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BETATRON AND DISPERSION MATCHING OF THE TT2/TT10 TRANSFER LINE FOR THE 26 GEV/C FAST EXTRACTION

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Abstract

The tight emittance budget for the SPS as LHC injector demands for an accurate matching of the transfer line TT2/TT10 between the PS and SPS machines in order to minimise blow-up at injection into the SPS. The LHC beam is delivered from the PS to the SPS by means of a fast extraction. Since the LHC beam is characterised by both small emittance and large momentum spread, simultaneous Twiss parameter and dispersion matching is mandatory. The optics parameters of the injection line for the 26 GeV/c fast extration were carefully measured during the 1998 run. Such a measurement, combined with a theoretical model of the beam line, allowed to recompute the optics in order to improve the injection matching into the SPS machine. In this note the measurement techniques are presented and the experimental results discussed.

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Summary

The tight emittance budget for the SPS as LHC injector demands for an accurate matching of the transfer line TT2/TT10 between the PS and SPS machines in order to minimise blow-up at injection into the SPS. Since the LHC beam is characterised by both small emittance and large momentum spread, simultaneous Twiss parameter and dispersion matching is mandatory. The LHC beam is delivered from the PS to the SPS by means of a fast extraction at 26 GeV/c. The optics parameters of the injection line for the 26 GeV/c fast extraction were carefully measured during the 1998 run in the 26 GeV/c segment in parallel with physics. Such a measurement, combined with a theoretical model of the beam line, allowed to recompute the optics in order to improve the injection matching into the SPS machine. In this note the measurement techniques are presented and the experimental results discussed.

1 Introduction

The TT2/TT10 beam line connects the PS and SPS machines. It is used to transfer a variety of positively charged particles into the SPS, such as protons and lead ions for the fixed-target physics, protons to simulate the future LHC-type beam and positrons for LEP. In recent years, there has been a renewed interest in the optics of the transfer line, the main reason being that it will play an important role in the LHC injection chain. The maximum emittance growth allowed for the transport of the LHC beam from PS extraction to SPS extraction is 0.5 μm [1] (i.e. a 17% emittance blow-up). However, only a small fraction of this is assigned to mismatch at injection [2]. Since this beam has a small emittance and a large momentum spread, dispersion mismatch is a major concern. Simultaneous Twiss parameter and dispersion matching is therefore mandatory in order to prevent beam blow-up at injection into the SPS.

2 Mismatch of Optical Parameters and its Measurement

The optical parameters α and β all along a circular accelerator are uniquely determined by the properties of the magnetic lattice. This is a consequence of the periodic boundary condition imposed. On the other hand, the Twiss parameters at any point in a transfer line depend on the values of α and β at the beginning of the line and on the setting of the magnets of the line itself. Therefore the knowledge of the initial Twiss parameters is mandatory to compute the optics for a given transfer line.

The initial values of α, β can be obtained by measuring the optical parameters at a given location and then by back-propagating them up to the entry point of the line. The optical parameters can be obtained by measuring the beam profile at three different locations in the line, using e.g. secondary emission (SEM) monitors (three of them are installed in the TT2 line - `MSG257, MSG267, MSG277` and three are also present in the TT10 section - `BSG1027, BSG1028, BSG1029`) or optical transition radiation (OTR) monitors (three of such monitors are installed in the TT10 line - `BTV1024, BTV1025, BTV1026`). Under the hypothesis that the transfer matrices between the three monitors as well as the value of the dispersion function at the three monitor locations[1] are known, the emittance and α and β can be computed. The method is known as three-target method [4][2].

Two quantities can be considered to evaluate the blow-up due to the mismatch of the Twiss parameters α, β at injection [5] [6]: the *geometrical blow-up* G_b and the *blow-up after filamentation* H. G_b is the ratio between the area of the circle having the major axis of the mismatched ellipse as diameter and the area of the circle representing the matched beam (see Fig. 1). H provides the emittance blow-up

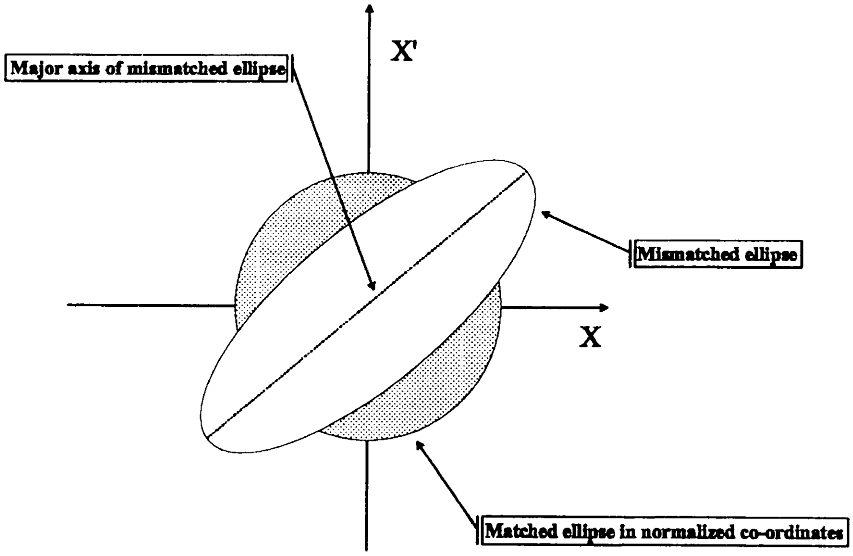

Figure 1: Matched and mismatched ellipse at injection.

once the dilution due to filamentation is taken into account. The mathematical expressions for the two above quantities are [7]:

$$G_b = H + \sqrt{H^2 - 1}, \tag{1}$$

where

$$H = \frac{1}{2}\left[\frac{\beta_0}{\beta_m} + \left(\alpha_0 - \alpha_m\frac{\beta_0}{\beta_m}\right)^2 \frac{\beta_m}{\beta_0} + \frac{\beta_m}{\beta_0}\right] \tag{2}$$

while the following holds

$$\varepsilon_{\text{after fil.}} = \varepsilon_0 H. \tag{3}$$

[1] Actually this last condition can be dropped provided one measures more profiles, see Ref. [3] for more details.

[2] The same parameters can be computed if the beam profile is measured at one monitor for three different settings of an upstream quadrupole ('three-gradient method'). The knowledge of the dispersion and its derivative at the entrance of the quadrupole is required.

In the previous equations α_m, β_m stand for the measured Twiss parameters while α_0, β_0 are the nominal Twiss parameters. It can be seen, that the blow-up after filamentation, which is the relevant quantity, is much smaller than the geometrical blow-up.

Dispersion mismatch was determined by measuring the dispersion in the injection line and in the first turn in the SPS ring, considered as a continuation of the transfer line. The measurement of the dispersion was performed by varying the momentum of the beam extracted from PS in steps and by recording the transverse displacement at each available beam position monitor (see Fig. 2). The mo-

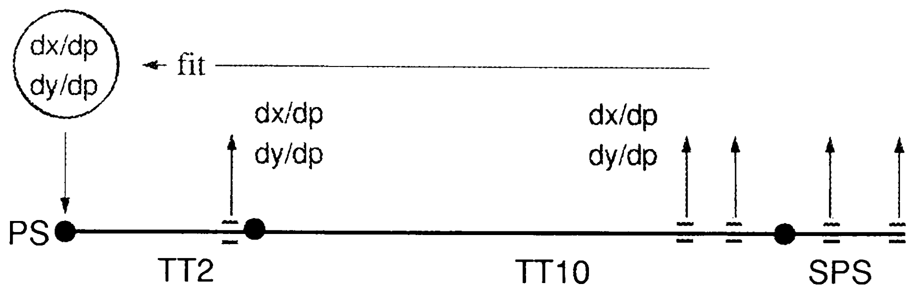

Figure 2: Schematic representation of the dispersion measurement.

mentum offset Δp with respect to the reference momentum p is calculated by measuring the change in radial position ΔR of the beam in its first turn and by applying the relation:

$$\frac{\Delta p}{p} = \frac{1}{\alpha_p} \frac{\Delta R}{R} \tag{4}$$

That requires the knowledge of the radius R of the SPS machine and its momentum compaction factor α_p [8]. The measurements of the beam displacement as a function of the momentum offset are fitted to a straight line for each beam position monitor and the slope dx/dp is obtained. A three-parameter ($(dx/dp)_m$, $(dx'/dp)_m$, δ) least-squares fit of the calculated $(dx/dp)_i$ by the function

$$C_i \left(\frac{dx}{dp}\right)_m + S_i \left(\frac{dx'}{dp}\right)_m + \xi_i \delta \tag{5}$$

is performed in the horizontal plane while in the vertical plane $\delta = 1$ is assumed. C_i, S_i, ξ_i are the elements of the transfer matrix

$$\begin{bmatrix} C & S & \xi \\ C' & S' & \xi' \\ 0 & 0 & 1 \end{bmatrix} \tag{6}$$

from the measurement point m to the i^{th} beam position monitor (ξ and ξ' are the dispersion and its derivative for zero dispersion and dispersion derivative at the beginning of the line) and δ is a calibration factor to correct for possible scaling errors in the measurement of the momentum offset. As a result of the fit we get:

$$D_m^{fit} = \frac{(dx/dp)_m^{fit}}{\delta^{fit}} \tag{7}$$

$$D_m'^{fit} = \frac{(dx/dp)_m^{fit}}{\delta^{fit}} \tag{8}$$

at any point in the line if the transfer matrix (6) from the measurement point to any beam position monitor is known. Normally this is the case for the injection transfer line and the SPS ring with the exception of the beginning of the line that is affected by the stray field of the combined function magnet (unit 16) in the extraction region of the PS ring. The presented method takes advantage of the large number of beam position monitors in the SPS ring (108 per plane) and provides an immediate picture of the mismatch with respect to the dispersion in the ring.

In presence of dispersion mismatch the beam will suffer filamentation thus producing an emittance blow-up. Once again, it is possible to quantify those effects by introducing two indicators, namely the geometrical blow-up G_d and the blow-up after filamentation J [6]:

$$G_d = 2J - 1, \tag{9}$$

where

$$J = 1 + \frac{\Delta D^2 + (\Delta D' \beta_0 + \Delta D \alpha_0)^2}{2\, \varepsilon_0 \beta_0} \left(\frac{\Delta p}{p}\right)^2_{\text{r.m.s.}} \tag{10}$$

and the beam emittance after dilution is given by

$$\varepsilon_{\text{after fil.}} = \varepsilon_0 J \tag{11}$$

where α_0, β_0 are the nominal Twiss parameters and ΔD ($\Delta D'$) is the difference between theoretical and measured dispersion (dispersion derivative).

3 *MAD* Model

The above measurement techniques require the knowledge of the transfer matrix between the reference point and any of the monitors used for the measurement. Furthermore, once the initial optics parameters have been measured, an optics model is required to re-match the line at the injection point. During the 1998 measurement campaign considerable effort was spent to verify the beam line model and to accurately measure the beam parameters (Twiss parameters and dispersion) at the beginning of the injection line.

In a first step, the complete TT2/TT10 line was modelled using the program *MAD* [9]. The geometry of the model was cross-checked versus the official CERN survey data [10] and the correct magnetic behaviour of the elements was confirmed in a series of measurements [11].

4 Experimental Conditions

The main constraints to the characteristics of the beam required for the measurements are imposed by the dispersion measurement and by the beam instrumentation. The emittance and momentum spread of the beam must be small in order to avoid scraping during the momentum scan performed for the dispersion measurement. It seems furthermore reasonable to have a momentum spread much smaller than the momentum span, which is limited by the momentum acceptance of the transfer line. This quantity was measured in 1995 to be about $\pm 3 \times 10^{-3}$. The TT10 and SPS couplers have a narrow band around 200 MHz, therefore the bunch length should be limited to about 5 ns in order to measure the beam position. Momentum stability of the beam extracted from the PS is also important to minimise measurement errors. A dedicated proton beam was therefore set up.

The magnetic cycle has a length of 2.4 s (see Fig. 3 upper part). It consists of an injection flat bottom of 20 ms at 1.7 GeV/c, where controlled longitudinal blow-up is applied, then a second plateau at 3.5 GeV/c is used to change the radio-frequency (rf) harmonic number from 8 (at injection) to 16 (up to extraction). The beam is then accelerated up to 26 GeV/c and extracted on a flat top in one turn (fast extraction) by the standard scheme based on bumper, septum and kicker. The nominal setting of these

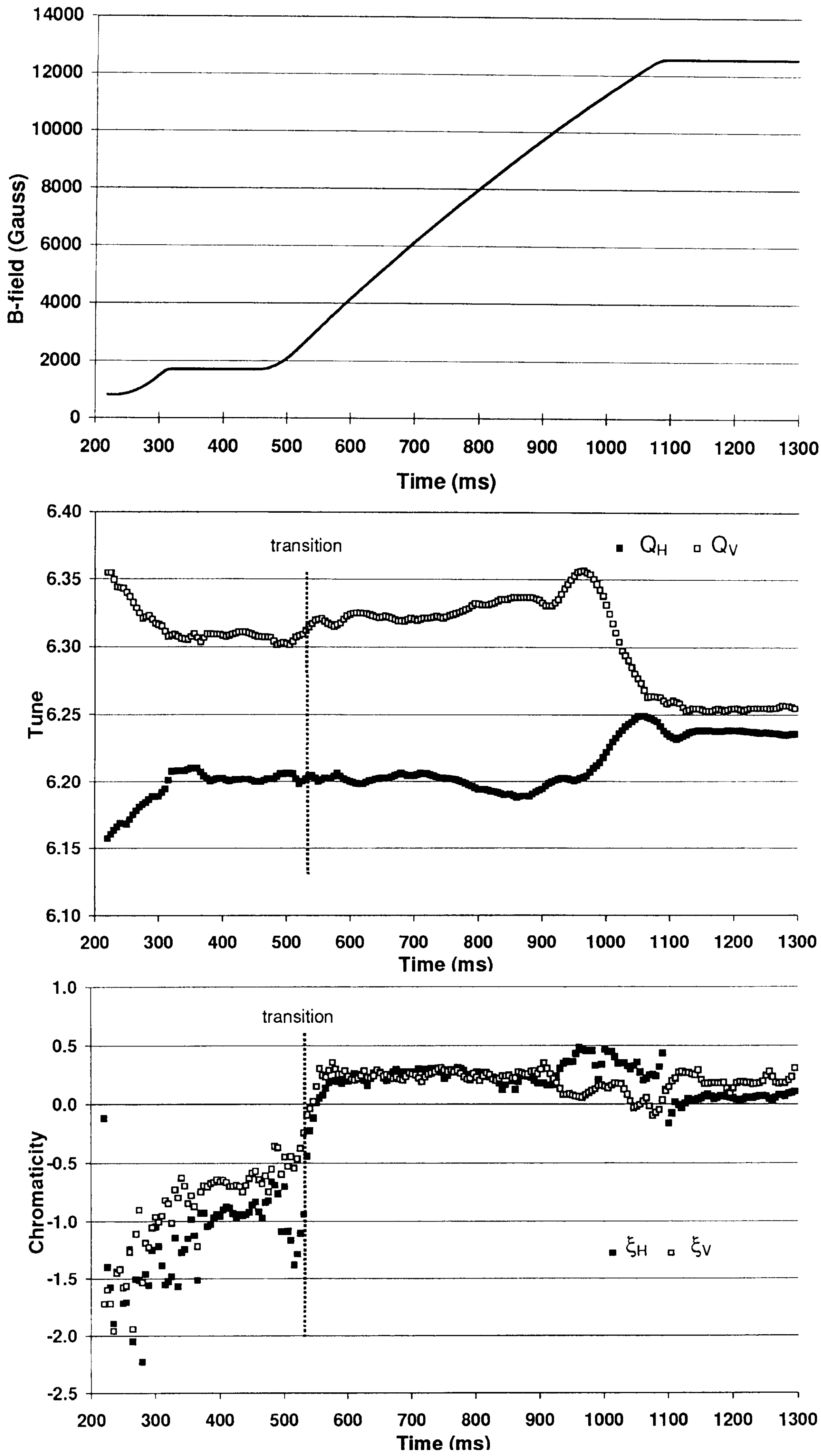

Figure 3: Magnetic cycle (upper), tunes (centre) and chromaticity (lower) measured during the MD sessions. The position in time of the transition crossing is also shown.

Element	Value
PE.KFA71 [kV]	710
PE.SMH16 [A]	28200
PE.BSW16 [A]	1350
PE.QKE16 [A]	1550
PE.DHZ15 [A]	250

Table 1: Nominal setting of the extraction elements for the 26 GeV/c extraction.

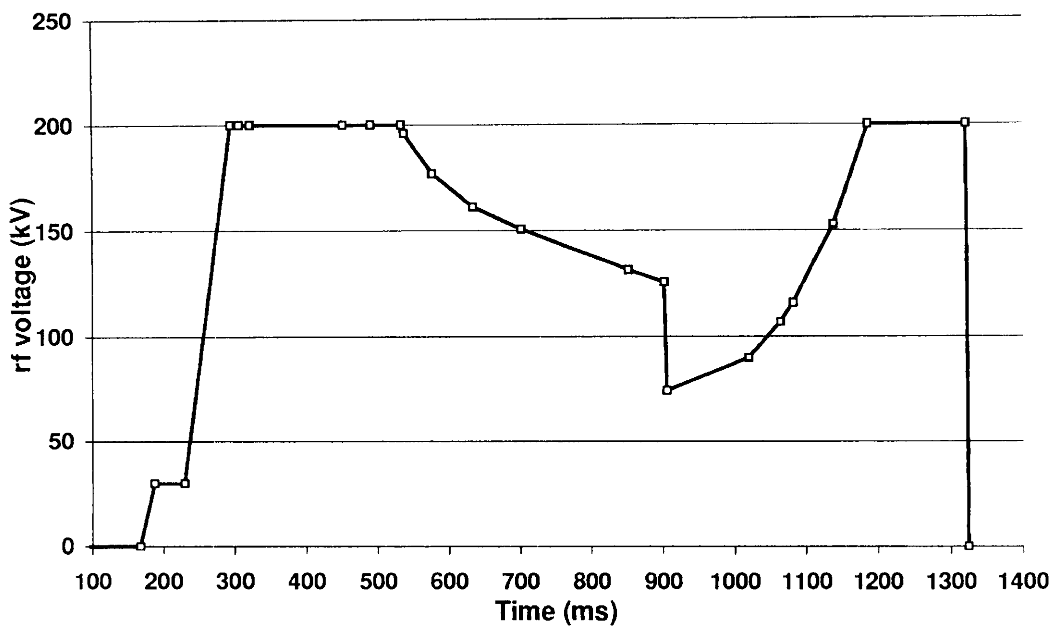

Figure 4: Voltage applied to the cavities as a function of time.

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 Pole Face Windings (PFW) all along the magnetic cycle (the low energy quadrupoles are not used for this type of beam). 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 $Q_H = 6.24, Q_V = 6.25$. The chromaticities are also controlled by means of the PFWs. The vertical chromaticity is slightly modified 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 $\xi_H = 0.1$ and $\xi_V = 0.3$.
The injected beam intensity is of the order of 2.5×10^{12} ppp, while at extraction the intensity is reduced to 2.5×10^{11} ppp. This is due to the longitudinal scraping applied at the end of acceleration. The rf voltage is reduced (see Fig. 4 for more details) in order to reduce the bunch length and therefore allow the monitoring system installed in TT10 to measure the beam position. The main beam parameters are listed in Table 2.

p [GeV/c]	26
intensity [p/batch]	$2 - 3 \times 10^{11}$
ε_H [μm] (normalised, r.m.s) ε_V [μm] (normalised, r.m.s)	5.8 3.6
$\frac{\Delta p}{p}$ (r.m.s.) [10^{-3}] bunch length [ns] (4σ) ε_l [eVs]	0.2 5-7 0.1

Table 2: Parameters of the proton beam used to study the injection transfer line optics for the 26 GeV/c fast extraction.

5 Experimental Results

The 1998 run was started with an optics that had been matched by using only the TT10 quadrupoles and the last TT2 quadrupole (QFO375) to initial Twiss parameters obtained from a *MAD* simulation of the fast extraction from the PS. The values are given in Table 3. The dispersion D at the various

	Horizontal plane	Vertical plane
β [m]	48.68	4.26
α	-4.58	0.32
D [m]	3.81	0.0
D'	0.47	0.0

Table 3: Initial optical parameters obtained from a *MAD* simulation of the fast extraction from the PS. These values were used as input for the 1997 optics.

monitor locations was determined by using the fitting procedure described in Section 2, where the measurement point is the so-called *R-point* corresponding to the entry of the first quadrupole of the TT2 line (QFO105). Figure 7 shows the measured horizontal dispersion in the line and in the SPS for the initial optics. The error bars associated to the measured points are obtained by using the error estimate of the fit. The r.m.s. of the beam position at each beam position monitor and for each momentum has been assumed as error. For each momentum offset 10 trajectory measurements have been taken in the SPS, 30 trajectory measurements in TT10, 10 profile measurements with the TT10 SEM grids, 3 profile measurements with the TT10 OTR monitors and 10 profile measurements with the TT2 SEM wires. The momentum offset was varied from -2.47×10^{-3} to 1.02×10^{-3}. Figure 9 shows measured (squares) and theoretical (triangles) horizontal dispersion in the SPS before matching the injection line, while Fig. 11 shows the same quantities for the vertical plane. The disagreement between the theoretical and measured values of the dispersion in the SPS is clearly visible.

The measured dispersion at the TT2 SEM wires and at the TT10 SEM grids is listed in Tab. 4. Once the dispersion values at the beam profile monitors were known, the Twiss parameters at the SEM grid BSG1027 could be measured. They are listed in Tab. 5. The Twiss parameters measured at both locations have been tracked back up to the *R-point*. The initial parameters measured in 1998 are listed in Tab. 6. The geometric blow-up and the blow-up after filamentation are listed too, both for the betatronic and dispersive components.

Monitor	D_H [m]	D_V [m]
MSG257	1.47 $\pm$ 0.02	0.90 $\pm$ 0.01
MSG267	-1.62 $\pm$ 0.01	-0.82 $\pm$ 0.01
MSG277	-3.05 $\pm$ 0.02	-0.27 $\pm$ 0.01
BSG1027	-0.06 $\pm$ 0.03	-0.27 $\pm$ 0.02
BSG1028	3.60 $\pm$ 0.05	-0.73 $\pm$ 0.01
BSG1029	6.09 $\pm$ 0.03	-0.62 $\pm$ 0.01

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

Monitor	β_H [m]	α_H	β_V [m]	α_V
MSG257	-	-	-	-
BSG1027	32.30 $\pm$ 0.96	-1.01 $\pm$ 0.04	89.31 $\pm$ 8.4	2.13 $\pm$ 0.1

Table 5: Measured α and β at SEM monitors.

	Horizontal plane	Vertical plane
β [m]	57.72	7.58
α	-5.06	-3×10^{-2}
D [m]	5.34	-0.03
D'	0.48	-0.02
G_b	1.46	2.18
H	1.07	1.32
G_d	22.1	1.02
J	11.6	1.01

Table 6: Measured optical parameters at the *R-point*, geometrical blow-up and blow-up after filamentation for the optics available at the beginning of 1998.

	Horizontal plane	Vertical plane
β [m]	48.68	4.26
α	-4.58	0.32
D [m]	5.34	-0.03
D'	0.48	-0.02

Table 7: Initial optical parameters used as input for re-matching the line.

6 Betatron and Dispersion Matching

Because of the large dispersion mismatch as compared to the betatronic one the line was matched to the *measured* values of the dispersion and its derivative and the *calculated* Twiss parameters at the *R-point* (see Tab. 7) and the nominal optical parameters at the injection point in the SPS (see Tab. 8). Figure 5 shows the horizontal and vertical β-function in the line for the matched optics as computed by *MAD.* Note the smaller β-functions in the TT2 part of the line required by the smaller physical aperture of the vacuum chamber as compared to TT10.

Figure 6 shows the horizontal and vertical dispersion in the transfer line for the matched optics as computed with *MAD.* Note that the dispersion is close to zero in both planes at injection. This new

	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 8: Nominal SPS optical parameters at injection for the standard working point Q_H = 26.62, Q_V = 26.58.

optics has been tested in operation and a new set of measurements has been carried out to confirm the optical parameters for the new setting. The dispersion measurement was repeated, the results are shown in Figs. 8, 10 and 12. Contrary to the previous plots, the agreement between theoretical values of the dispersion function in the SPS and the measured ones is rather good. The measured dispersion at the TT2 SEM wires and at the TT10 SEM grids is presented in Table 9. The Twiss parameters at `MSG257` and `BSG1027` could be measured and are listed in Table 10. The values obtained for the Twiss parameters at the *R-point* are listed in Table 11. 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 12.

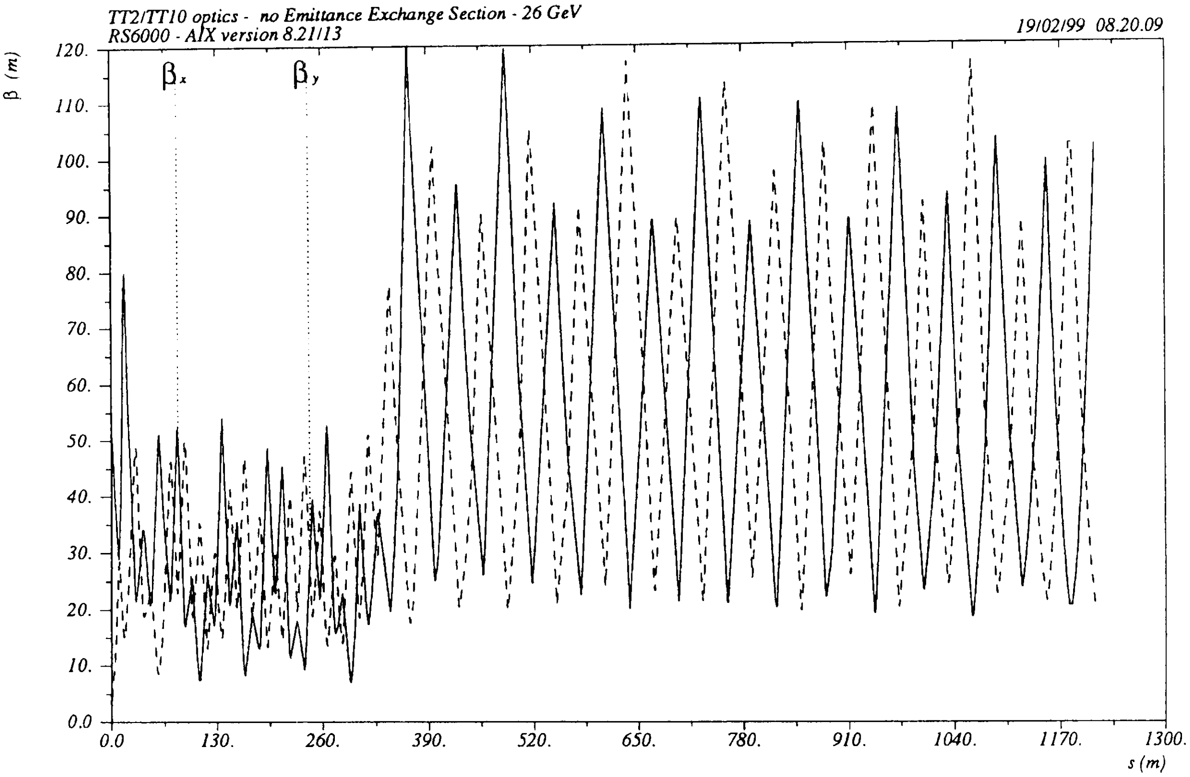

Figure 5: Horizontal and vertical β-function in TT2/TT10 for the matched optics as computed by *MAD*.

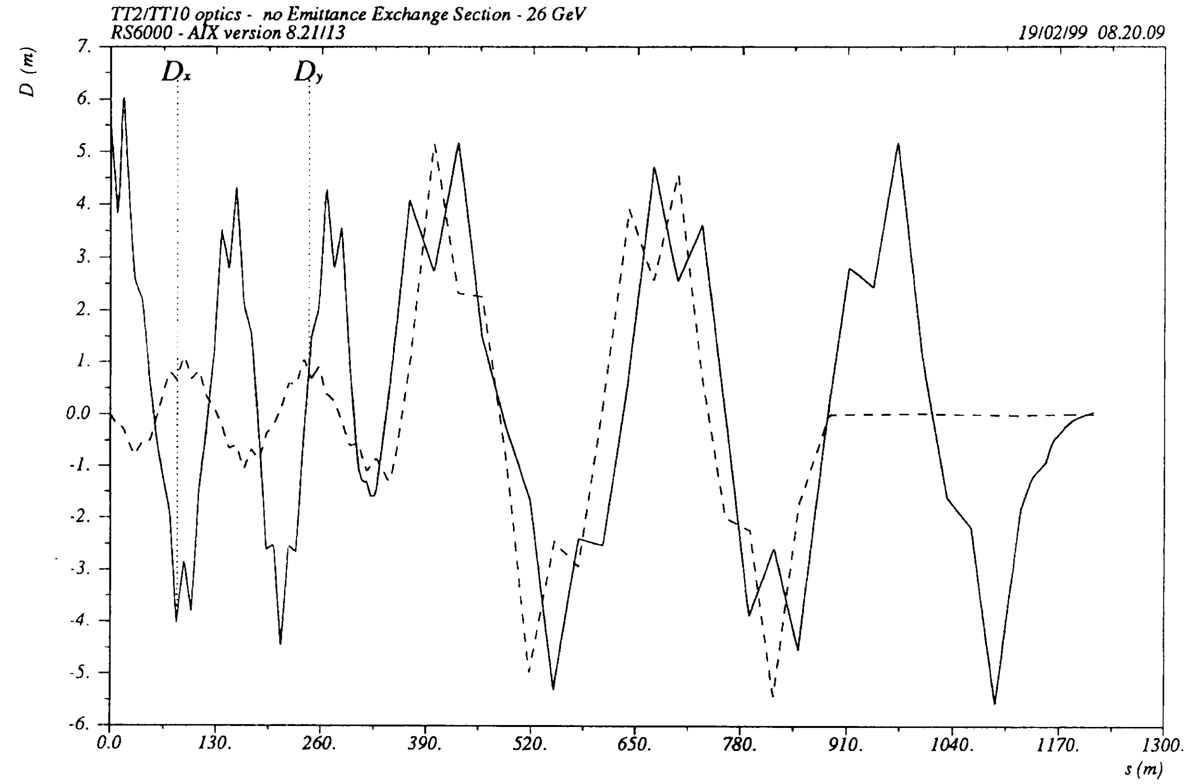

Figure 6: Horizontal and vertical dispersion in TT2/TT10 for the matched optics as computed by *MAD*.

Monitor	D_H [m]	D_V [m]
MSG257	1.35 $\pm$ 0.01	-0.77 $\pm$ 0.01
MSG267	-0.87 $\pm$ 0.01	-0.56 $\pm$ 0.01
MSG277	-2.37 $\pm$ 0.01	-0.01 $\pm$ 0.01
BSG1027	-5.31 $\pm$ 0.09	-0.04 $\pm$ 0.03
BSG1028	-4.18 $\pm$ 0.08	0.11 $\pm$ 0.02
BSG1029	0.96 $\pm$ 0.03	0.16 $\pm$ 0.03

Table 9: Measured dispersion at SEM monitors after re-matching.

Monitor	β_H [m]	α_H	β_V [m]	α_V
MSG257	9.71	0.95	27.73	-0.83
BSG1027	63.54	-2.32	68.90	1.57

Table 10: Measured α and β at SEM monitors after re-matching.

	β_H [m]	α_H	β_V [m]	α_V
from MSG257	44.50	-4.07	8.00	0.31
from BSG1027	42.87	-3.63	4.23	-0.07

Table 11: Measured α and β tracked back from SEM monitors to *R-point*.

	Horizontal plane	Vertical plane
β [m]	43.69	6.12
α	-3.85	0.12
D [m]	3.63	0.01
D'	0.28	-0.01
G_b	1.3	1.0
H	1.0	1.0
G_d	2.33	1.01
J	1.7	1.0

Table 12: Measured Twiss parameters at the *R-point*, geometrical blow-up and blow-up after filamentation for the new optics.

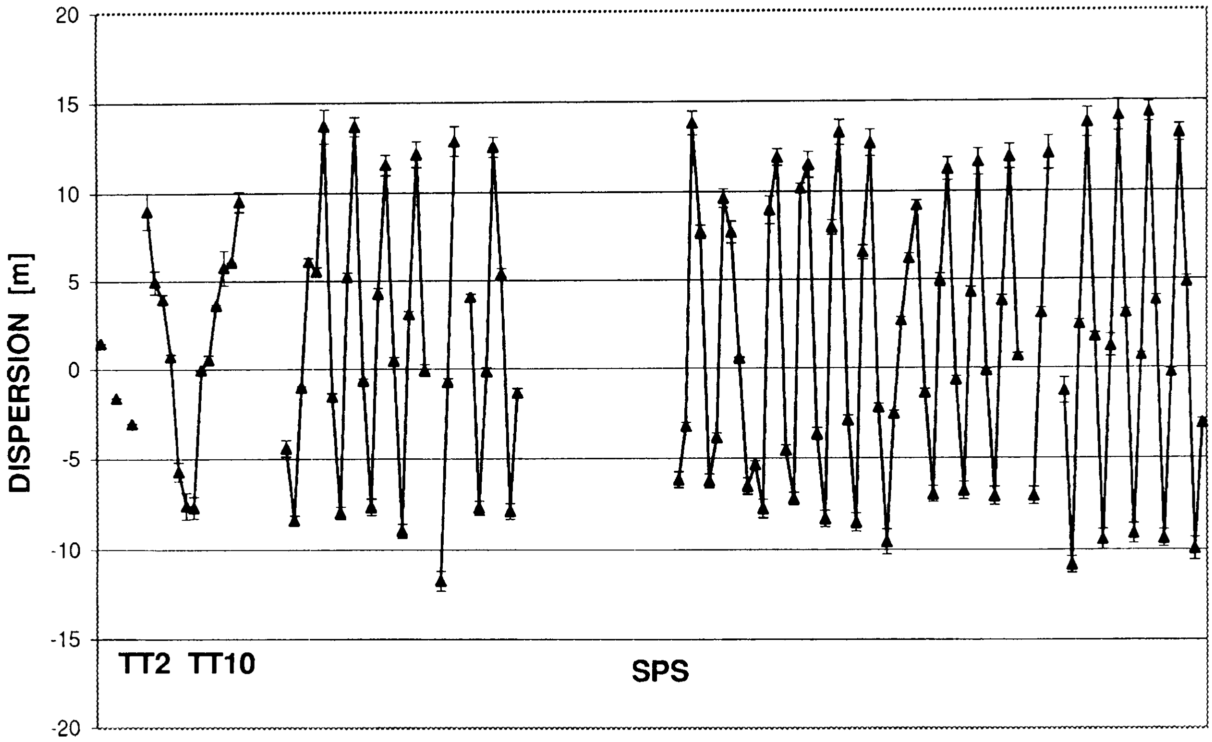

Figure 7: Measured horizontal dispersion in the transfer line and the SPS machine before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

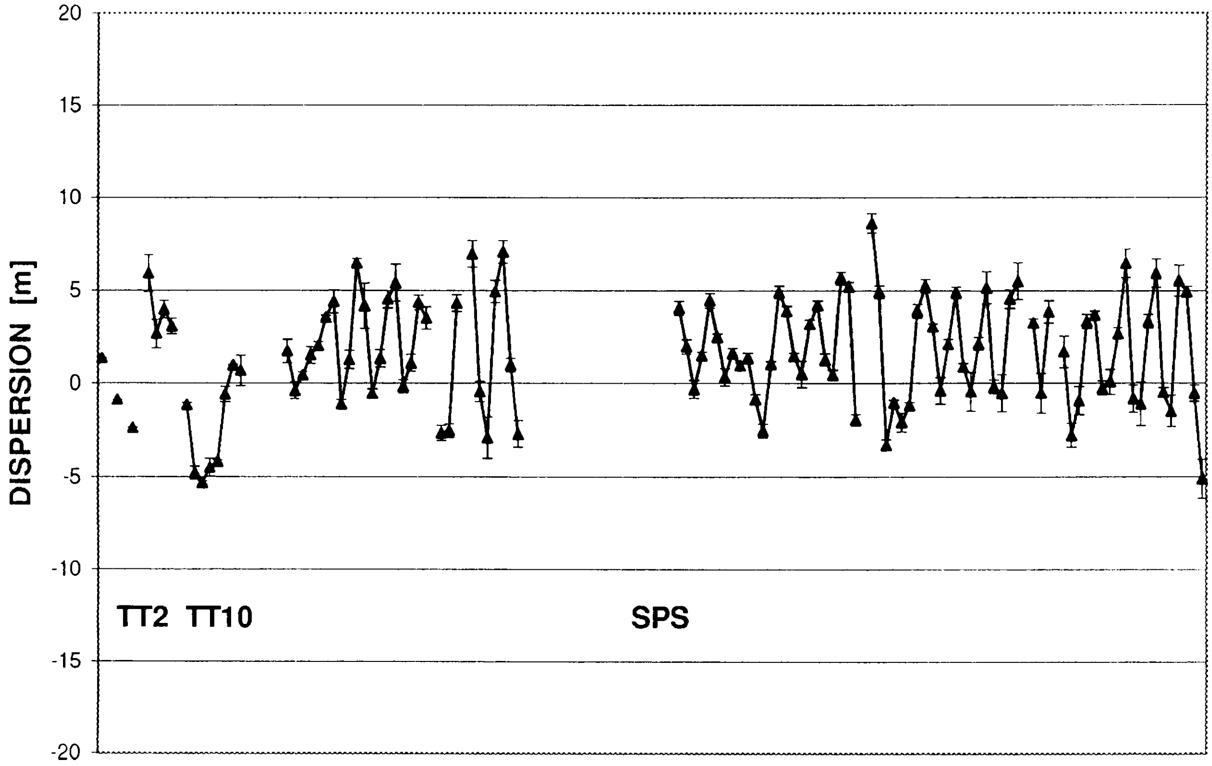

Figure 8: Measured horizontal dispersion in the transfer line and the SPS machine after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

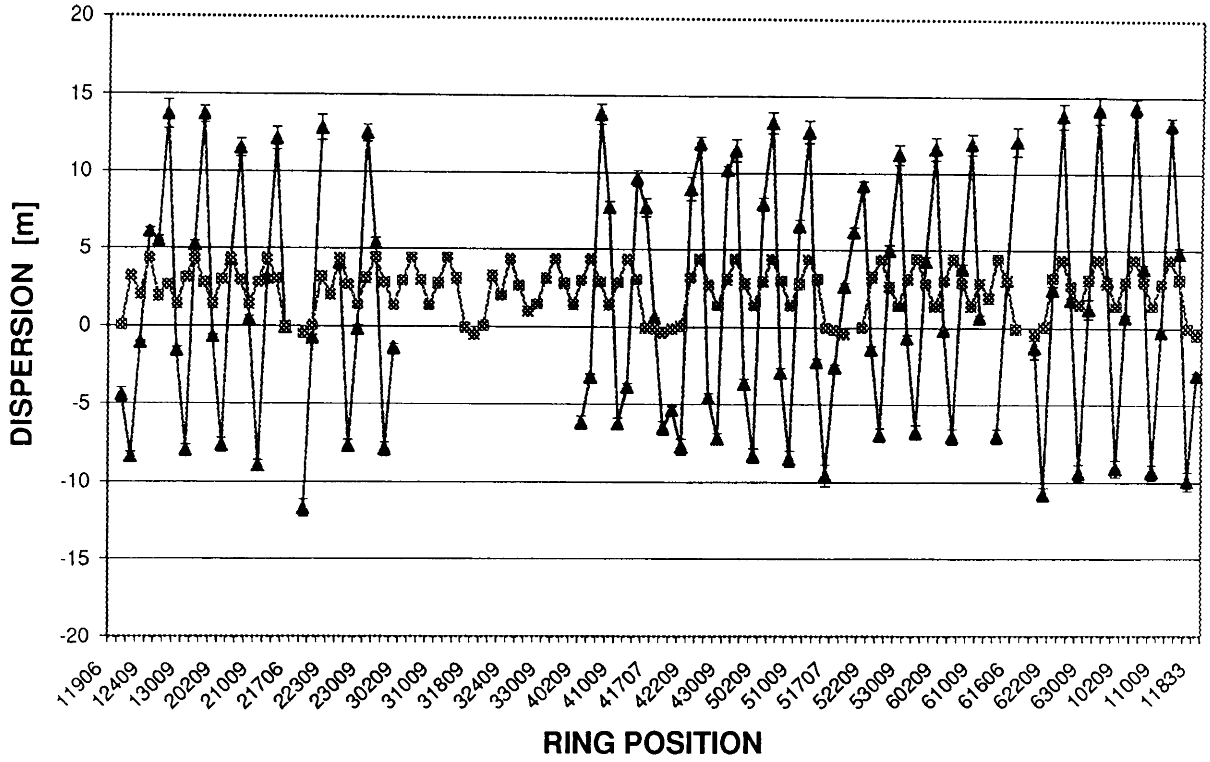

Figure 9: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS before matching the injection line.

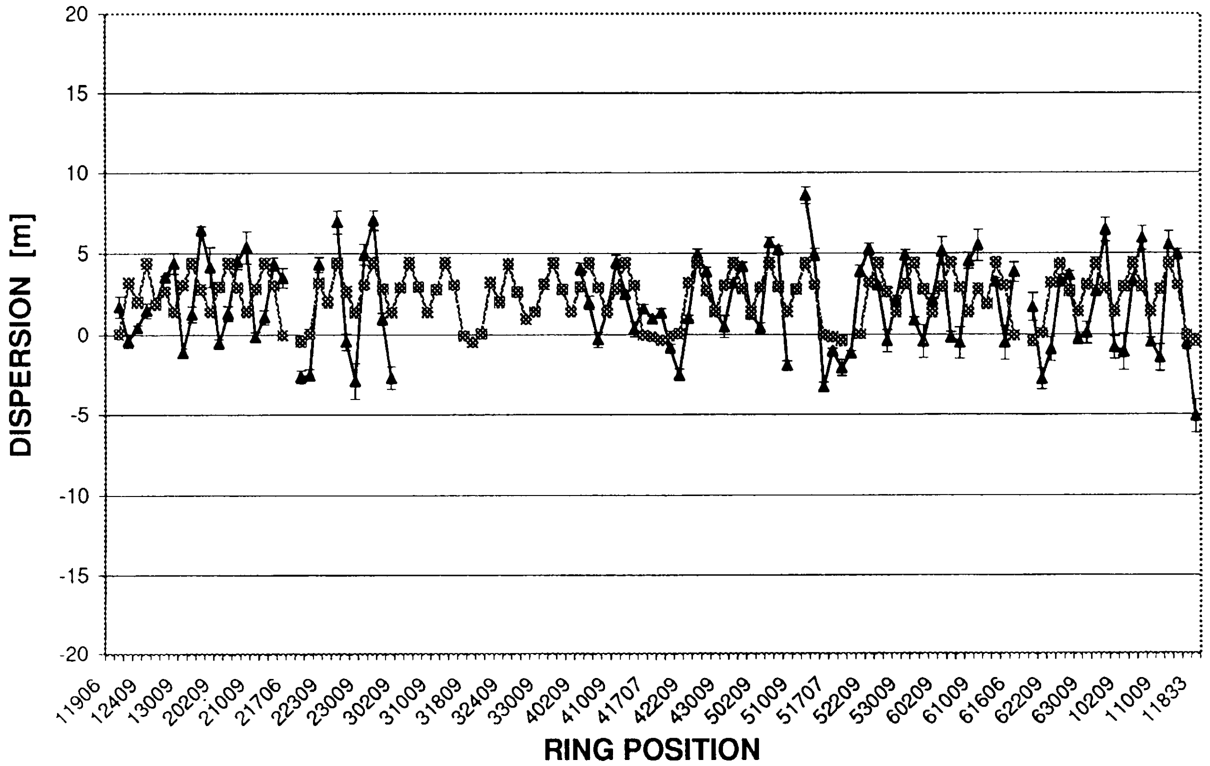

Figure 10: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS after matching the injection line.

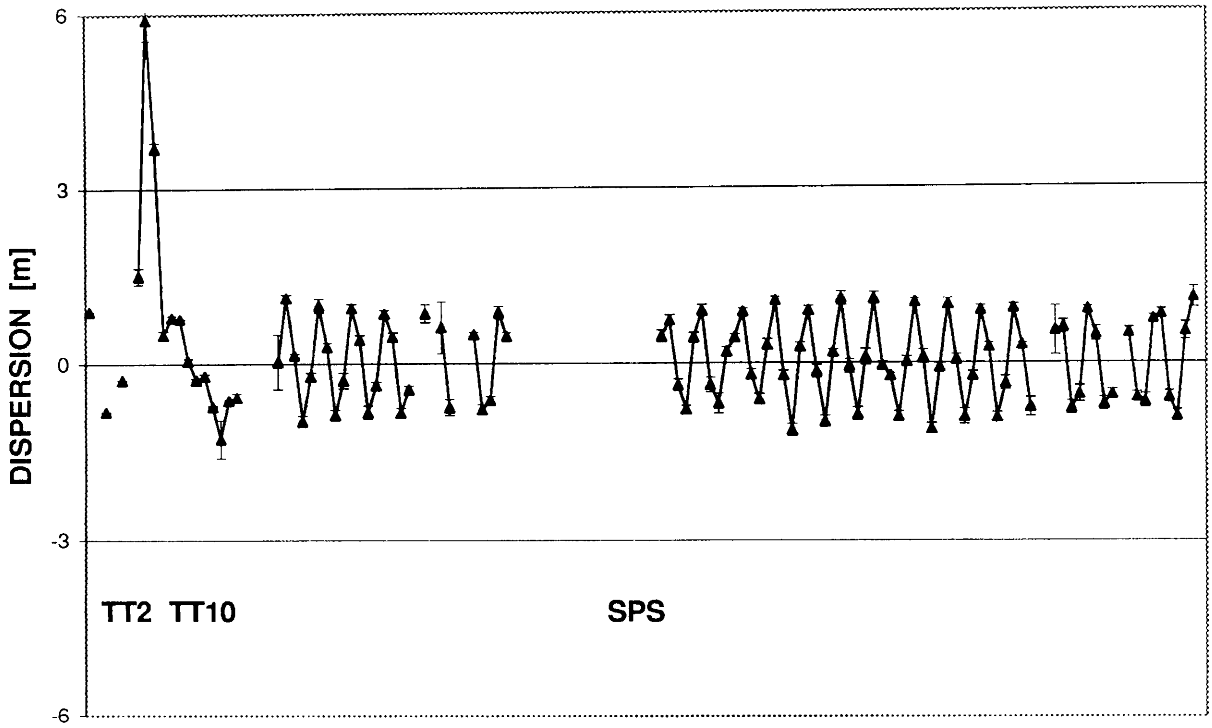

Figure 11: Measured vertical dispersion in the transfer line and the SPS machine before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

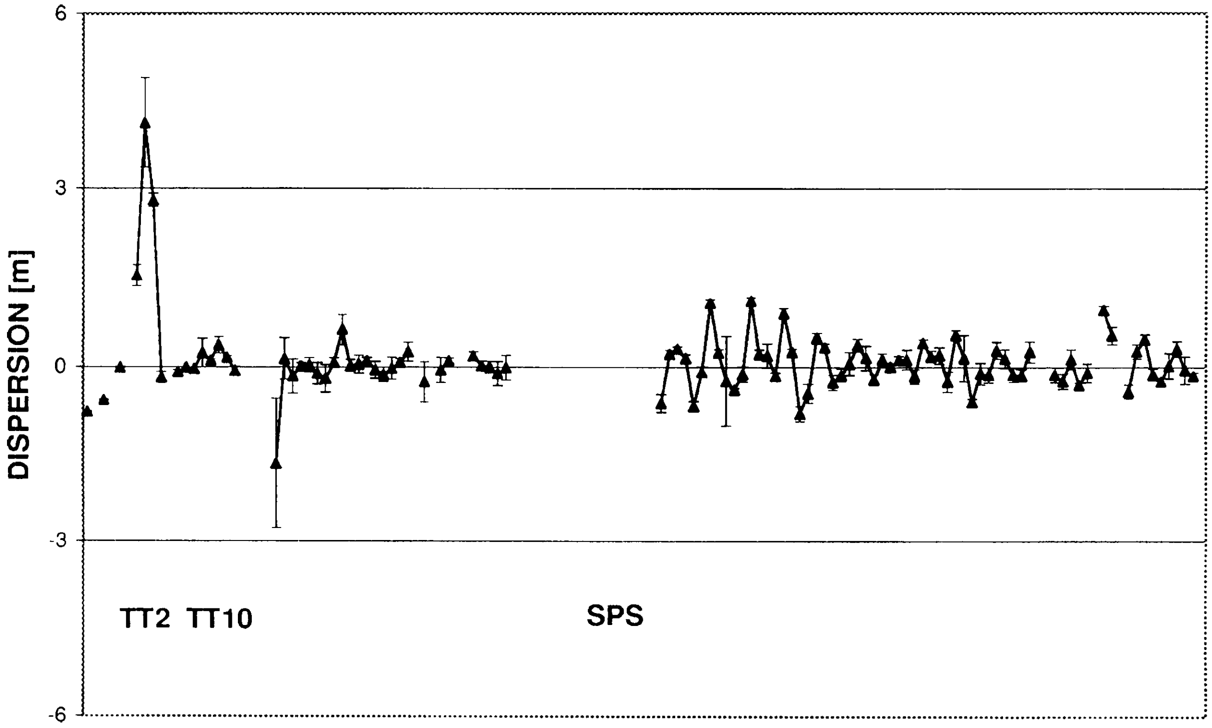

Figure 12: Measured vertical dispersion in the transfer line and the SPS machine after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

7 Conclusions

A measurement of the beam parameters in the TT2/TT10 transfer line was performed during the 1998 run for the 26 GeV/c fast extraction transfer. Simultaneous Twiss parameter and dispersion matching was performed based on the Twiss parameters simulated with *MAD* and the measured dispersion and dispersion derivative as initial conditions. A measurement performed afterwards has evidenced an important reduction of the blow-up though dispersion mismatch in the horizontal plane is still a major concern (see Table 13). The study will continue during the 1999 run. The following improvements of the maesurement method and subjects for further investigation have been individuated:

- Precise measurement of the energy of the beam and adjustment of its control value accordingly (see Ref. [5]).
- Extension of the error analysis to all the stages of the measurement.
- Measurement of the dependence of the mismatch on the extraction conditions (energy, extraction trajectory).
- On-line measurement and matching correction (see Ref. [12]).

	Old optics		New optics	
	mismatch (geometrical)	mismatch (filamentation)	mismatch (geometrical)	mismatch (filamentation)
β_H	1.5	1.1	1.3	1.0
β_V	2.2	1.3	1.0	1.0
D_H	22.1	11.6	2.3	1.7
D_V	1.0	1.0	1.0	1.0

Table 13: Measured geometrical and filamented betatron and dispersion blow-up.

Acknowledgements

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[12] G. Arduini, G. Ferioli, K. Hanke, R. Jung, in preparation, (1999).

Distribution List

B. Autin	PS/DI
J. Boillot	PS/OP
R. Cappi	PS/CA
M. Giovannozzi	PS/CA
J-Y. Hémery	PS/CA
M. Lindroos	PS/OP
D. Manglunki	PS/CA
M. Martini	PS/CA
G. Métral	PS/OP
D. Möhl	PS/DI
J-P. Riunaud	PS/CA
K. Schindl	PS/DI
D.-J. Simon	PS/DI