NUMERICAL INVESTIGATION OF STOCHASTIC COOLING AT NICA COLLIDER

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Abstract

At the heavy ion collider NICA promoted at the Dubna, JINR, the stochastic cooling will play the crucial roles to manipulate the beam. The primary goal is to prevent the IBS diffusion effects to keep the high luminosity during the experimental cycle. The other purpose is to accumulate the beam intensity up to several times 1e10 from the injector Nuclotron with use of barrier bucket method. With this method, the short bunch formation is not necessary in the Nuclotron, and is transferred to the collider as a long bunch condition. After the BB accumulation the coasting beam is adiabatically bunched with the help of RF field and the stochastic cooling. In the present paper the detailed simulation results are presented for the above three process mainly longitudinal freedom.

INTRODUCTION

The low energy heavy ion collider is proposed at the JINRwhich aims to achieve the 1-4.5 GeV/u (kinetic energy) gold beam head-on collision with the luminosity 1e27/cm2/sec. [1] The number of bunches in the collider is ~24 and each bunch should contain the ion number of ~5e9/bunch, depending upon the operation energy. Thus totally around 1e11 ions should be accumulated in the collider ring. The injector for the collider is planned to use the existing superconducting heavy ion synchrotron, Nuclotron which provides the beam 1-4.5 GeV/u with the intensity of 1e8-1e9/cycle, the cycle time of 10 sec. The bunch length of the beam from the Nuclotron is around 1/3 of the circumference, 300 nsec. [2]

The main task of the beam cooling is to realize the beam parameters required for the experiment, beam accumulation and the short bunch formation and keep their qualities during the experimental cycle.

In the present scenario, the beam is transferred to the collider without the manipulation of short bunch formation in the Nuclotron which allows us much easier operation of the Nuclotron. The long bunch beam is transferred in the longitudinal injection area which is provided by the barrier voltages, and is accumulated with the assistance of stochastic cooling, for low energy operation, say below 2 GeV/u, the electron cooling will be used.

Thus accumulated high intensity heavy ion beam in the collider is the coasting beam condition, and then the large voltage RF field is applied adiabatically as well as the stochastic cooling. The beam is gradually bunched to the required rms bunch length for the collision experiment, 2ns (rms). The bunch length is the equilibrium condition of the RF filed, stochastic cooling force and the Intra Beam Scattering (IBS) force.

In the present simulation work, the RF field (barrier or normal RF), IBS heating effects and the cooling force are taken into account. The space charge repulsion force is not included which might be significant effects at the low energy, high intensity and short bunch condition. This subject will be treated in the future work.

Table 1 Basic parameters of NICA collider

Ion species	197Au79+	Transverse Emittance	1.0 Pi mm.mrad
Operation energy	1-4.5 GeV/u	Momentum spread	1.0-1.5e-3
Circumference	503.04 m	Beat function at colliding point	0.35 m
Number of ions/bunch	3e8-5e9	Expected luminosity	3e27/cm2/sec
Number of bunch/ring	24	Bunch length (rms)	0.6 m
Injector	Nuclotron	Injected intensity	1e9/cycle
Emittance	0.5 Pi mm.mrad	Momentum spread (rms)	3e-4
Bunch length	300 nsec		

LATTICE AND IBS GROWTH RATE

The Intra Beam Scattering (IBS) effects are critical diffusion factor for the low energy high charge state ion collider. The growth rate is numerically calculated with use of the formula by Martini including the lattice function in Fig. 1. The lattice structure is the race-track shape with two long straight sections for the colliding experiments and the arc section, basically being composed of the FODO structure. The IBS growth rate can be analytically obtained for the high energy, much higher than the transition energy, and for the lattice structure with only normal lattice. The present lattice is a complicated structure and the IBS growth rate has to be numerically analyzed.

The bunched \beam IBS growth rates of the energy 4.5 GeV/u with 6e9/bunch and 1 GeV/u with 3e8/bunch are given in Fig. 2. The typical growth rates for 4.5 GeV/u are 3.65e-3 (momentum spread), 4.86e-4 (horizontal beam size) and -6.1e-5 for the vertical beam size. For 1.0 GeV/u, they are -7.95e-5, 3.86e-3 and 6.03e-3, respectively.

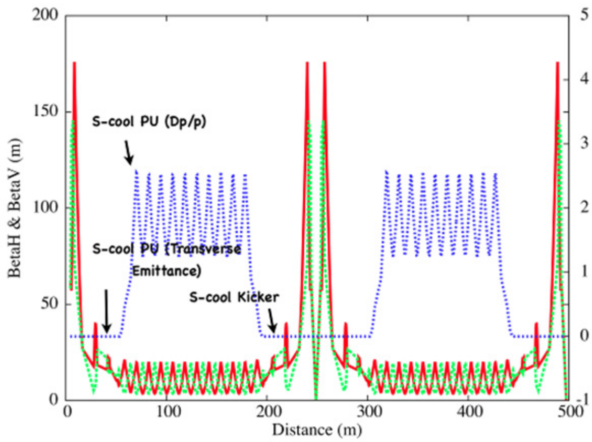

Fig. 1 The lattice function of Collider. The red line shows the horizontal beta function, the green line the vertical beta function and the blue the horizontal dispersion. The transition energy is 7.09.

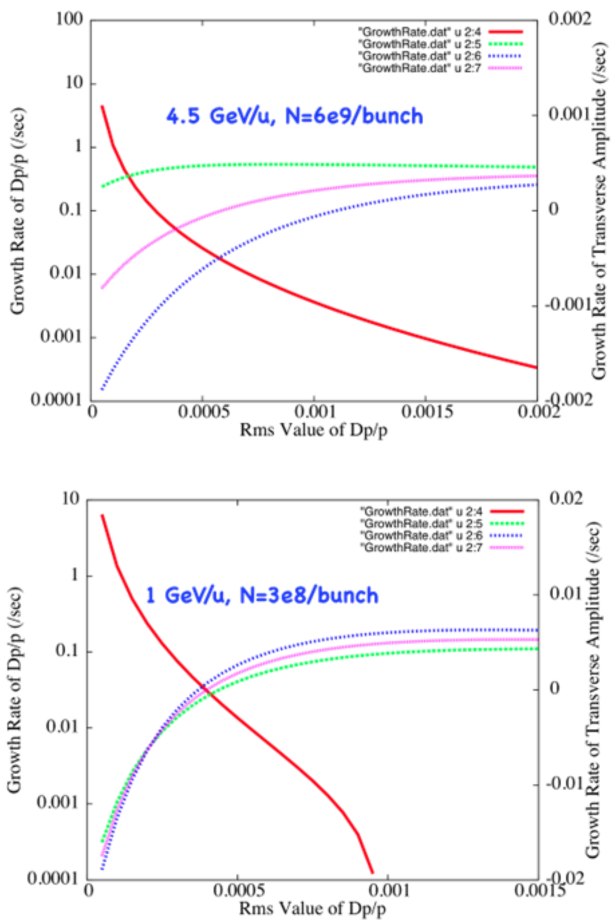

Fig. 2 The IBS growth rate calculated with Martini formula. The top is for the 4.5 GeV/u and the bottom the 1 GeV/u.

The negative IBS growth rate means the shrinkage of beam size or momentum spread so as to exchange the energy to become the isotropic temperature condition in the particle rest frame.

SLIPPING FACTOR & BAND WIDTH

The operation energy of the collider is from 1 GeV/u to 4.5 GeV/u where the relativistic factor, gamma is largely varied and hence the ring slipping factor is also drastically changed. In Table 2 the ring slipping factor (transition gamma is fixed as 7.09) and the local slipping factor from the stochastic cooling PU to Kicker is tabulated. The distance from PU to kicker is assumed as 170 m as is illustrated in Fig. 1. The bunching factor is defined as

$$Bunching\ Factor = \frac{Circumference}{2\sqrt{\pi}\sigma_s N_b}$$

where σ_s is the rms bunch length and N_b the bunch number in the ring. The coasting equivalent particle number is given as the product of bunch number/ring, number of ions /bunch and the bunching factor. Thus obtained coasting equivalent particle number is corresponding to the condition that the peak intensity of the bunched beam are populated as the coasting beam in the ring.

Table 2 Beam Parameters for Various Energies
Transition gamma is fixed as 7.09.

Energy (GeV/u)	1.5	2.5	3.0	4.5
Ring slipping factor	0.1268	0.0537	0.0350	0.00949
Local slipping factor	0.1173	0.0442	0.02546	-5.4e-5
Particle number/bunch	3.0e8	1.50e9	2.50e9	6.0e9
Coasting equivalent particle number	7.26e10	3.63e11	6.05e11	1.45e12

The band width of the stochastic cooling system is preferably as wide as possible because the cooling is inversely proportional to the band width. On the other hand the momentum acceptance of the cooling system is, in general, becomes narrower for the wider band width. Also the momentum acceptance is closely related with the ring slipping factor as well as the local slipping factor.

In Fig. 3 the evolution of momentum spread are analyzed with use of the Fokker-Planck solver for various energies with two band widths, 3-6 GHz and 2-4 GHz. The IBS effects are not included in this analysis, just to compare the momentum acceptance of two bands. For the 4.5 GeV/u, the ring slipping factor is well small and the momentum acceptance is wide enough for both band widths while for 2.5 GeV/u the slipping factor (ring and local) are 0.04~0.05 and then the momentum acceptance becomes critical for the band 3-6 GHz. Presently we are discussing the possibility of two band systems.

Typical example of momentum cooling including IBS effects are given in Fig. 4. Beam parameters are as follows. Energy=4.5 GeV/u, particle number=1.44e12 coasting equivalent beam intensity, Initial momentum spread=1.5e-3 (rms)., band width=3-6 GHz, gain=47 dB.

The ring slipping factor=0.00927, and the local slipping factor=-0.0018.

The IBS effects are included from the calculated results as a function of momentum spread as in Fig. 2. Transverse emittance are assumed as constant as 1.1 Pi (horizontal) and 0.9 Pi mm.mrad, respectively. This assumption will be realized with the application of horizontal and vertical stochastic cooling to keep the transverse emittance as constant.

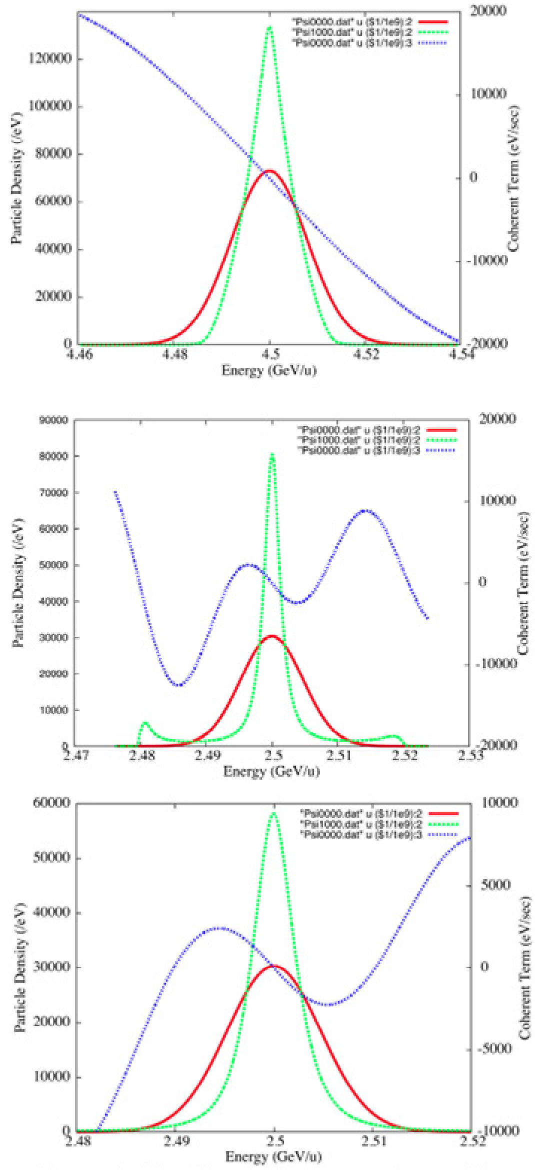

Fig. 3 The analysis of momentum cooling with Fokker-Planck code without IBS effects. Red: initial particle distribution corresponding to *Dp/p*=1.5e-3 (rms). Green: particle distribution after 1000 sec cooling. Blue: the cooling term. The system gain is set as 50 dB. (Top) 4.5 GeV/u, 3-6 GHz, (Middle) 2.5 GeV/u 3-6 GHz, (Bottom) 2.5 GeV/u 2-4 GHz.

It is found that the momentum spread is gradually increased due to the IBS heating effects and after 1000 sec later, it reaches to the equilibrium value 2.1e-3. Required microwave power is around 2 Watt as the gain is as small as 47 dB to suppress the Schottky diffusion noise.

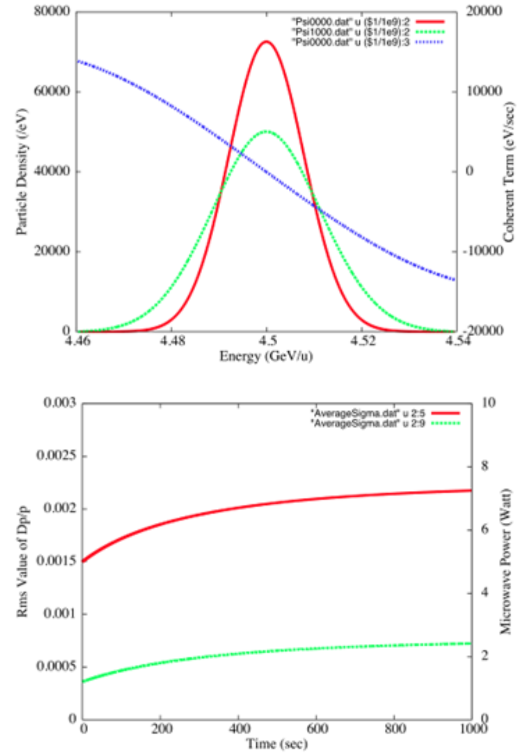

Fig. 4 Typical example of momentum cooling with IBS diffusion effects. Beam energy is 4.5 GeV/u, particle number is 1.44e12 coasting equivalent, initial momentum spread=1.5e-3 (rms) and the cooling gain=47 dB.

BARRIER BUCKET ACCUMULATION

The beam accumulation in the collider is designed to use the barrier bucket accumulation method which was experimentally verified at the POP (Proof Of Principle) experiment at the ESR GSI. [3, 4] The parameters of stochastic cooling system and the barrier voltage for the BB accumulation are tabulated in Table 3.

Table 3 Parameters of Stochastic Cooling & Barrier Voltage

Particle	197Au79+, 4.5 GeV/u
Ring circumference	503.04 m
Number of injected particle	1e9/cycle
Injected momentum spread	3e-4 (rms)
Injected bunch length	300 nsec (uniform)
Ring slipping factor	0.00845
Dispersion at PU & Kicker	5.0 m & 0.0 m
Band width	2 – 4 GHz
Number of PU & Kicker	128
PU Impedance	50 Ohm
Gain	120 dB
Atmospheric temperature	300 K
Nose temperature	40 K
Barrier voltage	2 kV
Barrier Frequency	2.5 MHz (T=400 nsec)
Injection kicker pulse width	500 nsec
Transverse emittance	0.3 Pi mm.mrad

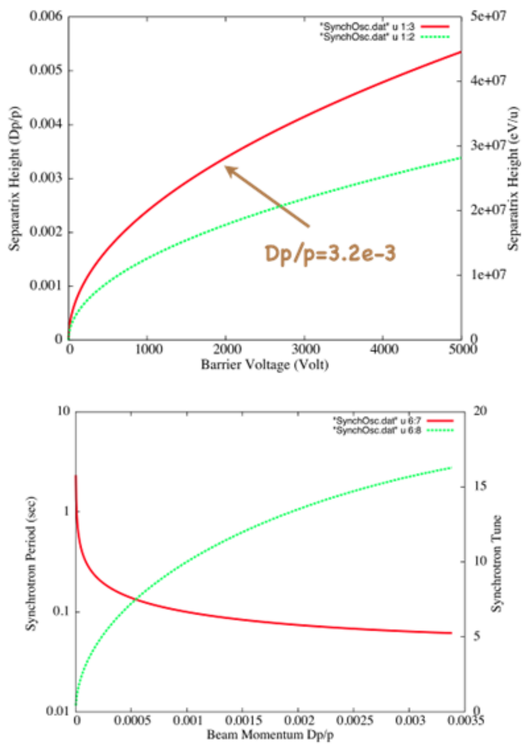

Fig. 5. The separatrix height (top) is given as a function of barrier voltage. Red: Separatrix height of *Dp/p* (left scale) and *DeltaE* (right scale). The synchrotron period (bottom red line; left scale)) and the synchrotron tune (Green, right scale).

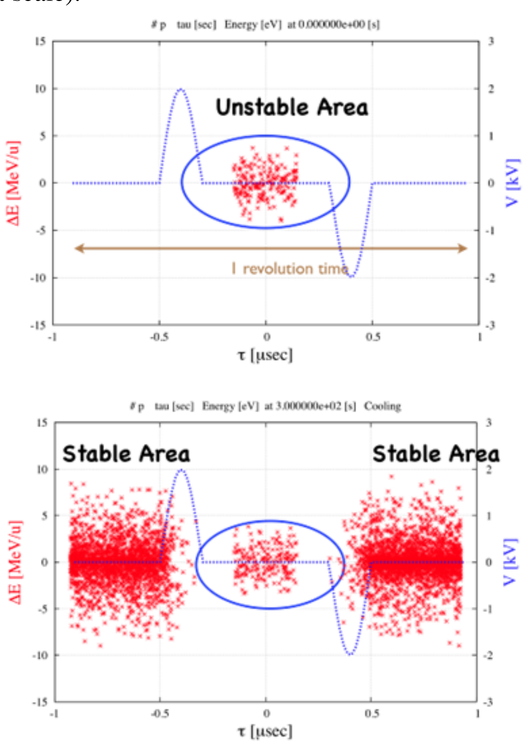

Fig. 6 Phase space mapping of the particles at the 1st injection (top) and after 30 stacking (bottom). The particles are represented with red points and the barrier voltage is blue line. The injected beam is located in the central part.

The separatrix height and the synchrotron tune are calculated as a function of barrier voltage as is given in Fig. 5. The separatrix height is 3.2e-3 *(Dp/p)* when the BB voltage is 2 kV. The synchrotron period is around 0.1 sec at the edge of separatrix. The particles are injected in the unstable area between two barrier pulses and they are flowed into the lower potential region, stable area within the cycle time of 10 sec. The particle distribution after 30 pulse stacking is represented in Fig. 6. Details of beam simulation code are given in the reference paper [5]. The increase of the accumulated particle number is given as a function of time in Fig. 7 where also the accumulation efficiency is given. The accumulation efficiency is defined as the ratio of accumulated particle number to the total injected particle number. It is gradually decreased to 90 % after 50 pulse injection. The cooling system gain should be reduced against the increase of particle number so as to suppress the Schottky noise as given in Fig. 8. The required microwave power is 800 Watt at the beginning of the gain 115 dB.

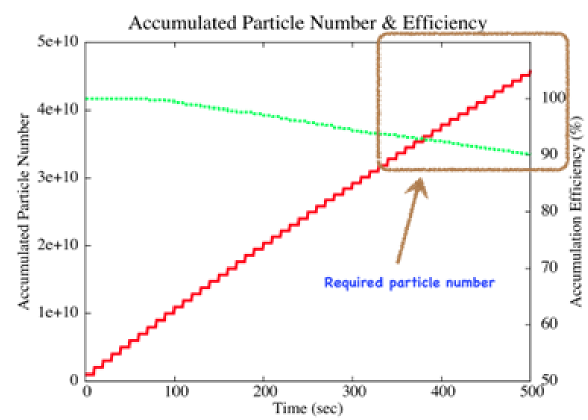

Fig. 7 Increase of accumulated particle number as a function of time. red line: Accumulated particle number. green line: Accumulation efficiency.

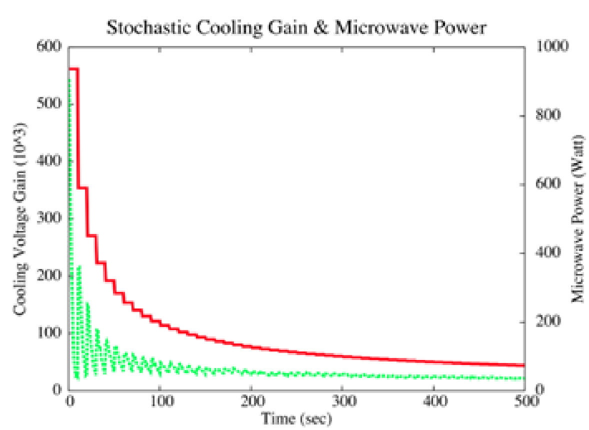

Fig. 8 Variation of cooling gain during the accumulation process (red line, left scale) and the required microwave power (green line, right scale)

SHORT BUNCH FORMATION

The accumulated beam with the barrier bucket method is a coasting beam condition. We have to make the required short bunches from this coasting beam. The one method is to use the phase jump technique of which the simulated process is illustrated in Fig. 9. First the RF voltage of harmonic number being equal to the required bunch number (h=26) is adiabatically applied to the coasting beam. (a) and (b) in Fig. 9. The maximal RF voltage is 200 kV. After the adiabatic bunching is completed, the phase of RF is changed by 180 degrees (c). After stretching the bunch length (d), the phase is changed back to the original position (e), and the bunch is rotated 1/4 synchrotron oscillation (f). Then apply the higher harmonic number RF voltage (*h*=130) of 500 kV to maintain the short bunches.

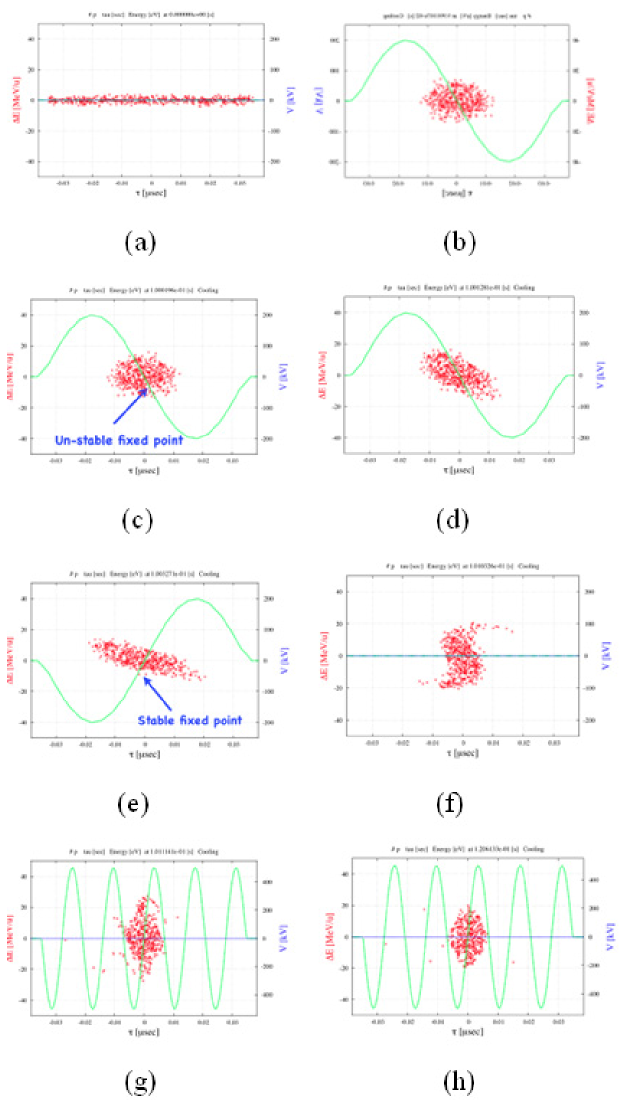

Fig. 9 Phase jump method to make the short bunch. From the top left to right and bottom is a sequence of bunching process. (a) t=0 sec, (b) t=0.1 sec, Vrf=200 kV, (c) t=0.100019 sec, (d) t=0.10012 sec, (e) t=0.10032 sec, (f) t=0.101 sec, (g) t=0.1011 sec, Vrf=500 kV, (h) t=0.1206 sec.

The other way of making the short bunch is to use the stochastic cooling with RF field. The process can be separated two steps as similar to the phase jump method. In the first step the RF voltage of harmonic number equal to the required bunch number (*h*=26), is adiabatically applied. In parallel the stochastic cooling system is applied of which the gain is gradually decreased as is given in Fig. 10.

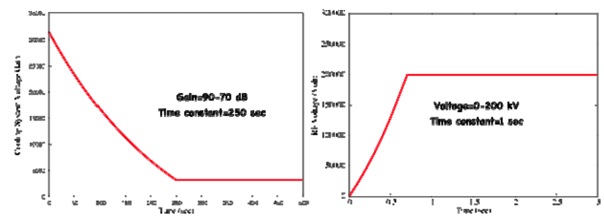

Fig. 10 Adiabatic gain reduction and the RF voltage increase for the short bunch formation. Harmonic number is 26.

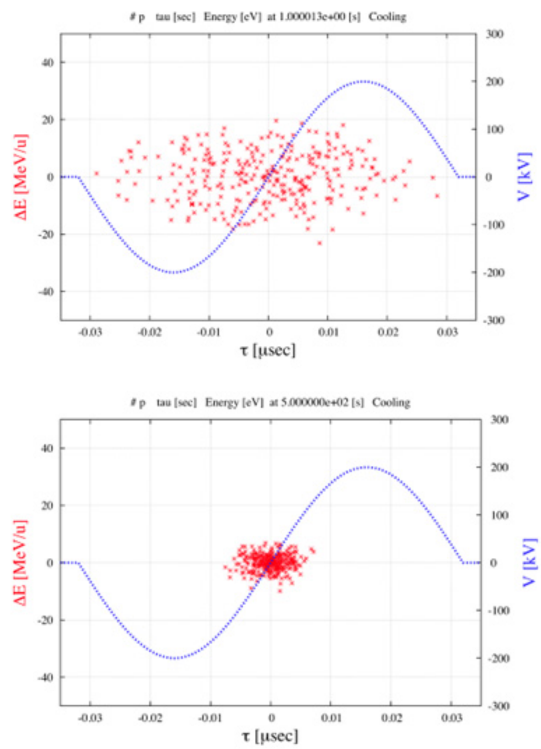

Fig. 11 The phase space mapping at the time= 1 sec (top) and 500 sec (bottom). red: particles, blue: RF voltage.

Thus formed pre-bunched beam is re-captured by the higher harmonic RF voltage. The pre-bunched beam has the bunch length of 3 ns (rms) and *Dp/p* of 6e-4 (rms). (Gaussian distribution in both dimensions). This bunch is re-captured by the RF field of harmonic=130. Again the RF voltage is increased from 0 to 500 kV with the time constant of 1 sec for the adiabatic capturing.
The gain of stochastic cooling system is kept constant as 80 dB and wait further cooling and bunching.

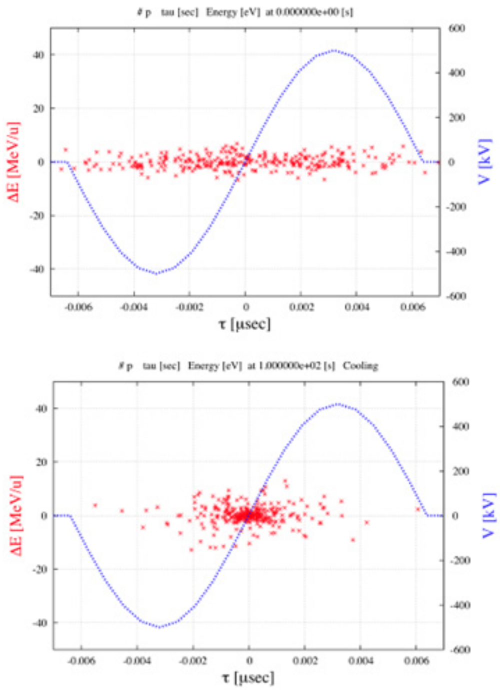

Fig. 12 The final bunching process with higher harmonic number=130 which is 5 times larger than the harmonic number for the pre-bunching. From the top to bottom, time=0 sec and 100 sec.

The evolution of bunch length and the relative momentum spread during the final bunching process are given in Fig. 13. When the stochastic cooling is applied, the equilibrium values of bunch length is attained at 1.2 nsec and *Dp/p* (rms) is 8e-4 while they are increased gradually due to the IBS heating effects without cooling.

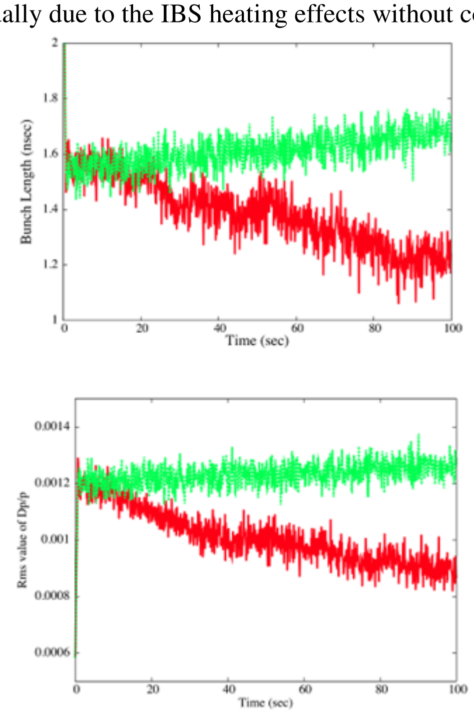

Fig. 13 The evolution of rms bunch length (top) and the *Dp/p* (bottom) are illustrated as a function of time. red: with stochastic cooling, green: without stochastic cooling.

ELECTRON COOLING

In the preceding sections we have investigated the BB accumulation and the short bunch formation with stochastic cooling with RF field. However for the lower energy than 2.5 GeV/u the stochastic cooling could not work as the ring slipping factor becomes so large (see Table 2). For such low energy operation, obviously the electron cooling is effective. The designed electron cooler parameters are given in Table 3.

Table 3 Parameters of Electron Cooler for NICA

Particle	197Au79+,2.0 GeV/u
Ring circumference	503.04 m
Cooler length	6 m
Electron current	1 A
Electron diameter	2 cm
Effective electron temperature	1 meV
Transverse electron temperature	1 eV
Longitudinal magnetic field	0.1 T
Beta function at cooler section	16 m

Typical cooling process is illustrated in Fig. 14 where the beam energy is 2 GeV/u and the particle number is 3e11 as a coasting beam equivalent. The equilibrium values are attained at 25 sec cooling as the emittance (h)= 0.12, emittance (v)=0.09 mm.mrad and *Dp/p*=3.7e-4, respectively. The IBS effects are included.

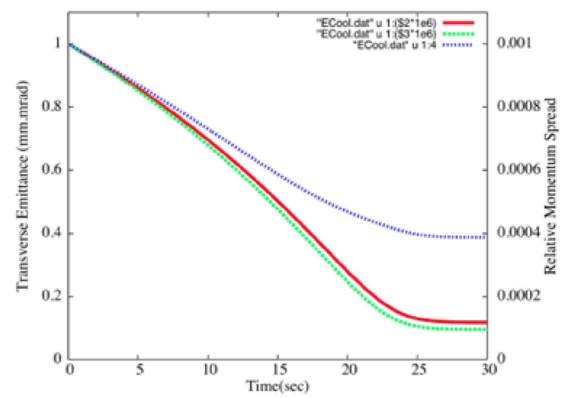

Fig. 14 Evolution of emittance (red: horizontal, green: vertical) and *Dp/p* (blue) of 2 GeV/u beam with electron cooling.

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