NOVEL IDEAS IN ELECTRON COOLING

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Abstract

The development of electron cooling started in 1966 from proposal by G.I.Budker. He used this system for proton-proton colliders. Now electron cooling is used for many ions accelerators for shrinking ion beam emittance and for accumulation of rare ions beam at a very broad energy range. Many ideas were used for increasing the cooling power and many problems were opened at the time of this development. The new ideas for extended the energy of cooled beam will be discussed in this report. The energy of cooler up to 8 GeV is still required for HESR to suppress the scattering antiproton in inner target. The experience of commissioning a 2 MeV cooler is used. These results are a practical test bench for estimating different solutions for the cooling systems.

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 than 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. 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 ^{o}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 discovered 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 cool to temperature of about 1K. 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. 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.

IDEAS THAT WAS REALIZED AT COOLERS

1 An electron gun was put into a solenoid producing the longitudinal guiding magnetic field, which accompanies the beam until it reaches the collector [4]. As initially and up to now continues the discussion of the other alternative systems magnetic optic with using quadruples or wigglers magnets. But the all operated coolers have solenoid field at cooling section. The strong magnet field suppressed transverse motion of electrons.

2 The effect of magnetization the own transverse motion of the electrons help to reach the Kelvin range of the ion beam temperature [5,6]. The nice features solenoid field is the free motion the light electrons along magnet lines. It help to have the fast cooling by absorbing the kinetik energy of the moving ions. The kinematic suppression longitudinal motion of electrons after acceleration gives temperature close to 0 at the cooling section. The transverse motion by the space charge of electron beam should be suppressed the high longitudinal field (B).

$$V_{\perp} = c\frac{2\pi n_e e x}{B}$$

For testing cooling force for the magnetized electrons beam was designed cooling section with strong magnet field up to 4 kG show Figure 1 [7]. The proton or H$^-$ 1MeV beam after single pass the electron beam send at spectrometers for measure losses energy. Results measuring cooling force versus magnet fields shows Fig. 2. From this figure clear see that increasing magnet field open space for increasing the electron beam density (op-

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timal electron current) and significant increasing cooling force.

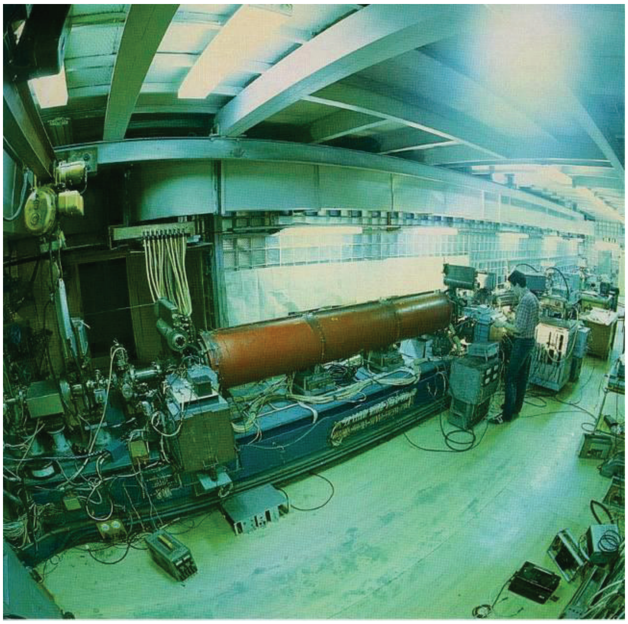

Figure 1: Test bench for direct measuring cooling force at strongly magnetized electron beam.

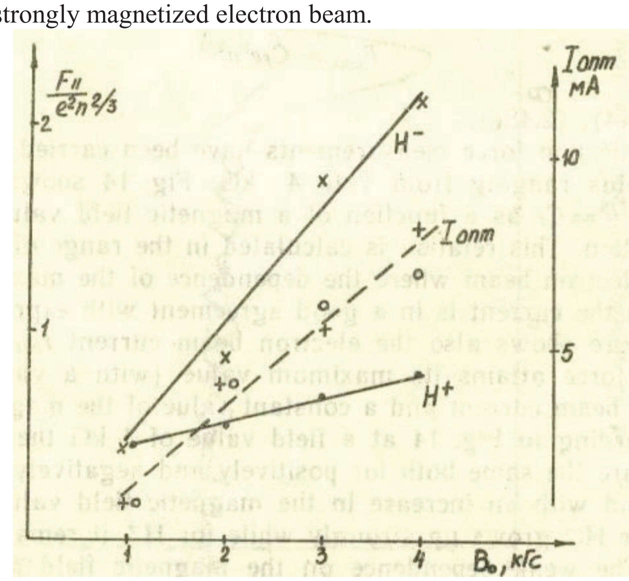

Figure 2: The cooling force F for H+ and H- versus magnet field at cooling section and optimal electron beam current versus magnet field.

After this results BINP team for the next coolers try to used the maximal magnetized electron beam for made the electron cooling rate as high as possible.

3 Compass for measuring and then correction the magnet lines straightness at cooling section [7] But good cooling required high straightness for having low effective electrons temperature.

4 Electron gun with variable profile [8] The cooling rate decreased with amplitude the betatron oscillation as cubic power amplitude. It means that central ions with amplitude 10 times less cooled down at 1000 time faster then ions with edge amplitude. As results at the center can formed very dense and instable core of an ion beam. Decreasing the central electron beam density increased the life time ion beam by the recombination capture.

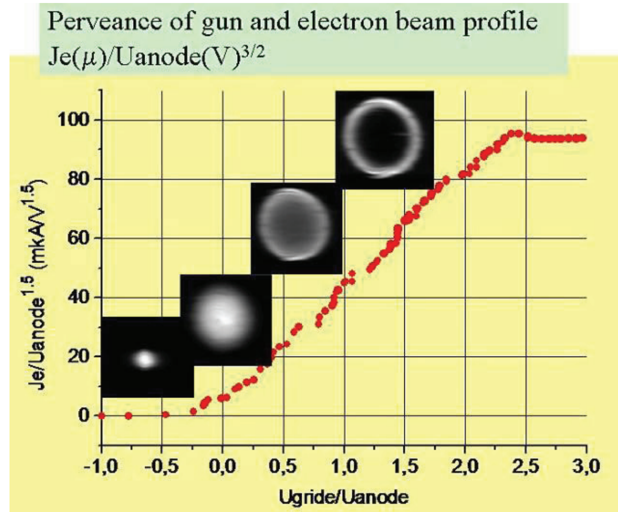

Figure 3: Beam profile and perveance of electron gun with variable profilec.

But the high density electrons for the high amplitude of ions compensated the kinematic decreasing cooling rate and return this ions at the core of ion beam.

5 Electrostatic field for compensation centrifugal drift electron beam [9]. The bend of electron beam inside toroids traditionally made with transfer magnet field turns electron beam with the same radius as turn solenoidal field line. But reflected from collector back moved electron have two times high drift and bombarded inner surface vacuum chamber. The idea used electric field first time was tested Tim Ellison. The first coolers that used the electrostatic bending installed at CSRm and CSRe. The currents bombarded vacuum chamber decreased at 100-1000 times that made vacuum at cooling section very good. Late we successfully used the electrostatic bending at LEIR cooler for obtain good vacuum condition increasing life time of high charge lead ions beam.

6 Low magnet field cooler for antiprotons beam TEVATRON [10]. The cooler system with low magnet field was realized at antiproton accumulator for TEVATRON. The cooling rate for this ring need to be not too high and optic system was optimized for single energy at the storage ring with permanent magnets. It was very effective and economical reasonable solution but not for fast cooled systems with high electron beam density.

7 Cascade transformer for powering solenoid sections along accelerator tube. The COSY 2 MeV cooler used local solenoid coils around acceleration tubes. At each high voltage section was PS for this coils and about 300 Wt power was take out from power feedthrough along cascade transformer to high voltage terminal. The core of this cascade transforme was made from amorphous iron that can used for AC current with frequency 20 kHz.

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8 Four electrodes modulation electron gun.

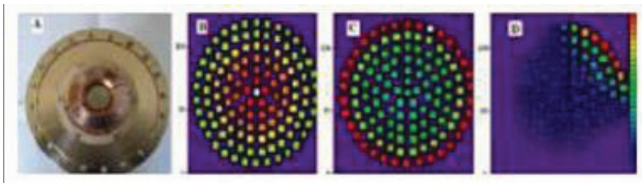

Figure 4: A is electron gun, B is parabolic shape with maximum at center, C- hollow beam with minimum at center, D- with positive voltage on the single sector.

The symmetrical modulation of beam show at signal pick-up electrodes the center of beam. Slow changing magnet field change phase of Larmor rotation and looking on cycle at plane Y-X we can measure radius of transverse rotation of beam. Using 2 short dipole magnets kicked the electron beam at Y, X direction we compensated this rotation as show Figure 4. Initially radius rotation was 1.5 mm and after correction was 0.1 mm, that correspond changing energy of transverse rotation (at beam system) at magnet field 1.5 kG from 4 keV to 17 eV!

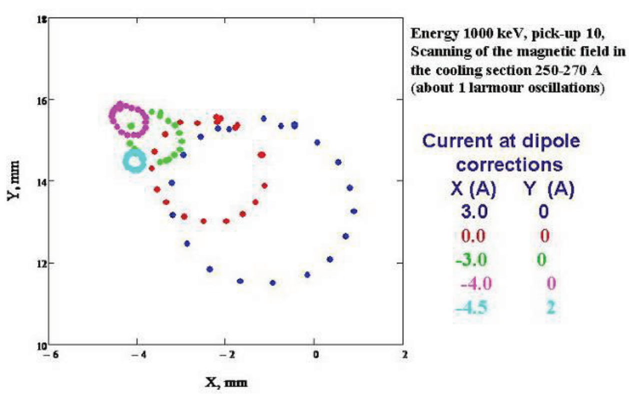

Figure 5: Minimization of Larmor rotation radius of electron beam at cooling section. The minimal radius was obtain for -4.5A for X corrector and 2 A at Yl correctors.

The four sectors modulation electrodes at the new electron gun for COSY cooler open interesting possibilities at the electron beam diagnostic. Initially this idea was invented for the generation 3D electric field fluctuations that can be used for stochastic cooling. The four off center AC electron beam used at time of commissioning cooler at Novosibirsk for carefully investigation magnet optic not only at central orbit. Figure 4 show variation of position Y, X for 4 different fractions of electron beam and symmetrical modulation (all 4 sectors have the same RF voltage) show stable position center of electron beam. It indicated existing not only dipole (synchronic) rotation of electrons but existing and quadruple Larmore rotation with amplitude increasing to edge of the electron beam.

The influence of the space charge of secondary ions accumulated inside of the electron beam was clear measured as changing slow spiral drift motion of the fore fractions

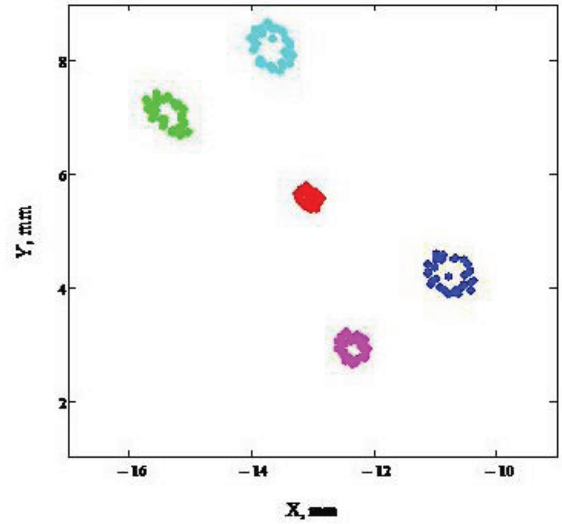

Figure 6: Measuring variation positions of 4 edges beams and central beam (when all 4 sectors have the same RF voltage) with variation magnet at cooling section. Clear see quadruple motion of edges beams.

of electron beam along cooler. Now new high voltage cooler commissioned with electron beam at BINP and assembled in COSY ring (see reports V.Reva and S Kamerdjiev COOL13) [19].

Figure 7: COSY cooler arrived at COSY hall (end 2012).

IDEAS THAT STILL WAIT REALISATION

1 The idea increased the cooling rate by amplification the cooling force with using instability at electron beam was discussed from 1980 [11]. The system should operate as different high frequency electronic tube with using intensive electron beam. Development of this idea at BNL [12] looks as the high energy FEL where initial fluctuation produced moving ion then electron beam pass line with amplification this fluctuation and then electron beam return at ion beam for kicking this moving ion at the

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proper directions for cooled down ions beam. Idea looks very promising but the test bench for demonstration of coherent electron cooling looks very expensive.

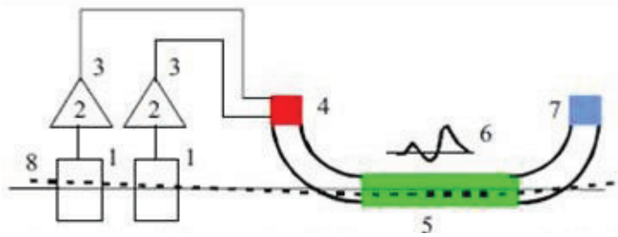

Figure 8: The stochastic cooling with using electron cooler as kickers.

2 One of the first step at direction the full scale coherent cooler can be normal cooler that can produce required plasma fluctuation at the electron gun [13], see Fig. 7. Experimental electron gun for this purpose was made at BINP for COSY cooler. At this system motion of the ions at beam measured normal pick-up and the special electronic system prepare pulses for kicking at X,Y and s direction. This signals gain with using normal (for stochastic cooling) high band amplifiers and then send in the electron gun for produce 3D fluctuation fields that will moved synchronous with ions sample at cooler. For COSY system as prototype of HESR cooler results can be very interesting. And the spending on this experiments look not too high. After successfully testing for low energy cooler this technology can used and for RF recuperators for made the electron cooling system for very high energy storage ring (for example RHIC).

3 The storage ring with longitudinal magnet field for generation high energy intensive electron beam looks suitable for using [14]. But the very strong focusing and very high tune for this type storage ring need new ideas at magnet optic for the compensation overlapping transverse resonances. The life time at model this system LEPTA demonstrate decreasing life time of beam with increasing energy of the electron beam Fig. 6.

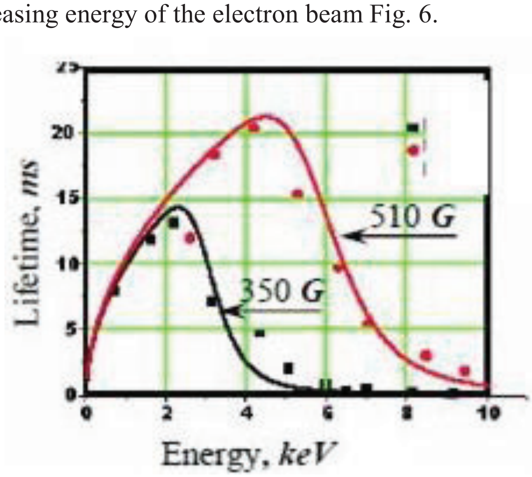

Figure 9: Life time beam in LEPTA vs. electrons beam energy for different magnet fields.

At COSY cooler we can see excitation of the transverse rotation at time of the single pass beam (shown in Fig. 4 and Fig. 5) for few times more high energy and magnet fields. How to build the magnetic optic not sensitive for this phenomenon are still open question. For system with strong longitudinal field effective tune $Q_{\perp} = Circ/(pc/eBs)$ for 500 Gs and energy 10 kV near Q=700 and so strong focusing ring need new optic for having the good dynamic aperture.

More easy solution can be recycler system with low frequency RF as used for FEL. At this systems single pass electron open perspective obtain extremely low emitance of electron beam. The RF linac cooling system was designed for RHIC cooler [15].

4 .The carbon therapy system with using electron cooling still dream of our BINP team [16]. Few years ago started project with China company but economic crisis stopped development this idea. Few experiment with cooling carbon beam demonstrated high quality of cooled on energy 400 MeV/u carbon beam fig 9. Nice results of treatment (CSRm, IMP) with using carbon beam stimulated BINP continue efforts at development system with using cooling system. The cooling storage ring open new method for treatments with high energy ions. The cooler open perspective to used the injection system more simple and the reliable.

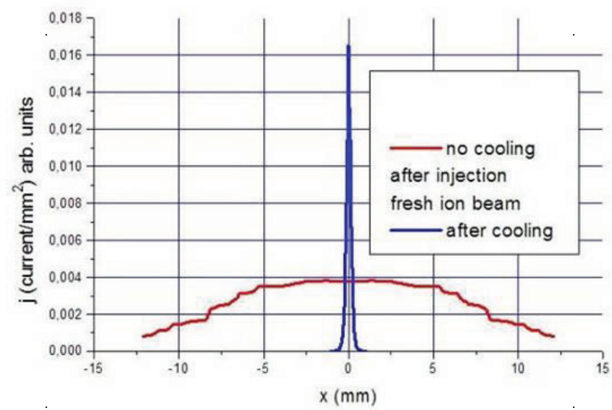

Figure 10: The transverse profile carbon beam at CSRe on 400 MeV/u before cooling and after.

For example, the positron emission ion beam can be accumulated after conversion main beam form buster on target.

5 The cascade transformer looks optimal up to 2 MeV energy for powering solenoids along acceleration tube. For this cooler used 33 sections of cascade transformer and decreasing voltage from initial ring to final about 10-15%. It is clear that for 8 MeV cooler this solution looks impossible by too strong decay of the initial voltage. At the collaboration with COSY team [18] we development pneumatic electrical generator with using pressed gases SF6 and individual generator for each sections along high voltage columns Fig. 8.

The prototype of this generator was made and tested with high voltage sections. But life time of our generators was not satisfied requirement and we turn to cascade transformer for this project. From the point of design, using turbine generators is still interesting by combination of the many advantages. Using turbine we can produce

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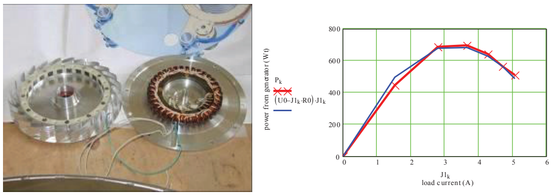

Figure 11: Prototype of turbine generator and results of measuring loading efficiency.

energy at any place inside high voltage system. The exhaust gas, with low temperature after turbine, will use for cooling the magnet and the high voltage power supply. We successfully used our prototype turbine generator at Acceleretor Mass Spectrometers for many years.

At nearest future we hope to continue the collaboration with:

• Forschungszentrum Jülich (FZJ), Institut für Kernphysik Dr. V. Kamerdzhiev

• Technische Universität Dortmund (TUD), department of physics, Accelerator Physics, Prof. Dr. Dr.h.c. Jürgen Dietrich

• Budker Institute of Nuclear Physics (BINP), 63090 Novosibirsk, Russia, Prof. Dr. V.V. Parkhomchuk.

The subject will be a 4 MV relativistic electron cooling system for the High Energy Storage Ring (HESR) for antiprotons of the Facility for Antiproton and Ion Research (FAIR) at the GSI in Darmstadt. Up to now such an ambitious electron cooler is not realize at the technical design. The investigation include an upgrade to 8 MV for the future Electron Nucleon Collider project (ENC@FAIR).

CONCLUSION

Electron cooling demonstrate high potential to obtain high brightness ion beams. The energy range of cooled ion beams from 0 to 8 GeV was used. There exist many ideas not yet realized, that can increased the potential of using electron cooling. I hope more interesting ideas will be discovered in the near future, maybe during discussion at our COOL13 workshop.

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