COMMISSIONING AND PERFORMANCE OF LEIR

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Abstract

The Low Energy Ion Ring (LEIR) is a key element of the LHC ion injector chain. Under fast electron cooling, several long pulses from the ion Linac 3 are accumulated and cooled, and transformed into short bunches with a density sufficient for the needs of the LHC. Experience from LEIR commissioning and the first runs in autumn 2006 and summer 2007 to provide the so-called "early LHC ion beam" for setting-up in the PS and the SPS will be reported. Studies in view of the beam needed for nominal LHC ion operation are carried out in parallel to operation with lower priority.

INTRODUCTION

The LHC [1,2], presently under construction at CERN will, in addition to proton operation, provide ion collisions for physics experiments. For the moment, only lead ion operation is part of the approved program, but other species may be used as well. The ion accelerator chain existing before the LHC era was not capable to provide the ion beams needed for the LHC.

Thus, fundamental upgrades of the CERN ion accelerator complex, based on ion accumulation experiments [3] carried out with LEAR, had to be implemented. The resulting ion accelerator chain is depicted in Fig. 1 and nominal values for some key parameters are listed in Tab. 1.

Since nominal LHC ion operation is very demanding for both the LHC and the injector chain, first LHC ion operation will take place with a lower luminosity and less bunches using the so-called "early scheme" [3-5]. In this scheme, every LEIR/PS pulse will provide only one LHC bunch, the SPS will accumulate only up to four batches and the LHC will be filled with 62 bunches per ring.

OVERVIEW OF LEIR

The most fundamental upgrade of the CERN ion accelerator chain [4-6] for the LHC was the addition of the Low Energy Ion Ring LEIR (reconstructed and upgraded LEAR). The role of this small accumulator ring, equipped with a new state-of-the-art electron cooler (constructed in the frame of a collaboration by BINP), is to convert several 200 µs long Linac3 pulses into short high brilliance bunches needed for LHC ion operation.

Fig.2 shows the LEIR ring after installation. A typical 3.6 s LEIR cycle needed for nominal operation and producing the beam intensity for four LHC bunches is shown in Fig. 3. On an accumulation plateau several Pb^{54+} pulses from Linac3 are accumulated alternating:

- An elaborate multiturn injection of the 200 µs long Linac pulses with stacking in momentum and in both transverse phase spaces [4]. For this injection scheme, momentum ramping of the Linac3 (mean beam energy increases by ~4 10^{-3} during the duration of the Linac3 pulse) is required as well as a large dispersion at the injection and an inclined injection septum.
- Fast (in 200 ms to 400 ms) electron cooling [4,7,8] .

After accumulation of a sufficient intensity, the beam is bunched with harmonic number two and accelerated during about 1 s. Finally the two bunches, each one corresponding to two LHC bunches, are ejected and

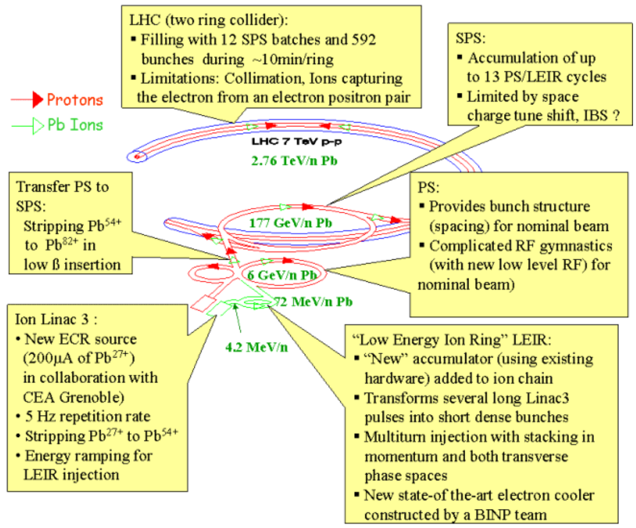


Figure 1: Overview of the LHC ion injector chain.

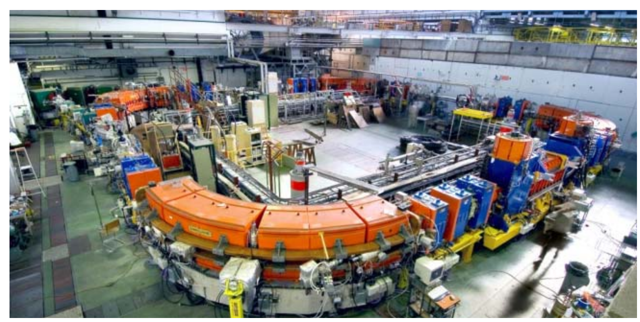


Figure 2: LEIR ring after completion of installation.

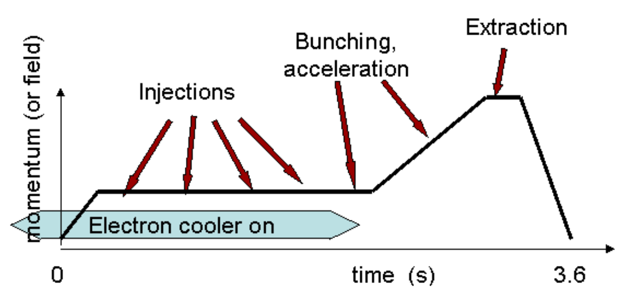


Figure 3: Nominal LEIR cycle.

transferred to the PS, the next machine in the chain. The PS has to provide already four bunches with the spacing needed in the LHC with the help of RF gymnastics. 12 SPS shots, each one accumulating up to 13 LEIR/PS shots, fill the LHC.

The "early" beam provides, with a 2.4 s cycle and only one injection, only one bunch for the PS and the LHC. Only four LEIR/PS batches are accumulated in the SPS.

LEIR optics

The basic shape of LEIR (see Fig. 2) is a "square" with long 90^{o} bending sections in the corners separating four straight sections.

Rather different lattice parameters are needed in the injection section (large dispersion and small horizontal ß-function) and the electron cooler section (ß-function of about 5m in both planes and small dispersion). These requirements can be fulfilled by installing injection and the cooler in adjacent straight sections and a basic (without perturbation by the cooler) lattice with twofold periodicity and symmetry.

The electron cooler introduces strong lattice perturbations especially at low energy during accumulation. The coupling between the two transverse planes induced by the cooler solenoid is compensated with short compensation solenoids; those add significant additional focusing. This additional focusing is compensated globally by readjusting all quadrupole families and trim power supplies close to the cooler, rather than locally just by changing quadrupole gradients close to the perturbation. The lattice functions of the lattice obtained are shown in Fig. 4 for one half of the ring (second half is the mirror image) extending from the section opposite to the cooler, through the injection section to the electron cooler section.

Another perturbation of the lattice, which had been considered a challenge, occurs during acceleration. Since the LEIR bending sections are C-shaped and the vacuum chamber is connected to ground at many locations (fully bakeable and constructed initially for a slow cycling

Table 1: Key beam parameters along the accelerator chain for LHC ion operation with the "early" and nominal scheme.

	Linac 3	LEIR		PS		SPS		LHC	
Parameter		nominal	early	nominal	early	nominal	early	nominal	early
energy per nucleon	4.2 MeV	4.2 MeV		5.9 GeV		72 MeV		2.76 TeV	
Charge state	27→54	27 → 54		54 → 82		82		82	
Shots accumulated		~5-7	1	1	1	8,12,13	4	12	16
LHC bunches/shot	≤ 1	4	1	4	1	≤ 52	4	592	62
Ions/LHC bunch		$2.25\ 10^{8}$		$1.2\ 10^{8}$		$0.9\ 10^{8}$		$0.7\ 10^{8}$	
Ions/shot (filling)	$11.5\ 10^{8}$	$9\ 10^{8}$	$2.25\ 10^{8}$	$4.8\ 10^{8}$	$1.2\ 10^{8}$	$\leq 47\ 10^{8}$	$3.6\ 10^{8}$		
Bunch spacing		350 ns		99.8 ns	1350ns	99.8 ns	1350ns	99.8 ns	1350 ns
Norm. rms emittance	0.25 μm	0.7 μm		1.0 μm		1.2 μm		1.5 μm	
Long. emitt./LHC bunch ($4\ \pi\ \sigma_E\ \sigma_\tau$)		0.025 eVs/n		0.05 eVs/n		0.24 eVs/n		1 eVs/n	
rms bunch length		50 ns		1 ns		0.41 ns		0.25 ns	
Cycle/Filling time	>200ms	3.6s	2.4s	3.6s	2.4s	~50s	~16s	~10 min	~4 min
β*								0.5 m	1.0 m
Initial luminosity								10^{27} cm^{-2}s^{-1}	$5\ 10^{25}$ cm^{-2}s^{-1}
Initial lumi. decay time (2 experiments)								~5.5 hrs	~ 10 hrs

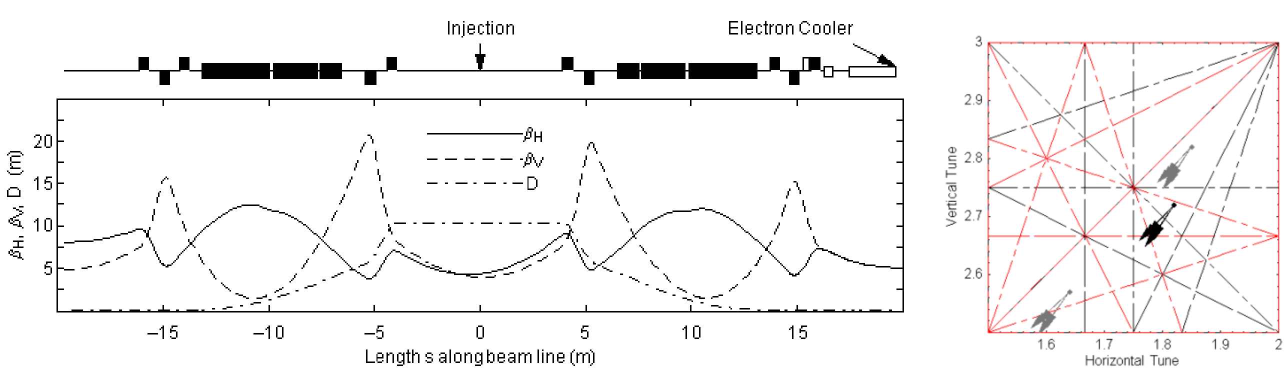


Figure 4: LEIR lattice. The left image shows Twiss parameters for the nominal lattice for one half of the circumference; the right image shows a resonance diagram with the nominal working point (black) and two other envisaged working points. The arrows point from the zero intensity working point to the one with the largest space charge tune shift.

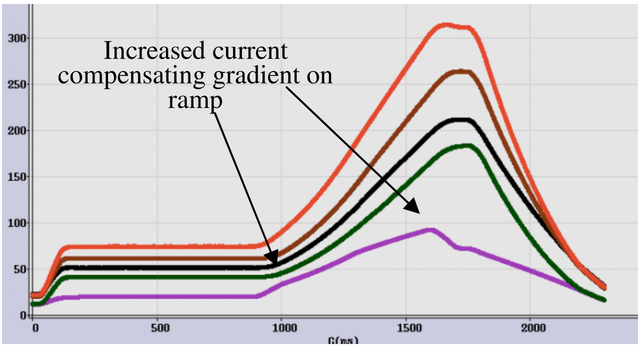


Figure 5: Time evolution of quadrupole currents with corrections to compensate gradients due to ramping.

machine), ramping induces net currents flowing along the chamber inducing, in turn, defocusing gradients acting on the lattice. Thus a compensation scheme, adjusting the quadrupole currents during the ramp has been implemented. The effect of these corrections is clearly visible on the acquisitions of quadrupole current versus time shown in Fig. 5.

LEIR COMMISSIONING AND PERFORMANCE

LEIR Commissioning

LEIR commissioning [9] has taken place in stages partly in parallel with installations. Commissioning of the Linac3 to LEIR transfer line has taken place in spring 2005 and has suffered from "teething" problems of the new controls system and first difficulties with injection matching. After bringing the beam up to the LEIR injection in July 2005, LEIR commissioning has been interrupted to complete the installations of the ring.

Commissioning of the LEIR ring started in autumn 2005 with O^{4+} (beam rigidity very close to Pb^{54+}, but longer life-times had been expected). First circulating beam and satisfactory injection efficiency could be obtained quickly after work on improving the transfer line optics. However, due short life-times, which later-on were traced back to ions hitting a piece of the vertical ionization profile monitor and degrading the vacuum, only weak signs of cooling and no accumulation have been observed. Another problem encountered during this period was that cables between position pick-up and their head-amplifiers were damaged by currents induced by the ramp [9]. In consequence, the ramp rate had to be reduced.

During a short shutdown at the beginning of 2006, the machine has been opened to install a new vertical ionisation profile monitor with collimators intercepting circulating ions before they hit surfaces with high beam loss induced outgassing yields. The damage of pick-up cables due to ramp induced currents has been cured by insulating the head amplifier boxes from ground.

Ring commissioning resumed in the middle of February 2006 with Pb^{54+} ions. At the very beginning, progress was slowed down by difficulties to tune the injection efficiency with Pb^{54+} ions, again due to problems with injection matching. After improving the injection line setting [10] and setting-up of the transverse damper, clear signs of cooling could be observed on 3rd March without particular difficulties.

LEIR commissioning has been completed, almost as scheduled, in May 2006 with the proof that the early LHC ion beam can be produced and transported to a region just upstream from the PS injection.

Experience from first LEIR Runs

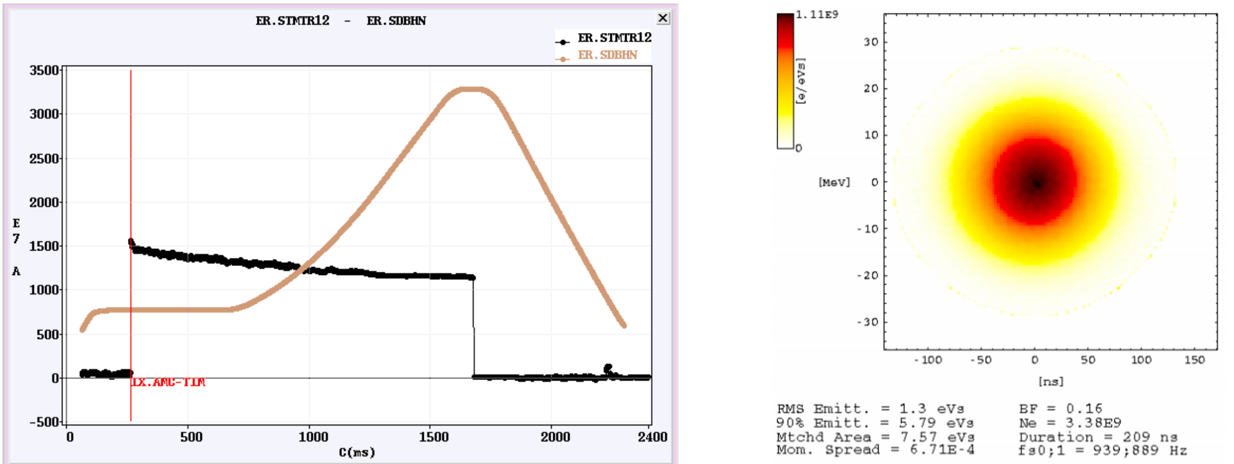
The first regular LEIR run has taken place in autumn 2006 in order to provide the beam for setting up the PS with the "early LHC ion beam". The beginning of the start-up had been delayed due to technical problems (vacuum leak at the collector of the electron cooler). However, the start-up with beam was smooth and the beam was available almost on time for the PS. The machine has been running in general with good reliability. Strong fluctuations of the trajectory in the injection line, caused by stray field of the PS ring and lead to a jitter of the injection efficiency.

The second LEIR run started at the beginning of August 2007. Again, the start-up with beam has been carried without particular difficulties. The fluctuations of the injection trajectory and efficiency have been reduced to an acceptable level by magnetic shielding of the beam pipe in regions close to the PS. LEIR now delivers routinely the beam needed for SPS setting-up with the "early LHC ion beam". Work to sort out various minor technical problems and, with lower priority, to produce the not yet demonstrated nominal LEIR beam is going on in parallel.

LEIR Performance

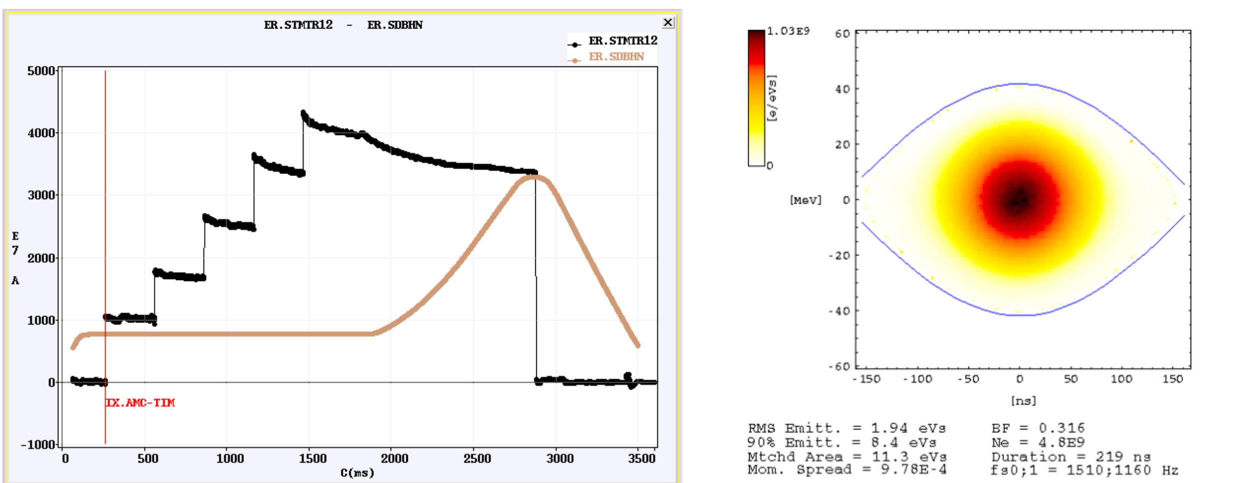
Table 2: Comparison of LEIR design performance and obtained performance for the nominal beam and the beam needed for first LHC ion run(s).

	Nominal		"early"	
Parameter	design	obtained	design	obtained
Linac3 current (μA)	50	25	50	25
Cycle time (s)	3.6	3.6	2.4	2.4
Inj. efficiency (%)	50	50	50	50
Accumulated. Int. (10^8 Pb^{54+})		~10		~2.5
Int. for PS (10^8 Pb^{54+})	9	~7	2.25	2.25
Hor. norm. rms emitt. (μm)	0.7	0.5	0.7	0.52
Vert. norm. rms emit. (μm)	0.7	0.2	0.7	0.24
Long. emitt. $4\pi\ \sigma_E\sigma_\tau$ per bunch (eVs/n)	0.05	0.04	0.025	0.025

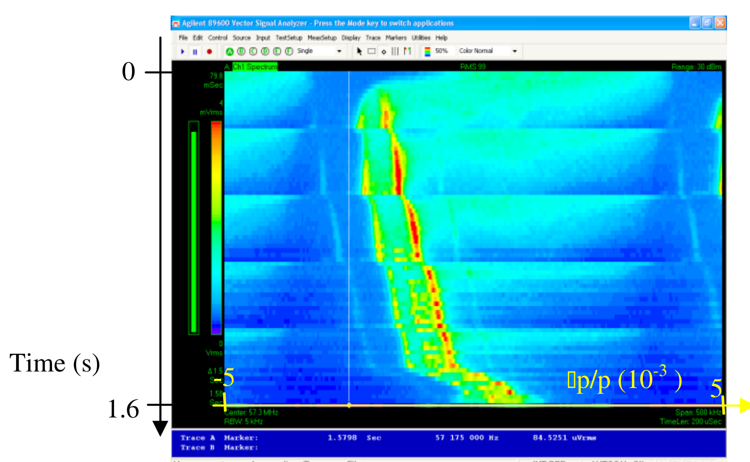


(a) (b)

Figure 6: LEIR performance for the "early" beam used routinely for setting-up of the PS and SPS with the beam needed for the first LHC ion run. The images show the evolution of the beam current (a) and a tomographic reconstruction of the longitudinal phase space (b).



(a) (b)



(c)

Figure 7: LEIR performance with a high intensity beam. The images show the evolution of the beam current (a), a tomographic reconstruction of the longitudinal phase space (b) and the evolution of longitudinal Schottky spectra(c).

Tab. 2 compares LEIR performance as observed during the present run 2007 with design values for the "early" beam needed for the first LHC ion runs and the nominal beam. One observes that the design performance has been reached for the "early" beam with transverse emittances significantly below specifications. Fig. 6a shows some details. After injection, a bit more than the design intensity is circulating; with some losses mainly during the cooling plateau, the design intensity is ejected. The tomographic reconstruction of longitudinal phase space show that the design longitudinal emittance (the number quoted in the figure is the rms for all 208 nucleons) is reached.

Fig. 7 shows some measurements for high intensity beams obtained so far. The evolution of the beam current (with higher Linac3 currents, higher beam currents, exceeding the design value at ejection, have been obtained at the end of the accumulation plateau) shows a loss at the beginning of the ramp. This loss is more pronounced for higher beam currents and, thus, the design current has not yet been obtained at ejection. However, investigations on these losses and the nominal LEIR beam are carried out only with low priority and in parallel to operation. The emittances in all three phase spaces are well within specifications.

Vacuum Limitations

Beam loss induced vacuum degradation had been a fundamental limitation of proof of principle experiments [3]. Thus systematic investigations of beam loss induced outgassing have been carried out [11]. Based on these results, the LEAR vacuum system has been upgraded carefully and, in particular, Au coated collimators [12] with a low outgassing yield, intercepting lost ions before they can hit the normal vacuum chamber, have been installed and, where it was possible, the vacuum chamber was coated with low temperature NEG. Fig. 8 shows that beam life-times, sufficient for accumulation the nominal intensity, have been obtained. During the 2006 run, intensities by more than a factor two larger than the design nominal intensity have been accumulated on very long plateaus.

CONCLUSIONS AND OUTLOOK

LEIR has been successfully installed and commissioned. The second regular run takes place at present. The beam needed for the first LHC ion runs is delivered reliably during routine operation for setting up the PS and the SPS for the first LHC ion run. The present run aims at (i) demonstrating that the "early" LHC ion beam can be obtained at SPS extraction and (ii) carrying out machine studies to better understand potential SPS limitations (IBS, direct space charge tune shift during a long front porch) with the nominal LHC ion beam. The first LHC ion run is expected to take place in 2009.

Even though no fundamental limitation has been identified so far, further work on the production of the nominal beam has still to be carried in parallel to operation. Experiments have expressed strong interest in

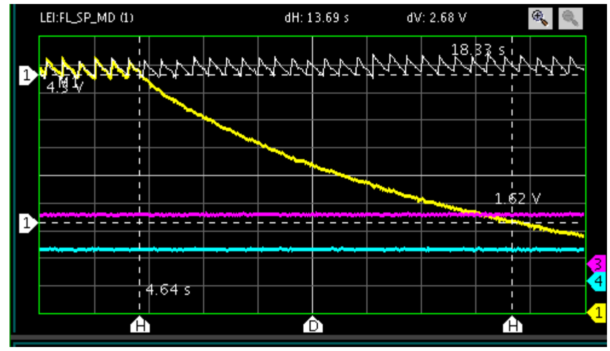


Figure 8: Beam intensity (yellow trace) versus time (2s/div) after accumulation on a very long plateau. The peak intensity is about 16 10^8 Pb^{54+} ions; and the beam life-time about 14 s.

LHC runs with lighter ions, even though this is not foreseen in the LHC program. Furthermore, first studies on using LEIR to provide various ions species for SPS fixed target experiments have started recently.

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