RECENT LEAD ION STORAGE TESTS ON LEAR

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1. INTRODUCTION

With the completion of the antiproton physics program, the Low Energy Antiproton Ring is now available to be used as an accumulator ring for heavy ions in the LHC injector chain. The proposed scheme for the injection of lead ions [1] is shown in Fig. 1, where an intensity gain of 125 is obtained by accumulating lead ions with electron cooling in the LEAR ring. With a linac cycling at 10 Hz and cooling times faster than 100 ms, 20 pulses can be accumulated in 2 s before transfer to the PS, the next machine in the chain. A number of machine experiments [2] have been performed, and will continue this year, in order to establish the techniques required.

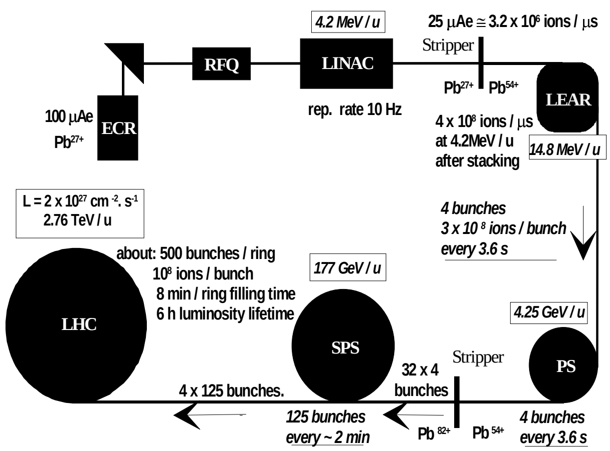

Figure 1. The lead-ion injection scheme for LHC.

2. INJECTION LINE TESTS

The lead ions follow a transfer line which includes a U-turn linking the linac to the transfer tunnel to LEAR. Despite problems matching the beam, we always succeeded in injecting around 10^8 charges per single turn injection.

For the multi-turn scheme, which combines injection into horizontal and longitudinal phase space [3], a number of tests have been made to determine whether the acceptance of the transfer channel is large enough to transmit a momentum width of $8x10^{-3}$ and to make preliminary measurements on the energy ramping of the linac. In effect, with this type of injection the mean energy of the beam coming from the linac varies during the injection of the pulse. An energy change of 70 keV (corresponding to a momentum shift $\delta p/p = 8x10^{-3}$) in a time $\Delta t = 60$ μs will increase the number of 'useful' turns that can be injected and make full use of the faster longitudinal cooling.

To test the momentum acceptance of the line, Pb^{53+} and Pb^{54+} ions were simultaneously transmitted by adjusting the magnetic filter line after the stripper to a large momentum width. The two beams passed the whole line, and the beam spots on a scintillator screen in front of the septum were superimposed proving that the momentum acceptance of the line was greater than $18x10^{-3}$ and also that the residual dispersion of the line at the septum was small, as required by this type of injection.

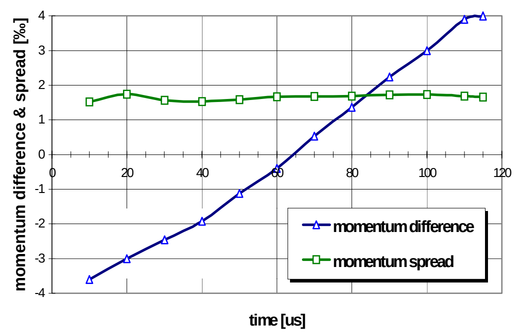

Figure 2. Linac momentum and momentum spread (4σ) versus time for an energy ramped injected beam.

Energy ramping was first tried out by ramping the ITF (Ion Transport Filter) debuncher phase. The maximum momentum change achieved was ±0.2% in 55 μs. This was the fastest ramp which gave stable debuncher operation. By ramping the linac tank 3 RF amplitude synchronously with the debuncher, a momentum swing of ±0.4% in 100 μs was obtained, but a small blow-up of the momentum dispersion along with a low energy tail were observed (Fig. 2). These results were obtained by using the LEAR machine as a spectrometer through measurement of the longitudinal distribution by means of Schottky noise.

machine:	1	4	7
β_h ss1/3 [m]	1.9	9.5	4.8
β_v ss1/3 [m]	6.4	10.5	5
D ss1/3 [m]	3.5	0	5
β_h ss2/4 [m]	1.9	3.6	1.1
β_v ss2/4 [m]	6.4	7.2	6.2
D ss2/4 [m]	1.9	9.9	2
Q_h	2.31	1.62	2.55
Q_v	2.62	2.42	2.7

Table 1. Lattice functions for the LEAR machines 1,4, and 7 that were used in the experiments.

3. MACHINE EXPERIMENTS

Experiments to test the influence of various parameters such as the machine lattice functions (Table 1) or the electron beam intensity, on the beam lifetime and cooling down times have been performed with lead ions of charge states 52+ to 55+. These different charge states can be selected with sufficient intensity after stripping the beam from the linac at an energy of 4.2 MeV/u.

Ion beam lifetime and vacuum measurements

The beam lifetime τ was measured by recording the ion intensity versus time. The intensity is deduced from the longitudinal Schottky signal where the total power in a frequency band around a harmonic of the revolution frequency was measured. The decay rate, $1/\tau = 1/\tau_{vac} + 1/\tau_{rec}$ has contributions from the charge exchange from the residual gas, $1/\tau_{vac}$,and from the presence of the electron cooling beam, $1/\tau_{rec}$. The former is constant while the latter varies with the electron intensity I_e. By plotting $1/\tau$ versus I_e, (Fig. 3) we can deduce the two contributions to the beam lifetime.

The gas composition can be measured in each straight section of the machine by residual gas analysis and the expected vacuum lifetime can be computed. The vacuum lifetime varied between 10 and 20 s. The proportion of He and CH_4 varied quite strongly between runs even though the average machine pressures did not. Local pressure bumps also play an important role in the lifetime of Pb ions, decreasing it by a factor 2 for example when beam is lost at injection, causing outgassing from the vacuum chamber. Our estimations of the vacuum lifetime agreed well with the theoretical value based on the formula found in [4], and no difference could be detected between the different charge states.

In contrast a very strong dependence on the charge state was found for the lifetime due to the recombination processes with the cooling electrons. The rate coefficients $\alpha_r = 1/\tau_{rec}/n_{eff}$ [in 10^{-8} cm^3 s^{-1}], normalised to the effective electron density seen per turn n_{eff}, were computed for each charge state from the slope of the curves in Fig. 3. Values of 60 were measured in all runs independent of machine settings for Pb^{53+} ions. For the other charge states values between 5 and 12 were observed with an apparent dependence on the machine lattice for Pb^{54+}. These values have to be compared to coefficients of about 2.5 that are obtained from existing theory for radiative electron capture for all the charge states of interest. Attempts to explain these high rates have been made through resonant dielectronic capture [5] and could apply to Pb^{52+}, Pb^{54+} and Pb^{55+}. However the rate for Pb^{53+} indicates that an unusually strong capture resonance or other mechanisms are involved.

To observe capture phenomena, a moveable scintillator screen has been installed in the first bending magnetic downstream from the cooling section. Here we can intercept the $Pb^{(q-1)+}$ ions that are created due to electron capture by the circulating Pb^{q+} ions. When placed in its expected position (25mm horizontally outward from the circulating beam) a strong counting rate was measured which was enhanced when Pb^{53+} ions were in the machine. More refined experiments also using an X-ray detector are under preparation.

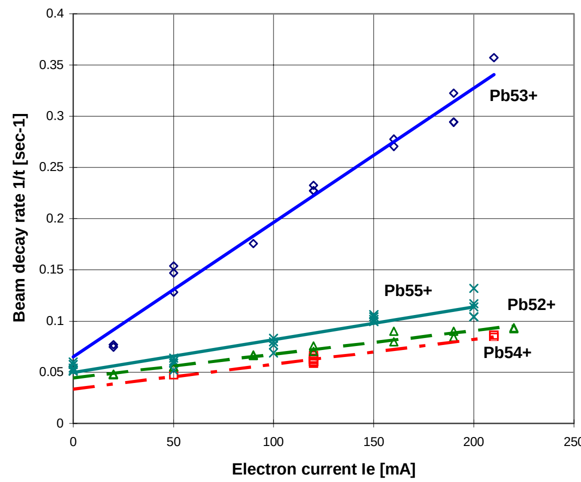

Figure 3. Plot of the inverse lifetime as a function of electron current for all the charge states investigated.

Cooling time measurements

For the accumulation of lead ions using multi-turn injection, the phase space occupied by the in-coming beam has to be quickly reduced to leave space for a new pulse. To accumulate 20 linac pulses in 2 s, cooling down times in all three planes of less than 100 ms are required. The cooling time depends on various parameters, amongst them : the electron beam intensity, the cooling length and the relative angle between the circulating ions and the electron beam. Up to now our tests have focused on obtaining of stable high intensity electron beams and on the influence of the machine parameters on the cooling process. The lengthening of the cooling section is one of our modifications for this year's experiments.

To measure such fast cooling times we have developed a system that measures simultaneously in all three planes the signal from the Schottky pick-ups and then reconstructs the Schottky power distribution profiles as a function of time. The down-mixed Schottky signals are acquired by a PC [6] which performs a FFT on time slices of the data buffer and then displays a mountain range graph of the evolution of the profile. In this manner we are able to monitor the beam size evolution tightly in the three planes, with a time resolution of about 4 ms. A second method to observe the transverse emittance is based on the ionisation profile monitor (BIPM). This uses position sensitive channel plates to detect the ionisation of the residual gas and hence the beam dimensions in the transverse planes.

Two different techniques were used to measure the cooling down times. The first method consists in recording the beam size evolution for an injected beam, whilst the second analyses the decay of the betatron oscillation of a well-cooled beam deflected by a fast ejection kicker. Typical 2 rms emittance values for an injected beam are : $\Delta p/p=1x10^{-3}$, $\varepsilon_v=7\ \pi$ mm mrad and $\varepsilon_h=50\ \pi$ mm mrad , and the equilibrium values with an electron beam current of 350 mA were $\Delta p/p=0.15x10^{-3}$, $\varepsilon_v= \varepsilon_h=4\ \pi$ mm mrad. For the injected beam, cooling proceeds simultaneously in all three planes whereas with the kick method only the horizontal betatron oscillations can be tested for a beam that is already cooled in the longitudinal and vertical degrees of freedom.

Cooling down times were measured as a function of various parameters including the electron beam current, the lattice parameters at the cooler and the degree of neutralisation of the electron beam [7]. Fig. 4 shows some measurements made on electron beam neutralisation, and in Fig. 5 are displayed the cooling down times as a function of the machine settings.

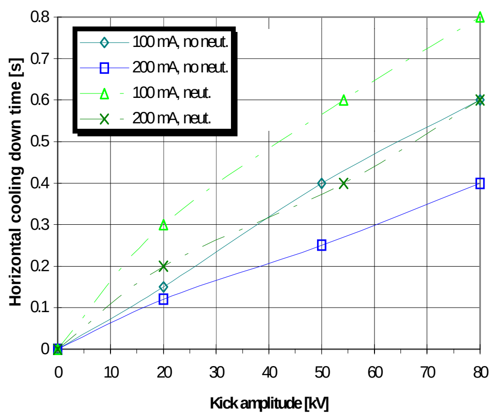

Figure 4. Horizontal cooling down time (40 π mm mrad to 4 π mm mrad) vs. kick amplitude for neutralised and non neutralised electron cooling beams (machine 4 optics).

From the results we have found that there is no advantage in using a neutralised electron beam but that it is important to monitor the degree of neutralisation as, if unstable, it can be detrimental to the cooling process. Cooling times under 100 ms in all planes were measured for $4x10^6$ ions of Pb^{54+}, but an unusual dependence on the lattice parameters has been observed which might indicate large transverse velocities at the edge of the electron beam.

4. CONCLUSIONS AND FUTURE EXPERIMENTS

The required fast cooling times have been obtained, but only at low ion intensity. A factor of more than 100 in intensity has to be gained by multi-turn injection and stacking, and at this high intensity, collective effects can become important.

Charge exchange with the residual gas and recombination with cooling electrons severely limit the lifetime. The choice of Pb^{54+} which has a lifetime of 6 s with a nominal electron current of 400 mA is acceptable.

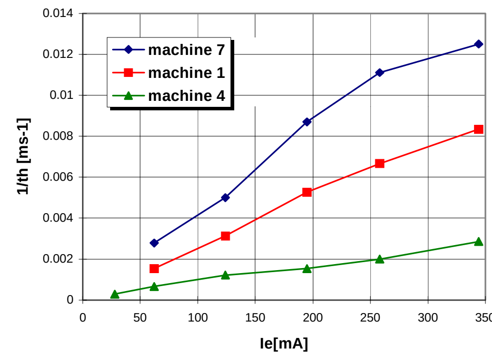

Figure 5. Cooling rate (inverse of the time to go from 40 π to 4 π mm mrad horizontally) as a function of the electron current for 10^7 Pb^{54+} ions for different optical settings.

This year LEAR will run from May to September in a dedicated machine experiment session. Fast bumpers have been installed to test fully the combined multi-turn injection scheme, and the instrumentation in the transfer line and in the machine has also been upgraded. To improve the vacuum quality, pumps have been added at various points around the machine where beam loss is most likely and additional non evaporable getter (NEG) pumps have been installed in the electron cooling section. To further enhance the cooling process, the cooling length has been doubled and the vacuum chamber has been made uniform to avoid problems with electron beam neutralisation.

5. REFERENCES

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