SL-Note-99-018 MD
PS-Note-99-009 CA

PS/SPS

March 25, 1999

Betatron and Dispersion Matching of the TT2/TT10 Transfer Line for the Fixed-Target Lead Ion Beam

G. Arduini, G. Crockford, C. Despas, M. Giovannozzi, K. Hanke, D. Manglunki, M. Martini, G. Métral, C. Niquille

Run no.	Date
	05/10/98
	19/10/98
	26/10/98
	30/11/98

Keywords: PS Machine, SPS Machine, Optics, Lead ion

Summary

The TT2/TT10 transfer line optics was re-matched during the 1998 lead ion run. Blow-up at injection could be minimised by accurate Twiss parameter and dispersion matching. As an immediate result of the matching, the transmission through the SPS and hence the intensity delivered to the targets increased by more than 10%.

1 Introduction

The TT2/TT10 transfer line between the PS and SPS machines at CERN was modelled and matched in order to optimise the performance of the SPS during the 1998 lead ion run. By minimising the blow-up due to injection mismatch in the SPS, the transmission through the SPS and hence the intensity delivered to the targets increased by more than 10 %.

2 *MAD* Model for the Fixed-Target Lead Ion Beam

The measurement of the dispersion and of the Twiss parameters requires 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 are measured, an optics model is required to re-match the line at the injection point. During the 1998 run, considerable effort was spent to verify the beam line model and to accurately measure the optics parameters (Twiss parameters α and β, dispersion D and its derivative D') at the beginning of the injection line. The complete TT2/TT10 line was modelled using the program *MAD* [1]. The geometry of the model was cross-checked versus the official CERN survey data [2] and the correct magnetic behaviour of the elements was confirmed in a series of measurements in TT10 [3].

3 Experimental Conditions

The magnetic cycle has a length of 1.2 s (see Fig. 1 upper part). The PS main power supply imposes a maximum value of the B-field variation with time of 22 G/ms (see Fig. 1 lower part). For this reason the injection point is moved with respect to the other PS magnetic cycles: the beam, consisting of Pb^{53+} ions, is injected 160 ms after the starting point of the magnetic cycle. Normally, the injection time occurs 55 ms later. The injection flat bottom lasts 10 ms, then the B-field is increased at a rate of 20 G/ms until the extraction flat top is reached. This occurs 680 ms after the start of the magnetic cycle at a value of 9500 Gauss, corresponding to an equivalent proton beam momentum of 20 GeV/c.

The 16 bunches are injected in the PS and accelerated up to the flat top. No bunch splitting is

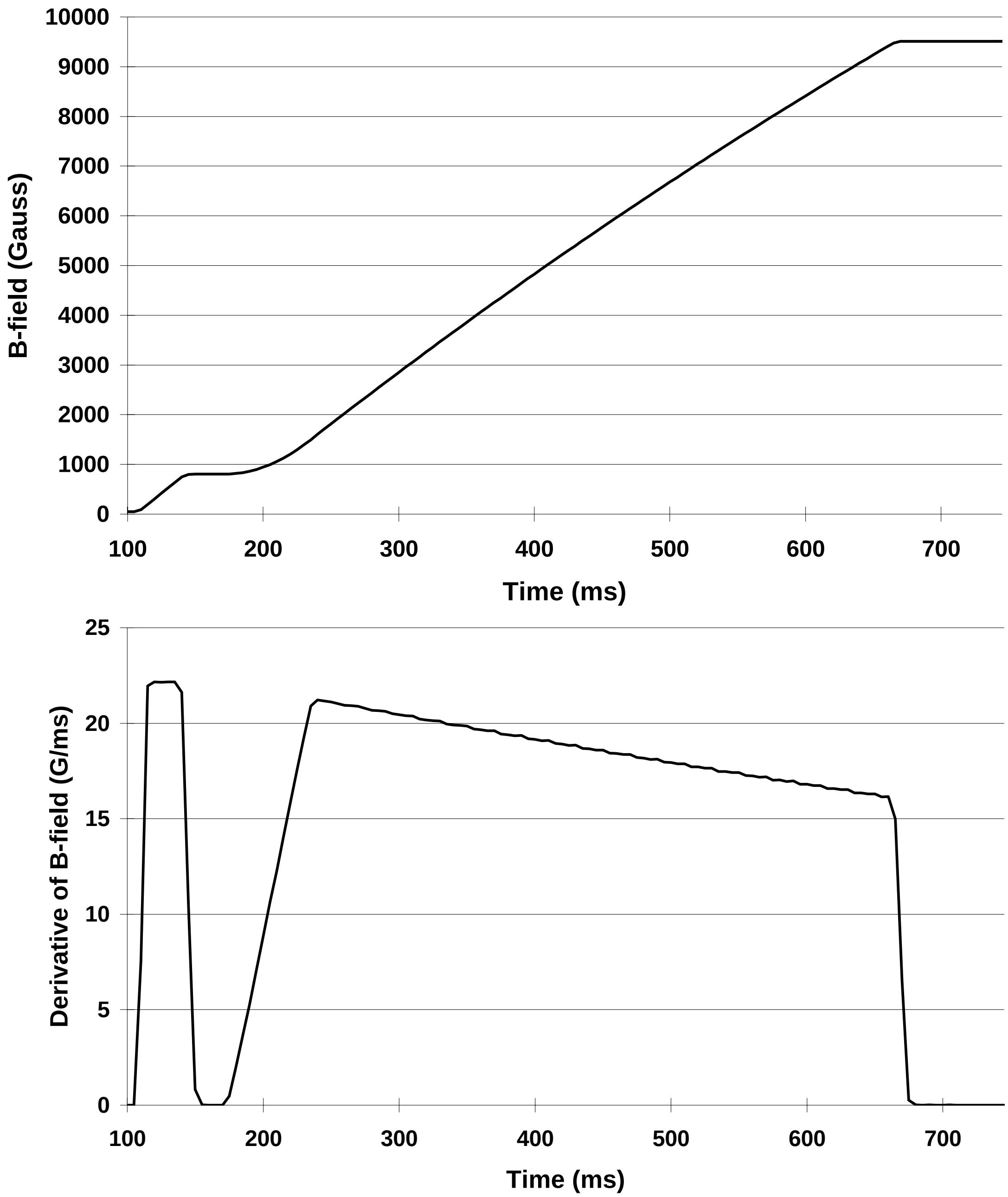

Figure 1: Magnetic cycle used during the lead ion run (upper part) and derivative of the B-field as a function of time (lower part).

Element	Value
`PE.KFA71` [kV]	720
`PE.SMH16` [A]	21590
`PE.BSW16` [A]	1100
`PE.QKE16` [A]	959
`PE.QKE58` [A]	959
`PE.DHZ15` [A]	157

Table 1: Nominal setting of the extraction elements for the lead ion beam.

performed. At high energy the rf voltage is reduced to control the bunch length and the momentum spread.

The working point at low energy is simply determined by the combined function magnets. The low energy quadrupoles and the PFWs are not used for this type of beam as the low intensity ($2-3\times10^{10}$ charges, see Table 2) and the fact that the extraction energy is below the transition energy make the beam intrinsically stable.

The beam is extracted on a flat top in one turn (fast extraction) by the standard scheme based on bumper, kicker and septum. The nominal setting of the extraction elements is reported in Table 1.
After extraction, the lead ions are transferred into the SPS going through a 0.8 mm thick aluminum stripping foil. This results in a complete ionization of the atoms with an efficiency of about 96 % [4], thus generating a beam of Pb^{82+} ions.

The beam parameters for the physics run in 1998 are given in Table 2.

p [GeV/c/u]	5.11
Intensity [charges/batch]	$2-3\times10^{10}$
ε_H [μm] (normalised, r.m.s.)	3.4
ε_V [μm] (normalised, r.m.s.)	1.9
Δp/p	1.5×10^{-4}
bunch length [ns] (4σ)	9
ε_l [eVs/u]	0.022

Table 2: Parameters of the fixed-target lead ion beam in 1998 after the stripper.

4 Experimental Results

Due to the small beam momentum spread, the contribution of the dispersion function to the beam size as measured by the beam profile monitors used to determine the Twiss parameters is negligible, compared to the betatronic component. A pragmatic approach was therefore initially pursued and the measurement of the Twiss parameters was performed before measuring D. Table 3 lists the measured Twiss parameters at the SEM monitors in TT2 and TT10. The Twiss parameters were then tracked back to the beginning of the line (entry point of the quadrupole `QFO105`, sometimes called *R-point*). For the vertical plane, an average of the TT2 and TT10 measurement was taken. Because of the large horizontal beam size at the SEM grids in TT10 an important part of the beam was not visible and the corresponding measurement was not reliable. Therefore for the horizontal plane only a measurement from TT2 was available. Table 4 lists the Twiss parameters at the beginning of the line obtained from the measurement given in Table 3 and the betatronic mismatch factors (see Ref. [5] for the definitions) for this optics.

Monitor	β_H [m]	α_H	β_V [m]	α_V
MSG257	14.17	1.08	58.10	-2.41
BSG1027	-	-	120.17	3.69

Table 3: Measured α and β at SEM monitors before Twiss parameter matching.

	Horizontal plane	Vertical plane
β [m]	28.49	7.04
α	-2.35	0.57
G_b	1.9	2.1
H	1.2	1.3

Table 4: Twiss parameters at the entry of the line before Twiss parameter matching.

Based on these input parameters, betatron matching was performed using the TT10 quadrupoles and the last quadrupole in TT2 (QFO375). The dispersion was not taken into account. An immediate result of the betatron matching of TT10 was the increase of the transmission through the SPS from about 75% to 88% in one step. The intensity delivered to the targets increased in the same way. Figure 2 shows the average number of lead ions per cycle logged for the day when the matched optics was put into operation. Each point corresponds to an average over 15 min, and only cycles with beam are taken into account. A step can be seen clearly when the new optics was loaded on 19/10/1998.

With this optics, the Twiss parameters at the SEM monitors in TT2 and TT10 were measured again. The results are given in Table 5. From this measurement, the initial Twiss parameters at the entry of the line could be obtained. Table 6 lists the initial Twiss parameters as well as betatronic mismatch factors obtained after Twiss parameter matching.

Monitor	β_H [m]	α_H	β_V [m]	α_V
MSG257	17.63	1.35	40.53	-1.91
BSG1027	56.84	-1.84	69.21	2.10

Table 5: Measured α and β at SEM monitors after Twiss parameter matching.

	Horizontal plane	Vertical plane
β [m]	29.42	5.71
α	-2.51	0.29
G_b	1.2	1.3
H	1.0	1.0

Table 6: Twiss parameters at the entry of the line after Twiss parameter matching.

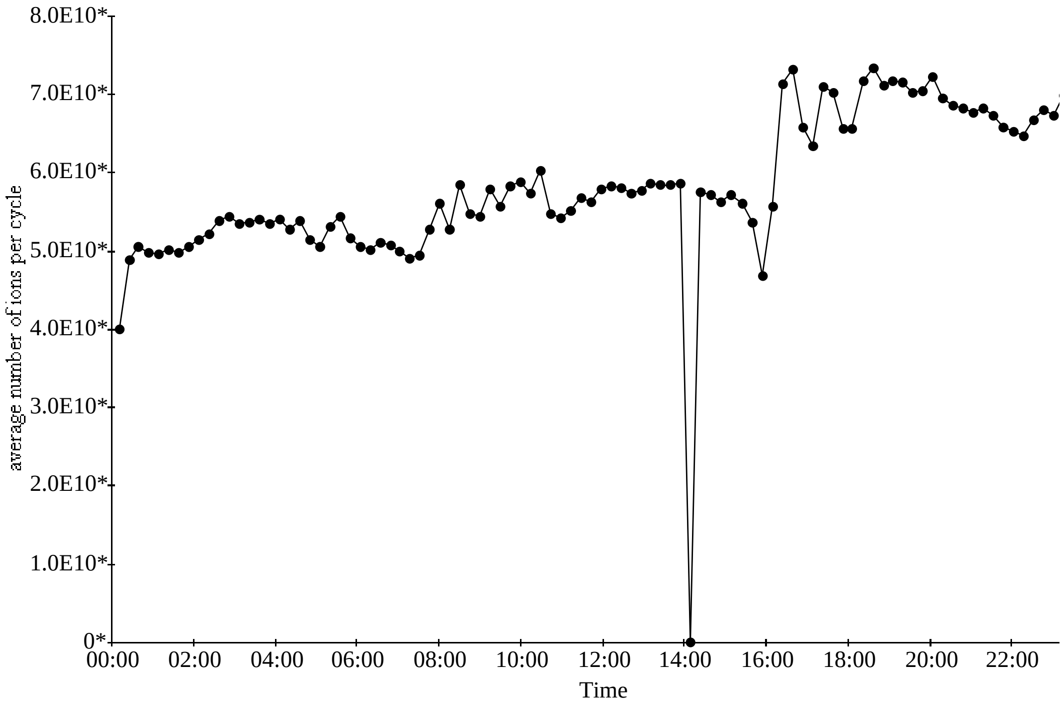

Figure 2: Average number of lead ions per cycle logged over 24 hours. The step function in efficiency at 16:25 is due to the installation of a new, matched optics in TT10. The drop at 14:00 is due to a power supply failure.

Dispersion measurement imposes stringent constraints on the beam characteristics. 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 bandwidth around 200 MHz. Therefore the bunch length should be limited to about 5 ns in order to measure the beam position. For the above reasons the voltage program for the acceleration was modified in order to produce shorter bunches at extraction and the measurement was performed with the unstripped Pb^{53+} ion beam to avoid the emittance blow-up due to the stripper. The beam parameters used for the dispersion measurement (conducted on the MD cycle in parallel with physics) are listed in Table 7

p [GeV/c/u]	5.11
Intensity [charges/batch]	$1 - 1.5 \times 10^{10}$
ε_H [μm] (normalised, r.m.s.)	2.7
ε_V [μm] (normalised, r.m.s.)	1.2
Δp/p	1.5×10^{-4}
bunch length [ns] (4σ)	5-7
ε_l [eVs/u]	0.022

Table 7: Parameters of the Pb^{53+} beam used during the MD.

The dispersion function was measured in the injection line and in the first turn in the SPS ring, considered as a continuation of the transfer line. The experimental technique has been described in details in Ref. [5]. The momentum offset with respect to the reference momentum was varied between -1.47×10^{-3} and 0.06×10^{-3}. The presence of an obstacle in the PS extraction magnetic septum `SMH16` [6] did not allow to increase the momentum span any further. Figure 3 shows the measured horizontal dispersion in the line and in the SPS. Figure 5 shows measured (squares) and theoretical (triangles) horizontal dispersion in the SPS before matching the injection line, while Fig. 7 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 values of the dispersion at the TT2 SEM-wires and at the TT10 SEM-grids location are listed in Table 8.

Monitor	D_H [m]	D_V [m]
`MSG257`	3.20 $\pm$ 0.85	-1.38 $\pm$ 0.18
`MSG267`	-1.52 $\pm$ 0.22	-0.62 $\pm$ 0.23
`MSG277`	-4.72 $\pm$ 1.03	0.51 $\pm$ 0.12
`BSG1027`	-7.04 $\pm$ 0.27	-1.36 $\pm$ 0.16
`BSG1028`	-7.37 $\pm$ 0.22	1.41 $\pm$ 0.10
`BSG1029`	-0.26 $\pm$ 0.30	1.41 $\pm$ 0.19

Table 8: Measured dispersion at SEM monitors before dispersion matching.

The measured initial Twiss parameters and the measured initial dispersion were used as input for a complete matching taking into account both Twiss parameter and dispersion. The initial parameters measured in 1998 are listed in Table 9.

	Horizontal plane	Vertical plane
β [m]	29.42	5.71
α	-2.51	0.29
D [m]	4.13	-0.47
D'	0.41	0.03
G_b	1.2	1.3
H	1.0	1.0
G_d	1.3	1.2
J	1.0	1.0

Table 9: Measured optical parameters at the *R-point*, geometrical blow-up and blow-up after filamentation. These values were used as input for complete matching of Twiss parameters and dispersion.

The Twiss parameters correspond to those given in Table 6, the values of D and D' are obtained from the dispersion measurement just mentioned. The geometric blow-up and the blow-up after filamentation are listed too, both for the betatronic and dispersive components [7, 8]. The Twiss parameters, dispersion and its derivative were matched to the measured ones at the *R-point* (see Table 9) and to the nominal values at the injection point in the SPS (see Table 10). The dispersion and its derivative as well as the β-function have been minimised at the stripper position in order to reduce the emittance blow-up

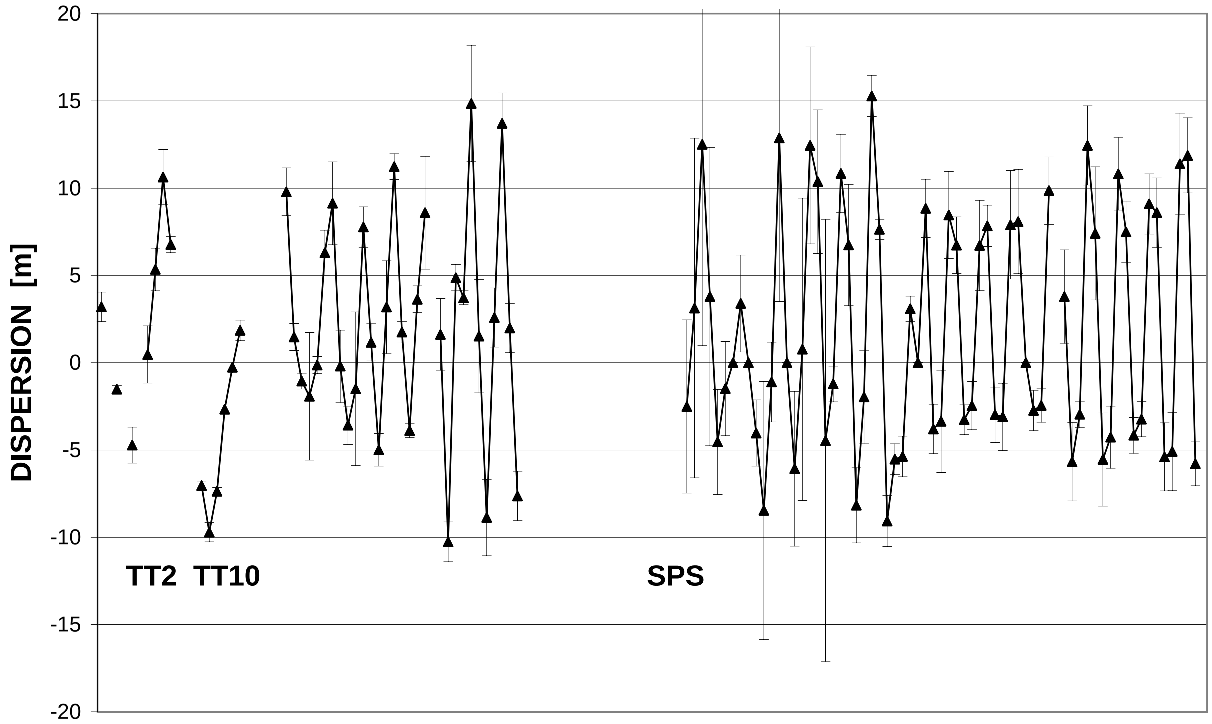

Figure 3: Measured horizontal dispersion in the transfer line and the SPS before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

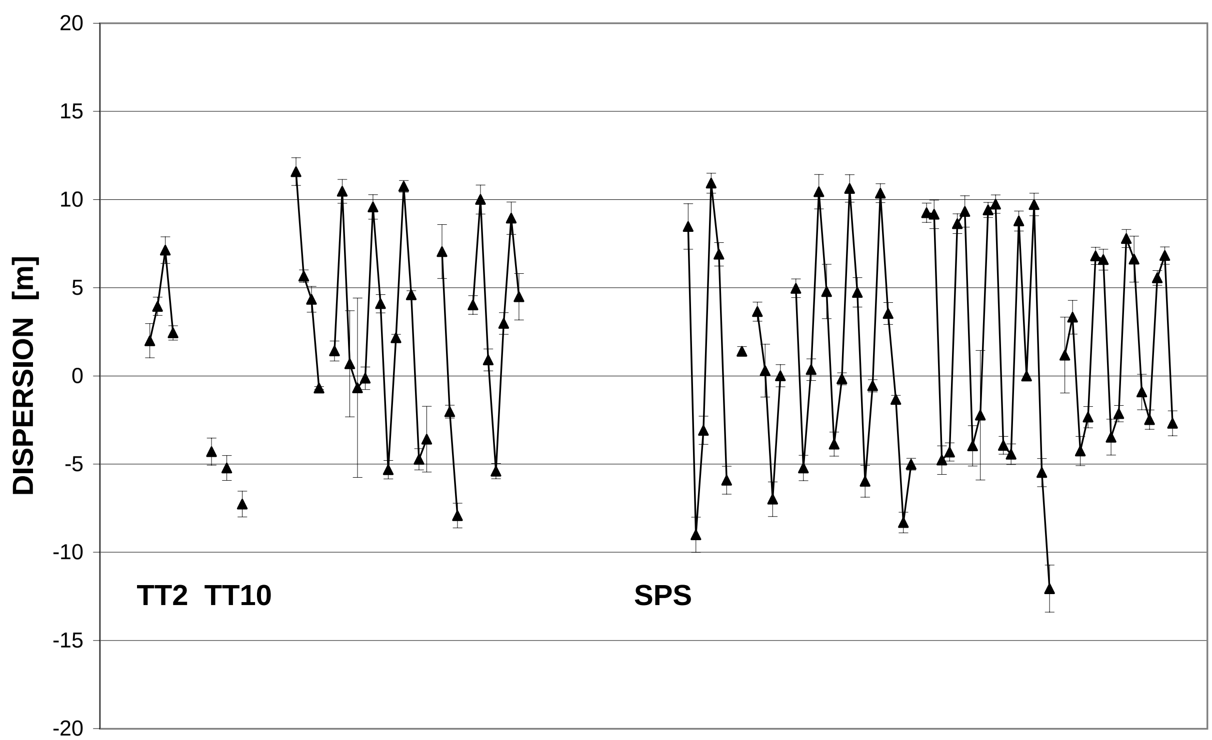

Figure 4: Measured horizontal dispersion in the transfer line and the SPS after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

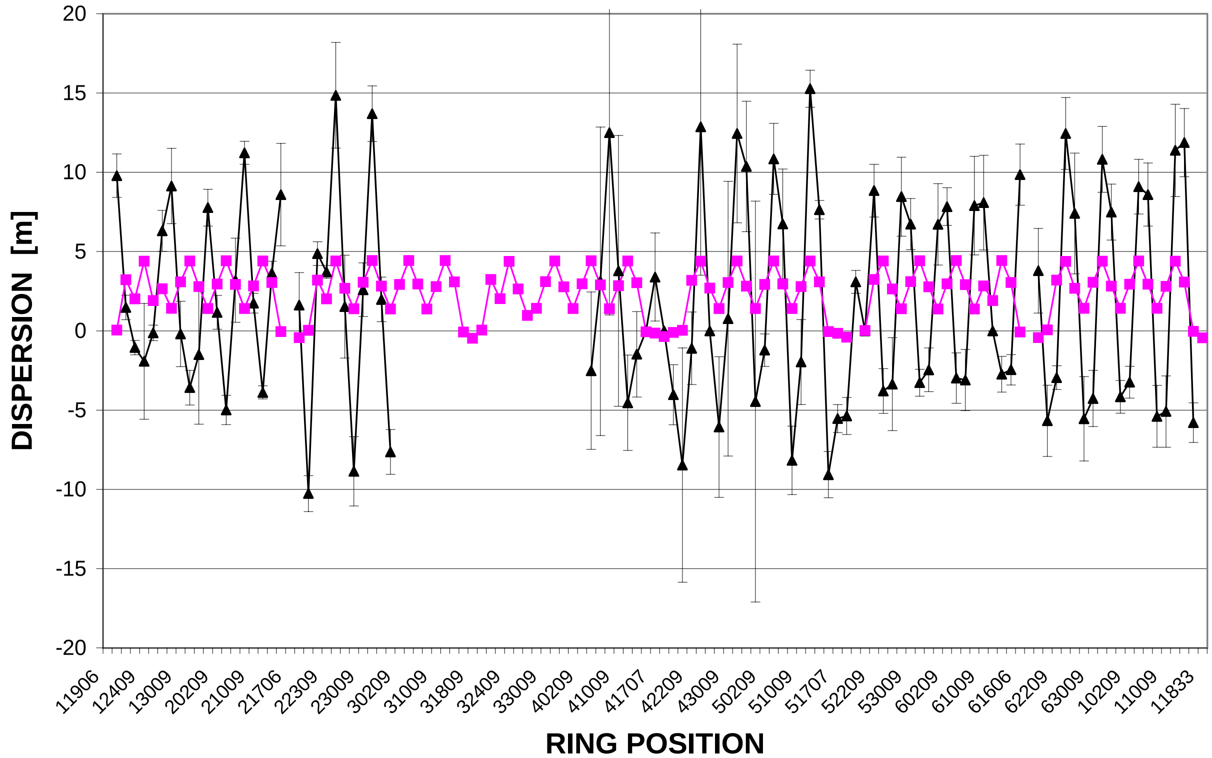

Figure 5: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS before matching the injection line.

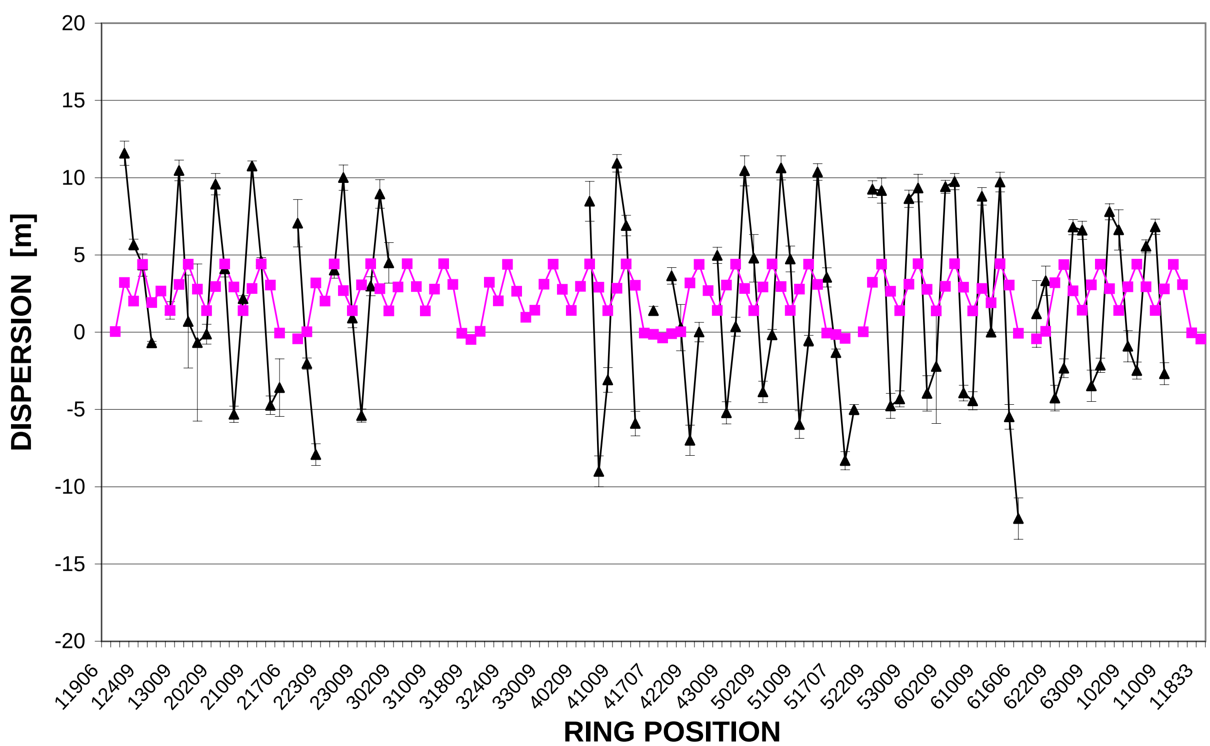

Figure 6: Measured (triangles) and theoretical (squares) horizontal dispersion in the SPS after matching the injection line.

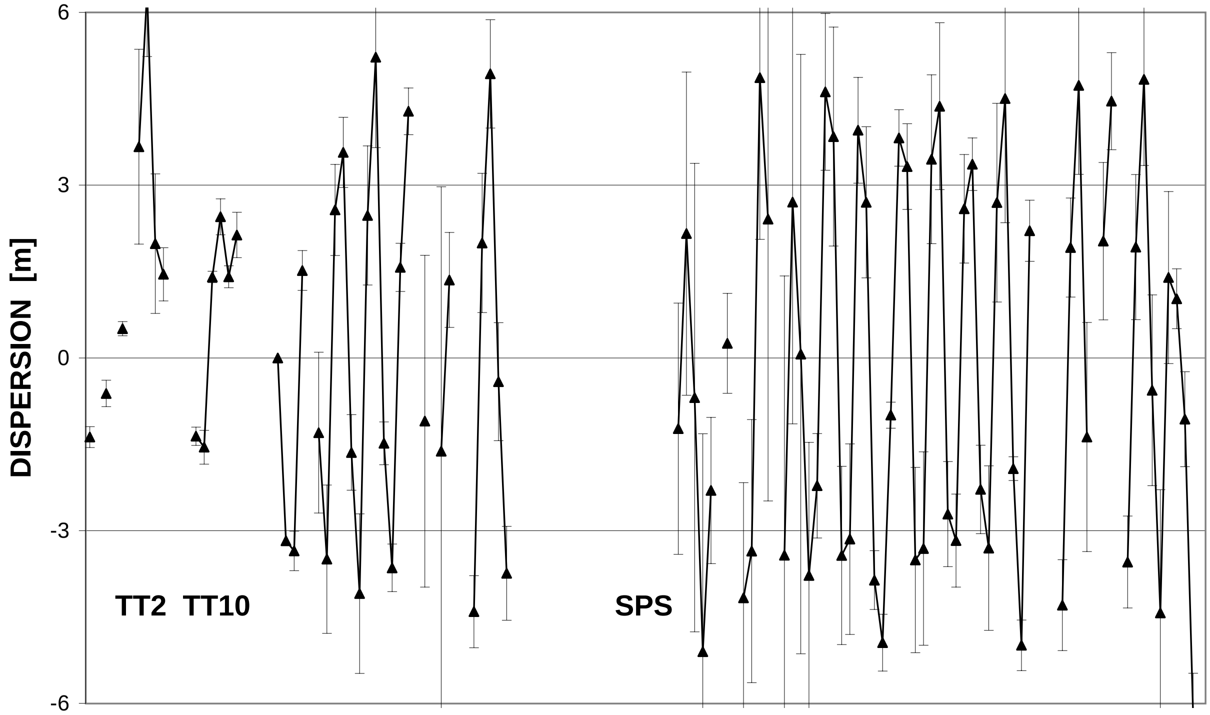

Figure 7: Measured vertical dispersion in the transfer line and the SPS before matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

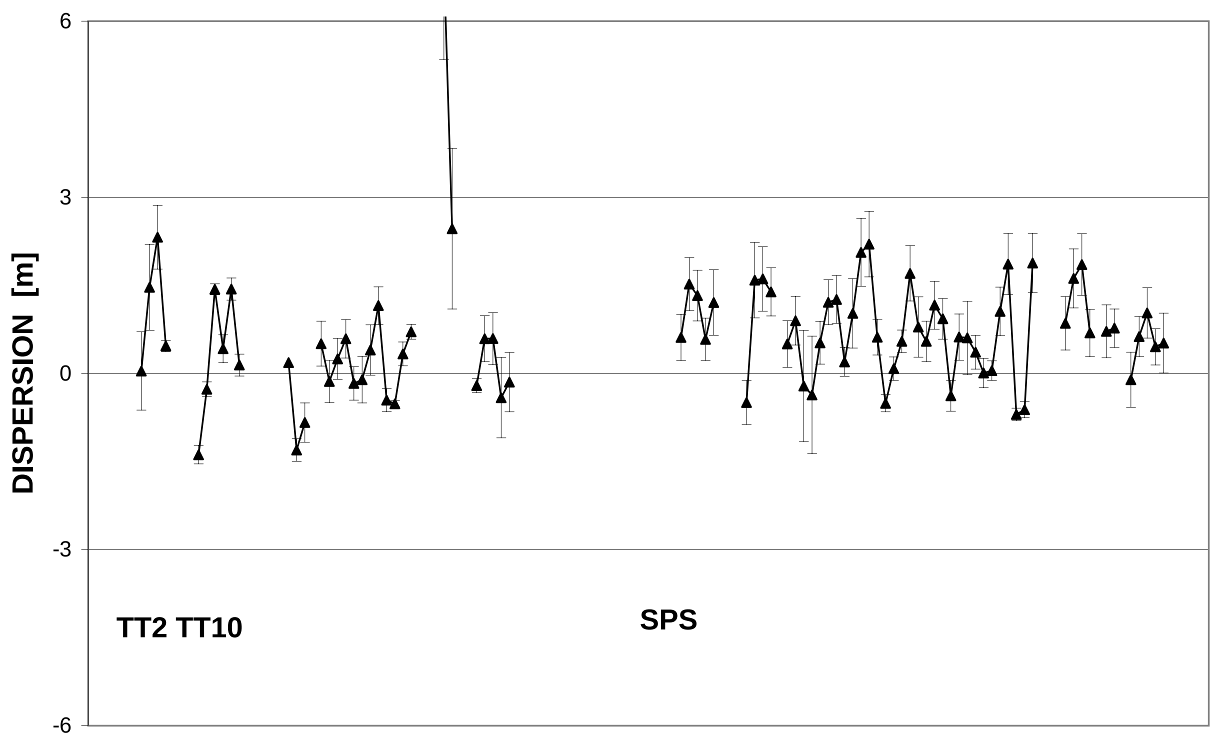

Figure 8: Measured vertical dispersion in the transfer line and the SPS after matching the injection line. The gap in the SPS data is due to the missing pickup read-out in one of the sextants.

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

and the coupling between transverse and longitudinal planes. All the available quadrupoles, or set of quadrupoles, having independent power converters in TT2/TT10 have been used for the matching. Figure 9 shows the horizontal and vertical β-function along the line for the matched optics as computed with *MAD*. Figure 10 shows the horizontal and vertical dispersion function along the transfer line for the same optics. Table 11 lists the optical parameters at the stripper position for the old and the new optics.

	Old optics		New optics	
	horizontal plane	vertical plane	horizontal plane	vertical plane
β [m]	23.64	22.25	16.12	25.22
α	-1.62	1.41	-0.64	1.23
D [m]	-2.21	-0.22	0.07	0.13
D'	-0.37	-0.004	-0.21	-0.01

Table 11: Optical parameters at the stripper for the old and new optics as calculated with *MAD*.

The new optics has been tested in operation. The dispersion measurement was repeated and the new results are shown in Figs. 4, 6 and 8. The optics parameters at `MSG257` and `BSG1027` were measured and are listed in Table 12. The values obtained for the Twiss parameters at the *R-point* are reported

Monitor	β_H [m]	α_H	β_V [m]	α_V
`MSG257`	38.20$\pm$0.45	1.98$\pm$0.02	47.72$\pm$0.19	-1.18$\pm$0.01
`BSG1027`	54.7$\pm$1.3	-1.93 ± 0.12	33.68$\pm$0.44	1.1$\pm$0.02

Table 12: Measured α and β at SEM monitors after re-matching.

in Table 13. Different results are obtained from the SEM monitors in TT2 and TT10. This indicates the uncertainty of these measurements. A detailed error analysis of all stages of the measurement will be performed during the 1999 run. The Twiss parameters at the *R-point*, the geometric blow-up and the blow-up after filamentation for the new optics are summarised in Table 14. For the initial Twiss parameters, the average of the values obtained in TT2 and TT10 was used. In particular, it can be seen that the set of initial beam parameters is different from the one obtained for the first optics (Tab. 9). This indicates that the measurement is affected by a significant error which has to be investigated in detail.

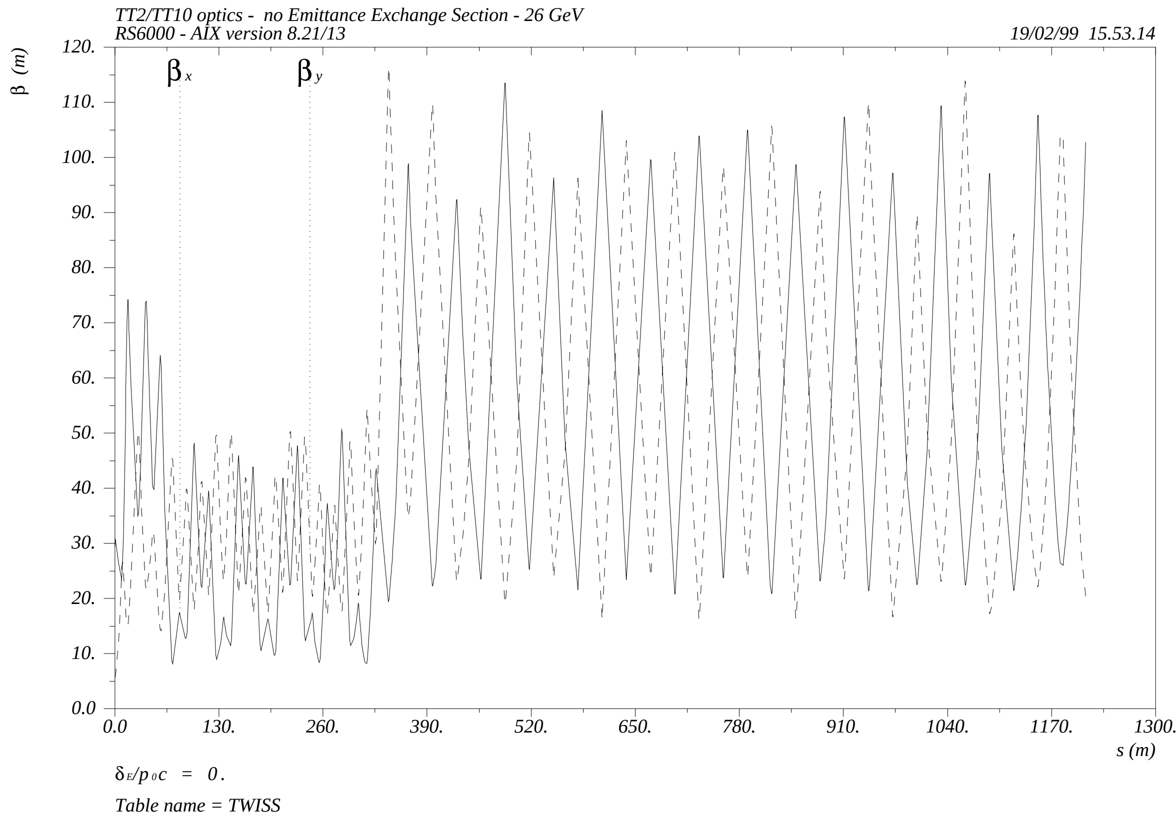

Figure 9: Horizontal and vertical β-function for the matched optics as computed with *MAD*.

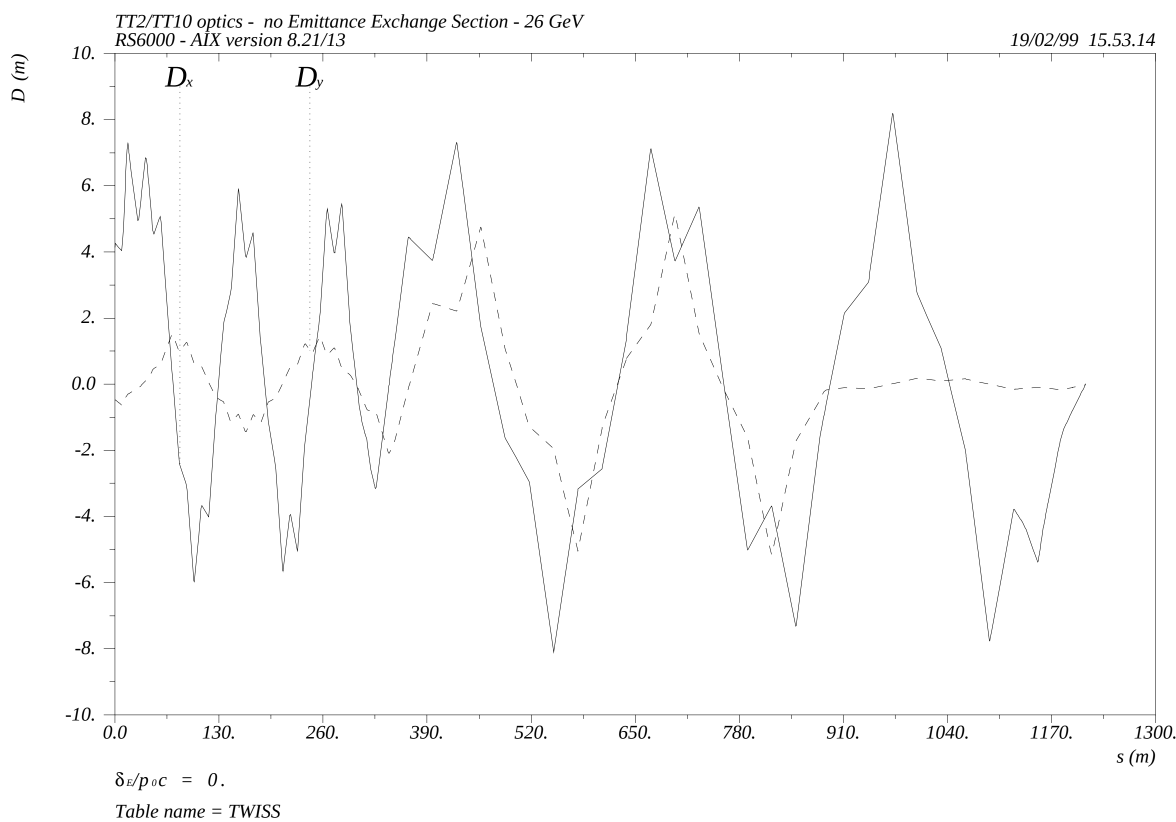

Figure 10: Horizontal and vertical dispersion for the matched optics as computed with *MAD*.

	β_H [m]	α_H	β_V [m]	α_V
from `MSG257`	39.2	-3.83	8.62	1.07
from `BSG1027`	47.34	-3.97	8.34	0.38

Table 13: Measured α and β tracked back from SEM monitors to *R-point*.

	Horizontal plane	Vertical plane
β [m]	43.27	8.48
α	-3.9	0.73
D [m]	6.01	-0.27
D'	0.52	0.03
G_b	1.2	1.3
H	1.0	1.0
G_d	1.3	1.0
J	1.0	1.0

Table 14: Measured optical parameters at the *R-point*, geometrical blow-up and blow-up after filamentation. These values were obtained after full Twiss parameter and dispersion matching.

	Old optics		New optics	
	mismatch (geometrical)	mismatch (filamentation)	mismatch (geometrical)	mismatch (filamentation)
β_H [m]	1.9	1.2	1.7	1.1
β_V [m]	2.1	1.3	1.5	1.1
D_H [m]	1.3	1.0	1.3	1.0
D_V [m]	1.2	1.0	1.0	1.0

Table 15: Measured geometrical and filamented betatron and dispersion mismatch factors.

5 Conclusions

Consequent measurement of the beam parameters in the TT2/TT10 transfer line was performed during the 1998 run. Simultaneous Twiss parameter and dispersion matching was performed based on the measured initial conditions. Table 15 shows the betatron and dispersion mismatch factors for the matched optics.

The following subjects for further investigations have been determined:

- Precise measurement of the energy of the beam and adjustment of its control value accordingly (see Ref. [9]), taking into account the energy loss in the stripper.

- Extension of the error analysis to all the stages of the measurement.

Furthermore, the optics at the stripper location affects the amount of beam blow-up [8]. As a consequence of the improved knowledge of the optics a few measurements have been taken in order to evaluate the blow-up due to the stripper. No conclusive result could be drawn from the data collected and the study will be continued in 1999 because of its interest for the LHC lead ion beam.

Acknowledgements

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

References

[1] H. Grote, F. C. Iselin, "The *MAD* Program, User's Reference Manual", *CERN SL (AP)* **90-13** (1990).

[2] G. Arduini, M. Giovannozzi, K. Hanke, J.-Y. Hémery, M. Martini, "*MAD* and *BeamOptics* Description of the TT2/TT10 Transfer Line - Part I: Optics without Emittance Exchange Insertion", *CERN PS Note (CA)* **98-014** and *CERN SL Note (OP)* **98-040** (1998).

[3] G. Arduini, M. Giovannozzi, K. Hanke, J.-Y. Hémery, " Study of the TT2/TT10 Transfer Line Optics via Transfer Matrix Measurement", *CERN PS Note (CA)* **98-020** and *CERN SL Note* **98-058 MD** (1998).

[4] G. Arduini *et al.*, in *Proceedings of the Fifth European Particle Accelerator Conference*, edited by S. Myers, A. Pacheco, R. Pascual,Ch. Petit-Jean-Genaz and J. Poole (10-14 June 1996, Sitges (Barcelona), Spain),1996, p. 380-382.

[5] G. Arduini, G. Crockford, C. Despas, M. Giovannozzi, K. Hanke, D. Manglunki, M. Martini, G. Métral, C. Niquille, " Betatron and Dispersion Matching of the TT2/TT10 Transfer Line for the 26 GeVc Fast Extraction", *CERN PS Note (CA)* **99-007** and *CERN SL Note* **99-003 MD** (1999).

[6] J. Borburgh, A. Martinola, "Magnetic Measurements of the Modified Septum SMH16 (Lead Ion)", *CERN PS Note (CA)* **98-11** (1998).

[7] G. Arduini, P. Raimondi, "Emittance Blow-up due to Injection Errors", in preparation, (1999).

[8] P. J. Bryant,"Beam Transfer Lines", *CERN Yellow Report* **94-01**, p. 219-38, (1994).

[9] G. Arduini, in *Proceedings of the Workshop on LEP-SPS Performance Chamonix IX*, edited by J. Poole (25-29 January 1999, Chamonix, France),CERN-SL-99-007 DI, p. 103-9.

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