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CHANGES TO THE TRANSFER LINE COLLIMATION SYSTEM FOR THE HIGH-LUMINOSITY LHC BEAMS

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Abstract

The current LHC transfer line collimation system will not be able to provide enough protection for the high brightness beams in the high-luminosity LHC era. The new collimation system will have to attenuate more and be more robust than its predecessor. The active jaw length of the new transfer line collimators will therefore be 2.1 m instead of currently 1.2 m. The transfer line optics will have to be adjusted for the new collimator locations and larger beta functions at the collimators for absorber robustness reasons. In this paper the new design of the transfer line collimation system will be presented with its implications on transfer line optics and powering, maintainability, protection of transfer line magnets in case of beam loss on a collimator and protection of the LHC aperture.

INTRODUCTION

The transfer line collimators in the SPS-to-LHC transfer lines have been designed to attenuate and be robust enough for ultimate LHC intensity at 450 GeV. 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 [1]. The beam characteristics after the LHC Injector Upgrade (LIU) and the LHC ultimate beam which are relevant for the discussion in this paper are summarized in Table 1.

Table 1: LIU beam parameters in the SPS at 450 GeV [1]. BCMS stands for the beam production scheme "Batch Compression, Bunch Merging and Splitting"

	$p^+/bunch$	ε	$N_{bunches}$
Ultimate	1.7×10^{11}	3.5 μm	288
Standard LIU	2.3×10^{11}	2.1 μm	288
BCMS LIU	2.0×10^{11}	1.3 μm	288

The impact of 450 GeV LIU beams on a collimator will create high energy deposition within a few microseconds and hence very high dynamic loads. The jaws will have to be made of materials of high shock resistance. Highest shock resistance can be found in carbon based materials with densities of 1.4 g/cm^3 to 1.8 g/cm^3. As the damage potential for equipment scales with brightness, the new collimators will have to provide roughly a factor 3 more attenuation to arrive at the same protection level as the current collimation system. The collimator jaws will therefore have to become 2.1 m long instead of the 1.2 m. The material choice will be detailed below.

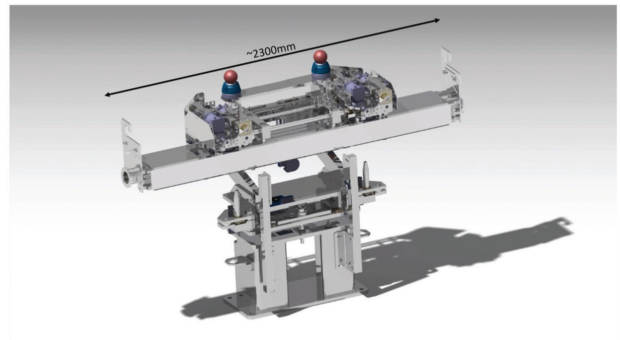

Figure 1: First version of 3D design of LIU transfer line collimator.

In the following the solution for the LIU transfer line collimators (TCDIs) and the remaining uncertainties on the design choice will be presented. The required modifications of the TI 8 optics will also be summarized and the implications on the protection of the LHC at injection discussed. A detailed functional specification of the LIU SPS-to-LHC transfer line collimation system can be found in [2].

CONCEPTUAL DESIGN OF THE LIU SPS-TO-LHC TRANSFER LINE COLLIMATORS

The design of the LIU TCDIs is based on the existing collimators installed in TI 2 and TI 8 [3]. The main difference is the requirement for longer jaws. A first version of the 3D design is shown in Fig. 1. The tolerances for jaw movement range, setting and alignment are also compatible with those originally specified. The allowed surface roughness will however be ± 100 μm instead of currently ± 50 μm.

Another difference might be the jaw material. Currently Steinemann R4550 Graphite is used. The peak energy deposition seen in the jaw varies as a function of the impact parameter, with larger values seen as the impact parameter increases. The increase in peak energy deposition and, correspondingly, temperature is not reflected in the thermomechanical stresses seen in the material, which are worst in the case of a 1 σ impact parameter. The results of the simulations with BCMS beam impacting a TCDI jaw at 1 σ, for both Steinemann R4550 Graphite (density1.83 g/cm^3) and 3D carbon-carbon (density 1.7 g/cm^3) jaw materials, are summarized in Table 2. For each material a different equivalent stress criterion was used [4]. The relevant robustness criterion for graphite is the Mohr-Coulomb criterion

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see equation (1), while for C/C the maximum and minimum principal stress criterion, equations (2) and (3) :

$$F_s = \left[\frac{\sigma_1}{\sigma_{t.l.}} + \frac{\sigma_3}{\sigma_{c.l.}} \right]^{-1} \quad (1)$$

$$F_{s,t} = \left[\frac{\sigma_{t.l.}}{\sigma_1} \right] \quad (2)$$

$$F_{s,c} = \left[\frac{\sigma_{c.l.}}{\sigma_3} \right] \quad (3)$$

where σ_1 is the maximum principal stress at a given point in the material, σ_3 the minimum principal stress and $\sigma_{c.l.}$ and $\sigma_{t.l.}$ the compressive and tensile material limit. For the material to survive a certain stress load, the relevant safety factors have to be larger than 1. According to these criteria, graphite would fail with both BCMS and standard LIU beams while 3D C/C would withstand them.

Despite the slightly insufficient robustness of Graphite R4550, it is still the baseline and 3D C/C the reserve material. The final decision will be taken after an experiment where the actual material will be impacted by LHC type beam attempting to reproduce as closely as possible the conditions that the absorbers could see during LIU operation. The experiment will be carried out at the HiRadMat facility [5].

CHANGES OF LAYOUT AND INTEGRATION OF THE LHC TRANSFER LINES

With the LIU transfer line collimators the transfer line lattices have to fulfill two requirements. First of all enough free space has to be available for the longer collimators with about 5 m distance to the downstream magnetic elements to reduce the impact of secondary showers. The second requirement comes from the beam spot size, the product of the beam sizes $\sigma_x \times \sigma_y$ at the collimators. It has to be sufficiently large to reduce the generated stresses in the absorbers. It was decided that the product of the beta functions $\beta_x \times \beta_y$ has to be larger than 3600 m^2 [6]. Whereas the current optics of the TI 2 line fulfills both requirements, a new optics with new transfer line collimator locations had to be found for TI 8. A first proposal for a new TI 8 optics was already presented in [6]. It was further optimized, such that only two new independent quadrupole power supplies are now necessary to obtain the additional flexibility for optics matching for the LIU TCDI criteria as well as matching to the LHC injection point. The changes to the layout of the transfer lines can be summarised as: removal of all 12 existing downstream TCDI betatron collimators and installation of 12 new collimators (3 horizontal and 3 vertical, for both TI 2 and TI 8); installation of 2 additional independent power supplies in TI 8 for the quadrupoles MQIF.87000 and MQID.87100, with associated cabling. The location of the 3 horizontal collimators in TI8 will change significantly (by about 50 m). BLMs are required close to all new collimators. In three cases this corresponds to a significant change of the BLM location of about 50 m.

Another concern of the version presented in [6] was the reduced aperture for the LIU optics for TI 8 (horizontal aperture at MQIF.87600 was reduced from $n_x = 9.12$ to $n_x \approx 5$). The aperture restrictions in the line in the horizontal and vertical plane as well as at the LHC injection septum MSI at the end of TI 8 are summarized in Table 3 for the latest LIU TI 8 optics and the current optics. The situation is much improved.

The locations of the masks downstream of the TCDIs remain the same as for the current collimation system. The load on the masks and the distance to the collimators will however change. The initial requirement to have at least 5 m between the exit of the collimator and the start of the mask could not be fulfilled for all locations. Simulations were carried out to study the efficacy of the masks in case of 5 σ impact on the upstream TCDI. The two worst cases were considered: TCDIM.29472 in TI 2 and TCDIM.88132 for TI 8. In both cases the distance from the centre of the collimator to the start of the mask (2.55 m and 3.25 m respectively) is significantly shorter than in previous studies. The protection of the downstream magnets can be guaranteed with these configurations, see Table 4.

Most of the TCDIM masks are made of stainless steel 304L. Only recently the stresses were calculated in the material for the above given energy deposition simulations. According to these results 304L will fail. The materials Invar, Titanium and Inconel are currently investigated as alternative for the most affected masks.

IMPACT ON MACHINE PROTECTION

The primary objective of the transfer line collimators is to protect the LHC from wrongly injected beams caused by errors upstream of the MSI. The secondary objective is to protect the tight aperture of the MSI from damage caused by erroneous transfer. The required setting of the collimators is 4.5 σ - 5 σ from the reference trajectory. In addition, the collimation system should limit the offset of the beam energy to $\pm 2 \times 10^{-3}$, [3].

In the case of TI 8 the last horizontal collimator in the line will not be directly upstream of the LHC injection septum with the LIU version, but further upstream at the exit of the magnet chain MBIAH (circuit RBIH.87833). Failures of the RBIH.87833 circuit are hence only partially covered for the MSI and LHC with passive protection. The active protection system seems nevertheless sufficient. The MBIAH power converter is surveyed by two systems. The absolute current has to be within a window around a reference. The last verification of the current occurs however up to 4 ms before extraction. The other surveillance system is a Fast Magnet Current Change monitor (FMCM), that interlocks on fast relative current changes. With the FMCM surveillance the maximum trajectory excursion during an MBIAH failure would be less than 0.6 σ in the LHC.

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Table 2: Summary of thermo-structural behaviour studies after beam impact at 1σ impact parameter

Material	**Beam Type**	**Density** $[g/cm^3]$	**Mohr-Coulomb S.F**	**T** $[°C]$	$\sigma_{t.l.}/\sigma_1$ [MPa]	$\sigma_{c.l.}/\sigma_3$ [MPa]
Graphite R4550	Standard LIU	1.8	0.98	1210	30/29	118/67
Graphite R4550	BCMS	1.8	0.8	1455	30/37	118/87
3D C/C	BCMS	1.7	-	1370	186/56	91/53

Table 3: The aperture restrictions in the TI 8 transfer lines for the current as well as the LIU optics both matched to SPS Q20 optics. The available aperture was defined according to [7]

Element	s [m]	current optics		LIU optics	
		n_x	n_y	n_x	n_y
MBI.87507	2405.722	-	6.35	-	6.86
MQIF.87600	2428.052	9.12	-	8.75	-
MSIB.C6R8	2629.605	6.88	2.55	6.94	2.97

Table 4: Peak energy deposition and corresponding temperatures seen in the masks less than 5 m downstream of collimators and magnetic elements behind the mask

Element	ΔE [J cm^{-3}]	Δ T [K]
TCDIM.29472	913	225
MQID.29500	35	10
TCDIM.88132	836	207
MBIAH.87833	28	8

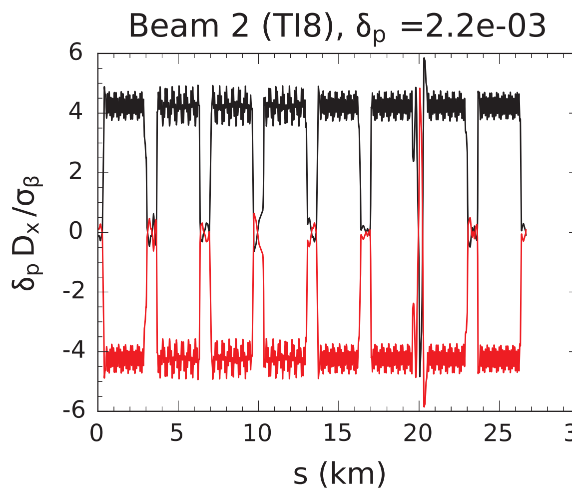

Figure 2: Worst-case off-momentum trajectory in the LHC for beam 2 with a momentum cut of $\Delta p/p = \pm 0.22\%$ in TI 8.

Changes to Momentum Collimation

There is significant horizontal dispersion at the end of both transfer lines where the betatron collimators are located, such that efficient momentum collimation can be achieved. It is the first collimator in both lines that would first intercept an off-momentum beam. The LIU transfer line collimation system will not have any dedicated momentum collimators.

The worst-case beam momentum offsets through the lines will be $\Delta p/p = \pm 0.16\%$ and $\pm 0.22\%$ for TI 2 and TI 8, respectively. Without other errors, the off-momentum beam follows the closed-orbit dispersion with maximum amplitudes of less than $\pm 3\ \sigma$ in for Beam 1 and $\pm 5\ \sigma$ for Beam 2, where σ is the nominal beam size, see Fig. 2 for beam 2.

CONCLUSION

The current SPS-to-LHC transfer line collimation system will not be adequate for the high brightness beams for the High Luminosity LHC era. They will have to attenuate by a factor 3 more and be more robust than the current system. The length of the new transfer line collimators and optics of the lines has been defined. For the transfer line TI 8 3 new collimator locations were proposed and 2 additional quadrupole power converters to have enough optics matching flexibility. Apart from replacing the current collimators with new ones, the TI 2 transfer line will stay unchanged. The main open question concerns the material choice for the collimator jaws. Two materials have been proposed with the currently used type of graphite being the baseline. Robustness tests in the HiRadMat test facility will be carried out to finalize the choice. The changes of the transfer line collimation system will also have an impact on the protection provided by the collimators in the transverse plane and against off-momentum beam. The impact has been evaluated. The reduction of protection is within the error margins at injection.

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