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DETAILED CHARACTERISATION OF THE LEIR INTENSITY LIMITATIONS FOR A Pb ION BEAM

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Abstract

The equilibrium emittance of the Pb beam in the CERN Low Energy Ion Ring (LEIR) results from the interplay of electron cooling and heating processes, as intra-beam scattering and space charge. In this paper we present the measurements of the emittance evolution as a function of intensity, working point and resonance excitation, and compare them with the simulations of the heating processes. Optimum settings for normal and skew sextupoles have been found for the compensation of resonances excited by the lattice.

INTRODUCTION

The Low Energy Ion Ring (LEIR) is the first synchrotron of the heavy ion injector chain for the Large Hadron Collider (LHC). The nominal ion species for LEIR is Pb^{54+}. The LEIR cycle has a long injection plateau at a kinetic energy of 4.2 MeV/u for accumulating 7 pulses from Linac3. LEIR features a multi-turn injection with simultaneous stacking in momentum and in transverse phase space. In-between injections, the phase space volume of the beam is reduced by means of electron cooling. At the end of the accumulation process, the transverse emittances and momentum spread of the beam reach an equilibrium between the cooling and heating processes such as space charge (SC) and intra-beam scattering (IBS).

During the 2018 Pb-ion run, a record of accumulated beam intensity of 14e10 charges has been achieved, as shown in Fig. 1. Before acceleration, when the electron cooler is switched off and the coasting beam is captured into bunches by means of the radio-frequency (RF) cavities, a fraction of the beam is lost. This fraction is larger the higher the intensity of accumulated beam. Despite the higher losses a record intensity of 10.9e10 charges, 7% higher than in the previous Pb run of 2016, was extracted from LEIR in 2018. For comparison, the LEIR target intensity required for the LHC Injectors Upgrade project is about 9e10 charges [1].

To understand the driving mechanism of the losses, detailed studies of the interplay of SC forces and excited betatron resonances have been performed for different machine working points. The emittance growth and subsequent losses were simulated with the code *PyORBIT* [2], using a SC solver based on an adaptive frozen potential. A qualitative agreement with the measurements was found, as reported in [3–5]. Some excited resonances in the tune diagram were identified as a source of losses. However, the results of SC simulations could not account for all the emittance growth and beam loss observed in the measurements. In this paper we present the analytical and experimental studies of emittance growth due to IBS.

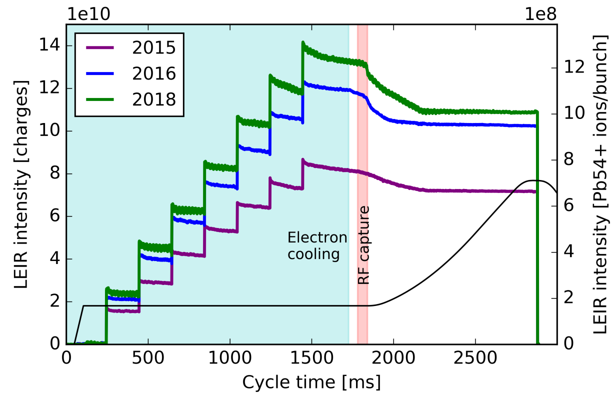

Figure 1: LEIR magnetic cycle of the nominal beam for heavy ion physics at LHC. The accumulated intensity was increased by 17% in 2018 (green), and the extracted intensity out of LEIR by 7% as compared to 2016 (blue).

MEASUREMENTS

To perform a detailed study of the IBS after the electron cooler is switched off, we measured the intensity, transverse emittances, momentum spread and bunch length evolution along the injection plateau. The beam intensity was measured with a Beam Current Transformer (BCT) at a sampling rate of 1 ms. The momentum spread before the RF capture was derived from the revolution frequency measurements taken with a longitudinal Schottky monitor, and the bunch length after the RF capture was measured with a wall current monitor. We derived the transverse emittances from the optical functions of the model and the measurements of the transverse beam sizes performed with a horizontal and a vertical Ionization Profile Monitor (IPM) at a sampling rate of 5 ms. We studied different cases: low and high-intensity beams (with 1 and 5 injections from Linac3, respectively), coasting and bunched beams, and we performed static tune scans to probe the intensity and emittance evolution as a function of the vertical tune Q_y.

The results of a static tune scan are shown in Fig. 2. A single pulse is injected from Linac3 at t = 245 ms and the large initial emittances are cooled to their equilibrium values. At t = 526 ms the cooler is switched off and the emittances start to grow as IBS and SC are no longer counteracted. At t = 580 ms the beam is captured in bunches. As the beam is compressed longitudinally it is more affected by collective

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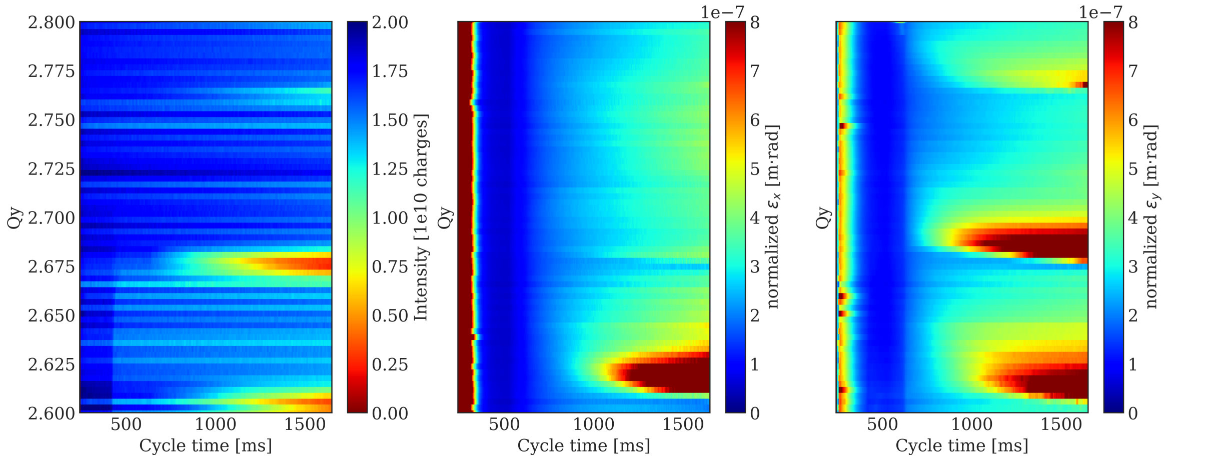

Figure 2: Evolution of the intensity and transverse emittances at the injection field for different vertical tunes with RF capture at 580 ms.

effects and the transverse emittance growth is enhanced. The growth depends on the vertical tune and large values are found above the vertical resonance at Q_y=2.66 and above Q_y=2.59, where the normal third order coupling resonance $Q_x + 2Q_y$ crosses the nominal horizontal tune Q_x=1.82.

The aperture model of LEIR was carefully updated in 2018 including the bending magnets of the arcs. Losses are predicted for geometrical emittances above 26 mm·mrad (horizontal) and 6 mm·mrad (vertical), which corresponds to normalized emittances of 2.46 mm·mrad (horizontal) and 0.57 mm·mrad (vertical) at injection energy [6,7]. Thus, the losses observed in Fig. 2 (left) are associated to the vertical emittance growth beyond the physical aperture for vertical tunes in the vicinity of the above mentioned resonances, as shown in Fig. 2 (right).

Next, we studied the nature of these resonances to understand if they are driven by SC or by lattice components (e.g. by sextupoles, fringe fields, etc). The third-order non-systematic coupling resonance $Q_x + 2Q_y = 7$ was excited by sextupolar errors in the lattice and its compensation by means of two normal sextupoles was achieved and reported in [4]. The resonance at Q_y=2.66 could be a third-order skew systematic resonance ($3Q_y$=8) excited by skew sextupole components in the lattice. We tried to compensate it with the use of a pair of skew sextupoles with appropriate phase advance. An extended range was used as compared to the study reported in [4], in which only partial compensation had been achieved. We optimized the strength of the sextupoles by performing a dynamic tune scan, i.e. maximizing the transmission while crossing the excited resonance. Almost perfect compensation was achieved, as shown in Fig. 3.

A projection of the above tune scan for a cycle time of $t = 1000$ ms is shown in Fig. 4 for two cases, with no compensation of the resonance at $Q_y = 2.66$ (top), and compensating it with the use of skew sextupoles with optimized strength (bottom). In the latter case, the losses and the emittance growth are almost constant along the vertical tune scan,

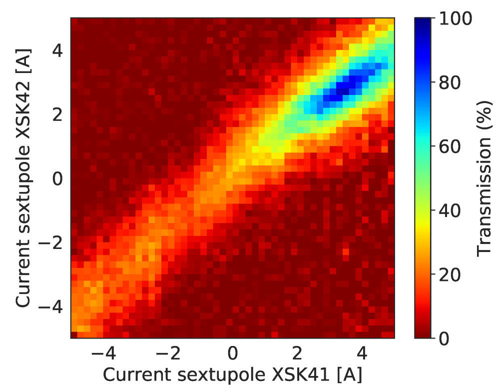

Figure 3: Beam transmission while crossing the resonance at Q_y=2.66 as a function of the currents in the sextupoles.

illustrating the compensation of the resonance and furthermore pointing towards IBS as possible source of the growth as discussed below.

COMPARISON WITH SIMULATIONS

To estimate the emittance growth caused by IBS we performed analytic calculations with the use of the IBS module included in the *MADX* code [8]. The algorithms implemented in this module have been derived from the formalism presented by J. D. Bjorken and S. K. Mtingwa [9], including the extension by M. Conte and M. Martini [10] generalized to the case of nonzero vertical dispersion. An element-by-element description of the lattice is used for the calculations and the transverse particle distribution is assumed to be bi-Gaussian. Measurements of the equilibrium beam size performed with the IPMs confirm the validity of this assumption. The IBS growth times, τ_x, τ_y, τ_s, are obtained as simulation outputs. The emittances are then calculated as a function of cycle time as $\epsilon_u(t) = \epsilon_{0u} \cdot e^{t/\tau_u}$, for $u = x, y, s$. To run adaptive IBS simulations along the injection plateau the input parameters are updated with a time step of 0.01 s.

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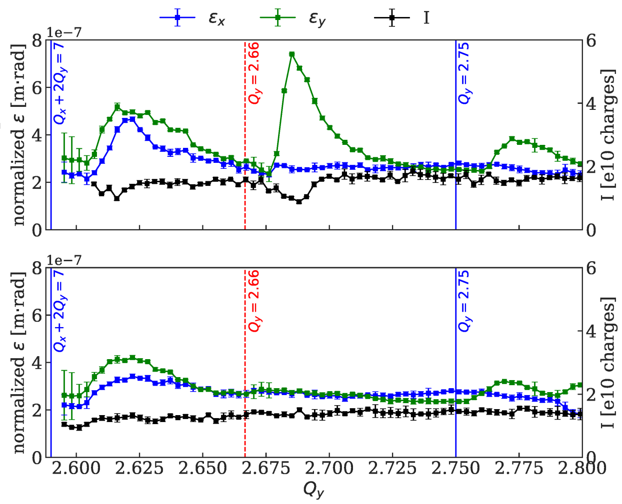

Figure 4: Measured emittances and intensity as a function of the vertical tune at t=1000 ms for the standard machine settings (top) and after compensating the excitation of the skew resonance $Q_y = 2.66$ by means of a pair of skew sextupoles (bottom).

The duration of the time steps has been optimized following a convergence study [7].

A benchmark of the MADX IBS module against the code JSPEC (Jlab Simulation Package for Electron Cooling) [11], an open source numerical package for IBS simulation developed at JLab, allowed some bug fixing and to obtain a good agreement between these two codes both for the bunched beam and the coasting beam cases.

We started the comparison of measured emittance growth with the predicted growth from IBS calculations for the nominal tunes (Q_x=1.82, Q_y=2.72). The measured beam parameters at the end of the cooling and at the end of the RF-capture were used as inputs for the coasting and bunched beam calculations, respectively. To take into account the intensity decay in the analytical calculations we updated the intensity input with the experimental intensity value for every time step of the calculation. Fig. 5 shows the measured and calculated emittances for a coasting beam with high intensity and for a bunched beam with low intensity.

A good agreement between the measurements and the IBS calculations, with differences < 2.5%, is found for the horizontal emittance growth in both, coasting and bunched beam cases. Instead, in the vertical plane, the calculations reproduce only a small fraction of the measured emittance growth, i.e. 3% vertical growth in calculations compared to the 33% measured for the coasting beam case and 34% (calculations) vs. 123% (measurements) for the bunched beam case. Investigations about possible sources for the missing vertical blow-up are ongoing [7]. Among them the vertical dispersion and transverse coupling, which are present in the machine (a vertical dispersion of 0.1 m and a coupling coefficient of 0.01 have been measured) but are not included in the lattice model used for the calculations. We

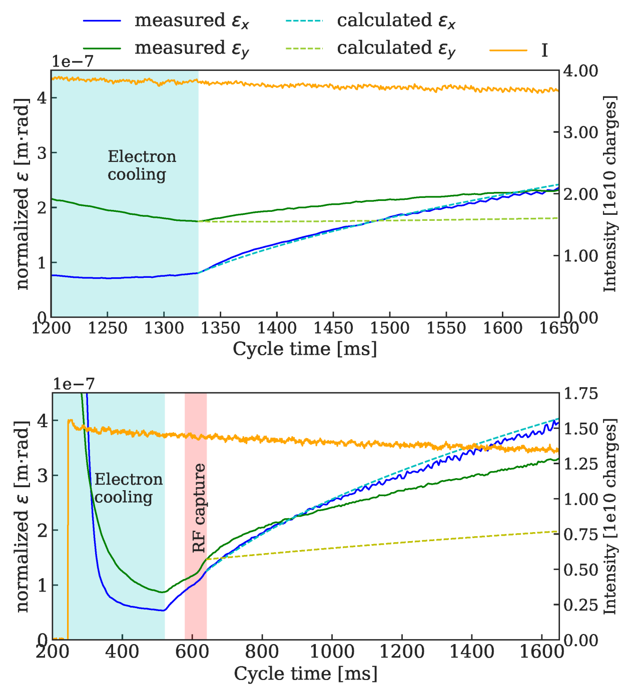

Figure 5: Comparison of the measured emittance blow-up with the calculated emittance blow-up caused by IBS for a coasting beam with high intensity (top) and for a bunched beam for low intensity (bottom).

also considered as a possible source a vertical IPM measurement which could overestimate the emittance used as input. This could be caused by a non-zero vertical dispersion at the position of the IPM. None of these effects seems to be a likely explanation, as unrealistic assumptions, e.g. a 4 times smaller vertical emittance, have to be made to explain the observed vertical growth and the emittance growth in both planes cannot be reproduced at the same time.

We also calculated the growth caused by IBS as a function of the vertical tune Q_y and found practically no dependence, as expected from the measurements shown in Fig 4 (bottom).

SUMMARY AND CONCLUSIONS

A record intensity was extracted out of LEIR during the Pb ion run in 2018. However, the losses observed when the beam is captured in bunches were enhanced with the higher intensity. Detailed experimental studies have been performed to characterize the intensity limitations and compensate excited lattice resonances. The observed emittance growth in the horizontal plane is very well reproduced by analytical IBS calculations. However IBS seems to play only a minor role for the emittance growth in the vertical plane and does not explain the experimental observations. The source of the vertical emittance growth remains to be understood. Future studies will include simulations combining the SC and IBS effects.

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