NEW RESULTS ON TT2-TT10 MATCHING

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7.1 Abstract

The progress achieved in the last two years in the TT2-TT10 matching studies for the LHC beam transfer is reported. While the reliability of the optics model and a measurement campaign have allowed a substantial reduction of the dispersion mismatch, as demonstrated in various machine study results, the extensive use of OTR profile monitors in TT10 and in the SPS has allowed evidencing the presence of coupling in the LHC beam transfer. The measurement techniques and the algorithms applied to quantify the observed coupling and individuate its source (e.g. measurement of the 4×4 transfer matrix, determination of complete 5×5 beam covariance matrix from OTR profiles), as well as cross-comparison with TT2 measurements, are presented. Finally, an outline of future directions for study and improvement in the areas of configuration, procedure, and algorithm is also presented.

1 OVERVIEW

As an important link in the LHC injection chain, the transfer of proton beam from the PS to the SPS through the lines TT2 and TT10 will need to be executed with high precision. At issue are the preservation of projected transverse emittances through TT2/TT10, and correct matching into the SPS. This report summarises the machine studies and analyses performed in the year 2000, as part of an ongoing effort[1] to achieve better understanding and control of the TT2/TT10 transfer properties, as well as the beam characteristics out of the PS.

Three main factors in the TT2/TT10 transfer can contribute to emittance degradation in the SPS. Firstly, if the twiss parameters are not matched into the SPS, emittance blow-up will ensue due to filamentation in the SPS. Secondly, un-suppressed dispersive oscillation in the beam into the SPS will result in an apparent mismatch, effectively blowing up the emittance also through filamentation. Finally cross-plane coupling either in the beam out of the PS or in the transfer line itself will cause increase in the projected emittances of the beam even if the latter is apparently matched into the SPS.

This report will focus on the investigation into these three possible causes of emittance degradation in the TT2/TT10 transfer. Implemented schemes, as well as those under evaluation, for combating these effects will also be discussed.

2 OUTLINE OF STUDIES PERFORMED

A conceptual layout of the TT2-TT10 transfer is shown in Fig. 1, where various machine studies and analyses performed on these lines are also illustrated. These include:

- Dispersion measurement by beam position monitor (BPM) response to energy variations from the PS,
- Difference orbit measurement by BPM response to dipole corrector changes in the TT2 line,
- Transfer matrix determination from TT2 to TT10,
- 5×5 beam covariance matrix measurement using TT10 and SPS profile monitors (OTR),

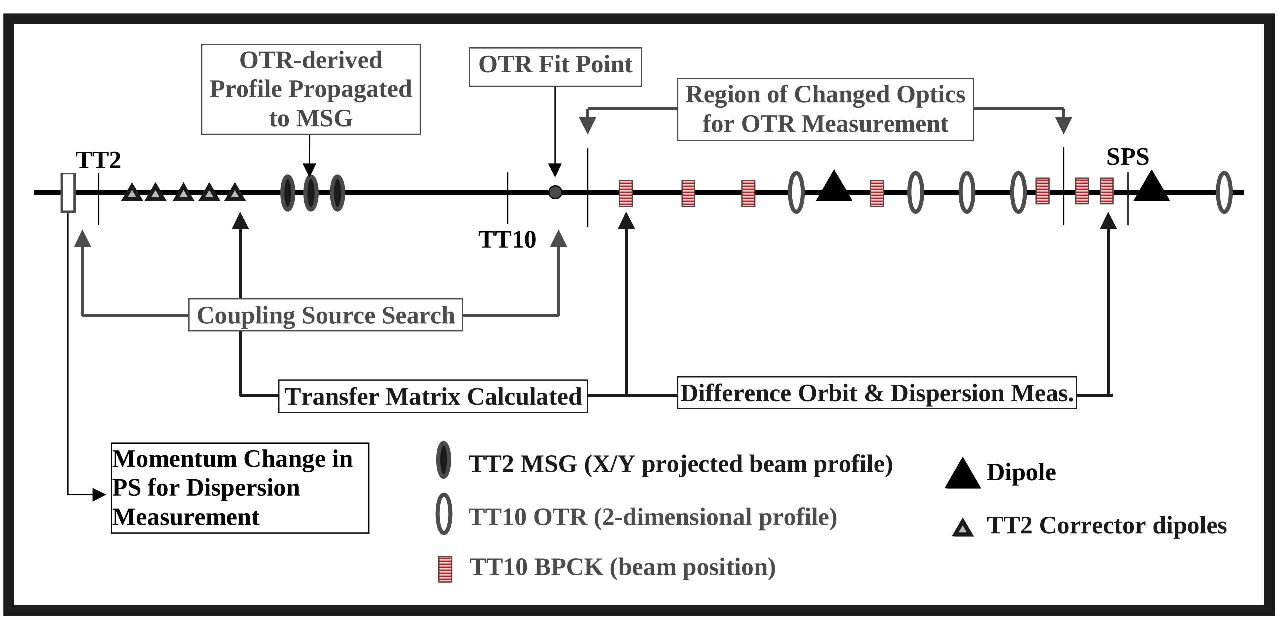

Figure 1. Conceptual Layout of Machine Studies Performed

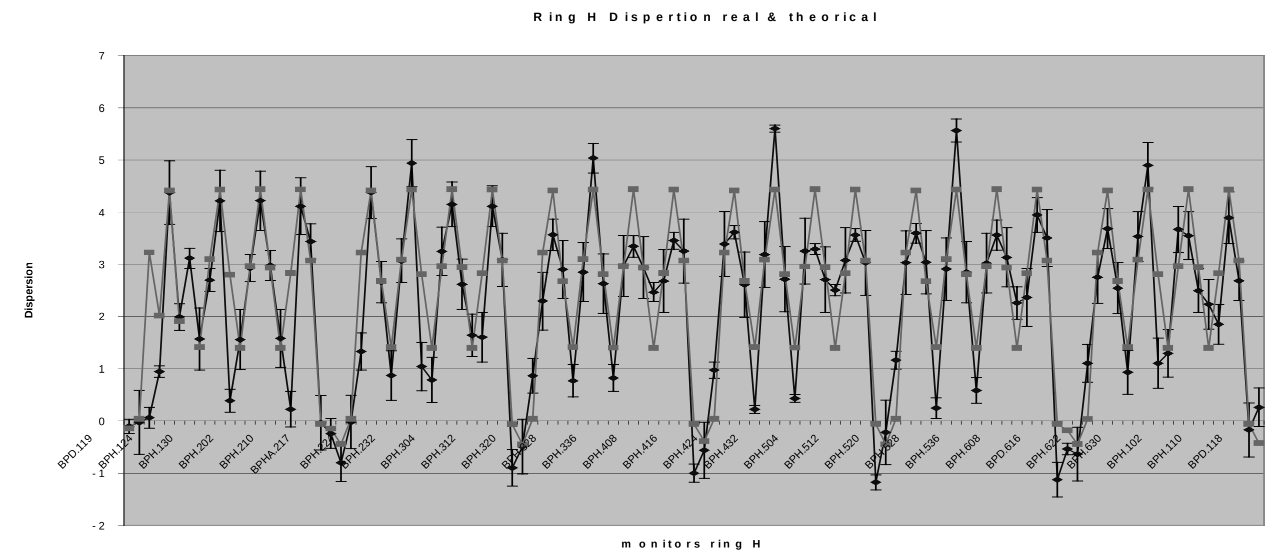

Figure 2(a) Horizontal Dispersion for SPS First Turn (•: Model ♦: Measurement)

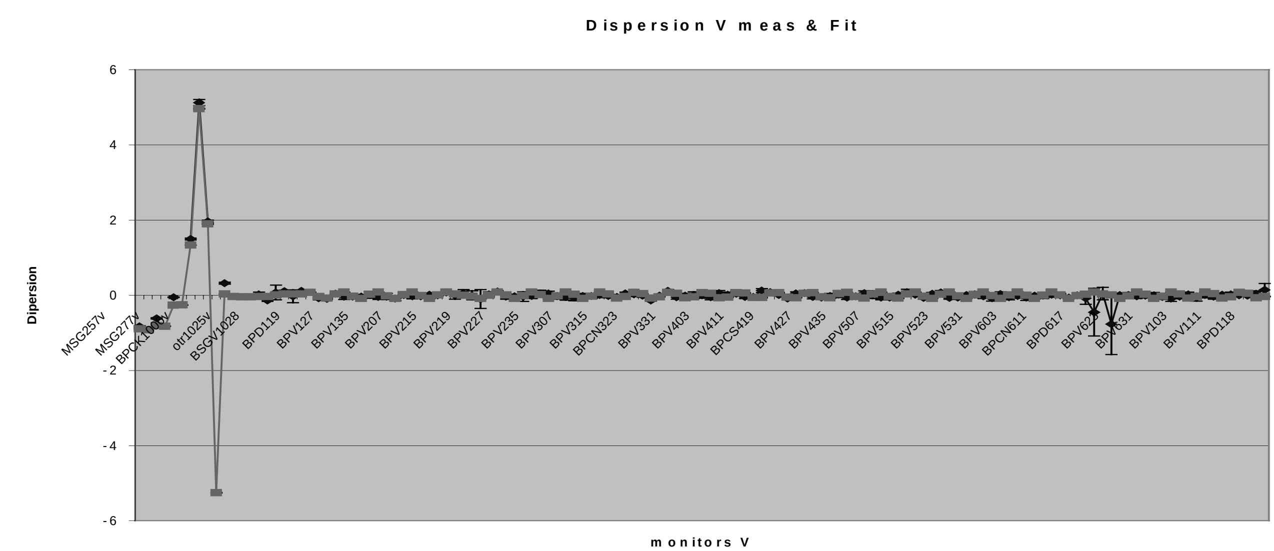

Figure 2(b) Vertical Dispersion for SPS First Turn (•: Model ♦: Measurement)

- Propagation of measured beam covariance matrix to the profile monitors (MSG) in TT2 for cross-comparison,
- Search for point source of coupling using both the difference orbit and the beam covariance data.

In the following sections more detailed account will be given to the techniques, the outcome, and remaining issues related to each study.

3 DISPERSION SUPPRESSION

With the implementation of an automated tool for BPM data acquisition and analysis based on PS-SL Passerelle[1], dispersion measurement throughout the TT2-TT10 transfer and into the first turn of SPS became much more efficient. A new dispersion-matched optics was thus obtained and implemented at the beginning of the 2000 run. This resulted in very good dispersion suppression into the SPS. Figs. 2(a) and 2(b) show the measured dispersion in both planes, in contrast to the model values, for the first turn in the SPS. Very effective dispersion suppression due to the new matching is evident.

A more quantitative comparison is demonstrated in Table 1, where the mismatch factors[2] due to dispersion as measured in 1999 and 2000 are shown. Therefore in the new optics of 2000 negligible emittance degradation in the SPS can be attributed to dispersion mismatch in the TT2-TT10 transfer.

[1] Developed by D. Jacquet

Table 1. Mismatch Factors due to Dispersion

Dispersion Mismatch	Geometric		Filamentation	
	X	Y	X	Y
1999	4.63	1.18	1.66	1.00
2000	1.00	1.00	1.00	1.00

4 DIFFERENCE ORBIT MEASUREMENT

More elaborate efforts were devoted to difference orbit measurements aimed at verifying the optics in the TT2-TT10 lines with a more complete phase-space coverage, and at scrutinising these lines for anomalies.

Orbit oscillations on the order of 10 mm were launched with the corrector dipoles BHZ and BVT at the beginning of TT2 (see Fig. 1), and the responses at 7 BPM's distributed in TT10 recorded using the same acquisition tools as in dispersion measurements. An off-line program was developed to analyse the data thus acquired. Each corrector is excited to 5 different strengths, resulting in 4 difference orbits spanning the 7 BPM's in each plane. Each difference orbit is subjected to a trajectory fit based on the model. The comparison between the fitted trajectories and the measured data is demonstrated in Fig. 3, with 2 out of the 5 correctors shown. The in-plane agreement between measurement and model is remarkable, while in the cross-plane oscillations on the order of 5% of the in-plane orbit amplitude can be seen. This coupling, albeit small, is unmistakable in the sense that normalised correlations between the in-plane and cross-plane orbits exceed 90% in all cases analysed.

Fig. 3 demonstrates the model effectiveness across TT10 where the BPM's are located. To evaluate the model in TT2, the fitted trajectories above were each back-propagated to the beginning of TT2 where the oscillations originated. All 5 back-propagated trajectories crossed zero at locations very close to those of their respective launching correctors, demonstrating the effectiveness of the in-plane model across TT2. This is shown in Fig. 4.

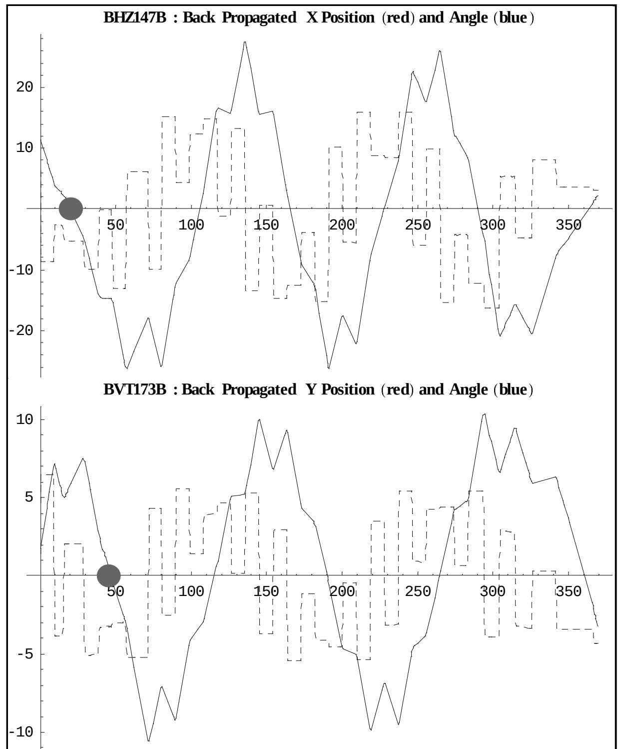

Figure 4. Back Propagated Position (mm solid) and Angle (100 μrad dashed) vs Distance in TT2 (m):
Top: Horizontal Orbit from BHZ147
Bottom: Vertical Orbit from BVT173
(Launching corrector positions marked by dots)

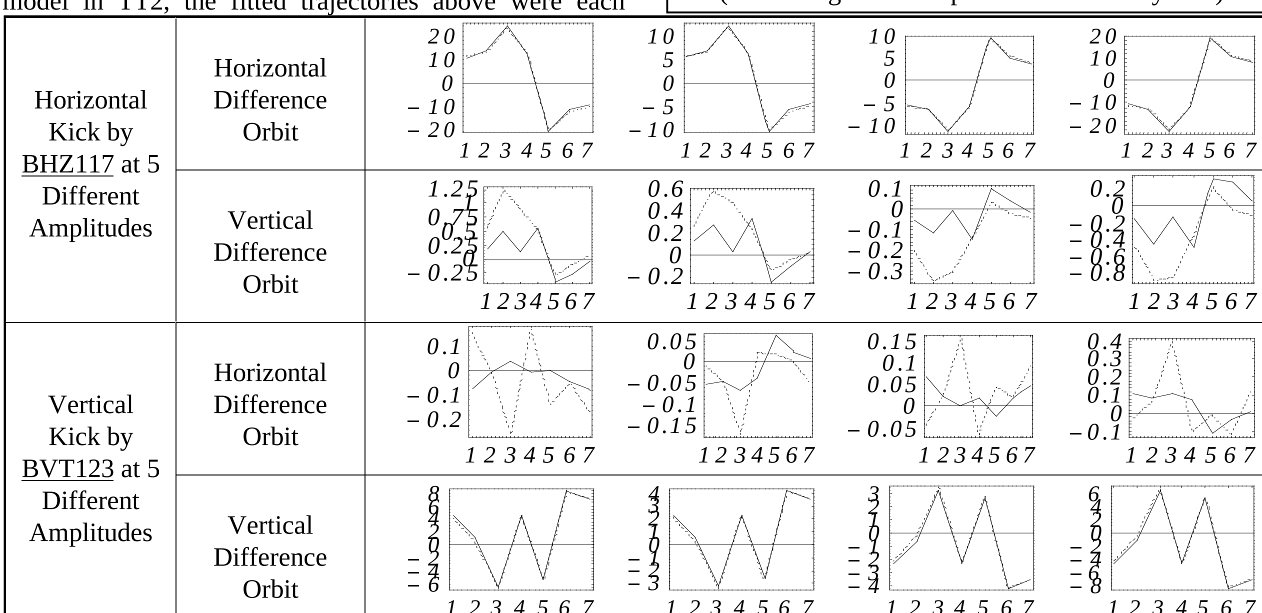

Figure 3. Measured Difference Orbit (Dotted) vs Trajectory Fit to the Model (Solid) in mm at 7 BPM's

The zero-crossing in the back-propagated trajectories in the cross-plane in principle should reveal possible source of coupling. This was studied for all 5 corrector patterns. However a single zero crossing point common to all 5 cross-plane trajectories could not be identified.

The difference orbit technique was also employed to quantify the potential coupling induced in a stray field region between the PS extraction and the beginning of TT2. Different settings in both the PS extraction orbit bump and the extraction septum were invoked to launch orbit oscillations with reasonable coverage in amplitude and phase angle across this region. The conclusion at this point is that the cross-plane orbit induced in this region is below 2%, even smaller than that induced inside TT2-TT10.

5 BEAM PROFILE MEASUREMENT

With the installation of 4 Optical Transition Radiation (OTR) monitors in the TT10 line, and one in the SPS capable of multi-turn acquisition, possibilities opened up for obtaining true 2-dimensional information on the beam distribution. Fig. 5 shows the on-line application for viewing OTR data in two different modes[2]. It is important to be able to quantify and eventually control structural defects in the beam that may lead to emittance growth. For example without the 2-dimensional information on the beam shown in Fig. 5, it is difficult to ascribe the visible tilt in the profile to the correct mix between coupling and dispersion. The implication of these two effects for emittance degradation, on the other hand, can be quite different. This issue can be resolved if a robust technique is established taking advantage of the 2-dimensional information from the OTR's. It is also necessary to be able to demonstrate consistency between different measurements in TT2 & TT10 on the beam characteristics. The techniques described in this section were motivated by these goals.

5.1 Method of OTR-Based Beam Profile Measurement

The method used for completely characterising the beam distribution in 4 or 5 dimensional phase space, represented by the 4 × 4 or 5 × 5 covariance matrix, is briefly described below.

In a dispersive beam line the betatron and dispersive components of the beam are always mixed in a measured beam profile, which is simply the projection of the full distribution onto the X, Y, or other rotated axis. So far as beam profile measurement is concerned, the independent parameters to be extracted from each OTR profile are the <**XX**>, <**XY**>, and <**YY**> correlations. These parameters

[2] This program allows the user to view the 2D and 3D contours by intensity, as well as projections on the X and Y-axes.

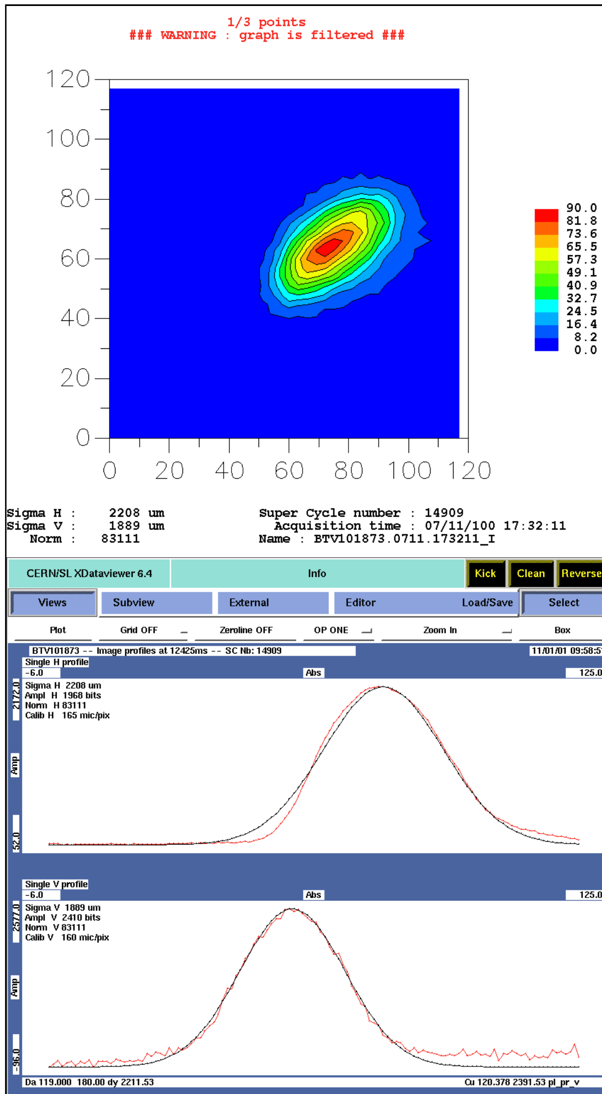

Figure 5. OTR Displays:
Top: 2D Contour, Bottom: Projections

at all OTR's are functions of the 5 × 5 beam covariance matrix at an arbitrary point **P** and the transport optics encompassing the OTR region and **P**. If the latter is known with confidence, with sufficient number of OTR's or different optics, or both, one can then solve for the beam covariance matrix at **P**.

As is true with any experiment, measurement errors can overwhelm the underlying signal and render the data analysis a futile effort. This is especially true if the system has low redundancy or is numerically ill-conditioned. Furthermore simple degree-of-freedom count does not guarantee that all signals can be independently resolved. The discussion of these considerations will be given in the following sub-sections.

If one is certain of the following facts:

- the dispersion associated with the beam transport (not the beam itself) is well-measured at the OTR's,
- there is no intrinsic betatron-momentum correlation within the beam prior to the point where

energy is varied to perform the above dispersion measurement,

then one can confidently account for all dispersive components in the beam covariance based on the measured dispersion, and proceed to only solve for the 4×4 covariance matrix and the momentum spread, which is not known a priori. In this case the redundancy in the system is improved and one can expect higher immunity to error.

In the analysis performed the momentum spread quoted from the PS measurements is often used to further constrain the fit. Therefore there are 4 options for the fitting configuration:

- 15-Parameter Fit: All 15 independent beam covariance matrix elements are used as fitting parameters.
- 14-Parameter Fit: Same as the above but with the momentum spread imposed as constraint.
- 11-Parameter Fit: Assuming no intrinsic betatron-momentum correlation, and well-known dispersion.
- 10-Parameter Fit: Same as the above but with the momentum spread imposed as constraint.

In all cases the number of OTR-based constraints in the fit is always given by

$$\mathbf{N_{CONST.} = 3 \times N_{OTR} \times N_{OPTICS}}$$

where N_{OTR} and N_{OPTICS} are the number of OTR's and number of optics used respectively.

5.2 Robustness of Existing OTR Configuration

Before taking data from the OTR and performing analysis, it is important to evaluate the numerical system to be used for analysis, as afforded by the transport optics and location of the OTR's. If this system is poorly conditioned, the analysis would be plagued by signals overwhelmed by noise or un-resolvable degrees of freedom. For this purpose an analysis based on singular value decomposition (SVD) was performed on the existing OTR configuration to evaluate the degree of independence of the signals[3], and to identify possible weak signals or nearly un-resolvable combinations. The outcome is compared to 9 other possible OTR configurations based on existing optics. It turned out that the existing OTR configuration compares favourably to almost all other configurations, with the exception in one or two signals being only slightly more degenerate than one of the other possibilities. No singular combinations are present, as opposed to some of the more obvious options for OTR configuration[4]. This provides enhanced confidence in the ensuing OTR measurement and analysis.

Since momentum-related degrees of freedom are an important part of the analysis, the OTR configuration must include at least one intervening dipole magnet with sufficient bend strength to resolve them. This is found in the vertical dipole MBIV1021 after the first OTR. Further inclusion of the SPS OTR would also bring in the family of horizontal dipoles at the SPS injection as momentum-related signal enhancers.

5.3 Current Status of the Technique and Experiments Performed

The current state of the technique can be summarised in the following.

- Procedure for extracting the correlations <**XX**>, <**XY**>, and <**YY**> from the OTR's is well established. At an early point the use of the gaussian-fitted projected profiles was abandoned in favour of the current method, which directly calculates the correlations from the pixel population. The latter method has been shown to generate much more robust and physically meaningful results[5].
- Also it was realised early that optics other than the standard one in TT10 may be needed to provide extra redundancy needed to override isolated non-physical OTR correlations, to enhance orthogonality, and to boost the signal levels of certain covariance matrix elements. In each experiment three different optical settings were downloaded in turn, each followed by a session of OTR data-taking. This proved to have achieved the above objectives.
- A complete analysis package is developed. This package takes in the optical configuration(s), constructs the numerical fitting system, and performs the fitting based on input OTR correlations. All 4 fitting options discussed in section 5.1 can be invoked. In the case of more than 4 OTR's, it can alternatively fit on input from different subsets of the entire OTR ensemble. This program also performs a certain degree of check on the internal consistency of the raw OTR input.
- A separate program was developed to search for point source of coupling in the transfer line based on

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[3] This does not include momentum-related degrees of freedom.

[4] For example, placing OTR's at 4 successive alternating quadrupoles would result in degeneracy in the coupled block of the covariance matrix.

[5] For example the consistency conditions for the <u>fitted</u> correlations

$$\left.\begin{array}{c} -1 \le \langle AB \rangle \big/ \sqrt{\langle AA \rangle \langle BB \rangle} \le 1 \\ \langle AA \rangle > 0 \end{array}\right\} \quad A,B = X_\beta, X'_\beta, Y_\beta, Y'_\beta.$$

are much more readily satisfied using the current method.

fitted OTR profile and in-plane model optics. This will be elaborated in detail in a later section.

- It became clear, as the experiments progressed, that model verification across the OTR region is of critical importance. A positively confirmed model usually leads to highly trustable and robust outcome, while ambiguity may arise when there is insufficient data to support the assumed model. This may hardly be surprising, but the degree to which the success of the beam profile measurement depends on careful verification of the model is certainly an important lesson learned through these tests.
- The SPS OTR appears to be a reliable addition to the TT10 OTR collection. It also appears consistent in the sense that its inclusion or exclusion in the fitting does not drastically alter the characteristic of the fit. Its main value may eventually lie in providing extra momentum-related signal.

Major experiments performed in 2000 are listed in Table 2 with relevant parameters. On November 1st PS beam at 20 GeV was used as opposed to the 26 GeV beam. The resulting beam profile was different. On November 2nd the SPS OTR was included in the measurement for the first time.

Table 2. OTR Experiments in 2000

Date	Energy (GeV)	No. of Optics	No. of OTR's	Data per set	No. of sets
0910	26	3	4	36	3
0111	20	3	4	36	3
0211	26	3	5	45	5

5.4 Results of Measurements and Analyses

The outcome of the three beam profile measurements performed in 2000 will be summarised in the following.

October 9th Measurement

The beam profile measurement performed on October 9th generated by far the most robust and physically meaningful result. Table 3 shows a typical data set analysed, with resulting normalised[6] beam covariance matrices shown, under the 4 fitting options described earlier. A few observations can be readily made:

- A nontrivial amount of XY-coupling in the beam can be seen in all cases.
- The momentum spread obtained from the 11-parameter fit is about a factor of 2 off the PS-quoted value. This is not considered a gross discrepancy,

[6] This means that in the diagonal are displayed the σ's of X, X', Y, Y', and dP in units of m, radian or unity, while in the off-diagonal are displayed the normalised cross-correlations, which can be between –1 and +1.

Table 3. Normalised Covariance Matrix (09/10) from Various Fitting Modes

Assuming no intrinsic betatron-dP correlation

(A). Fit including σ^p (11-parameter)

X	X'	Y	Y'	dP	
0.002	-0.846	0.459	0.265		X
	0.0001	-0.292	-0.057		X'
		0.0006	0.843		Y
			0.00005		Y'
				0.00006	dP

(B). Fit with imposed σ^p =0.00015 (10-parameter)

X	X'	Y	Y'	dP	
0.002	-0.842	0.454	0.255		X
	0.0001	-0.264	-0.041		X'
		0.0006	0.889		Y
			0.00005		Y'
					dP

Assuming intrinsic betatron-dP correlation

(C). Fit including σ^p (15-parameter)

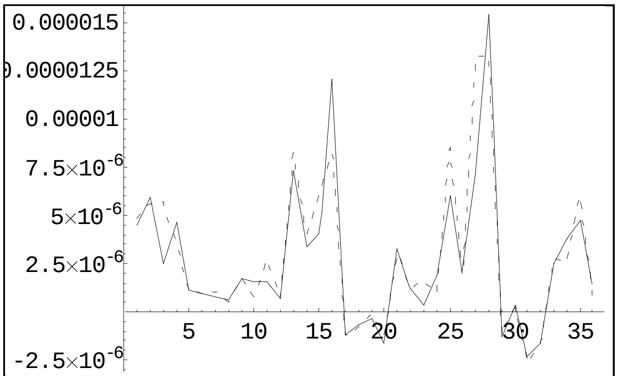
X	X'	Y	Y'	dP	
0.002	-0.843	0.444	0.264	0.040	X
	0.0001	-0.310	-0.056	-0.091	X'
		0.0007	0.805	0.416	Y
			0.00005	0.070	Y'
				0.0002	dP

(D). Fit with imposed σ^p =0.00015 (14-parameter)

X	X'	Y	Y'	dP	
0.002	-0.838	0.417	0.275	-0.088	X
	0.0001	-0.285	-0.067	0.031	X'
		0.0007	0.817	0.439	Y
			0.00005	0.156	Y'
					dP

especially considering the fact that in obtaining the PS momentum spread a certain bunch shape was assumed, whereas in the OTR-based fitting no bunch shape was assumed.

- The fitted momentum spread becomes even closer to the PS value when the fit is further relaxed to allow for intrinsic betatron-momentum correlation (or uncertainty in measured dispersion), at the expense of a nontrivial correlation between Y and dP.
- The fit quality is quite good in all cases, as can be seen in Fig. 6, where the 36 measured OTR correlations are compared against the fitted, or model interpreted, values. Reproduction of measurement is especially good at the <**XY**> components, important for resolving coupled degrees of freedom.



order along horizontal axis:
<**XX**> for 4 OTR's, <**XY**> for 4 OTR's, <**YY**> for 4 OTR's, repeated for 3 optics

Figure 6. Measured (dashed) vs Fitted (solid) correlations in m^2

- The data displays a high degree of reproducibility and robustness to different fitting modes.

The last point above is demonstrated in Table 4, listing the twiss parameters of the beam derived from 3 sets of data, each analysed by 4 different modes of fitting described in section 5.1 and Table 3. Failure for the data to reproduce or sensitivity to fitting mode would cause each column of 12 twiss parameters to fluctuate substantially. This is not the case. If one takes an "average" of each column and compares them with the model twiss parameters, a qualitative agreement with the model, although not exact match in any sense, can be seen. Note that this measurement was performed on the beam under the matching based on previous year's beam measurement, which was done using completely different assumptions and technique, e.g., using gaussian-fitted projection instead of true correlations. These numbers can be translated into mismatch factors[2], also given in Table 4, together with their counterparts from 1999 taken after an optical re-matching.

Also shown in Table 4 is the "measure of coupling", denoted ρ, whose definition as given in Table 4 roughly measures the increase in combined XY-phase space volume occupied by the beam due to XY-coupling. Thus it can be taken as a measure for emittance growth in the 4-dimensional phase space. It is seen that the measured twiss parameters correspond to an increase by 10% in this combined emittance.

November 1st Measurement

On November 1st measurement was performed on PS beam at 20 GeV, which displayed different characteristics from the previous case. Notable facts about this measurement are:

- Data analysis again exhibited general insensitivity to mode of fitting, especially for un-coupled σ-matrix elements.
- Coupling became smaller (normalised elements ≤

Table 4. Twiss Parameters from Oct. 09 Analysis: Emittance ε (mm-mrad), β (m), α and coupling measure ρ

$$\rho = \left[Det\left(M_x\right) \cdot Det\left(M_y\right) / Det\left(M_{4D}\right) \right]^{1/4}$$

Twiss at BEGTT10	ε_x	β_x	α_x	ε_y	β_y	α_y	ρ
11-Param. (A)	0.111	39.399	1.587	0.018	21.951	-1.565	1.115
	0.109	41.741	1.607	0.017	21.304	-1.396	1.089
	0.113	39.750	1.559	0.021	23.171	-1.466	1.102
10-Param. (B)	0.109	39.099	1.564	0.014	23.808	-1.938	1.135
	0.107	41.540	1.589	0.015	21.904	-1.600	1.093
	0.112	39.478	1.536	0.017	24.027	-1.687	1.108
15-Param. (C)	0.110	38.694	1.565	0.022	21.799	-1.359	1.107
	0.112	42.449	1.660	0.020	21.516	-1.268	1.113
	0.116	39.865	1.589	0.024	23.432	-1.310	1.121
14-Param. (D)	0.109	38.333	1.539	0.022	22.921	-1.417	1.093
	0.111	42.166	1.638	0.020	22.666	-1.327	1.099
	0.114	39.381	1.553	0.024	25.101	-1.398	1.101
Average Twiss	**0.111**	**40.158**	**1.583**	**0.020**	**22.800**	**-1.478**	**1.106**
Model Twiss		**31.378**	**0.739**		**18.719**	**-0.879**	**1.000**
Mismatch Factors							
Filamentation		**1.189**			**1.087**		
Geometrical		1.833			1.515		
From 1999							
Filamentation		1.03			1.0		
Geometrical		1.3			1.0		

0.1), and thus were more sensitive to mode of fitting.
- Fitted momentum spread is within 30% of PS provided value.

Table 5 shows one set of data subjected to the 10 and 11-parameter fits, illustrating the points above. A few issues requiring further investigation surfaced during data analysis. These are:

- The 15-parameter fit resulted in un-physical momentum spread, possibly reflecting reduced data redundancy when significantly more free parameters were added but not counteracted by constraints from additional OTR's. However, dispersion data taken in conjunction with the OTR measurement failed to fit to the model optics, indicating possible uncertainty about the model during the measurement[7]. The model correctness in the OTR region is not demonstrable at this point.
- Nonetheless, the un-coupled elements from the 15-parameter fit were still close to those from 11 or 10-parameter fits.
- Taking 15-parameter fit at face value, again it suggested nontrivial <**YdP**> correlation.

<u>November 2nd Measurement</u>

The November 2nd measurement was unique in its inclusion of the SPS OTR, for enhanced redundancy, signal-to-noise ratio, and momentum signal. Notably:

- Analyses using <u>all 5, the first 4, or the last 4 OTR's</u> in all fitting modes showed that, although appearing to exert more "pull" in the fit for momentum signals, the SPS OTR showed no major inconsistency with the TT10 OTR's. Namely, the fit was not drastically altered with its inclusion or exclusion.
- However, relative insensitivity to choice of OTR's was achieved only through 15-parameter fits, indicating potential non-trivial betatron-momentum correlation or errors in the assumed dispersion.
- Non-trivial coupling was observed again.

The result of one relatively stable 15-parameter fit is given in Table 6. Some issues surfaced during data analysis:

- More sensitivity to mode of fitting or OTR combination was seen, especially in all off-diagonal elements, sometimes leading to un-physical results.
- As mentioned above, there was strong indication that the assumption of zero betatron-momentum correlation was not valid.
- The fitted momentum spread appeared to be at least twice as large as measured in the PS.
- Most fitted σ-matrix elements were different from October 9th.
- The beam itself was very different from October 9th, as can be discerned directly from the OTR image. Indeed the profile-fitting program in TT2 performed on the same beam on November 2nd using sem-wires also failed in the Y-plane.

In this case, the measured beam profiles, apparently deviating from the nominal, and the assumed transfer properties in TT2-TT10 constituted an inconsistency that was correctly reflected in the unstable analysis result observed. A useful lesson learned here is that, although the method appears capable of interpreting the measurement with the model even in this case, it can also signal inconsistency in the input when the analysis

Table 5. Normalised Covariance Matrix (01/11) from Various Fitting Modes

<u>Assuming no intrinsic betatron-dP correlation</u>

(A). Fit including σ^p (11-parameter)

X	X'	Y	Y'	dP	
0.002	-0.866	-0.108	-0.028		X
	0.0001	0.125	0.030		X'
		0.0008	0.543		Y
			0.00008		Y'
				0.00033	dP

(B). Fit with imposed σ^p =0.00025 (10-parameter)

X	X'	Y	Y'	dP	
0.002	-0.874	-0.0089	-0.0001		X
	0.0001	0.018	-0.0008		X'
		0.0009	0.526		Y
			0.00008		Y'
					dP

Table 6. Normalised Covariance Matrix (02/11) from 15-Parameter Fit Using 5 OTR's (PS-derived momentum spread=0.0002)

<u>Assuming intrinsic betatron-dP correlation</u>

(C). Fit including σ^p (15-parameter)

X	X'	Y	Y'	dP	
0.0033	-0.919	0.238	0.477	0.233	X
	0.00017	-0.191	-0.435	-0.048	X'
		0.00153	0.805	0.229	Y
			0.00008	0.849	Y'
				0.00034	dP

[7] The automated BPM acquisition was unavailable on November 1st. As a result the dispersion data had to be extracted from OTR records, with much lower orbit resolution and data redundancy.

becomes overly mode-dependent. The coincident failures in both the TT2 and the TT10 programs to arrive at an unambiguous answer demonstrate this point. When this happens, necessary steps need to be taken to ensure that the correct information is obtained on both the beam and the transfer properties. In this regard, model accuracy, data accuracy, and conditioning of the fitting system are of central importance to the success of the method. This will be the focus of the next step for improvement.

5.5 Planned Improvement on the Algorithm

A few tasks are being carried out to improve the current algorithm or better understand its limitations. These include:

- "Principal Axes" based data extraction from the OTR: This efficient algorithm defines a cut-off boundary more naturally conforming to the beam distribution than rectangular boxes, therefore better interpreting the tilt in the beam profile. This can be crucial in analysing coupling. Application of this algorithm on real OTR data is illustrated in Fig. 7, where the elliptical boundaries (in black) are derived from pixel population without resorting to gaussian fits. Cut-off thus defined changes both the **<YY>** and the normalised **<XY>** correlations by 14% from rectangular cut-off for the case shown. The difference should be even more pronounced for more tilted beam.
- Better handle on errors in OTR correlations: In order to interpret, or to use with confidence, the outcome of this measurement, we need information on the errors on individual fitted quantities, as well as their covariance. An effort is being launched to start the error analysis from the OTR level, eventually leading to quotable errors on the fitted quantities.
- Making sure that no more information than is sustainable by the system configuration and error magnitude is being drawn out of the analysis. For this purpose condition analysis of the fitting system taken one step further than described in section 5.2 is needed. Questions such as relative sensitivity of fitted quantities to input, and near singular combinations of parameters will be studied.

The last two tasks will provide a clear picture of the reliability of the analysis, their impact on other applications such as matching, and guidance for possible improvement on configuration or alternative optics.

6 TRANSFER MATRIX AND PROFILE COMPARISON

With the results obtained from the difference orbit measurement, one can construct an empirical transfer

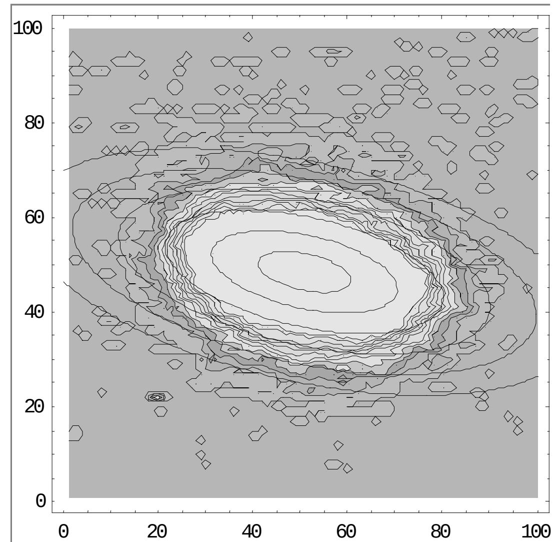


Figure 7. Noise Cut-off Based on Principal Axes of Raw Beam Distribution

matrix from the beginning of TT2 to the OTR region where the coupling is observed. The main purpose for this is to narrow in on the cause of coupling in the beam. The outcome also serves as a useful cross-comparison with the profile measurements in TT2 using sem-wires. In the absence of BPM's at the beginning of TT2, a more rigorous derivation of the empirical transfer matrix was difficult. An approximated transfer matrix was obtained by first back-propagating the fitted trajectories due to TT2 corrector kicks back to the beginning of TT2 using model optics, then calculating the off-diagonal components of the transfer matrix using the back-propagated trajectories and the cross-plane orbits recorded in the TT10 BPM's. As a result we obtain a transfer matrix across the major span of TT2-TT10. Its on-diagonal components are those of the model, since we are confident of its correctness as discussed in section 4, while its off-diagonal components are empirical. The latter contain the relevant information for unfolding the beam coupling. This transfer matrix was then connected to various sem-wires through transfer over short distances so that the beam covariance matrix measured on October 9th can be transported to these locations.

Table 6(a). Comparison between MSG-derived σ's and those back-propagated from TT10 OTR

Oct. 09	σ_x (mm)		σ_y (mm)	
	Meas.	Prop.	Meas.	Prop.
MSG257	1.34	1.01	1.03	0.91
MSG267	1.29	1.34	0.84	0.83
MSG277	1.87	1.75	0.91	0.62

Table 6(b). Comparison between MSG and OTR - derived ε's (mm-mrad)

Oct. 09		MSG	OTR fit (11 parm.)
	X	0.141	0.111 (0.107 - 0.116)
	Y	0.028	0.020 (0.014 - 0.024)

Table 6(a) shows the comparison between the profiles directly calculated from the sem-wire measurements and those back-propagated from TT10. Both cases include the momentum contribution. A reasonable agreement can be demonstrated with a few exceptions. The back-propagated σ's are smaller than the direct measurements in most cases. One should however keep in mind that for the TT2 sem-wire calculations the gaussian-fitted projections were used, as opposed to direct 2D correlations used to obtain the back-propagated σ's.

Table 6(b) shows the same comparison for the calculated emittances. For the OTR-derived numbers the averages over the 12 fitting results of Table 4, as well as their ranges are given. Again very different techniques used in obtaining the twiss parameters should not be neglected in accounting for the difference. Another factor to consider is the fact that the transfer matrix as constructed, although close, is not strictly symplectic due to the small off-diagonal elements.

When the OTR-derived 4 × 4 beam covariance matrix is back-propagated by the empirical transfer matrix, the nontrivial off-diagonal elements persist to the sem-wires at the beginning of TT2, as shown in Table 7. This suggests likely attribution of the coupling in the beam to sources upstream of TT2.

Table 7. Back-Propagated Covariance Matrices at MSG

X	X'	Y	Y'	dP	
0.0010	-0.600	-0.194	-0.276		X
	0.00013	0.400	0.390		X'
		0.0009	0.924		Y
			0.00005		Y'
MSG257					dP

X	X'	Y	Y'	dP	
0.0013	-0.161	0.197	-0.003		X
	0.00008	0.290	0.310		X'
		0.0008	0.834		Y
			0.00004		Y'
MSG267					dP

X	X'	Y	Y'	dP	
0.0017	-0.833	0.069	-0.247		X
	0.00011	0.098	0.324		X'
		0.00062	0.675		Y
			0.00004		Y'
MSG277					dP

7 SEARCH FOR POINT SOURCE OF COUPLING

Considerable effort has been devoted to the search for possible point source of coupling in the TT2-TT10 line that may explain part of the observed beam coupling. Apart from the effort using difference orbit data described in section 4, methods were also developed taking advantage of the multitude of beam covariance matrix data generated by the OTR measurements. The efforts involved fall under two groups of closely-related methods, to be described below.

7.1 Signal for Onset of Coupling

If the back-propagated beam covariance is tabulated by element index, and there exists a thin skew-quadrupole type element **E** responsible for most of the observed coupling, then the following functions of the back-propagated beam covariance elements should go very close to zero on both sides of **E**[8]:

$$\frac{\sigma_{23}}{\sigma_{14}} - \frac{\sigma_{33}}{\sigma_{11}} = 0$$

$$\frac{-\sigma_{12}\sigma_{23} + \sigma_{24}\sigma_{33} - \sigma_{23}\sigma_{34}}{\sigma_{33}} = 0$$

$$\frac{-\sigma_{12}\sigma_{14} + \sigma_{24}\sigma_{11} - \sigma_{14}\sigma_{34}}{\sigma_{11}} = 0$$

$$\frac{\sigma_{13}^2}{\sigma_{11}\sigma_{33}} = 0$$

Thus by observing 2 contiguous near-zero-crossing of the above parameters when back-propagated, one can hope to identify predominant point source of coupling, e.g., grossly rotated quadrupole, if it exists. OTR-derived covariance matrices from all measurements have been used in such a search, with some potential offenders entered into the suspect list. These were subjected to a more definitive test to be described in the following sub-section.

7.2 Solving for Coupling Strength

To first order across the point coupling source, the off-diagonal part of the σ-matrix transforms as

$$\begin{pmatrix} \sigma_{13} & \sigma_{14} \\ \sigma_{23} & \sigma_{24} \end{pmatrix} \rightarrow \begin{pmatrix} \sigma_{13} & \sigma_{14} + \sigma_{11} t \\ \sigma_{23} + \sigma_{33} t & \sigma_{24} + \sigma_{12} t + \sigma_{34} t \end{pmatrix}$$
$$= \begin{pmatrix} \sigma_{13} & \sigma_{14} \\ \sigma_{23} & \sigma_{24} \end{pmatrix} + \begin{pmatrix} 0 & \sigma_{11} \\ \sigma_{33} & \sigma_{12} + \sigma_{34} \end{pmatrix} \cdot t$$

where ***t*** is the skew quadrupole strength. If one constructs the vectors

$$v_C = \begin{pmatrix} \sigma_{23} & \sigma_{14} & \sigma_{24} & \sigma_{13} \end{pmatrix}$$
$$m_C = \begin{pmatrix} \sigma_{33} & \sigma_{11} & \sigma_{12} + \sigma_{34} & 0 \end{pmatrix}$$
$$v_C = m_C \cdot t$$

[8] These parameters are properly scaled to avoid confusion over near-zero-crossing due to varying betatron functions.

then $\boldsymbol{t}$ can be solved in a least square sense. The degree of degeneracy of the 2 × 4 matrix composed of $M_C = (v_C, m_C)$ will give a measure of how likely the observed XY-coupling comes from a point source with one single degree of freedom $\boldsymbol{t}$.

The degree of degeneracy of M_C can be measured either by the smallest singular value of M_C or by calculating the normalized inner product between the two components of M_C. In either case proper scaling between the 4 components is important due to normalisation. This can be done through row-wise scaling either by beta functions or by beam correlation:

$$\bar{M}_C = \begin{pmatrix} \frac{\sigma_{33}}{\sqrt{\beta_y\gamma_x}} & \frac{\sigma_{23}}{\sqrt{\beta_y\gamma_x}} \\ \frac{\sigma_{11}}{\sqrt{\beta_x\gamma_y}} & \frac{\sigma_{14}}{\sqrt{\beta_x\gamma_y}} \\ \frac{\sigma_{12}+\sigma_{34}}{\sqrt{\gamma_y\gamma_x}} & \frac{\sigma_{24}}{\sqrt{\gamma_y\gamma_x}} \\ 0 & \frac{\sigma_{13}}{\sqrt{\beta_y\beta_x}} \end{pmatrix}, \begin{pmatrix} \frac{\sigma_{33}}{\sqrt{\sigma_{22}\sigma_{33}}} & \frac{\sigma_{23}}{\sqrt{\sigma_{22}\sigma_{33}}} \\ \frac{\sigma_{11}}{\sqrt{\sigma_{11}\sigma_{44}}} & \frac{\sigma_{14}}{\sqrt{\sigma_{11}\sigma_{44}}} \\ \frac{\sigma_{12}+\sigma_{34}}{\sqrt{\sigma_{22}\sigma_{44}}} & \frac{\sigma_{24}}{\sqrt{\sigma_{22}\sigma_{44}}} \\ 0 & \frac{\sigma_{13}}{\sqrt{\sigma_{11}\sigma_{33}}} \end{pmatrix}$$

Once $\boldsymbol{t}$ is solved for, its inverse is actually incorporated into the back-propagation of the covariance matrix. If this corresponds to the coupling predominantly responsible for the beam coupling, then a drastic reduction in the off-diagonal elements should be seen upstream of this point. The suspects identified in the previous sub-section were put through this test. Unfortunately, mainly because σ_{13} is never sufficiently close to zero at any location, none of the suspects could be unambiguously convicted as the culprit for beam coupling.

Based on the studies described in sections 4, 6, and the current section, it can be preliminarily concluded that no compelling evidence exists for point source of coupling in TT2-TT10 predominantly responsible for the observed coupling in the beam[9].

[9] In practice one has to assume that the entire region where optics is varied has the correct model because the OTR fit point has to be outside this region, thus the search for coupling source can only be conducted upstream of this region (Fig. 1). The fact that entire quadrupole strings have to be varied to change the optics therefore puts a limit on the allowed search range. One can however be reasonably convinced that cross-plane coupling was already unambiguously seen at the first few BPM's in TT10 (Fig. 3), not far from the OTR fit point. The back-propagated difference orbits in the cross plane on the other hand could not be entirely relied on to pinpoint a coupling source due to their very low signal level and poor fit to the model. Strictly speaking, this leaves an un-searched gap between QID1001 and BPCK1004 encompassing a number of magnetic elements, which can hopefully be bridged if the quadrupoles in the strings can be varied independently to reduce the span of optics change.

8 FUTURE DIRECTIONS

It is useful to identify areas where future efforts should be directed. These will be classified below by the nature of work involved.

8.1 Procedure

- Streamlined dispersion measurement: This would make model checking more efficient, and operation crew and experimenter more encouraged to use it as a routine tool.
- Procedure for using OTR profiles for matching verification: Once an optical matching is achieved, an efficient OTR-based procedure should be in place for routine verification of the established matching condition.
- Standardised beam profile measurement procedure: The OTR based beam profile measurement needs to be refined and optimised before becoming an integral part of the machine set-up procedure. Reconciliation with MSG-based results should be achieved.
- Matching: With the presence of dispersion almost across the entire TT2-TT10 line, exact matching of twiss parameters and dispersion simultaneously is extremely challenging, if not impossible. Approximate solutions taking advantage of local optical features is being studied.

8.2 Algorithm and Data Analysis

- Rigorous transfer matrix from TT2 to TT10: This is currently under progress. The outlook is greatly improved by possible installation of BPM's in the TT2 line.
- Beam profile measurement: As already outlined in section 5.5, this will include
  - Extracting OTR correlation based on principal axes of raw data,
  - Better evaluation of errors from OTR correlations and their impact,
  - Condition analysis of the fitting system to understand sensitivity and parameter dependence.

  These are all under progress with preliminary results, some of which may lead to improved OTR configuration or alternative optics used in beam profile measurement.

8.3 Configuration

- OTR configuration: Monitoring true 2D beam characteristic becomes possible with the proposal of installing an extra OTR in TT2. This may also trigger procedural improvement in beam profile measurement across the entire TT2-TT10 region.
- BPM in TT2: Proposed installation of BPM's in the TT2 line would bring about more efficient

operation, and more efficient and rigorous model checking including transfer matrix measurement.

- Independent quadrupole control in TT10: The scheme of using trim power supplies to independently control TT10 quadrupoles currently running off a string is being studied. Possible advantages include the flexibility of supporting more effective matching schemes, and ability to invoke alternative optics over a much shorter range of beam line for profile measurement, so that it is less invasive, and search for anomaly can be extended over a larger section of TT10.

8.4 Machine Studies

Machine studies with well aimed objectives to resolve issues arising from off-line analysis and to demonstrate viability of improvements in procedure and configuration are a natural part in the continuing effort to achieve complete control of the beam transport from the PS to the SPS.

9 CONCLUSION

In this report the current status of the ongoing program to achieve understanding and control of the TT2-TT10 transport and beam characteristics is summarised. New experiments performed in 2000 indicated the following facts:

Transport

- Dispersion matching implemented in 2000 proved to be effective.
- TT2-TT10 optics model was unambiguously confirmed with difference orbits.
- Slight but unmistakable coupling is present in TT2-TT10 transport, so far not attributable to stray field region at the beginning of TT2.
- Point source cannot be identified in TT2-TT10 for observed coupling.

Beam Profile

- Technique for 5D beam σ-matrix determination was developed.
- OTR's in TT10 and SPS were used in machine studies under this scheme.
- Proof-of-principle test (Oct. 09) demonstrated viability of the method in hardware, procedure and algorithm, and produced useful information on beam characteristics.
- Subsequent tests (Nov. 01 & 02) with extended features provided further data points and insight into beam property, in the mean time revealing potential pitfalls. These will be the focus of efforts on improvement.
- Coupling in beam was observed at 26 GeV, which appeared reduced at 20 GeV. Emittance dilution factor due to coupling is about 1.1 for the 26 GeV beam.
- Nontrivial intrinsic **<YdP>** correlation is suspected in some cases.

Comparison between the Model and Measurements in TT2 & TT10

- OTR-derived Twiss parameters (Oct. 09) were close to design, but not perfect. Emittance dilution factor due to betatron mismatch, before further matching effort, was close to 1.
- Projected beam RMS values largely agree between TT2 & TT10. OTR-derived emittances are smaller. Error estimates and reconciling difference in techniques are needed.
- Observed beam coupling currently cannot be attributed to coupling in TT2-TT10 transport line, but likely come from upstream.

These have pointed to the following directions for future improvements.

Future Directions

- New or improved procedures for more effective optics related operation are under study.
- Improvements on measurement and analysis techniques are in progress.
- Effective procedures for matching and profile verification are under evaluation.
- Evaluation of configuration enhancement and modification, including OTR's, BPM's and independent quadrupole control, are in progress.

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