

# STUDY OF BEAM LOSSES AT TRANSITION CROSSING AT THE CERN PS

S. Aumon<sup>\*</sup>, S. Gilardoni, M. Martini, CERN, Geneva, Switzerland

## Abstract

A series of studies has been carried out to understand and alleviate the beam losses in the CERN PS Proton Synchrotron. Losses appear especially at transition crossing during the pulsing of special quadrupoles used to create a gamma jump scheme. However, this causes a large optics and orbit distortion. After a brief summary of the gamma jump scheme at the PS, experimental and simulation results of the loss and reduction studies are presented.

## INTRODUCTION

The ramp rate of the CERN PS main magnetic field is limited by the main magnets power supply and also by the iron dominated magnets to 20 G/ms. Consequently, a gamma jump scheme has been used in the PS since the 70's to increase the speed of the transition crossing [2]. Two groups of seven quadrupoles arranged in four doublets and two triplets are pulsing for about 100 ms to dynamically distort the nominal PS optics and change the natural gamma transition. The pulsing of those quadrupoles has been chosen to reduce the time during which  $\eta = |1/\gamma^2 - 1/\gamma_{tr}^2|$  remains below the threshold of 0.004. If  $\eta$  is below that limit by more than 1 ms, beam instabilities evolve [1]. On one hand, this optics deformation allows to cross transition fast enough to avoid generating a negative-mass instability [3][4], but on the other hand it might make the envelope too large and cause losses.

## GAMMA JUMP SCHEME AND ENVELOPE STUDIES

The CERN PS synchrotron is composed by 100 combined function magnets arranged in a FOFDOD lattice. Each dipole magnet has a focusing quadrupolar gradient in one part and a defocusing gradient in the other part. These dipole magnets are separated by 100 straight sections (SS, numbered from 00 to 99) which host auxiliary magnets. The nominal PS optics is shown in Fig. 1.

In general, the transition energy,  $\gamma_{tr}$ , is defined as:

$$\frac{1}{\gamma_{tr}^2} = \frac{\Delta C/C}{\Delta p/p} = \frac{1}{C} \oint \frac{D(s)}{\rho(s)} ds. \quad (1)$$

Here  $C$  is the nominal machine circumference,  $\Delta C$  the circumference change of particles with the momentum deviation  $\Delta p$  with respect to the nominal momentum  $p$ ,  $D$  the nominal dispersion and  $\rho$  the nominal bending radius of the dipole magnets. The  $\gamma_{tr}$  of the PS is about 6.1.

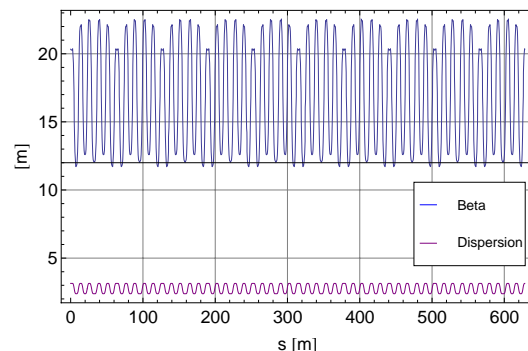


Figure 1: Horizontal beta and dispersion as function of  $s$ .

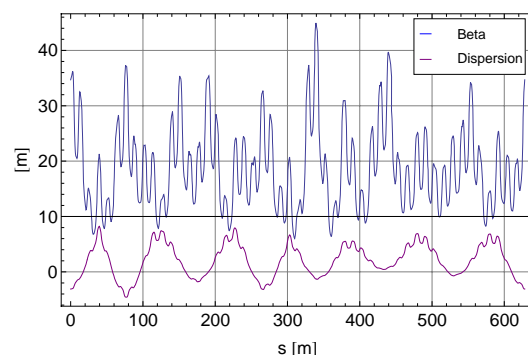


Figure 2: Horizontal beta and dispersion before the transition as function of  $s$ , i.e. at the maximum current of the doublets.

Near transition, two sets of quadrupoles are pulsing in such a way that the nominal dispersion is varied according to Fig. 2. To achieve this dispersion change, two cells composed of one triplet and two doublets are installed according to Fig. 3 and pulsing with the currents shown in Fig. 4. The roles of the two groups of magnets are the following: the triplets cause a slow optics variation, until the sudden sign inversion of the currents of the doublets triggers the real gamma jump, with a  $\Delta\gamma_{tr}$  around 1.2. The optics is distorted in such a way that the envelope, defined by the Eq. 2, increases in few sections of the machine.

$$\sigma(s, t) = \sqrt{\epsilon\beta(s, t) + \left(D(s, t) \frac{\Delta p(t)}{p}\right)^2} \quad (2)$$

Here  $\epsilon$  is the horizontal physical emittance,  $\beta(s, t)$  the horizontal Beta Twiss parameter,  $D(s, t)$  the dispersion as function of  $s$  and the time  $t$  during the pulsing of the gamma jump quadrupoles and  $\Delta p(t)$  the momentum spread at the time  $t$ . Fig. 5 shows the envelope versus the horizontal aperture horizontal (physical emittance=4.03 mm mrad, 1 sigma RMS and

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<sup>\*</sup> Clermont-Ferrand University, FR, now at the EPFL, Lausanne, CH  
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$\frac{\Delta p(t)}{p} = 3.5 \times 10^{-3}$ , 1 sigma RMS), computed before the inversion of the gamma jump doublets. In a few locations the envelope approaches the horizontal aperture which causes losses, particularly in SS63. These are measured by the PS beam loss monitors as presented in Fig. 6.

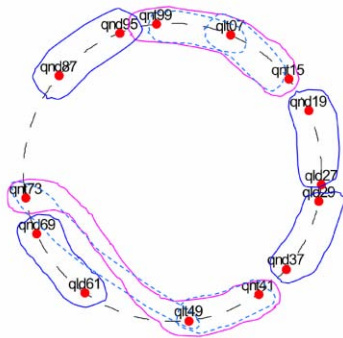


Figure 3: Distribution around the PS machine of the quadrupole doublets (marked in blue) and triplets (marked in pink) for the gamma jump. For each magnet, the SS and the magnet type is indicated.

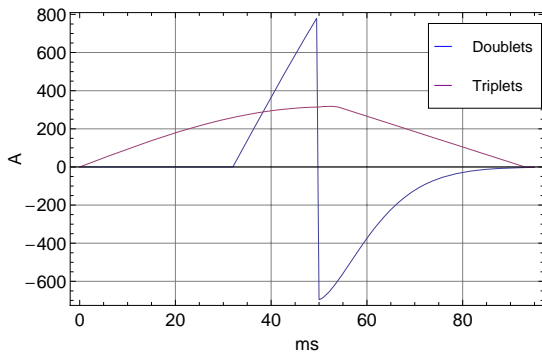


Figure 4: Gammajump quadrupoles currents versus time during the pulsing.

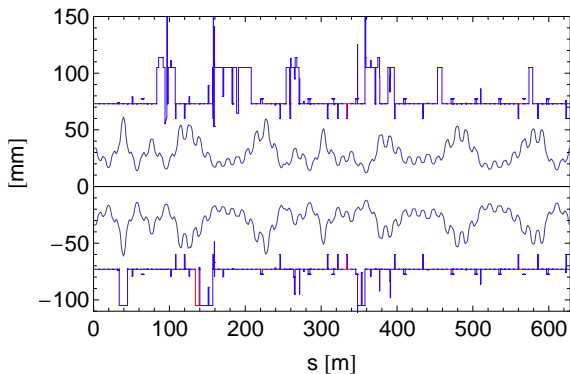


Figure 5: Horizontal beam envelope ( $3 \sigma$  transversally,  $2 \sigma$  longitudinally) before for the doublets inversion as function of  $s$  and the horizontal aperture. The straight section 63 is located around  $s=400m$ .

The optics distortion could be one of the reasons to account for those losses. Actually, the aperture seems to be large enough to accommodate the envelope, so the orbit at

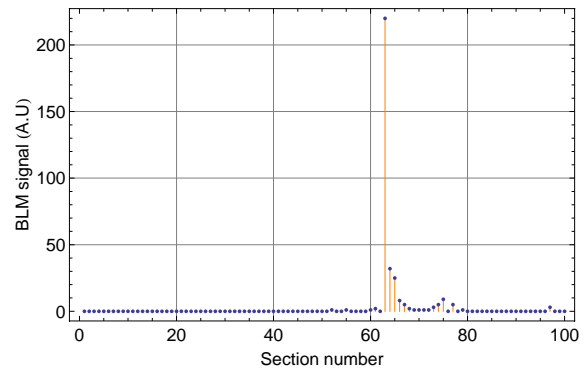


Figure 6: BLMs signals during the transition crossing in arbitrary unit as function of the section number. The most important losses appear in SS63.

the transition crossing has to be included to determine the real machine aperture available.

### ORBIT DISTORTION

A series of orbit measurements near transition proved that an orbit distortion appears once the gamma jump elements are pulsing, as shown in Fig. 7. This distortion is triggered by the relative misalignments between the beam and the gamma jump quadrupoles, dynamically evolving with the currents of the quadrupoles. Once the quadrupoles start pulsing, the orbit becomes distorted while the mean radial position (MRP) of the beam is drifting towards the center of the machine by 3.5 mm, as shown in Fig 8. This variation, which should be compensated by the radial loop acting on the RF system, is enhanced by the increase of the quadrupole currents. The MRP eventually jumps with the inversion of the doublets. Consequently, the distorted orbit has to be added to the beam size calculations, as shown in Fig. 9. It can be noticed by doing so that SS63 becomes an aperture restriction. A straightforward correction is to force a radial position of +3.5 mm before the transition crossing, in order to compensate for the MRP drift. The need of a radial steering is also the sign that the RF radial loop can not correct the real radial position at transition, since the system seems too slow to correct a sudden MRP change, which takes typically less than 5 ms.

### ENVELOPE DISTORTION

A possible correction, in addition to the radial steering, would be to displace the envelope maximum in SS63 to sections with larger machine aperture. This can be done by de-balancing the two quadrupole cells, increasing the current in one cell and decreasing in the other. The resulting envelope is shown in Fig. 10. The implementation of this correction as well as the aforementioned radial steering lead to a loss reduction by about a factor 10, i.e. from 2% of a  $1.3 \times 10^{13}$  proton beam down to 0.2%, as shown in Fig. 11.

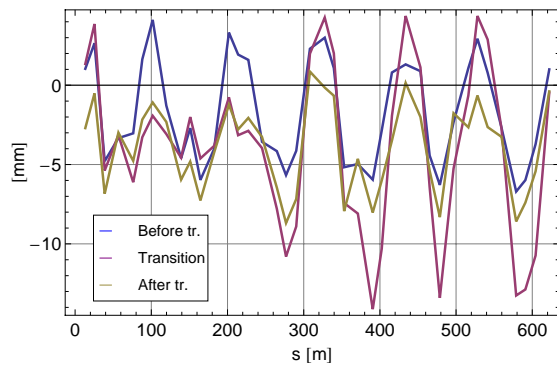


Figure 7: Horizontal orbit versus  $s$  at different time: before the gamma jump quadrupoles begin to pulse, during and after the transition.

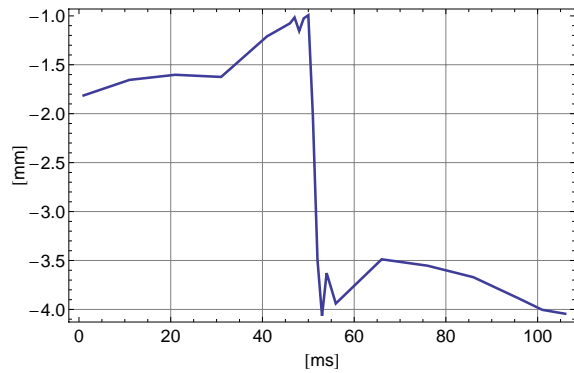


Figure 8: Mean radial position during the pulsing of the gamma jump quadrupoles.

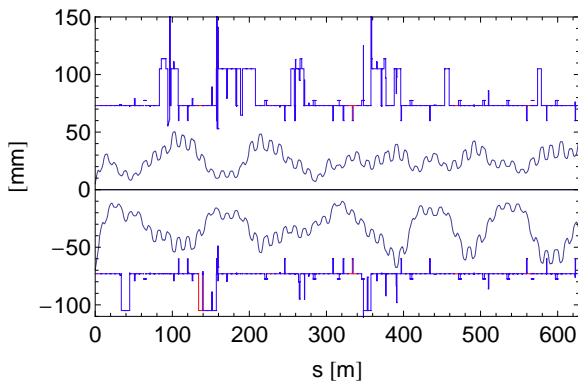


Figure 9: Horizontal beam envelope ( $3\sigma$  transversally,  $2\sigma$  longitudinally) considering the distorted orbit, before for the doublets inversion as function of  $s$  and the horizontal aperture. The straight section 63 is located around  $s=400m$ .

### CONCLUSIONS

The cause of losses during the gamma jump at the CERN PS has been identified as the combination of a large envelope and an orbit distortion. Thanks to the introduction of a radial steering and optics distortion of the nominal gamma jump, the losses could be reduced from 2% down to about 0.2% of a  $1.3 \times 10^{13}$  proton beam.

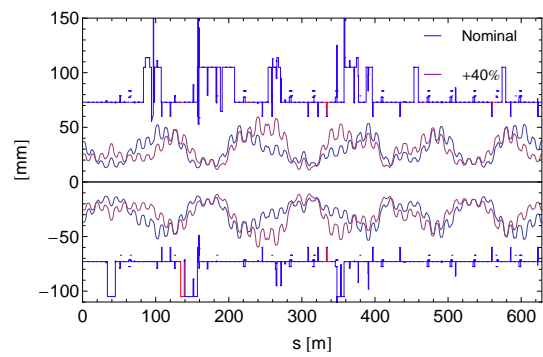


Figure 10: Horizontal beam envelope ( $3\sigma$  transversally,  $2\sigma$  longitudinally) before for the doublets inversion as function of  $s$  and the horizontal aperture. In blue, the beam envelope with the nominal values of the gamma jump quadrupoles currents. In purple, these currents have been increased of 40% in the second part of the machine, precisely around the SS63, and decreased of the same amount in the first part.

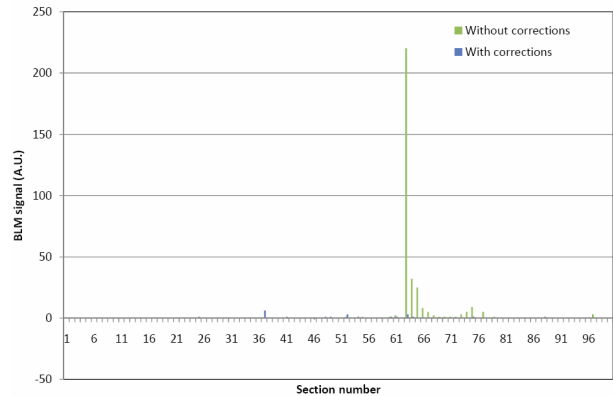


Figure 11: BLMs signals during the transition crossing with and without the proposed corrections, i.e. a radial steering of 3.5 mm and the de-balanced quadrupoles.

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