

**TT2/TT10 TRANSFER LINE STUDIES,
FOR THE 14 GEV/C CONTINUOUS TRANSFER**

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Abstract

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%.

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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.

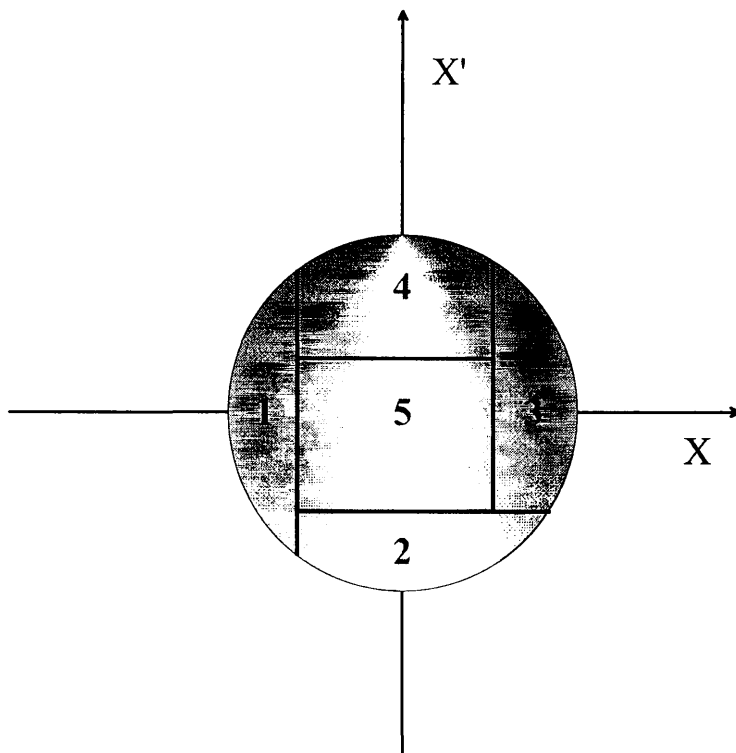


Figure 1: Principle of the five-turns extraction.

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

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.

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

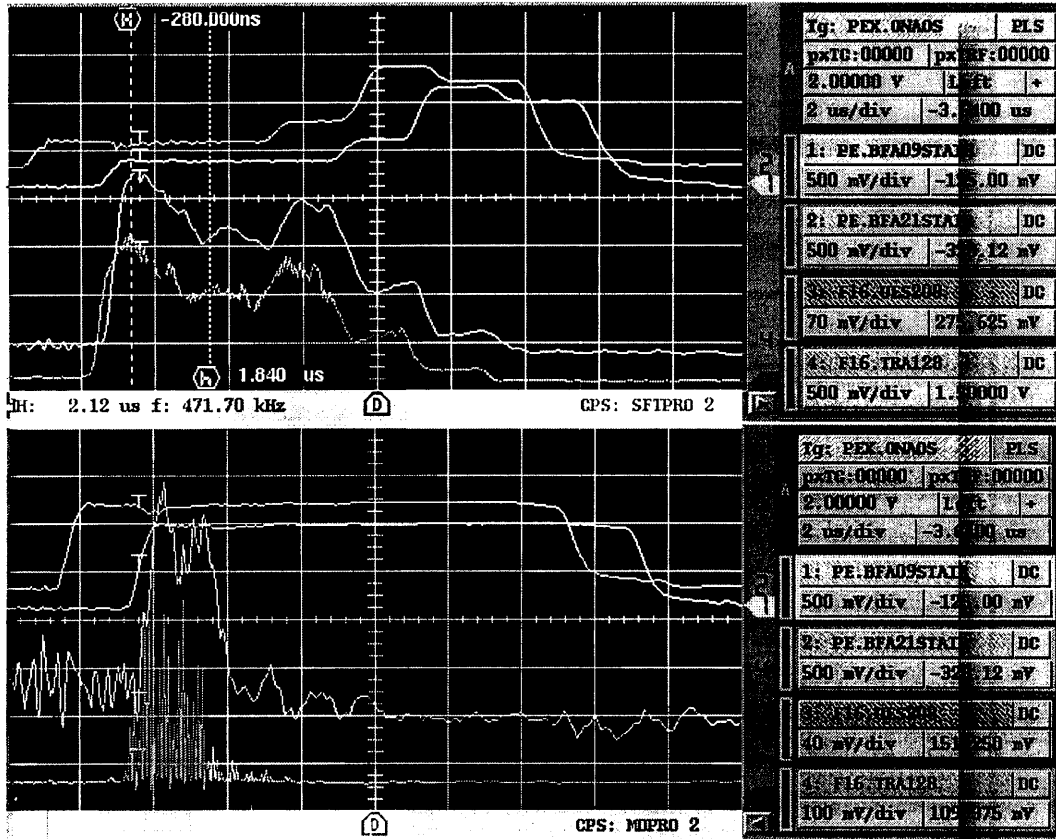


Figure 2: Setting of the extraction elements (PE.BFA09STAIR, PE.BFA21STAIR) for the standard CT five-turns extraction (upper part) and for the special CT one-turn extraction used during the MD (lower part). The extracted beam intensity as a function of time is also shown (F16.TRA128).

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)

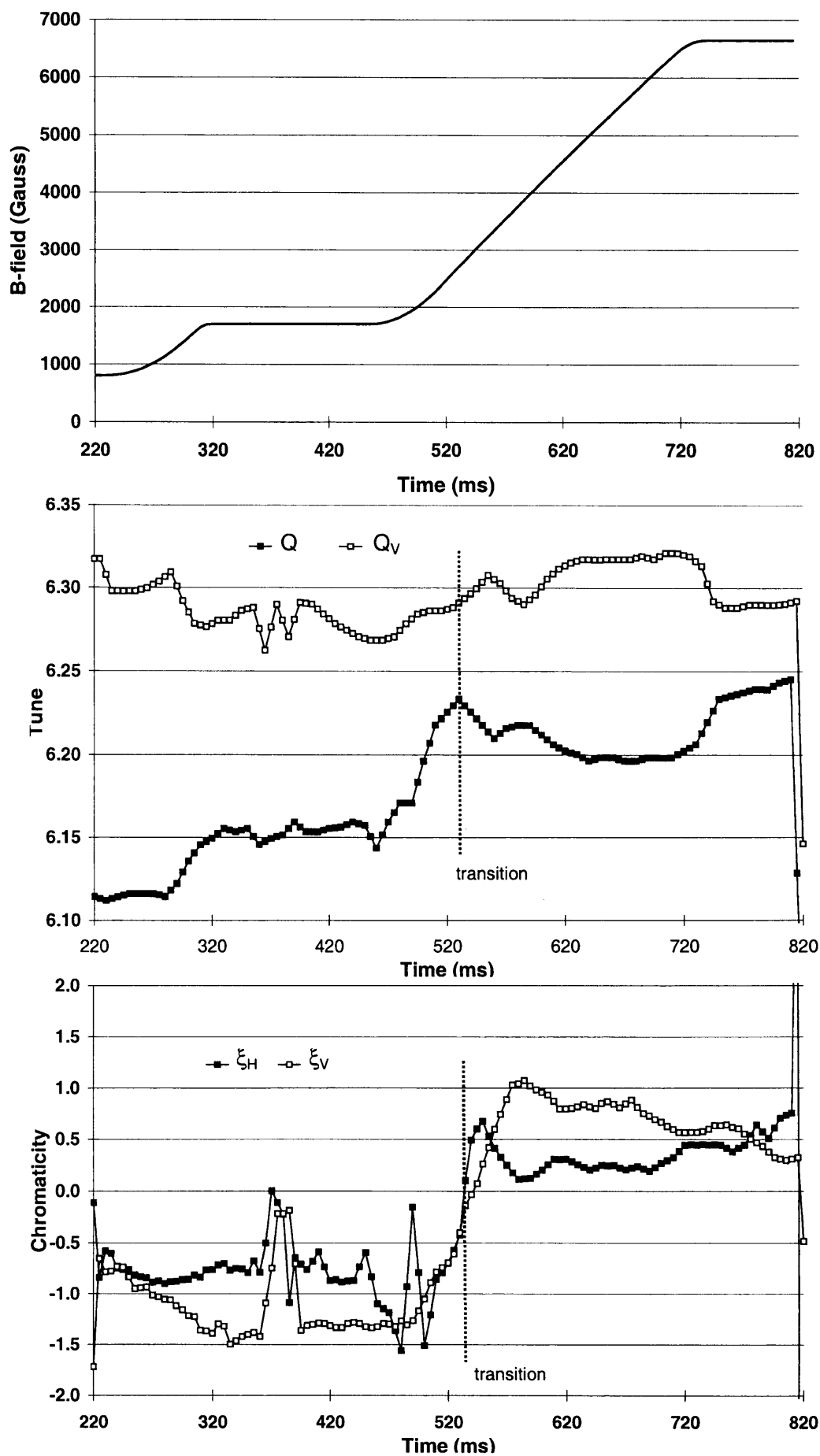


Figure 3: Magnetic cycle (upper), tunes (centre) and chromaticity (lower) measured during the MD sessions. The position in time of the transition crossing is also shown.

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-

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.

wire MSG257, SEM-grid MSG258¹ 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

¹The 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		New optics	
	D_H [m]	D_V [m]	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
<i>R-point</i>	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.

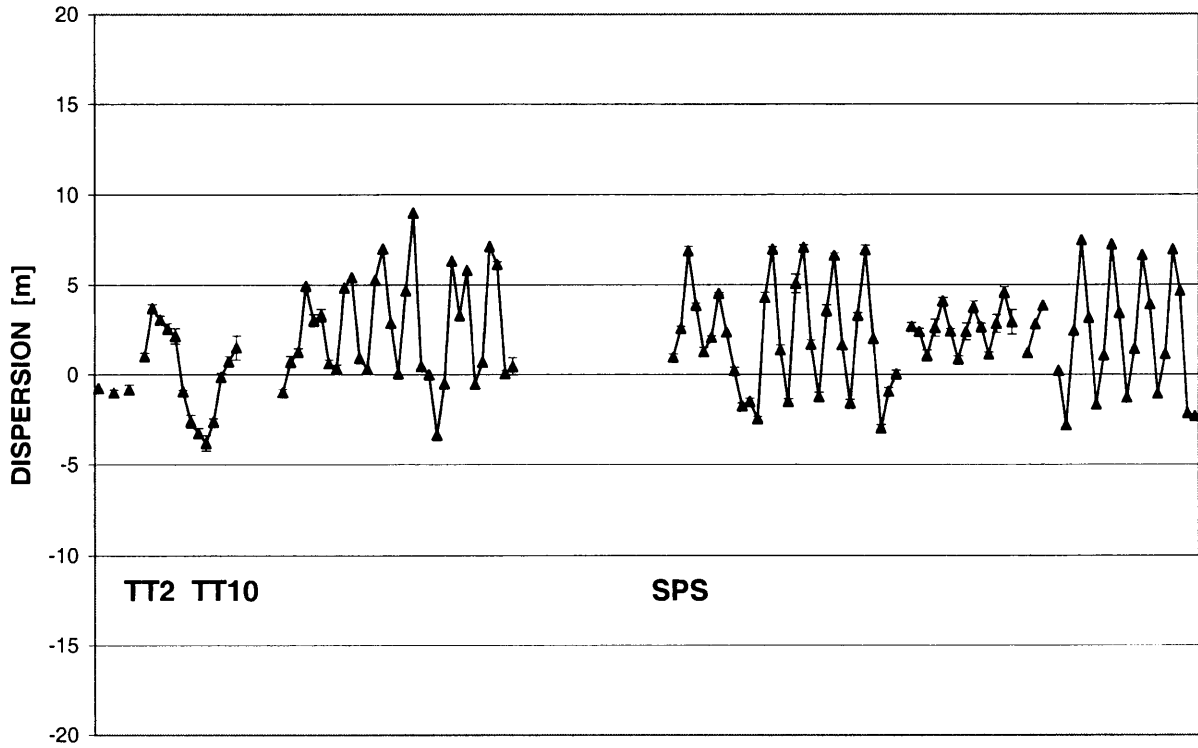


Figure 4: Measured horizontal dispersion in the transfer line and the SPS machine before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

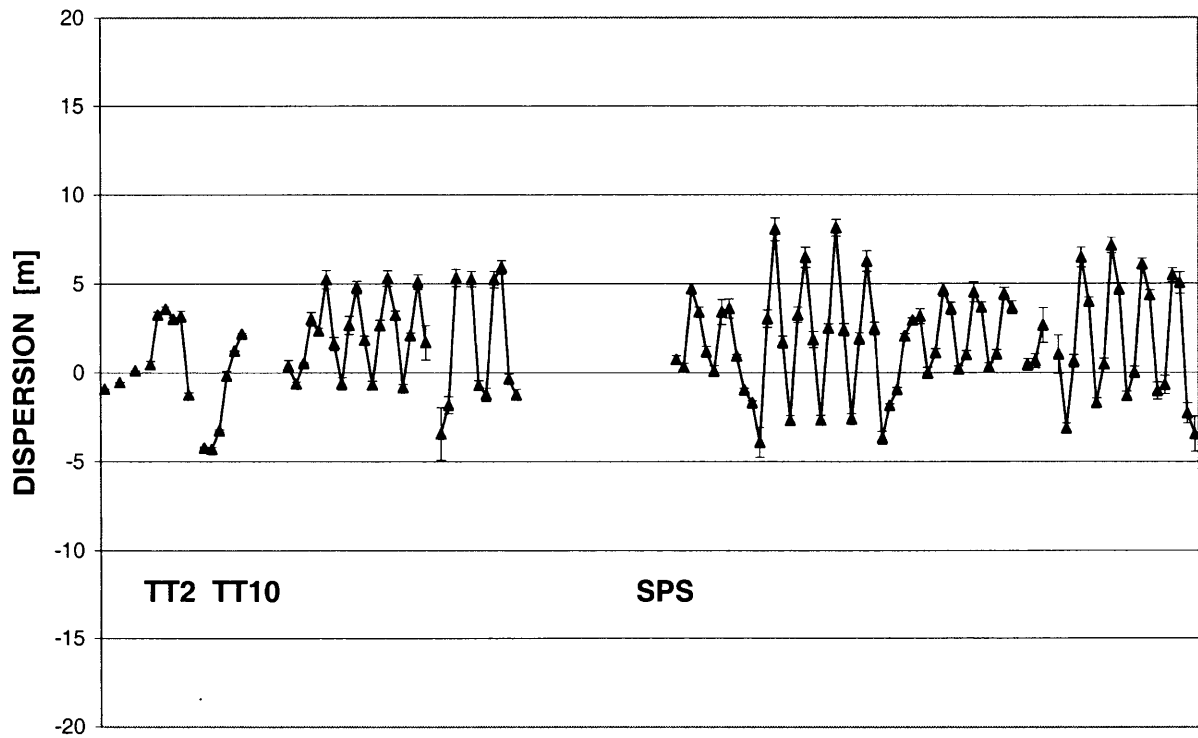


Figure 5: Measured horizontal dispersion in the transfer line and the SPS machine after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

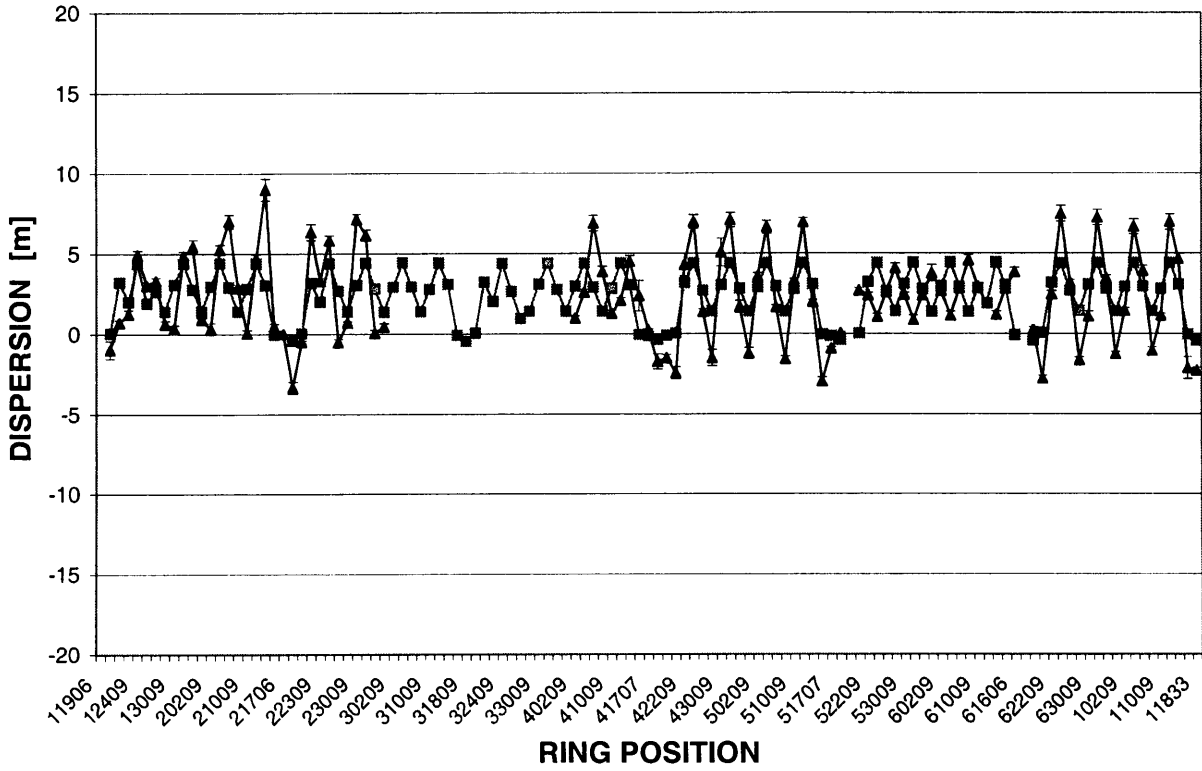


Figure 6: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS before matching the injection line.

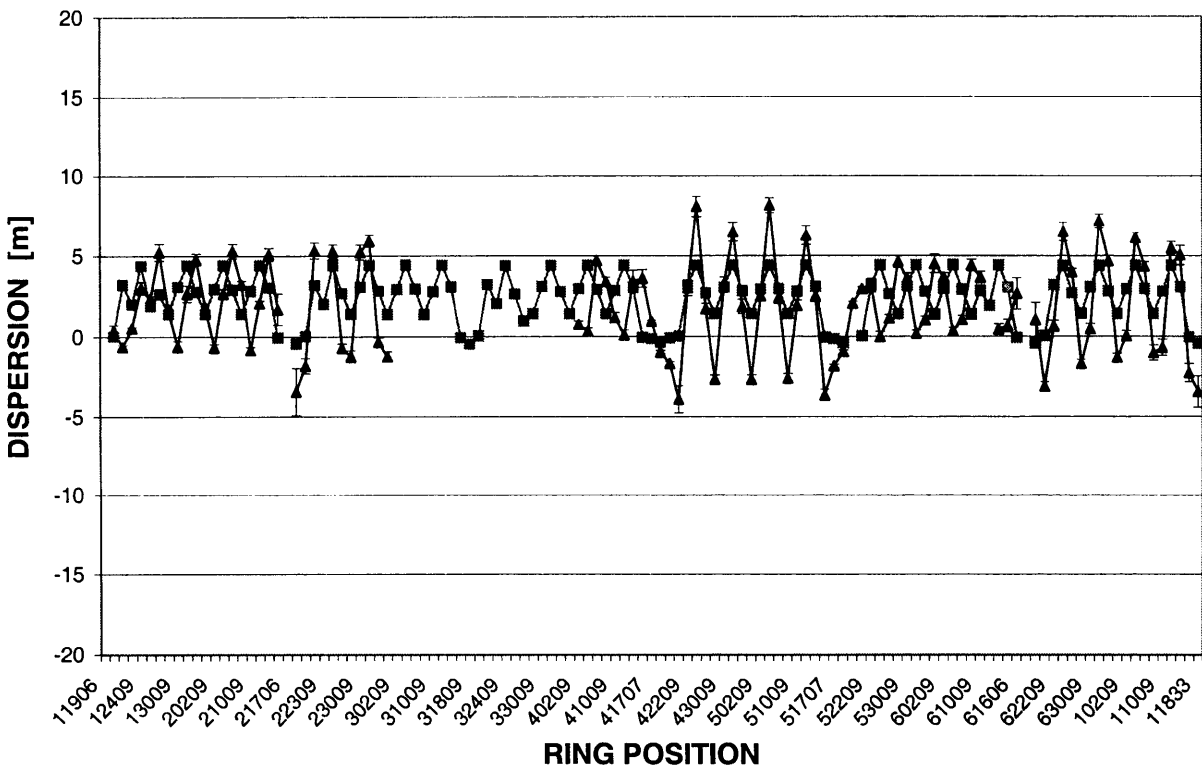


Figure 7: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS after matching the injection line.

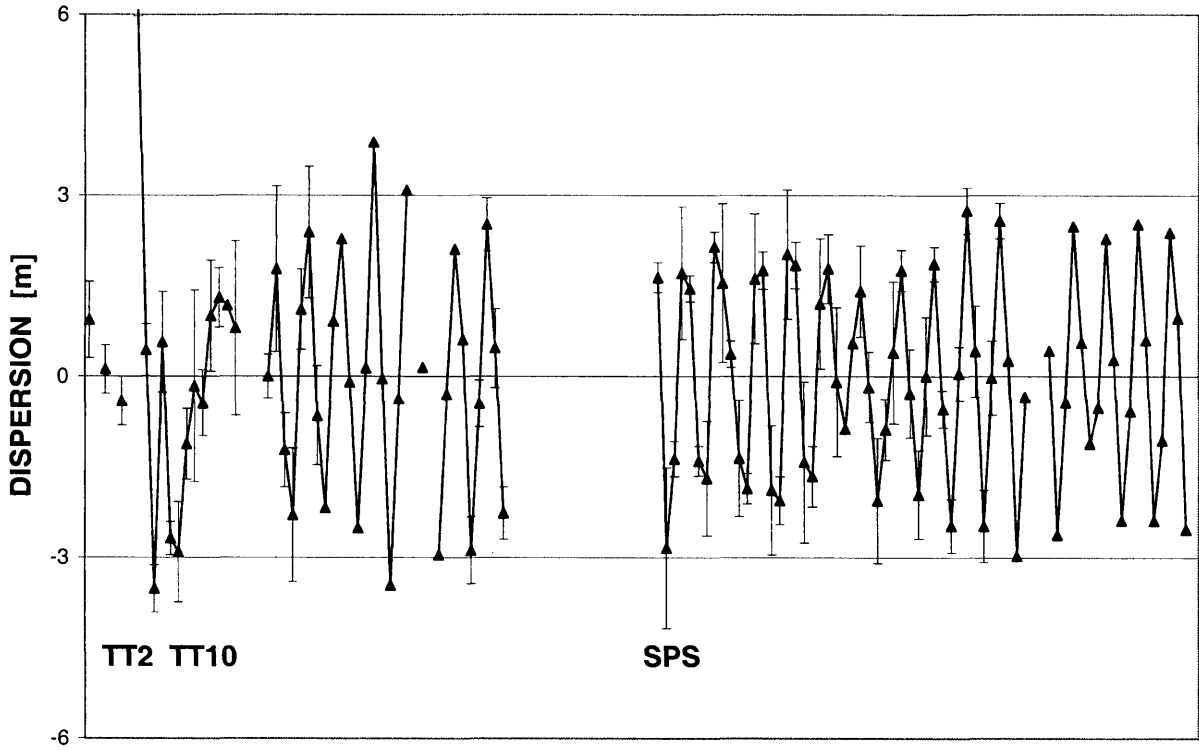


Figure 8: Measured vertical dispersion in the transfer line and the SPS machine before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

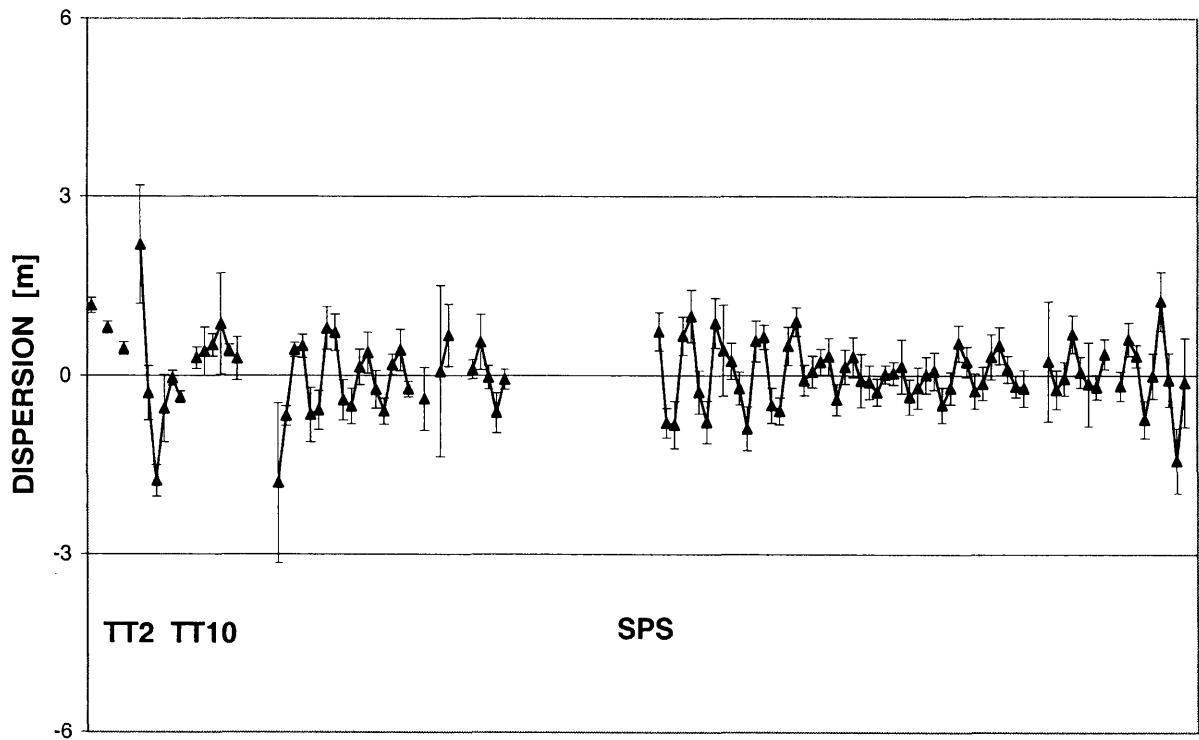


Figure 9: Measured vertical dispersion in the transfer line and the SPS machine after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

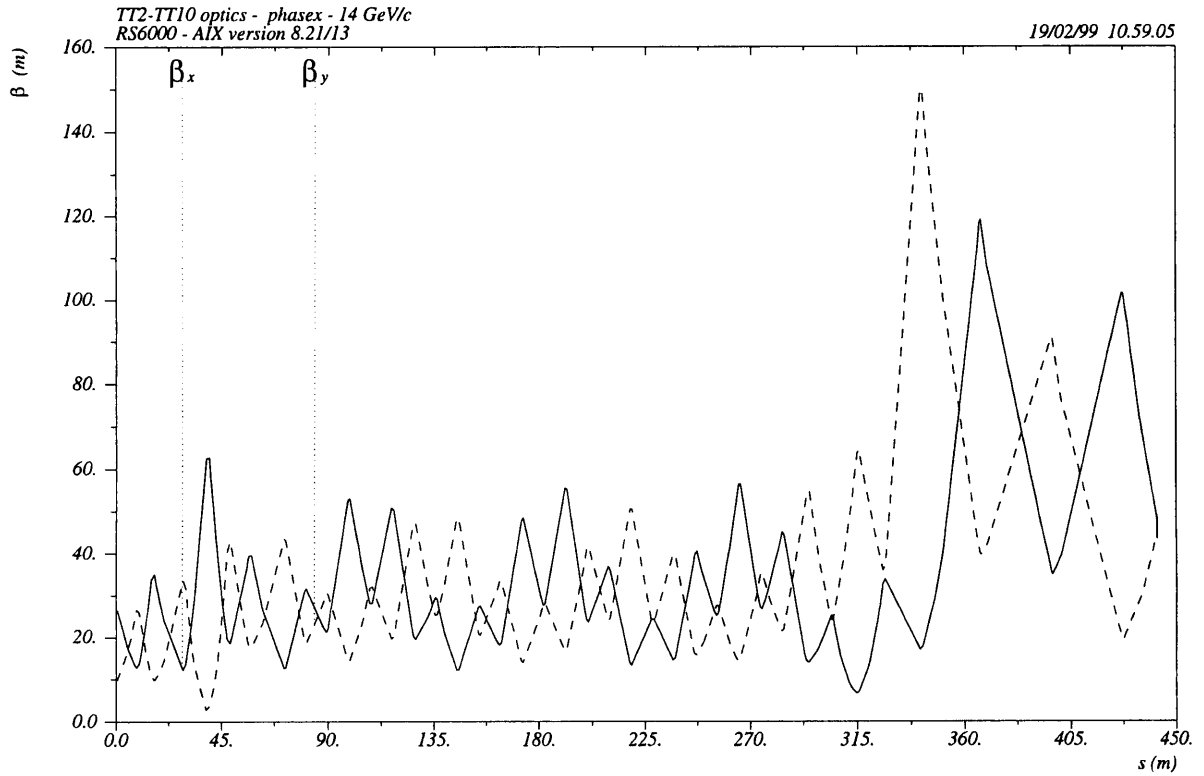


Figure 10: Horizontal and vertical β -function upstream of the emittance exchange insertion for the matched optics as computed by MAD.

