ELECTRON COOLING AT ACR

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Abstract

The Accumulator-Cooler Ring (ACR), one component of the Multi-USe Experimental Storage rings(MUSES) proposed for RIKEN RI beam factory[1] aims at accumulation and cooling of RI beams and stable heavy ion beams. Beam accumulation will be done by combining the repeated multiturn injection with RF stacking. The stacked beam experiences stochastic and electron cooling at the top of stack. The ion species which will be cooled in the ACR range from $^{12}C^{6+}$ to $^{238}U^{92+}$ at typical energies between 500MeV/u and 150MeV/u. Accordingly, an electron cooling system is required for electron of energy up to 300keV and the maximum current of 4.0A. This paper describes briefly the conceptual design of the e-cooler. Simulation of the electron cooling process, taking into account betatron and synchrotron oscillations of particle and space charge effect of electron beam, is reported.

1. INTRODUCTION

In addition to stochastic cooling, the use of electron cooling is planned at ACR for compression of the phase space volume of multiturn-injected and RF-stacked ion beam at the top of stack, which helps to increase the intensity of accumulated beam. Following this requirement, a conceptual design of the electron cooling system is described. Afterwards, simulation of the cooling process for the typical ion beam $^{132}Sn^{50+}$ at injection is presented, and the time evolution of the beam emittance and momentum spread are given.

2. GENERAL CONSIDERATION OF ELECTRON COOLING SYSTEM

Heavy ion beams injected into ACR have energies from 150MeV/u to 500MeV/u, the corresponding energies of electron beam range from 82 to 274keV. Therefore, voltage for the electron gun cathode is required to be adjustable within a range of 70-300kV.

Higher electron current might be required to achieve fast cooling during injection of hot ion beam. However, cooler operation with higher current may cause the loss of stored highly charged ions due to the radiative electron capture process in the cooling section. In compromise, a maximum electron current of 4.0A is chosen.

The multiturn injected ion beam which has a maximum emittance of 120π mm·mrad horizontally with beta function in the cooling section of β_h=5m should be totally immersed in the electron beam. Therefore, the electron beam diameter in cooling section is determined as 50mm.

ACR has a circumference of 168.48m, taking L_{cooler}=3.6m is moderate, i.e. the relative cooler length η_{ec} = 0.021.

Because the electron beam with low transverse temperature is preferable for faster cooling, ACR electron cooler will utilize a magnetically expanded electron beam[2]. Normally, a solenoid field strength of 0.5-1.2kG is required for maintaining the magnetized cooling regime. If we plan for adiabatic expansion of the magnetic field by a factor of 10, the gun solenoid field corresponds to be 0.5-1.2 Tesla. This expansion scheme allows to lower the electron beam transverse temperature by a factor of 10 because the transverse energy of electron divided by the strength of the longitudinal magnetic field is an adiabatic invariant under the changes of field strength. The area of the electron beam cross section times the magnetic field strength is also an adiabatic invariant, so in order to keep the electron beam diameter 50mm in the cooling solenoid, a flat cathode must be made with a diameter of 16mm.

The electron gun optics consists of a flat cathode, a Pierce electrode, an anode and an acceleration column, somewhat similar to that of TARN-II[3]. Fig.1 shows an example of the calculated electron trajectories.

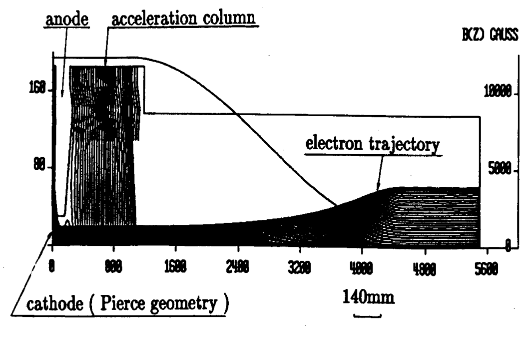

Fig.1 Computer generated plot of electron gun, acceleration column and expanded electron beam

In summary, the main parameters of ACR electron cooling system are listed in table 1.

Table 1 Parameters of ACR electron cooling system

Energy range	of the cooled ion 150-500 MeV /u of electron 70-300 keV
Maximum electron current	4.0A
Gun design	Pierce geometry + adiabatic focusing electrodes
Cathode diameter	16mm
Electron beam diameter at cooling section	50mm
Maximum solenoid field at acceleration section	1.2T
Maximum solenoid field at cooling section	1.2kG
Length of cooling section	3.6m
$B_\perp/B_\parallel$ in cooling section	$<1.0\times10^{-4}$
Bending angle of toroids	90^o
Collector efficiency	>99.98%
Voltage stability of HVPS	$\pm1.0\times10^{-5}$

By using this system, one can expect the cooling time of the order of 10sec, depending on different ions and their energies.

3. ELECTRON COOLING TIME AND SIMULATION OF ELECTRON COOLING PROCESS

In the practical application of electron cooling at ACR, the cooling time and its dependence on some parameters must be known. The simulation presented below, calculates the variations of bunched beam emittance and relative momentum spread with time, by using analytical cooling force formulae of I.N.Meshkov[4], taking into account the betatron and synchrotron oscillations of particle and the influence of electron beam space charge in the cooling section.

In the simulation procedure, the ring is divided into two parts: the first part from the cooling section exit up to its entrance, and the second part going through the cooling section. After the first part, the phase of the ion with respect to RF and its relative momentum spread are calculated from the phase motion equations

$$\frac{d\phi}{dt} = h\omega_s \cdot \eta_p \cdot \frac{\Delta P}{P_s}$$

$$\frac{d}{dt}\left(\frac{\Delta P}{P_s}\right) = \frac{\omega_s}{2\pi} \cdot \frac{qeU_a}{AM_n c^2 \beta^2 \gamma} \cdot (\cos\phi - \cos\phi_s)$$

The horizontal and vertical betatron positions and divergence after passage through the first part, are given by the following matrix expression

$$\begin{pmatrix} x_j \\ \theta j \end{pmatrix}_1 = \begin{bmatrix} \cos(\mu_j)+\alpha_j \sin(\mu_j) & \beta_j \sin(\mu_j) \\ -\gamma_j \sin(\mu_j) & \cos(\mu_j)-\alpha_j \sin(\mu_j) \end{bmatrix} \cdot \begin{pmatrix} x_j \\ \theta j \end{pmatrix}_0 ,\ j = h, v$$

$u_j = 2\pi u_j(1-\eta_{ec})$, α_j, β_j and γ_j are Twiss parameters at the entrance or exit of the cooling section (symmetric points).

On each passage through the cooling section, the ion experiences cooling force which decreases the velocity components but doesn't change the position coordinates evidently. Therefore by means of numerical evaluation of the equation

$$\frac{d\theta_j}{ds} = \frac{F_j}{AM_n c^2 \beta^2 \gamma},\ j = h, v\ ,1$$

and employing the θ_j and $\Delta P/P_s$ values at the entrance of cooling section, one can obtain the corresponding values at the exit of cooling section.

In the lab frame, the cooling forces may be expressed as

$$\vec{F}_j^{lf} = -2\pi \frac{I_e}{\pi r_b^2 \cdot e\beta\gamma c} \cdot Q_i^2 \cdot r_e^2 \cdot m_e c^2 \cdot \frac{\vec{\theta}_j}{\beta^2\gamma^3} \cdot \begin{cases} \frac{1}{\theta^3}(2L_{FH} + K_t \cdot L_{MH}), \theta > \theta_{et} \\ \frac{2}{\Delta_{et}{}^3}(L_{FL} + N_L L_{AL}) + K_t \cdot \frac{L_{ML}}{\theta^3}, \theta_{el} < \theta < \theta_{et} \\ \frac{2}{\theta_{et}{}^3}(L_{FS} + N_S L_{AS}) + \frac{L_{MS}}{\theta_{el}{}^3}, \theta < \theta_{el} \end{cases}$$

$$\vec{F}_l^{lf} = -2\pi \frac{I_e}{\pi r_b^2 \cdot e\beta\gamma c} \cdot Q_i^2 \cdot r_e^2 \cdot m_e c^2 \cdot \frac{\vec{\theta}_l}{\beta^2\gamma^2} \cdot \begin{cases} \frac{1}{\theta^3}(2L_{FH} + K_l \cdot L_{MH} + 2), \theta > \theta_{et} \\ \frac{2}{\theta_{et}{}^2\theta_l}(L_{FL} + N_L L_{AL}) + (K_l \cdot L_{ML} + 2) \cdot \frac{1}{\theta^3}, \theta_{el} < \theta < \theta_{et} \\ \frac{2}{\theta_{et}{}^2\theta_{el}}(L_{FS} + N_S L_{AS}) + \frac{L_{MS}}{\theta_{el}{}^3}, \theta < \theta_{el} \end{cases}$$

in which

$$K_t = 1-3(\theta_l/\theta)^2,\ K_l = 3-3(\theta_l/\theta)^2$$

and the “L” denotes Coulomb logarithms[4].

Because of the electron beam space charge depression, electron at different radius inside the beam has a different longitudinal velocity. Accordingly, the longitudinal velocity component of ion at certain radius should be defined with respect to that of electron at the same radius.

Signifying f_n the neutralization factor of space charge, one gets the longitudinal divergence deviation θ_l^n given by

$$\theta_l^n = \theta_l - \frac{I_e}{2\pi\varepsilon_0\beta^3 c}\cdot\frac{e}{m_e c^2\gamma^2}\cdot\frac{r^2}{r_b^2}\cdot(1-f_n)$$

in which the radius r is related to the horizontal dispersion D_h in the cooling section by

$$r = \sqrt{(D_h\cdot\frac{\Delta P}{P_s}+x_h)^2 + x_v^2}$$

The time evolution of transverse emittance and longitudinal momentum spread with time resulting from the simulation are shown in Fig.2 for a ion beam $^{132}Sn^{50+}$ of 210MeV/u with initial horizontal and vertical emittance of 120 and 5πmm·mrad respectively and momentum spread of $\pm 2.5\times10^{-4}$.

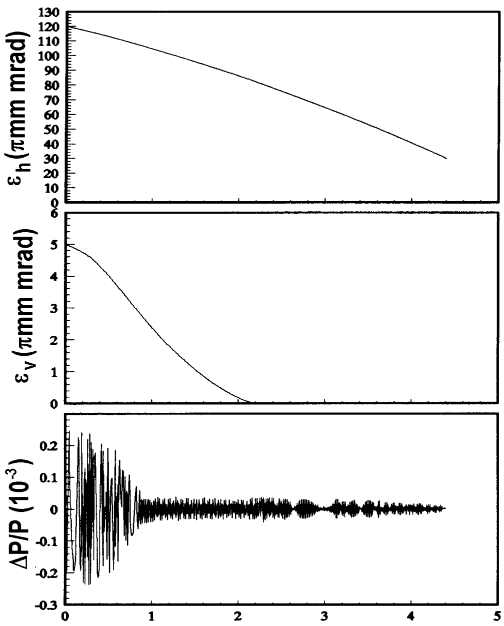

Fig.2 The time evolution of beam emittance and momentum spread with time.

In order to investigate the electron beam space charge effect, one changes the neutralization factor f_n. Fig.3 shows the simulation results of the longitudinal cooling for f_n= 90%, 50% and 0 respectively, keeping other parameters the same and dispersion free in cooling section. It can be seen from the figure that neutralizing the space charge of electron beam makes the longitudinal cooling much faster.

Also, the transverse temperature kT_t of electron beam is one of the critical factors that influence the cooling speed. In the simulation, kT_t is assumed to be 0.01, 0.04,

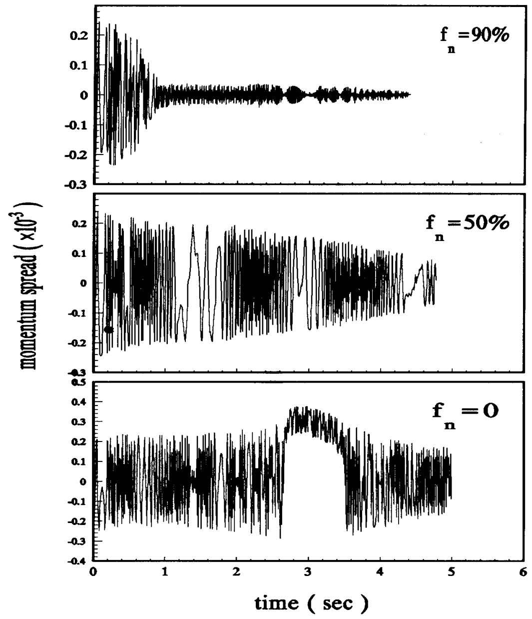

Fig.3 Longitudinal cooling resulted from the simulation for three values of neutralization factor.

0.1 , 0.2 and 0.6eV. As a result, the destination cooling time i.e. the time duration needed to cool the ion beam from the starting horizontal emittance to a specified values of 30 πmm·mrad, equals to 3.73, 3.94, 4.15, 4.40 and 5.08 sec respectively, as shown in Fig.4. Therefore, an electron beam with low transverse temperature is expected to fasten the cooling process.

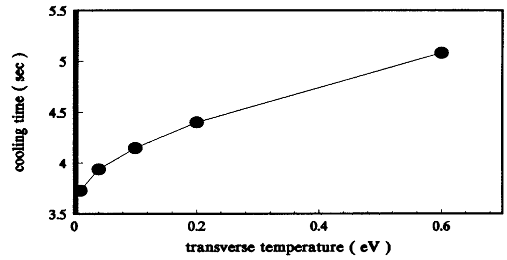

Fig.4 The transverse cooling time as a function of the electron beam transverse temperature. In these calculations, $f_n = 90\%, D_h = 0m$.

In conclusion, neutralizing the space charge of electron beam with much low transverse temperature is preferable for faster cooling.

References

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