I-LHC PROJECT OVERVIEW AND STATUS

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Abstract

The LHC physics programme with heavy ions (lead-lead) collisions at a luminosity of 1027 cm-2s-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] is completed and the beam commissioning has already started. The installation and modification of PS (new injection system, rf gymnastics), the stripping insertion between PS and SPS and their commissioning in the coming years is discussed. The milestones, schedule and an estimate 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.

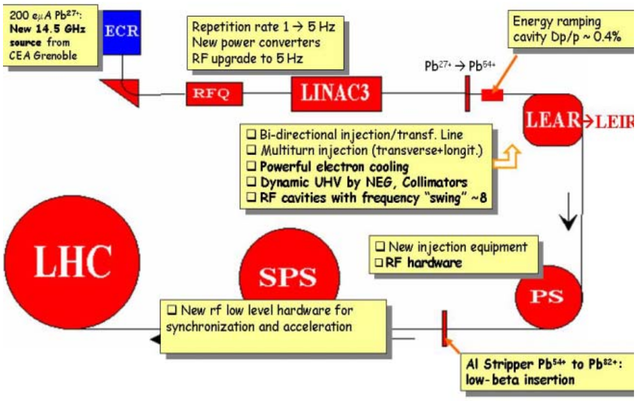

Figure 1: Hardware upgrades in the LHC injector chain.

In the nominal scheme, the injector chain provides the LHC with 592 bunches of 9×10^7 Pb^{82+} ions per ring. The 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 in the LHC. 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) has fewer bunches (only 60 per LHC ring with 1.35 µs bunch spacing) with the same bunch intensity and β^*=1 m (instead of 0.5 m), yielding a luminosity of 5.10^{25} $cm^{-2}s^{-1}$ suitable for the first year.

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

ION SOURCE AND LINAC3 COMMISSIONING

A new electron cyclotron resonance (ECR) source, designed and built at CEA/Grenoble [4], operating in "afterglow mode" at 14.5 GHz, will deliver the required current of 200 eµA Pb^{27+}. Compared to the older source (ECR4), it has increased transverse confinement by a stronger permanent hexapole; a strong longitudinal field (up to 1.4 T); a larger plasma chamber; RF couplers for both 14.5 and 18 GHz microwaves and the possibility to install two micro-ovens. It performed well in first tests and the beam commissioning of the source is described in [5]. Pulsed power converters for magnets to LEIR are being upgraded for the operation at 5 Hz. A dedicated ramping cavity, installed directly downstream of the Linac3 stripper, varies the beam momentum by ±0.4% along the pulse by a linear modulation of the cavity phase by ±40°. The debunching cavity placed 11 m downstream has to be phase-modulated in the same range to compensate for the change in ion time of flight and to minimise momentum spread. The ramping system has been successfully tested with beam in static mode; dynamic tests have started and are described in [6]. This is required for momentum stacking in LEIR. During the lead accumulation test in LEAR in 1997[6], 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 were:

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

LEIR COMMISSIONING

LEIR machine

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. The beam commissioning started in October 2005 is described in [7].

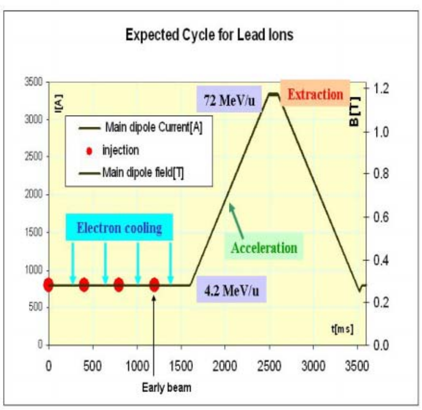

Figure 2: LEIR cycle, nominal and early beam

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 is added. The beam commissioning of the injection line is described in [7].

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 60 mA. The new system, manufactured at INP Novosibirsk and, assembled at CERN, has a length of 2.5 m 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 of ions of the stack with electrons. The first beam commissioning is described in [8].

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. The LEIR vacuum system [1] is 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) 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 down to a reasonable 60 kW. The cavities are being commissioned.

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

Other systems

Most of the 164 power converters for LEIR and its transport lines have been recuperated and rebuilt from past machines, notably LEP. 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. The power converters have been installed and are being successfully commissioned with beam.

Beam diagnostic devices are largely recovered from LEAR but have been 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).

LEIR serves as test-bed for a newly developed unified accelerator control system that will also be employed for the LHC. The commissioning of this system and of the application software is described in [9].

PS AND 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. All the hardware is already installed and ready to be tested before the end of March.

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 [10] involving harmonic changes and bunch splitting and making use of the RF systems (3–10, 80 MHz) that produce the LHC proton beam. All the hardware will be installed for the end of March.

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. The expected ion emittance growth due to the stripping is 0.12 μm. In order to meet the tight emittance budget, 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.

All the PS injection, acceleration and the low-β insertion systems have been installed and the hardware tests will be completed for the end of March 2006.

SPS RING

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 but even higher tune shifts are tolerable. Calculated intrabeam scattering growth times are acceptable. Due to the stripping in the TT2 transfer line the beam rigidity drops to 57.03 Tm at the injection of the SPS compared to the 86.67 Tm at the PS ejection. Thus, the SPS injection cannot be pre-adjusted with proton beam. At injection, a bunch-to-bucket transfer using the existing 200 MHz travelling wave RF system will be used. At this energy, the RF frequency is outside of the bandwidth of the cavity, a non-integer harmonic number will be used. At higher energies when the RF frequency is already inside the bandwidth of the cavity, this technique is replaced by normal fixed harmonic number acceleration. This method has been successfully used for ion acceleration in the SPS fixed target programme since 1994. At the highest energy some new hardware is needed to synchronize the extraction to LHC.

LHC MAIN RING

Lead ion collisions will be provided in three of the LHC experiments. The commissioning plan for lead ion running [11] is based on the simple principle that, at the same magnetic rigidity, lead ions behave magnetically in the same way as protons, Assuming that the LHC is already operational with protons, and that the ion injector chain is available, the time required to switch the LHC main rings over from their p-p collider mode will be minimised by keeping the magnetic cycle identical through beam transfer, injection, ramp and squeeze (with the exception that it will be necessary to squeeze a third IP (ALICE) to $\beta^* = 1\,\mathrm{m}$ in the early ion scheme). It will of course be necessary to adjust the RF frequency, capture a different bunch pattern and adapt the use of the beam instrumentation. On this basis, the switchover from proton to ions should be possible in less than a week.

Comparison with precedents where a proton collider switched over to ions, or vice-versa are relevant here. The most obvious is RHIC which switched species a few times, typically taking a week to set up and a further week for performance "ramp-up". However the magnetic cycle for ions in RHIC involves a ramp through transition energy unlike that for protons. A better comparison can perhaps be made with the first ion collider at CERN, the ISR, which switched very quickly from regular p-p mode to collide deuterons and alpha particles a few times. Indeed our argument about the magnetic cycle echoes the explanation given almost three decades ago in [12]:

"At a fixed momentum deuterons behave magnetically in the same way as protons. Hence the beam transfer trajectory, the closed orbits and the working lines required no changes. Other parameters which affect the actual Q values in the stack, such as the incoherent image force Q shift, also remain unchanged and the usual mode of Q compensation is applicable."

An even faster transition [11] to Pb-Pb collisions in the LHC with luminosity of about $5.10^{24}\,\mathrm{cm^{-2}s^{-1}}$ may be feasible during the initial proton commissioning, when all IPs will collide with β^* at injection values.

TENTATIVE SCHEDULE

In order to meet the deadline for the lead collisions in the LHC, end 2008, the project has to keep to the milestones compiled in Table 2. While progress is satisfactory for most of the system, the schedule is ambitious. In 2006, in order to help the PS start-up with the large diversity of beams after the long 18-month shutdown, LEIR will stop at the end of April. It will restart to produce ion beam for the PS commissioning as from September. Alternative schedules, with machine commissioning delayed, have been discussed but the main reasons to maintain the commissioning schedule for Pb-ion injectors are as follows:

- All the hardware (except for SPS) will be operational by the end of March 2006, the LHC is not running in 2006 and early 2007.
- As this year is not a standard year (with most accelerators restarting after an 18-month shutdown), the expected beam time requirement for CNGS is less demanding in protons. Thus, it will be easier to accommodate commissioning periods for the PS and SPS.

Table 2: Tentative schedule

	hardware test	**Start with beam**	**Problems**
Source, Linac3	Feb. 2005	Mar 2005	New source
LEIR inj. line	Mar 2005	Jun 2005	
LEIR ring	Apr. 2005	Oct.2005	Commissioning through winter to April 2006
PS/TT2	Feb. 2006	Sept. 2006	Stop from April-August 2006
SPS		summer 2007	SPS experts busy commissioning LHC ring at the end of 2007
LHC		End of 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 task of the injectors is facilitated by the early beam scheme. The project is on schedule to finish the LEIR commissioning at the end of April 2006, to start the PS as from September, the SPS in 2007 and finally the LHC at the end of 2008 after the first proton run. But we should remember that the early beam scenario is just the first step: studies on the nominal beam have to be pursued as from 2007, even before the commissioning of the injectors is finished, in order to go forward to the nominal LHC luminosity. After the early scheme run, the number of bunches can progressively be increased towards nominal and to complete the first phase of LHC ion programme as from 2009.

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