SIMULATION STUDY OF STOCHASTIC COOLING OF HEAVY ION BEAM AT THE COLLECTOR RING OF FAIR

T. Katayama, C. Dimopoulou, A. Dolinskii, F. Nolden and M. Steck, GSI, Darmstadt, Germany

Abstract

In the modularized start version of the FAIR project, the New Experimental Storage Ring is not included and therefore the task of the stochastic cooling system at the Collector Ring (CR) is now focused on the 3 GeV anti-proton beam. On the other hand, recently the SPARC collaboration has proposed to perform the high energy atomic physics experiments in the HESR ring with stable ions, typically a $^{238}U^{92+}$ beam, employing an internal target. Furthermore the future possibility of the nuclear physics experiments with rare isotope beams (RIBs), typically a $^{132}Sn^{50+}$ beam, in the HESR is envisaged. In the present report, the beam dynamics, mainly the longitudinal motion from the fragment separator SuperFRS to the end of beam cooling in the CR are described emphasizing the process of stochastic cooling of the rare isotope beam.

INTRODUCTION

Nuclear and atomic physics experiments with heavy ions are envisaged at the High Energy Storage Ring (HESR) of which the primary goal has been planned to perform the anti-proton beam experiment with the internal target at the PANDA detector. Through the optimization process of the anti-proton beam experiment, the acceptance of HESR ring for the lattice of gamma transition=6.2, is as follows. The transverse acceptance is 7 π mm.mrad and the momentum acceptance $\Delta p/p$ is +/- $2\mathrm{x}10^{-3}$. Then the rms value of the transverse emittance of the injected beam has to be less than 1.1 π mm.mrad considering that the full acceptance should be larger than the 6 times the rms value. The momentum spread of the injected beam should be less than $7\mathrm{x}10^{-4}$ (rms).

The transverse and longitudinal emittances of the RI beam produced through the beam fragmentation process at the superFRS are estimated using the simulation code MOCADI. [1] The relative momentum spread is $\Delta p/p$ (rms)=$1.25\mathrm{x}10^{-2}$, and the horizontal and vertical emittance (rms) are 90.7 and 44.3 π mm.mrad, respectively. They should be scraped and matched to the acceptance of Collector Ring (CR) of +/- 1.5% (momentum spread) and 45 π mm.mrad (rms) (transverse emittance). As the rare isotope beam has much larger transverse and longitudinal emittances which cannot be accepted by the HESR ring, the cooling of RIBs in the CR is indispensible.

Details of the recent progress of stochastic cooling system for the CR are presented in a separate report emphasizing the hardware development [2].

In the present report numerical results of the stochastic cooling process investigated with the Fokker Planck approach for the longitudinal cooling are described.

BUNCH ROTATION

The bunch length of the primary ion beam from the SIS100 is estimated as around 12 nsec (rms). Thus the bunch length of the injected beam is short enough compared with the revolution period in the CR and then the bunch rotation is effective to reduce the relative momentum spread. The parameters of bunch rotation are as follows: ion beam energy is 740 MeV/u, RF voltage 200 kV, harmonic number 1, momentum slip factor 0.178, initial $\Delta p/p$ +/-1.5 % (the acceptance limit of CR) and initial bunch length +/-37.5 nsec (truncated Gaussian at the value of +/- 3 rms value), respectively.

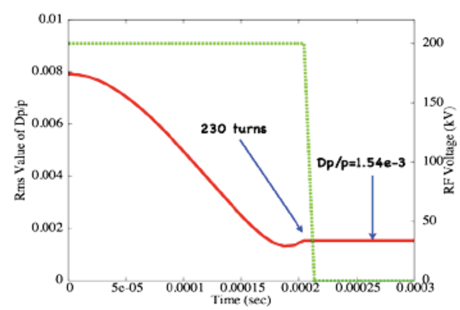

Figure 1: The variation of $\Delta p/p$ (rms) (red) and the RF voltage (green) as a function of time.

During the bunch rotation the momentum slip factor varies according to the change of their momentum spread. This effect is included in the present calculation. The RF voltage is applied during 1/4 synchrotron period and then switched off. In Fig. 1 the variation of the rms value of $\Delta p/p$ and the RF voltage are given as a function of time. The rms value of $\Delta p/p$ is reduced to $1.54\mathrm{x}10^{-3}$ after the 1/4 bunch rotation corresponding to 230 turns in the ring. The momentum distribution has a quasi uniform shape.

STOCHASTIC COOLING OF RI BEAM

The overall layout of the stochastic cooling system at the CR is presented in [2]. It is foreseen to use the three cooling methods for the heavy ion cooling, Palmer, Time Of Flight (TOF) and notch filter cooling. The Palmer pickup is located at the drift section with the finite dispersion of 6.58 m while the PUs of the notch filter cooling system are located at the dispersion-free section. The kicker systems are all located at the dispersion-free section. To apply the TOF cooling the notch filter system is removed from the cooling chain and the phase is

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adjusted [3, 4]. As there is no noise filtering function in the TOF system, the diffusion term is not rejected and therefore the small gain is inevitable to attain the well cooled beam. In Fig. 2 the coherent cooling force is compared for the three cooling methods (Palmer, TOF and filter). The beam distribution is $\Delta p/p$=+/- 4.4x10^{-3} (ΔE= +/- 5 MeV/u) uniform (pink) and the Gaussian beam with $\Delta p/p$=5x10^{-4} (rms) with +/- 2 sigma truncated (light blue). The latter would just fit into the acceptance of the notch filter cooling system.

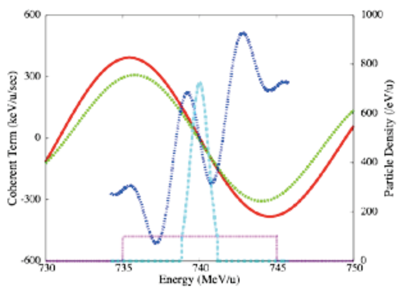

Figure 2: Comparison of coherent cooling force as a function of energy. Palmer (red), TOF (green) and Filter (blue) cooling methods.

It is shown that the Palmer and TOF cooling system have wide enough momentum acceptance to cool the beam after the bunch rotation (ΔE=+/- 5 MeV/u or $\Delta p/p$=+/-4.4x10^{-3}) while the notch filter system has narrower acceptance. Therefore the cooling has to start with Palmer or TOF, and after the beam is well pre-cooled, the notch filter system could be used to attain the beam of smallest momentum spread.

In the following sections, the results of investigation of three cooling methods are described. In the present calculation, as a good approximation, the structure of PU and Kicker is assumed as lambda/4 strip line structure, and the system gain is adjusted so that the required microwave power does not exceed the several hundreds Watt which is presently available for the longitudinal cooling. In all cases the number of ions is assumed as 1x10^{8} in a coasting beam.

Palmer Cooling

The variation of the rms value of $\Delta p/p$ and the required microwave power are given in Fig. 3. The gain of the cooling system is selected as 125 dB and the equilibrium $\Delta p/p$ (rms) is achieved at 6.6x10^{-5} within 8 sec. The required microwave power is 450 Watt at the beginning of cooling which is mainly Schottky power and the thermal power is negligibly small as the gain is reduced to 125 dB. The atmospheric temperature is assumed as 300 K.

The particle distributions during the cooling process are given in Fig. 4 as well as the coherent cooling force. The initial particle distribution is given as the uniform distribution with $\Delta p/p$=+/- 4.38x10^{-3}. After 8 sec cooling it reaches the equilibrium.

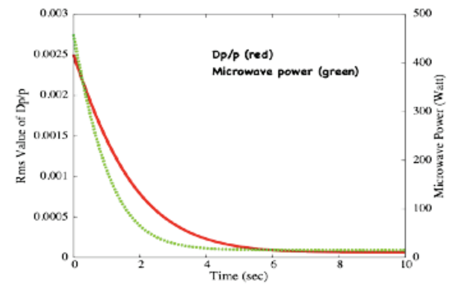

Figure 3: The variation of $\Delta p/p$ (rms) (red) and the microwave power (green) as a function of time. Ion number is 1e8 and the gain is 125 dB.

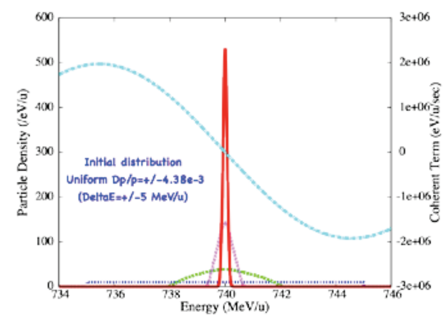

Figure 4: The evolution of the particle distribution during the cooling. Time=0 sec (blue), 2 sec (green), 4 sec (pink) and 10 sec (red). The cooling force is given in the light blue colored line.

TOF Cooling

The variation of the rms value of $\Delta p/p$ and the required microwave power are given in Fig. 5. The gain of the cooling system is selected as 113 dB and the equilibrium $\Delta p/p$ (rms) is achieved at 3.14x10^{-4} within 8.0 sec. The required microwave power is 430 Watt at the whole period of the cooling process which is contrasting to the case of Palmer cooling.

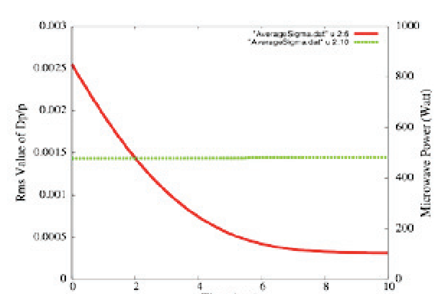

Figure 5: The variation of $\Delta p/p$ (rms) (red) and the microwave power (green) as a function of time. The ion number is 1x10^{8} and the gain is 113 dB.

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Combination of TOF, Palmer and Filter Cooling

In the previous chapters the cooling process with the Palmer and TOF method was found to be well suited for the pre-cooling of the beam after the bunch rotation while the filter cooling has not enough momentum acceptance. Then the natural idea is that after the pre-cooling by Palmer or TOF cooling, the filter cooling is subsequently applied to attain lower momentum spread. In Table 1 the cooling parameters for the combination of the cooling methods are given.

Table 1: Parameters for Combination of Cooling Methods

Beam kinetic energy	740 MeV/u, $^{132}Sn^{50+}$
Number of particles	$1x10^8$
Objective cooling time	10 sec (in the simulation)
Initial energy spread	$\Delta p/p$ = +/-$4.38x10^{-3}$(uniform distribution)
Momentum slip factor	0.178
Slip factor from PU to K	0.1346 (TOF & Filter), 0.0998 (Palmer)
Type of PU and Kicker	Lambda/4 loop coupler
Temperature at PU	Atmospheric 300 K (Palmer), 40 K (TOF & Filter) Noise 40 K
TOF from PU to Kicker	$0.336x10^{-6}$ sec (TOF &Filter) $0.208x10^{-6}$ (Palmer)
Dispersion at PU	0.0 m (TOF &Filter), 6.58 m (Palmer)
Dispersion at Kicker	0.0 m
Number of PU/Kicker	48/48 (TOF & Filter) 24/48 (Palmer)
Loop height, width	$126x10^{-3}$ m, $50x10^{-3}$m (No plunging)
Coupling impedance	50 Ohm
Band width	1-2 GHz
Cooling System Gain	100~125 dB

TOF Plus Filter Cooling

The TOF system is switched over to the filter cooling at 5 sec, and the gain of TOF and filter cooling system are 113 dB and 120 dB, respectively. The variation of the rms value of $\Delta p/p$ is given in Fig. 6. The equilibrium value of $2.5x10^{-5}$ is reached after 10 sec of cooling.

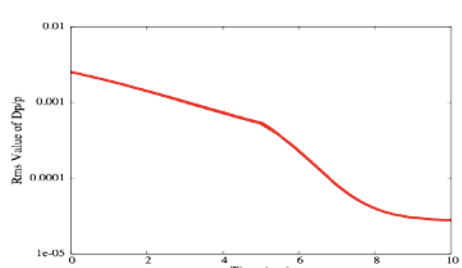

Figure 6: The variation of $\Delta p/p$ (rms) as a function of time. The ion number is $1x10^8$. The handover from the TOF cooling to filter cooling occurs at 5 sec.

Palmer plus Filter cooling

The Palmer system is switched over to the filter cooling at 5 sec, and the gain of Palmer and filter cooling system are 125 dB and 120 dB, respectively. The variation of the rms value of $\Delta p/p$ is given in Fig. 7. The equilibrium value is $3.2x10^{-5}$ after 10 sec cooling.

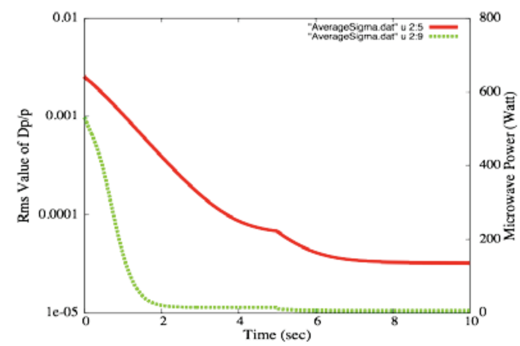

Figure 7: The variation of $\Delta p/p$ (rms) (red) and microwave power (green) as a function of time. The handover from the Palmer cooling to filter occurs at 5 sec.

CONCLUSIVE REMARKS

The Palmer and TOF cooling system have wide enough energy acceptance, around +/- 8 MeV/u which well covers the RI beam energy spread after the bunch rotation. Then both methods can be used effectively as a pre-cooling system. The main cooling system could be the filter cooling which could cool the RI beam to the low momentum spread. For $N=10^8$ (or less), both TOF and Palmer method can achieve the pre-cooling during 5 sec and then handover to the filter cooling system. The beam is cooled down after 10 sec by filter cooling to $\Delta p/p$ (rms) of around $3x10^{-5}$. Note that the goal for the CR is to cool the RIBs down to $\Delta p/p$ (rms) < $7x10^{-4}$ (HESR acceptance).

The main power source is Schottky power ($N=10^8$ and 10^9 case) and the thermal power is negligible compared to the Schottky power. Then the atmospheric temperature could be set to be the room temperature of 300 K for the Palmer method while for TOF and filter cooling, the atmospheric temperature is 40 K (and the noise temperature is 40 K) as they are also used for the 3 GeV anti-proton beam cooling.

The slot line structure, presently being developed at GSI, has larger shunt impedance compared with lambda/4 structure. Then the required system gain and the required microwave power are expected to be lower [2].

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