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PERFORMANCE OF THE CERN LOW ENERGY ION RING (LEIR) WITH XENON BEAMS

R. Alemany, S. Albright, O. Andujar, M.E. Angoletta, J. Axensalva, H. Bartosik, G. Baud, N. Biancacci, M. Bozzolan, S. Cettour Cave, K. Cornelis, J. Dalla Costa, M. Delrieux, A. Dworak, A.J. Findlay, F. Follin, A. Frassier, M. Gabriel, A. Guerrero-Ollacarizqueta, M. Haase, S. Hirlander, S. Jensen, V. Kain, L. Kolbeck, Y. Le Borgne, D. Manglunki, O. Marqversen, S. Massot, D. Moreno, D. Nicosia, S. Pasinelli, L. Pereira, D. Perez, A. Rey, J. Ridewood, F. Roncarolo, A. Saa Hernandez, R. Scrivens, O. Sveen, G. Tranquille, E. Veyrunes, CERN, Geneva, Switzerland

Abstract

In 2017 the CERN Low Energy Ion Ring demonstrated once more the feasibility of injecting, accumulating, cooling and accelerating a new nuclei, $^{129}Xe^{39+}$. The operation of this new ion species started at the beginning of March with the start up of the xenon ion source and the Linac3. Ten weeks later the beam arrived to the Low Energy Ion Ring (LEIR) triggering the start of several weeks of beam commissioning in view of providing the injector complex with xenon beams for different experiments and a series of machine development experiments in LEIR. Two types of beams were setup, the so called EARLY beam, with a single injection into LEIR from Linac3, and the NOMINAL beam with up to seven injections. 2017 was as well an interesting year for LEIR because several improvements in the control system of the accelerator and in the beam instrumentation were done in view of increasing the machine reliability. This paper summarises the beam commissioning phase and all the improvements carried out during 2017.

INTRODUCTION

Over the past years LEIR has provided $^{208}Pb^{54+}$(2011-2014, 2016) and $^{40}Ar^{11+}$(2015) beams to the accelerator complex. In 2017 a new ion species, $^{129}Xe^{39+}$, was commissioned and delivered to the different users: the NA61/SHINE SPS experiment, the LHC for Xe-Xe collisions and xenon crystal collimation, the SPS for UA9 and for the Gamma-Factory study using partially stripped xenon ions, and the PS for the irradiation facility CHARM. In parallel, LEIR took advantage of improving the understanding of the beam dynamics through a long series of machine development (MD) sessions, commissioning newly installed hardware, including the transfer lines, and finally, further improving the control software. All this is motivated by the need of assuring reliable, stable and reproducible operation with the lead beams as required by the LIU-ions program, since the main objective, delivering the required beam parameters for the High Luminosity LHC (HL-LHC) upgrade of 8.1×10^8 *ions* per bunch at LEIR extraction has already been demonstrated during the 2016 ion run.

MACHINE CHECKOUT

The initial commissioning phase of every accelerator starts with a meticulous preparation of the hardware, which undergo a series of validation tests by equipment experts before the systems are handed over to the operation team. Further tests, from the control room, to verify the control of the various accelerator systems with the high level software applications and eventually the interplay between them is carried out. This phase covered the period from 18th April to 5th May 2017.

On Thursday, one day before the end of the machine check-out, the Departmental Safety Officer (DSO) test took place ensuring the proper functioning of all systems related to personnel protection. Following the DSO test validation, beam could be injected into LEIR.

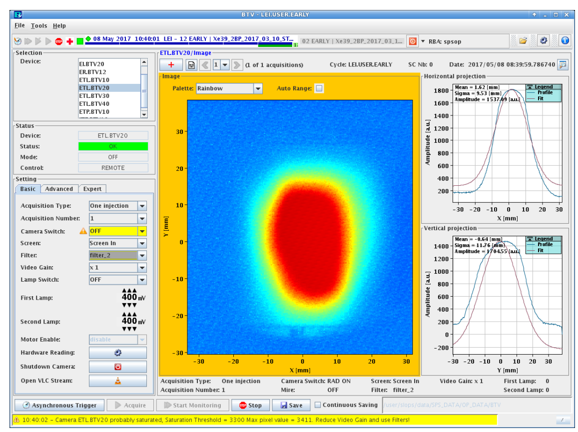

Figure 1: First image of the xenon beam going down the transfer line from Linac3 to LEIR.

BEAM COMMISSIONING

On Monday 8th of May the partially stripped xenon beam $^{129}Xe^{39+}$went down the transfer line from Linac3 to LEIR. An image of the beam can be seen in Fig. 1. However, after injection steering, the beam did not circulate and was lost in sector 1. On the afternoon of Wednesday the 10th the magnetic rigidity of the machine was reduced by 1.4%, as done with argon and lead in previous years, allowing successful injection. This result suggests that Linac3 kinetic energy might be lower than 4.2 MeV per nucleon (MeV/u) as quoted in the design report. Using the scaling factor obtained from the magnetic rigidity, the energy should be 4.11 MeV/u. This needs, however, to be confirmed by measurements. Figure 2 shows the injected intensity jump to $\approx 1.2 \times 10^{10} e$ at 16:52,

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showing the first circulating beam. As the RF was not yet commissioned the beam was lost at the start of the ramp. RF commissioning took place on Thursday and Friday, and on Friday afternoon the first extractions towards the transfer line to PS were carried out, once a long standing problem with the circuit EE.BHN1020 (the interlock cable was not plugged in) and a fault in the injection magnetic septum ER.SMH11 were fixed.

The following days were dedicated to the optimization of the EARLY beam: setting up capture and acceleration in first place, followed by the measurement and correction of the transfer line trajectory, injection, orbit, tune and chromaticity. On 19th of May another record intensity for the xenon beam, $2.54 \times 10^{10}e$, was achieved.

LEIR was coupled to the rest of the complex on Tuesday 23rd of May in the afternoon and the beam was transferred to the PS in the evening. With an initial RF setup, the xenon beam was quickly captured and accelerated up to transition in the PS. The very first circulating xenon beam at injection energy in PS can be seen in Fig. 3.

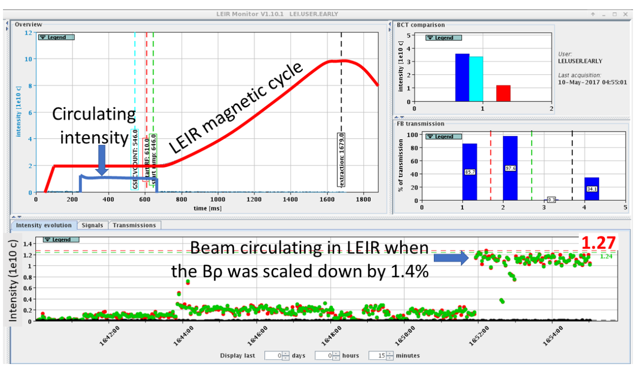

Figure 2: First circulating xenon beam in LEIR.

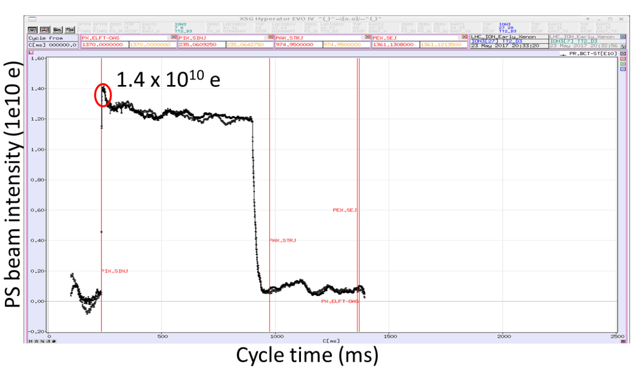

Figure 3: First circulating xenon beam in PS. Initial injected intensities $\approx 1.4 \times 10^{10}e$.

Table 1 shows the parameters for the $^{129}Xe^{39+}$beam at injection and extraction energies. Iave and Imax are the average and maximum total intensity injected and extracted for the EARLY beam. In parenthesis and for reference are the kinetic energy and beam rigidity values for the lead beam.

An analysis of the transmission efficiency of the EARLY xenon beam from LEIR injection up to SPS injection has been performed. The efficiencies are very similar to the ones obtained for the NOMINAL lead beam in 2016 [1]. The transmission efficiency from LEIR injection to extraction is (73±3)%; from LEIR extraction to PS injection is (96±4)%; from PS injection to extraction is (93±4)%; and from PS extraction to SPS injection (94±6)%.

Table 1: Summary of Xenon Beam Parameters

	K (MeV/u)	Bρ (Tm)	Iave ($10^{10}e$)	Imax ($10^{10}e$)
Inj	4.11 (4.11)	0.97 (1.13)	2.25±0.25	2.75±0.25
Ext	96.8 (72.2)	4.8 (4.8)	1.6±0.2	2.1±0.2

NEW BEAM INSTRUMENTATION

LEIR injection efficiency is strongly linked to the Linac3 beam parameters stability. It is not easy to separate the various causes (stripper foil degradation, intensity variations from the source, PS stray fields) of LEIR intensity variations over time, which can reach up to 30%. Measurements to try to disentangle and compensate the parameter fluctuations are being prepared and are summarized in the following. Besides the upgrades in the instrumentation, for the first time in LEIR a series of combined Linac3-LEIR machine studies were performed along the year to study the LEIR injection efficiency as a function of the Linac3 parameters [2].

Transfer Line Beam Position Monitors (BPM)

In March 2017 two BPMs were installed in the ITE loop. Initially, strong signal offsets were present due to charges collected on the electrodes. Simulations were launched to understand the source of the charges: electrons from beam-wall or beam-gas interactions, or ions from beam-gas interactions. The results indicated the dominant presence of wall electrons and the addition of a magnetic field and electrode bias greatly improved the signal. Additionally, the baseline distortion provoked by common mode currents from the neighbouring quadrupoles was greatly improved by adding ferrite chokes to the input coaxial cables of the head amplifiers. During the 2017-2018 winter shutdown (YETS17-18), seven more BPMs were installed in the line. During the 2018 beam commissioning the new BPMs will become operational and included as part of the automatic line steering. Moreover, the continuous monitoring of the beam trajectory will allow drifts in the beam position be easily measured.

New Orbit Acquisition

The old analog orbit acquisition system was replaced by a new digital system in 2017. The commissioning phase showed that the new system provides the same accuracy as the old one but much better precision as can be seen in Fig. 4. On top of this, the new digital electronics will allow turn-by-turn acquisitions, which is a very important functionality for optics studies, and it will also bring the possibility of first turn correction to improve the injection efficiency. These two new functionalities will be commissioned in 2018.

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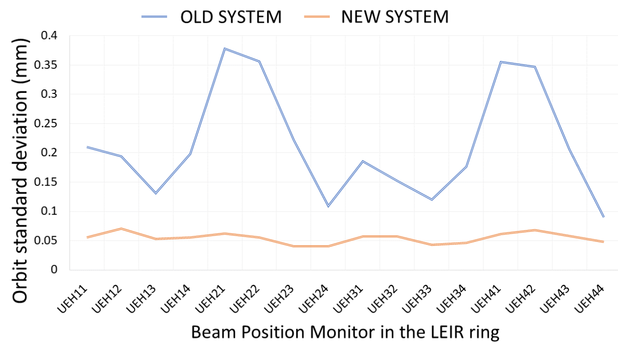

Figure 4: Comparison of the standard deviation measured by the old and new LEIR orbit acquisition system.

NEW LOW LEVEL RF DEVELOPMENTS

In 2017 a new harmonic combination (h=3+6) was tested to produce three, rather than two, bunches as a possible mitigation in case SPS slip-stacking does not perform as expected for the LHC injector upgrade. The h=3+6 operation required LLRF upgrades such as delivering the new harmonics, and a new extraction synchro-algorithm. The beam was sent to the PS where it was injected, accelerated and compressed to 75 ns bunch spacing. Figure 5 shows the three bunches at PS injection. The bunch compression to 75 ns would allow the number of bunches in the LHC to be increased. More tests with high intensity lead bunches will be performed in 2018.

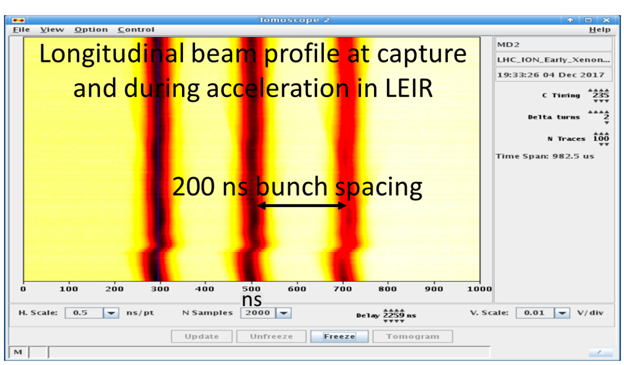

Figure 5: h=3+6 in LEIR at 200 ns bunch spacing. The three bunches are transferred to PS where, after acceleration, they are compressed to 75 ns.

Motivated by studies in the Booster demonstrating space charge reduction, a harmonic composition of h = 2+4+6 was tested in LEIR. This harmonic composition requires using both RF cavities: h=2+4 from CRF41, h=6 from CRF43. DSP code modifications allowing the two cavities to operate at different harmonics were needed. Results show a tendency to improve transmission as intensity increases, which will be validated in 2018 with the high intensity lead beam.

Several upgrades of the FPGA and DSP LLRF code were carried out for other purposes: validation of the LLRF-new Btrain interfacing via White Rabbit (WR) protocol and its effectiveness for the frequency program and to provide real time revolution frequency data over fiber to the orbit system.

During 2017 recurrent problems with High Voltage power converters for both cavities were experienced. Finally it was traced back to bad electromagnetic insulation of the electronics. Once this was improved, no more trips were observed. However, the development of h = 2+4+6, using two cavities simultaneously, disclosed problems in HLRF controls which were finally solved. Two problems remain to be understood and fixed, crowbar faults and screen and grid problems on CRF41 cavity.

MORE HARDWARE UPGRADES

New Control Electronics for Power Converters

A total of 24 power converters were upgraded during YETS17-18 to Function Generator Controller version 3 (FGC3) in the transfer line in order to cope with the possibility of injecting every 100 ms in LEIR, instead of 200 ms. Moreover, the new FGCs are within the CERN electronics standards providing easier maintenance and more reliability. The commissioning of those power converters has been carried out during the 2018 hardware commissioning phase.

New Beam Dump System

For a few years the PS-ion injector chain has run from spring to December and every year the beam intensity extracted from LEIR increased, with beams not delivered to PS lost in the transfer line. The new beam dump system, installed during YETS17-18 at the position of the ETL.BHN10 magnet, will allow a controlled beam disposal.

CONTROL SYSTEM IMPROVEMENTS

During 2016 many improvements in the LEIR accelerator settings management were performed allowing, in 2017, the beam commissioning of a completely new ion species in two weeks, which previously took months. More improvements in this front were carried out along the year. For example, the automatic generation of the Bρ function. Automatic recovery of the faulty power converters in LEIR and Linac3 with the so called Big Sister. New sequences were created to more easily control equipment such as the LEIR circuits, the electron cooler, the RF cavities, the vacuum valves, etc.

DIAGNOSTICS TOOLS IMPROVEMENTS

The signal analysis from the longitudinal Schottky was significantly improved allowing a novel way of studying the beam losses at injection [3]. The acquisition system of one of the secondary emission grids in the ETL transfer line was upgraded to be able to measure the 200 μs pulse coming from Linac3 with 4 μs resolution.

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CONCLUSION

In 2017 LEIR provided successfully a new nuclei, $^{129}Xe^{39+}$, to the accelerator complex for different experiments and for a series of LEIR MDs. LEIR and Linac3 are the first machines that demonstrated the capability of delivering the required HL-LHC beam parameters during an operational year, 2016. The focus is now assuring reliable, stable and reproducible operation for which new hardware and software have been installed during EYETS16-17 and commissioned during the 2017 xenon run as presented in this paper.

Further installations and upgrades have been done during YETS17-18. During the 2018 run, with the NOMINAL lead beam, LEIR will have to demonstrate that the goal is routinely achieved.

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