# MEASUREMENTS OF TRANSVERSE SPACE-CHARGE EFFECTS IN THE CERN PROTON SYNCHROTRON

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## *Abstract*

Several beam dynamics codes are used in the design of the next generation of high beam power accelerators. They are all capable of simulating the full six-dimensional motion through a machine lattice in the presence of strong space-charge effect and beam-to-wall interaction. A key issue is the validation of these codes. This is usually accomplished by comparing simulation results against available theories, and more importantly, against experimental observations. To this aim, a number of well-defined test cases, obtained by accurate measurements made in existing machines, are of high interest. This paper reports and discusses precise measurements of transverse emittance blow-up due to space-charge induced crossing of the integer or half-integer stop band.

## 1 INTRODUCTION

Space-charge tune shifts can drive the beam onto linear and/or non-linear resonances generating transverse emittance blow-up and sometimes subsequent beam loss. Depending on how the space-charge tune spread overlaps the resonance, i.e. whether the centre or the tail of the particles distribution is in the stop-band, the beam behaviour will be completely different. The first case leads to a loss-free (if the mechanical aperture is sufficiently large) core-emittance blow-up, where the distribution is almost conserved. The second case leads to diffusion of the tail particles into a halo of increasing size, which may lead to particle losses due to the reduced dynamic aperture close to the resonance, extracting the halo particles [1].

Benchmarking experiments, which have been carried out in the CERN Proton Synchrotron (PS) for the transverse emittance blow-up due to space-charge induced crossing of the integer or half-integer stop band, are presented in this paper.

## 2 MEASUREMENTS

Three cases have been examined in detail, recording the evolution of the transverse beam profiles and emittances. All the measurements have been performed with no measurable loss. The study has been made on the long 1.2 s injection flat-bottom at 1.4 GeV kinetic energy, using a single-bunch beam of $1.7\text{x}10^{12}$ protons, with nominal horizontal and vertical rms normalised emittances of 3.3 μm and 2.6 μm respectively, and varying both the bunch length and the working point. A small amount of linear coupling due to skew quadrupoles

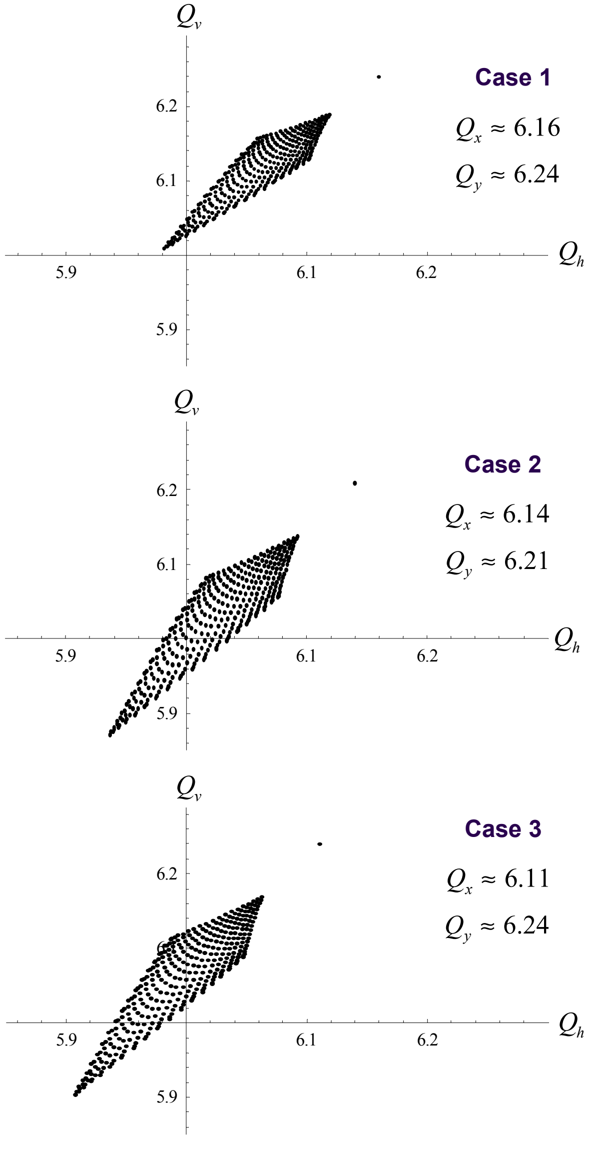


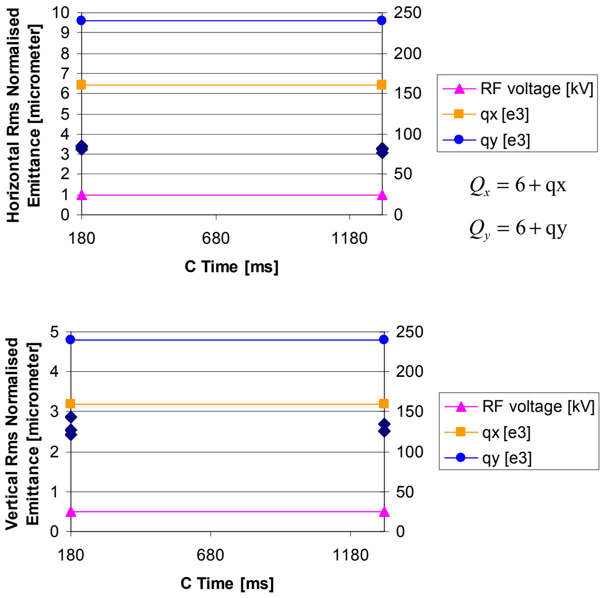
Figure 1: Plots of the computed necktie-shaped area in the tune diagram for the three cases of space-charge tune spreads considered. Case 1: full (4σ) bunch length of 180 ns, and relative momentum spread (2σ) of $2.15\text{x}10^{-3}$. Cases 2 and 3: full (4σ) bunch length of 106 ns, and relative momentum spread (2σ) of $4\text{x}10^{-3}$.

was introduced to damp a horizontal head-tail instability [2]. The skew quadrupole current was -0.33 A, which corresponds to a closest tune approach of 0.043 [2]. The three cases of space-charge tune spreads are represented in Fig. 1.

Note that the space-charge tune spreads of Fig. 1 have been computed using the Keil formula, which considers a bi-Gaussian in the horizontal and vertical plane [3]. A gap without particles between the low-intensity working point and the incoherent working points is observed as the third (longitudinal) distribution is not taken into account (see Ref. [4] where a tri-Gaussian in the horizontal, vertical and longitudinal plane is considered).

## *2.1 First case*

The first case has been chosen to be close to the emittance blow-up limit. Figure 2 shows the evolution of the horizontal and vertical rms normalised emittances (in µm) vs. time (in ms). The horizontal axis is labelled “C Time”, as all the processes in the machine are referenced with respect to a certain timing C0. In this notation, the injection is at C170. The vertical scale on the right-hand side of the picture is used for three parameters, the RF voltage (in kV), and the fractional part of the horizontal and vertical tunes ($\times 10^3$). In this first case, the RF voltage is kept constant at 25 kV, as well as the horizontal and vertical tunes, which are equal to 6.16 and 6.24 respectively. Three data have been recorded for each measurement point. It is seen in Fig.2 that there is no emittance blow-up in this case.



$$Q_x = 6 + \mathrm{qx}$$

$$Q_y = 6 + \mathrm{qy}$$

Figure 2: Horizontal and vertical rms normalised emittance vs. time, from C180 (i.e. 10 ms after injection, which is at C170) to C1300 (i.e. 1120 ms after).

The transverse beam profiles with a Gaussian fit are represented in Fig. 3. It can be seen that there is no core-emittance blow-up and that the particle distribution is conserved.

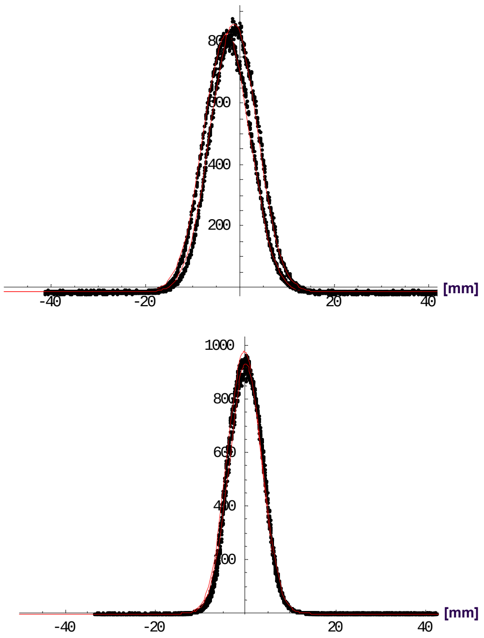


Figure 3: Initial (C180) and final (C1300) horizontal and vertical beam profiles with a Gaussian fit.

## *2.2 Second case*

In the second case, the initial (at C180) parameters are the same as in the first case. Then, steps in the RF voltage and the transverse tunes are programmed between C185 and C200, and C1200 and C1215 (the steps are

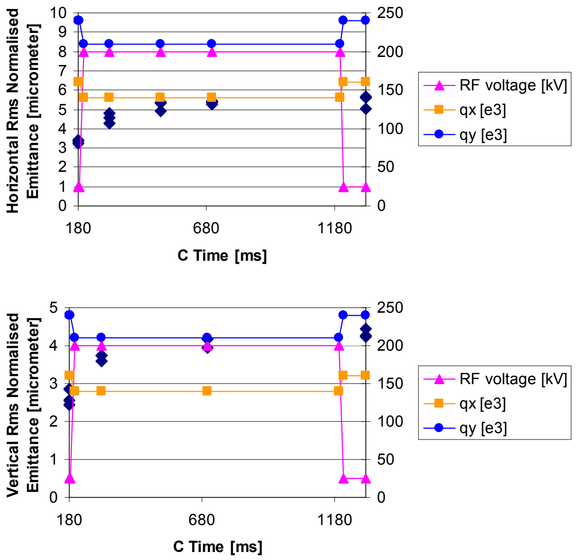


Figure 4: Horizontal and vertical rms normalised emittance vs. time, from C180 to C1300.

performed at the same time for the three parameters). The results for the transverse emittance blow-up and beam profiles are summarized in Figs. 4 and 5 respectively.

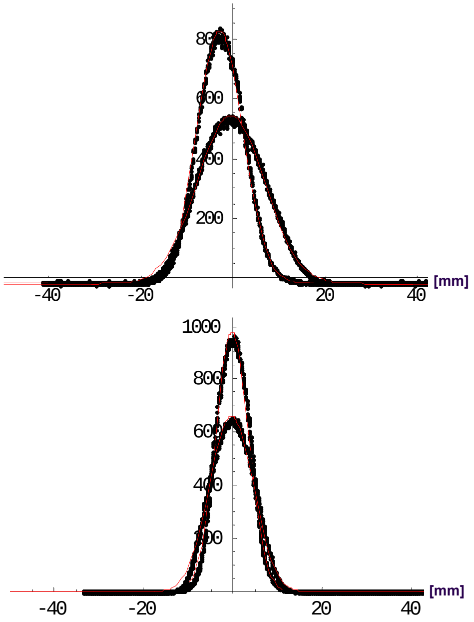


Figure 5: Initial (C180) and final (C1300) horizontal and vertical beam profiles with a Gaussian fit.

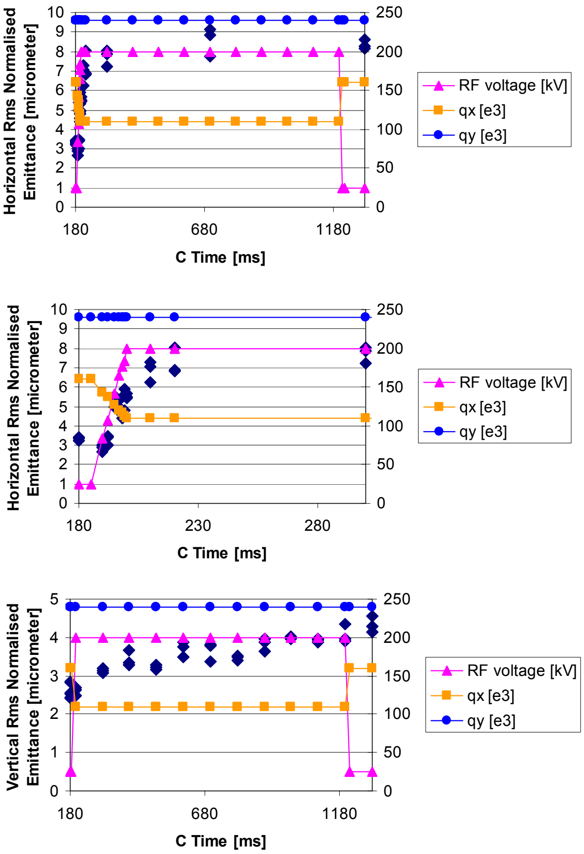


Figure 6: Horizontal and vertical rms normalised emittance vs. time.

## 2.3 *Third case*

The results for the third case are summarized in Figs. 6 and 7.

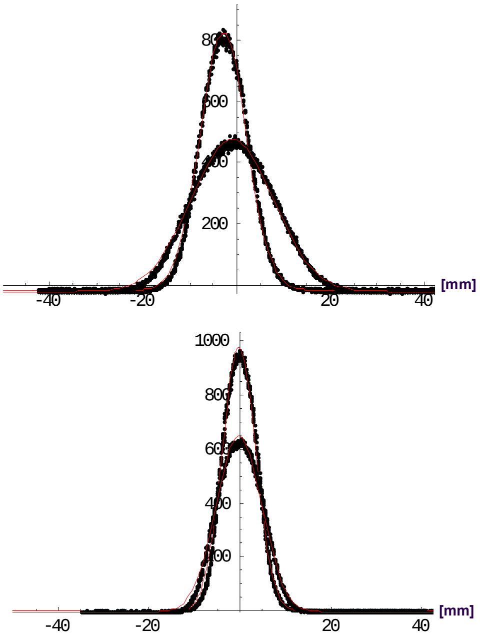


Figure 7: Initial (C180) and final (C1300) horizontal and vertical beam profiles with a Gaussian fit.

Flat bunches with reduced peak line density have also been looked at, expecting a higher transverse space-charge limit. Unfortunately, no measurable improvement has been observed. This may be due to the fact that the increase of bunching factor was less significant than what has been already achieved (~10% during these measurements, compared to ~20-30% during the 2001 run). Furthermore, the bunching factor was already very good due to the longitudinal blow-up. These measurements have to be re-done.

## 3 CONCLUSION

Measurements of transverse emittance blow-up due to space-charge induced crossing of the integer or half-integer stop band, have been performed in the CERN PS. These results could be used to benchmark the beam dynamics codes, which are used in the design of the next generation of high beam power accelerators.

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