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THE PS IN THE LHC INJECTOR CHAIN

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This is an overview of the PS for LHC beam requirements in terms of beam characteristics and an inventory of various issues and problems to be solved to reach the desired performance.

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1 INTRODUCTION

This paper is a description of the role of the PS machine as part of the LHC injector chain.[1,2] The second chapter is an inventory of the characteristics, with some explanations, of the beam the PS has to provide and send to the SPS. The third chapter is a review of the methods foreseen to achieve this performance, with indications of the present status and some pending problems.

2 THE PS BEAM PARAMETERS AND JUSTIFICATIONS

The PS machine as part of LHC injector chain has to provide to the SPS a proton beam with the following characteristics:

(a) *Momentum*, $p = 26\,\mathrm{GeV}/c$. This corresponds to the maximum momentum achievable in the PS machine. It allows injection into the SPS above the transition energy ($\sim 23\,\mathrm{GeV}/c$) and avoids a transition crossing.

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(b) *Bunch spacing*, $t_b = 25$ ns. Such a bunch spacing, conserved in the LHC, is required by the LHC detectors in terms of collision repetition rate, data processing, etc.

(c) *Number of bunches*, $k_b = 84$. This value follows from the ratio machine circumference/bunch spacing. However, some bunches (~ 4) will be lost during the fast extraction procedure (see later).

(d) *Bunch length*, $\tau_b \sim 3.8$ ns (4σ). It has to be less than 5 ns to be captured inside the 200 MHz RF SPS bucket.

(e) *Momentum spread*, $dp/p = 2.5 \times 10^{-3}$ (2σ). This relatively large value is dictated by stability requirements against longitudinal microwave instabilities in the SPS machine at injection front porch.[3] The resultant longitudinal emittance is $\varepsilon_l = 0.35$ eV s.

(f) *Bunch intensity*, $N_b = 10^{11}$ p/b for the nominal beam, 1.7×10^{11} p/b for the so-called "ultimate" beam; in this latter case the total PS beam intensity is 1.4×10^{13} p/pulse.

(g) *Transverse emittances*, $\varepsilon_x^* \sim \varepsilon_y^* \sim 3\,\mu$m (rms normalised, i.e. $\varepsilon_x^* = \beta\gamma\sigma_x^2/\beta_x$).

(h) *Beam brightness*, defined as the ratio $N_b/\varepsilon_{x,y}^*$. The LHC luminosity is directly proportional to this parameter which is actually more than twice the brightness of the present best PS beam. Important PSB and PS modifications have to be made to reach this performance.

3 PROBLEMS AND ADOPTED SOLUTIONS

To summarise, in the transverse domain the main problem is to provide a beam of high brightness. While in the longitudinal plane the main problem is to generate a train of very short (3.8 ns) bunches spaced by 25 ns starting from very long (200 ns) bunches coming from the PSB.

The solution adopted is to accelerate in the PSB a beam with the right transverse emittance but half the intensity, and inject two PSB pulses into the PS machine. The total circumference of the 4 PSB rings being equal to the PS circumference, a necessary condition in order to fill only one-half of the PS with a single PSB shot, is to use a $h = 1$ RF system in the booster (at present $h = 5$). In this way by adjusting the PSB extraction timing it is possible to fill only half of the PS circumference with the first shot and the second half with a second shot, 1.2 s later (=4 + 4 bunches).[4] The nasty consequence is that the first batch (4 bunches) has to circulate during 1.2 s on the injection flat bottom in strong space charge regime while awaiting for the second batch. The PS cycle length will be 3.6 s instead of the typical 2.4 s.

The eight 200 ns long bunches are captured by the PS RF system at $h=8$ and split into 16 with an adiabatic $h=8$ to 16 harmonic change. They are subsequently accelerated to 26 GeV/c where the beam is debunched and rebunched at 40 MHz to provide the 25 ns spacing. Finally, the 84 bunches are compressed to 3.8 ns with a 2nd harmonic RF system (80 MHz cavities, 300 kV each)[5] and fast extracted to the SPS.

The PSB beam transverse emittance is about 2.5 µm, very close indeed to the desired 3 µm value at PS extraction. Such a tight emittance budget imposes a rigorous handling of all possible sources of blow-up along the injector chain.

3.1 Injection Errors

Each bunch comes from a different PSB ring or a different PSB pulse. They are vertically recombined in the PSB–PS transfer line, therefore the beam optics are also different. Steering and matching errors are the first candidates for potential beam blow-up at PS injection. The effects of steering errors can be evaluated with the following formula:

$$\varepsilon^*_{x,y,f} = \varepsilon^*_{x,y,i} + \frac{1}{2}\frac{a^2}{\beta_{x,y}}\beta\gamma, \tag{1}$$

where $\varepsilon^*_{x,y,f}$ is the final emittance value (rms, normalised), $\varepsilon^*_{x,y,i}$ is the initial emittance value (rms, normalised), a is the amplitude of the bunch oscillations induced by steering injection errors (position and/or angle), $\beta_{x,y}$ is the machine beta function and β and γ are the usual relativistic factors. Note that the 2nd term at rhs of (1) corresponds to an additional emittance independent of the beam emittance. With the PS values at injection, to keep this term less than 10%, a has to be smaller than ~2 mm.

Systematic steering errors can be traced and corrected by Automatic Beam Steering procedures,[6] but pulse to pulse fluctuations, at present estimated about ± 1 mm, have to be corrected by a transverse damper.

At injection, the distance between bunches is ~90 ns. Analysing the injection kicker rise and fall time, see Figure 1, it is evident that some bunch (or some part of a bunch) will be quite affected.

Note that a 1% distortion in kicker deflection will generate about 3% of horizontal emittance blow-up.

Concerning mismatch errors, first tentative measurements seem to indicate possible emittance blow-ups of 10–30% from ring to ring.[7] At present the main problem is measurement accuracy and consistency. A big effort is being done in the PSB and PS to set up various diagnostic systems to analyse these effects. For example: wire scanners in the PSB rings, SEM grids in the measurement line at the PSB extraction and at injection in the PS, quadrupolar pick-up in the PS ring, are among the envisaged instruments.

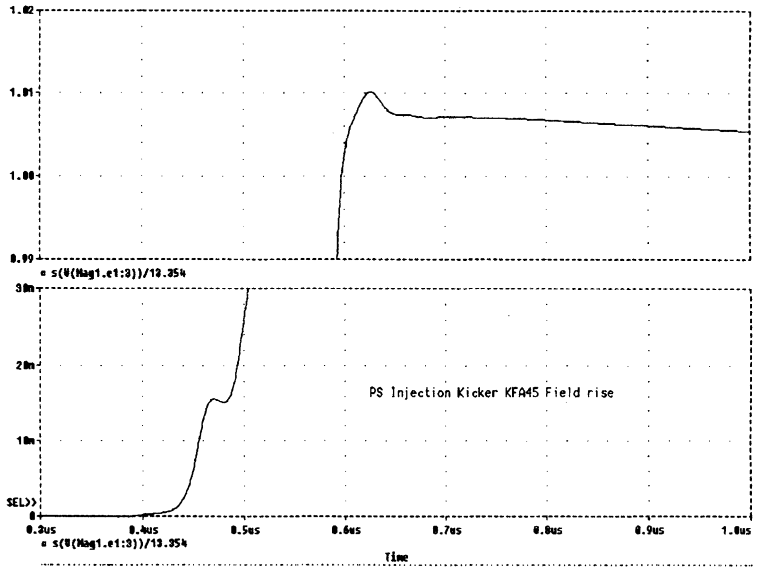

FIGURE 1(a) Zoomed injection kicker field rise. Vert. scale = 1% of the nominal kicker value/div.; Hor. scale = 100 ns/div.

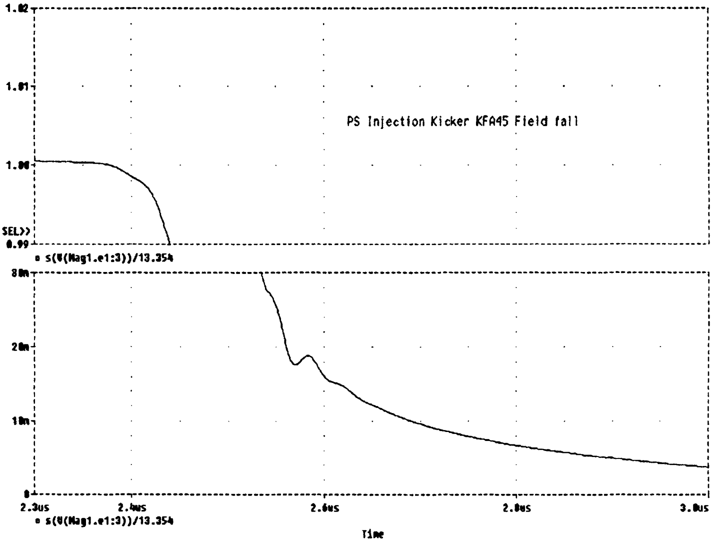

FIGURE 1(b) Zoomed injection kicker field fall. Vert. scale = 1% of the nominal kicker value/div.; Hor. scale = 100 ns/div.

3.2 Space Charge

Space charge tune shifts can convey the beam onto nonlinear resonances generating transverse emittance blow-up. Considering for simplicity only the vertical plane (the horizontal values being similar), the tune shift of the particle located in the centre of a (transversally) Gaussian bunch, also called "incoherent" or "self-field" tune shift (the wall effects are negligible), is given by

$$\Delta Q_y = -\frac{2r_0}{ec}\frac{I_\mathrm{p}\beta_y R}{(\beta\gamma)^3}\frac{1}{b(a+b)}, \tag{2}$$

where r_0 is the proton radius, c is the speed of light, e is the proton charge, $I_\mathrm{p} = 3eN_\mathrm{b}/2\tau_\mathrm{b}$ is the peak current of the parabolic bunch, τ_b is the total bunch length, R is the machine radius,

$$a = \sqrt{2\left[\frac{\varepsilon_x^*\beta_x}{\beta\gamma} + \left(D_x\frac{\sigma_p}{p}\right)^2\right]}$$

is $\sqrt{2}$ times the rms horizontal beam dimension, D_x is the horizontal dispersion, σ_p/p is the rms momentum spread and

$$b = \sqrt{2\left[\frac{\varepsilon_y^* \beta_y}{\beta\gamma}\right]}$$

is $\sqrt{2}$ times the rms vertical beam dimension. The vertical tune shift of the "ultimate" LHC beam with a PS injection energy of 1 GeV is $\Delta Q_y \sim -0.4$.

Some experiments[8] were performed in the PS during 1993 to measure the emittance blow-up on a 1.2 s long flat-bottom at 1 GeV, simulating the LHC beam conditions. The results are shown in Figure 2. Even after optimization of the working point, an emittance blow-up of 30% was measured for an intensity corresponding to the "ultimate" LHC beam. Increasing the energy to 1.4 GeV, $\Delta Q_y \sim -0.3$, the emittance increase was negligible.

3.3 Head–Tail Instabilities

Transverse head–tail instabilities, driven by the resistive wall impedance, can develop during the long flat-bottom at injection energy.

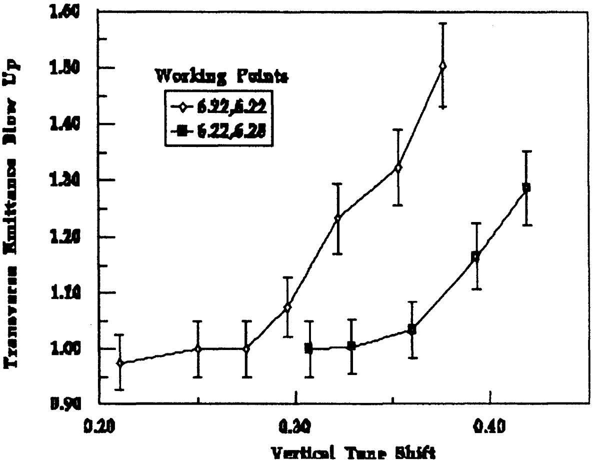

FIGURE 2(a) Emittance blow-up measured at the end of a 1.2 s flat-bottom at 1 GeV as function of the space charge vertical tune shift ΔQ_y.

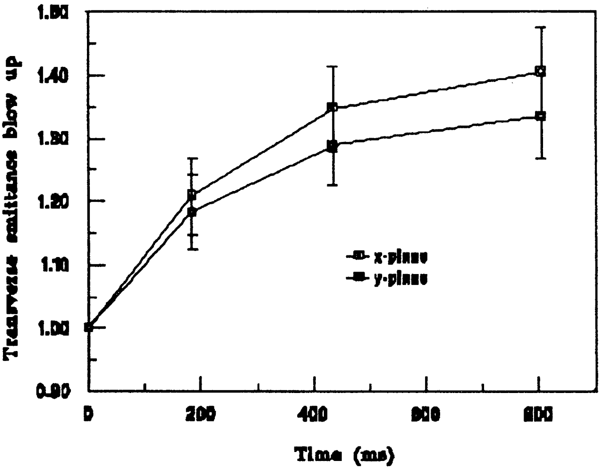

FIGURE 2(b) Horiz. and vert. emittance blow-up versus time with $\Delta Q_y = -0.44$.

The Sacherer–Zotter theory predicts, for such a long (200 ns) bunch, modes of oscillations with an unusually large mode number, i.e. $m \sim 5$ to 7, see Figure 3. Instabilities of this kind were occasionally observed during the 1993 test, see Figure 4. However, being very close to the stability threshold, increasing the energy to 1.4 GeV was sufficient to stabilize the beam.[9,10]

Modifications to the present transverse feedback should cure these instabilities in the case that they will be present also at 1.4 GeV.

3.4 Transition Crossing

Since many years, after the implementation of a γ-transition jump scheme, transition crossing is no longer a major problem in the PS machine. At present, beams of much higher intensity than the LHC beam are crossing transition without measurable transverse emittance blow-up. Nevertheless, to improve Landau damping and avoid longitudinal instabilities, not only at transition, the longitudinal emittance has to be made larger than ~ 0.5 eV s. For this reason a controlled longitudinal blow-up is foreseen at low energy, after the bunch splitting from $h = 8$ to 16, to set $\varepsilon_l \approx 1$ eV s. The installation of new 40 and 80 MHz cavities do not preclude, however, the possibility of

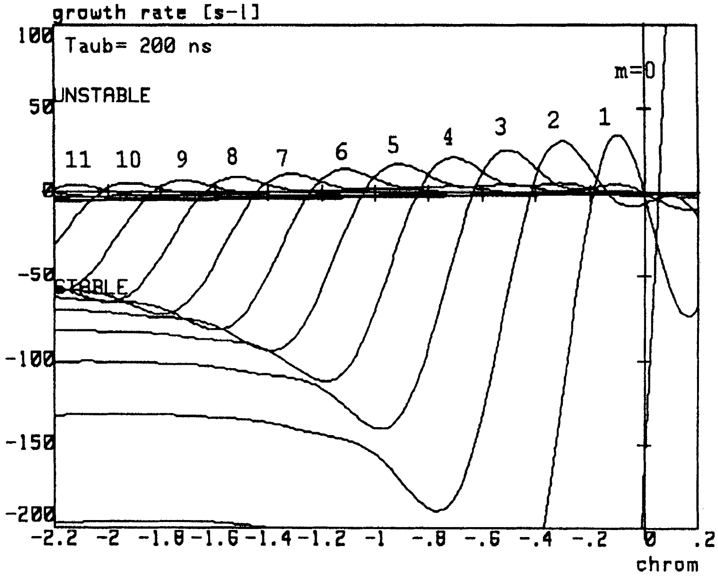

FIGURE 3 Sacherer–Zotter theory prediction of transverse head–tail instability growth rate versus machine chromaticity at 1 GeV. For the natural PS chromaticity ($\xi=(\Delta Q/Q)/(\Delta p/p)=-1$) the most probable modes are $m\sim 5$ or 6 with rise time ~ 100 ms.

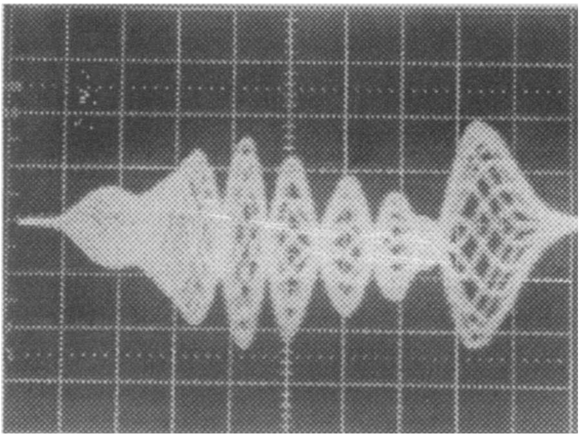

FIGURE 4 Observation of radial head–tail instabilities at 1 GeV. The signal coming from a radial pick-up is observed on ~ 15 consecutive turns. The 5 nodes are the signature of a $m=5$ oscillation mode. Time base: 20 ns/div.

creating some longitudinal coupled bunch instability which could eventually necessitate a longitudinal feedback.

3.5 Head–Tail Instabilities after Transition

High intensity beams suffer typically from head–tail instabilities, induced by the broad-band impedances, if the sign of the chromaticity is not changed from negative to positive after transition. This is achieved in the PS by a careful tuning of the pole face winding currents as a function of energy. The chromaticity is adjusted from -1 at low energy to $+0.1$ at high energy (crossing the zero value at transition). The working point ($Q_{x,y}$) is also optimised. The machine is reproducible enough to guarantee a stable operation on a large time scale (months).

3.6 Debunching–Rebunching

As already mentioned, on the 26 GeV/c flat-top, before beam extraction, the 16 bunches have to be converted into 84 bunches spaced by 25 ns via an adiabatic debunching–rebunching operation.[5] The longitudinal emittance margin $(84 \times 0.35\,\mathrm{eV\,s})/(16 \times 1\,\mathrm{eV\,s}) = 1.8$ is not so large considering the imperfect adiabaticity of the operation and the possible onset of microwave instabilities during the debunching process. Longitudinal collective effects during this process could produce a non-uniform bunch population and/or longitudinal emittance growth. First experiments are encouraging, but this operation, in particular for the ultimate beam, remains a weak point and other strategies, not all obvious, are under investigation.[5]

3.7 Fast Extraction to SPS

The rise time of the PS extraction kicker is at present ~ 132 ns (1–99%), see Figure 5. Studies are in progress to still improve this figure. Nevertheless, at least four of the 84 bunches will be lost during the extraction. This is an unpleasant effect which increases the machine irradiation and some methods, complicated however (e.g. a barrier bucket forming a longitudinal gap), are under study to solve this problem.[5] A kicker defect of $\pm 1\%$ will produce in the SPS a horizontal emittance increase of ~ 0.1 μm if not corrected by a damper.

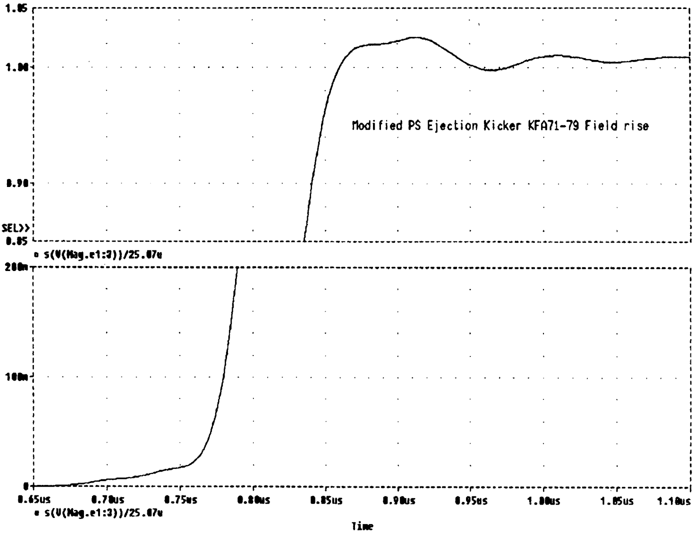

FIGURE 5 Zoomed extraction kicker field rise. Vert. scale = 10% of the nominal kicker value/div.; Hor. scale = 50 ns/div.

3.8 Stray Fields at Extraction

The extracted beam is relatively wide due to its large momentum spread ($\sim 5 \times 10^{-3}$ total). The very first part of the extracted beam trajectory goes across a region of nonlinear stray fields due to the last main bending magnet. The modelling of these effects[11] predicts different matching conditions for the parts of the beam at $\pm 2.5 \times 10^{-3}$ with respect to the nominal energy. Preliminary measurements, using SEM grids in the PS–SPS transfer line, seem to confirm these predictions. Such a mismatch could induce in the SPS an emittance blow-up of $\sim 20\%$. An intense campaign of machine studies is starting, with the collaboration of SPS experts, to confirm and more precisely evaluate these effects, with the aim also to envisage eventual corrections.

4 CONCLUSION

The PS machine, once the foreseen modifications are implemented in 1999, should be able to provide the nominal LHC beam without major problems, and eventually the ultimate LHC beam despite the very tight tolerances. Nevertheless, many machine experiments will have to be performed, starting already from now, to better investigate and elucidate the beam behaviour on some delicate item.

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The various contributors to machine physics issues can be recognized as authors in the list of references.

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