protect the magnet coils from secondary showers. A distance of a least 5 m had to be observed between the exit face of the collimator and the next magnetic element to reduce the heating from secondary particles.

During LHC run 1 the transfer line collimators were in beam for all injections with high intensity. Their setting was $\pm 4.5\sigma$ to $\pm 5\sigma$ around the reference trajectory. In 2012, the last year of LHC run 1, the LHC was running with 50 ns bunch spacing (maximum 144 bunches from the SPS) and also 25 ns bunch spacing (maximum 288 bunches from the SPS). About 10^4 high intensity injections took place in 2012 alone. High intensity beam was never lost on the transfer line collimators throughout LHC run 1.

TRANSFER LINE COLLIMATION REQUIREMENTS FOR LIU BEAM PARAMETERS

The TCDIs have been designed to attenuate and be robust enough for ultimate intensity. After the high luminosity upgrade the LHC will require beams from injectors with a brightness much increased with respect to the nominal or even ultimate LHC intensities.These parameters will only be achievable after substantial upgrades in the LHC injectors themselves [3]. The beam characteristics after the LHC Injector Upgrade (LIU) which are relevant for the discussion in this paper are summarized in Table 2.

As can be seen from Table 2, not only the bunch intensity will be much increased but also the transverse emittance will be significantly reduced. As the damage potential of the beam depends on the number of protons per unit area,

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Table 2: LIU beam parameters in the SPS at 450 GeV [3]. BCMS stands for the beam production scheme "Batch Compression, Bunch Merging and Splitting" .

	$p^+/bunch$	ε	$N_{bunches}$
Standard LIU	2.3×10^{11}	2.1 μm	288
BCMS	2.0×10^{11}	1.3 μm	288

intensity and emittance count. The most severe conditions for the transfer line collimators and attenuation requirements are presented by the BCMS beam. A full SPS BCMS batch has to be attenuated by a factor 70 to be below material damage limit, i.e. equation (1).

$$\frac{N_{afterTCDI}}{\varepsilon_{afterTCDI}} = \frac{1}{20} \times \frac{N_{ultimate}}{\varepsilon_{ultimate}} = \frac{1}{70} \times \frac{N_{BCMS}}{\varepsilon_{BCMS}} \quad (1)$$

For graphite this attenuation requirement at 450 GeV implies a collimator length of ~ 1.9 m instead of 1.2 m.

Thermo-mechanical simulations revealed another problem with the increased brightness of the LIU beams. Beam impact close to the surface of the graphite collimator, e.g. 1 σ impact parameter, causes stresses above the material strength. The generated stresses depend strongly on the beam size of the impacting beam. It was hence decided to not only look for locations with sufficient space to install 1.9 m long jaws, but also to modify the optics of the lines such that the beta functions at the entrance of the collimators fulfill the criterion $\beta_x \times \beta_y > 3500\,m^2$. A full redesign of the LHC transfer line collimation system was inevitable to deal with LIU beams.

The spot size criterion ensures that the maximum temperature reached with BCMS stays below 1500° C [4]. Optics changes in the lines in this range were still deemed feasible. As is however discussed in [4], the beam size increase is still not sufficient to safely conclude that the transfer line collimators would survive beam impact under all conditions. Different materials were studied. Graphite R4550 is still the best compromise. The limitation in material strength is mainly true for BCMS beams. Static simulations with ANSYS and also shock wave simulations suggest that graphite R4550 would survive for the LIU standard beam parameters. To get the full picture for BCMS beams, beam tests are required. Different material samples will be tested in the facility HiRadMat [5] with beam parameters as similar as possible to the LIU parameters.

FEASIBILITY OF LIU TCDIS IN TI 8 AND TI 2

The transfer line collimators have to be as close as possible to the LHC to cover the maximum of failure cases. They will thus be in the matching section where the transfer line optics is matched to the LHC injection point optics. The optics can therefore not be changed arbitrarily. Also for an active jaw length of 1.9 m, 2.5 m space have to be reserved to be able to foresee quick-plugin interconnect modules. This length would also allow to possibly design the new TCDIs with button BPMs if found necessary. In summary the transfer lines have to fulfill the following criteria to be equipped with the new TCDIs:

- 2.5 m free space per collimator
- 60° phase advance between two neighboring collimators in one plane
- 5 m distance from the collimator to the next magnetic element downstream
- all collimators as close as possible to the LHC
- $\beta_x \times \beta_y > 3500\,m^2$
- allow to match to LHC optics

The original TCDI locations in TI 2 already fulfill the above criteria. The collimator positions and beta functions are summarized in Table 3.

Table 3: Proposed exit locations of the TCDIs in TI 2 in the horizontal and vertical plane with their beta functions and the phase advance from the neighboring collimator.

TCDI	**s [m]**	β_x **[m]**	β_y **[m]**	$\Delta\mu$ [°]
TCDIH.29050	2972.2	82.1	87.0	0.0
TCDIH.29205	3016.1	45.4	95.4	58.6
TCDIH.29465	3099.7	45.0	245.9	58.7
TCDIV.29012	2953.2	232.2	23.6	0.0
TCDIV.29234	3029.7	83.3	57.0	59.0
TCDIV.29509	3108.2	48.9	230.1	58.4

Finding a solution for the more space constrained line TI 8 was a challenge. The criteria can be met with 4 additional power supplies to increase the number of individually powered quadrupoles at the end of TI 8. The collimator coordinates and beta functions are summarized in Table 4. One new horizontal collimator location and two new vertical ones had to be found. Integration into the existing transfer line layout with all its equipment has not been started yet. The maximum beta function in the horizontal plane is increased from currently ~ 230 m to ~ 290 m, Fig. 1 and the dispersion in the horizontal plane also increases towards the end of the line, Fig.2. Thus the aperture in the horizontal plane at the location with the beta function and dispersion peak is reduced (from 9 σ to 5.6 σ) but still sufficient.

The matching conditions at the LHC injection point are fulfilled.

ALTERNATIVE SOLUTION FOR TRANSFER LINE COLLIMATORS

Mainly due to the uncertainty on the robustness of the longer graphite jaws during LIU beam impact, also another solution for the transfer line collimators is studied. This

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Table 4: Proposed exit locations of the TCDIs in TI 8 in the horizontal and vertical plane with their beta functions and the phase advance from the neighboring collimator.

TCDI	s [m]	β_x [m]	β_y [m]	$\Delta\mu$ [°]
TCDIH.NEW1	2509.0	65.5	81.3	0.0
TCDIH.87904	2547.3	34.7	261.8	60.6
TCDIH.88121	2623.1	74.4	195.7	57.7
TCDIV.NEW1	2440.9	173.0	28.1	0.0
TCDIV.NEW2	2488.7	86.9	42.1	60.0
TCDIV.88123	2620.5	70.6	210.1	59.3

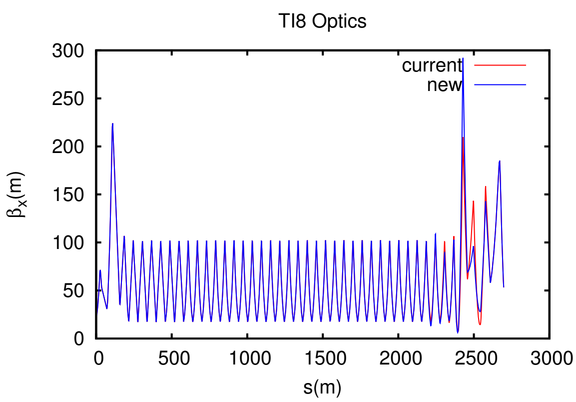

Figure 1: Horizontal beta function in TI 8 for current and LIU optics.

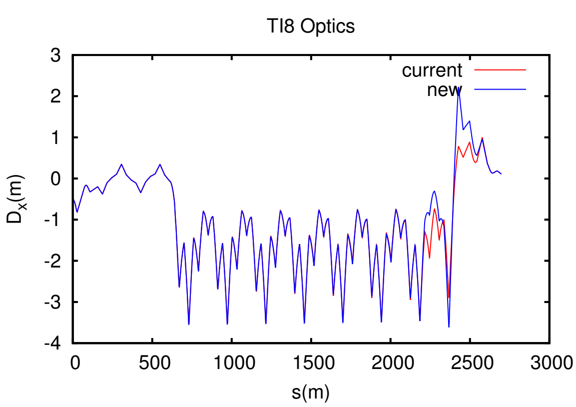

Figure 2: Horizontal dispersion function in TI 8 for current and LIU optics.

option consists of collimators made of a sandwich structure of two or three materials starting with high density graphite and ending with a material with slighter higher density e.g. Al300 (density = 3.76 g/cm^3). The jaws would be 1.2 m long, like the original TCDIs, and the attenuation with the higher Z materials would be a factor 70 according to requirements. These collimators would be intentionally sacrificial and would have to be replaced in case of beam impact. Full protection of the LHC would be guaranteed. No optics modification would be required and the current space allocation of the TCDIs would be adequate. The materials would have to be chosen such that the damage stays contained and surrounding equipment is not contaminated in case. In spite of the low probability of full beam impact on the TCDIs as demonstrated during LHC run 1, this option was chosen to only be a backup solution. Also to-date no suitable material to follow the high density graphite could be found that guarantees sufficient attenuation over a short distance and does not reach melting temperatures during impact [4].

CONCLUSION

The intensity injected into the LHC from the SPS at 450 GeV is more than an order of magnitude above the damage limit of accelerator equipment. Collimators are installed at the end of the transfer lines between the SPS and the LHC to protect the LHC in case of erroneous extractions. The graphite collimators provide full space coverage and attenuate the beam to a save level.

The LHC injectors will be upgraded in view of the requirements of the high luminosity LHC project. After the LHC injector upgrade (LIU) much brighter beams will be available. The LHC transfer line collimators will have to be upgraded as well to provide more attenuation. Collimator survival after LIU beam impact might be an issue even with graphite jaws.

The preferred solution consists of 1.9 m long graphite collimators with sufficiently large beam sizes in both dimensions at the collimator locations. For the transfer line TI 2 the space and optics requirements are already fulfilled with the current collimator locations. New locations however had to be found for TI 8. The optics requirements could only be fulfilled by adding 4 more individually powered quadrupoles.

A backup solution is also being studied. It consists of jaws made of a higher Z sandwich structure to fit into the original locations and length of the current transfer line collimators but fulfilling the attenuation requirement for LIU beams. These collimators would be sacrificial and would need exchange after high intensity beam impact.

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