SIMULATION STUDY OF SIMULTANEOUS USE OF STOCHASTIC COOLING AND ELECTRON COOLING WITH INTERNAL TARGET AT COSY AND HESR

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Abstract

The small momentum spread of proton or anti-proton beam has to be realized and kept in the storage ring during the experiment with dense internal target such as pellet target. The stochastic cooling alone cannot compensate the mean energy loss by the internal target, and the barrier bucket cavity will help this energy loss. In addition the further small momentum spread can be realized with use of electron cooling. In the present study, the simulation results on the simultaneous use of stochastic cooling and electron cooling at COSY and HESR are presented.

INTRODUCTION

A stochastic cooling is useful tool to cool a hot beam with smaller number of beam particles even in the high kinetic energy regime. While an electron cooling is useful for lower energy and cold beam, and has also advantage for effective cooling even in the large number of beam ions.

In HESR of FAIR project [1] a large number of anti-protons with high kinetic energy should be stored in the storage ring. The small momentum spread of anti-proton beam has to be realized and kept in the storage ring during the experiment with dense internal target such as pellet target.

In this study, we propose the simultaneous use of the stochastic cooling and electron cooling. The stochastic cooling can collect the protons or anti-protons with large momentum spread into the central energy regime, in addition the further small momentum spread can be realized with use of electron cooling.

SIMULATION MODEL

A Fokker-Planck equation is often used as an investigation tool in the stochastic momentum cooling process. The simplified Fokker-Planck equation for a model of a stochastic momentum cooling is given by [2]

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

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

The coherent and incoherent terms in the Fokker-Planck equation mean the cooling force and the diffusion process, respectively. The terms are derived by the electrical characteristics of the feedback system for the stochastic cooling [3]. Also the coherent term coefficient includes the electron cooling force as

$$F = F_{scool} + F_{ecool}, \qquad (2)$$

where F_{scool} is the cooling force due to the stochastic cooler and F_{ecool} is the cooling force caused by the electron cooler. For the calculation model of the electron cooling drag force, we carry out the Parkhomchuk empirical formula [4].

In this study, we simulate numerically the particle distribution during the cooling process using the Fokker-Planck equation solver [5] based on a constrained interpolation profile (CIP) method with a rational function [6].

Table 1 shows the parameters for COSY simulation [7] including the electron cooler option [8].

Table 2 shows the parameters for HESR simulation [1].

NUMERICAL SIMULATION RESULTS

COSY

Figure 1 shows the energy spread history during the cooling in COSY parameters. Here the energy spread σ is calculated by

$$\sigma^2(t) = \frac{1}{N}\int_{-\infty}^{\infty} E^2 \Psi(E,t)\, dE, \qquad (3)$$

where N is the total particle number in the ring.

As shown in Fig. 1, the energy spread can be improved well by the stochastic cooling in the case without the internal target. In the case with the internal target, the stochastic cooling does not compensate the energy loss, and the energy spread increases. When the electron cooling is simultaneously applied with the stochastic cooling, the energy spread can be improved until 500 sec in the case with the internal target. However even if in cooperation of the electron cooling of 0.25 A, the energy loss due to the internal target is not compensated in the later stage.

HESR

Figure 2 shows the particle distributions as a function of energy during the stochastic cooling in HESR at each cooling time. The anti-protons can be collected into the

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Table 1: Parameters for COSY Simulation

Beam	
Momentum	3.224 GeV/c
Kinetic energy	2.42 GeV
Particle number	10^{10}
Energy spread (1σ)	0.774 MeV
Ring Dispersion	-0.1
Momentum acceptance	+/- 1.5 × 10^{-3}
Stochastic cooling system	
Band width	1 $\sim$ 1.8 GHz
Gain	96 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
Beam current	0.1 or 0.25 A
Effective energy spread	0.001 eV
Beam diameter	0.01 m
Cooler length	2 m

Table 2: Parameters for HESR Simulation

Beam	
Kinetic energy	8 GeV
Particle number	10^{11}
Ring circumference	573.1 m
Stochastic cooling system	
Band width	2 $\sim$ 4 GHz
Gain	105 dB
Effective temperature	80 K
Electrode length	25 mm
Electrode width	25 mm
Gap height	26 mm
Impedance	50 Ω
Number of pickup and kicker	64
Electron cooling system	
Beta function at cooler	100 m
Dispersion at cooler	0 m
Beam current	0.1 A
Effective energy spread	0.001 eV
Beam diameter	0.01 m
Cooler length	25 m

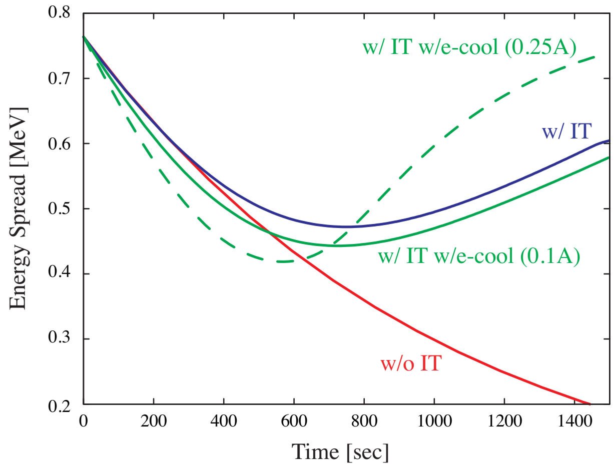

Figure 1: Energy spread history during cooling in COSY. The red curve shows the stochastic cooling result without the internal target, the blue line shows the stochastic cooling result with the internal target, the green lines indicate the internal target results with the stochastic and electron coolers for the electron beam current of 0.1 A (solid) and 0.25 A (dashed), respectively.

central energy of the beam due to the stochastic cooling.

Figure 3 shows the energy spread history during the stochastic cooling in HESR at each initial energy spread. The final energy spread is 0.35 MeV, which is as the momentum spread $\Delta p/p = 4 \times 10^{-5}$.

Figure 4 shows the energy spread history during cooling in HESR parameters at each cooling option. Here “s“ means the stochastic cooling, “e“ indicates the electron cooling, “s+e“ indicates the simultaneous use of the stochastic cooling and electron cooling, “s→e“ implies the switching from the stochastic cooling to electron cooling at each time, and “s+e→e“ indicates the switching from the simultaneous use of the stochastic cooling and electron cooling to electron cooling alone at each time, respectively.

The smallest final energy spread is obtained with the electron cooling after the simultaneous use of the stochastic cooling and electron cooling, “s+e→e“. Because in the smaller momentum spread beam, the diffusion term D of the stochastic cooling affects the collected protons around the central beam energy. For this reason, it is favorable to switch off the stochastic cooler in the later stage of the simultaneous use of the two cooling schemes. As shown in Fig. 4, the scheme also gives the fastest cooling speed.

The simulation results for the initial energy spread $\sigma_0 =$ 2.8 MeV with the different cooling methods are summarized as Table 3. In the table, the cooling time to attain the energy spread of σ_0/e, $\sigma_0/10$, and $\sigma_0/20$ are given for each cooling method. From Table 3, “s+e→e at 600 s“ case is best situation in the condition. As a result, the switching method from the simultaneous use of the stochastic cooling and electron cooling to electron cooling alone has advantage for the fast cooling, and the switching time has the optimal value.

Figure 5 shows the energy spread history during the cooling in HESR with and without the internal target. The

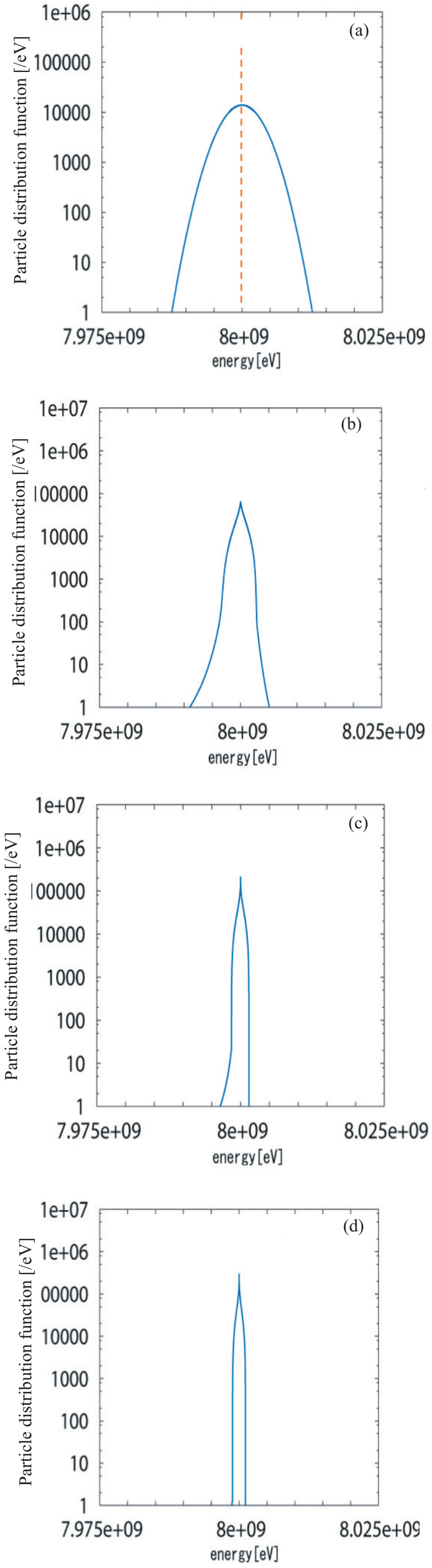

Figure 2: Particle distribution as a function of energy during stochastic cooling in HESR for the initial energy spread in $\sigma_0 = 2.8$ MeV, (a) for the initial condition, (b) for 400 sec, (c) for 800 sec, and (d) for 1200 sec, respectively.

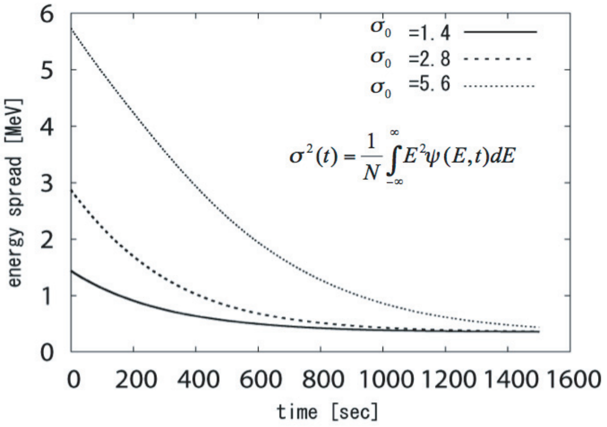

Figure 3: Energy spread history during stochastic cooling in HESR for the initial energy spread $\sigma_0 = 1.4$ MeV (solid), for $\sigma_0 = 2.8$ MeV (dashed), for $\sigma_0 = 5.6$ MeV (dotted), respectively.

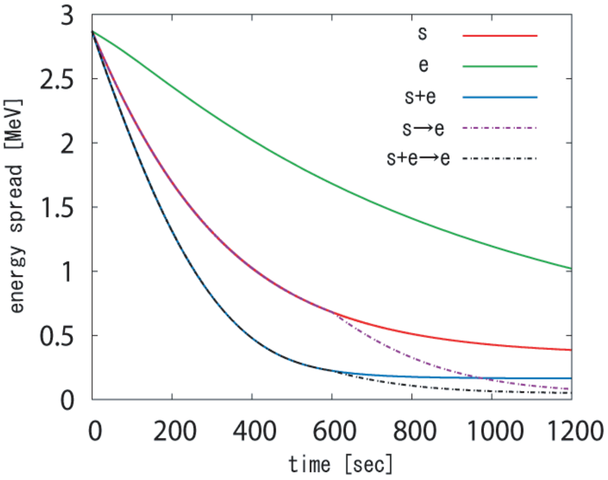

Figure 4: Energy spread history during cooling in HESR at each cooling combination method. The red curve shows the stochastic cooling result, the green line indicates the electron cooling result, the blue line shows the result with stochastic cooling and electron cooling, the red and dashed curve indicates the result for the electron cooling after the stochastic pre-cooling, and the black and dashed line shows the electron cooling result after the stochastic cooling and electron cooling, respectively.

stochastic cooling is carried out as the main beam cooler. Here if the barrier bucket voltage can be applied to compensate the mean energy loss at the internal target, the coherent term does not include the energy loss [9]. As shown in Fig. 5, the energy spread increase is not prevented by the stochastic cooling alone in the case with the internal target. On the other hand, the mean energy loss compensation by the barrier bucket voltage is a useful option. The simultaneous use of the electron cooler has an advantage for the energy loss compensation with fast cooling.

Table 3: Required Time for Cooling in HESR at each Method. The symbol “–” means that those values cannot be achieved.

		Time [sec]	
Cooling method	for σ_0/e	for $\sigma_0/10$	for $\sigma_0/20$
s	400	–	–
e	1200	–	–
s+e	250	530	–
s→e at 400 s	400	850	1050
s→e at 600 s	400	880	1050
s→e at 800 s	400	950	1150
s+e→e at 400 s	250	580	810
s+e→e at 600 s	250	530	730
s+e→e at 800 s	250	530	860

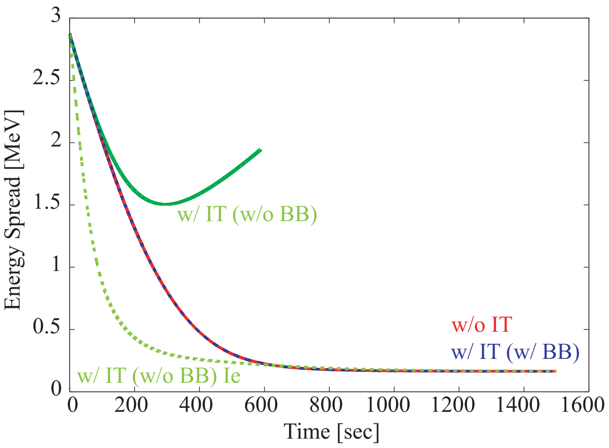

Figure 5: Energy spread history during stochastic cooling in HESR. The red curve shows the result without the internal target, the green line indicates the result with the internal target, the blue line shows the result with the internal target and the barrier bucket voltage, and the green dashed curve shows the result with the internal target and the electron cooling for the current of 0.1A, respectively.

CONCLUSION

The simultaneous use of the stochastic cooling and electron cooling was proposed and was investigated numerically using the Fokker-Planck equation with the rational function CIP solver in this study. The small momentum spread of proton beam has to be realized and kept in the storage ring during the experiment with dense internal target. The stochastic cooling alone could not compensate the mean energy loss by the internal target, and the barrier bucket cavity will help this energy loss. In addition the further small momentum spread could be realized with use of electron cooling. Since the diffusion term of the stochastic cooling affects the collected particles around the central beam energy, it is favorable to switch off the stochastic cooler in the later stage of the simultaneous use of the two cooling schemes. The optimal switching time exists for the smallest momentum spread and the fast cooling. The simulation results showed that the simultaneous use method of the stochastic cooling and the electron cooling is useful scheme even in the case with the internal target.

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