SL-Note-99-013 MD
PS-Note-99-008 CA

PS/SPS

March 19, 1999

TT2/TT10 Transfer Line Studies for the 14 GeV/c Continuous Transfer

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Run no.	Date
	06/05/98
	13/05/98
	03/06/98
	15/07/98
	22/07/98

Keywords: PS Machine, SPS Machine, Optics

Summary

Since several years the values of the emittance of the fixed-target beam measured with SEM-wires in the TT2 line and with SEM-grids in the TT10 line were in disagreement by up to 50 %. The measurement of the beam emittance by means of beam profile monitors (BPMs) relies on the knowledge of the dispersion function at the monitor location. For these reasons a measurement campaign of the dispersion function and, in general, of the optical parameters of the TT2/TT10 transfer line was carried out in 1998. The model of the line was verified and the TT2/TT10 transfer line was re-matched according to the measured values of the Twiss parameters and of the dispersion and its derivative. As a result of this work the discrepancy between the emittance values measured in TT2 and TT10 has been brought down to less than 10 % in both planes and the blow-up at injection in the SPS minimised. The transmission through the SPS and hence the intensity delivered to the targets could be increased by about 2 %.

1 Introduction

Since several years the values of the emittance of the fixed-target beam measured with SEM-wires in the TT2 line and with SEM-grids in the TT10 line were in disagreement by up to 50 %. Preliminary measurements performed in 1997 [1] showed that a reasonable agreement on the emittance values could be obtained for a one-turn extraction. The measurement of the beam emittance with BPMs relies on the knowledge of the dispersion at the monitor location. For that reason, a measurement of the dispersion function in the injection transfer line for the 14 GeV/c continuous transfer (CT) was tried during a machine development session on 11/11/97 but the collected data proved not to be consistent.

An important campaign of studies of the injection line was undertaken during the 1998 run in order to understand the optics of the transfer line.

2 *MAD* Model

The measurement of the dispersion function D, of its derivative D' and of the Twiss parameters α, β requires the knowledge of the transfer matrix between the reference point and any of the monitors used for the measurement. Furthermore, once the initial optical parameters are measured, the transfer line model is required to match the beam line optics at the injection point in the SPS. During the 1998 run considerable effort was spent to verify the beam line model and to accurately measure the beam parameters at the beginning of the injection line. The complete TT2/TT10 line was modelled [2] using the program *MAD* [3]. The geometry of the model was cross-checked versus the official CERN survey data and the correct magnetic behaviour of the elements was confirmed in a series of measurements in TT2 and TT10 [4].

An emittance exchange insertion is included in the TT10 part of the line (see for instance Refs. [5] [6]) as the vertical emittance of the extracted beam is larger than the horizontal one while the most stringent constraints in the physical aperture of the SPS are present in the vertical plane. The section starts at element `QISK100637` and ends at element `QISK101036`. Three skew quadrupoles are used to exchange the horizontal and vertical phase planes. Such an insertion cannot be easily modelled with *MAD*, therefore a pragmatic approach has been adopted. The TT2/TT10 line is split up into two parts: upstream of the emittance exchange section and downstream of it. The exchange section is modelled via a linear matrix which interchanges the two phase planes. The disadvantage of this model is that the computation of the transfer line optics must be done in two steps.

3 Experimental Conditions

The CT extraction was setup for the fixed target programme. The extracted beam is cut in five parts by means of the electrostatic septum `SES31` [7] to respect the ratio between the length of the PS and SPS machines (5/11) and to satisfy the constraint of filling the SPS with two PS batches. Having set the horizontal tune to the value $Q_H = 6.25$ five parts are generated according to the scheme plotted in Fig. 1. At each turn one beam slice is extracted out of the PS machine by means of fast dipoles: each part receives a different kick, the strongest one being that imparted to the beam core. In Fig. 2 (upper part) is shown the strength of the dipoles used to extract the beam as a function of time.

The main constraints on the beam characteristics required for the studies are imposed by the dispersion measurement and the beam instrumentation. The beam emittance and momentum spread must be small in order to avoid scraping during the dispersion measurement. It seems furthermore reasonable to have a momentum spread much smaller than the momentum span, which is limited by the acceptance of the transfer line. This quantity was measured in 1995 to be about $\pm 3 \times 10^{-3}$. Furthermore, the TT10 and SPS couplers have a narrow bandwidth around 200 MHz. Therefore the bunch length should be limited to about 5 ns in order to be able to measure the beam position.

The CT extraction scheme makes the dispersion function measurement extremely difficult. The five slices extracted will have slightly different positions and angles as the beam momentum is changed during the dispersion measurement. These differences cannot be compensated by other elements otherwise the dispersion function will be perturbed as well. Furthermore, the profile monitors in the TT2/TT10 line will integrate the beam profiles over the five slices, giving a wrong value for the beam position and width.

For these reasons it has been decided to modify the extraction scheme in order to have a *one-turn* extraction. A beam of reduced intensity (hence corresponding to the single piece labelled **5** in Fig. 1) is extracted using only one kick having exactly the same amplitude used to kick the fifth slice during the standard operation. In Fig. 2 (lower part) the new setting of the extraction dipoles is shown. By carefully adjusting the different parameters we have checked that the beam is really extracted in one single turn.

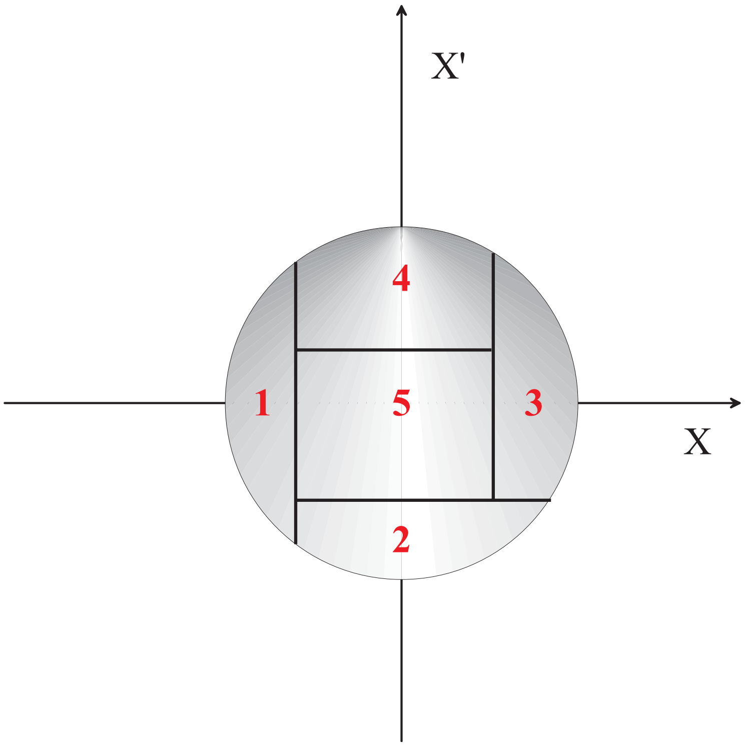


Figure 1: Principle of the five-turns extraction.

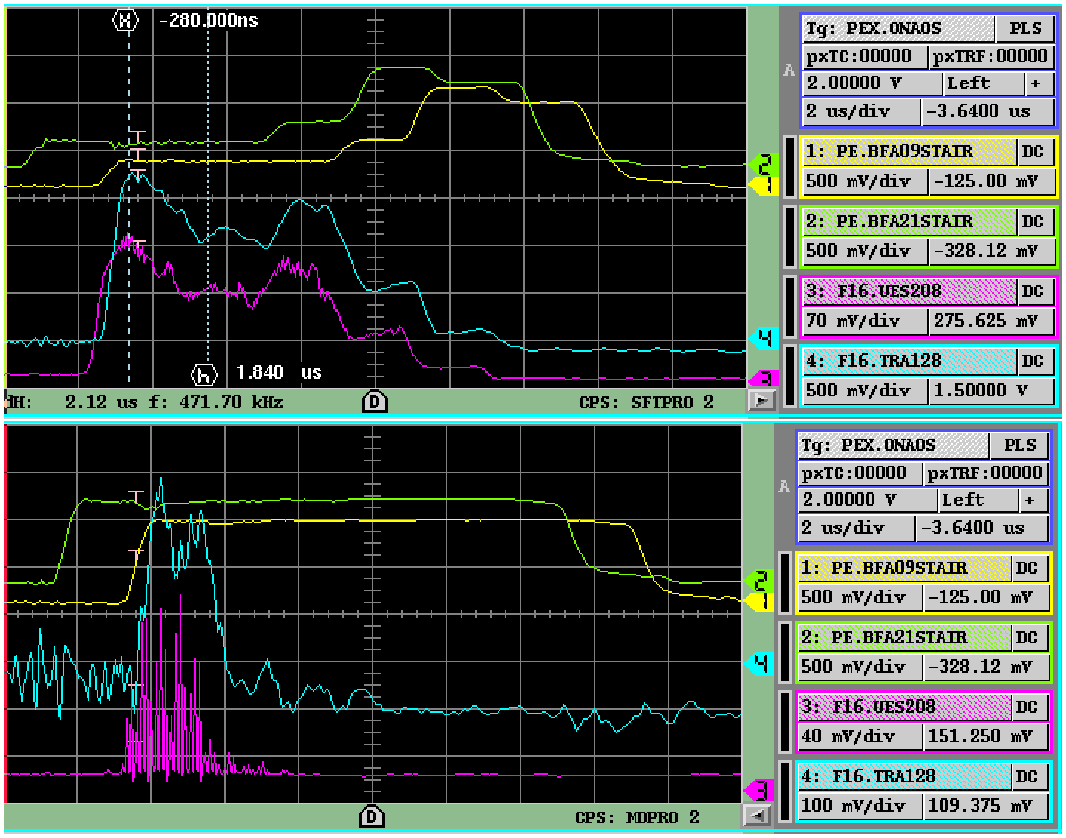
The magnetic cycle used for this operation has a length of 1.2 s (see Fig. 3 upper part). It consists of an injection flat bottom of 20 ms at 1.7 GeV/c, where longitudinal blow-up is applied, then a second plateau at 3.5 GeV/c is used to change the rf harmonic number from 8 (at injection) to 16 (up to extraction). The beam is then accelerated up to 14 GeV/c and extracted on a flat top using the scheme previously described. The nominal setting of the extraction elements is reported in Table 1.

Transition crossing occurs at 5.7 GeV/c (about 2700 Gauss of magnetic field).

The working point is controlled by means of the low energy quadrupoles up to 3.5 GeV/c where the Pole Face Windings (PFW) take over to control the tune and chromaticity. The tunes are plotted in Fig. 3 (centre part) all along the magnetic cycle. On the extraction flat top the tunes are set to the nominal values $Q_H = 6.24$ (Q_H is carefully set to 6.25 just before the five-turns extraction) and $Q_V = 6.29$. The chromaticities are also controlled by means of the PFWs. The vertical chromaticity is slightly modified

Element	Value
`PE.SMH16` [A]	15380
`PE.SES31` [kV]	176
`PE.BSW16` [A]	740
`PE.BSW31` [A]	306
`PE.QKE16` [A]	1940
`PE.BFA9S` [kV]	30
`PE.BFA9P` [kV]	30
`PE.BFA21S` [kV]	30
`PE.BFA21P` [kV]	30

Table 1: Nominal setting of the extraction elements for the 14 GeV/c CT-beam.



Tg: PEX.ONAOS PLS
pxTC:00000 pxTRF:00000
2.00000 V Left +
2 us/div -3.6400 us
1: PE.BFA09STAIR DC
500 mV/div -125.00 mV
2: PE.BFA21STAIR DC
500 mV/div -328.12 mV
3: F16.UES208 DC
70 mV/div 275.625 mV
4: F16.TRA128 DC
500 mV/div 1.50000 V

Tg: PEX.ONAOS PLS
pxTC:00000 pxTRF:00000
2.00000 V Left +
2 us/div -3.6400 us
1: PE.BFA09STAIR DC
500 mV/div -125.00 mV
2: PE.BFA21STAIR DC
500 mV/div -328.12 mV
3: F16.UES208 DC
40 mV/div 151.250 mV
4: F16.TRA128 DC
100 mV/div 109.375 mV

Figure 2: Setting of the extraction elements (`PE.BFA09STAIR, PE.BFA21STAIR`) for the standard CT five-turns extraction (upper part) and for the special CT one-turn extraction used during the MD (lower part). The extracted beam intensity as a function of time is also shown (`F16.TRA128`).

before transition $\xi_V = -1$ instead of -1.5, after transition crossing both ξ_H and ξ_V are set to positive values (see Fig. 3 (lower part)) and on the flat top one has $\xi_H = 0.5$ and $\xi_V = 0.5$.

No debunching procedure is applied on the extraction flat top and the rf voltage is kept to the maximum value of 200 kV. No 200 MHz structure is present. These two ingredients made the campaign of measurements with the CT-beam a success contrary to a previous machine development session (11/11/97) which gave inconsistent results.

The main beam parameters are listed in Table 2.

4 Experimental Results

The dispersion function for the optics used in TT2/TT10 since several years (see Table 3) was measured in the injection line and in the first turn in the SPS ring, considered as a continuation of the transfer line. The measurement method has been described in detail in reference [8]. The momentum offset with respect to the reference momentum was varied between -1.5×10^{-3} and 2.0×10^{-3}. Figure 4 shows the measured horizontal dispersion in the transfer line and in the SPS. Figure 6 shows measured (squares) and theoretical (triangles) values of the horizontal dispersion D_H in the SPS before matching the injection line, while Fig. 8 shows the same quantities for the vertical plane. The disagreement between the theoretical and measured values of D in the SPS is clearly visible in the vertical plane.

The measured values of the dispersion at the TT2 SEM-wires and at the TT10 SEM-grids location are listed in Table 4 while the dispersion and its derivative at the *R-point* (entry of the quadrupole `QF0105`)

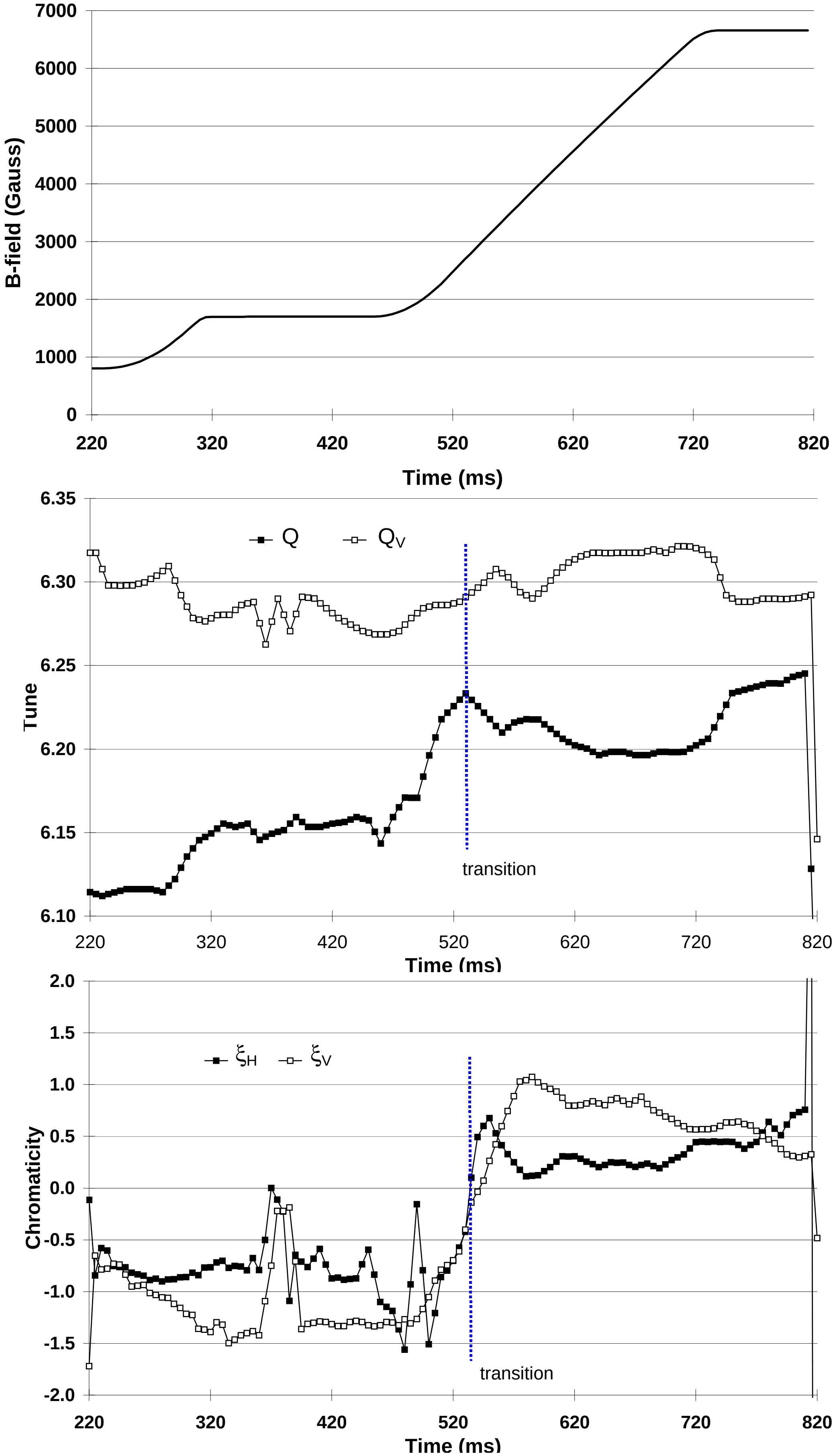


Figure 3: Magnetic cycle (upper), tunes (centre) and chromaticity (lower) measured during the MD sessions. The position in time of the transition crossing is also shown.

p [GeV/c]	14
Intensity [p/batch]	2×10^{12}
ε_H [μm] (normalised, r.m.s)	5.0
ε_V [μm] (normalised, r.m.s)	6.7
$\frac{\Delta p}{p}$ (r.m.s.) [10^{-3}]	0.2
bunch length [ns] (4σ)	6-8
ε_l [eVs]	0.1

Table 2: Parameters of the proton beam used to study the injection transfer line optics for the 14 GeV/c CT extraction.

are presented in Table 5. Once D is known at the BPMs location, the Twiss parameters at the SEM-wire `MSG257`, SEM-grid `MSG258`[1] and at the SEM-grid `BSG1027` could be measured during normal operation. The measurement in the vertical plane has been performed also with the TT2 SEM-grids because the CT-beam with physics intensity is filling completely the SEM-wires and the tails are not visible. The results are listed in Table 6. The Twiss parameters measured at both locations have been tracked back up to *R-point*. The values obtained for the Twiss parameters at the *R-point* are listed in Table 7. The initial parameters measured in 1998 are summarised in Table 8. The Twiss parameters

Quadrupole	Old optics Current [A]	New optics Current [A]
`QFO105`	291.9	291.9
`QDE120`	121.8	121.8
`QFO135`	105.5	105.5
`QDE150`	135.2	135.2
`QFO165`	110.1	110.1
`QDE180`	131.6	131.6
`QFO205`	76.5	76.5
`QDE210S`	98.4	102.9
`QFO215S`	113.2	105.4
`QFO375`	113.2	142.8
`QIID1001`	64.89	87.93
`QIIF1002`	85.43	127.08
`QIID1003`	76.80	73.34
`QIF1004`	92.64	76.04
`QID1005`	64.58	62.25
`QIF1006`	90.02	65.95
`QISK1006`	37.15	37.15
`QID1007`	79.55	79.44
`QIF1008`	79.56	79.43
`QID1011`	73.74	73.74
`QIF1012`	79.20	79.20

Table 3: Setting of the quadrupoles of the TT2/TT10 line for the old and new optics.

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[1] The dispersion at the SEM-grids has been calculated with *MAD* by using the measured values of the dispersion and its derivative at the *R-point* as initial conditions

Monitor	Old optics D_H [m]	 D_V [m]	New optics D_H [m]	 D_V [m]
`MSG257`	0.93 ± 0.07	-0.77 ± 0.07	1.17 ± 0.13	-0.92 ± 0.02
`MSG267`	0.12 ± 0.14	-1.01 ± 0.06	0.81 ± 0.10	-0.53 ± 0.01
`MSG277`	-0.40 ± 0.16	-0.83 ± 0.06	0.45 ± 0.11	0.12 ± 0.01
`BSG1027`	-3.26 ± 0.07	-0.16 ± 0.17	-4.23 ± 0.05	0.30 ± 0.18
`BSG1028`	-2.63 ± 0.05	1.0 ± 0.14	-3.27 ± 0.07	0.51 ± 0.19
`BSG1029`	0.73 ± 0.03	1.17 ± 0.16	1.22 ± 0.04	0.42 ± 0.11

Table 4: Measured dispersion at SEM monitors before and after re-matching the line.

	Horizontal plane	Vertical plane
D [m]	1.30 ± 0.03	0.09 ± 0.01
D' [1]	0.102 ± 0.003	0.020 ± 0.001

Table 5: Measured dispersion and dispersion derivative at the *R-point* before re-matching the line.

have been obtained as an average of the values listed in Table 7 from the TT2 and TT10 measurements (MSG257 and BSG1027 for the horizontal plane and MSG258 and BSG1027 for the vertical plane). The geometric blow-up and the blow-up after filamentation are listed too, both for the betatronic and dispersive components [5][9].

5 Betatron and Dispersion Matching

The Twiss parameters, the dispersion and its derivative were matched to the measured ones at the *R-point* (see Table 8) and to the nominal values at the injection point in the SPS (see Table 9). The quadrupoles in the emittance exchange section are not available for matching as the conditions for the emittance exchange have to be maintained. Only six independent quadrupoles are therefore available for matching in TT10 while 8 constraints are required from the betatron and dispersion matching. For that reason also the quadrupoles of the TT2 strings `QDE210S` and `QFO215S` and the quadrupole `QFO375` were considered for the matching.

Figures 10, 11 show the transverse Twiss parameters, β_H, β_V, upstream and downstream the emittance exchange section in TT10, respectively, while D_H, D_V upstream and downstream the exchange section are presented in Figs. 12, 13.

This new optics (see Table 3) has been tested in operation. It brought a reduction of the injection losses by a factor 2 and a corresponding improvement of the transmission efficiency of about 2 %. The dispersion measurement was repeated and the new results are shown in Figs. 5, 7 and 9. No significant improvement has been achieved in the horizontal plane while a significant reduction of the mismatch factors has been obtained in the vertical plane. Nevertheless, it must be pointed out that the dispersion blow-up was already small for the previous optics. The measured dispersion at the TT2 SEM-wires and at the TT10 SEM-grids is presented in Table 4, while the Twiss parameters at `BSG1027` were measured and are listed in Table 10 as well as the values at *R-point* obtained by tracking back the measured values. The optical parameters at the *R-point*, the geometric blow-up and the blow-up after filamentation for the new optics are summarised in Table 8.

Monitor	β_H [m]	α_H	β_V [m]	α_V
`MSG257`	18.25	0.6	47.25	-1.24
`MSG258`	-	-	44.72	-1.25
`BSG1027`	86.9 ± 1.1	-3.06 ± 0.06	42.2 ± 0.99	0.81 ± 0.02

Table 6: Measured α and β at SEM monitors.

	β_H [m]	α_H	β_V [m]	α_V
from `MSG257`	27.01	-2.13	10.20	0.54
from `MSG258`	-	-	10.47	0.67
from `BSG1027`	25.88	-2.18	10.11	0.84

Table 7: Measured α and β tracked back from SEM monitors to entry of the line for the old optics.

	Old optics		New optics	
	Horizontal plane	Vertical plane	Horizontal plane	Vertical plane
β [m]	26.44	10.29	21.45	13.48
α	-2.16	0.76	-1.61	0.77
D [m]	1.30	0.09	1.42	-0.112
D'	0.102	0.02	0.108	0.112
G_b	2.1	1.8	1.58	1.09
H	1.3	1.2	1.11	1.00
G_d	1.02	1.03	1.04	1.00
J	1.01	1.02	1.02	1.00

Table 8: Measured Twiss parameters at the *R-point*, geometrical blow-up and blow-up after filamentation for the optics available at the beginning of 1998 and for the new optics.

	Horizontal plane	Vertical plane
β [m]	102.01	20.75
α	-2.33	0.56
D [m]	0.05	$0.29 \cdot 10^{-2}$
D'	$0.57 \cdot 10^{-2}$	$-0.55 \cdot 10^{-4}$

Table 9: Nominal SPS optical parameters at injection for $Q_H = 26.62, Q_V = 26.58$.

Monitor	β_H [m]	α_H	β_V [m]	α_V
`BSG1027`	58.1 ± 0.4	-1.328 ± 0.005	55.0 ± 0.3	1.4 ± 0.4
R-point	21.45	-1.61	13.45	0.77

Table 10: Measured α and β at SEM monitor after re-matching. The values of the optical parameters tracked back from SEM monitors to *R-point* are also shown.

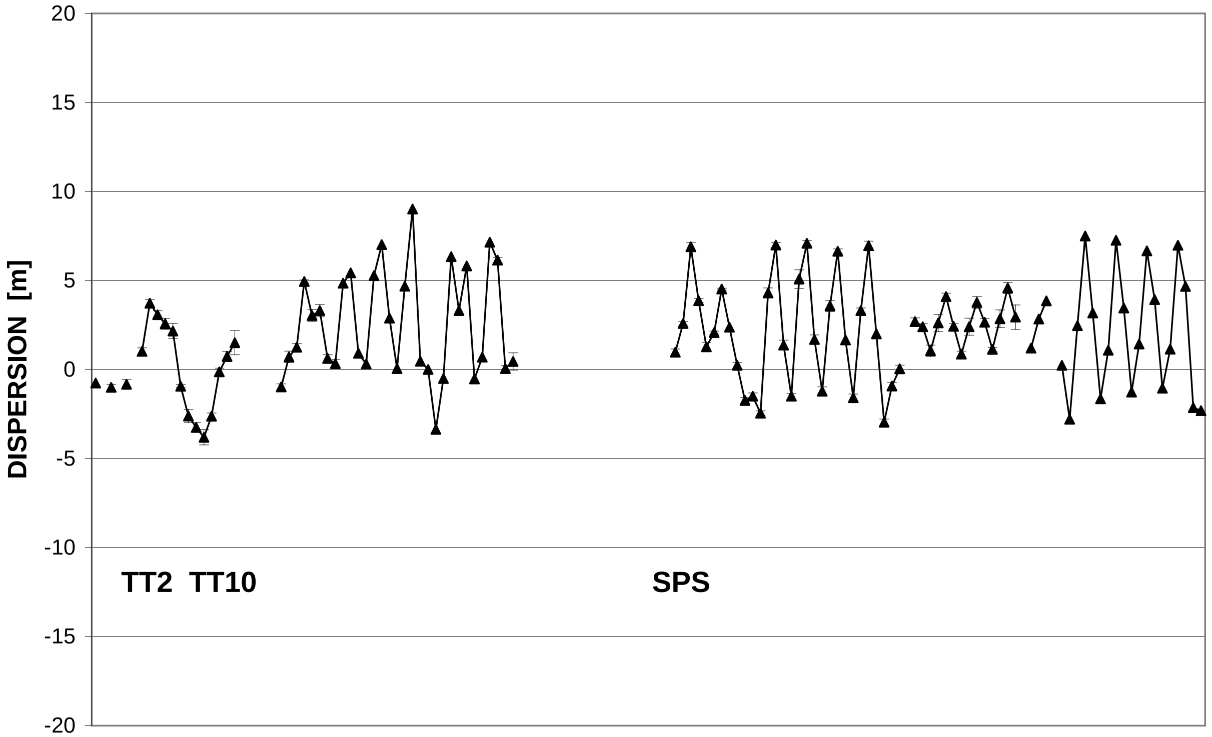

Figure 4: Measured horizontal dispersion in the transfer line and the SPS machine before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

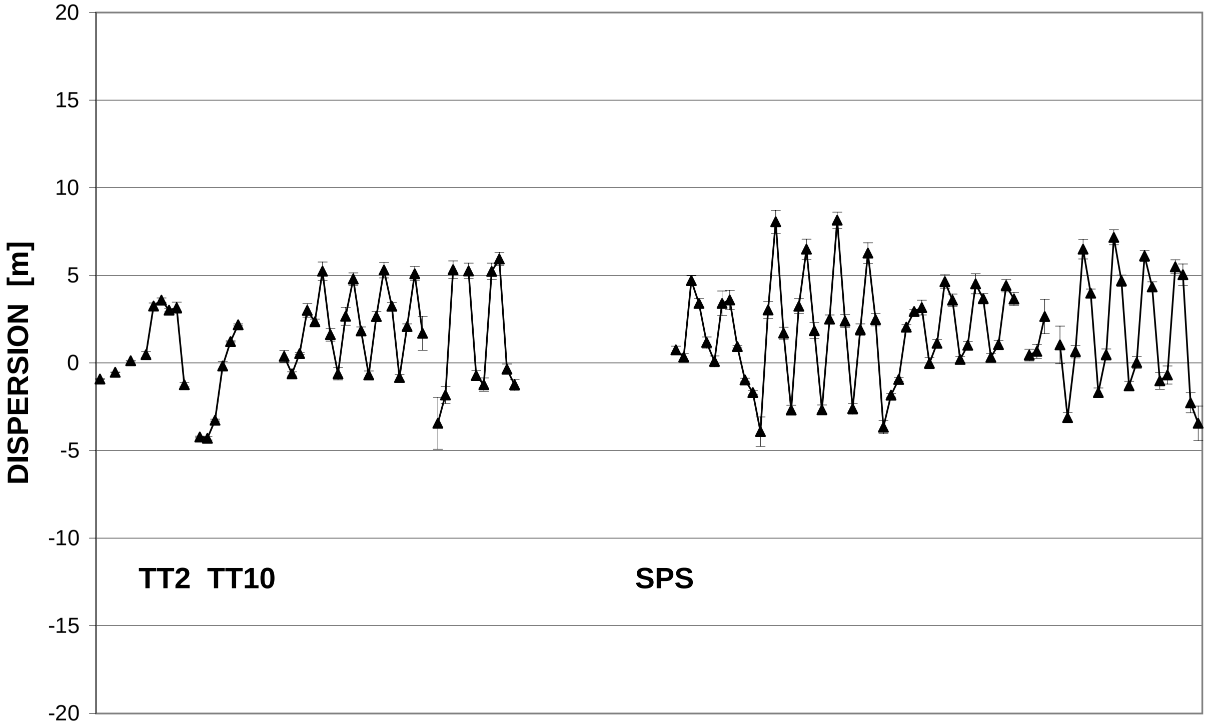

Figure 5: Measured horizontal dispersion in the transfer line and the SPS machine after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

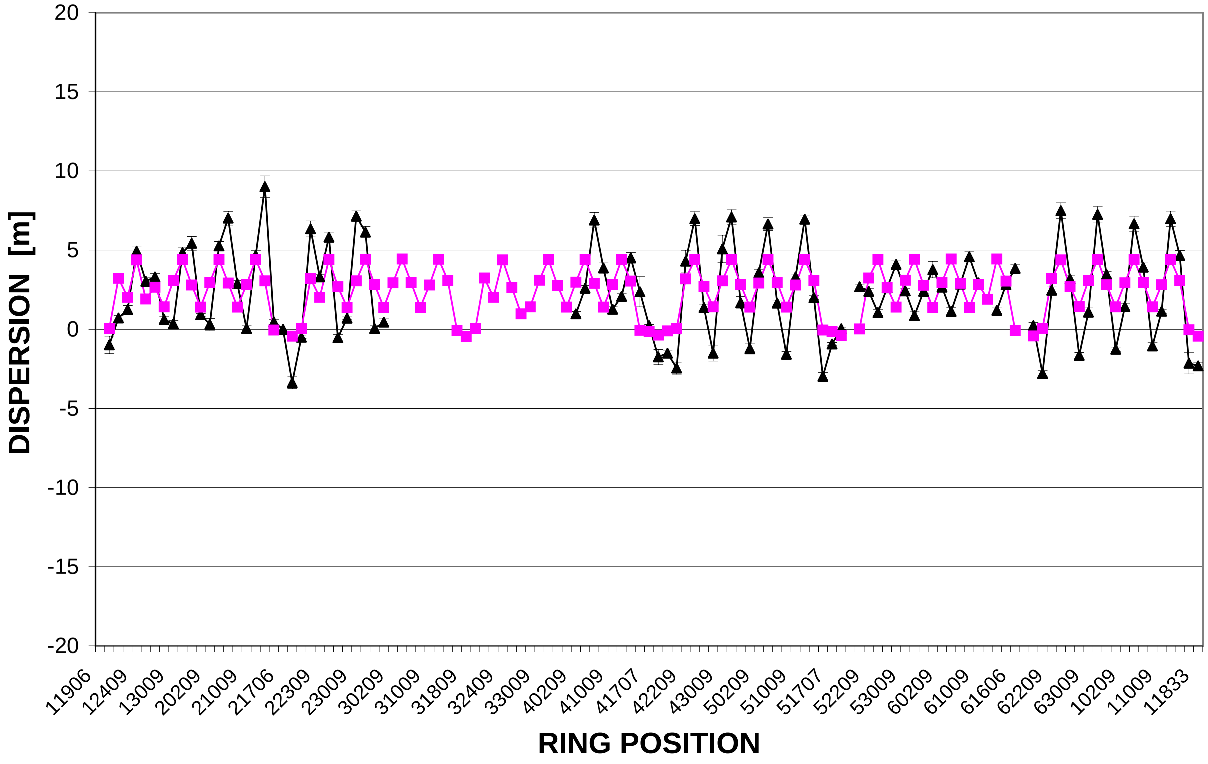

Figure 6: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS before matching the injection line.

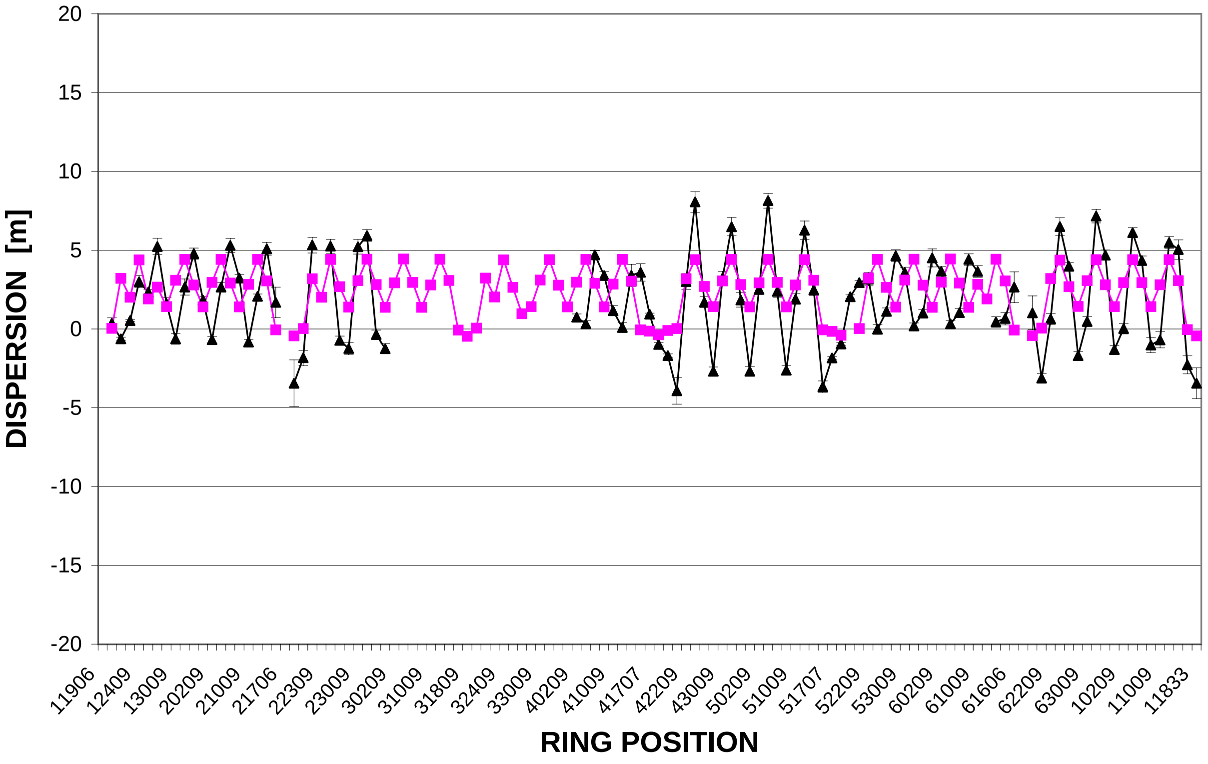

Figure 7: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS after matching the injection line.

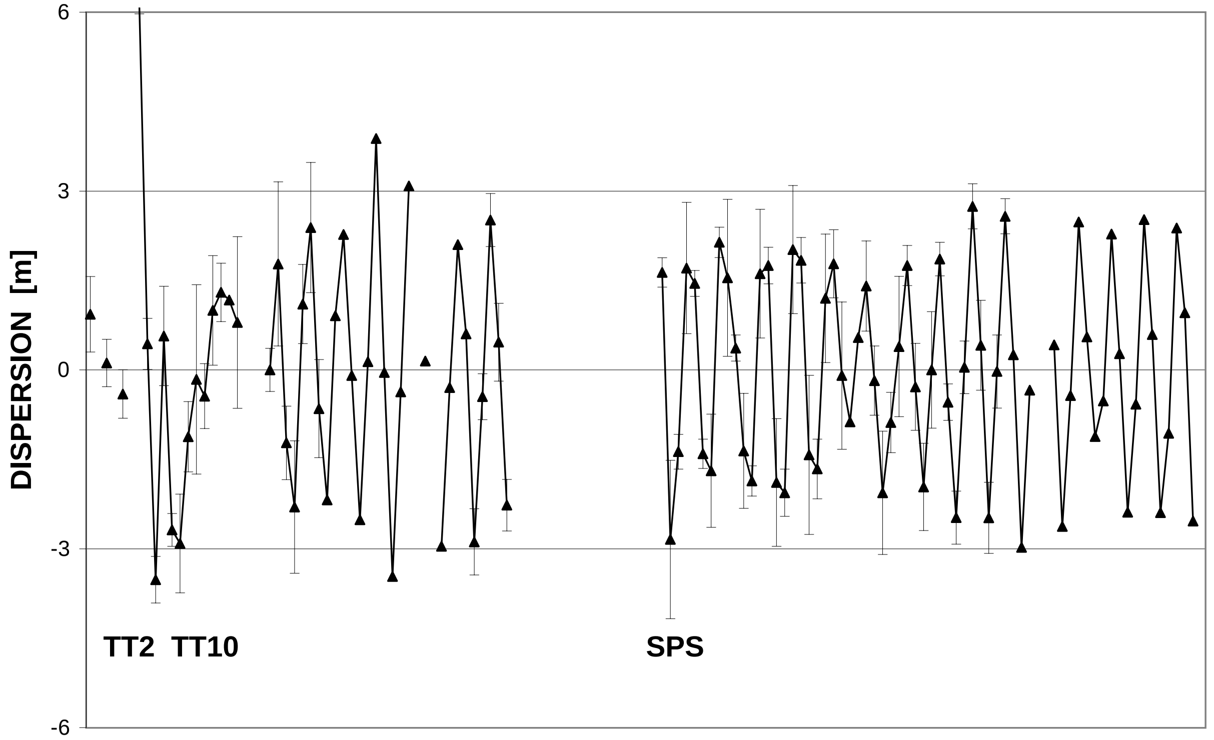

Figure 8: Measured vertical dispersion in the transfer line and the SPS machine before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

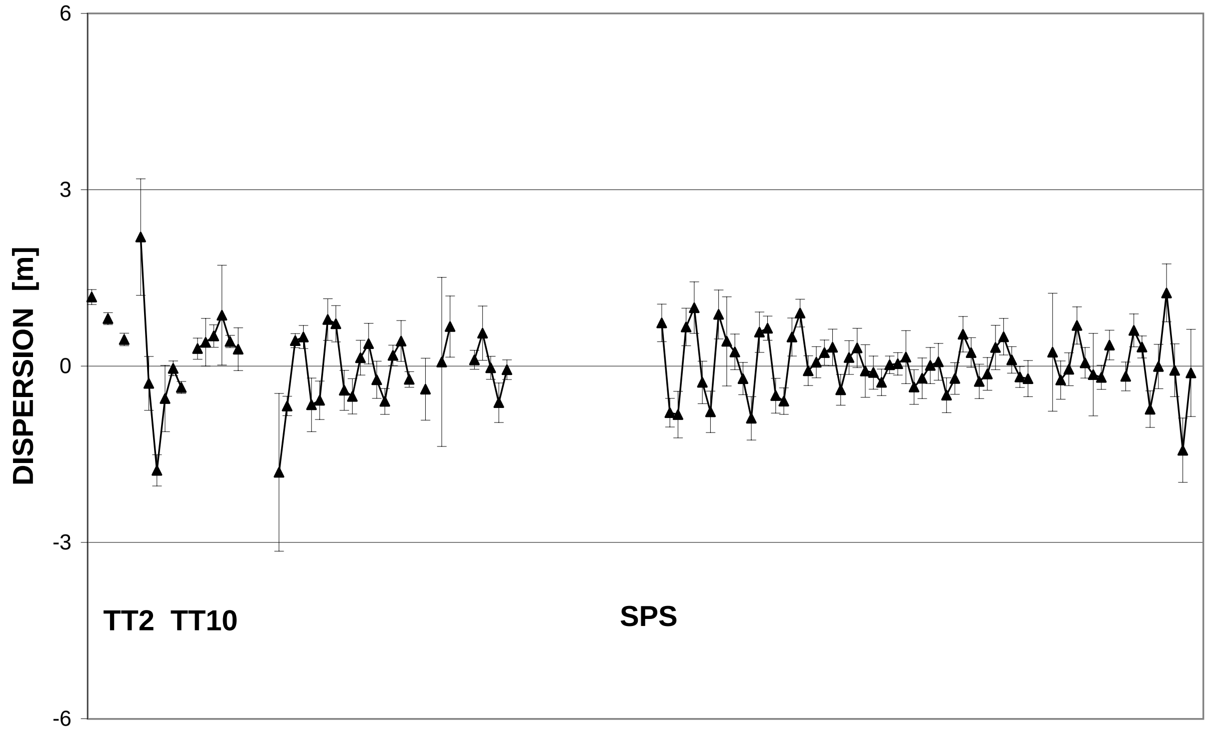

Figure 9: Measured vertical dispersion in the transfer line and the SPS machine after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

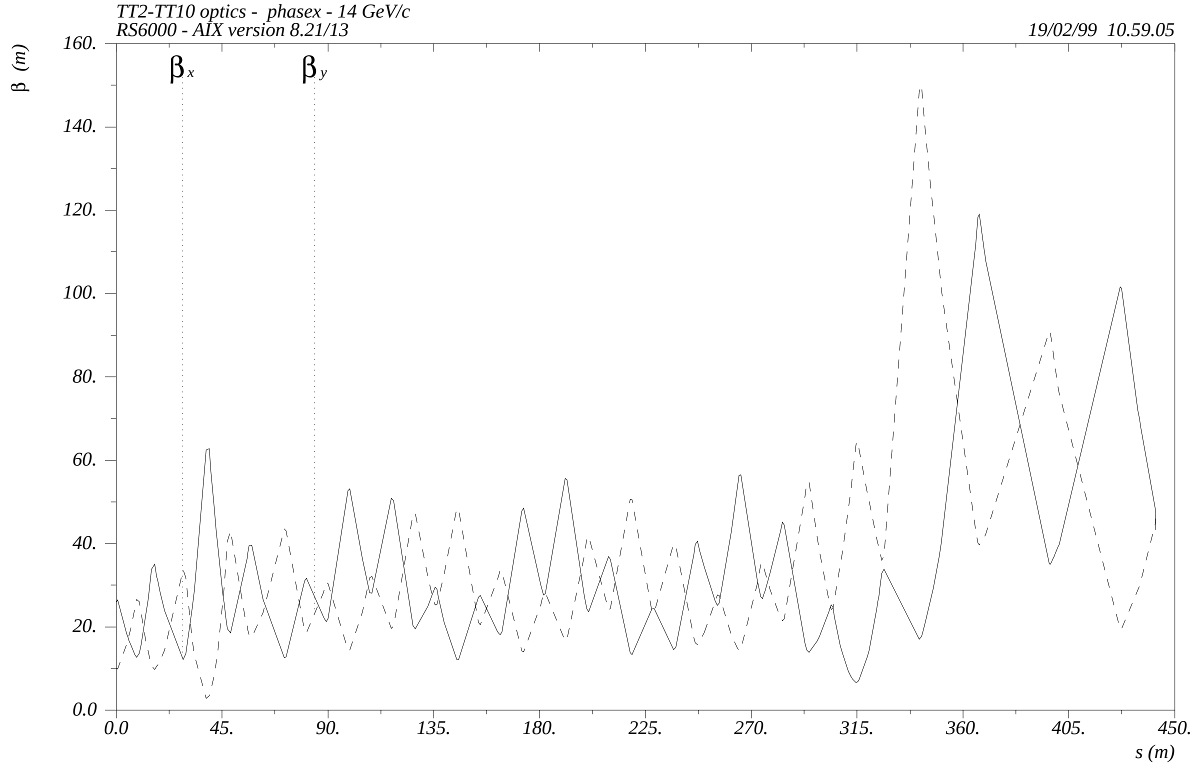

Figure 10: Horizontal and vertical β-function upstream of the emittance exchange insertion for the matched optics as computed by *MAD.*

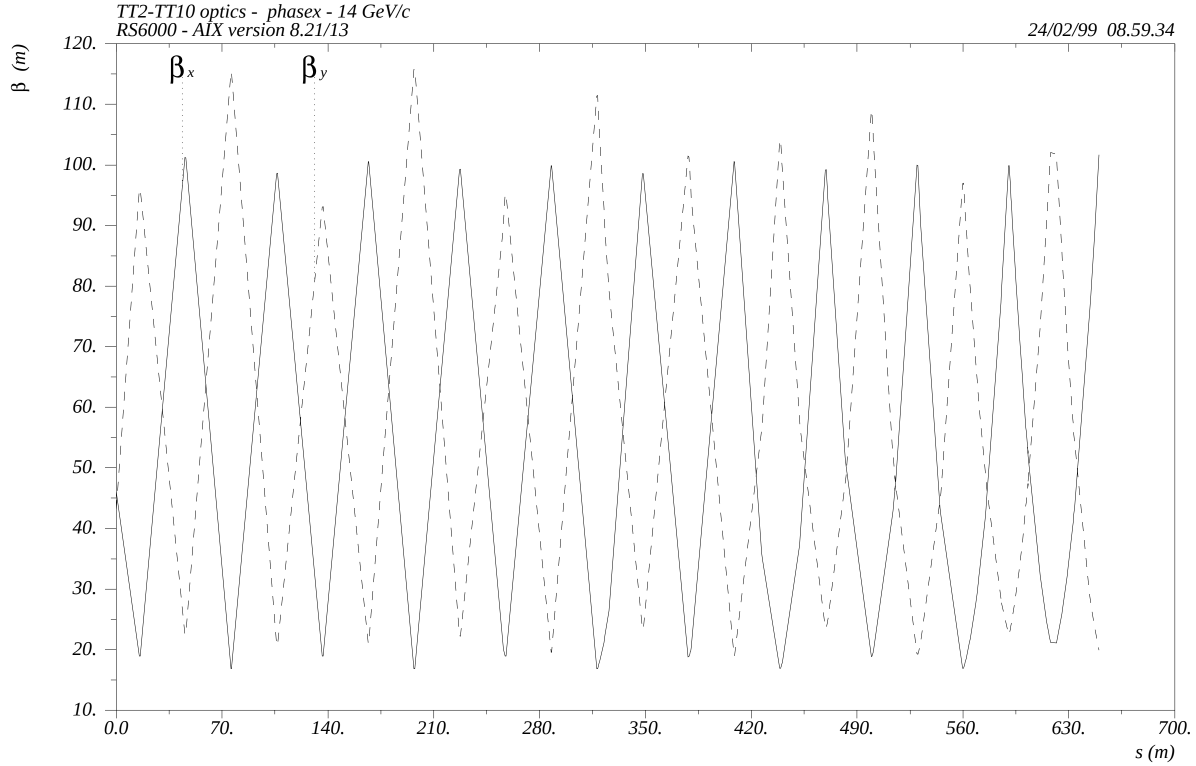

Figure 11: Horizontal and vertical β-function downstream of the emittance exchange insertion for the matched optics as computed by *MAD.*

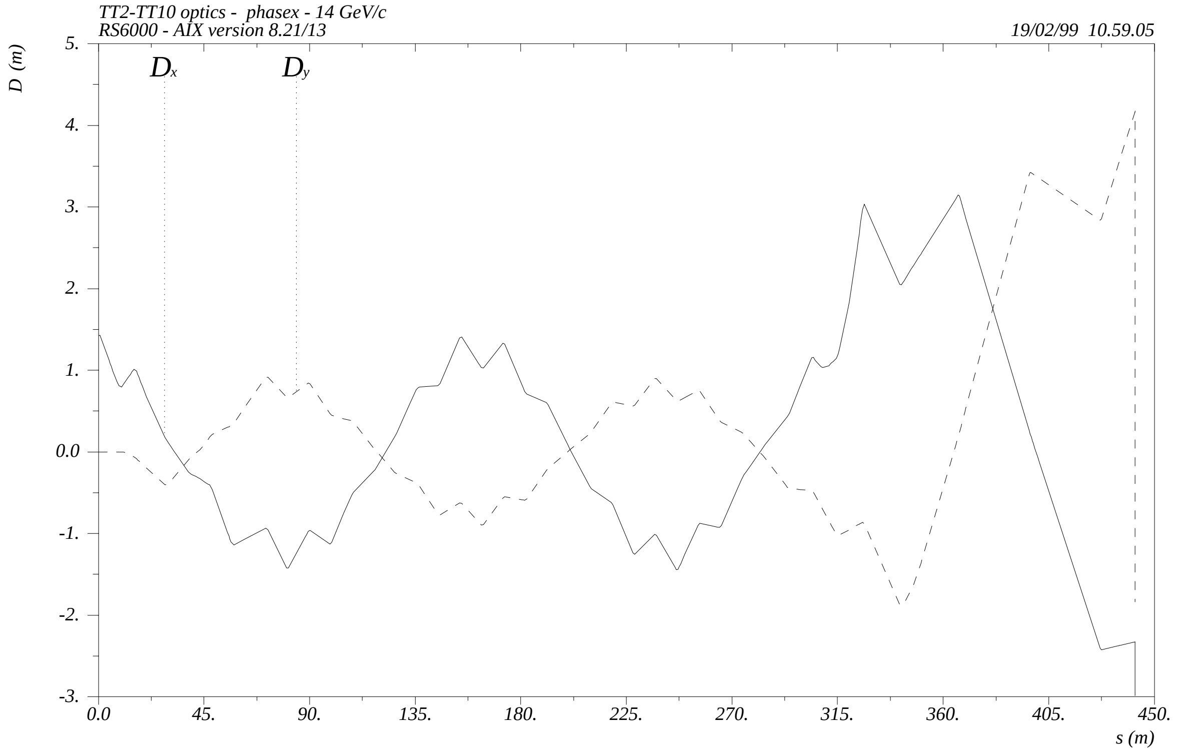

Figure 12: Horizontal and vertical dispersion upstream of the emittance exchange insertion for the matched optics as computed by *MAD.*

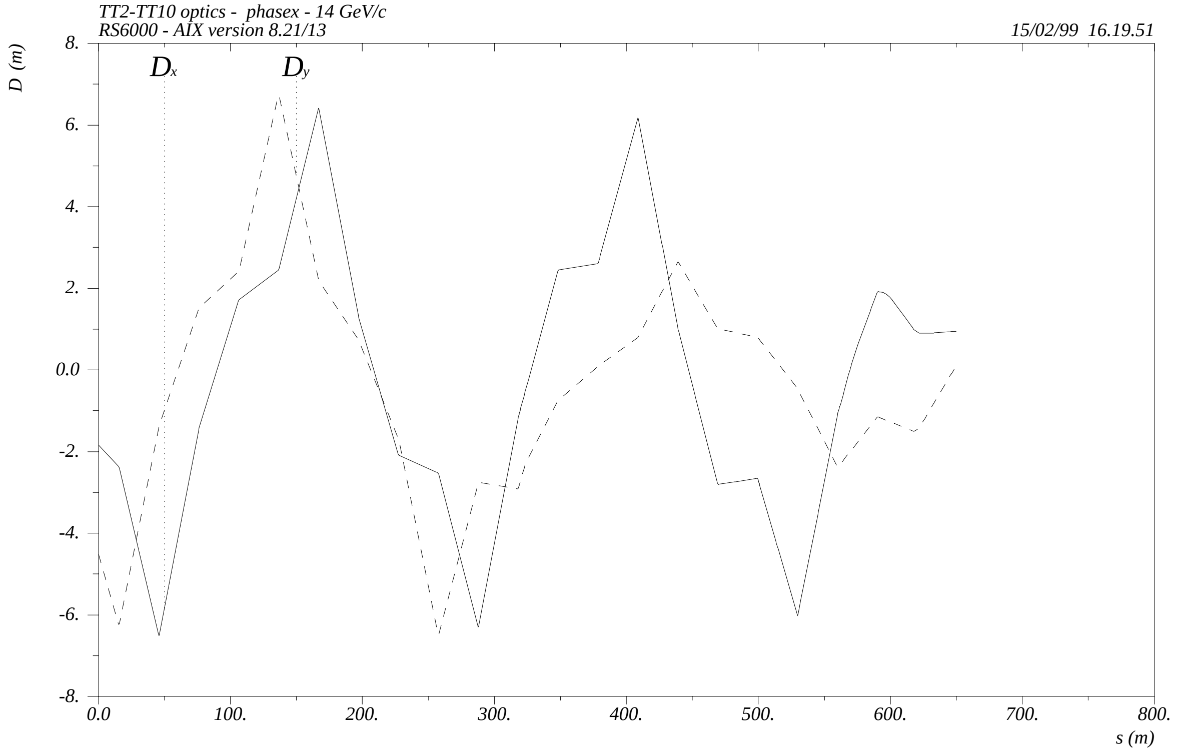

Figure 13: Horizontal and vertical dispersion downstream of the emittance exchange insertion for the matched optics as computed by *MAD.*

6 Emittance Measurements

The campaign of measurements of the optical parameters in TT2/TT10 allowed to improve not only the matching at injection, but also the agreement between the emittance values measured using the monitors in TT2 and those in TT10. After the measurement of the dispersion in the injection line an experiment was carried out to determine the discrepancy between the emittance measurement performed in TT2 and in TT10. The results are shown in Table 11. It is clearly seen that after using the measured optical parameters of the transfer line to compute the beam emittance the agreement improved considerably. The SEM-wires offer a better precision with respect to the SEM-grids due to the smaller distance between consecutive wires (0.5 mm for the SEM-wires against 2.5 mm for the SEM-grids). Nevertheless the SEM-wires span a smaller size than the SEM-grids and in the vertical plane the beam size exceeds the monitor's acceptance, thus making the outcome of the measurement less reliable. The most precise

Monitor	ε_H [π mm mrad]	ε_V [π mm mrad]
TT2 SEM-wires (spline fit)	1.93	1.99
TT2 SEM-grids (spline fit)	2.4	2.8
TT10 SEM-grids (gauss. fit)	2.74	2.1

Table 11: Comparison of the emittance measured in TT2 and TT10. The quoted values of the emittances refer to a 2 σ contour. Note that the horizontal (vertical) values in TT2 should be compared with the vertical (horizontal) ones in TT10, because of the presence of the emittance-exchange section

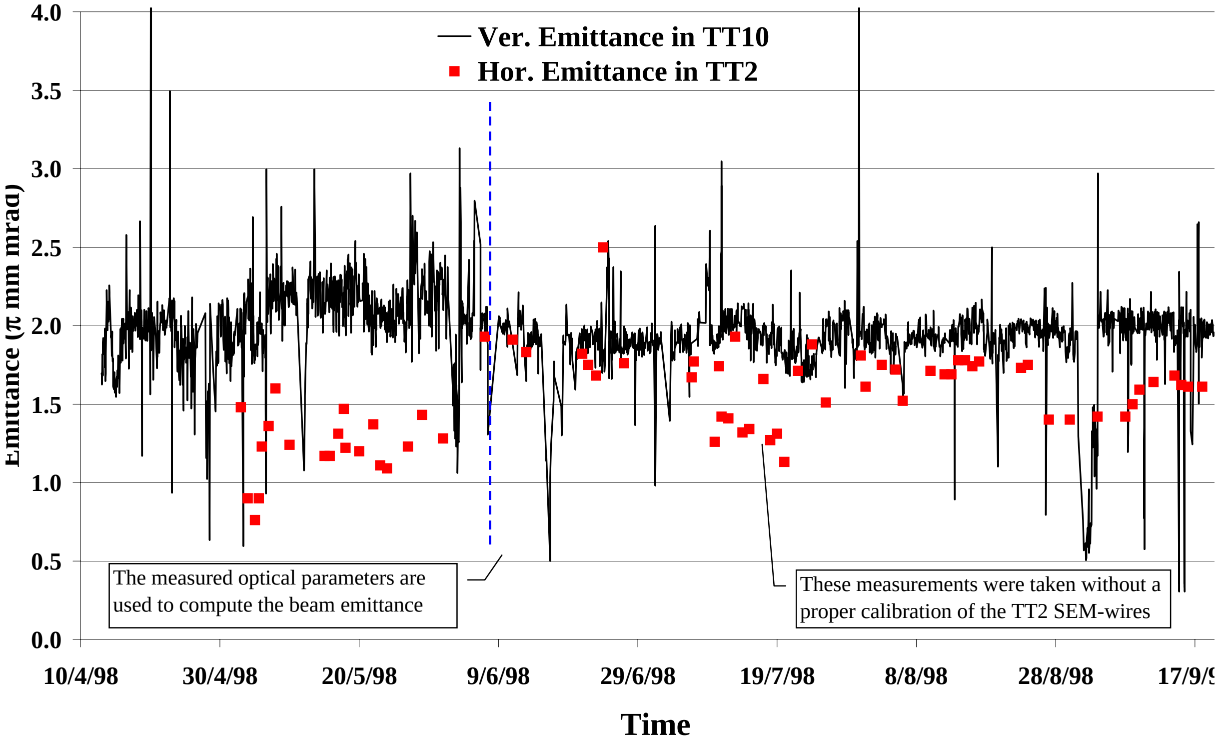

Figure 14: Comparison between the emittance value measured using the monitors in TT2 and those in TT10 during the 1998 physics run. The better agreement resulted from the use of the measured optical parameters of the transfer line is clearly shown.

procedure should consist in measuring the vertical profile in TT2 with the SEM-grids and the horizontal one with the SEM-wires. From Table 11 it appears that the discrepancy between the horizontal (vertical) TT2 measurement and the vertical (horizontal) TT10 measurements is less than 10 % (5 %). Part of the error might be caused by the different fitting routines applied for the beam size determination. In Fig. 14 the emittance values during the 1998 physics run measured in TT2 (horizontal) and in TT10 (vertical) is shown. It is clearly seen that after using the measured optical parameters of the transfer line to compute the beam emittance the agreement improved considerably.

7 Conclusions

A campaign of measurements of the optical parameters of the TT2/TT10 injection line for the fixed-target proton operation has been carried out during the 1998 run.

Simultaneous Twiss parameter and dispersion matching was performed based on the measured initial conditions. A significant reduction of the blow-up at injection has been obtained (see Table 12) with a corresponding improvement by 2 % of the overall transmission efficiency in the SPS. The application of the measured dispersion values at the position of the BPMs allowed to reduce the discrepancy between the emittance measurements performed in TT2 and TT10 to less than 10 %.

It is foreseen to repeat the measurement during the 1999 start-up and in the future for reference purposes. The following improvements to the measurement technique are also foreseen:

- Precise measurement of the energy of the beam and adjustment of its control value accordingly (see Ref. [10]).
- Extension of the error analysis to all the stages of the measurement methods.
- The emittance measurement should be performed according to the procedures illustrated in Section 6.

	Old optics		New optics	
	mismatch (geometrical)	mismatch (filamentation)	mismatch (geometrical)	mismatch (filamentation)
β_H	2.1	1.3	1.6	1.1
β_V	1.8	1.2	1.1	1.0
D_H	1.0	1.0	1.0	1.0
D_V	1.0	1.0	1.0	1.0

Table 12: Measured geometrical blow-up after filamentation in the case of betatron and dispersion mismatch. The values shown refer to the old optics and the matched optics.

Acknowledgements

The authors would like to thank the PS and SPS operation teams for their support.

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