CONTROLLED TRANSVERSE EMITTANCE BLOW-UP IN THE CERN SPS

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Abstract

For several years, a large variety of beams have been prepared in the LHC injectors, such as single-bunch and multi-bunch beams, with 25 ns, 50 ns and 75 ns bunch spacings, nominal and intermediate intensities per bunch. As compared to the nominal LHC beam (i.e. with nominal bunch intensity and 25 ns spacing) the other beams can be produced with lower transverse emittances. Beams of low transverse emittances are of interest during the commissioning phase for aperture considerations and because of the reduced long-range beam-beam effects. On the other hand machine protection considerations might lead to prefer nominal transverse emittances for safe machine operations. The purpose of this paper is to present the results of controlled transverse emittance blow-ups using the transverse feedback and octupoles. The procedures tested in the SPS in 2008 allow to tune the transverse emittances up to nominal values at SPS extraction.

INTRODUCTION

If the transverse emittances of some LHC beams produced in the PS complex are too small, with respect to LHC requirements, a controlled transverse emittance blow-up is now available in the SPS. The method proposed and tested relies on a combination of excitation of transverse oscillations, using the transverse feedback, and octupole lenses to favour filamentation and convert the oscillation amplitude into an emittance increase. This mechanism was already studied in 2003 [1] and applied in 2007 during machine studies on electron cloud [2], but no remote control was available at that time, and the adjustments on the transverse feedback had to be made locally in BA2. During the 2008 run, a remote control was implemented and many studies were performed to try and have an operational controlled transverse emittance blow-up by the end of the year.

The way the excitation is done with the transverse feedback is discussed in the first section, while the amplitude detuning from octupole lenses is reviewed in the second section. The results obtained for both single-bunch and multi-bunch beams are summarized in the third section, before drawing conclusions in the fourth section. The magnetic cycle used in both cases, called LHCFAST, is shown in Fig. 1 and compared to the nominal cycle which will be used for LHC filling. The differences between the two cycles are the following: (i) LHCFAST lasts 7 basic periods (i.e. 8.4 s) instead 18 basic periods (i.e. 21.6 s) for the nominal cycle, which allows for 4 batch injection; (ii) the acceleration starts 60 ms after injection on LHCFAST and the ramp is faster than on the nominal LHC cycle.

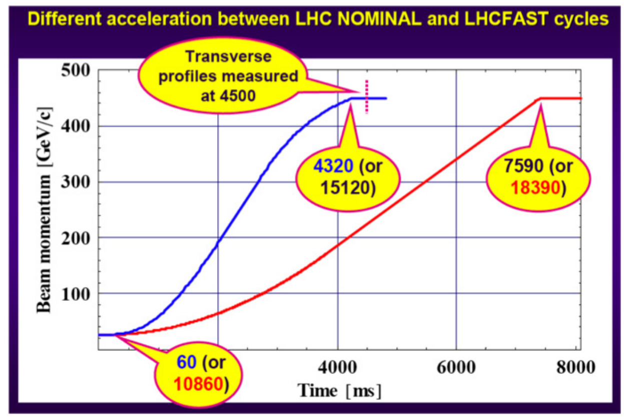

Figure 1: Comparison between the LHCFAST cycle, which was used for the blow-up studies, and the nominal LHC cycle which will be used for LHC filling with nominal intensity bunch trains.

TRANSVERSE FEEDBACK

Two feedback systems per plane are available in the SPS to stabilize the transverse coupled-bunch instabilities induced (mainly) by the resistive-wall impedance. Only one was used in each plane for the controlled transverse emittance blow-up studies. The kickers and power systems of the transverse feedback system can be used to apply an arbitrarily modulated transverse kick function to the beam within the bandwidth of the system. For the present studies the kicks were always applied in baseband, at a frequency above the half integer, i.e. $0.5 < f_{ext} / f_{rev} < 1$ where f_{ext} and $f_{rev} = 43.308$ kHz are the excitation and revolution frequency, respectively. For fractional tunes of the LHC beams in the SPS of horizontally $q_x = 0.13$ and vertically $q_y = 0.185$ the corresponding excitation frequencies cover a range from 37.7 kHz down to 35.3 kHz. The reason for choosing an excitation frequency above the half integer at the image tune line is the fact that the transverse feedback has a higher kick strength for these frequencies than at the very low frequencies corresponding to the fractional LHC beam tunes.

For a given bunch the horizontal and vertical kicks received at turn n can be expressed as

$$\Delta x'_n = \frac{L_x\, e\, V_x(n)}{d_x\, p\, c}\,, \qquad \Delta y'_n = \frac{L_y\, e\, V_y(n)}{d_y\, p\, c}\,, \qquad (1)$$

where $L_x = 2.396$ m ($L_y = 1.536$ m) is the horizontal (vertical) kicker length, e the elementary charge, $d_x = 142$ mm ($d_y = 38$ mm) the distance between the plates, p the longitudinal average momentum of the beam, and c the velocity of light (ultra relativistic beams are assumed). The horizontal and vertical kicker voltages are modulated according to

$$V_{x,y}(n) = V_{x,y}^{\max} \sin\left[\left(1 - q_{x,y}\right) n\right]. \qquad (2)$$

The maximum voltage $V_{x,y}^{\max} = 1$ kV is obtained for a control value Vpp (peak-to-peak voltage) of 1 (1.4) in the horizontal (vertical) plane. Therefore, maximum kicks of 0.649 μrad (1.555 μrad) are available at 26 GeV/c in the horizontal (vertical) plane. In practice the peak kick amplitude on a single turn is a fraction of the beam size σ down to a few percent of it. The blow-up is done during the ramp, taking into account the fact that the energy should be sufficiently high to be away from the critical point of the start of the accelerating ramp (with changing beam parameters) and to gain in aperture, but sufficiently low so that the transverse feedback system can still deliver reasonable kicks.

OCTUPOLE LENSES

In the SPS there are two families of octupoles, called LOF and LOD: 18 LOF octupoles located at large horizontal betatron function β_x ($\beta_x \approx 96$ m, $\beta_y \approx 23$ m) and 18 LOD octupoles located at large β_y ($\beta_x \approx 23$ m, $\beta_y \approx 96$ m). The nonlinear octupole lenses induce an amplitude detuning which can be written as [3]

$$Q_x\left(J_x, J_y\right) = Q_{x0} + a_x J_x + b J_y\,,$$
$$Q_y\left(J_x, J_y\right) = Q_{y0} + b J_x + a_y J_y\,, \qquad (3)$$

with

$$a_x = \frac{3}{8\pi}\int \beta_x^2 \frac{O_3}{B\rho} ds\,, \qquad a_y = \frac{3}{8\pi}\int \beta_y^2 \frac{O_3}{B\rho} ds\,, \quad (4)$$

$$b = -\frac{3}{8\pi}\int 2\beta_x \beta_y \frac{O_3}{B\rho} ds\,, \qquad < J_{x,y} > = \varepsilon_{x,y}^{rms}\,, \quad (5)$$

$$B_y = O_3\left(x^3 - 3 x y^2\right)\,, \qquad B_x = O_3\left(3 x^2 y - y^3\right)\,, \quad (6)$$

$$K_3\,[\mathrm{m}^{-4}] = \frac{1}{B\rho} \times \frac{\partial^3 B_y}{\partial x^3} = 6\, O_3\,, \qquad (7)$$

where $Q_{x0,y0}$ are the unperturbed (low-amplitude) transverse tunes, $J_{x,y}$ the betatron action variables (whose average values are equal to the physical rms transverse emittances) and $B\rho$ is the beam rigidity. The relations between the octupole strengths and currents at 26 GeV/c are given by [4]

$$K_3^D\,[\mathrm{m}^{-4}] = -\frac{0.819}{0.677} I_D\,[\mathrm{A}] = -1.2097\, I_D\,[\mathrm{A}]\,,$$
$$K_3^F\,[\mathrm{m}^{-4}] = -\frac{0.217}{0.705} I_F\,[\mathrm{A}] = -0.3078\, I_F\,[\mathrm{A}]\,. \qquad (8)$$

Here, 0.677 is the length of the LOD in the MAD sequence, while 0.705 in the length of the LOF. Note that in the application in the control room the relations were found to be slightly different

$$K_3^D\,[\mathrm{m}^{-4}] = -\frac{1}{0.8045} I_D\,[\mathrm{A}] = -1.2430\, I_D\,[\mathrm{A}]\,,$$
$$K_3^F\,[\mathrm{m}^{-4}] = -\frac{1}{2.9997} I_F\,[\mathrm{A}] = -0.3334\, I_F\,[\mathrm{A}]\,. \qquad (9)$$

In the measurements presented below for both single-bunch and multi-bunch beams, the octupoles were pulsed as shown in Fig. 2, which allowed a sequential blow-up, (firstly in the vertical plane, and secondly in the horizontal one).

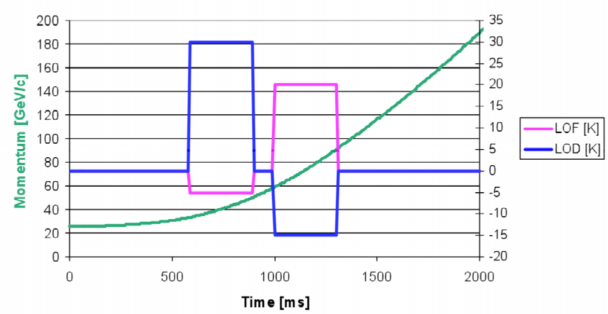

Figure 2: Excitation of the 2 families of octupoles vs. time for the blow-up studies performed in 2008.

MEASUREMENTS IN 2008

The first measurements were performed on the LHCPROBE bunch which has the smallest transverse emittance (~ 1 μm), longitudinal emittance (~ 0.2 eVs) and intensity (between ~ 2E9 p/b and ~ 5E9 p/b) [5]. An intensity of ~ 4E9 p/b was used and the four transverse feedbacks were OFF as they are not necessary for beam stabilization. Therefore in this case the transverse feedback was used only to produce a blow-up. It was shown that it is possible to blow-up the beam to ~ 3-3.5 μm in a reproducible way [6].

The results obtained with 72 bunches of ~ 1/10 of the nominal intensity will be discussed in some detail. This case is more difficult in principle than with a single bunch, as the four transverse feedbacks are already used for beam stabilization. On top of that two feedback systems should produce a controlled transverse emittance blow-up. The excitation from the vertical (horizontal) feedback started 600 ms (1000 ms) after injection and lasted 10000 turns in both cases, i.e. ~ 231 ms. The control values (Vpp) were set to 0.15 (0.1) in the horizontal (vertical) plane. It can be checked, looking at Fig. 3, that the beam was indeed kicked transversally.

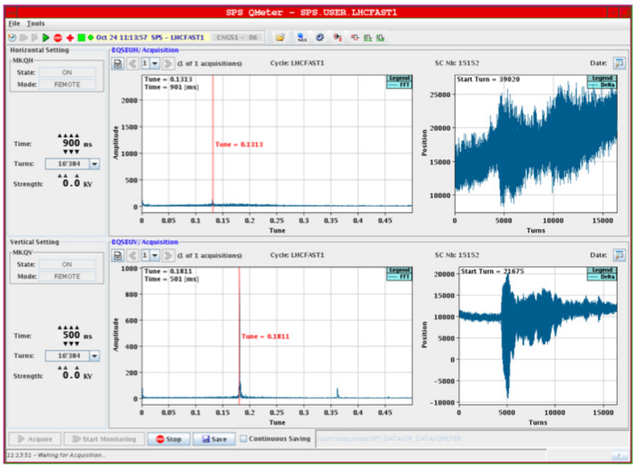

Figure 3: One of the applications used to kick the beam transversally and measure the tunes, called Qmeter: (upper left) horizontal tune and (lower left) vertical tune; (upper right) horizontal position and (lower right) vertical positions of the beam. Note the different timings.

The transverse beam profiles were measured at 450 GeV/c (see Fig. 1) using the wire scanners BWSH51995 and BWSV51995 for the horizontal and vertical planes respectively, located at small horizontal dispersion. As can be seen in Fig. 4, in the absence of controlled blow-up the transverse (rms. norm.) emittances were smaller than 1 μm. In the presence of blow-up, the emittances were increased to ~ 3 μm. As concerns reproducibility, the standard deviation of several measurements of the horizontal beam size was ~ 2.5% (i.e. ~ 5% in emittance) and ~ 5% in vertical (i.e. ~ 9% in emittance). Furthermore, according to Fig. 4 it seems

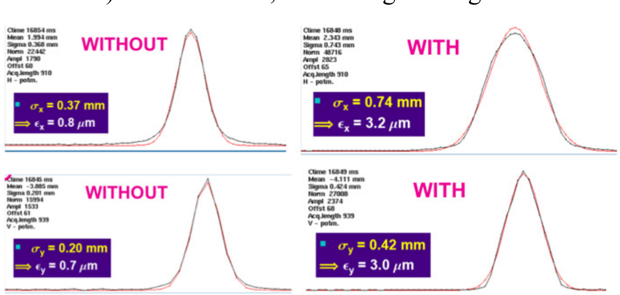

Figure 4: Transverse beam profile measurements using the wire scanners BWSH51995 and BWSV51995 at 4500 ms (see Fig. 1): horizontal/vertical profiles without and with controlled blow-up (upper/lower).

that no significant tails were produced, at least within the sensitivity of the measurement device.

CONCLUSIONS AND OUTLOOK

A controlled transverse emittance blow-up for both single-bunch and multi-bunch beams is available in the SPS from the control room since the 2008 run. It was shown that it is possible to increase, in a reproducible way, the beam transverse (rms. norm.) emittances from ~ 1 μm to ~ 3-3.5 μm. The final value of 3-3.5 μm was chosen as it is the nominal one but larger blow-ups can be achieved as well.

A simulation model [7] previously used for estimating the resulting blow-up from injection errors in LHC under the influence of damping, chromaticity and a quadratic dependence of tune with amplitude as caused by octupolar fields, could be used in the future to run simulations and compare the results with the quantitative ones presented in this paper. Furthermore, simulations can be used to further tailor the excitation program and optimize the octupole settings to achieve a given blow-up and beam profile while keeping losses to a minimum. A small modulation of the excitation frequency around the tune is expected to give good results. Band-limited noise offers the potential to achieve smoother blow-up and tailor the resulting beam profile. Simulations could be performed to try and understand better all the mechanisms involved and improvements to the already well working scheme presented in this paper could be proposed.

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