

# LEIR: THE LOW ENERGY ION RING AT CERN

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## Abstract

Amongst all the modifications of the PS Complex to produce the LHC ion beams, the conversion of the old Low Energy Antiproton Ring (LEAR) into the Low Energy Ion Ring (LEIR) is a major issue. The accumulation in LEIR of  $9 \cdot 10^8$  Lead ions in normalized transverse emittances of  $0.7 \mu\text{m}$  allows the production of 4 of the 592 bunches needed in one LHC ring, in one LEIR cycle. Then, it will take around 10 min to fill one LHC ring. The requested luminosity of  $10^{27} \text{ cm}^{-2}\text{s}^{-1}$  for lead ion collisions is reachable and is  $\sim 1000$  times more than the actual chain (Linac3, PSB) can do. The production of Lead ion beams is described, with particular attention to electron cooling, the injection system and the beam lifetime.

## 1 OVERALL DESCRIPTION OF THE LEAD ION FILLING SCHEME OF LHC

To reach the desired luminosity for the lead experiments in LHC, the required number of ions is  $0.7 \cdot 10^8$ /bunch at 2.7 TeV/u within normalised emittances ( $\beta\gamma\sigma^2/\beta_{h,v}$ ) smaller than  $1.5 \mu\text{m}$ . The upper number of lead ions per bunch in LHC is determined by both the quench limit (interactions at collision points) and the saturation of the Alice central detector. The corresponding lower limits are given by the beam orbit observation system and by the minimum acceptable luminosity in Alice. The emittance budget has been set to  $1.2 \mu\text{m}$  at the exit of the SPS,  $1 \mu\text{m}$  at the end of the stripper in the TT2 line, and  $0.7 \mu\text{m}$  at the exit of LEIR.

To fulfil this requirement, it has been proposed [1] to add an accumulator ring LEIR. An improved ECR ion source (from 100  $\mu\text{A}$  to 200  $\mu\text{A}$  of  $\text{Pb}^{27+}$ ) is foreseen to feed the Linac3, pulsing at up to 5 Hz. At the end of the Linac3, a first stripping takes place to obtain a beam of  $\text{Pb}^{54+}$  (40  $\mu\text{A}$ , 450  $\mu\text{s}$  actually). From LEIR to LHC collision flat top, an overall transfer efficiency of 30% is assumed.

A combined longitudinal-transverse multiturn injection is envisaged for LEIR [2]. About  $2 \cdot 10^8$  ions are then cooled and stacked per injection. Further injections, followed by cooling and stacking, take place until the number of ions required is reached. To obtain fast cooling and stacking, the electron-cooling device has an interaction length of 3 m and an electron current of up to 600 mA. To avoid the losses by charge-exchange with the residual gas, the vacuum has to be very good and the outgassing of the chamber walls by the lost ions has to be minimised. The improvements foreseen to the source, the injection efficiency, the vacuum in LEIR and the cooling

and stacking efficiency all contribute to the objective of reaching the required number of ions per bunch, in the small emittance and in a time as short as possible.

The beam is then accelerated on harmonic 2 in LEIR and extracted towards the PS, where the 2 bunches are captured by an rf voltage at harmonic 16 (PS is 8 times longer than LEIR). The chosen transfer energy is a compromise between the limitations by space charge at the PS injection ( $\Delta Q_{\text{incoherent}} < 0.25$ ), the gap needed between two consecutive bunches for the rise of the extraction kicker (150 ns, kick error  $< 1\%$ ), the cycle length, and the minimum frequency available with the basic PS rf system. After a first acceleration in the PS, the 2 bunches are gradually transferred from  $h=16$  to  $h=12$ , then they are split [3] into 4 ( $h=24$ ) and finally there is another transfer from  $h=24$  to  $h=21$ . After acceleration to high energy (5.9 GeV/u), a transfer to  $h=169$  (42 MHz cavities) and a final splitting of the 4 bunches to four pairs of two bunchlets is foreseen. To decrease the space charge and the IBS during the long SPS injection flattop, the ions are transferred from the PS to the SPS at the highest possible energy and the bunch population is decreased as much as possible. The harmonic in the PS is chosen to reach the 100 ns bunch spacing in LHC and is compatible with the SPS rf system (around 200 MHz). In the TT2 line between PS and SPS the ions are fully stripped [4]. In the SPS, several batches from the PS are stacked, and then accelerated. The 4 pairs of bunchlets are recombined in 4 bunches and extracted to the LHC at 177 GeV/u. This procedure is repeated until the two LHC rings are filled with 592 bunches each. The filling takes about 10 min per ring.

## 2 THE MAIN CHALLENGES

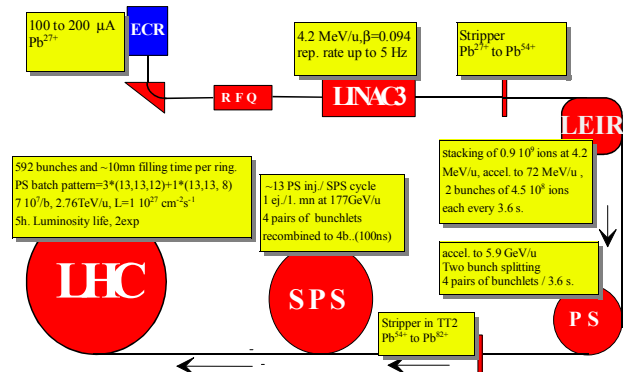


Figure 1: The general layout foreseen to fill LHC with lead ions.

## 2.1 Linac3

The ECR ion source has to be improved. A European collaboration [5] has already shown that increasing the plasma heating frequency from 14 GHz to 28 GHz is the right way to raise the delivered current when the source is used in continuous mode. Tests are under way for the after-glow pulse mode. A special rf cavity will be installed just after the last rf tank of Linac3 to allow a 1% ramping of the ion beam momentum in 200  $\mu$ s as required for multiturn injection in LEIR.

## 2.2 LEIR injection

The electron cooling is faster in the longitudinal plane than in the transverse. Thus a combined longitudinal horizontal injection has been proposed, as it limits the transverse emittance to a reasonable value compared to normal multiturn injection. This requires an increase of the momentum during the Linac3 pulse, a zero dispersion at the end of the injection line (to avoid the position change of the beam), a normalised dispersion  $D/\sqrt{\beta}$  of more than 5  $m^{1/2}$  to limit the momentum spread injected, and a “not too large” dispersion ( $\sim 10$  m) in the machine at the injection point. Furthermore, an inclined septum is foreseen in LEIR to permit improved injection efficiency by also exploiting the vertical phase space for stacking. This solution is preferred, rather than a strong coupling in LEIR which could certainly deteriorate the large beam emittance obtained after injection. An orbit bump system (linear bump decrease of  $\sim 0.5$  mm/turn), which was used already during the 1997 tests [7], will be employed. About 70 turns (200  $\mu$ s) will be injected per injection, with efficiency better than 50%. The characteristics of the beam after injection are:  $\Delta p/p=4\%$ ,  $\epsilon_h=70 \pi$  mm.mrad and  $\epsilon_v=30\pi$  mm.mrad.

## 2.3 LEIR Electron Cooling

The electron cooling (Table 1) system should provide, at 4.2 MeV/u, a transverse cooling time of 0.2 s for lead ions. This could be achievable with an electron current of 0.3 A, an e-beam radius of 30 mm and an interaction length of 3 m. The cathode (25 mm diameter) will be convex [6] to increase the perveance to about 6  $\mu$ P and immersed in a large solenoidal field (up to 0.6 T). Finally an adiabatic magnetic field reduction (to 0.075 T) will be inserted between the gun and the interaction part to increase the electron beam radius to 35 mm and to reduce the transverse electron temperature, which could improve the cooling time. Although a small dispersion at the cooler is favourable [7] for efficient cooling, zero dispersion at the electron cooler is preferred, to ease the operation. Transverse beta functions of about 5m are chosen at the cooler. The electron beam intensity and energy can be adjusted independently. To match the electron beam diameter to the ion beam dimension, it will be possible to adjust the adiabatic expansion factor. When

the ion beam is cooled at the centre of the electron beam, the cooling forces are enhanced but also the electron-ion recombination rate. To reduce the electron beam density at the centre of the electron beam, a cathode where the central part is less heated than the outer part has been proposed. Despite the reduced cooling forces, the ion beam stack will then be maintained under sufficient cooling, but the recombination rate is reduced leading to less ion losses from the stack.

MAGNETIC SYSTEM		
Gun solenoid field (max. field)	0.4 (0.6)	T
Adiabaticity solenoid length	0.4	m
Toroid and drift solenoid field (max. field)	0.075 (0.15)	T
ELECTRON BEAM CHARACTERISTICS		
Cathode voltage	0 to 40	kV
Cathode diameter	25	mm
Gun perveance	3 to 6	$\mu$ A/V <sup>1.5</sup>
Max. electron current at $\beta=0.094$	0.6	A
Maximum electron current	3	A
Maximum expansion factor	8	
Maximum electron beam diameter	70	mm
Drift length (effective length)	3 (2.7)	m

Table 1: The electron cooler main parameters

## 2.4 The LEIR lattice

To keep symmetry 2 to the lattice, injection and cooling are in two consecutive sections. The extraction is in the section where the dispersion is zero. To obtain the required Twiss parameters, a triplet (Figures 2 and 3), instead of a simple doublet is needed in the electron cooling section. There are five quadrupole families and their independent powering allows an easy modification of the Twiss parameters in two consecutive sections. This lattice leads to a momentum acceptance of 8% together with  $(A_h, A_v) = (100, 50) \pi$  mm.mrad when using the actual vacuum chamber dimension.

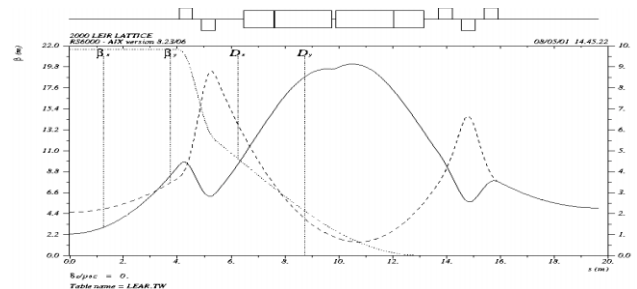


Figure 2: The LEIR lattice. One half of a period (i.e. a quarter of the machine) extending from injection where the dispersion is 10 m, to the centre of the cooler ( $\beta_h=\beta_v=5m, D=0$ ) is shown.

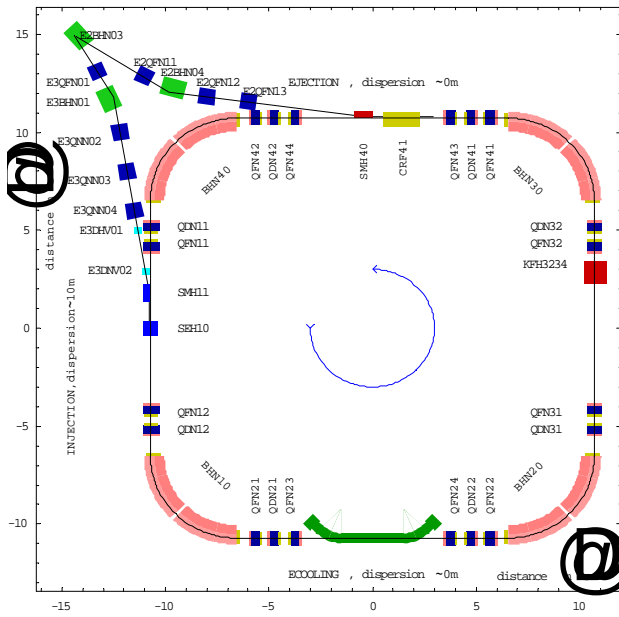


Figure 3: The LEIR machine layout, with only the main elements, is shown.

2.5 The vacuum

During the tests in 1997 in the LEAR ring, it was found that the loss of ions on the vacuum chamber walls provokes a strong outgassing [7,8] which has been estimated from measurements at injection energy to be about  $10^4$  molecules per ion lost. The lifetime of the circulating beam is then decreased, and this limits the number of ions which can be accumulated in the machine. Tests [9] using the beam of Linac3 have been launched to find the best vacuum chamber treatment to decrease this limiting phenomenon. The beam scrubbing (long term bombardment) has been found to be very effective and is one of the simple solutions to be applied to obtain a good vacuum, even in the presence of ion beam losses.

2.6 Acceleration in and extraction from LEIR, and injection in the PS.

Once the required number of lead ions ( $\sim 10^9$ ) is accumulated and cooled in LEIR, the beam is bunched on harmonic 2, accelerated to 72 MeV/u ( $B\rho=4.8$  Tm), extracted by a kicker and a septum, and transferred to the PS by the old E2 line. Part of this line has now to be pulsed between the injection and extraction settings. A typical LEIR cycle will last for 3.6 s, of which 1.2 s will be used for stacking and cooling [Figure 4].

3 PLANNING

The LHC planning calls for a lead ion physics run in 2008, and the lead ion beam should be ready for tests in LHC at the end of 2006. The preliminary planning shows that LEIR commissioning can be done at the beginning of 2005 with lead ions, the PS commissioning in 2005 or

2006, and the SPS in 2006. Other ions are foreseen only later on [10].

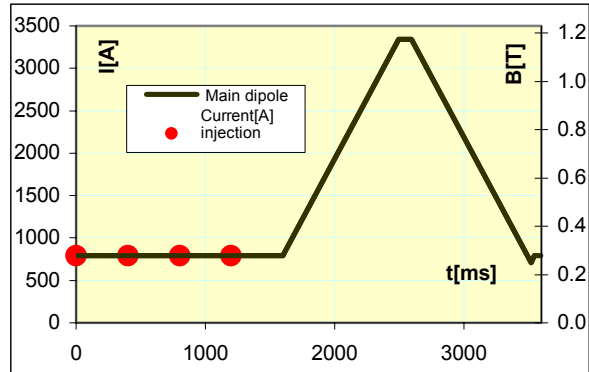


Figure 4: LEIR cycle expected for Lead ions.

4 CONCLUSION

The scheme for the lead ions is well established. The main challenges are efficient multiturn injection, electron cooling, the space charge limits, the vacuum quality, and the emittance conservation (as for protons but with the stripping in addition) through the entire injector chain.

5 ACKNOWLEDGMENTS

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REFERENCES

[1] P.Lefèvre, D. Möhl, "A Low Energy Accumulation Ring of Ions for LHC (a feasibility study)", CERN/PS 93-62, LHC Note 259.  
 [2] C. Carli, S. Maury, D.Möhl, Combined longitudinal and transverse multiturn injection in a heavy ion accumulator, 17<sup>th</sup> PAC, Vancouver, pp 976-978  
 [3] S. Hancock, private communication.  
 [4] L. Durieu, M. Martini, S. Maury, D. Möhl, A.S. Müller, A Low Beta Insertion in the PS-SPS Transfer Line to Limit Emittance Blow-up Due to Stripping of Lead Ions for LHC, CERN-PS-2001-006-AE.  
 [5] INFN-LNS-Catania, CEA/DSM/DRFMC/SI2A Grenoble, UJF-ISN-Grenoble, CERN-PS-Geneva, GSI-Darmstadt  
 [6] C. Dimopoulou, Design of a High-Perveance Electron Gun, Thesis, CERN/PS 2002-004(BD)  
 [7] J. Bosser and 12 co-authors, "Experimental Investigation of Electron Cooling and Stacking of Lead Ions in a Low Energy Accumulation Ring", Particle Accelerators, Vol. 63, pp.171-210.  
 [8] N. Madsen, "Vacuum changes during accumulation of Pb54+ in LEIR", PS/DI Note 99-21.  
 [9] E. Mahner, J. Hansen, D. Kuchler, M. Malabaila, M. Taborelli, "Ion Stimulated Gas Desorption Yields and their Dependence on the Surface Preparation of Stainless Steel", WEPDO030, this conference.  
 [10] D. Brandt, "Review of the LHC Ion programme", LHC Project Report 450.