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OPTICS MEASUREMENTS AND MATCHING OF TT2-TT10 LINE FOR INJECTION OF THE LHC BEAM IN THE SPS

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A well matched injection in the SPS is very important for preserving the emittance of the LHC beam. The paper presents the algorithms used for the analysis and the results of the optics measurements done in the transfer line TT2-TT10 and in the SPS. The dispersion is computed by varying the beam momentum and recording the offsets at the BPMs, while the Twiss parameters and emittance measurements in TT2-TT10 are performed with beam profile monitors equipped with OTR screens. These results are completed by those obtained with a matching monitor installed in the SPS as a prototype for the LHC. This device makes use of an OTR screen and a fast acquisition system, to get the turn by turn beam profiles right at injection in the ring, from which the beam mismatch is computed and compared with the results obtained in the line. Finally, on the basis of such measurements, a betatron and dispersion matching of TT2-TT10 for injection in the SPS has been performed and successfully put in operation.

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A well matched injection in the SPS is very important for preserving the emittance of the LHC beam. The paper presents the algorithms used for the analysis and the results of the optics measurements done in the transfer line TT2-TT10 and in the SPS. The dispersion is computed by varying the beam momentum and recording the offsets at the BPMs, while the Twiss parameters and emittance measurements in TT2-TT10 are performed with beam profile monitors equipped with OTR screens. These results are completed by those obtained with a matching monitor installed in the SPS as a prototype for the LHC. This device makes use of an OTR screen and a fast acquisition system, to get the turn by turn beam profiles right at injection in the ring, from which the beam mismatch is computed and compared with the results obtained in the line. Finally, on the basis of such measurements, a betatron and dispersion matching of TT2-TT10 for injection in the SPS has been performed and successfully put in operation.

INTRODUCTION

After the changes in the PS extraction due to the removal of the quadrupole doublet QKE58 [1], a re-matching campaign of the TT2-TT10 line has been done in 2007 for proton beams at 26 GeV. The new optics, which is operational since the 17th October'07, has been computed based on the measurements of dispersion and Twiss parameters performed on the 31st of July, using 1-4 bunches with nominal LHC parameters.

DISPERSION MEASUREMENTS

The dispersion measurements have been done by recording the transverse beam position at the pick-ups in TT2-TT10 and in SPS (first turn) via the *Passerelle*, a tool which provides access to PS and SPS equipments from Windows platform. The *Excel application* described in [2] has been used as a starting point to fit the dispersion and its derivative at the beginning of the line and in a second step it has been improved to take into account different calibration factors for the different kind of monitors [3]. The beam momentum has been varied by a few per-mill around its nominal value and the momentum offset $(\Delta p/p)$ computed by first turn measurements. The dispersion at every BPM is obtained by a linear fit applied to the beam displacement as a function of the $(\Delta p/p)$ and then a fit is applied to obtain the values at the beginning of TT2.

In the original version of the *Excel application*, the function to be minimized with respect to $(\bar{D}_0, \bar{D}'_0, \alpha)$ was:

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{D_i - (C_i \bar{D}_0 + S_i \bar{D}'_0 + \alpha \tilde{D}_i)}{\sigma_i} \right)^2 \qquad (1)$$

where C_i and S_i are the cos-like and sin-like function, $\tilde{D}_i$ is the dispersion for zero initial conditions, α is a fit parameter for calibration errors in the momentum offset, $\bar{D}_0 = D_0\alpha$ and $\bar{D}'_0 = D'_0\alpha$ are the measured initial conditions, scaled by α.

The application has been modified [4] to take into account the possibility to have different calibration errors b_k for the different kind of monitors (k = TT2,TT10,SPS BPMs, BTVs,...), so that the χ^2 function will be:

$$\chi^2 = \sum_{i=1}^{N} \frac{1}{\sigma_i^2} \left[\sum_k b_k \delta_{k,m_i} D_i - (C_i D_0 + S_i D'_0 + \tilde{D}_i) \right]^2 \qquad (2)$$

where m_i is the type of monitor installed in the i-th measurement point and δ_{k,m_i} is equal to 1 if $k = m_i$ and 0 otherwise. In Fig. 1 are shown the measured dispersion. A very large horizontal mismatch was found, between the measurements and the preliminary optics which have been loaded at the end of 2006 run. Table 1 shows the results in terms of dispersion and its derivative at the entry of TT2.

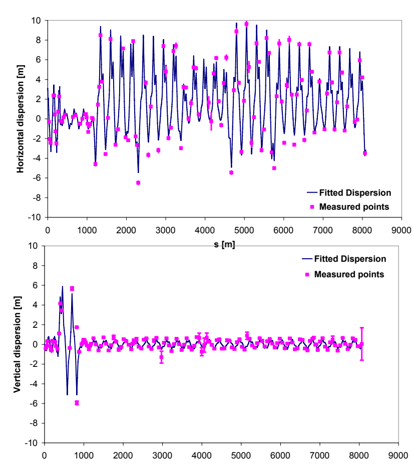

Figure 1: Horizontal and vertical dispersion measurements

Table 1: Results of dispersion measurements, in parenthesis the values measured in Nov'06 and assumed for a preliminary matching. The statistical error associated with the fitted measurements is $\sim 0.2\%$

	Horizontal	Vertical
D_0	3.04m *(3.913m)*	0.024m *(0.084m)*
D'_0	0.25 *(0.38)*	-0.014 *(-0.018)*

TWISS PARAMETERS MEASUREMENTS

To compute the beam emittance and the Twiss parameters at the beginning of the line, beam profiles measurements are taken at the SEM-wires in TT2 and in TT10 and at the BTVs equipped with OTR screens (F16.MTV201, BTV1018, BTV1024, BTV1025, BTV1026). For the BTVs, the horizontal and vertical beam sizes are calculated by applying a bi-Gaussian fit to the 2D profiles, after the correction for image distortion due to the fact that the screens are placed at 45^o with respect to the beam [5].

The standard approach of the 3-monitor method is extended to N profiles, using a least-square fit, assuming no coupling and that optics, momentum spread $\delta = dp/p$ and dispersion D_i at the monitor location are known. The function to be minimized is:

$$\chi^2 = \sum_{i=1}^{monitors} \left(\frac{\sigma^2_{\beta,i} - \varepsilon(C_i^2\beta_0 - 2C_iS_i\alpha_0 + S_i^2\gamma_0)}{\Delta_i} \right)^2 \tag{3}$$

with respect to the Twiss parameters at the beginning of the line multiplied by the emittance ($\varepsilon\beta_0$, $\varepsilon\alpha_0$, $\varepsilon\gamma_0$). C_i and S_i are the cos– and sin–like functions $\sigma^2_{\beta,i}$ is the squared betatron beam size $\sigma^2_{\beta,i} = \sigma_i^2 - D_i^2\delta^2$ where σ_i is the r.m.s. measured beam size and Δ_i is the error associated to $\sigma^2_{\beta,i}$.

Multiple Coulomb Scattering at the Screens

At 26GeV, in case all the OTRs are inside the beam, the blow-up due to Coulomb scattering at the screens is important and has to be taken into account. With the assumption of a thin screen, the contribution due to the scattering adds quadratically to the beam size, and it is still possible to use Eq. 3, by replacing $\sigma^2_{\beta,i}$ with [4]:

$$\tilde{\sigma}^2_{\beta,i} = \sigma^2_{meas,i} - D_i^2 \left(\frac{dp}{p}\right)^2 - \sum_{k=1}^{i-1} S^2_{ki} \left\langle \theta^2 \right\rangle_k \tag{4}$$

being S_{ki} the sin–like function from the k-th to the i-th monitor. The r.m.s. scattering angle is [6]:

$$\sqrt{\langle\theta^2\rangle} = 2.557\ \chi_{cc} \frac{\sqrt{t[cm]}}{E[GeV]\beta^2_{rel}} \tag{5}$$

with $\chi^2_{cc} \approx (0.39612 \times 10^{-3})^2 Z_s \frac{\rho}{W} \left[GeV^2cm^{-1}\right]$ It depends on the energy of the incident protons E, the screen thickness t and the other properties of the scattering material through the parameter χ^2_{cc}, where ρ is the material density, $W = \sum_{i=1}^{N} n_iA_i$ is the molecular weight and Z_s is defined as $Z_s = \sum_{i=1}^{N} n_iZ_i(Z_i + 1)$ being n_i the number of moles of element i in a mole of material and Z_i the atomic number.

For F16.MTV.201, equipped with a $12\mu m$ thick Ti screen, $\sqrt{\langle\theta^2\rangle}$ is $9.31\ 10^{-6}$, while for the TT10 screens, made of $25\mu m$ thick Aluminized Mylar, it is $4.57\ 10^{-6}$.

For these measurements, the beam was extracted from the PS without the bunch rotation (usually performed to shorten its bunch length) to have a low $dp/p = 2.8e-4$. Table 2 and Figure 2 show the results. The mismatch factor H, defined as:

$$H = \frac{1}{2}\left[\frac{\beta_0}{\overline{\beta}} + \left(\alpha_0 - \alpha_m\frac{\beta_0}{\overline{\beta}}\right)^2\frac{\overline{\beta}}{\beta_0} + \frac{\overline{\beta}}{\beta_0}\right] \tag{6}$$

is below 1.01. Neglecting the scattering at the screens introduces an error in the beam emittance of $\Delta\varepsilon_C \sim 6\%$ in the horizontal plane.

Table 2: Twiss parameters at the beginning of TT2.

	Horizontal	Vertical
β	26.14 m	10.88 m
α	-2.23	0.76
ε^*	1.11 μm	1.11 μm
H	1.004	1.01
$\Delta\varepsilon_C$	6%	2%

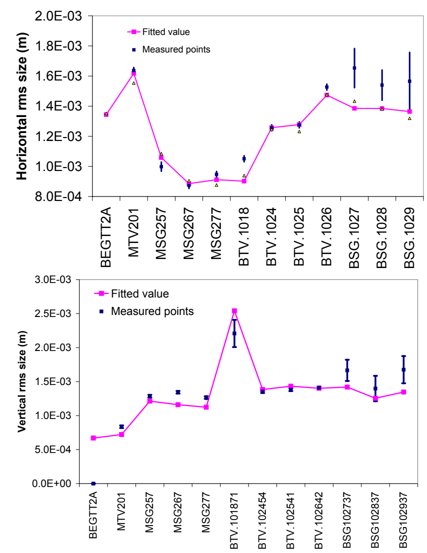

Figure 2: Horizontal and vertical beam size at the monitors

SPS MATCHING MONITOR

The matching at injection in the SPS has been checked also during a dedicated measurement period by means of a matching monitor installed in the SPS, similar to the one that will be installed in the LHC. The system consists of an OTR screen (20μm thick, Aluminized Mylar) intercepting the beam together with an acquisition apparatus that captures, through an optical system, an image of the screen every turn for approximately 3ms. To acquire these set of images, a fast acquisition CCD camera is used. The camera is synchronized externally by means of the beam synchronous timing system (BST) ad the acquired images are read through an Ethernet link. The camera and the timing electronics controls as well as data read outs are handled through a FESA server running continuously on a LynuxOS power PC. Each time the beam is injected, an acquisition of a few hundred images is performed and a notification sent for application clients to retrieve and display the acquired data. This is not a tool used in operation, as it will be planned for the LHC, since the camera is not shielded from radiations and therefore needs to be installed and then removed. Unfortunately there were problems with the camera, resulting in pixels offset in a large region of the acquired images, but it was anyway possible to retrieve useful informations. The cameras have been sent back for calibration to the manufacturer and the measurements will be repeated in 2008.

In case the beam has some betatron or dispersion mismatch (i.e. at the first passage it has parameters $\overline{\beta}$, $\overline{\alpha}$, $D = D_0 + \overline{\Delta D}$ and $D' = D'_0 + \overline{\Delta D'}$) the expected beam size at the k-th turn is given by the formula (assuming the monitor is in a location with zero dispersion) [3]:

$$\sigma_k^2 = \beta_0\varepsilon(H + J_D - 1) + \beta_0\,\varepsilon\sqrt{H^2-1}\cos\left(4k\pi Q+\delta\right) + \beta_0\varepsilon(J_D - 1)\cos(4k\pi Q + 2\psi) + \sum_{i=1}^{k-1} S_{ik}^2 \left\langle\theta^2\right\rangle \quad (7)$$

with $\sqrt{\langle\theta^2\rangle} = 4.0875e{-6}$; J_D is the dispersion mismatch:

$$J_D = 1 + \frac{\overline{\Delta D}^2 + \left(\overline{\Delta D'}\beta_0 + \overline{\Delta D}\alpha_0\right)^2}{2\varepsilon\beta_0}(dp/p)^2 \quad (8)$$

Q is the tune, $\delta = \arctan\left[-(\alpha_0\overline{\beta} - \overline{\alpha}\beta_0)/(\overline{\beta} - \beta_0 H)\right]$ and $\psi = \arctan\left[(\alpha_0\overline{\Delta D} + \beta_0\overline{\Delta D'})/(\overline{\Delta D})\right]$

Figure 3 shows the measured horizontal and vertical beam sizes, turn by turn, together with the curve of the expected size (Eq. 7) obtained from beam parameters measured in TT2-TT10 and the expected beam size taking as initial condition the parameters fitted with the 3-monitor method at around the 40th turn. The very fast filamentation is explained by the high chromaticity in the machine [3].

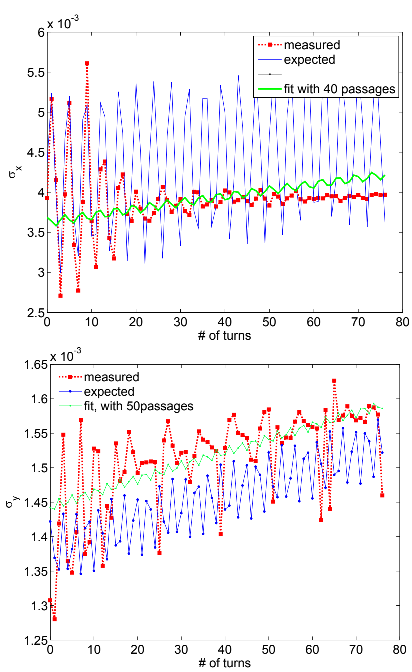

Figure 3: Beam sizes at the matching monitor

NEW TT2-TT10 OPTICS

Starting from the initial conditions reported in Table 1 and 2, a matched optics for the injection in SPS has been computed [7]. In Fig. 4 are plotted the horizontal and vertical β–functions in TT2-TT10. The new optics was calculated with the aim of having a phase advance of 45^o in the TT2 FODO structure and of 90^o in the TT10 one. This constrain is then "relaxed" to allow for a good matching in betatronic and in dispersion at the SPS injection.

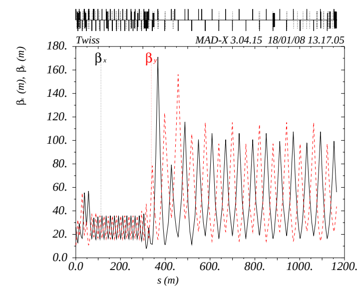

Figure 4: Horizontal and vertical β function in TT2-TT10

The quality of the new optics, which is operational since the 17/10/07, has been checked by several measurements in the line and in the SPS.

CONCLUSIONS

Thanks to dispersion and Twiss parameters measurements in TT2-TT10 and in the SPS, a new optics has been successfully prepared and put in operation to minimize the mismatch at injection in the SPS after the changes in the PS extraction due to the removal of the QKE58. Measurements withthe matching monitors in SPS have been performed, but need to be repeated with lower intensity beam (i.e. lower chromaticity) and the new LHC cameras, better calibrated.

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