CHARACTERIZATION OF LOSSES AND EMITTANCE GROWTH FOR ION BEAMS ON THE SPS INJECTION PLATEAU

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Abstract

Losses and transverse emittance growth in the Super Proton Synchrotron (SPS) impose presently the main performance limitation on the Large Hadron Collider (LHC) ion injector chain. In this paper we present the measurements performed in 2016 with Pb82+ ions and the analysis to characterize the observations of beam degradation during the long injection plateau. Residual gas scattering, intrabeam scattering (IBS) and resonance excitation have been studied.

INTRODUCTION

The LHC Injectors Upgrade project (LIU) aims at consolidating and upgrading the existing accelerator chain at CERN in view of the increased beam performance required for the High-Luminosity LHC (HL-LHC) project. The ion beam production scheme involves Linac3, the Low Energy Ion Ring (LEIR), the Proton Synchrotron (PS) and the SPS to finally inject into the LHC. The main performance limitation of the ion chain is imposed presently by the losses and transverse emittance growth in the SPS [1]. The losses increase as a function of the bunch intensity, as shown in Fig. 1 for the case of 7 consecutive injections from the PS, which was the configuration used for the LHC p-Pb physics run in 2016. For comparison, the nominal LIU bunch intensity is 3.6×10^8 Pb ions at SPS injection [2].
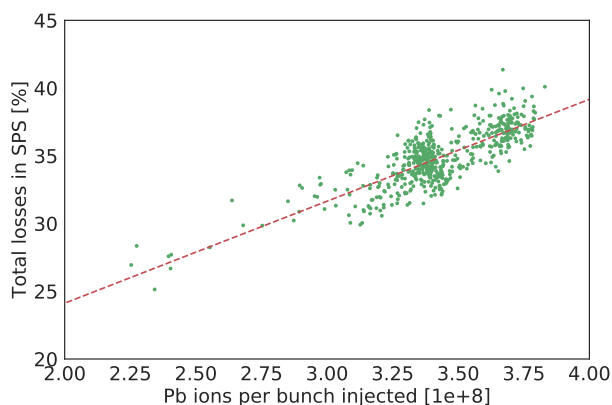

Figure 1: Total losses in the SPS as a function of bunch intensity. The nominal bunch intensity for LIU is 3.6×10^8 Pb ions at SPS injection.

A big fraction of the beam degradation occurs on the SPS injection plateau, also referred to as flat bottom (FB) in the following. At injection energy (γ=7.31, below transition energy) the beam suffers losses and transverse emittance blow-up. A 47 s long FB is needed to accumulate 14 injections from the PS and reach the required LIU beam parameters.

MEASUREMENTS

During the measurement campaign in 2016, a single injection from the PS was done at the start of the FB (defined as $t = 0$) of each cycle. Further injections were avoided in order to enable direct measurements of emittance and intensity evolution along the FB. A cycle with a 22 s long FB was prepared and the SPS was tuned to the default Pb-ion working point (WP) of Qx = 20.30, Qy = 20.25. The beam intensity measurements were taken with a bunch current transformer (BCT) with a 10 ms sampling rate. The bunch length evolution was measured with the beam quality monitor (BQM), which is triggered at each injection timing (i.e. every 3.6 s). The emittance of the beam cannot be directly measured. However, we derived the transverse emittances from the optical functions and the measurements of the transverse beam sizes performed with a horizontal and a vertical Beam Gas Ionization monitor (BGI). An advantage of the BGI over the wire scanners for beam size measurements is that the former enables measurements all along the cycle while the latter can only be used for two measurements per cycle.

Initially, we studied the beam degradation along the FB for bunches with constant intensity. We noticed that the input horizontal emittance was approximately 50% larger than the vertical one, as shown in Fig. 2 (bottom).
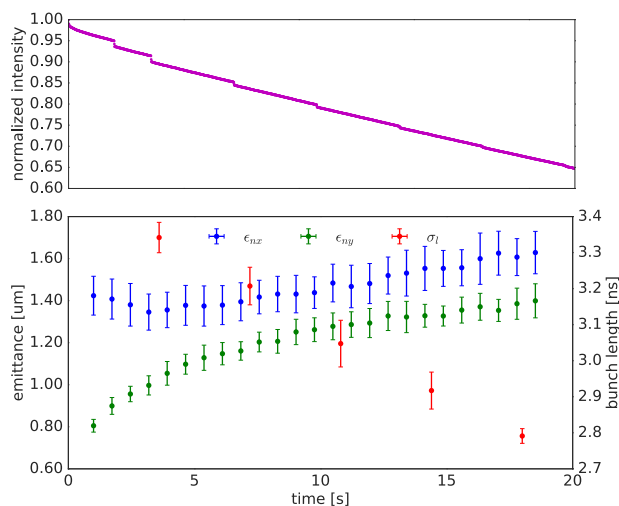

Figure 2: Normalized intensity (top), bunch length and transverse emittance (bottom) evolution along the FB for a bunch intensity of 3.5×10^8 Pb ions/bunch. The sudden intensity drops along the cycle correspond to the times a kicker in the SPS is fired in order to eliminate uncaptured beam.

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The emittances also evolved differently for both planes; while it increased steadily in the vertical plane, the overall increase in the horizontal plane was much smaller, showing even a small decrease in the first half of the cycle. A bunch length reduction of around 15 % was observed for intensity losses along the FB of the order of 35 %, as shown in Fig. 2 (top). Afterwards, we studied the beam degradation as a function of the bunch intensity. A linear decay of the transmission with a slope of 10 %/(ions per bunch [$\times 10^8$]) was measured along the FB [3].

To understand if the excitation of nearby resonances could cause the intensity losses, and to search for alternative WPs with a higher transmission and lower emittance blow-up, we explored the resonance diagram around the nominal WP by performing dynamic and static tune scans. To probe the resonances independently we used an unbunched beam, which is not affected by space charge and has an almost point-like tune footprint. Thus, we dynamically scanned the tune diagram while measuring the loss rate as a function of the working point in the absence of RF. As shown in Fig. 3, the highest loss rates were measured at the point $Q_x = Q_y = 20.33$, where the crossing of the resonances at the diagonal ($Q_x - Q_y = 0$ or $2Q_x - 2Q_y = 0$), the third order integer resonance ($3Q_x = 61$) and the third order coupling resonance ($Q_x + 2Q_y = 61$) occur. Also the third order coupling resonance ($Q_x - 2Q_y = -20$) is clearly excited. These resonances are excited by magnetic multipole errors in the machine (e.g. sextupole magnets or sextupole field errors of the main dipoles). Resonances other than the diagonal and the normal third order resonances appear to be much weaker. When the RF cavities are switched on and the beam is captured into bunches, the space-charge detuning is no longer negligible. Indeed, for the nominal beam parameters the space charge causes a maximum tune shift of $\Delta Q_x = -0.15$, $\Delta Q_y = -0.24$ at injection. The resulting tune footprint, represented in Fig. 3 over the tune scan, overlaps the excited third order resonance $Q_x - 2Q_y = -20$.

STUDIES OF BEAM DEGRADATION

Various sources may cause the measured losses and emittance blow-up; namely collective effects (IBS, space charge), RF noise, residual gas scattering, and aperture limitations. While all of them will eventually be studied, we started our investigations with the residual gas scattering and the collective effects.

Residual Gas Scattering

The scattering of the ions with the residual gas in the beam pipe may cause emittance blow-up and losses. The residual gas scattering is proportional to the ratio of the atomic number over the mass number and inversely proportional to the rest energy of the beam. Thus, a much smaller contribution is expected in the ion case compared to the proton case. We did an analytical estimation following the work from [4, 5], where the emittance blow-up of a proton beam was measured at SPS for three different energies; 55, 120 and 270 GeV, and
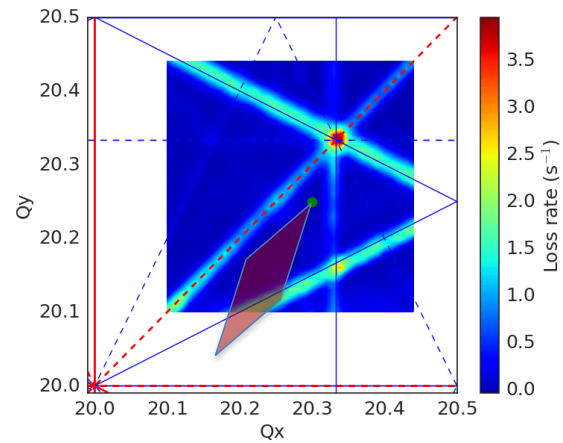

Figure 3: Tune diagram showing resonances up to third order: systematic resonances are plotted in red and non-systematic in blue, normal resonances are plotted with solid lines and skew ones with dashed lines. The standard working point is represented by a green dot. The color-code indicates the loss rate $\frac{\Delta N(t)}{N(t)}/\Delta t$ during a dynamic scan for an unbunched beam. Losses were measured at third order resonances excited by lattice imperfections. The tune footprint caused by space charge when the beam is captured into bunches overlaps the third order resonance $Q_x - 2Q_y = -20$.

compared with the corresponding analytical calculations. The radiation length parameter was used as a free parameter to match the calculations to the measurements for the three energies. The vacuum composition is likely to be similar, so we assumed the same radiation length in the ion case and calculated the contribution of residual gas scattering to the emittance blow-up to be 6×10^{-5} μm for a period of 20 s (the length of the FB). This contribution is approximately three orders of magnitude smaller than the measured emittance blow-up for the same period (see Fig. 2).

Additionally, we note that residual gas scattering is independent of the bunching factor, and predicts the same effect for an unbunched and a bunched beam. However, the emittance growth and the losses are essentially no longer observed once the RF is switched off and the beam starts debunching, as shown in Fig. 4. Thus, in the case of ion beams, vacuum effects seem to play a negligible role in the beam degradation at the SPS FB.

Collective Effects

The IBS is caused by the interaction via Coulomb scattering and momentum exchange of the ions within a bunch. For small scattering angles the random addition of events can lead to an emittance growth. As the ions are injected into the SPS below transition energy, ions with higher energy have a shorter path length and the sum of horizontal, vertical and longitudinal oscillation amplitudes is bounded. Earlier studies of IBS as a function of the SPS optics were presented in [6]. To estimate the emittance growth contribution due to IBS we performed analytical calculations with the use of the IBS module included in the MADX code [7]. When we use
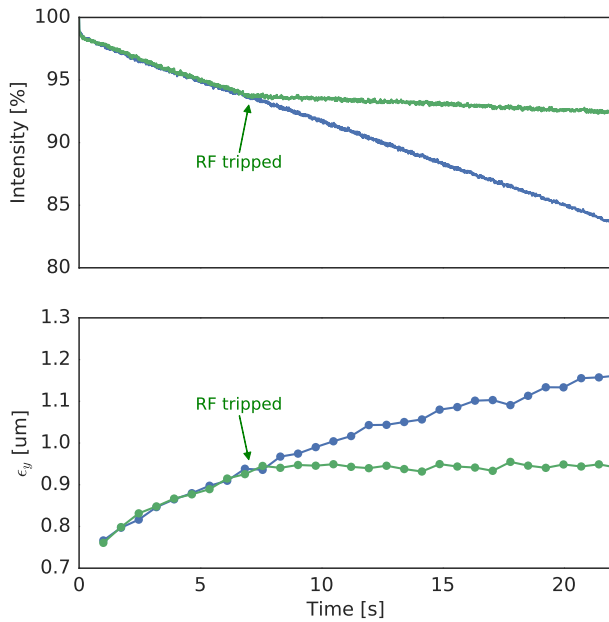
Figure 4: Comparison of intensity (up) and emittance blow-up (down) along the FB for two consecutive cycles; the first one with the RF ON (blue) and a second one in which the RF tripped at t = 7 s (green).

as input parameters for the calculations the beam parameters measured at t=0 the predicted transverse emittance growth and bunch length decrease caused by IBS are smaller than the measured ones, as shown in Fig. 5 (top). However, if we run an adaptive IBS simulation in which we update the input parameters with a time step of t=0.2 s, the difference between the modelled and the measured emittance decreases along the FB, as shown in Fig. 5 (bottom). Thus, at the beginning of the FB other mechanisms seem to dominate. It should be mentioned that the ion beam in the SPS fills the RF bucket and thus IBS might also bring particles out of the longitudinal separatrix. This needs to be studied further.

To get an estimation of the importance of space charge, we calculated the maximum tune shift it causes along the FB, see Fig. 6, as the bunch intensity is reduced and the transverse emittances increase. The third order nonlinear coupling resonance $Qx - 2Qy = -20$ is crossed by the tune footprint at injection. This resonance might explain the fact that the beam tends to become round after a few seconds of storage time. The interplay of IBS and space charge will be subject of future simulation studies.

CONCLUSIONS

A strong degradation of the Pb-ion beam is observed during the long injection plateau of the SPS, consisting of a significant reduction of the transmission and a transverse emittance blow-up. The beam losses increase linearly with the bunch intensity. The nominal working point was optimized for beam transmission. However, the large tune footprint caused by space charge overlaps an excited third
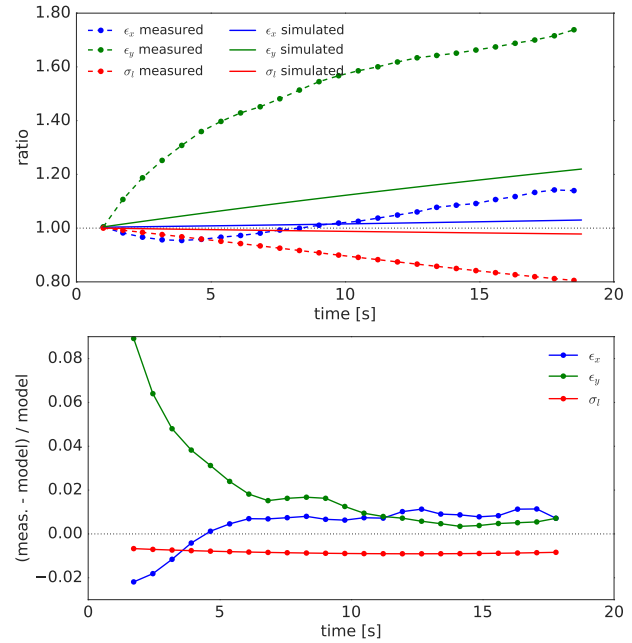

Figure 5: Measured transverse emittance growth and bunch length decrease along the FB and corresponding simulations including IBS (top). The difference between the measurements and the simulations including IBS decrease when we update the input parameters every t=0.2 s (represented as dots) along the FB (bottom).
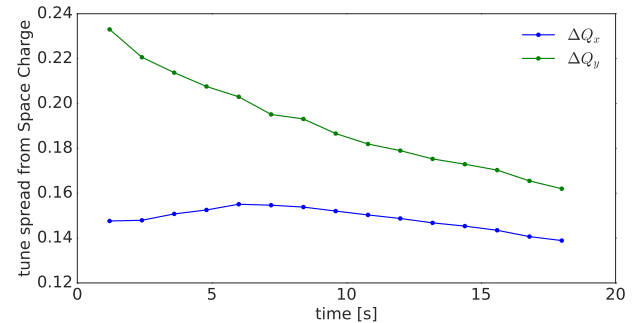

Figure 6: The maximum direct space charge tune shift varies along the cycle, mainly for the vertical plane. This occurs as intensity is reduced and the vertical emittance increases.

order coupled resonance, which might cause the beam to become round after a few seconds of storage time. We studied some possible causes of the beam degradation: the residual gas scattering seems to play a minor role, since for an unbunched beam no emittance blow-up is observed and losses stabilize. IBS cannot explain the initial vertical emittance growth rate, but can explain the growth rate once the average emittance reaches ∼1.2 μm. The difference between the measurements and the simulations including IBS is larger at the beginning of the injection plateau, where the tune shift caused by space charge is larger. Tracking simulations including space charge, IBS, and aperture limitations will follow. The impact of RF noise also needs to be studied.

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