COMMISSIONING OF THE LEIR ELECTRON COOLER WITH Pb^{+54} IONS

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Abstract

The new LEIR cooler with a variable profile of the electron beam and electrostatic bending was commissioned in 2005-2006. In this paper we present our experience with the commissioning of the new device as well as the first results of the ion beam Pb^{+54} cooling with a high-intensity variable-density electron beam.

BASIC FEATURES OF THE COOLER

Variable Profile of Electron Beam

The electron gun with a control electrode was designed to produce the electron beams with variable profiles [1]. The gun is immersed into the 700-1000 Gs longitudinal magnetic field. The convex oxide cathode of Ø29 mm is used. The control electrode is situated near the cathode edge, so its potential strongly affects the emission from this area. By varying the potential of this electrode it is possible to obtain the beam with the parabolic, flat or hollow profile on the gun output as shown in Fig. 1

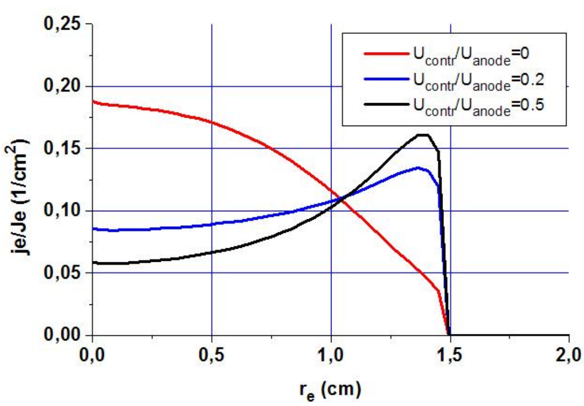

Figure 1: The profile of electron beam for different setting of the electrode voltage.

Electrostatic Bending

Convergence of the electron and ion beams at the cooling section entrance as well as electron beam passage into collector are based on the balance of radial forces inside every toroidal bending:

$$F = \frac{\gamma\beta^2 m_e c^2}{R} + \frac{qB_Z \cdot V}{c} + qE_R = 0\,, \quad (1)$$

where R – radius of electron orbit, E_R – electric field, B_Z – transverse to orbit magnet field and V – electron velocity in a strong longitudinal (azimuth) magnet field. Moreover, the integral condition $\int Fds=0$ over cooler length may be used instead of condition (1) if the energy of the electron beam is not too high.

The collector efficiency is defined as a ratio of surface-reflected current to the main beam current. The efficiency increases with beam current by the space charge cutoff of the low-energy reflected electrons. The suppressor electrode voltage can change the efficiency of our collector in range interval ~10^{-3} -10^{-4} [2].

Usually pure magnet bending(E_R=0) was used for the electron coolers. In this case electron trajectory depends on its velocity direction, and so the centrifugal drift only of the main beam electrons is compensated. The collector surface-reflected electrons receive a double centrifugal drift shift backwards B_Z on their pass from the collector to the gun. As a result, the reflected electrons can escape out the collector aperture. The suppresser is main toll for suppressing losses in this case. In measurements the relative losses decrease from 2×10^{-3} down to 8×10^{-5} with the change of suppresser voltage U_{sup} from 1.25kV to –0.7kV. At voltage less then –0.7kV the outer layer of the primary beam (tails of beam) reflects from collector entry and losses increases very sharp. The collector voltage was equal to 1.25kV, the electron energy was 5keV.

Advantage of the pure electrostatic bending (B_Z =0) is independent compensation of centrifugal drift for both velocity directions. As a result, the collector surface-reflected electrons return into collector after collector-gun-collector oscillation. Such a reuse of collector strongly decreases relative losses, which arise only from drift due to energy spread of electrons. The level of relative losses ~$5\cdot10^{-7}$-$10^{-6}$is achieved at U_{sup}~0.2-0.5kV. As a result, a possibility for operation at lower collector voltage appears.

Magnet System Design

The magnet system consists of tree independently powered coils: the electron gun and collector, toroids (bending part) and drift (cooling) sections. The independent control of the value of magnet fields values at gun H_c and drift section H_d change the electron beam size at cooling section as $a_c(H_c/H_d)^{1/2}$ that opens the way for new opportunities for optimization of the ion beam accumulation. The transverse component $B_\perp$ must be kept very small so that the ratio $B_\perp/B$ should never exceed 10^{-4} all along the cooling section. To achieve this field quality, careful adjustment of the “pancake” structure of the solenoids was made before final installation in the LEIR ring. The angular position of each “pancake” section was mechanically adjusted after magnet field line measuring.

LIFE TIME MEASURING

The idea for the design of a variable profile electron beam was invented for suppression of the so-called "electron heating" discovered at CELSIUS ring experiments [3]. The interpretation of a poor life time for intensive ion beam as result of electron ion plasma oscillations pushed for decreasing electron beam density at the center of electron beam [4]. The first experiments for comparison of cooling with two different electron beam profiles are made with the accumulation of ion beam. For both settings (U_{contr}=0, U_{anode}=1800 V, U_{contr}=200 V, U_{anode}=900 V) the electron beam current was near 0.1 A but accumulated intensity of the ion beam increased from 0.7×10^9 up to 1.3×10^9 as shown in Fig. 2a and 2b. The main reason of increasing the ion beam current is clearly seen in figures as improved the life time from 6 sec to 12 sec. after stop of injection.

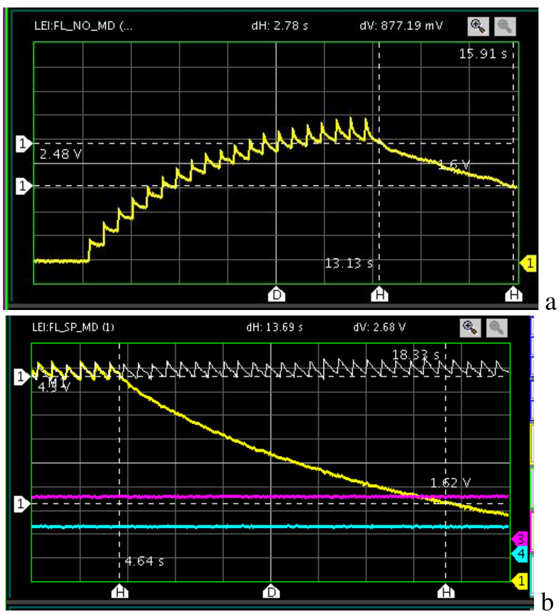

Figure 2: a- the ion beam accumulation for maximum density at center, b- the minimum density at center. The lifetime after stop of injection was 6.3 s for "a". For "b" life time is 13.8 s.

The comparison of Fig. 2a and Fig. 2b shows that the strongest decreasing took place for the initial life time just after injection. For the first profile of electron beam there is a very fast initial decay of the ion beam current between new injections. There are the basic problems for "electron heating". Decreasing decay rate for the electron beam profile with lower density at center are good evidence to prove the idea of hollow beam cooling.

THE PROFILE MONITOR RESULTS

Almost all our measurements were performed with the standard magnetic cycle lasting 2.4 or 3.6 seconds during which 2 or 3 Linac pulses are cooled and stacked at 4.2 MeV/u, then accelerated to 72 MeV/u before being extracted to the PS ring. The results presented in this section are therefore not direct measurements of the cooling time constant but rather an indication of the capabilities of the new cooler. Systematic measurements of the cooling time will be made during the next commissioning period planned for the end of the year.

Fig. 3 shows the typical magnet cycle and ion beam intensity (number of ions) for our measurement.

Figure 3: The standard magnet cycle of acceleration of ion beam: magneto line is the magnet field value, green line is the anode voltage for the control of the electron beam current, yellow line is the number of ions at beam.

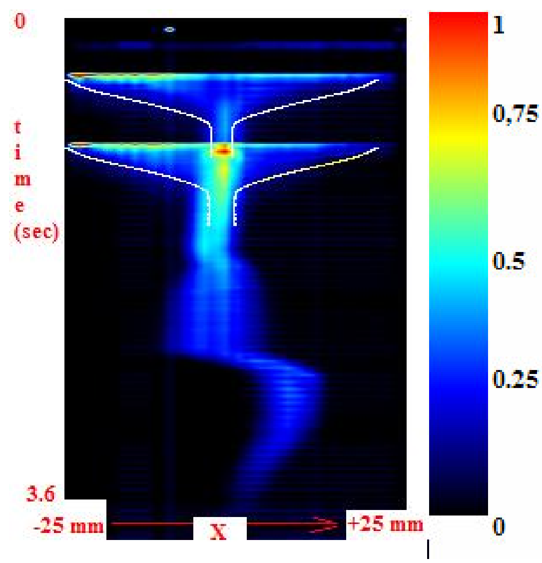

Figure 4: The change of the ion beam profile in LEIR cycle. Its initial moment shows the 2 injections and cooling, then acceleration from 5 MeV/u to 71 MeV/u. White colour lines show simulation made with "trubs.exe" code with the initial ion amplitude 25 mm.

The white lines on Fig. 4 show the simulation of the cooling Pb+54 ions with initial current of 1 mA and 2 mA (second injection) based on model with cooling force described in [4]. As easy seen the calculation results of the ion beam size are rather close to these measuring profile data.

Fig. 5 shows that the cooling time is about 0.25 s and after switching off the electron beam, the emittance blows up from 0.1 up to 0.35 mm*mrad*π (2-2.2 sec) by IBS action. At time of acceleration emittance stays constant near 0.35 *mm*mrad*π inside accuracy of measuring.

The results of measuring cooling for different expansion factor are shown in the Fig. 6 as a function of equilibrium emittance of the ion beam (r.m.s. normalized) versus the electron beam radius.

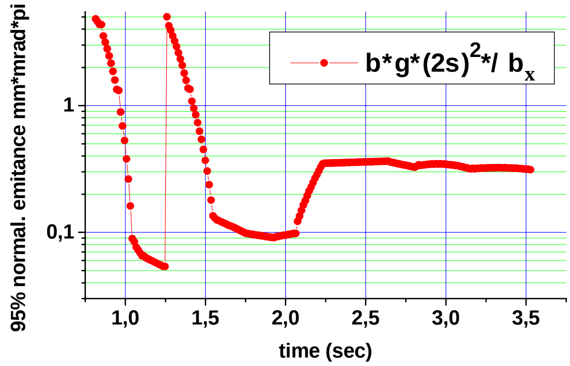

Figure 5: The normalized emittance (95%) variation versus time inside the magnet cycle.

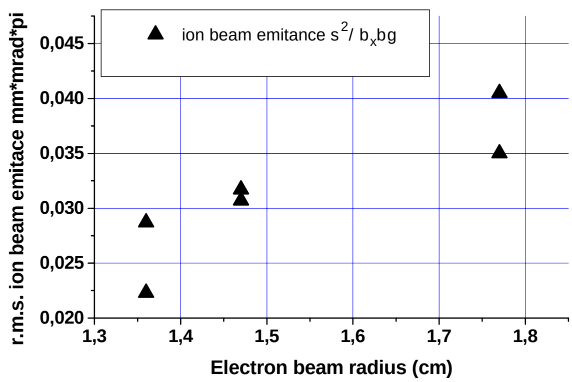

Figure 6: The equilibrium r.m.s. emittance versus the electron beam radius at drift section. The electron beam 0.1 A, Ucontr=200 V Uanode=900 V.

The results show that at equilibrium, the ion beam radius r.m.s. is near 0.11-0.12 fraction of value of the electron beam radius. The number of ions in a beam was $N_i=2.5*10^8$ and value of Lasllet tune shift calculated for figure 6 changed with the electron beam shrinking from $\Delta Q=0.1$ to $\Delta Q=0.14$. This experiment was made by decreasing the current at the electron gun solenoid from 360 A to 120 A that corresponds to change of the electron beam radius at cooling section from 1.78 cm to 1.36 cm . When electron beam radius was 1.36 cm, it was found an interesting phenomenon that the first injection was cooled slower than the second one. The reason of this may be the intensive energy (temperature) exchange between hot ions (new injection) and ions cooled after first injection. For the accumulation processes, this phenomena can be very useful and it will need careful study both a theoretically and experimentally. As it is clear seen from Fig. 7, the small electron beam radius leads to faster cooling the ion beam after second injection when intensity of ion beam is higher and exist exchange energy between hot (new injected) and cooled ion beam from previous injection.

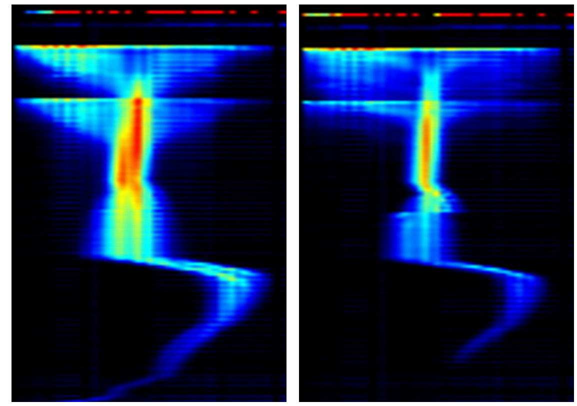

Figure 7: Comparison of cooling with different electron beam radii 1.78 cm and 1.37 cm. The cooling for the second injection is faster when the cooled ion beam from first injection presents.

CONCLUSIONS

The new electron cooler for LEIR has been integrated in the LEIR environment and successfully 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 2008. Clear indications of the usefulness of high-intensity electron beams with variable density distributions for effective beam cooling have been observed, but a more systematic study of the influence of the different variables on the cooling performance still needs to be done.

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