SPACE CHARGE EFFECTS AND LIMITATIONS IN THE CERN PROTON SYNCHROTRON

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Abstract

Space charge produces a large incoherent tune-spread which, in presence of betatronic resonances, could lead to beam losses and emittance growth. In the CERN Proton Synchrotron, at the current injection kinetic energy (1.4 GeV) and even at the future kinetic energy (2 GeV), space charge is one of the main limitations for high brightness beams and especially for the future High-Luminosity LHC beams. Several detailed studies and measurements have been carried out to improve the understanding of space charge limitations to determine the maximum acceptable tune spread and identify the most important resonances causing losses and emittance growth.

SPACE CHARGE AT INJECTION

The production of the LHC beams in the CERN Proton Synchrotron (PS) features a double batch injection scheme, the two injections occurring at an interval of 1.2 s during the 1.4 GeV (kinetic energy) flat-bottom [1]. This long waiting time on the injection plateau represents one of the main limitations for high brightness beams, due to the fact that for large Laslett tune shift, particles can cross deleterious resonances many times. A study of the betatronic resonances [2] has shown the most dangerous ones. As shown in Fig. 1, the resonances are identified by losses caused by their crossing.

The current operational working points are within the area Q_x=[6.1:6.24] and Q_y=[6.1:6.245], as illustrated in Fig. 1, to avoid resonances and damp head-tail instability using the transverse coupling introduced by the Q_x- Q_y =0 resonance [3], in addition to linear coupling from skew quadrupoles.

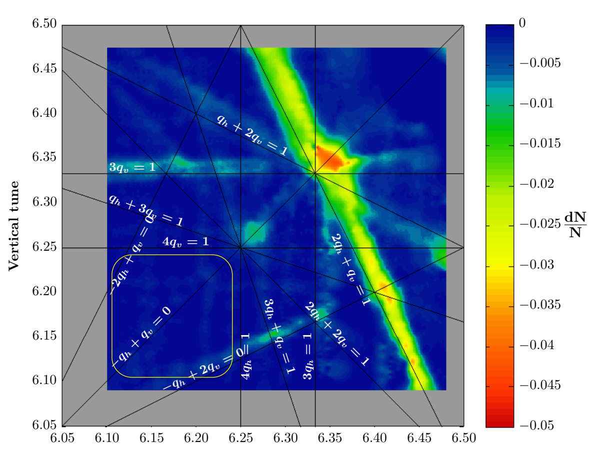

Figure 1: Tune loss map. The color code indicates losses. The operational working area is identified by the rectangle.

The typical detuning due to space charge of the nominal LHC type beams is about -0.2 in the horizontal plane and -0.28 in the vertical one [1], which means that the tune footprint is very close and sometimes even overlaps the integer stop-band. Moreover, the High Luminosity LHC beam parameters [1] imply a detuning between -0.34 and -0.37, with an allocated budget for losses and transverse emittance growth for the PS of 5% each. Therefore a study of the effect of the integer resonance is necessary, especially considering different maximum tune spreads due to space charge.

FOURTH ORDER RESONANCE

During the tune loss map measurements (with a low brightness beam), no beam losses were noticed while crossing the $4Q_y$ =25 resonance, while significant losses were observed when the vertical tune exceeded 6.25 for the measurements with a high brightness beam. This seems to indicate that the resonance $4Q_y$ = 25 is excited by space charge.

In order to observe the effect of space charge related to this resonance, losses were measured during a ramp of the vertical tune crossing the resonance twice, as shown in Fig. 2. This measurement was done for four beams with different space charge to verify if effectively space charge could excite octupolar errors present in the lattice and hence to be the cause of the excitation of the resonance.

Table 1: Maximum Detuning Due to Space Charge

Beams	ΔQ_x	ΔQ_y
Beam 1	-0.22	-0.40
Beam 2	-0.18	-0.37
Beam 3	-0.08	-0.24
Beam 4	-0.01	-0.01

The space charge forces are quantified in Table 1 using the maximum detuning due to space charge, which is estimated for the different beams according to the following equations [4]:

$$\Delta Q_x = -\frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \oint \frac{\beta_x(s)}{\sigma_x(s)\left[\sigma_x(s)+\sigma_y(s)\right]}\, ds,$$

$$\Delta Q_y = -\frac{\lambda_{max} r_p}{2\pi\beta^2\gamma^3} \sqrt{\frac{1}{\varepsilon_y}} \oint \frac{\sqrt{\beta_y(s)}}{\sigma_x(s)+\sigma_y(s)}\, ds.$$

Where, $\sigma_x(s) = \sqrt{\beta_x(s)\varepsilon_x + D_x^2(s)(\frac{\Delta p}{p})^2}$ is one standard deviation of the horizontal beam size and

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$\sigma_y(s) = \sqrt{\beta_y(s)\varepsilon_y}$ one standard deviation of the vertical beam size. λ_{max} is the maximum line density in units of number of protons/m, r_p the classical proton radius, β and γ are the relativistic factors, $\beta_{x,y}(s)$ the horizontal/vertical beta functions at longitudinal position s, $\varepsilon_{x,y}$ the horizontal/vertical physical emittances, $D_x(s)$ the horizontal dispersion function and $\frac{\Delta p}{p}$ is the rms momentum spread.

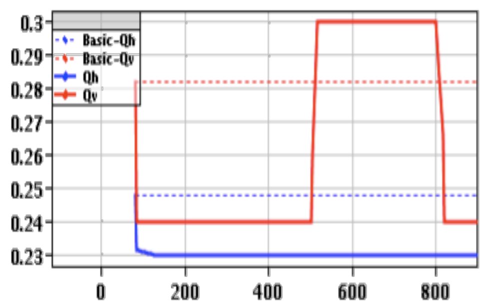

Figure 2: Horizontal and Vertical programmed tunes (continuous lines) and nominal horizontal and vertical tunes (dashed lines) along the measurement magnetic plateau.

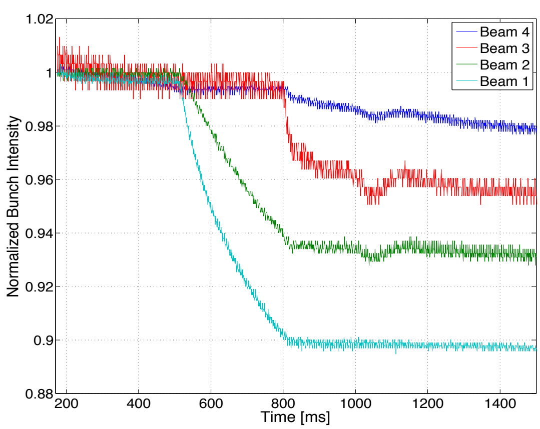

Figure 3: Losses during crossing $4Q_y = 25$ resonance.

Figure 3 shows the intensity normalized to the initial one, as function of time and for the four different beams. The main observation is that the losses are more important for beams with higher tune spread, therefore the $4Q_y = 25$ resonance seems to be excited by space charge. In the case of beam 3, losses occur only when the tune is ramped down. The reason is presently unclear will be investigated and studied in details.

EFFECT OF THE INTEGER RESONANCE

Previous Studies

Emittance blow-up and its time evolution were measured for different tune spreads and working points in a previous study in the PS [5]. A similar study was repeated taking into account the current and future requirements in terms of losses, blow-up and beam parameters, to understand the limitations and necessary improvements.

Measurement Settings

The aim of this study is to measure the emittance blow-up and losses after 1.2 s at injection energy, representing the same conditions as for the first batch of the LHC beams.

The working point Q_x= 6.23 and Q_y= 6.255 was chosen for the first measurements to have less than 5% losses.

The transverse profiles were measured using a wire scanner, which averages the beam profile during about 1000 turns. Then, using the optics model ($\beta_{x,y}(s)$ and $D_x(s)$) of the machine, emittances could be computed from the beam profiles.

The bunch was compressed adiabatically during 20 ms after injection (see Fig. 4) using a ramp of the RF voltage to vary the space charge forces. Then the beam is stored for 1.2 s at 1.4 GeV kinetic energy. Depending on the maximum voltage of the bunch compression, beams could have different space charge forces.

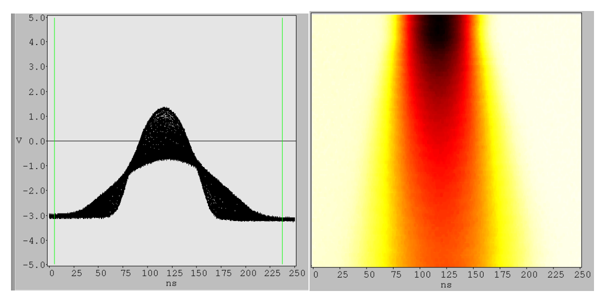

Figure 4: Longitudinal beam profiles during an adiabatic bunch compression.

The measurements were done with a single bunch beam with 1.15 10^{12} protons, a 1σ normalized emittance of about 1.6 µm in horizontal and 1.25 µm in vertical plane, rms momentum spread of 10^{-3} and a full bunch length of 180 ns before compression.

Horizontal Profile

The horizontal emittance did not show significant variations since the maximum tune spread in the horizontal plane did not exceed -0.22 with a horizontal tune of Q_x = 6.23. Therefore in the following sections, only the vertical emittance is shown.

Vertical Emittance Growth

Figure 5 presents the vertical emittance growth and losses for two working points and different tune spreads.

From the analysis of the data, the maximum beam tune spread seems to be limited between the $4Q_y$ = 25 resonance and the integer resonance. Increasing the zero current vertical tune decreases the effect of the integer resonance and therefore decreases the emittance blow-up. On the other hand it increases the population of protons crossing the 4^{th} order resonance and therefore increases losses. The choice of the working point must be a

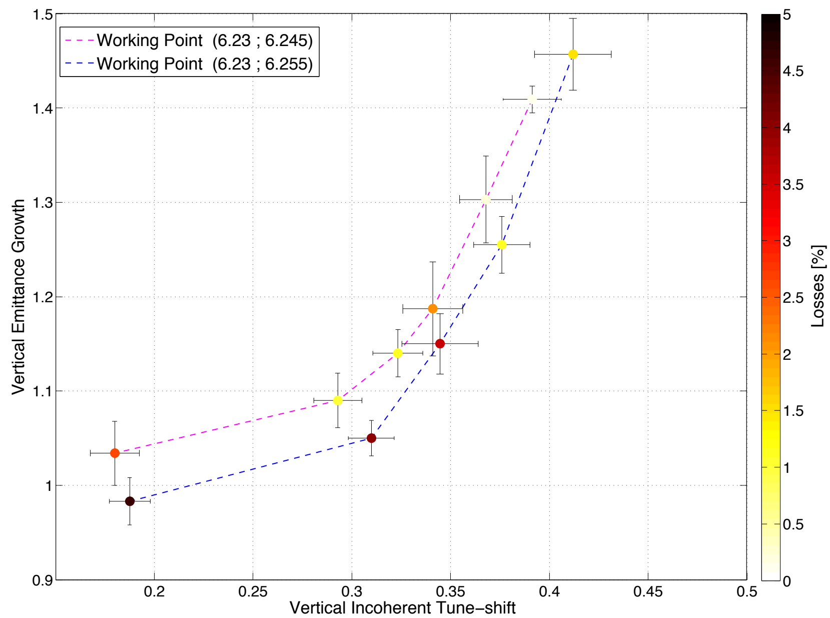

Figure 5: Emittance growth and losses after 1.2 s at 1.4 GeV kinetic energy for two different working points.

compromise between emittance growth due to the integer resonance crossing and losses coming from the crossing of the 4th order resonance.

For the same working point, losses are lower for higher tune spreads because a higher maximum detuning means fewer protons crossing the 4th order resonance.

Time Evolution of the Vertical Emittance

The time evolution of the transverse emittance blow-up was also measured for different Laslett tune shifts. The results, presented in Fig. 6, show that there are two growth regimes. The first one is a fast growth of the emittance, which lasts less than 200 ms, then the second one is much slower. The contribution of the two regimes to the final emittance increase depends on the tune spread.

This result would support the choice of single batch production scheme for LHC beams, for which a too large Laslett tune shift would be required (>-0.34), since bunches would then spend less than 200 ms at injection energy.

OUTLOOK AND CONCLUSIONS

Currently, the PS working point area for space charge dominated beams seems to be limited by the integer and the 4th order resonance. The choice of the working point is a compromise between losses caused by the $4Q_y = 25$ resonance and emittance growth due to the integer.

There are different solutions under investigation to overcome this limitation: reducing the harm of these resonances by compensating them, shortening significantly the flat-bottom, compensating the higher order resonances (*e.g.* $3Q_y = 19$) to be able to increase the vertical tune towards the half integer, reducing the tune spread by using flat bunches, increasing the average dispersion to increase the beam size.

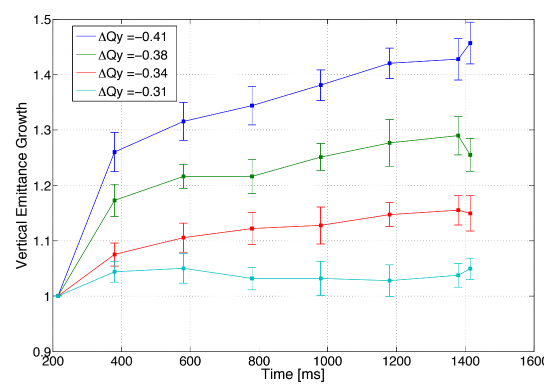

Figure 6: Time evolution of the vertical emittance blow-up for four different space charge maximum detuning.

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