PROTECTION DEVICES IN THE TRANSFER LINES TO THE LHC

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Abstract

Beams will be transferred from SPS to LHC through two transfer lines, each of over 2.5 km length, equipped with conventional resistive magnets with relatively small apertures. Beam energy densities will be roughly 4 orders of magnitude above the LHC quench limit and about one order above damage level. Possible failures of the various elements in the transfer lines and the SPS machine are discussed, together with results from tracking studies. The benefit from installing protection devices in the transfer lines is discussed, along with related layout aspects and the required protection performance.

1 INTRODUCTION

Beams will be injected from the SPS into the LHC through the two transfer lines TI 2 and TI 8 [1], see Fig. 1.

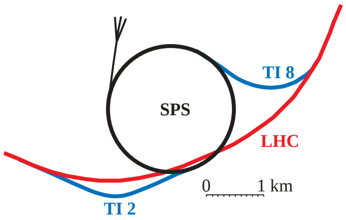

Figure 1: Schematic view of the LHC injection transfer lines.

Protection devices in the transfer lines should be safe for nominal beam intensities and also survive the impact of beams of ultimate intensities, which will be about 50 % above the nominal intensities. Parameters are summarized in Table 1.

Table 1: Nominal beam parameters for LHC injection.

Proton momentum	$450\,\mathrm{GeV/c}$
Normalized emittance	$\epsilon_N = 3.75\,\mu\mathrm{m}$
Emittance	$\epsilon = 7.82\,\mathrm{nm}$
Protons per bunch	1.1×10^{11}
Bunches per batch	72
Number of batches	3 or 4
Nominal intensity	$4 \times 72 \ \times 1.1 \times 10^{11}$ $= 3.2 \times 10^{13}$

The batches are extracted in $4/11$ of an SPS turn or 7.86 μs. The damage level for fast losses is about 2×10^{12} protons and the quench level in the LHC of the order of 10^9 protons [2]. An attenuation by at least a factor of 20 and better by a factor of 100 should be achieved to prevent damage by the injected beam [3].

Primary collimators in the LHC will be set to $6 - 7\,\sigma$ at injection and secondary collimators to $7 - 8.2\,\sigma$. This reduces the tertiary halo of the circulating beams to below the quench level at physical apertures (at $> 10\,\sigma$). Wrongly injected beams could however do damage before they even arrive at the collimation sections in the LHC.

Cleaning of the injected beams is best done as early as possible. A ‘shaving’ to $3.5\,\sigma$ (corresponding to less than 0.05 % loss for Gaussian beams) is foreseen in the SPS.

The combined effect of closed orbit errors, SPS extraction and transfer lines ripple and drifts corresponds to an increase by $1.5\,\sigma$ [1]. This adds up to a $5\,\sigma$ envelope for the injected beams in the LHC.

Injection steering will be done with low intensity (pilot) beams, well below the damage level. When everything is well adjusted and a pilot circulates in the LHC, the injection of high intensity batches can start.

2 POSSIBLE FAILURES AND PROTECTION

Protection against mis-firing of the extraction kickers in the SPS is foreseen. The septum MSE which follows the extraction kicker MKE will be protected by the septum diluter (TPSG, about 4 m of C + Al, [4]). Protection against mis-firing of the MKI kickers at the end of the transfer lines into the LHC is provided by the injection beam stopper TDI, the D1 shielding TCDD and the TCL injection collimators. They will be set to about $8.5\,\sigma$ vertically. There is at present no passive horizontal protection for the injected beams in the LHC.

The transfer lines are pulsed, use warm magnets and are turned off when no injection is needed. The beam is horizontally extracted from the SPS (MKE kicker). The lines are several kilometres long with many horizontal and some vertical bending magnets. Wrong bending fields could result in local loss of the full intensity. Active protection based on monitoring of the currents of the magnets in the transfer lines is planned. Large injection oscillations could still be caused for example by problems with corrector settings in the transfer lines or timing faults [5].

Most critical is the end of the line with the tight septum (MSI) aperture and the injection region in the LHC. Passive protection for the septum is needed, which at the same time can be used to limit injection oscillations in the LHC.

Fig. 2 shows the septum MSI in TI 8 as seen from the side. It consists of five (two MSIA and three MSIB) each 4 m long steel septum magnets. The aperture available for the injected beam is indicated by dotted lines. It reduces from effectively 17 mm on the right to 13 mm on the left, which leaves $7\,\sigma$ in both planes to the beam.

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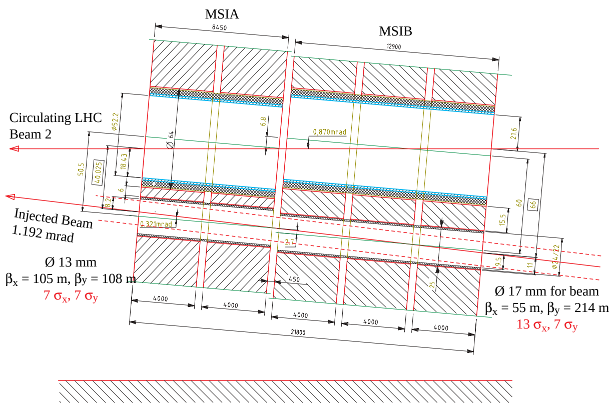

Figure 2: Septum MSI in TI 8, seen from the side.

3 OPTICS AND POSSIBLE POSITIONS OF COLLIMATORS

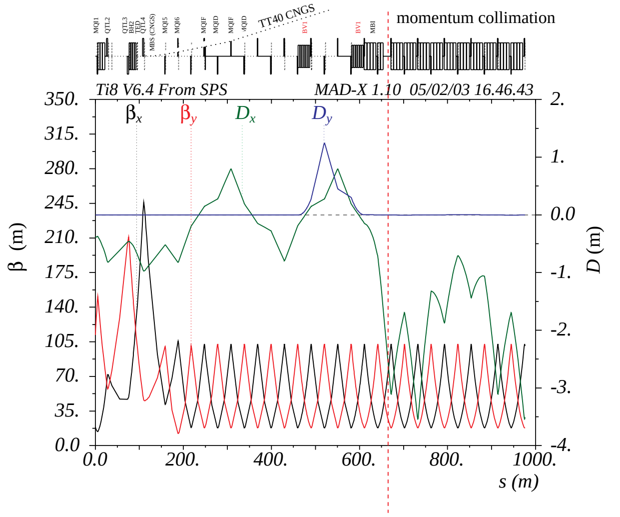

Figure 3: Optics at the beginning of TI 8 and proposed position for momentum collimation.

The optics of the first kilometre of the transfer line TI 8 is shown in Fig. 3. The beam energy is constant through the transfer line. Momentum collimation can be done in the first available space with high dispersion. The betatron collimation should be able to protect the tight septum aperture and the injection region against any bending errors upstream. It should therefore be placed towards the end of the line. As a first proposal to be looked at more closely, we will follow the following strategy to place collimators "TCDI" in the transfer line:

- Momentum collimation in the first available place with large dispersion (which is in the horizontal plane).
- Vertical collimation at about 90° phase advance upstream of the septum (and about 180° in H).
- Horizontal collimation at about 90° upstream of the septum.
- Septum protection, combined in H and V.

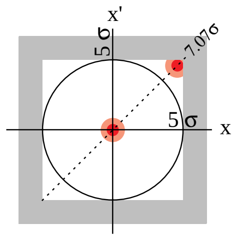

Figure 4: Illustration of the phase space with two collimators at 90° set to $5\,\sigma$.

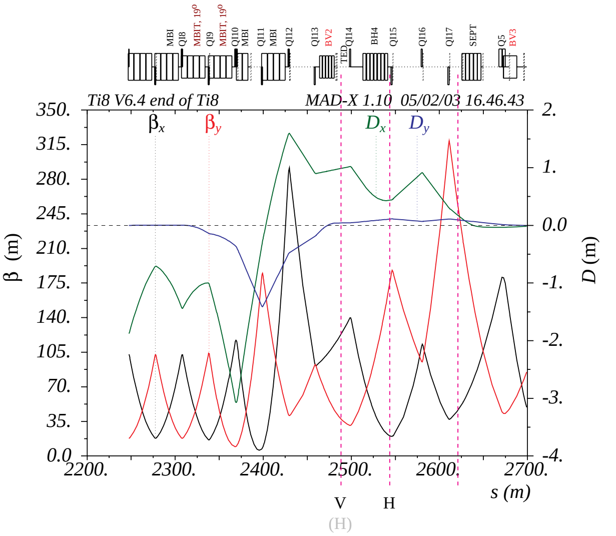

Figure 5: Optics at the end of TI 8 and proposed positions for betatron collimation.

The phase space limits obtained from collimation at $5\,\sigma$ with 90° phase difference are sketched in Fig. 4. The beam spots of a centred beam and the worst case of a displaced beam are also sketched.

A first detailed proposal for positions of collimators has been worked out for the line TI 8. The numbers are given in Table 2. The end of the line with the proposed positions for betatron collimation is also shown as Fig. 5. The table gives s positions in the transfer lines, the optics parameters β and dispersion and the phase advance relative to the beginning of the septum.

$5\,\sigma$ settings would imply rather narrow settings, ± 2.3 mm at QI15 in H and ± 2.8 mm in V. To allow for injection steering, the collimators at QI14 and QI15 should be retractable. The first betatron collimator COLLQI14 has been placed close to the beam stopper TED at a phase advance of 90° in the vertical plane from the septum. The β_x in this place is relatively large and the horizontal phase advance to the septum not too far from 180°. Adding also horizontal collimation in this position is considered and would allow to limit the aperture in both planes to reduce losses close to the septum.

4 PERFORMANCE ESTIMATE

The critical impact parameter b_c, below which scattering from the collimator edge is significant, is about $b_c = 12\,\mu$m

Table 2: Optics at transfer line collimators.

Name	s, m	β_x, m	D_x, m	σ_x, mm	$\Delta\mu_x$ to MSI	β_y, m	D_y, m	σ_y, mm	$\Delta\mu_y$ to MSI
COLLMOM	671	102	-3.08	1.69	-20°	18.2	-.001	0.38	117°
COLLQI14	2487	122	0.99	1.08	163°	38.4	0.042	0.55	87°
COLLQI15	2546	19.8	0.44	0.45	97°	186	0.11	1.20	29°
COLLMSI	2627	54.3	0.11	0.65	0°	218	0.09	1.31	0°

at 450 GeV/c [6]. For a uniform impact over a distance d, there will be roughly a fraction of d/b_c protons scattered back in the beam pipe.

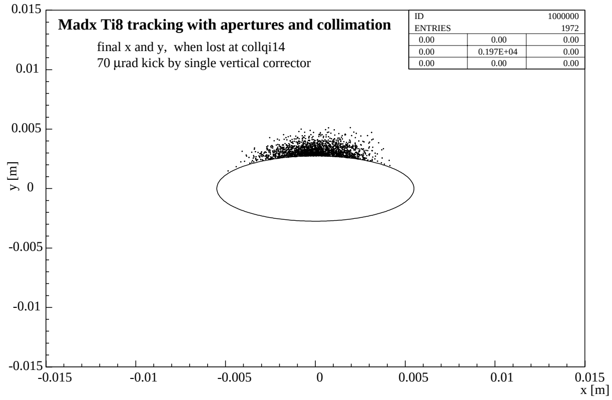

Figure 6: MAD-X TI 8 tracking with apertures.

Impact distributions for the proposed transfer line collimators have been studied using MAD-X [7] tracking for the transfer line TI 8 with apertures and collimators. In the most favourable case, losses are distributed homogeneously in the available aperture, resulting in a flat loss distribution over 5 mm on the collimator. For this case, we estimate an attenuation by a factor or $5\,\mathrm{mm}/12\,\mu\mathrm{m} \approx 400$. A result for the least favorable case, in which the beam impacts directly without any blow-up is shown in Fig. 6. The attenuation based on the r.m.s beam size $\sigma = 0.5\,\mathrm{mm}$ is then $5\,\mathrm{mm}/12\,\mu\mathrm{m} \approx 40$. Not all particles scattered back elastically into the beam pipe will be lost in critical places. The scattering angle can be estimated from multiple scattering:

$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p}\sqrt{x/X_0}\,[1 + 0.038\log(x/X_0)] \qquad (1)$$

Numerical estimate for graphite: one nuclear interaction length is $\lambda \approx 26\,\mathrm{cm}$ and one radiation length $X_0 \approx 19\,\mathrm{cm}$. The effective distance x before absorption is estimated as 2λ. The result for the average scattering angle is $\theta_0 \approx 50\,\mu\mathrm{rad}$. This is about 2 or 3 times more than the beam divergence. It implies that the back-scattered proton losses will be rather distributed. Together with the attenuation of 40 estimated above, there are good reasons to believe that the performance of the transfer line collimators would in fact be sufficient to prevent damage. This should be verified by tracking with simulation of the interactions in the collimators.

The proposed setting at $5\,\sigma$ at two phases separated by 90° will limit oscillations to below $\sim 8\sigma$ at any phase. This still leaves some margin for tolerances up to the LHC physical aperture of about $10\,\sigma$ in the LHC.

Whether the momentum collimation at the beginning of the line is really needed will depend on the reliability of the quality check/interlock system planned for the extraction from the SPS. The passive protection proposed here would reduce the momentum aperture in the line from about $\pm 0.8\,\%$ (estimated with $r = \pm 3.2\,\mathrm{cm}$ aperture and $D_x = 3.5\,\mathrm{m}$ dispersion in the transfer line arc) to about $\Delta E/E \pm 0.24\,\%$, as estimated for momentum collimation at $D_x = 3\,\mathrm{m}$, $\beta_x \approx 100\,\mathrm{m}$, $1\,\sigma = 1.7\,\mathrm{mm}$ with a setting at $5\,\sigma$ or $\pm 8.5\,\mathrm{mm}$. This is sufficient to prevent localized losses due to energy errors.

5 SUMMARY AND OUTLOOK

A collimation at $5\,\sigma$ in the transfer line will be important to protect the LHC injection regions against serious damage and to limit injection oscillations in the LHC. Issues presently under study include

- fixed or mobile apertures,
- attenuation performance,
- exact positioning,
- necessity of momentum collimation.

In parallel, work leading to a detailed technical design has started.

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