PAPER • OPEN ACCESS

Space Charge studies on LEIR

To cite this article: A. Saa Hernandez *et al* 2018 *J. Phys.: Conf. Ser.* **1067** 062020

IOP Conf. Series: Journal of Physics: Conf. Series **1067** (2018) 062020 doi:10.1088/1742-6596/1067/6/062020

Space Charge studies on LEIR

A. Saa Hernandez, D. Moreno, H. Bartosik, N. Biancacci, S. Hirlander, A. Huschauer
CERN, Geneva, Switzerland

Abstract. The performance of the CERN Low Energy Ion Ring with electron cooled ion beams is presently limited by losses occurring once the beam has been captured in the RF buckets. An intense machine study program was started by the end of 2015 to mitigate the losses and improve the performance of the accelerator. The measurements pointed to the interplay of direct space charge forces and excited betatron resonances as the most plausible driving mechanism of these losses. In this paper, we present the systematic space-charge measurements performed in 2017 and compare them to space-charge tracking simulations based on an adaptive frozen potential.

1. The LEIR synchrotron

The Low Energy Ion Ring (LEIR) is the first synchrotron of the heavy ion injector chain towards the Large Hadron Collider (LHC). It is a square-shaped accelerator with a 78.5 m circumference, consisting of four 90° dipoles and five families of quadrupole magnets. The nominal working point (WP) has a horizontal tune (Q_x) of 1.82, and a vertical tune (Q_y) of 2.72. The periodicity of the optical functions is two, as shown in Fig. 1, thus all resonances $mQ_x + nQ_y = L$ with L being an even number become systematic. LEIR is equipped with two normal and two skew sextupoles at zero-dispersion locations for the correction of third-order lattice resonances. Eight additional sextupoles are used to correct the chromaticity to zero in both planes. However, due to the large dispersion and the small tunes, the beam dynamics remains essentially linear after the chromaticity correction.

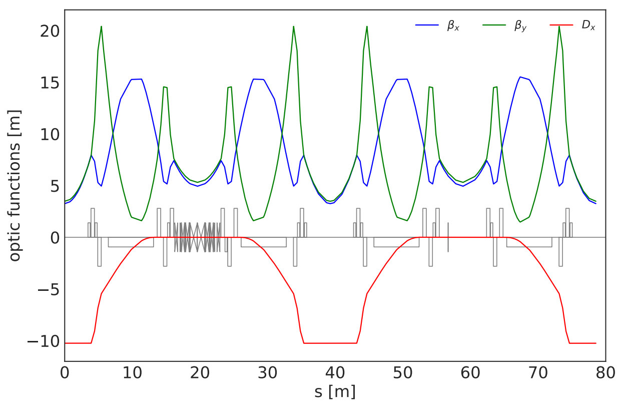

Figure 1: LEIR magnet layout and optical functions.

The beam is cooled at injection energy, where the relativistic β is 0.0945, by means of an electron cooler (EC). The EC is operated during beam accumulation and is switched off just before RF capture. A skew quadrupole and a short solenoid are placed at each side of the EC to compensate for the optics distortion and the coupling effects caused by the solenoidal field of the EC. Large losses and transverse emittance blow-up are observed just after RF capture, when the space-charge detuning increases up to $\Delta Q = 0.2$ for a high brightness bunched beam, which overlaps excited resonances. Direct space-charge forces have been identified as the most plausible mechanism for these losses and an important contribution to non-linearities in LEIR [1].

2. Measurements

During 2017 we launched a measurement campaign with Xe ions aimed to study space charge in LEIR. A single injection was made from Linac3 in order to enable clearer measurements of emittance and intensity evolution along 0.5 s of the injection plateau or flat bottom (FB). The beam intensity measurements were taken with a Beam Current Transformer (BCT) at a sampling rate of 1 ms. The bunch length was measured with the Tomoscope after the RF capture. We derived the transverse emittances from the optical functions obtained from simulations 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 performed static tune scans to probe the resonance diagram nearby the nominal WP. The experimental procedure consisted of 1) injection at the nominal WP, 2) displacement of the tunes to the desired values with the electron cooling on, to minimize the beam losses during resonance crossing, 3) RF capture, and 4) measurements of the intensity and the beam size evolution of the bunched beam along the FB. The emittance blow-up is defined as the ratio of the emittances measured at 0.5 s after RF capture compared to the measurements just after RF capture. All scans were repeated between three and five times. The measured values were averaged and the standard deviations are represented as error bars. As an example, the losses and transverse emittance blow-up measured along a vertical tune scan, at a fixed Q_x=1.82, are shown in Fig.2. We repeated the measurements as a function of the beam intensity and observed a broadening of the beam response for higher intensities, for which the space charge tune spread is correspondingly larger.

3. Model and Simulations

We have modelled LEIR as an ideal lattice with no magnetic field errors. However, as the quadrupoles are short magnets with a large aperture, their fringe fields have been included in the lattice model. The magnetic field of the EC has been included in the model as a series of solenoids with skew quadrupole kicks on both ends, following the field measurements from [2]. The gradients of the compensation elements, the skew quadrupoles and the small solenoids, result from an iterative optimization process which rematches the optics, thus restoring the two-fold periodicity of the lattice as much as possible. The dipole kicks on both EC ends have not been implemented. To bring the model closer to the measurements we have also included a tune ripple, which was observed during the 2017 run at a frequency of 550 Hz, with a horizontal amplitude of $2.5{\times}10^{-3}$ and a vertical amplitude of $7{\times}10^{-3}$.

We have performed tracking simulations including space charge using the code pyORBIT [3]. The space-charge solver is based on an adaptive frozen potential, in which the space-charge kick is calculated for a bi-Gaussian particle distribution using the field derived by Basetti and Erskine [4]. The potential is updated every n turns. For our simulations, we set typically n=1000 and track for $2{\times}10^5$ turns, equivalent to a 0.5 s long FB. We implemented 141 space-charge kicks along the lattice (17 per β-wavelength) and ran a convergence test to ensure that with 10 times more kicks the same results were obtained. The ion beam is simulated by 5000 macroparticles. The input beam parameters for the simulations, namely the intensity, the

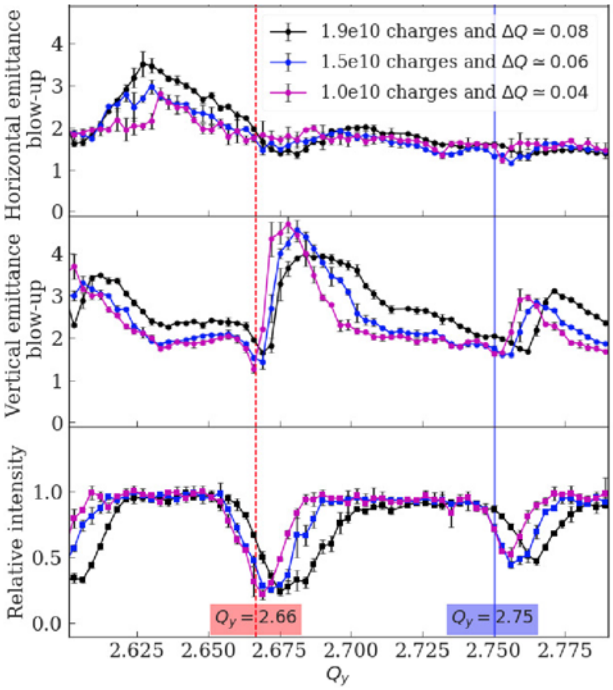

Figure 2: Static vertical tune scan, for a fixed Q_x=1.82, showing the emittance blow-up and losses along the flat bottom for different beam intensities.

transverse emittances and the bunch length, are taken from the measurements. A constant energy spread of $\Delta E = 1.45$ MeV has been considered.

4. Measurements vs. Simulations

With the aim to associate the losses to excited resonances we performed 2D static tune scans, following the procedure described above. Fig. 3 (left) shows the loss measurements over a resonance diagram. Beam loss occurs over the vertical resonances at Q_y=2.75 and Q_y=2.66, and also at the coupling resonance $Q_x + 2Q_y$ (bottom left corner). The beam is also lost at the highest limits of the 2D scan (for Q_x >1.85 and Q_y >2.80) due to the tight optics of LEIR. We compared the measured losses with the simulated ones for a similar period of time and found a qualitative agreement, as shown in Fig. 3 (right). We note that the tune shift in the simulations is larger than the one in the measurements. The simulated losses are a factor 20 smaller than the measured ones. A more precise model of the physical apertures, including not only the straight sections but also the arcs, is presently under development and it will be implemented in the next upgrade of the simulations.

We also measured the emittance blow-up for both transverse planes. As shown in Fig. 4, the vertical plane is more affected especially in the area close to the nominal WP. Three different regions, from bottom to top, can be differentiated: the blow-up which extends diagonally above $Q_x + 2Q_y$, the one which extends horizontally above Q_y=2.66, and the one which extends horizontally above Q_y=2.75. In this latter case, an emittance swap between the horizontal and vertical planes was observed when the diagonal coupling resonance $Q_x = Q_y$ was crossed (top left corner).

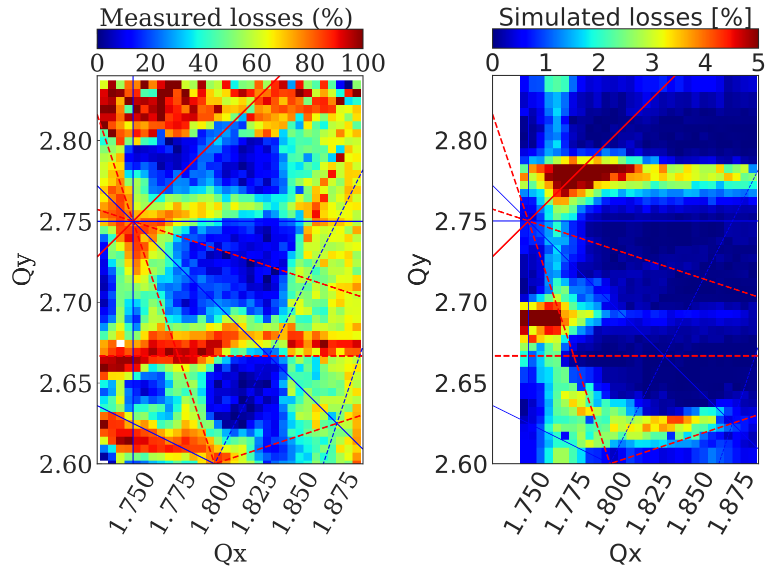

Figure 3: Losses along the FB: (left) from intensity measurements as a function of the measured tunes, (right) simulated losses as a function of the bare tunes.

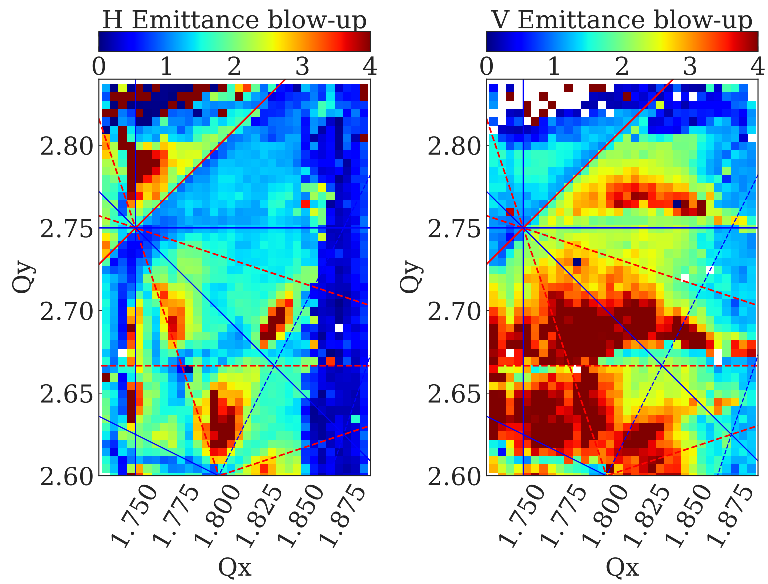

Figure 4: Measurements of emittance blow-up.

4.1. Resonance Identification and Compensation

Next, we studied the nature of these resonances to understand if they are driven by space charge or by lattice components (e.g. by sextupoles, fringe fields, etc). The third-order non-systematic resonance $Q_x + 2Q_y = 7$ could be excited by a non-periodic sextupolar error in the lattice. We identified two sextupoles, *XFN11* and *XFN32*, with a convenient phase advance, that is, with ϕ_x+2ϕ_y close to 90°. Then, we performed a vertical dynamic tune scan and crossed the resonance $Q_x + 2Q_y$ between t=1450 and t=1500 ms of the FB. We scanned the strength of both sextupoles and observed the transmission while crossing the resonance, as shown in Fig. 5.

We define as optimum sextupole settings those for which a transmission of 87% was reached, as shown in Fig. 6.

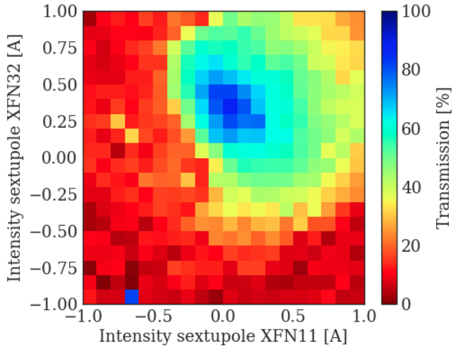

Figure 5: Beam transmission while crossing the resonance Q_x+$2Q_y$ as a function of the sextupole magnet current.

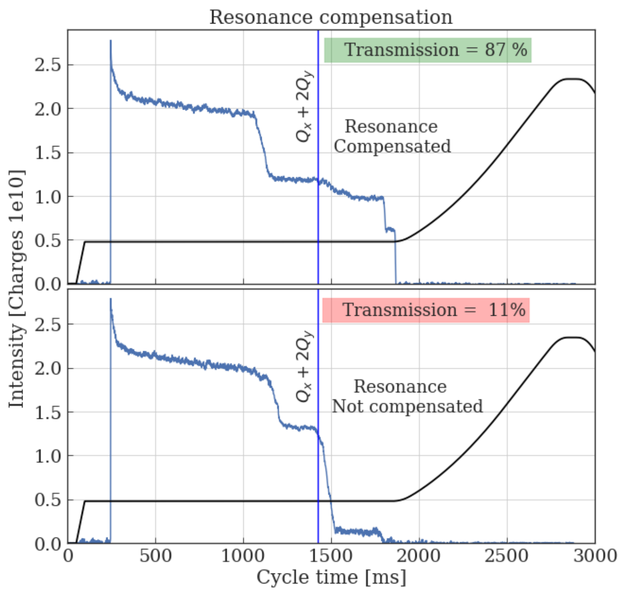

Figure 6: Beam transmission during a vertical dynamic tune scan. The resonance $Q_x + 2Q_y$ is crossed between t=1450 and t=1500 s. For the standard sextupoles settings the resonance is not compensated (bottom). With optimized sextupole settings the resonance is compensated and a 87% transmission is reached (top).

The resonance at Q_y=2.66 could be a third-order skew systematic resonance ($3Q_y$=8) excited by skew sextupolar components of the lattice. We tried to compensate it by means of the skew sextupoles using the same technique as described above. However, in this case no optimum settings were found to compensate the resonance, and the transmission could only be slightly improved, from 45% to 55%. This result could be explained if the resonance is instead a sixth-order systematic resonance ($6Q_y$=16), which can be driven by space charge [5]. We performed tracking simulations with and without space-charge kicks and compared the results. When no space-charge kicks were included a linear phase space was found. Instead, when the space-charge

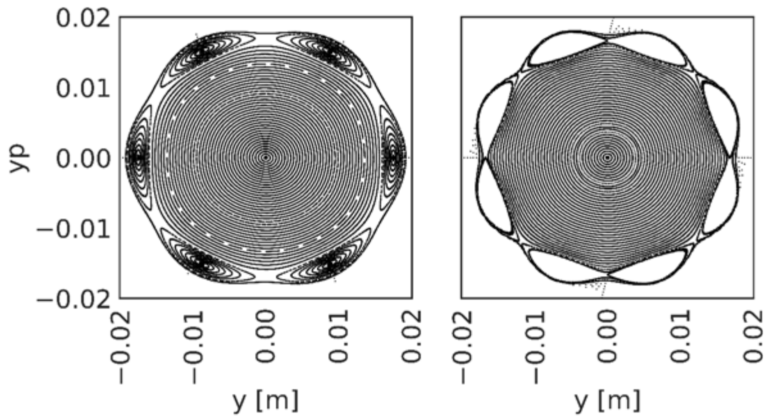

Figure 7: Vertical phase space from tracking simulations including space charge at Q_y=2.66 (left) and Q_y=2.75 (right).

kicks were included the phase-space topology of the sixth order resonance is clearly visible, as shown in Fig. 7 (left).

The resonance at Q_y=2.75 can either be a fourth-order non-systematic resonance ($4Q_y$=11) excited by octupolar components of the lattice, or an eighth-order systematic resonance ($8Q_y$=22) excited by space charge. In this case, we could not try to compensate it as there are no octupole magnets in the lattice. We ran tracking simulations with and without space-charge kicks and found a linear phase space when no space-charge kicks were included. Instead, when they were included the phase-space topology of the eighth-order resonance is clearly visible, as shown in Fig. 7 (right). These sixth and eighth order space-charge driven resonances cause the losses observed in the simulations.

5. Conclusions

Systematic space-charge studies were performed on LEIR in 2017. Several measurements were taken in order to characterize the losses and emittance blow-up for bunched beams at injection energy. Comparing the experimental data to the tracking simulations including space charge, we conclude that at least part of the losses are caused by space-charge driven resonances.

6. Acknowledgments

We acknowledge S. Albright, R. Alemany, D. Nicosia and R. Scrivens for their support in the control room.

References

[1] H. Bartosik, S. Hancock, A. Huschauer, V. Kain, *Space Charge Driven Beam Loss for cooled Beams and mitigation Measures in the CERN Low Energy Ion Ring*, in Proc. of HB2016, Malmö, Sweden.
[2] C. Carli, P. Belochitskii, M. Chanel, J. Pasternak, *LEIR Lattice*, in Proc. of EPAC 2006, Edinburgh, Scotland.
[3] A. Shishlo, S. Cousineau, J. Holmes, T. Gorlov, *The Particle Accelerator Simulation Code PyORBIT*, Procedia Computer Science, 51 (2015).
[4] M. Bassetti and G. A. Erskine, *Closed expression for the electrical field of a two-dimensional Gaussian charge.*, CERN-ISR-TH/80-06 (1980).
[5] S. Y. Lee *et al.*, *Emittance growth mechanisms for space-charge dominated beams in fixed field alternating gradient and proton driver rings.* New Journal of Physics 8, 11 (2006).