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LHC LEAD ION BEAM OPTICS WITH LOW-BETA INSERTION FOR THE PS TO SPS TRANSFER LINE

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Abstract

In the context of the LHC operation with lead ions programme, a low-β insertion was implemented in the PS to SPS transfer line TT2, for the stripping foil installation, in order to reduce the beam emittance blow-up at the foil to values consistent with the tight emittance budget of the LHC. Extra quadrupoles and power converters had to be installed in TT2, in order to obtain a satisfactorily low-β at the stripper location and a good quality matching of the line at the SPS injection. The performance of the new optics is discussed and measurements results in TT2 and in the SPS with the "early ion beam" are presented.

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1. INTRODUCTION

In the framework of the LHC ion programme Pb^{54+} ion bunches are ejected and fully stripped to Pb^{82+} in the TT2 transfer line to SPS after acceleration to 5.88 GeV/u in the PS (i.e. momenta of 26 and 17.1 GeV/c proton equivalent before and after ion stripping). To cope with the tight transverse emittance budget, a low-β insertion has been studied [1-3] and subsequently implemented to minimise emittance increase as a result of multiple scattering in the stripping foil. The commissioning steps for the low-β insertion and the matching of the line to the SPS are discussed. The performance of the low-β stripping insertion is compared to that of the former fixed-target ion programme, where the stripper was located close to the junction of the TT2-TT10 transport lines between PS and SPS.

2. PERFORMANCE IN 2006 (TT2)

Ion stripping with low-β insertion in TT2

The transverse emittance values of the ion beams required to achieve the mandatory luminosity for the lead experimental programme in the LHC is reminded in Table 2.1. Emittance preservation is vital because of the small 0.3 μm emittance increase permitted for the blow-up between the LEIR and PS machines.

Table 2.1: Normalized r.m.s. emittance figures for the LHC ion programme.

Machine (at top energy)	Normalized r.m.s emittances $\varepsilon^*_{H,V}$ [μm]			
	LEIR	PS	SPS	LHC
Ions for LHC	0.7	1.0$^{(1)}$	1.3	1.5

$^{(1)}$ Value after the stripping process just before injection into the SPS.

Lead and indium ions were used in the past for SPS fixed-target experiment runs. The lead ions were stripped in TT2 from Pb^{53+} to Pb^{82+} at 4.25 GeV/u by a 0.8 mm thick aluminium foil. Indium ions were stripped from In^{37+} to In^{49+} at 5.58 GeV/u by a 0.5 mm thick aluminium foil. For the lead ion SPS fixed-target runs the optical parameters at the former stripper location for the related optics are listed in Table 2.2.

Table 2.2: Optical parameters at ex-stripper position for the past lead ion optics (without low-β insertion).

Location	Horizontal				Vertical			
	β_H[m]	α_H	D_H[m]	D'_H	β_V[m]	α_V	D_V[m]	D'_V
TT2 entry	26.42	-2.35	3.63	0.40	5.72	0.31	-0.48	0.03
Old stripper	23.50	-1.71	-2.95	-0. 34	22.13	1.13	-1.06	0.06

Measurements of lead ion emittance growth due to stripping were performed in 1995 for a 0.8 mm thick aluminium foil. Measured transverse normalized r.m.s emittance increments due to the stripper foil at 4.25 GeV/u were about 0.58 to 0.77 μm [4, 5] while calculations for this situation gave about 0.42 to 0.45 μm (cf. Table 2.5 below). Such blow-ups are incompatible in future with the LHC beam requirements for the transverse emittances.

To restrict the above mentioned blow-ups, a low-β insertion at stripper was implemented at about 70 m from the entrance of TT2, upstream the beginning of the present two quadrupole strings (called families QDE210.S and QFO215.S). The stripper foil was moved from its past location at TT2 end (≈302 m) to the new location (≈70 m from TT2 entry). Detailed analysis showed that the quadrupole arrangement used up to now lacked to match the optical parameters at the junction of the TT2 and TT10 lines. Therefore, four new quadrupoles were added and the first quadrupole of the two quadrupole strings had to be powered individually to complete the matching [3].

First nominal TT2 ion optics at 5.88 GeV/u with low-β insertion

The earlier TT2 ion optics with low-β insertion [1, 2] conceived for ion transfer energy at 4.25 GeV/u has been modified to fit the present 5.88 GeV/u ion energy and was preliminary tested during the 2006 pre-commissioning of the transfer line [6]. Next, in 2007 a revised first nominal TT2 optics with low-β insertion was re-calculated using the optical parameters at the entrance of TT2 obtained from the latest (2007) TT2-TT10 optics measurement [7] for the LHC proton beam (at 26 GeV/c). Figure 2.1 illustrates this first TT2 ion optics. Table 2.3 lists the optical parameters at the stripper position. Although the optics parameters at TT2 entrance are subject to inherent uncertainties, this optics is sufficiently flexible to guarantee stable conditions at the stripper for different initial parameters in the proximity of those measured while keeping the optics at the end of the TT2-TT10 line matched to the SPS optics at the injection point. On the whole, with the low-beta insertion and the rise of the PS ejection energy from 4.25 to 5.88 GeV/u, the betatron functions and thus the emittance blow-up due to multiple Coulomb scattering should be reduced to about 20% of the value attained by way of the former fixed-target optics.

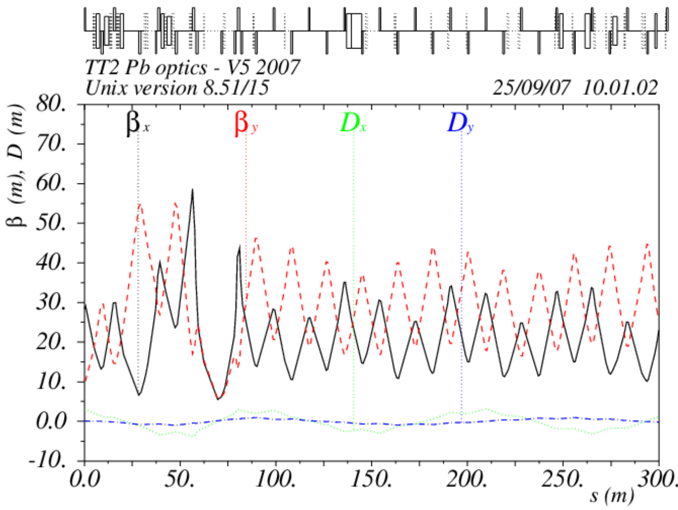

Figure 2.1: Betatron and dispersion functions of the first nominal optics in TT2 with low-β insertion for the LHC lead ion programme (distance from entrance of TT2, the stripping foil is at 69.27 m from TT2 entry).

Table 2.3: Optical parameters at stripper position and TT2 entry/exit for the first nominal optics with low-β insertion at the stripper.

Location	Horizontal				Vertical			
	β_H[m]	α_H	D_H[m]	D'_H	β_V[m]	α_V	D_V[m]	D'_V
TT2 entry [(1)]	28.380	-2.526	2.960	0.200	10.460	0.820	0.100	-0.025
Stripper	5.547	-0.008	-0.006	0.234	5.658	0.040	0.129	0.058
TT2 exit [(1)]	37.633	0.997	2.021	0.018	15.388	-0.385	-0.279	-0.040

[(1)] Optics parameters at TT2 entry and TT2 exit (i.e. TT10 entry) are those of the LHC proton optics, derived from recent measurements and re-matching [7].

Table 2.4 displays the effect of the foil thickness and beam energy on the relative emittance increase. It shows that the blow-up at 5.88 GeV/u contracts to around 74% of its value at 4.25 GeV/u (using the same 0.8 mm thick foil) and to about 46% of its 4.25 GeV/u value when decreasing the foil thickness to 0.5 mm. Unfortunately, the global benefit in emittance blow-up reduction is counterbalanced by a decrease of stripping efficiency as the foil thickness gets smaller.

Table 2.4: Simple scaling of normalized emittance blow up for lead ion stripping ($\Delta\varepsilon^*_{H,V} \propto d/\beta^3\gamma$).

Kinetic energy E_k	4.25 GeV/u	5.88 GeV/u	5.88 GeV/u
Stripper thickness d	0.8 mm	0.8 mm	0.5 mm
Emittance blow up ratio $\Delta\varepsilon^*_{H,V\,at\,E_k} / \Delta\varepsilon^*_{H,V\,at\,4.25\,GeV/u}$	1	0.74	0.46

Measurements carried out at 4.25 GeV/u [4, 5] showed that the efficiency drops from about 96% to 83% when reducing the aluminium foil thickness from 0.8 mm to 0.5 mm. It follows that the choice of the stripper thickness is a trade-off between the emittance blow-up and the stripping efficiency. A 0.5 mm thick aluminum foil was installed for the former indium ion run. Simulations (using a version of the GSI programme CHARGE working for kinetic energies up to 2 GeV/u [8]) showed that the stripping efficiency of indium ions remains very close to 100% for aluminum foil thicknesses from 1 mm (99.9%) down to 0.3 mm (where it reaches 99.5%), then the efficacy drops to 96.7% at 0.2 mm and 77% at 0.1 mm. Unlike indium ions, Figure 2.2 shows that the lead ions stripping efficiency decreases more regularly as the foil thickness shrinks. A 0.8 mm thick aluminum foil has been selected for the TT2 low-β insertion stripper. It should be mentioned that the stripping efficiency should increase with energy therefore the quoted values are pessimistic.

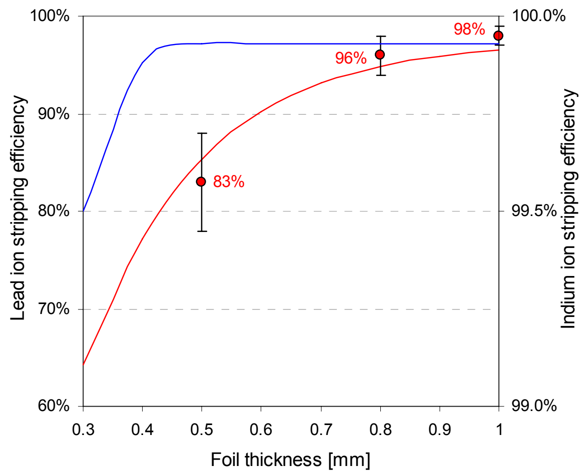

Figure 2.2: Lead and indium ion stripping efficiency versus aluminum foil thickness [mm]. The solid line shows the efficiency computed by the GSI CHARGE code; the dots show the measured lead efficiency after stripping.

Notice that a non-zero dispersion function value at stripper can give rise to further emittance growth due to coherent energy loss following ion stripper crossing (estimated to ≈12 MeV/u, i.e. 0.2% of the 5.88 GeV/u energy). If needed, this occurrence can be prevented by scaling down the magnet strength after the stripper for the lower energy. Finally, the energy spread introduced by the straggling effect (incoherent energy loss) for a 0.8 mm thick aluminium foil produces a minor relative momentum spread of approximately 4×10^{-5} at 5.88 GeV/u. The emittance blow-ups computed for the past SPS ion fixed-target optics and the new LHC ion optics with low-β are shown in Table 2.5 for the measured [4, 5] and "scaled" low-β optics.

Table 2.5: Normalized r.m.s emittance blow-ups as a result of multiple Coulomb scattering and energy straggling in a 0.8 mm thick aluminium stripping foil. Calculated blow-ups apply to the past lead ions optics at 4.25 GeV/u and to the new low-β optics at 5.88 GeV/u. Emittance blow-ups using "scaled" low-β optics are defined as the ratio of the computed blow-up with a low-β insertion over the computed blow-up without a low-β insertion (weighted with the proper energy), times the measured blow-ups (observed without a low-β insertion in TT2).

Optics	$\Delta \varepsilon^*_H$ [μm]		$\Delta \varepsilon^*_V$ [μm]	
	Scattering	Straggling	Scattering	Straggling
Calculated past (4.25 GeV/u)	0.45	3×10^{-3}	0.42	2×10^{-4}
Calculated low-β (5.88 GeV/u)	0.07	4×10^{-3}	0.06	3×10^{-4}
Measured 1995 (4.25 GeV/u)	0.77		0.58	
"Scaled" low-β (5.88 GeV/u)	0.14		0.12	
Measured 2006 (5.88 GeV/u)(1)	0.12		0.09	

(1) Emittance blow-ups derived from measurements made with the stripper in and out (quadrupole currents scaled downstream the stripper to cope with the charge state when the stripper is out) and using the 2006 optics.

First quadrupole and converter characteristics for the low-β insertion

The first two quadrupoles of the TT2 strings QDE210.S and QFO215.S (made up 14 and 13 quadrupoles) are now powered independently with individual converters and have been named QDE210 and QFO215 with the names of their first quadrupoles. The strings have been renamed QDE220.S and QFO225.S. Henceforth the number of TT2 quadrupoles available to tune the low-β ion optics will be equal to 13 instead of the 7 quadrupoles used thus far to match the proton optics. The layout for the low-β insertion with the magnet characteristics and the nominal power converter currents of the first nominal TT2 ion optics are depicted in Figure 2.3 and in Table 2.6. The maximum integrated gradients for the five types of installed quadrupoles Q50A (of length 0.5 m), QF101 (0.7 m), Q80 (0.8 m), Q82 (0.82 m) and Q120B (1.2 m) are 5.57, 13.92, 15.64, 16.66 and 23.20 T, respectively. Note that the converters connected to the magnets do not allow all the quadrupoles to reach their maximum strength. The former magnet QFO215 of type Q80 (now disconnected from the string) has been removed, renamed as the new QDE217, then installed at that new location and replaced by a longer magnet of type Q120B because of the high strength required by QFO215 for the ion optics. Among the four new magnets, QDE207, QDE213 and QDE217 have a 100 mm aperture, similar to that of the other quadrupoles in TT2, while QDE163 has a larger aperture of 130 mm. Since these new magnets are installed very close to other TT2 quadrupoles, they have been equipped with the same type of vacuum chamber (round or elliptic) of their adjacent quadrupoles but for QDE163 whose aperture is larger. It should be emphasized that, except for QDE163, the vacuum pipe aperture in the TT2 drifts is systematically larger (130 mm) than that of the quadrupoles. During the 2006 commissioning one quadrupole (QFO205) was equipped with a power converter limited in current. The first nominal low-β optics was thus re-calculated at best to overcome the quadrupole current constraint (maximum current of 330 A in place of 450 A primarily foreseen) and tested. Figure 2.4 displays the TT2 aperture over the first 100 m of the line and the half-beam envelopes ($\pm 2.5\sigma_{H,V}$), assuming a transverse normalized emittance of 1.5μm and a momentum spread of 0.5e-3 (nominal ion beam).

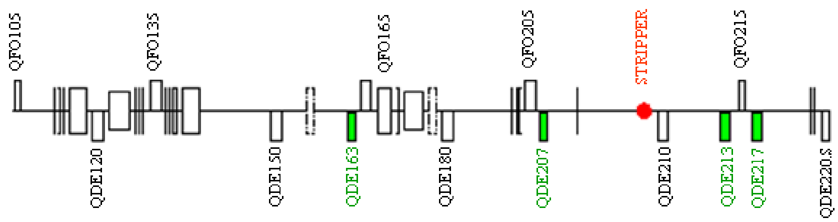

Figure 2.3: The first 90 m of the TT2 transfer line with the first low-β insertion optics. 6 individual converters supply the 4 new quadrupoles QDE163, QDE207, QDE213, QDE217 and QDE210, QFO215 disconnected from the strings.

Table 2.6: TT2 quadrupole characteristics for the present ion optics and the first nominal ion optics with low-β insertion, [1] new quadrupole, [2] new power converter, [3] $B\rho^{54+}$=86.7 Tm, $B\rho^{82+}$=57.1 Tm after stripping.

Quadrupole	Type (magnetic length)	4.25 GeV/u ion optics (past SPS fixed target)		5.88 GeV/u ion optics (LHC ion programme)			
		Integrated gradient	Current	Integrated gradient	Current	Max |current|	Strength
QF0105	QF101 (0.7 m)	7.26 T	395.5 A	11.805 T	550.0 A	550 A	0.21117 m^{-2}
QDE120	Q120B (1.2 m)	-8.23 T	-233.4 A	-10.349 T	-200.9 A	265 A	-0.09950 m^{-2}
QFO135	Q120B (1.2 m)	7.91 T	213.7 A	11.060 T	214.7 A	220 A	0.10634 m^{-2}
QDE150	Q120B (1.2 m)	-6.31 T	-151.8 A	-6.384 T	-124.2 A	250 A	-0.06139 m^{-2}
QDE163 [1,2]	Q50A (0.5 m)			-4.532 T	-235.7 A	300 A	-0.10459 m^{-2}
QFO165	Q120B (1.2 m)	5.85 T	94.3 A	12.473 T	242.3 A	250 A	0.11993 m^{-2}
QDE180	Q120B (1.2 m)	-5.30 T	-131.2 A	-8.401 T	-163.2 A	250 A	-0.08078 m^{-2}
QFO205	Q120B (1.2 m)	5.80 T	122.6 A	21.778 T	449.7 A	450 A	0.20940 m^{-2}
QDE207 [1,2]	Q120B (1.2 m)			-18.676 T	-371.0 A	450 A	-0.17957 m^{-2}
Stripper (Al 0.8 mm) [3]							
QDE210 [2]	Q82 (0.82 m)	-6.02 T	-219.3 A	-0.985 T	-27.7 A	400 A	-0.02105 m^{-2}
QDE213 [1,2]	Q80 (0.8 m)			-10.953 T	-316.0 A	400 A	-0.23990 m^{-2}
QFO215 [2]	Q120B (1.2 m)	6.56 T	241.2 A	20.227 T	408.0 A	500 A	0.29534 m^{-2}
QDE217 [1,2]	Q80 (0.8 m)			-7.788 T	-222.5 A	300 A	-0.17057 m^{-2}
QDE220.S	Q82 (0.82 m)	-6.02 T	-219.3 A	-4.953 T	-139.0 A	250 A	-0.10583 m^{-2}
QFO225.S	Q80 (0.8 m)	6.56 T	241.2 A	5.640 T	161.2 A	330 A	0.12353 m^{-2}
QFO375	Q80 (0.8 m)	3.70 T	255.0 A	4.730 T	135.3 A	330 A	0.10360 m^{-2}

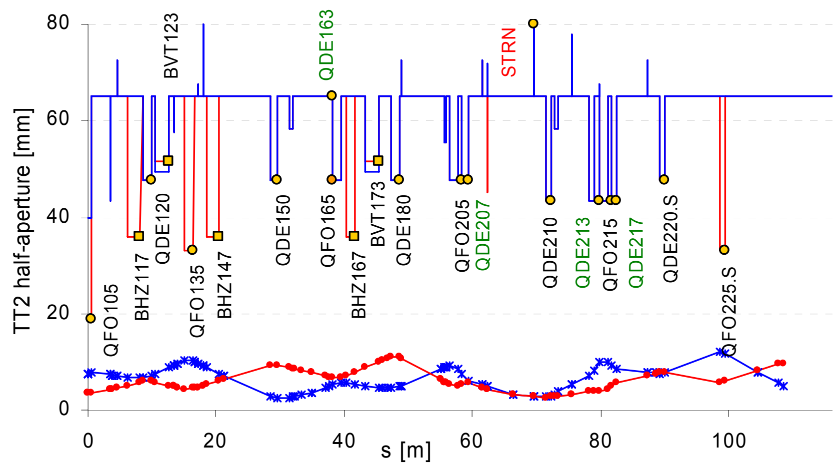

Figure 2.4: Horizontal and vertical half-apertures and beam half-width and half-height (at ±2.5 $\sigma_{H,V}$) of the TT2 transfer line [mm] along the first 100 m for the new low-β insertion optics. Only the dipole and quadrupole magnets together with the stripper are labelled. The vacuum chamber aperture in the straight sections is 130 mm (round pipe diameter). The beam emittance and momentum spread are ε*=1.5μm and $\sigma_{\Delta p/p}$=0.5e-3 (nominal ion beam).

3. PROTONS COMPATIBILITY

The many proton beams shaped by the PS for the SPS are sent throughout the TT2-TT10 transfer lines between the two rings. For these beams the 4 new quadrupoles QDE163, QDE207, QDE213 and QDE217 (used for the lead ion optics with low-β) must be set to zero gradient values for not disturbing the related proton optics and thus not causing any mismatch. It has been estimated that the magnet residual field can induce gradient errors not exceeding 0.1% (of the maximum gradient). Figure 3.1 displays the results of simulations that have been performed to evaluate the expected relative increase in transverse emittances due to the dispersion and betatron mismatches attributable to small variations of the 4 new quadrupole gradients (e.g. a gradient error of 1.2% would correspond to an equivalent residual quadrupole current of about 5 A). Simulation show that the r.m.s. emittance blow-up of proton beams due to the residual field in the new quadrupoles should be less than 0.1% for residual field gradient errors below 0.1%.

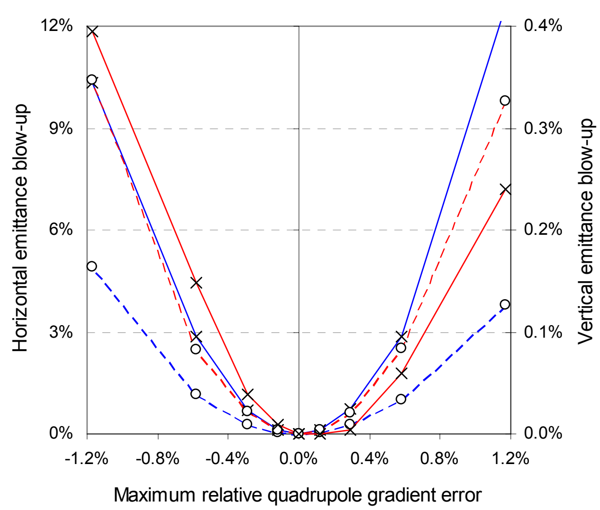

Figure 3.1: Relative expected horizontal and vertical emittance blow-ups of proton beams in the SPS due to dispersion (continuous lines) and betatron (dashed lines) mismatches attributable to the mean relative quadrupole gradient errors (w.r.t. maximum possible gradient value) because of the residual field in the extra quadrupoles required for the ions low-β insertion.

4. PERFORMANCE IN 2007 (TT2-TT10)

During the 2007 re-commissioning of the PS to SPS transfer line (via the "Early ion beam") new TT2 nominal ion optics with low-β insertion has anew been re-calculated based on optics measurements at TT2 beam profile monitor locations (SEM-wire MSG257, MSG267, MSG277, sited downstream the stripping foil) and by taking into account the effect of Coulomb scattering at the stripper.

From the SEM-wires measurements, the Twiss parameters, dispersion function and its derivative are computed at the first monitor MSG257 and propagated back to the stripper location, where the correction due to multiple Coulomb scattering at the foil is applied. Then, the corrected optical parameters are further tracked back to the beginning of TT2 and are used for a re-matching of the line. The matching has been done in two steps: from the entrance of the line to the stripping foil (low-β insertion) and the rest of TT2 and TT10 to the injection in SPS. At the stripping foil location, the Twiss parameters modification due to multiple Coulomb scattering is again taken into account.

Scattering and Twiss parameter change

The change in Twiss parameters due to the scattering process in the stripper is given by the formulae [2]:

$$\alpha = \frac{\alpha_0 \varepsilon_0 - \frac{L}{2}\langle\theta^2\rangle}{\varepsilon_0 + \Delta\varepsilon} \quad \beta = \frac{\beta_0 \varepsilon_0 + \frac{L^2}{3}\langle\theta^2\rangle}{\varepsilon_0 + \Delta\varepsilon} \quad \gamma = \frac{\gamma_0 \varepsilon_0 + \langle\theta^2\rangle}{\varepsilon_0 + \Delta\varepsilon} \qquad (1)$$

In these expressions α_0, β_0, γ_0 and α, β, γ denote the Twiss parameters before and after scattering, L is the length of the stripper and $\langle\theta^2\rangle^{1/2}$ the r.m.s. scattering angle given by

$$\sqrt{\langle\theta^2\rangle} = \frac{13.6\, z}{\beta\, \mathrm{p}} \sqrt{\frac{\chi}{X_0}} \left(1 + 0.038 \ln \frac{\chi}{X_0}\right) \qquad (2)$$

where X_0 is the radiation length of the stripper material, z, p, β and χ are the charge state, the total momentum (MeV/c), the usual relativistic parameter and stripping foil thickness. The resulting emittance growth due multiple scattering throughout the stripper is

$$\Delta\varepsilon = \frac{1}{2}\langle\theta^2\rangle \left(\beta_0 + L\alpha_0 + \frac{L^2}{3}\gamma_0\right) \qquad (3)$$

New optics parameters at TT2 entry

From the SEM-wire profiles and dispersion measurements, the Twiss parameters, dispersion and its derivative are computed at the first monitor MSG257 (as displayed in Table 4.1) and tracked back to the stripping foil. Figure 4.1 shows the MAD-X results of the backward propagation of the optical parameters to the stripper location.

Table 4.1: Optics measurement at SEM-wires with the first nominal TT2 ion low-β optics.

Location	Horizontal				Vertical			
	β_H [m]	α_H	D_H [m]	D'_H	β_V [m]	α_V	D_V [m]	D'_V
MSG257	15.61	1.00	-1.859	0.146	41.50	-1.99	0.282	0.010
MSG267			-0.378 (1)				0.143 (1)	

(1) The dispersion D_H at a 2nd monitor is required to derive the derivative D'_H at the 1st monitor via the transfer map between the two monitors.

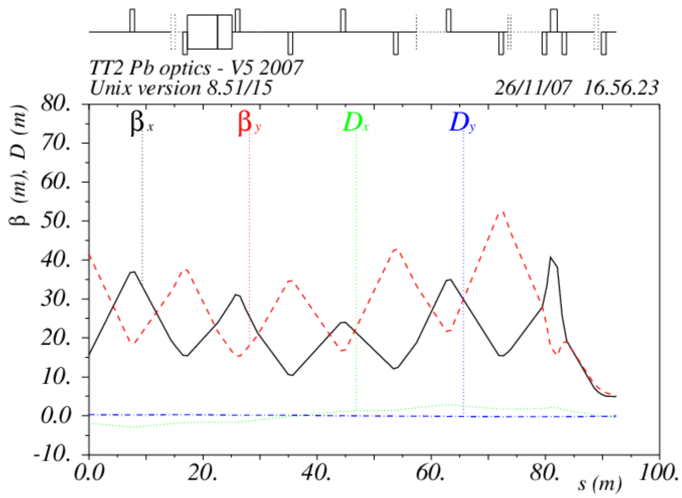

Figure 4.1: Betatron and dispersion functions of the first nominal optics in TT2 with low-β insertion (tracking back from the first beam position monitor MSG257 to the stripping foil, the covered distance being 92.4 m). At stripper entry (after scattering): $\alpha_{H,V}$ =-0.172/0.062 and $\beta_{H,V}$ =4.98/5.07 [m] (backwards direction, the beam moves from right to left).

At the stripper, the effect of multiple Coulomb scattering is computed from the formulae (1)-(3) for a 0.8 mm thick aluminium foil (p=208×6.748 GeV/c, β=0.991, z=82, χ=0.8 mm, X0=89 mm, L=0.8 mm). Since it is a backtracking, the optical parameters and emittance before the scattering have to be computed by knowing the ones at the exit of the foil. The results are summarized in Table 4.2, while Figure 4.2 shows the change of shape of the horizontal and vertical phase plane ellipses before and after the scattering.

Finally, the optical parameters can be propagated back from the stripper location to the entrance of TT2 using the transfer matrices to provide updated initial conditions allowing a proper re-matching of the line, as illustrated in Figure 4.3.

Table 4.2: Change in Twiss parameters and normalized beam emittances due to multiple scattering in the stripper.

	Before scattering			After scattering		
	$\alpha_{H,V}$	$\beta_{H,V}$ [m]	$\varepsilon^*_{H,V}$ [μm]	$\alpha_{H,V}$]	$\beta_{H,V}$ [m]	$\varepsilon^*_{H,V}$ [μm]
Horizontal	-0.199	5.75	0.51(1)	-0.172	4.98	0.59(2)
Vertical	0.073	5.94	0.47(1)	0.062	5.07	0.55(2)

(1) Calculated with formulae (2)-(3), (2) 2007 measurements with SEM-wire monitors.

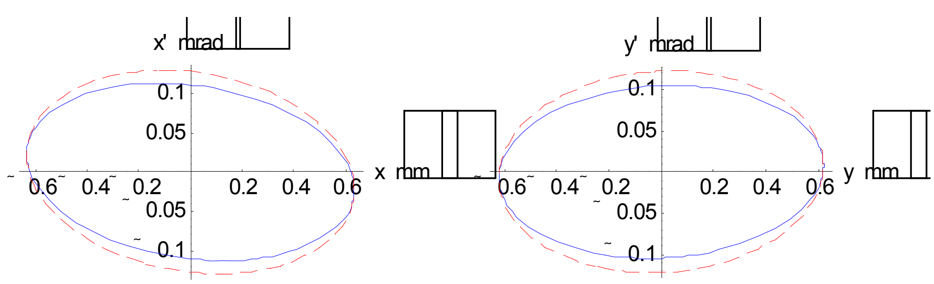

Figure 4.2: Change of horizontal (left) and vertical (right) phase plane ellipses due to the scattering through the stripper for the first nominal low-β ion optics (continuous/dashed curves represent ellipses before/after the scattering process).

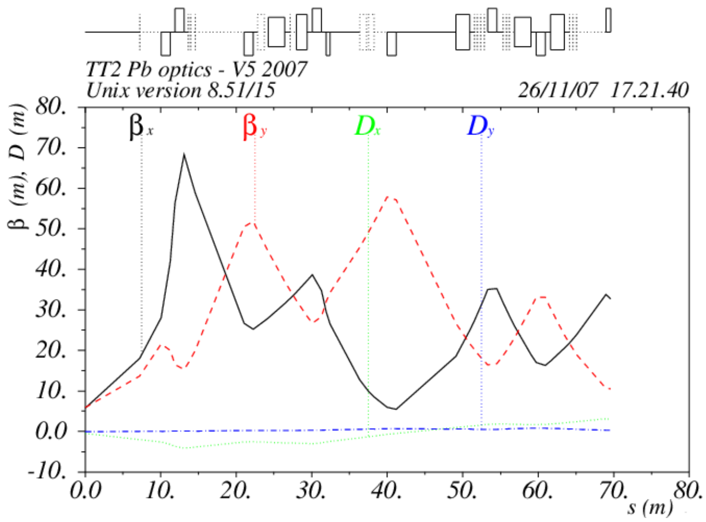

Figure 4.3: Betatron and dispersion functions of the first nominal optics in TT2 with low-β insertion (tracking back from the stripping foil to the entrance of TT2, the covered distance being 69.6 m). At stripper exit (before scattering): $\alpha_{H,V}$ =-0.199/0.073 and $\beta_{H,V}$ =5.75/5.94 [m] (backwards direction). At TT2 entry: $\alpha_{H,V}$ =3.074/-0.706 and $\beta_{H,V}$ =32.74/10.56 [m] (backwards direction, the beam moves from right to left).

New nominal TT2-TT10 ion optics with low-β insertion

Matching to the stripping foil

Using the latest initial conditions at the entrance of TT2 derived from measurements, a new nominal optics in TT2 has been re-calculated. In order to minimize the emittance blow-up due to scattering at the foil, the optics of the line has been matched to have at the stripper location β=5.5m and α=0 in both planes and dispersion and its derivative as small as possible (compatible with the constraints on the maximum currents of the quadrupole converters). Table 4.3 displays the optical parameters at TT2 entry and at the stripper position and Figure 4.4 shows this new nominal TT2 ion optics up to the stripper position.

Table 4.3: Optical parameters at stripper position and at TT2 entry for the new nominal optics with low-β insertion.

Location	Horizontal				Vertical			
	β_H[m]	α_H	D_H[m]	D'_H	β_V[m]	α_V	D_V[m]	D'_V
TT2 entry	32.738	-3.074	3.097	0.250	10.561	0.706	0.301	0.018
Stripper	5.500	0.000	-0.004	0.213	5.500	0.000	0.002	-0.018

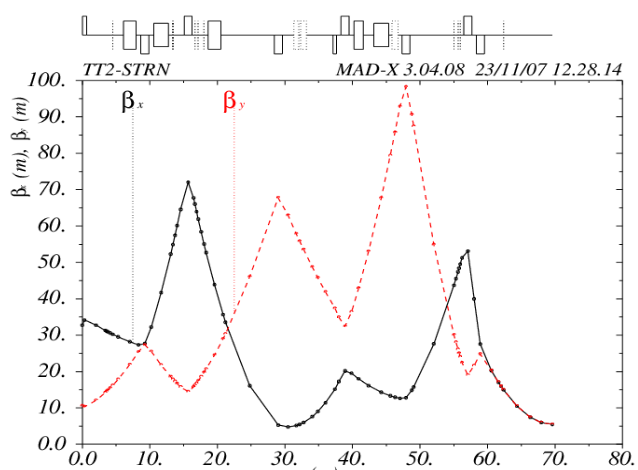

Figure 4.4: Betatron functions of the new nominal low-β insertion optics in TT2 (distance from entrance of TT2 to the stripping foil, at 69.27 m from TT2 entry). At TT2 entry: $\alpha_{H,V}$ =-3.074/0.706 and $\beta_{H,V}$ =32.74/10.56 [m]. At stripper entry (before scattering): $\alpha_{H,V}$ =0.00/0.00 and $\beta_{H,V}$ =5.50/5.50 [m].

Multiple Coulomb scattering at the stripping foil

Before proceeding with the matching of the rest of the transfer line, the multiple scattering through the stripping foil is another time taken into account (see formulae (1)-(3)). The modification of shape of the horizontal and vertical phase plane ellipses after the scattering is illustrated in Figure 4.5, while Table 4.3 presents the Twiss parameters changes and the emittance increase at the foil.

Table 4.3: Change in Twiss parameters and normalized beam emittances due to multiple scattering in the stripper (forward direction, the table is read from left to right).

	Before scattering			After scattering		
	$\alpha_{H,V}$	$\beta_{H,V}$ [m]	$\varepsilon^*_{H,V}$ [μm]	$\alpha_{H,V}$	$\beta_{H,V}$ [m]	$\varepsilon^*_{H,V}$ [μm]
Horizontal	0.00	5.50	0.51(1)	0.00	4.77	0.58(1)
Vertical	0.00	5.50	0.47(1)	0.00	4.72	0.55(1)

(1) Calculated with formulae (2)-(3).

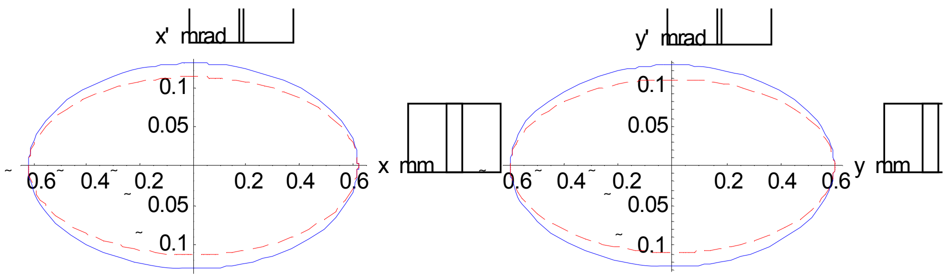

Figure 4.5: Change of horizontal (left) and vertical (right) phase plane ellipses due to the scattering through the stripper for the new nominal low-β ion optics (continuous/dashed curves represent ellipses before/after the scattering process).

Matching the rest of the transfer line to injection in the SPS

The second part of the matching is done form the exit of the stripping foil, after the scattering has been taken into account, to the end of TT10 line, where the optics should be matched for the injection in the SPS.

A preliminary matching has been made on the rest of TT2 line, following the strategy of the first optics, to have at the TT10 entry the same parameters as for the LHC 26 GeV protons optics. As a second step, the matching quadrupoles in TT10 and the very last quadrupole in TT2 (QF0375) have been used to get a matched beam at the FODO structure of TT10, designed for a 90° phase advance. Finally the matching to the TT10 FODO lattice has been relaxed in order to match to the injection conditions in the SPS. Figure 4.6 show the betatron and dispersion functions from the stripping foil position to the end of TT10. The maximum value for β_y is 163 m at QID.100700, with no problems in terms of aperture. In Figure 4.7 the optics in the injection line and in the SPS (considered as a transfer line), matched both in the betatron and dispersion functions is shown.

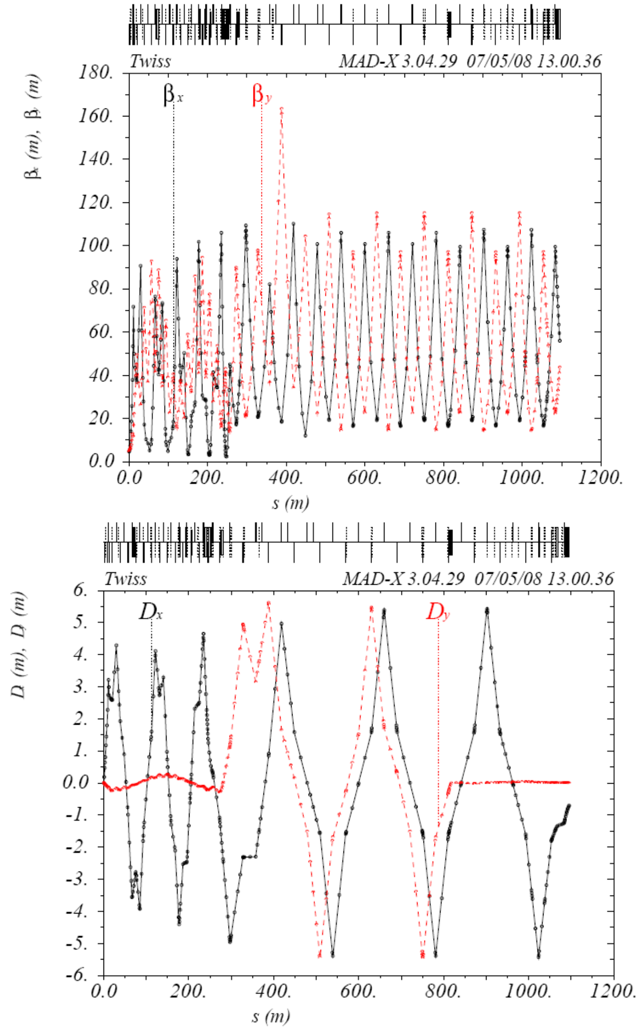

Figure 4.6: Betatron functions (top) and dispersion (bottom) of the new nominal low-β insertion optics in TT2-TT10 (distance from the stripping foil to TT10 exit).

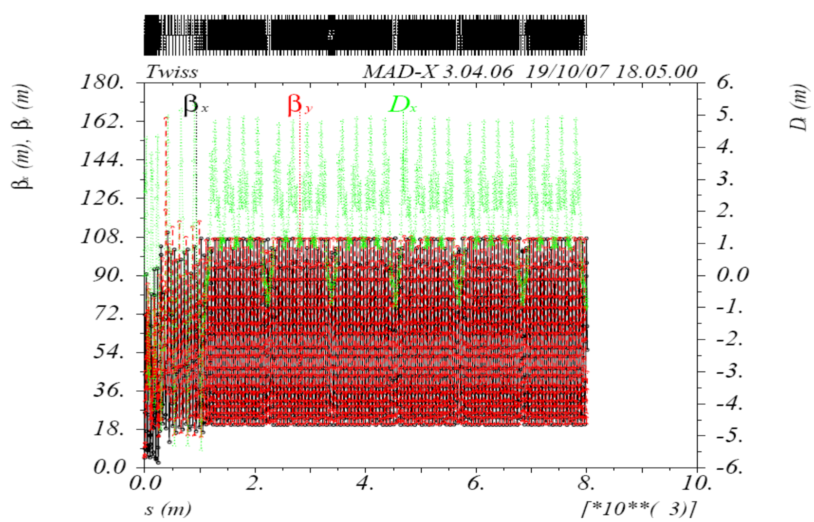

Figure 4.7: Betatron functions of the new nominal low-β insertion optics in TT2-TT10 and SPS ring (distance [km] from the stripping foil to the SPS exit).

New quadrupole and converter characteristics for the low-β insertion

The quadrupole characteristics and the power converter currents of the new nominal TT2-TT10 ion optics re-calculated in the 2007 re-commissioning of the transfer lines are displayed in Table 4.4 and 4.5.

Table 4.4: TT2 quadrupole characteristics for the new nominal low-β ion optics, (1) $B\rho^{54+}$=86.7 Tm before tripping, $B\rho^{82+}$=57.1 Tm after stripping.

Quadrupole	Type (magnetic length)	5.88 GeV/u ion optics (LHC ion programme)			
		Integrated gradient	Current	Max |current|	Strength
QF0105	QF101 (0.7 m)	9.592 T	447.1 A	550 A	0.17159 m^{-2}
QDE120	Q120B (1.2 m)	-9.497 T	-184.4 A	265 A	-0.09131 m^{-2}
QFO135	Q120B (1.2 m)	11.025 T	214.0 A	220 A	0.10600 m^{-2}
QDE150	Q120B (1.2 m)	-6.814 T	-132.5 A	250 A	-0.06552 m^{-2}
QDE163	Q50A (0.5 m)	-1.740 T	-89.6 A	300 A	-0.04015 m^{-2}
QFO165	Q120B (1.2 m)	12.865 T	250.0 A	250 A	0.12370 m^{-2}
QDE180	Q120B (1.2 m)	-10.229 T	-198.6 A	250 A	-0.09835 m^{-2}
QFO205	Q120B (1.2 m)	21.759 T	449.1 A	450 A	0.20921 m^{-2}
QDE207	Q120B (1.2 m)	-15.609 T	-305.1 A	450 A	-0.15008 m^{-2}
Stripper (Al 0.8 mm) (1)					
QDE210	Q82 (0.82 m)	-5.489 T	-153.9 A	400 A	-0.11730 m^{-2}
QDE213	Q80 (0.8 m)	-8.763 T	-250.6 A	400 A	-0.19194 m^{-2}
QFO215	Q120B (1.2 m)	18.557 T	368.3 A	500 A	0.27096 m^{-2}
QDE217	Q80 (0.8 m)	-8.376 T	-239.4 A	300 A	-0.18346 m^{-2}
QDE220.S	Q82 (0.82 m)	-4.649 T	-130.4 A	250 A	-0.09933 m^{-2}
QFO225.S	Q80 (0.8 m)	6.058 T	173.1 A	330 A	0.13268 m^{-2}
QFO375	Q80 (0.8 m)	7.203 T	205.7 A	330 A	0.15777 m^{-2}

Table 4.5: TT10 quadrupole gradients for the new nominal low-β ion optics.

Quadrupole	Strength
QIID.1001	-0.11173 m^{-2}
QIIF.1002	0.17126 m^{-2}
QIID.1003	-0.08334 m^{-2}
QIF.1004	0.09903 m^{-2}
QID.1005	-0.07550 m^{-2}
QIF.1006	0.09054 m^{-2}
QISK.1006m	0.00000 m^{-2}
QID.1007m	-0.07640 m^{-2}
QIF.1008m	0.10045 m^{-2}
QID.1011m	-0.09403 m^{-2}
QIF.1012m	0.09403 m^{-2}

Measurements in TT2 and in the SPS

The quality of the matched optics has been checked by SEM-wire measurements in TT2 (Figure 4.8) and wire scanner measurements in the SPS (Figure 4.9). The normalized r.m.s. emittances deduced from the six TT2 beam profiles were ε^*_H=0.49 μm and ε^*_V =0.65 μm. Table 4.6 displays the normalized emittances derived from the corresponding SPS beam profiles. The Gaussian fit which can be applied at the profiles at injection (scan in) at top energy (scan out) and the absence of tails indicate that no filamentation has occurred due to mismatch. Figure 4.10 shows the beam emittances measured in TT2 and in the SPS.

Table 4.6: Optical parameters at the SPS wire scanner location and normalized emittances (r.m.s. momentum spreads at 5.88 GeV/u injection(1) $\sigma_{\Delta p/p}=5.0\times10^{-4}$, $\beta\gamma$=7.246 and at 177 GeV/u top energy(2) $\sigma_{\Delta p/p}$ unknown, so the pessimistic case of $\sigma_{\Delta p/p}$=0 is assumed, $\beta\gamma$=191.013), (3) $\sigma^2_{H,V}=\sigma_\beta{}^2_{H,V}+D^2_{H,V}\times\sigma^2_{\Delta p/p}$ where $\sigma_{\beta H,V}$ is the r.m.s. betatron size

	BWSD.51731		Measured at injection (1)		Measured at top energy (2)	
	$\beta_{H,V}$ [m]	$D_{H,V}$ [m]	$\sigma_{H,V}$ (3) [mm]	$\varepsilon^*_{H,V}$ [μm]	$\sigma_{H,V}$ (3) [mm]	$\varepsilon^*_{H,V}$ [μm]
Horizontal	21.33	0.35	1.302	0.57	0.315	0.89
Vertical	101.86	0.02	2.788	0.55	0.667	0.83

Figure 4.8: Horizontal (left profiles) and vertical (right profiles) SEM-wire measurements in TT2 at 5.88 GeV/u. Normalized r.m.s. emittances: ε^*_H=0.49µm, ε^*_V =0.65 µm ($\beta\gamma$=7.246).

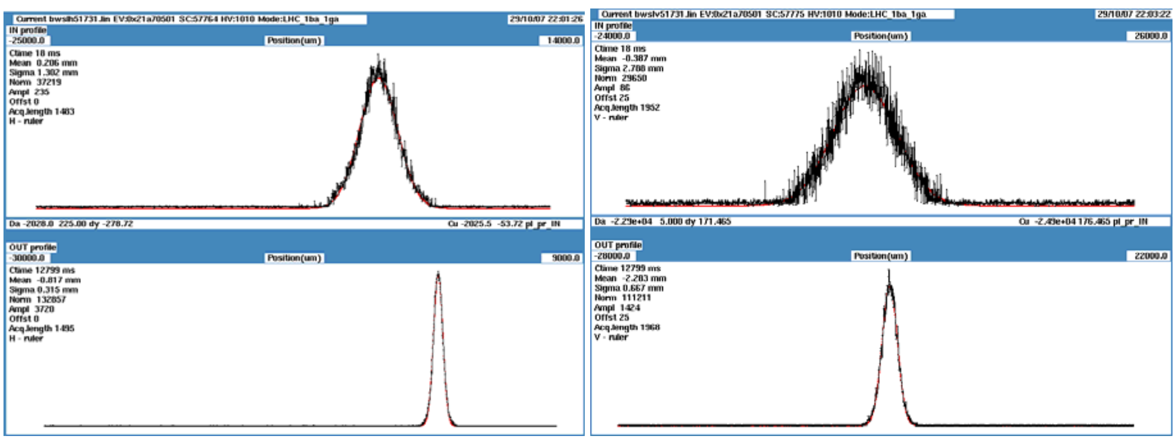

Figure 4.9: Horizontal (left profiles) and vertical (right profiles) wire scanner measurements at 5.88 GeV/u injection energy (scan in, top profiles) and 177 GeV/u top energy (scan out, bottom profiles).

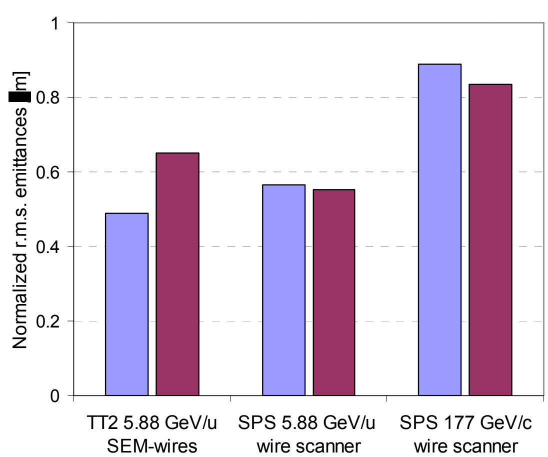

Figure 4.10: Horizontal and vertical r.m.s. ion beam emittances measured in TT2 (after stripping) at 5.88 GeV/u and in the SPS at 5.88 GeV/u injection energy and 177 GeV/u top energy (Table 4.6). Since the momentum spread is not know at 177 GeV/c, it has been assumed $\sigma_{\Delta p/p}$ =0 (pessimistic case).

5. CONCLUSION

The displacement of the stripping foil in the TT2 line and the optics and hardware modifications, implemented to obtain a low-β insertion, have allowed meeting the tight requirements in terms of emittance blow-up at the stripper. Also, the dedicated matching to the injection in the SPS has further ameliorated the quality of the beam transfer, by minimizing the filamentation in the SPS due to mismatch, as it is confirmed by wire-scanners measurements in the ring. The transverse emittances achieved at SPS top energy, after full stripping in TT2, were of the order of 0.6-0.8 μm for bunch populations (to be compared with the nominal value of 1.2 μm) corresponding to 90% of the design value.

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