

DESIGN STUDIES OF THE UPGRADED COLLIMATION SYSTEM IN THE SPS-TO-LHC TRANSFER LINES

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Abstract

In the framework of the LHC Injectors Upgrade (LIU) Project, the collimators in the SPS-to-LHC transfer lines are presently under re-design, in order to cope with the unprecedented beam intensities and emittances required by the High Luminosity LHC (HL-LHC). Factors ruling the design phase are the robustness of the jaws on one side and, on the other side, the proton absorption and the emittance blow-up, essential for an effective protection of the equipment in the LHC injection regions and the LHC machine. In view of the new design, based on the one of the currently installed TCDI collimators and past investigations, the FLUKA Monte Carlo code is used to address these two factors. The present studies are intended to give essential feedback to the identification of viable solutions.

INTRODUCTION

In view of the High Luminosity LHC (HL-LHC) Project, aiming to boost the LHC luminosity well beyond its nominal value [1, 2], the LHC Injectors Upgrade (LIU) Project [3] is in charge of providing the LHC with improved beam parameters. Those proposed for the proton beams [4] for 25 ns bunch spacing are reported in Table 1, along with the Nominal and Ultimate LHC ones at injection [5], and those presently available at extraction in the SPS.

Table 1: LIU proton beam parameters for 25 ns bunch spacing, along with Nominal and Ultimate LHC values at injection, and those presently available at extraction in the SPS: number of bunches, bunch population and normalised emittance.

	N_b []	N_p [10^{11}]	$\epsilon_{x,y}^N$ [μm]
Standard LIU	288	2.3	2.1
BCMS LIU	288	2.0	1.3
Nominal LHC	288	1.15	3.5
Ultimate LHC	288	1.7	3.5
present	144	1.8	1.5

The challenging new beam parameters, especially the BCMS LIU ones, require the re-design of the collimation system presently installed in the SPS-to-LHC Transfer Lines (TLs) [6]. In particular, due to the higher density of protons, heat loads and thermal stresses will increase, exceeding the

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capabilities of the present collimators. For the same reason, the attenuation and dilution of the surviving beam should be improved as well [6]. Fluka [7, 8] simulations were therefore carried out to identify a jaw design fulfilling these requirements, in case of an accident scenario. Ansys [9] simulations were run whenever a more detailed thermo-mechanical picture was needed, to further characterise the working conditions.

The upgraded collimation system is still under design, due to the extreme complexity of fulfilling many constraints at the same time [6]. Thus, optics, jaw materials and lengths have not been finalised yet: different options are being explored, and key results are presented.

CONSTRAINING THE OPTICS

A parametric study was performed to identify a range of values of the product of the optics functions $\beta_x \times \beta_y$ (related to the spot size $\sigma_x \times \sigma_y$) inducing acceptable heat loads in case of LIU BCMS beam parameters. Figure 1 shows the maximum energy deposition as a function of the beam spot size, for central impact onto the jaw material of the present TCDI collimators, i.e. graphite Steinemann R4550. Two

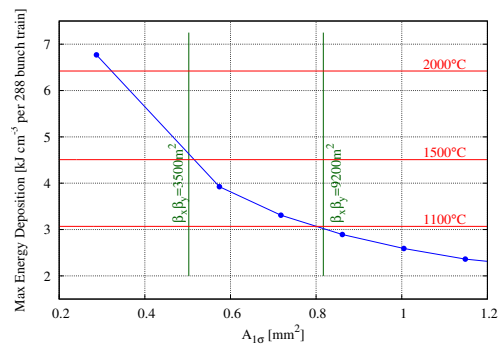


Figure 1: Expected maximum energy deposition in graphite Steinemann R4550 as a function of the beam spot size, in case of central impact of LIU BCMS beams. Values inducing a temperature rise of $\approx 1500^\circ\text{C}$ and $\approx 1100^\circ\text{C}$ are shown as well, together with their translation into $\beta_x \times \beta_y$. The blue line through the points is meant to guide the reader's eye. Statistical errors are smaller than the point size.

key values were identified, corresponding to temperature rises of $\approx 1500^\circ\text{C}$ and $\approx 1100^\circ\text{C}$, clearly below the melting point; they translate into $\beta_x \times \beta_y \approx 3500 \text{ m}^2$ and 9200 m^2 , respectively. Further Ansys analyses showed that while for the former the tensile stresses are still slightly above the limit (cfr. Table 2, second line), the latter represents a clearly safe

operational condition. Moreover, if the Standard LIU beam parameters are applied to the latter spot size, a temperature rise of $\approx 1200^\circ\text{C}$ and $\beta_x \times \beta_y \approx 3600 \text{ m}^2$ are found, resulting in a safe operation of the jaw.

MATERIAL CHOICE

Materials with low density and atomic number are most suitable for use in collimation, as they are subject to lower energy densities, meaning their robustness is less of a concern. Moreover, a limited number of radioisotopes determines the induced activity. On the downside, long jaws are needed, in order to achieve the requirements on the attenuation of the primary beam surviving the jaw: the space available in the SPS-to-LHC TLs is a further constraint, to be solved together with possible integration issues [6].

Boron nitride and CfC carbon fibers were explored as alternative materials to graphite Steinemann R4550 [10]. Table 2 summarises their characteristics relevant for energy deposition studies. Fluka and Ansys were run in cascade, in order to characterise the induced stresses. A unique case of 1σ impact of LIU BMCS beams with a spot size satisfying $\beta_x \times \beta_y > 3500 \text{ m}^2$ was considered. While values of compressive stresses are always largely acceptable, all three materials suffer due to tensile stresses, as maximum values are above the limits (cfr. last column in Table 2), with graphite Steinemann R4550 being the best ranked. It should be kept in mind that these limits, provided by the suppliers, do not consider dynamic loads, pertinent in case of very short time scales, like the one of the bunch train, i.e. $7.2\mu\text{s}$: further material tests should be performed to obtain more realistic strength limits and failure mechanisms under thermal shock conditions.

Table 2: Comparison among different low density materials: density, inelastic scattering length, radiation length, and expected tensile stresses compared to the limit.

name	ρ [g cm ⁻³]	λ_I [cm]	X_0 [cm]	Tensile stress / limit [MPa]
BN5000	1.93	43.26	21.31	11 / 3
R4550	1.83	44.56	23.33	32 / 29
CfC	1.7	47.96	25.12	20 / 12.8

On the other hand, materials with high density and atomic number fulfill the requirements on the attenuation of the primary beam in a shorter length, but they are subject to much higher energy densities, especially if they are directly impacted by the beam. Thus, a multi-material structure with an increasing profile in density is advisable.

Different combinations of materials were studied in Fluka, featuring a first layer of few tens of cm made of graphite, followed by materials with intermediate densities, e.g. SiC, TiC, Alumina, or BorSiC; if needed, few cm of Cu or W were added at the end, up to about 1.2 m of total length, to attain the required attenuation. In all the cases, at least

one material (never graphite) melts, as can be seen in Fig. 2, where the peak energy deposition patterns are shown for a couple of studied options.

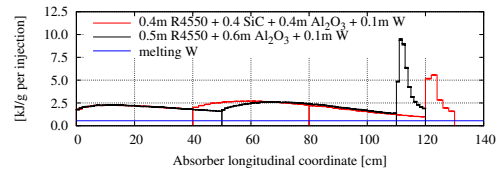


Figure 2: Expected peak energy deposition in the TCDI jaw with a sandwich structure, including materials with high atomic number and density, for a couple of studied cases of 1σ impact with LIU BCMS beam parameters. Error bars, when visible, refer to the statistical uncertainty only.

BEAM BLOW UP

Beam particles surviving the interaction with the jaw get scattered by several phenomena (e.g. Coulomb, nuclear elastic, single diffractive scatterings...), leading to blowing up the phase space occupied by the beam (see Fig. 3, for instance). This translates into a lower particle density in real space all along the trajectory of the surviving beam, except locations with a phase advance of $n\pi$ (with n integer). Moreover, filamentation does not take place in one single pass. Accordingly, despite its effectiveness, the beam phase space blow up cannot be quantitatively used for an a-priori evaluation of the beam dilution. As a consequence, the length of the new TCDI jaw [6] is constrained purely by the attenuation of primary particles due to nuclear inelastic processes.

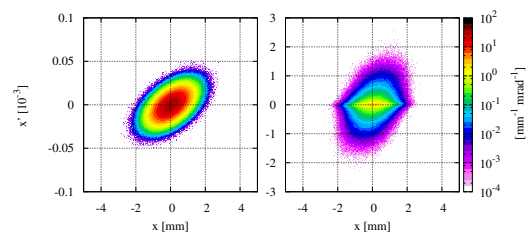


Figure 3: Example of particle density in phase space at impact onto a TCDI jaw (left frame) and after a thickness equivalent to 2 inelastic scattering lengths (right frame) obtained with Fluka. Integrals are normalised to 1.

LOCAL PROTECTION

Previous Fluka studies [11] systematically evaluated the effectiveness of metallic masks protecting warm magnets immediately downstream of the TCDI collimators from energy deposition induced by secondary particle cascades, for superseded upgrade configurations. Since the design of the upgraded system is still evolving, any similar study is premature at the present stage. Nevertheless, a couple of cases were run, to check heat loads (see Fig. 4) with the

updated beam parameters, and in case of two twin modules of the present TCDI collimators [6]. The geometries were built using the Fluka Element DataBase (FEDB) and the Line Builder (LB) [12]. Values are compatible with results previously found [11].

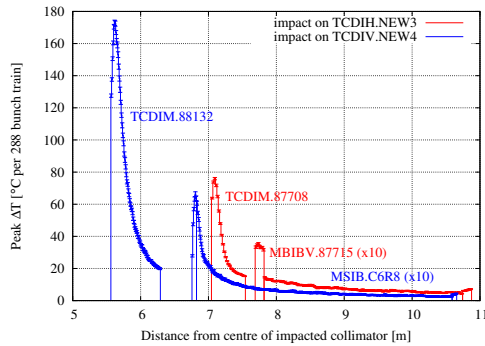


Figure 4: Expected temperature rise in the magnet (magnified by a factor of 10, for the sake of clarity) downstream of TCDI collimators and in the protecting mask, for a couple of selected cases. Error bars, when visible, refer to the statistical uncertainty only.

CROSS-TALK TO LHC MAGNETS

For the present collimation system in the SPS-to-LHC TMs, Fluka studies [13] were run to assess levels of energy deposition in the nearby LHC superconducting magnets by secondary particle showers in case of direct losses on the TCDI collimators. Preliminary studies have been carried out, considering a full beam loss on the TCDIH.87904, operationally the most loaded collimator [14]. Standard LIU beam parameters were considered in a couple of impact positions. A case with two twin modules of the present TCDI collimators was run as well. The geometries of the LHC and the TL were separately built with FEDB and LB, and then manually merged. There is no major dependence of values on the impact parameter in the investigated range, as from the totals in Fig. 5 and the peak patterns in the superconducting coils in Fig. 6. On the contrary, the addition of the second twin module helps in attenuating secondary particles directed longitudinally, but increases the lateral emission, as clearly visible in the profile of peak energy density in the superconducting coils in Fig. 6. It should be noted that, in all the studied configurations, maximum values of energy deposition in the superconducting coils, despite comparable to estimates of quench thresholds [15], are far below the damage limit [16].

CONCLUSIONS

The design of the upgraded collimation system in the SPS-to-LHC TMs is still on-going, driven by challenging requirements on jaw robustness, beam attenuation, optics and integration [6]. Fluka simulations have been extensively run to characterise materials and beam impact conditions, com-

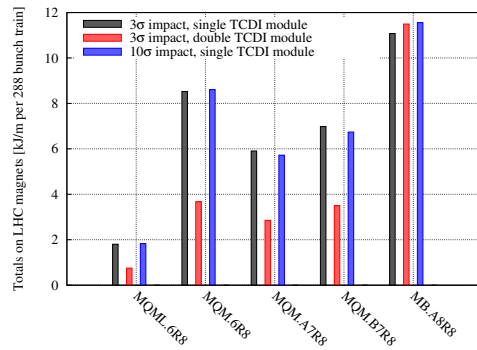


Figure 5: Total energy deposition in the LHC magnets closest to the TCDIH.87904. The beam comes from the right.

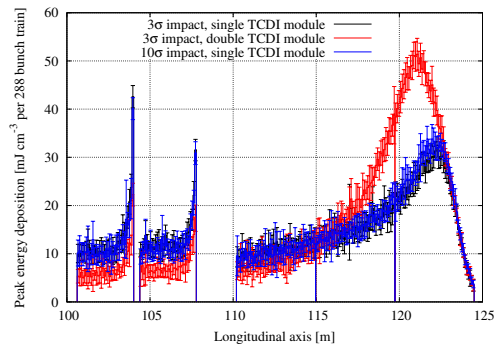


Figure 6: Peak energy deposition in the coils of the LHC superconducting magnets closest to the TCDIH.87904. The beam comes from the right. Error bars refer to the statistical uncertainty only.

plemented by Ansys whenever detailed thermo-mechanical analyses were needed. Fluka simulations were run also to characterise the protection of downstream equipment and nearby LHC magnets at this early stage of design.

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