MILESTONES FOR THE LEAD INJECTOR COMPLEX COMMISSIONING

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Abstract

The LHC physics programme with heavy ions (lead-lead) collisions at a luminosity of 10^{27} $cm^{-2}s^{-1}$ can be achieved by upgrading the ion injector chain: Linac3-LEIR-PS-SPS [1]. The conversion of the Low Energy Antiproton Ring (LEAR) to a Low Energy Ion Ring (LEIR) [2,3] has already started. The conversion includes new magnets and power converters, a high-current electron cooling system, broad-band rf cavities, upgraded beam diagnostics and vacuum equipment to achieve 10^{-12} mbar. The start-up of the beam commissioning is planned for summer 2005. The impact on the proton LHC start-up of the major hardware changes in Linac3 (installation of the new ECR source and the test of the energy ramping cavity), LEIR, PS (new injection system, rf gymnastics), the stripping insertion between PS and SPS and their commissioning is discussed The milestones, schedule and an estimation of the lead beam brilliance and intensity in LHC are tentatively shown.

OVERVIEW

The major hardware changes along the injector chain are summarized in Fig. 1. Central to the ion injection scheme is LEIR and its powerful new electron cooling system.

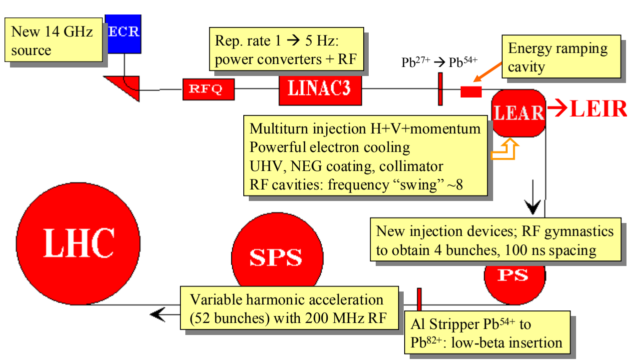

Figure 1: Hardware upgrades in the LHC injector chain.

In the nominal scheme, 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} $cm^{-2}s^{-1}$. The nominal lead beam may be subject to limitations in the injectors and even damage LHC equipment [11]. 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" (Table 1) features fewer bunches (only 60 per LHC ring with 1.35 µs bunch spacing) with the same final bunch intensity and β^{*}=1 m (instead of 0.5 m). Easier for the injectors, it yields a luminosity of 5.10^{25} $cm^{-2}s^{-1}$. This is adequate for early physics discoveries, reduces beam requirements for the injector chain and relaxes the tight commissioning schedule.

Table 1: Nominal parameters of the lead ion injectors.

LHC Pb Injector Chain: Key Parameters
for Early Beam ***(Pb-Pb Luminosity 5 10^{25} cm^{-2} s^{-1})***

	ECR Source →	Linac 3 →	LEIR →	PS → (4, 2)	SPS → (12)	LHC
Output energy	2.5 KeV/n	4.2 MeV/n	72.2 MeV/n	5.9 GeV/n	177 GeV/n	2.76 TeV/n
^{208}Pb charge state	27+	27+ → 54+	54+	54+ → 82+	82+	82+
Output Bρ [Tm]		2.28 → 1.14	4.80	86.7 → 57.1	1500	23350
number of bunches			1 (1/8 of PS)	1	4, 2	62/ring
ions/pulse[1, 2]	$9\ 10^{9}$	$1.15\ 10^{9}$	$2.25\ 10^{8}$	$1.2\ 10^{8}$	$\leq 3.6\ 10^{8}$	$4.3\ 10^{9}$
ions/LHC bunch	$9\ 10^{9}$	$1.15\ 10^{9}$	$2.25\ 10^{8}$	$1.2\ 10^{8}$	$9\ 10^{7}$	$7\ 10^{7}$
bunch spacing [ns]					1350	1350
ε*(nor. rms) [µm][3]	~0.10	0.25	0.7	1.0	1.2	1.5
ε (phys.rms) [µm][3]	50	2.5	1.75	0.14	0.0063	0.0005
Repetition time [s]		2.4	2.4	2.4	18	~5'fill/ring
total bunch length [ns]			200	3.9	1.65	1

[1] 200 eµA x 200 µs (Pb^{27+}) from ECR source, 50 eµA_e x 200 µs (Pb^{54+}) from Linac3 after stripping
[2] Pessimistic assumptions on losses in LEIR. Optimistically LEIR can produce up to 4.5 10^{8} Pb ions per cycle with a single Linac3 pulse.
[3] Same physical emittance as protons. ε*(normalized) = β γ ε (physical) invariant if no blow-up

Stripping foil

LINAC3 UPGRADE

To supply the nominal ion beam, a source current of 200 eµA Pb^{27+} is required (yielding ~50 eµA 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 [4]. 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 and was delivered to CERN in January 2005.

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 ± 0.4% during the linac pulse. This is required for momentum stacking in LEIR. During the lead accumulation test in LEAR in 1997[5], the required early beam intensity has been produced with the present source without margin by injecting 2/3 pulses (the beam was not accelerated in 1997). From this test, the main improvements needed to reach the nominal beam requirement are:

- to double the linac intensity,
- to build a faster electron cooling system,
- to improve the beam lifetime and the injection efficiency.

UPGRADE OF LEAR TO LEIR

LEIR cycle

The role of LEIR is to transform a series of long (~200 µs), low-intensity ion pulses from Linac3 into short (~200 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. For the early beam only one Pb^{54+} linac pulse is injected (instead of 4 for the nominal), cooled, adiabatically captured on h=1 and accelerated to 72 MeV/n. The sequence of events is sketched in Fig. 2; for the early beam the length of the LEIR cycle is reduced by 1.2 s.

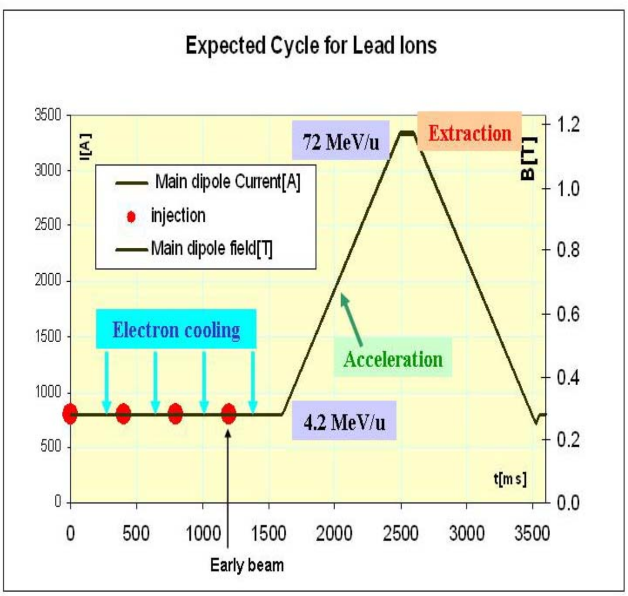

Figure 2: LEIR cycle, nominal and early beam

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 [5] 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, manufactured at INP Novosibirsk and, at present, assembled at CERN, 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 [5], 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 [6]. The LEIR vacuum system [1] features a bake-out at 300°C; NEG-coating wherever possible; low-outgassing collimators to control ion losses [7]; and "beam scrubbing" (lost ions enhance desorption and clean the vacuum envelope) if necessary.

RF and feedback systems

Two new large-bandwidth cavities based on Finemet® high-permeability magnetic alloy have been 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. The cavities are installed and being commissioned.

LEIR is the first CERN accelerator to be equipped with all-digital signal processors for the low-level RF. Prototype modules have been tested successfully in the PS Booster.

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. Some of the power converters have been installed and ready for being commissioned.

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 importance are the DC current transformer (2 µA 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). Some of the devices have been installed, and others like the transformer are under manufacturing.

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 development of application software for this has been started.

PS AND THE TRANSFER 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 a rather elaborate procedure [8] involving harmonic changes and bunch splitting and making use of the RF systems (3–10, 80 MHz) that produce the LHC proton beam.

After extraction from the PS, the Pb^{54+} beam is fully stripped to Pb^{82+} by a 0.8 mm aluminium foil, where Coulomb scattering leads to transverse emittance blow-up [9]. The expected ion emittance growth due to the stripping is 0.12 µm. In order to meet the tight emittance budget (see Table 1), the stripper foil must be at low β. Four new quadrupoles and six new power converters are needed to generate the low-β insertion in the PS-SPS line (β is lowered by a factor of 5). All the proton beams produced by the PS for the SPS are being sent through this transfer line. For these proton beams the 4 new quadrupoles must be set to zero gradient for perfect matching. The rms emittance blow-up of the proton beam due to the residual field in the new quadrupoles is less than 0.1 %.

SPS

In the early ion LHC filling scheme, up to 4 PS batches are injected into the SPS on a 7.2 s injection plateau at 5.9 GeV/n. At an intensity of 1.2×10^8 Pb^{82+} ions/bunch, the space-charge tune shift is ~0.07; the measurements with proton beams suggest that even higher tune shifts are tolerable. Calculated intrabeam scattering growth times are acceptable [10].

TENTATIVE SCHEDULE

In order to meet the deadline for the lead collisions in the LHC, April 2008, the project has to keep to the milestones as compiled in Table 2. While progress is satisfactory for most of the system, the schedule is ambitious and particularly optimistic concerning LEIR installation because to date, only two vacuum sectors out of 5 are completely installed. New bellows required for the other sectors are not yet delivered (already 4 months delay). To avoid delaying the construction of the machine, old bellows from the stock have been used. A delay on the construction is not compatible with commissioning LEIR with beam from August 2005 to March 2006 through the winter shutdown. In 2006, in order to help the PS start-up with the large diversity of beams after the long 18-months shutdown, LEIR will stop at the end on March. It will restart to produce ion beam for the PS commissioning as from September (rather than June 2006) only because LEIR operators run also the AD machine. The last period of the year is very tight, but as in 2007 all the experts will be busy with LHC, it will be judicious to make or at least to start SPS commissioning with ions in 2006.

Table 2: Tentative schedule

	hardware test	Start with beam	Problems
Source and Linac3	Feb. 2005	March 2005	New source
LEIR injection line	March 2005	June 2005	
LEIR ring	Apr. 2005	Aug. 2005(?)	LEIR conversion completed ? Running-in through winter to March 2006
PS/TT2	Feb. 2006	Sept. 2006(?)	April-August 2006: No LEIR operators (AD)
SPS		late 2006 spring 2007	SPS experts busy commissioning LHC ring in 2007
LHC		from April 2008(?)	Physics with the early beam in LHC

CONCLUSION

The baseline LHC ion programme foresees lead-lead collisions with reduced luminosity (early ion scheme) in 2 or 3 experiments in 2008. The early beam scenario is just the first step, so even before the commissioning of the injectors is finished, studies on the nominal beam have to be pursued as from 2007 in order to have nominal LHC luminosity in 2009. The task of the injectors is facilitated by the early beam scheme. Moreover, in case of problems for producing the required intensity or density, more pulses from Linac could be accumulated, the LEIR cycle length could be increased and vertical plane multiturn injection exploited. To relax the PS/SPS commissioning, LEIR could be re-started in June 2006, if a solution of operating AD and LEIR in parallel between June and August 2006 is found.

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