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 accelerates 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.
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].

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During the conversion of the machine for ions, its two ferrite-based RF cavities have been replaced by Finemet™ RF cavities [7].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.

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].

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 $\sim 7 \times 10^7$ bunches of Pb$^{82+}$, with a $\beta^*$ 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
unnecessary. It was then decided to start the ion collisions with an “Early Scheme” [19], at a luminosity 20 times lower ($5 \times 10^{23} \text{cm}^{-2} \text{s}^{-1}$), 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.

This second LHC Pb-Pb run accumulated an integrated luminosity of 160 $\mu\text{b}^{-1}$ at 3.5 ZTeV/beam, with a peak luminosity of $5 \times 10^{26} \text{cm}^{-2} \text{s}^{-1}$, 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.

<table>
<thead>
<tr>
<th>Machine</th>
<th>Linac3</th>
<th>LEIR</th>
<th>PS</th>
<th>SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>2013</td>
<td>2013</td>
<td>2013</td>
<td>2013</td>
</tr>
<tr>
<td>Output energy</td>
<td>4.2 MeV/u</td>
<td>72.2 MeV/u</td>
<td>5.9 GeV/u</td>
<td>177 GeV/u</td>
</tr>
<tr>
<td>208Pb charge state</td>
<td>29+ -&gt; 54+</td>
<td>54+</td>
<td>54+ -&gt; 82+</td>
<td>82+</td>
</tr>
<tr>
<td>Output Bp [Tm]</td>
<td>2.12 -&gt; 1.14</td>
<td>4.80</td>
<td>86.7 -&gt; 57.1</td>
<td>1500</td>
</tr>
<tr>
<td>Nr of batches for next machine</td>
<td>4-5</td>
<td>6-7</td>
<td>1</td>
<td>13,12,8</td>
</tr>
<tr>
<td>Bunches/ring</td>
<td>N/A</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Ions per pulse</td>
<td>$1.15 \times 10^8$</td>
<td>$4.6 \times 10^8$</td>
<td>$9 \times 10^8$</td>
<td>$1.1 \times 10^9$</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>352</td>
<td>100</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>$\delta_r$ [rad]</td>
<td>0.25</td>
<td>N/M</td>
<td>0.7</td>
<td>&lt;0.7</td>
</tr>
<tr>
<td>$\delta_t$ [eVs/u/bunch]</td>
<td>0.05</td>
<td>0.07</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>Repetition time [s]</td>
<td>0.4-0.2</td>
<td>0.2</td>
<td>3.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>
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].

**Acknowledgments**

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

**References**


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