DEVELOPMENT OF ELECTRON COOLERS IN NOVOSIBIRSK

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Abstract

An electron cooling method was proposed by G. Budker almost 50 years ago. Since the first demonstrations of strong cooling in 1972, the Novosibirsk Institute of Nuclear Physics has continued to develop this technique for various machines with increasingly higher energy beams. Recent application of the e-cooling method at LEIR appeared as a crucial application for a high luminosity achieved in lead-lead ion beam collisions at LHC. This talk should describe the fundamental mechanism of strong cooling, describe historical progress at the BINP and present recent results achieved at the LHC. New 2MeV cooler for COSY ring under commissioning just now at BINP.

INTRODUCTION

The history of the development of electron cooling began at the Institute of Nuclear Physics (Novosibirsk) just after the first successful experiments there with electron-electron and electron-positron colliding beams. Radiation cooling plays a decisive role in the achievement of high luminosity in electron and electron-positron colliders. Cooling based on ionization losses in matter was suggested but interaction with the target nuclei did not allow the application of this method because it makes the beam lifetime too short.

The idea of using electron cooling, proposed by G.I. Budker in 1965 [1], was to shift from cooling with a stationary target to the use of a pure beam of electrons (without nuclei). Electron cooling work began in 1967 with theoretical studies [2] and the development of an electron beam facility [3]. These were aimed at verification of the electron cooling concept. The electrons would travel with the same average velocity as the proton beam.. Of course, the electron beam density is much smaller then the electron density in condensed matter, but in this case, electrons are traveling together with the proton beam and the interaction efficiency between the two beams depends only on the spread of relative velocities of the protons and the electrons. For suppressed drift motion by the electrons beam space charge repulsion the high value magnet field B along the electrons trajectory used $V_d = c*2\pi n_e a_e / B$. After cooling the ions temperature tend to temperature of electron beam. The electron beam emitted from the cathode has a temperature close to the cathode temperature $T_к$ – about 1000 °K ~0.1 eV. After acceleration in the electrostatic field the longitudinal velocity spread becomes very small since the energy spread is in the laboratory system $\delta V = T_c/(m_e V_0)$. This simple effect (practically 0 longitudinal electron beam temperature) was experimentally opened at study longitudinal cooling force versus relative velocity ion electron beam. The strong magnet fields keeps the transverse motion electrons inside small Larmor cycle. As results the effective electron beam temperature becomes very small and ions beam can cooled to temperature about 1K. It is natural that the longitudinal temperature will be determined by other factors. The most essential factor seems to be the relaxation of the initially arbitrary mutual position of the electrons. Immediately after acceleration, relaxation of the energy due to the electrons mutual repulsion results in a longitudinal temperature approximately equal to: $T_\parallel = 2e^2 n_e^{1/3}$,where e- is the electron charge and n_e is the electron beam density.

Already in the first experiments at NAP-M, after appear magnetized cooling, it was experimentally demonstrated that the increase in the electron beam transverse temperature caused a weak decrease of the cooling rate but noticeably reduced recombination between protons and electrons. For the project of incorporating electron cooling in the RHIC collider, this effect turned out be rather important. Special experiments have been carried out to verify the effect of reducing recombination by high electron temperature for the highly charged ions at GSI in the ESR storage ring. In the RHIC collider, the lifetime of ion beams should be of many hours with rather fast cooling. For suppression of recombination, it was suggested using a “transversely hot” electron beam in a strong magnetic field [4]. The temperature of transverse motion of an electron beam should be increased up to 100 eV but the cooling time should not be substantially longer.

FIRST ELECTRON COOLER AT NAP-M STORAGE RING

An electron gun was put into a solenoid producing the longitudinal guiding magnetic field, which accompanies the beam until it reaches the collector [5]. The longitudinal magnetic field enabled us to pass an electron beam over the required, rather long, (a few meters) distance without the inevitable beam dilution and without angular excitation with the use of axially focusing lenses. Sections with a toroidal magnetic field were used for merging the proton and electron beams. For compensation of centrifugal drift, we have used a horizontal magnetic field superposed in the toroidal sections. After the cooling section, the electron beam was decelerated and captured by the electron collector. In order to provide high vacuum, ion pumps were installed in all accessible places.

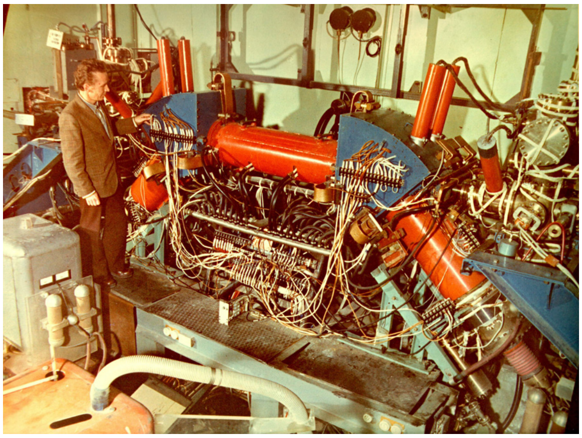

Figure 1: The first electron cooling installation in the NAP-M storage ring.

These first experiments with electron cooling carried out in Novosibirsk in 1974 have demonstrated the possibility of obtaining high cooling rates and low equilibrium temperatures[5,6]. Since that time, electron cooling has became important in advancing elementary particle and nuclear physics and even for atomic physics.

TEST BENCH FOR MAGNETISED COOLING

The high rate cooling at NAP-M stimulated to designed test bench with high magnet field at cooling section. Strong field solenoid up to 4 kG and low energy 1 MeV Van-De-Graff accelerator H^- beam used for verification of model magnetised electron cooling. The electron beam with energy 500 eV generated inside solenoid. Fig.2 show Andrey Sery measured cooling force [6].

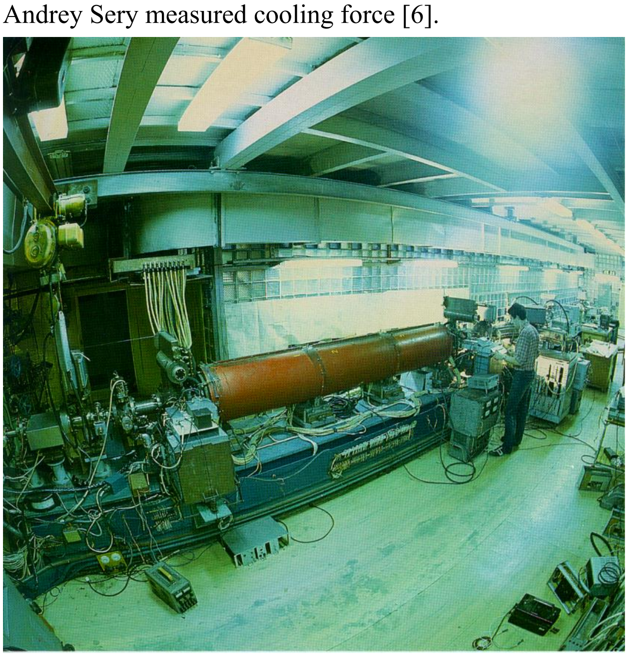

Figure 2: Test bench for direct measuring cooling force.

These experiments still are remain of basis for BINP electron coolers. As is seen (Fig.3), as the magnet field increases, the electron current at which the maximum cooling force is attained is increased.

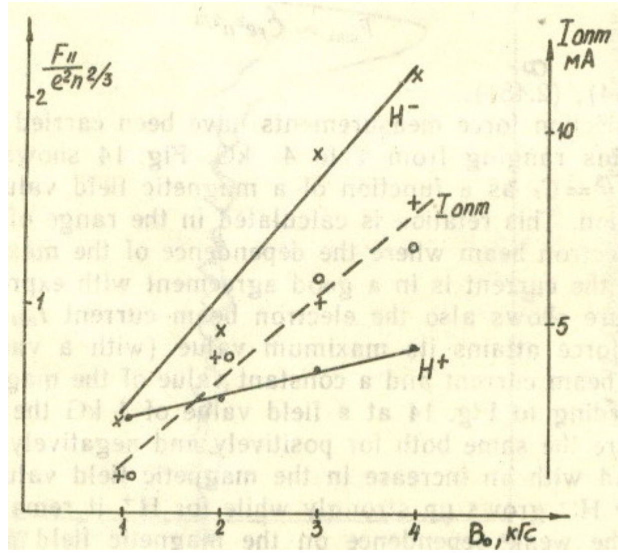

Figure 3: The cooling force F for H+ and H- versus magnet field at cooling section. Optimal electron beam current for maximum cooling force.

These results proved that to obtain maximally high cooling rate the high magnet field is great importance. And late, at next cooler BINP team try to used maximal magnetized electron beam for the electron cooling.

SIS-18 COOLER

At 1998 the new cooler for GSI synchrotron SIS-18 was designed and produced at BINP. The cooling rate increases for highly charged ions and it is attractive for fast beam accumulation especially for rear ions that can not produced with high intensity at ion source.

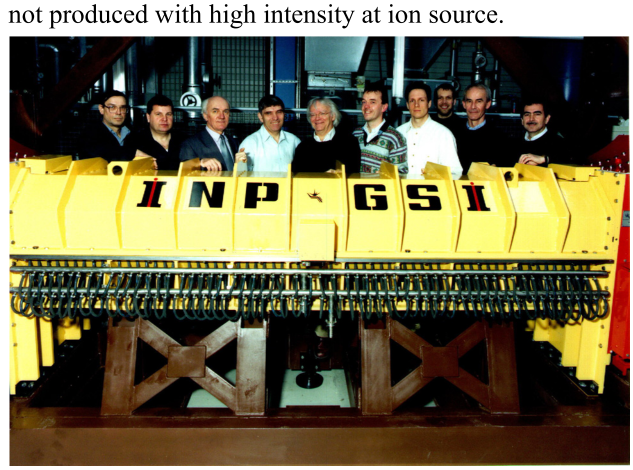

Figure 4: The electron cooler for SIS-18.

The design of this cooler had aim to made cooler for existing synchrotron SIS-18. Requirement for the cooler was to obtain high level reliability for long life time cooler operation (about 20 years). For obtain high cooling rate the straightness of magnet lines at cooling section should be as high as possible. The pancake coils for

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cooling section with the individual spacers for the adjust position of coils after magnetic line measurements used at this cooler(see Fig.4). High efficiency beam accumulation was demonstrated SIS-18 cooler [7]. But the high achievement of high-intensity and high brightness ion beams open possibility to development instability. The experiment with ion beams at CELSIUS and SIS-18 show that increasing electron beam density lead for same problems interaction storage dense ion beam with electrons. As results was invented idea to decrease the electron beam density at centre of beam (where high density ion beam) with keeping the electron beam density high at zone fresh injected ions beam where should be high cooling rate. For realization of this idea was designed new electron gun with variable electron beam profile [8]. With this electron beam it was possible to optimised cooling decreasing too fast cooling at centre storage ion beam zone.

CSRM AND CSRE COOLERS

China Institute of Moder Physics at Landzou was need for designed at this time (2000) coolers on 30 kV CSRm and 300 kV CSRe [9]. BINP team propose to made new generator coolers with the variable electron beam profile [8] and the electrostatic bending for decreasing losses electron current on vacuum chamber. Decreasing desorption help at many times decreased the vacuum pressure that extremely important for obtain long life time of the high charge ions beam.

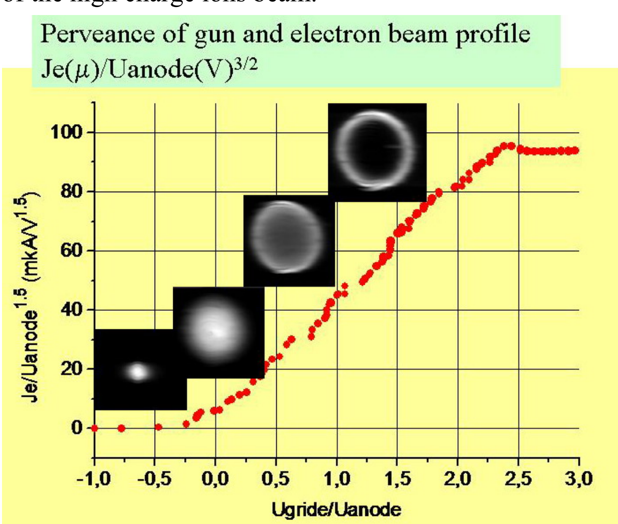

Figure5: Beam profile and perveance electron gun with variable profiles.

The electron gun with special electrode for changing profile demonstrated good performance for modification profile from narrow parabolic shape to hollow electron beam with almost empty central part as show fig 4. The CSRe (300kV) cooler was equipped the special high voltage generator installing at vessel with SF6 gas isolation. The connections high voltage terminal to the electron gun cathode and to electron beam collector was made with the concentric transmission line filled SF6 as show fig. 7. The electron cooling rate was sufficient high for repetition injection period 0.5 second for C^{+6} with energy 7 MeV/u. Fig.8 show example of cycle accumulation and them acceleration beam up to 600 M/u.

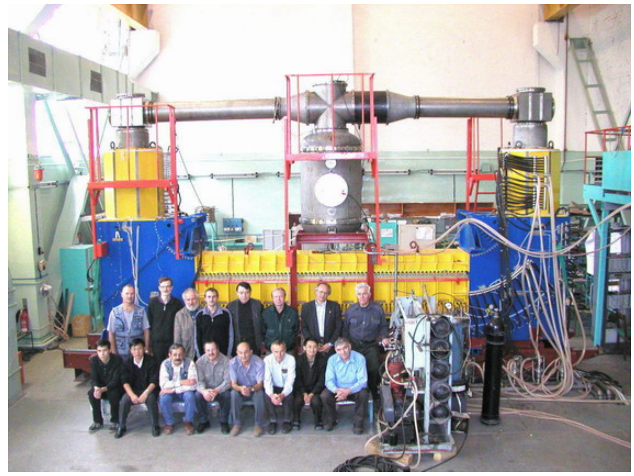

Figure 6: CSRe cooler after finishing commissioning at BINP.

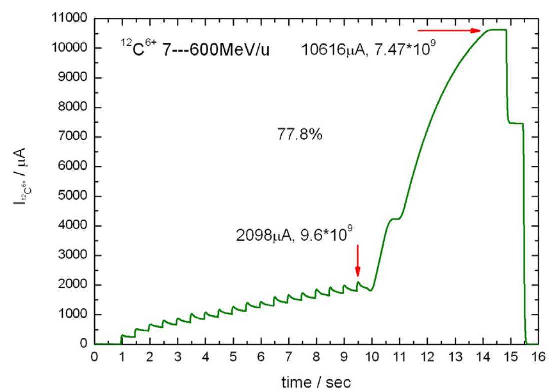

Figure 7: CSRm accumulation C beam and accelereation t0 600 MeV/u.

Successfully using at IMP China the carbon high quality ion beams for the hadrons therapy stimulated BINP team on development the special synchrotron with electron cooling system for cancer therapy. But ther is not too easy subject made same new for medicine and this project development very slowly

LEIR COOLER

The low energy cooler for LEIR was designed after commissioning CSRm and CSRe and it design include main features: electrostatic bending, electron gun with variable profile, possibilities of adjust vertical and horizontal angles pancake coils for good magnet lines straightness. Additional improvement was to using NEG pumping technology with NEG cassette installed near gun and collector and NEG coating the vacuum chamber at straight section. The good vacuum was very critical by using cooler for Pb^{+54} ions having high crossection capture electrons from the atoms residual gas.

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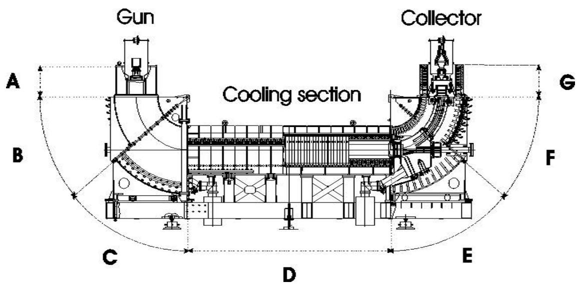

Figure 8: Schematic diagram of the LEIR cooler. A is the gun solenoid with the longitudinally varying magnetic field for expanding the electron beam radius, B and F are small 45-degree toroids with electrostatic deflecting plates, C and E are the main toroids for the joint ion and electron beams, D is the cooling straight section, and G is the collector solenoid.

Figure 9: LEIR cycle- two pulse of injection with electron cooling and them acceleration .

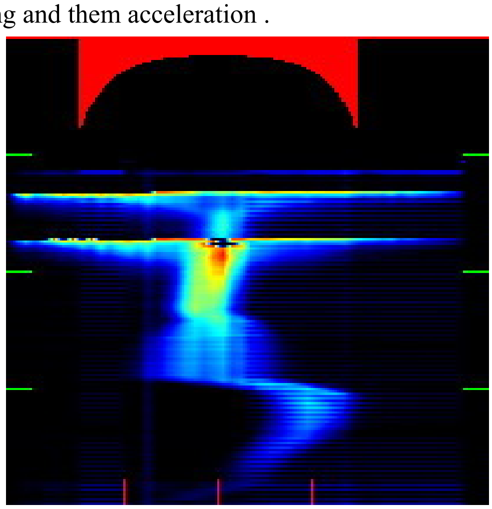

Figure 10: LEIR cicle- two pulse of injection with electron cooling and them acceleration .

Fig 10. show variation Pb ions beam horizontal profile at process injection, electron cooling and them acceleration. At top side of figure show (red) the electron beam profile used at this experiments. We can see shrinking the ion beam by electron cooling, clear see increasing equilibrium size by IBS after second injection and fasexpansion after swith off electron cooling (IBS) and then adiabatic cooling at time of acceleration. The electron cooling at LEIR help to prepare good bunches for operation LHC at ion*ion collision.

COSY COOLER

Now at BINP new high voltage cooler commissioned with electron beam. The electron cooler of a 2 MEV for COSY storage ring FZJ is assembling in BINP. The cooler sections is designed on the classic scheme of low energy coolers like cooler CSRm, CSRe, LEIR that was produced in BINP before. The electron beam is transported inside the longitudinal magnetic field along whole trajectory from an electron gun to a collector. This optic scheme is stimulated by the wide range of the working energies 0.1(0.025)-2 MeV. The electrostatic accelerator consists of 34 individual unify section. Each section contains two HV power supply (plus/minus 30 kV) and power supply of the magnetic coils. The electrical power to each section is provided by the cascade transformer. The cascade transformer is the set of the transformer connected in series with isolating winding. (fig.11) .

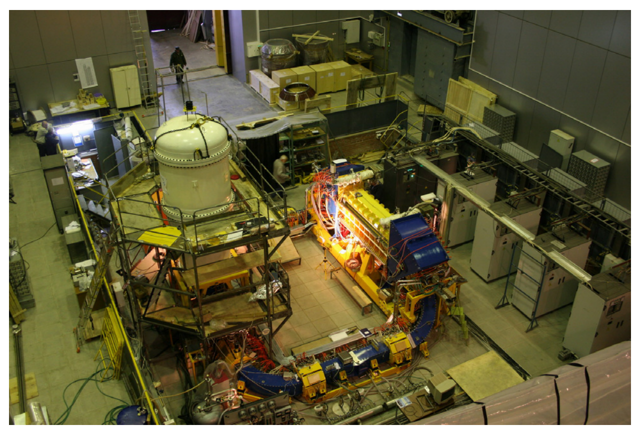

Figure 11: COSY cooler under commissioning at BINP.

The high voltage testing was made up to 2 MeV voltage and now the electron beam transport line with electron beam tuned for different energy. For 1 MV the electron beam current successfully 0 kV electron beam pass from the electron cathode to collector. The collector of this cooler consist form the usual collector and special filter with crossing the magnetic and the electric fields for suppressing back moving electron beam. The efficiency collector near 3E-3 and additional suppression the secondary electron flax from the collector about 100. So the efficiency of collector about 2E-5 and radiation level near cooler with 1 MV and 0.2 electron beam current near 0.01 Sv/hour. We hope that after final testing this cooler will sended soon at Julich for assembling again at COSY synchrotron.

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