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STOCHASTIC COOLING SIMULATION OF RARE ISOTOPE BEAMS ON THE SPECTROMETER RING OF THE HIGH ENERGY AND HIGH INTENSITY ACCELERATOR FACILITY*

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Abstract

Among various cooling methods, stochastic cooling is an effective way of cooling low intensity beams with larger size[1]. For the HIAF (High energy and high Intensity Accelerator Facility) project, stochastic cooling will be built on the SRing (Spectrometer Ring). This paper mainly concerns on cooling effects based on different stochastic cooling methods, aiming at finding the optimal cooling method and cooling parameters for different physical experiment purposes. Besides, TOF cooling combined with filter cooling was also studied. Simulation analysis will provide theoretical reference and support for the engineering construction.

INTRODUCTION TO HIAF STOCHASTIC COOLING SYSTEM

The High Intensity heavy ion Accelerator Facility (HIAF) is high intensity facility in nuclear physics and related research fields, and stochastic cooling system will be built on the Spectrometer Ring (SRing) of the HIAF project. For the SRing stochastic cooling, 2 pickup tanks and 2 kicker tanks will be performed for both transverse and longitudinal cooling. The cooling electrodes will be installed in the straight section without dispersion, and it is advantageous to prevent the coupling between phase subspaces. For transverse cooling, the designed betatron phase advances between pickup and kicker are almost 90 deg.

The momentum spread of the radioactive beam injected into SRing is almost ±1.5e-2. Stochastic cooling is not suitable for cooling this kind of hot beam, because the cooling frequency would be designed relatively smaller, which will greatly reduce the performance. Fortunately, it is planned to decrease the momentum spread to ±4.0e-3 firstly by using bunch rotation, and then stochastic cooling combined with electron cooling will further decrease the momentum spread to the desired value.

For the SRing stochastic cooling system, the beam energy is 740 MeV/u, bandwidths are different based on the different initial momentum spreads. With bunch rotation, the initial momentum spread for stochastic cooling is ±4.0e-3, but without bunch rotation, the initial momentum spread is ±1.5e-2. Therefore, bandwidth is designed differently in order to involve initial momentum spread with the cooling acceptance.

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For longitudinal cooling on SRing, TOF cooling [2,3] will be used for cooling of hot beam firstly, and filter cooling [4] will be used for continuous cooling to further reduce the momentum spread subsequently.

LONGITUDINAL STOCHASTIC COOLING SIMULATION ON SRING

Cooling with Bunch Rotation

Table 1: Longitudinal Stochastic Cooling Parameters

Physical parameters	values
Ion	$^{132}Sn^{50+}$
Kinetic energy	740 MeV/u
Total number of RI	1.0e5
Initial Δp/p	±4.0e-3/±1.5e-2 (TOF Cooling) ±7.0e-4/±2.0e-3 (Filter Cooling)
γt	3.37
Local γt	2.752
Bandwidth	0.6-1.2 GHz/0.2-0.6 GHz
Number of slot rings for Pickup/Kicker	64/64
Temperature	300 K
Lpk	92.01 m

The SRing stochastic cooling parameters are listed in Table 1. Slot ring coupler is adopted for the pickup and kicker structure, for the shunt impedance per meter of the slot ring structure is higher compared to other structures such as Faltin structure. The shunt impedance response per cell is shown in Fig. 1.

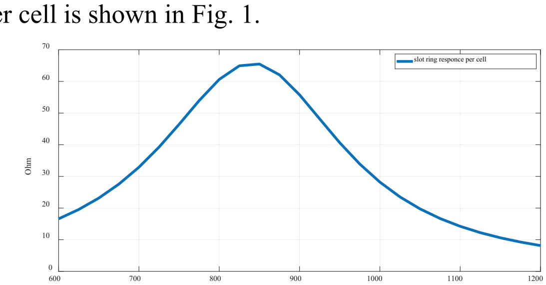

Figure 1: Shunt impedance response of slot ring structure per cell.

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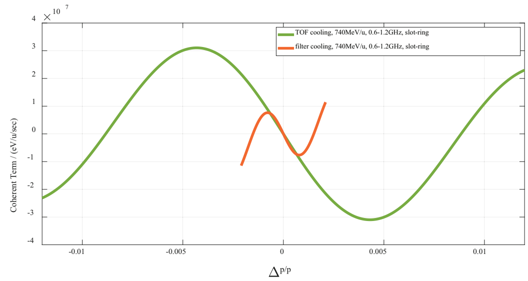

Figure 2: Coherent terms of TOF cooling and filter cooling.

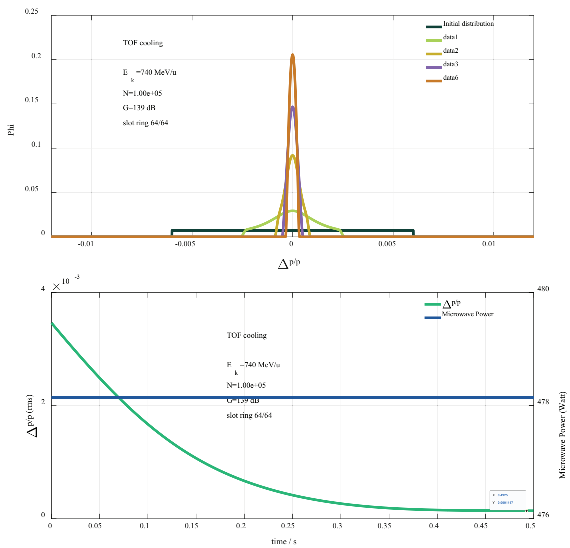

Figure 3: Results of TOF cooling simulation (Ek=740 MeV/u, 0.6GHz≤f≤1.2GHz). (up)Beam distribution during cooling. (down) Evolution of momentum spread (rms) and microwave power.

In Fig. 2 it is obviously that TOF cooling acceptance is much larger than filter cooling acceptance, therefore, TOF cooling is used for longitudinal stochastic cooling simulation at first. When the particle number is 1e5, cooling bandwidth is from 0.6 to 1.2 GHz, number of slot ring coupler is 64 both for pickup and kicker and the amplifier gain is 139 dB, the total cooling time is about 0.5 second which is shown in Fig. 3. From the simulation results, it is clearly that TOF cooling has the ability of cooling the beam to the equilibrium momentum spread of 1e-4 when the amplifier gain is 139 dB.

If the equilibrium momentum spread is expected to be smaller, then the amplifier gain should be decreased which can lead to slower cooling subsequently. As is shown in Fig. 4, cooling with amplifier gain of 125 dB is much slower than that of 139 dB, but the equilibrium momentum spread is smaller than the other.

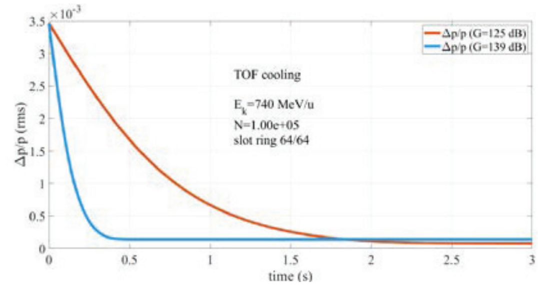

Figure 4: cooling comparisons between different amplifier gains.

When the momentum spread is decreased which can fit inside the filter cooling acceptance, it is better to use filter cooling method for subsequent cooling process. Similar to TOF cooling, filter cooling has the ability of cooling beam to the equilibrium momentum spread of 1e-6, which is smaller than the TOF cooling equilibrium value. Result is shown is Fig. 5.

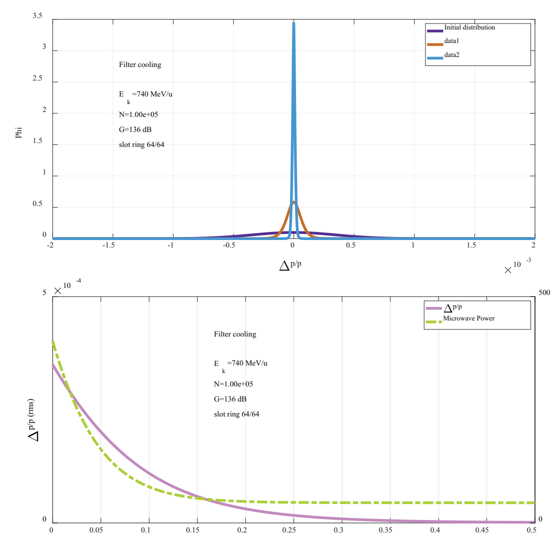

Figure 5: Results of filter cooling simulation (Ek=740 MeV/u, 0.6GHz≤f≤1.2GHz). (up) Beam distribution during cooling. (down) Evolution of momentum spread (rms) and microwave power.

In order to obtain less cooling time and smaller equilibrium momentum spread, it is better to use TOF cooling combined with filter cooling. For TOF cooling combined with filter cooling, it should be very careful to decide the switch time from TOF to filter cooling. When the kinetic energy is 740 MeV/u, particle number is 1e5 and number of slot ring cell are 64 for both pickup and kicker, the switch time from TOF to filter should be longer than 0.3 s from simulation.

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The results are clearly as shown in Fig. 6. When the switch time is at 0.2 sec, heating is obvious. When the switch time is 0.25 sec, although it is not obvious, heating also occurs slightly as seen in the middle part of the Fig.6. Therefore, the suitable switch time from TOF to filter cooling should be larger than 0.3 sec. Besides, switch from TOF to filter at 0.35 sec is also studied, but the cooling effect is not good enough. Therefore, the optimum switch time t_{opt} from TOF to filter should be 0.25 sec<t_{opt}<0.3 sec. after TOF cooling is switched to filter cooling, the higher the gain, the faster the cooling will be, as is obvious in the down part the Fig. 6.

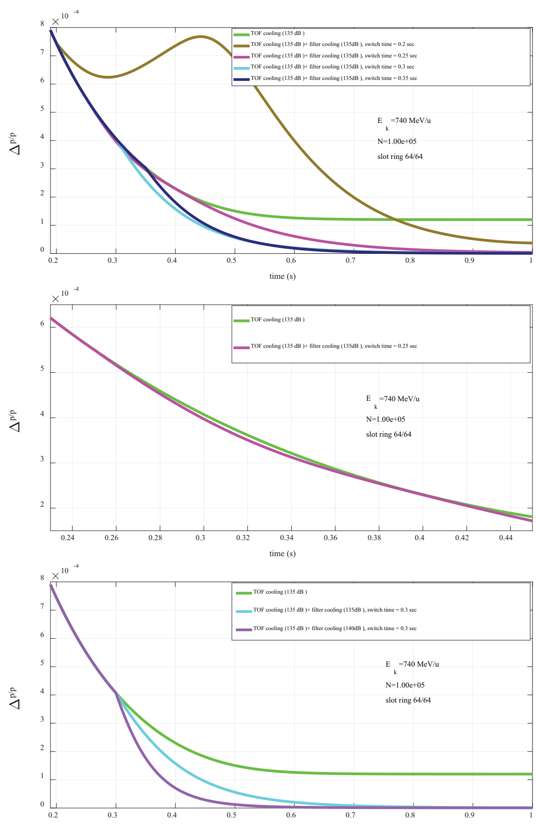


Figure 6: Simulation of different switch times from TOF cooling to filter cooling.

However, it should be noticed that the switch time 0.3 s is not fixed. The optimum switch time from TOF cooling to filter cooling is at the time when the momentum spread is decreased to fit just inside the filter cooling acceptance, and the cooling acceptance of filter method relies on many factors, such as the beam kinetic energy, bandwidth, the distance between pickup and kicker and the circumference of the storage ring, as shown in Eq. (1)-Eq. (6) [5].

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

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

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

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

The frequency slip factor is

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

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

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

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

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

Cooling without bunch rotation

Without bunch rotation, the initial beam spread should be $\pm$1.5% instead of $\pm$0.04%, therefore cooling bandwidth should be reduced to 0.2-0.6 GHz in order to accept the initial beam spread. Compared to 0.6-1.2 GHz, cooling acceptance is much larger for the frequency from 0.2-0.6 GHz, as is shown in Fig. 7. Cooling results are shown is Fig. 8. Cooling comparisons between with and without bunch rotation is shown in Fig. 9. It is clearly that it is better to use bunch rotation before the stochastic cooling process, for the cooling time is much shortened when bunch rotation is used. Filter cooling result is shown in Fig. 10 and the shunt impedance response for the frequency from 0.2-0.6 GHz is shown in Fig. 11.

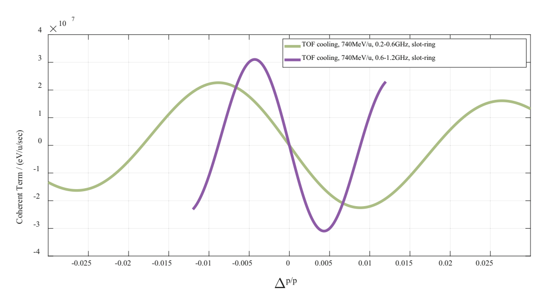
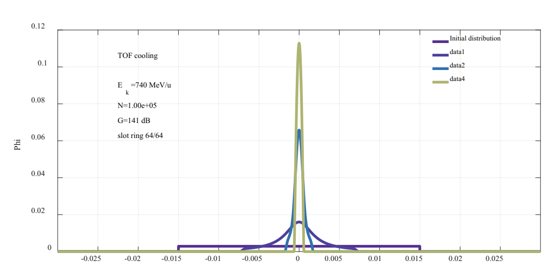


Figure 7: comparisons of cooling acceptances.



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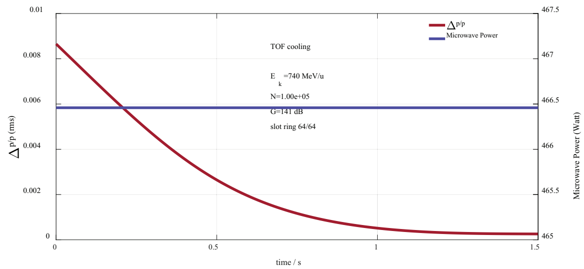

Figure 8: Results of TOF cooling simulation (Ek=740 MeV/u, 0.2GHz≤f≤0.6GHz). (up)Beam distribution during cooling. (down) Evolution of momentum spread (rms) and microwave power.

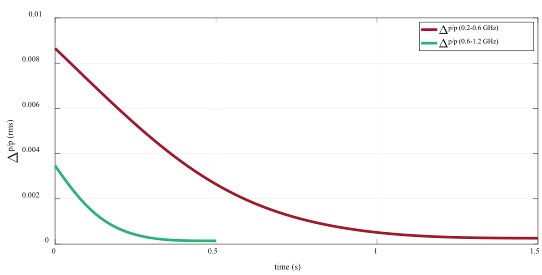

Figure 9: cooling comparisons between different bandwidths.

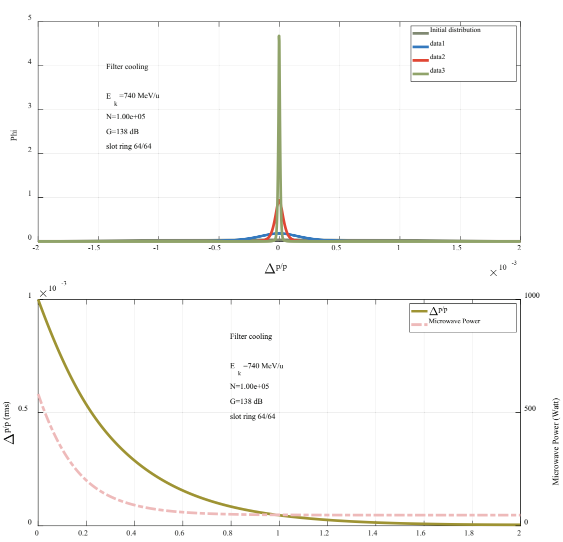

Figure 10: Results of filter cooling simulation (Ek=740 MeV/u, 0.2GHz≤f≤0.6GHz). (up)Beam distribution during cooling. (down) Evolution of momentum spread (rms) and microwave power.

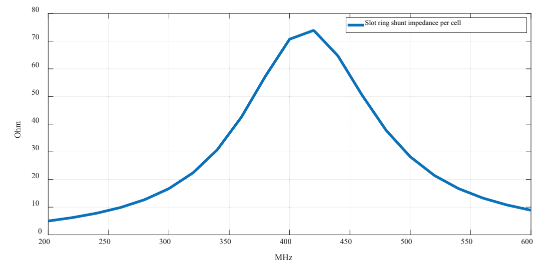

Figure 11: slot ring shunt impedance per cell for the cooling frequency from 0.2 GHz to 0.6 GHz.

CONCLUSION

Stochastic cooling simulation is investigated in this paper, and both TOF and filter cooling method are studied at the same time. From simulation results analysis, it is better to switch from TOF cooling to filter cooling at an appropriate time during the whole cooling process. This is because after switches, cooling is obviously faster than before.

Without bunch rotation, the initial beam spread should be ±1.5% instead of ±0.04%, therefore cooling bandwidth should be reduced to 0.2- 0.6 GHz, in order to accept the initial beam spread. With the new system bandwidth, cooling is slower than previous system which has bandwidth of 0.6-1.2 GHz. Slot ring structure is adopted for the pickup and kicker structure, for the shunt impedance is higher compared to other structures such as Faltin structure.

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