APERTURE AND DELIVERY PRECISION OF THE LHC INJECTION SYSTEM

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Abstract

The main LHC injection elements in interaction regions 2 and 8 comprise the injection septa (MSI), the injection kickers (MKI), together with three families of passive protection devices (TDI, TCDD and TCLI). The apertures of the two circulating beams are detailed for these elements, together with a summary of recent design modifications. The errors in the SPS, the transfer lines and the injection system are analysed, and the expected performance of the system derived, in terms of the expected delivery precision of the injected beam.

INTRODUCTION

The LHC proton beams are injected into the LHC at 450 GeV, via the transfer lines TI 2 and TI 8, in IR2 and IR8. The injection system in each IR comprises 5 horizontally deflecting septum magnets MSI, 4 vertically deflecting kicker modules MKI, a movable 2-sided vertical absorber TDI, an additional retractable shielding element TCDD, and two movable auxiliary vertical collimators TCLI. Fig.1 illustrates the layout in IR8.

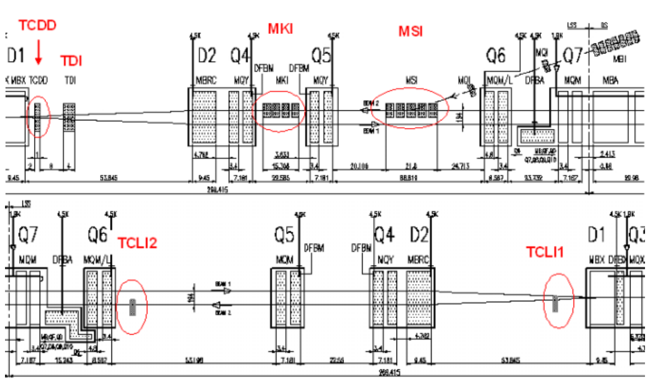

Figure 1: Injection region in IR8

In the first part of this paper the apertures of the various elements are presented, highlighting the critical areas where special measures have been taken. In the second part, an analysis [1] of the expected delivery precision of the injected beam is summarised, with contributions from the various ripples and drifts in the SPS, the transfer lines and the injection regions.

INJECTION SYSTEM APERTURE

From [2] the aperture is calculated in RMS transverse beam units and in 2D. It is parameterised with the primary halo size n1 delimited by the primary collimators and specified to be n1 $\geq$ 7. Some room is granted for the secondary halo (n_{radial} = 1.4 n1). The formula also takes into account orbit errors, alignment errors and optical effects such as beta-beating and parasitic dispersion. An example of the calculated secondary halo shapes in the MSI vacuum chamber is seen in Fig.2. For the conventional magnets in the warm insertions, this specification has been relaxed somewhat to n1 $\geq$ 6.5. In order to correctly calculate apertures at the extreme locations, the Twiss parameter values are calculated at the ends of the vacuum chambers, and not (as is the case for the published LHC optics) at the magnetic extremities of the elements. The n1 values are shown in Table 1.

Table 1: Minimum circulating beam 1 and 2 apertures (n1) for injection elements.

Element	IR2-b1	IR2-b2	IR8-b1	IR8-b2
MSI	8.5	7.3	8.3	8.3
TDI	-	10.5	16	-
TCDD	13	11	15	9
TCLI1	-	12	16	-

Main Equipment Design Aspects

The injection septum MSI will be aligned to the vertical axis of the injected beam. To provide adequate aperture for the circulating beams, the same enlarged vacuum chamber as the extraction septum MSD will be used. The chamber provides 52.4 mm clear aperture, after all tolerances are included.

The TDI absorber cross-section has been modified to accommodate the second circulating beam with LHC V6.5 optics. The absorber has also been moved 8 mm away from the vacuum axis. The inner jaw shape the TDI with the new layout is shown in Fig.3, together with the n1 = 7 secondary halo shape.

The longitudinal TCDD position has changed slightly due to requirements on the position of the nearby beam position monitor BPMSX. This has little incidence on the aperture, but will result in a reduced protection efficiency, which has still to be evaluated fully. The cross-section of the TCDD is shown in Fig.4.

The TCLI collimator [**?**] locations and specification have been defined. The collimators at D1 inside the common beampipe section require a half-jaw design to provide enough aperture for the circulating non-collimated beam. The preliminary cross-section of this TCLI is shown in Fig.5.

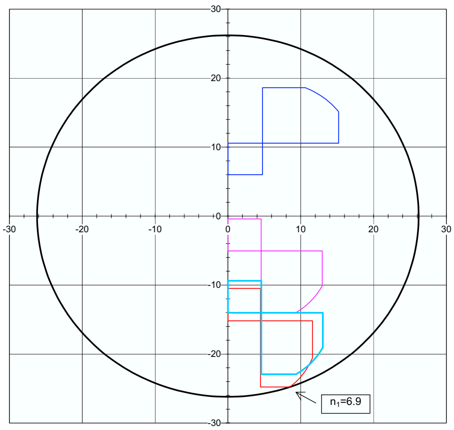

Figure 2: Beam 2 in IR2 in the MSI. Secondary beam halo shapes with maximum errors are shown at various locations along the vacuum chamber (only the worst-case quadrants are shown). n1 = 7.3.

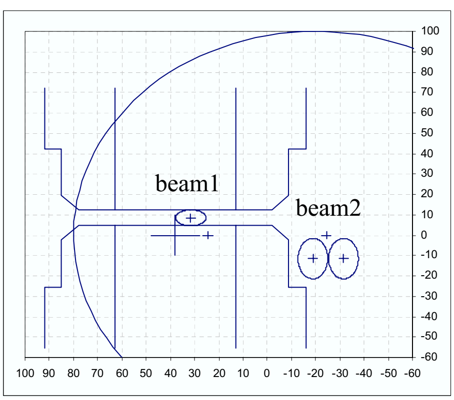

Figure 3: IR2 TDI, showing injected beam 1 between the jaws, and a beam extending to 8.4σ for the adjacent beam 2. n1 = 10.5

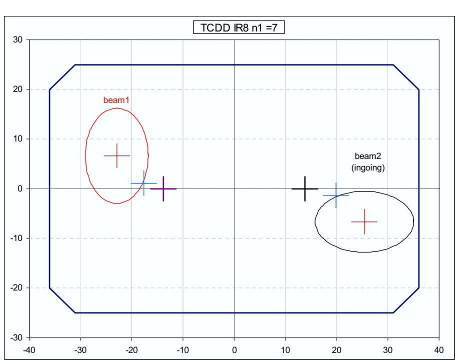

Figure 4: IR8 TCDD, showing beams extending to 8.4σ for beams 1 and 2. n1 = 9 for beam2.

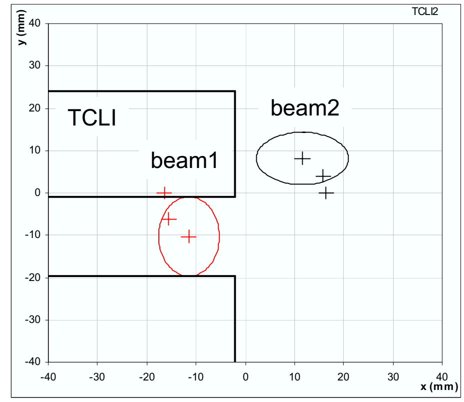

Figure 5: IR2 TCLI1, showing injected beam 1 between the jaws, and a beam extending to 8.4σ for the adjacent beam 2. n1 = 12.

DELIVERY PRECISION

The expected delivery precision of the injected beam is important for the specification of the LHC damper, for estimating the emittance blow-up at injection, for deriving the settings of the protection devices in the transfer line, injection region and LHC, and also for estimating losses at injection into the LHC and on the first turns. The delivery precision depends on the stability of the SPS orbit, and on the stability of the magnetic elements and power convertor ripple in the SPS extraction channel, the SPS to LHC transfer lines and the LHC injection systems. Uncorrected drifts of the trajectory in the transfer line will also contribute. In addition to these random variations, there are systematic effects from the reproducible magnetic field waveforms of the SPS extraction kickers and the LHC injection kickers.

The specified errors in the strengths of the magnet families considered were introduced as field errors in MAD. For the main quadrupoles MQI, a trajectory was used with 0 mm mean, 1.5 mm rms cut at 4 mm. The resulting x,x' or y,y' offsets were extracted from MAD at the reference location and transformed into beam sigma by calculating the maximum amplitude in phase space.

Failure modes (power convertor trips, setting error, kicker erratics, etc.) were ignored in the analysis. Contributions from ripple in the corrector magnets in the transfer line were also ignored. The effect of the quadrupoles was analysed but only the (minor) contribution from the MQI family of quadrupoles powered in series is included explicitly in the results, since the contributions from the individually powered matching quadrupoles in the lines is negligible, at below the $10^{-3}\sigma$ level. The effect of quadrupole ripple on the optical effects (mismatch, beta-beating and coupling) was ignored.

Random errors

The random errors are rms values in $\Delta K/K$ (for the magnets) or mm offset at a nominal beta function (orbit/trajectory). The errors for magnets driven in series are assumed to be fully correlated. The power convertors are characterised by a specified tolerance $\pm I/I_{max}$, which is assumed for the purposes of this analysis to a $\pm 2\sigma$ variation. Magnets were assumed to be perfectly aligned with respect to the reference frame, so that there is no effect in the orthogonal plane (except for the MBIT magnets in TI 8 which are powered in series with the main dipoles MBI but are tilted to rather large angles as part of the line geometry).

Transfer Line Stability and Trajectory Correction

The transfer lines will exhibit drift due to temperature, alignment or other effects, which will be manifested as a change in the position and angle of the beam at the injection point. This drift can be corrected, with the error level determined by the accuracy of the BPM readings and the correction strategy. The reproducibility of the BPMs is $200\ \mu m$ rms for the single pilot bunches foreseen for rough setting-up, and $50\ \mu m$ for a nominal bunch. Studies using BPM noise signals at these levels and real correction algorithms have shown that the orbit can be corrected to give a peak offset of about 0.4 mm at the injection point, including effects such as drift in the line. Considering this as a peak (2σ) value, the rms variation is then taken as 0.2 mm. This is considerably lower than the magnitude of the rms trajectory excursion in the transfer lines in general, of the order of 1 - 1.5 mm [3].

Systematic Effects

The known systematic effects are the SPS extraction MKE and LHC injection MKI kicker waveforms, in the horizontal and vertical planes respectively. Bunches will reproducibly sample all amplitudes within this range for each batch injected into the LHC. For both MKE and MKI, the total flat-top variation is 1%, corresponding to a range of $\pm 0.5 \times 10^{-3}$.

Results

The details of the various errors and the corresponding offsets are given in Table 2 for the SPS extraction channel LSS6 plus dipole groups in TI 2 (beam1) and in Table 3 for the SPS extraction channel in LSS4 plus dipole groups in TI 8 (beam2).

The random rms variation at injection expected from the random effects in various elements is about 0.35σ horizontally and about 0.30σ vertically for both LHC beams. A further systematic 'offset' of about 0.25σ horizontally and 0.35σ vertically has to be added for the kicker waveforms. Taking a 99% confidence limit for the random effects, the overall precision is then 1.25σ in both H and V for LHC beams 1 and 2.

Table 2: Main contributions to delivery imprecision for beam 1 (LSS6, TI 2 and the IR2 injection).

Error source	tolerance $\Delta I/I_{nom}$	$\Delta\sigma_x$	$\Delta\sigma_y$
Random effects			
SPS Orbit $\pm$ 0.10mm		0.113	0.113
Line stability $\pm$ 0.20mm		0.226	0.226
MSE	$\pm$ 1.3E-04	0.104	0.000
BH1	$\pm$ 5.0E-05	0.083	0.000
MSI	$\pm$ 5.0E-05	0.096	0.000
MBI	$\pm$ 2.5E-05	0.171	0.000
BV1	$\pm$ 2.5E-05	0.000	0.112
rms sum (1 σ)		0.342	0.279
Systematic effects			
MKE (systematic)	$\pm$ 5.0E-03	0.224	0.000
MKI (systematic)	$\pm$ 5.0E-03	0.000	0.354

Table 3: Contributions to delivery imprecision for beam 2 (LSS4, TI 8 and the IR8 injection).

Error source	tolerance $\Delta I/I_{nom}$	$\Delta\sigma_x$	$\Delta\sigma_y$
Random effects			
SPS Orbit $\pm$ 0.10mm		0.113	0.113
Line stability $\pm$ 0.20mm		0.226	0.226
MSE	$\pm$ 1.3E-04	0.130	0.000
BH1	$\pm$ 5.0E-05	0.055	0.000
BH2	$\pm$ 5.0E-05	0.083	0.000
BH4	$\pm$ 5.0E-05	0.088	0.000
MSI	$\pm$ 5.0E-05	0.091	0.000
MBI	$\pm$ 2.5E-05	0.091	0.035
BV2	$\pm$ 5.0E-05	0.000	0.084
rms sum (1 σ)		0.335	0.270
Systematic effects			
MKE (systematic)	$\pm$ 5.0E-03	0.241	0.000
MKI (systematic)	$\pm$ 5.0E-03	0.000	0.353

SUMMARY

The aperture for the circulating beams at the injection elements with the latest LHC version and element design is larger than the specified minimum of n1 = 7. The expected delivery precision at both injection points, of the order of 1.25σ in both planes, is better than the specified 1.5σ, taking a 99% confidence limit.

ACKNOWLEDGEMENT

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[2] J.B.Jeanneret, R.Ostojic, "Geometrical acceptance in LHC version 5.0", LHC note 111, CERN.

[3] Y.C.Chao, V.Mertens, "Analysis and Optimisation of Orbit Correction Configurations Using Generalised Response Matrices and its Application to the LHC Injection Transfer Lines TI 2 and TI 8", LHC project report 470, CERN.