STUDY OF BEAM LOSSES AT INJECTION IN THE CERN PROTON SYNCHROTRON

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Abstract

The maximum intensity the CERN PS has to deliver is continuously increasing. In particular, during the next years, one of the most intense beams ever produced in the PS, with up to 3000 10^{10} proton per pulse, should be delivered on a regular basis for the CNGS physics program. It is now known that the existing radiation shielding of the PS in some places is too weak and constitutes a major limitation due to large beam losses in specific locations of the machine. This is the case for the injection region: losses appear on the injection septum when the beam is injected in the ring and during the first turn, due to an optical mismatch between the injection line and the PS. This paper presents the experimental studies and the simulations which have been made to understand the loss pattern in the injection region. Possible solutions to reduce the beam losses will be described, including the computation of a new injection optics.

INTRODUCTION

Since the construction of the PS Booster (PSB), the transfer line between the PSB and the PS has been operated with a rather large dispersion mismatch. This was acceptable for beams with relatively large transverse emittance and small momentum spread. Even if the injection is not a problem for the LHC-beams with a horizontal and vertical physical transverse emittance of 2.5π μm rad, it is not the case for high intensity beams like CNGS or nToF [1] with an horizontal and vertical emittance of respectively 40π μm rad and 20π μm rad. Those beams are problematic because large losses appear at the injection due to an optical mismatch between the transfer line and the PS optics and an important aperture reduction at the injection septum. The aim of this work is to reduce the losses at injection in the context of an eventual PS intensity upgrade. This paper presents first how the causes of the losses were determined. Then an optics study was made at the PS injection, in which the optical parameters have been measured and benchmarked with MADX [3]. Finally, possible solutions to alleviate the losses will be discussed like a new optics with the installation of a collimator before the injection area.

INJECTION SYSTEM OF THE PS

The CERN Proton Synchrotron receives beams from PS-Booster, which is composed by four vertically superposed rings. The transfer line between the PSB and the PS, called BT-BTP, recombines vertically the beam from each ring as shown in the Fig. 1: the ejection from rings 3 and 4 are recombined in the BTU line and rings 1, 2 in the BTL line. These two lines will give further the BT-line. At the end of BT-line, a separation takes place to send the beam either to the ISOLDE facility or in the transfer line to the PS (BTP) on which this work is focused. The end of BTP passes through the stray field of one of the PS main magnets. The PS single turn injection consistes of the following elements, presented in the Fig. 2: the beam is injected via a magnetic septum on a bump created by four dipole bumpers and a fast kicker deflects the beam on the central orbit.

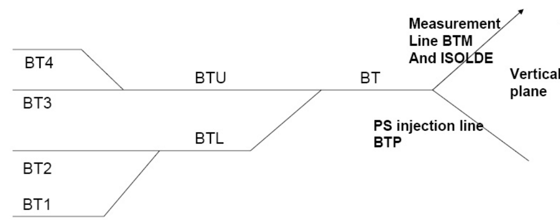

Figure 1: Layout of the transfer line between the PSBooster and the PS.

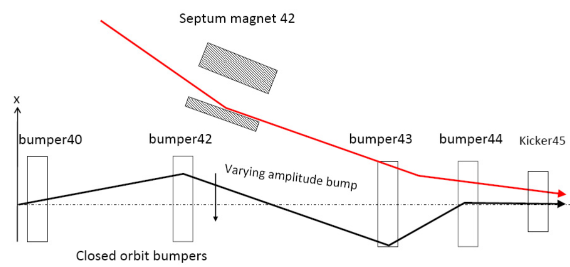

Figure 2: Layout of the PS injection.

LOSS EXPERIMENTS ON THE RADIATION LEVEL AT ROAD GOWARD

The losses at the PS injection induce a high radiation doses on a bridge (Road Goward) which passes on top of the shielding of the PS tunnel. In order to determine the causes of the injection losses, three LHC-type Beam Loss Monitors (BLMs)[4] have been installed in the transfer line BTP, as shown Fig. 3, to establish the source of radiation at the Road Goward and as a consequence determine if the losses at PS injection are produced at the septum or in the line.

Losses have been forced close to each one of the BLMs and the resulting radiation has been observed at a radiation monitor (ionisation chamber) installed close to the road.

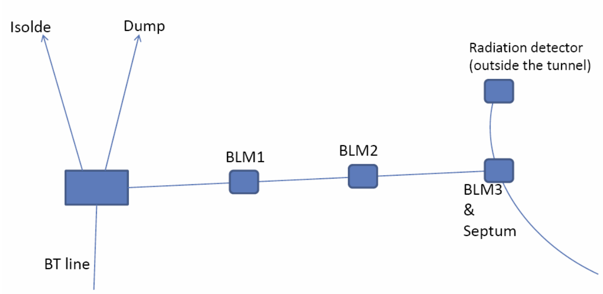

Figure 3: BLMs location for the experiment.

Losses produced close to the BLM 1 and 2 do not increase the radiation level on the road. However, if the losses are forced on the septum, i.e. close to the BLM3, an increase of the radiation level is observed. As a conclusion, the losses at the PS injection inducing the radiation on the road do not come from the transfer line but from the septum. The acceptance at the injection septum has to be determined and the mismatch between the line and the PS as well.

OPTICS MISMATCH MEASUREMENTS

The horizontal and vertical dispersion have been measured in the transfer line for the recombination of the ring 3 and during the first turn of the beam in the PS as well with the method described in reference [2]. The ring 3 is at the same level as the PS, so no residual vertical dispersion from the vertical recombination is expected. The dispersion D can be evaluated from the difference in position Δx at the Beam Position Monitors (BPMs) as a function of the difference in momentum $\frac{dp}{p}$ by fitting the following expression:

$$\Delta x = D \cdot \frac{\Delta p}{p} \quad (1)$$

Concerning the Twiss β-function, the 3-monitors method [2] has been used with the help of three SEM-wires installed in the ring. These monitors measure the r.m.s beam size $\sigma_{meas,i}$ at the monitor i and the β-function can be determined at the monitor location by:

$$\sigma_{meas,i} = \sqrt{\sigma_{\beta,i}^2 + D_i^2\left(\frac{\Delta p}{p}\right)^2} \quad (2)$$

where $\sigma_{\beta,i}^2$ is the r.m.s. betatron beam size and the second term is the contribution of the dispersion. The betatron beam size can be written in terms of the sin-like and cos-like functions and the Twiss parameters are determined at the beginning of the PS by the following expression:

$$\sigma_{\beta,i}^2 = \epsilon\beta_i = \epsilon(C_i^2\beta_0 - 2C_iS_i\alpha_0 + S_i^2\gamma_0) \quad (3)$$

with ϵ is the physical emittance, $\beta_0, \alpha_0, \gamma_0$ are the initial Twiss parameters at the PS injection and C, S are the cos-like and sin-like functions. By knowing σ_β at these locations, it is possible to obtain the emittance and the Twiss parameters at the reference point i. An single bunch beam with the intensity of $6 \cdot 10^{11}$ protons with a horizontal and vertical 2σ physical emittance of 5 μm rad have been used for the measurements.

Dispersion Measurements

The horizontal and vertical dispersion have been measured in the transfer line with nine BPMs and the initial conditions for the dispersion D and its derivative D' at the beginning of the line have been calculated. This allows to compute the theoretical optics with these starting conditions into the MADX. The results for horizontal and vertical dispersion are presented in Fig. 4. A good agreement between the measurements and the MADX dispersions in both planes is observed.

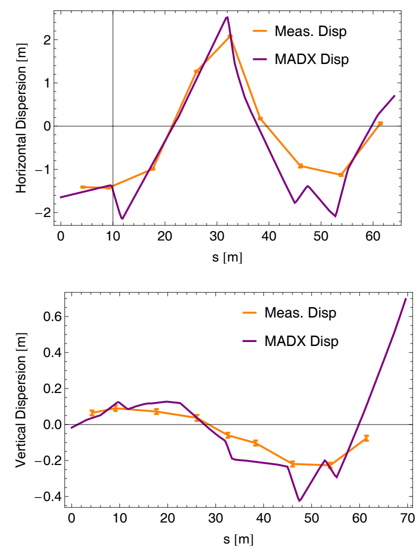

Figure 4: Horizontal and vertical measured dispersion in the transfer line shown with the theoretical dispersion from MADX with the stray field included in the simulation.

The dispersion in the horizontal plane has been measured at the PS injection during the first turn with the 40 BPMs located in the ring. The results are shown in Fig. 5. The vertical dispersion is too small to be measured with a satisfying accuracy. The dispersion has been plotted with the periodic one and the theoretical dispersion from MADX calculated with the starting conditions computed from the measurements. In spite of a good agreement between the MADX model and the measurements, the measured dispersion is about twice as large as the periodic one, indicating an important mismatch.

The blow-up after filamentation J in presence of dispersion mismatch is defined as [2]:

$$J = 1 + \frac{\Delta D^2 + (\Delta D'\beta_0 + \Delta D\alpha_0)^2}{2\epsilon\beta_0}\left(\frac{dp}{p}\right)^2 \quad (4)$$

We assume a beam with an physical emittance $\epsilon(2\sigma) = 5$ μm rad and $< \frac{dp}{p} >= 1.56\ 10^{-3}$. ΔD and $\Delta D'$ are the difference between the measured and the periodic dispersion (and derivative) at a chosen point in the

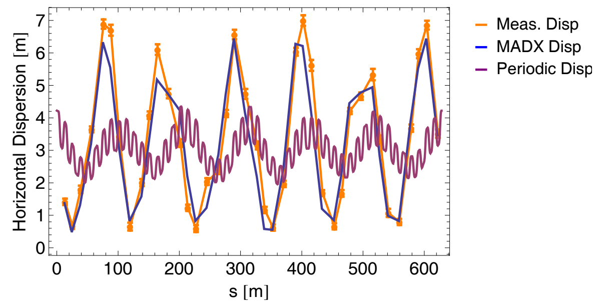

Figure 5: Measured horizontal dispersion with the theoretical dispersion from MADX and the periodic dispersion at the first turn in the PS.

ring and β_0, α_0 are the corresponding Twiss parameters for the closed machine. In the injection area, $J_{PS} = 1.032$ according to (4) and the average J_{PS} overall the PS ring is $J_{PS} = 1.138$ with a standard deviation of 0.218. However, at some places, J can reach 2.355, which confirm that the PS is operating with a large dispersion mismatch at injection.

Beam Profile Measurements

The 1D horizontal and vertical beam profiles have been recorded at the SEM wires in the PS ring and the horizontal and vertical beam size were computed with the equation (2) at each monitor by applying a Gaussian fit. The geometrical betatron mismatch is then obtained from the multigrid measurements according to the equation [2]:

$$H = \frac{1}{2}\left(\frac{\beta_m}{\beta_0} + \frac{\beta_0}{\beta_m} + \left(\alpha_m - \alpha_0\frac{\beta_m}{\beta_0}\right)^2 \frac{\beta_m}{\beta_0}\right) \qquad (5)$$

The β-functions in the horizontal and the vertical plane at the PS injection are reconstructed in the same way as the dispersion and the resulting β-functions can be compared to the periodic one, as shown Fig. 6.

According to equation 5, the betatron mismatch parameter H was calculated in the horizontal plane and does not undergo large variations around the PS ring: $H = 1.015$ with a standard deviation of $5\ \ 10^{-11}$. Concerning the vertical plane, the average of the betatron mismatch is $H = 1.068$ with a standard deviation of 10^{-10}. The transfer line is operating with betatron mismatches lower than in the case of the dispersion. This is convenient for LHC-beams, which are working with small emittances. However, this optics is not suitable for beams with larger emittances and larger momentum spread. By the studying the beam envelope in the transfer line, an important physical aperture restriction appears at the injection septum, which is at 2σ of the beam size for a physical emittance of 5μm·rad. This fact explains why around 5% of the beam can be lost at the injection.

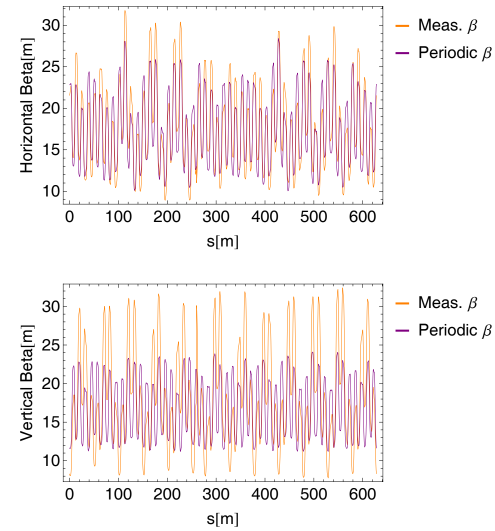

Figure 6: Horizontal and vertical measured beta-functions shown with the periodic beta at PS injection

CONCLUSIONS AND OUTLOOK

The current optics in the transfer line between the PSB and the PS is operating with a small betatron and large dispersion mismatch, convenient for the LHC-beams. The aperture at the septum is also very tight. For high intensity beams, this causes large losses and high radiation. A solution would be to increase slightly the betatron-mismatch in order to reduce the beam size at the septum with a matched dispersion. A collimator could be installed at a convenient place before the septum to cut the tails which exceed outside the septum aperture. This new optics has to take into account the losses at injection in the ring and the aim is to move them to a better location. In addition, the new optics should respect the demands of the LHC-beams concerning the emittance blow-up, otherwise the transfer line has to operate with different settings for two consecutive different cycles.

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