ELECTRON COOLING OF HEAVY IONS INTERACTING WITH INTERNAL TARGET AT HESR OF FAIR

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Abstract

The High Energy Storage Ring (HESR) is designed and optimized to accumulate and store the anti-proton beam for the internal target experiment. The recent demand of atomic physics has initiated the use of the HESR facility also as a storage ring of heavy ions. In this concept the bare heavy ions are injected at 740 MeV/u from the Collector Ring. In the HESR the 2 MeV electron cooler is prepared with the maximal electron current of 3 A and the cooling length of 2.7 m.

The electron cooling process of typically $^{238}U^{92+}$ beam is simulated for the hydogen and Xe internal target with simultaneous use of barrier voltage to compensate the mean energy loss caused by the interaction with internal target. In the present report the detailed simulation results of 6D phase space obtained by the particle tracking are discussed.

INTRODUCTION

When the internal target is operated in the HESR ring for the experiment, the energy of circulating particles is decreased due to the mean energy loss and the energy spread is enhanced due to the straggling effects in the target. In addition the transverse emittance is also increased due to the multiple scattering. Such deterioration of beam quality is linearly proportional to the target density and then could be expected to be compensated by the electron or stochastic cooling force at the low intensity target. However to obtain the high luminosity the thick target, typically 10^{13}~10^{15} atoms/cm^2, is required and in that case the deterioration of beam quality could not be compensated by the cooling force alone. Especially the large mean energy loss induces beam loss from the ring.

The barrier voltage could be expected to compensate the energy loss as it generates the separatrix in the longitudinal phase space and the particle performs the synchrotron motion in the separatrix and receives the RF force to compensate the mean energy loss.

In the present report the six dimensional beam dynamics are investigated in the case of electron cooling including the target effects, barrier RF field, Intra Beam Scattering (IBS) and cooling force with use of the multi-particle tracking code. The study of the stochastic cooling case is reported in a separate paper [1].

ELECTRON COOLING FORCE

Among several formulae for the electron cooling force, we will use the V. Parkhomchuk empirical formula [2] which is well verified to reproduce the electron drag force. With the use of this empirical formula, the transverse emittance ε and the energy deviation ΔE are given by following coupled equations

$$\frac{d\varepsilon}{dt} = -2G\varepsilon \qquad \frac{d}{dt}(\Delta E) = -G\,\Delta E$$

$$G = \frac{4r_e r_n c n_e \eta_c}{\gamma^2[\beta^2\gamma^2\frac{\varepsilon}{\beta_{cool}} + (\frac{\Delta E}{\beta E})^2 + \frac{T_{eff}}{m_e c^2}]^{3/2}}\frac{Z^2}{A}\ln\xi$$

where n_e is the electron density in the Laboratory Reference Frame, T_{eff} is the effective electron temperature and $ln\xi$ is the Coulomb logarithm. In Fig. 1 the typical longitudinal cooling force with the cooler parameters in Table 1 are illustrated with three different transverse emittances, 0.01, 0.1 and 1.0 π mm.mrad, respectively. It should be noted that the cooling force is largely dependent upon the value of transverse emittance, and the cooling energy range is as narrow as +/- 0.5 MeV/u. In general the electron cooling force is strong for small emittance and small momentum spread which is the intrinsic feature of the electron cooling. On the contrary the stochastic longitudinal cooling force could cover the wider energy range and is independent upon the transverse emittance.

Table 1: Parameters of the electron cooler at HESR

Cooler length	2.7 m
Max. electron energy (Ion energy)	2.1 MeV (4 GeV/u)
Electron current	0.5 A
Electron diameter	2.0 cm
Effective electron temperature	1e-2 eV
Transverse electron temperature	0.2 eV
Longitudinal magnetic field	0.1 Tesla
Beta function at cooler section	10 m (horizontal and vertical)

INTERNAL TARGET

The interaction of the circulating ion beam with internal target causes the deterioration of beam quality such as increase of transverse emittance, decrease of beam energy due to mean energy loss and the diffusion of beam energy spread which could be calculated with formulae given in reference [3]. In Figure 2 the mean energy loss and the mean squared momentum spread are illustrated for the hydrogen target with a density of 4e15 atoms/cm^2.

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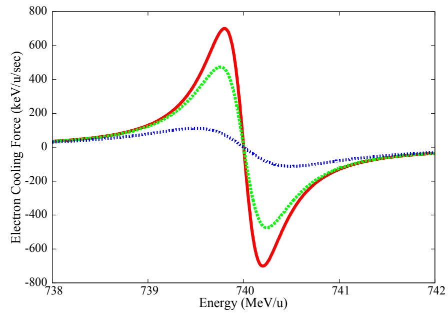

Figure 1: Longitudinal electron cooling force for $^{238}U^{92+}$, 740 MeV/u ion beam as a function of beam energy. The horizontal scale is beam energy and the vertical scale is the longitudinal cooling force. The parameters are transverse emittance, 0.01 (red), 0.1 (green) and 1.0 π mm.mrad (blue), respectively.

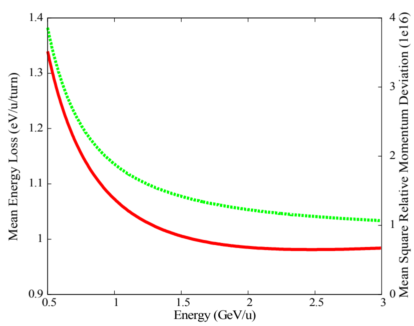

Figure 2: The mean energy loss (red line, left scale) and mean squared momentum deviation (green line, right scale) of $^{238}U^{92+}$ ion beam in the hydrogen target, 4e15 atoms/cm^2.

INTRABEAM SCATTERING AND BARRIER VOLTAGE EFFECTS

The cooled heavy ion beam is easily (especially at low energy) suffering from the Intra Beam Scattering effect and the transverse emittance and momentum spread are increased according to the IBS growth rates. In the present study, the Martini model [4] is employed to calculate the IBS growth rate with the use of the HESR Twiss lattice structure.

The barrier voltage of two half Sin waves, is applied to compensate the mean energy loss. Particles are trapped inside the separatrix formed by the barrier voltage and move around with the synchrotron motion. In Fig. 3 the separatrix height is illustrated for 740 MeV/u $^{238}U^{92+}$ ion beam. The planned barrier voltage at the HESR ring is 2 kV and the separatrix height (half height) is $\Delta p/p$=3.5e-4 or ΔE=0.45 MeV/u.

RESULTS OF SIMULATIONS

The computing process of the simulation of the particle motion in 6 D is as follows. Initially the particles are assumed to be distributed in the energy and transverse emittance (horizontal and vertical) spaces as Gaussian, truncated at +/- 3 sigma values. In the time domain of the longitudinal phase space, the particles are assumed to form a coasting beam around the ring (numerically the uniform random). The coherent terms such as the electron cooling force and the mean energy loss by the target are calculated at every revolution cycle.

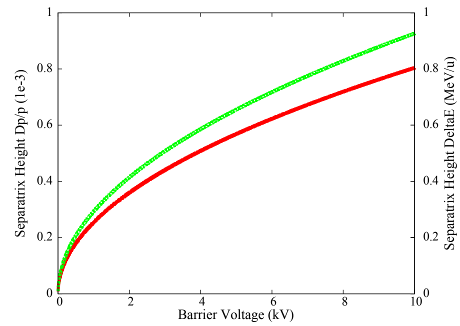

Figure 3: The separatrix height of the barrier bucket as a function of barrier voltage for $^{238}U^{92+}$, 740 MeV/u ion beam. The vertical scale is the barrier height with $\Delta p/p$ (red line, left scale) and ΔE (green line, right scale).

The cooling force is the function of energy, horizontal and vertical emittances, and the cooling equations are solved with the Runge-Kutta method. The synchrotron equation related with barrier RF field is solved with the symplectic way for the synchrotron motion. The diffusion force such as target straggling and IBS growth rates are given as statistical kick to each particle every turn in the ring.

Table 2; HESR Ring Parameters

Circumference	575 m
Betatron tune Qx, Qy	7.62/7.62
Transition gamma γ_t	6.23
Ring slipping factor η	0.286 (740 MeV/u)
Momentum acceptance δ_{acc}	+/- 2.5e-3
Barrier voltage V_b	2 kV
Barrier frequency f_b	5 MHz (T=200 nsec)

1) 740 MeV/u, $^{238}U^{92+}$ beam in hydrogen target and barrier voltage=0

The density of the hydrogen target is assumed at 4e15 atoms/cm^2 and the circulating number of uranium ions is 6e8. The transverse emittance is1.0 πmm.mrad (rms) and the relative momentum spread $\Delta p/p$=2.0e-4 (rms) and the particle distribution is Gaussian. The increase of transverse emittance is 0.854e-9 mm.mrad/turn, the mean energy loss is 1.16 eV/u/turn and the mean square of relative momentum spread δ^2_{loss} is 7.50e-14, respectively.

In Fig. 4 the energy spectra are given for different time. It is clearly shown that the particles are losing energy due to the mean energy loss and the electron cooling force does not compensate the energy loss.

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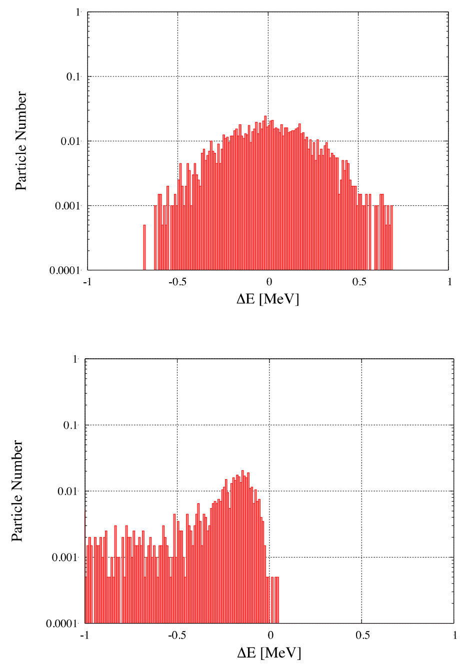

Figure 4: The energy spectra for different time. From the top, time=0 sec and 8.0 sec, respectively without barrier voltage.

2) 740 MeV/u $^{238}U^{92+}$ beam in hydrogen target and barrier voltage=2 kV

The particle distribution and the energy spectra after 8 sec cooling are illustrated in Fig. 5.

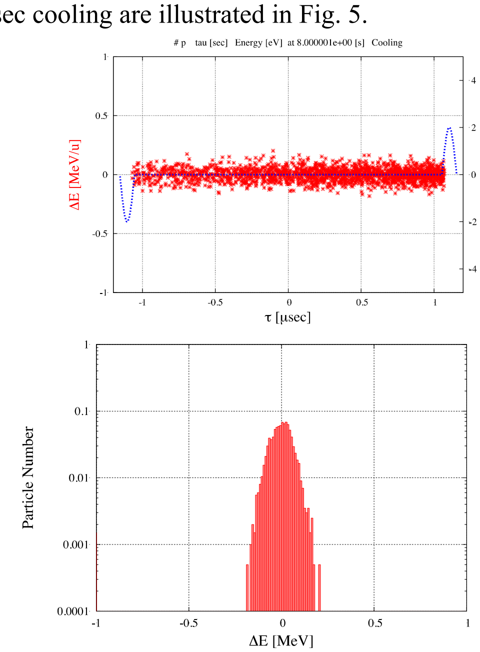

Figure 5: Particle distribution in the longitudinal phase space (top), and the energy spectrum (bottom) after 8 sec cooling. The barrier voltage is 2 kV.

In Fig. 6 the ratio of particle number confined in the specified momentum range to the total particle number is illustrated. The number of particles in the core region, being defined as -5e-5 < *Δp/p* < 5e-5 is increased from 20 % to 60 % within 3 sec due to the cooling force and the barrier voltage supports to compensate the mean energy loss. The number of particles in the momentum range -6e-4 < *Δp/p* <6e-4 are slightly decreasing to 92.5 % after 3 sec. From these results we can find that the almost all the particles are well confined in the momentum range +/- 6e-4 as the mean energy loss are compensated by the barrier voltage and the electron cooling force.

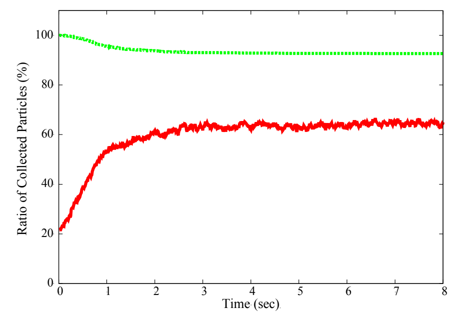

Figure 6: The red line shows the ratio of the particle number within -5e-5 < Δp/p <5e-5 and green line -6e-4< Δp/p< 6e-4. The barrier voltage is 2 kV.

The evolution of transverse emittances are illustrated in Fig. 7 where we find that the equilibrium rms values are around 0.25 πmm.mrad (horizontal) and 0.15 πmm.mrad (vertical) after 8 sec cooling.

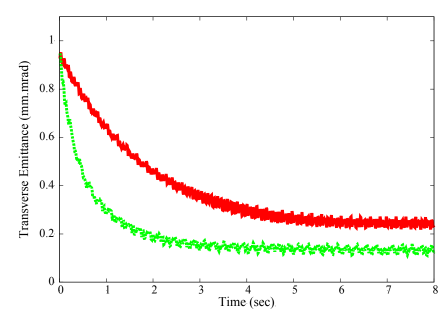

Figure 7: The evolution of transverse emittance. Red: horizontal emittance and Green: vertical emittance.

It is conclusively noted that the bare ion beam, typically $^{238}U^{92+}$ 740 MeV/u ion could be stored in the HESR ring with the operation of internal target, hydrogen 4e15 atoms/cm2, with simultaneous use of electron cooling and 2 kV barrier voltage. The equilibrium *Δp/p* is 5e-5 (rms) and the transverse emittances (rms) are 0.25 (horizontal) and 0.15 (vertical) π mm.mrad, respectively, after 8 sec cooling. Beam loss is estimated at around 7 %.

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