

THE LHC LEAD INJECTOR CHAIN

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Abstract

A sizeable part of the LHC physics programme foresees lead-lead collisions with a design luminosity of $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. This will be achieved after an upgrade of the ion injector chain comprising Linac3, LEIR, PS and SPS machines [1,2]. Each LHC ring will be filled in 10 min by almost 600 bunches, each of 7×10^7 lead ions. Central to the scheme is the Low Energy Ion Ring (LEIR) [3,4], which transforms long pulses from Linac3 into high-brilliance bunches by means of multi-turn injection, electron cooling and accumulation. Major limitations along the chain, including space charge, intrabeam scattering, vacuum issues and emittance preservation are highlighted. The conversion from LEAR (Low Energy Antiproton Ring) to LEIR involves new magnets and power converters, high-current electron cooling, broadband RF cavities, and a UHV vacuum system with getter (NEG) coatings to achieve a few 10^{-12} mbar. Major hardware changes in Linac3 and the PS are also covered. An early ion scheme with fewer bunches (but each at nominal intensity) reduces the work required for early LHC ion operation in spring 2008.

OVERVIEW

The major hardware changes along the injector chain are summarized in Fig. 1. Central to the ion injection scheme is LEIR (previously LEAR) and its powerful new electron cooling system. CERN is taking particular advantage of the mothballed LEAR and, even more so, of the experience gained with that machine.

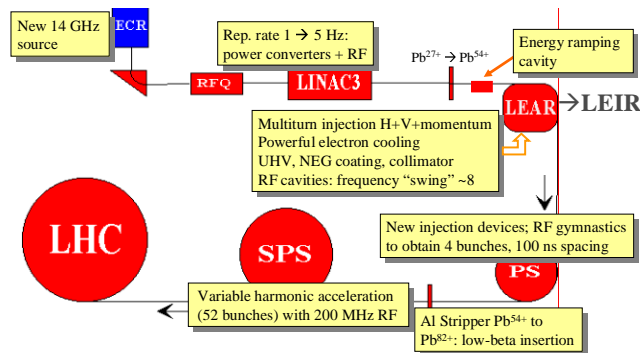


Figure 1: Hardware upgrades in the LHC injector chain.

In the nominal scheme (see Table 1), the SPS at the end of the injector chain provides the LHC with 592 Pb^{82+} bunches per ring, each of 9×10^7 ions (7×10^7 at collision). The ion beam sizes and bunch length at SPS extraction and at collision in the LHC are the same as for protons, resulting in a lead-lead luminosity of $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$.

Table 1: Nominal parameters of the lead ion injectors.

	Linac3	LEIR	PS	SPS
Output energy	4.2 MeV/n	72.2 MeV/n	5.9 GeV/n	177 GeV/n
^{208}Pb charge state ¹	27+/54+	54+	54+/82+	82+
Output Bp [Tm] ¹	2.28/1.14	4.80	86.7/57.1	1500
# batches to fill next machine	4-5	1	13,12,8	12
Bunches/ring		2 (1/8 PS)	4	52,48,32
Ions per pulse ²	1.15×10^9	9×10^8	4.8×10^8	$< 4.7 \times 10^9$
Ions/LHC bunch	1.15×10^9	2.25×10^8	1.2×10^8	9×10^7
bunch spacing [ns]		352	100	100
ϵ_{rms}^* [μm]	0.25	0.7	1.0	1.2
$= (\beta\gamma)_{\text{rel}} \sigma^2 / \beta_{\text{twiss}}$				
ϵ_l [eVs/u/bunch]		0.05	0.05	0.24
4 σ bunch length		200 ns	4 ns	2 ns
repetition time [s]	0.2-0.4	3.6	3.6	~50

¹Values before/after stripping.

² $50 \mu\text{A} \times 200 \mu\text{s}$ Pb^{54+} Linac3 output after stripping.

LINAC3 UPGRADE

To supply the nominal ion beam, a source current of $200 \mu\text{A}$ Pb^{27+} is required (yielding $\sim 50 \mu\text{A}$ Pb^{54+} after stripping at 4.2 MeV/n). The present electron cyclotron resonance (ECR) source, operating in "afterglow mode" at 14.5 GHz, delivers only half of this. An ECR source with improved performance has been developed at CEA, Grenoble [5]. It is also based on 14.5 GHz but features increased transverse confinement by a stronger permanent hexapole; a larger plasma chamber; and RF couplers for both 14.5 and 18 GHz microwaves. This source, which is compatible with Linac 3, has been ordered from CEA.

Pulsed power converters for magnets and RF systems in Linac3 and the line to LEIR are being upgraded from the nominal 2.5 Hz operation to 5 Hz in order to provide some performance margin. A new energy ramping cavity enables the beam momentum to be varied by $\pm 0.4\%$ during the linac pulse. This is required for momentum stacking in LEIR.

UPGRADE OF LEAR TO LEIR

LEIR Cycle

The role of LEIR is to transform a series of long ($\sim 200 \mu\text{s}$), low-intensity ion pulses from Linac3 into short ($\sim 200 \text{ ns}$), high-brightness bunches using multi-turn injection, electron cooling and accumulation. Each Pb^{54+} linac pulse is injected with a 70% efficiency by stacking 70 turns into horizontal, vertical (by an inclined electrostatic septum) and longitudinal (by energy ramping) phase space. On a 4.2 MeV/n plateau in LEIR,

the electron cooler strongly reduces the phase space volume of the beam in less than 400 ms and decelerates it into a stack sitting slightly inside the central orbit. After accumulating 4 or 5 such pulses, the beam is adiabatically captured in 2 bunches and accelerated to 72 MeV/n. The sequence of events is sketched in Fig. 2.

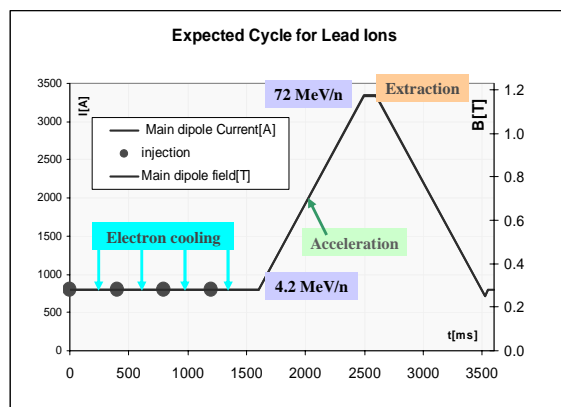


Figure 2: 3.6 s LEIR cycle with linac pulses every 0.4 s.

Transfer Lines

The 4.2 MeV/n beam from Linac3 and the 72 MeV/n one extracted towards the PS share ~60 m of a common transfer line in which they travel in opposite directions within 1.2 s of each other. This necessitates laminated magnets. Beam diagnostics, vacuum equipment and other infrastructure have been recovered from the former LEAR injection line, but most of the power converters are new. Whereas the bending magnets have to change polarity, this was avoided for the quadrupoles by special optics in both directions, leading to significant savings in power converter costs. An emittance measurement device comprising three secondary emission grids will be added.

Layout and Lattice

LEAR's basic shape, a square made up of four 90° bending magnets connected by four straight sections (SS), is retained for LEIR. Its circumference, 1/8 of the PS, is unchanged, but unlike in LEAR, the beam circulates anti-clockwise. LEAR's fourfold symmetry is replaced by a twofold one featuring large dispersions (10 m required for momentum stacking) in SS10 (injection) and SS30, and zero dispersion in SS20 (electron cooling) and SS40 (RF, extraction). To this end, four quadrupoles are added to form four doublets and four triplets. The optics allows for some flexibility to optimize multi-turn injection and electron cooling. The injection equipment is rearranged and comprises a DC magnetic septum, a new inclined electrostatic septum, and four fast bumper magnets (with new pulse generators) incorporating ceramic chambers and providing bump collapse times of 120–500 μs for multi-turn injection. All correction dipoles and multipoles are recovered from LEAR. For beam extraction at 4.8 Tm, the former LEAR injection kicker modules are powered by new pulse generators and a new pulsed septum provides 0.8 T through a thin-walled stainless

steel vacuum chamber. All these elements have to be compatible with a bake-out at 300°C.

Electron Cooling

This key element produces the required beam brightness, which is a factor of 30 higher than for fixed-target ion operation. Tests in 1997 with lead ions in LEAR [6] demonstrated a cool-down time of 400 ms at 4.2 MeV/n using a 3 m electron cooler and an electron current of 100 mA. The new system, being manufactured at INP Novosibirsk, has about the same length but a current of up to 500 mA. The aim is a cool-down time of 200 ms. A control electrode will allow hollow electron beams to be generated in order to minimize the recombination with ions. While the main purpose of the system is to operate at LEIR injection, it may also work at extraction (40 keV electron beam energy).

Vacuum

Pb^{54+} ions at 4.2 MeV/n tend to capture electrons from the residual gas molecules. For a beam lifetime of ~15 s, an average dynamic pressure in the low 10^{-12} mbar range is required. However, as observed during LEAR ion accumulation tests [6], ions hitting the wall desorb molecules, thus generating a much higher dynamic pressure and degrading the beam lifetime. Desorption yields of 2×10^4 molecules per Pb^{53+} ion have been measured in experiments at Linac3 [7]. The LEIR vacuum system features a bake-out at 300°C; NEG-coating wherever possible; low-outgassing collimators to control ion losses; and "beam scrubbing" (lost ions enhance desorption and clean the vacuum envelope) [7].

RF and Feedback Systems

Two new large-bandwidth cavities based on Finemet® high-permeability magnetic alloy are being built in collaboration with KEK. They cover a very wide frequency range (0.35–5 MHz) without any tuning. Acceleration at LEIR's moderate ramp rate requires an RF voltage of less than 4 kV, keeping the amplifier power to reasonable 60 kW. The available frequency range covers lead ions at harmonic $h=2$ or $h=1$ and keeps open the option of lighter ions at a later date.

LEIR is the first CERN accelerator to be equipped with all-digital signal processors for the low-level RF.

Other Systems

Most of the 164 power converters for LEIR and its transport lines are being rebuilt or recuperated from past machines, notably LEP. There are more than 20 different types. Most are based on thyristor or switch-mode technologies, but there are also pulsed power converters as well as HV supplies for RF and electron cooling. In spite of an effort towards standardization, the diversity of power equipment for this small machine is impressive.

Beam diagnostic devices are largely recovered from LEAR but have to be adapted to ions as well as to new standards for electronics and control. Of particular note

are the DC current transformer (2 μ A to 50 mA), the Schottky pick-ups (to measure the emittance and energy spread of the coasting beam), and beam ionization profile monitors (to observe beam dimensions during cooling).

LEIR will serve as testbed for a newly developed unified accelerator control system that will also be employed for the LHC. It must be capable of so-called "pulse-to-pulse modulation" in order to permit new beams to be tested in the ion complex on a cycle-to-cycle basis. LEIR will be synchronized with the other accelerators by a dedicated timing and sequencing system. The application software for this is being specified.

PS AND THE LINE TO SPS

The beam is injected into the PS via the former PS-LEAR antiproton line by two pulsed bumper magnets, an upgraded kicker magnet and a new pulsed septum.

The two bunches fill 1/8 of the PS, which in turn has to provide four bunches to the SPS. This is achieved by virtue of the partial PS filling. The rather elaborate procedure [8] involves harmonic changes and bunch splitting and makes use of the RF systems (3–10, 80 MHz) that produce the LHC proton beam.

After extraction from the PS, the Pb⁵⁴⁺ beam is fully stripped to Pb⁸²⁺ by a 0.8 mm aluminium foil, where Coulomb scattering leads to transverse emittance blow-up. In order to meet the tight emittance budget (see Table 1), the stripper foil must be at low β . Four new quadrupoles and five new power converters are needed to generate the low- β insertion in the PS-SPS line.

SPS

In the nominal ion LHC filling scheme, 13 PS batches are injected into the SPS on a 43.2 s injection plateau at 5.9 GeV/n. At an intensity of 1.2×10^8 Pb⁸²⁺ ions/bunch, the space-charge tune shift is ~ 0.08 , potentially leading to excessive emittance blow-up or losses. However, measurements with proton beams suggest that even higher tune shifts are tolerable, as are the calculated intrabeam scattering growth times [9]. Should it prove necessary, a scheme that halves the bunch intensity by injecting 8 "bunchlets" and merges them back to 4 bunches by means of an additional 100 MHz system after acceleration could be implemented.

EARLY ION SCHEME

The nominal lead beam may be subject to limitations in the injectors and even damage LHC equipment [10]. As these effects are not easy to predict accurately, it is prudent to start with a beam whose characteristics allow the limitations to be explored with reduced risk. The "early ion scheme" features fewer bunches (only 60 with 1.35 μ s bunch spacing); the same final bunch intensity; and $\beta^* = 1$ m (instead of 0.5 m). It yields 5% of the design luminosity. This is adequate for early physics discoveries,

reduces beam requirements for the injector chain and relaxes the tight commissioning schedule.

OUTLOOK

The baseline LHC ion programme foresees lead-lead collisions with reduced luminosity (early ion scheme) in 2 or 3 experiments after the end of the first LHC proton physics run. Nominal luminosity will be made available for the subsequent ion runs. The most critical item is the hardware upgrade of LEIR, which should be finished by mid-2005. If high priority is assigned to the LHC ion programme, the commissioning schedule of the injectors could be as follows: LEIR until spring 2006, PS in 2006, SPS in 2007, and ions into the LHC by spring 2008. Other schemes, such as proton-lead or lighter ion collisions, are not part of the baseline programme and will require additional resources. However, care has been taken to ensure that major hardware systems comply with these future options of the LHC ion programme.

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