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ION ACCUMULATION FOR LHC

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Abstract

The overall modifications of the PS complex (Linac3, LEIR, PS) to produce the LHC ion beams is described. While the main emphasis is put on lead, some considerations will be given to other ion species, which are or may be requested. The different systems are reviewed with particular attention to electron cooling, the injection systems and 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 $0.7\mathrm{x}10^8$/bunch at 2.7 TeV/u within normalised emittances ($\beta\gamma\ \sigma^2/\beta_{h,v}$) smaller than 1.5 μm. The number of lead ions per bunch in LHC is limited by both the quench limit (interactions at collision points) and the saturation of the Alice central detector. The emittance budget has been set to 1.2 μm at the exit of the SPS, 1 μm at the end of the stripper in TT2 line, and 0.7 μm at the exit of LEIR.

To fulfil this requirement, it has been proposed to add an accumulator ring LEIR to the existing lead ion source [1](Fig. 1). For the future an improved ECR ion source (from 100 μA to 300 μA of Pb^{27+}) is foreseen to feed the Linac3, pulsing at up to 10 Hz. At the end of the Linac3 a first stripping takes place to obtain a beam of Pb^{54+} (~20 μA, 450μs actually). From LEIR to LHC collision flattop, an overall transfer efficiency of 30% is assumed.

A combined longitudinal-transverse multiturn injection is envisaged for LEIR[2]. About $2\mathrm{x}10^8$ 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 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 limitation by space charge at the PS injection($\Delta Q_{incoherent}<0.25$), 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 acceleration to 1.44 GeV/u in the PS, the bunches are gradually transferred from h=12 to h=10, then the 2 bunches are split [3] into 4(h=20) and finally there is another transfer from h=20 to h=17. This harmonic 17 in the PS is chosen to reach the 125 ns bunch spacing in LHC and is compatible with the SPS RF system (around 200 MHz). The beam is then further accelerated to 4.25 GeV/u and extracted towards the TT2 line where the ions will be fully stripped. In the SPS, several batches of the PS are stacked, then accelerated and extracted to the LHC at 177 GeV/u. This procedure is repeated until the two LHC rings are filled with 608 bunches each. The filling time of each ring will take about 10 min.

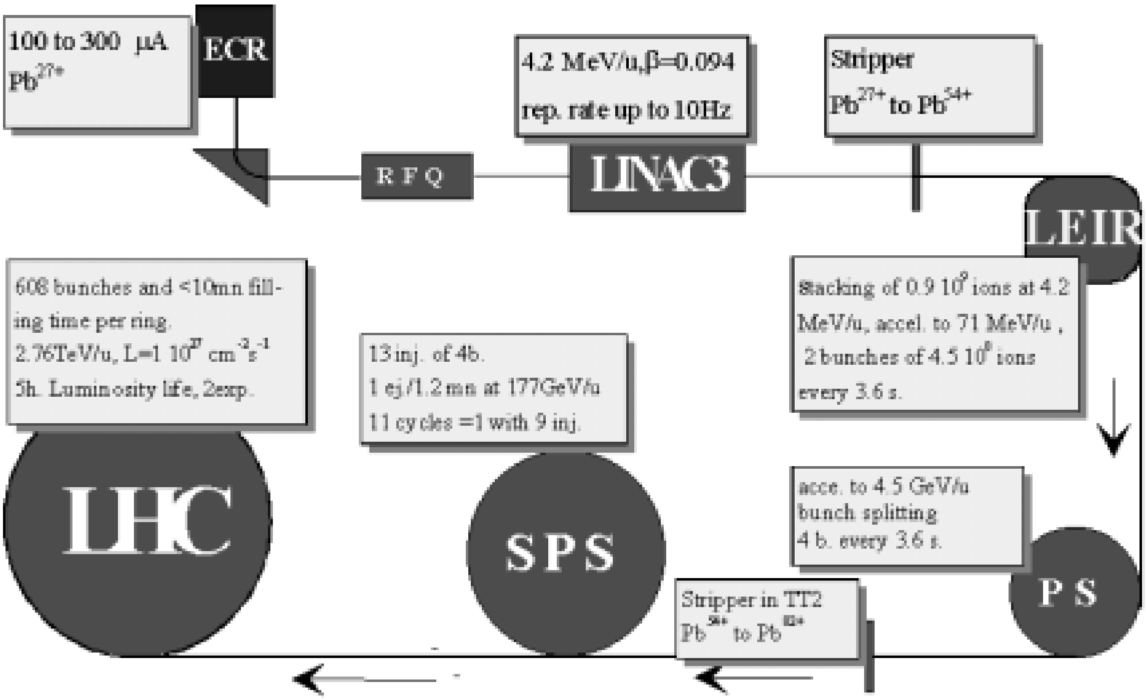

Figure 1 : The general layout foreseen to fill LHC with lead ions.

2 THE MAIN CHALLENGES

2.1 Linac3

The ECR ion source has to be improved. A European collaboration [4] has already shown that increasing the plasma heating frequency from 14 GHz to 28 GHz is the right way to increase 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 µs.

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 (done by a special cavity at the end of Linac3), 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 (~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 is equivalent to a x-y plane rotation) which could certainly deteriorate the large beam emittance obtained after injection. A bump system (linear bump decrease of ~0.5 mm/turn) which was used already during the 1997 tests will be employed. About 70 turns (200 μs) will be injected per injection with an efficiency better than 50%. The characteristics of the beam after injection are: $\Delta p/p$=4‰, ε_h=70π mm.mrad and ε_v=30π mm.mrad.

2.3 LEIR Electron Cooling

The electron cooling (table 1) system should provide a transverse cooling time of 0.1 s for lead ions. This could be achievable with an electron current of 0.6 A, an e-beam radius of 30 mm and an interaction length of 3 m. The cathode (25 mm diameter) will be convex to increase the perveance to about 6 μP 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 [5] 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.

Table 1: The electron cooler main parameters

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	$10^{-6}A/V^{1.5}$
Maximum electron current at β=0.094	0.6	A
Maximum electron current	3	A
Maximum expansion factor	8	
Maximum electron beam diameter	70	mm
Drift length (effective interaction length)	3 (2.7)	m

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 Twiss parameters defined above, a triplet (Figs 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) π mm.mrad when using the actual vacuum chamber dimension.

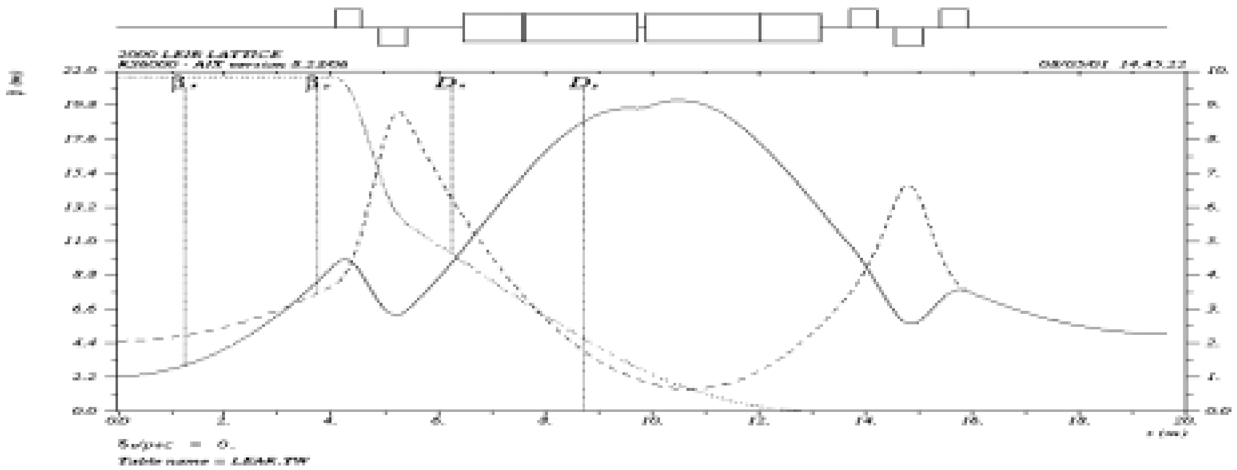

Figure 2: The LEIR lattice. One half of a period (i.e. a quarter of the machine) extending from injection where the dispersion is 10m, to the centre of the cooler (β_h=β_v=5m) is shown.

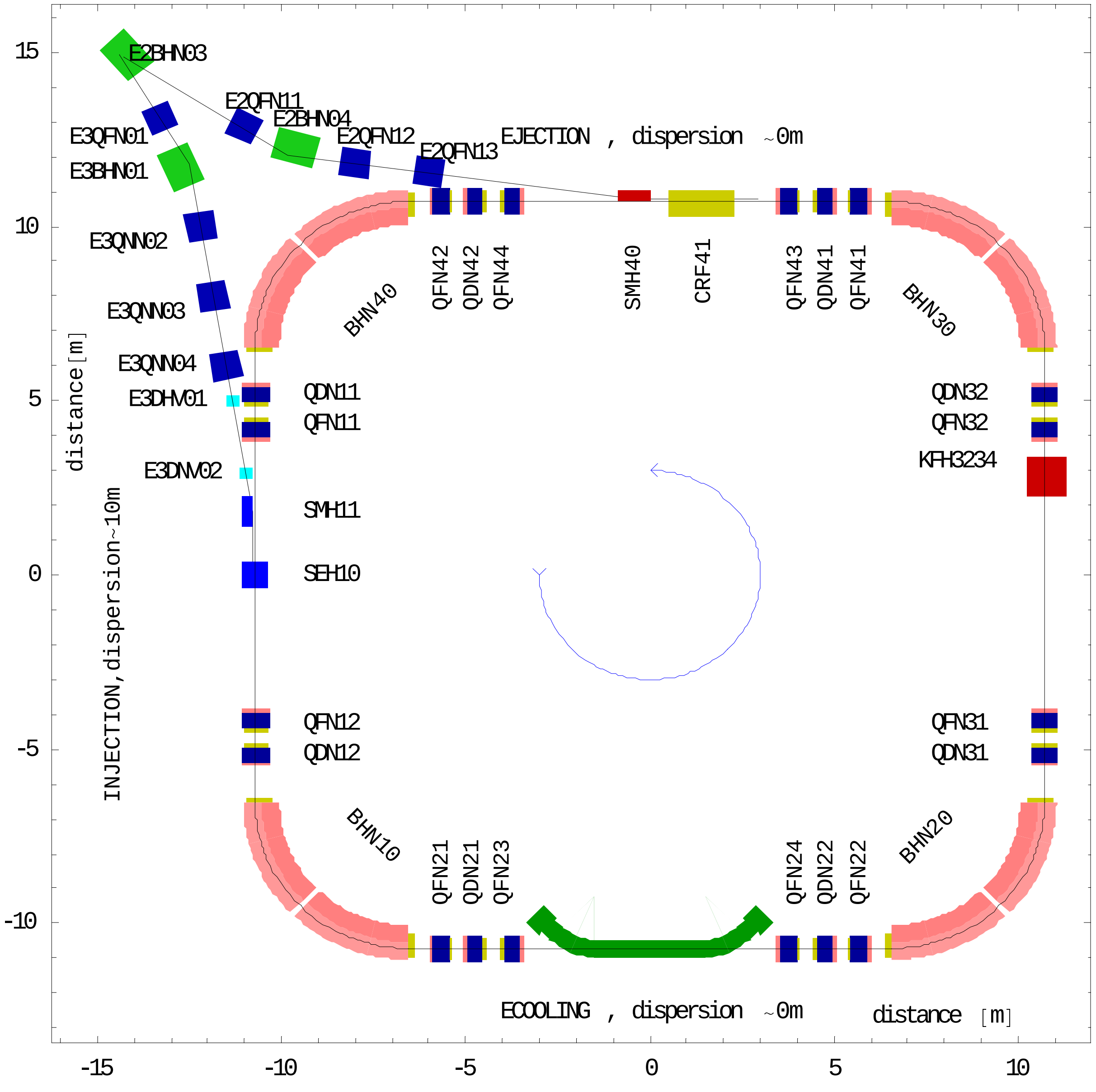

Figure 3: The LEIR machine layout with only the main elements.

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 [5,6] which has been estimated from measurements at injection energy to be about 10^5 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 using the beam of Linac3 have been launched to find the best vacuum chamber treatment to decrease this limiting phenomenon. The first results [Fig. 4] of the on-going tests of surface desorption by a lead ion impact confirm the observations made in LEAR:

- 2 10^4 molecules/lead ion (53+) are desorbed from a normally-treated stainless steel surface (vacuum firing and bake-out at 300°C). This desorption is also roughly proportional to the charge squared, and there is a strong influence of the impact angle. Carbone oxide molecules are the main species desorbed.
- The desorption from a NEG-coated surface activated at 200ºC is not better than a normally-treated wall surface, except that the large amount of pumping provided by the NEG decreases the mean vacuum pressure.
- The chamber treated by argon glow discharge does not show a desorption improvement.

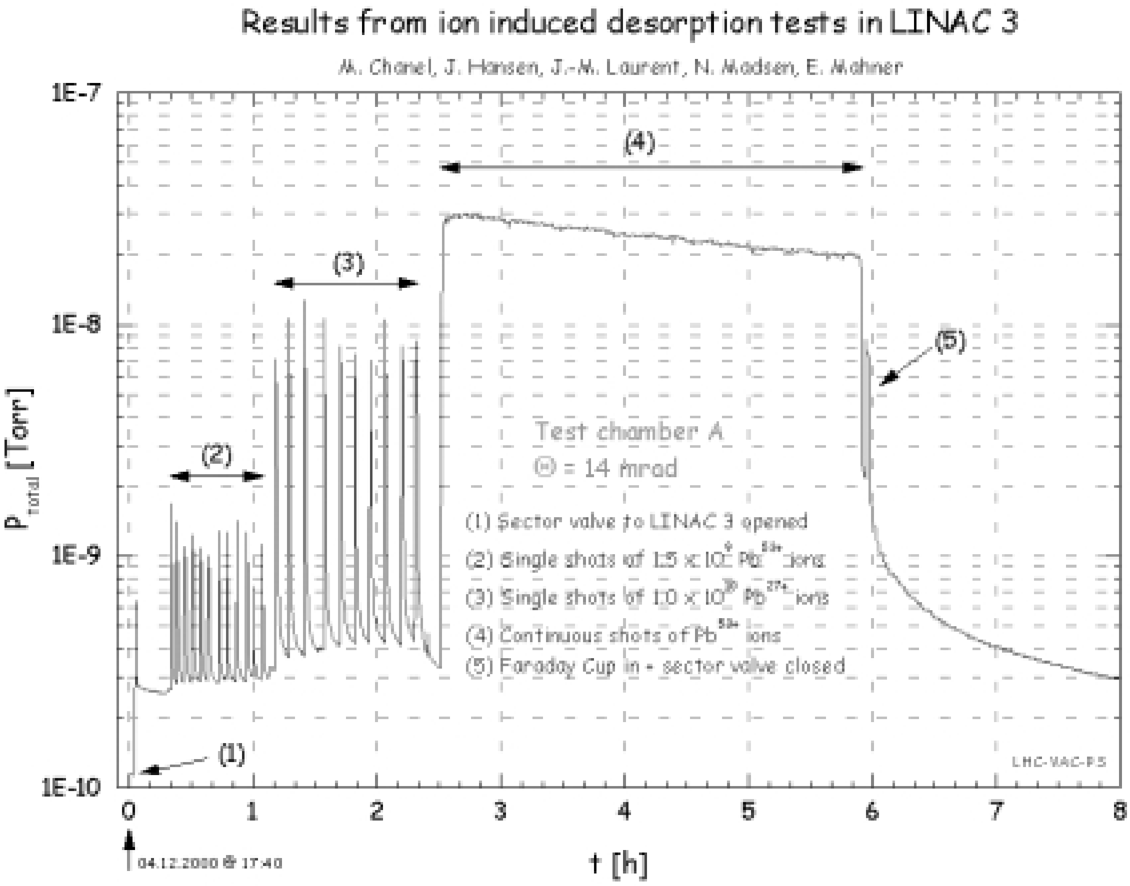

Figure 4: Pressure in a test chamber during some hours of the experiment. The particles were incident with 14mrad grazing angle .1) a sector valve between the experiment and the Linac3 is opened. The pressure in Linac3 is worse than the base pressure in the experiment. 2) A series of single shots of $1.5*10^9$ Pb^{53+} ions. The time between the shots is the time needed for the vacuum to return to the conditions before each shot. 3) A series of single shots of $1.0*10^7$ Pb^{27+} ions. 4) Pb^{53+} shots are injected continuously with a repetition rate of 1.2 s.

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

Once the required number of lead ions (~10^9) is accumulated and cooled in LEIR, the beam is bunched on harmonic 2, accelerated to 71 MeV/u ($B\rho$=4.7 Tm), extracted by a kicker and a septum, and transfered 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.

2.7 The PS and the PS-to-SPS transfer line

The change of the injection elements, the RF manipulation described above and bunch compression are the ingredients foreseen in the PS. In the TT2 line (Fig. 5), a low-β insertion has to be added around the stripper [7]. A solution (4 new quadrupoles and 6 power supplies) has been found which permits reducing the actual measured emittance growth by a factor 4, which nevertheless leads to a 0.2 μm emittance increase. This value is evaluated assuming that the energy shift and the coherent mismatch occurring in the stripper are corrected downstream the line.

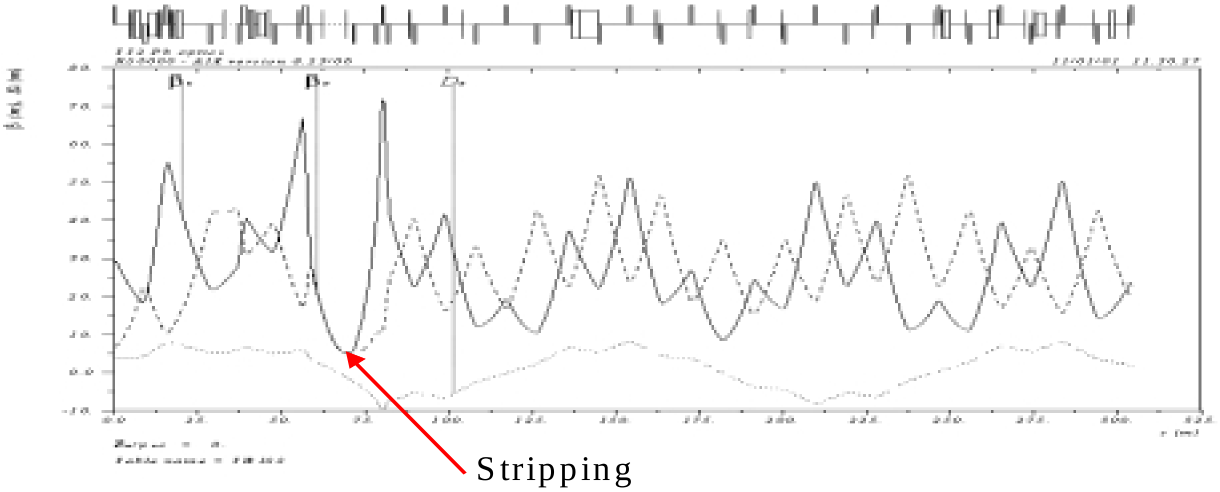

Figure 5: The Twiss function along the first part of the transfer line from PS to SPS

3 THE OTHER IONS

In addition to lead, the Alice experiment has also asked for lighter ions. Intensity limits for the LHC have been established by D. Brandt [6] (Table 2). However the PS complex has difficulties in providing this intensity due to the severe space charge limitations at injection in the PS. It is only possible to reach the LHC limits by accelerating ions in the PS complex which are not completely stripped and then doing the same rf gymnastic as for lead ions. The small missing factor can be overcome by shaping the momentum distribution with the electron beam just prior to stopping the cooling. For that, the energy of the electron beam is modulated at a frequency around 1 kHz.

For light ions with low charge state, the cooling time needed to reach the requested emittance is quite long, leading to a long filling time of LHC. For oxygen and helium, using an ion source delivering around 1 mA, it seems possible to fill the LHC faster by directly injecting from Linac3 into the four rings of the PSB, prior to acceleration in the PS.

Table 2: Ions required for LHC. The PS space charge limits ($\Delta Q_{incoh}<0.25$) are computed assuming a transfer of 2 bunches from LEIR at Bρ=4.7 Tm (1.4 GeV/c proton equivalent). These 2 bunches are split into 4 bunches in the PS. Stripping has not always been applied at the exit of Linac3.

ION / ion charge state in LEIR and PS	"required" PS ions/bunch at injection (2 bunches)	space-charge limit in PS ions/bunch	ratio: obtainable/ required
Pb(82) / 54+	$4.6*10^{8}$	$9*10^{8}$	2.0
In(49) / 37+	$1.4*10^{9}$	$1.4*10^{9}$	1.0
Kr(36) / 29+	$2.2*10^{9}$	$1.8*10^{9}$	0.8
Ar (18) / 16+	$8.6*10^{9}$	$3.8*10^{8}$	0.44
O(8) / 4+	$4.0*10^{10}$	$1.58*10^{10}$	0.39
He / 1+	$5.0*10^{10}$	$5.0*10^{10}$	1.0

4 PLANNING

The assumption is that there will be a lead ion physics run in the LHC in 2007, and the lead ion beam should be ready for tests in LHC at the end of 2006.

The established preliminary planning shows that the LEIR commissioning can be done at the beginning of 2004 with lead ions, the PS commissioning in 2004-2005, and the SPS in 2005-2006. Other ions are foreseen only in 2009.

5 CONCLUSION

The scheme for the lead ions is now well established. The main challenges are efficient 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.

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[8] D. Brandt, “Review of the LHC Ion programme”, LHC Project Report 450. See also LEMIC 42, PLC 59 and 60