ELECTRON COOLING EXPERIMENTS AT LEIR

G. Tranquille, CERN, Geneva, Switzerland

Abstract

The LEIR electron cooler is the first of a new generation of coolers utilising high-perveance variable-density electron beams for the cooling and accumulation of heavy ion beams. It was commissioned at the end of 2005 and has since been routinely used to provide high brightness Pb ion beams required for future LHC ion runs. High perveance, or intensity, is required to rapidly reduce the phase-space dimensions of a newly injected "hot" beam whilst the variable density helps to efficiently cool particles with large betatron oscillations and at the same time improve the lifetime of the cooled stack. In this report we present the results of recent measurements made to check and to better understand the influence of the electron beam size, intensity and density profile 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 through multi-turn injection, cooling and accumulation [1]. 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.

The cooling time is influenced by a number of machine and cooler parameters [2]. The electron current, I_e, and the relative angle difference between the ions and the electrons, θ, are two parameters that are easily accessible for experiments. The new electron gun also opens up the possibility to investigate the influence of the electron beam size and density profile on the cooling process.

ELECTRON GUN PERFORMANCE

The high perveance gun provides an intense electron beam in order to reduce the cooling time. However, with the higher electron density an increase of the recombination rate (capture by the ion of an electron from the cooler) and the electron azimuthal drift velocity is observed. Increased recombination is detrimental to the ion beam lifetime and the larger drift velocity will lengthen 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 1 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 ($V_{cont} = V_{grid}$). The maximum design current is 600 mA but for the normal operation of the cooler only 200 mA are used.

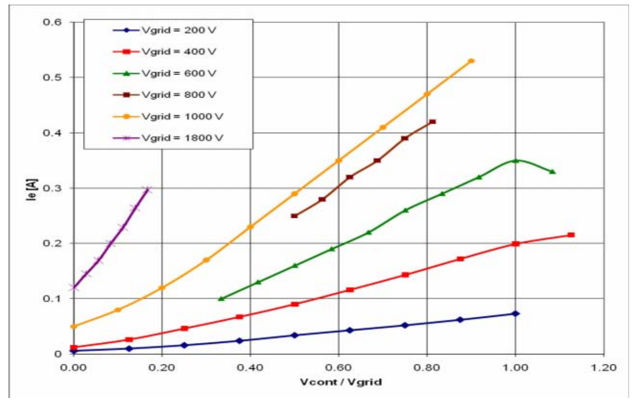

Figure 1: Electron beam current as a function of the ratio V_{cont}/V_{grid} , for an electron beam energy $E_e = 2.3$ keV.

EXPERIMENTAL SETUP

The cooling of ion beams was studied in parallel with the commissioning of the ions for LHC injector chain [3]. As it was difficult to obtain long cycles dedicated to electron cooling studies, most of our measurements were performed on the standard magnetic cycle lasting 2.4 or 3.6 seconds during which 2 to 5 Linac pulses are cooled and stacked at 4.2 MeV/u. Schottky diagnostics, ionisation profile monitors (IPM) and the beam current transformer (BCT) were used to measure the phase-space cooling characteristics and to investigate the ion beam lifetime. The electron beam position was also measured during our measurements to ensure that the two beams were always correctly aligned [4].

COOLING EXPERIMENTS

The short duration of the injection plateau imposed that we used the momentum spread and the transverse beam size after 400 ms as the parameters to characterise the cooling performance. LEIR uses a multi-turn injection in all three planes and the injected beam has a transverse emittance of about 2.5 μm and a momentum spread of $4x10^{-3}$. After cooling, the beam emittance is reduced by a factor of 10 and the longitudinal momentum is a few 10^{-4}.

Influence of Beam Expansion

The beam size can be varied by applying a stronger longitudinal field in the gun region. A maximum expansion factor, k, of 3 is available thus making it possible to vary the electron beam radius up to 24 mm. Figure 2 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) whilst varying k from 0.86 (r = 13 mm) to 2.57 (r = 22.4 mm).

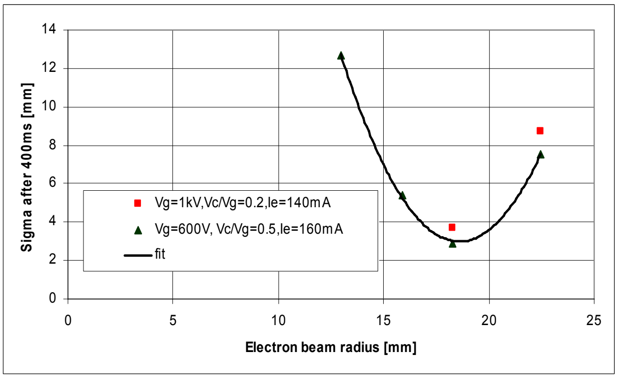

Figure 2: Beam size 400 ms after first injection as a function of the electron beam radius.

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 when the electron beam radius was greater than 20 mm. Subsequent injections were cooled to dimensions almost twice smaller than on the first injection.

Influence of the Electron Intensity and Density

As explained earlier, the electron beam intensity and density distribution can be varied by applying voltages to the grid and control electrodes. Roughly speaking, the grid determines the intensity whilst the control electrode changes the density distribution by enhancing the emission from the edge of the cathode.

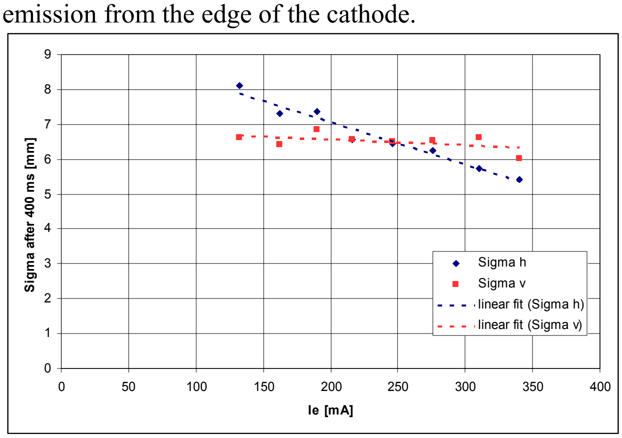

Figure 3: Ion beam size as a function of the electron cooler current (V_{grid} = 1.1 kV, k = 2.57, r = 22.4 mm).

A first set of measurements were made to confirm that the increase in electron current did improve the cooling efficiency. This is shown in figure 3 where the ion beam size is plotted as a function of the electron current with a fixed grid voltage of 1.1 kV. The decrease in the beam size as the current is increased is a clear sign of better cooling even though the effect was less pronounced in the vertical plane.

With the grid voltage fixed we were able to explore the influence of the electron beam distribution on the cooling performance by simply increasing the control voltage. Figure 4 shows the result of one set of measurements where the grid voltage was held at 600 V and the control voltage was increased to 85% of the grid value. The beam size decreases as expected as the current is increased, but as the beam distribution becomes hollower the increase in electron current is no longer beneficial and the cooling is less efficient.

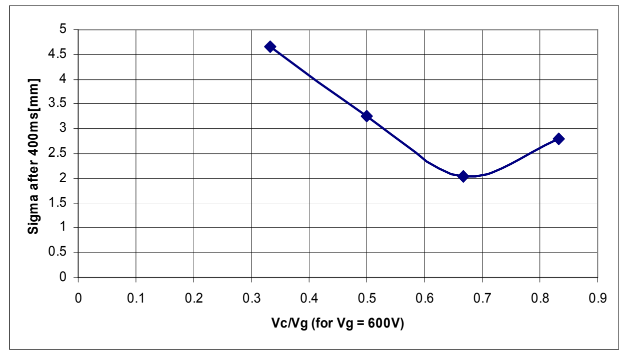

Figure 4: Beam size after 400 ms as a function of the electron beam distribution for a constant value of 600 V on the grid electrode (k=1.7, r=18 mm).

To further understand the influence of the density distribution, measurements were made where the electron current was kept constant and the density distribution modified. The results (see Fig. 5) clearly show that the determining parameter for obtaining small beam sizes is the electron current and not the density distribution.

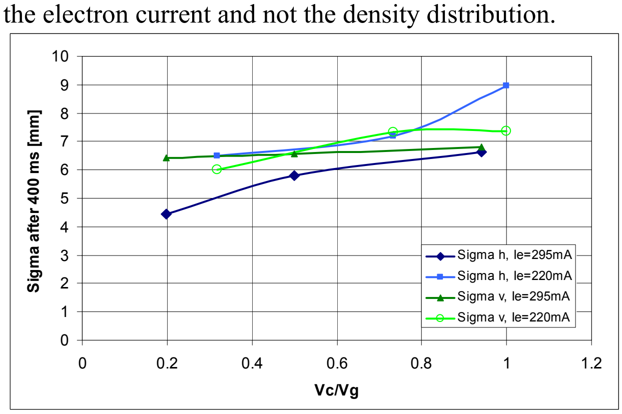

Figure 5: Ion beam size as a function of the density distribution for a constant electron current (k = 2.57, r = 22.4 mm).

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 show the usual decreasing momentum spread as the electron current is increased.

The influence of the density distribution of the electron beam on the longitudinal cooling was also investigated. The Schottky spectrum was recorded during the cooling/stacking process for three electron density distributions. One sees from the plots below that the best cooling is obtained with a uniform electron beam density. As the electron beam becomes hollow the cooling time increases and fewer particles are dragged into the stack.

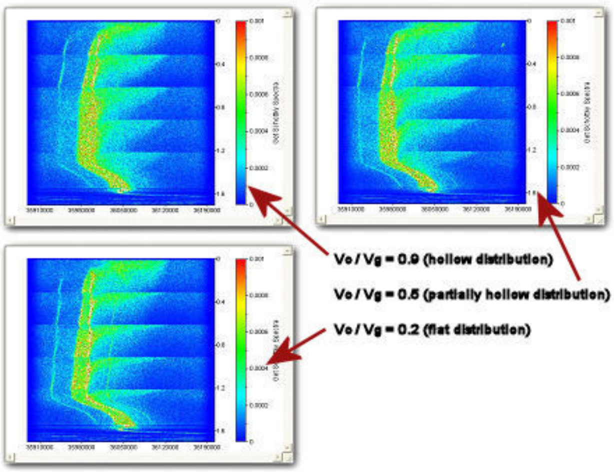

Figure 6: Evolution of the momentum spread during the cooling/stacking process with a constant electron current of 295 mA. The density distribution is changed from a flat distribution (V_{cont}/V_{grid} = 0.2) to a completely hollow one (V_{cont}/V_{grid} = 0.9).

LIFETIME STUDIES

In previous tests 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.

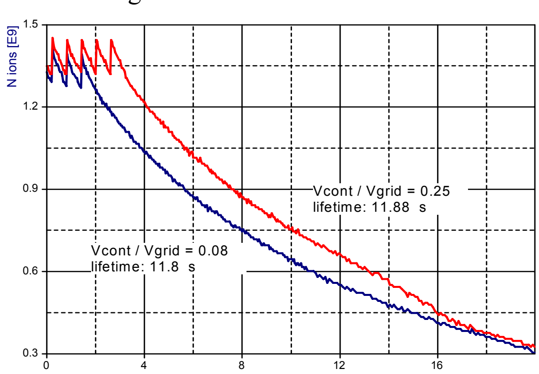

Figure 7: Beam lifetime for a parabolic (blue) and a slightly hollow (red) electron beam distribution.

In our measurements intensities well above $1.2x10^9$ ions could easily be accumulated with an injection repetition rate of 1.6 Hz. If the repetition rate is increased, the maximum number of stacked ions decreases proportionally.

The lifetime of the cooled ion beam was measured by recording the evolution of the BCT signal as a function of time. Comparing for a parabolic and a hollow electron beam distribution (Figure 7), we see that this parameter 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 [1]. Other processes related to the vacuum conditions or the injection scheme could be more dominant.

A compilation of all our lifetime measurements for different intensities and density distributions is shown in figure 8. The slope of the curves gives the lifetime due to the electron beam whilst the intersection with the y-axis gives the vacuum lifetime. Compared with measurements made in 1997, a gain by a factor of 2 in the vacuum lifetime is observed but the lifetime due to the electron beam is only slightly improved and is not influenced by the electron beam distribution.

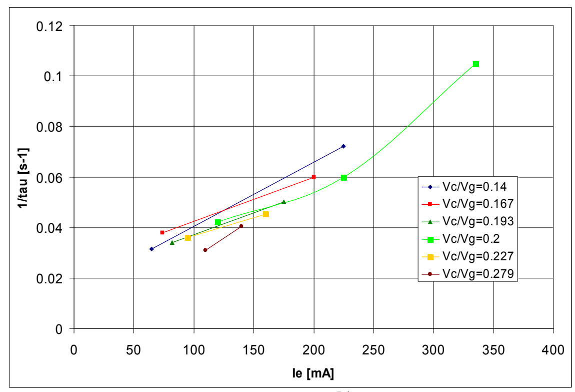

Figure 8: Inverse lifetime of Pb^{54+} ions as a function of electron current and density distribution.

CONCLUSION

Our experiments on LEIR have shown that the main parameter that enhances the cooling process is the electron beam current. Up to 600 mA of electron current can be obtained with the new gun, but the interplay between the electron beam size, density distribution and intensity is such that the best cooling is obtained with an electron beam having; approximately the same size as the injected ion beam, a flat density distribution and an intensity less than 300 mA. It is clear that systematic measurements need to be continued and dedicated machine time is needed to explore the full potential of the new device.

REFERENCES

[1] J. Bosser et al, "The Production of Dense Lead ion Beams for the CERN LHC", NIM Phys. Res., A 441(2000) 60-3.

[2] G. Tranquille, "Optimum Parameters for Electron Cooling", COOL01, Bad Honnef, May 2001.

[3] D. Manglunki et al, "Ions for LHC: Status of the Injector Chain", APAC'07, Indore, January 2007.

[4] G. Tranquille et al, "Cooled Beam Diagnostics on LEIR", this conference.