STOCHASTIC COOLING SIMULATION OF RARE ISOTOPE BEAM AND ITS SECONDARY*

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Abstract

Stochastic cooling is a broadband feedback system, which is very effective for reducing the beam size without beam loss [1]. It has advantage over electron cooling in cooling low intensity beam with large emittance and momentum spread, and is required for precise study of the decay properties of RIB (Radioactive Ion Beam) by use of the SMS (Schottky Mass Spectrometry) method [2]. This paper mainly concerns on cooling of primary beam and its secondary beam, pointing out the range of mass-to-charge spread that could be cooled for secondary particles. Meanwhile, TOF cooling combined with filter cooling was also studied. The simulation results provide theoretical supports for analysing different ions circulating in the ring at the same time in the experiments.

INTRODUCTION TO HIAF STOCHASTIC COOLING SYSTEM

The High Intensity heavy ion Accelerator Facility (HIAF) was proposed by the Institute of Modern Physics in 2009. As one of 16 large-scale research facilities proposed in China, HIAF is the next-generation high intensity facility for advances in nuclear physics and related research fields.

Stochastic cooling will be built on the Spectrometer Ring (SRing) of the HIAF project. The space for pickups and kickers is reserved in advance for SRing stochastic cooling system. There are 4 m for pickups and 4 m for kickers. All of the electrodes will be installed in the straight section without dispersion, and it has the advantage of preventing the coupling between phase subspaces, especially the transverse heating due to longitudinal kicks. It is planned to have 2 pickup tanks and 2 kicker tanks which would perform both transverse and longitudinal cooling. The betatron phase advances from pickup to kicker are almost 90 deg for both horizontal and vertical cooling.

The kinetic energy was designed to be 400 MeV/u, for the consideration of nuclear physics and atomic physics. The radioactive ion beam injected into SRing has large momentum spread of ±1.5e-2. If stochastic cooling is used for such kind of beam, the cooling frequency would be small in order to have large cooling acceptance. Fortunately, bunch rotation was proposed to decrease the momentum spread to ±4.0e-3, which is suitable for stochastic cooling to be cooled to the appropriate values, and then combined with electron cooling for further momentum spread decrease.

COOLING METHODS FOR SRING LONGITUDINAL STOCHASTIC COOLING

By comparisons of different cooling methods, TOF cooling has the maximum cooling acceptance for longitudinal cooling than the others. Therefore, TOF cooling [3,4] was proposed to be used for SRing longitudinal stochastic cooling for beam with large momentum spread. After the beam momentum spread was decreased to a small value stage, filter cooling [5] was used for continuous cooling in order to achieve a reasonable value for subsequent electron cooling.

For the beam energy 400 MeV/u, when the bandwidth was 1-2 GHz, the TOF cooling acceptance was smaller than the initial beam momentum spread ±4.0e-3. Therefore, the bandwidth was reduced to 0.6-1.2 GHz, and then the TOF cooling could be able to cool this kind of beam with its initial momentum spread within TOF cooling acceptance.

LONGITUDINAL STOCHASTIC COOLING SIMULATION ON SRING

Cooling of Primary Beam

Table 1: Longitudinal Stochastic Cooling parameters

Physical parameters	**values**
Ion	$^{132}\mathrm{Sn}^{50+}$
Kinetic energy	740 MeV/u, 400 MeV/u
Total number of RI	1.0e5, 1.0e8
Initial Δp/p	±4.0e-3 (TOF Cooling) ±7.0e-4(Filter Cooling)
γt	3.317
Local γt	2.568
Bandwidth	0.6-1.2 GHz
Number of slot rings for Pickup/Kicker	64/128, 112/224
Number of faltin for Pickup/Kicker(0.75 m)	2/4
Temperature	300 K
Lpk	75.25 m

The SRing stochastic cooling parameters are listed in Table 1. $^{132}\mathrm{Sn}^{50+}$ was chosen for the primary beam. We assumed the beam kinetic energy to be 740 MeV/u or 400 MeV/u for comparisons, and the particle number to be

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1.0e5 or 1.0e8. Two different electrode structures were proposed for the cooling system, and will be involved in the cooling simulation.

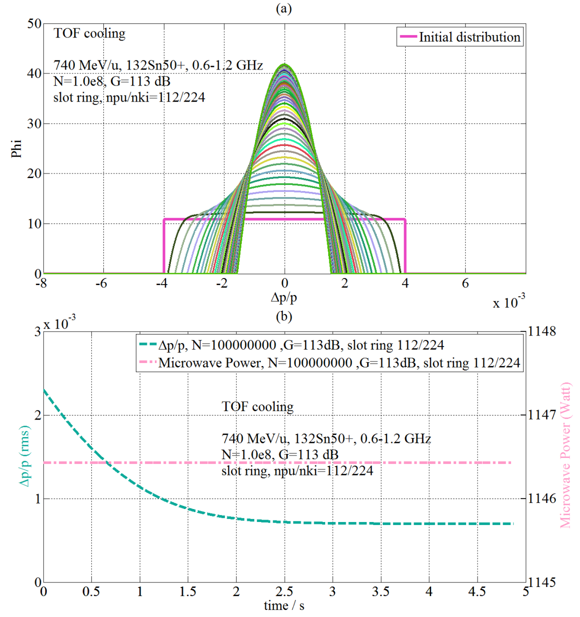

Figure 1: Results of TOF cooling simulation (Ek=740 MeV/u). (a) Beam distribution during cooling. (b) Evolution of momentum spread (rms) and microwave power.

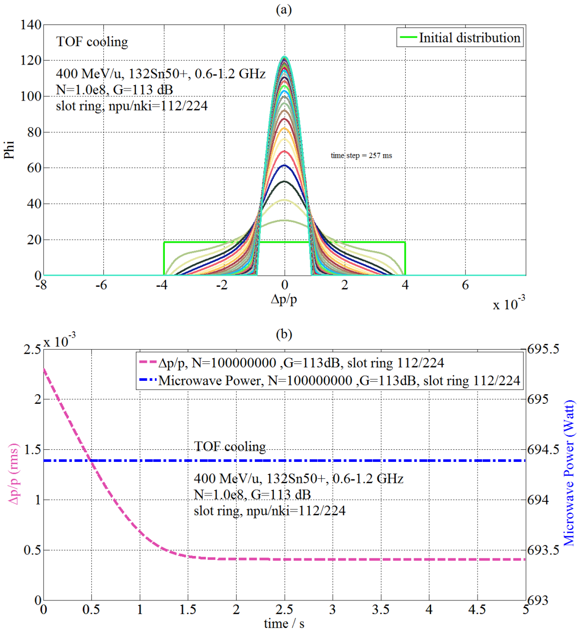

Figure 2: Results of TOF cooling simulation (Ek=400 MeV/u). (a) Beam distribution during cooling. (b) Evolution of momentum spread (rms) and microwave power.

Firstly, TOF cooling was used for longitudinal stochastic cooling simulation of two different beam kinetic energies with other beam parameters were kept the same.

When the beam kinetic energy is 740 MeV/u, beam distribution and evolution of momentum spread (rms) and microwave power are shown in Fig. 1, and cooling results with kinetic energy 400 MeV/u are shown in Fig. 2. From the simulation results, it is clearly that TOF cooling has the ability of cooling the beam to the equilibrium momentum spread of 1.e-4. For lower energy, cooling is a little bit faster and the equilibrium momentum spread is relatively smaller. Meanwhile, the microwave power needed for lower energy is also lower than the higher energy case.

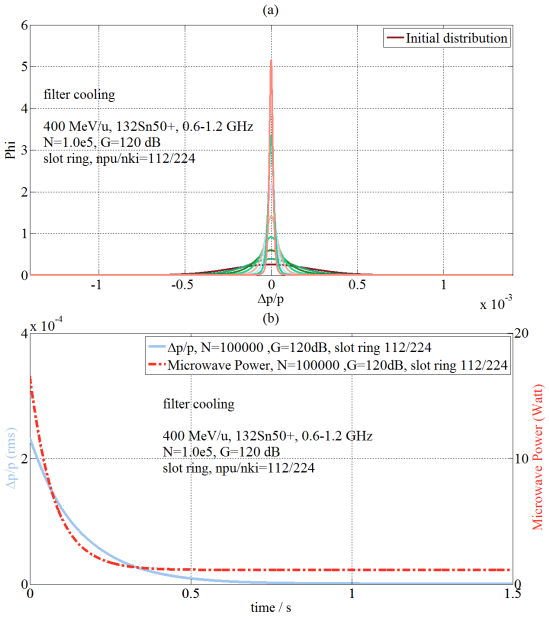

Figure 3: Filter cooling simulation results with particle number 1.0e5 and amplifier gain 120 dB. (a) Beam distribution during cooling. (b) Evolution of momentum spread (rms) and microwave power.

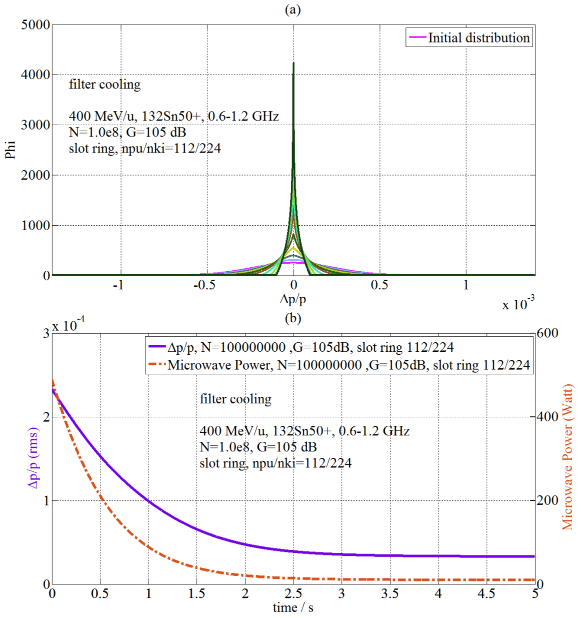

Figure 4: Filter cooling simulation results with particle number 1e8 and amplifier gain 105 dB. (a) Beam distribution during cooling. (b) Evolution of momentum spread (rms) and microwave power.

Then, filter cooling method was used for the simulation comparisons of different particle numbers. As shown in Fig. 3 and Fig. 4, similar to TOF cooling, filter cooling also has the ability of cooling beam to the equilibrium momentum spread of 1.0e-5, which is smaller than the TOF cooling equilibrium value. Meanwhile, when the particle number is less, cooling is faster, equilibrium momentum spread is smaller as well as the power needed is lower too. Therefore, stochastic cooling is more suitable for cooling beam with low intensity.

For HIAF stochastic cooling, two electrode structures were proposed for the cooling system, one is the slot ring structure and the other one is the faltin structure. By simulation of these two different structures in three cases, the results show that if the structure adopts slot ring with 112 and 224 cells for pickup and kicker respectively, cooling is always better than other cases, as shown in Fig. 5.

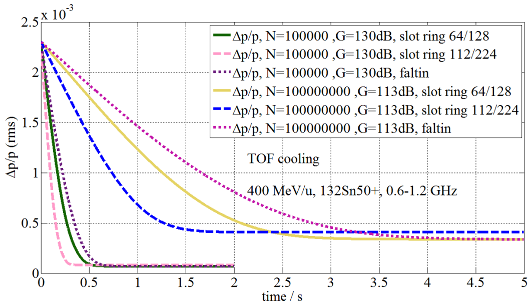

Figure 5: By TOF cooling simulation with two different electrode structures in three cases, slot ring with 112 and 224 cells for pickup and kicker is a better choice.

Cooling of Secondary Beam

For stochastic cooling of secondary beam, we choose ^{132}Sn^{50+} as the primary beam for simulation.

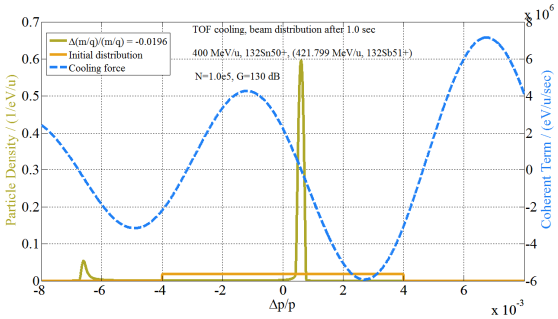

Figure 6: Stochastic cooling of secondary beam ^{132}Sb^{51+} by TOF method.

By simulation, TOF cooling has the ability of cooling the secondary beam such as ^{132}Sb^{51+} with mass-to-charge spread -0.0196. However, it is worth noting that a small part of beam is lost after cooling due to the TOF cooling acceptance. As shown in Fig. 6.

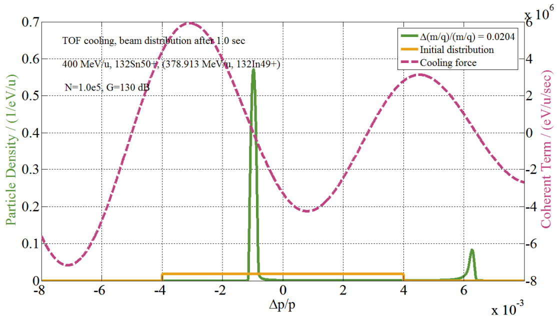

Figure 7: Stochastic cooling of secondary beam ^{132}In^{49+} by TOF method.

In addition, TOF cooling can also be able to cool the secondary beam ^{132}In^{49+} with mass-to-charge spread 0.0204. Like the Sb case, still a small part of beam is lost after cooling, as show in Fig. 7.

TOF cooling has the ability of cooling secondary beam for some special cases, and filter cooling could also be able to cool some kind of secondary beam, such as ^{129}In^{49+} with mass-to-charge spread -0.0028, which is shown in Fig. 8. However, after cooling, the secondary beam lies on the edge of the cooling acceptance and is at risk of loss.

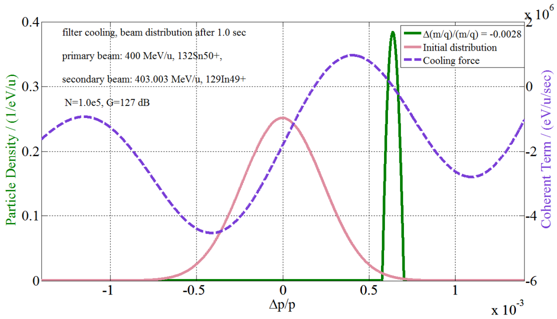

Figure 8: Stochastic cooling of secondary beam ^{129}In^{49+} by filter method.

Furthermore, TOF cooling can be able to scrape out the secondary beams in a range of mass-to-charge spread, $7.5e-4 \leq |r| \leq 1.5e-2$, $r=\Delta(m/q)/(m/q)$, as shown in Fig. 9.

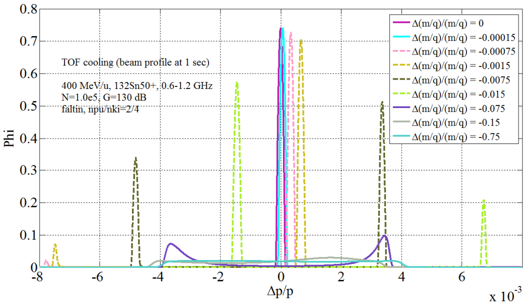

Figure 9: Secondary beam with mass-to-charge spread $7.5e-4 \leq |r=\Delta(m/q)/(m/q)| \leq 1.5e-2$ could be scraped out by TOF cooling method after 1.0 sec.

Meanwhile, filter cooling could also be able to scrape out the secondary beams in a range of mass-to-charge spread, $1.5e-4 \leq |r| \leq 1.5e-2$, $r=\Delta(m/q)/(m/q)$, as shown in Fig. 10.

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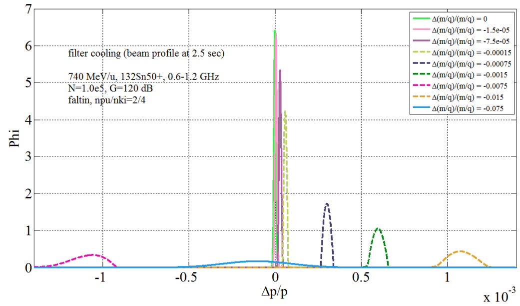

Figure 10: Secondary beam with mass-to-charge spread 1.5e-4≤|r=Δ(m/q)/(m/q)|≤1.5e-2 could be scraped out by filter cooling method after 2.5 sec.

Combination of TOF and Filter Cooling

For TOF cooling combined with filter cooling, the switch time from TOF to filter is critically important to be considered. When the kinetic energy is 400 MeV/u, the switch time from TOF to filter should be longer than 0.37 s from simulation.

At the same time, different switch times from TOF to filter were also simulated. The results clearly indicate that if the switch time is less than 0.37 s, heating occurs during cooling process. Then, if switch time longer than 0.37 s, cooling effect could not be good enough. Therefore, the optimal switch time from TOF cooling to filter cooling is exactly 0.37 s from the simulation analysis. Result is shown in Fig. 11.

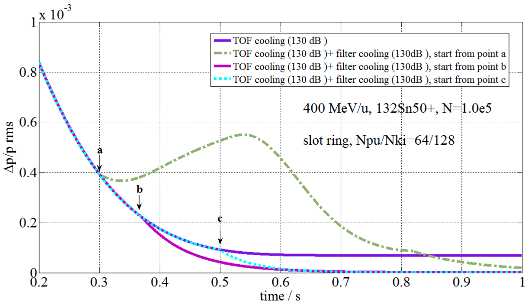

Figure 11: Simulation of different switch times from TOF cooling to filter cooling. Point a is the switch time less than 0.37 s, point b is the switch time 0.37 s and point c is the switch time larger than 0.37s.

It is worth noting that the switch time 0.37 s is not fixed, and depends on many factors, such as the beam kinetic energy, bandwidth, the distance between pickup and kicker and the circumference of the storage ring, and so on. This is because the maximum off-momentum to be cooled by filter method relates to those factors mentioned above, as shown in Eq. (1)-Eq. (6) [6].

$$2m\left|2x\eta_{pk}+\eta\right|\left|\frac{\delta p}{p}\right|<1. \tag{1}$$

Here x is the ratio of paths between pickup and kicker and the closed orbit circumference C.

$$m=\frac{f_{min}+f_{max}}{2f_{rev}} \tag{2}$$

$$x=\frac{s_k-s_p}{C} \tag{3}$$

The frequency slip factor is

$$\eta_{pk}=\gamma^{-2}-\alpha_{pk} \tag{4}$$

With the relativistic Lorentz factor γ and the local momentum compaction factor

$$\alpha_{pk}=\frac{1}{s_k-s_p}\int_{s_p}^{s_k}\frac{D(s)}{\rho(s)}ds \tag{5}$$

$D(s)$ is the dispersion function, and $\rho(s)$ is the local orbit curvature. s_p and s_k are the azimuthal coordinates of pickup and kicker.

Here η stands for the usual frequency slip factor for one revolution around the ring, calculated using Eq. (5) with the usual momentum compaction factor

$$\alpha_P=\frac{1}{C}\int_0^C\frac{D(s)}{\rho(s)}ds \tag{6}$$

Therefore, the optimum switch point from TOF cooling to filter cooling is at the maximum off-momentum where the filter cooling could be able to deal with. In reality, many factors should be taken into consideration for the choice of switch point from TOF cooling to filter, such as amplifier noise, and the delay and so on.

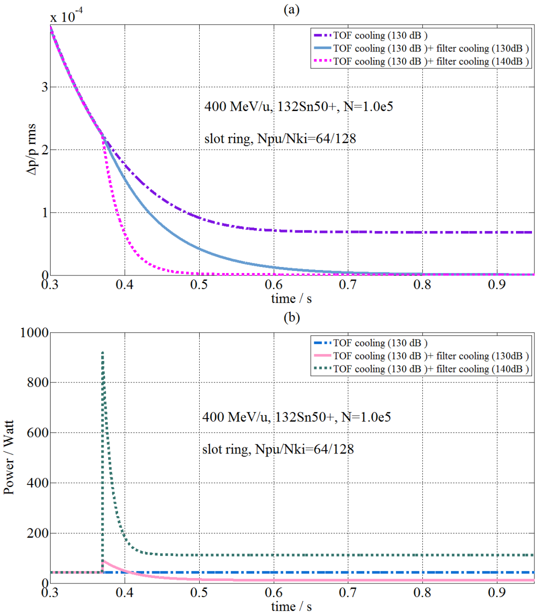

Figure 12: filter cooling simulation with different amplifier gain followed by TOF cooling.

It is clearly from the Fig. 12 that it is a better choice for switching from TOF to filter at an appropriate point during the whole cooling process. This is because after switches, cooling is obviously faster than before. Besides, after TOF cooling was switched to filter cooling, higher amplifier gain leads to faster cooling, such as 140 dB. However, more microwave power is needed to compensate this optimum cooling process.

CONCLUSION

Stochastic cooling is an effective way to provide a fast precooling of radioactive fragment beams with a large emittance.

For longitudinal stochastic cooling, TOF cooling has maximum acceptance among various methods, and it will be used for SRing stochastic cooling for beams with large momentum spread. Once the momentum spread is reduced to small value stage, filter cooling will be used if the momentum spread could be able to fit into the filter cooling acceptance.

For low beam energy 400 MeV/u, the TOF cooling acceptance is smaller than the initial beam spread ±4.0e-3 if the bandwidth is 1-2 GHz. So the bandwidth is changed to 0.6-1.2 GHz, where TOF cooling could be able to deal with.

For lower energy or less particle number, cooling is a little bit faster, equilibrium momentum spread is relatively smaller as well as the power is lower too.

For the electrode structure, cooling would be better if the structure is slot ring with 112 and 224 cell numbers for pickup and kicker respectively.

For TOF cooling combined with filter cooling, the best choice of switch point from TOF cooling to filter cooling is at the maximum off-momentum that fit inside the filter cooling acceptance. In reality, many factors such as amplifier noise, and the delay and so on should be taken into consideration for the choice of switch point from TOF cooling to filter.

TOF cooling can be able to cool the secondary beam but at the expense of losing some particles after cooling.

Both TOF and filter cooling have the ability to scrape out the secondary beam in a range of mass-to-charge spread.

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