# ELECTRON COOLING

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**In the report presented here the description is given of the history of electron cooling development. Electron cooling was proposed by the founder of INP, G.I.Budker in the middle of 60's and was experimentally studied at INP. The results of experimental test turned to be much better than expected that stimulated the use of this technique at many world known accelerator laboratories. The results of commissioning electron cooler for heavy ion synchrotron GSI developed and manufactured at INP in 1996-97 are given.**

## 1 The history of electron cooling

### 1.1 *Primary idea*

In 1966, G.I.Budker proposed the method of electron cooling [1], based on the transfer of proton oscillation energy to cool an electron beam accompanying the proton beam with the same average velocity. In the process of cooling, the particles travelling in an electron beam are subjected to various occasional pushes leading to a diffusion growth of the squared momentum deviation. In the simplest case, when the main diffusion is bound up with electron temperature motion, the equilibrium state corresponds to equilibrium in the temperatures of the electron and ion beams, and consequently the spread in the velocities turns to be described by the following relation:

$$< V^2 >= \frac{m}{M} < V_e^2 > \qquad (1)$$

(V is the particle velosity, $V_e$ is the electron velosity, m and M are masses of electron and cooled particle, respectively). The development of electron cooling kinetics in papers by Ya.S.Derbenev and A.N.Skrinsky [2] enabled one to select the parameters and start the development of NAP-M facility for experimental test of the method in 1971. Even in the first attempts of the cooling system development for the transportation of electron beam it was suggested to use the magnetic field and electron beam energy recuperation after its passage through cooling section [3].

### 1.2 *The first facility with electron cooling-NAP-M*

The first installation with electron cooling was commissioned in 1974. The installation consisted of the proton beam injection, Van-de-Graff accelerator at an energy of 1.5 MeV, a 150 MeV synchrotron with a possibility to stop acceleration at any energy and carry out experiments at constant energy, and an electron beam installation. The NAP-M facility parameters are given in Table 1.

| | |
|---|---|
| Circumference (m) | 47.2 |
| Lengh of cooling section (m) | 1 |
| Energy of proton beam (MeV) | 1.5-150 |
| Energy of electron beam (keV) | 0.7-75 |
| Electron beam current (mA) | 2- 500 |
| Radius of electron beam (cm) | 1-2 |
| Proton beam current (mA) | 0.02-2 |

Table 1:

The magnetic system consisted of four magnets with bending radii of 3 m and straight section of 7.1 m in length. For the successful operation of the storage ring it was necessary to provide good vacuum of $\sim 10^{-10}$ Torr. This was related to the use of simple nonlaminated magnets which put limits on the energy rise and at low injection energy, the beam lifetime was only a few seconds. The operation cycle is the following: the proton beam is injected into an increasing magnetic field and upon attainment of required energy the field rise stopped, the accelerating voltage is switched off and electron beam installation is switched on for cooling.

During the development of NAP-M device, special attention was paid to measuring devices of cooled beam parameters. Thin wires intersecting at high speed the beam and thin magnesium vapor jets were used. In the magnesium jet method, the ionization of magnesium vapour was detected to be proportional to the proton beam density. By putting the magnesium jet into the center of proton beam one can measure the expansion of the proton beam after kick and then the decrease in its size during the process of electron cooling. These measurements are presented in Fig.1.

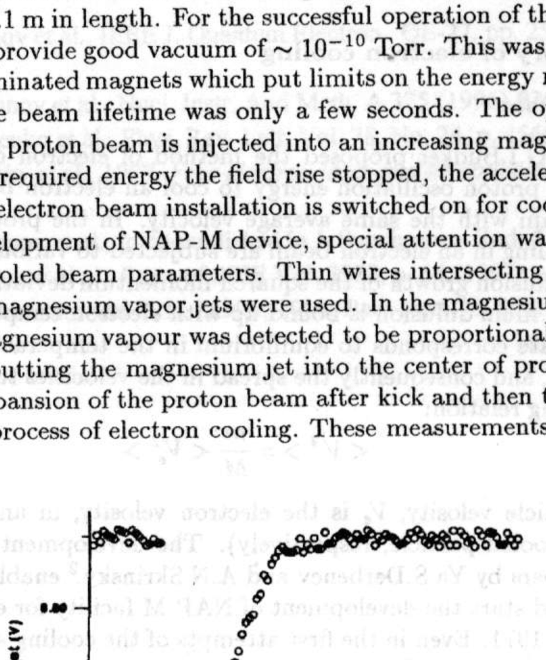

Figure 1: The signal Mgjet monitor after exciting the betatron oscilation by the kicker.

### *1.3 Discovery of fast electron cooling*

In the first electron cooling experiments, the cooling times were obtained to be 1-2 s that was in a good agreement with primary estimates but during the measurement of the dependence of the longitudinal electron cooling on the proton beam energy deviation it was found out that longitudinal temperature of electron beam is practically zeroth because of electrostatic acceleration on electron gun. At acceleration in a longitudinal magnetic field the electron transverse momentum does not change in practice and an energy of electron transverse motion is close to the energy of thermal motion on the hot cathode $\Delta E_\perp \sim T_c$. Different situation occurs for the longitudinal motion $\Delta E_\| = p\Delta V_\| \sim T_c$ which causes the temperature in an accompanying system to be:

$$T_\| = \frac{T_c^2}{\gamma^2\beta^2 mc^2} \sim T_c \frac{T_c}{2E_{kin}} (for \beta << 1), \tag{2}$$

($E_{kin}$ is the kinetic energy of electrons in a beam).

At an energy of electron beam of 20-50 kV the decreasing factor for longitudinal temperature becomes so strong 0.1/20000 , that in accompanying system, the motion of electrons along the beam can be neglected. As a result of cooling by such a "flattened" electron beam the force of longitudinal cooling grew nearing the average electron velocity and jumpingly changed its sign when exceeding its mean velocity. The cooling decrement proportional to the friction force derivative:

$$\lambda = \frac{dF_\|}{M dv}, \tag{3}$$

turned to be hundred times larger than its primary estimates. The discovery of this phenomenon changed the understanding of the electron cooling kinetics for the transverse direction too [6, 7]. The matter is that the Coulomb interaction is important at large impact parameters too. During the particle pass at impact parameter $\rho$ with relative velocity $V$ the particle with a charge $Ze$ transfers to electron the momentum to be equal to

$$\Delta p = \frac{2Ze}{V\rho}. \tag{4}$$

During the motion in an electron beam the total friction force consists of contributions from various impact parameters:

$$\vec{F} * \vec{V} = -\int \frac{\Delta p^2}{2m} n_e 2\pi\rho V d\rho = -\int \frac{4\pi n_e Z^2 e^4}{mV} \frac{d\rho}{\rho}. \tag{5}$$

As it is easily seen, the contributions into the total energy loss from the range $10^{-5} < \rho < 10^{-3}$ is the same as that from the range $10^{-2} < \rho < 1$. This is relevant for the case of the same value of relative velocity. Let us recall now that an electron beam is in the magnetic field and in the transverse direction electrons are rotated along the Larmour circle with a radius:

$$\rho_L = \frac{mV_\perp}{eH} \sim 10^{-3} \quad cm (H = 1kGs). \tag{6}$$

Then, during the collisions of a slowly moving particle at distances $\rho > \rho_L$ the relative velocity is only determined by low particle velocity but during the collisions at short distances $\rho << \rho_L$, the fast transverse motion of electrons attenuates strongly the contribution from this range of distances. The cooling by such a "magnetized" electron beam led to the discovery of a fast electron cooling in transverse direction too [10, 7, 11]. As is seen from Fig.1, upon upgrading the NAP-M facility, the cooling time of transverse oscillations decreased down to 0.05 0.1 c. These improvements were mainly related to the magnetic field quality in order to decrease the cross angles of the force lines at cooling sections.

### *1.4 Supercool proton beam*

The proton beam cooling by super cool "Larmour" electron "circles" enabled one to attain low temperature of a proton beam. Instead of 1000 K (cathode temparature) the proton longitudinal motion was managed to be cooled down to up to 1 K. The standard method for measuring an energy spread in proton accelerators consists in kicking out a small fraction of a proton beam along its orbit and in observing by pickups how fast this "hole" is washed off due to longitudinal motion of particles. Experiments at NAP-M revealed that particle velocities excited by the spatial charge fields on the edges of the "hole" exceed thermal motion velocities of protons even at currents of a few microamperes. The most appropriate method for measuring longitudinal temperatures turned to be the method of measuring the so-called "Shottky noises" by longitudinal pickups. Each particle of a beam passing the pickup electrode produces the short voltage spike repeated with rotation period of this particle ($T_i = 2\pi\omega(p_i)$). If the beam particles can be considered independent, the total power spectrum would consist of $\delta(\omega T_i)$, where the periodical delta function is determined as follows:

$$\delta(\theta) = \sum_{n=-\infty}^{\infty} \frac{e^{in\theta}}{2\pi}. \tag{7}$$

In the beam of N particles, near some specific rotation harmonic $n\omega_0$, N such picks will be observed with a frequency spread depending on spread momenta $\Delta\omega = n\eta\omega_0\Delta p/p$. The width of such a spectrum is proportional to the spread of momenta and a power is proportional to the number of particles in a beam. In the first experiments on the observation of these beam signals we have seen the beam noise spectrum prior to cooling and after cooling, the signal decreased sharply and vanished in noises of electronics instead of spectrum compression with an increase in amplitude as it was expected.

The theoretical analysis was performed for cool beam noises [8] and the quality of measuring electronics was improved [9]. As a result of this analysis it was found out the informatively reach measuring technique. It was turned out that the inner pushes of particles in a cool beam lead to quite strong suppression of the Shottky noises. Kinetic energy of particle motion turns to be insufficient for the motion of particles independent of each other along the orbit. It is clear that at zeroth temperature, the relative particle motion freezed completely and particles are distributed homogeneously along the orbit. The characteristic of particle interaction in a beam is the coherent shift value:

$$\Omega_n^2 = (n\omega_0)^2 \frac{Nr_i(0.5 + ln(a_{chumb}/a_{beam}))}{P\gamma^3\beta^2}, \tag{8}$$

where $r_i$ is classic ion radius, P is storage ring circumference, $\omega_0$ is rotation frequency, n is the rotation frequency harmonic number along which the measurement is performed. The spectrum amplitude calculation can be given in the form:

$$|A_n|^2_\omega = \frac{N}{2\pi}\left(\frac{n\Delta\omega}{\Omega_n}\right)^2 \frac{Im(\epsilon(\omega))}{|\epsilon(\omega)|^2}, \tag{9}$$

where $\epsilon$ is an efficient specific inductive capacitance which can be given in the form of a series:

$$\epsilon(\omega) = 1 + 2\left(\frac{\Omega_n}{n\omega_0}\right)^2 * \left(1 + \frac{i\omega}{q\lambda - i\omega} * \left(1 + \frac{q}{1 + q - i\omega/\lambda} + \frac{q^2}{(1 + q - i\omega/\lambda)(2 + q - i\omega/\lambda)} + ....\right)\right), \tag{10}$$

$q = n\Delta\omega/\lambda$.

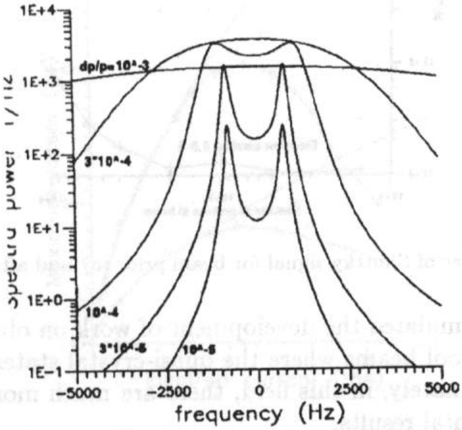

Figure 2: Spectra of Shottky signal on 25 harmonic for different momentum spread at the proton beam.

Fig.2 shows the change of fluctuation spectrum near n=25 harmonic of rotation frequency for NAP-M facility parameters with a decrease in an energy spread in a beam. It is seen that the spectrum initial narowing is limited as soon as the thermal spread $\Delta\omega$ achieves the value of the coherent shift and then, the spectrum becomes to be a two-peak spectrum at frequencies $n\omega_0 \pm \Omega_n$. This means that fluctuations remained only in the form of two longitudinal waves travelling along and opposite the beam direction. The total power of a signal around nth-harmonic is:

$$|A_n|^2 = \frac{N * N_{th}}{N + N_{th}}, \tag{11}$$

where the threshold number is determined by the equation:

$$N_{th} = \frac{N * (n\Delta\omega)^2}{2\Omega_n^2} = \frac{P\eta(\Delta p/p)^2\beta^2\gamma^3}{2r_i(0.5 + ln(a_{chumb}/a_{beam}))}. \tag{12}$$

Fig.3 shows the thermal noise measurement results for a proton beam prior and after cooling for various values of proton current. It is seen that after cooling, the noise power decreases more than by two orders of magnitude and for low proton currents, it is independent of the beam current. In this region, the noise value corresponds to the momentum spread according 12 to be equal to $\Delta p/p = 10^{-6}$, thus meaning that longitudinal temperature value is 1 K.

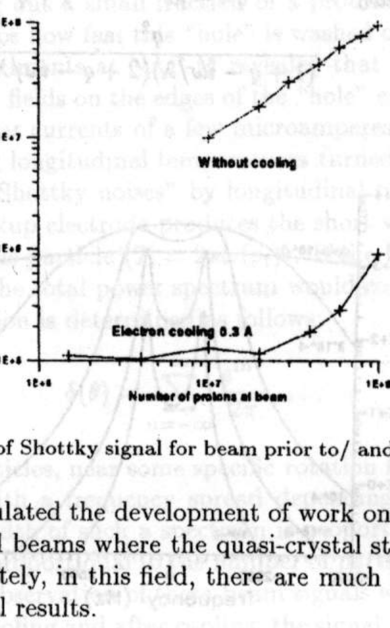

Figure 3: The power of Shottky signal for beam prior to/ and after electron cooling.

These results stimulated the development of work on obtaining and studying properties of super cool beams where the quasi-crystal states of a beam could be observed [12]. Unfortunately, in this field, there are much more theoretical predictions than experimental results.

### 1.5 *Study of electron cooling in precise solenoid*

The discovery of electron cooling served as a basis for the development of a single flight system for studying electron cooling in a wide range of parameters. In such a scheme, one could have a large magnetic field in cooling section without taking care of the closed orbit distortion. In the so-called MOSOL-installation, the magnetic field of up to 4 kG was produced in the length of 3 m by a precise solenoid where the force lines were $10^{-5}$ in parallel. High density of an electron beam enabled the reliable measurement of friction force with 0.9 MeV proton beam. The high precision spectrometer for measuring the proton beam energy was placed at the output of electron beam section. Fig.4 shows the measurement results for ion beam energy variation $\Delta E = F * l$ (F is a friction force, l is length of cooling section). It is seen that at an electron beam velocity lower than the ion velocity, electrons decelerate ions but at slightly higher energy, ions are accelerated.

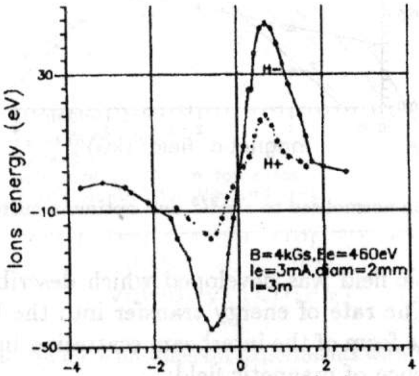

Figure 4: The energy losses after pass the electron beam for H+ and H- ions .

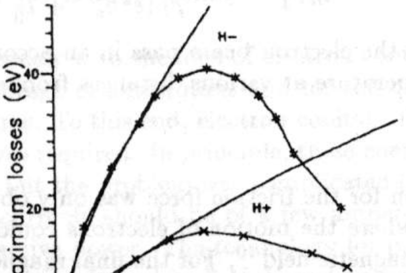

Figure 5: The friction vs. electron beam current .

With the electron current rise the cooling effect becomes stronger but, in this case, an efficient temperature of electron beam increases and from some value of beam density the cooling efficiency decreases as shown in Fig.5.

In principle, an increase in magnetic field enables one to decrease an influence of spatial charge of electron beam and to increase the useful density of electron current. The results of such measurements are given in Fig.6.

For the description of these effects a simple model for interbeam scattering at

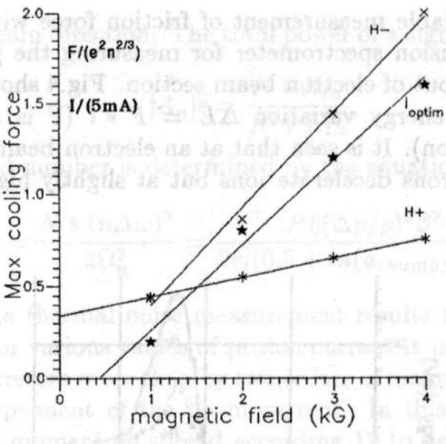

Figure 6: The friction normolised to $e^2n^{2/3}$ and optimum current at units 5mA .

the presence of magnetic field was developed which describes these results more or less completely[13]. The rate of energy transfer into the longitudinal degree of freedom is written in the form of the interbeam scattering inside an electron beam suppressed by the presence of magnetic field:

$$dT/dt=\frac{2\pi e^4n_e}{mV_\perp}exp(-\frac{2.8e^2}{\rho_L(e^2n_e^{1/3}+T_{||}}) \tag{13}$$

By integrating along the electron beam pass in an accompanying system, we get the longitudinal temperature at various distances from electron gun.

### *1.6 Friction force*

Analytical expression for the friction force was only obtained for the case of a strong magnetic field where the motion of electrons could be considered to be proceed only along the magnetic field[10]. For the final magnetic field, one can use a simple formula matching the friction force and experimental results[14]:

$$\vec{F}=-\frac{4e^4n_e}{m}\frac{\vec{V}}{\sqrt{V^2+V_{effe}^2}^3}ln(\frac{\rho_{max}+C_z\rho_{min}+\rho_L}{\rho_{min}+\rho_L}), \tag{14}$$

where $V_{effe}=\sqrt{V_{||e}^2+\Delta V_{\perp e}^2}$, $\Delta V_{\perp e}$ is the transverse motion of electrons affected by the magnetic and electric fields, $\rho_{max}=min(V/\omega_e,\tau V,a)$, $C_z=1$ for positively charged particles and $C_z=4$ for negatively charged particles,$\rho_{min}=e^2/mV^2$, $\tau$ is the time of interaction with an electron beam, V is particle velocity, $V_e$ is an electron velocity, $\omega_e$ is plasma frequency. Fig. 7 shows various experiments and fitting curves calculated by this equation. By using these formulae and experimental data we can predict with quite high accuracy the cooling rate and established temperatures in the design of new facilities with different parameters.

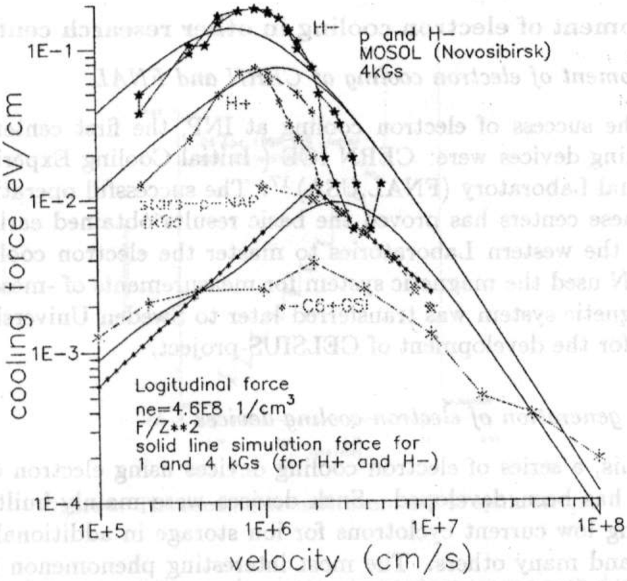

**Figure 7: The friction force for different experiments with fitting line .**

### *1.7 High voltage device for electron cooling*

Actually, simultaneously with the idea of electron cooling A.N.Skrinsky suggested its use for the storage of antiprotons and for the development of proton-antiproton colliding beams. To this end, electron cooling of electron beams in the energy range 2-5 MeV was required. In principle, these energies of electron beams were already attainable but the problem was complicated by the fact that in this cas, minimum electron currents should be of a few amperes that corresponds to tens of megawatts of reactive power. The technology for producing industrial accelerators with energy ranging from 1 to 3 MeV and power of up to 100 kW was developed at the Institute. The decision was made to develop the device for recuperation of an electron beam energy on the basis of such accelerators at an energy of 1 MeV and current of 1 A. Such a device enabled one to verify the principle of energy recuperation at high voltage and to study the behaviour of accelerating tubes during the acceleration of the ampere beams without use of quite expensive megawatt devices[15]. The longitudinal magnetic field of up to 900 G was produced in a simple solenoid embracing the accelerating tube, drift section, and decelerating tube with collector. The beam energy of 1 MeV and beam current of 1A were obtained at a minimum loss not exceeding 0.2 mA. The experiment demonstrated that high stability of voltage and quiding field are necessary. The energy pulsation inevitable in simple rectifier caused the beam trembling and some difficulties in obtaining stable low losses. In this experiment, the reactive power of 1 MW was first obtained in electron cooling device.

## 2 Development of electron cooling in other research centers

### *2.1 Development of electron cooling at CERN and FNAL*

After the success of electron cooling at INP, the first centers constructed electron cooling devices were: CERN ICE ( Initial Cooling Experiment )[16] and Fermi National Laboratory (FNAL,USA)[17]. The successful operation of electron cooling at these centers has proved the basic results obtained earlier at NAP-M and enabled the western Laboratories to master the electron cooling technique. ICE at CERN used the magnetic system for measurements of -meson momentum and this magnetic system was transferred later to Sweden University at Uppsala as the basis for the development of CELSIUS-project.

### *2.2 Second generation of electron cooling devices*

After this, a series of electron cooling devices using electron cooling in real experiments has been developed. Such devices were mainly built in heavy ion centers having low current cyclotrons for ion storage in additional storage rings [18, 20, 19, 21] and many others. The most interesting phenomenon found out out with these devices was the discovery of the so-called electron heating which was the most vividly demonstrated at CELSIUS[20]. With the attempt of cooling high proton current stored with the charge-exchange injection the major fraction of current was lost. The authors attributed this phenomenon to the nonlinear dynamics due to the distortion of optics in the presence of a limited electron beam. The strong increase in an electron beam size did not improove the situation. To my mind, this phenomenon is the display of the ion coherent interaction with an electron beam similar to a two-beam instability being developed at relative motion of beams. This problem is discussed in more detail in[14]. In conclusion, I will just list the facilities with electron cooling: LEAR, IUCF, CELSIUS, TARN2, TSR, ESR, SIS+cooler, CRYRING, ASTRID, COSY.

## 3 Participation of INP in the development of electron cooling devices

### *3.1 Cooler for heavy ion synchrotron SIS at GSI, Darmstadt*

The successful operation of electron cooling at ESR[19], inclined GSI physicists to the decision to equip their old synchrotron SIS with the cooler for storing heavy ions. The synchrotron is used for the storage with the charge-exchange injection of ions from the UNILAC linear accelerator with their further acceleration up to 2 GeV. For some kind of ions there is a problem in attaining sufficient intensity at the linac output but the use of electron cooling will allow the multiple injection and storage of such ions prior to their acceleration. The project of such a cooler was developed[22] and the magnetic system, electron gun, and collector were manufactured at INP for GSI. In April, 1998, the electron cooling system was commissioned and the first results on storage were obtained .Fig. 8 shows the Kr-ion storage by the multiple injection and further acceleration with fast rise of current during the acceleration.

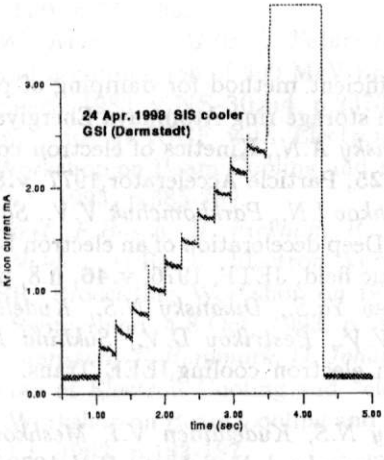

Figure 8: The accumulation Krbeam at SIS synhrotron .

In the development of the cooler magnetic system, some new design principles were used for the design of precise solenoid. Short multiwinding sections were manufactured with normal accuracy and the section parameters were measured on a specially constructed stand for magnetic measurements. Additional processing of each section surfaces according to measurement results enabled us to achieve the required accuracy in the direction of magnetic field force lines better than $10^{-4}$, and with the use of correction coils - better than $10^{-5}$. The development of this technology for long solenoids will also enable the use of electron cooling at high energies where requirements to accuracy are even more rigid.

### *3.2 New projects with the use of electron cooling*

The use of electron cooling at electron beam energy 5-300 keV, corresponding to energies 10-500 MeV/n, became to be well known technique.In this field, now available are, for example, K4-K10 project at Dubna and chinese project of the heavy ion facility at Lanjou. The most serious project is related to the use of electron cooling for the improvement of operation of the proton-antiproton collider TEVATRON [23]. In this work, it is planned to use electron cooling with a beam energy of 5 MeV for cooling and storing antiprotons in a special recirculator ring. Another project at GSI[24] studies the feasibility of obtaining ion-electron collisions with the formation of the ion beam emittance by electron cooling at an energy of up to 50 GeV/n. These and higher energies require new schemes of electron beam formation. The simplest scheme seems to be that where an electron beam is generated in a linear accelerator at continuous operation run [25]. A study of optical schemes of highly intense electron beam formation with recuperation of energy from RF generators is in progress and on this way we expect interesting discoveries and inventions.

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