Beam Accumulation and Bunching with Cooling

T. Katayama, T. Kikuchi, I. Meshkov, M. Steck
and H. Stockhorst

Outline
1. RF Stacking & Cooling, ISR and TARN
2. Stochastic Stacking, AA & RESR
3. Barrier Bucket Accumulation, ESR, HESR & NICA
4. Bunching, COSY & NICA
5. Summary & Outlook
ISR: Intersecting Storage Ring 1971-1983

Increase of 25 GeV Proton Current in ISR Achieved ~10A
Luminosity=\~1e29/cm^2/sec

1.7 GeV/c Proton Beam, Momentum Stochastic Cooling at ICE (1977-78)
TARN (Test Accumulation Ring for NUMATRON) 1978-1985
Circumference: 31.7m
Ion energy: 7 MeV/u
Injector: SF cyclotron
Multiturn injection + RF stacking & Stochastic Momentum cooling

Increase of Accumulated He Ion Current

Beam Profiles in TARN

28 MeV 4He2+ Momentum Stochastic Cooling at TARN with Notch Filter system
Dp/p 1e-2 --> 6e-4 (Cooling time=400 sec)
Stochastic Stacking
Collector Ring & RESR Ring of FAIR Project

From Antiproton Separator
Cycle Time=10 sec (5 sec)

3 GeV, N=1e8 Pbar Cooling & Stacking with 2 Rings

Collector Ring
- Circumference 216.25 m
- Phase slipping factor 0.0107
- Bunch Rotation \( \frac{Dp}{p} \) +/-3\% (Uniform) -> 2.45e-3 (rms)
- Stochastic Cooling \( \frac{Dp}{p} \) 2.5e-3 -> 5.0e-4 (rms)

RESR Ring
- Circumference 239.9 m
- Phase slipping factor 0.03-0.11
- Stochastic stacking Up to 1e11 pbar (1000 stacking)
- Deceleration 3GeV-100 MeV (with Ecool)

Dp/p cooling /stacking PU
Dispersion=13m
Fokker-Planck Equation
(Longitudinal cooling process)

\[
\frac{\partial \Psi}{\partial t} + \frac{\partial}{\partial E} \left( F(E)\Psi - D(E,t) \frac{\partial \Psi}{\partial E} \right) = 0
\]

\[
\Psi(E,t) = \frac{dN}{dE}
\]

Distribution Function of Particles

\[F(E): \text{Cooling Force}\]

\[D(E,t): \text{Diffusion Force}\]

**Cooling Force**: Function of Band width, Gain, PU and Kicker sensitivity, Delay of signal, Ring slipping factor etc.

**Diffusion Force**: Function of Particle density, Band width, Gain, PU temperature, IBS diffusion force.
RESR 3 GeV Antiproton
Stacked Beam Profile during Stacking

- Ring slipping factor = 0.05
- Cycle = 5 sec
- \( N = 1 \times 10^8 \)
- Deposited Beam \( Dp/p = 1 \times 10^{-4} \) (rms)
- Tail frequency = 1~2 GHz
- Core frequency = 2~4 GHz
- Tail1 Gain = 120 dB
- Tail2 Gain = 106 dB
- Core Gain = 90 dB
- Notch Depth = 30 dB
- Tail1 Delay Time = -0.320 ns
- Tail2 Delay Time = -0.360 ns
- Core Delay Time = -0.167 ns

Particle Density (eV)

Energy (eV)
CERN AA Stacked Beam Profile
(Simulation by Developed Code)

Parameters are from S.vd. Meer paper (1984)
T=2.6 GeV, N=5e7, Dp/p=1.65e-4 (rms), Cycle
time=5 sec, Ring slipping factor=-0.1,
Tail frequency=1-2 GHz, TailGain=126 dB
Core frequency=2-4 GHz, Core Gain=80 dB
The European Physical Journal H

Fig. 7. Evaluation of the longitudinal density of the stack in the Fermilab Accumulator (computed, \[58\]). The new batch is deposited with an energy difference at around +10 MeV from the bottom of the stack every 2 s.

Table 5. Basic design parameters of the cooling systems for the Fermilab Debuncher (design values 1984, adapted from \[58\]).

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>2–4 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pick-up pairs (loops)</td>
<td>128</td>
</tr>
<tr>
<td>Amplifier equivalent noise temperature</td>
<td>100 K</td>
</tr>
<tr>
<td>Amplifier gain (net)</td>
<td>138 dB (variable)</td>
</tr>
<tr>
<td>Output power</td>
<td>-Schottky 100 W (typical) -Thermal 400 W (typical)</td>
</tr>
<tr>
<td>Number of TWT' amplifiers</td>
<td>8</td>
</tr>
<tr>
<td>Number of kicker pairs (loops)</td>
<td>128</td>
</tr>
</tbody>
</table>

The value of \(\eta = \left| \gamma - \frac{2}{\gamma} \right|\) transition - \(\gamma - \frac{2}{\gamma} \left|\right|\) is carefully chosen in both rings. In the Debuncher a compromise between the RF requirement for the bunch rotation (which favors a small \(|\eta|\)) and stochastic cooling (which favors a larger \(|\eta|\)) leads to the choice of \(\eta = 0\). In the accumulator a value of about 0.02 allowed the operation of the Palmer-Hereward type core cooling system up to 4 GHz and the filter type stack tail systems up to 2 GHz. To decrease the noise-to-signal ratio \(U\), which tends to be large for the low intensity systems in the Debuncher and the stack tail systems in the accumulator, a large number of high-impedance pick-ups are used (Tabs. 5 and 6) to increase the beam signal and cryogenic cooling of the pick-up terminating resistors and the preamplifiers to reduce the noise. The number of kicker units chosen lead to a power requirement of 1600 W for the stack tails system and of 2 \(\times\) 600 W for the Debuncher. These values require a large number of the 200 W travelling wave tube amplifiers to be used.

The Fermilab antiproton source started operations at the end of 1985 with an increase of the 3 dimensional density of several 10\(^6\) and proton-antiproton collisions in the 1 TeV Tevatron of a luminosity of about 0\(\times\)10\(^{30}\) cm\(^{-2}\)s\(^{-1}\) early 1987 [60]. Since then the system has been continuously improved.

(Ref) Design Report Tevatron 1 Project, Fermilab-design-1983-01
Stacking of 3 GeV Pbar Beam in HESR with Use of Barrier Bucket and Stochastic Cooling System

(RESR is postponed in the modularized start version of FAIR)

Three Necessary Conditions for the Barrier Bucket Accumulation

1. Beam momentum spread should be within the momentum acceptance of cooling system.

2. Momentum spread of cooled and stacked beam should be less than the separatrix height of barrier bucket system.

3. Cooled and stacked beam should not be disturbed by the injection kicker field.

B. Franzke invited one of authors T.K in 2005 to GSI and suggested to investigate the possibility of Barrier Bucket Stacking Scheme of Antiproton beam.
Separatrix and Beam Trajectory at RF (H=1) System

Separatrix
Stable Area
RF field

Without Beam Cooling

Injected beam

Time=0 sec

Time=12.9 sec

Without Beam Cooling

With Beam Cooling
Separatrix and Beam Trajectory at Fixed Barrier Bucket System

Separatrix
Stable Area
RF field

Without Beam Cooling

With Beam Cooling

Time=0 sec

Time=11.7 sec

Time=12.9 sec
### Accumulation & Cooling Parameters for HESR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injected Beam</td>
<td>3 GeV, Antiproton</td>
</tr>
<tr>
<td>Injected Beam Intensity</td>
<td>1e8</td>
</tr>
<tr>
<td>Injected Momentum Spread</td>
<td>5e-4 (rms)</td>
</tr>
<tr>
<td>Ring Slipping Factor</td>
<td>0.03</td>
</tr>
<tr>
<td>Cooling System</td>
<td>Notch Filter, 2-4 GHz</td>
</tr>
<tr>
<td>Injected Beam Width</td>
<td>~ 500 nsec</td>
</tr>
<tr>
<td>Revolution Period</td>
<td>~2000 nsec</td>
</tr>
<tr>
<td>Injection Kicker magnet</td>
<td>1000 nsec (250 nsec Falling/Rising time)</td>
</tr>
<tr>
<td>Cycle Time</td>
<td>10 sec</td>
</tr>
<tr>
<td>Barrier Voltage</td>
<td>+/- 2 kV</td>
</tr>
<tr>
<td>Barrier Voltage Frequency</td>
<td>5 MHz (T=200 nsec)</td>
</tr>
<tr>
<td>Barrier Voltage Rising/Falling Time</td>
<td>0.2 sec</td>
</tr>
<tr>
<td>Barrier Voltage Moving Time</td>
<td>0.5 sec</td>
</tr>
</tbody>
</table>
Fokker-Planck Calculation of Coasting Beam Condition at HESR

N=1e8, Gain=120dB, Dp/p=5e-4

N=1e10, Gain=110dB, Dp/p=5e-4

Energy Acceptance of Cooling System
DeltaE=+/- 6.0 MeV/u (Dp/p=+/-1.6 e-3)

Time=0 sec (red), 5 sec (Green), 10 sec (Blue).
Cooling Term (Pink)
**HESR BB parameters**

BB Voltage = 2 kV  
BB frequency= 5 MHz (T1=200 nsec)  
Ring slipping factor: 0.03

**Separatrix Height of BB System**

\[
\Delta E_b = \left( \frac{2\beta^2 E_0 \varepsilon e V_0 T_1}{\pi \eta T_0} \right)^{1/2} \\
\varepsilon = \frac{Q}{A} \\
E_0 = \text{Total Energy/nucleon}
\]
Particle Tracking Code for Momentum Cooling and Synchrotron Motion in Barrier RF System

Synchrotron Motion in (τ, ΔE) Phase Space

\[
\frac{d(\Delta E)}{dt} = \frac{q\omega_0}{2\pi} V(\tau) + F(\Delta E) + \xi_s(\Delta E,t) + \xi_{th}(\Delta E) + \xi_{IBS}(t)
\]

\[
\frac{d(\tau)}{dt} = -\frac{\eta}{\beta^2 \gamma E_0} \Delta E
\]

Random energy kicks due to Diffusion such as Schottky, Thermal Effects (Stochastic cooling case) + IBS growth effects

Random energy kick leads to diffusion in phase space.

\[ q : \text{Chrage State of Ion} \]
\[ \eta : \text{Ring Slipping Factor} \]
\[ V(\tau) : \text{Barrier Voltage} \]
\[ F(\Delta E) : \text{Cooling Force} \]
\[ \xi_s : \text{Schottky Diffusion} \]
\[ \xi_{th} : \text{Thermal Diffusion} \]
\[ \xi_{IBS} : \text{IBS Diffusion} \]
Moving Barrier Bucket System, Voltage=2000 Volt

Phase Space Mapping

Blue: barrier Voltage
Red: Particle distribution

Particle distribution along the Ring Circumference

Cooling Acceptance

Newly injected beam.

Time=0.0 sec

Normalized Particle Number

Normalized Particle Number

Becomes coasting beam

Time=1.0 sec

E [MeV/u]

# p  tau [sec]  Energy [eV]  at 0.000000e+00 [s]

# p  tau [sec]  Energy [eV]  at 1.000080e+00 [s]  Cooling
Time=9.5 sec

2nd batch injected

Time=10.0 sec
HESR Moving Barrier Bucket System,
Voltage=2000 Volt
Cycle time= 10 sec

Blue: Accumulation Efficiency
(right scale)

Green: Cooling Gain (right scale)

Red: Accumulated Particle Number
(left scale)

Reduction of cooling gain is essential!
Fixed Barrier 1000 Volt (Phase mapping)

Time=0.0 sec

Cooling Acceptance

Separatrix Height=+/-2.7 MeV

Time=1.0 sec

Time=9.0 sec

Time=10.0 sec

# p  tau [sec]  Energy [eV]  at 0.000000e+00 [s]  Cooling

# p  tau [sec]  Energy [eV]  at 1.000051e+00 [s]  Cooling

# p  tau [sec]  Energy [eV]  at 9.000063e+00 [s]  Cooling

# p  tau [sec]  Energy [eV]  at 1.000004e+01 [s]  Cooling

Cooling Acceptance
Fixed Barrier Bucket System, Voltage=1000 Volt

Accumulation efficiency
= Accumulated Particle Number / Total Injected Particle Number

Green: Accumulation Efficiency (right scale)
Red: Accumulated Particle Number (left scale)
Celebration of Success of POP Experiment
2010 September 9th, at ESR Control Room
GSI, FZJ, JINR & CERN Collaboration

Spokesman of POP Experiment: M. Steck
Parameters of Stochastic Cooling and Barrier Voltage at POP Exepriment at ESR

1. Particle: $^{40}\text{Ar}^{18+}$, 0.4 GeV/u, Gamma=1.426, Beta=0.713
2. Ring circumference: 108.36 m, Revolution Period=500 nsec
3. Number of injected particles from SIS18: 5e6 ions/shot.
4. Injected momentum spread: 5.0e-4 (1 sigma)
5. Injected bunch length: 150 nsec (Assumed as uniform)
6. Ring slipping factor: 0.309
7. Dispersion at PU: 4.0m, Dispersion at Kicker=4.0 m (Palmer stochastic cooling method)
8. Band width: 0.9-1.7 GHz
9. BB Voltage: 0.12 kV
10. BB Frequency: 5 MHz ($T=200$ nsec) for Fixed barrier Case
    10 MHz ($T=100$ nsec) for Moving barrier case
11. Injection Kicker Pulse Width: 200~300 nsec
12. Transverse emittance (rms): 1.25 Pi mm.mrad (constant)
Comparison of Experimental and Simulation Results of Momentum Cooling at ESR

**Experimental Results**

36Ar\(^{18+}\) 390 MeV/u

- Circles: horizontal width
- Squares: momentum width
- Full symbols: \(N=5\times10^6\)
- Open symbols: \(N=5\times10^7\)

- \(\text{rms momentum width} (\times10^{-3})\)
- \(\text{rms horizontal width [mm]}\)
- \(t \text{ [sec]}\)

**Simulation Results**

with Fokker Planck code

- \(\text{Dp/p(initial)}=8\times10^{-4} \text{ (rms)}\)
- Gain=130dB
- Red: \(N=5\times10^6\)
- Green: \(N=5\times10^7\)

(Ref) F. Nolden et al., EPAC 2000
Fixed Barrier Case Vbb=120 V, Stochastic Cooling Gain=120dB

Accumulated Particle Number & Efficiency

Accumulation Efficiency = Accumulated Particle Number / Total Injected Particle Number

Un-Stacking
- No Beam injection but Kicker is fired -

Accumulation Efficiency (%)

Time (sec)

Stacking

Experimental Result

Simulation Result

Fig. 3: Derivative of kicker pulses. Kicker Module 1 to 3. Time scale 200 ns/div.

In figure 3 ringing of the kicker pulses are visible which lasts longer than 200 ns. The pulse duration is \( \leq 300 \) ns and is thus longer than the gap (200 ns). Therefore some particles are lost when the kicker is fired.

Accumulation with fixed barrier pulses:

Figure 4: Accumulation over \( \geq 500 \) s. Injection every 13 s. Saturation is reached (?) after 500 s with 320 \( \times \) or \( N = 6 \times 10^7 \) Argon ions.

From figure 4: It seems that on average a current \( I \) \( \geq 0.01 mA \) is injected in the ESR every 13 s. This corresponds to \( \frac{Inj}{N} \times q \times f \) particles. Thus on average Argon ions are injected per cycle.

Figure 5: No beam in SIS18. Injection kicker still fires every 20 s.

Figure 6: The SIS18 bunch is kicked in the gap created with the barrier pulses.
Phase Space Mapping

Blue: Barrier voltage
Red: Particle distribution

Particle distribution along the Ring Circumference

Time=0.0 sec

Time=11.7 sec

Cooling Acceptance

# p  tau [sec] Energy [eV] at 0.000000e+00 [s]

Normalized Particle Number

Normalized Particle Number

E [MeV/u]
V [kV]

# p  tau [sec] Energy [eV] at 1.170002e+01 [s] Cooling

Normalized Particle Number

Normalized Particle Number

E [MeV/u]
V [kV]
Moving Barrier Case, Gain=120dB
Vbb=120V, Ie=0A

Experimental Results: No beam accumulation!
Moving Barrier Case, Gain=120 dB
Vbb=120V, Cycle time=20 sec, Kicker period=200 nsec, with Electron Cooler Ie=0.3 A

Accumulated Particle Number & Efficiency

Accumulation Efficiency (green)
Accumulated particle number (red)

Figure 9: Horizontal stochastic cooling is switched OFF after 200s and again On after 400s. Reason for reduction of stacking efficiency when horizontal cooling is OFF: horizontal heating by kicker?

Figure 10: Moving barrier accumulation with stochastic and electron cooling. Barrier voltage 130 V.
Barrier timing: Switch ON within one turn 500 ms standing 900 ms moving 200 ms standing and injection in particle free area switch OFF

Simulation Result
Experimental Result
Momentum Cooling of Ar18+ 400 MeV/u
Beam at ESR at Moving Barrier Case

Electron Cooler at ESR
Length 2 m
Electron Diameter 5 cm
Electron Current 0.2 A
Effective Electron Temperature 1e-3 eV
Beta Function at Cooler 16 m

Dp/p=2e-5
Moving Barrier Case

Phase Space Mapping

Particle distribution along the Ring Circumference

Time = 0.0 sec

Time = 0.4 sec
Time = 20.0 sec

- $\Delta E$ [MeV/u]
- $V$ [kV]
- Normalized Particle Number

Graph shows the distribution of particle number normalized over time.

$\theta_p$, $\tau$ [sec], Energy [eV] at 2.000001e+01 [s]
ESR Moving Barrier Case, Gain=120 dB
Vbb=2kV, Ie=0 A
(2 kV BB system is under construction & Experiment could be in 2014)

Accumulated Particle Number & Efficiency

Stacking

Un-Stacking

Accumulation Efficiency (%)
Beam Accumulation & Short Bunch Formation at NICA Collider

1. Beam Accumulation
Accumulation of 197Au79+ beam in the Collider from Nuclotronup to N=2.4e10 (24 batches). Barrier bucket system with stochastic and/or electron cooling is envisaged.

2. Short Bunch Formation
Short bunch formation with RF and beam cooling. The goal of expected bunch length=1ns (rms).

3. Compensation of IBS Diffusion
At the collider mode, the Intra Beam Scattering diffusion effects have to be compensated by beam cooling.
Circumference=503.04 m  
Transition Gamma=7.09  
Injected Beam Parameters from Nuclotron  
  Energy: 1.0 - 4.5 GeV/u  
  Intensity: 1.0e9 / 10 sec  
  Transverse emittance: 0.5-1.0 Pi.mm.mrad  
  Bunch length: 300 nsec *  
  Dp/p=3e-4 (rms)*  
*Note: Could be smaller values with booster synchrotron with electron cooler.

NICA Collider FODO Lattice

Stochastic Cooling System

Electron Cooler  
Length=6m  
Current=1 A  
Diameter=2 cm  
Beta function at Cooler=16 m
Simulation Results of Beam Accumulation at NICA Collider

Beam stacking with electron cooling @1.5 GeV/u

Beam stacking with stochastic cooling @3.5 GeV/u

Accumulated Particle Number & Efficiency (Initial Gain=120dB)

Red: Accumulated particle number
Blue: Accumulation Efficiency

Required particle number is 2.4e10 (nb=24)
Intra Beam Scattering (IBS) effect

\[ \frac{1}{\sigma_i} \frac{d\sigma_i}{dt} \propto \frac{N Q^4}{A^2 \varepsilon_x \varepsilon_y \sigma_p \sigma_s \beta^3 \gamma^4} F_i(\sigma_x, \sigma_y, \sigma_p, \text{Lattice Function}) \]

Bunched Beam IBS Growth Rates (Calculated with Martini/Parzen Formulae)
Emittance H = 1.2 \( \pi \) mm.mrad, Emittance V = 0.9 \( \pi \) mm.mrad
Bunch length (rms) = 0.6 m

Red: 1/\( \tau_P \), Green: 1/\( \tau_H \), Blue: 1/\( \tau_V \)
Pink: (1/\( \tau_H \)+1/\( \tau_V \))/2.0

1/\( \tau_P \) (dp/p=1e-3)= 3.65E-03 (tau=270 sec)
1/\( \tau_H \) (dp/p=1e-3)= 4.86E-04 (tau=2050 sec)
1/\( \tau_V \) (dp/p=1e-3)= -6.1E-05 (tau=-16000 sec)

1/\( \tau_P \) (dp/p=1e-3)= -7.95E-05 (tau=-12000 sec)
1/\( \tau_H \) (dp/p=1e-3)= 3.86E-03 (tau=260 sec)
1/\( \tau_V \) (dp/p=1e-3)= 6.03E-03 (tau=166 sec)
Short Bunch Formation from the Accumulated Coasting Beam at 3.5 GeV/u  
(First Step Harmonic=24)

Initial beam parameters after Barrier Bucket Accumulation
Dp/p (rms)=4e-4 (Gaussian)
Bunch shape=Coasting beam (Uniform Random)

1. RF voltage is increased from 0 to 200 kV (harmonic=24) with time constant 5 sec for the adiabatic bunching.
2. Gain of stochastic cooling system is reduced from the initial value 90dB to 75 dB within time constant 250 sec.
Evolution of Rms Bunch Length & Dp/p

Red: Bunch Length (rms)
Blue: Dp/p (rms)

Evolution of IBS Heating Term & Dp/p

Red: IBS heating term
Blue: Dp/p (rms)
Short Bunch Formation from the Accumulated Coasting Beam at 3.5 GeV/u
(Second Step Harmonic=96)

Initial beam parameters after 1st Step of Short Bunch Formation
Dp/p (rms)=4.01e-4 (rms)
Bunch length=0.56m (rms)

1. Gain of stochastic cooling system is kept constant as 80 dB.
2. RF voltage is increased from 50 kV to 500 kV (harmonic=96) with time constant 1 sec for the adiabatic bunching.

Final Beam Parameters after 100 sec cooling
1. Bunch length=0.275 m (rms), 0.94 nsec (rms)
2. Dp/p =5.9e-4 (rms)
Vrf=50-500 kV (Adiabatic increase within 1 sec)

Harmonic number=96 RF field

Time=0 sec

Time=100 sec, Equilibrium condition

Evolution of Rms Bunch Length (red) & Dp/p (blue)
Comparison of Results by Lars and Takeshi

L. Thorndahl: Contribution to this workshop

coasting beam method, T. Katayama

Red: Bunch length
Green: Dp/p (rms)

time-domain method, sim. initial gain -0.0022/turn, nica init. gain -4.4e-8/turn, 20 000 sim. particles, window ± 8 ns, pc sim. time 28 hrs.
Exponentially decreasing gain over first 250 s by -15 db, afterwards constant gain
small bunch shape oscillations caused by the sped up simulation cooling by factor 5e4.

Red: Bunch length scale enlarged
Coasting beam method, T. Katayama

Red: Bunch length
Green: Dp/p (rms)
Beam Bunching Experiment with Stochastic Cooling at COSY

(Ref.) T. Katayama et al., IPAC10 in Kyoto

Simulation Results

Red: $t=0$ sec,
Green: $t=100$ sec,
Blue: $t=400$ sec cooling, Gain=110 dB

Experimental Results

 Evolution of Bunch Length

Red: Gain=110 dB,
Green: 107 dB
Blue: 112 dB
Blue points: Measured data
Suppression of Beam Heating due to IBS with Stochastic Cooling (Vrf=500 kV)

3.5 GeV/u 197Au79+ , N=1e9/bunch

Evolution of Rms Dp/p

Gain=80 dB cooling, With IBS effect (Red)
Gain=0 dB no cooling, With IBS effect (Green)

Initial increase from 6e-4 to 1.2e-3 is due to the bunching with re-capture of the beam by the 500 kV RF field.

Evolution of Rms Bunch Length

Initial reduction from 3e-9 to 1.6e-9 is due to the bunching with re-capture of the beam by the 500 kV RF field.
In the Laboratory Reference Frame, the longitudinal electric field due to the space charge is given by

\[ E_z(z) = -\frac{g}{4\pi\varepsilon_0\gamma^2} \frac{\partial \rho(z)}{\partial z} \]

where \( g = 1 + 2.0 \ln(b/a) \)

From this electric field the energy variation of ions per unit time is derived and the synchrotron motion is represented by the following equation:

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

\[
\frac{d\tau}{dt} = \frac{\eta}{\beta^2} \frac{\Delta E}{E_0}
\]

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.

Particle tracking has been done with Particle-In-Cell method.
Space Charge Effects during BB stacking of 1.5 GeV/u 197Au79+ ion in NICA Collider

Accumulated Particle Number & Efficiency

Time=200 sec (20 times injection)

Accumulated Particle Number (arb. unit)
Space Charge Potential (Volt)

-1 -0.5 0 0.5 1
-1 -0.5 0 0.5

Accumulated Particle Number (arb. unit)
Space Charge Potential (Volt)

-200 -100 0 100 200
0 50 100 150 200

Accumulated Particle Number
Accumulation Efficiency (%)

Time=50 sec (5 times injection)  Time=100 sec (10 times injection)

Accumulated Particle Number & Efficiency

Time=100 sec (10 times injection)

Accumulated Particle Number (arb. unit)
Space Charge Potential (Volt)

-1 -0.5 0 0.5
-1 -0.5 0 0.5

Accumulated Particle Number (arb. unit)
Space Charge Potential (Volt)

-50 -25 0 25 50
0 50 100

Accumulated Particle Number
Accumulation Efficiency (%)

Time=200 sec (20 times injection)

Accumulated Particle Number (arb. unit)
Space Charge Potential (Volt)

-200 -100 0 100 200
0 50 100 150 200

Accumulated Particle Number
Accumulation Efficiency (%)

5th Injected Beam
10th Injected Beam
20th Injected Beam
Space Charge Effects during Short Bunch Formation of 1.5 GeV/u 197Au79+ ion in NICA Collider

Bunch Shape (red) & Space charge potential (Green)

RF voltage (red) & Space charge potential (Green)

Time=1 sec

Charge Distribution (arbitrary)

Space Charge Potential (kV)

Charge Distribution (arbitrary)

Space Charge Potential (kV)

Time=100 sec

Charge Distribution (arbitrary)

Space Charge Potential (kV)

Charge Distribution (arbitrary)

Space Charge Potential (kV)

Time=100 sec

RF Voltage (kV)

Space Charge Potential (kV)

RF Voltage (kV)

Space Charge Potential (kV)

+/-40 nsec

+/-4 nsec
Summary & Outlook

1. **Beam accumulation** with barrier bucket system assisted with stochastic and/or electron cooling is proved to be quite useful way to obtain the required beam intensity in the storage ring and the collider such as HESR and NICA. The results of simulation and POP experiment at GSI ESR are well in agreement.

2. To attain the high luminosity in the collider, the short bunch formation has be attained with the application of high RF voltage and beam cooling, stochastic cooling for high energy and electron cooling for low energy ion. Careful adjustment/reduction of cooling gain is essential to get the short bunch length as well as momentum spread. The onset of instability of the short bunch is found in the Lars simulation. Further study of theory, simulation and experiment is necessary to assure the short bunch formation such as 1 nsec(rms).