USING ELECTRON COOLING FOR OBTAINING ION BEAM WITH HIGH INTENSITY AND BRIGHTNESS

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Abstract

Electron cooling is used for damping both transverse and longitudinal oscillations of heavy particle. This effect is widely used in the existing and is being designed storage rings. This article describes the last experiments with electron cooling carried out on the cooler EC-300 produced by BINP. The ultimate sizes of the ion beam are discussed. The accumulated experience may be used for the project of electron cooler on 2 MeV (COSY) for obtaining high intensity proton beam with internal target. Using electron beam enables to have physics experiment with high quality of the ion beams at despite of the target interaction.

INTRODUCTION

One way to increase or keep constant by compensation scattering the luminosity in hadron storage ring is using electron cooling. In this method hadron and electron beams with equal velocity are brought together in an interaction section. Because of Coulomb interactions the hadrons transfer own thermal energy to the electron beam. In presence time the main goal of the electron cooling devices is operation at the injection energy with purpose to storage a maximum storage current. The main reason of such using the electron coolers is insufficient electron energy of the typical medium energy coolers device (30 kV). However, there is permanently desire of the electron technique for high energy [1-2] that can provide luminocity upgrade of the physics experiment. The electron cooler is considered as essential part for the PANDA experiment at the planned HESR storage ring for antiprotons at the new GSI facility [3-4]. The 2 MeV cooler for COSY storage ring is under construction now will be used with the internal target.

The operation with internal target imposes the requirement on the cooling rate. This value should be large enough for the suppression of the target effects that can be categorized into longitudinal (energy loss due to ionization) and transverse effects (due to Rutherford scattering on target nuclei). So, the cooling rate should be enough high. The HESR facility requires the cooling rate about a few sec [4].

The strong cooling can only be achieved by the so-called magnetized cooling requiring a strong longitudinal magnetic field ($B \geq 0.5$ T) that guides the electron beam along the entire interaction region. The requirements on the parallelism of the magnetic field are very strong ($B_r/B_z \leq 1\times10^{-5}$) and it is necessary for fast electron cooling.

The 4.34 MeV cooler is used for cooling antiproton beam at RECYCLER [5] and preparing the antiproton bunch for TEVATRON. Conclusion about efficiency the electron cooler made in [6]: "Without the Recycler and electron cooling, we estimate that the yearly integrated luminosity would be half of its current level". But FNAL project is not focused to achieve the considerably higher cooling rates with magnetized cooling. The system electron cooling for experiments with inner target need few order magnitude faster cooling-instead hour cooling time it should be few seconds.

New generation of the electron coolers designed and produced at BINP has made with classical scheme and has purposed to obtain the maximum friction force. The coolers were commissioned with ion beams during last years at storage rings CSRm, LEIR and CSRe. These coolers have a few specifics features:

a. The electron guns of these coolers have possibility for the easy variation of the electron beam profile from the parabolic shape with maximum at center to the hollow electron beam with deep minimum at the center of the beam. Such type of profile can be used for optimizations of accumulation, when accumulated beam interacts with low density electron beam. As results we can control the recombination rate and prevent the overcooling storage ion beam.

b. For bending electron beam at toroid the electrostatic field is used. This bending doesn't depend from the direction of the electron velocity and helps to return main part of the reflected from collector electrons again at collector. In this case the resulting efficiency of the electron capture of collector becomes better then 10^{-6}. The low losses of the electron beam at cooling section lead to good vacuum condition and high life-time of high charge ions.

c. The design of the cooling section magnet system from moveable pancake coils lets to have very good straightness magnet lines at cooling sections. Increasing the cooling rate for the low ions amplitude play key roles for obtain high luminosity with internal target.

COOLING FORCE MEASURING

First cooling of a carbon beam with energy 400 MeV/u was made in CSRe coolers at May 2009. The ion beam was accumulated with electron cooling at CSRm ring (energy 7 MeV/u), was injected at CSRe after acceleration and was cooled down as it is shown in Fig 1 and Fig. 2. The typical life-time at the cooling process was about 500-1000 sec.

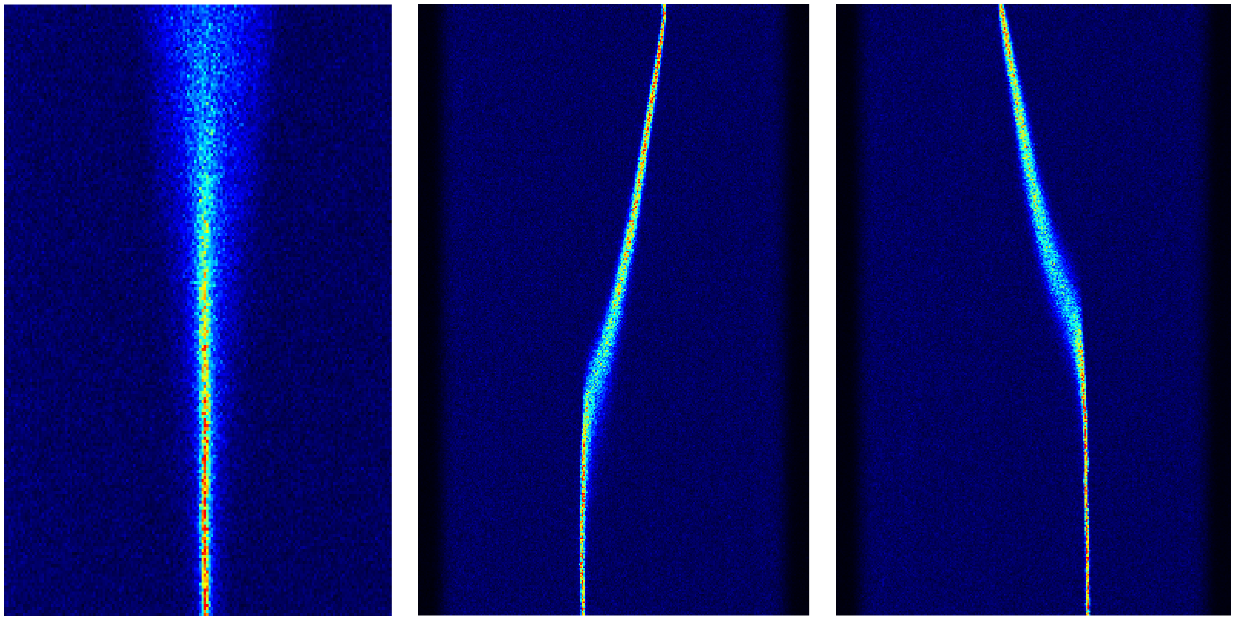

Figure 1: Schottky signal from pick-up electrodes during cooling process. The left picture illustrates the cooling down of the initial injection of carbon beam. The centre and right pictures illustrates the procedure of the cooling force measurement. The horizontal axis is the frequency, the vertical is time and the intensity is the power of spectral harmonics.

The obtaining measurements of the cooling force were performed by the following method. After injection the ion beam was cooled down to the equilibrium state and then the fast jump of the energy of the electron beam was done. The dynamic of the ion beam to the new equilibrium state was measured with Schottky Beam Diagnostics.

The cooling force is calculated using equation:

$$F = \frac{1}{\eta_e}\frac{dp}{dt} = \frac{\gamma\beta Mc}{\eta_e \eta_p}\frac{df_c}{f_0 dt} \text{ , (1)}$$

Where η_e is fraction the electron beam at the ion beam orbit, $\eta_p = dp/df * f/p$ is coefficient of frequency variation of particle circulation with momentum p, f_0 is central frequency of Schottky spectra analyzer. An example of such a friction force measurement is shown in Fig. 1 and Fig. 3.

The fitting of cooling force in the beam reference system of ion with velocity V is made with equation [7]

$$F = m_e c^4 \frac{4 r_e^2 Z_i^2 n_e}{(V^2 + V_{eff}^2)^{3/2}} V * \ln(\frac{\rho_{\max} + \rho_L + \rho_{\min}}{\rho_L + \rho_{\min}}) \text{ (2).}$$

All parameters in Eq. (2) are taken in the beam reference system, r_e^2 is the classical radius of electron, n_e is the density of electron beam, m_e is the mass of the electron, $Z_i = 6$ is charge of the carbon nuclei, V is the ion velocity $V^2 = V_\perp^2 + V_{||}^2$, $\rho_L = m_e c v_{e\perp} / eB = 3 \cdot 10^{-3} cm$ is the r.m.s. Larmour radius of the electron beam, the maximum impact parameter $\rho_{\max} = \tau\sqrt{V^2 + V_{eff}^2} > 0.08cm$, $\tau = l_{cool}/\gamma\beta c$, l_{cool} is the length of the cooling region, the minimal impact parameter is $\rho_{\min} = e^2/(m_e(V^2 + V_{eff}^2)) < 4*10^{-6} cm$. The effective "temperature" of the electron gas V_{eff}^2 is one from main parameter that determines the cooling rate.

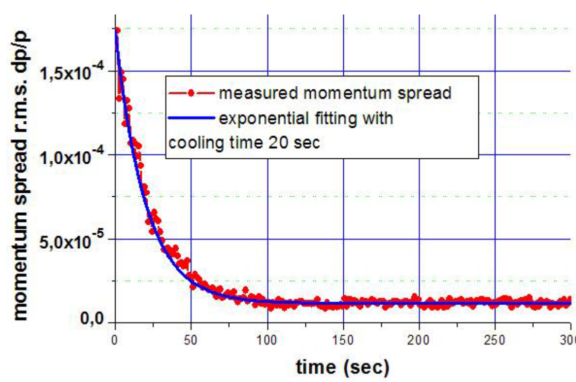

Figure 2: Momentum spread (r.m.s) versus time during cooling down of 400 MeV/u $^{12}C^{+6}$ carbon beam. The initial momentum spread is $2 \cdot 10^{-4}$ and one is $2 \cdot 10^{-5}$ after cooling down.

The main component of the effective temperature may be written as

$$V_{eff}^2 = V_{\Delta\Theta}^2 + V_{E\times B}^2 + V_e^2 \text{ ,}$$

where $V_{\Delta\Theta} = \gamma\beta c\sqrt{\langle\Delta\Theta^2\rangle}$ is the effective velocity induced by the curve $\langle\Delta\Theta^2\rangle = \frac{1}{l_{cool}}\int \Delta\Theta^2 ds$ of the magnetic field lines (the velocity spread due to transverse components of the guiding magnetic field of the cooling device), $V_{E\times B}$ is the electron drift velocity in the crossed the space charge fields of the beams and the guiding magnetic field, $m_e V_{\parallel e}^2$ is the longitudinal temperature of the electron beam. The effective velocity obtained from the experiment is $V_{eff} = 8 \cdot 10^6 \, cm/\sec$ (see Fig. 4.).

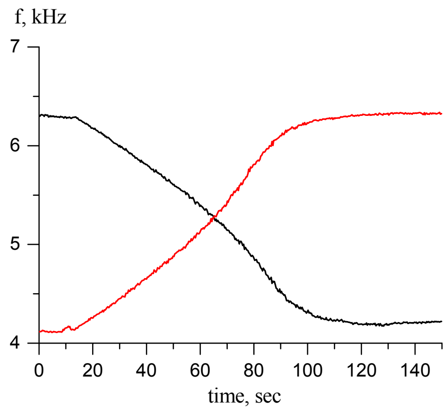

Figure 3: Central Schottky frequency 400 MeV/u carbon beam versus time after the electron beam energy jump on ±400 eV.

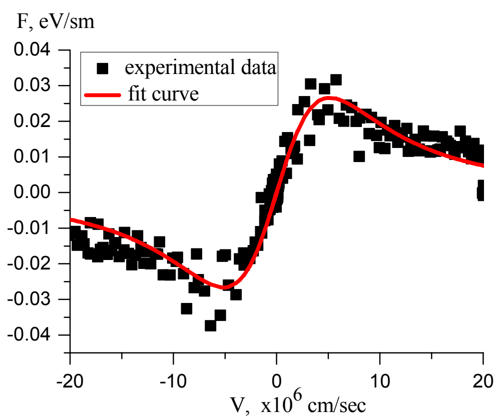

Figure 4: Cooling force versus velocity between the ion and electron beams. The velocity is taken in the beam reference system.

If the effective velocity is defined only by quality of the magnetic field then the effective angle is about 10^{-4}. At the commissioning time the effective angle of the magnetic field was tuned $2 \cdot 10^{-5}$ at the magnetic field level 750 G [8]. The deterioration of the magnetic force can be induced by the incorrect value of the longitudinal magnetic field in the cooling section and toroid. The alignment of the magnetic field is effective only for the value of the magnetic fields installed at time of the alignment procedure. Another factor that can have influence on the magnetic field quality is the order of the magnetic field switching on. The incorrect order of the applying magnetic field can induce the parasite residual magnetic field. This residual magnetic field can be removed by the special repeating procedure of the switching on/off the power supply but the operation with the magnetic field of the cooler demands to pay the attention to this problem. Moreover, the mechanical displacement of the magnetic elements during long operation period of the cooler may be important.

According the equation [2] the corrugation of the magnetic field is the most important at the high energy. So, the device for the measuring of the force line of the magnetic field is requires apparently during the experimental process. In present time the life-cycle of the cooler device includes the magnetic field measurement procedure at the initial assembling only. Because the researcher hasn't information about the real quality of the magnetic field and should rely on indirect measures only. The measure of the magnetic field can be done with compass like device installed in the vacuum chamber [9] or with the set of the pick-ups [10].

The Fig. 5 shows the influence of the quality of the magnetic field on the cooling process. The most parameters of the estimation are taken from COSY ring [11]. The electron beam is 1 A, the electron beam radius is 0.5 cm, the proton energy 1 GeV and the thickness of the hydrogen target is 10^{16} cm^{-2}. One can see that the good quality of the magnetic field strongly improves the quality of the ion beam with target interaction.

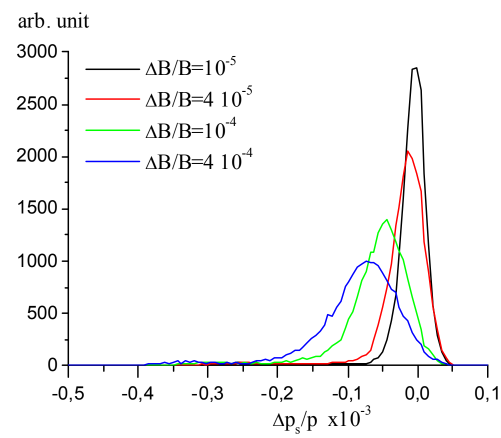

Figure 5: Estimation of distribution function at the different quality of the magnetic field lines.

The compass device in the vacuum chamber enables to give high accuracy of the measurement of the force line of the magnetic field but it has a complicate vacuum moving mechanics. The set pick-up is very good passive devices but the resolving power of such method is restricted by the finite number of the measuring points. The project of 2 MeV cooler for COSY contains the compass for the measurement of the magnetic force line. This experience enables to experimentally clarify the problem of the maximum target density. This experiment will be very useful for the realization of high resolution (HR) mode of HESR experiment in FAIR project [4].

BUNCH BEAM COOLING

The cooling of bunch ion beam (with RF voltage on) is important part of experiments with inner target and ion collision system. The short length of an ion bunch increases the peak luminosity and gives a start-time point for using of the time-of-flight methodic.

The experiments with bunch cooling were made with at CSRe on 200 MeV/u energy and RF cavity voltage 1 kV, first harmonic. The electron energy was 110.4 keV and the electron current was 0.3 A. During cooling process the signal from pick-up electrodes was observed. The typical oscillograms are shown in Fig. 6. The signal has a small amplitude and large level of the noise in the initial time of the cooling process. In the finale stage the signal growths and becomes very narrow that is evidence of the small size of the ion beam in the longitudinal direction. The most of the particle is condensed on the well of RF potential. After finish of the cooling process the typical life-time of intensive 1 mA ion beam was about 200 sec. During cooling process the particle was being lost, the ion current was decreased and the life-time was increased. For the low intensive ion beam <0.1 mA increased up to 1200 sec as it is shown in Fig. 7.

Figure 8 shows that with increasing ion beam current the bunch length was increased as $J_{ion}^{1/3}$ but for current J_{ion}>0.15 mA increasing became more fast as $J_{ion}^{1.7}$. At the same time for high ion beam current we see additional noise at pickup signal Fig. 6 and fast decreasing the ion beam life time. The low intensity zone can be easy interpreted as compensation of the RF voltage by own space charge electric field of the ion bunch. For parabolic shape ion bunch with bunch length σ_s the pick current is

$$J(s) = J_{ion} \cdot \frac{\Pi}{\sigma_s} \cdot \frac{3}{2} \cdot \left(1 - \left(\frac{2s}{\sigma_s} \right)^2 \right).$$

Averaged over circumference Π the electric field RF system is equal to

$$E(s) = \frac{U_{RF}}{\Pi} \cdot \sin(2\pi s / \Pi) \approx U_{RF} 2\pi \frac{s}{\Pi^2}.$$

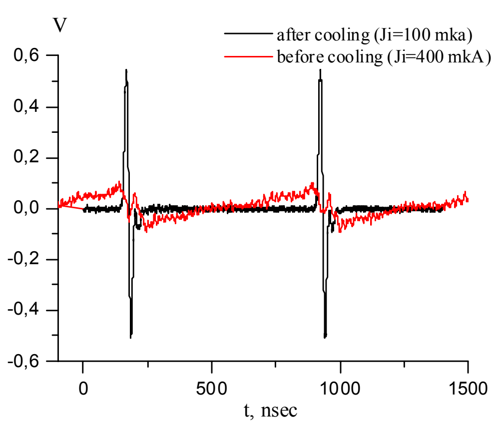

Figure 6: Signal from the pickup electrodes (input impedance 50 oHm, 54 dB preamplifier, 1 GHz bandwidth).

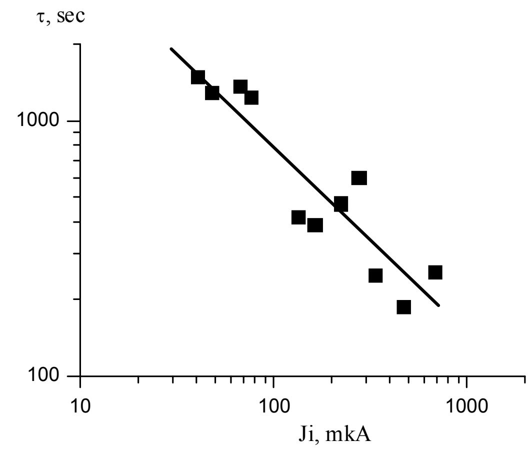

Figure 7: Life-time of ion beam versus ion current during cooling process.

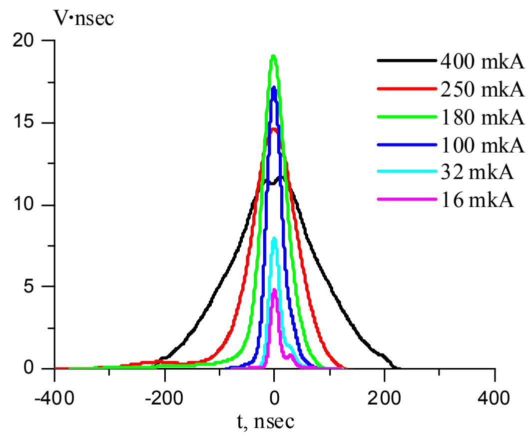

Figure 8: Shape of ion bunch for different ion beam current.

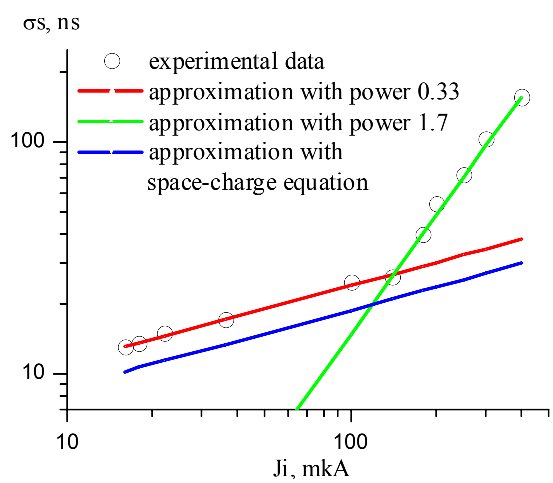

Figure 9: Ion bunch length at nanosecond versus DCCT ion current.

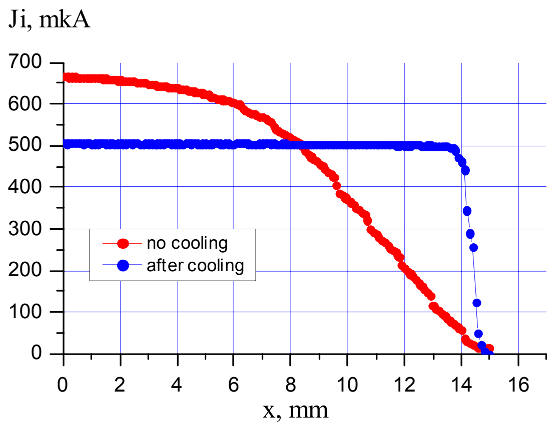

Figure 10: Ion bunch length versus DCCT ion current.

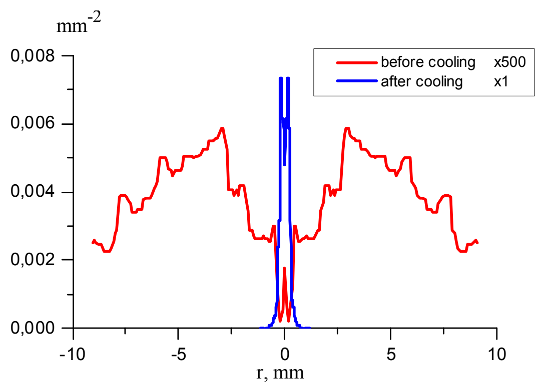

Figure 11: Radial density of ion beam before and after cooling. After cooling 400 MeV/u beam the effective diameter is near 1 mm.

At equilibrium electric field (with including AC magnet fields from bunch) along bunch should compensate RF action and we can estimate bunch length as

$$\sigma_s(J_i) = \left[\frac{3}{2\gamma^2\beta}\Pi^3 \frac{J_{ion}\left(1+2\ln(b/a)\right)}{cU_{RF}}\right]^{1/3}.$$

We can see that this estimation correspond measurement but only for low current. For high ion beam current the noise fluctuation increased longitudinal temperature ions and the bunch length was increased faster.

MEASURING OF THE TRANSVERSE BEAM SIZE

In order to estimate of the cooling efficiency in the transverse direction the technique of the beam size measuring with scrapper was used. Moving with velocity 1 mm/s scrapper crosses the ion beam orbit and the ion beam current is measured. If the scrapper touches with the ion beam then it is lost. Figure 10 shows that the cooling strongly shrinks the size of the ion beam and the resulting size becomes about 1 mm (see Fig. 11). The beam profiles are calculated as $P = dN/(2\pi \cdot r \cdot dr)$ and correspond to the phase plane density. So, the phase density of the ion beam was increased to 400 times in the radial direction and to 20 times in the momentum spread.

The emittance of the cooled down ion beam was about $\varepsilon = 0.01 \cdot \pi \cdot mm \cdot mrad$. The tune shift induced by the space-charge of the ion beam was about $\Delta Q = 0.02$. Probably the effects of the induced by space charge tuning determine the minimal size of the ion beam in these experiments.

CONCLUSION

The obtained experimental results from the electron cooler with magnetized cooling are useful for prediction of the process in high-voltage cooler designed for operation with the detector and internal target. The electron cooling device of EC-300 enables to increase the phase density of the particle to about 10^4 times. But the understanding of the ultimate possibility of the electron cooling process is restricted by the lack of the information about the quality of the magnetic field. So, the presence of the system for the measurement of the quality of the magnetic field during operating period may be very useful for the understanding of the experimental condition and the possibility to obtain the maximum cooling rate.

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