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A LOW-β INSERTION IN THE PS-SPS TRANSFER LINE TO LIMIT EMITTANCE BLOW-UP DUE TO STRIPPING OF LEAD IONS FOR LHC

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Abstract

This paper presents an insertion to reduce the emittance blow-up due to the final stripping ($Pb^{54+} \rightarrow Pb^{82+}$) by a factor of four, to $\Delta\varepsilon^* \approx 0.2$ μm instead of ≈ 0.8 μm measured at the present set up. Reduction to such a small value is motivated by the tight emittance budget for the LHC which calls for a (normalised, r.m.s.) emittance $\varepsilon^* = 1.5$ μm of the lead ion beams at collision energy. Cost estimates of the insertion are given, taking use of existing hardware into account. Fast "switch off" of the insertion is preserved, so that ion and proton beams can be handled on alternate cycles even within the same supercycle. As the commissioning will need a very long MD programme it is proposed to finish the installation during the shut-down 2001–2002.

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1 Introduction

In the preparation and the later operation of the PS complex as an ion injector for the LHC, Pb^{54+} ion beams will be accelerated in the PS machine to 4.25 GeV/u and then ejected and fully stripped to Pb^{82+} in the TT2/TT10 transport channels between PS and SPS.

This paper proposes the implementation of a low-β insertion to limit transverse emittance blow-up due to the multiple Coulomb scattering in the stripping foil. In the presence of non-zero dispersion at the foil, the stripping process may also lead to additional emittance increase due to coherent energy loss and straggling of the ions traversing the stripper. A careful analysis of these different effects is carried out, motivated by the tight emittance budget for the LHC injector chain. The performance of the new low-β stripping insertion is compared to the current situation where the stripper is located near the junction of the TT2 and TT10 transfer lines at a location with relatively large beta valúes.

A cost estimate of the magnets and power supplies required to implement the new stripping facility along with a possible housing of the power supplies is also given.

2 Emittance Budget of the LHC Lead Ion Beam

The transverse emittance budget of the ion beams required to obtain the specified luminosity for the lead experiment programme in the LHC is listed in Table 1 (see [1]). The quoted PS emittance $\varepsilon^*_{h,v} = 1.0$ μm (normalised, r.m.s.), or $\varepsilon_{h,v} = 0.18$ μm (physical, r.m.s.), refers to the value at the end of the TT2 transfer line after the stripping process. One concludes that all along the chain, small emittances (about $\frac{1}{3}$ to $\frac{1}{4}$ of the present lead ion beam emittances) are required. Thus emittance preservation is of great importance.

MACHINE (at top energy)	Ions for LHC [2] $\varepsilon^*_{h,v}$ [μm]	Protons for LHC [2] $\varepsilon^*_{h,v}$ [μm]	Ions for SPS fixed target exp. [3] $\varepsilon^*_{h,v}$ [μm]
LHC	1.5	3.75	–
SPS	1.2	3.5	4.0–4.5[1]
PS	1.0[2]	3.0	3.8
LEIR	0.7	–	–
BOOSTER	–	2.5	3.0

Table 1: *Emittance budget (normalised r.m.s.) for the LHC ion programme [1].*

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[1] Emittance at SPS top energy not specified in [3].

[2] After stripper in TT2/TT10.

3 Present Situation

In the fixed-target lead ion runs performed up to now the charge state of the ions is changed from 53^+ to 82^+ in TT2 using a 0.8 mm thick aluminium stripping foil installed at about 302 m from the entrance of TT2. Machine experiments have been performed in 1995 and 1998 to verify the model of the TT2/TT10 lines and to measure the Twiss parameters at the entrance of TT2 in order to rematch the beam to the SPS using the last quadrupole in TT2 (downstream the present stripper location) and all the quadrupoles in TT10 [4, 5]. The improvement of betatron re-matching based on the initial optics parameters lead to an increase of the transmission through the SPS of about 13%. Following the re-matching the dispersion was measured in TT2/TT10 using unstripped Pb^{53+} beams with small transverse emittances The relative momentum spread of the beam was $1.5 \cdot 10^{-4}$ (see Table 7 in [4]). Initial optics parameters at the entrance of TT2 derived from the measurements (see Table 9 in [4]) and optics parameters at the present stripper location as calculated with MAD are listed in Table 2. It is worth noting that the optics parameters (in particular the dispersion function) at the stripper (`STR373`) are extremely sensitive to the initial values at the beginning of TT2 (entry of the quadrupole `QF0105`) for the present optics.

Location	Horizontal				Vertical			
	β_h [m]	α_h	D_h [m]	D'_h	β_v [m]	α_v	D_v [m]	D'_v
`Entry TT2`	29.42	-2.51	4.13	0.41	5.71	0.29	-0.47	0.03
`STR373`	23.56	-1.70	-2.94	-0.34	22.05	1.12	-1.03	0.06

Table 2: *Optical parameters at the entry of TT2 derived from measurements given in [4] and at the present stripper position (STR373) derived from the initial parameters Table 9 of [4] with the optics given in Table 3.*

The quadrupole strengths in TT2 yielding the current optics are given in Table 3 along with the layout ("magnetic structure") of the matching section and beginning of the string. This setting of quadrupoles has been kept in operation during the 1999–2000 lead ion runs although a further complete re-matching of TT2/TT10 has been tried but was not retained because no significant improvement on beam performance has been observed and no conclusive result could be drawn from additional optics measurements (see Tables 13-14 in [4]).

The horizontal and vertical betatron and dispersion functions of the current lead ion optics in the TT2 transfer line computed with MAD based on the initial optical parameters of Table 2 are shown in Fig. 1.

We anticipate that the measured emittance blow-up due to stripping is about 0.58–0.77 μm [6] while calculation for this situation gives a minimum of 0.42–0.45 μm (subsection 4.2).

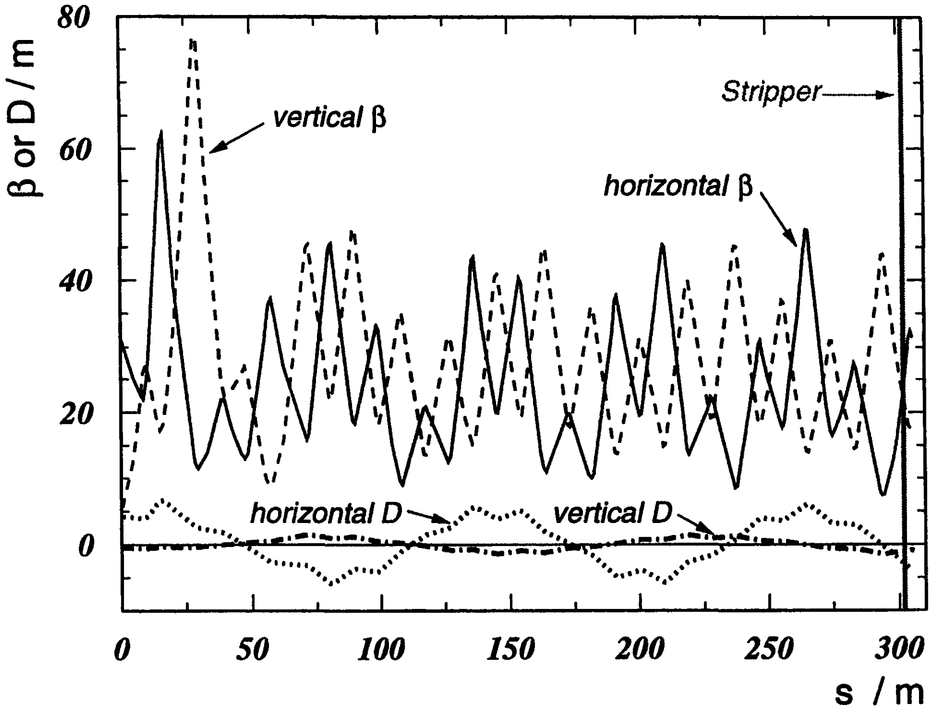

Figure 1: *Horizontal and vertical betatron and dispersion functions of the present lead ion optics in the TT2 transfer line. The solid line at around 302 m denotes the current position of the stripper.*

Quadrupole name	Normalised gradient $[m^{-2}]$
QF0105	0.1687
QDE120	-0.1028
QF0135	0.0988
QDE150	-0.0789
QF0165	0.0731
QDE180	-0.0662
QF0205	0.0724
QDE210.F	-0.1100
QF0215.F	0.1230
QF0375	0.1072

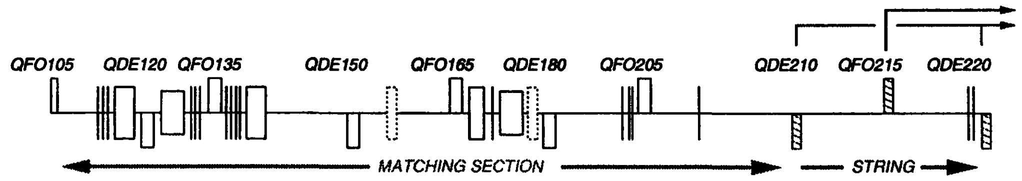

Table 3: *TT2 present normalised quadrupole gradients.* `QDE210.F` *and* `QF0215.F` *denote a string composed of two families of quadrupoles each powered by means of a single power supply. Quadrupole* `QF0375` *is located about 2 m downstream the stripper STR373.*

4 Proposal for a Low-β Insertion in TT2

4.1 Optics

The minimisation of the emittance blow-up from multiple Coulomb scattering requires betatron functions as small as possible at the stripper according to Eq. (1) Appendix A. To achieve this, a low-β insertion is proposed at about 70 m from the beginning of TT2, just before the beginning of the quadrupole string (families `QDE210.F` and `QF0215.F`). Detailed studies showed that the existing quadrupoles are insufficient to match Twiss parameters and dispersion function in the horizontal and the vertical plane and at the same time respect the "geometrical" constraints imposed by the aperture of the vacuum chamber. To create the insertion, four quadrupoles had to be added and in addition the first two quadrupoles of the string had to get individual supplies. An additional constraint in the matching process was the available space for the additional magnets. The quadrupole gradients for this new optics including the four additional quadrupoles are given in Table 5.

Figure 2 shows the horizontal and vertical betatron and dispersion functions of the proposed lead ion optics in the TT2 transfer line. Details of the magnetic structure are shown in Fig. 3 which is a zoom into the first 90 m of TT2. The shaded elements represent the additional quadrupoles

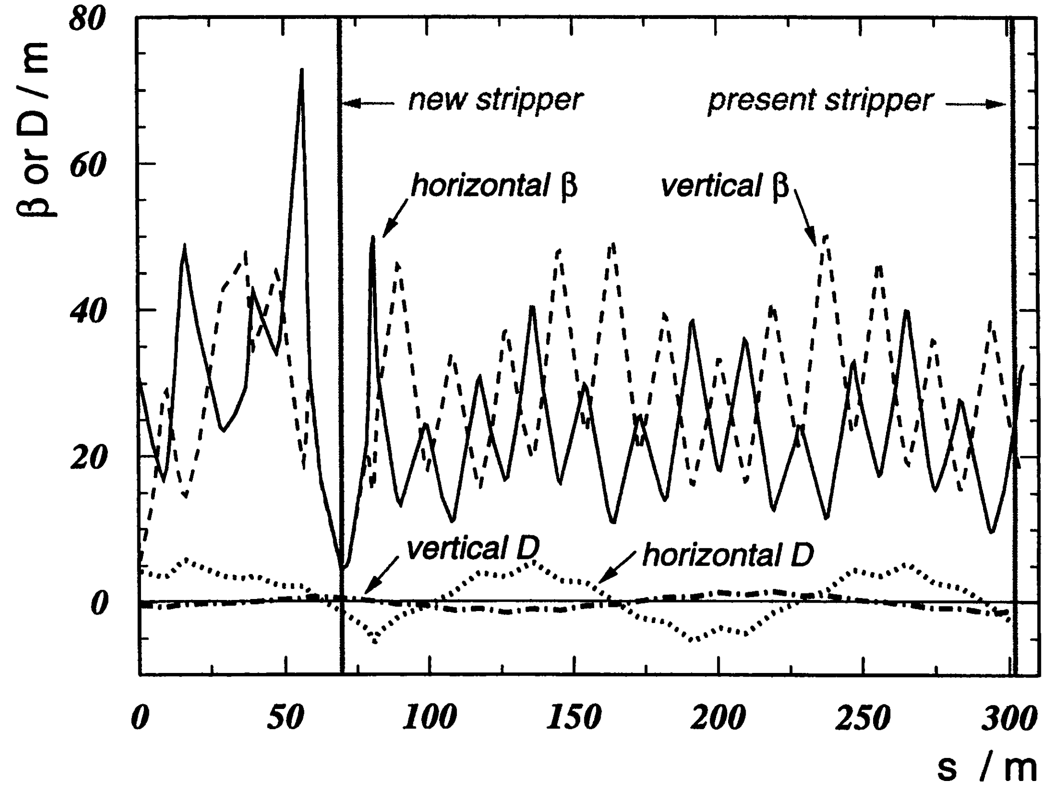

Figure 2: *Horizontal and vertical betatron and dispersion functions of a new lead ion optics in the TT2 transfer line with a low-β insertion. The solid line at around 70 m denotes the new stripper position, the line at around 302 m the current position of the stripper.*

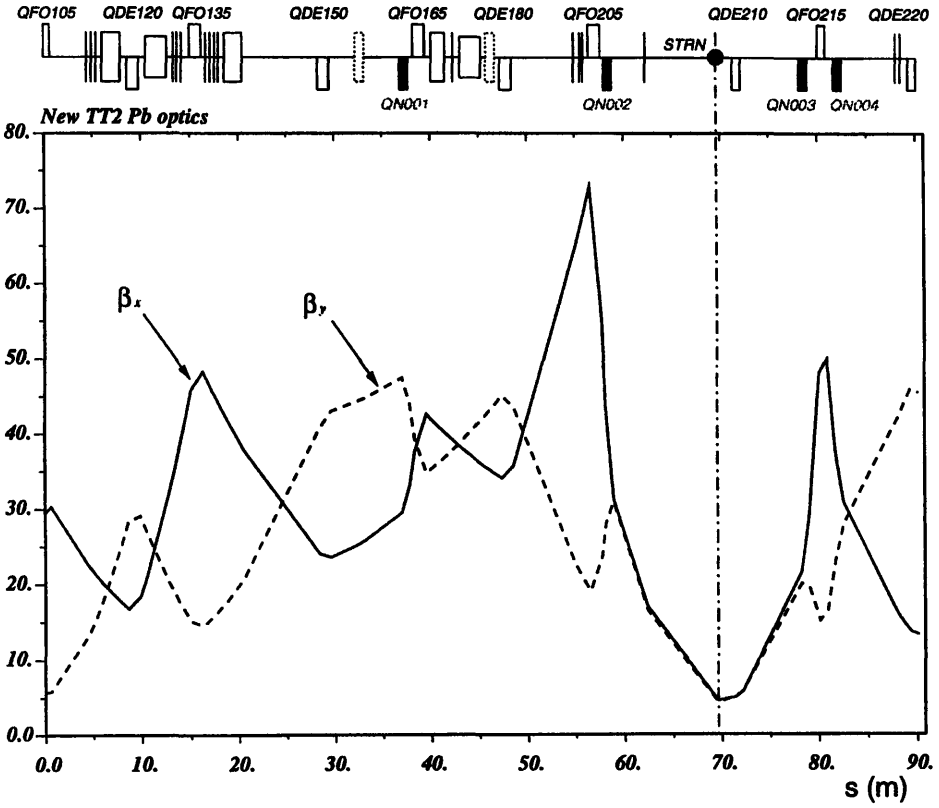

Figure 3: *A zoom in the first 90 m of TT2 reveals the magnetic structure. The shaded elements represent the new quadrupoles needed for the insertion.*

needed for the insertion. The optical functions at the stripper are given in Table 4.

Horizontal				Vertical			
β_h [m]	α_h	D_h [m]	D'_h	β_v [m]	α_v	D_v [m]	D'_v
4.56	$7{\cdot}10^{-2}$	-1.41	-0.24	4.33	$8{\cdot}10^{-3}$	0.51	-0.02

Table 4: *Optical parameters at the new stripper position (STRN).*

Comparison between Table 2 and Table 4 shows that the betatron functions and therefore the emittance blow-up due to multiple Coulomb scattering could be reduced by about a factor five (Table 7) compared to the optics used since 1999. At first sight the non-zero dispersion at the stripper seems to be a drawback but the net influence on the emittance can be compensated by carefully adjusting the downstream optics to cope with the coherent energy loss in the stripper as shown in subsection 4.2. Since the optics parameters at TT2 entrance have been derived from measurements they are subject to intrinsic uncertainties. However the proposed optics is flexible enough to guarantee stable conditions at the stripper for a reasonable range of initial parameters.

Quadrupole name	Normalised gradient [m^{-2}]
QF0105	0.1904
QDE120	-0.1148
QF0135	0.0827
QDE150	-0.0289
QN001[3]	-0.1423
QF0165	0.1106
QDE180	-0.0530
QF0205	0.2476
QN002[3]	-0.3500
QDE210[4]	-0.0183
QN003[3]	-0.2597
QF0215[4]	0.4572
QN004[3]	-0.1858
QDE210.F	-0.1008
QF0215.F	0.1151
QF0375	0.0958

Table 5: *TT2 quadrupole gradients for the proposed new optics with the low-β insertion.*

Quantity	Horizontal	Vertical
betatronic $\Delta\varepsilon_u/\varepsilon_u$	$3{\cdot}10^{-5}$	$3{\cdot}10^{-4}$
dispersive $\Delta\varepsilon_u/\varepsilon_u$	$3{\cdot}10^{-7}$	10^{-5}

Table 6: *Emittance blow-up due to mismatch between TT2 and TT10 if no correction in TT10 is applied.*

If not perfectly corrected by rematching in TT10 the differences of the optics parameters at the end of TT2 between the present optics and the new optics with low-β insertion will generate emittance blow-up after injection and filamentation into the SPS machine. Equations (7) and (9) (see Appendix A) have been used to quantify this effect. The resulting blow-ups without additional mismatch correction outside TT2 are given in Table 6, which shows that this effect is small.

4.2 Emittance Blow-Up Due to the Stripper

The main mechanism leading to emittance blow-up is the multiple Coulomb scattering mentioned before which leads to an effective increase in angle and therefore in emittance. The corresponding relations are Eqs. (1) and (2) in Appendix A. The calculated emittance increase is given in Table 7 for the present and the new low-β optics assuming fully stripped lead ions (charge state

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[3] New quadrupoles.

[4] New power supplies.

z=82). Together with an increase in emittance the multiple Coulomb scattering also causes a modification of the Twiss parameters downstream the stripping foil which has to be taken into account for the final re-matching.

Optics	$\Delta\varepsilon^*_h$ [μm]		$\Delta\varepsilon^*_v$ [μm]	
	Scattering	Straggling	Scattering	Straggling
Calculated present	0.447	0.003	0.418	0.0002
Calculated low-β	0.086	0.003	0.082	0.0003
	Combined		Combined	
Measured 1995[5]	0.766		0.584	
"Scaled" low-β[5]	0.175		0.158	

Table 7: *Increase in normalised r.m.s. emittance due to multiple scattering and energy straggling for the calculated present and proposed low-β optics and for the measured (1995) and "scaled" low-β optics.*

Another major contribution to the emittance increase is caused by coherent and incoherent energy loss in the stripping foil. The coherent (average) loss in kinetic energy of the lead ions described by the Bethe-Bloch formula (3) is $\Delta T \approx 2.5$ GeV (≈ 12 MeV/u) which is in reasonable agreement with the measurements performed earlier [6]. If this coherent energy loss stays uncorrected it leads to an additional normalised emittance contribution after filamentation. However this can be avoided by adjusting the optics downstream of the stripper for the lower reference momentum.

The incoherent energy loss ("energy straggling") is caused by the variance of the energy loss distribution. For a thick aluminium foil (0.8 mm) the energy loss distribution can be treated in the Gaussian limit. The energy spread introduced by the straggling process is $\sigma_T \approx 42$ MeV (≈ 201 KeV/u) (see Eq. (5)) yielding a relative momentum spread $\sigma_p/p \approx 4\,10^{-5}$. The increase in emittance due to this effect using Eq. (6) at the stripper is reported in Table 7. Measurements [7] indicate a larger value of the energy straggling ($\sigma_T \approx 75$ MeV) which translates into larger calculated emittance blow-ups: $\Delta\varepsilon^*_h \approx 0.011$ μm and $\Delta\varepsilon^*_v \approx 0.007$ μm (normalised, r.m.s.) for the present optics.

Careful measurements of the emittance blow-up due to stripping were performed in 1995 [6]. The optics then was slighly different from the one used in 1999 and 2000. The experimental results for a 0.8 mm aluminium stripper are given in [6] as $\Delta\varepsilon_{h_{2\sigma}} \approx 0.56$ μm and $\Delta\varepsilon_{v_{2\sigma}} \approx 0.43$ μm (physical, 2σ-emittance), corresponding to $\Delta\varepsilon^*_h \approx 0.77$ μm and $\Delta\varepsilon^*_v \approx 0.58$ μm (normalised, r.m.s.). Considering the betatron functions β_h=20 m and β_v=16 m at the stripper location quoted in [6] an approximate reduction by factors 4.4 and 3.7 in betatron functions would be obtained with the proposed new low-β region leading to "scaled" emittance blow-ups $\Delta\varepsilon^*_h \approx 0.18$ μm and $\Delta\varepsilon^*_v \approx 0.16$ μm.

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[5] Measured emittances include the multiple scattering and the energy straggling effects.

Stripper thickness [mm]	Bare ion fraction [%]
0.5	83 ± 5
0.8	96 ± 2
1.0	98 ± 1

Table 8: *Measured bare ion fraction vs. Al stripper thickness [6].*

All results so far assume an aluminium stripper of 0.8 mm thickness. Measurements of stripping efficiency versus foil thickness, also given in [6], are reproduced in Table 8 for convenience. A foil of 0.8 mm represents a good compromise between the stripping efficiency and the emittance blow-up which scales linearly with the thickness.

Finally a remark concerning the foil material: The ratio between stripping and scattering seems to depend only very weakly on the material. This can for example be concluded from [8]. Little can therefore be gained by using a stripper different from the aluminium one considered above.

5 Technical Feasibility

Three of the four quadrupoles needed can be recuperated from the decomissioned FA58 line (former electron extraction from PS for LEP). As the stronger gradient lens (`QN002`) the quadrupole `QFS17` at present on store can be used.

Some but perhaps not all the power supplies are recoverable from the FA58 line but will need some refurbishing. Additional costs come from the changes needed in the mechanical supports, vacuum pipes, magnet cabling and cooling and possibly a new building needed to house the power supplies. Table 9 shows a very preliminary and rough cost estimate.

Item	Low figure	High figure
Quadrupole maintenance	100 kCHF	100 kCHF
Mechanical changes, pipes ...	150 kCHF	150 kCHF
Power supplies and cabling	260 kCHF	620 kCHF
Power supply building	≈0 kCHF	300 kCHF
Manpower	10 kCHF	10 kCHF
Total estimate	≈500 kCHF	≈1200 kCHF

Table 9: *Cost estimate.*

6 Conclusion

A detailed study of possibilities to reduce the emittance blow-up due to the final stripping of the lead ion beam has been performed. It leads to the proposed insertion with four extra quadrupoles in TT2. These lenses and probably also the power supplies needed can be recuperated from the decommissioned FA58 line and/or from stock. A long program of machine experiments is necessary to achieve the strict emittance conservation required by the LHC. The runs to commission and develop the insertion should start very soon in order to avoid interference with the busy work on ions for the LHC (LEIR, PS, SPS) foreseen to begin in 2004.

7 Acknowledgements

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A Relevant Formulae

The emittance increase (physical, r.m.s. emittance) due to multiple Coulomb scattering is given by [9]

$$\Delta\varepsilon_u = \frac{1}{2}\,\beta_u\,\langle\,\theta^2\rangle \tag{1}$$

Here the subscript u denotes either the horizontal or the vertical plane and $\sqrt{\langle\,\theta^2\rangle}$ is the root mean square projected angle due to multiple scattering [10]

$$\sqrt{\langle\,\theta^2\rangle} = 13.6\,z\,\frac{1}{\beta p}\sqrt{\frac{x}{X_0}}\left\{1 + 0.038\,\ln\frac{x}{X_0}\right\} \tag{2}$$

In (2) X_0 is the radiation length of the stripper material (Al), z, p, β the charge state, total momentum (in MeV/c) and velocity of the incident ion relative to the speed of light and x the thickness of the stripping foil ($x = 0.8$ mm for the TT2 stripper to obtain more than 95% stripping efficiency [6]). In addition to the blow-up of the emittance by multiple scattering there is also a contribution from the energy loss. The average energy loss in the stripper material is described by the Bethe-Bloch formula [11]

$$-\frac{dE}{dx} = 4\pi\,N_a\,r_e^2\,m_e c^2\,\rho\,\frac{Z}{A}\,\frac{z^2}{\beta^2}\left[\frac{1}{2}\ln\left(\frac{2m_e c^2\beta^2\gamma^2 T_{max}}{I^2}\right) - \beta^2\right] \tag{3}$$

where N_a is Avogadro's number, r_e and $m_e c^2$ the classical electron radius and rest mass, I the mean excitation energy ($I \approx 16\,Z^{0.9}$ eV), A and Z atomic weight and charge number of the stripper material, ρ its density and $\gamma = 1/\sqrt{1-\beta^2}$. The maximum energy transfer in a single collision is

$$T_{\max} = \frac{2m_ec^2\beta^2\gamma^2}{1+2\frac{m_e}{M}\sqrt{1+\beta^2\gamma^2}+\left(\frac{m_e}{M}\right)^2} \tag{4}$$

where M is the mass of the lead ion. Since $M \gg m_e$ the maximum energy transfer in a single collision is $T_{\max} \approx 2m_ec^2\beta^2\gamma^2 = 30.6$ MeV for a kinetic energy of $T = 208\times4.25$ GeV/u = 884 GeV ($\beta = 0.984$). The variance of the energy loss distribution for a thick stripper is given by [11]

$$\sigma_T^2 = 4\pi\, N_a\, r_e^2 \left(m_ec^2\right)^2 \rho\, \frac{Z}{A}\, z^2\, x \left(\frac{1-\frac{1}{2}\beta^2}{1-\beta^2}\right) \tag{5}$$

The other symbols are the same as those in Eqs. (2) and (3). The change in momentum is related to the change in kinetic energy by $\sigma_p = \sigma_T/(\beta c)$. The corresponding increase in emittance after filamentation is described by (see also [9])

$$\Delta\varepsilon_u = \frac{1}{2}\left(\beta_u D_u'^2 + 2\alpha_u D_u D_u' + \gamma_u D_u^2\right)\left(\frac{\sigma_p}{p}\right)^2 \tag{6}$$

The emittance blow-up due to Twiss parameter mismatch of the new low-β TT2 optics with the current TT10 optics is given by [12]

$$\begin{aligned} \Delta\varepsilon_u &= (H_u - 1)\,\varepsilon_u, \quad \text{with} \\ H_u &= \frac{1}{2}\left[\frac{\beta_{u_0}}{\beta_u} + \left(\alpha_{u_0} - \alpha_u\frac{\beta_{u_0}}{\beta_u}\right)^2 \frac{\beta_u}{\beta_{u_0}} + \frac{\beta_u}{\beta_{u_0}}\right] \end{aligned} \tag{7}$$

where α_{u_0} and β_{u_0} are the Twiss parameters of the reference optics. Equation (7) describes the blow-up after filamentation, the corresponding geometrical blow-up is

$$G_{u_\beta} = H_u + \sqrt{H_u^2 - 1}. \tag{8}$$

The blow-up due to dispersion parameter mismatch of the new TT2 optics with the current TT10 optics is given by [12]

$$\begin{aligned} \Delta\varepsilon_u &= (J_u - 1)\,\varepsilon_u, \quad \text{with} \\ J_u &= 1 + \frac{\Delta D_u^2 + (\Delta D_u'\beta_{u_0} + \Delta D_u\alpha_{u_0})^2}{2\varepsilon_u\beta_{u_0}}\left(\frac{\sigma_p}{p}\right)^2 \end{aligned} \tag{9}$$

where ΔD_u and $\Delta D_u'$ are the differences between the respective values and σ_p is the r.m.s. momentum dispersion. Equation (9) describes the blow-up after filamentation, the corresponding geometrical blow-up is

$$G_{u_D} = 2J_u - 1. \tag{10}$$

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