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Considerations on the Transverse Emittance of the Fixed-Target Beam in the SPS in the PS2 Era

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Abstract

The range of the acceptable transverse emittances the Fixed-Target beams delivered to the SPS in the PS2 era is determined based on acceptance and other beam dynamics considerations in the SPS.

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1. Introduction

One of the input parameters required for the design of the PS2 is the emittance of the Fixed-Target beams to be delivered to the SPS. The range of acceptable transverse emittances of the Fixed-Target beams to be delivered to the SPS in the PS2 era is determined based on acceptance and other beam dynamics considerations in the SPS.

2. SPS Acceptance considerations

The theoretical physical acceptance of the SPS is 30.7 π mm mrad in the horizontal plane and 4.6 π mm mrad in the vertical plane (no momentum spread included) for a perfect machine with no beta beating and no closed-orbit error. This is the minimum among all the elements of the machine of the ratio $A_{H,V,i}^2/\beta_i$ where $A_{H,V,i}$ is the half-size of the physical aperture at element i and β_i is the corresponding Twiss beta function value at that element. The aperture model of the SPS is available in [1].

The optics parameters for Fixed-Target operation of the SPS are summarized in Table 1.

Tune (H/V)	26.62/26.58
Maximum Beta (H/V) [m]	108/109
Beta beating (H/V) [%]	<10/<10
Peak-to-peak dispersion beating (H/V) [m]	±0.3 / ±0.1
Peak-to-peak orbit distortion (H/V) [mm]	±3 / ±2
Maximum momentum offset [10^{-3}]	±1
Peak-to-peak mechanical alignment offset (H/V) [mm]	±0.8 / ±0.6 [2]

Table 1. Optics parameters and required tolerances for the Fixed-Target beam in the SPS (see Appendix 1).

During the machine studies conducted in 2004 for the high intensity in the SPS the beam parameters and performance observed are summarized in Table 2 [3].

Momentum [GeV/c]	14
Total beam Intensity [10^{13} p]	5
Bunch intensity (average) [10^{10} p]	1.2
r.m.s. normalized transverse emittances (H/V) [μm]	8/6
2σ-relative momentum spread after capture(*) [10^{-3}]	±2.4
Losses at injection [%]	4-5

Table 2. Beam parameters during the high intensity tests conducted in 2004. (*)After capture in 0.8 MV at injection and adiabatic voltage rise to 2.5 MV.

The proposed parameters of the PS2 Fixed-Target beam in the SPS after capture are listed in Table 3.

Momentum [GeV/c]	26
Total beam Intensity [10^{13} p]	10
Bunch intensity (average) [10^{10} p]	12.3
Filling pattern (#)	5×(163b+17e)+24e
r.m.s. normalized transverse emittances (H/V) [μm]	9/6
2σ-longitudinal emittance [eV.s]	0.45
2σ-relative momentum spread after capture(&) [10^{-3}]	±4
Bunch length (4 σ) [ns]	2.9

Table 3. Fixed target beam parameters for operation of the SPS with PS2 after capture [4]. (b=filled 25 ns slots, e=empty 25 ns slots). The filling pattern providing an abort gap of 1.05 μs (this is the present value of the abort gap in the SPS adapted to the present rise-time of the beam dump kicker) has been considered. (&)After capture in 2 MV at injection and adiabatic voltage rise to 3 MV.

The apertures (in σ) and expected losses (assuming a bi-variant Gaussian distribution in each of the two transverse planes) for the Fixed-Target beam during the 2004 high intensity run and for the PS2 beam with parameters listed in Table 2 and Table 3, respectively, are summarized in Table 4.

	Betatronic aperture (H/V) – [sigma]	Expected losses [%]
High Intensity 2004	5.2/2.7	2.6
PS2	6.5/3.7	0.1

Table 4: Apertures and expected losses.

The difference between the expected and measured losses is due to the presence of bottle-necks that have been eliminated during the SD 2004-6 (TIDVG Ti foil deformation) and during the SD 2008-9 (ball bearing in MBB30950 and deformation of the ion trap on ZS5) [5].

The aperture is calculated for the particles at the edge of the bucket and for a position of the momentum scraper TIDP at +20 mm which is a typical value for the operation with Fixed-Target beams.

In the PS2 era the relative losses at injection (26 GeV/c) for the Fixed-Target beam should be reduced by at least a factor 4 with respect to the present ones in order to compensate for the higher injection energy and the higher intensity. This should allow keeping the activation levels in the SPS to values comparable to the present ones in the assumption that the amount of remanent radioactivity due to beam losses scales with energy and intensity. Given that no detailed study of the loss mechanisms and of localization of the losses has been done so far a safety margin needs to be taken and it seems to be reasonable to consider a reduction of the losses by an order of magnitude.

According to the simple criterion of a reduction of the losses by at least an order of magnitude the proposed transverse parameters for the Fixed-Target beam for the PS2 are acceptable and the maximum acceptable r.m.s. normalized vertical emittance is approximately 7 μm assuming that the horizontal emittance remains unchanged.

In the above:

- No detailed study of the loss distribution and impact on remanent radiation and radiation damage has been performed.
- No detailed study of the machine protection issues associated with the unprecedented intensity and beam stored energy has been conducted.
- No aspect other than acceptance has been considered.
- It is assumed that the SPS upgrade programme required to preserve the brightness of the LHC beam provided by the PS2 has been implemented.

Whenever the horizontal emittance of the Fixed-Target beam delivered by the PS2 is smaller than the vertical emittance the need of an emittance-exchange section in the transfer line from PS2 to SPS is not excluded for the sake of reducing radiation which must be kept as low as reasonably achievable.

3. Collective effects

Collective phenomena define the minimum transverse and longitudinal emittances of the Fixed-Target beams. The LHC beam will be taken as a reference assuming that the SPS upgrade programme will be implemented such to allow the preservation of the brightness of the PS2 LHC beam in the SPS. The parameters of the LHC beam after capture in the SPS in the LHC era are summarized in Table 5.

Momentum [GeV/c]	50
Total beam Intensity [10^{13} p]	13.4
Bunch intensity (average) [10^{10} p]	40
Filling pattern	2×(168b+12e)+564e
r.m.s. normalized transverse emittances (H/V) [μm]	3/3
2σ-longitudinal emittance [eV.s]	0.6
2σ-relative momentum spread after capture$^{(\&)}$ [10^{-3}]	±2.0

Bunch length (4 σ) [ns]	4

Table 5. LHC Beam parameters for operation of the SPS with PS2 after capture (b=filled 25 ns slots, e=empty 25 ns slots). (&)After capture in 2 MV at injection and adiabatic voltage rise to 3 MV.

A lower limit to the r.m.s. normalized transverse emittance of the Fixed-Target beam might come from collective effects and in particular from the space charge tune spread at injection. The values of the space charge tune spread at injection for the Fixed-Target beam and the LHC beam provided by PS2 are listed in Table 6.

	ΔQ_H	ΔQ_V
Fixed target	0.019	0.031
LHC	0.030	0.042

Table 6: Space charge tune spread for the Fixed-Target and LHC beams after capture in the SPS.

The space charge tune spread corresponding to the Fixed Target beam is approximately 25% lower than that for the LHC beam. Emittances lower than 25% are therefore acceptable for the Fixed-Target beam. This is even more the case taken into account that the first batch of the LHC beam will spend 1.2 s at injection in the SPS while a single batch of Fixed-Target beam will be injected in the SPS.

The main expected sources of single bunch transverse instability for the Fixed-Target and LHC beams in the SPS during the PS2 era are the Transverse Mode Coupling Instability (TMCI) and the vertical electron cloud instability [6]:

- The threshold for the onset of the TMCI instability (if damping mechanisms due to space charge are not considered as a conservative approach) does not depend on the transverse emittance and an approximate scaling for the threshold bunch intensity N_{TMCI} is given by:

$$N_{TMCI} \propto \eta \varepsilon_L$$

  where η is the slip factor and ε_L is the longitudinal emittance. Assuming that at injection the values of the longitudinal emittance for the Fixed Target beam and for the LHC beam are those quoted in Table 3 and 5, respectively, the ratio of the bunch population for the Fixed-Target beam N_{FT} to the corresponding threshold for the TMCI $N_{TMCI\text{-}FT}$ is comparable to the corresponding ratio for the LHC beam, i.e.

$$\frac{N_{FT}}{N_{TMCI-FT}} \approx \frac{N_{LHC}}{N_{TMCI-LHC}}$$

  therefore any impedance reduction measure allowing preserving the brightness of the LHC beam (even in the absence of damping mechanisms like space charge) should also allow preserving the brightness of the Fixed-Target beam, irrespectively of the transverse emittance.

- The electron cloud saturation density is almost independent from the transverse emittance while the threshold for the onset of the vertical electron cloud instability increases with decreasing the transverse beam size (and in particular the vertical one) [7]. Simulations of the electron cloud build-up for the LHC beam with the parameters listed in Table 5 and for the Fixed-Target beam with the parameters listed in Table 3 and r.m.s. normalized transverse emittances reduced by 25% (i.e. 6.5 μm–H and 4.5 μm–V) have shown that there is no electron cloud formation for values of the maximum Secondary Electron Yield (δ_{max}) below 1.3. Using then the electron distribution at saturation obtained from the build up simulations with δ_{max} of 1.3 and 1.4, vertical instability simulations have been done, which show that the Fixed-Target beam is less prone to the vertical electron cloud instability as compared to the LHC beam even in the case in which the Fixed-Target beam has reduced transverse emittances (Fig. 1).

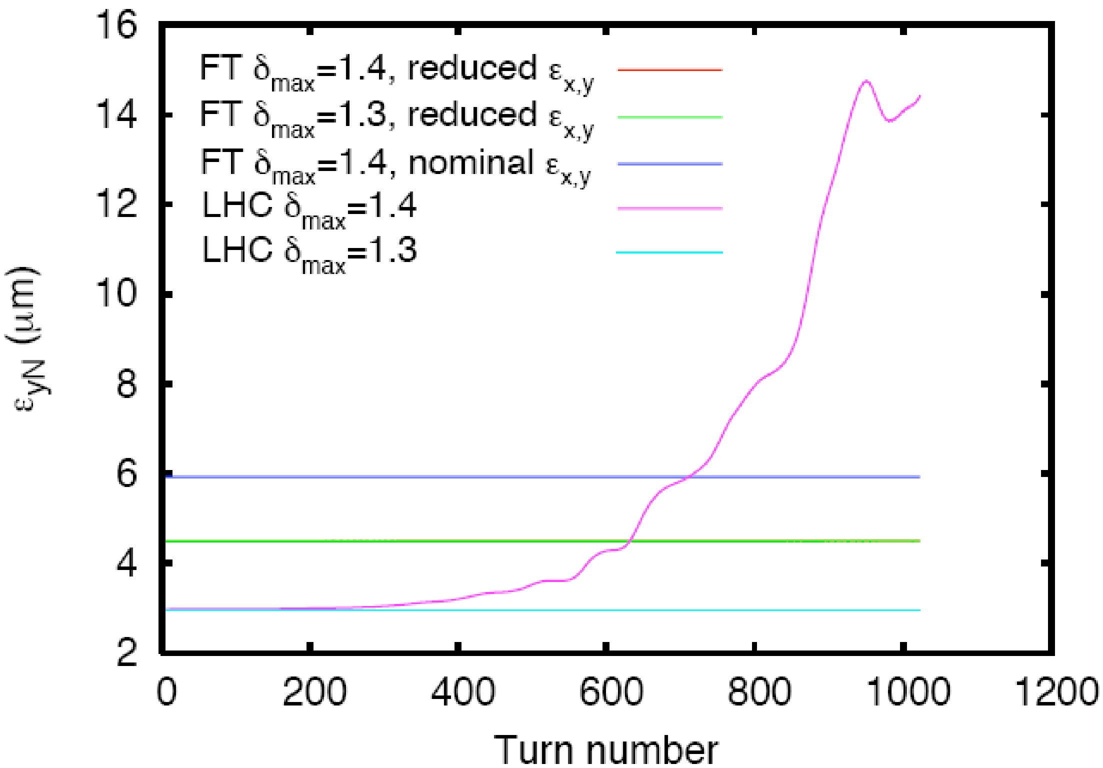

Fig. 1. R.m.s. normalized vertical emittance evolution of the and of the LHC beam and of the Fixed-Target beam with parameters specified in Table 3 (nominal $\varepsilon_{x,y}$) and with transverse emittances reduced by 25 % with respect to those listed in Table 3 (reduced $\varepsilon_{x,y}$) for δ_{max} of 1.3 and 1.4. The (red) line representing the r.m.s. normalized vertical emittance evolution for the Fixed-Target beam with reduced emittance and δ_{max}=1.4 is underlying the (green) line representing the r.m.s. normalized vertical emittance evolution for the Fixed-Target beam with reduced emittance and δ_{max}=1.3.

4. Conclusions

The proposed r.m.s. normalized transverse emittances of 9 μm (H) and 6 μm (V) at injection in the SPS during the PS2 era for the Fixed-Target beam with parameters indicated in Table 3 are acceptable based on very basic assumptions on acceptance and losses considerations. According to the same criterion the maximum acceptable r.m.s. normalized vertical emittance is approximately 7 μm assuming that the horizontal emittance remains unchanged. Other preliminary considerations based on collective effects indicate that smaller transverse emittances (down to 75% of the above ones) could be acceptable.
In the above:

- No detailed study of the loss distribution and impact on remanent radiation and radiation damage has been performed.
- No detailed study of the machine protection issues associated with the unprecedented intensity and beam stored energy has been conducted.
- It is assumed that the SPS upgrade programme required to preserve the brightness of the LHC beam provided by the PS2 has been implemented.

Whenever the horizontal emittance of the Fixed-Target beam delivered by the PS2 is smaller than the vertical emittance the need of an emittance exchange section in the transfer line from PS2 to SPS is not excluded and even encouraged for the sake of reducing radiation which must be kept as low as reasonably achievable.

5. References

[1] http://isscvs.cern.ch/cgi-bin/viewcvs-all.cgi/?root=camif

[2] C. Podevin, private communication, 4/5/2009.

[3] Minutes of the APC Meeting held on 10th December 2004, https://ab-div.web.cern.ch/ab-div/Meetings/APC/2004/apc041210/apc041210.html.

[4] E. Shaposhnikova – SPS Upgrade Working Group meeting held on 5th July 2007, http://paf-spsu.web.cern.ch/paf-spsu/meetings/2007/M05-07/spsu5_7_7.pdf

[5] G. Arduini, S. Cettour-Cave, K. Cornelis, E. Métral, Minutes of the IEFC Meeting held on 11th June 1009, https://espace.cern.ch/be-dep/IEFC/Minutes/2009-06-11.pdf.

[6] G. Rumolo, E. Métral, E. Shaposhnikova, *SPS performance with the PS2*, LHC-LUMI-06 Proceedings, CERN-2007-002, pp. 129-134.

[7] G. Rumolo, G. Arduini, E. Metral, E. Shaposhnikova, E. Benedetto, R. Calaga, G. Papotti, B. Salvant, *The dependence of the electron cloud instability on the beam energy*, Phys. Rev. Lett. 100, 144801 (2008).

Appendix 1

The values for the dispersion beating are based on measurements performed in 1998 on the Fixed-Target cycle (see fig. A.1 and A.2)

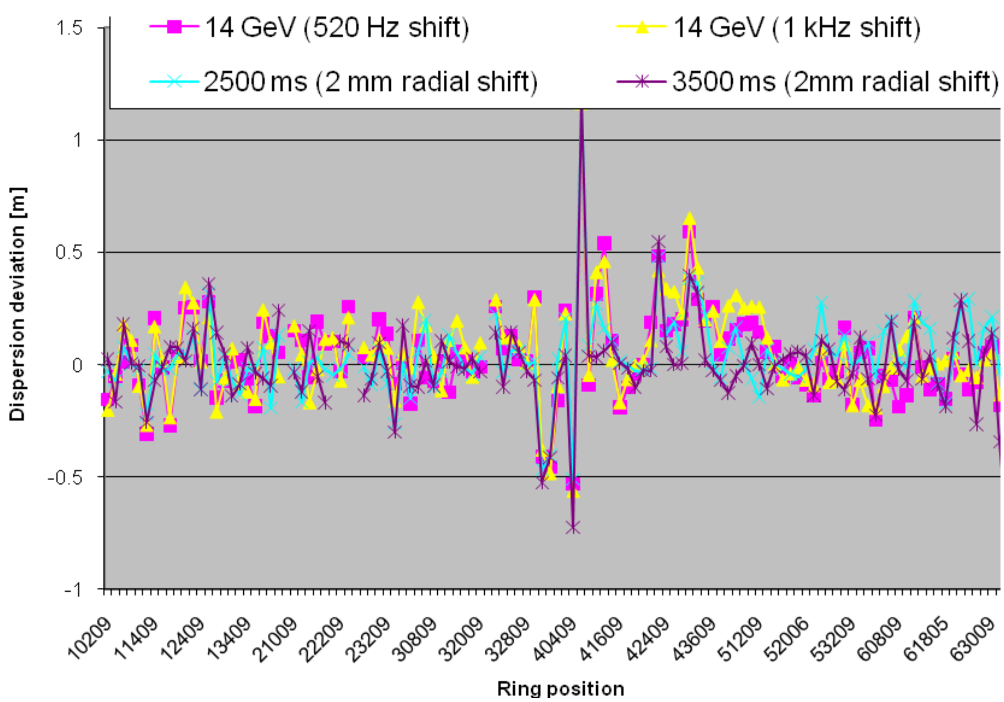

Fig. A.1 Deviation of the measured dispersion with respect to the expected (horizontal plane). Measurement taken on the Fixed-Target cycle in 1998 at flat-bottom (14 GeV/c) and during the ramp 2500 and 3500 ms after the first injection.

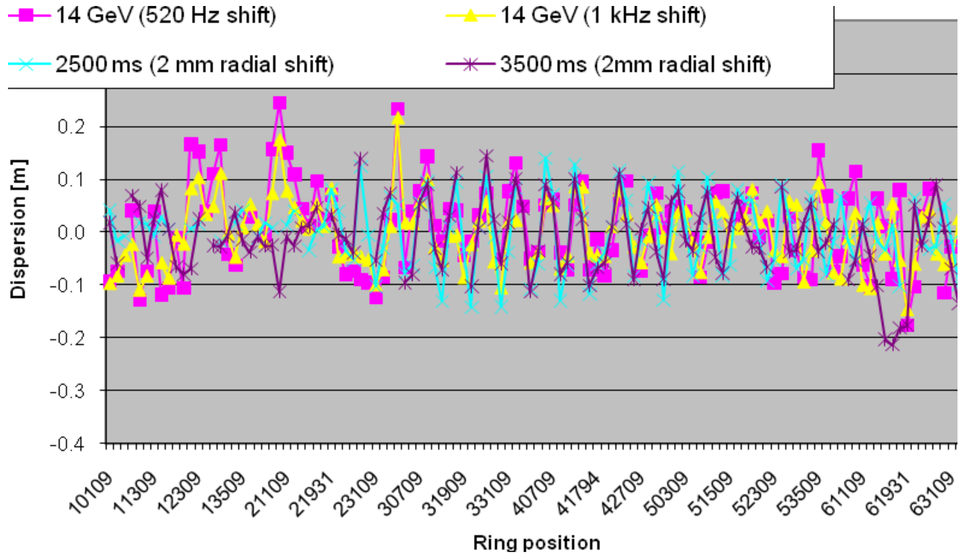

Fig. A.2 Measured vertical dispersion. Measurement taken on the Fixed-Target cycle in 1998 at flat-bottom (14 GeV/c) and during the ramp 2500 and 3500 ms after the first injection.