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PERFORMANCE OF THE LOW ENERGY ION RING AT CERN WITH LEAD IONS IN 2022

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Abstract

2022 was a performance consolidation year for the Low Energy Ion Ring (LEIR) at CERN that demonstrated its capability of delivering the target beam parameters required for high luminosity production in the LHC in a reproducible and reliable way. The main steps that have led to the high performance reach of this beam, together with the machine stability improvements deployed, are detailed in this paper.

INTRODUCTION

LEIR is the synchrotron, within the LHC ion injector chain, that transforms low-intensity ion pulses from Linac3 into high-brightness, short bunches using multi-turn injection, accumulation and phase-space electron cooling. In 2022, LEIR once more delivered the target beam parameters required by the LHC Injectors Upgrade Project [1] (LIU) in a reliable and stable manner. Moreover, the ion injector chain provided the beams for a short lead-lead collision test at LHC [2], for SPS North Area (NA) physics and for PS East Area (EA) experiments. In this paper, we summarise the machine stability improvements carried out in 2022, as well as the lead transmission efficiencies across the complex.

ION COMPLEX BEAM PERFORMANCE

LEIR beam commissioning started on 28 June 2022 with the injection transfer line set-up, followed by the setting up the single injection cycle (EARLY cycle) on 6 July. The high intensity cycle (NOMINAL [3] cycle) commissioning started on 10 August with the beam brought to specifications in just two days. The continuous improvements of the machine equipment and beam physics understanding allowed the LEIR team to do the fastest ever NOMINAL beam commissioning. Figure 1-left shows the evolution of the time needed to establish circulating beam and the time needed to bring the beam to LIU specifications, 9 10^{10} charges at LEIR extraction, starting from the first day of beam commissioning. While the time needed to bring the beam to specifications improves dramatically, the time needed to establish circulating beam remains constant at ≈1 week. The addition of LEIR first turn beam position measurements may improve this time in the future. Figure 1-right shows that the average extracted intensity is systematically peaked above the LIU target since the last three operational years; a clear demonstration of the capability of delivering the target beam parameters in a reproducible and reliable way.

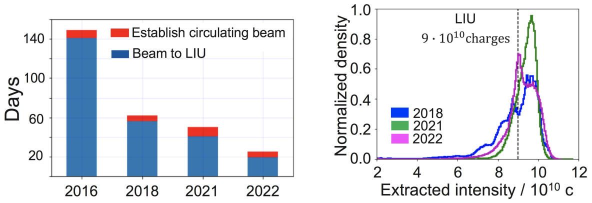

Figure 1: Left: time needed to establish circulating beam and to bring the beam to LIU specifications. Right: average extracted lead beam intensity during the last three runs.

In 2022, LEIR and the ion injector chain delivered the beams for a short lead-lead collision test at LHC [2], for NA61 physics and for PS East Area experiments. The intensity, emittance and transmission efficiencies across the injectors are summarised in Fig. 2. In Fig. 2-top, the number of ions per bunch has been calculated considering a four bunch train (1 PS batch) in order to compare with the LEIR efficiency. All transmission efficiencies have reached the 2018 values, except in the PS, where the efficiency is lower than in 2018. Further studies will be carried out in 2023 to identify potential issues and improvements.

During Run 2, many different performance improvements and consolidation activities were conducted in LEIR and its transfer lines which are described in [4]. During the Long Shutdown 2 (LS2) and the beginning of Run 3, several others were started and are listed here:

1. PS stray fields compensation.
2. Linac 3 stripper foil performance evolution monitoring.
3. Improvement of ring optics measurements.
4. Improvement of dipole (ITE.BHN40) current regulation.
5. Transfer line optics studies.
6. First turn beam position measurement.
7. E-cooler e$^-$ beam trajectory measurement.
8. Geodetic survey of Linac3, transfer lines and LEIR.
9. LEIR Autopilot prototype test.

Extensive details on each item can be found in [5]. LEIR injection efficiency modelling, including items one and two above are described in the companion paper [6]. The ring

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Beam Position Monitor (BPM) system low level software is being upgraded since LS2 to facilitate, amongst other things, optics measurements. In 2022, a thorough commissioning and analysis of turn-by-turn data from the new BPM system took place. The details of this study and the most relevant results and prospects for 2023 can be found in [7]. It is worth mentioning that a new way of programming the Low Level RF voltage based on high level physics parameters is under development [8]. The current paper focuses on items four to eight of the above list.

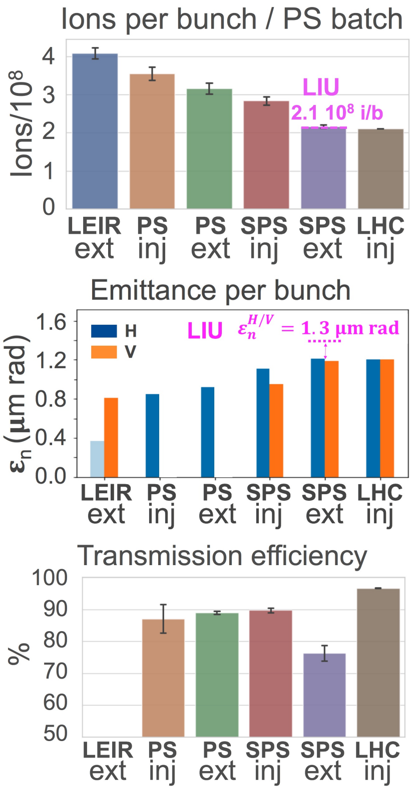

Figure 2: Intensity, emittance and transmission efficiencies across the injectors in 2022. The LIU target values [1] at SPS extraction (first two figures) corresponds to 14 injections from PS to SPS, while in 2022 only 4 were done.

INFLUENCE OF ITE.BHN40 ON THE BEAM TRAJECTORY

The analysis of the transfer line BPM signals in 2021 for the NOMINAL cycle showed that each of the seven injections, labelled with a different colour in Fig. 3, had a different position while all of them should be the same. This undesired feature significantly reduces the available aperture in the transfer line. Tests were performed to understand the origin of the position-differences. During the test, ITE.BHN40 and ETL. BHN10, the two dipoles suspected of causing these position differences, were set to constant injection currents (DC in the figure); first ETL.BHN10, then ITE.BHN40 and finally both, to disentangle the different contributions. As can be seen in Fig. 3-top the beam position changes according to which circuit is in DC. The tests indicated the existence of a different dipole field for each injection, being stronger for the first injections (larger position offset) and decaying exponentially for the rest. When suppressed, by keeping the circuits at a constant current value, data points in the light-green area of Fig. 3-top, the seven injections have, approximately, the same position. Precision measurements on the ITE.BHN40 circuit disclosed a substantial current overshoot with exponential decay when going to injection. Once the regulation was improved, new beam position measurements were obtained in 2022. Figure 3-bottom shows that the ITE.BHN40 problem is solved, however, the effect from the ETL.BHN10 is still present. Further studies in 2023 will be needed to fully address the problem.

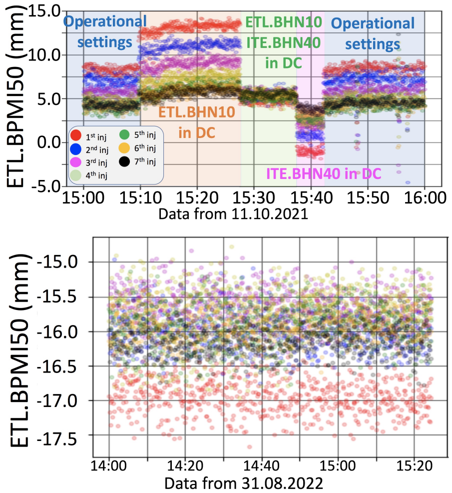

Figure 3: Top: horizontal beam position as measured by ETL.BPMI50. The different data point colours label a different injection. Bottom: same plot with 2022 data, after the improvement of the ITE.BHN40 current regulation.

TRANSFER LINE OPTICS STUDIES

In 2021, while commissioning the injection line, predictive orbit correction was not working as expected, due to incorrect quadrupole settings in one part of the transfer line called ITH, rendering them incompatible with the theoretical model. To verify the accuracy of the transfer function of the different quadrupoles and BPM scalings, a series of measurements were conducted the following year by turning off the quadrupoles between correctors and BPMs. The results indicated a factor 2 missing between the model and data for the ITE.BHN10 response, while the signal-to-noise ratio of the ITE.BHN30 measurements did not permit a conclusive determination. After loading the correct optics into the control system, kick response measurements were repeated, and the new factors required to minimise the model-measurement error were obtained. Figure 4 is an example for the ITH line where measurements are well in agreement with the optics-free data. The ETL line also shows good agreement, yet the ITE line requires major corrections to match the model.

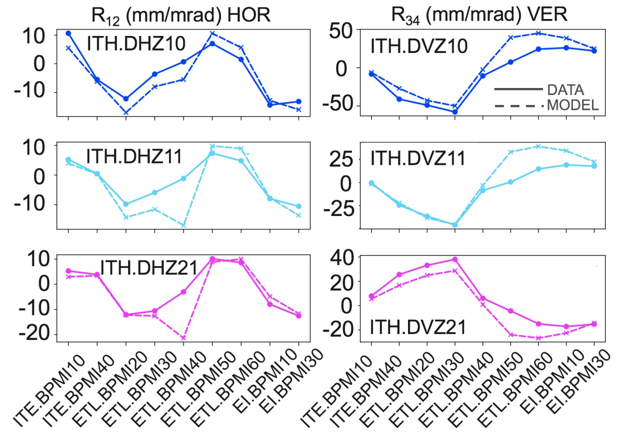

Figure 4: ITH line kick response. R12 and R34 coefficients as a function of the BPM and for the three dipole correctors in the line. Left is horizontal and right vertical.

FIRST TURN POSITION MEASUREMENT

First turn beam position measurement in LEIR would facilitate the steering between transfer line and ring but is not possible with the actual BPM hardware. An upgrade of the actual system has been proposed to work at a higher frequency. In 2022, a test amplifier with 20 dB gain at 100 MHz was developed and installed in the horizontal plane for testing and validating the prototype. During the test, the amplifier could detect the Linac3 101.28 MHz component of both the circulating and the single pass beam, as shown in Fig. 5, where the orange dot indicates where the signal should be found given that the 101.28 MHz is under-sampled with RF harmonic $h = 69$ and revolution frequency $f_{rev} = 361$ MHz. This encouraging result motivated the preparation of a prototype (with sum and delta signals) which will be finished and tested in the laboratory by spring 2023. After installation in the ring and further tests during the 2023 ion run, the system will be validated for final production and installation during year-end technical stop 23-24.

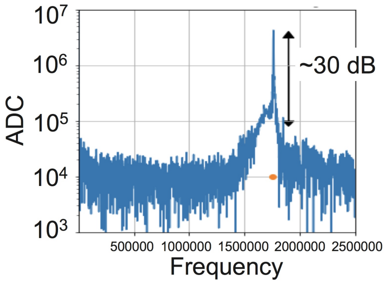

Figure 5: Single pass beam signal from the horizontal BPM14; orange dot indicates where the beam signal should be found for the chosen configuration.

e- TRAJECTORY MEASUREMENT

The process of ion cooling optimisation acts on the ion beam position inside the electron cooler to maximise the transmission efficiency at injection. Since 2021, an electron beam position measurement to complement the ion position measurement and improve cooling performance has been under development. The e$^-$ beam intensity is modulated through a coupling transformer installed inside the electron grid HV cage. A sinusoidal signal at a chosen h of the ion beam f_{rev} is generated by the BPM front-end electronics, amplified by a factor 15 and injected into the coupling transformer. Very promising results are shown in Fig. 6 for one BPM inside the electron cooler. The electron position is clearly measured at $\simeq$1 mm for several harmonics except for $h = 6$, where it is not possible to reconstruct a stable orbit. The signal from a BPM not exposed to the e$^-$ beam was also analysed with only noise found as expected. The development of the system will continue in 2023 with the aim of deployin it operationally in 2024.

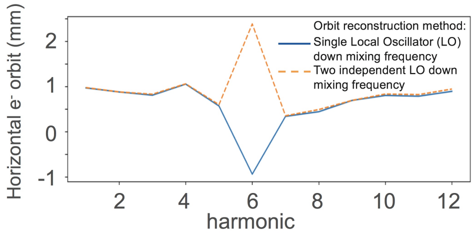

Figure 6: e$^-$ orbit reconstruction at one e-cooler BPM using raw data analysed in digital frequency domain for different h of f_{rev}.

GEODETIC SURVEY OF LINAC3, TRANSFER LINES AND LEIR

A complete geodetic survey campaign of Linac 3, LEIR and its transfer lines started in 2020. 3D measurements of the whole complex were taken to determine the precise geometry of the machines relative to each other. The measurements showed a significant difference between the model and the real machines. Position offsets in all coordinates were found as well as important roll angles. Reference [9] shows all the results of the survey campaign and the work that remains to be done. It is recommended to proceed with a re-alignment campaign in LEIR and its transfer lines when possible.

CONCLUSIONS

Many different new developments in LEIR are reported in this paper, the key ingredients of another successful year for the lead ion injector chain that saw beams delivered to the LHC, the SPS North Experimental Area and the PS East Experimental Area. This paper shows that a proper power converter regulation is fundamental for the machine performance. New beam instrumentation developments will be validated in 2023 and made operational for the 2024 run, hopefully in time for the special LHC Oxygen run that will take place that year.

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