BEAM COOLING AT NICA COLLIDER

T. Katayama, GSI, Darmstadt, Germany
I. Meshkov, A. Sidorin and G. Trubnikov, JINR, Dubna, Russia.

Abstract

At the heavy ion collider NICA presently promoted at the JINR, the beam cooling will play the crucial roles to attain the designed performance. The primary goal of the collider is to achieve the high luminosity ~1e27 /cm^2/sec, preventing the IBS diffusion effects by beam cooling to keep the luminosity during the experimental period. The other purpose of the cooling is to accumulate the required beam intensity up to several times 1e10 from the injector Nuclotron with use of the barrier bucket method. After the BB accumulation the coasting beam is adiabatically bunched with the help of RF field and the beam cooling. In the present paper the detailed simulation results are presented for the above process mainly in the longitudinal freedom.

INTRODUCTION

The heavy ion collider proposed at the JINR aims to achieve the head-on collision of 1-4.5 GeV/u, $^{197}Au^{79+}$ ion beam with the luminosity of ~1e27/cm^2/sec. [1] The number of bunches in the collider is 24 and each bunch contains the ion number of ~1e9, depending upon the operation energy. Thus totally around ~2.4e10 ions should be accumulated in the collider ring. The injector for the collider is the existing superconducting synchrotron, Nuclotron, which could provide the beam of 1-4.5 GeV/u with the intensity of 1e8-1e9/cycle of the cycle time 5 sec. The bunch length of the beam from the Nuclotron is around 1/3 of the circumference, 300 nsec. [2, 3]

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

Thus accumulated heavy ion beam is the coasting beam condition, and then the large RF voltage is applied adiabatically as well as the beam cooling. The beam is gradually bunched to the required rms bunch length for the collision experiment ~2ns (rms). The bunch length is the equilibrium state of RF field, beam cooling, Intra Beam Scattering (IBS) and space charge repulsion. Especialy at low energy, the IBS diffusion and space charge force could affect the beam motion at the short bunch condition.

The detailed analysis of the beam dynamics for the stochastic cooling application was reported elsewhere [4] and here the main emsphasis is given on the electron cooling and space charge problem.

STOCHASTIC COOLING

The operation energy of the collider is from 1 GeV/u to 4.5 GeV/u where the ring slipping factor is drastically changed. In Table 1 the ring slipping factor, transition gamma being fixed as 7.09 and the local slipping factor from the stochastic cooling PU to Kicker are tabulated. The distance from PU to kicker is assumed as 170 m. 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 1. Beam parameters for various energies

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 bandwidth of the stochastic cooling system is preferably as wide as possible because the cooling time is inversely proportional to the bandwidth. On the other hand the momentum acceptance of the cooling system is, in general, becomes narrower for the wider bandwidth. Also the momentum acceptance is closely related with the ring slipping factor as well as the local slipping factor. In the present scenario the Palmer cooling method is envisaged where only the local slipping factor limits the momentum acceptance. Presently two bandwidth, 2-4 GHz and 3-6GHz are candidates.

Barrier Bucket Accumulation with Stochastic Cooling

The beam accumulation is designed to use the fixed barrier bucket method whose concept was experimentally verified at the POP (Proof Of Principle) experiment at the ESR GSI.[5] It should be noted that the POP experimental results are in well agreement with the simulation results. [6] The parameters of the barrier voltage as well as the stochastic cooling in the collider are tabulated in Table 2.

In the present simulation, the PU and kicker structure is assumed as the classical $\lambda/4$ electrode structure. In the meanwhile the new structure is being developed [7] which has the larger sensitivity and then the small number of electrode could be enough. Then the parameters of stochastic cooling system could be slightly changed in the construction phase.

ISBN 978-3-95450-125-0

The particles are injected in the unstable area between two barrier voltages 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. 1 for 3.5 GeV/u ions. Details of beam simulation code are given in the reference paper [8].

Table 2. Parameters of Stochastic Cooling & Barrier Voltage

Particle	$^{197}Au^{79+}$
Ring circumference	503.04 m
Number of injected particle	1e9/cycle
Injected momentum spread	3e-4 (rms)
Injected bunch length	300 nsec
Ring slipping factor	0.00845
Dispersion at PU & Kicker	5.0 m & 0.0 m
Band width	2 - 4 GHz or 3-6 GHz
Number of PU & Kicker	128 or 64
PU Impedance	50 Ohm
Gain	120 dB
Atmospheric temperature	300 K
Noise 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 π mm.mrad

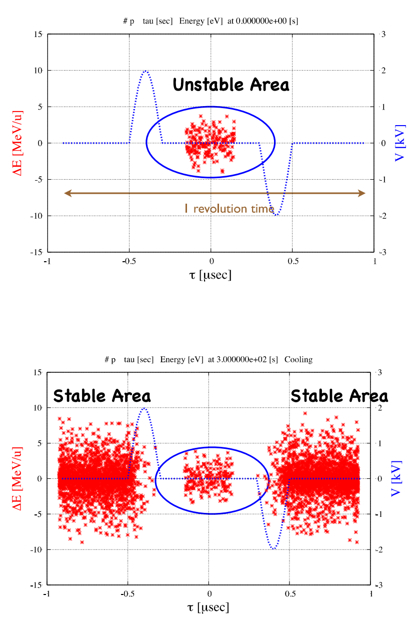

Fig. 1. Phase space mapping of the particles at the 1st injection (top) and after 30 stacking (bottom). The particles are represented with red dots and the barrier voltages are blue line. The injected beam is located in the central unstable area. Ion energy is 3.5 GeV/u.

The increase of the accumulated particle number is given as a function of time in Fig. 2 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. The required microwave power is 800 Watt at the beginning of gain 115 dB.

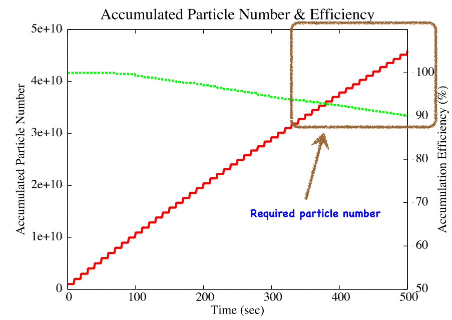

Fig. 2. Increase of accumulated particle number as a function of time. Red line: accumulated particle number. Green line: accumulation efficiency. Energy is 3.5 GeV/u.

Short Bunch Formation with Stochastic Cooling

The process of short bunch formation can be separated in two steps. At the first step the 200 kV RF voltage of harmonic number equal to the required bunch number (h=24), is adiabatically applied to the coasting beam. In parallel the stochastic cooling system is applied of which the gain is gradually decreased. Thus pre-bunched beam has the bunch length of 3 ns (rms) and $\Delta p/p$ of 6e-4 (rms). In the 2nd step, this bunch is re-captured by the 500 kV RF field of harmonic 96 or 120. The gain of stochastic cooling system is kept constant as 80 dB in the 2nd step during further bunching.

The evolution of bunch length and the relative momentum spread during the 2nd bunching process are given in Fig. 3. When the stochastic cooling is applied, the equilibrium values of bunch length is attained at 1.2 nsec and $\Delta p/p$ (rms) is 8e-4 while they are increased gradually due to the IBS heating effects without cooling.

The RF hardware for these beam manipulation is now being designed [9].

ELECTRON COOLING

For the lower energy less than 2.5 GeV/u the stochastic cooling could not work well as the 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.

ISBN 978-3-95450-125-0

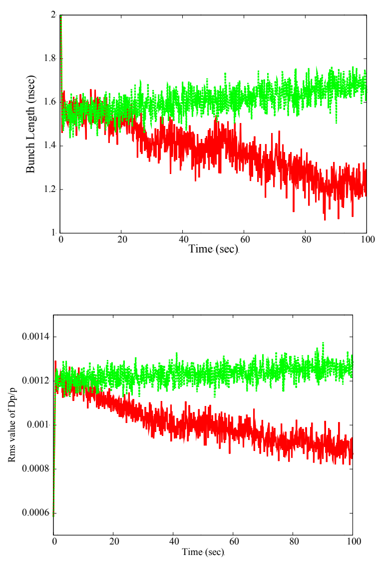

Fig. 3. The evolution of rms bunch length (top) and the $\Delta p/p$ (bottom) are illustrated as a function of time. Red: with stochastic cooling, Green: without stochastic cooling.

Table 3. Parameters of electron cooler for NICA collider

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. 4 where the beam energy is 2 GeV/u and the particle number is 3e11 as a coasting beam equivalent. The equilibrium values are attained after 25 sec cooling as the transverse emittance of 0.12/0.09 (H/V) π mm.mrad and $\Delta p/p$=3.7e-4, respectively where the IBS effects are included. In the present analysis, the electron cooling force is derived from the Parkhomchuk empirical formula.

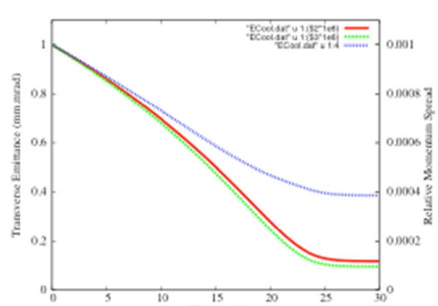

Fig. 4. Evolution of emittance (red: horizontal, green: vertical) and $\Delta p/p$ (blue) of 2.0 GeV/u ions with electron cooling. The IBS effects limit the equilibrium values.

In order to estimate the cooling time for several energies, the cooling process are calculated without IBS effects as in Fig. 5. The rough estimation of full cooling times are 3 sec (1 GeV/u), 20 sec (2 GeV/u), 70 sec (3 GeV/u), 200 sec (4 GeV/u) and 300 sec (4.5 GeV/u), respectively. Thus it could be concluded that the electron cooling would not help enough beyond the energy 2.0 GeV the cooling mechanism of the barrier bucket accumulation method with cycle time 10 sec as the cooling time is much longer than the cycle time.

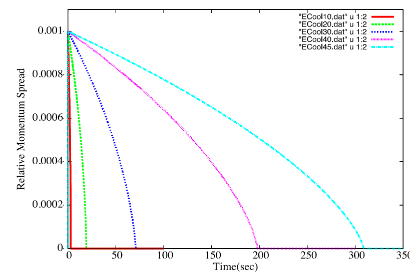

Fig. 5. Evolution of momentum spread for 1.0 (red), 2.0 (green), 3.0 (blue), 4.0 (pink) and 4.5 GeV/u (light blue). The IBS effects are not included. Initial values are, 1.0 π mm.mrad (transverse) and 1.0e-3 ($\Delta p/p$).

Barrier Bucket Accumulation with Electron Cooling

The energy of ion is 1.5 and 3.5 GeV/u, and the initial $\Delta p/p$ is assumed as 5e-4 (rms). Injected particle number is 1e9/shot with cycle time 10 sec. The calculated increase of accumulated particle number and the accumulation efficiency is given in Fig. 6.

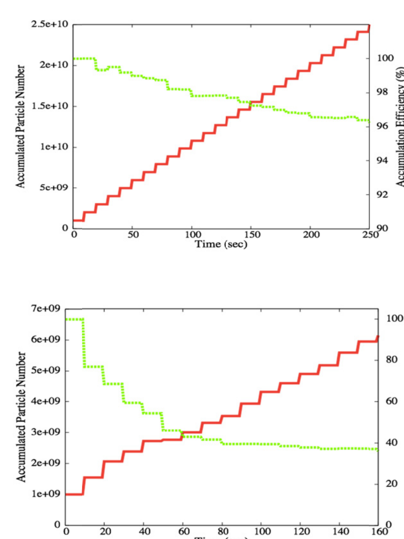

Fig. 6. The increase of accumulated particle number (red) and accumulation efficiency (green) during 25 times injection. Top: 1.5 GeV/u and bottom: 3.5 GeV/u

ISBN 978-3-95450-125-0

The accumulation efficiency is around 90 % after 25 times injection at 1.5 GeV/u while it becomes as low as 40 % at 15 times injection at the energy of 3.5 GeV/u. The summary of simulation results of barrier bucket accumulation are tabulated in Table 4.

Table 4/ Summary of barrier bucket accumulation with electron cooling

Energy (GeV/u)	Rms $\Delta p/p$ (1e-4)	Efficiency (%) & Particle Number at 150 sec	Rms Beam Size at 150 sec (mm)	Rms $\Delta p/p$ at 150 sec (1e-4)
1.5	5	98/1.5e10	0.3~1.0	1.0
1.5	10	87/1.4e10	0.4~1.2	2.5
2.5	5	68/1.1e10	0.8~1.2	2.0
2.5	10	54/8e9	1.0=1.5	5.0
3.5	5	28/5e9	1.5~2.2	4.5

SPACE CHARGE EFFECTS

In the previous chapters, results of longitudinal beam dynamics are given without taking account the space charge effects. In the present chapter, the space charge fields are included in the simulation of beam accumulation and short bunch formation. In order to save the computing time the IBS effects are not included in the present study. The energy of ion is selected as 1.5 GeV/u because the space charge effect is proportional to γ^{-2} and the lowest energy is most sensitive to the space charge effects.

The particle tracking including the space charge field is performed with use of the scheme of Particle In Cell (or Cloud In Cell) method. [10]

The longitudinal electric field due to the space charge is given by

$$E_z(z) = -\frac{g}{4\pi\varepsilon_0\gamma^2}\frac{\partial\rho(z)}{\partial z} \qquad (1)$$

where g is the geometric factor, ρ(□) is the line charge density, z is the longitudinal position. From this electric field the energy variation of ions per unit time is derived and the synchrotron motion is represented by following equation.

$$\frac{d\Delta E}{dt} = \frac{Z}{A}\frac{V_{rf}}{T_0} - E_{cool} - \frac{Z}{A}\frac{g}{4\pi\varepsilon_0\gamma^2}\frac{d\rho}{d\tau} \qquad (2)$$

Here the V_{rf} means the external RF field, E_{cool} the cooling effects and the 3rd term in the right hand side shows the space charge effects. Z is the charge state of ion and A the mass number. The accompanying phase equation is given as usual as

$$\frac{d\tau}{dt} = \frac{\eta}{\beta^2}\frac{\Delta E}{E_0} \qquad (3)$$

The geometric factor is simply given by

$$g = 1 + 2.0\ln(b/a) \qquad (4)$$

where a is the bunch radius and b is the radius of beam pipe.

The beam accumulation process can be performed using the equations (2) and (3). The parameters are as follows; ion energy 1.5 GeV/u, injected ion number 1e9/shot, cycle time 10 sec, ring slipping factor 0.1268, initial momentum spread 5e-4(rms). Barrier voltage=2 kV, barrier frequency=2.5 MHz, injection kicker firing time=0.6e-6 sec.

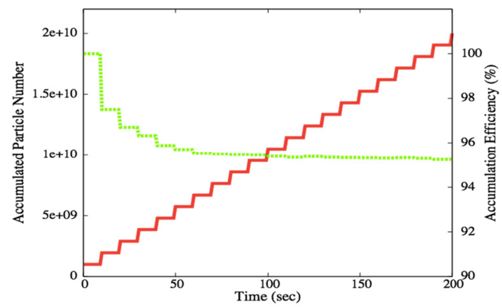

Fig. 7. The accumulated particle number (red) and the accumulation efficiency (green) up to 20 times injection including the space charge effects. Energy is 1.5 GeV/u

Comparing with the result without space charge effects (in Fig. 6), the accumulation efficiency is slightly decreased.

The space charge potential after the accumulation of ions are illustrated in Fig. 8 where the particle density is given in red colour and the space charge potential with green colour. In the central area the injected particle density is shown while two flat areas at left and right sides show the accumulated particle density. The space charge potential arises at the central part due to the derivative of the injected particle density and two sharp peaks are observed at the edge of accumulated area. The space charge potential after 20 times accumulation reaches to +/- 150 Volt while the space charge potential due to the injected particle (1e9 ions) is +/- 10 Volt.

It is clear from these results that the space charge effects do not affect the beam accumulation process as the barrier voltage is large enough 2 kV comparing with the space charge potential.

The next step is the short bunch formation with application of 200 kV RF voltage of harmonic number 24 and electron cooling force.

The comparison of space charge potential and the external RF voltage at the short bunch formation are illustrated in Fig. 9. Just at the starting of bunch formation the space charge potential is less than +/- 1 kV while it reaches to +/- 20 kV at the equilibrium state of bunch length +/- 3 nsec after 100 sec cooling.

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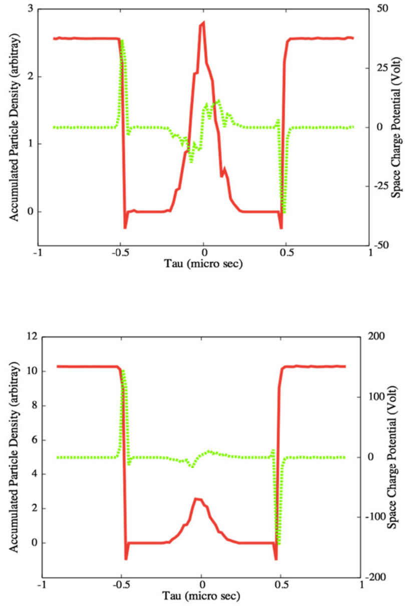

Fig. 8. Accumulated particle density (red) and space charge potential (green). From the top to the bottom, time is 50 (5 times injection) and 200 (20 times injection) sec, respectively.

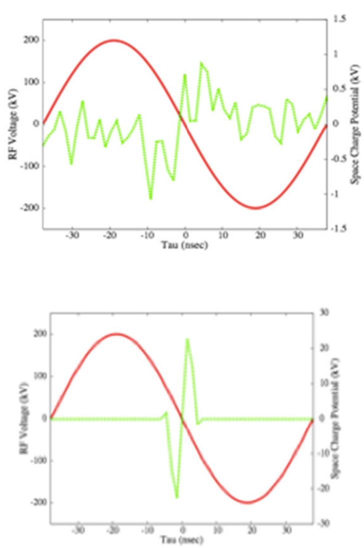

Fig. .9 Comparison of external 200 kV RF (red) & space charge potential (green). From the top to the bottom, time is 1 and 100 sec, respectively. The ion number is 1e9/bunch.

CONCLUSIVE REMARKS

We have performed the simulation work on the barrier bucket accumulation and short bunch formation with stochastic cooling and electron cooling at the operation energy from 1.5 GeV/u to 4.5 GeV/u. It is found that the stochastic cooling well works at the energy beyond 2.5 GeV/u while at the less energy the momentum acceptance of stochastic cooling system becomes too narrow due to the large slipping factor. On the other hand below 2.5 GeV/u the electron cooling could work to accumulate the beam as well as the short bunch formation. In this sense, both cooling method are perfectly complimentary each other.

The space charge potential becomes around +/- 20 kV at 1.5 GeV/u at the bunch length of +/- 3 nsec while at the higher energy the potential becomes small value. Considering the external RF voltage, 200 kV-500 kV, this space charge problem could be minor effects to the short bunch formation.

ACKNOWLEDGEMENT

Authors are indebted to the discussion with A. Smirnov for simulation of the accumulation with the electron cooling. L. Thorndahl confirmed the short bunch formation by the stochastic cooling with use of another algorithm. One of authors (T. K) appreciates the collaboration of space charge code development to T. Kikuchi.

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ISBN 978-3-95450-125-0