Overview of the LHC injection and transfer line optics configurations and tolerances

H. Burkhardt (CERN, Geneva)

Abstract

The SPS and LHC optics have already changed during the LHC design phase and can be expected to further evolve during operation. The combined system of SPS, TI 2, TI 8 and the LHC should be well matched for clean injection and emittance conservation. This implies that the transfer lines have to provide some flexibility. In addition to the requirement to match to the SPS and LHC, new internal constraints in the transfer lines for the phase advance differences between collimators have come up. The expected range of optics changes and the requirements to match these will be critically analysed.

INTRODUCTION

For injection into LEP, it used to be sufficient to make sure that a good fraction of the injected particles was captured. Emittance preservation was not an issue due to the presence of strong radiation damping.

In the LHC instead, any emittance blow-up at injection will directly reduce the luminosity. The LHC design allows for an only 7% emittance increase (3.5 to 3.75 μm in normalized emittance) from extraction in the SPS up to collisions in the LHC. In consequence, an excellent matching at injection is required for the LHC.

Restrictions on particle losses, aperture and beam halo re-population further constrain the already tight requirements on the injection optics. A single injection with 288 bunches of design intensity is well above damage (about $20\times$) and four orders of magnitude above quench level. The geometrical emittance in the LHC is largest at injection and the physical aperture very tight ($\sim 7.5\,\sigma$).

REQUIRED PRECISION IN INJECTION MATCHING

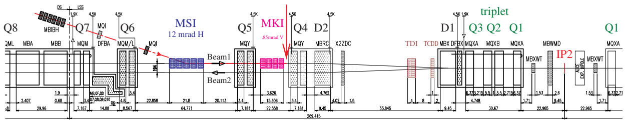

Figure 1: Left side of IR2 with the injection region for LHC ring 1.

At the end of the transfer lines to the LHC, the incoming beams are horizontally deflected in the septum magnets (MSI) and finally vertically deflected on the LHC orbit by the injection kickers (MKI). Optics matching at injection refers specifically to a point (defined by a marker in the Mad-X sequence, LHCINJ.B1 for ring 1 and LHCINJ.B2 for ring 2) between the kicker MKI and the quadrupole Q4, see also Fig. 1. At this point, the β functions are about 60 m and the dispersions of order $D = 10\,\mathrm{cm}$, in both rings and transverse planes (x, y).

There are known theoretical expressions for the emittance increase $\Delta\epsilon/\epsilon$ from mismatch at injection and there is also experience at CERN on injection matching and emittance preservation [1–4]. To remain within the total 7% emittance budget from the SPS up to LHC collisions, we aim at individual contributions not exceeding the 2% level.

- Steering. The specified injection precision is $1.5\,\sigma$ [5]. The transverse damper in the LHC is expected to damp injection oscillations quickly [6] which keeps the emittance blow-up from mis-steering small, on the order of order 0.5%.
- β match. Based on

  $$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2}\frac{(\Delta\beta/\beta)^2 + (\Delta\alpha + \alpha\ \Delta\beta/\beta)^2}{1 + \Delta\beta/\beta}$$

  we estimate, that β functions at injection should be matched to within 10% to keep the emittance blow-up from this source below 2%.
- Dispersion match. Using

  $$\frac{\Delta\epsilon}{\epsilon} = \frac{1}{2}\frac{(\Delta D)^2 + (\beta\Delta D' + \alpha\Delta D)^2}{\sigma^2}\left(\frac{\sigma_p}{p}\right)^2$$

  and a momentum spread of $\sigma_p/p = 5\times10^{-4}$, we find that a dispersion matching to about 10 cm and 4 mrad in D' is required at injection.

A more detailed study on matching requirements at injection, based on analytical expressions and simulation with an evaluation of the effects of geometrical mismatch, coupling, energy errors and tail re-population is planned [7].

OPTICS FLEXIBILITY REQUIRED IN THE TRANSFER LINES TI 2 AND TI 8

On the SPS-side, the most significant optics change in the last years was that the working point was lowered from roughly 26.6 to 26.2 (similar in x, y) which resulted in a 3% change in $\beta_{x,y}$ at extraction and about 10 cm in dispersion. Both transfer lines start with SPS-matching sections which have the flexibility to adapt to changes of this size.

Matching on the LHC side is more difficult. More changes than on the SPS side can be expected and there are more constraints to respect, mainly from phase advance differences between collimators which were added at a later stage [8] to the transfer line design [9].

To see in more detail which flexibility can be expected from the transfer lines on the LHC side, the following points will be discussed in more detail.

1. Q3 move, rematch transfer lines to LHC optics V6.5;
2. Various crossing angle configurations;
3. LHC working point. Integer tune changes;
4. Alignment optics;
5. Change of β^* at injection;
6. Match to the real LHC optics with magnet and alignment errors.

1) Rematch transfer lines to LHC optics V6.5

To leave space for additional non-linear correctors, the Q3 (MQXA) magnets were moved by 0.3 m towards the IP in IR 1,2,5 and 8.

Table 1: Comparison of optics parameters at LHCINJ.B2 between optics versions 6.4 and 6.5 (sep. bumps off).

	β_x m	α_x	D_x m	β_y m	α_y	D_y m
V6.4	49.13	-1.69	-0.11	84.93	1.24	0.00
V6.5	53.23	-1.73	-0.11	75.20	1.22	0.00

The result was a change of about $\pm 10\%$ in $\beta_{x,y}$, see Table 1. The strengths of the Q5 magnets which are common to the LHC and the transfer lines, also changed by about 10%. To re-match the transfer lines to these changes turned out to be particularly difficult for TI 8 [10]. Already previously, it had been difficult to fit the transfer line collimators (TCDI) at four phases $0, 45, 90, 135°$ in the little available space in TI 8 [11]. After the rematch, phase advance offsets increased by up to 24°. Together with cost arguments, this triggered a re-optimisation of TCDI positions at three phases $0, 60, 120°$. These three phases fit much better in the tight space of TI 8 and are easier to adjust than the previous four phases, at a similar level of protection $(1/\cos(60°/2) = 1.15\,, 1/\cos(45°/2) = 1.08)$.

The LHC layout is frozen. Major changes like the Q3 move are not expected in future.

2) Crossing angle configurations

Frequent changes in crossing angles and spectrometer polarities (ALICE in IR2, LHC-B in IR 8) are expected. A summary of the various configurations can be found in the LHC design report [12]. The spectrometer bumps are closed within the Q1 magnet positions left and right of the interaction point (IP) and should not affect the injection at Q4. The external crossing bumps are closed within Q6-Q6 and do not change β-functions (to first order). Changes with crossing angles only effect position and dispersion. See Fig.2 for IR2.

The expected range of dispersion at injection in IR2 is $D_x = -11$ to $-15\,$cm and $D_y = \pm 5\,$cm as a result of polarity changes of the vertical crossing angle within $\pm 170\,\mu$rad.

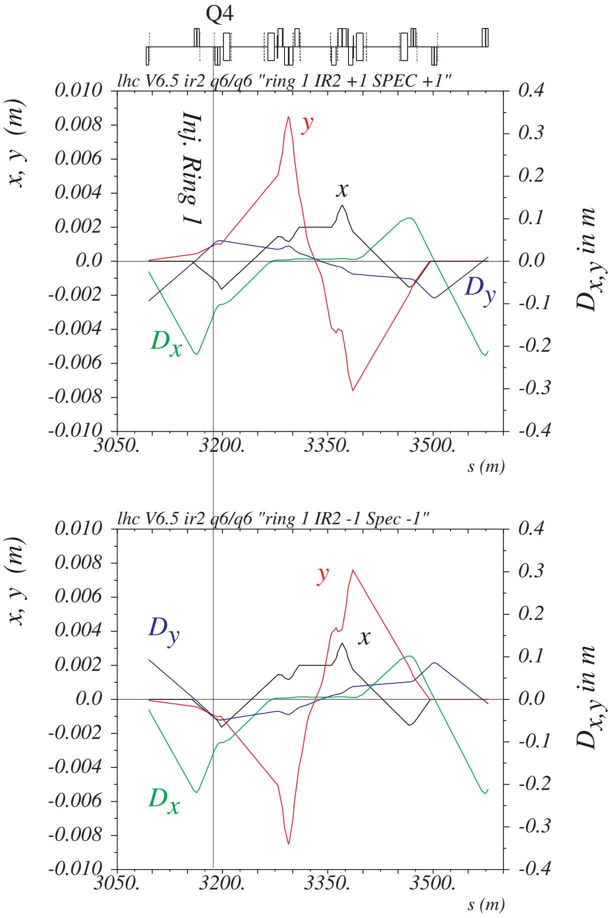

Figure 2: Orbit and dispersion for positive and negative vertical crossing angles at IR2.

For injection in ring 2 at IR8, the crossing angle is in the horizontal plane, see Fig.3.

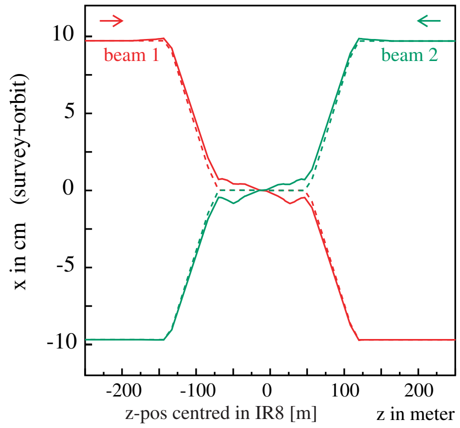

Figure 3: Horizontal beam positions in IR8 with (solid) and without (dashed line) horizontal crossing at IP 8.

Negative external crossing angles would interfere with the geometrical separation between ring 1 and 2 and are not foreseen. The range of dispersion for injection at IR8 to consider is $D_x = -6$ to -11 cm and $D_y = 0$ to 0.4 cm from zero horizontal crossing angle up to $+170\,\mu$rad.

3) LHC working point. Integer tune changes

It used to be some kind of tradition to discuss and decide on major LEP optics changes in Chamonix workshops for various reasons like coupling, beam-beam and emittance. Over the years we had a whole range of optics configurations with $60°/60°$ (with integer tunes at 70/78, 71/77 and 71/76), $90°/90°$, $90°/60°$ and $102°/90°$.

The tunes of the design optics for the LHC are $Q_x = 64.28$ and $Q_y = 59.31$, with an integer tune difference of $\Delta Q = 5$. A possible alternative could be the "resonance-free" lattices considered by A. Verdier for the LHC [12] with $Q_x = 59.28, Q_y = 51.31$ or $Q_x = 67.28, Q_y = 59.31$ (both with $\Delta Q = 8$). A discussion of advantages and drawbacks (problems with beam-beam etc.) is outside the scope of this contribution.

Here it is sufficient to note that the change in the integer part of the tunes can be achieved with the quadrupoles in the arcs and that it is possible to match the insertions using the quadrupoles Q6 to Q13 in a way which is transparent for injection, [13]. The phase advance between the kicker and TDI ($\Delta\mu_y = 90°$) and the optics at injection close to Q4 remain unchanged.

4) Alignment optics

Special alignment optics, in which the triplet quadrupoles Q1-Q3 are turned off have been studied for the low β insertions IR1, IR5 and more recently also been considered for IR2, see Fig. 4.

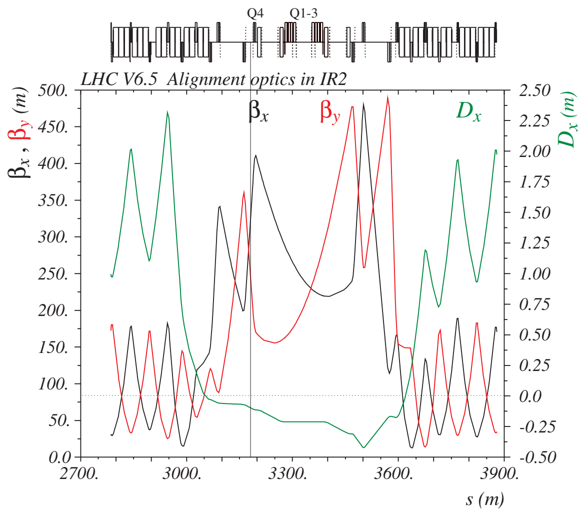

Figure 4: IR2 alignment optics.

The β functions at injection close to Q4 increase by about a factor of five compared to the standard optics and the $90°$ phase advance between the kicker and TDI is lost (reduced to $\Delta\mu_y \approx 20°$). This is not suitable for injection, except maybe for very low intensity pencil beams for special machine studies.

It should however be possible to completely avoid injection into an IR with alignment optics. Measurements with the alignment optics in IR2 can be done using beam 2 injected with the standard optics in IR8 and vice versa.

5) Change of β^* at injection

We currently have $\beta^* = 10$ m in IR2, 8 at injection. What would happen if β^* would be increased to $\beta^* = 18$ m as in IR1 5 ? A. Lombardi recently rematched the IR8 optics with the MKI/TDI constraint for $\beta^* = 13, 15$ and 18 m. The optics at injection close to Q4 (at the LHCINJ.B2 marker) increased about linearly with the β^*. A change from $\beta^* = 10$ m to $\beta^* = 18$ m implies an 80% increase in β at injection and a re-match would require hardware modifications.

6) Match to the real LHC optics with magnet and alignment errors

We assume that large optics and alignment errors will already have been corrected in the LHC, to a level of about 20% in β and 10% in residual dispersion (about 12 cm at injection). A first level of corrections in the LHC at injection will primarily be driven by aperture considerations rather then luminosity as magnet errors will change with the ramp&squeeze.

To minimise blow-up at injection, the transfer lines should allow to match to the real LHC optics (be able to adjust to 20% changes in $\beta_{x,y}$ and at least 10 cm in dispersion) at the injection points.

FLEXIBILITY OF THE TRANSFER LINES TO ADAPT TO OPTICS CHANGES

In principle, we require a match to β and β' (α), D and D' both in x, y and both on the SPS and LHC side and in addition there are constraints on the phase advance differences between the TCDI transfer line collimators. The rematch for optics V6.5 following the Q3 move has shown that already changes of the order of $\pm 10\%$ in β may be very hard to accommodate, in the presence of the additional constraints.

A more flexible optics solution was meanwhile obtained for TI 8 with fewer $0, 60, 120°$ TCDI collimators and modification of one quadrupole position (of MQID879 in the LHC matching section by about 2 m). TI 2 has more space and should be easier to adapt. The TI 2 optics with $0, 60, 120°$ TCDI positions is being finalised and first flexibility checks on TI 2 have started.

Several particular cases to adapt to changes on the LHC side have been considered and two of these will now be used to illustrate the existing flexibility.

Fig. 5 shows the current TI 8 optics towards the end of the line with the LHC matching section. The result of a re-match for a 20% increase in β_x at the end of the line

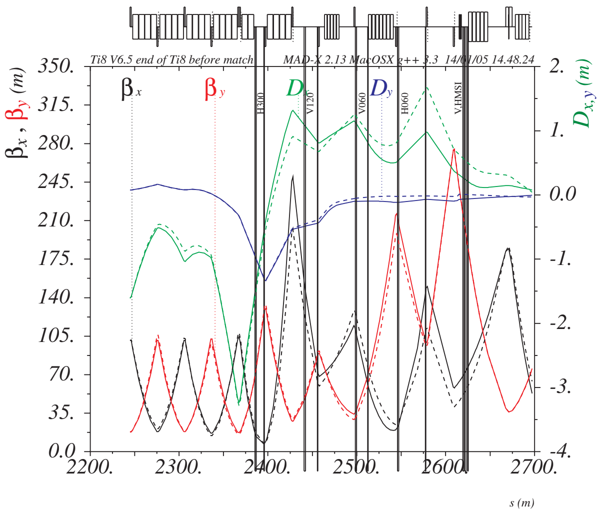

Figure 5: Optics towards the end of TI 8 before (solid line) and after (dashed line) the re-match for a 20% increase in β_x at injection into the LHC.

at injection into the LHC is shown as dashed line. The positions of the TCDI collimators and shields is indicated by vertical lines. As a result of the re-match, the horizontal phase advance between the TCDI collimators changed by $+15°$ for TCDIH060 and $-6°$ for TCDIH300. This implies a loss in the protected aperture of the order of 10% (to be verified by tracking).

Fig. 6 shows a re-matching based on the current TI 2 optics version with $0, 60, 120°$ TCDI positions. The result of a re-matching to increase the vertical dispersion D_y by +12 cm using the existing flexibility is shown on the top. It results in some β and dispersion beating. A cleaner re-match was found when two extra quadrupoles (marked in red in Fig. 6) were allowed to vary in strength. This could be realised with two separately powered circuits, at a price tag of about 280 kCHF.

REMARK ON DISPERSION MATCHING

Dispersion matching can in principle also be achieved using orbit correctors. There has been good experience in LEP using orbit correctors to minimise dispersion, with the possibility of dispersion free steering [14]. A potential advantage in using orbit correctors rather than quadrupoles to match dispersion is that this would to first order de-couple dispersion and β-function matching. It could be a good solution for the small dispersion changes depending on the various crossing angle schemes.

Dispersion matching at injection using orbit correctors could be done in principle from both sides, the transfer lines and the LHC. It remains to be shown that this can be done with the available correctors and without significant reduction in aperture.

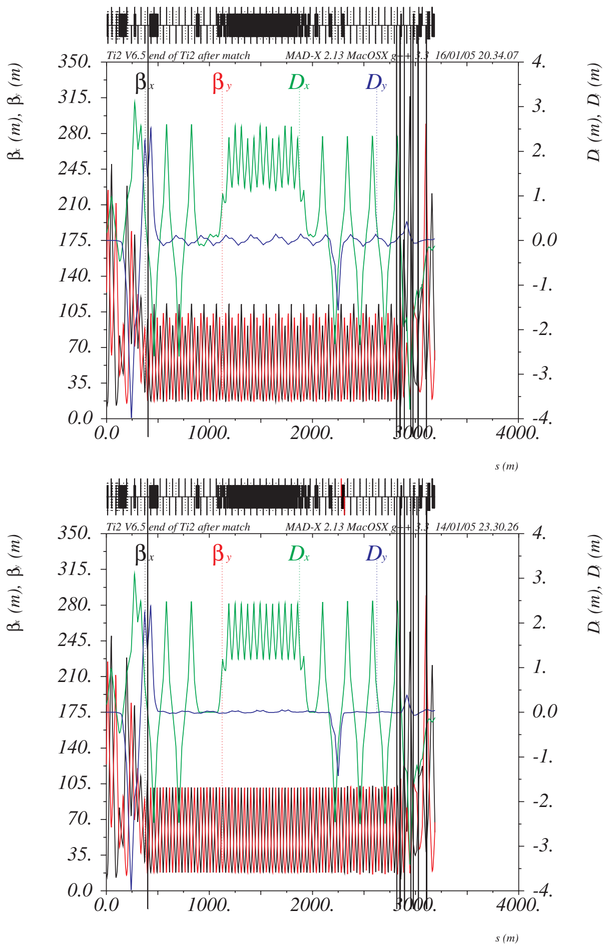

Figure 6: TI 2 optics rematched for a 12 cm increase in D_y. The result of a rematch with the existing flexibility is shown on the top and the result of a rematch with two extra power supplies on the bottom.

SUMMARY

Excellent optics matching at injection is important for the LHC. A flexibility of about 20% in β-functions and 10 cm in dispersion is required to be able to adapt to crossing angles and to match to the real LHC machine including errors and tolerances. This is feasible with the transfer lines but implies compromises in collimation. The transfer line collimators (TCDI) are located in the LHC matching sections which couples β-functions and phase advance between the TCDIs. A 20% change in β can cause a change in phase advance between TCDIs of $15°$ and reduce the protected aperture by about 10%.

Much larger changes in β (for example by a factor of 1.8 to follow the change of β^* from 10 to 18 m) cannot be expected to be matched without hardware changes.

The alignment optics (Q1-3 off) should not be used in the IR where the beam is injected.

Some gain in flexibility (demonstrated for dispersion), can be achieved with extra power converters, but probably also using orbit correctors. Orbit optimisation ("golden orbits") used to be very important in LEP at collision energy to improve luminosity. In the LHC it may be worth to carefully study orbits at injection, to match well dispersion at injection and optimise aperture.

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