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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 ~ 1000 times more than the actual chain (Linac3, PSB) can do. The production of Lead ion beams is described, with particular attention to the cooling, the injection system and the beam lifetime.

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1 OVERALL DESCRIPTION OF THE LEAD ION FILLING SCHEME OF LHC

1.1 Description of the full scheme

To reach the desired luminosity for the lead experiments in LHC ($10^{27} \text{cm}^{-2}\text{s}^{-1}$), the required number of ions is $0.7 \times 10^8/\text{bunch}$ 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 saturation of the Alice central detector and the quench limit (the particles produced by Electron Capture by Pair Production and Electromagnetic Dissociation at collision points are lost in the cold bending section or in the collimators). 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. From LEIR after accumulation to LHC collision flattop, an overall transfer efficiency of 30% is assumed.

To fulfil this requirement, it has been proposed [1] to add an accumulator ring LEIR (figure 1). An improved ECR ion source (from $100 \mu\text{A}$ to $200 \mu\text{A}$ of Pb^{27+}) is foreseen to feed Linac3, pulsing at up to 5 Hz. At the end of the Linac3, a first stripping takes place to obtain a beam of Pb^{54+} ($50 \mu\text{A}$, $450 \mu\text{s}$).

A combined longitudinal-transverse multiturn injection is envisaged for LEIR [2]. About 2×10^8 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 2.5 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 LHC 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 $h=169$ (80 MHz cavities) and a final splitting of the 4 bunches to four pairs of two bunchlets (each shorter than 4 ns) is foreseen using the 200MHz cavities at $h=423$. To decrease space charge and IBS (Intra Beam scattering) 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 number 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.

1.2.1 Early phase scheme

As the experiments are requesting a lower luminosity ($5 \cdot 10^{25} \text{cm}^{-2}\text{s}^{-1}$) for the first run, which should take place at the beginning of 2008, and to simplify the commissioning of all the machines as a lot of new operations have to be set up in 2006 and 2007 (after an 18 months stop in 2005), it has been proposed to simplify the scheme for the first year. The above luminosity can be reached using about 60 nominal bunches ($7 \cdot 10^7$ ions/bunch) per ring in LHC and a β^* value of 1 m (instead of 0.5 m) at the interaction point. This can be achieved with a single bunch of $2.5 \cdot 10^8$ transferred from LEIR to the PS and SPS. Then, all the complicated bunch splittings in the PS are not necessary providing the SPS can accept an incoherent tune shift of 0.1 at injection. This is being studied and the first results are encouraging. The SPS injection flat bottom is also reduced from 43s to 10s, which gives less worry for the losses due to IBS. The accumulation of $2.5 \cdot 10^8$ in 1.2s has already been achieved in LEAR during the tests made in 1997 which gives a lot of confidence in this early scheme.

2 THE MAIN CHALLENGES

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. The Linac source will receive a new generator at 18 GHz and the solenoid field will be increased. The hexapole magnet will not be changed, as it is already a state of the art permanent magnet. Studies are being made to try to accelerate two or more charge states in the Linac3. A special Radio-Frequency cavity will be installed just after the last RF tank of Linac3 to allow a 1% ramping of the ion beam momentum in 200 μs as required for multiturn injection in LEIR.

2.2 LEIR injection

The electron cooling is faster in the longitudinal plane than in the transverse one. Thus a combined longitudinal horizontal injection has been proposed, as it limits the transverse emittances 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 $5 \text{ m}^{1/2}$ to limit the momentum spread injected, and a “not too large” dispersion ($\sim 10 \text{ m}$) 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. The latter would certainly deteriorate the large beam emittance obtained after injection mainly in the vertical plane, which has a restricted acceptance. An orbit bump system (linear

bump decrease of ~ 0.5 mm/turn), which was used already during the 1997 tests [6], will be employed. About 70 turns ($200 \mu\text{s}$) will be injected per injection, with efficiency better than 50%. The characteristics of the beam after injection are: $\Delta p/p=4\%$, $\varepsilon_n = 50 \pi$ mm.mrad and $\varepsilon_v=30\pi$ mm.mrad.

2.3 LEIR Electron Cooling

The electron cooling 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 diameter of 50 mm and an interaction length of 2.5 m. The cathode (29 mm diameter) will be convex [7] to increase the perveance to about $6 \mu\text{P}$ and immersed in a large solenoid field (up to 0.23 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 25 mm and to reduce the transverse electron temperature, which could improve the cooling time. Although a small dispersion at the cooler is favourable [6] for efficient cooling, zero dispersion at the electron cooler is preferred, to ease 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 control electrode is added [8]. 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.

2.4 Lattice

As a lattice with symmetry is proposed, 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, triplets (Figures 2 and 3), rather than doublets are needed in the electron cooling and extraction sections. 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 transverse acceptance of $(A_h, A_v) = (100, 50) \pi$ mm.mrad when using the actual vacuum chamber dimension. The linear coupling from the electron cooling solenoid is compensated by two solenoids installed in the same section such as $\int B_s dl=0$ in this section. The tune change given by the whole set of solenoids is compensated by adding trim power supplies on the neighbouring quadrupoles.

2.5 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 [6,9] which has been estimated (from measurements at injection energy of 4.2 MeV/n) 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 [10] using the beam of Linac3 have been launched to find the best vacuum chamber treatment to decrease this limiting phenomenon. Beam scrubbing (long term bombardment) has been found to be very effective (figure 4) and is one of the simple solutions to be applied to obtain a good vacuum, even in the presence of ion beam losses. Another solution, which decreases the outgassing rate by a factor 10, consists of adding gold plated collimators at the place where most of the ions are lost.

2.5 Beam acceleration , 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 through the old E2 LEAR injection line. Part of this line has now to be pulsed between the injection and extraction settings. A typical LEIR cycle (Figure 5) will last for 3.6 s, of which 1.2 s will be used for stacking and cooling (Table 1).

4 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 2007. The preliminary planning shows that LEIR commissioning can be done at the beginning of 2005 with lead ions, the PS commissioning in 2006, and the SPS in 2006 and 2007. Other ions are foreseen at a later stage [11].

5 CONCLUSION

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

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Figure 1 : General scheme for the production of Lead ions beam in collision in LHC

Figure 2 : Layout of the LEIR machine.

Figure 3 : 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 ($\beta_h = \beta_v = 5\text{m}, D=0$) is shown.

Figure 4: Beam scrubbing tests using lead ions at the end of the LINAC3 with different treatment for the vacuum chamber. The measurements A shows that a dose of $1.6 \cdot 10^{11}$ ions cm^{-2} (lead 53+) on the wall of a vacuum chamber leads to a decrease of the outgassing by a factor 10 for the "normal" treated stainless steel vacuum chamber (950 degrees vacuum firing and 300 degrees bake-out for 24 hours). The vacuum chamber C (Neg coated) shows a better vacuum level mainly due to the high pumping speed in the volume (500 times larger).

Figure 5: Expected cycle for accumulation, cooling, acceleration and extraction of the lead ions.

Table 1 : Main parameters of the LEIR machine for Lead ions

INJECTION		
B ρ	1.13	Tm
β/γ	0.0946/1.004	
Frev(h=2)	361(722)	kHz
Magnetic / electrostatic septum deflexions	175/28	mrاد
Bumpers deflexion max	10	mrاد
LATTICE		
Bending radius (length)	4.17(6.55)	m
Quadrupole length	0.5058	m
Quadrupole max strength	1.35	m ⁻²
Tunes H/Tune V	1.82/ 2.71	
$\beta_h/\beta_v/D$ sections 1(inj.) & 3	2/6/10	m
$\beta_h/\beta_v/D$ sect. 2(cool) & 4(ext.)	5/5/0	m
Natural chromaticity (h,v)	-1.7, -1.7	$\Delta Q/\Delta p^*p/Q$
γ_{tr}	2.9	
RF CAVITIES		
Frequency range	0.36/4.67	MHz
Voltage max/cavity	4	kV
EXTRACTION		
B ρ	4.8	Tm
β/γ	0.374/1.078	
Frev(h=2)	1.42(2.84)	MHz
Kicker/septum deflexions	6/130	mrاد