SPACE CHARGE DRIVEN BEAM LOSS FOR COOLED BEAMS AND MITIGATION MEASURES IN THE CERN LOW ENERGY ION RING

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Abstract

The performance of the CERN Low Energy Ion Ring (LEIR) with electron cooled lead ion beams is presently limited by losses, which occur during RF capture and the first part of acceleration. Extensive experimental studies performed in 2015 indicate that the losses are caused by the interplay of betatron resonances and the direct space charge detuning, which is significantly enhanced during bunching. Mitigation measures have already been identified and successfully tested, such as reducing the peak line charge density after RF capture, i.e. increasing the rms longitudinal emittance, and compensating third order resonances using existing harmonic sextupole correctors. New record intensities at extraction have been achieved. This talk describes the main experimental results from the 2015 measurement campaign including already implemented mitigation measures and the proposed strategy for even further increasing the LEIR intensity reach in the future.

INTRODUCTION

The Low Energy Ion Ring (LEIR) is the first synchrotron of the Large Hadron Collider (LHC) heavy ion injector chain at CERN. LEIR has accumulated, cooled and stacked ion beams of oxygen (O^{4+}), lead (Pb^{54+}) and argon (Ar^{11+}). During several machine development studies (MDs) with lead ions in late 2012 and early 2013, total intensities of up to 9.5×10^{10} charges could be achieved during the coasting beam phase. However, significant beam loss during and after RF-capture limited the available intensity at extraction to about 6.3×10^{10} charges [1,2]. In the framework of the LHC Injectors Upgrade (LIU) project, this intensity limitation for lead ion beams in LEIR has been identified as one of the main performance bottle-necks of the LHC ion injector chain [3]. In view of achieving the beam parameters required for the future LHC operation with lead ions in the High Luminosity LHC (HL-LHC) era [4], an intense machine development program was started at the end of 2015, with the aim of understanding and mitigating the particle loss in LEIR. The main outcomes of these studies will be presented in this paper.

The LEIR cycle presently used for filling the LHC with lead ion beams has a length of 3.6 s. In this scheme, seven injection pulses from Linac3, which are spaced by 200 ms (5 Hz injection rate), are accommodated on the injection plateau at a kinetic energy of 4.2 MeV/u. LEIR features a multi-turn injection with simultaneous stacking in momentum and in both transverse phase spaces. The nominal machine optics with the working point $(Q_x, Q_y) = (1.82, 2.72)$ was tuned to optimize the injection efficiency [5]. Injection efficiencies of 50-70% are achieved in routine operation, which is close to the maximum efficiency predicted by simulations [6]. Figure 1 shows the optics functions with their quasi-twofold periodicity around the 78 m machine circumference of LEIR.

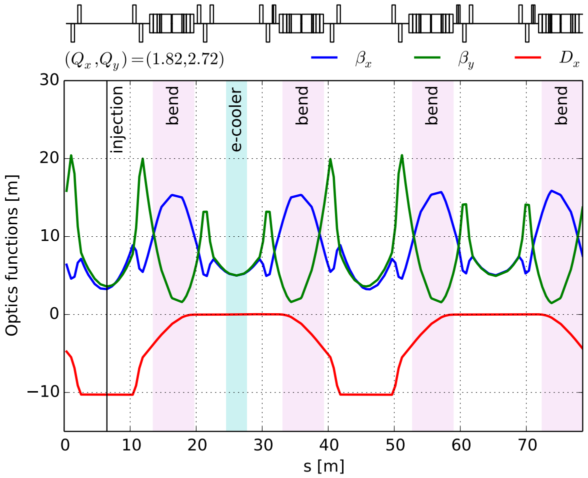

Figure 1: Optics functions along the LEIR circumference. The solenoid of the electron cooler slightly perturbs the lattice symmetry.

The phase space volume of the injected and accumulated beam is reduced by electron cooling. Subsequently, the coasting beam is captured into two bunches using a double harmonic RF system (h=2+4) in bunch lengthening mode, accelerated to a kinetic energy of 72.2 MeV/u and extracted towards the Proton Synchrotron (PS). The basic machine and beam parameters for Pb^{54+} ions are summarized in Table 1.

Table 1: LEIR Parameters for Pb^{54+} Ions

	Injection	Extraction
kinetic energy	4.2 MeV/u	72.2 MeV/u
relativistic β	0.095	0.392
relativistic γ	1.0045	1.087
circumference	25 πm	
transition γ_t	2.84	
working point Q_x/Q_y	1.82 / 2.72	

Figure 2 shows the intensity evolution along the LEIR magnetic cycle for different Linac3 beam current levels with typical loss patterns. Injection efficiencies of 50-70% and low beam loss rates during the electron cooling on the injection plateau are achieved even with the presently maximum available Linac3 pulse current of about 30 μA. At the moment, the accumulation of seven Linac3 pulses does not

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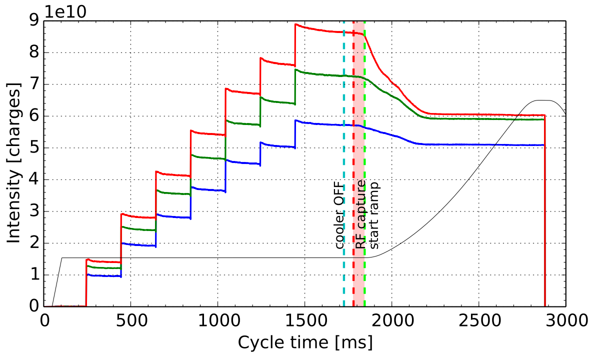

Figure 2: Intensity evolution along the LEIR cycle for different Linac3 current levels. The vertical lines indicate the cycle times where the electron cooler is switched off (cyan), and where the RF capture (red) and the acceleration (green) start. RF capture takes 60 ms as indicated by the red area. The magnetic field of the LEIR main bending magnets in arbitrary units is illustrated by the grey line.

constitute an intensity limitation in LEIR, but the achievable maximum intensity at the end of the injection plateau is determined by the Linac3 performance. However, losses after RF capture and during the early part of the acceleration critically depend on the accumulated beam current, and the maximum reachable intensity at the extraction plateau appears to saturate. Until recently, the underlying mechanism causing these losses was not understood. Among others, transverse space charge, transverse instabilities induced by the beam coupling impedance, electron cloud effects, and hardware issues have been suspected. As discussed in detail below, the experimental studies performed at the end of 2015, and the few weeks of beam operation in 2016, indicate that the losses are induced by the interplay of betatron resonances and the direct space charge detuning, which is significantly enhanced during bunching. No indication for coherent instabilities could be identified so far.

CHARACTERIZATION OF THE LEIR PERFORMANCE LIMITATION

Dependence of Losses on Line Charge Density

Figure 3 shows a comparison of the intensity evolution along the LEIR cycle for three different longitudinal phase space distributions. In all three cases the RF voltage functions were programmed such as to perform an iso-adiabatic capture of the coasting beam. The momentum spread of the coasting beam just before RF capture was adjusted using a periodic modulation of the electron gun voltage [5]. This allowed to tailor the longitudinal emittance of the two bunches after capture. In two cases the beam was captured in single harmonic. The losses clearly decrease when the bunching factor (BF), i.e. the average line density divided by peak line density, becomes larger. In other words, enhanced losses are observed in case the peak line charge density is too big. Note that the incoherent tune spread due to direct space charge is directly proportional to the peak line charge density, or inversely proportional to the bunching factor.

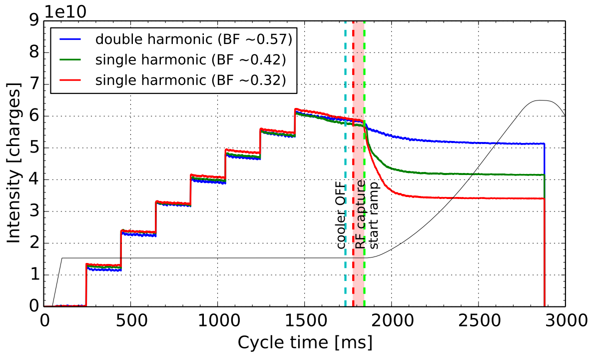

Figure 3: Comparison of losses for different line densities. The bunching factor is indicated in the legend.

Transverse Emittance and Space Charge Tune Shift

The Beam Ionization Profile Monitors installed in LEIR allow to measure the transverse beam sizes along the cycle. The normalized emittances can be reconstructed using the optics functions of the MAD-X model and the rms momentum spread measured with the longitudinal Schottky monitor (typically around 1×10^{-3} after cooling). Figure 4 shows the measured normalized transverse emittances, the intensity along the cycle, and the calculated transverse direct space charge tune spread relative to the nominal bare machine working point in the tune diagram together with resonances up to third order: at the moment when the electron cooler is switched off, the beam is still coasting and the space charge induced tune spread is concentrated in the lower half between the bare working point and the maximum tune shift. The tune footprint is on top of the skew sextupole resonance $3Q_y = 8$ and the vertical emittance starts to grow (partially also due to intra beam scattering). This emittance growth is enhanced during the RF capture process and for the bunched beam. Once the beam is fully bunched, the direct space charge tune spread reaches its maximum value, and significant losses are observed. At that point, the tune footprint covers several betatron resonances (skew and normal) of third (and fourth) order.

A special configuration of the LEIR cycle was used in order to check the behaviour of the bunched beam after RF capture on the injection plateau. Thanks to the improved current from Linac3 in 2016, intensities of almost 8×10^{10} charges could be accumulated with only four injections. Figure 5 shows the intensity evolution along the cycle in this configuration, together with the space charge tune spread at the moment when the electron cooler is switched off (600 ms earlier compared to the standard settings) and after RF capture is completed (advanced by 200 ms).

Vertical emittance growth is observed as soon as the cooling is switched off; however, this does not lead to a change

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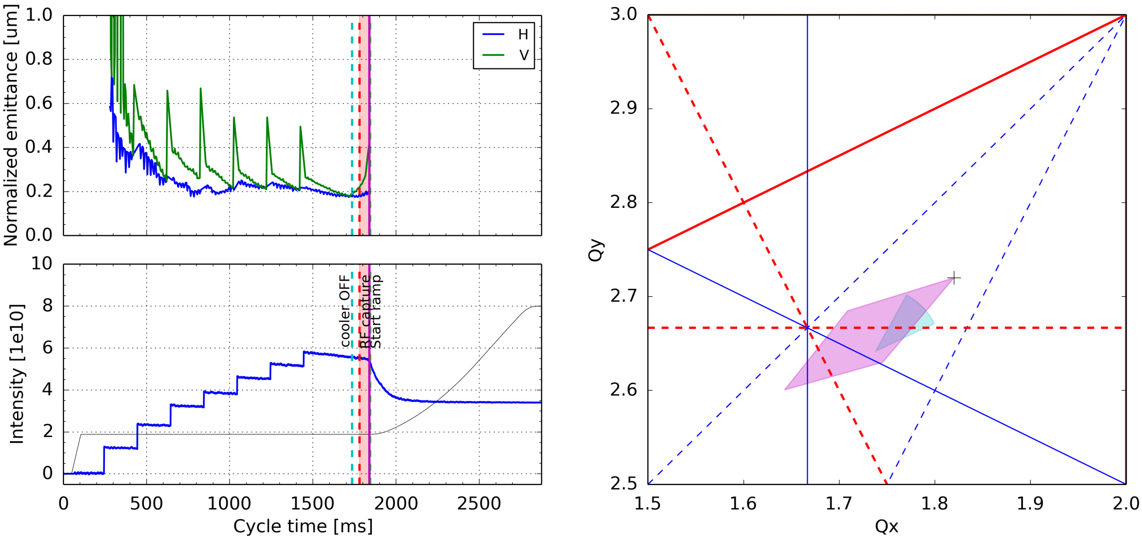

Figure 4: Normalized transverse emittances and intensity along the LEIR cycle in the operational configuration (left). The vertical cyan and magenta lines indicate the cycle times where the electron cooler is switched off and the capture process is completed, respectively. The corresponding calculated space charge tune spreads relative to the bare working point are illustrated in the tune diagram with the same colours (right).

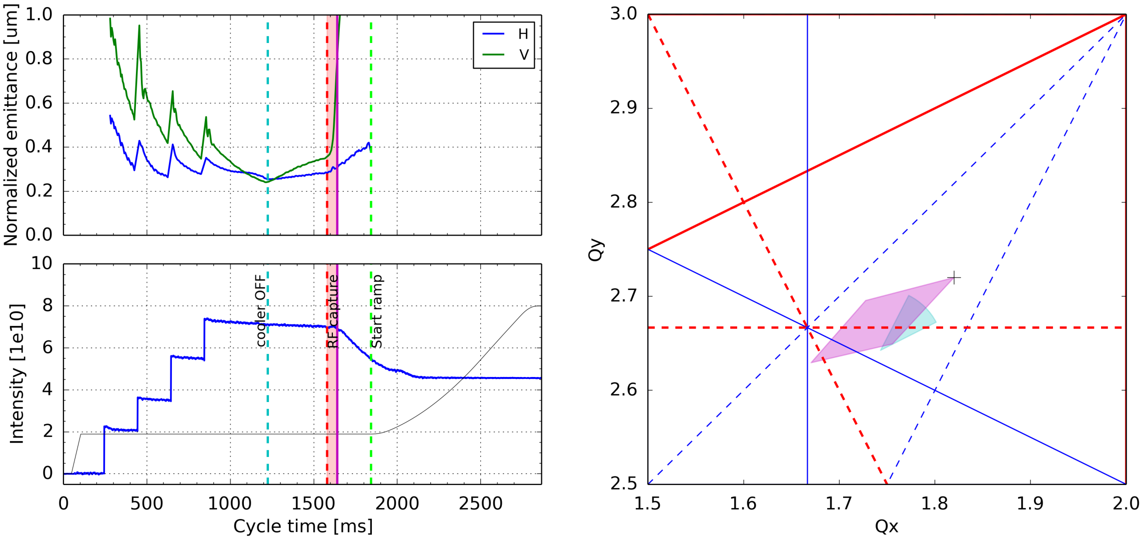

Figure 5: Normalized transverse emittances and intensity along the LEIR cycle in a special configuration, where the electron cooler is switched off after four injections and the RF capture is advanced by 200 ms (left). The calculated tune footprints are shown in the tune diagram (right) at the moment when the e-cooler is switched off (cyan) and after RF capture (magenta).

of the loss rate. Only for a significantly enhanced space charge tune spread during bunching the vertical emittance grows excessively. This growth is accompanied by beam loss at the vertical aperture bottlenecks of LEIR, which are the locations of large vertical β-function in the four bending magnets (see Fig. 1), where the height of the vacuum chambers is only 55 mm. Experimentally, this was demonstrated by creating small closed orbit bumps in these locations of the ring, which had a clear impact on the loss rate.

Therefore, it can be concluded that the loss mechanism is not related to the acceleration process itself, but rather to the changing particle density when the beam is bunched. It is also interesting that the loss rate for the bunched beam does not change significantly between the injection plateau and the first part of the ramp.

Tune Scan - Beam Survival

In order to identify the betatron resonances, which contribute to the observed emittance growth and losses, a tune scan was performed. For this measurement, a special LEIR cycle with five injections on the nominal working point was prepared. After the last injection, but still on the injection plateau with active electron cooling, the betatron tunes were moved to a new working point, the cooling was switched off,

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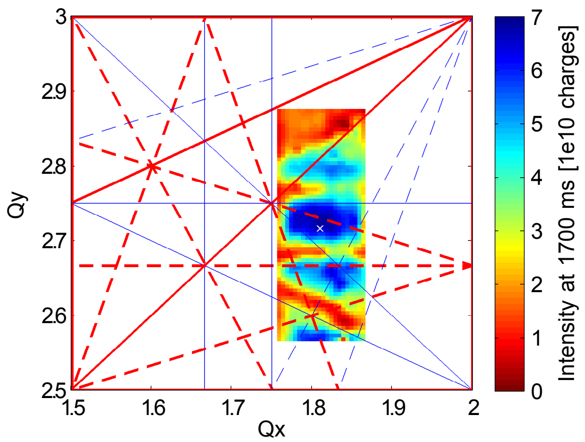


Figure 6: Beam survival after 400 ms storage of the bunched beam as function of the measured coherent tunes. Linear Chromaticity was corrected to $Q' \approx -1$. The nominal working point is marked by the white cross.

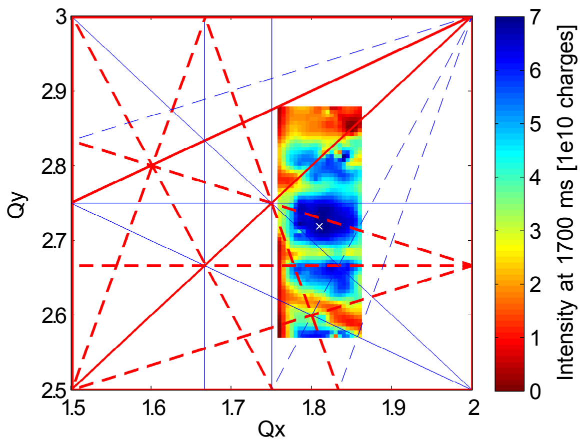


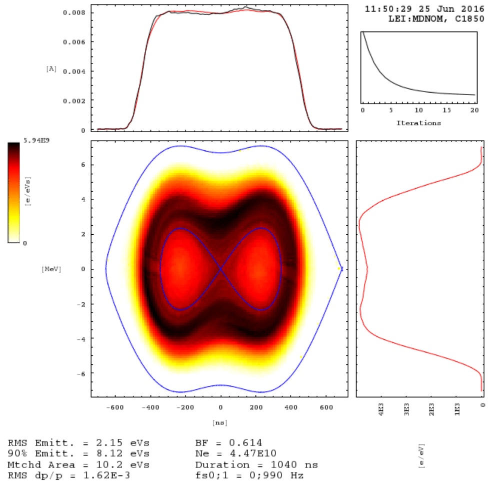
Figure 8: Beam survival after 400 ms storage of the bunched beam as function of the measured coherent tunes for reduced current in the chromatic sextupoles. The nominal working point is marked by the white cross.

and the beam was captured. Figure 6 shows the surviving intensity at 1700 ms cycle time after storing the captured beam on the injection plateau for about 400 ms for various measured coherent tunes in the tune diagram (about 300 working points). Enhanced losses are clearly observed above the skew $3Q_y = 8$ and the normal $Q_x + 2Q_y = 7$ third order resonances. These two resonances seem to be the most critical for driving the emittance growth described above. It is not yet understood why the skew sextupole resonance is so strongly excited. Notable losses are also observed above the $4Q_y = 11$ and the $4Q_x = 7$ fourth order resonances.

MITIGATION MEASURES

MaximizinG Bunching Factor

As described above, the space charge tune spread, and consequently the emittance blow-up and losses, can be reduced by maximizing the bunching factor. In LEIR, this can be achieved by programming an offset between the capture frequency and the central energy where the cooler deposits the beam. With the capture process suitably off-center, the core of the coasting beam distribution ends up surrounding the inner separatrices in the h=2+4 bucket. This results in a "hollow" distribution with an extremely flat longitudinal bunch profile as shown by the phase space tomography [7] in Fig. 7. This distribution can be preserved to some extent up the early part of the ramp by maintaining both the inner and outer acceptances constant. Bunching factors of up to 0.62 could be experimentally reached with this technique.



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RMS Emitt. = 2.15 eVs        BF = 0.614
90% Emitt. = 8.12 eVs        Ne = 4.47E10
Mtchd Area = 10.2 eVs        Duration = 1040 ns
RMS dp/p = 1.62E-3           fs0;1 = 0;990 Hz
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Figure 7: Measured longitudinal phase space distribution resulting from iso-adiabatic capture with RF frequency offset.

Reduction of Sextupole Resonance Excitation

Following the observations of strong losses close to sextupolar resonances with low beam intensity, a first attempt was made to use the two independently powered normal sextupole correctors and two independently powered skew sextupole correctors of LEIR to compensate resonances. It was not possible to measure resonance driving terms so far and therefore a systematic scan of sextupole currents was performed. Some improvement of the losses could be achieved [3].

In 2016 it was found that the chromatic sextupoles used for controlling chromaticity contribute to the resonance excitation and the beam loss encountered after RF capture. Reducing the current in the chromatic sextupoles makes the chromaticity more negative (closer to the natural chromaticity of the machine) and hence increases the tune spread due to the momentum spread of the beam. It should be mentioned that with active transverse feedback, the beam is stable throughout the cycle almost independent of the chromaticity setting.

With the best sextupole settings found so far, the chromatic tune spread is in the order of 10^{-2} only, which is still small compared to the space charge induced tune spread.

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Using these sextupole settings, the losses close to the resonances are somewhat reduced as shown in Fig. 8, where the chromaticity was reduced by about 2 units in both planes. Interestingly, also the region just above the $3Q_y = 8$ resonance is improved, even though it is a skew resonance. This needs to be investigated in more detail in future studies, e.g. by measuring resonance driving terms. This could also help in understanding the source of this strongly excited resonance.

Implementation

Figure 9 illustrates the effect of the two mitigation measures described above on the achievable intensity at LEIR extraction when accumulating around 10×10^{10} charges. With deregulated RF capture frequency, which generates a hollow distribution with a BF of about 0.6, and reduced current in the chromaticity sextupoles, 9×10^{10} charges could be reached at extraction, which constitutes a new record for LEIR.

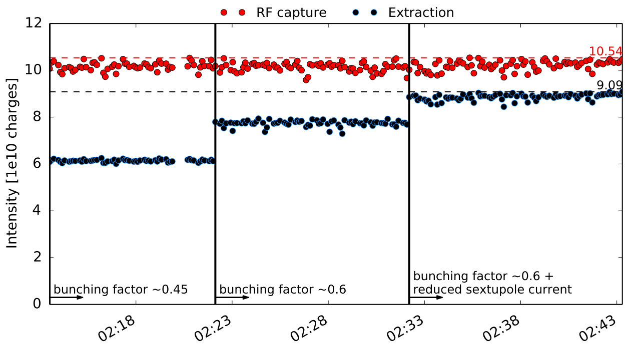

Figure 9: LEIR intensity with progressive implementation of the mitigation measures described in the text. The red and black dashed lines indicate the maximum achieved intensity at RF capture and extraction, respectively.

OUTLOOK

Following the hardware upgrades in the Linac3 complex during the last winter stop [3], it is possible to operate with 10 Hz injection rate by spacing the Linac3 injections by 100 ms. Experimental studies in the near future will therefore concentrate on exploring possible intensity limitations for the accumulation of up to 13 Linac3 pulses on the LEIR injection plateau with an increased electron current in the cooler. In case the accumulated intensity can be significantly increased, losses after RF capture are expected to remain a limitation. The following options for further mitigation will be considered:

- Ideally, the machine optics can be modified to obtain a working point in the lower quadrant of the tune diagram, e.g. fractional tunes of $q_x = 0.15$ and $q_y = 0.25$, which is far from low order resonances. However, the optics functions have to meet several constraints in the location of the electron cooler and in the injection region, while providing sufficient vertical acceptance [5].

- Further studies on the betatron resonances, e.g. resonance driving term measurements, should allow to better understand the main drivers for the excitation of the sextupole resonances, in particular the skew resonance below the nominal working point. Eventually, it should be possible to compensate these resonances (at least partially) using the existing chromatic and harmonic sextupole correctors. Therefore, hardware upgrades are currently ongoing to make this type of measurements possible.

- Further increasing the longitudinal emittance and thereby reducing the space charge tune spread. Additional RF voltage will be required in order to maintain a high bucket area throughout the acceleration cycle. This will become available by operating both existing RF cavities at the same time with the new digital low level RF.

In the long term, detailed simulation studies will be instrumental for fully characterizing and optimizing the LEIR beam performance, such as the development of a machine magnetic model including the nonlinearities (e.g. induced by the electron cooler guide fields), and space charge simulations. Furthermore, it should be mentioned that the LEIR impedance model is presently under development in the context of studying coherent effects.

SUMMARY AND CONCLUSIONS

The main intensity limitation of LEIR is beam loss during and after RF capture. The experimental studies presented here indicate that these losses are caused by the interplay of betatron resonances and the large direct space charge detuning. Maximizing the bunching factor and reducing the sextupole excitation allowed to mitigate the losses and reach record intensities with Pb^{54+} ions out of LEIR. In case significantly more intensity can be accumulated with the increased injection rate from Linac3, losses after RF capture are expected to remain a limitation and will be addressed with additional mitigation measures (e.g. a new machine optics if feasible). The improved performance of LEIR opens the possibility for further optimizing the lead ion beam production schemes for the HL-LHC era.

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