COOLING RESULTS FROM LEIR

G. Tranquille, CERN, Geneva, Switzerland

Abstract

The LEIR electron cooler has been successfully commissioned for the cooling and stacking of Pb^{54+} ions in LEIR during 2006. The emphasis of the three short commissioning runs was to produce the so-called “early” beam needed for the first LHC ion run. In addition some time was spent investigating the difficulties that one might encounter in producing the nominal LHC ion beam.

Cooling studies were also made whenever the machine operational mode made it possible, and we report on the preliminary results of the different measurements (cooling-down time, lifetime etc.) performed on the LEIR cooler. Our investigations also included a study of the influence of variable electron density distributions on the cooling performance.

INTRODUCTION

The LHC program foresees lead-lead collisions in 2009 with luminosities up to 10^{27} $cm^{-2}s^{-1}$. In LEIR, ion beam pulses from the LINAC3 are transformed into short high-brightness bunches needed for the LHC. This is obtained through multi-turn injection, cooling and accumulation. The electron cooler plays an essential role in producing the required beam brightness by rapidly cooling down the newly injected beam and then dragging it to the stack.

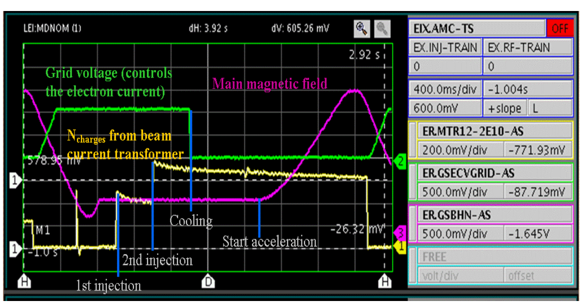

Figure 1: A standard 3.6s LEIR cycle during which 2 LINAC pulses are cooled-stacked in 800ms at an energy of 4.2 MeV/n. After bunching the Pb ions are accelerated to 72 MeV/n for extraction and transfer to the PS.

The goal of the LEIR commissioning runs in 2006 was to produce the Pb ion beam with the characteristics required for the first LHC ion run ($N_{ions} = 2.2x10^8$, $\varepsilon_{h,v} <$ 0.7 μm) and to subsequently transfer this beam to the next accelerator in the injection chain, the Proton Synchrotron (PS), for beam studies. Figure 1 shows a typical LEIR cycle in which two pulses are cooled and stacked to obtain the required intensity and emittance after which the beam is accelerated to top energy and extracted to the PS. These tests were so successful that the Pb ion beam was also extracted towards the Super Proton Synchrotron (SPS) for tests of the beam transport system and the stripping foil. Initial investigations into the production of the optimum beam ($N_{ions} = 1.2x10^9$, $\varepsilon_{h,v} <$ 0.7 μm) for LHC were also made on dedicated machine cycles. A full report of the LEIR commissioning can be found in [1].

ELECTRON COOLER HARDWARE COMMISSIONING

Hardware commissioning of the electron cooler concentrated on ensuring the vacuum [2] compatibility of the new device as well as exploring the performance limits. The main parameters of the cooler have been given in previous papers [3]. Two operational regimes can be used depending on the momentum of the ions to be cooled. If the small normalized emittances required cannot be reached at injection energy e.g. due to direct space charge detuning, operation of the cooler at the extraction energy will be necessary. In this scenario (unlikely for Pb ion operation, but a possible option for an eventual later upgrade to lighter ions), the LEIR magnetic cycle must contain an additional plateau at a suitable higher energy.

Electron Gun Characteristics

The high perveance gun provides an intense electron beam in order to decrease the cooling rate. However, in theory, increasing the electron density induces first an increase of the recombination rate (capture by the ion of an electron from the cooler), which is detrimental to the ion beam lifetime, and secondly increases the electron azimuthal drift velocity, thus increasing the cooling time. To combat the increase in electron-ion recombination, the electron gun has a “control electrode” used to vary the density distribution of the electron beam. The beam profile is adjusted in such a way that the density at the centre, where the cold stack sits, is smaller and thus the recombination rate is reduced. At larger radii, the density is large and allows efficient cooling of the injected beam executing large betatron oscillations.

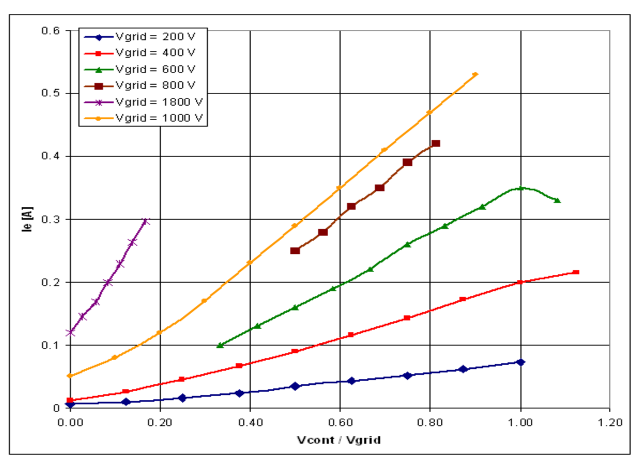

Figure 2: Electron beam current as a function of Vcont/Vgrid for Ee = 2.3 keV.

Figure 2 shows the measured electron beam intensity as a function of the control to grid voltage ratio. As the control electrode voltage is increased, the electron beam distribution changes from a parabolic beam (V_{cont} < 0.2 V_{grid}) to a completely hollow beam ($V_{cont} = V_{grid}$). A maximum stable current of 530 mA with a hollow distribution has been obtained but for operational purposes only 200 to 300 mA are used.

The effectiveness of the electrostatic bend has also been demonstrated when trying to obtain the highest electron currents. With only the B field in the toroids the relative losses are an order of magnitude higher than with a crossed electrostatic and magnetic field and it is very difficult to obtain a stable beam. With a polarisation voltage of 240 V and a careful steering of the electron beam into the collector, currents of up to 530 mA can be obtained. Figure 3 shows the dependence of the relative beam losses on the electron current for the two regimes.

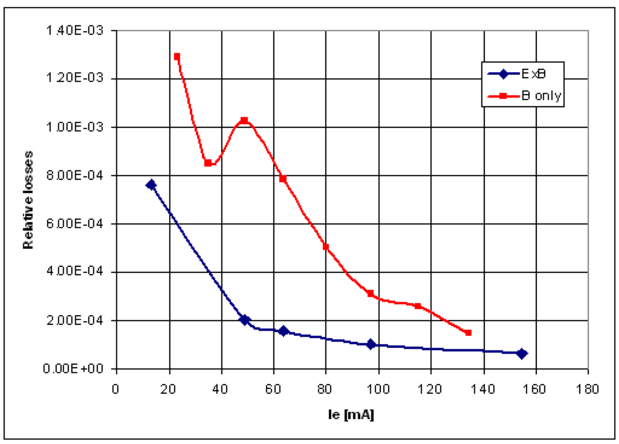

Figure 3: Relative electron beam loss as a function of the electron current, showing the influence of the electrostatic bend on the electron collection efficiency.

A system for measuring the beam position was also implemented and is used to align the electron and ion beams more efficiently. The measurement is done by the direct modulation of the electron intensity by a high frequency sine wave applied on the grid electrode. The sum and difference signals from the two position pick-ups installed in the cooling section are then acquired and calibration coefficients and offsets are applied to obtain the electron beam position. Using the different correction coils, the electron beam position and angle are adjusted such that the alignment with the circulating ion beam is optimum.

COOLING AND LIFETIME STUDIES

The cooling of ion beams was studied in parallel with the commissioning of the LEIR ring. Schottky diagnostics, ionisation profile monitors (IPM) and beam current transformers (BCT) were used to measure the phase-space cooling characteristics and to investigate the influence of the electron beam profile on the ion beam lifetime [4,5]. During the measurement we encountered many problems with the ionisation profile monitors which severely limited the quality of our measurements and limited the measurements to the horizontal plane only. These monitors have been redesigned and will be used in future measurement sessions.

As many of the LEIR systems had to be commissioned at the same time it was difficult to obtain long cycles dedicated to electron cooling studies. Almost all our measurements were performed on the standard magnetic cycle lasting 2.4 or 3.6 seconds during which 2 to 4 Linac pulses are cooled and stacked at 4.2 MeV/u. Due to the short duration of the injection plateau the momentum spread and the horizontal beam size after 400 ms were used as the measured parameters to characterise the cooling performance.

Influence of Beam Expansion

On the LEIR electron cooler the beam size can be varied by applying a stronger longitudinal field in the gun region. A maximum expansion factor of 3 is available thus making it possible to vary the electron beam radius from 14 mm to 24 mm. Figure 4 shows the result of a series of measurements made for two electron beam distributions (uniform for Vc/Vg = 0.2 and hollow for Vc/Vg = 0.5) with similar currents (~150 mA).

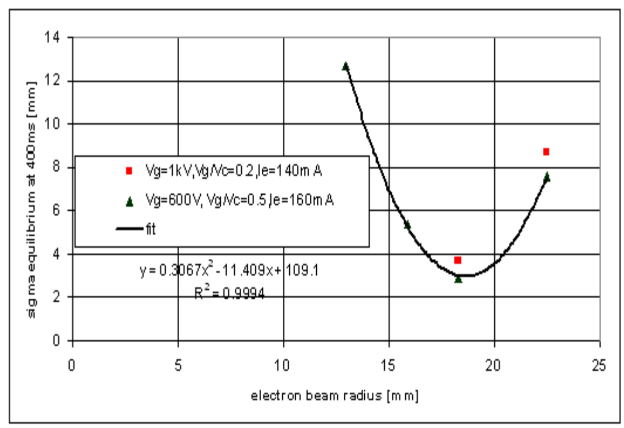

Figure 4: Beam size 400 ms after first injection as a function of the electron beam radius.

What one sees is that beam expansion becomes less useful when the electron beam radius is greater than 20 mm, roughly the size of the injected beam. Another phenomenon that was observed with larger electron beams is the relatively bad cooling of the first injected beam. In all our measurements, regardless of the number of injections, the first beam was never fully cooled to make space for another injection. Subsequent injections were cooled to dimensions almost twice smaller than the first one.

Influence of the Density Distribution

The electron beam density distribution can be varied from a parabolic distribution to a completely hollow one by applying a voltage on "control electrode" in the gun. For a grid voltage to control voltage ratio (Vg/Vc) below 0.2 the electron beam essentially has a parabolic distribution. Above this ratio the distribution changes from uniform to hollow. In figure 5 the electron beam distribution is varied as the intensity is increased. Again we observe a minimum in the curve corresponding to a slightly hollow distribution.

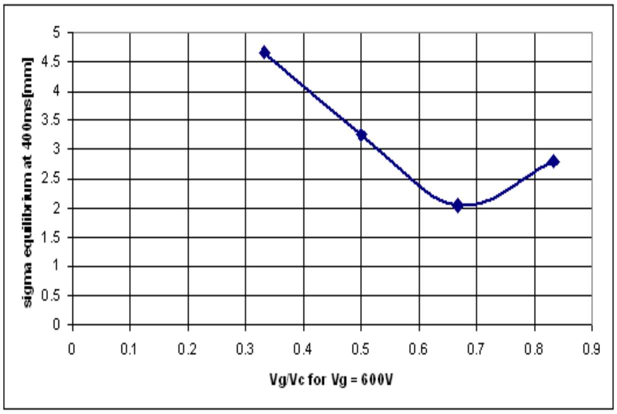

Figure 5: Beam size after 400 ms as a function of the electron beam distribution for the operational value of expansion (k=1.7, r=18 mm).

It is clear from the above measurements that a more detailed study of the interplay between beam size, intensity and density distribution needs to be made in order to optimise the transverse cooling.

Longitudinal Cooling

The momentum spread after 400 ms of cooling was measured using a down-mixed longitudinal Schottky signal captured with a fast ADC and treated mathematically to produce the spectral density distribution as a function of time. The results shown on the scatter plot of figure 6 do not exhibit any particularly strange behaviour, with a decreasing momentum spread as the electron current is increased.

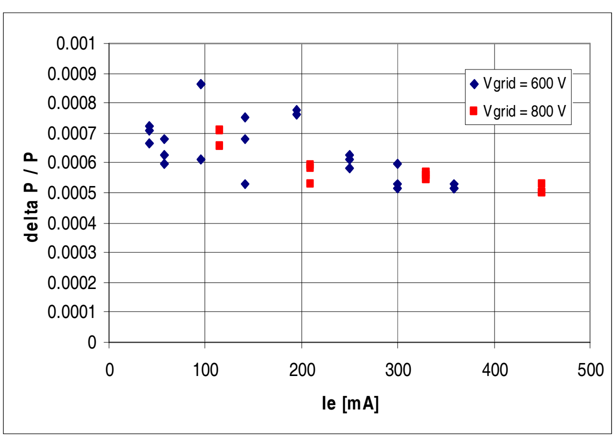

Figure 6: Momentum spread of the cooled ion beam after 400 ms as a function of electron current.

If we look more closely at the actual Schottky spectra (Figures 7a and 7b) then we see that, as the intensity goes up, and the distribution becomes more hollow, the final energy of the cooled ions vary well after the equilibrium momentum spread has been reached.

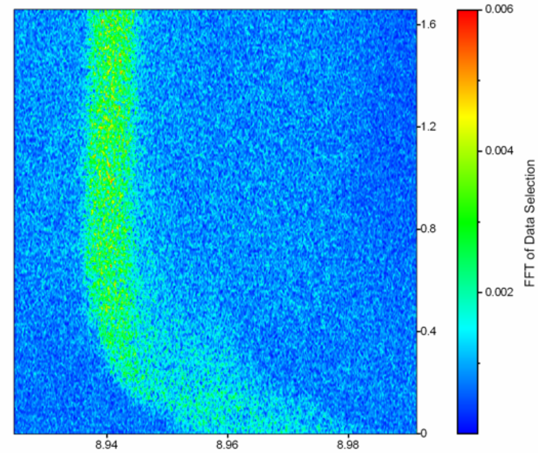

Figure 7a: Longitudinal Schottky evolution for uniform electron beam distribution.

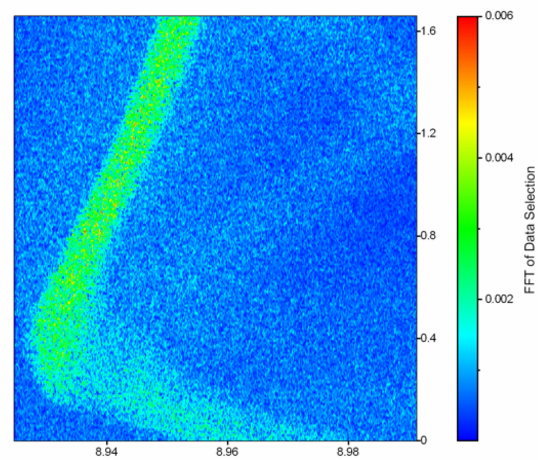

Figure 7b: Longitudinal Schottky evolution for a hollow electron beam distribution.

Lifetime Studies

In previous tests [6] the maximum accumulated intensity was a factor 2 lower than that required for the nominal LHC ion beam (1.2x10^9 ions). This was in part attributed to a short lifetime due to the recombination of ions with the cooling electrons and also to the limited electron current that could be obtained for effective cooling with the old electron gun.

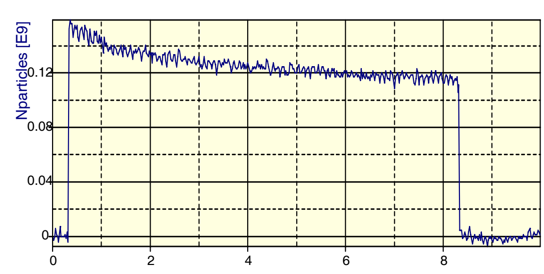

Figure 8: Example of the BCT signal for lifetime measurements.

In our measurements intensities well above 1.2×10^9 ions could easily be accumulated with an injection repetition rate of 1.6 Hz and an electron current of 110 mA. If the repetition rate is increased, the maximum number of stacked ions decreases proportionally for the same electron current.

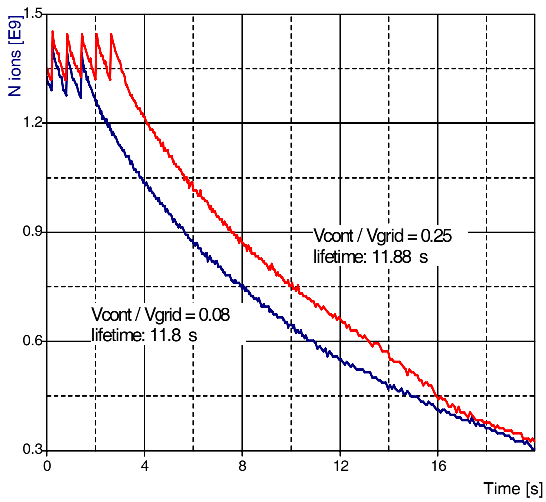

Figure 9: Beam lifetime for a parabolic (blue) and hollow (red) electron beam distribution.

The lifetime of the cooled ion beam can be measured by recording the evolution of the BCT signal as a function of time (Figure 8). The lifetime of the circulating beam was also compared for a parabolic and a hollow electron beam distribution (Figure 9). From the plot we see that the electron beam distribution does not significantly influence the lifetime indicating that recombination may not be after all the main cause of the short lifetime measured in the 1997 tests. Other processes related to the vacuum conditions or the injection scheme could be more dominant.

A complete plot of all our lifetime measurements for different intensities and density distributions is shown in figure 10. The slope of the curves gives the lifetime due to the electron beam whilst the intersection with the y-axis gives the vacuum lifetime. Comparing with the measurements made in 1997, we see a definite gain by a factor of 2 in the vacuum lifetime. The lifetime due to the electron beam is also slightly improved but does not seem to be influenced by the electron beam distribution.

CONCLUSIONS

The new electron cooler for LEIR has been successfully integrated in the LEIR environment and commissioned. It has been used routinely for the LEIR ring commissioning with O^{4+} and Pb^{54+} ions where its role has been central in obtaining the Pb ion beam characteristics required for the first LHC ion run planned for 2009. First investigations on the cooling performance and ion beam lifetime clearly indicate of the usefulness of high-intensity electron beams with variable density distributions [7] but the expected gain in ion beam lifetime with hollow electron beams is not clearly observed. More systematic studies of the influence of the different variables on the cooling performance still need to be done making use of the recently upgraded diagnostic systems (IPM and spectrum analysers).

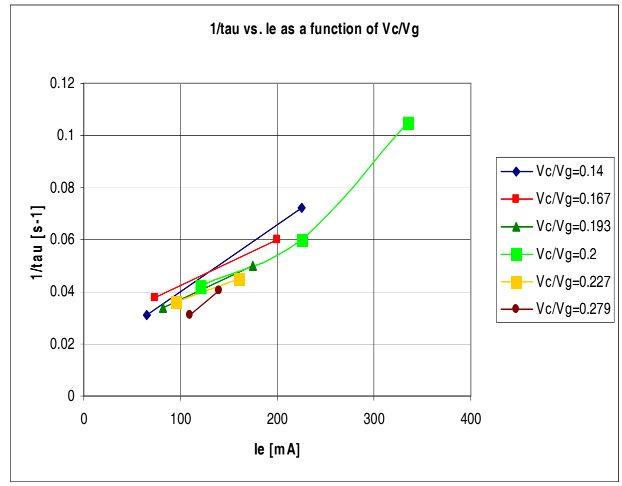

Figure 10: Inverse lifetime of Pb54+ ions as a function of electron current and density distribution.

REFERENCES

[1] C. Carli, "Commissioning and Performance of LEIR", These proceedings.
[2] E. Mahner, "The Vacuum System of the Low Energy Ion Ring at CERN: Requirements, Design and Challenges", CERN AT-2005-013.
[3] G. Tranquille, "Specification of a new Electron Cooler for the Low Energy ion Ring, LEIR", Proceedings of COOL03, Yamanashi, Japan, 2003.
[4] J. Tan and G. Tranquille, "Beam Diagnostics with Schottky Noise in LEIR", EPAC'06, Edinburgh, June 2006, p. 1214.
[5] C. Bal, V. Prieto, R. Sautier, G. Tranquille, "First Results from the LEIR Ionisation Profile Monitors", To be published in the DIPAC07 proceedings.
[6] J. Bosser, C. Carli, M. Chanel, R. Maccaferri, D. Mohl, G. Molinari, S. Maury, G. Tranquille , "The Production of Dense Lead-ion Beams for the CERN LHC", Proceedings of ECOOL99, Uppsala, Sweden, 1999, and CERN/PS 99-042 (BD).
[7] V. Parkhomchuk, "Comparison of Hollow Electron Device and Electron Heating", These proceedings.