

# COMPARISON OF THE HOLLOW ELECTRON BEAM DEVICES AND ELECTRON HEATING

V. Parkhomchuk, BINP, Novosibirsk, Russia

## Abstract

In the previous two years after COOL05 a new generation of low energy electron coolers with variable electron beam profile was successfully commissioned with  $Pb^{+54}$  ion beams at CERN LEIR and at IMP (China, Lanzhou) CSRm with  $C^{+6}$ . A hollow electron beam profile with low electron beam density at the center helps to suppress recombination at the accumulation zone and to increase the lifetime of the ion beam. First experiments with a vertically offset electron beam (with aim to control overcooling the storage stack of ion beam) were made at the RECYCLER high energy electron cooler (FNAL) with very different conditions for accumulation and cooling antiprotons. In this paper the parameters of these different experiments with electron cooling are discussed in the frame of a model of electron heating. The aim is to integrate the experience of using the hollow electron beam cooling, test model and to find recommendations for the next generation electron coolers for the FAIR p.

## ELECTRON COOLING AND HEATING

Cooling manifests itself in damping single particle oscillations and coherent oscillations of ion beams. The presence of the electrons in the cooling section and high phase space density of the ion beam after cooling can be sources of the development of instabilities and beam losses [1]. These problems were the subjects of discussions of many reports [2,3] but their final understanding is still far in future. Modulation of the electron beam energy helps to increase the threshold current of the ions [4]. The square-wave modulation of the electron beam energy decreases the cooling rate for the central (equilibrium) energy but helps cooling of the tail energy ions. Control of the transverses ion beam profile after cooling was not so easy because of a very fast increase of the cooling power for small amplitude radial oscillations of the ions.

In order to avoid overcooling in the transverse direction a so called "painted" electron beam position has been proposed. A fast manipulation of the transverse positions and angle of the electron beam in a high energy cooler so that tails cooled more intensively was discussed for the projected cooler for RHIC [5]. At high voltage the cooling time is about a few hours and fast manipulation of the electron beam energy and of the transverse positions can be made relatively easily. But for the low energy coolers with cooling times of a few milliseconds the electron gun with a special control electrode was designed to produce electron beams with variable profiles [6]. In this electron gun the control electrode voltage can

produce a practically hollow electron beam in a steady mode. In the moment of passing the cooling section the ions with not have an equilibrium energy but move in the rest electron gas. By the action of the friction force they lose momentum as:

$$\delta p = - \frac{4\pi e^4 Z^2 n_e \ln\left(\frac{\rho_{\max}}{\rho_{\min}}\right) \tau}{m M V^3} p = -\lambda \times p, \quad (1)$$

where  $e$  is the electron charge,  $Z$  is the ion charge in units  $e$ ,  $n_e$  is the electron beam density,  $m$  and  $M$  are the electron and ion masses, respectively,  $\tau$  is the time of flight through the cooling section in the reference frame of the beam system,  $r_{\max}$ ,  $r_{\min}$  are the maximum and minimal impact distances, and  $\lambda$  is the single pass cooling decrement. There is normal cooling interaction, but the neighbouring ions inside distance  $r_{\max}$  obtain almost the same momentum kick  $\delta p$  and a slight increase of the kinetic energy in the ion beam (these ions do not have a correlation  $\delta p V$  and the term  $\langle \delta p * V \rangle = 0$  is equal to 0):

$$\delta E_{ion} = -\delta p V + \frac{\delta p^2}{2M} n_i \frac{4\pi}{3} \rho_{\max}^3 = \quad (2)$$

$$(-2\lambda + \lambda^2 \times N^*) E_{ion} = -2\lambda (1 - \omega_e^2 \omega_i^2 \tau^4 g) E_{ion}$$

where  $\omega_e$ ,  $\omega_i$  are the plasma frequencies of the electron and ion beams,  $N^*$  is the number of neighbouring ions inside the distance  $r_{\max}$ ,  $g$  is a numerical factor close to unity which can be calculated more carefully by numerical integration in the interaction zone of the ion. The meaning of this equation is that the single pass cooling decrement should be limited by the number of ions in the interaction zone  $1 < 2/N^*$ . Practically there exists a limit of the product of electron and ion beam densities [7]:

$$n_i \times n_e \leq \frac{6}{r_e r_i (c\tau)^4 * g (4\pi)^2 \ln(\rho_{\max} / \rho_{\min})}. \quad (3)$$

Decreasing the electron beam density at the center of the storage zone opens additional space for the accumulation of a more intense ion beam.

## FNAL COOLER EXPERIMENTS

In september 2005 cooling experiments have been performed with the RECYCLER cooler with a vertical offset of the electron beam. Initially the electron beam was shifted by 9 mm and then moved step by step inside the antiproton beam as demonstrated in fig.1. Straight lines along the longitudinal emittance data were used for the calculation of the longitudinal cooling time which changed from 40 hours for 9 mm offset to 2 hours for 1.5 mm offset. The experience of using electron cooling in

the RECYCLER shows the too strong overcooling of the antiproton beam that leads to a degradation of the lifetime and to a fast loss of antiprotons. With offset cooling it was possible to cool the tail of the beam without overcooling the centre zone of the beam. On 4 oct. 2005 the RECYCLER operators had achieved a record number of antiprotons and a world record of initial luminosity of the hadron collider TEVATRON:  $1.413 \times 10^{32} (1/cm^2 \cdot sec)$  with using a vertical offset of the electron beam. It was complicated gymnastics with the vertical position of the electron beam so that the lifetime was high but the antiproton beam was cooled before injection into the TEVATRON.

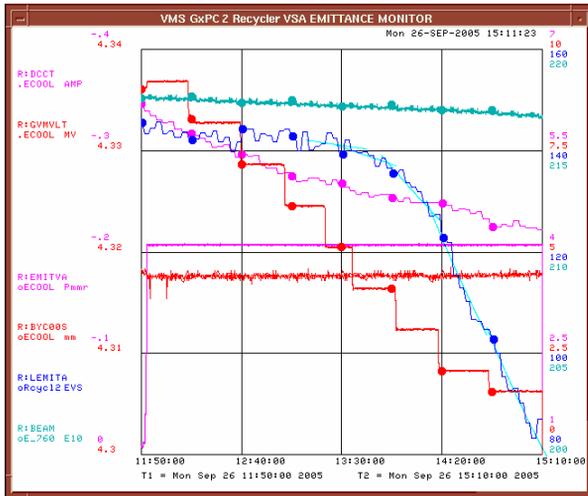


Figure 1: The RECYCLER cooling with vertical offset of the electron beam: red line: position of electron beam - 9,8,7,6,5,4,3,2,1.5 mm, blue line: cooling of longitudinal emittance (80-160 eV\*s scale).

These were the first experiments with using the technique of “painting” in the transverse direction for the distribution of the electron beam cooling power.

### LEIR EXPERIMENTS AT CERN

Experiments with comparison of cooling with two different settings of the voltage in the electron gun are done for the accumulation of an ion beam of Pb<sup>+54</sup> for ( $U_{contr}=0, U_{anode}=1800$  V, parabolic shape of the electron beam with maximum at center) and ( $U_{contr}=200$  V,  $U_{anode}=900$  V slightly hollow electron beam with 20% decrease of the density at the center of the electron beam). For both settings the electron beam current was close to 0.1 A but the accumulated ion beam current increased from  $0.7 \times 10^9$  up to  $1.3 \times 10^9$  Pb ions as is shown in figs. 2a and 2b. The main reason of this increase of the ion beam current is clearly seen in the figures as an improved lifetime from 6 sec to 12 sec. after end of injection.

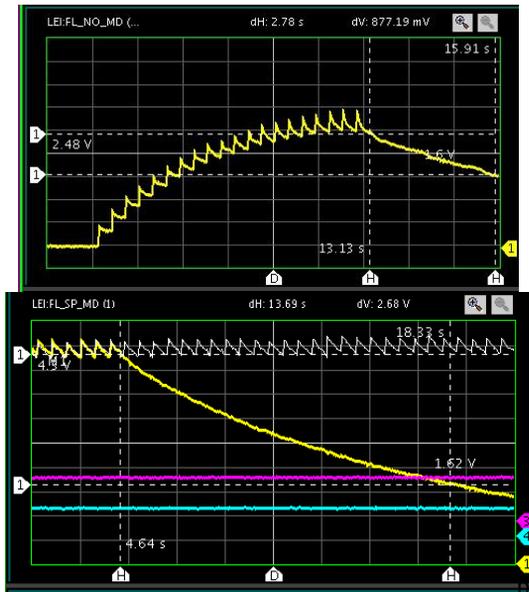


Figure 2 (a,b): Ion beam accumulation at maximum density at center (a), and minimum density at the center (b).

The lifetime after end of injection is 6.3 s for an “a” profile of the electron beam and with initial decay at several times faster (1-2 sec). For a “b” shape profile the lifetime is 13.8 s and without fast losses just after injection. There are basic problems of “electron heating” and decreasing the decay rate for the electron beam profile with lower density at the center which support this plasma oscillations model. For these first experiments, the lifetime in the LEIR ring varies by no evident reasons and in the next experiments, this phenomenon should be studied more carefully.

Almost all our measurements were performed with the standard magnetic cycle lasting 3.6 seconds during which 2 linac pulses are cooled and stacked at 4.2 MeV/u, then accelerated to 72 MeV/u before being extracted to the PS ring. Fig. 3 shows the typical magnet cycle used for our measure of the number of ions in the beam.

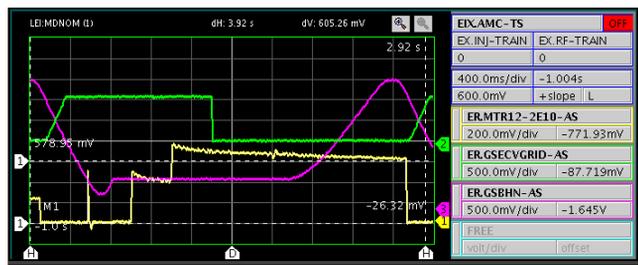


Figure 3: The standard magnet cycle of acceleration: magenta line: magnet field value (3), green line: anode voltage for the control of the electron beam current (2), yellow line: number of ion (1) at beam.

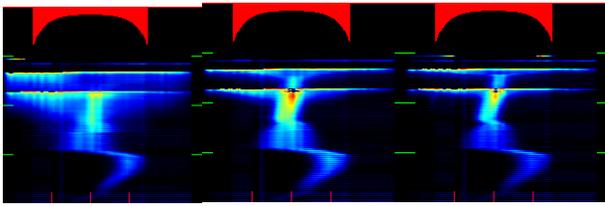


Figure 4: Cooling with the same profile but different electron beam current  $U_{anode}(V)=300,600,900$ ,  $U_{contr}(V)=150,300,450$ ,  $J_e(mA)=60,110,260$ , emittance (mm\*mrad)=0.15,0.05,0.03, cooling time (s)= 0.5, 0.08, 0.05. Red color shows the profile of the electron beam.

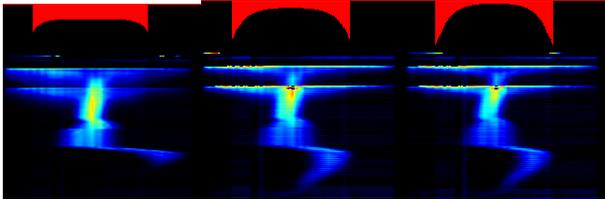


Figure 5: Cooling with different profiles,  $U_{anode}(V)=1000,600,500$ ,  $U_{contr}(V)=200,300,600$   $J_e(mA)=140,160,280$ ,  $e$  (mm\*mrad)= 0.07, 0.07, 0.07,  $t_{cooling}(s)=0.3,0.1,0.07$ .

Figs. 4 and 5 show signals of the ion beam profile monitor measured for different shapes of the electron beam profile. From fig.5c is clearly seen that a hollow electron beam cools very effectively ions with high amplitude (up to 2.5 cm) and without large increase of the equilibrium emittance. Fig.6 shows that the cooling time is about 0.2 s and after switch off the electron beam, the emittance blows up from 0.1 to 0.35 mm\*mrad\* $\pi$  (2-2.2 sec) by the action IBS.

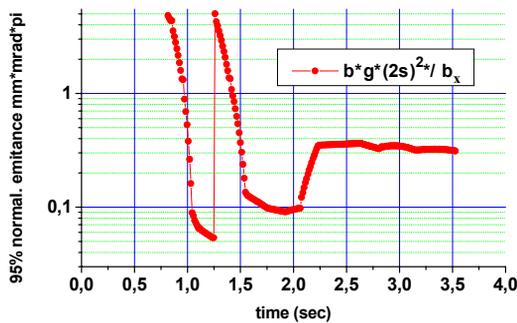


Figure 6: Variation of the normalized emittance (95%) variation vs. time inside the magnet cycle. (ooling current 0.1 A)

At time of acceleration the normalized emittance stays constant close to 0.35 \*mm\*mrad\* $\pi$  within measuring accuracy.

### CSR (IMP) EXPERIMENTS

A first demonstration of successful electron cooling and accumulation of an  $C^{+6}$  ion beam was made in July 2006. At the beginning of 2007 a systematic study of the

accumulation and acceleration at high energy and with different ion beam was started. Let us discuss just some experiments with electron cooling with a hollow electron beam. From fig.7 we can clearly see that the optimum of accumulation and acceleration is near  $U_{contr}/U_{grid}=0.4$  when the ratio of the electron beam density at the center to the average density is near 0.5. This acceleration was made after accumulation with electron cooling and with 10 injections.

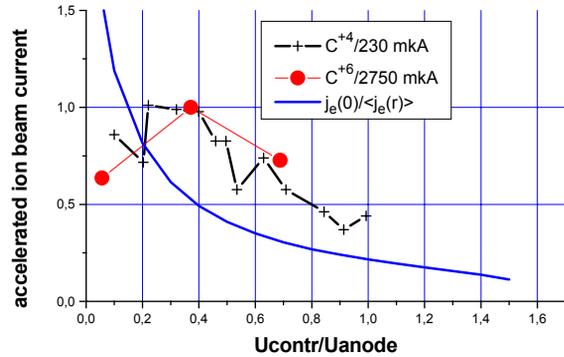


Figure 7: Maximum ion beam currents for ions  $C^{+4}, C^{+6}$  accelerated at CSRm vs. the ratio of grid anode voltage which change of the shape of the electron beam profile. Blue line: ratio of the electron beam density at the center to the average density (for a flat beam  $j(0)/\langle j(r) \rangle = g_e = 1$ ).

An experiment with accumulation of maximal  $C^{+6}$  is shown in fig. 8. For fitting the data is used a model with two components. The cooled ion beam has a decay time of 10 sec but some part of the newly injected ions have decay times of just 0.2 sec. This fast decay fraction increases with accumulating more current and for an 600 $\mu$ A ion beam current almost all newly injected beam was lost. After this further accumulation is stopped- all newly injected ions are lost.

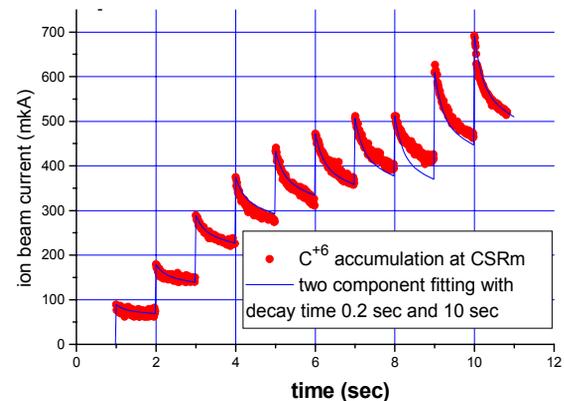


Figure 8: Example of accumulation at CSRm:  $C^{+6}$  ion beam with fitting to the two component model.

Increasing the ratio  $U_{contr}/U_{anode}= 0.217kV /0.586kV$  demonstrates accumulation up to 1500 $\mu$ A. After stop of injection the initial lifetime was very short but

after decay of the ion beam to a current of less than 600 $\mu$ A the lifetime became very long  $\sim$ 400 sec. This high lifetime (400s) means that the fast loss is generated by space charge fluctuations in the accumulated intensive ion beam. The diffusion by this space charge noise of the plasma oscillations at the core of the ion beam killed all newly injected ions with high amplitudes that have weak cooling.

### LIFETIME WITH ELECTRON COOLING

The presence of plasma oscillations can be demonstrated by the variation of the lifetime with different electron coolers. Fig. 9 shows the lifetimes in different rings with electron cooler in units of number of turns vs. the parameter which characterises the interactions of the ions with the electrons:  $\delta = \omega_e^2 \omega_i^2 \tau^4$ . The data in for the coolers are listed at table.1.

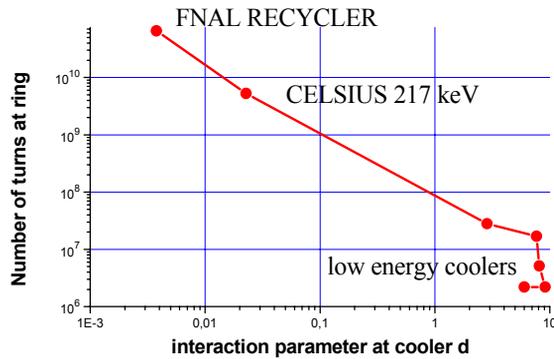


Figure 9: Ion lifetime vs. the parameter  $\delta$  for the different coolers.

Table 1: Parameters of different coolers

ring	$E_e$ keV	$J_e$ mA	$a_e$ cm(g)	Ion	$J_i$ mA	$a_i$ mm	$\Delta Q_L$	$\tau$	$\delta$
SIS	6.5	400	2.2(1)	Kr <sup>+34</sup>	5	4.5	0.12	62	6
LEIR	2.5	100	2.12(2)	Pb <sup>+54</sup>	2.5	2	0.12	67	9
LEIR	2.5	100	2.12(0.5)	Pb <sup>+54</sup>	5	3	0.11	67	8
CSRm	3.8	100	2.12(0.4)	C <sup>+6</sup>	1.5	5	0.05	100	7.6
CELSIUS	6	60	1(1)	He <sup>+2</sup>	0.5	1	0.05	43	2.8
CELSIUS	217	600	1(1)	p <sup>+1</sup>	6	0.7	0.01	6	0.023
RECYCLER	4300	200	0.3(1)	$\bar{p}^{-1}$	32	2.5	0.008	7	0.003

The effect of electron heating is very similar to so called beam-beam effects in colliders. Usually the lifetime of luminosity decreases with the beam-beam tune shift  $\Delta Q_{bb}$  as  $N_{turns} \sim 1/(\Delta Q_{bb})^3$  [9]. The relation between tune shift for a symmetric collider and  $\delta$  is determined as:  $\delta = \omega_e^2 \omega_i^2 \tau^4 = (4\pi \Delta Q_{bb} l_b / \beta^*)^2$ . From fig. 9 we can see the fast decrease of the lifetime under electron cooling for high values of the space charge parameter  $\delta$ . For next generation storage rings (e.g. HESR) will be used electron cooler systems with long coolers and high intensity electron beams. The proper distribution of the

the electron beam profile can help to optimise the luminosity and the ion beam lifetime.

### CONCLUSION

First successful cooling experiments with using hollow electron beams demonstrated the high potential of these coolers with variable profiles of the electron beam. Effects from the nonlinear electric field that were discussed as source of problems for hollow electron beams [10] were not detected. Parameters of ion beams after cooling obtained at LEIR and CSRm are close to the proposed ones. The technique of hollow electron beam cooling has a high potential for optimization. It will be interesting to test this cooling in experiments with internal targets.

### REFERENCES

- [1] D. Reistad, L.Hermansson, T. Bergmark, O. Johanson, A.Simonsson, A.V. Burov, "Measurements of electron cooling and electron heating at CELSIUS", Proceedings of the Workshop on Beam Cooling and Related Topics, Montreux, Switzerland, 4-8 October 1993, CERN 94-03, p.183.
- [2] V.V. Parkhomchuk, A.N. Skrinsky, "Electron cooling: 35 years of development", Physics-Uspehi 43,(5) 433-452 (2000)
- [3] V. V. Parkhomchuk, L. Hermansson, D. Reistad "Problems of Electron Cooling of High Brightness Ion Beams", IICFA Beam Dynamics Newsletters, No21, April 2000 pp.106-110.
- [4] L.Hermansson, D.Reistad, "Electron cooling at CELSIUS", NIM in Phys.Res. A 441(2000) 140-144.
- [5] Electron cooling for RHIC, BNL, C-A/AP 47 April 2001. "RHIC, 50 MeV cooling", [http://www.agsrhicome.bnl.gov/AP/ap\\_notes/ap\\_note\\_47.pdf](http://www.agsrhicome.bnl.gov/AP/ap_notes/ap_note_47.pdf)
- [6] A. Bublely, "The electron gun with variable beam profile for optimisation of electron cooling", EPAC02, <http://www.jacow.org/e02/PAPERS/WEPRIO49.PDF>
- [7] V.V. Parkhomchuk, Cool05, 18-23 Sept.2005, AIP conference proceedings, 821, p.249-258. [http://conferences.fnal.gov/cool05/Presentations/Thursday/R01\\_Parkhomchuk.pdf](http://conferences.fnal.gov/cool05/Presentations/Thursday/R01_Parkhomchuk.pdf)
- [8] L.R.Prost, "Status of high energy electron cooler in FNAL's RECYCLING ring". RUPAC06, <http://www.jacow.org/r06/PAPERS/WEB002.PDF>
- [9] P.M. Ivanov, I.A. Koop, "Luminosity and the beam beam effects", Third advanced ICFA beam dynamics workshop on beam-beam effects in circular colliders", 29 May- 3June 1989, Novosibirsk.
- [10] V.Ziemann, "Electron cooler driven transverse resonances". EPAC98. <http://www.jacow.org/e98/PAPERS/THP27F.PDF>