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RECENT RESULTS ON LEAD-ION ACCUMULATION IN LEAR FOR THE LHC

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Abstract

To prepare dense bunches of lead ions for the LHC it has been proposed to accumulate the 4.2 MeV/u linac beam in a storage ring with electron cooling. A series of experiments is being performed in the low-energy ring LEAR to test this technique. First results were already reported at the Beam Crystallisation Workshop in Erice in November 1995. Two more recent runs to complement these investigations were concerned with: further study of the beam lifetime; the dependence of the cooling time on optical settings of the storage ring and on neutralization of the electron beam; tests in view of multiturn injection. New results obtained in these two runs in December 1995 and in April 1996 will be discussed in this contribution.

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1 INTRODUCTION

After the completion of the antiproton programme, the Low-Energy Antiproton Ring (LEAR) becomes available to serve as an accumulator ring for heavy ions in the injector chain for the future Large Hadron Collider (LHC) [1]. The scheme proposed [2] for the injection of lead ions is sketched in Fig. 1. It is based on a 'present day' ECR source delivering a current of 100 μAe of Pb^{27+}. Multiturn injection and accumulation with the aid of electron cooling are required to gain a factor of $\sim$ 125 in intensity. A multiturn scheme has been proposed [3] which combines injection into the transverse and the longitudinal phase planes. This holds the promise of a large number of injectable turns, and facilitates the optimization of the resulting three-dimensional emittance distribution for electron cooling. With a linac cycling at 10 Hz, cooling times faster than 100 ms are desirable to accumulate 20 pulses in 2 s.

A series of machine experiments [4]–[7] has been performed to test the techniques required. Since the main duty of LEAR, up to the end of 1996, is to supply high-quality antiproton beams to its users, these tests were limited in time and scope. In fact multiturn injection and stacking could not be tried because they require a new configuration of bumpers and septa (Fig. 2) which is not compatible with the ultra slow extraction of LEAR.

A workshop report on the first two experimental sessions was given in Ref. [8]. In the present note we summarize the subsequent results (Dec. 1995 and April 1996 runs) which might be of interest to the community present at this symposium.

Figure 1: Sketch of the lead-ion injection scheme for the LHC.

Figure 2: Present configuration of LEAR and modifications proposed for future experiments. A thin septum and four fast bumper magnets have to be installed to test multiturn injection. The electron cooling is moved to straight section 2 to have different Twiss functions in the cooling and the injection section whilst keeping the symmetry of two of the lattice. It is also proposed to increase the cooling length in order to test the resulting improvement of the cooling strength.

2 MACHINE PARAMETERS

Experiments were performed with lead ions of three different charge states (53+ to 55+) which can be selected with sufficient intensity after stripping the beam from the lead-ion linac 'linac 3' at 4.2 MeV/u. Lead 55+ was tested for the first time, the other charge states including Pb^{52+} had already been used in previous runs. Some comparative measurements were also made with protons from linac 2 (see Table 1). Seven different optical settings of LEAR ('machine 1–7', Table 2) were used to test the influence of the lattice functions on cooling and beam lifetime. To have sufficient margin in the choice of the dispersion (D) and focusing (β_h) at the cooler, it was necessary to abandon the usual four-fold symmetry (same D and β in all four straight sections) of LEAR. However, two-fold symmetry had to be retained resulting in identical Twiss parameters in the straight sections SS1 (injection) and SS3 (electron cooling) on the one hand, and in SS2 and SS4 on the other hand (Table 2). We plan to move the cooler in 1997 to SS2 (Fig. 2) so that the Twiss functions for injection and cooling can be adjusted more independently.

Care was taken to record the vacuum conditions at the beginning and at the end of each run and during intermediate times. Four mass spectrometers installed in different straight sections of LEAR were read via a PC to obtain the gas composition and to evaluate the expected lifetime. The average vacuum pressure and especially the gas composition turned out to be different from run to run (Table 3).

A pressure rise was observed, when large losses of ions occurred, especially when the injection kicker was not pulsed so that the whole beam was lost on the first turn. Pulsing the linac continuously with a repetition rate of 1/1.25 s whilst the LEAR kicker was disabled, the final increase in ring average pressure was as big as a factor of 2 (from typically 2×10^{-11} to 4×10^{-11} torr). The pressure rise was concentrated in those parts of the ring where the beam was lost.

Table 1: Main parameters of proton, lead-ion, and electron cooling beams

	Protons	Ions (Pb^{53+} and Pb^{54+})
Ion energy	50 MeV	4.2 MeV/u
Velocity factor $\beta = v/c$	0.31	0.094
Current I_i	few mA	20–25 μAe
Corresponding no. of particles	few 10^9	2–3 $\times 10^6$ ions
Electron cooling energy	27 keV	2.3 keV
Cooling length/circumference η_cool	0.02	0.02
Electron beam radius a_e	25 mm	25 mm
Magnetic field in cooler	0.06 T	0.06 T
Typical electron current I_e	1–2.2 A	0.06–0.4 A

Table 2: Some data for the different optical settings of LEAR ‘machines 1–7’. Lattice functions at the cooler are given by the values in SS1/SS3.

Machine	1	2	3	4	5	6	7
β_H SS1/SS3 [m]	1.9	1.3	10.9	9.5	1.7	0.65	4.8
β_v SS1/SS3 [m]	6.4	9.6	4.1	10.5	13.4	5.5	5.0
D SS1/SS3 [m]	3.5	0	0	0	9.8	0	5.0
β_H SS2/SS4 [m]	1.9	9.6	6.4	3.5	13.5	25.4	1.1
β_v SS2/SS4 [m]	6.4	11.9	14.8	7.2	14.9	5.3	6.2
D SS2/SS4 [m]	3.5	9.8	9.6	9.9	0.06	10.1	2.0
Q_H	2.31	2.46	1.82	1.62	1.40	2.76	2.55
Q_v	2.62	2.42	2.42	2.42	2.24	2.72	2.70

Table 3: Ring average vacuum conditions estimated from the readings of four gas analysers. No detailed analysis of the residual gas was done in the December 1994 run.

Residual gas	Partial pressures, in 10^{-12} torr, ring average			
	Dec. 94	June 95	Dec. 95	Apr. 96
H_2	–	14.5	41.7	7
He	–	1.9	0.5	1.3
CH_4	–	1.4	3.4	2.7
H_2O	–	1.4	0.9	0.8
CO	–	0.4	0.4	1.2
N_2	–	0.1	0	3.4
O_2	–	0	0	0.5
Ar	–	0.1	0.6	0.3
CO_2	–	0.1	0.2	0.4
Sum	11	19.9	47.7	17.6

3 BEAM LIFETIME MEASUREMENTS

The beam lifetime (τ) was estimated by recording the ion intensity versus time deduced from the longitudinal Schottky signal, as in the previous runs [4]–[7]. The decay rate $1/\tau = 1/\tau_{\mathrm{vac}} + 1/\tau_{\mathrm{c}}$ has contributions due to the charge exchange with the residual gas and due to the presence of the cooling electron beam. The former is constant whereas the latter increases with electron current (I_{e}). From a plot of $1/\tau$ vs. I_{e} we can deduce $1/\tau_{\mathrm{vac}}$ and $1/\tau_{\mathrm{c}}$ (I_{e}) (see the example reproduced in Fig. 3.)

We have used the formula of Franzke [9] to estimate τ_{vac} for the vacuum conditions given in Table 3 and found good agreement (Table 4) with the measured values. No difference in τ_{vac} between the different charge states Pb^{52+} to Pb^{55+} could be detected, in agreement with theory which predicts similar cross-sections.

In contrast to this a very strong and unexpected charge-state dependence of $1/\tau_{\mathrm{c}}$ was found in the previous runs [4, 5]. These observations were confirmed and complemented by the new results. The situation is summarized in Table 5 where we compile rate coefficients α_τ (in units of $10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$). These give the slope of the $1/\tau$ vs n_{eff} curve where the electron beam density effective per turn is given by the true density of the electron beam and the fraction η_{cool} of the circumference covered by the electron cooler $n_{\mathrm{eff}} = n_{\mathrm{e}}\eta_{\mathrm{cool}}$.

Figure 3: Dependence of the inverse lifetime on electron current for three different Pb-ion charge states. The 'machine 4' optics is used in this example.

Table 4: Beam lifetime due to charge exchange with the residual gas for the vacuum conditions summarized in Table 3. The 'theoretical values' are obtained by adding the decay rates due to the different components. The semi-empirical formula of Ref. [9] is used to obtain the electron capture — and loss cross-sections of the Pb ions with the molecules of the residual gas.

Beam lifetime (s)	Dec. 94	June 95	Dec. 95	Apr. 96
Theoretical	–	17	13	12
Measured	20	16	10	9

Table 5: Rate coefficients ($10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$) for the different charge states and different lattice functions at the cooler

Run	Rate coefficient for the different charge state				'Machine' no. (Table 2)
	Pb^{52+}	Pb^{53+}	Pb^{54+}	Pb^{55+}	
Dec. 94		64			1
June 95	11	60	9		1
Dec. 95		63	5	12	4
Apr. 96		60	9		1
		60	6		4
			7		7

For the LEAR cooler (Table 1) at 2.3 keV electron energy:

$$n_{\mathrm{eff}} \simeq 2 \times 10^{-2} n_{\mathrm{e}} = 2.2 \times 10^{6}\,[\mathrm{cm}^{-3}\mathrm{A}^{-1}] \times I_{\mathrm{e}}\ .$$

The following can be observed from Table 5: the rate coefficient of Pb^{53+} is unusually strong. Values close to $60 \times 10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ were measured in all runs independent of the optical setting (machine 1 and 4) of LEAR. For Pb^{52+} and Pb^{55+}, coefficients of the order of $10 \times 10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ were found. Both were measured only once, for Pb^{52+} with the normal LEAR lattice and Pb^{55+} with 'machine 4' which has large beta-functions and zero dispersion at the cooler. For Pb^{54+} coefficients in the range of 5–9 $\times\ 10^{-8}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ were measured, apparently depending on the lattice functions at the cooler.

We note that these rate coefficients are not easily explainable by existing theory. For radiative electron capture, coefficients of only 2–3×10^{-8} are expected at the electron temperatures of the LEAR cooler which are estimated to be 0.1 to 0.2 eV from the H^0 rate when protons are cooled. Rates up to 10 times faster than radiative recombination have been reported in the literature for special partially stripped ions and attempts to explain them by resonant dielectronic capture have been made, see Ref. [5] and references given therein. The same explanation could apply to Pb^{52+}, Pb^{54+}, and Pb^{55+}. However, the rate of Pb^{53+} is especially fast and points to an unusually strong capture resonance or other mechanisms.

Several tests were made to further elucidate this question. The longitudinal magnetic field of the cooler was varied between 200 and 800 G for Pb^{53+} and Pb^{54+}. No marked differences in the lifetimes were detected. The energy of the electron beam was set off by a large amount. In this case the lifetime increased and reached a value only slightly shorter than the 'vacuum lifetime' in the absence of the electron beam. The difference can be explained by the pressure bump created by the collector inefficiency. When the electron beam was neutralized a further reduction of the 'vacuum lifetime' was observed which was especially pronounced when neutralization jumps occurred. These effects were the same for all the charge states investigated.

For the April 1996 run a movable scintillation screen was installed in the first bending magnet downstream of the cooling section to intercept the $\mathrm{Pb}^{(Q-1)+}$ ions created due to electron capture by circulating Pb^{Q+} ions. A strong counting rate, especially for circulating Pb^{53+}, was observed when the scintillator covered the expected position of the recombined ions (in our case ~ 25 mm horizontally outwards from the circulating beam). A large reduction of the signal occurred when the electron cooling was switched off or when the screen was withdrawn by more than 25 mm from the main beam thus indicating that indeed capture of cooling electrons by cooled ions is responsible for at least a fraction of the losses. More refined experiments are in preparation.

To summarize the results of this section: we have found that both charge exchange with the residual gas (including the neutralizing ions in the cooling section) and capture of cooling electrons have a very critical influence on the lifetime of the circulating ion beam. A high-quality vacuum (pressure and gas composition) is essential to obtain the desired $\tau_{\mathrm{vac}} \approx 40$ s. Losses — both of the circulating beam and of the electron beam — have to be minimized to avoid outgassing. Full neutralization of a strong cooling beam is problematic.

The recombination of Pb^{53+} leads to an uncomfortably short lifetime ($\tau_{\mathrm{c}} \approx 2$ s at $I_{\mathrm{e}} = 400$ mA). For Pb^{54+} the lifetime ($\tau_{\mathrm{c}} \approx 16$ to 20 s at $I_{\mathrm{e}} = 400$ mA) is acceptable.

4 MEASUREMENTS OF THE COOLING TIME

The measurements of the cooling time had two main objectives:

i) to test the effect of neutralization of the electron beam
ii) to assess the influence of the lattice functions of the storage ring.

As in the previous runs the evolution of the momentum spread was deduced from the Schottky noise signal near a harmonic (n) of the revolution frequency. The transverse emittances were observed via the Schottky signal induced by the coasting beam at one of the betatron sideband frequencies $(n \pm Q)\, f_{\mathrm{rev}}$ on a horizontal or vertical position pick-up. A second method to observe the transverse emittance is based on Beam Ionization Profile Monitors (BIPMs) which use position-sensitive channel plates to detect the ionization of the residual gas and thereby the beam width and height.

Two different techniques to measure the 'cooling times' were used: The 'cooling down' of the injected beam was analysed and/or a well-cooled beam was kicked (using a fast 'ejection' kicker to provide a deflection smaller than the aperture) and the decay of the betatron oscillation was recorded with the BIPM (the Schottky noise is more difficult to use in this situation).

The beam after injection had 'typical' emittances of $\Delta p/p = 1 \times 10^{-3}$, 2 rms; $\epsilon_{\mathrm{v}} = 7\pi$ mm mrad, $\epsilon_{\mathrm{H}} = 50\pi$ mm mrad. Equilibrium values, e.g. for cooling with $I_{\mathrm{e}} = 350$ mA are $\Delta p/p \approx 0.15 \times 10^{-3}$, $\epsilon_{\mathrm{v}} \approx \epsilon_{\mathrm{H}} \approx 4\pi$ mm mrad. For the comparison of different lattices and neutralization states we use the 'cooling down times' (hereafter simply called 'cooling times') defined as:

$\tau_{\Delta p}$: the time it takes to decrease $\Delta p/p$ from 1 to 0.2×10^{-3};
τ_{H}: the time for ϵ_{H} to decrease from the initial value down to $4\,\pi$ mm mrad.

Clearly, for the injected beam, cooling proceeds simultaneously in all three planes whereas with the kick method the cooling of horizontal betatron oscillations can be tested for a beam that is already cooled in the longitudinal and vertical degree of freedom. Thus the kick method simulates to some extent the conditions after horizontal multiturn injection.

The December 1995 run was mainly used to test the influence of neutralization. Owing to the improvements made [6, 8] it had become possible to work with stable neutralization levels that could be chosen between 0 and 100% for currents up to $I_e = 200$ mA. A large number of measurements were made varying the neutralization and/or the intensity of the electron beam. The injected beam method was used for the 'machine 4' optics and the kick method for 'machine 1' and 'machine 4'. Results may be summarized by stating that no appreciable gain in the cooling times was obtained with neutralization. In some situations we saw a small improvement whereas in other cases neutralization was detrimental to the cooling process. More experiments are necessary to get a clearer picture.

The influence of the lattice functions was tested in the April run where care was taken to have zero neutralization during all measurements. A first series of tests was performed with protons which are easier to handle due to the long lifetime and the higher intensity. The 'kicked-beam method' was applied simulating a beam with a horizontal emittance of about 40 π mm mrad in all cases. The electron current was 1.2 A. Results of τ_H for four different optical settings are plotted in Fig. 4 against the horizontal focusing function (β_H) at the cooler. It appears that 'machine 1' ($\beta_H \approx 2$ m) and 'machine 7' ($\beta_H \approx 5$ m) are fairly close to the optimum. It should be mentioned that the 'machines' considered, in addition to the difference in β_H also have different D at the cooler. Therefore the effect of D may be superimposed on the influence of β_H, and may even be the dominant effect.

Figure 4: Plot of the proton beam cooling time versus the horizontal β-function at the cooler. The electron current was $I_\mathrm{e} = 1.2$ A. The time to cool $\sim 2 \times 10^9$ protons at 50 MeV after a kick corresponding to 40 π mm mrad to 4 π mm mrad horizontal emittance is given. The measured points are for 'machines 6, 1, 7 and 4' ($\beta_\mathrm{H} = 0.65$, 1.9, 4.8 and 9.5 m), see Table 2. The curve corresponds to a fit $\tau_\mathrm{H} = 0.2\ \beta_\mathrm{H}^2 + 13/\beta_\mathrm{H}^{3/2}$. Note that in addition to β_H, the dispersion D is different for the 'machines' tested. This might add to the effect of β_H and could even be the dominant factor for the difference of cooling time.

Guided by the results for protons (which are for different electron energy and current!) three different optical settings were explored with Pb^{54+} ions. The measurements are illustrated in Fig. 5 in the form of a plot of the cooling rate ($1/\tau_\mathrm{H}$) vs. electron current (I_e). One notes that 'machine 7' has now the fastest horizontal cooling, 'machine 1' leads to a somewhat longer one and 'machine 4' to a significantly longer cooling time τ_H. Qualitatively these observations can be explained by the interplay of the ion velocity spread $\Delta v_\mathrm{H} = \beta c \sqrt{\epsilon_\mathrm{H}/\beta_\mathrm{H}}$ which tends to reduce the cooling force when β_H becomes too small, and the 'overlap factor' $a_\mathrm{H}/a_\mathrm{e}$ which reduces the cooling efficiency when the ion beam radius $a_\mathrm{H} = \sqrt{\epsilon_\mathrm{H}\beta_\mathrm{H}}$ becomes larger than the electron beam ($a_\mathrm{e} = 25$ mm in our case). Naïvely one would expect an optimum for $a_\mathrm{H} \approx a_\mathrm{e}$ which for $\epsilon_\mathrm{H} = 40\ \pi$ mm mrad gives an 'optimum' $\beta_\mathrm{H} \approx 15$ m compared with the measured $\beta_\mathrm{H} = 5$ m. An 'effective' electron beam radius $a_\mathrm{eff} \approx 15$ mm (instead of $a_\mathrm{e} = 25$ mm expected from the design of the electron gun) could explain the measurements.

Figure 5: Cooling rate (inverse of time to go from 40 π to 4 π mm mrad horizontally) as a function of the electron current, for $\sim 10^7$ Pb^{54+} ions at 4.2 MeV/u.

To summarize the results of this section we have found (so far?) no advantage in using a strongly neutralized electron beam. However, the possibility to monitor and control neutralization at a constant level (especially $\eta = 0$) has proven essential. A strong dependence of the (horizontal) cooling time on the lattice functions has been observed with an optimum ($\beta_\mathrm{H} \approx 5$ m) lower than expected ($\beta_\mathrm{H} \approx 10$–15 m) from simple theory. The influence of the dispersion (D) in the cooling section, which could influence these results, has to be investigated in future runs.

5 TESTS TO PREPARE FOR MULTITURN INJECTION

For the multiturn scheme which combines injection into horizontal and longitudinal phase space [3] the energy of the linac has to be ramped by about 12×10^{-3} in 50 μs (about 20 turns in LEAR). The transfer line must have sufficient acceptance to transmit this momentum width ($\delta\Delta/p = 6 \times 10^{-3}$) plus the instantaneous momentum spread ($\Delta p/p \approx 2 \times 10^{-3}$, 4 rms) of the linac beam. At the injection septum the dispersion of the line must be $|D| < 0.2$ m to have a beam displacement $d \lesssim 1$ mm during the ramp. A new optics of the $\sim$ 100 m long transfer line including the 'U-turn' between linac 3 and LEAR has been calculated [10]. To test this optics Pb^{53+} and Pb^{54+} were simultaneously transmitted by adjusting the magnetic filter line after the stripper to a large momentum width. After fine adjustment, the two beams passed the whole line, and the beam spots on a scintillator screen in front of the LEAR septum were superimposed with good accuracy.

This proves that the momentum acceptance of the line was greater than 18×10^{-3} and the residual dispersion at the septum was small, as required.

A second series of tests concerned the energy ramping of the linac. An energy change of 70 keV (corresponding to a momentum shift $\delta p/p \approx 8 \times 10^{-3}$) in a time $\Delta t \gtrsim 60$ μs could be obtained by modulating the RF level of tank 3 and simultaneously the phase of the debuncher cavity installed in the line downstream of the linac [6, 11]. As mentioned, only single-turn ($t_{\mathrm{rev}} \approx 2.7$ μs) injection into LEAR was possible. However, the effect of the energy variation could be tested by displacing the timing of the injection kicker 'statically' along the ramp.

From the longitudinal Schottky scan in LEAR the mean energy and the energy spread as a function of the injection timing could be deduced. After careful synchronization of tank 3 and the debuncher, the momentum spread of the single-turn injected beam ($\Delta p/p \approx 2 \times 10^{-3}$, 4 rms) was virtually independent of the injection timing all along the ramp and practically the same as with constant linac energy.

These results look promising for multiturn injection with energy ramping.

6 CONCLUSIONS

Charge exchange with the residual gas and recombination with cooling electrons limit the lifetime of the partially stripped ion beam.

Residual gas pressures of $\leq 5 \times 10^{-12}$ torr for H_2 and $< 1 \times 10^{-12}$ torr for heavier residual gas components like N_2 are desirable to obtain a good 'vacuum lifetime'. Recombination, especially for Pb^{53+}, is stronger than expected. The lifetime of Pb^{54+} at the nominal electron current of 400 mA is acceptable for 2 to 4 seconds of storage. Optimum beta-functions at the electron cooler are found to be ~ 5 m instead of the 10 to 15 m expected from simple theory.

The required fast cooling times have been obtained, but only at low intensity so far. A factor of more than 100 in intensity has to be gained by multiturn injection and stacking. At this high intensity collective effects, which have not shown up in the experiments so far, can become important.

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