EXPERIMENTAL OBSERVATION OF LONGITUDINAL ELECTRON COOLING OF DC AND BUNCHED PROTON BEAM AT 2425 MeV/c AT COSY

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Abstract

The 2 MeV electron cooling system for COSY-Julich started operation in 2013 years. The cooling process was observed in the wide energy range of the electron beam from 100 keV to 908 keV. Vertical, horizontal and longitudinal cooling was tested at bunched and continuous beams. The cooler was operated with electron current up to 0.9 A. This report deals with the description of the experimental observation of longitudinal electron cooling of DC and bunched proton beam at 2425 MeV/c at COSY.

SETUP DESCRIPTION

New generation of the accelerators for study nuclear physics at range of relativistic energy 1-8 Gev/u requires very powerful cooling to obtain high luminosity. In the present time the large experience of using magnetized cooling was collected. The first experiments in BINP and further experiments in the others scientific centers 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-Julich has the highest energy from all coolers that were made with idea of magnetized electron cooling and transport of the electron beam. The COSY cooler is designed on the classic scheme of low energy coolers like coolers CSRm, CSRe, LEIR that were produced in BINP before. It can be used for beam cooling at injection energy and for testing new features of the high energy electron cooler for COSY and HESR.

The schematic design of the setup is shown in Fig. 1. The design of the cooler and its main parameters are described in [1-2]. The electron beam is accelerated by an electrostatic generator that consists of 33 individual sections connected in series. Each section has two high-voltage power supplies with maximum voltage 30 kV and current 1 mA. The electron beam is generated in electron gun immersed into the longitudinal magnetic field. After that the electron beam is accelerated, moves in the transport line to the cooling section where it will interact with protons and deuterons of COSY storage ring. After interaction the electron beam returns to electrostatic generator where it is decelerated and absorbed in the collector.

The optics of 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 whole trajectory from a gun to a collector. This decision is stimulated by requirement to operate in the wide energy range from 25 keV to 2 MeV. So, the longitudinal field is higher then transverse component of the magnetic fields. The bend magnets and linear magnets of the cooler are separated by a section with large coils for the location of the BPMs, pumps and a comfort of the setup assembling.

EXPERIMENTS SETUP

The detailed experiments with electron cooling were carried out with the proton energy 2425 MeV that corresponds to the electron energy 908 keV. This working point was investigated carefully in the previous experiments and there was a large collection of the hardware setups for the operation. Moreover the stochastic cooling was accessible at this energy. The experimental setup involves the barrier bucket and RF of 1-st harmonic. The diagnostic of the proton beam was based on IPM (ionization profile monitor), BPM and pickup of the stochastic cooling system. The proton current is measured by DCCT.

The main parameters of COSY regime at this point are listed in Table 1.

Table 1: COSY Regime Parameters

Parametere	Value
Gamma transition	2.26
Alpha	0.196
Proton numbers	10^8-10^9
Vacuum	10^{-9}-10^{-10} mbar
Qx	3.589
Qy	3.675
Slip-factor	-0.066
Perimeter	183.5 m
Kinetic energy	1.662 GeV
Gamma	2.771
Frequency	1.5239 MHz
Dipole field	1.156 T
Horizontal beta function in cooling section	9 m
Vertical beta function in cooling section	15 m
Dispersion in cooling section, m	0

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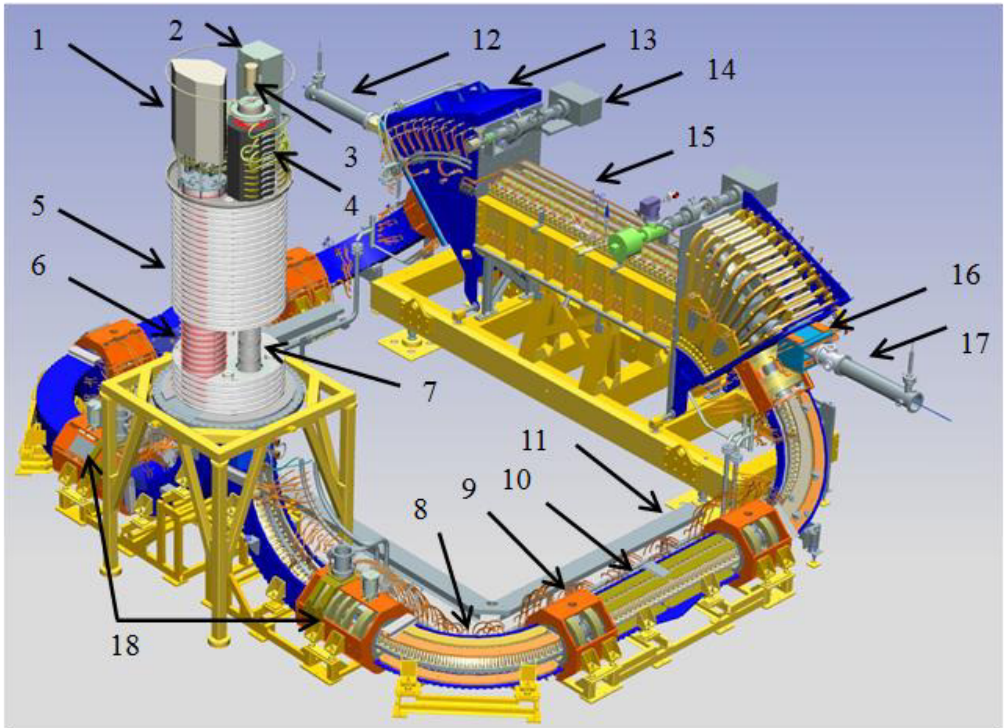

Figure 1: 3D design of 2 MeV COSY cooler. Collector PS is 1, SGF system is 2, ion pump of collector is 3, collector with magnetic system is 4, HV section is 5, cascade transformer is 6, acceleration tube is 7, bend 90 degrees is 8, straight section is 9, line section is 10, cable path is 11, input of the proton beam is 12, toroid 45 is 13, vacuum pump is 14, cooling section is 15, ion dipole is 16, output of the ion beam is 17, the elements with short dipole kicks of the electron beam is 18.

ELECTRON COOL TUNING

The first attempts of the cooling shows the essential role of the coherent Larmor rotation to the cooling process. That is why the e-cool tuning to the given working point contains the following procedures. The vertical and horizontal overlap of the proton and electron beam was adjusted using the BPM. The scan of the electron energy gives the possibility to obtain initial cooling process. The difference in 200-500 V is enough for significant influence on the cooling process because the exact energy value isn't easy to calculate from the experimental value of the proton energy. In final the Larmor rotation is minimize. The magnetic field in the cooling section was changed in order to see the Larmor motion of the e-beam center in the BPM located after cooling section. The short magnetic dipole coils located in the section Fig. 1, 18 enable to provide additional dipole kicks eliminating the initial Larmor motion. As result the Larmor oscillation with radius 10-30 um can be reached in the transport channel. Unfortunately this oscillation depends on the most parameters of the electron beam: energy, position in the cooling section and current. So, the tuning of the optimal parameters of the electron beam was done with several iterations. Each iteration allows reaching the improvement of the cooling process.

As the result the proton beam with the momentum spread $\Delta p/p = \pm 2 \cdot 10^{-3}$ was cooled down during about 200 s. The Schottky spectrum shown in Fig. 2. demonstrates this process. The initial proton momentum spread was widened using white noise beam excitation for the process demonstration. The electron current was 400 mA and the proton number $7 \cdot 10^{8}$ in this experiment.

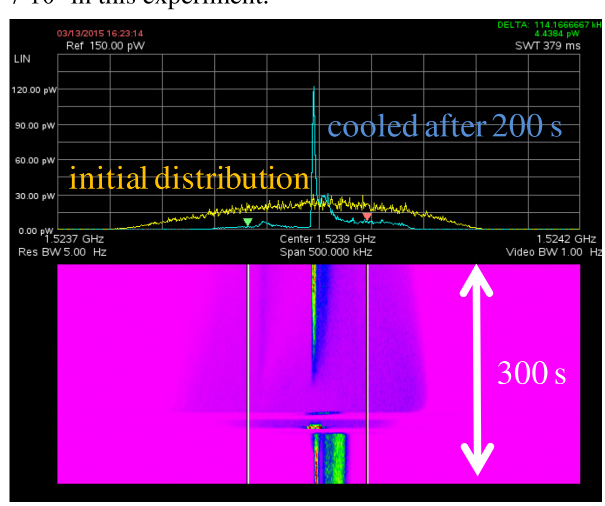

Figure 2: Schottky spectrum (linear scale) of the proton beam during cooling ($\gamma > \gamma_{tr} = 2.26$).

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Figure 2 shows that the distribution function of the proton beam consists from the central high peak and the tail directed to the low energy area. The location of the working point above gamma transition leads to the location of the low energy area in right side of the spectrum. This tail was observed in the most experiments with cooling of the proton beam so this problem was investigated in more detail. Results of our investigations are described below.

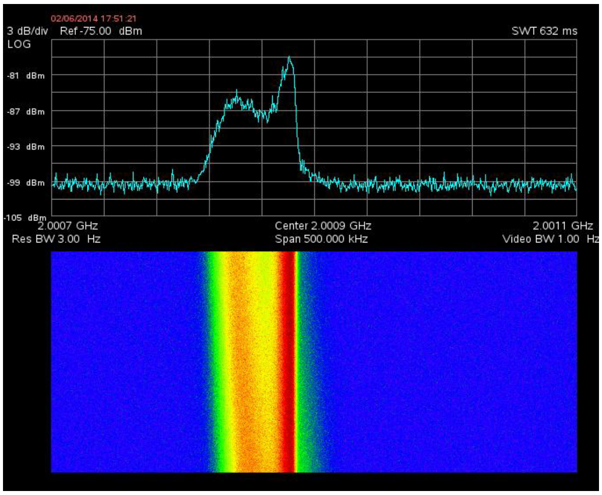

Figure 3: Schottky spectrum (log scale) of the proton beam under cooling process at the case $\gamma<\gamma_{tr}$=4.2. The proton number is Np=5.5·10^8. The electron current is 310 mA.

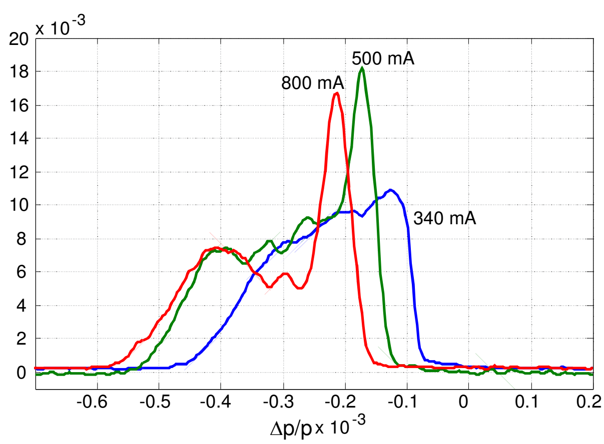

Figure 4: Distribution function of the longitudinal momentum for cooling with different electron current. The time is fixed as 370 s after the injection. The distribution function is normalized to unity (scale is linear). The proton number is Np=3·10^8.

The exact shape of the distribution function depends from both parameters of the proton and electron beam: number of particles and the electron current (see Fig. 4). The shift of the peak to the lowest value of the proton energy can be explained by the space charge. The changing energy in the center of the electron beam can be calculated from the equation

$$\frac{\Delta p}{p}=\frac{eJ}{\gamma\beta^3 c}\frac{1}{m_e c^2}\left(2\ln\left(\frac{b}{a}\right)+1\right).$$

that gives $\Delta p/p$ =8.5·10^{-5} at the parameters Je=500 mA, b=5 cm, a=3 cm. So, the shift of the peak of the distribution function can be described by the space charge, but the tail itself can't be described with simple theory.

The potential sagging inside the electron beam induced by the space charge leads to the maximum momentum distribution

$$\frac{\delta p}{p}=\frac{eJ}{\gamma\beta^3 c}\frac{1}{m_e c^2}.$$

that gives $\delta p/p$ =1.3·10^{-5} at the electron current Je=500 mA that isn't enough from the quantitative point of view. Moreover the effect of the potential sagging leads to an increase of energy of all particles respect to the particle passed through the center of the electron beam. So, the position of the proton beam in alignment with the electron beam should effect the tail on the high energy side. The opposite behavior is observed.

The role of the vacuum can't be significant either. The ionization loss can be estimated as

$$\frac{\delta p}{p}f_0=\frac{4\pi n_a r_e^2 c}{\gamma\beta^3}\frac{m_e}{m_p}L_C$$

where n_a=1.3·10^8 cm^{-3} is the density of the residual gas in COSY, r_e is classical electron radius, $L_C\approx20$ is Coulomb logarithm, m_e/m_p - ratio between electron and ion mass. The loss rate of the energy is about 2·10^{-8} c^{-1} that isn't enough for describing of the experiments. Moreover the direct experiment with the degradation of the vacuum condition in COSY to a few times doesn't show the visible effect in the picture of the cooling process.

The effect related to the different Larmor radiuses in cross-section of the electron beam may also induce the cooling to the different electron energies. Suppose that the outer electrons oscillate with radius R_L=100 um and the electron in the center has R_L=0 um than the difference of the longitudinal energy between edge and center of the e-beam will be

$$\frac{\Delta p_{\parallel}}{p}=\frac{1}{2}\left(\frac{eB}{\gamma\beta m_e c^2}\right)^2 R_L^2$$

$\Delta p_{\parallel}/p$ =1.2·10^{-5} at the magnetic field B=1500 G. So, this effect is negligible too.

COHERENT INSTABILITY HYPOTHESIS

The behaviour of the cooled and noncooled proton beam may be significantly different [3]. The electron cooling decreasing the momentum spread can reveal the problems that were hidden by high momentum spread of the proton beam. As it is known the “Landau damping” suppressed many natural coherent instability like negative mass instability or instability at

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interaction with resonance mode. Decreasing the momentum spread of the proton beam to the range 10^{-4} suppressed the Landau damping. So, because of the interaction with surrounding electrodes the quality of such beams can be limited by coherent instabilities. In this section we evaluate the behaviour of the distribution function due to instability of coherent oscillations. The direct simulation of the set of the particle was taken as model. The macro-particle interacts with surrounding electrodes with impedance

$$Z_q = R \cdot \frac{1 + iQ_{res}\left(\frac{q_{res}}{q} - \frac{q}{q_{res}}\right)}{1 + Q_{res}^2\left(\frac{q_{res}}{q} - \frac{q}{q_{res}}\right)^2}$$

where q_{res} is number of resonance harmonic, Q_{res} is quality factor, R= $Z_0 \cdot Q_{res} \cdot q_{res}$ is taken in such way that Z_q limits to the impedance of the smooth vacuum chamber at $q \to 0$.

The cooling step is taken as approximation of the Parkhomchuk's equation [4]

$$\delta p_{n+1} = \delta p_0 + \left(\delta p_n - \delta p_0\right) \cdot$$
$$\cdot \exp\left[-\frac{N_M A_{cool}}{\left(\left(\delta p_n - \delta p_0\right)^2 + \gamma^2 \theta_{eff}^2\right)^{3/2}}\right]$$

where $A_{cool} = \frac{4 r_e r_p L_{cool}}{\gamma^2 \beta^3 c \pi a_e^2} Ln_C\left(\frac{J_e}{e}\right)$.

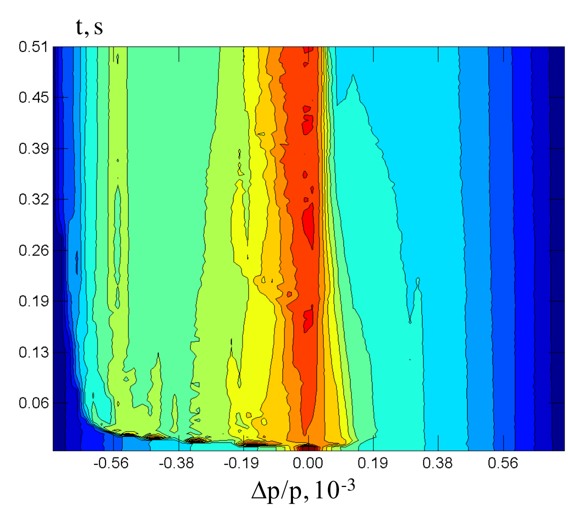

Figure 5: Spectrogram (Ln scale) of the longitudinal distribution function versus time as result of simulation. The colour scale as rainbow denotes the number of the particle in the momentum scale (x -axis) during time process (y-scale).

During each macro-step the coherent field was calculated with Fourier transformation of the density distribution of the particle. The distribution density along azimuthally angle was estimated with 64 space cells. As result the momentum and azimuthal position of the macro-particle was calculated taking into account e-cool force and impedance inducing field. This model may be expanded to the estimation of the external RF field (sin-like or barrier-bucket types). The complexity of the algorithm makes simulations of longer time intervals difficult. Because the instability rate was artificially increased in order to analyze the qualitative factors. The process of the initial cooling also is eliminated from simulation. The result of simulation of another computer code is used as initial parameters of the particles.

The simulation parameters: $Np=1.2 \cdot 10^{10}$ is particle number, Π=180 m is perimeter of the storage ring, a=0.5 cm is radius of the proton beam, b=5 cm is radius of the vacuum chamber, η=-0.05 is slip-factor, Je=0.3 A is the electron current, Ee=908 keV is the electron energy, a_e=0.5 cm is electron beam radius, Ln_c=5.0 and $\theta_{eff}=3 \cdot 10^{-5}$ is Coulomb logarithm and effective angle in the equation for the cooling force, L_{cool}=250 cm is length of the cooling section, number of the macro-particle for the simulation is 300 000, the number of the macro-step is 40 000, the number of the revolution turns in one macro-step is N_M=20, the harmonic multiplier is 2, the maximum harmonic number is 32, the impedance parameters are Q_{res}=20, q_{res}=19.05.

Figure 5 shows that the initial cooled beam acquires very fast the tail of the particle. After that the tail is stable and is located on the low energy side. The particle having positive momentum shift continues cooling to the equilibrium energy. The distribution function may have an additional peak located at some distance from the equilibrium energy about δp_0=0. This behavior is similar to the experimental facts shown in Fig. 2-4.

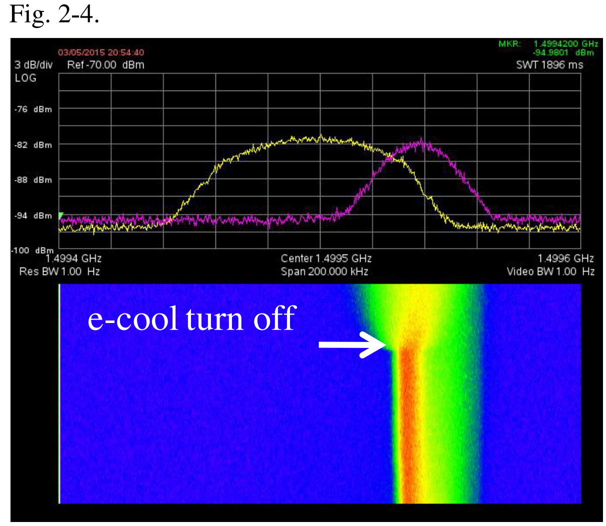

Figure 6: Schottky spectrum (log scale) of the proton beam at time of switching off electron current. The proton number is $Np=8.5 \cdot 10^8$, $\gamma > \gamma_{tr}$=2.25. The electron current is 300 mA.

Besides the qualitative simulation analysis of the coherent process, the additional experimental facts can be explained by some coherent phenomena.

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The tail effect is strongly related to the e-cooling process. Figure 6 shows that turning off of the electron beam makes the tail disappear and to changes the distribution function to a symmetrical shape.

The presence of stochastic cooling and barrier bucket also suppresses the collective behaviour. The stochastic cooling may be considered as broadband feedback system, so this system can suppress the fluctuation of the space charge. The top picture (see Fig. 7) shows the proton beam deeply cooled by e-cool system. One can see very narrow peak and tail. The switching on of the stochastic cooling system makes the distribution function symmetrical and wider. The middle picture (see Fig. 7) shows the distribution function under action of the stochastic cooling. The bottom picture shows transition from one state to the other.

The barrier bucket RF action can be described in the following way. The loss energy particle acquires energy from RF voltage. So, a mixing process in the phase space occurs here. Thus the shape of distribution function becomes symmetric shape (see Fig. 8).

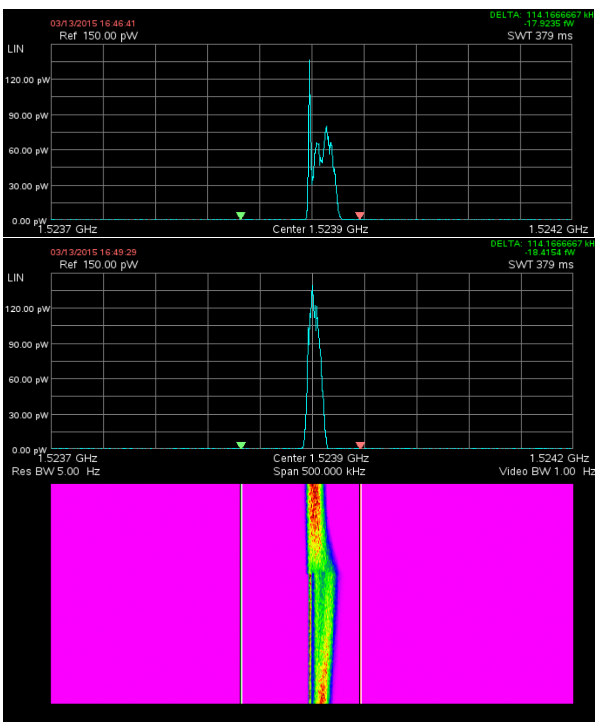

Figure 7: Schottky spectrum of the proton beam under cooling process without (top picture) and with stochastic cooling (middle picture). The proton number is Np=7·10^8, $\gamma > \gamma_{tr}$=2.25. The electron current is 400 mA.

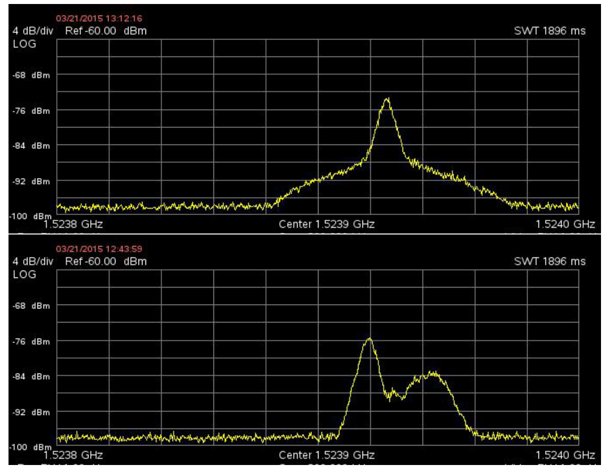

Figure 8: Schottky spectrum (log scale) of the proton beam under cooling process with (top picture) and without RF (bottom picture). The proton number is Np=3·10^8, $\gamma > \gamma_{tr}$=2.25. The electron current is 810 mA. Amplitude of barrier bucket RF voltage is 240 V.

SUMMARY

The electron cooling can reveal the problems that were hidden by high momentum spread of the proton beam. The collective effects can describe some features of behaviour of the distribution function during cooling process in COSY. Certainly, the simulation gives only the general description of the cooling process in the presence of the collective instability. Improvement of the situation with coherent instability may be obtained by paying additional attention to impedance budget or use of working point with larger slip-factor.

REFERENCES

[1] N. Alinovsky et al., “The first commission results of the high-voltage magnetized cooler for COSY” ECOOL’11, Alushta, Semptember 2011, THIOA02, p. 37-42; http://www.JACoW.org.

[2] V. B. Reva, N.I. Alinovskiy, T. V. Bedareva et al. Proc. “Commissioning COSY cooler with electron beam at Novosibirsk”. COOL-13, Murren, Switzerland, 2013, p.79-83

[3] N.S. Dikansky and D.V. Pestrikov., “The Physics of Intense Beams and Storage Rings” AIP Press (1994).

[4] V.V.Parkhomchuk. “New insights in the theory of electron cooling”. Nucl. Instr. Meth. A 441 (2000), p. 9-17.

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