TRANSVERSE PERFORMANCE OF THE PROTON BEAM DELIVERED BY THE CERN PS COMPLEX FOR THE FUTURE LHC

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Abstract

The performance of the CERN LHC will depend heavily on the high-brightness beam delivered by the injector chain. In 1999, after completion of the programme of hardware upgrades of the PS Complex, a major effort was devoted to producing a proton beam with the nominal transverse characteristics foreseen for LHC operation. This paper focuses on the different beam dynamics issues encountered during the setting up of such a beam, in the Linac2, the PS-Booster (PSB), the PS, and the TT2 transfer line to the SPS. During the setting-up, single-particle issues, like stop-band compensation, correction of injection oscillations during the double-batch injection process, and the correction of the high-energy closed-orbit in the PS, were addressed. Furthermore, collective effects, such as high-order head-tail instabilities induced by the resistive-wall impedance, were observed and cured. The compensation of these harmful phenomena permitted to achieve the goal, namely the generation of small transverse beam emittances and their conservation along the chain of different machines.

1 EMITTANCE EVOLUTION IN LINAC2

The initial emittance of the proton beam is given by the duoplasmatron source. This emittance, determined by the extraction aperture, the electrode shape and the space charge in the extraction region, is about $0.4\ \mu$m.[1] After the source, the beam is adiabatically bunched and accelerated in a Radio Frequency Quadrupole (RFQ2) under high space charge conditions (proton current $I_\mathrm{p} = 200$ mA) which accounts for an unavoidable emittance growth, yielding an emittance of $0.6\ \mu$m out of the RFQ2 (measured on a test stand [1]). The RFQ2 was installed in 1993 as a preliminary step towards the higher brightness ($I_\mathrm{p}/\varepsilon^*$) required in the PS Complex for the LHC, leading to a reduction of the linac emittance, measured at the PSB entrance, from 1.6 to about $1.4\ \mu$m.

Fine-tuning of the 50 MeV Drift Tube Linac (DTL) and of the transfer line to the PSB for maximum current and minimum emittance growth has been a long and delicate process. An emittance growth by a factor of 2 along the linac is predicted by the simulation codes, and cannot be improved with the present machine. This is mainly due to the longer focusing period in the matching line between RFQ2 and Linac2 and to the space charge effects in the first section of the linac. It could be avoided only by redesigning the linac front end for higher injection energy.

[1]The following definition is used in the paper: $\varepsilon^*_{\mathrm{x,y}} = \beta\,\gamma\,\sigma^2_{\mathrm{x,y}}/\beta_{\mathrm{x,y}}$

Emittance growth in the linac was reduced by precise realignment of the beam at the linac entrance, whilst further reduction was achieved after a change in the optics of the Linac2-PSB transfer line, modified to a 'quasi-FODO' layout with constant phase advance per period. This is the optimum configuration for a beam with high space charge. This led to measured emittances below $1.2\ \mu$m, which is the limit for the present system [2].

2 TRANSVERSE PROPERTIES OF LHC-TYPE BEAM IN PSB

In the PSB, the transverse emittances of the LHC-type beam are defined, since multi-turn injection is employed to accumulate the beam coming from Linac2. By contrast, in the accelerator chain downstream, the beam is always transferred in a single-turn way, so that the transverse emittances are basically unchanged apart from residual mismatch or high-intensity effects. In the PSB, not only must an upper limit for the emittances be respected, but also a certain beam brightness has to be achieved [3], to guarantee the required LHC luminosity.

2.1 Double-Batch Operation Mode

The limiting factor for the production of the required high-brightness beam in the PSB is the space charge tune shift at injection (50 MeV kinetic energy). To overcome this problem it was decided to fill the PS with two consecutive batches. This reduces the beam intensity in the PSB and also the space charge tune shift at injection by a factor two from an unmanageable $\Delta Q \approx -0.8$ to $\Delta Q \approx -0.4$. Table 1 gives the proton intensities per ring, the normalised r.m.s. emittances (equal for both planes) and the resulting tune shifts for the nominal and ultimate LHC beams in the PSB (double-batch operation mode). Figure 1 shows the tune diagram with tune shifts at RF capture and ejection (1.4 GeV kinetic energy) for the ultimate LHC beam with 1.80×10^{12} protons per ring.

Table 1: LHC beam parameters in the PSB/ring.

	Intensity	ε^*	$\Delta Q_{Injection}$
Nominal	1.15×10^{12}	2.5μm	≈ -0.2
Ultimate	1.80×10^{12}	2.5μm	≈ -0.4

Double-batch injection in the PS (four times the circumference of one PSB ring) can only be performed when using the harmonic number $h = 1$ for acceleration in the

PSB. For this, the existing $h = 5$ RF-system had to be replaced [4] and the PSB is now working on $h = 1$. A second harmonic system ($h = 2$) is used for high-intensity beams (bunch flattening to decrease the tune shift) and is needed for the ultimate LHC beam while the nominal beam was achieved with $h = 1$ only.

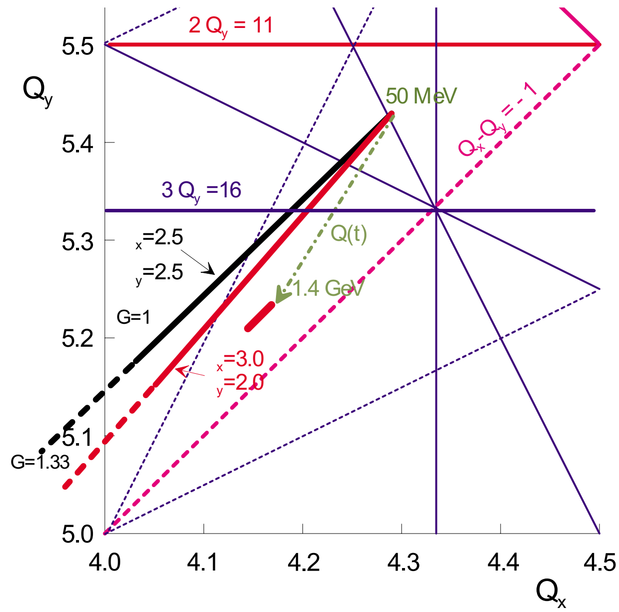

Figure 1: Tune diagram and tune shifts for the PSB. The dynamic variation of the working point is also shown.

2.2 Multi-Turn Injection

Even though the very high Linac2 current (about 180 mA) would allow the desired beam current to be reached with single turn injection, it was found that horizontal betatron stacking (2-3 turns) provides a more stable and brighter beam [5]. The reason might be that the Linac2 beam with a single turn results in a tune shift of $\Delta Q \approx -1$ and leads to a fast and uncontrolled transverse blow-up on integer stop-bands.

During injection and acceleration, the linear coupling line $Q_{\mathrm{x}} - Q_{\mathrm{y}} = -1$ is enhanced to transfer emittance from h- to v-plane, resulting in a rounder beam, preferred for the LHC. The stop-bands $Q_{\mathrm{x}} + 2Q_{\mathrm{y}} = 15$, $2Q_{\mathrm{x}} + Q_{\mathrm{y}} = 14$ and $3Q_{\mathrm{y}} = 16$ are compensated to provide space in the tune diagram at low-energy. The working point during acceleration is changed dynamically to move the beam away from stop-bands as the space charge tune shift shrinks (Fig. 1).

3 TRANSVERSE PROPERTIES OF LHC-TYPE BEAM IN PS

The most critical points for the setting-up of the PS for the conservation of the high-brightness beam delivered by the PSB are: (i) space charge effects; (ii) instabilities appearing during the long low-energy flat bottom; (iii) correction of the closed-orbit at top energy.

3.1 Double-Batch Injection

The double-batch injection scheme requires that the first batch of four bunches circulates during 1.2 s on the injection flat bottom with negligible transverse emittance blow-up. Raising the injection energy from 1 to 1.4 GeV reduced the space charge tune shift to $\Delta Q_{\mathrm{x}} \approx -0.16$ and $\Delta Q_{\mathrm{y}} \approx -0.20$, thus minimising emittance blow-up on the long flat bottom.

Instabilities of many kinds can dilute and even destroy the beam. According to Sacherer formula [6], the most dangerous one is a horizontal single-bunch instability induced by the resistive-wall impedance with mode number $m = 6$. On top of this, horizontal coupled-bunch instabilities having head-tail mode number $m = 5$ and coupled-bunch mode number $n = 1$ can develop once the second batch is injected. The former was observed in 1993 [7] and also last year [8] (see Fig 2). Octupoles or transverse feed-

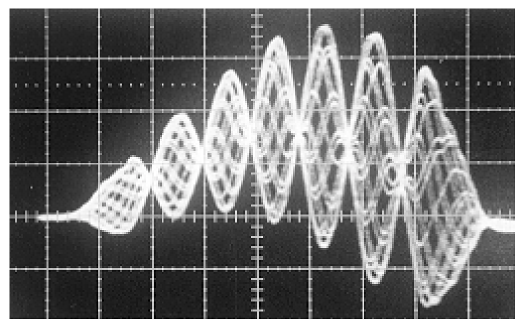

Figure 2: ΔR signal from a horizontal beam-position monitor during 20 consecutive turns. The time scale is 20 ns/div.

back are the classical means to damp such an instability. Recently, another method was developed, based on x-y linear coupling generated by skew quadrupoles [9]. Theory predicts that the necessary condition for the stability of the mth mode by linear coupling is

$$V^m_{\mathrm{eqx}} + V^m_{\mathrm{eqy}} \leq 0, \qquad (1)$$

where $V^m_{\mathrm{eqx,y}}$, the uncoupled transverse instability growth rates, are computed from the classical Sacherer formula. If Eq. (1) is satisfied, then the mode can be stabilised by increasing the skew gradient and/or by getting closer to the coupling resonance $Q_{\mathrm{x}} = Q_{\mathrm{y}}$, where $Q_{\mathrm{x,y}}$ are the horizontal and vertical uncoupled coherent tunes in the presence of wake fields. Theory also predicts the value of the modulus of the skew gradient needed to stabilise the mode [9]. This approach has been applied and proved to be very efficient, without any measurable emittance blow-up and without using octupoles. Similar results were obtained for the coupled-bunch instabilities and for the ultimate LHC beam.

3.2 Closed-Orbit Correction at High-Energy

The horizontal closed-orbit distortion in the PS shows a steady increase with energy. There is a small intermediate maximum of the orbit distortions around 3.5 GeV, where the low-energy orbit correctors are no longer efficient. Then, a significant growth of the distortions is observed, starting at about 15 GeV. A detailed analysis of the closed-orbit data showed that the main source of the distortion at high-energy are the shims and 'pipe shields' installed to screen the extracted beam from fringe fields [10]. Two dipoles in straight sections 15 and 60 reduce the orbit distortion by more than a factor two.

4 EXTRACTION TOWARDS THE SPS

The maximum allowed emittance blow-up in the transfer from the PS to the SPS is 17 %. Since the beam has a small emittance and a large momentum spread, $(\Delta p/p)_{r.m.s.} = 1 \times 10^{-3}$, dispersion mismatch is a major concern. A measurement campaign was undertaken to define and improve the model of the TT2 transfer line and to measure the Twiss parameters, the dispersion D, and its derivative D'. This allowed the computation of new transfer line optics with reduced blow-up factors H, J at injection in the SPS [11], where

$$2\,H = \frac{\beta_{\rm nom}}{\beta_{\rm mea}} + \left(\alpha_{\rm nom} - \alpha_{\rm mea}\,\frac{\beta_{\rm nom}}{\beta_{\rm mea}}\right)^2 \frac{\beta_{\rm mea}}{\beta_{\rm nom}} + \frac{\beta_{\rm mea}}{\beta_{\rm nom}}$$

$$J - 1 = \frac{\Delta D^2 + (\Delta D'\,\beta_{\rm nom} + \Delta D\,\alpha_{\rm nom})^2}{2\,\varepsilon\,\beta_{\rm nom}} \left(\frac{\Delta p}{p}\right)^2_{\rm r.m.s.}$$

and $\Delta\varepsilon^*/\varepsilon^*$ is given by $H - 1$ or $J - 1$. The values of H, J for the old and new optics used for the LHC beam are listed in Table 2.

Table 2: Measured betatron (H) and dispersion (J) r.m.s. emittance blow-up factors for old and new optics.

	Old optics	New optics
H (h/v-plane)	1.1/1.3	1.0/1.0
J (h/v-plane)	11.6/1.0	1.7/1.0

Although a noticeable improvement was achieved, new optics are under study to further improve the dispersion matching and to reduce J_h.

5 RESULTS: EMITTANCE EVOLUTION IN THE PS AND TT2

A measurement campaign was undertaken to evaluate the emittance blow-up between the injection of the first batch in the PS and the extraction in the TT2 transfer line for the transverse LHC beam. The beam emittance was measured at different points along the PS cycle by means of horizontal and vertical flying wires, as well as in the extraction transfer line using Secondary Emission Monitors (see Fig. 3). The absolute accuracy of such measurements is about 15-20 %. In the vertical plane almost no blow-up is observed between injection and TT2 transfer line (5 %), while in the horizontal plane a bigger effect is visible (26 %). However, the transverse beam emittance for both horizontal and vertical planes stays well below the upper limit of 3 μm and the beam is almost round as required by the LHC.

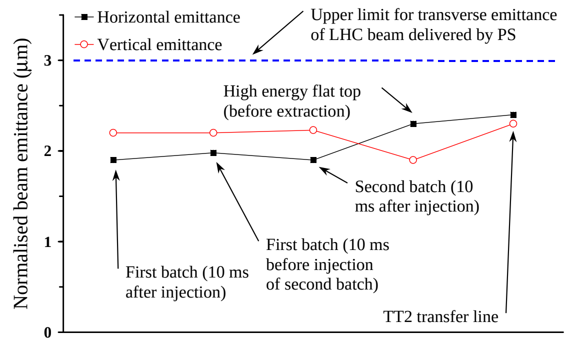

Figure 3: Evolution of the normalised transverse beam emittances $\varepsilon^*_{\rm x,y}$ from PS injection to TT2 extraction line.

6 CONCLUSION

During the 1999 run, the PS Complex produced a beam with transverse characteristics suitable for the LHC. The double-batch injection scheme was successfully tested and transverse beam emittances well below 3μm were achieved. Emittance increase from injection to extraction in the PS was measured to be about 26% and 5% in the horizontal and vertical planes respectively.

The goal for the future runs will be the production of the beam with nominal characteristics in both transverse and longitudinal planes [12].

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