Electron Cooling of Hadrons in GeV Energy Range

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Abstract

The electron cooling is used for accumulation of beams and shrinking emittance of ions: from p up to uranium ions. Today electron cooling is used for ions relatively small beam energy 1-200 MeV/n that corresponds to electron beam energy 0.5-100 keV. At this report the different variant of the systems of electron cooling for high energy beams are discussed. The project of electron cooling system of Fermilab Recycler Ring is use as example for beams parameters list. The results of study using of electron cooling for project Electron Nucleon Collider (ENC) are presented. The limitations for beam parameters and possible problems are discussed.

1 BASIC PARAMETERS OF ELECTRON COOLING

The electron cooling method was suggested by G. Budker in the middle sixties. The original idea of the electron cooling was published in 1966 [1]. The design activities for the NAP-M project was started in November 1971 and the first run using a proton beam occurred in September 1973. The first experiment with both electron and proton beams was started in May 1974. In this experiment good result [2] was achieved very close to the theoretical prediction for an usual two component plasma heat exchange. But the basically new results about electron cooling were obtained a few years later following experimental and theoretical investigation [3]. The magnetic field 'magnetizes' the transverse electron motion, and as a result the cooling particles interact with a cool Larmor circle, but not with a hot free electron. The effective temperature of a Larmor circle is only 1° K but free electrons have temperature of over 2000° K! A temperature 1°K of the particles' longitudinal motion was obtained for a proton beam with an energy of 65 MeV. The class of phenomena discovered aroused so much interest that the authors specifically called the process 'fast electron cooling'. The main results about this magnetization cooling were obtained at 'MOSOL' facility with very intensive electron beam and magnetic field up to 4kGs [4],[6]. The fast cooling can used electron beam with high temperature and transverse motion of electrons (transverse emitance) is not decrease the cooling rate. Therefor only magnetized regime can be used for obtain reasonably small cooling time at high energy .

The Recycler is fixed 8 GeV kinetic energy storage ring for refresh antiproton beams from Accumulator and the Tevatron Collider and to inject more antiprotons into the Tevatron. The effective stacking rate can be increase by cooling antiprotons and reintegrating them into the Recycler stack. At the system of reference the rest beams the parameters of cooling antiprotons (for beta function 200 m, normalised emittance 1 π μm and $\Delta p/p = 10^{-3}$ next table.

longitudinal velocity (cm/s)	$.3 \cdot 10^7$
longitudinal temperature (eV)	4.7
transverse velocity (cm/s)	$.83 \cdot 10^7$
transverse temperature (eV)	36

The Electron Nucleon Colliders with high luminosity now discusses at many acceleration centers. ENC under development in collaboration GSI-BINP [7]. This project is example of using high energy electron cooling for reaching high luminosity $10^{33} cm^{-2} s^{-1}$. The parameters of electron cooler for this project are - the electron beam energy 5-15 MeV and electron current more the 0.1-1A. Numerical estimation of the cooling and another parameters of U ion beam show at the next table

A=238
Z=90
Number of ions $N_i = 1.4 \cdot 10^8$
Number of electrons $N_e = 6.25 \cdot 10^{10}$
Ions kinetic energy = 8000 MeV/n
Electrons kinetic energy = 4087 MeV
Emittance (normolize) $\epsilon = 0.2 \cdot 10^{-6}$ m
Bunch spacing D= 5 m
Beta at IP $\beta^* = 5$ cm
Beta cooling section β_c= 60 m
Circumference P = 1 km
Length of ion bunch = 5 cm
Length on cooling section l_c= 60 m
Eta η=l/P = 0.06
Cooling current $I_c = 0.1$ A
Beam radius at cooling section = 1.0 mm
luminosity ion-electron Lie= $410^{30} cm^{-2} s^{-1}$
luminosity nucl-electron Lue= $10^{33} cm^{-2} s{-1}$
Electron cooling kin energy MeV= 5 MeV
Electron beam density (lab system) $4 \cdot 10^8$ $1/cm^3$
Electron beam density (beam system) $4 \cdot 10^7$ $1/cm^3$
density of ions (beam system)= $1 - 10 \cdot 10^7 1/cm^3$
Momentum spread dp/p= $1.57 \cdot 10^{-5}$
$\Delta H_\perp / H = 6 \cdot 10^{-6}$
cooling time = 0.02 sec

2 FRICTION FORCE AND OPTICS OF THE COOLING SECTION

The calculation for the stronger magnetic field when the electron can move only along the magnetic line was made at [10]. The friction force components along $F_{||}$ and transverse $F_{\perp}$ to the magnetic field is equal to:

$$F_{||} = -\frac{2\pi e^4 n_e Lnc}{m}\frac{V_{||}V_{\perp}}{V^5}, \tag{1}$$

$$F_{\perp} = -\frac{2\pi e^4 n_e Lnc}{m}\frac{V_{\perp}(V_{\perp}^2 - 2V_{||}^2)}{V^5}, \tag{2}$$

where e,m-electron charge and mass, n_e-electron beam density,Lnc-Coulomb logarithm,$\vec{V}$-ion velocity. The problems with using this equations for calculation of the cooling process is the negative value $F_{\perp}$ for $V_{\perp} < \sqrt{2}V_{||}$. As a result when we have modulation of electron velocity we should see heating at transverse direction, but at real cooling experiments we had only decreasing of cooling but not heating. For the finite magnet field we can use in the simplest equation for the friction force as result of some fitting to the experimental and the theoretical data [11]:

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

where $V_{effe} = \sqrt{V_{||e}^2 + \Delta V_{\perp e}^2}$, $\Delta V_{\perp e}$-transverse motion of electron caused by transverse magnetic and electric fields, , $\rho_{max} = min(V/\omega_e, \tau V, a)$, $\rho_{min} = e^2/mV^2$, $\rho_L = mV_e/eH$-electron Larmor radius, τ is the time of a particle's single path through the electron beam, V-is the particle velocity, V_e is the electron velocity, ω_e is the electron plasma frequency, $C_z = 1$ for the positively charged ion and $C_z = 3-4$ for the negatively charged ions. The transverse magnetic fields associated with misalignments of the solenoid coils in the cooling section will be a hard problem for high energy cooling. The effective velocity at beam reference system is equal to $V_{eff} = \Delta H/H\gamma v0$, where v0 velocity of electrons at lab. system and $\gamma = 1/\sqrt{1-(v0/c)^2}$. For the electron beam energy 5 MeV and $\Delta H/H = 10^{-5}$ the effective velocity is equal to $V_{eff} = 310^6 cm/s$ that corresponds the effective temperature 25 K Kelvin. The antiprotons beam with normalized emittance 20 π mm*mrad (for $\beta_x = 200m$ -beta function at cooling section) have the same spread velocity but its effective temperature at 1836 times more 40000 grad K. It means that the cooling rate will drop down if we have the misalignments at the magnet line more then 10^{-5}. The experience of production of magnet system for SIS cooler [21] shows that it is possible to have this quality of the magnet field using the special technology . The value of magnetic field is a key parameter for the cooling facilities. The intrabeam scattering inside the electron beam can heat the electrons so that the cooling decrease for large electron current. The fig. 1 shows how the cooling rate changes vs. electron density for different values of the magnetic field at cooling section. It is easy to see that for large electron current we need more strong focusing field at cooling section. Let me to remind that this intrabeam scattering is dengerous for the cooling rate at the case the single pass electron beam. It of course will be the main problem for the multi turn systems where the electron beam should rotate at the storage ring.

3 THE COOLING ELECTRON BEAM

To carry out electron cooling, an electron beam with the same average velocity as the cooled particles should be placed in the straight section of the particle orbit. It is evident that the larger the fraction of the orbit occupied by the electron beam, and the more intensive it is the quicker the particles will be cooled. The basic cooling rate at the system of reference of the particles is limited only by intensity and by effective temperature of the electron beam. When we try to increase the electron beam intensity the action of the space charge and intrabeam scattering increases effective temperature and after same maximum can see degradation of cooling rate for large electron beam current. Fig.1 shows how changing cooling rate versus the electron beam current for three different cooling system: first cooling system NAP-M [2], MOSOL [4] and SIS cooler [5]. For the transition of an intense electron beam at large distances a transverses homogeneous magnetic field is most frequently used.

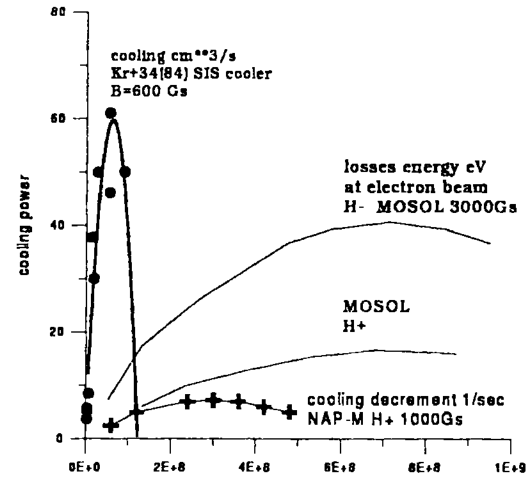

Figure 1: The cooling rate for different solenoid fields, 0.6,1,4 kGs.

Hear, the larger the magnetic fields H, the less are the transverse electron velocities produced by the space charge of the electron beam:

$$V_{drift} = c * \frac{2\pi n_e ea}{H}, \tag{4}$$

where a-the electron beam radius. While accelerating the electrons, the longitudinal temperature happens to drop so that the interaction of electrons in the beam becomes essential, raising the longitudinal temperature due to the mutual repulsion of initially chaotic (at space) electrons:

$$T_{||} = 2e^2 n_e^{1/3} \qquad (5)$$

The transverse motion of electrons is determined (if we do not use expansion at beam size) by the cathode temperature T_c:$Ve_\perp = \sqrt{T_c/m}$. Under this condition, when the longitudinal temperature of electron beam is several orders of magnitude lower then the transverse temperature, of great importance is the problem of preserving this state over a sufficiently long path. Intrabeam electron scattering tends to equalize these temperatures, and, neglecting the influence of the magnetic field, the heating rate is determined from equation:

$$\frac{dT_{||}}{dt} = \frac{2\pi e^4 n_e Lc}{mVe_\perp}, \qquad (6)$$

where Lc- Coloumb logarithm at electron-electron collisions.

The cooling time versus magnetic fields is shown at fig 2. for different electron beam currents.

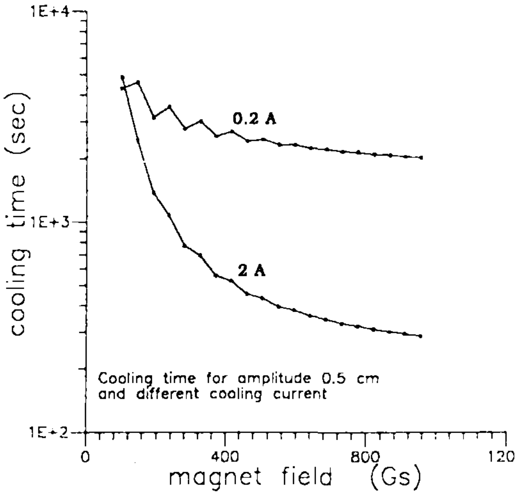

Figure 2: The cooling time of 8Gev antiprotons for different current, 0.2,2 A.

4 CORRECTION SYSTEM

4.1 *Correction of Larmor rotation*

The misalignments at acceleration columns and the bending magnets results increasing the transverse motion of electron beam. The experience of running of electron cooling devise NAP-M (Movosibirsk) shows that it is possible to significant improve the cooling rate using the special correction plate to exited the Larmor rotation at electron beam. We have same misalignments at the electron gun and action this plates compensated this motion and cooling rate to increased at 4 times [8]. It is necessary to kick the electron beam at point were it the transverse velocity have maximum for best result. But this point is not possible to predicted before real measurement of motion electron beam at real magnet system. More easy to have two correction systems situated at place with difference in the phase of Larmor rotation $\pi/2$, $\sim 50cm$. This system should consist of the two (short $\sim 30cm$) coils that generating the transverse kick. If we estimate possible transverse angle for the error at magnet system 10^{-2} the magnet field generating this coils should be more then 5 Gs. The constructions of this coil not too complicate. This dipole correction will consist of 4 coils installed before income in cooling section.

It seems that very useful to have the correction for adjusting the focusing at the same place. During the process of acceleration electrons beam passes the focusing elements with not exactly known strength. For example defocusing by the own space charge produces the transverse kick. As a results the beams will have the Larmor rotation with amplitude linearly changing with the distance from axis of beam. The two focusing elements at the same position as the dipole correction can help to correct this mismatching. The cheapest solution is the separated power sources connected to 4 sections of the main solenoids. The additional current at this sections will introduce the modulation of longitudinal fields and adjust motion of electron beam. Fig. 3 show working of this system for compensation the transverse angle after acceleration. The value of the magnetic filed at compensation coils chosen so that compensation should be for magnetic field 500 Gs.

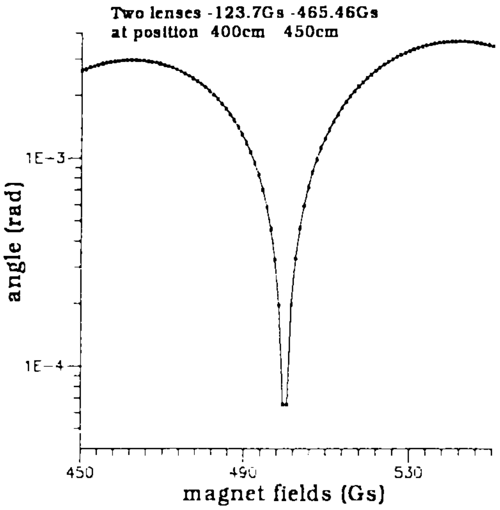

Figure 3: The transverse angle after acceleration at the longitudinal field with 0.1 modulation with period 6 cm and two lenses for compensation the transverse motion at 500 Gs

4.2 *Position and angle correction of electron beam*

The usual way to correct the position of electron beam moving along magnetic longitudinal fields is to use the transverse magnetic field and bend direction of the magnetic field lines. This method works perfectly for low energy electron beam when length of Larmor spiral λ_L less then aperture of solenoid. It this case, the angle of the direction of electron beam change slow and the transverse Larmor rotation do not exited. In high energy case for using this way we need too long distance for slow increasing of the transverse field. It looks reasonable to use the transverse field from two flat region. At initial moment the electron came in at the field value 0.5*H and after path distance $\lambda_L/2 \sim 1m$ came in the field H. Using this way we can produce the low temperature electron beam for cooling.

5 THE ALTERNATIVE SYSTEMS OF ACCELERATION OF THE ELECTRON BEAM

The simplest system for generation of the electron beam is DC acceleration by electrostatic fields. But for the higher electron energy (above 5MV), the difficulties of implementation sharply increase and set of natural limits for such method in arise.

Thus, to obtain the electron cooling for the project collider ENC for GSI storage ring, it is necessary to have an electron beam with an energy 15 MeV and current up to 1 A. The ion beam for this type colliders usually should be bunched with a $\sigma \sim 10$ cm and distance between bunches equal to 5-10 m. The system of RF linear acceleration that is using the low frequency cavity has large perspective as accelerator the electron beam for electron cooling [15]. Using the superconduting linac, operating in CW-mode was under study at [17]. This type of systems with RF acceleration and recuperation of the electron beam energy after using by decelerations are discussed not only for electron cooling but meanly as the Free Electron Laser drive [16]. The main problems of this type system for using as electron cooler is problem to inject the low emittance beam at cooling section, with magnet field. For intensive electron beam it needs DC acceleration at the longitudinal magnet field up to few MeV and them acceleration at RF cavities. But this way looks complicate and too expensive. This problem needs more development to made this system more realistic.

The system with storage electron beam move along close orbit looks very cheap solution for the energy range 5-20 MeV [18],[19]. The main problem of this systems is the fast heating of the electron beam by intrabeam scattering (so called Tushek effect). From equation 6 easy to see that time of initial temperature relaxation $2e^2n_e^{1/3}$ is equal to (at beam reference system):

$$\tau = \frac{2e^2n_e^{1/3}}{dT/dt} = \frac{V_{e\perp}}{\pi Lncc^2n_e^{2/3}r_e} \qquad (7)$$

For the electron beam density $n_e = 10^8 1/cm^3$ the length of relaxation $l = \tau c\beta\gamma$ is equal to 20 m (for $\gamma = 10$) and very fast Tushek heating does gives not too much perspective for this way.

And finally for very high energy (few hundred MeV (electron)) it is possible to use storage ring with the electron beam cooled by syhrotron radiation. For this type of ring, the emittance will be equilibrium between the intrabeam scattering inside intensive electron bunch and the cooling by syhrotron radiation. Good solution for injection the electron beam from storage ring into the cooling section with magnetic field was development Derbenev Ya.S. [20]. At this paper was proposed to use special section with sqew quadruples to match the cooling solenoid and storage ring. Using this way it is possible to inject ultrarelativistic electron beam into cooling section ,with high longitudinal magnetic field so that the horizontal emittance becomes responsible only for the electron beam cross-section in the solenoid, while the transverse temperature in solenoid is determined by vertical emittance at the storage ring. By from my point of view there are more preferable to use magnetization cooling and to let electron beam at storage ring be at the round option with the same vertical and horizontal emittances. At this case the electron beam density (at 6 dimensional phase space) not so large and this electron bunches with the high peak current more easy to accumulate at the damping ring.

6 CONCLUSION

For the electron beam energy range less them 5 MeV only DC acceleration at electrostatic accelerator with electron beam immersed in the longitudinal magnet field can be used without very large new effort at research and development activities. Using RF linac type system for energy more them 5 MeV looks very promising but needs more intensive theoretical and experimental investigation.

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