BEAM DYNAMICS SIMULATION ON SIMULTANEOUS USE OF STOCHASTIC COOLING AND ELECTRON COOLING WITH INTERNAL TARGET

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Abstract

Simultaneous operation of stochastic and electron coolers are proposed, and the numerical simulation results at COSY are presented in this study. Small momentum spread of proton beam has to be realized in a storage ring during an experiment with a dense internal target. It is found that the transverse emittance growth and the transverse cooling are important to maintain the small momentum spread.

INTRODUCTION

To maintain small momentum spread is one of crucial issues for the high resolution experiment in a storage ring with internal target. To realize such a beam quality, stochastic cooling will be used as the main cooler in High Energy Storage Ring (HESR) of FAIR project [1]. It is expected that the stochastic cooling could attain the required energy resolution of anti-proton beam in the energy range of 3-15 GeV [1].

Furthermore the better quality of the beam could be obtained with the simultaneous use of stochastic cooling and electron cooling [2, 3]. As a test pilot of this concept, the 2 MeV electron cooler is under construction at FZJ to install into COSY 2 GeV proton storage ring [4].

In this study, we propose the simultaneous use of the stochastic cooling and electron cooling for the internal target experiment in the COSY, and numerical investigations are presented.

SIMULATION MODEL

A Fokker-Planck equation is used as an investigation tool in the stochastic momentum cooling process. The simplified Fokker-Planck equation in energy E for a model of the stochastic momentum cooling is given by [5]

$$\frac{\partial \Psi}{\partial t} + \frac{\partial}{\partial E}\left(F\Psi - D\frac{\partial \Psi}{\partial E}\right) = 0, \quad (1)$$

where $\Psi \equiv \Psi(E,t) \equiv dN/dE$ is the particle distribution function (N is the total particle number in the ring), $F \equiv F(E)$ is the coefficient for the cooling force, and $D \equiv D(\Psi(E), t)$ is the coefficient for the diffusion process.

Coherent Term Coefficient of Momentum Cooling

The coherent term coefficient includes the stochastic and electron cooling forces as

$$F = F_{scool} + F_{ecool} - F_{IT}, \quad (2)$$

where F_{scool} is the cooling force due to the stochastic cooler and F_{ecool} is the cooling force caused by the electron cooler. The terms are derived by the electrical characteristics of the feedback system for the stochastic cooler [6]. For the calculation of the electron cooling drag force, we use the Parkhomchuk empirical formula [7],

$$F_{ecool} = -Gk_c\Delta E, \quad (3)$$

where $\Delta E = E - E_k$ and E_k is the kinetic energy of the beam, G is derived by

$$\frac{1}{G^{2/3}} = \frac{\beta^2\gamma^2\epsilon}{\beta_c} + \left(\frac{\Delta E}{\beta E_t}\right)^2 + \frac{2T_{eff}}{m_e c^2}, \quad (4)$$

and k_c is obtained by

$$k_c = \frac{4r_e r_p c n_e \eta_c L_p}{\gamma^2}\frac{q^2}{m}. \quad (5)$$

Here β is the beam velocity divided by light speed c, γ is the relativistic factor of the beam, ϵ is the transverse emittance at the energy E, β_c is the beta function at the cooler section, E_t is the total energy of the beam, T_{eff} is the effective temperature of the electron beam, m_e is the electron mass, r_e and r_p are the classical electron and proton radii, n_e is the number density of the electron beam, $L_p = 2$ is the Coulomb logarithm, η_c is the ratio of the cooler length to the circumference of the ring, and q and m are the charge state and the atomic mass number of the beam particle.

Although, F_{IT} is the mean energy loss by the interaction due to the internal target, the coherent energy loss term is ignored in this study, because the barrier bucket cavity will compensate the energy loss.

Incoherent Term Coefficient of Momentum Cooling

The incoherent term coefficient is obtained by

$$D = D_s + D_{IBS} + D_{IT}, \quad (6)$$

where D_s is the Schottky noise due to the stochastic cooling, D_{IBS} is the diffusion coefficient due to the intra-beam

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scattering (IBS), and D_{IT} is the diffusion effect due to the internal target. The cluster or pellet target is used for the internal target experiments at COSY. Typical target thickness is 2×10^{15} atoms/cm^2, and the measured mean energy loss is 24 meV/turn. The straggling effect is expressed with the formula in [8]. The diffusion effect D_{IT} is given by

$$D_{IT} = \frac{1}{2} f_{rev} \left(\frac{1+\gamma}{\gamma} E_k \, \delta_{loss} \right)^2, \qquad (7)$$

where f_{rev} is the revolution frequency. The measured δ_{loss} is 2.4×10^{-8}.

When the particle density in 6 dimensional phase space becomes dense by the beam cooling, the scattering effects between particles become dominant. The IBS effect is formulated by Martini [9], and the numerical results of growth rates are used for the diffusion term by IBS in the present study. The equilibrium momentum spread is determined by the IBS effect in the case without the internal target. However when we use the internal target, the diffusion effects by the target is order of magnitude larger than the IBS term. (In the previous study [3], the IBS effect was considered as small in comparison with the internal target.)

Transverse Emittance

The multiple scattering induces the transverse emittance increase. Typical emittance increase is calculated, and the emittance increase of 2 $\times10^{-9}$ m-rad/sec is used for the present simulation study [8]. The transverse emittance of the beam is described by

$$\frac{d\epsilon}{dt} = -\frac{\epsilon}{\tau_c} - 2Gk_c\epsilon + \Delta\epsilon_{IT}, \qquad (8)$$

where τ_c is the transverse cooling time by the stochastic cooling and $\Delta\epsilon_{IT}$ is the emittance increase by the interaction between the internal target.

Calculation Parameters

Table 1 shows the parameters for the numerical simulation in COSY [10] including the electron cooler option [4].

Table 1: Parameters for COSY Simulation

Beam	
Synchronous kinetic energy	2.0 GeV
Particle number	10^{10}
Energy spread (1σ)	0.774 MeV
Ring circumference	184 m
Ring dispersion	-0.1
Momentum acceptance	+/- 2.5 $\times 10^{-3}$
Stochastic cooling system	
Band width	1 $\sim$ 1.8 GHz
Gain	106 dB
Effective temperature	80 K
Electrode length	32 mm
Electrode width	20 mm
Gap height	20 mm
Impedance	50 Ω
Number of pickup and kicker	24
TOF from pickup to kicker	0.3229 μsec
System delay	-0.04 ns
Electron cooling system	
Beta function at cooler	6 m
Dispersion at cooler	0 m
Effective energy spread	0.001 eV
Cooler length	2.7 m
Beam current	3 A
Beam diameter	3 cm

NUMERICAL SIMULATION RESULTS

We simulate numerically the particle distribution during the cooling process using the Fokker-Planck equation solver [11]. Figure 1 shows the momentum spread history during the internal target experiment for simultaneous operation of stochastic and electron coolers in COSY parameters with the emittance increase due to the internal target interaction. The rms momentum spread is calculated by

$$\frac{\Delta p}{p} = \frac{1}{E_t \beta^2} \sqrt{\frac{1}{N} \int_{-\infty}^{\infty} E^2 \Psi(E,t)\, dE}. \qquad (9)$$

Figures 2, 3, and 4 show the transverse emittance as a function of kinetic energy of the beam during the simultaneous use of stochastic and electron coolers for τ_c = 250 sec, τ_c = 100 sec, and $\tau_c = \infty$ sec, respectively. As shown in Figs. 2 and 3, the transverse emittance in the kinetic energy is decreased by the beam cooling effect. In the numerical model given by Eq. 8, the stochastic cooling decreases the transverse emittance in whole range of kinetic energy. While the electron cooling decreases strongly the emittance and the momentum spread around the synchronous kinetic energy. In the case without the transverse cooling $\tau_c = \infty$ sec, as shown in Fig. 4, although the transverse emittance around the synchronous kinetic energy is decreased by the electron cooling force, the whole emittance increases due to the interaction with the internal target. The momentum spread and the transverse emittance are connected as described in Eq. 4. Consequently, in comparison with Fig. 1 and Figs. 2$\sim$4, it is found that the transverse emittance growth due to the internal target interaction and the transverse cooling with the smaller cooling time are important to realized the small momentum spread.

CONCLUSION

The simultaneous use of the stochastic cooling and electron cooling was proposed, and was investigated numerically using the Fokker-Planck equation solver including the IBS effect in the internal target experiment at the COSY. The simulation results showed that the simultaneous operation method of the stochastic cooling and the electron

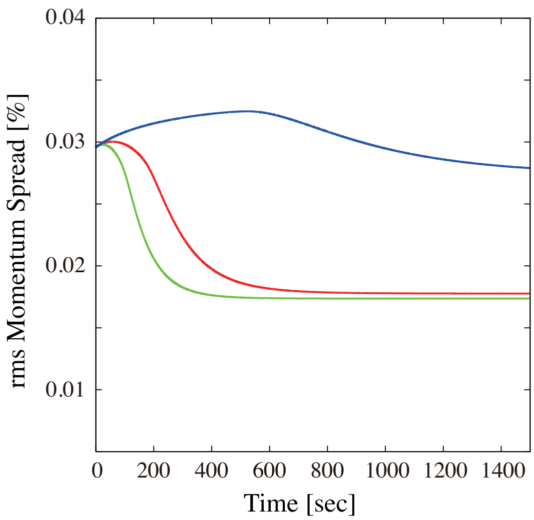

Figure 1: Momentum spread history with simultaneous use of stochastic and electron coolers. The red, green and blue curves show the results with the transverse stochastic cooling time of 250 sec and 100 sec, and without the transverse stochastic cooling ($\tau_c = \infty$ sec), respectively.

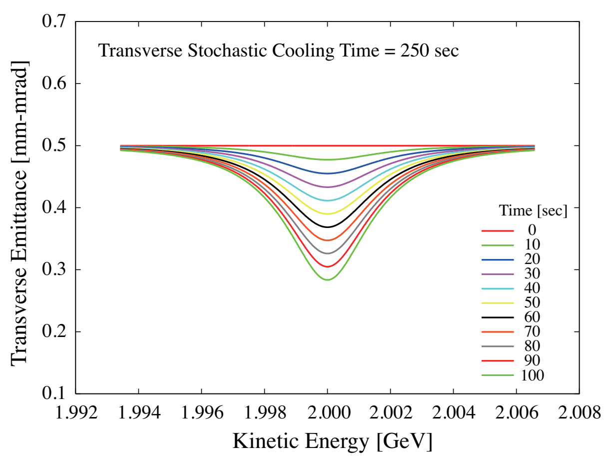

Figure 2: Transverse emittance during simultaneous use of stochastic and electron coolers for the transverse stochastic cooling time $\tau_c = 250$ sec.

cooling is useful scheme even in the case with the internal target. The momentum spread and the transverse emittance were increased due to the internal target interaction. It is found that the transverse emittance growth and the transverse cooling are also important to maintain the small momentum spread.

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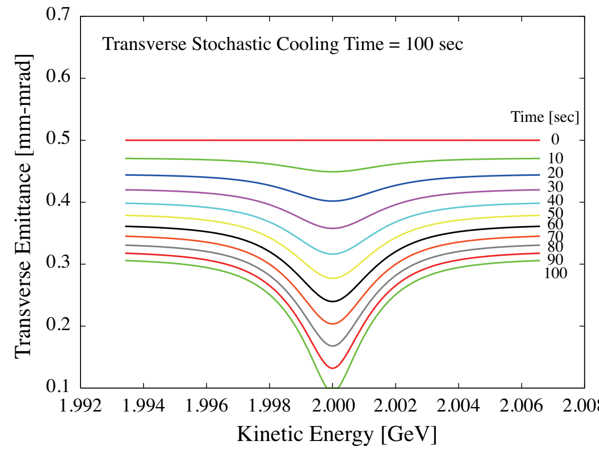

Figure 3: Transverse emittance during simultaneous use of stochastic and electron coolers for the transverse stochastic cooling time $\tau_c = 100$ sec.

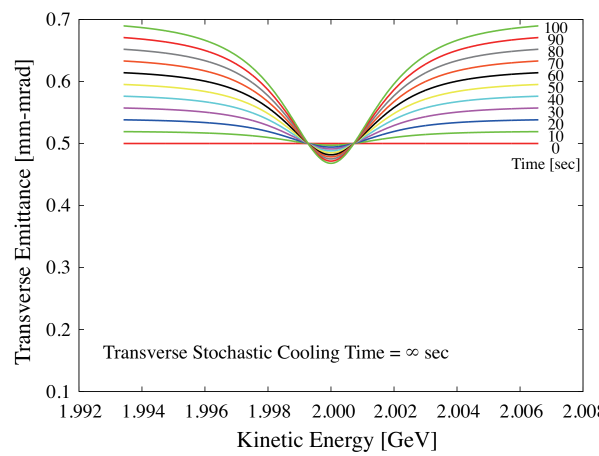

Figure 4: Transverse emittance during simultaneous use of stochastic and electron coolers for the transverse stochastic cooling time $\tau_c = \infty$ sec (without transverse stochastic cooling).

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