HIGH INTENSITY OPTIONS FOR THE CERN HEAVY ION PROGRAMME

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Introduction

A design study for producing a lead ion beam, at the Super Proton Synchrotron(SPS), for fixed targets physics has been completed [1]. This study was engaged in following the successful production of oxygen and sulphur ion beams [2]. Requests for higher intensities were formulated, in particular for a Large Hadron Collider(LHC), which is proposed to be constructed in the existing Large Electron Positron (LEP) ring tunnel [3]. Collisions with highly relativistic ions are now regarded as an important facet of future LHC operations. The studies [4] reported in this paper were launched to look into the problems of obtaining sufficiently intense bunches of ions that have the required emittances for injection into the SPS, and subsequently, into the LHC. The relatively low ion beam intensity planned for fixed target experiments is insufficient to obtain the required luminosity in the LHC.

The Current Concept for a Lead-Ion Facility

The Injector

The Electron Cyclotron Resonance (ECR) source seems, for the time being, to be the optimum choice for a high charge state ion source, because it keeps the injector costs low. The ions will be injected into a Radio Frequency Quadrupole (RFQ) and a following linear accelerating structure. The source will provide at least 30 µA of lead ions with charge states in the range of 25 to 30+. The pulse length to be used is 400 µs, while the extraction voltage will be between 20 and 25 kV. There will be preselection of the required charge state. The RFQ will accelerate the ions to an energy of 250 keV/u, while either an Alvarez or Interdigital H (TE mode) structure will accelerate them further to 4.2 MeV/u. At this energy, stripping with a carbon foil produces a charge state distribution that peaks around state 53+ (i.e. $_{208}Pb^{53+}$), which will be selected, checked for beam quality, analyzed and transported to the Proton Synchrotron Booster (PSB). A summary of the principal parameters at the end of the linac is given in Table 1.

Table 1. LINAC OUTPUT PARAMETERS

Before Stripper	
Particle Type	Lead Ion ($_{208}Pb^{25+}$)
Output Energy	4.2 MeV/u
Current	25 µAe (electric) = 1 µAp (particle)
Pulse Length	400 µs at 0.83 Hz repetition rate i.e. 2.5×10^9 ions/pulse
Normalized Emittance	$2\pi.10^{-6}$ m.rad
Longitudinal Emittance	$3.2\ \pi.10^{-6}$ eV.s/u
After Stripper (Carbon foil)	
Selected Charge State	53+
Current (53+)	0.16 µAp i.e. 4.10^8 ions/linac pulse
ALL OTHER OUTPUT PARAMETERS AS BEFORE STRIPPER	

Lead ions with this charge state and energy have a magnetic rigidity that is 13% higher, and a velocity three times lower, than the 50 MeV protons which are normally injected into the PSB. The injection time for ions is 400 µs compared with less than 150 µs for protons. The magnetic elements, especially the pulsed ones, will be upgraded.

The PSB and the Proton Synchrotron(PS)

Electron exchange with ions due to the residual gas pressure would lead to considerable beam losses with the present vacuum systems. Recapture of electrons at low energies in the PSB is the principal source of loss. It has been calculated that a pressure approaching 10^{-9} mbar, compared with the present several 10^{-8} mbar, is needed. The low beam intensity requires an improvement in both diagnostic and radiofrequency beam control equipment. Because of the lower ion velocity, the radiofrequency system will have to operate on harmonic no. 17 (h=17) instead of 10, with rebunching at an intermediate flat top. There will also have to be a significant increase in the pulse length for the injection and ejection kickers.

Forty PSB bunches will be recombined and captured in twenty PS buckets. Complete stripping (to charge state 82+) will be done after ejection from the PS. The main PS parameters are given in Table 2.

Table 2. PS PARAMETERS

	Injection	Ejection
Magnetic Rigidity (T.m)	5.634	66.6
Magnetic Induction (T)	0.0804	0.9504
Rate of Change (T/s)	0	0
Kinetic Energy per Nucleon (GeV/u)	0.094	4.235
β	0.4169	0.9834
γ	1.100	5.5134
f_{rev} (revolution frequency (kHz))	198.93	469.22
h (harmonic no.)	20	20
RF Frequency (MHz)	3.978	9.384
Q_x	6.19	6.25
Q_y	6.31	6.30

The SPS

The vacuum problem for the SPS is eased because charge-exchange reactions are no longer a problem. However, because of the low intensity, an upgrading of the instrumentation is required.

The accelerating structures of the SPS, of the travelling wave type, have too small a bandwidth to accommodate the required RF frequency swing (1.7 %) if conventional acceleration is to be used. However, the filling time of the structures being small compared to one revolution period, it is possible to accelerate the beam (which only occupies a fraction of a turn) at constant frequency and rephase the RF voltage every turn to ensure synchronism. Such a technique has already been successfully tested with protons [5].

The transmission efficiency from the linac stripper to the SPS, including the PSB multiturn injection losses, is estimated to be 14 %. Figure 1. shows the schematic layout of the accelerator complex.

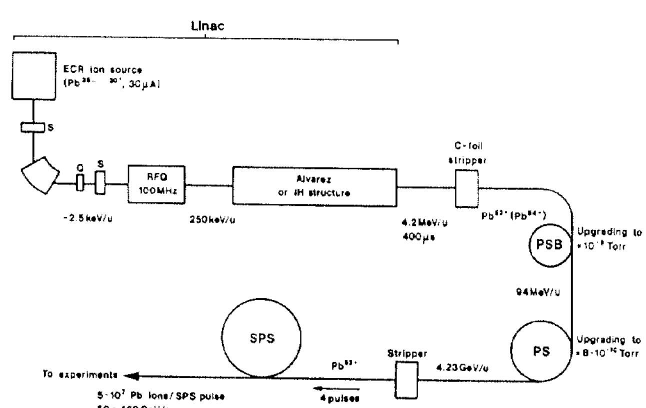

Fig. 1: Schematic layout of the accelerator complex

LHC requirements

The LHC, a high luminosity proton collider, can operate as a heavy ion collider without any major modifications. However in this mode of operation the attainable luminosity is limited by many physical phenomena. In collision mode at high energy, the Weizsäcker-Williams effect (electromagnetic nuclear excitation followed by loss of a nucleon) and the electron pair production, followed by the capture of an electron, both reduce the luminosity half life to a few hours when the luminosity per bunch crossing reaches about 10^{25} $cm^{-2}s^{-1}$. Using the normal bunch spacing of the CERN PS, which is 105 ns, one can fill one LHC ring with 800 bunches and in this way produce a luminosity of the order of 10^{28} $cm^{-2}s^{-1}$, as requested by experimenters. The number of ions per bunch necessary to achieve this is $1.6x10^8$, which is about thirty times higher than the intensity per PS bunch expected in the current concept described above. The LHC beam specifications are given in Table 3.

Table 3. LHC BEAM PARAMETERS (proton equivalent)		
	Injection	**High Energy**
Energy (GeV)	450	8000
Longitudinal emittance (eV.s)	2.0	5.0
Normalized transverse emittances (π.µm.rad)	10	10
r.m.s. bunchlength (σ in m)	0.1	0.077
r.m.s. ΔE/E	$1.06x10^{-3}$	$1.92x10^{-4}$
Intra-beam scattering growth times for Pb		
τ_E (h)	25.1	22.2
τ_X (h)	4.4	6.5
τ_Z (h)	137.0	∞

Several possibilities are foreseen to upgrade the lead ion facility for its possible use as LHC injector.

Possible Linac Improvements

Linac Current Limits

Increasing the linac intensity eventually leads to limitations due to space-charge and to thermal damage to the carbon foil stripper.

For Pb^{25+} ions, the proposed quasi-Alvarez structure has a space-charge limited current of 50mAe (2mAp), while the figure for a 100MHz RFQ is 0.5mAp. Another, more stringent, limitation arises from overheating the carbon stripper. This limits the beam to about 10µAp for a 400µs pulse. The heating effect can be avoided by using a gas stripper. However, for gas strippers, the charge state distribution peaks at a lower value than for solid ones, for ions with the same velocity. An ion energy of 14 MeV/u would be required to arrive at a charge state of 53+; lower charge states would lead to excessive losses due to electron-capture in the PSB. This increase in energy would increase the cost of the linac and the PSB injection component modifications.

Ion Source Improvements

Nevertheless, as an intermediate step, the most promising avenue is improvements in ECR design, leaving the RFQ and linac unchanged. The source design proposed in the Lead Ion Facility Design Study report [1] is continually being improved. Recent measurements [6] with such a source gave 100µAe for Bi^{25+} with a pulse length of 400µs. A major change in technology, e.g. superconducting solenoids and pulsed magnet extraction, might be needed to make further significant improvements in output current, but the amount of research taking place in several independent laboratories should ensure continued development of this source type.

Another option is to use a high-current low charge-state source, implying major changes in the low energy acceleration, the stripping and perhaps in the linac and in the beam transport (linac energy increased to 14 MeV/u). This should only be pursued if all other schemes fail to live up to their promise.

Simultaneous Acceleration of Several Charge States

As the ECR source will produce significant beam currents in the charge states adjacent to 25+, it has been suggested that a useful increase, perhaps a doubling, of the accelerated current could be obtained by the simultaneous acceleration of several charge states. In principle the successive stages through the injector must have sufficient longitudinal acceptance for the different charge states. An analysis of the dependence of acceptances on charge shows that, for charge states 24+ and 26+, there is appreciable acceptance for a structure adjusted to accept charge state 25+.

At the entrance of the region where the stripping, charge filtering and debunching takes place, the mean energy for all charge states will be the same, so there will be a unique optimum charge state (53+) after the carbon stripper. In order to ease the task of the downstream machines, the relative energy spread must be reduced from about ±0.65% to ±0.1%. It should be possible to do this for regular longitudinal emittances up to 2.10^{-5} eV.s (200 MHz) by using a debuncher giving peak modulation of 50 keV/u at 100 MHz.

Accumulating and Cooling Possibilities

Satisfying LHC requirements by increasing the linac intensity involves difficulties and costs. At CERN there are storage rings, developed for the antiproton programme, that could provide solutions to reducing emittances and increasing the average linac current by increasing the linac repetition rate, while retaining the present structure design. Also, it may be possible to install a stochastic cooling system in the PS ring. Some of these ideas would, perhaps, prove too costly if they had to be implemented from the beginning, but since the rings already exist, studies have been made to see how they might be used. Three scenarios are considered:-

1. Ion stacking and cooling in the Low Energy Antiproton Ring(LEAR)
2. Ion stacking and cooling in the Antiproton Accumulator Complex(AAC)
3. Ion cooling in the PS.

In all three cases, the beams are transferred to the SPS at the same value of magnetic induction (B = 1.25T), with a cycle time of 3.6s in the LEAR case and 2.4s in the other two cases. This is dictated by intra-beam scattering lifetimes in the SPS. There are certain limitations, on the PS beam, governing extraction:-

1. Momentum acceptance limitation : $\Delta p/p < \pm 3.10^{-3}$
2. Maximum bunch length : $T_b \leq 4$ ns (capture at 200 MHz frequency in the SPS)
3. Distance between bunch centroids in case of multi-bunch transfer : 1/20 of PS circumference (≈ 105 ns).

In this paper, only the outlines of the many mergings, coolings and transfers are given. Fuller details are available in [4].

Stacking and Cooling in LEAR

The sequence is as follows:-

1. LEAR takes a total of 30 pulses of ions, charge state 53+, from the linac, which pulses at 10 Hz. The ions are then cooled and stacked at a kinetic energy of 4.2 MeV/u. Each multi-turn injection is limited to a duration of 60 µs (≈ 20 turns) with 50 % efficiency. Electron cooling is applied during the horizontal betatron stacking process. The final beam contains a total of 10^9 lead ions and its emittances (not normalized) are :

$$\varepsilon_H = 40.\pi 10^{-6} \text{m.rad}$$

$$\varepsilon_V = 20.\pi 10^{-6} \text{m.rad}$$

$$\Delta p/p = \pm 1.10^{-3}$$

2. The stack is then captured with the RF system on h=4 (f_{RF} = 1.436MHz) and accelerated to 14.8 MeV/u (f_{RF} = 2.688MHz). The four bunches are then fast extracted and transferred to the PS in four adjacent buckets using h=32 (also f_{RF} = 2.688MHz, as the circumference ratio PS to LEAR is 8).
3. The time needed in LEAR to accelerate and extract the beam and to decrease the field is 0.6 s. With a 3.6 s cycle, the nominal source current is adequate to ensure $1.6x10^8$ ions in the successive bunches from the PS, with 85 % efficiency in the PS, 90 % LEAR-PS and 50 % multiturn in LEAR. Consequently, the filling time for the LHC is 12 minutes per ring. An optimistic estimate, resulting from doubling the source current, is 8 minutes.
4. Acceleration in the PS takes place, on h=32, up to an intermediate flat-top at 740 (MeV/c)/u (f_{RF} = 9.5MHz).
5. To achieve the correct bunch spacing, the bunches are transferred into four consecutive buckets, first on h=28 (f_{RF} = 8.31MHz), then on h=24 (f_{RF} = 7.12MHz) and later on with h=20 (f_{RF} = 5.94MHz). The longitudinal emittance is blown up to 0.35 eV.s/charge, using phase modulated radiofrequency at 200 MHz.
6. Acceleration then proceeds up to the extraction momentum (6.7 (GeV/c)/u; (f_{RF} = 9.46MHz).

7. Synchronization to the SPS and bunch compression down to 4 ns are performed before fast extraction.
8. Stripping from charge state 53+ to state 82+ is done in the PS to SPS transfer line.

In summary, four bunches, of 1.6×10^8 ions each, can be easily sent to the SPS every 3.6 s, resulting in a filling time for one LHC ring of ≈ 12 minutes.

Stacking and Cooling in the AAC

The AAC complex consists of two concentric storage rings, the Antiproton Collector(AC) and the Antiproton Accumulator (AA) connected by a transfer line and with transfer lines to the PS.

Some preliminary Pb ion cooling simulations have been made using antiprotons in the AAC. From these it can be concluded that the $\Delta p/p$ can be reduced by a factor larger than 10 in the AC and larger than 2 on the AA injection orbit using precooling. Simultaneously one envisages cooling the transverse emittances by a large factor. The intra-beam scattering blow up during the 50s accumulation cycle can be counterbalanced by the AA core cooling systems.

The following operations are performed :

1. The four rings of the PSB accelerate 10^8 ions, charge state 53+, every 1.2s and deliver forty bunches (momentum is 430 (MeV/c)/u and h=10) to the PS.
2. A funnelling scheme [7] is applied in the transfer line, using a radiofrequency dipole for beam deflection (the dipole and PSB both operating at a frequency of 7.96 MHz). The forty PSB bunches are then injected into twenty out of the forty PS buckets, filling ½ of the circumference (PS frequency 7.96 MHz and h=40).
3. The twenty bunches are combined into ten, using a quasi-adiabatic merging process [8]. They finish with a longitudinal emittance of 0.22 eV.s/charge/bunch, in ten adjacent buckets on h=20 (f_{RF} = 3.98MHz).
4. Acceleration takes place on that harmonic number, up to a plateau on the magnet cycle (momentum, 1.40 (GeV/c)/u; B=0.26T; f_{RF} = 7.95MHz).
5. With a technique comparable to the one used in step 3, the ten bunches are merged into five (ε_l = 0.53eV.s/charge/bunch), still occupying ½ the circumference, but with h=10 (f_{RF} = 3.97MHz).
6. In order to fit into the AC circumference, which is four times smaller than that of the PS, the beam is squeezed into ¼ of the PS ring, by an adiabatic increase of the harmonic number from 10 to 20 [8].
7. To minimize the momentum spread, the RF voltage is reduced before ejection to the AC. The bunches, with a longitudinal emittance of 0.64 eV.s/charge, fill the buckets for h=20. The total relative momentum spread is 1.7×10^{-3}.
8. Stripping from charge state 53+ to state 82+ occurs in the PS to AA transfer line.
9. Operations 1 to 8, lasting 1.2s, are repeated forty times, until a stack of 3.2×10^9 ions is cooled and accumulated in the AAC. This is the maximum intensity compatible with tolerable intra-beam scattering growth rates.
10. The fully stripped ion beam is sent back to the PS with a momentum of 1.40 (GeV/c)/u (B=0.169 T), the unstacking process, with h=1 in the AA (ε_l = 0.6 eV.s/charge/bunch), being repeated eight times. The eight PS buckets (h=8,f_{RF} = 3.18MHz) are then filled.
11. After debunching and recapture on h=20 in the PS (f_{RF} = 7.95MHz), the twenty bunches (ε_l = 0.35 eV.s/charge/bunch) are finally accelerated to a momentum of 10.4 (GeV/c)/u (B = 1.25 T).
12. Synchronization with the SPS and bunch compression to 4ns are performed before fast extraction.

In summary, twenty bunches, of 1.6×10^8 ions each, are sent to the SPS every ≈50s. The filling time for one LHC ring is then ≈ 30 minutes.

Cooling and Single Bunch Compression in the PS

The following steps are envisaged :

1. The first three operations, for filling the PS, are the same as for the previous scheme. The entire PS circumference is filled with 2.10^8 lead ions, charge state 53+, from 2 PSB cycles.
2. The beam is accelerated on h=20 (ε_l = 0.22 eV.s/charge/bunch) up to a plateau at a momentum of 1.69 (GeV/c)/u, where it is adiabatically debunched (ε_l = 5.3 eV.s/charge).
3. Stochastic cooling is applied in all planes during 1.2s. The longitudinal emittance is reduced to 0.4 eV.s/charge.
4. Rebunching is made at h=1 (f_{RF} = 418kHz), and the bunch length is reduced by increasing the RF voltage to 4.0 kV. The bunch, with a longitudinal emittance of 0.5 eV.s/charge, is then short enough (250 ns) to be captured inside a single bucket (f_{RF} = 3.34MHz, h=8).
5. The beam is then accelerated, with h=8, to a momentum of 6.7 (GeV/c)/u (B=1.25 T; f_{RF} = 3.78MHz). Synchronization with the SPS and bunch length compression down to 4ns are performed as in the previous scheme.
6. Stripping from charge state 53+ to state 82+ is done in the PS to SPS transfer line.

In summary, one bunch of 1.6×10^8 ions is sent every 4.8s to the SPS. The filling time for one LHC ring is then ≈ 1 hour. If the linac beam intensity would be increased by a factor of two, only one PSB cycle would be required, reducing the LHC filling time by a quarter.

Conclusion

Several schemes are feasible to achieve higher ion intensities in the CERN accelerator complex. In particular, for the (possibly) main user in the future, the LHC, different stacking and cooling scenarios seem to be possible. The final choice will, of course, depend on relative cost, complexity of operation and last but not least advances in ion source technology.

Acknowledgements

We would like to thank B.Autin, D.Boussard, M.Chanel, D.Manglunki, M.Martini, S. van der Meer and H.Schönauer for their collaboration and E.Tanke for bringing this paper into a readable form.

References

[1] H.Haseroth (Ed.), "Concept for a Lead-Ion Accelerating Facility at CERN," CERN Yellow Report 90-01, February 1990.
[2] N.Angert, E.Brouzet, R.Garoby, S.Hancock, H.Haseroth, C.E.Hill, K.Schindl, and P.Têtu, "Accelerating and Separating Mixed Beams of Ions with Similar Charge to Mass Ratio in the CERN PS Complex," Proc. European Particle Accelerator Conf., vol. 2, p. 1367, 1988.
[3] G.Brianti,K.Hubner, "The Large Hadron Collider in the LEP Tunnel," CERN Yellow Report 87-05, May 1987.
[4] D.Brandt, E.Brouzet, J.Gareyte, R.Garoby, H.Haseroth, P.Lefèvre, S.Maury, D.Möhl, F.Pedersen, K.Schindl, T.R.Sherwood, L.Thorndal, and D.Warner, "Notes on High Intensity Options for the CERN Heavy Ion Programme," CERN Report PS 90-21 (DI), 1990.
[5] D.Boussard,J.M.Brennan,T.P.R.Linnecar, "Fixed Frequency Acceleration in the SPS," CERN Report SPS/RF 89-49, 1989.
[6] R.Geller, Private communication, 1990.
[7] G.Nassibian,K.Schindl, "RF Beam Recombination ("Funnelling") at the CERN PSB by Means of an 8 MHz Dipole Magnet," IEEE Transactions On Nuclear Science, vol. NS-32, p. 2760, October 1985.
[8] R.Garoby, "New RF Exercises Envisaged in the CERN PS for the Antiproton Production Beam of the ACOL Machine," IEEE Transactions On Nuclear Science, vol. NS-32, no. 5, p. 2332, October 1985.