PROGRESS IN THE UNDERSTANDING OF THE PERFORMANCE LIMITATIONS IN THE CERN LOW ENERGY ION RING

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Abstract

The performance of heavy ion beams in the CERN Low Energy Ion Ring is mainly limited by beam loss occurring during the radio-frequency capture and the first part of acceleration. Since October 2015, the driving mechanism of these losses has been studied in detail and an interplay of direct space charge forces and excited betatron resonances was identified as the most reasonable explanation of the phenomenon. In this paper we summarize the current understanding of the loss mechanism by presenting recent experimental and simulation studies. We discuss strategies to mitigate beam loss and further improve the performance of the accelerator in the future.

INTRODUCTION

The Low Energy Ion Ring (LEIR) is at the heart of CERN's heavy ion physics programme and was designed to provide the high phase space densities required by the experiments at the Large Hadron Collider (LHC). LEIR is the first synchrotron of the LHC ion injector chain and it receives a quasi-continuous pulse of lead ions (Pb^{54+}) from Linac3, exploiting a sophisticated multi-turn injection scheme in both transverse and longitudinal planes. Seven of these pulses are injected and accumulated, which requires continuous electron cooling at low energy to decrease the phase space volume of the circulating beam in between two injections. Subsequently, the coasting beam is adiabatically captured in two bunches, which are then accelerated and extracted towards the Proton Synchrotron (PS). Figure 1 shows the LEIR magnetic cycle and the different steps required for beam production.

To achieve the ion intensity requirements of the High-Luminosity LHC (HL-LHC) [1,2], the major LEIR intensity limitation, namely beam loss at radio-frequency (RF) capture and during the first part of acceleration, has been studied since 2015. These studies, carried out in the framework of the LHC Injectors Upgrade (LIU) project, revealed the important interplay of betatron resonances and direct space charge effects during the bunching process [3].

In this paper, the results of more recent experimental and simulation studies, which further emphasize the importance of space charge effects, are summarized and the impact of these studies on the LEIR performance increase is discussed.

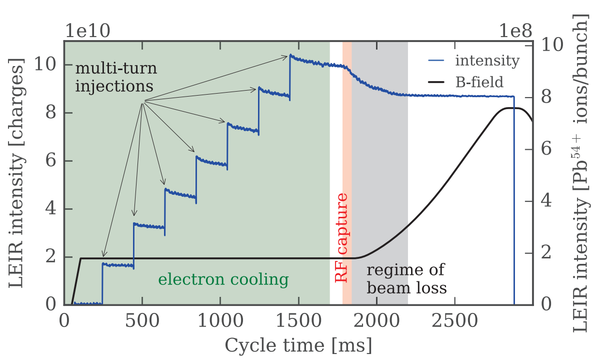

Figure 1: LEIR magnetic cycle of the nominal beam production scheme for heavy ion physics at the LHC. The intensity measurement represents values that were typically achieved during the 2016 p-Pb LHC run.

RESONANCE IDENTIFICATION STUDIES

In contrast to measurements presented in [3], a low-intensity tune scan was performed to characterize resonances close to the operational working point $(Q_{x_0}, Q_{y_0}) = (1.82, 2.72)$. A single pulse from Linac3 with roughly 2×10^{10} charges was injected and cooled at these nominal tunes, before the working point was moved to perform the scan. The beam was then bunched and stored for 500 ms at constant energy and the beam loss over this period was considered as figure of merit. This procedure was repeated for multiple working points and the results are shown in Fig. 2. The skew and the normal sextupolar resonances $3Q_y = 8$ and $Q_x + 2Q_y = 7$, respectively, are revealed to be especially strong. In addition, significant beam loss is observed close to the diagonal and the $4Q_y = 11$ resonance. For large horizontal tunes, i.e., $Q_x > 1.9$, beam loss is intrinsic to the way the lattice functions are controlled in LEIR, as the optical β-functions increase drastically.

An independent way to identify excited resonances is based on the measurement of transverse profiles. In LEIR,

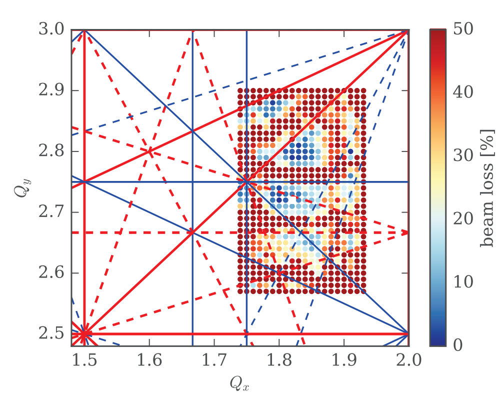

Figure 2: Measured tune diagram in the vicinity of the operational working point (indicated by the white square). The color scale shows beam loss after 500 ms of storage time. Systematic resonances are shown in red, solid and dashed lines correspond to normal and skew resonances, respectively.

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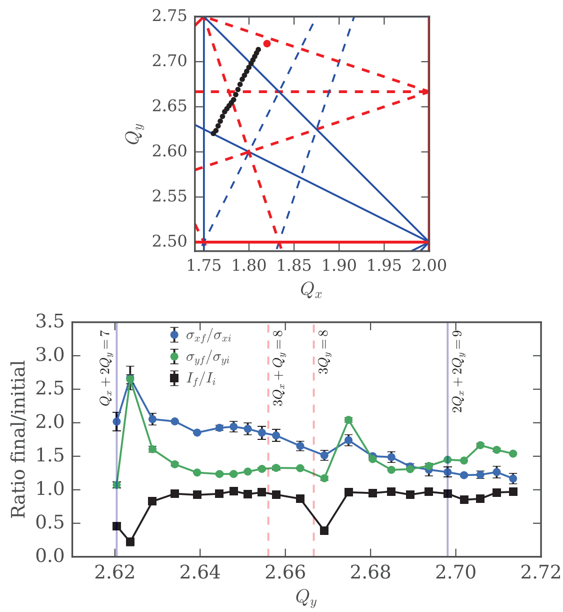

Figure 3: For each working point indicated in the tune diagram on the top, the ratio between final and initial beam sizes for each transverse plane and the corresponding intensity are shown in the bottom. The observed shift between maximum blow-up and theoretical position of resonance lines (blue and red vertical lines in the background) is compatible with the maximum direct space charge tune spread $\Delta Q_x \approx \Delta Q_y \approx -3 \times 10^{-2}$. The error bars correspond to the statistical fluctuations over three consecutive measurements.

horizontal and vertical beam gas ionisation (BGI) profile monitors are available and allow parasitic measurements of the beam size. In order to investigate the effect of the strong skew and normal sextupolar resonances on the beam, the beam size evolution at different working points was studied along the magnetic cycle and the results are shown in Fig. 3. In addition to the already discussed sextupolar resonances, an effect of the resonance $2Q_x + 2Q_y = 9$ is visible. Furthermore, for decreasing horizontal and vertical tunes, the horizontal beam size experiences a significant growth, possibly due to the resonance $4Q_x = 7$.

The driving term of these resonances remains unknown today. The presence of the electron cooler and its multitude of magnetic elements was expected to significantly contribute to the excitation of resonances. However, tests without the magnetic effects of the electron cooler were performed and no significant differences in terms of beam loss when crossing the resonances were observed. Therefore, it was concluded that the normal sextupolar resonances are likely to be excited by the main bending dipoles. A possible source of the skew sextupolar errors is yet to be determined.

Following an upgrade of the electronics of the ring pick-ups, turn-by-turn position measurements will be available in LEIR for the first time this year. This new system will then be used to study the feasibility of resonance driving term measurements.

Given the fact that the direct space charge tune spread $\Delta Q_{x,y}$ of operational beams reaches values larger than 0.1 during the RF capture process (see also [3]), particles experience the effect of multiple resonances simultaneously, which might lead to emittance blow-up and beam loss at the main aperture restriction of LEIR, i.e., the vacuum chambers inside the bending magnets. Therefore, additional studies, which are presented in the following, were performed to compensate or avoid the resonances. The latter can be achieved by modification of the machine optics.

RESONANCE COMPENSATION

With the current operational setup of LEIR, it is essential to control the transverse tunes precisely. One possible means to relax this constraint is to compensate resonances, which can be attempted by using either the eight installed chromatic or the two harmonic sextupoles. In fact, the latter are a combination of normal and skew sextupoles in a single element.

A first proof of principle has been presented in [3], where a reduction of the current in the chromatic sextupoles was observed to lead to reduced beam loss close to the resonances. Subsequently, a more systematic approach was pursued: using the Polymorphic Tracking Code (PTC [4]) library inside MAD-X [5], the resonance driving terms of the different sextupoles were computed and suitable pairs of sextupoles for compensation studies were determined. The feasibility of compensation with several of these pairs was then studied by programming the working point to lie on top of the $Q_x + 2Q_y = 7$ resonance, while scanning the current in the sextupoles and recording beam loss simultaneously. A subset of the results is shown in Fig. 4: for any combination of two chromatic sextupoles, but also by using one chromatic and one harmonic sextupole, resonance compensation can be achieved for certain currents. Surprisingly, however, no compensation could be achieved by using the pair of harmonic sextupoles, even though their functionality has been verified. This issue will be further investigated in the future.

In addition, the impact of resonance compensation on the evolution of the transverse profiles was studied. A low-intensity beam was injected, cooled and stored with active resonance compensation (corresponding to the optimum set-

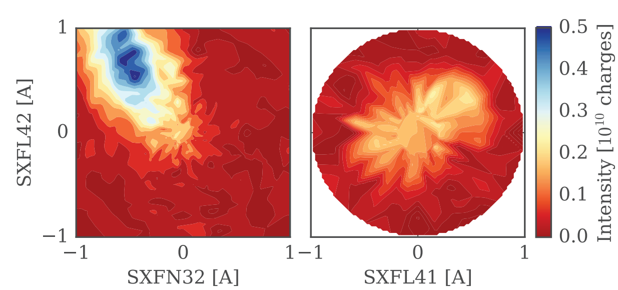

Figure 4: Beam survival after 600 ms of storage time as a function of current in the sextupoles. A combined use of harmonic (SXFL42) and chromatic (SXFN32) sextupoles clearly reveals reduced resonance excitation (left). Contrary to expectations, no such effect can be observed by using the pair of harmonic sextupoles (right).

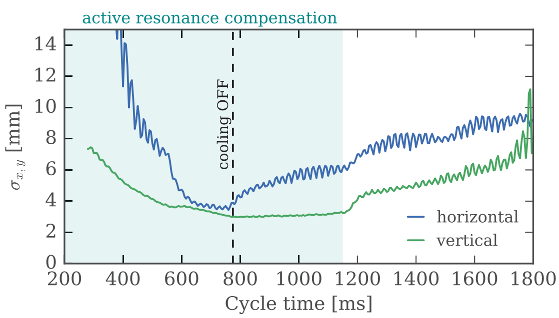

Figure 5: Impact of resonance compensation on the evolution of the horizontal and vertical beam sizes, σ_x and σ_y, respectively. Once the sextupoles are switched off, the beam immediately grows in both transverse planes.

tings found in Fig. 4) for several 100 ms. Subsequently, the compensating sextupoles were switched off and the evolution of the beam size during the entire magnetic cycle was recorded using the BGI monitor. In Fig. 5, the suppressed growth of the beam size during the first part of the cycle is clearly visible.

OPERATION AT A DIFFERENT WORKING POINT

The LEIR machine optics are significantly constrained by the multi-turn injection and electron cooling processes [6–8]. In order to modify the lattice optics and move the working point to a quadrant of the tune diagram that is less resonance dominated, a dedicated simulation study was performed and a suitable stable solution was obtained for the tunes $(Q_x, Q_y) = (2.18, 3.28)$. In Fig. 6, the optics functions for both setups are compared and the main difference concerns the β_y-functions at the entrance and exit of the bending magnets. Considering this fact, the optics modification is clearly unfavorable. However, if the overlap between the direct space charge tune spread and excited resonances is significantly reduced, emittance growth during the RF capture is also expected to be mitigated, resulting in an overall reduction of beam loss.

To investigate the resonance excitation in this new optics configuration, an additional measurement was performed.

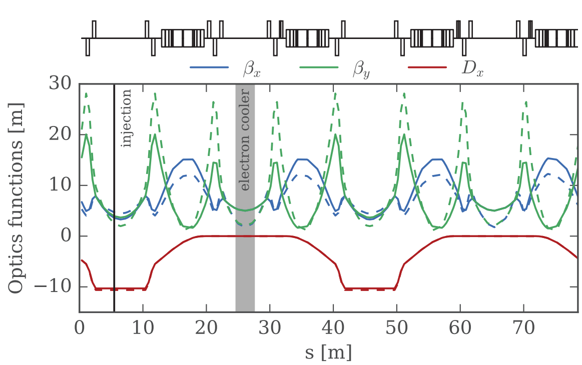

Figure 6: LEIR optics functions for the nominal (solid lines) and modified (dashed lines) settings.

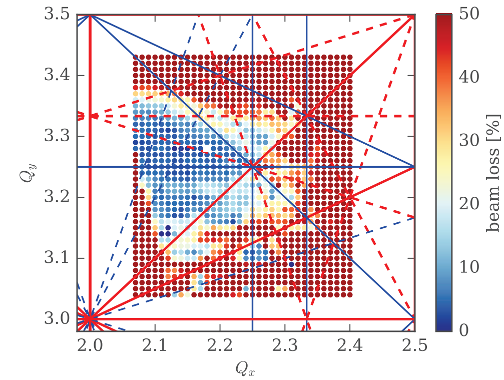

Figure 7: Measured tune diagram for the modified LEIR optics configuration. The design working point for this machine setup is indicated by the white square.

The result is shown in Fig. 7 and the resonance free area is found to be significantly increased compared to the measurements in the nominal configuration (see Fig. 2).

The continuation of the optimization of this new machine setup and the investigation of transverse emittance blow-up and beam loss are subject of future studies.

CONCLUSIONS AND OUTLOOK

The early part of LEIR operation in 2016 was fully dedicated to deepening the understanding of the performance limitations and to investigating mitigation possibilities. The combination of the results presented in this paper in combination with the excellent performance of Linac3 [9], and additional modifications of the RF capture process [10], led to the unprecedented Pb^{54+}-intensity of more than 10^{10} charges at LEIR extraction (see Fig. 8). Therewith, the HL-LHC ion intensity requirement has been operationally demonstrated in LEIR and the major remaining challenge is to maintain the high performance of the machine and Linac3, and to reduce the sensitivity of the performance to the various machine settings by exploiting resonance compensation or the modified optics configuration. Furthermore, the reduction of the time between two subsequent injections into LEIR and operation with increased electron current in the cooler is being studied to increase the accumulated intensity and provide margin for future operation.

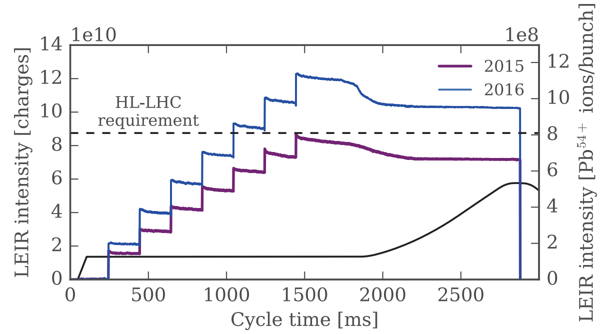

Figure 8: The extracted intensity out of LEIR was increased by 40% in 2016.

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