ELECTRON COOLING OF PB^{54+} IONS IN THE LOW ENERGY ION RING (LEIR)

J. Bosser, C. Carli, M. Chanel, R. Maccaferri, S. Maury, D. Möhl, G. Molinari, G. Tranquille,
CERN, Geneva, Switzerland.

Abstract

For the preparation of dense bunches of lead ions for the LHC, electron cooling will be essential for accumulation in a storage ring at 4.2 MeV/u. Tests have been carried out on the LEAR ring (renamed LEIR for Low Energy Ion Ring) in order to determine the optimum parameters for a future state-of-the-art electron cooling device which would be able to cool linac pulses of lead ions in less than 100 ms. The experiments focused on the generation of a stable high intensity electron beam that is needed to free space in both longitudinal and transverse phase space for incoming pulses. Investigations on the ion beam lifetime in the presence of the electron beam and on the dependency of the cooling times on the optical settings of the storage ring will also be discussed. This paper concentrates on the cooling aspects with the multiturn injection, vacuum, and high intensity aspects discussed in a companion paper at this conference.

1 INTRODUCTION

After the completion of the antiproton physics programme at the end of 1996, the Low Energy Antiproton Ring was modified for a final series of experiments to test the lead ion accumulation scheme that is foreseen for the Large Hadron Collider (LHC). The goals of the 1997 experiments were to test a new combined transverse and longitudinal multiturn injection scheme, the stacking of lead ions [1] and the optimisation of the electron cooling device for fast and efficient reduction of the beam dimensions. Previous experiments [2] had indicated the necessary modifications needed to be made to the ring in order to carry out the final tests. A long shutdown in the first half of 1997 was used for mechanical installation and an upgrading of the measurement systems. This was followed by five months of intensive data taking with Pb^{54+} ions and protons produced by the two CERN linacs.

2 EXPERIMENTAL SETUP

To measure the relevant beam properties, all the machine diagnostics were interfaced to a PC based data acquisition system. Schottky signals were used for the cooling time and lifetime measurements and proved to be very useful for measuring the intensity of lead ion beams which, for a single turn injection, was too low to be reliably measured with the beam current transformer. Beam ionisation profile monitors (BIPM) were used to complement the cooling time measurements as well as to obtain absolute measurements of the beam emittance. Residual gas analysers could also be accessed via the PC system for the measurement of the vacuum quality.

The electron beam used for the cooling experiments was generated by a variable intensity electron gun, which was developed in 1994 [3]. It consists of three electrodes, the Pierce electrode, the grid and the anode, and uses an adiabatic optics scheme in order to produce high intensity electron beams with low angular spread. The electron current density is controlled through the voltage control of the grid electrode. One problem encountered in the production of such dense beams is the storage of secondary electrons when the grid potential is positive with respect to the anode (which is kept at ground potential). This induces a reduction of the nominal electron current intensity and also creates instabilities in the electron beam. Up to 1 A of electron current at an energy of 2.5 keV was obtained by switching the grid voltage to 0 V for a short duration (1μs). In this way the Penning trap present at the cathode level is emptied and the nominal current is obtained. However as the trap fills with secondary electrons, the nominal current decreases again to the level before the grid pulse. Modifications and various feedback systems to cure electron beam instabilities have been reported in [2].

3 LIFETIME MEASUREMENTS

The beam lifetime was estimated by recording the ion intensity versus time deduced from the longitudinal Schottky signal. The decay rate, given by:

$$1/\tau = 1/\tau_{vac} + 1/\tau_{rec}$$

has contributions due to charge exchange with the residual gas and due to the presence of the cooling electron beam. The latter increases with electron current whereas the former is constant and depends on the residual gas composition. Figure 1 shows a plot of $1/\tau$ vs. the electron beam current I_e for charge states 52+ to 55+. From the Y-intercept the lifetime due to the residual gas can be obtained. These values are in good agreement with the values given by the formula of Franzke [4] which estimates τ_{vac} for given vacuum conditions. In contrast to this, a very strong and unexpected dependence of $1/\tau_{rec}$ on the charge state was observed. This dependency is not easily explainable from existing theory on electron-ion recombination, and indicates that an unusually strong capture resonance or other mechanisms are involved.

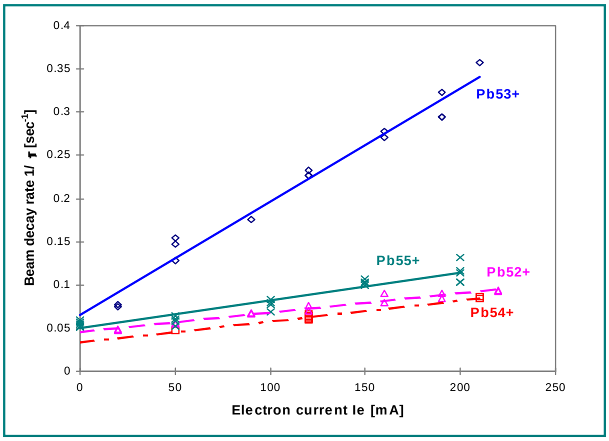

Figure 1: Dependence of the ion beam decay rate on the electron cooling current for Pb ion charge states 52+ to 55+.

Similar observations have been made on other storage rings in which partially stripped ions are electron-cooled [5]. From our investigations it is clear that a high quality vacuum (pressure and gas composition) is essential to obtain the desired lifetime of about 20 s. Losses, both of the circulating ion beam and of the electron beam, have to be minimised to avoid outgassing from the vacuum chamber. The recombination of Pb^{53+} ions with the cooling electrons leads to lifetimes that are too short for cooling and stacking in LEIR. For the LHC it has been decide to use Pb^{54+} ions, which are produced in equal quantities to Pb^{53+} ions, as they are well suited, having a lifetime of 16-20 s with an electron current of 400 mA.

4 COOLING TIME MEASUREMENTS

In the proposed accumulation scheme, the newly injected ion beam has to have its dimensions reduced in less than 100 ms by the electron cooling device in order to free space for a next pulse. Three parameters play a role in reducing the cooling time, they are; the electron beam intensity, the length of the electron cooling device itself, and the relative difference in angle between the electron and ion beams.

The beam intensity is adjusted by changing the voltage difference between the cathode and the grid anode. As a consequence, the cathode voltage has to be modified to compensate for the shift in energy due to the increase of the electron beam space charge. A strange effect that was observed during the measurements was an increase in the angle of the electron beam with increasing current. Correct alignment of the two beams is important when the fastest cooling times are required. Therefore care was taken to always check the beam positions before making the cooling time measurements. The definition of cooling time used throughout the experiments was the time needed to reduce the horizontal emittance from 40 π mm mrad to 4 π mm mrad. Figure 2 shows a compilation of cooling rate ($1/\tau_h$) measurements in which we clearly see the linear increase in cooling rate as a function of electron intensity.

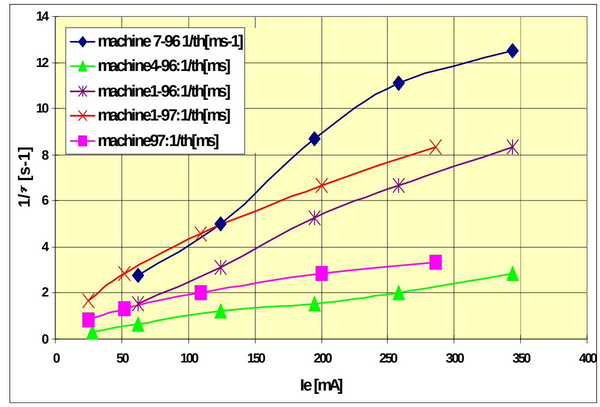

Figure 2: Cooling rates of Pb ions as a function of electron beam intensity for different lattice parameters at the electron cooling device. The values of the lattice parameters are given in Table 1.

On the same graph we see the effect of doubling the cooling section by a factor of 2. For this measurement we used the standard machine optics (machine 1) and compared the measurements made in 1996 (electron cooler length of 1.5 m, represented by * on the graph) with the 1997 measurements (x on the graph) where the cooling section was doubled in length. For low electron beam currents (<120 mA) we do see an increase in the cooling rate by a factor of 2. However for higher currents the gain becomes less pronounced. This can be explained by the fact that the increased space charge in the electron beam makes it more difficult to align the two beams over twice the length of the original set-up. Despite all the precautions taken to ensure the best possible conditions for fast cooling, some of the more extreme measurements were not possible or were difficult to do due to the lack of correcting power of the auxiliary coils.

Table 1: Lattice functions at the cooler for the different machine optical settings.

machine	*1*	*4*	*6*	*7*	*97*
β_h (m)	1.9	9.5	0.65	4.8	5.0
β_v (m)	6.4	10.5	5.5	5.0	5.0
D (m)	3.6	9.9	0.0	5.0	0.0

The lattice parameters (β and D) determine the size and angular distribution of the ion beam at the electron cooler. As electron cooling is most efficient for small angle differences between the two beams, one would imagine that a large value of beta ($\theta^2 \propto \varepsilon/\beta$, θ = ion beam angle) would give the best cooling results. Figure 3 shows the results of measurements made in 1996 with protons for four different optical settings. The best cooling times were obtained with machine 1 and machine 7, whilst machine 4 and machine 6 gave very mediocre cooling times. It should be mentioned that in addition to the difference in the horizontal beta function, machines 1 and 4 also have a non-zero dispersion function at the cooler. It then seems clear that the effect of D is superimposed on the influence βh and may even be the dominant effect.

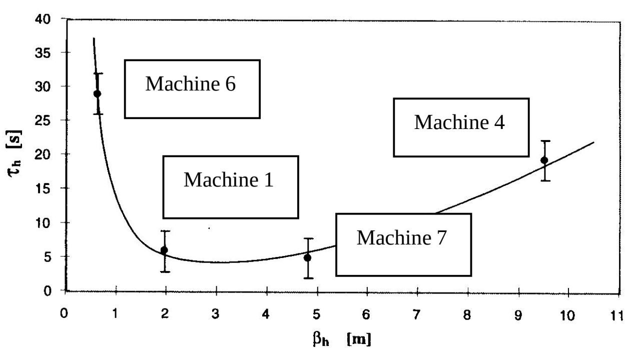

Figure 3: Plot of the proton beam cooling down time vs. the horizontal beta function at the cooler. The electron current was 1.2 A and the measured time was the time needed to cool $2x10^9$ protons at 50 MeV from an emittance of 40 π mm mrad to 4 π mm mrad.

Guided by our observations with protons, the cooling time results (figure 2) were confirmed with lead ions where we found that machine 7 was by far the best suited machine, in terms of optical parameters at the cooler, for fast cooling. In fact cooling times under 100 ms were obtained with only 350 mA of electron current.

To test the influence of dispersion on the cooling down time, a series of measurements were performed with protons using machine 97. This lattice was optimised for multiturn injection and therefore did not give the best cooling times. However, being a very flexible lattice, we were able to modify the dispersion at the cooler without changing the optical settings elsewhere.

Cooling times were measured as a function of the offset in position between the electron beam and the protons. The results are shown in figure 4 and it is quite clear that the dispersion plays a major role in horizontal cooling. The fastest cooling times were obtained with settings having a non-zero dispersion at the cooler. However with dispersion we see that cooling is no longer symmetric and, depending on the sign of the dispersion, is faster either to the interior of the machine (-ve dispersion) or to the exterior (+ve dispersion). In the case where the dispersion is zero we found a perfectly symmetric distribution of the cooling down time around the optimum with a loss of a factor of two in the cooling down times.

5 CONCLUSIONS

It has been shown that Pb^{54+} ions can be cooled in under 100 ms with a lifetime exceeding the requirements of the accumulation scheme for the LHC. The optical parameters, especially the dispersion function, at the cooler play an essential role in obtaining these fast cooling times and must be taken into account in the final design of a future accumulator ring. Enough experience has been obtained with the present electron cooling device to design and construct a new cooler that will be

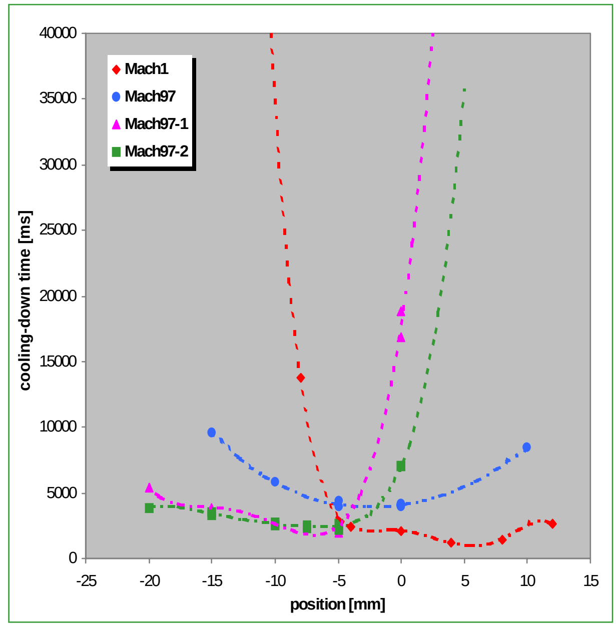

Figure 4: Cooling down times for protons at 50 MeV as a function of beam position offset between the electron and proton beams. Mach97(-1,-2) represent the results for machine97 with D=0 m, -1 m and –2 m respectively. Machine 1 are values for the standard machine which has a positive dispersion value at the cooler (D=3.6 m).

able to obtain high currents without being plagued by the stability problems encountered during the experiments. Another option for a new cooler would be beam expansion, and its usefulness is currently under theoretical and experimental investigations. A new test bench is also under consideration to investigate new gun and collector designs.

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