# SPACE CHARGE STUDIES WITH HIGH INTENSITY SINGLE BUNCH BEAMS IN THE CERN SPS

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*Abstract*

In order to reach the target beam parameters of the LHC injectors upgrade (LIU) project the beam degradation due to losses and emittance growth on the long injection plateau of the SPS needs to be minimized. A detailed study of the dependence of losses, transverse emittance blow-up and transverse beam tail creation as function of the working point is presented here for a high brightness single bunch beam with a vertical space charge tune spread of about 0.2 on the 26 GeV injection plateau. The beam behavior close to important betatron resonances is characterized and a region in the tune diagram with minimal beam degradation is identified. Implications about the performance for LIU beams are discussed.

## INTRODUCTION

The LHC injectors upgrade (LIU) project aims at significantly improving the performance of the CERN accelerator chain within the next years in view of the High Luminosity LHC (HL-LHC) project. In fact, the SPS will have to deliver 25 ns beams with twice higher intensity and almost twice higher beam brightness compared to the nominal LHC beam available nowadays. For these beam parameters, the direct space charge tune spread will be as large as 0.2 in the vertical plane. The incoherent tune footprint might even further increase due to other collective effects such as electron cloud [1] and beam coupling impedance [2], or machine non-linearities [3]. At the same time, beam degradation due to losses and emittance growth on the 11 s long injection plateau of the SPS cycle for LHC beams need to be kept at the percent level in order to reach the LIU target beam parameters and to minimize activation of the machine.

In 2015, the beam degradation on the 26 GeV/c SPS injection plateau was studied in an extensive measurement campaign. For this purpose the SPS pre-injectors prepared a high intensity single bunch beam with a brightness comparable to the one of the LIU target parameters, i.e. an intensity of $N \approx 2e11\ (\pm 10\%)$ p/b within normalized transverse emittances of $\epsilon_x \approx 0.85(\pm 10\%)\ \mu$m and $\epsilon_y \approx 1.10(\pm 10\%)\ \mu$m measured at PS extraction. For measuring transverse beam profiles in the SPS, we used the linear wire scanner BWS.51731 in the horizontal and BWS.52171 in the vertical plane. In the SPS Q20 optics [4] with betatron tunes $(Q_x, Q_y) = (20.13, 20.18)$, the horizontal dispersion function at the location of the horizontal linear wire scanner is about $D_x = -0.5$ m and the beta function about $\beta_x = 32.5$ m. Since the horizontal emittance of the injected beam is relatively small, the beam profile at the wire scanner location contains a relatively large contribution from the momentum distribution of the bunch. Furthermore, the dispersion function at that location varies considerably when changing the horizontal tune. Figure 1 shows the dispersion function and horizontal emittance as obtained from wire scanner measurements as a function of the horizontal tune, when assuming a Gaussian distribution in momentum and horizontal phase space. When taking into account the variation of the dispersion as predicted by the MADX optics model, the horizontal emittance is almost constant when changing the working point, except for the blow-up due to space charge when approaching the integer resonance.

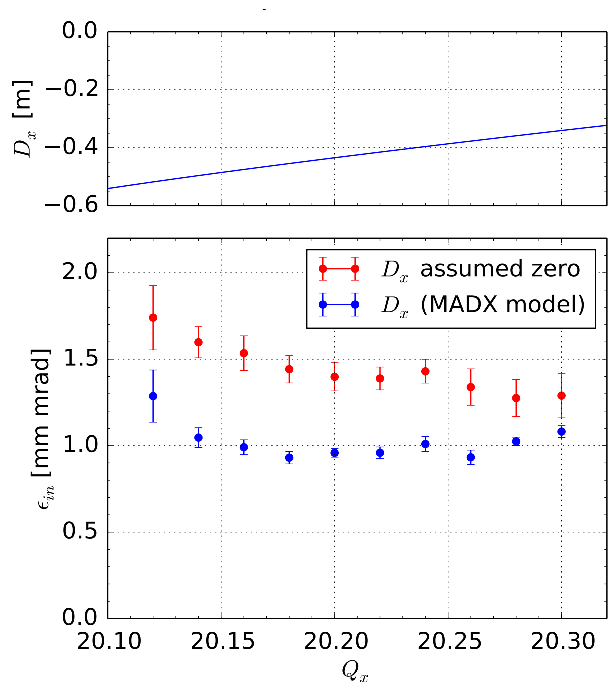


Figure 1: Theoretical horizontal dispersion at the location of the horizontal wire scanner BWS.51731 (top) and the emittance calculated with and without taking dispersion into account (bottom) as a function of the horizontal tune. The error bars correspond to the standard deviation of 5 measurements.

## DETAILED WORKING POINT SCAN

The working point operationally used for the nominal LHC beams in the SPS is $(Q_x, Q_y) = (20.13, 20.18)$. In order to avoid transverse emittance blow-up due to space charge, the vertical tune will need to be increased in order to accommodate the incoherent space charge tune spread of the future high intensity LHC beams. The aim of the study presented here was therefore to check if the area of the

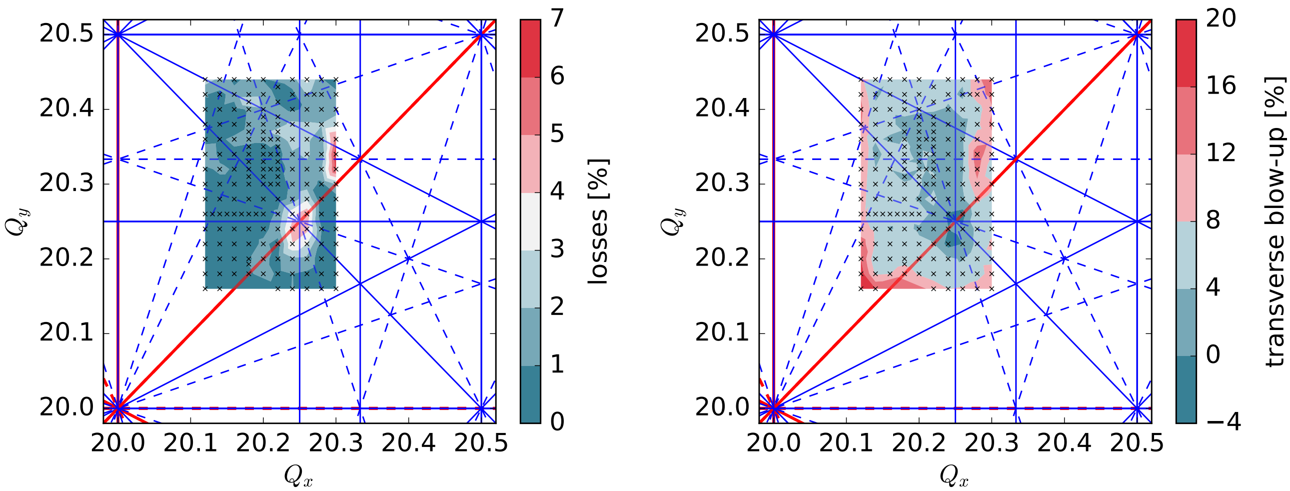


Figure 2: Relative losses (left) and transverse emittance growth averaged over both planes (right) in the tune diagram with resonances up to fourth order. The measurements were performed at the coherent tunes indicated by black markers.

tune diagram above the fourth order $Q_y = 20.25$ resonance is accessible for operation with high brightness beams.

A detailed working point scan was performed using a machine cycle with an injection plateau of around 3.5 s. For each working point, the transverse emittances were measured both at injection and just before the end of the injection plateau. Unfortunately the present hardware of the linear wire scanners does not allow to perform measurements in both planes during the same cycle. The transverse emittances were therefore determined as average of five measurements in the horizontal and five measurements in the vertical plane. Losses were calculated by relating the average intensity between 100 ms and 200 ms with the average intensity between 3000 and 3100 ms for the 10 cycles.

Figure 2 shows an overview of the relative losses (left) and of the relative emittance growth (right) for all tested working points. Losses of more than 5% and a slight reduction of the transverse emittances are observed for coherent tunes close to the crossing point of the fourth order resonances at $Q_x = Q_y = 20.25$. Even stronger losses in combination with transverse emittance blow-up of around 15% are encountered in the area around the crossing point of the third order resonances at $Q_x = Q_y = 20.33$. Excessive emittance growth but almost without losses occurs if the tunes are too close to the integer resonances, consistent with the calculated beam parameters at injection and the calculated space charge tune shift of $\Delta Q_x \approx -0.10$, $\Delta Q_y \approx -0.19$. An interesting region for operation with high brightness beams is the area below $Q_y = 20.33$ and sufficiently far away from the diagonal and the integer resonances, e.g. the working point $(Q_x, Q_y) = (20.20, 20.30)$. In this region the best beam brightness (i.e. intensity divided by emittance) was achieved, with losses of around 1% within 3 s and measured emittance growth of less than 5%. It should be emphasized that this level of blow-up is remarkably small, considering that a large part of it could be actually induced by the scattering of particles at the wire scanner during the measurement at injection [5]. The amount of emittance blow-up induced by the wire scanner measurement itself needs to be investigated in more detail in future studies in order to improve the accuracy of the results. In particular, similar measurements need to be performed with a longer storage time of the beam for estimating the beam degradation on the 11 s long injection plateau properly. Also the creation of transverse beam tails needs to be addressed in further experiments, as it was not possible to draw any conclusion on this aspect with the experimental data acquired so far.

## STUDIES OF LOSSES

The behavior of the losses in the optimal working point region identified above was studied in more detail.

First, the dependence of the losses on the transverse emittance was measured for constant beam brightness, i.e. for constant space charge tune spread. The corresponding experimental results are shown in Fig. 3. Single bunches with roughly constant brightness (about half compared to the beam used for the tune scan) were produced in the PSB by changing the number of injection turns from Linac2. An empirical fit was applied to the measured emittance as a function of the intensity in order to be able to plot the losses as a function of the average transverse emittance. Note that due to the beam coupling impedance [6] the horizontal tune remained constant during this experiment while the vertical coherent tune was changing with intensity. In fact the vertical tune reached values above the $3Q_y = 61$ resonance, which explains the losses for the cases with low emittance. Otherwise, the losses increase practically linearly with the transverse emittance for an almost constant beam brightness.

Second, the dependence of losses on the beam brightness was measured for constant transverse emittance. The corresponding experimental results are shown in Fig. 4. Adjusting the controlled longitudinal emittance blow-up before

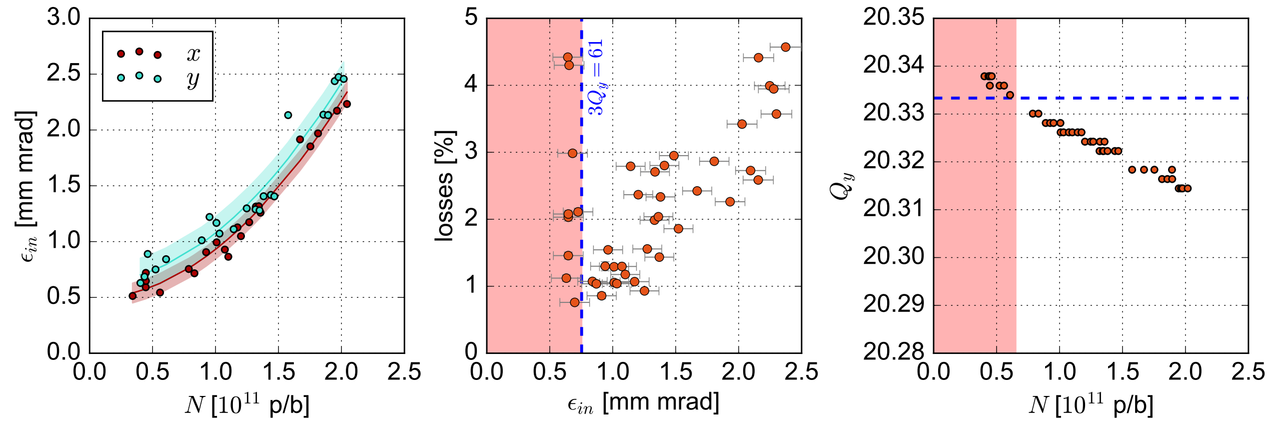


Figure 3: Constant Brightness: Transverse emittances as a function of intensity at injection (left), losses as a function of the average transverse emittance at injection (middle) and measured vertical tune as function of injected intensity (right) for a horizontal tune of $Q_x \approx 20.20$. The shaded red area indicates measurements for which the coherent tune was above the $3Q_y = 61$ resonance.

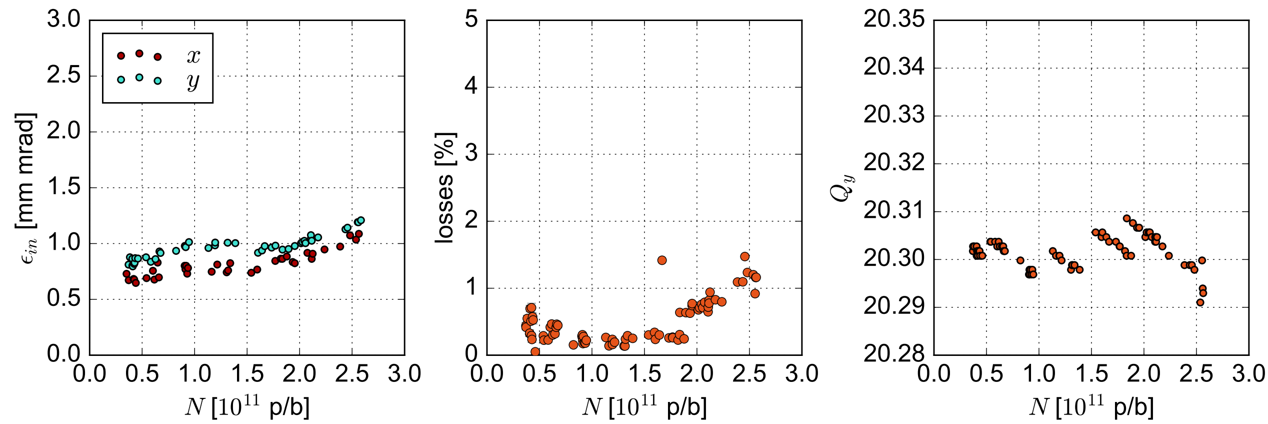


Figure 4: Constant Emittances: Transverse emittances (left), losses (middle) and measured vertical tune (right) as a function of intensity at injection for a horizontal tune of $Q_x \approx 20.20$.

going through a longitudinal acceptance bottle neck during acceleration in the PSB allows to control the intensity while keeping longitudinal and transverse emittances constant [7]. In this experiment the SPS quadrupole settings were adjusted with the change of the settings in the PSB so that the coherent vertical tune was kept close to $Q_y = 20.30$. Smallest losses are observed for intensities between 1e11 p/b and 1.8e11 p/b. The losses start to increase slightly for higher intensities. This could be either due to a dependence on the space charge tune spread, or due to the fact that the transverse emittance of the injected beam is slightly increasing. The latter would be consistent with the measurements presented in Fig. 3. For very low intensity there is also a tendency towards increasing losses.

## CONCLUSIONS AND OUTLOOK

The detailed working point scan performed in the SPS showed that the area of the tune diagram above the fourth order $Q_y = 20.25$ resonance is accessible for operation with high brightness beams. The optimum working point for a vertical space charge tune shift of $\Delta Q_y \approx -0.19$ is in the region around $(Q_x, Q_y) = (20.20, 20.30)$. In this region, the losses scale practically linearly with the transverse emittance for constant brightness. This effect needs to be studied in more detail, in particular with the LIU beam parameters, i.e. slightly higher intensity and transverse emittance. In order to exclude that the losses are caused by machine aperture limitations, future studies will aim at characterizing the SPS transverse acceptance in the Q20 optics. To this respect, the dependence of the losses on the transverse emittance but with constant intensity will also be studied.

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