OPTIMIZATION OF THE POSITION OF THE RADIAL LOOP PICKUPS IN THE CERN PS

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A part of the beam losses at transition crossing of high intensity beams in the CERN PS have been attributed to an excursion of the closed orbit. The orbit jump occurs simultaneously with the jump of the transition energy triggered by pulsed quadrupoles. Investigations showed that the position of the pickups used for the radial loop system was not optimized with respect to the dispersion change caused by the fast change of the transition energy. Thanks to new electronics of the orbit measurement system, turn-by-turn orbit data could be recorded around transition crossing. Their analysis, together with calculations of the transverse optics, allowed determining a new choice of pickup positions for the radial loop. In comparison to the previous pickup configuration, the new configuration improves the mean radial position not only during transition crossing, but all along the acceleration cycle.

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INTRODUCTION

It is well known that one of the bottlenecks limiting the performance of the CERN Proton Synchrotron (PS) is the acceleration of high intensity beams through the transition energy $\gamma_{\text{tr}}$. To minimize the duration during which the beam energy stays close to $\gamma_{\text{tr}}$, a so-called $\gamma_{\text{tr}}$ jump is applied [1]. Some 50 ms before the transition jump, $\gamma_{\text{tr}}$ is slowly pushed higher in energy. To cross the transition energy as quickly as possible, fast pulsed quadrupoles are triggered to rapidly change $\gamma_{\text{tr}}$. Measurements of the horizontal orbit show a mean radial position (MRP) excursion of about 3.5 mm at the same time as the $\gamma_{\text{tr}}$ jump, provoking significant beam losses. The radial position is controlled by the radial loop system which originally used the horizontal beam positions averaged over three dedicated pick-ups (PUs). With the help of orbit measurements, this study presents how an improved set of radial PUs has been identified to control the MRP. The method consists of analyzing the dispersion bump caused by the $\gamma_{\text{tr}}$ jump to find the best location of the PUs to be more sensitive to energy errors and reduce losses at transition crossing.

MEAN RADIAL POSITION AT TRANSITION CROSSING

Transition crossing at the CERN PS is carried out by a second order $\gamma_{\text{tr}}$ jump performed by quadrupoles arranged in doublets and triplets. Large losses have been measured for high intensity beams during the $\gamma_{\text{tr}}$ jump. A fraction of these losses were related to the large beam envelope due to the optics distortion of the $\gamma_{\text{tr}}$ jump. A solution was implemented in the PS as described in [2] to reduce the losses. However horizontal orbit measurements at transition crossing showed also a MRP excursion when the $\gamma_{\text{tr}}$ jump is performed. An example of measured MRP from a beam with a $1\sigma$ physical emittance of 20 mm.rad and an intensity of $1300 \cdot 10^{10}$ ppp is presented in Fig. 1. The radial position deviates by 3.5 mm at the $\gamma_{\text{tr}}$ jump due to the inversion of the currents of the doublets [3]. Of that excursion, 1 mm has been attributed to the misalignments of the quadrupoles used to perform the $\gamma_{\text{tr}}$ jump. An artificial radial steering was introduced to compensate this deviation, which appears to be a good temporary solution to reduce the losses. Further tests have been carried out to optimize the radial loop system controlling the radial position of the beam in order to automatically compensate this MRP drift.

Figure 1: Mean Radial Position in mm as a function of time during the transition crossing with the $\gamma_{\text{tr}}$ jump scheme. The transition time is situated at 50 ms.

CLOSED LOOP CONTROL OF RADIAL POSITION

During large parts of the acceleration, an RF frequency calculated from the measured field in the bending magnets would be sufficient to keep the beam close to the center of the beam pipe. However, according to $\Delta R/R = (\gamma_{\text{tr}}^2/\gamma^2 - 1)^{-1} \Delta f/f$, the offset of the radial position $\Delta R$ becomes significant for $\gamma \simeq \gamma_{\text{tr}}$ in case of small errors $\Delta f$ of the calculated frequency program. A radial loop therefore introduces a correction to the frequency program based on a measurement of the radial position offset of the beam. In the 1970s, four radial loop PUs had been installed in straight sections (SS) 22, 36, 51, 96, out of which the PU in SS36 had not been in use [5]. Each of the PUs delivers sum ($\Sigma$) and difference ($\Delta$) signals. The pairs of $\Sigma$ and $\Delta$ signals are then converted to an intermediate frequency ($f_{1F} = 21.4 \text{ MHz}$), selecting only the spec-
tial component of the beam at the RF frequency. The $\Delta/\Sigma$ division is performed by a time normalizer circuit \[6\], resulting in a radial offset per PU being largely independent from beam intensity and bunch length. The radial offsets measured at the different PUs are then averaged and injected, via an appropriate loop filter, as slow corrections to the RF frequency sent to the accelerating cavities. At transition crossing, i.e. when \((\frac{1}{\gamma_{tr}} - \frac{1}{\gamma}) \rightarrow 0\), the gain of the radial loop is inverted, which may introduce a transient. The stable phase program is switched from $\phi_s$ to $-\phi_s$ in addition. Ideally, this should move the reference phase of the optics change during the jump of $\gamma_{tr}$.

DISPERSION FUNCTION AT THE RADIAL PUS

Optimizing the locations of the radial PUs being averaged for the MRP fed into the radial loop with respect to the optics change during the jump of $\gamma_{tr}$ is the goal of this study. The average of the dispersion function has been computed with MADX \[4\] during the $\gamma_{tr}$ jump and compared with the one of each radial loop PUs. The results are shown on the Fig. 2 and Fig. 3. The PU in SS51 is less sensitive to energy error due to a lower dispersion during the $\gamma_{tr}$ jump compared to the two other PUs in SS22 and SS96 used in the old configuration. This is confirmed by observing the trajectories turn-by-turn through transition at the PUs locations (Fig. 4). The change in trajectory at the PU51 is smaller with respect to the other PUs. In addition the phase advance between the PUs in SS51 and SS96 is not suitable since it is not close to $\frac{2}{\pi}$. To replace the PU in SS51, the fourth radial loop pick-up has been put back into operation. Additionally, another pick-up has been installed in SS76 during the shutdown 2008/2009 (in total five dedicated PUs in SS22, 36, 51, 76, 96). SS76 is more appropriate considering the change in horizontal position through transition (Fig. 4) and the phase advance with respect to the other radial loop PUs. The dispersion function in SS76 from the Fig. 5 shows that its sensitivity to energy errors is increasing during the $\gamma_{tr}$ jump. The resulting dispersion of several PU combinations is also presented on the Fig 5. The set PUs in SS22, 36, 76, 96 would the most convenient to optimize the loop sensitivity to energy errors.

MRP MEASUREMENTS WITH A NEW SET OF RADIAL PUS

MRP measurements have been done in three configurations: first with the old set of radial PUs (PUs 22-51-96), in the second case a radial steering was added, and the third case was done with the new set of PUs (PUs 22-36-76-96) without any radial steering. The measurements were done exclusively with high intensity beams. The MRP is then calculated from the 40 Beam Position Monitors (BPMs) used to determine the beam closed orbit. The results are presented in the Fig. 7 and Fig. 6 for the beams named ToF and CNGS with respectively a 1 sigma normalized horizontal emittance of 5 mm.mrad and 12 mm.mrad and an intensity of $700 \cdot 10^{10}$ protons single bunch and $2500 \cdot 10^{10}$ on 16 bunches. The transition time are respectively 317 ms for the ToF beam and 580 ms for CNGS. The first remark is that the beam stays well centered in the machine even outside the $\gamma_{tr}$ jump due to the better phase advance be-
CONCLUSIONS

The new set of PUs is an improvement of the efficiency of the radial loop PUs system according to the optics change during the $\gamma_{tr}$ jump, allowing a better steering of the beam all along the magnetic cycle. Indeed the radial loop system is more sensitive to dispersion changes and the phase advance between the PUs is more suitable. Without many additional steering the operation of the beam during the $\gamma_{tr}$ jump steering would be easier.

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