LEIR OPERATIONS FOR THE LHC AND FUTURE PLANS

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Abstract

LEIR, CERN's Low Energy Ion Ring, is an essential part of the LHC ion injection chain. In addition, since 2010 the accelerator complex is also delivering ions to the fixed target programme of the SPS North Area. We review the operation of the machine during the recent runs, and we detail the plans for the coming years with Pb and other species.

THE LHC ION INJECTOR CHAIN

The ion injector chain of the LHC consists of six machines [1]:

- The ECR source [2] provides Pb^{29+} at 2.5 keV/u. It is followed by a spectrometer which filters out the other species and charge states.
- The Radio-Frequency Quadrupole bunches, focuses and accelerates the ions to 250 keV/u.
- The Interdigital Linear Accelerator (Linac3) accelerates the ions to 4.2 MeV/u. It is followed by a momentum ramping cavity which ac-/de-celerates part of the beam by 0.4%. At the exit of Linac3, a 0.3 µm carbon foil strips the Pb^{29+} ions to Pb^{54+}.
- LEIR, the Low Energy Ion Ring, (Fig. 1) accumulates one or several Linac3 pulses at 4.2 MeV/u; after cooling and bunching, the ion beam is accelerated to 72 MeV/u and extracted to the Proton Synchrotron (PS).
- The PS accelerates the ions to 5.9 GeV/u, and defines the bunch spacing by RF gymnastics. At the exit of the PS, a 1 mm aluminium plate fully strips the Pb^{54+} ions to Pb^{82+}.
- The Super Proton Synchrotron (SPS) defines the train structure, hence the collision pattern, and accelerates the ions to 177 GeV/u, the injection energy of the LHC, on a non-integer harmonic [3].

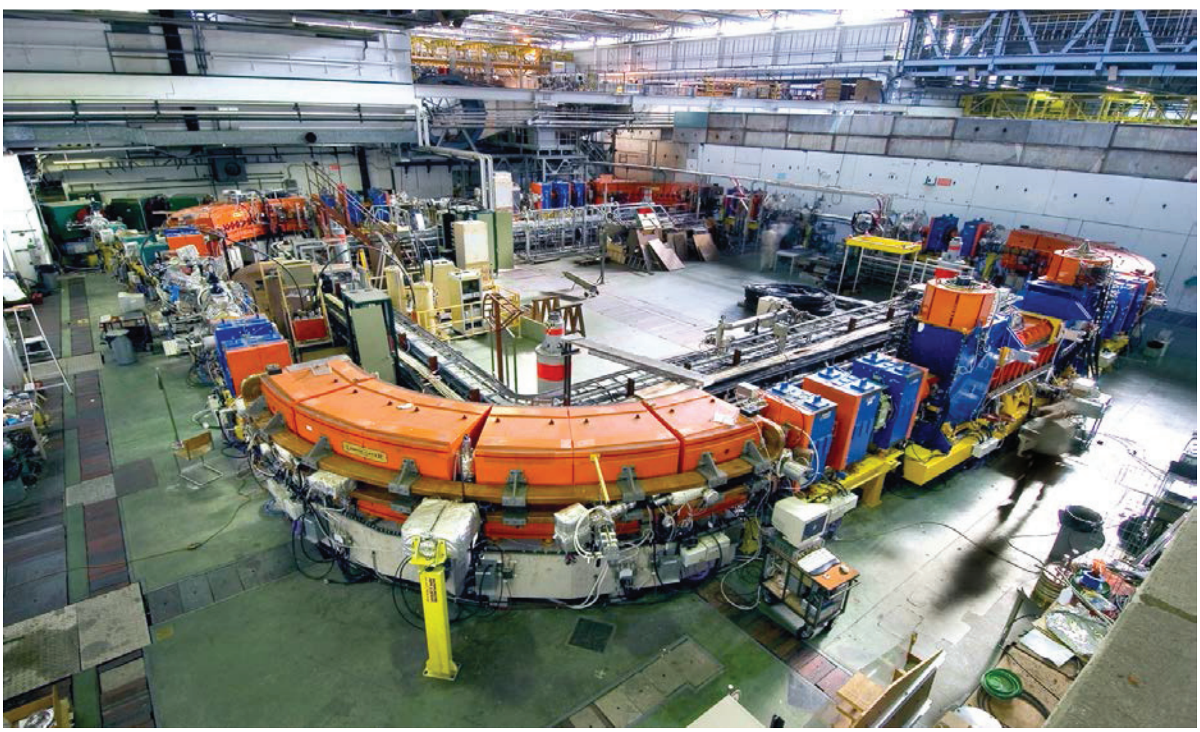

Figure 1: The LEIR machine is situated in CERN’s South Hall.

THE LOW ENERGY ION RING, LEIR

The role of LEIR is to transform a series of 200 µs long, low-intensity ion pulses from Linac3 into high-brightness, short (~200 ns) bunches using multi-turn injection, accumulation and phase-space cooling. After accumulating six such pulses, the resulting coasting beam is adiabatically captured on $h = 2$, and accelerated to 72.2 MeV/u. Figure 2 shows a typical cycle where the electron current is first established, then six Linac3 pulses are injected with a 200 ms repetition time. At the end of the flat bottom, the electron current is switched off and the ion beam is accelerated.

ISBN 978-3-95450-140-3

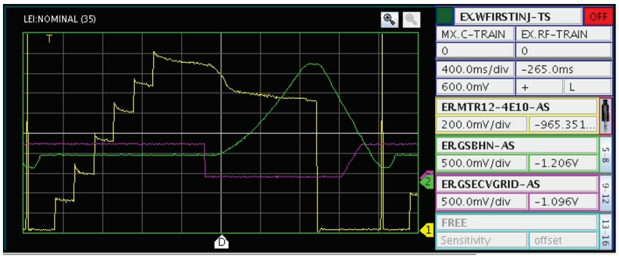

Figure 2: A 3.6 second Nominal LEIR cycle. Green: magnetic field; yellow: circulating intensity; magenta: electron cooling grid voltage.

Layout and Parameters

The LEIR machine has inherited much of the structure of the old Low Energy Antiproton Ring (LEAR), with some modifications to the optics, see Fig. 3. In particular, quadrupole triplets have been installed in the even straight sections, in order to provide a large horizontal dispersion (10 m) in the injection region, and zero-dispersion in the electron cooler and acceleration stations [4 – 6].

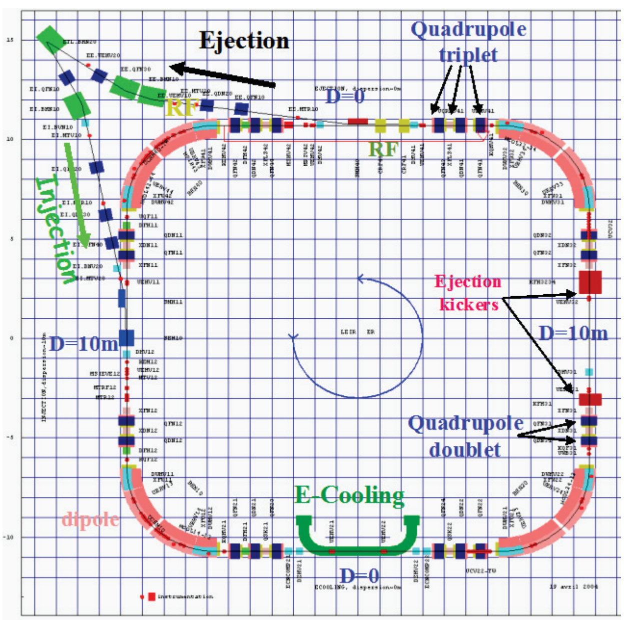

Figure 3: LEIR Layout.

Radio-Frequency system

During the conversion of the machine for ions, its two ferrite-based RF cavities have been replaced by Finemet™ RF cavities [7]. The low-level electronics have also been completely replaced by an all-digital system [8 – 10].

Injection Scheme

Central to its ability to deliver high-density beams for collider operations, is LEIR's three-plane stacking injection scheme (Fig. 4).

Each Pb^{54+} Linac3 pulse is injected by stacking 70 turns into the horizontal (using a 4-dipole decreasing bump), vertical (by an inclined electrostatic septum), and longitudinal (by energy ramping) phase spaces, with 70% injection efficiency. The electron cooler strongly reduces the phase space volume within 200 ms, and decelerates the beam into the stack which sits on the inside of the central orbit. The machine is then ready for the next injection.

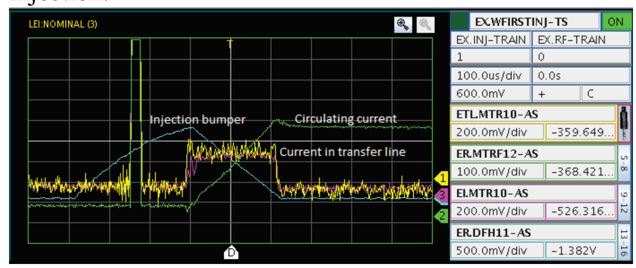

Figure 4: Multiturn injection. Green: circulating ion current; yellow/magenta: Linac3 pulse, measured at two different places in the transfer line; cyan: one of the injection bumpers.

Electron Cooler

The LEIR state-of-the-art electron cooler is now running with a current of 300 mA, and a slightly hollow electron beam distribution. This configuration results from an optimisation between the fastest possible cooling time (200 ms between injections, see Fig. 5), and a minimal recombination rate between the circulating ions and the electrons. [11 – 14].

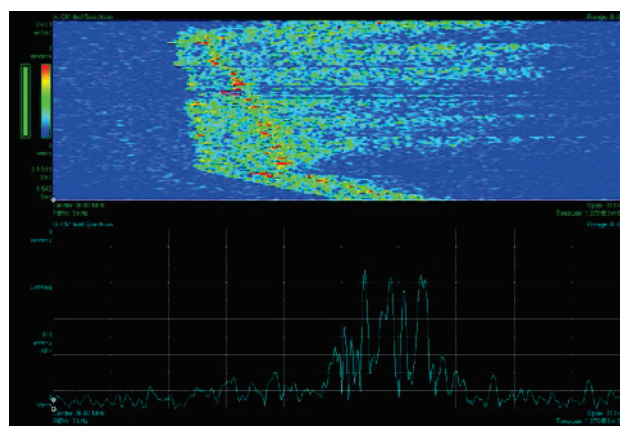

Figure 5: Schottky observation of momentum cooling during the injection process.

THE INITIAL NOMINAL SCHEME

The LHC was initially designed to reach a peak Pb-Pb luminosity of 10^{27} $cm^{-2}s^{-1}$ at 7 ZTeV per beam, colliding 592 bunches of ~7×10^{7} bunches of Pb^{82+}, with a β^{*} of 50 cm [15]. However, following the 2008 incident [16], it was decided to first limit it to 3.5 ZTeV per beam.

The high brightness demanded by the luminosity production implied severe intra-beam scattering and space charge conditions for the ion bunches on the long injection flat bottom of the SPS. A complicated mitigation scheme was devised (Fig. 6), involving an additional splitting in bunchlets in the PS and a merging at the end of the SPS flat bottom [1]. However, some calculations [17, 18] indicated that the bunchlet scheme might be

ISBN 978-3-95450-140-3

unnecessary. It was then decided to start the ion collisions with an "Early Scheme" [19], at a luminosity 20 times lower (5×10^{25}cm^{-2}s^{-1}), where the LEIR machine would only have to supply a single bunch per cycle, transmitted through the PS with RF gymnastics kept to a minimum.

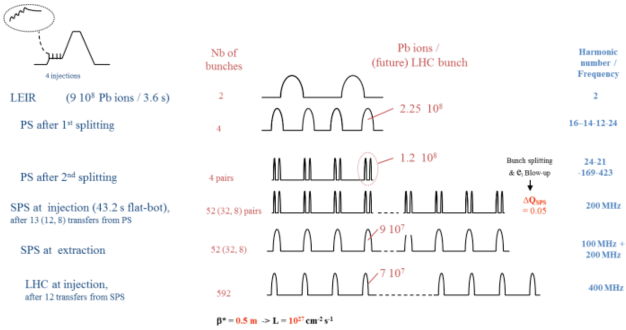

Figure 6: Initial Nominal scheme, involving a splitting into bunchlets.

EARLY RUN (2010)

Due to the delayed startup of the LHC, a lot of time could be devoted to the preparation of the injectors, which were ready with the early beam by 2007 [20, 21]. The first LHC Pb-Pb run eventually took place in Autumn 2010 [22], and accumulated an integrated luminosity of 10 μb^{-1} at 3.5 ZTeV/beam. The peak luminosity reached 3×10^{25}cm^{-2}s^{-1}, more than twice the expected one, scaled with the square of the energy. This excellent performance was mainly due to the bunch intensity delivered by the LEIR machine, 50% higher than specified, with lower transverse emittances.

SECOND RUN (2011)

The success of this Early run led to even higher expectations for the nominal beam from the experiments [23]. Considering the high density bunches survived the SPS flat bottom without too much degradation, it was decided to modify the "Nominal" scheme once more: leaving the two bunches delivered by LEIR accelerated without any splitting in the PS, effectively doubling the intensity of the bunches in the collider (1.4×10^8 vs. 7×10^7 ions/bunch), but at the expense of their number (358 vs 592) [24].

This second LHC Pb-Pb run accumulated an integrated luminosity of 160 μb^{-1} at 3.5 ZTeV/beam, with a peak luminosity of 5×10^{26}cm^{-2}s^{-1}, once again twice more than expected [25].

PROTON-LEAD RUN (2013)

At the beginning of 2012, the experiments confirmed their request for a proton-lead run before the long shutdown [26], a first extension to the LHC programme as defined in the Design Report. A pilot run took place in September 2012 [27], while the actual physics run was delayed until January 2013 [28]. Once again, the injector chain was able to benefit from the extra time and improve the beam performance [29].

Table 1 compares the design parameters of the Pb ion beam, as planned in the LHC design report, with the performance achieved in February 2013 during the p-Pb run.

FUTURE PLANS

LHC Beams

After the second Long Shutdown of the LHC (LS2), the ALICE experiment will have undergone an upgrade of its detector, allowing it to digest a luminosity at least 6 times larger than presently [30 – 32]. In order to satisfy the demand for this higher luminosity, provided the LHC itself can use it [33], a baseline strategy has been designed, as well as an alternative one, in the framework of the LHC Injector Upgrade project [34].

- The baseline strategy (Fig. 7) makes no assumption on an increase of the performance of the injector chain. It is mainly based on a batch compression in the PS and a new injection scheme in the SPS, with a shorter rise time (50 ns), resulting in a larger number of bunches in the train [35].
- The alternative scheme assumes the current limitation of the intensity in LEIR can be lifted and the bunch density can be doubled. Reintroducing a splitting in the PS, four bunches of ions will be delivered per batch to the SPS.

Table 1: Beam Parameters of the Lead Ion Injectors: Comparison Between Design and Operational Values in 2013.

Machine	Linac3		LEIR		PS		SPS	
	Design	2013	Design	2013	Design	2013	Design	2013
Output energy	4.2 MeV/u		72.2 MeV/u		5.9 GeV/u		177 GeV/u	
^{208}Pb charge state	29+ -> 54+		54+		54+ -> 82+		82+	
Output Bρ [Tm]	2.12 -> 1.14		4.80		86.7 -> 57.1		1500	
Nr of batches for next machine	4-5	6-7	1	1	13,12,8	12	12	15
Bunches/ring	N/A		2	2	4	2	52,48,32	24
Ions per pulse	1.15×10^9	4.6×10^8	9×10^8	1.1×10^9	4.8×10^8	8.8×10^8	$<4.7\times10^9$	4.4×10^9
Ions/LHC bunch			2.25×10^8	5.5×10^8	1.2×10^8	4.4×10^8	9×10^7	1.8×10^8
Bunch spacing[ns]			352		100	200	100	200
ε^*_{rms} [μm]	0.25	N/M	0.7	<0.7	1.0	<1.0	1.2	<1.2
ε_l [eVs/u/bunch]			0.05	0.07	0.05	0.07	0.24	0.24
Repetition time [s]	0.4-0.2	0.2	3.6	3.6	3.6	3.6	50	62.4

ISBN 978-3-95450-140-3

In any case, a thorough programme of upgrades has been launched in order to assess the feasibility of both schemes [24, 36]:

- The possibility of multiple charge acceleration in Linac3 [37] will be re-evaluated.
- The preinjector (ECR source, RFQ, Linac3, and transfer lines to LEIR) will be pulsed at 10 Hz.
- Simulations and machine developments will take place to try and understand the intensity limitation in LEIR, in particular the loss at the beginning of acceleration.

LEIR will also undergo a consolidation programme aimed at improving its reliability and operability. In particular, some essential diagnostics such as the Schottky measurements will become remotely accessible from the CERN Control Centre [38, 39].

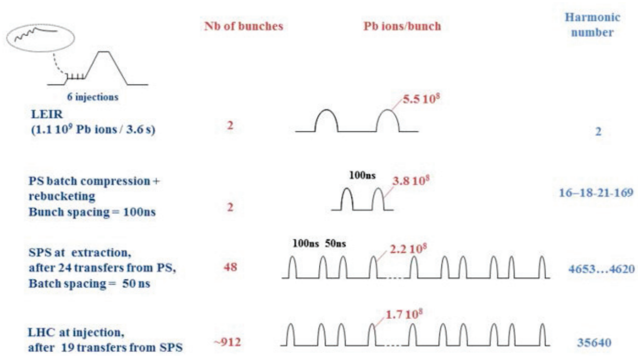

Figure 7: Baseline scheme for after LS2.

Fixed Target Beams

The renewed availability of heavy ion beams at CERN has triggered an interest in the fixed target community. In particular, already since 2006, NA61/SHINE [40] has requested a series of ion species at various energies (13, 20, 30, 40, 80, and 160 GeV/u) from the SPS. Because of the incompatibility with the LHC programme, and in the absence of a second ion source, only Pb ions have been available until now. Two Be runs were however made possible by the fragmentation of Pb ions [41 – 43]. The Be programme has been completed at the beginning of 2013, and the collaboration is now eager to pursue the experiment with other ions [44]: Ar in January 2015, followed by Xe, and later Pb.

In order to start commissioning the whole chain with the new species, Ar will thus be injected into LEIR in Summer 2014. Experience with Ar will also be useful for the LHC programme as some of the collider experiments have already expressed interest in Ar-Ar collisions [45].

Beams for Biomedical Experiments

For the sake of completeness, we have to mention the request for extraction of lighter ions (O, C, He, and even protons) for bio-medical experiments in the South Hall [46, 47]. These studies would need serious modifications to the LEIR machine, such as a redesign of a slow extraction, and the installation of a second extraction line. In order to ensure compatibility with the already approved physics programme, a second ion source would also need to be added to the complex. Finally, the LEIR shielding would have to be upgraded to cope with the requested higher energy per nucleon.

ACKNOWLEDGMENTS

This paper describes the work of the LEIR team: M.E. Angoletta, M. Bodendorfer, C. Carli, A. Findlay, S. Pasinelli, and G. Tranquille.

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ISBN 978-3-95450-140-3