BEAM ACCUMULATION AND BUNCHING WITH COOLING

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Abstract

The accumulation of antiproton beam in the storage ring was successfully performed at CERN and FNAL with the use of a stochastic stacking system. In the original version of the FAIR project such a concept was envisaged at the accumulator ring named RESR. However in the modularized start version of FAIR, the RESR was postponed and the new concept of antiproton accumulation in the High Energy Storage Ring (HESR) was strongly demanded. The barrier bucket (BB) system with stochastic cooling was found with simulation work to have enough capabilities to accumulate the pre-cooled 3 GeV antiproton beam in the HESR. The Proof Of Principle (POP) experiment was performed at the GSI storage ring ESR with ion beams employing both the stochastic and electron cooling. The experimental results were in good agreement with the prediction of the simulation study. The concept of BB accumulation could be applied to the planned Collider of the NICA project at JINR. In the present paper the concept of BB accumulation and the short bunch formation including the space charge effects are presented as well as the analysis of the POP experiment.

RF STACKING & COOLING

It is imperative to accumulate the hadron beam in the storage ring to perform the colliding experiment or the experiments with the use of an internal target. The first hadron collider was the CERN Intersecting Storage Ring, ISR [1] where the 25 GeV proton beam was injected from the PS and was RF stacked in the longitudinal phase space. It culminated in the maximal luminosity of $\sim 3\times10^{29}$ /cm^2/sec during the physics run with the accumulated circulating current of ~ 10 A. During the operation of ISR the first observation of Schottky signals was tried successfully and immediately the stochastic cooling (transverse cooling) was demonstrated. This discovery, stochastic cooling, brought out the decisive strategy of beam accumulation of secondary beams like antiproton or Rare Isotope Beam after that.

The low energy ion storage ring, TARN was constructed at the INS, Univ. of Tokyo where 28 MeV *He* ions were RF stacked from the Sector Focus cyclotron. The injected beam was adiabatically captured by RF and was accelerated (or decelerated) to the stack top energy where the RF was switched off and the beam was deposited there. Thus RF stacked ion beam had a large momentum spread and the stochastic cooling was subsequently applied to the stacked ion beam to reduce the momentum spread [2].

STOCHASTIC STACKING

The accumulation of antiproton beam in the storage ring was performed at CERN with the stochastic stacking system. It was based upon the exponentially decaying cooling force in the horizontal direction employing several pickups, named Tails and Core, at the large dispersion section of the ring. In the FAIR project the storage ring, RESR was designed to accumulate the 3 GeV antiproton beam with stochastic stacking system following the successful CERN results.

A simplified theoretical model of the stochastic stacking process was developed by S. van der Meer [3] where the diffusion terms by electronic noise and intra-beam scattering are neglected and beam feedback effects are not taken into account. While these assumptions are not fulfilled in the real stacking system, this simplified approach could give some basic parameters of the stacking system.

Realistic parameters were determined by the numerical analysis with the use of the Fokker Planck code including the electronic noise, intra-beam scattering, notch filter characteristics and other effects. In Fig.1 the simulation results of the antiproton distribution of RESR after the optimization of many parameters such as positioning of PUs, Gain and notch-filter are illustrated [4].

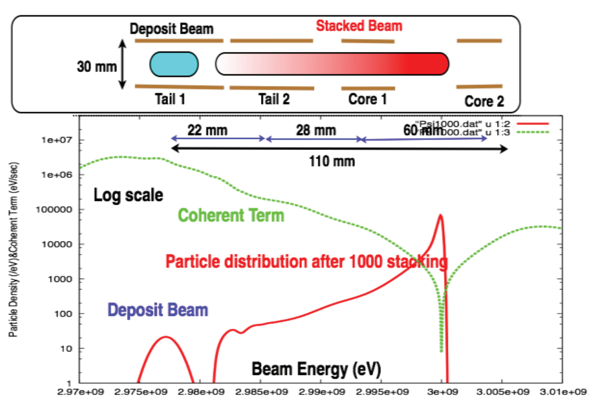

Figure 1: The layout of Tail1, Tail2, Core1 and Core2 PUs. Attained coherent term (green) and beam profile (red) of the 1000 times stacked 3 GeV anti-proton beam for RESR. The cycle time is 10 sec and the deposited particle number is 1×10^8/shot.

The frequency band of the two Tail's system are chosen as 1-2 GHz while for the Core system the wider band width 2-4 GHz is selected. The positioning of PUs, Tails

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and Core are determined from the results of numerical calculation. The beam feedback effects are included in the simulation process. Details of the design strategy and results are given in Ref. 4.

To check the validity of the developed code for the stochastic stacking, the stacking process at the CERN AA is simulated with parameters given in Ref. 3. Result given in Fig. 2 is rather satisfactory up to 1500 stacking.

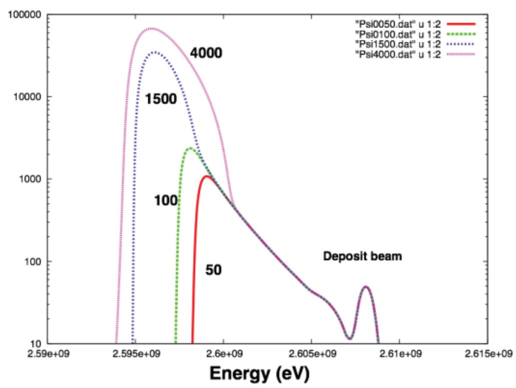

Figure 2: The simulated beam profile of 2.6 GeV anti-proton beam for different stacking numbers for the CERN AA. Cycle time is 5 sec and deposited particle number is 1×10^{8}.

BARRIER BUCKET ACCUMULATION

The other idea of beam accumulation is to use a barrier voltage and beam cooling. The circumference of the accumulator ring is separated into the injection and accumulation areas. With the assistance of beam cooling, the injected beam is moved into the accumulation area, lower potential area, until the next injection cycle.

HESR Stochastic Cooling System

The stochastic cooling system has been planned for the HESR to achieve small momentum spread to perform the high resolution/high luminosity internal target experiment compensating the deterioration of beam quality induced by interaction with the internal target [5].

Table 1: Stochastic Cooling Parameters of HESR Barrier Bucket Accumulation

Antiproton kinetic energy	3.0 GeV
Number of injected particles	1×10^{8}
Initial momentum spread	5.0×10^{-4} (rms)
Momentum slip factor	0.03
Type of pickup and kicker	Lambda/4 loop coupler
Notch filter method	Optical notch filter
Atmospheric temperature of PU	20 K
Noise temperature of PU	20 K
TOF from PU to kicker	0.7×10^{-6} sec
Dispersion at PU and kicker	0 m
Number of PUs and kickers	64
Coupling impedance	50 Ohm
Band	2-4 GHz
Gain	115-130 dB

Note that in the present simulation study the structure of PU and Kicker is assumed as lambda/4 strip line one while a new structure of simpler structure is invented and successfully tested at FZJ [6].

Barrier Bucket System

There are two schemes of barrier bucket accumulation, the fixed barrier scheme and the moving barrier scheme. In the former scheme, two half-wave barrier voltages are produced in one revolution period while in the latter case two full-wave barrier voltages are excited and the timing/phase position and voltages are controlled in proper way. In Table 2 the specification of barrier voltage and related parameters are given.

Table 2: Barrier Voltage Parameters for HESR

Injected beam length	500 nsec
Period of injection kicker magnet	1000 nsec
	(250 nsec fall/rise time)
Cycle time	10 sec
Barrier voltage	±2 kV
Barrier voltage frequency	5 MHz (T=200 nsec)
Barrier voltage rise/fall time	0.2 sec
Barrier voltage moving time	0.5 sec

Fixed Barrier Method

The simulation results for the fixed barrier method are given in Figure. 3. At time=0 sec, the beam is injected in the unstable area and after 10 sec cooling the beam is moved into the stable area with small momentum spread due to the cooling effect. The energy acceptance of cooling system is also given.

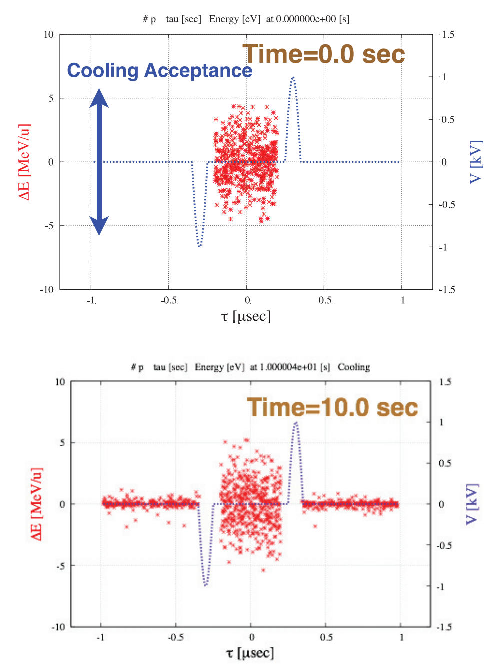

Figure 3: The particle distribution in the longitudinal phase space at time= 0 (top) sec and 10 sec (2[nd] injection) (bottom) for the fixed barrier method for HESR. Barrier voltage (blue) and particles (red points).

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The accumulated particle number and the accumulation efficiency, defined as the accumulated particle number/total injected particle number, are given in Figure 4.

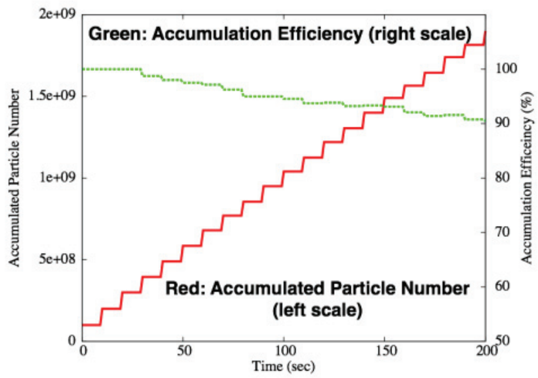

Figure 4: Increase of stacked antiproton number (red) and accumulation efficiency (green) at the fixed barrier method.

Moving Barrier Method

The simulation results for the moving barrier method ara given in Fig. 5. At time=0 sec, the beam is injected in the central stable area and the BB voltage is adiabatically reduced to zero.

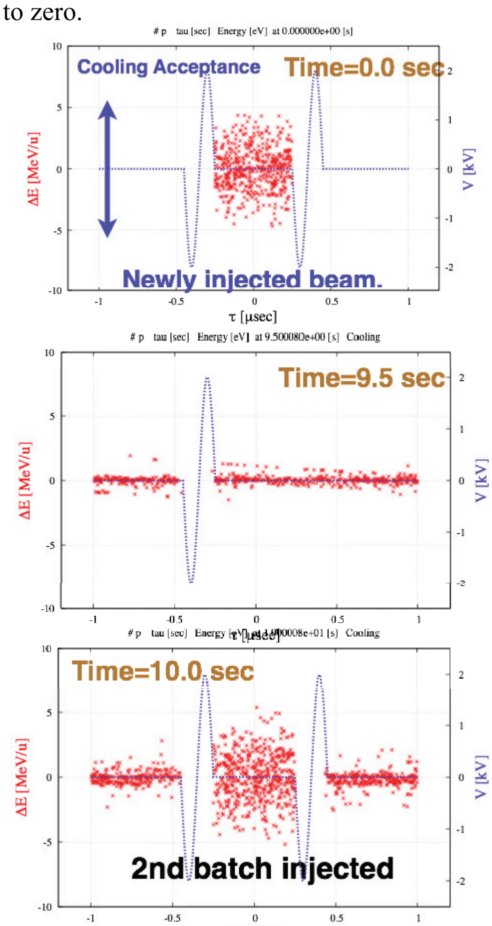

Figure 5: The particle distribution in the longitudinal phase space at time= 0 (top), 9.5 (middle) and 10 sec (2[nd] injection) (bottom) for the moving barrier method for the HESR. Barrier voltage (blue) and particles (red points).

The coasting beam is well cooled by the stochastic cooling system. After 9.5 sec the BB voltage is excited and the right hand side barrier voltage is moved to the original position pushing the well cooled beam into the accumulation area.

This process is repeated up to 100 times to obtain the required particle number of 1×10^{10}. In Fig. 6 the accumulated intensity and the electronic gain of the cooling system are given as a function of time. As a typical value the electronic gain is varied from 130 dB to 115 dB during the whole stacking cycle of 1000 sec.

The reduction of gain is essential as the Schottky diffusion term is increased due to the increase of particle number.

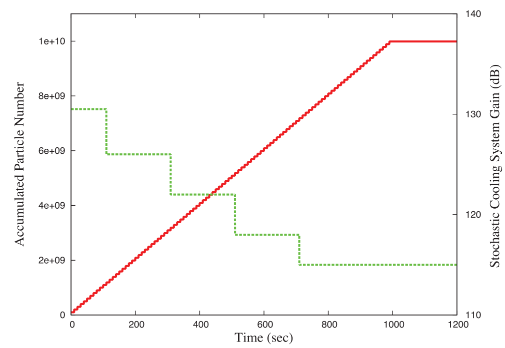

Figure 6: The accumulated particle number (red, left scale) and the electronic gain of the cooling system (green, right scale). Horizontal scale is time (sec).

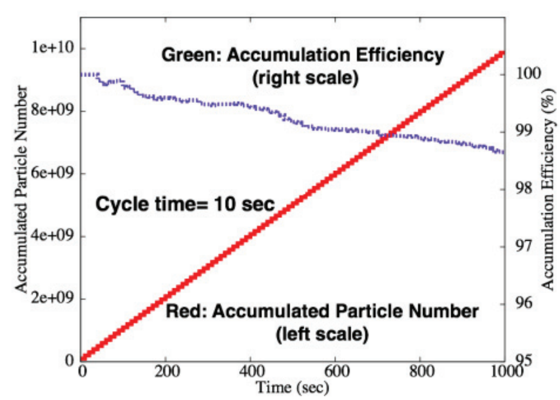

Figure 7: Increase of stacked antiproton number (red) and accumulation efficiency (green) for the moving barrier method.

POP Experiment at ESR

The idea of beam accumulation with barrier bucket with beam cooling was experimentally tried as the Proof Of Principle (POP) two times at the ESR of GSI where an electron cooler and a stochastic cooling system are available. The experiment was successfully achieved to demonstrate the possibility of beam stacking with BB system. [7]

In Table 3 the main parameters of stochastic cooling and electron cooler system are tabulated.

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Table 3: Main Parameters of Stochastic & Electron Cooler and Barrier Pulse at POP Experiment

Particle	$^{40}Ar^{18+}$, 0.4 GeV/u
Revolution Period	500 nsec
Number of injected particles	5×10^6 ions/shot
Injected momentum spread	5.0×10^{-4} (rms)
Injected bunch length from SIS18	150 nsec
Momentum slip factor	0.309
Palmer type stochastic cooling method	
Band width	0.9-1.7 GHz
Length of electron cooler	2.5 m
Electron diameter	5 cm
Electron current	0.2 A
Barrier voltage	0.12 kV
BB frequency	5 MHz (T=200 nsec)
Injection kicker pulse width	200~300 nsec

It has to be noted that the barrier voltage presently available is as small as 120 Volt and then the barrier bucket height is $\Delta p/p=\pm2.6\times10^{-4}$. (Compared with the momentum spread of injected beam $\Delta p/p$(rms)$=5\times10^{-4}$). The stochastically cooled momentum spread is too large to effectively push the beam to prepare the empty gap for the next beam injection. Resultantly we could not achieve the beam accumulation for the moving BB operation. Therefore we had to apply the electron cooling in addition to the stochastic cooling.

Typical experimental result of moving barrier BB is given in Figure 8 as well as the simulation results. The agreement of two results is remarkable.

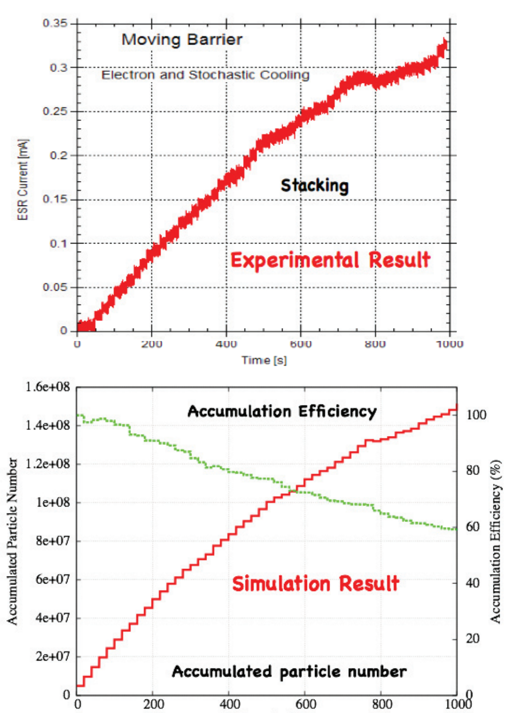

Figure 8: The experimental (top) and the simulation (bottom) results of the moving barrier operation. The red line in the bottom figure shows the accumulated particle number and the green line the accumulation efficiency.

At the POP experiment the fixed barrier method was also tried with only stochastic cooling. The experimental and simulation is also in good agreement [8].

Barrier Bucket Accumulation at NICA

The heavy ion collider NICA is under construction at the JINR. [9] The injector is the superconducting synchrotron Nuclotron which can provide a $^{197}Au^{79+}$ ion beam up to 4.5 GeV/u. The intensity is expected as 1×10^9 ions/shot after the major improvement of ion source, linac and the installation of a new booster synchrotron. The barrier bucket accumulation is naturally conceived as the accumulation method in the Collider up to the intensity 2.4×10^{10}, the target intensity in the Collider. The cooling method is inevitably the stochastic cooling for the high energy 3-4.5 GeV/u while for low energy less than 2 GeV/u electron cooling can be used. It is found with simulations that both methods work well for the BB accumulation. [10]

A typical example of the fixed barrier accumulation method with electron cooling at 1.5 GeV/u is given in Fig. 9.

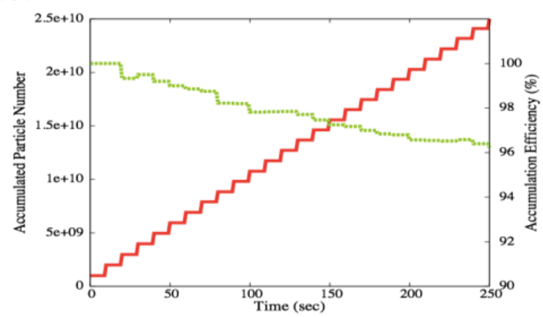

Figure 9: The increase of accumulated particle number (red) and accumulation efficiency (green) during 25 times injection. The cycle time is 10 sec.

SHORT BUNCH FORMATION

Procedure of Short Bunch Formation at NICA

To attain the high luminosity $\sim1\times10^{27}$/cm^2/sec in the collision experiment, short bunches of ~1nsec (rms) length have to be formed in the NICA collider. The procedure of the formation of short bunches from the coasting beam, is composed of two steps as follows. In this case the beam energy is 3.5 GeV/u and stochastic cooling is used.

As the 1st step, the RF voltage (harmonic=24) is increased from 0 to 200 kV with the time constant 5 sec for the adiabatic bunching. The initial beam condition is assumed as the coasting beam with $\Delta p/p$ (rms)$=4\times10^{-4}$ (Gaussian). The gain of stochastic cooling system is reduced from the initial value 90dB to 75 dB within time period 250 sec. The attained bunch parameters are $\Delta p/p$ (rms)$=4.0\times10^{-4}$(rms) and the bunch length=0.56m (rms).

As the 2nd step the RF voltage (harmonic=96) is increased from 50 kV to 500 kV within 1 sec for the adiabatic bunching. The gain of the stochastic cooling system is kept constant as 80 dB. The final beam

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parameters after 100 sec cooling at the 2nd step is calculated as follows. The bunch length=0.28 m (rms), 0.94 nsec (rms) and $\Delta p/p$=5.9×10^{-4} (rms) are well acceptable for the collision experiment.

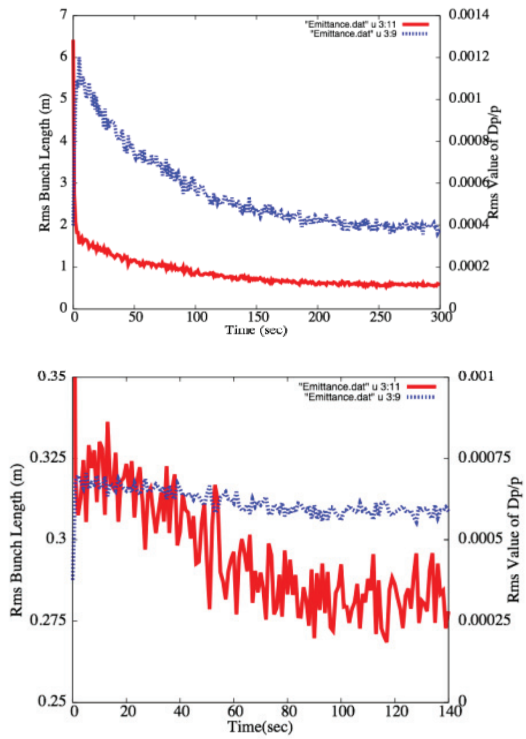

Figure 10: The evolution of bunch length (red) and $\Delta p/p$ (blue) in the process of short bunch formation at the 1st step (top) and the 2nd step (bottom).

Space Charge Effects

The space charge repulsion force could prevent the short bunch formation or even for the BB accumulation the accumulation efficiency could decrease. The simulation has been performed for 1.5 GeV/u $^{197}Au^{79+}$ ion beam because the space charge effect is inversely proportional to γ^2 and the lowest energy is most sensitive to the space charge effects. The calculation of the space charge field is performed with use of the scheme of Particle-In-Cell (Cloud-In-Cell) method [11].

It is found that the space charge potential during the beam accumulation reaches to 150-200 Volt after 20 batches accumulation (N=2×10^{10}) at the edge of the beam profile. However this value is small enough compared with the barrier voltage of 2 kV, and we could not find any deterioration of beam accumulation efficiency in both cases of fixed and moving barrier scheme.

In the short bunch formation, the bunch length becomes as short as ±3~5 nsec (full width) after 100 sec cooling, and the maximal space charge potential reaches ±20 kV while just at the starting of bunch formation the space charge potential is less than ±1 kV. The external RF voltage is assumed as 200 kV and it is ±60 kV at ±3 nsec. (Fig. 11). The slight deformation (lengthening) of the bunch shape should be anticipated but it could be managed [10].

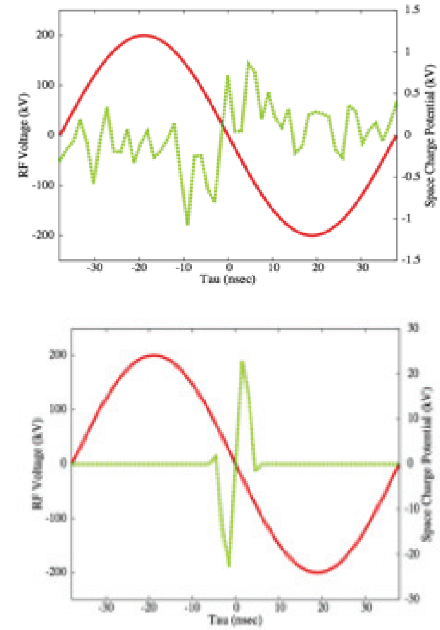

Figure 11: Comparison of external 200 kV RF (red) & space charge potential (green). From the top to the bottom, time is 1 and 100 sec, respectively. The ion number is 1×10^9/bunch.

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