APERTURE STUDIES OF THE SPS TO LHC TRANSFER LINES

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Abstract

The SPS to LHC transfer lines TI 2 and TI 8 are each several km in length and use magnets with small apertures. An aperture model for the lines has been developed in MADX format, with a full description of all installed vacuum elements and the possibility to interpolate at any length interval. This model has been used with tolerances and errors to simulate the expected line aperture available for the beam. The model features and simulation results are presented, with derived aperture limits. The results from aperture measurements made during the TI 8 beam commissioning in 2004 are presented and compared to expectations.

THE SPS TO LHC TRANSFER LINES

The LHC proton beams are fast-extracted from the SPS at 450 GeV/c, and transported to the LHC via the transfer lines TI 2 and TI 8 [1]. The 2.7 km long TI 8 line was commissioned in autumn 2004 [2]. Careful control of the trajectory is of key importance, given the limited mechanical aperture of the line magnets [3], the high intensity and energy in the beam, the limited numbers of correctors and pick-ups and the tight tolerances on the beam parameters at injection into the LHC [4]. The performance requirements of the lines (including the upstream TT40 and TT60 parts) is shown in Table 1.

Table 1: Main performance requirements for the SPS to LHC transfer lines (tolerance values)

Parameter	Unit	Value
Energy	GeV	450
Emittance from SPS (1σ norm.)	μm	3.5
Beam intensity (LHC ultimate)	10^{13} p+	4.9
Momentum spread (1σ)	Δp/p	0.0015
LHC Injection precision	σ	±1.5
Optical matching range (β)	%	±20
Emittance growth	$\Delta\epsilon/\epsilon_0$	1.05
Aperture (nominal ϵ)	σ	±6.0

Both lines use a FODO lattice with 90^o phase advance per cell and a half-cell length of 30.3 m, similar to the SPS. Each half-cell contains four dipoles. Short straight sections with space for instrumentation and dipole corrector magnets follow each quadrupole. The main optical parameters are summarised in Table 2.

The transferred beams must stay within the available aperture. The strongest aperture constraint comes from the main MBI dipoles of the transfer line, with their full gap height of only 25 mm. This aperture results in a maximum tolerable vertical trajectory excursion, near the defocusing quadrupoles, of ±4.5 mm. The aperture N in number of sigma available to the beam is derived using [5]:

Table 2: Main optics parameters for the SPS to LHC transfer lines (nominal optics)

Parameter	Unit	TI 2	TI 8
β_x max	m	308.5	240.8
β_y max	m	289.5	274.6
β_x max (arc)	m	101.2	101.2
β_y max (arc)	m	101.1	101.1
$\lvert D_x\rvert$ max	m	3.82	3.88
$\lvert D_y\rvert$ max	m	3.97	1.34
D_x rms	m	1.42	1.78
D_y rms	m	0.55	0.20
μ_x total	2π	12.07	10.54
μ_y total	2π	12.24	10.32
Total number of half-cells		95	85

$$N = ([A - E_{max}(\beta/\beta_{max})^{1/2} - D\Delta p/p]/K_\beta)/\sigma$$

where A is the physical half-aperture remaining after mechanical and alignment tolerances and sagitta (total 1.5 mm) are included. K_β = 1.1 is the optical mismatch factor, β_{max} the maximum beta function in the regular arc, E_{max} = 4.5 m the maximum allowed orbit excursion, $\sigma = \sqrt{\beta\epsilon}$ the betatron beam size and $\Delta p/p$ = 0.0015 the maximum allowed momentum spread.

APERTURE MODEL

A transfer line aperture model was developed for MADX to facilitate optics optimisation, beam loss studies and machine protection simulations. A maintainable, configurable model of the physical aperture of the two lines was produced, containing around 1000 elements for each line, including bending, focusing and correction magnets, as well as instrumentation, collimators and safety devices, together with the real vacuum pipes, flanges and bellows. The model allows interpolation at arbitrary intervals, and is fully interfaced to MADX, taking as input the sequence files for the lines, together with the specific configuration files for the apertures. It produces a sequence-edit file containing all aperture information and markers.

The physical models for both planes in TI 8, together with the beta functions, are shown in Figs. 1 and 2. Similar models were made for TI 2.

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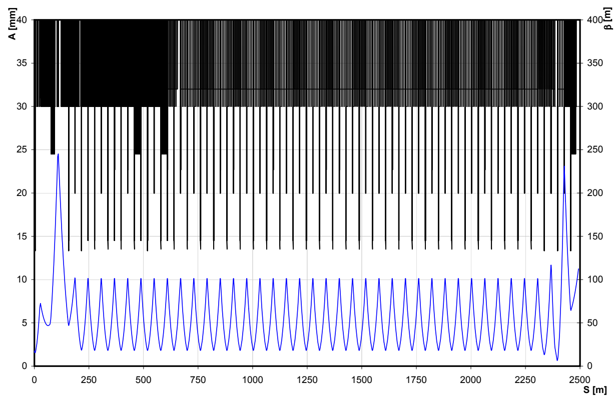

Figure 1: Horizontal physical aperture model for TI 8, together with the horizontal beta function.

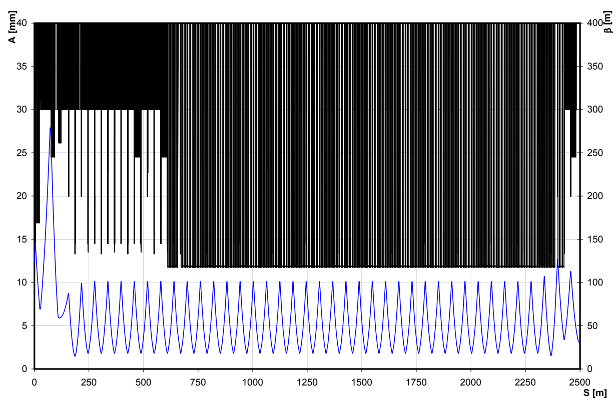

Figure 2: Vertical physical aperture model for TI 8, together with the vertical beta function.

APERTURE MEASUREMENTS

During the TI 8 commissioning in 2004 [2], aperture measurements were made by exciting betatron oscillations with different dipole groups to maximise phase coverage. To minimise the amount of beam lost and hence induced activity, the measurements were all performed with single bunches of 5×10^9 protons. The measured normalised emittances were $0.46\ \mu m$ (H) and $0.26\ \mu m$ (V). The successful transmission of the beam was monitored using the Beam Current Transformer (BCT) at the end of the line, on the Beam Position Monitors (BPMs) along the line and also on the Beam Loss Monitors (BLMs).

The aperture was probed by varying the strength of the dipoles, in steps of 1 nominal beam σ, until the transmission measured by the BCTs dropped below 1 or a significant BLM signal was recorded. The envelope of the aperture was then derived by estimating the position of the real edge of the beam (assumed to be at 3σ), calculated with the measured emittances. The resulting envelopes were superposed to show the available aperture, and compared with the expected aperture in σ calculated with the expression for N (given above).

First Test With Perturbed Optics

In the first series of measurements on 24 October 2004, an undetected 20% calibration error in the reference values for two matching quadrupoles at the start of the line meant that the optics was strongly perturbed. The aperture scans were (unwittingly) made using this perturbed optics (the error was discovered after the test, and the optics used in the calculation adjusted accordingly). For this test, the maximum horizontal beta values in the arc sections were of the order of 500 m, rather than the nominal 100 m. The aperture of the line was significantly reduced as a result; however, the test measurements still showed a good agreement with the expected aperture as calculated with the perturbed optics, Figs. 3 and 4.

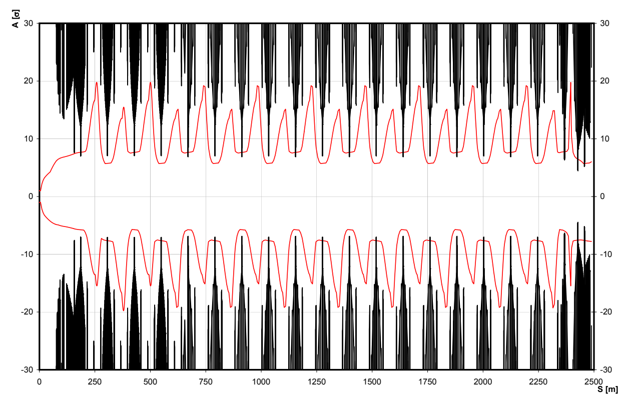

Figure 3: Expected and measured horizontal aperture in TI 8, for the perturbed beam optics. The measured aperture is about 5.8 nominal σ.

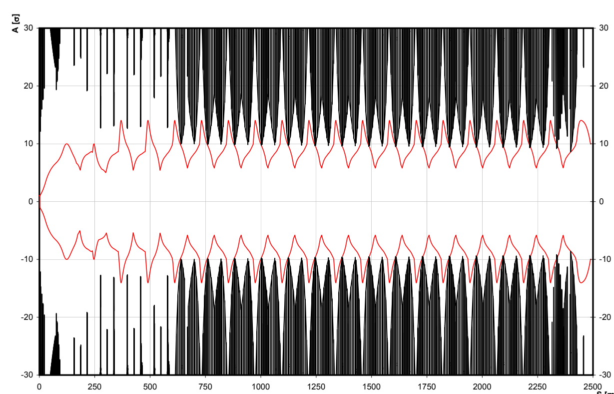

Figure 4: Expected and measured vertical aperture in TI 8, for the perturbed beam optics. The measured edge of the beam envelope (red) is compared to the calculated aperture (black). The measured aperture is about 5.1 nominal σ.

The available aperture of the TI 8 line was also simulated using a Monte-Carlo to generate a set of typical line states, including all errors such as BPM noise, misalignments, power supply ripple, etc. and realistic trajectory correction. The limiting apertures were derived; Fig. 5 shows the distribution of horizontal aperture limits expected with the perturbed optics for a critical MBI chamber.

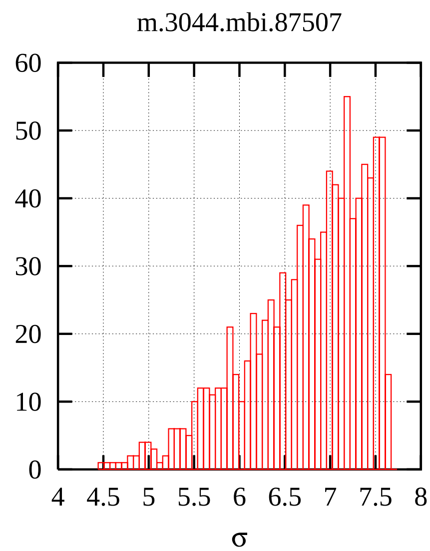

Figure 5: Monte-Carlo results (counts per 0.1 σ bin) showing the distribution of aperture limits for 1000 simulated TI 8 states with all errors.

Second Test With Nominal Optics

The second series of measurements on 7 November 2004 used the nominal optics, with 100 m maximum beta in both planes in the arcs. The aperture was only measured in the horizontal plane, due to time restrictions. Again, a good agreement with the expected aperture was obtained, Fig. 6. The measured aperture is 8.2 σ, larger than the specified value, which indicates that the actual line alignment and/or trajectory correction are somewhat better than assumed.

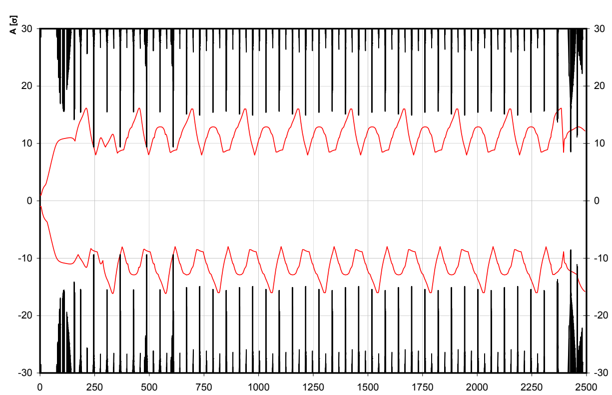

Figure 6: Expected and measured horizontal aperture in TI 8, for nominal beam optics. The measured aperture is about 8.2 nominal σ.

ENERGY ACCEPTANCE MEASUREMENTS

The energy acceptance of the line is a function of the aperture, the optics and the corrected trajectory. For TI 8 the acceptance was checked by simulating the transmission of a beam as a function of the energy offset, using the full aperture model and the various mechanical errors, for 1000 corrected trajectories simulated with all optical and alignment errors. The simulated distribution of transmissions is shown in Fig. 7. Defining the acceptance as the 90% transmission limit, the simulation predicts an energy acceptance for TI 8 of around $\pm$ 0.003.

The energy acceptance was measured with beam during the TI 8 commissioning tests, by varying the RF frequency in the SPS and measuring the transmission through TI 8 of a pilot bunch as a function of energy offset. The results are also shown in 7, where a good agreement with the simulation is evident. It is also possible from this measurement to see that the central energy appears to be mismatched by about 0.0005.

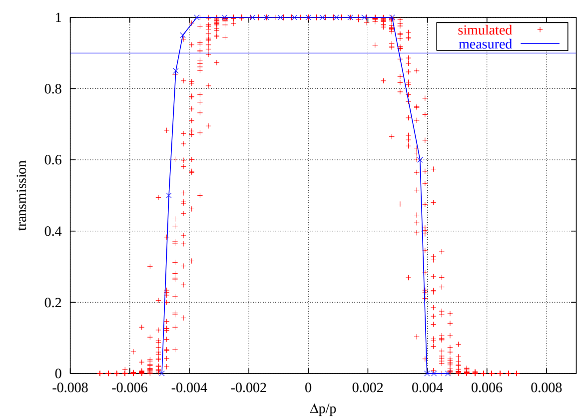

Figure 7: Simulated and measured transmission of TI 8, for different beam energy offsets, for nominal beam optics.

SUMMARY

The aperture of the SPS to LHC transfer lines has been modelled using MADX, and compared to measurements made during the 2004 TI 8 commissioning tests. First results show that the line aperture is in good agreement with the simulations, with a slightly larger aperture than expected in the horizontal plane for the nominal optics, indicating a better alignment and/or trajectory correction than assumed. The energy acceptance of the line was measured at ± 0.003, better than the specification and in good agreement with simulations.

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