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COSY EXPERIENCE OF ELECTRON COOLING

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Abstract

The 2 MeV electron cooling system for COSY-Jülich has highest energy for the electron cooler with strong longitudinal magnetic field. During operation the cooling process was detailed investigated at 908 keV energy of electron beam. The proton beam was cooled at different regimes: RF, barrier bucket RF, cluster target and stochastic cooling. This article deals with the experience of electron cooling at high energy.

INTRODUCTION

In the present time a large experience of using magnetized cooling was collected [1-3]. The first experiments in BINP and further experiments in the other scientific centres show the usefulness of the idea of magnetized cooling. There are many electron cooler devices that operate now at low and middle energy (CSRm, CSRe, LEIR, ESR, e.t.c). The 2 MeV electron cooling system for COSY-Jülich has the highest energy of all coolers based on the idea of magnetized cooling and transport of the electron beam [4-5].

The schematic design of the electron cooler is shown in Fig. 1. The electron beam is generated by an electron gun and accelerated by an electrostatic generator that consists of 33 individual sections connected in series. It is then guided to the cooling sections through the transport line by means of a longitudinal magnetic field. There it will interact with protons. After interaction the electron beam returns to the electrostatic generator where it is decelerated and absorbed in the collector.

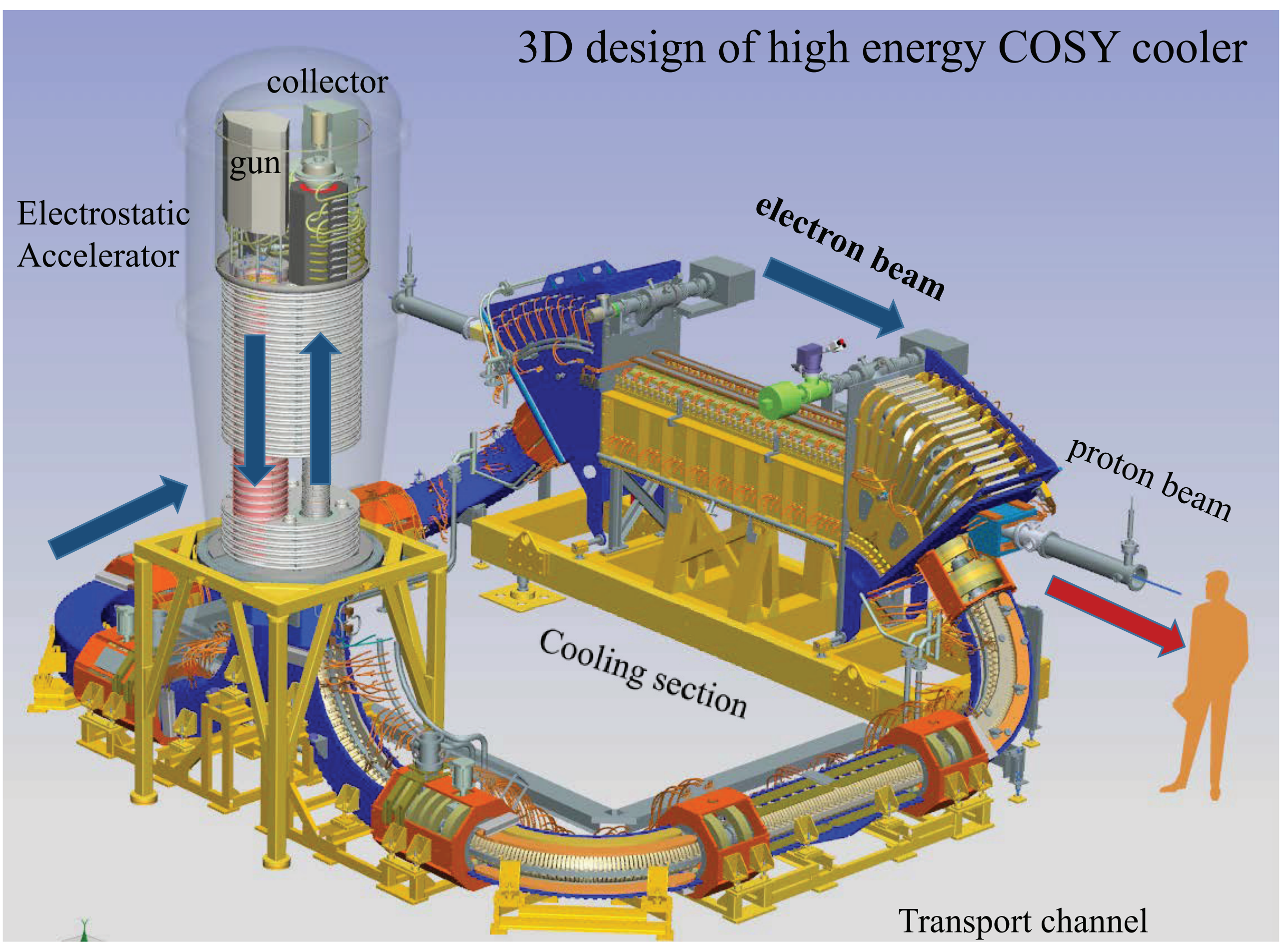

Figure 1: 3D design of 2 MeV COSY cooler.

The optics of the 2 MeV cooler for COSY is designed close to the classical low-energy coolers. The motion of the electron beam is magnetized (or close to magnetized conditions) along the whole trajectory from gun to collector.

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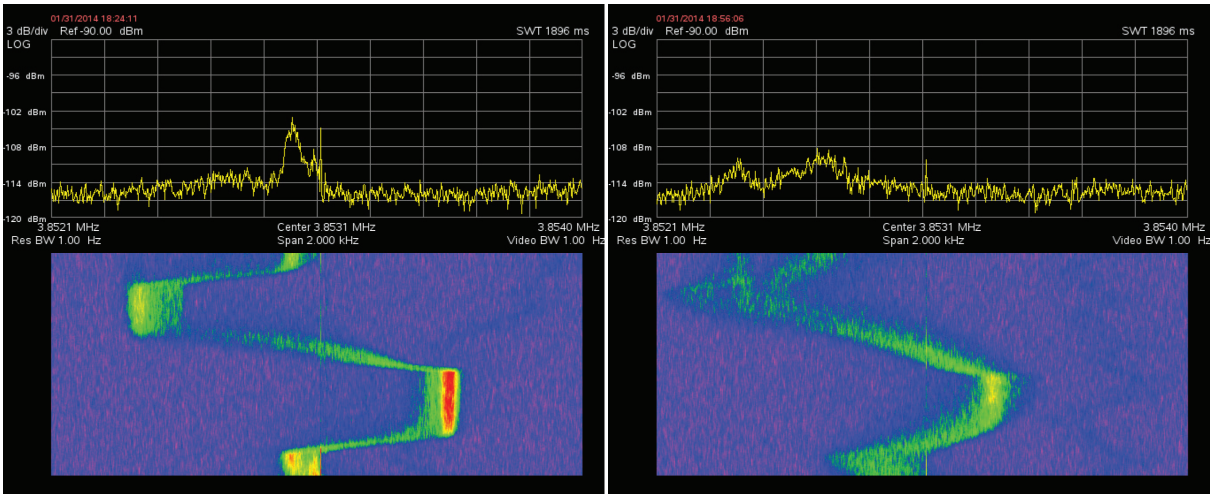

Figure 2: Cooling experiment with different Larmor oscillation of the electron beam in the cooling section. The left picture corresponds to zero oscillations, the right picture corresponds to a Larmor radius about 0.2 mm.

This decision is stimulated by the requirement to operate in a wide energy range from 25 keV to 2 MeV. At low energy the transverse fields is small and the trajectory of electron beam is difficult for the control especially at presents of space-charge effects. Strong longitudinal field helps to determine the electron trajectory. The bend magnets and linear magnets of the cooler are separated by a section with large coils for the location of the BPMs and pumps and comfort of the setup assembling. The length of the linear magnets is defined by the necessity to locate the electrostatic generator outside the shield area of the storage ring. At low electron energies the transverse momentum of the electrons is a less important parameter because the motion is adiabatic and there is no significant excitation of transverse motion. But at high energies the length of the electron's Larmor spiral is comparable with the characteristic lengths of the magnetic elements. Therefore the electron's motion is not adiabatic and strong excitation of transverse momentum is possible. So, the friction force can be reduced significantly compared to the approximation by a strong magnetization process [2].

BEAM COOLING EXPERIMENTS

The first experiments demonstrating the influence of the transverse motion on the electron cooling process was done at an energy of 316 keV. Figure 2 shows the change of the cooling rate due to the influence of the transverse motion. During the experiment, the energy of the electron beam was changed and the longitudinal momentum of the proton beam was changed too. The energy of the electron beam is 315.85 keV. The electron current is 0.26 A. The magnetic field in the cooling section is 1275 G over a length of 2.69 m. Whole duration of one cycle is 600 s. The electron energy was changed by ±300 eV every 100 s. For the measurement shown in the right picture the beam was kicked with a magnetic corrector inducing Larmor oscillations with a radius about $R_L \approx 0.2$ mm. The features of the dynamic of Schottky spectrum during experiment characterize the rate of the cooling process.

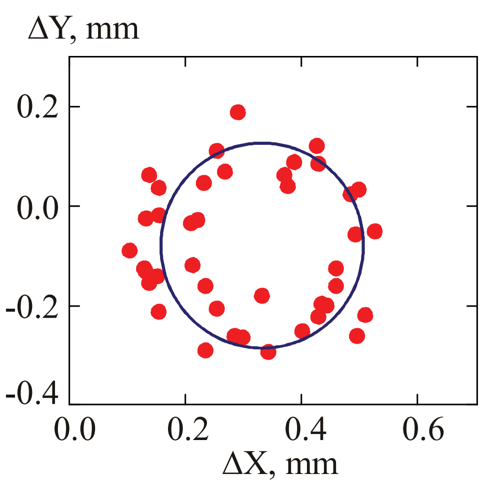

Figure 3: Observation cyclotron rotation of the electron beam with BPM at changing of magnetic field (i.e phase of motion) in the cooling section.

One can see that the cooling process becomes weaker at presence of Larmor oscillation of the electron beam. The area with high density in the Schottky signal disappears from the spectrogram and the motion to the new equilibrium point is slower. The amplitude of the Larmor motion was measured with a BPM because the kick of corrector had dipole component only. Figure 3 shows the transverse position of the electron beam while changing the longitudinal magnetic field strength in the cooling section that produces a phase shift in the Larmor rotation.

The interaction of ions and electrons is realized at different impact parameters. The maximum impact parameter can be estimated as $\rho_{\max} \approx V_i \tau_{cool}$

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Here V_i is the ion velocity and $\tau_{cool} = L_{cool}/(\gamma\beta c)$ is the interaction time in a co-moving reference system, L_{cool} is the length of the cooling section, γ and β are relativistic factors of the beams. The parameter $\rho_{\max}$ corresponds to the path length of an ion in the electron gas in co-moving frame of reference. The comparison of this value with Larmor radius indicates the number of the magnetized collision. If $\rho \approx \rho_L$ than the electron has no time for many Larmor oscillation during collision with ions.

During electron cooling process the size of the proton beam a_i is changed from 4 to 1 mm. Taking the beta function in the cooling section at about $\beta_{x/y} \approx 400$ cm the maximum impact parameter can be estimated as

$$\rho \approx \frac{a_i}{\beta_{x/y}} L_{cool} \approx 0.7 \div 2.7 \text{ mm}.$$

This result gives an initial estimation when Larmor rotations are significant for reducing the amount of magnetized collisions which may be a reason for the decreased cooling rate.

The next experiments were done at high energy 909 keV and the transverse and longitudinal cooling were measured. Main parameters of experiment are following. The electron energy is E_e = 907.7 keV, the proton energy is E_p = 1.67 GeV, the anode and grid voltages are U_{an} = 3.27, U_{grid} = 0.83 kV, the electron current is J_e = 600 mA. The magnetic field in the electron gun is 230 G, acceleration column is 400 G, collector is 500 G. Longitudinal magnetic field in the cooling section is 1300 G, in the toroid section is 1200 G, bend magnet is 860 G. The slip-factor of the proton beam is η = -0.035, the number of protons is N_p = 1.6-$1.8 \cdot 10^9$.

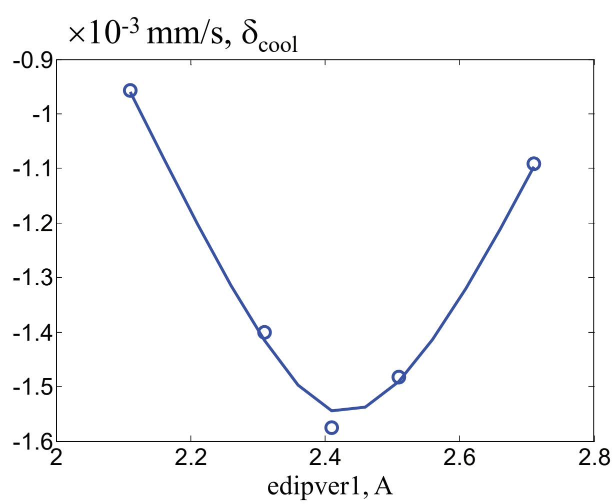

Figure 4: Horizontal increment as function of current of edipver corrector.

The longitudinal cooling was investigated with spectrum analyzer of Schottky signal at 2.438 GHz that corresponds to the 1600 harmonics of the revolution frequency. The transverse cooling was investigated with ion profile monitor (IPM). It measured the profile of the ions generated due to ionization of the residual gas by the proton beam. These ions are accelerated by an electrical field and absorbed by a special detector. This detector contains the microchannel plate, phosphor screen and charge-coupled device (CCD) for amplification, visualization and registration of the beam profile. The IPM contains two such systems allowing to measure horizontal and vertical profiles simultaneously.

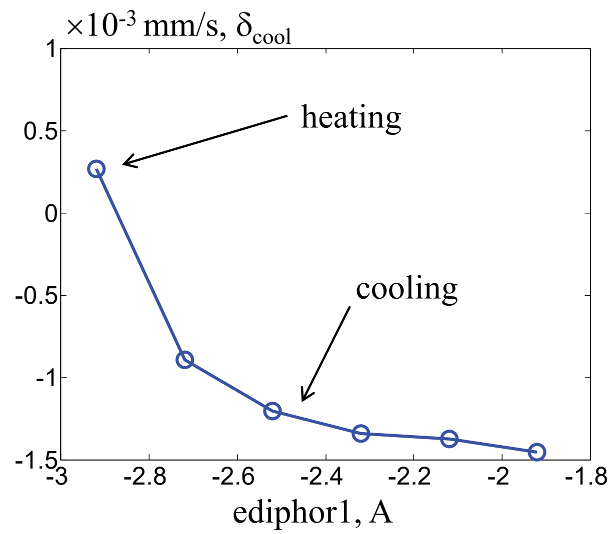

Figure 5: Horizontal increment as function of current of ediphor corrector.

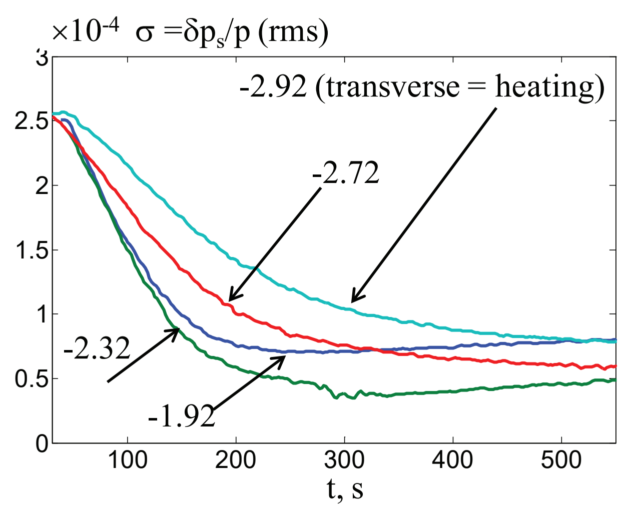

Figure 6: Longitudinal momentum spread as function of time for different values of current in electron dipole corrector ediphor1.

The amplitude of the Larmor rotation was changed with the help of short correctors: ediphor 1 and edipver 1. These correctors have a square shape with a size of about 10 cm and are located about 6.5 cm from the beam axis. There length is small compared to the length of the Larmor spiral.

Figure 4 shows the horizontal cooling rate as function of corrector current. One can see that the cooling rate changes significantly. Another example is shown in Fig. 5. One can see that an unfortunate choice of values of the correctors

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with short length can eliminate transverse cooling completely.

Despite of the decrease in the transverse cooling rate the longitudinal cooling was good enough. Figure 6 shows the longitudinal cooling rate for experimental parameters corresponding to Fig. 5. The value *ediphor1* = -2.92 A leads to transverse heating. The longitudinal cooling time is increased but cooling is still present.

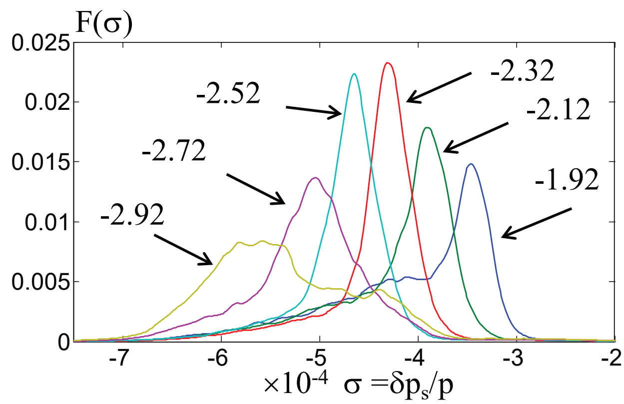

Figure 7: Longitudinal distribution function of the protons in time 500 s for different values of ediphor1 corrector.

Another effect caused by the Larmor oscillation is the connection of the equilibrium momentum distribution of the cooled proton beam to the transverse kick strength. Figure 7 shows the longitudinal distribution function of the protons after the equilibrium was reached. The minimal value of equilibrium momentum and worst longitudinal cooling is observed at *ediphor1*=-2.92 A. The maximum value of equilibrium momentum corresponds to *ediphor1*=-1.92 A when the cooling process is effective. This fact can be explained by decrease of the longitudinal momentum at increase of the transverse one. The estimation of Larmor radius that can be induce by 1 A of current in edip corrector is about $R_L \approx 0.35\ mm$ at electron energy $E_e = 909\,\text{keV}$ (see Fig. 8). It corresponds to change of longitudinal momentum on value

$$\delta\sigma = \frac{\delta p_{II}}{p_0} \approx \frac{1}{2}\left(\frac{R_L}{\rho}\right)^2 = 6\cdot 10^{-5} \qquad (1)$$

where

$$\rho = \frac{\gamma\beta m_e c^2}{eB_{cool}} = 3.2\ cm$$

is the longitudinal Larmor radius and

$$2\pi\rho = 20\ \ cm$$

is the length of Larmor spiral. One can see that the quality behavior is good. The quantitative difference can be explained by the assumption that the transverse motion already has nonzero amplitude of Lamour oscillation. In this case the change of longitudinal momentum is

$$\delta\sigma = \delta\sigma' - \delta\sigma_0$$

$$\delta\sigma' \approx \frac{1}{2}\frac{\left(\delta\vec{p}_{\perp 0} + \delta\vec{p}_{\perp}\right)^2}{p_0^2}\ ,\ \delta\sigma_0 \approx \frac{1}{2}\frac{\left(\delta\vec{p}_{\perp 0}\right)^2}{p_0^2}$$

where $\delta\vec{p}_{\perp 0}$ is the initial transverse momentum corresponding some Larmor radius R_{L0}, $\delta\vec{p}_{\perp}$ is additional transverse momentum induced by the corrector. One can see that shift of longitudinal momentum may be larger than it describes by equation 1.

CONCLUSION

The physics of electron cooling may contain an open question and this puzzle may have unopened area despite of 50 years of history. Understanding of physics behaviour of the transverse cooling is critical in order to improve transverse electron cooling compared to today's situation. The high-voltage cooler in COSY storage ring is located in the place with low beta function that is unusual for use of electron cooling method. So, the simple way of transverse cooling optimization may be connected with increase of the beta function in the iteration point.

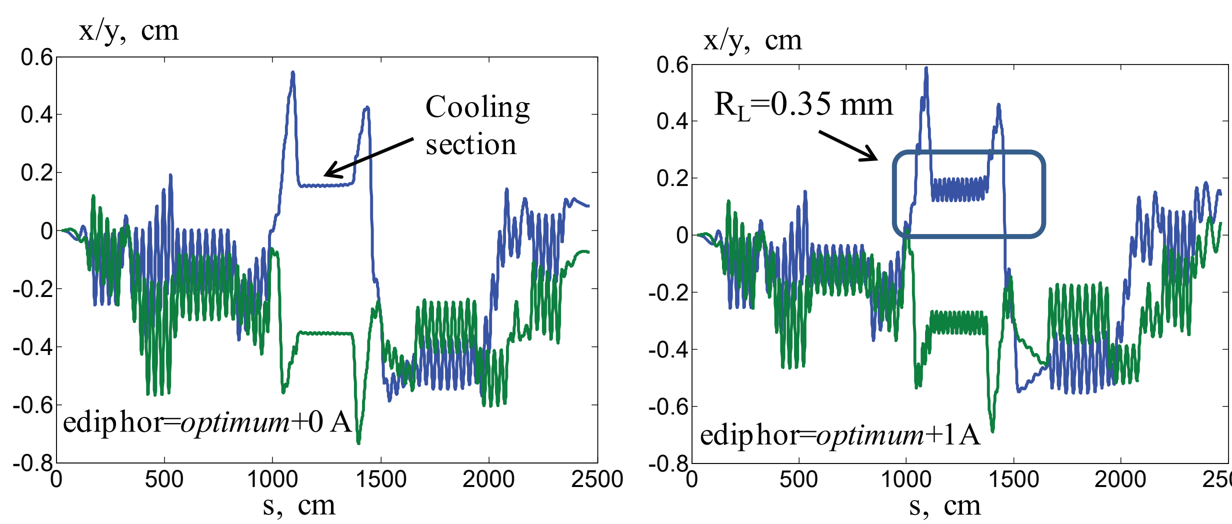

Figure 8: Demonstration of excitation of Larmor oscillation of electron induced by edip corrector.

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