Recent development in electron cooling and its applications

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Abstract

The electron cooling is used for accumulation and shrinking emittance of ions: from p up to uranium ions. Tts use today is limited by relatively small ions beam energy 1-200 MeV/n. The new the research and development programs have the aim to use the electron cooling for the higher electron energies (above 1-5 MeV) at antiproton accumulators (FNAL) [8]and at the ions colliders such as at GSI [9]. It requires new systems for generation of electron beams and a new level of the technical problems for the cooling straight section optics. The cooling of intensive ions beam has additional problems with coherent stability. The questions of using of electron cooling at this extremely condition are presented for discussion at this report.

1 INTRODUCTION

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 achived 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 result the cooling particles interact with a cool Larmor circle, but not with a hot free electron. The effective temperature a Larmor circle is only 1^o K but free electrons have temperature of over 2000^o K! A temperature 1^oK for 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 obtain at 'MOSOL' facility with very intensive electron beam and magnetic field up to 4kGs[4],[5]. For having reasonable small cooling time at high energy only magnetized regime can be used.

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[6]. For the finite magnet field we can use in the simplest form as result of some fitting to the experimental and the theoretical date[7]:

$$\vec{F} = -\frac{4e^4 n_e}{m}\frac{\vec{V}}{\sqrt{V^2+V_{effe}^2}^3} ln(\frac{\rho_{max}+\rho_{min}+\rho_L}{\rho_{min}+\rho_L}) \quad (1)$$

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, e,m-electron charge and mass, n_e-electron beam density, $\rho_{max} = min(V/\omega_e, \tau V, a)$, $\rho_{min} = e^2/mV^2$, $\rho_L = mV_e/eH$-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. The transverse magnetic fields connected with misalignments of the solenoid coils at cooling section will be a hard problem for high energy cooling. The effective velocity at beam reference system are equal $V_{eff} = \Delta H/H\gamma v0$, where v0 velocity of electrons at lab. system and $\gamma = 1/\sqrt{1-(v/c)^2}$. For the electron beam energy 5 MeV and $\Delta H/H = 10^{-5}$ the effective velocity equal $V_{eff} = 310^6 cm/s$. The antiprotons beam with normalized emittance 20 π mm*mrad (for $\beta_x = 200m$ -beta function at cooling section) have the same spread velocity. It means that the cooling rate will drop down if we have the misalignments at the magnet line more then 10^{-5}. The experience at production magnet system for SIS cooler [10] shows that using the special technology it is possible to have this quality of the magnet field. 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 change 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 scatering to destroy 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. The electron beam for electron cooling is traditionally obtained by direct electrostatic acceleration. But for the higher energy (above 5MeV), it looks more reasonable to use some of RF cavities systems. But requirements on the magnet fields along all the path of electron beam are very hard, The questions of operation the RF cavities inside DC magnet field is open now and should be investigated experimentally. It seems that sytems with initialy usual DC acceleration at the longitudiunal magnet field and them the acceleration up to final energy at the RF cavieties with the magnet optics have matrix elements equal units for caming

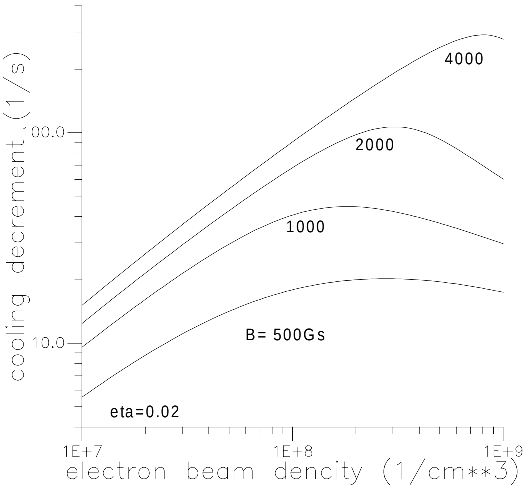

Figure 1: The cooling rate for different solenoid fields, 0.5,1,2,4 kGs.

at magnet field in cooling section have perspective.

3 LIMITATION ON THE ION BEAM INTENSITY

Some effects making limitations for obtaining high ion beam current are observed at interaction of an ion beam with an electron cooling beam. These effects so called electron heating are observed at CELSIUS facility [11] and the electron cooling ring at Indian University [12]. Let me for the explanations of nature of this limitation calculate losses of the energy at ion beam after passing the cooling section the some fluctuation inside ion beam. For example take the spherical region at the ion beam with displacement x and the velocity of motion v. The electric field at ion plasma generated this fluctuation is equal:$E = 4\pi n_i e x$, where n_i-density of ion beam, e-charge of ion. In a case moving fluctuation section displacement ions at time of flight the cooling section (τ) is equal $x = v\tau$. As the result of the action this field the electrons will shift from the equilibrium position on distance equal to: $\Delta x_e \sim \frac{eE}{m}\tau^2 = \frac{4\pi e^2 n_i \tau^3}{m} v$ and this disturbance of the electron flow generate the electric field: $E_e \sim 4\pi n_e \Delta x_e = \frac{(4\pi)^2 e^3 n_i n_e \tau^3}{m} v$ where n_e-density of the electron beam. This field produce the transverses kick at the ions near the region of fluctuation equal to:

$$\delta p = -A\frac{(4\pi)^2 e^4 n_i n_e \tau^4}{mM} Mv = -A\lambda p, \qquad (2)$$

where p-ion momentum, M-ion mass, A-numerical coefficient wich can be calculated by the careful integration of the motion equation at time of interaction. The parameter λ is useful for estimation of interaction between the ions and the electron beam:

$$\lambda = (4\pi)^2 e^4 n_e n_i r_e r_i (c\tau)^4 = \omega_e^2 \omega_i^2 \tau^4 \qquad (3)$$

where $r_e = e^2/mc^2$, $r_i = e^2/Mc^2$-the electron and ion classical radii, ω_e, ω_i-the electron beam and ion beam

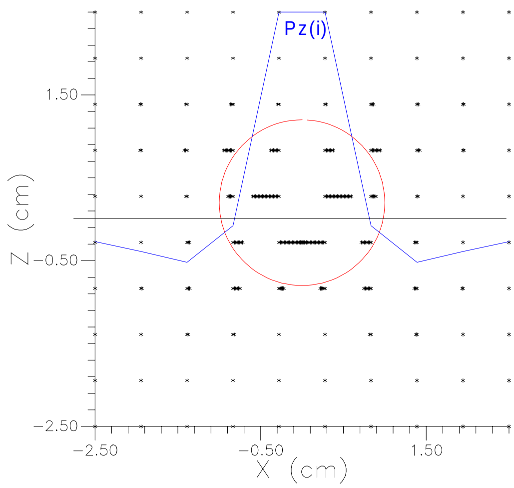

Figure 2: The crossection of ion beam after passing cooling section. The circular show region of fluctuation, the points the position of electrons, the line distribution of the transverse momentum by action of electric field.

plasma frequencies. On the fig. 2 model for the computer simulation with using the quasiparticles method is showed. The electric fields are calculated as differences between not movably background particles with a negative charge and moving particles. The quasiparticles were taken as spheres with a radius equal to half distance of grating. The fig. 3 shows the momentum kicks $\delta p/p_{x,v}$ and sum of squares of the momentum $\sum(\delta p/p_{x,v})^2$, where the normalized momentum is equal $p_v = vM_s, p_x = x/\tau M_s, M_s = M4\pi a^3/3 * n_i$-mass of coherent fluctuation. The momen-

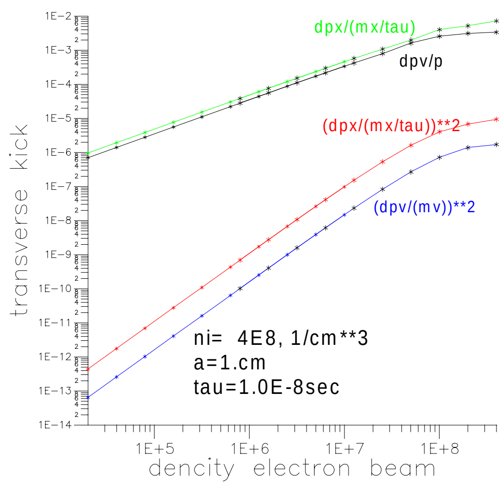

Figure 3: The momentum kicks the ion cloud for different density of electron and ion beams.

tum kick increases with the electron beam density up to density where the $\omega_e > 1/\tau$ and the time of interaction is limited by Debay screening. The numerical fitting of the result (for magnetization electron with small temperature) shows that the momentum kick can be write as:

$$\delta p = -2 \cdot 10^{-3} \lambda M v - 5 \cdot 10^{-3} \lambda M \frac{x}{\tau} \qquad (4)$$

and the energy losses after passing the electron beam equal:

$$\frac{\Delta E}{E} = -2 \cdot 10^{-3} \lambda + 10^{-5} \lambda^2 + 10^{-4} \lambda^2 (\frac{\beta}{l})^2 \qquad (5)$$

In this equation it is taken into account that for the amplitudes of fluctuation at the cooling section a relations $< x^2 >=< v^2 > /(v0\gamma)^2 * \beta_x^2$ and $< x * v >= 0$ exist. Fig. 4 show the variation of $\Delta E/E/\lambda$ for different

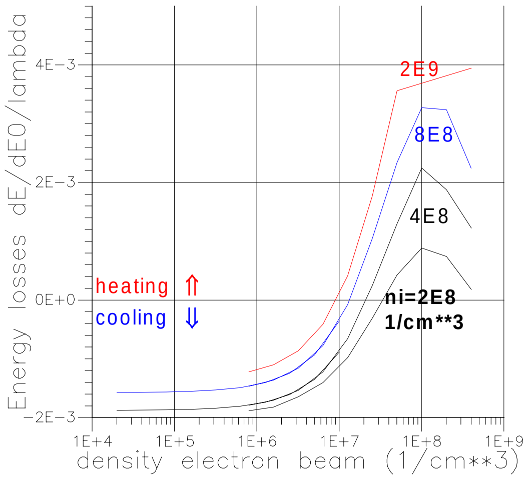

Figure 4: The losses energy of ion beam after passing cooling section: if looses negative it means cooling,if positive it means heating.

density the ion and electron beams. As easy see for the too high ion density cooling becomes heating (for $\tau = 10^{-8}$. From equation 5 we can estimate the threshold value of parameters λ_{th} as:

$$\lambda_{th} = \frac{20}{0.1 + (\beta_{x,z}/l)^2} \qquad (6)$$

The parameters λ is limited by the interaction ions inside beam (Laslet tune shift) and Debay screening inside electron beam. From results of computer simulation we can write estimation as $\lambda = (\omega_e \tau)^2 \Delta\nu_L \nu 2(2\pi\eta) * *2/(1.0 + (\omega_e \tau)^2/40)$, where ν and $\Delta\nu_L$- tune and Laslet tune shift, η-fraction cooling at beam orbit. For the standard parameters $\lambda_{max} \sim 2 - 10$. For the correct choice $\beta_x \sim l$ from equation 6 it is easy to see that the phenomenon of electron heating is not work $\lambda_{max} < \lambda_{th}$ but if $\beta_x >> l$ the heating can limited the ion beam intensity. This result - existing upper limit on intensity of cooling beam contrudict to culculation at [13] . It seems to me that the culculation of impedance is equvalent of culculation of transverse kick 4 but it is importante to culculate the second order terms (λ^2) as was made at 5 generating the phenomena of electron heating.

4 CONCLUSION

The using of electron cooling for ion beam parameters control opens now a lots advantages and can help to have good condition for experiments. Many cooler rings demonstrated successful operations. However from my point of view a few myths exist. One of them is that magnetized cooling exist only at Novosibirsk. I think that there is the same mistake in understanding connected with expectation that increasing magnetic field should automatically increase the cooling rate. Some disappointment usually connected with a not perfect alignment of the magnet system and if you pay attention to the straightness of magnet lines at cooling section you will recompense the better cooling rate. The second myth is that if you made longer cooling section you will have more powerful cooling. But as you can see from the equation 3 ($\lambda \sim l^4$!!) for intensive beams it may be a way to the heating but not to the cooling.

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