

# CHROMATICITY EFFECTS FOR SPACE CHARGE DOMINATED BEAMS IN THE CERN PS BOOSTER

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## Abstract

In view of the LHC Injectors Upgrade (LIU) project, an extensive campaign is on-going in the CERN PS Booster (PSB) to study collective effects for the future operation with the 160 MeV injection from Linac4. In operation, the machine is running with uncorrected natural chromaticity. This paper focuses on the study of the effects of chromaticity on losses and beam blow-up.

## INTRODUCTION

The CERN PS Booster is the first synchrotron in the LHC accelerator chain. In the framework of the LIU project, a campaign of renovations takes place to host the new H<sup>-</sup> injection energy of 160 MeV from Linac4, instead of the present 50 MeV proton injection from Linac2 [1]. The main physical reason for this change is the large incoherent space charge (s.c.) tune spread that presently limits the brightness of the beams (especially for those meant for the LHC). Through the Linac4 it will be possible to tailor the transverse and longitudinal emittances in the PSB to fit the requirements of the high-luminosity future LHC beams [2]. The purpose of this paper is to investigate the effects of the chromaticity in this machine in combination with space charge. To date, the PSB is always operated with the uncorrected natural chromaticities of ( $\xi_x = -0.8$ ,  $\xi_y = -1.6$ ). The chromatic detuning can be modulated via one family of 16 normal chromatic sextupoles, distributed one per period along the machine. This limitation leads to a coupled control of the horizontal and vertical chromaticities, as shown in Fig. 1.

The interaction between chromaticity and space charge will be taken into account for negative chromaticities, to avoid the development of coherent instabilities, since the PSB is operating below transition. At an energy of 160 MeV PSB experiments close to two different resonances are being discussed to underline the correlation between the incoherent space charge tune spread and the chromatic one. The simulations are being performed with the PTC-ORBIT code [3]. Lastly, a prediction for future LHC operations is being attempted for different chromatic conditions.

## SPACE CHARGE AND CHROMATICITY

The space charge field has a defocusing effect in both the horizontal and vertical plane, see e.g. [4]. Each particle feels a s.c. detuning, which depends on the line density (protons/m) and the size of the transverse amplitudes. In addition to that, the chromaticity also induces a detuning

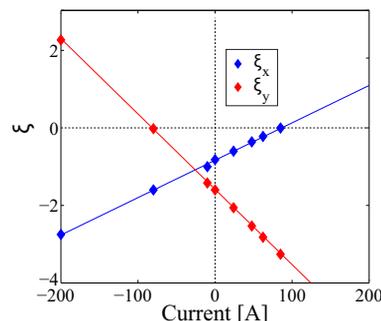


Figure 1: Measured vertical (red) and horizontal (blue) chromaticities vs. current [A] in the chromatic sextupoles.

which is proportional to the particle momentum offset  $\Delta p/p$  and the chromaticity  $\xi$  itself.

The particles in a bunch will in general feel both effects. Figure 2 shows the path of a particle with a large synchrotron amplitude, which goes from regions in which both the line density (s.c. component) and the momentum offset (chromatic component) are large, to the head or the tail of the bunch, in which the space charge tune shift is almost zero while the  $\Delta p/p$  can have a large excursion. In particular, one can consider three “branches” in its motion:

- AB - the space charge detuning is large. For positive  $\Delta p/p$  (and negative chromaticity, such as in the PSB) both effects are defocusing and they sum up;
- BC - in the vicinity of the bare tune, when the particle is sitting in the head or the tail of the bunch, the s.c. component is almost absent and the tune is moving on a line which slope depends on the ration between horizontal and vertical chromaticity;
- CD - the space charge component is large again, however for negative  $\Delta p/p$ , the chromatic detuning is positive, i.e. goes in the opposite direction with respect to the space charge one.

The orientation and the length of these three “branches” depends on the chromaticity value, on the synchrotron amplitude and on the particle actions in the horizontal and vertical plane, as explained in details in [5].

According to the chromatic working point, indeed, the entire tune footprint changes, as is shown in Fig. 3, and for the same bare tune it may or may not touch a given resonance line, e.g. the  $3Q_y = 13$ , in the case studied in this paper. Similarly to Fig. 2, Figure 4 analyses (in red) the different tune evolutions of particles performing large synchrotron oscillations, for different chromaticities: these particles are good candidates to be perturbed through the periodic resonance crossing mechanism [6].

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Table 1 shows the measured horizontal and vertical chromatic tune spread for three different sextupole settings and assuming a maximum momentum spread of  $\delta p/p=5 \times 10^{-3}$ . The maximum detuning due to chromaticity is of the order of 0.03 to 0.07. This should be compared with a space charge tune spread of 0.3 for the measurements at 160 MeV. For the present 50 MeV injection energy [4] and for the future upgrade scenario with injection at 160 MeV [2] it even exceeds 0.5.

Table 1: The maximum chromatic detuning for tunes (4.2, 4.31) and max  $\Delta p/p=5 \times 10^{-3}$  for 3 sextupole settings

| [A] | $\xi_x$ | $\xi_y$ | $\Delta Q_x$ | $\Delta Q_y$ |
|-----|---------|---------|--------------|--------------|
| 85  | -0.0026 | -3.26   | 0            | $\pm 0.071$  |
| 0   | -0.82   | -1.6    | $\pm 0.017$  | $\pm 0.035$  |
| -80 | -1.6    | -0.02   | $\pm 0.034$  | 0            |

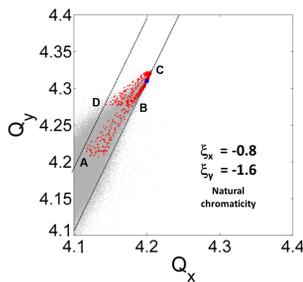


Figure 2: Zoom of the tune footprint close to the bare tune. In red the path of a particle performing large synchrotron oscillation. In blue the bare tune.

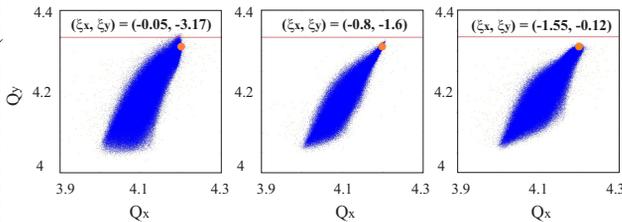


Figure 3: The space charge tune spread for different chromaticities - bare tunes (orange dot - 4.2, 4.31). The horizontal red line is the  $3Q_y = 13$  resonance.

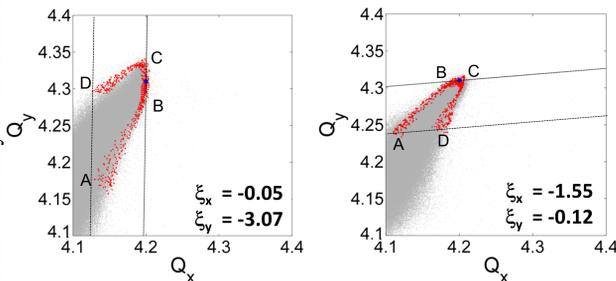


Figure 4: Path of a particle performing large synchrotron oscillations for varying chromaticities.

## THE $3Q_y=13$ RESONANCE

To investigate the upper part of the tune footprint, an artificial excitation of the  $3Q_y=13$  resonance (through a single skew sextupole powered at 30 A) has been performed in the PSB at a beam intensity of  $3.5 \times 10^{12}$  p. A systematic tune scan has been programmed: the horizontal tune is kept at  $Q_x=4.2$  while varying  $Q_y$  from 4.31 to 4.34 in steps of 0.01. For each of these points the measured losses in the machine are taken for various chromaticity values: Fig. 5 shows the case for  $Q_y=4.34$ . The chromatic change is from  $\xi_y=-1.8$  to  $\xi_y=-2.8$ , enhancing the vertical bare tune overshoot. Due to a wider part of the tune spread that interacts directly with the resonance line more losses are being found. Simulations are on-going to better understand the measurements.

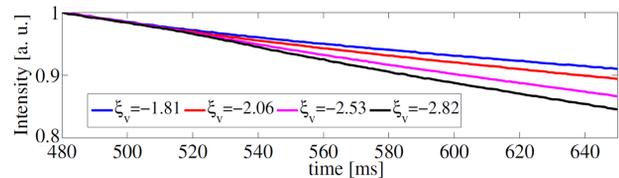


Figure 5: The measured  $3Q_y=13$  induced losses at (4.2, 4.34).

## THE $Q_x=4$ RESONANCE

The horizontal integer resonance  $Q_x=4$  is a big limitation for the future LHC beams brightness and quality [7]. Measurements have been performed to study the horizontal beam blow-up correlated with the chromaticity values, in a regime of zero losses, at low intensity ( $I=6.95 \times 10^{11}$  p) and with the horizontal tune close to the integer. The transverse profiles have been measured over 85 ms for two different values of the horizontal chromaticity:  $\xi_x=-0.15$  and  $\xi_x=-0.73$ , starting from the time in which the horizontal tune is brought down to the constant value of  $Q_x=4.06$  (at 575 ms in the cycle).

Table 2 parameters of the two sets of measurements and of the corresponding PTC-ORBIT simulations. The maximum tune shift is about  $\Delta Q_x \sim -0.12$  and  $\Delta Q_y \sim -0.14$ , however the footprints computed at the beginning of the measurement window (Fig. 6) have a different shape due to the difference in chromaticity. In both cases they overlap the horizontal integer.

Figure 7 shows the horizontal emittance evolution in both measurements and simulations, for the two chromaticities of interest, giving a positive indication that the chromaticity correction can help to reduce the beam degradation due to the interaction between a specific resonance and the global tune spread. The simulations are done with an error-less lattice, that might not fully represent the PSB measurements. However they show for the horizontal emittance a similar trend and trade-off in blow-up with respect to the measurements. In particular, most of the core blow-up occurs in the first 5 ms, that transforms the initial Gaussian shape of the beam into a wider profile. Figure 8 shows, in blue, the simulations profiles at the beginning and after 5 ms, together with the residuals (in gray) and the Gaussian fit (in red). The same behavior is present also in the wire scanners measurements.

Table 2: The  $Q_x=4$  Resonance - Study Parameters

| Initial beam parameters                | $(\xi_x, \xi_y)=(-0.73, -1.7)$ | $(\xi_x, \xi_y)=(-0.15, -2.8)$ |
|--|--------------------------------|--------------------------------|
| Bunch population [ $10^{11}$ p]        | 6.95                           |                                |
| $\epsilon_x^*, \epsilon_y^*$ [mm·mrad] | 1.66, 1.6                      | 1.68, 1.59                     |
| RF voltage (h=1, h=2)                  | 8kV, 8kV                       |                                |
| RF cavities relative phase             | $\pi$                          |                                |
| Total bunch length [ns]                | 630                            |                                |
| Momentum spread ( $1\sigma$ )          | $1.445 \times 10^{-3}$         |                                |
| Tunes [ $Q_x, Q_y$ ]                   | 4.06, 4.29                     |                                |
| Simulated [ $\Delta Q_x, \Delta Q_y$ ] | -0.121, -0.143                 | -0.117, -0.148                 |
| Simulation parameters                  |                                |                                |
| Long. s.c.                             | ON (128 bins)                  |                                |
| Transv. s.c.                           | 2.5D PIC-FFT w/o boundaries    |                                |
| N. of bins [x, y]                      | 128, 128                       |                                |
| N. of macrop.                          | 500000                         |                                |
| N. of s.c. nodes                       | 201                            |                                |

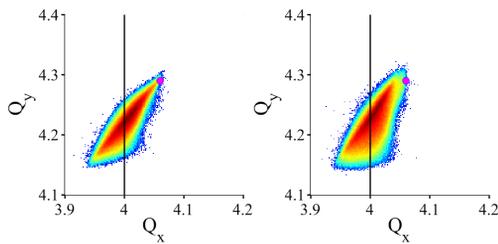


Figure 6: The tune spreads for the different chromaticities:  $\xi_x=-0.73$  - left;  $\xi_x=-0.15$  - right. The colorcode is the particle density (red - high density, blue - low density).

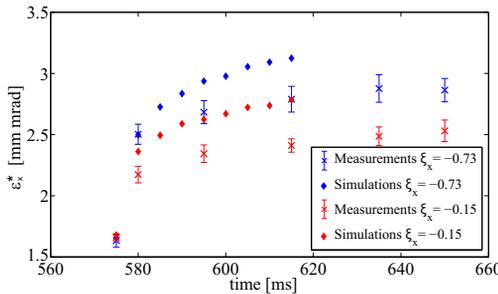


Figure 7: Normalized horizontal emittance evolution for different chromaticities (Gaussian interpolation), in measurements and simulations.

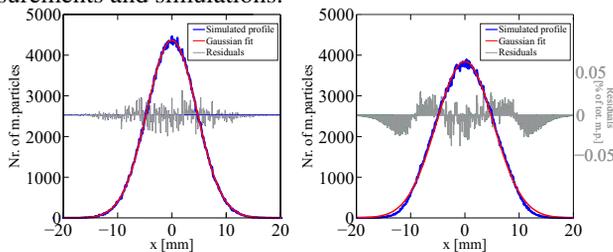


Figure 8: The simulated horizontal profile (blue) for  $\xi_x=-0.73$  at time zero - left - and after 5 ms - right.

## LIU HIGH BRIGHTNESS BEAMS PREDICTION

Lastly, preliminary simulations for the LHC beams in the LIU scenario have been performed for two settings of chromaticities,  $(\xi_x, \xi_y)=(-0.8, -1.6)$  - natural - and  $(\xi_x, \xi_y)=(-0.15, -2.8)$ .

Simulations include the modeling of the injection chicane bump, acceleration in a double harmonics bucket, injection working point of (4.28, 4.55) and target longitudinal emittance of 1.17 eVs, with the aim of defining the curve of the minimum emittance as a function of the intensity, as discussed in details in [7]. The interaction with the integer tune line causes beam blow-up, however space-charge tune spreads are in this case of the order of  $\Delta Q \sim 0.5$ . The horizontal chromaticity correction does not improve significantly the beam brightness. Figure 9 shows the normalized emittances evolution versus time assuming  $I=1.755 \times 10^{12}$  p and a starting value of  $0.4 \mu\text{m}$  in both planes. Indeed, the blow-up in the horizontal plane is reduced by a few %, as expected, due to the correction of the horizontal chromaticity. However, the vertical emittance is increasing by a similar amount, due to the fact that chromaticity, at present, is controlled by only one family of sextupoles, which causes the vertical chromatic spread to become larger, as discussed previously. An intermediate chromatic working point might be more effective.

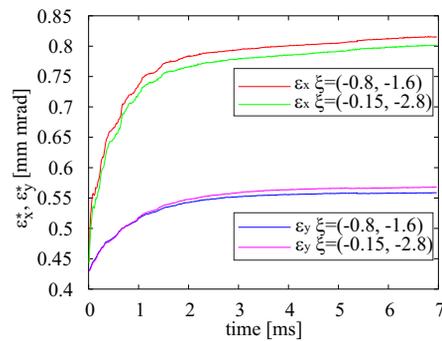


Figure 9: LIU simulations: emittance evolution.

## CONCLUSIONS

In this paper we have studied the relation between chromaticity and space charge tune spreads for the CERN PSB. For two different resonance lines the combined effect of chromaticity and space charge has been measured and simulated for space charge dominated beams. Simulations have been also performed for future high brightness LHC beams: since the correction of chromaticity in one plane (e.g. in the horizontal) as presently done in the PSB implies an increase of the chromatic tune spread in the other plane, the gain in terms of minimizing the emittance blow-up is limited. The use of chromatic sextupoles to set the chromaticity to a given value represents in any case a useful knob, e.g. if it is necessary to operate with a tune very close to a resonance line or to achieve certain beam conditions. More studies should be done, including also coherent effects, to investigate what would be the gain in getting even closer to zero chromaticity and in correcting at the same time both the horizontal and the vertical chromaticities, i.e. by installing an additional family of sextupoles in the machine.

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