Beam Accumulation with Barrier Cavity and Beam Cooling

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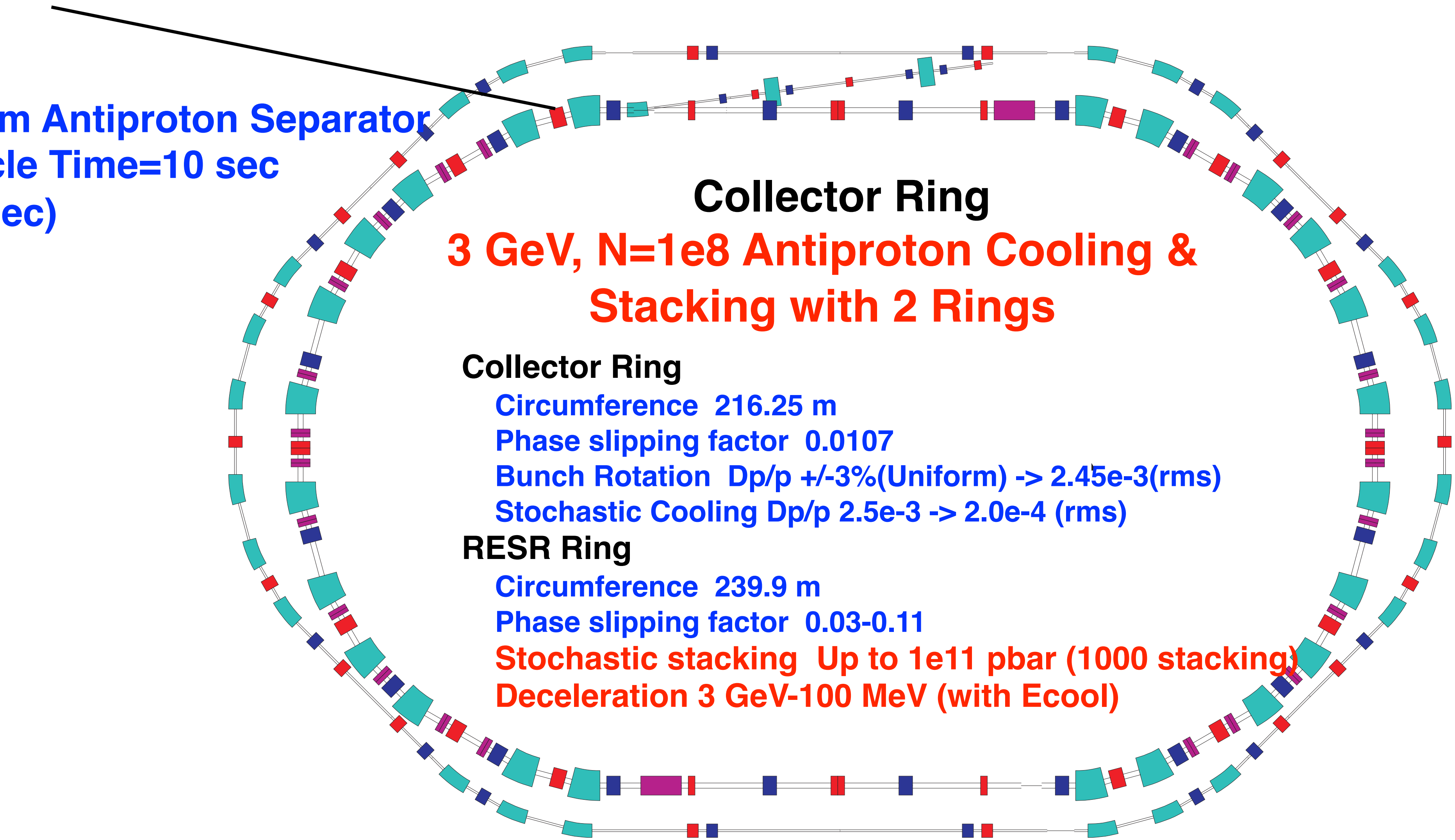
Outline

1. Principle of Barrier Bucket Accumulation
2. 3 GeV Antiproton Beam Accumulation in HESR
3. ESR Beam Experiments with Electron Cooling
4. POP Beam Experiments with Stochastic & Electron Cooling
5. Au Beam Accumulation in NICA Collider
6. Conclusion

Reference
1) M. Steck et al., "Demonstration of Longitudinal Stacking in the ESR with Barrier Bucket and Stochastic Cooling", COOL2011, Alushita.
2)T. Katayama et al., "Simulation Study of Barrier Bucket Accumulation with Stochastic Cooling at GSI ESR", COOL2011, Alushita.
3) T. Katayama et al. "Beam Cooling at NICA Collider", RuPAC 2012, St. Petersburg.

Collector Ring & RESR Ring

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



Collector Ring

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

Collector Ring

- Circumference 216.25 m
- Phase slipping factor 0.0107
- Bunch Rotation Dp/p +/-3%(Uniform) -> 2.45e-3(rms)
- Stochastic Cooling Dp/p 2.5e-3 -> 2.0e-4 (rms)

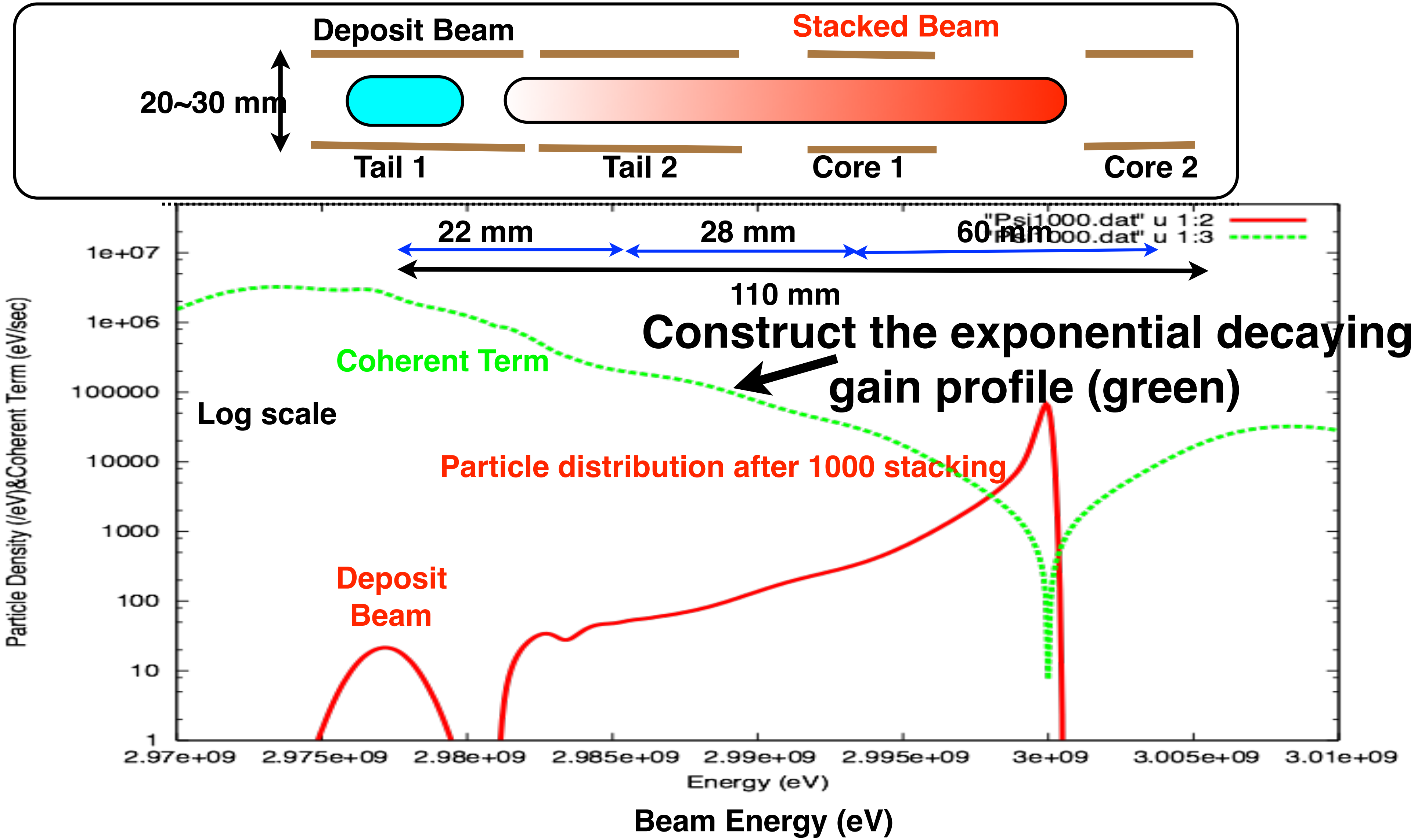
RESR Ring

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

RESR ring

M. Steck et al., "The Concept of Antiproton Accumulation in the RESR Storage Ring of the FAIR Project", Proc. of IPAC10, 2010, Kyoto, Japan

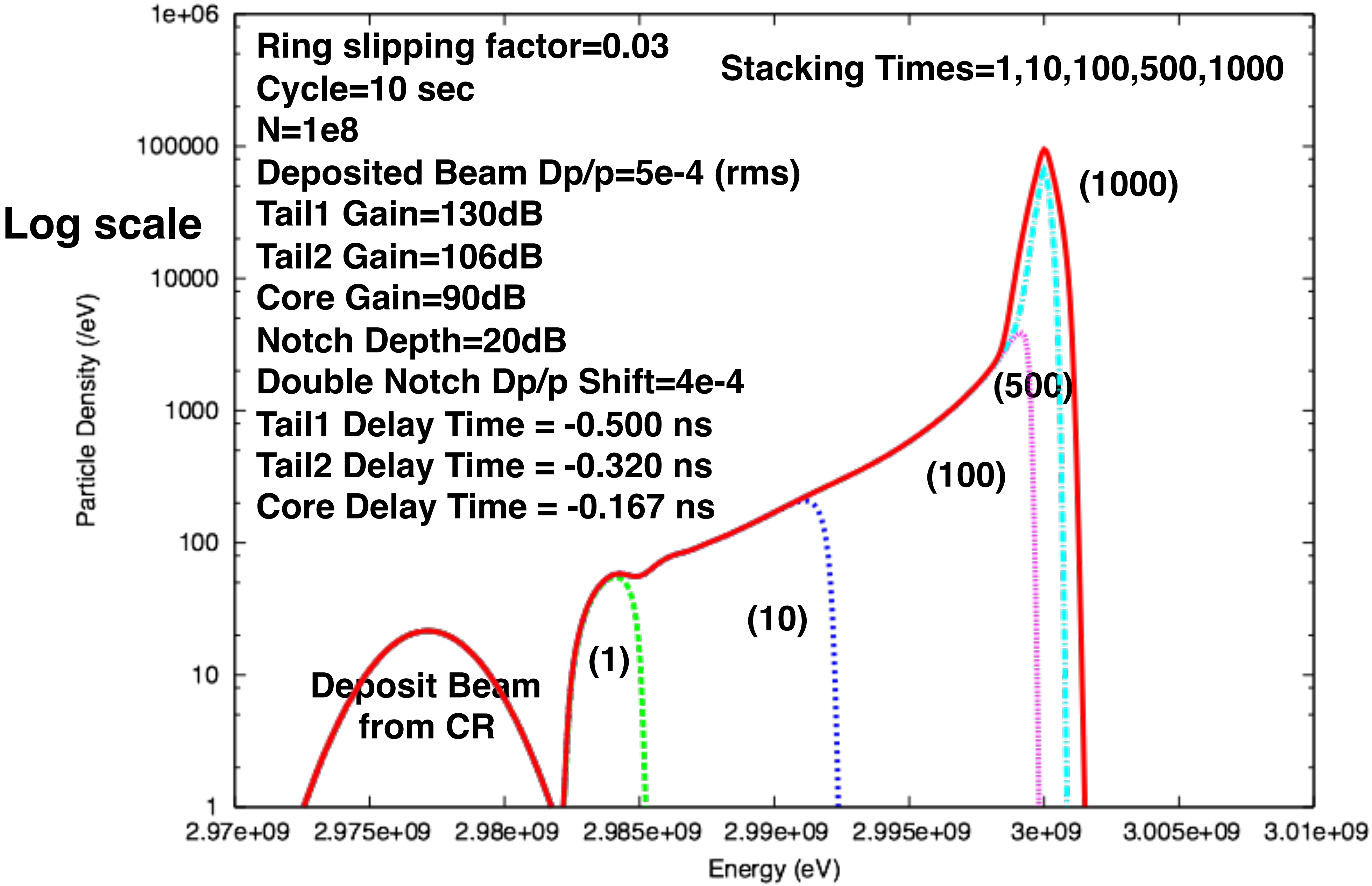
Schematic Layout of Tail and Core System at RESR



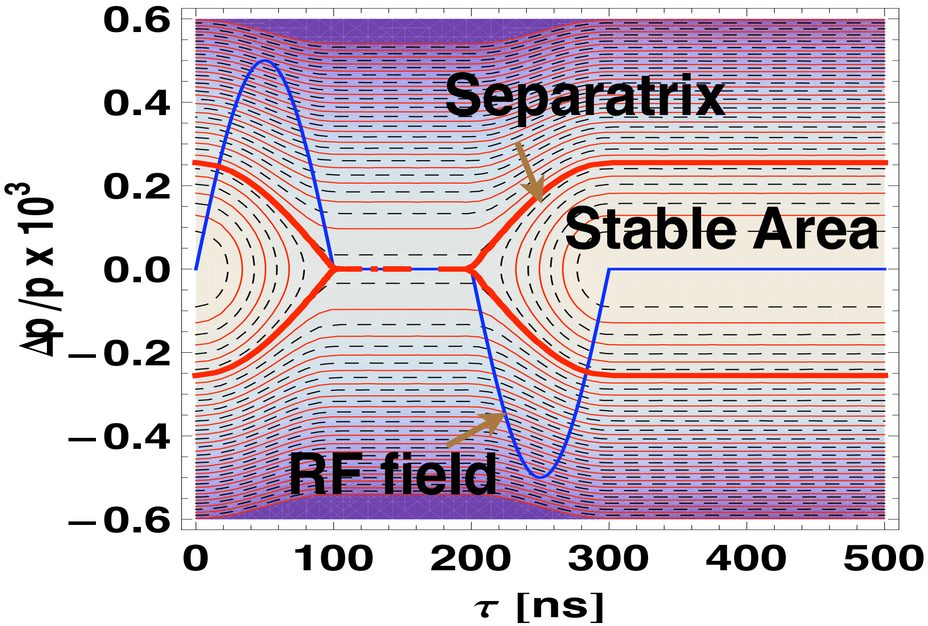
1) S. van der Meer, "Stochastic Stacking in the Antiproton Accumulator", CERN/PS/AA/78-22, 1978

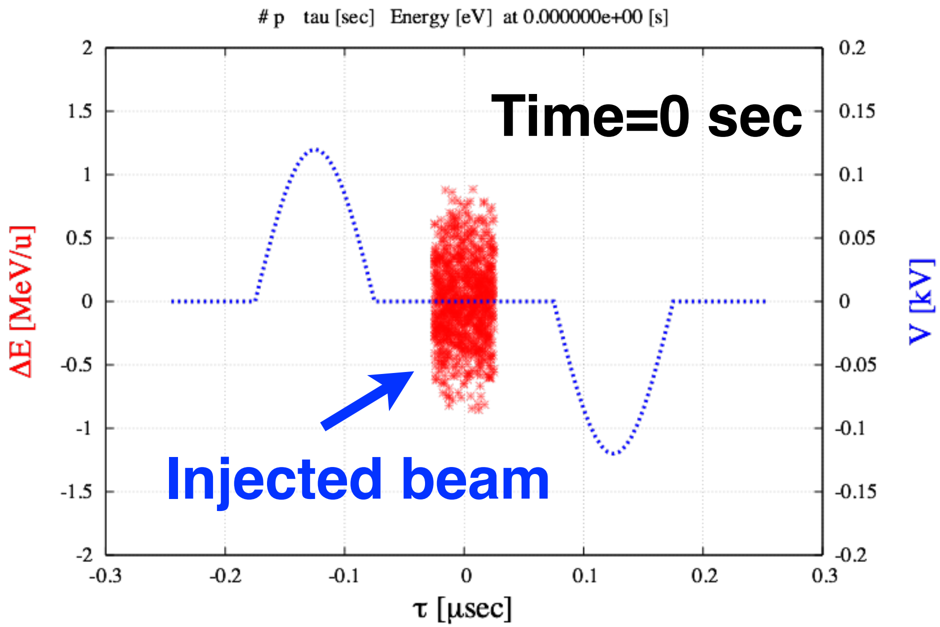
2) T. Katayama et al., "Numerical Design Study of Stochastic Stacking of 3 GeV Antiproton Beam in the RESR for the FAIR Project", Proc. of COOL09, 2009

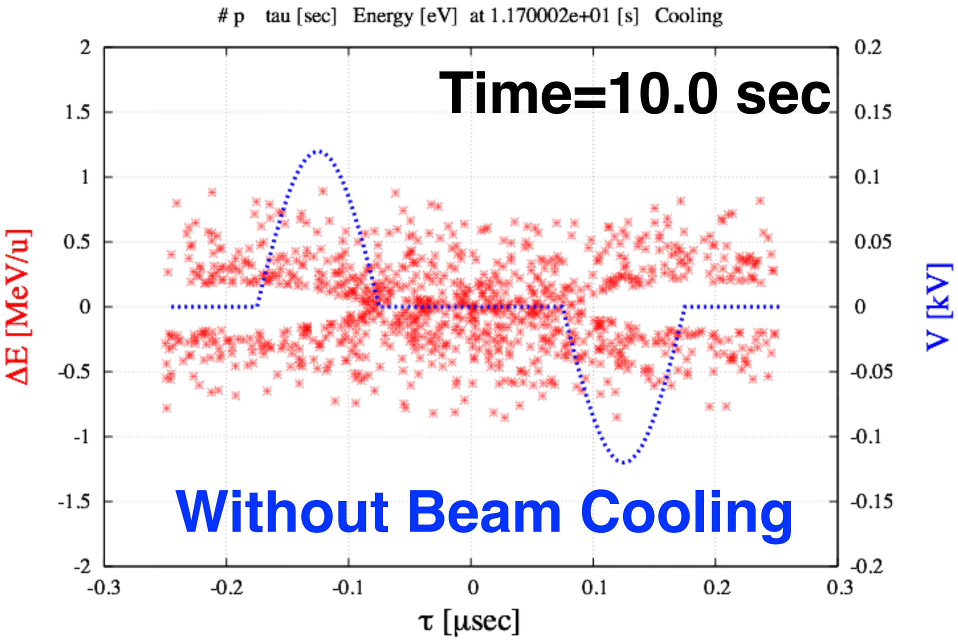
Beam Profile during Stacking at RESR

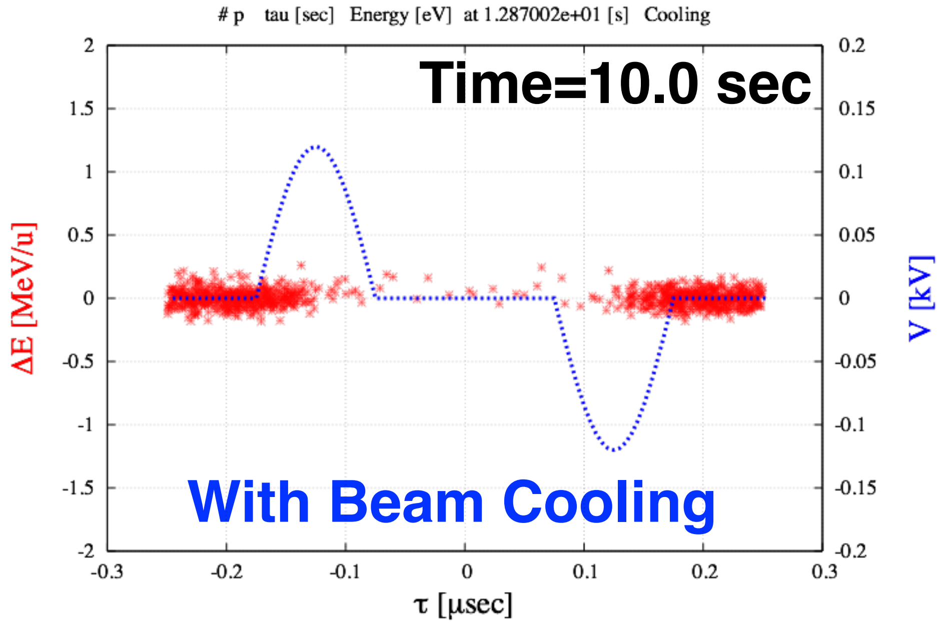


Separatrix and Beam Trajectory at Barrier Bucket System

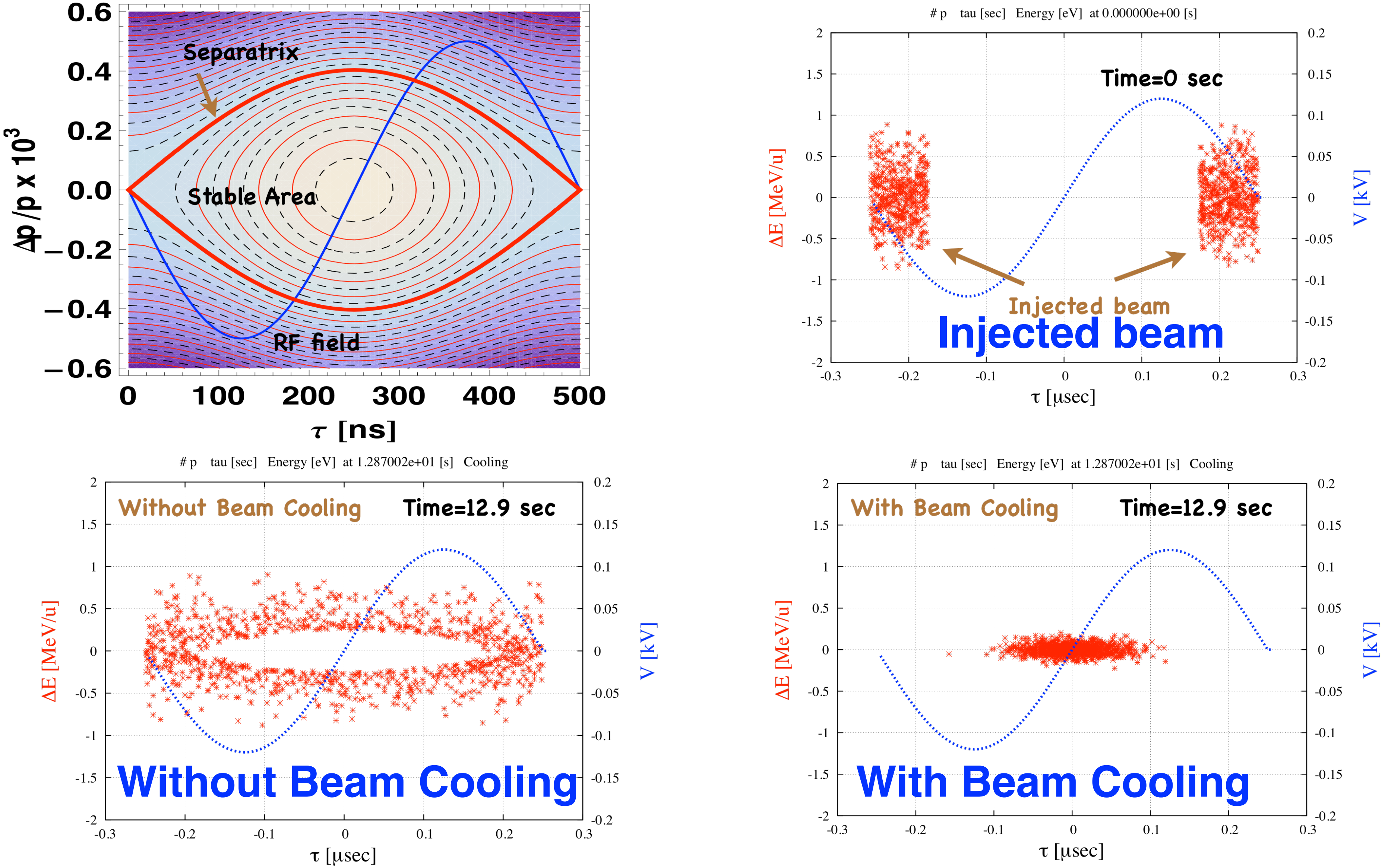








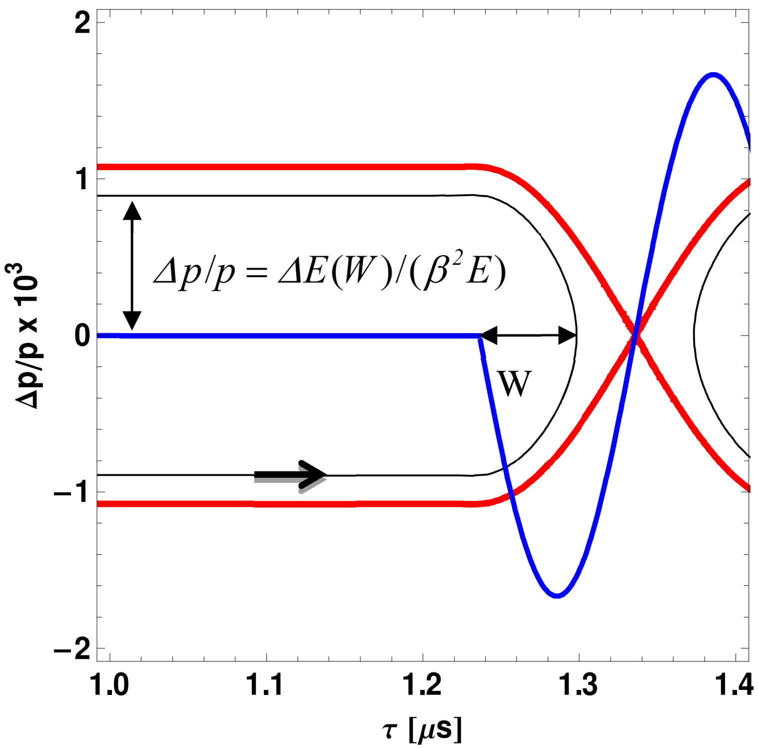
Separatrix and Beam Trajectory at Harmonic=1 RF System



Basic Formulae of Synchrotron Motion

Separatrix Height

$$\Delta E_b = \sqrt{\varepsilon \frac{2\beta^2 E\, eU_0}{\pi|\eta|} \frac{2T_1}{T_0}}$$



RF Voltage

$$U(\tau) = U_0 \sin(2\pi \frac{\tau}{2T_1})$$

$$\Delta E(W) = \Delta E_b \cdot \sqrt{\frac{1}{2} \cdot \left\{1 - \cos(\pi \frac{W}{T_1})\right\}}$$

$$T_C(W) = \sqrt{\frac{1}{\varepsilon} \frac{\pi}{2} \frac{\beta^2 E}{|\eta| eU_0} \frac{T_0}{T_1}} \cdot \int_0^W \frac{d\tau}{\sqrt{\cos(\pi \frac{\tau}{T_1}) - \cos(\pi \frac{W}{T_1})}} .$$

Synchrotron Oscillation Period

$$T_S(W) = 2 \frac{T_2}{|\eta|} \frac{\beta^2 E}{|\Delta E(W)|} + 4T_C(W) .$$

Multi-particle Tracking of Synchrotron Motion with RF Field and Stochastic/Electron Beam Cooling

Synchrotron Motion in $(\tau, \Delta E)$ *Phase Space*

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

Random energy kicks due to Schottky, Thermal and IBS diffusion

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

q : *Chrage State of Ion*

η : *Ring Slipping Factor*

$V(\tau)$: *Barrier Voltage*

$F(\Delta E)$: *Cooling Force*

ξ_s : *Schottky Diffusion*

ξ_{th} : *Thermal Diffusion*

ξ_{IBS} : *IBS Diffusion*

HESR Stochastic Cooling Parameters

Beam kinetic energy	3.0 GeV (Antiproton)
Number of injected particles	1e8
Initial momentum spread	5.0e-4 (1 sigma) truncated at +/-3 sigma
Ring slipping factor	0.031
Slipping factor from PU to K	0.0197
Type of Pickup and Kicker	Slot ring coupler
Notch filter method	Optical notch filter
Atmospheric Temperature at PU	20 K
Noise Temperature at PU	20 K
TOF from PU to Kicker	0.686e-6 sec
Dispersion at PU and Kicker	0 m
Number of PU and Kicker	128/64
Shunt impedance of PU & Kicker	9 Ohm/cell (PU) & 36 Ohm/cell (Kicker)
Band	2-4 GHz
Gain	115-130 dB (Varied during stacking cycle)

Stochastic Momentum Cooling at HESR

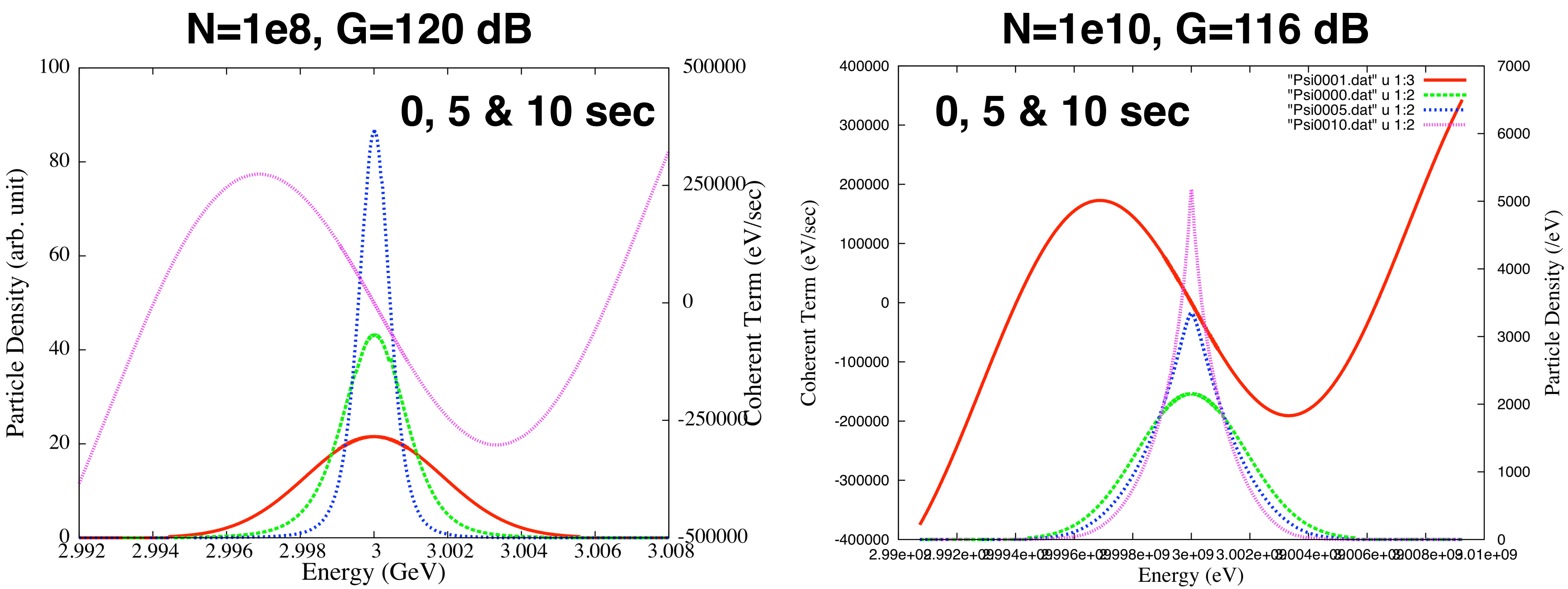


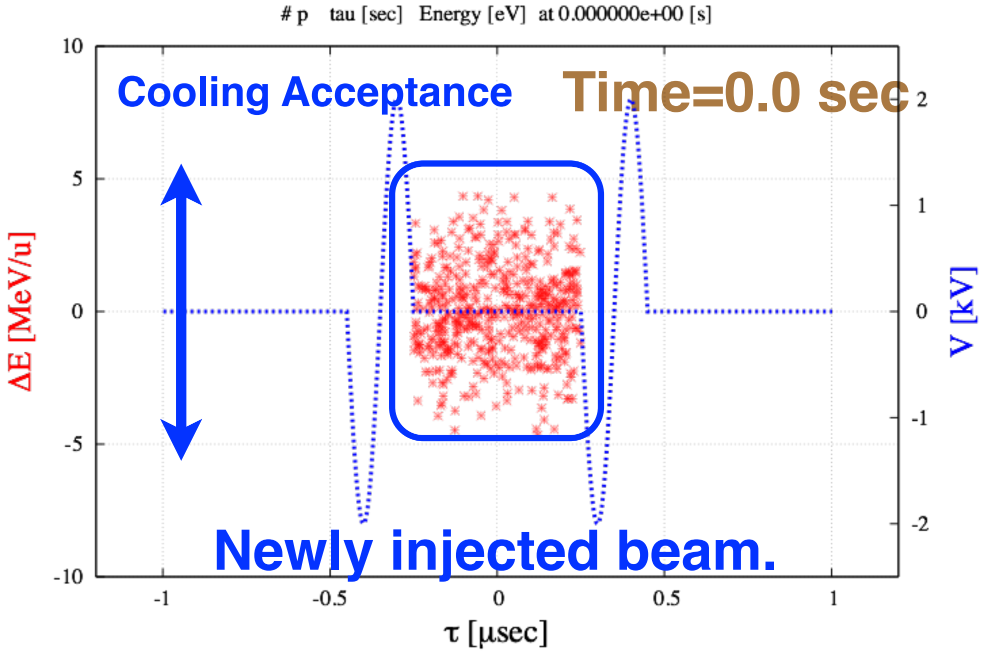
Figure 1 The evolution of stochastic cooling in the HESR ring. Particle number is 1e8 (left) and 1e10 (right). The stochastic cooling gain is 120 dB (left) and 116 dB (right), respectively.
The particle density are illustrated at 0, 5 and 10 sec, respectively. The coherent term is also illustrated (right scale). The injected momentum spread Dp/p (rms) is assumed as 5e-4.

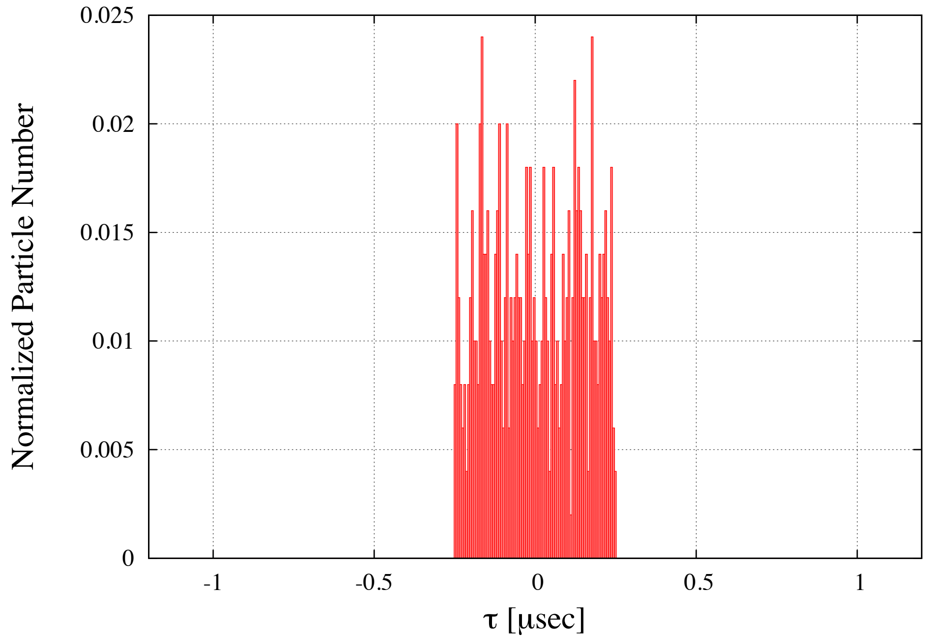
Moving Barrier Method

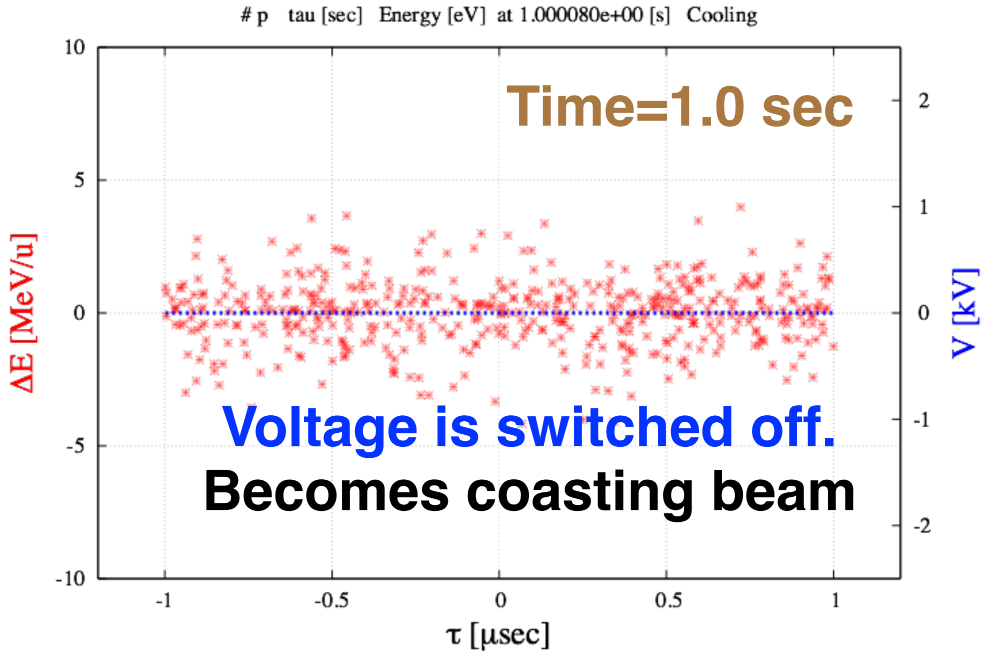
Phase Space Mapping

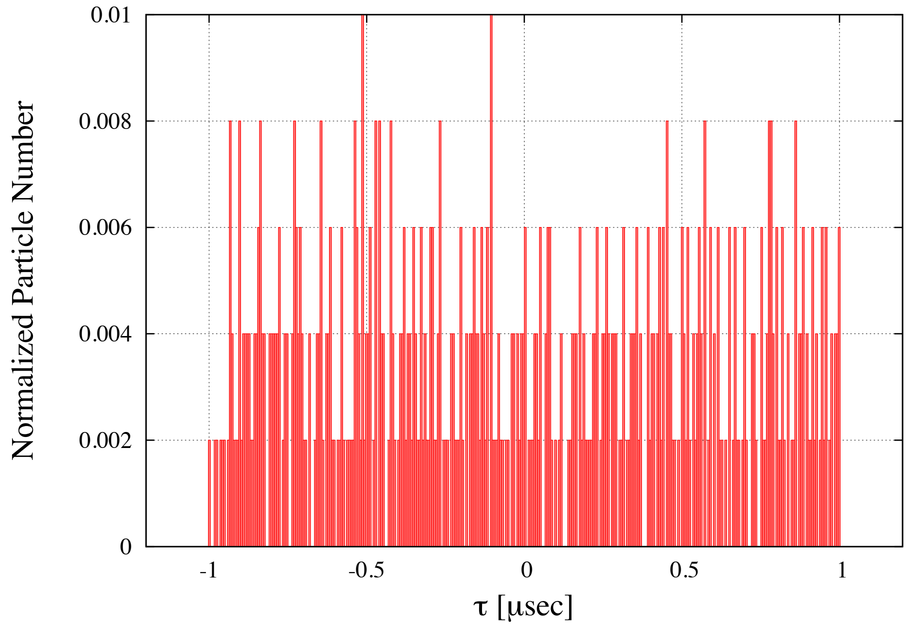
Blue: barrier Voltage
Red: Particle distribution

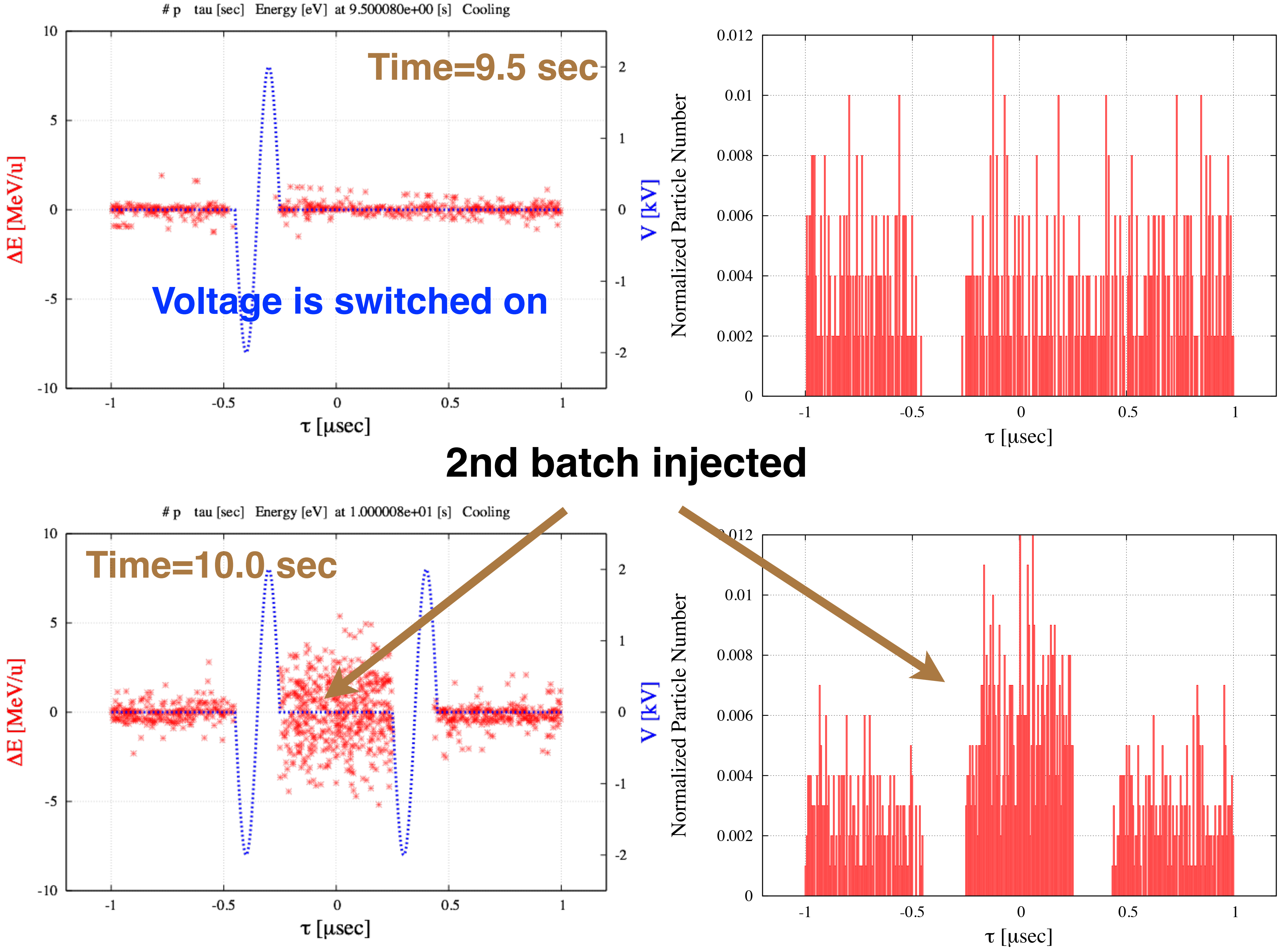
Particle distribution along the Ring Circumference









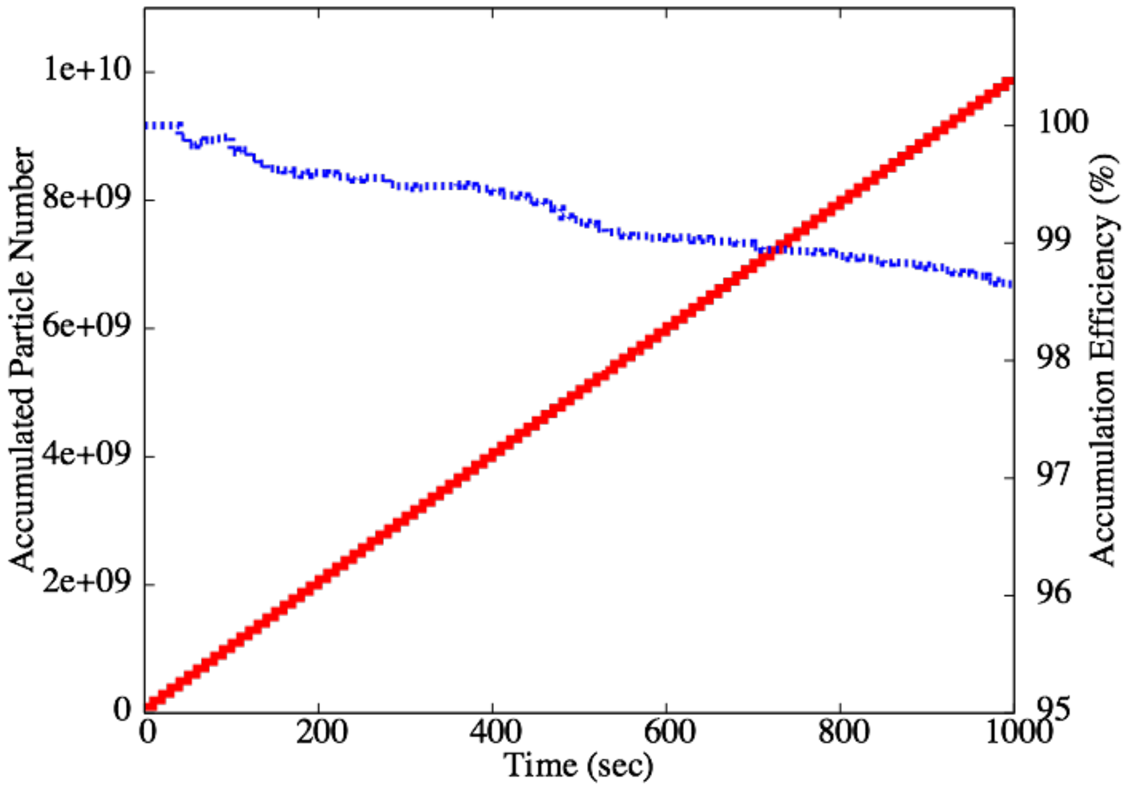


# p tau [sec] Energy [eV] at 9.500080e+00 [s] Cooling
Time=9.5 sec
Voltage is switched on
ΔE [MeV/u]
V [kV]
τ [μsec]
Normalized Particle Number
τ [μsec]
2nd batch injected
# p tau [sec] Energy [eV] at 1.000008e+01 [s] Cooling
Time=10.0 sec
ΔE [MeV/u]
V [kV]
τ [μsec]
Normalized Particle Number
τ [μsec]

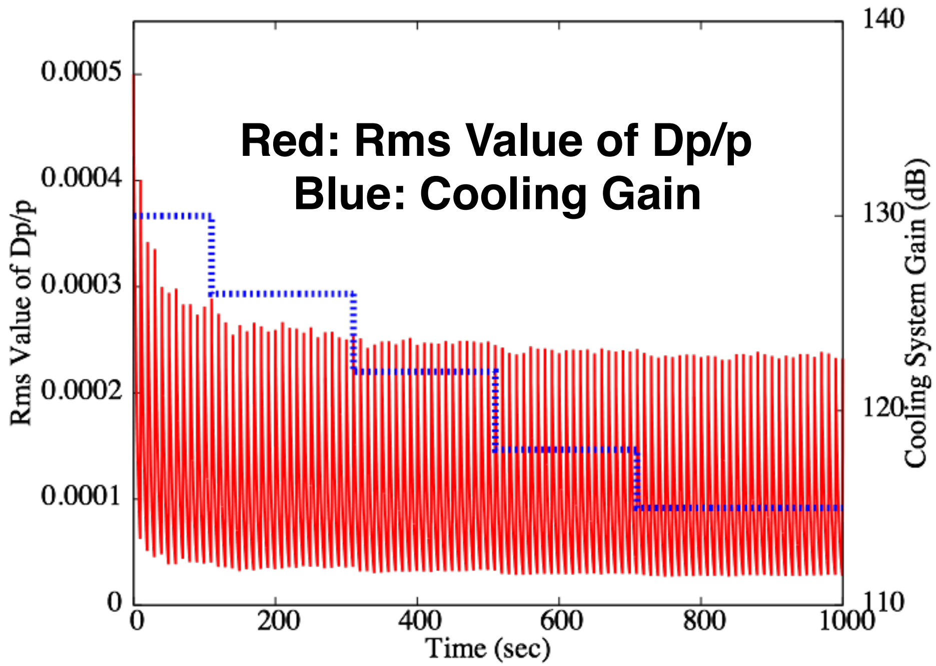
HESR, Beam Accumulation with Moving Barrier System, Voltage=2000 Volt

3 GeV Antiproton Beam is accumulated in HESR every 10 sec up to 1000 sec.

Blue: Accumulation Efficiency (right scale)

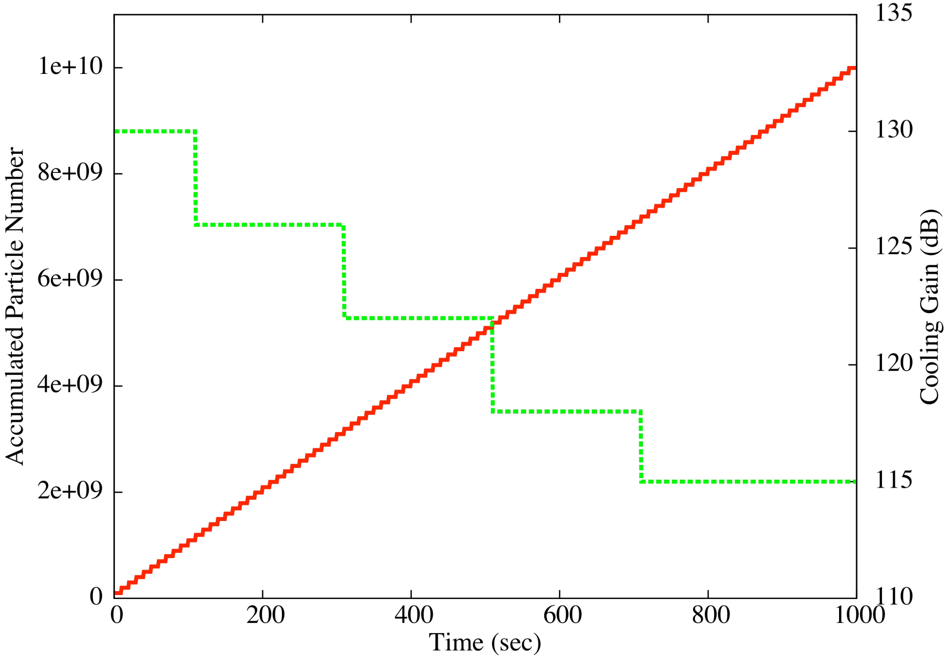


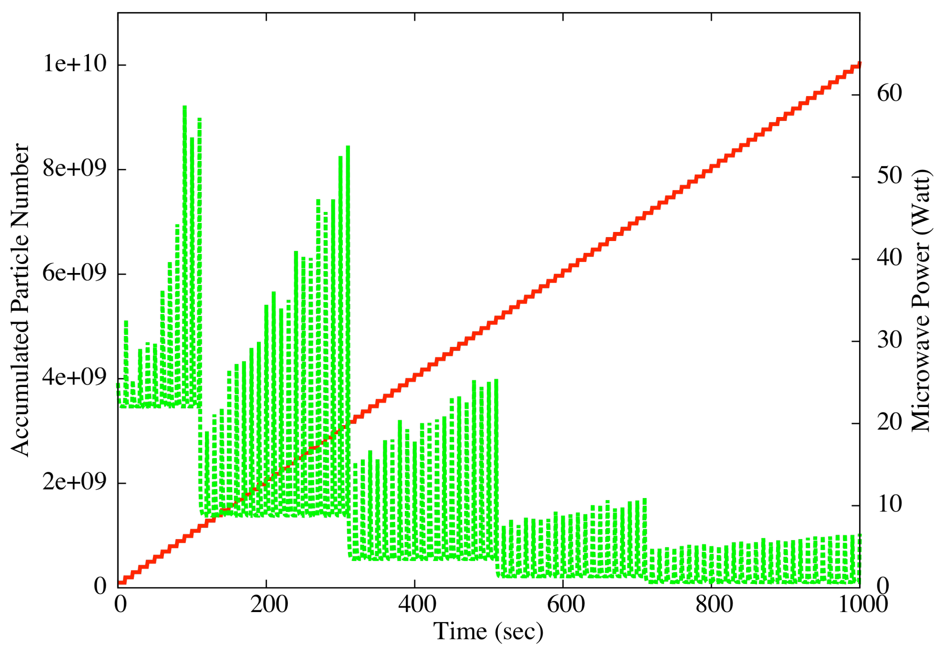
Red: Accumulated Particle Number (left scale)



Barrier Voltage Parameters of HESR

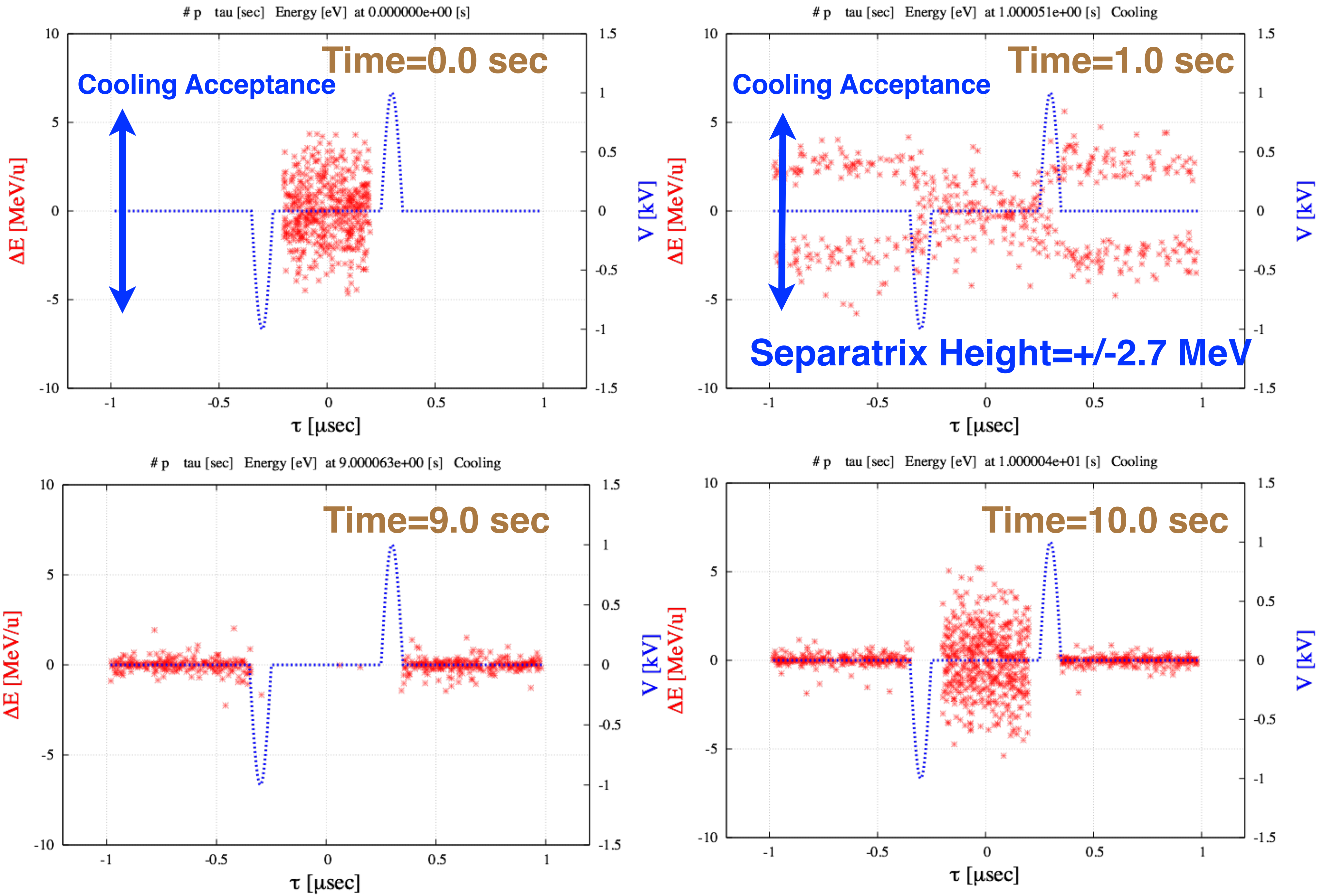
Injected Beam Width 500 nsec
Injection Kicker magnet 600 nsec
Cycle Time 10 sec
Barrier Voltage +/- 1 kV (+/- 2 kV max)
Barrier Voltage Frequency 5 MHz (T=200 nsec)
Barrier Voltage Rising/Falling Time 0.2 sec
Barrier Voltage Moving Time 0.5 sec





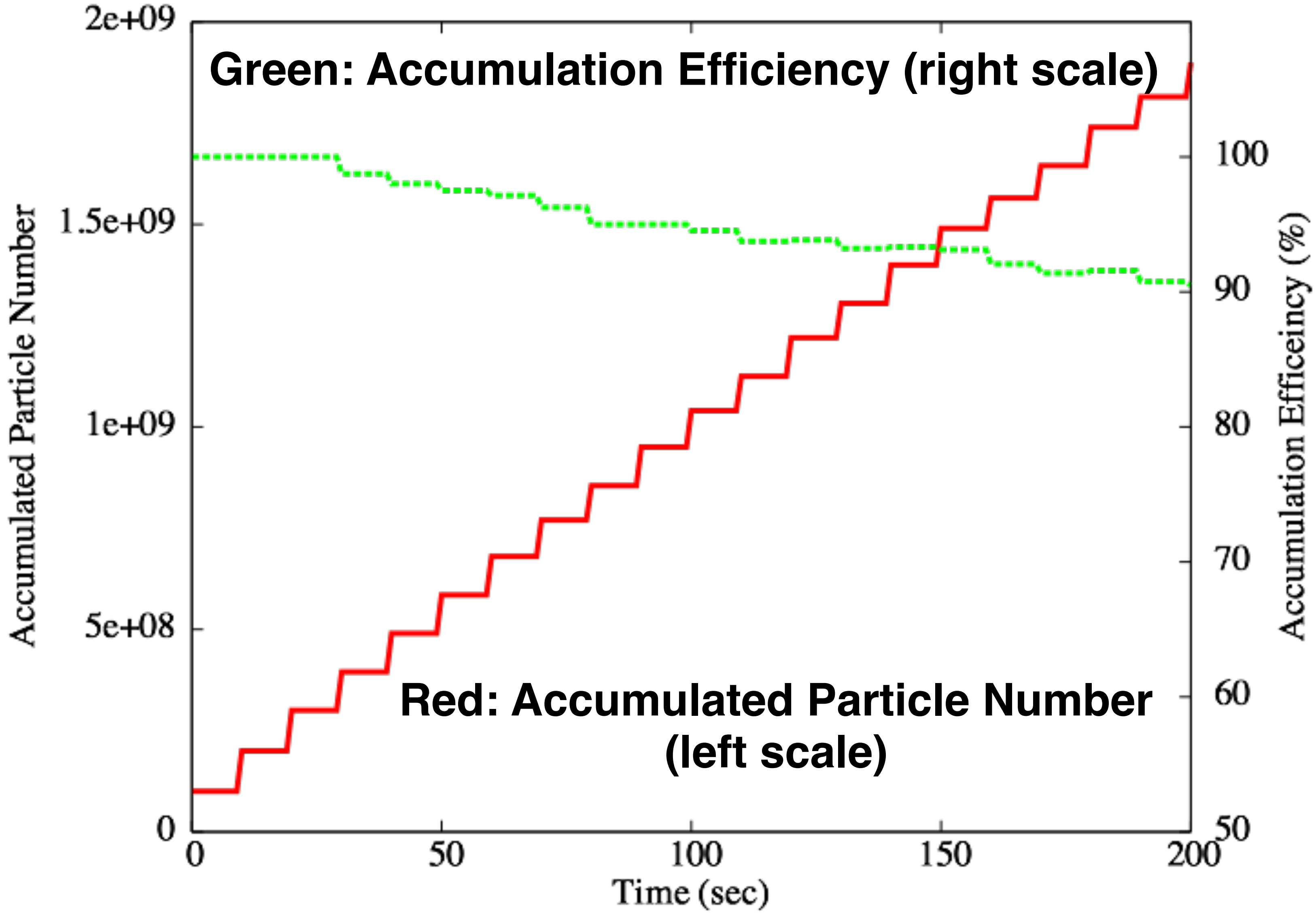
The accumulated particle number (red line, left panel) and the stochastic cooling gain (green line, left panel). The required microwave power (green line, right panel) during the accumulation up to 100 stacking (1000 sec).

Fixed Barrier voltage=1000 Volt case



Fixed Barrier Bucket system, Voltage=1000 Volt

Accumulation efficiency=Accumulated Particle Number /Total Injected Particle Number

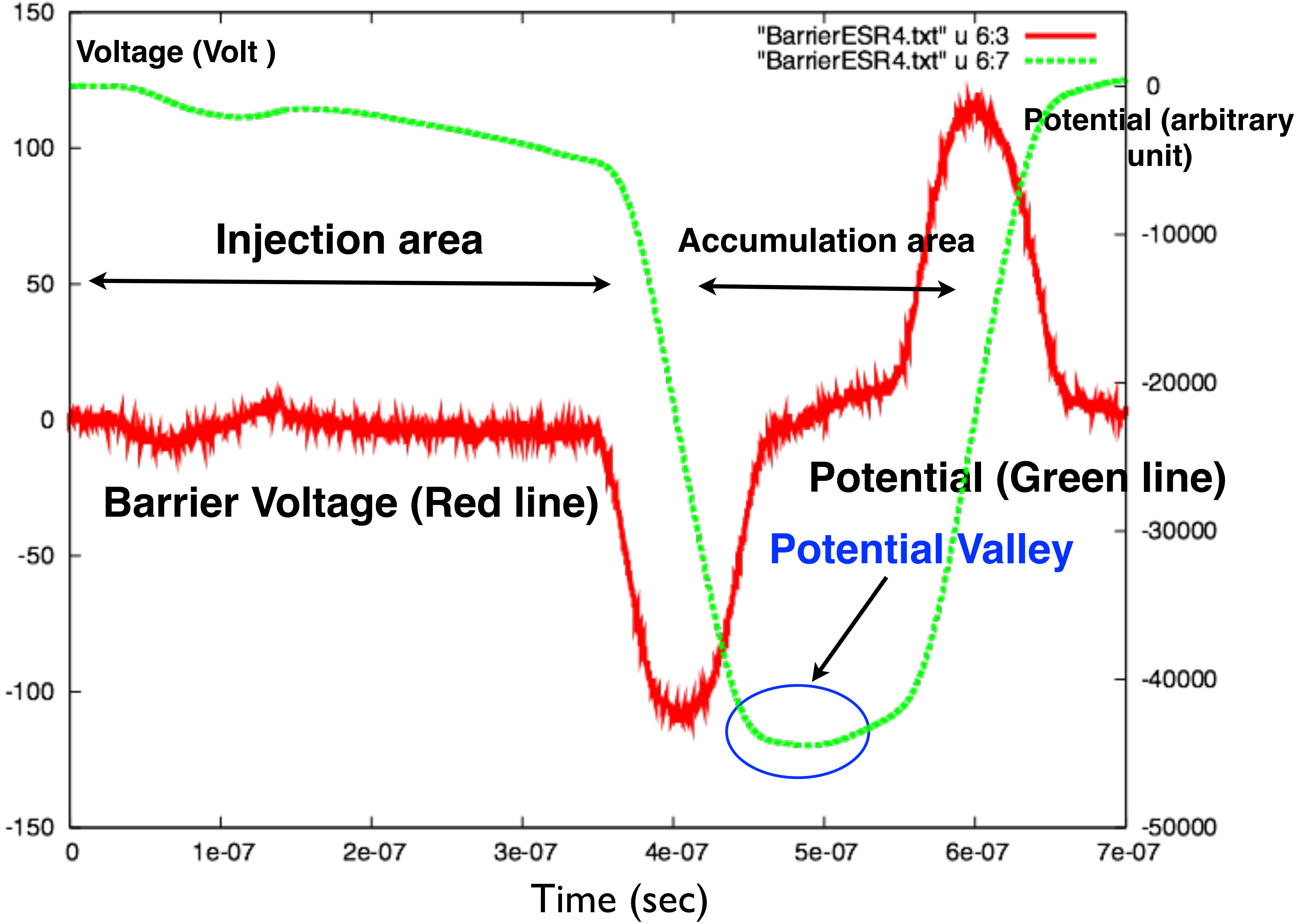


ESR Barrier Bucket Accumulation with Electron Cooling (2007)

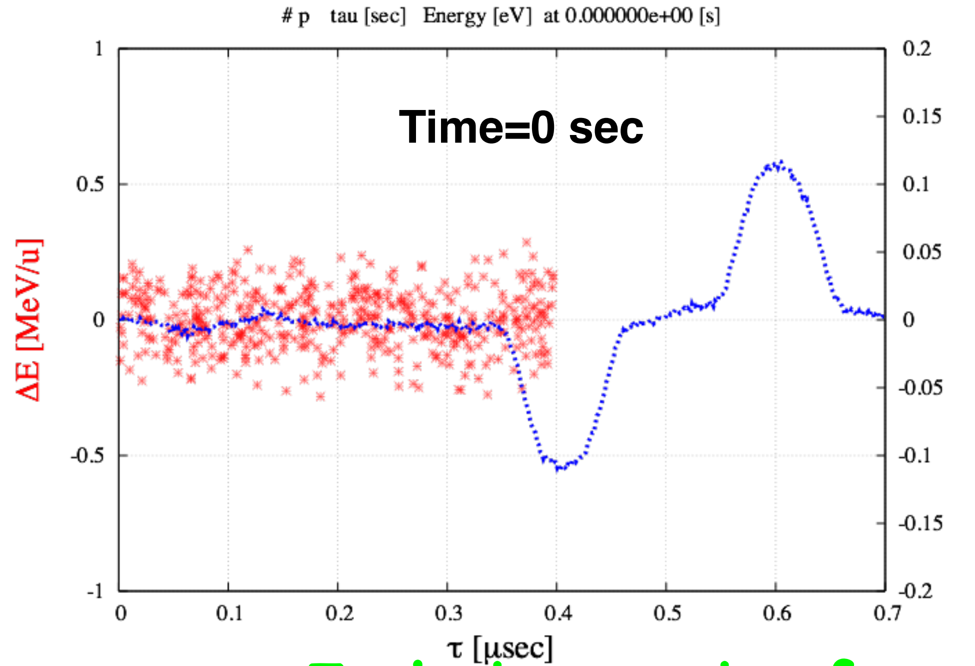
Beam energy: 65.3 MeV/u, 40Ar28+
Injected particle number: 7e7/shot
Initial relative momentum spread: 8.25e-4 (1 sigma)
Initial energy distribution: Gaussian truncated at +/- 3 sigma
Initial transverse (H & V) emittances: 1.35e-6 m.rad (1 sigma)
Initial transverse emittances distribution: Uniform random
Revolution period: 0.7e-6 sec
Ring slipping factor: 0.6959

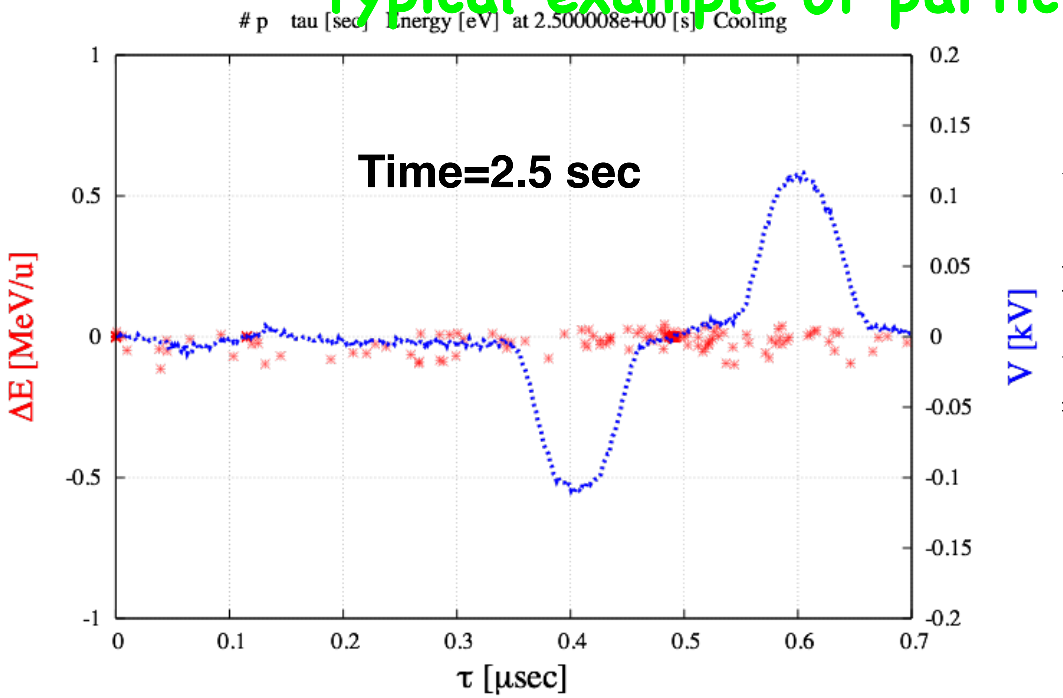
Barrier voltage: +/- 120 Volt
(Measured Barrier Voltage is used in the present analysis)
See the following slide.
Electron cooling current: 0.05, 0.1, 0.3 and 0.5 Ampere
In the simulation IBS effects are included while space charge effects are not included.

GSI ESR Measured Barrier Bucket Voltage and Potential

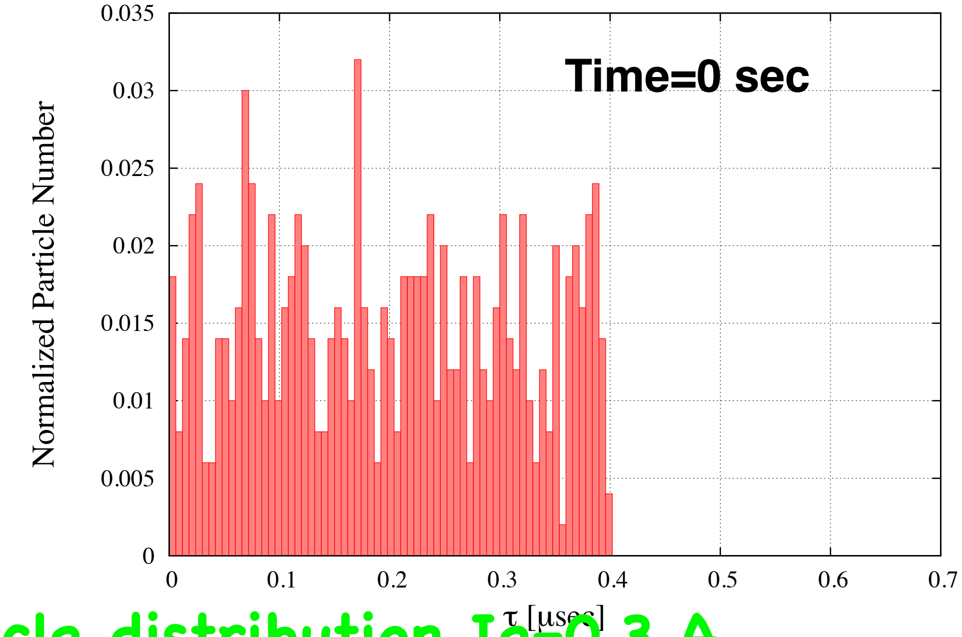


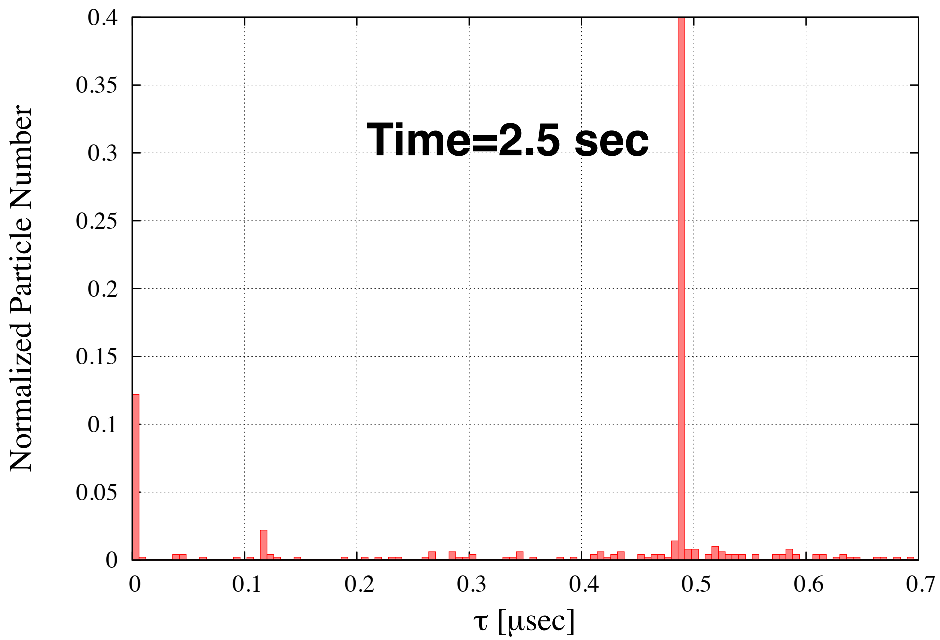
Phase Space Mapping



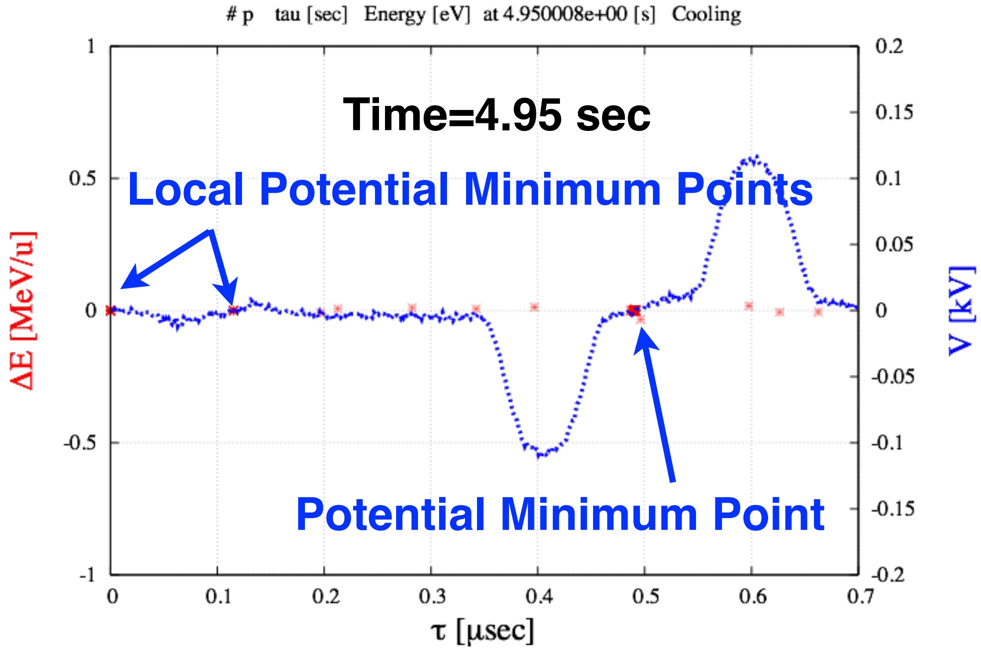


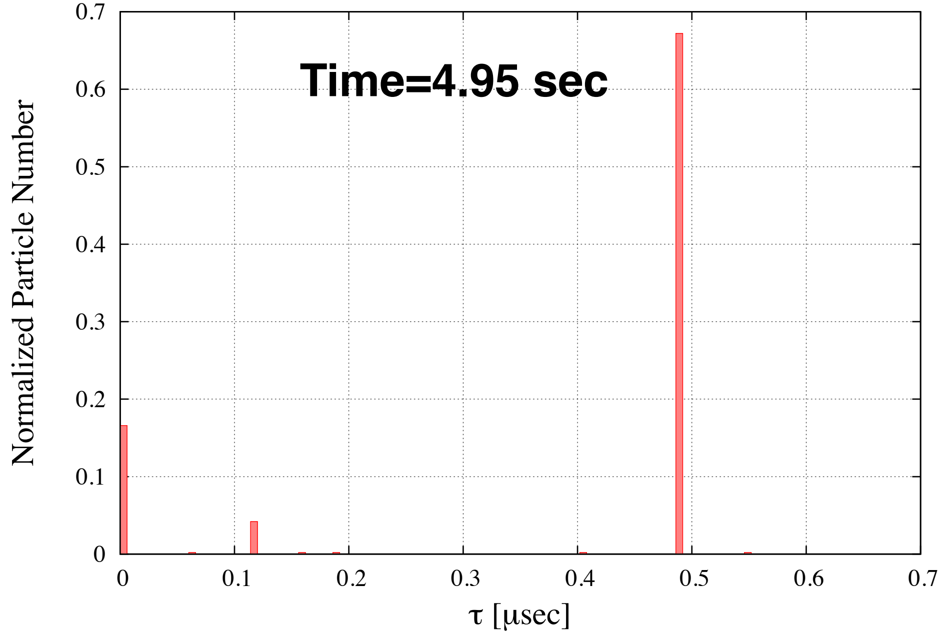
Particle Distribution along the Ring



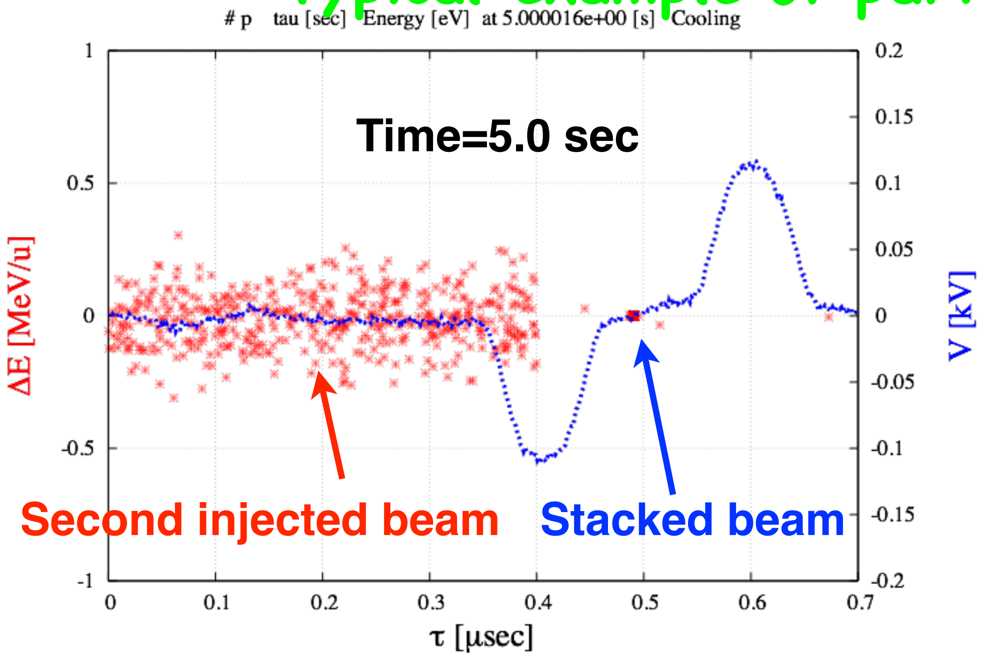


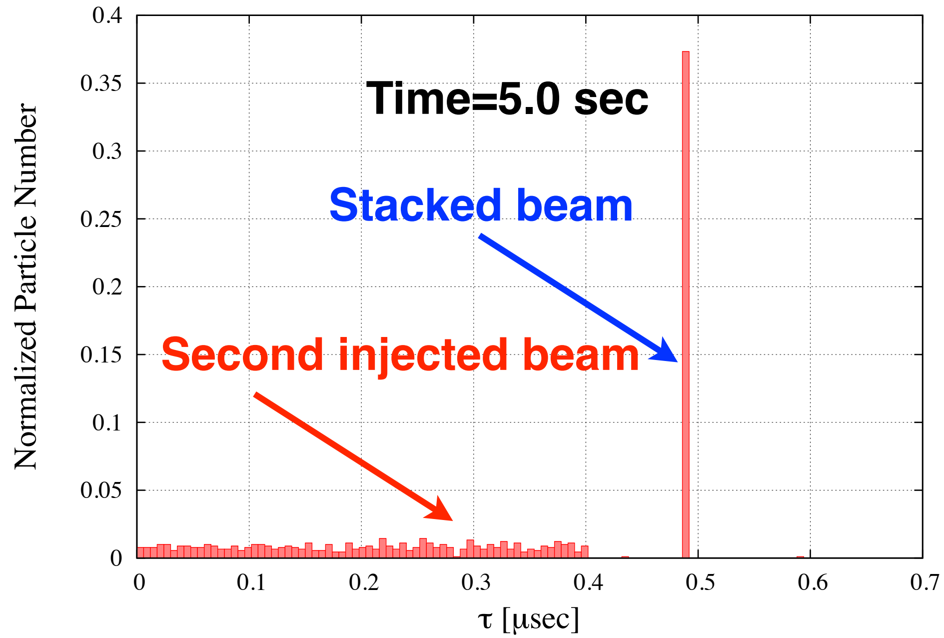
Typical example of particle distribution Ie=0.3 A





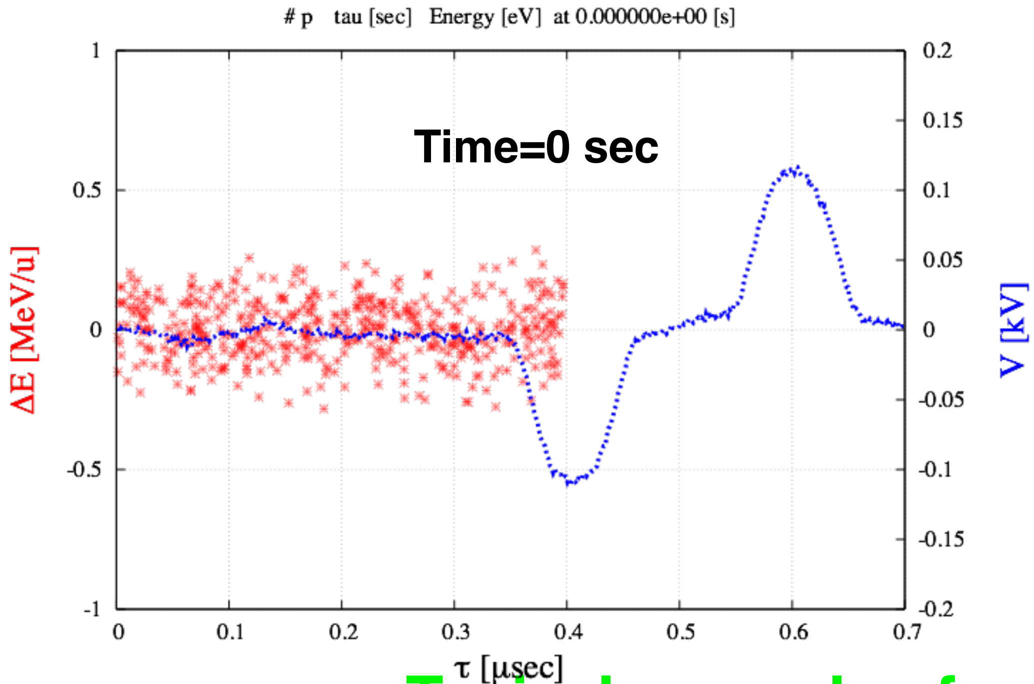
Typical example of particle distribution Ie=0.3 A

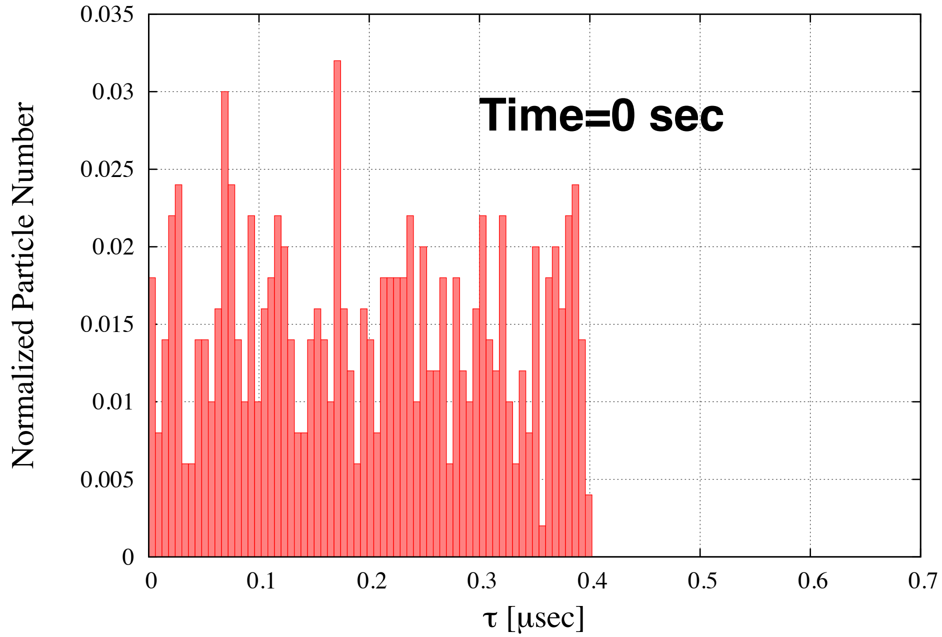




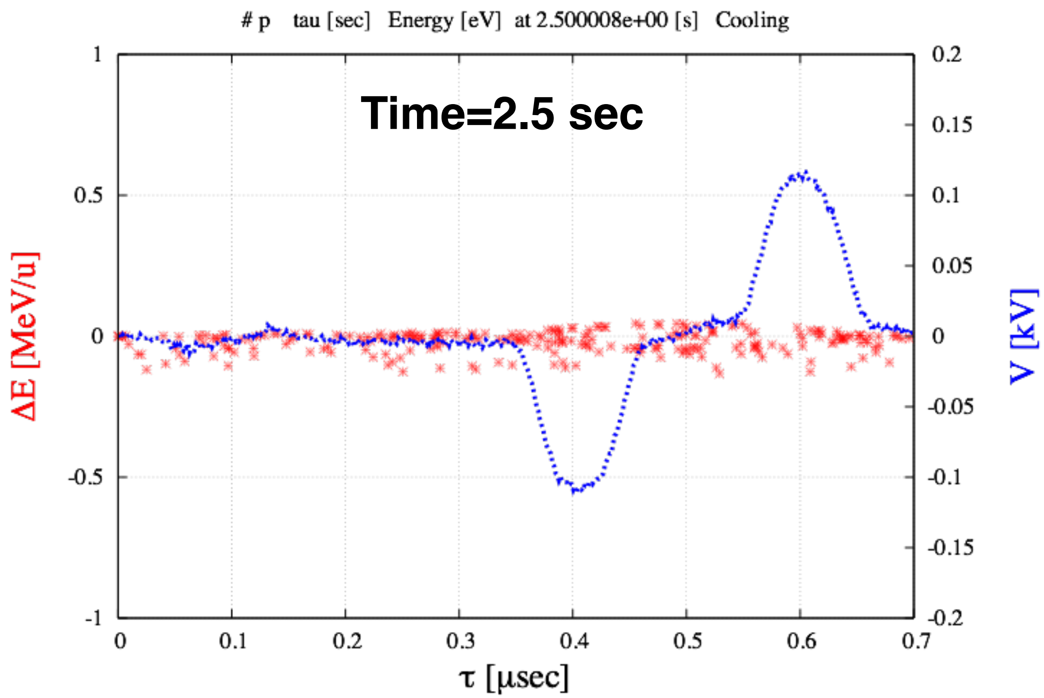
Phase Space Mapping

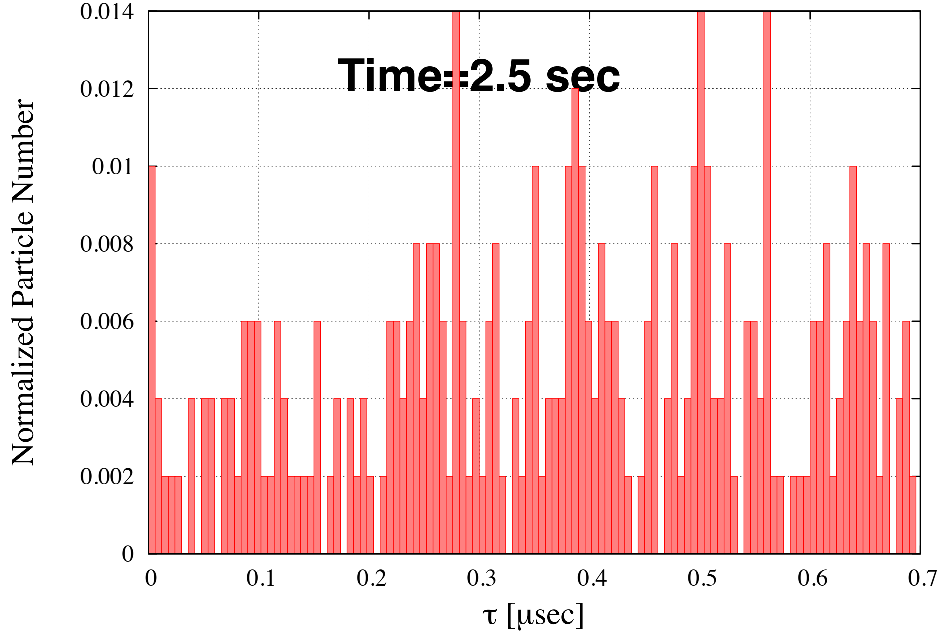
Particle Distribution along the Ring

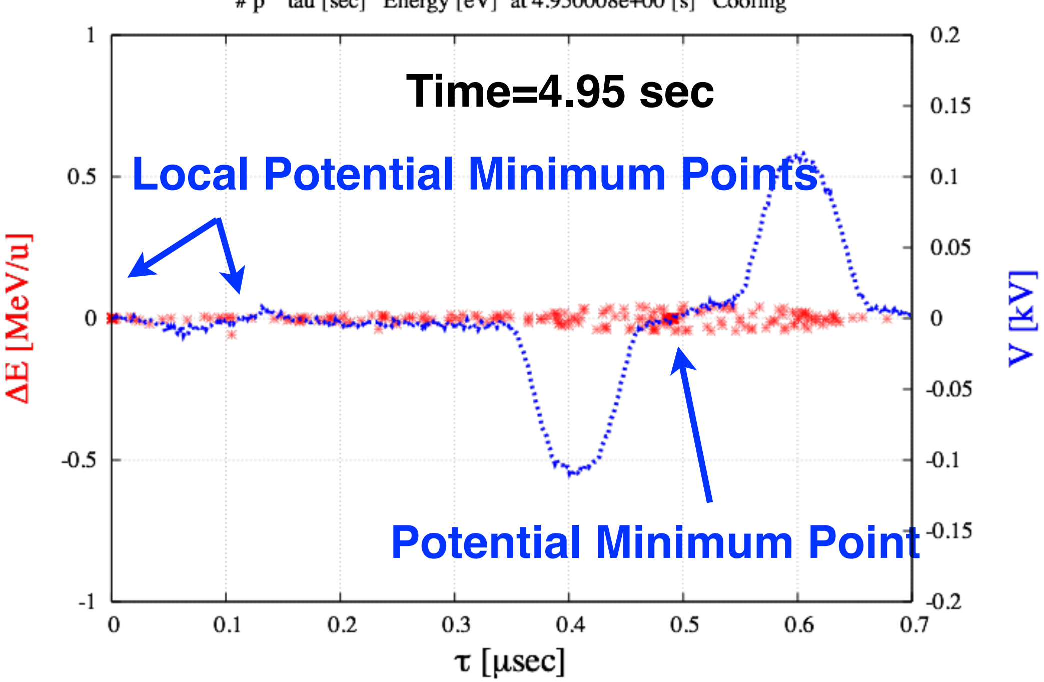


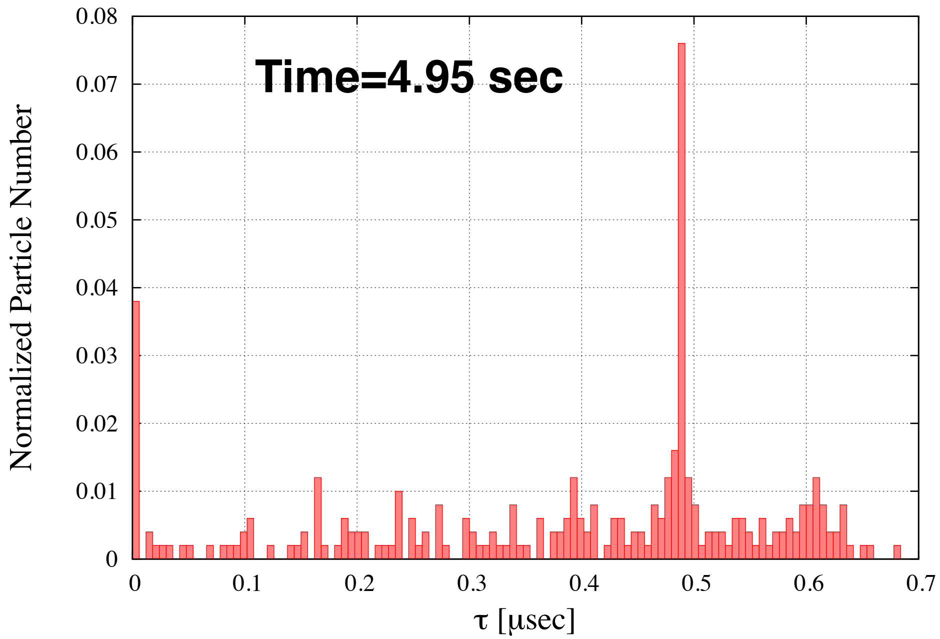


Typical example of particle distribution Ie=0.05 A

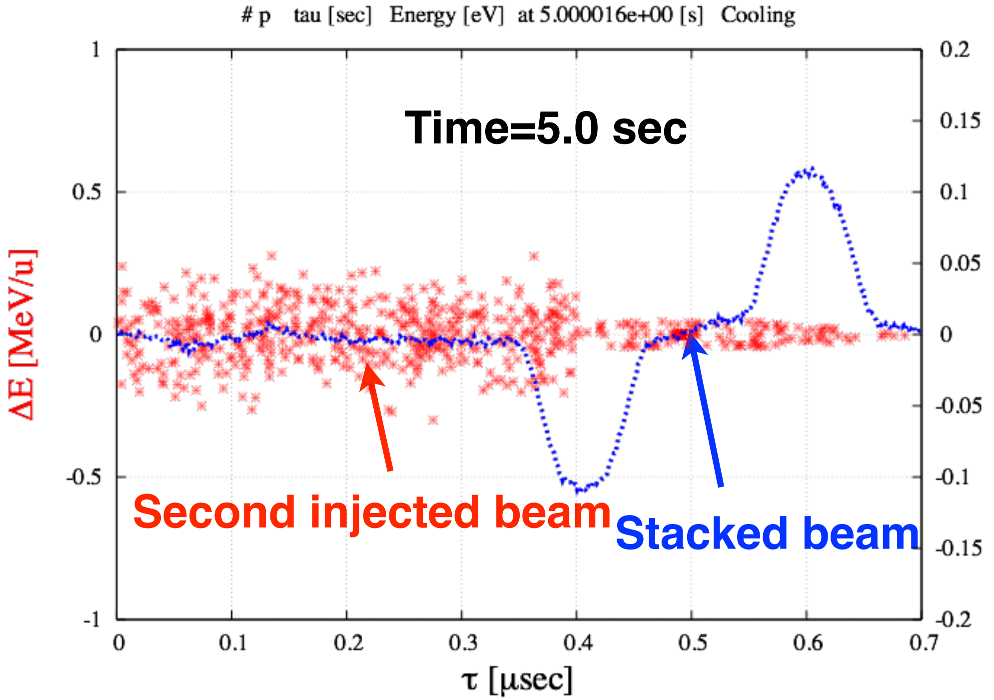


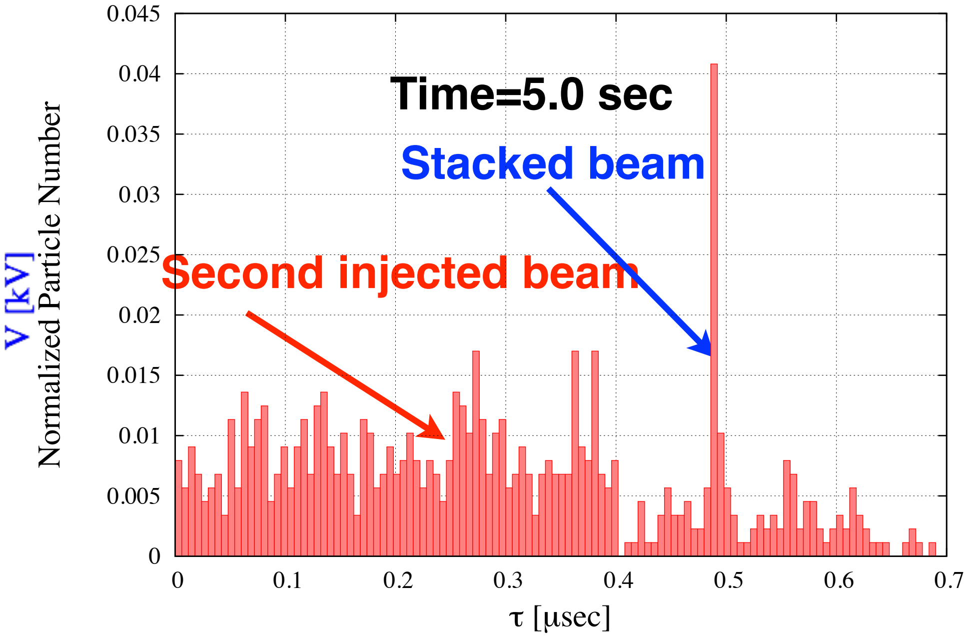






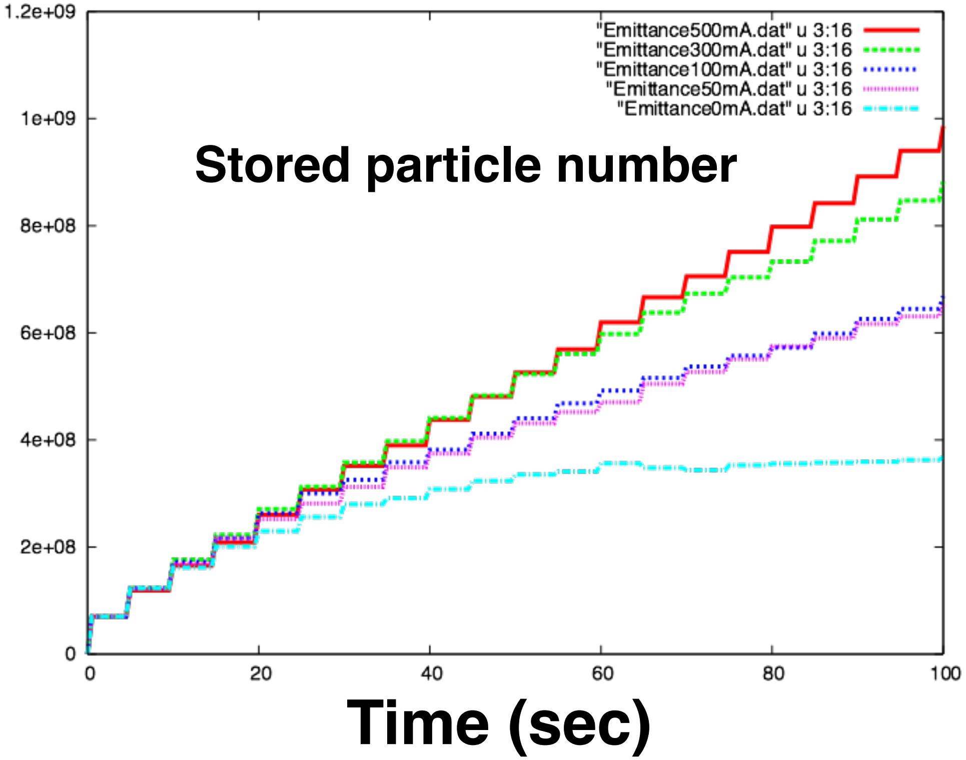
Typical example of particle distribution Ie=0.05 A

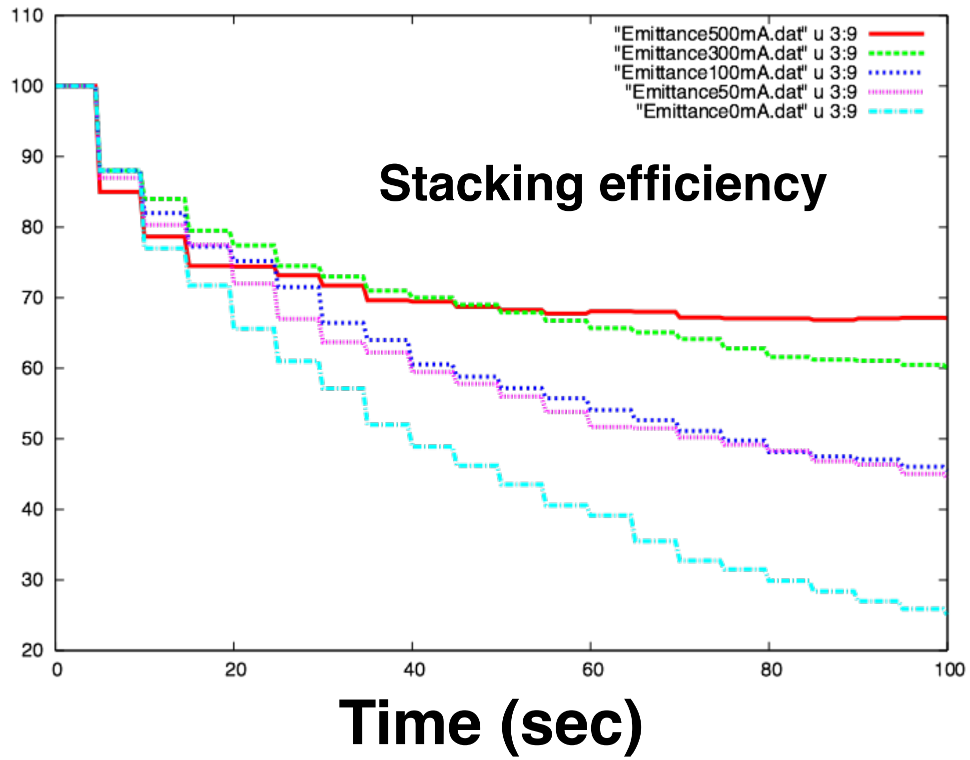


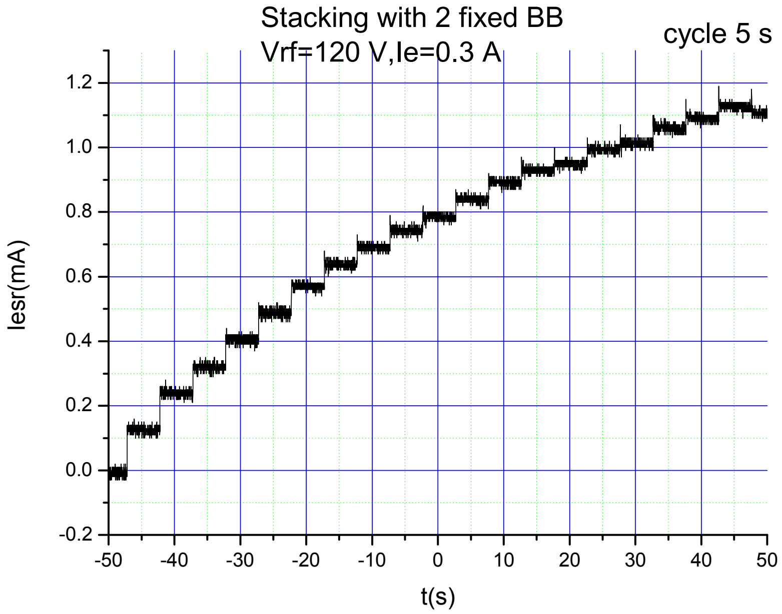


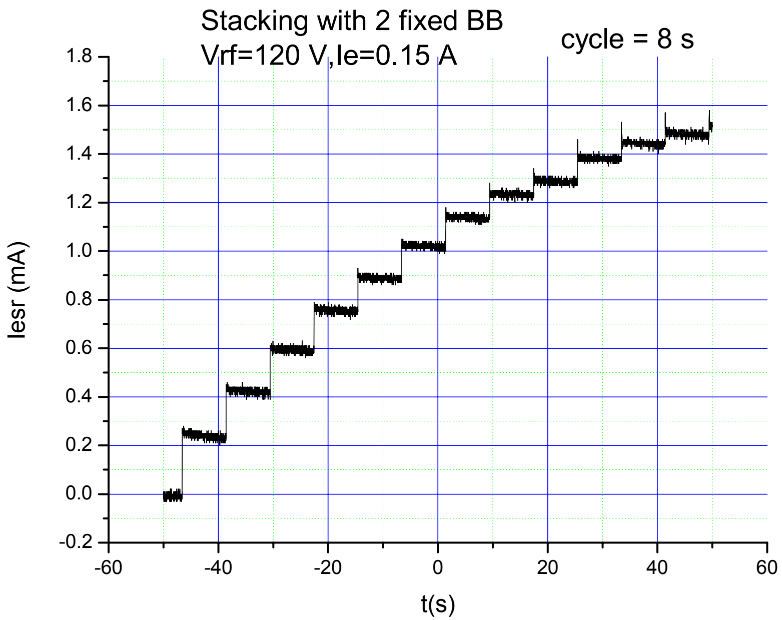
Stacked Particle Number and Stacking Efficiency for Various Cooling Current

Red: 500 mA
Green: 300 mA
Blue: 100 mA
Pink: 50 mA
Light blue: 0 mA









GSI ESR beam stacking experiment with barrier voltages assisted by electron cooling Ie=0.3A (not clear)

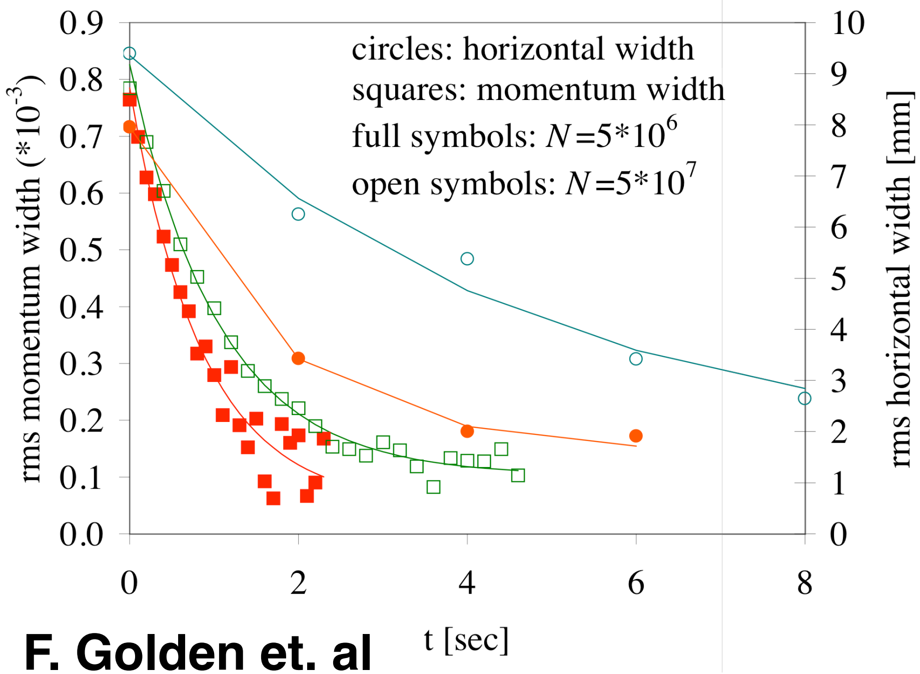
124Xe54+, 154MeV/u

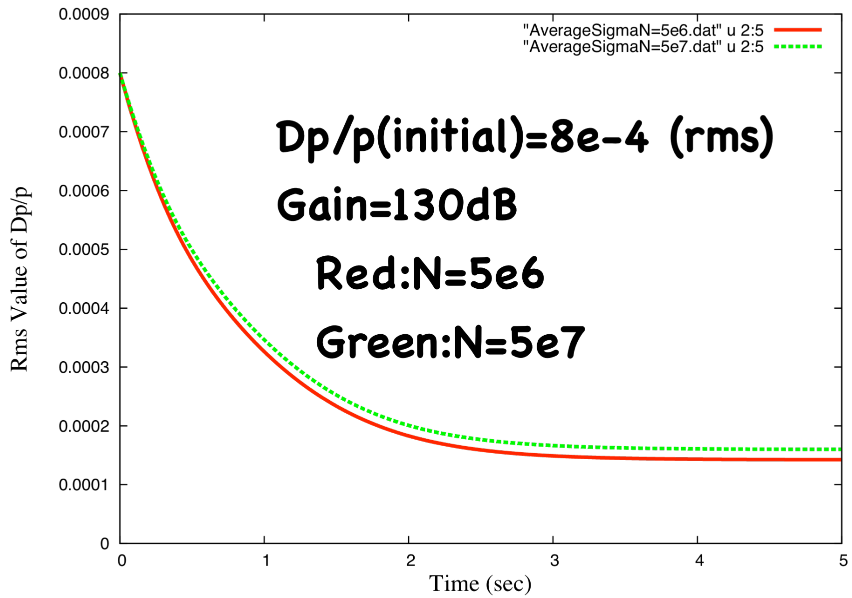
Parameters of Stochastic Cooling and Barrier Pulse at ESR for POP Experiment

Particle: 40Ar18+, 0.4 GeV/u, Gamma=1.426, Beta=0.713
Ring circumference: 108.36 m, Revolution Period=500 nsec
Number of injected particles from SIS18: 5e6 ions/shot.
Injected momentum spread : 5.0e-4 (1 sigma)
Injected bunch length : 150 nsec (Uniform)
Ring slipping factor: 0.309
Time of flight from PU to Kicker: 0.253e-6 sec
Dispersion at PU: 4.0m, Dispersion at Kicker=4.0 m
(Palmer stochastic cooling method)
Band width: 0.9-1.7 GHz
Number of PU, and Kicker: 8
Pickup Impedance: 50 Ohm
Gain: 90-130 dB.
Atmospheric Temperature: 300 K, Noise Temperature: 40 K
BB Voltage : 0.12 kV
BB frequency: 5 MHz (T=200 nsec) for Fixed barrier Case
10 MHz (T=100 nsec) for Moving barrier case
Injection Kicker Pulse Width: 200~300 nsec
Transverse emittance (rms) : 1.25 Pi mm.mrad (constant)

Proof Of Principle, POP Experiment at ESR

Stochastic Cooling Experiments and Simulation





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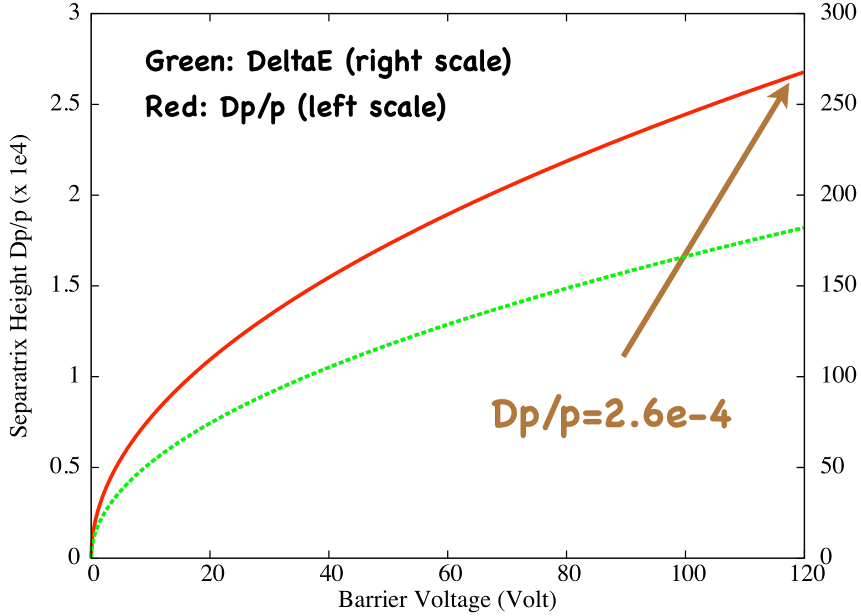
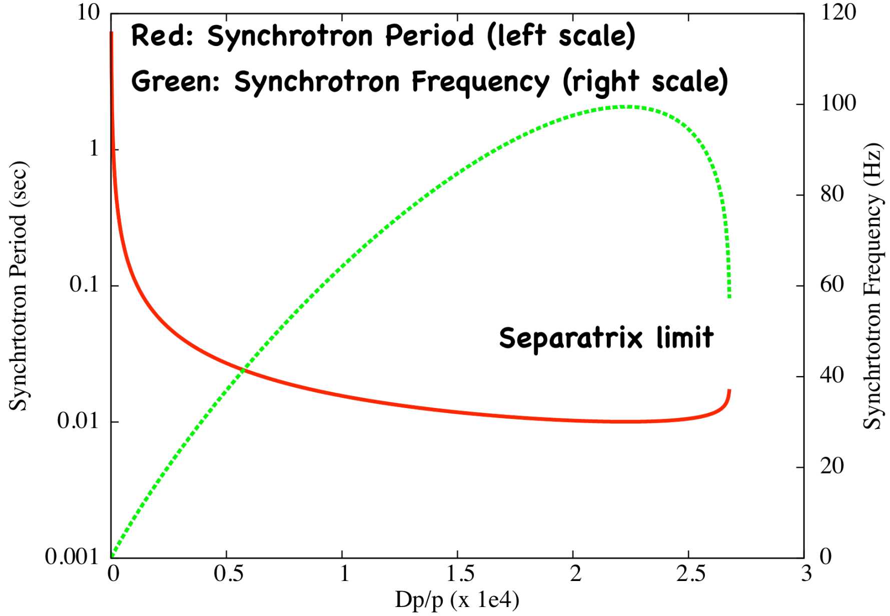
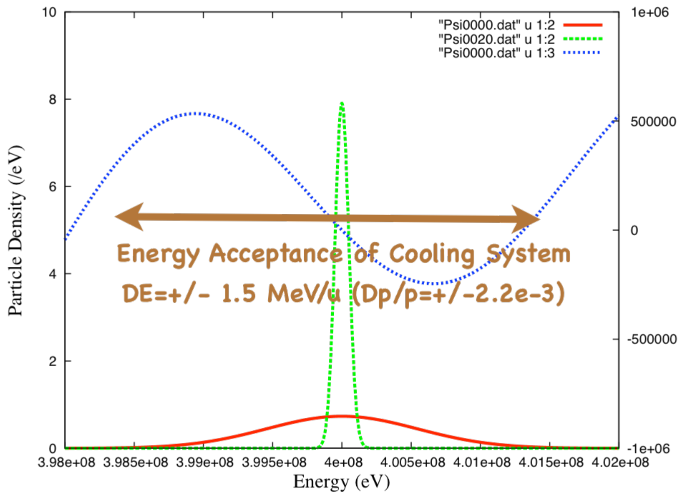
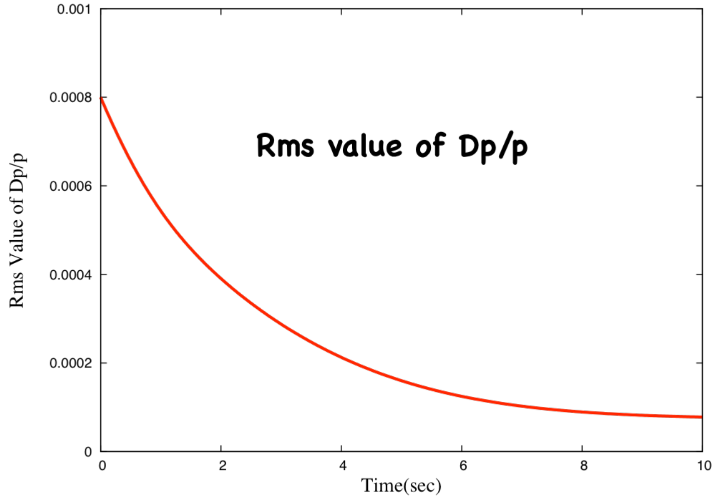
The experimental results of stochastic cooling of 390 MeV/u beam (left). The square full symbol (red) shows the evolution of momentum spread (rms) of N=5e6 while green open symbols the particle number N=5e7. The right panel shows the simulation results.

Separatrix Height and Stochastic Cooling in ESR



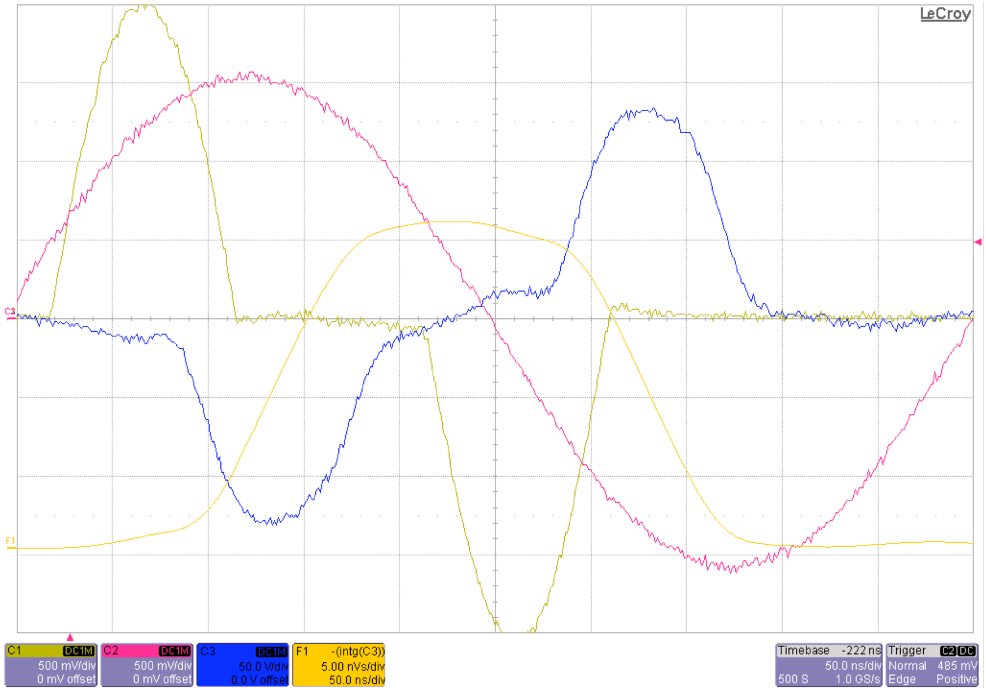


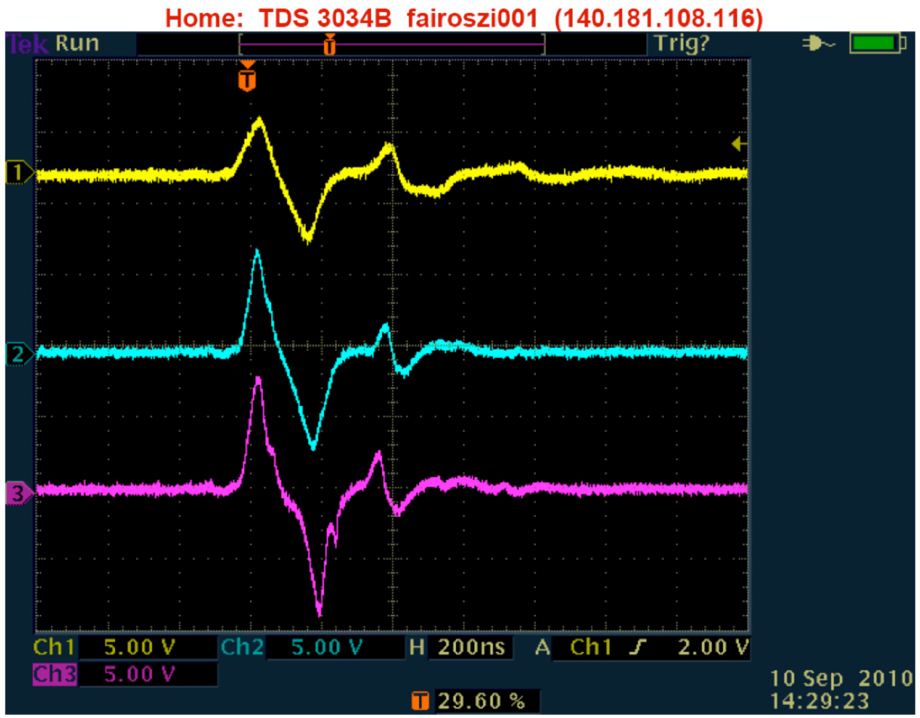




The calculated evolution of stochastic cooling of 400 MeV/u, N=1e8. The initial Dp/p=5e-4 (rms). The initial particle distribution is illustrated in red line in the left figure and the distribution at after 10 sec cooling is in green line. The energy acceptance of cooling system is +/-1.5 MeV/u (Dp/p=+/-2.2e-3) as given in blue color (left scale). The evolution of Dp/p is given in the right figure.

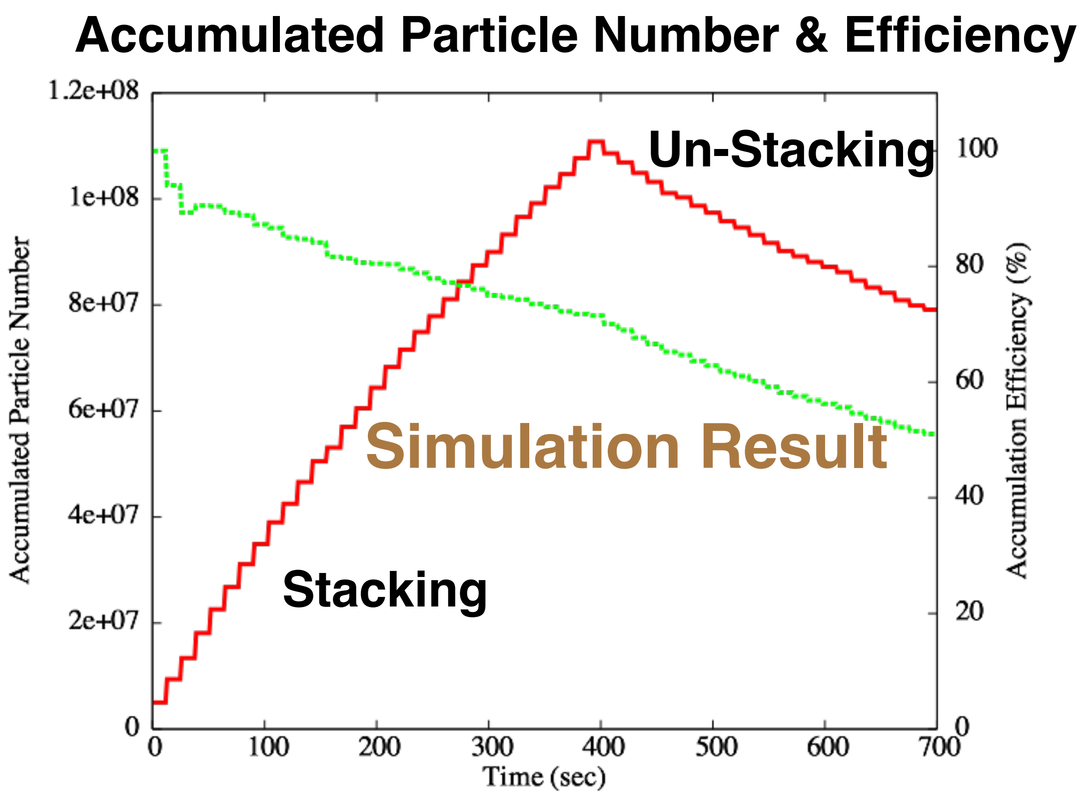
Barrier Voltage and Kicker Magnetic Field

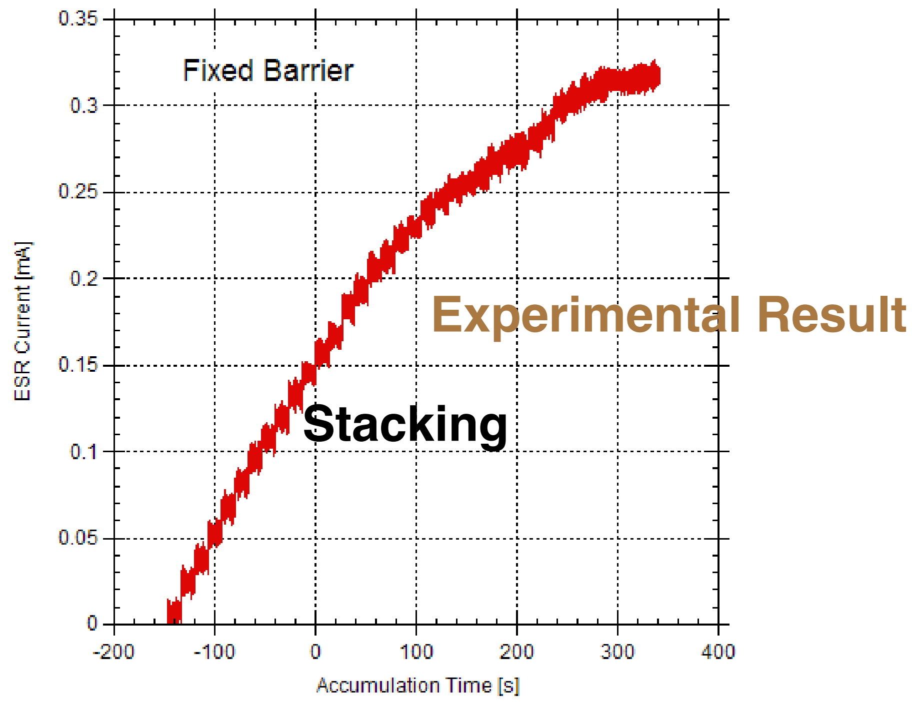




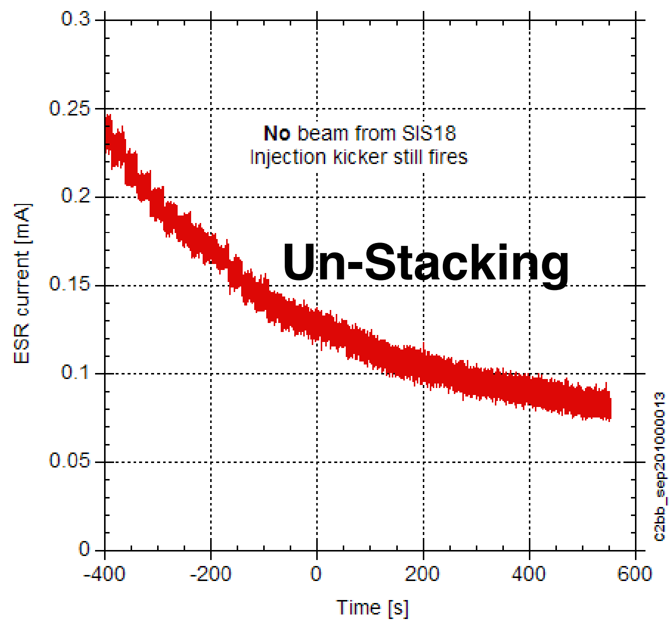
The left panel is the barrier voltage measured in the cavity (blue line) and the potential (orange line). In the right figure the measured derivative of magnetic filed of fast kicker magnetic field are given. The excited field continues as long as 300 nsec.

Fixed Barrier Case Vbb=120 V, Stochastic Cooling Gain=120dB

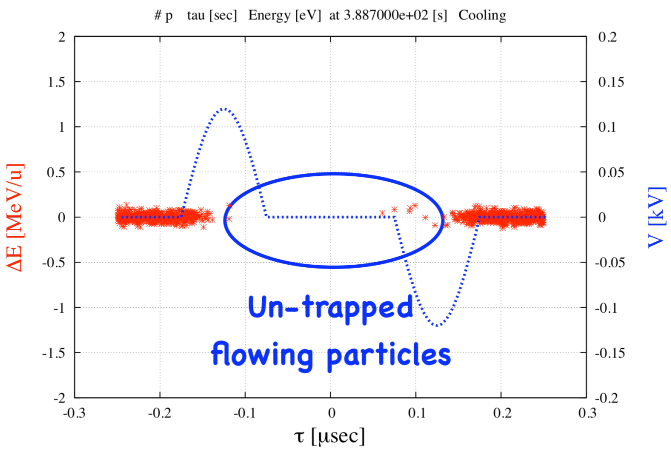


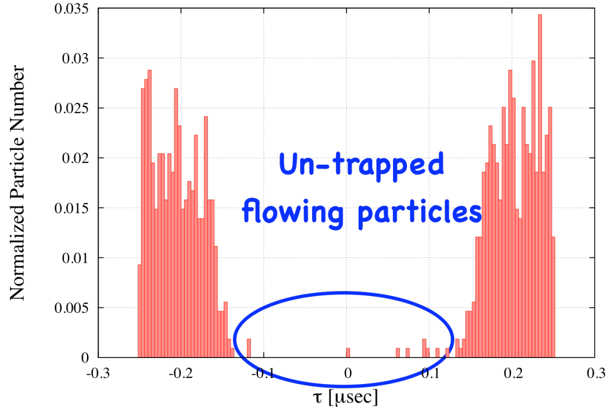


Un-Stacking
- No Beam injection but Kicker is fired -

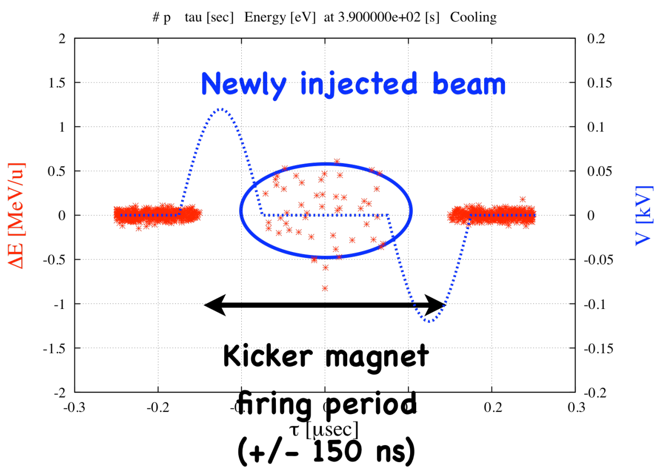


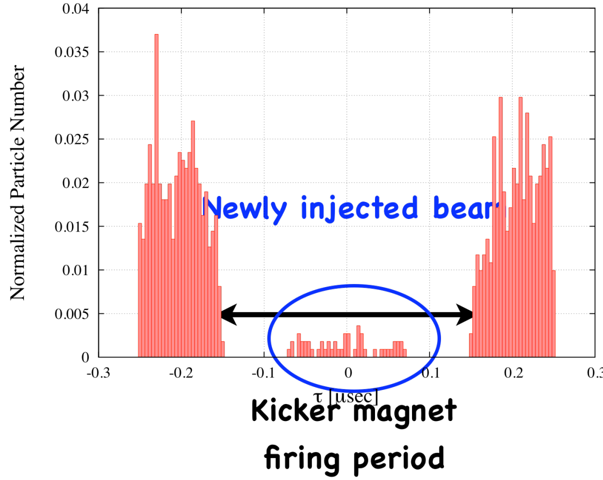
Just before the 30th injection (Time=389 sec)





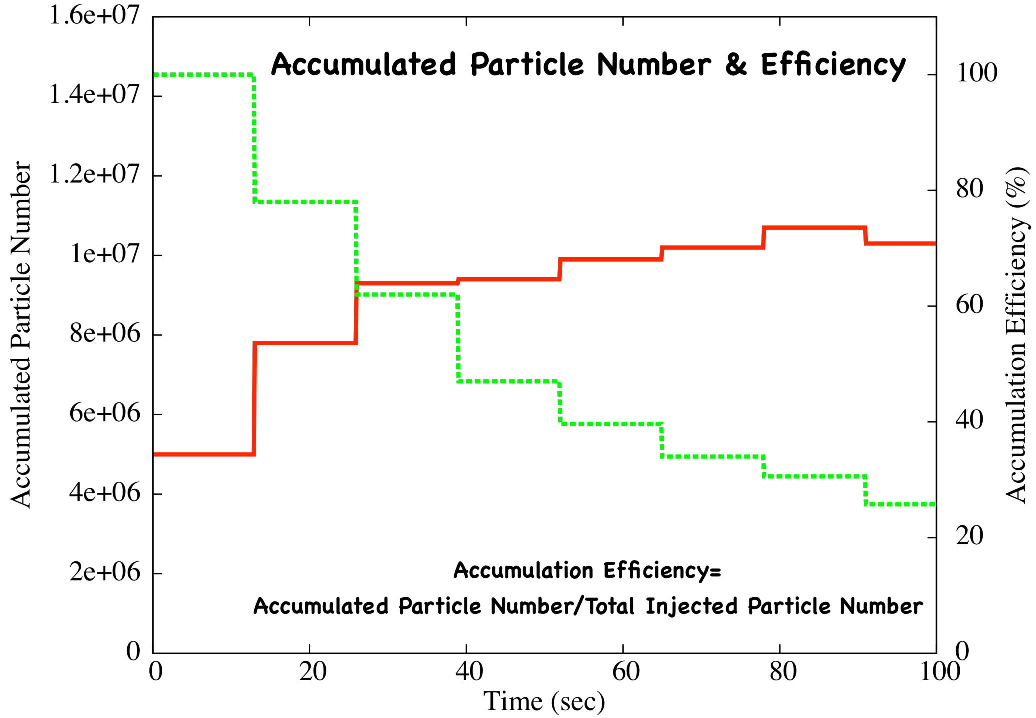
Just after the 30th injection (Time=390 sec)





Particle distribution just before the 30th injection and just after 30th injection.The kicker magnetic field is assumed as +/- 150 nsec, and the un-trapped flowing particles in the time range of the fast kicker magnetic field are kicked out and lost.

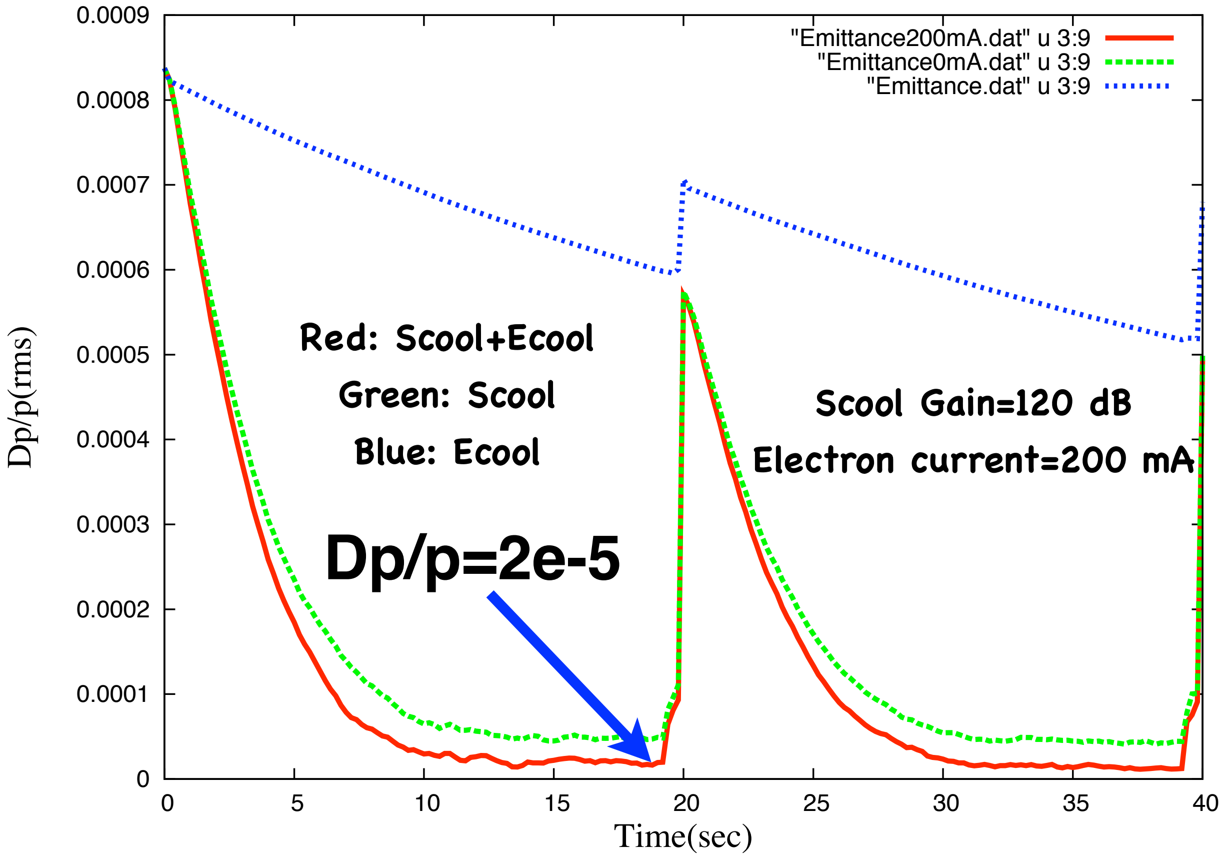
Moving Barrier Case Vbb=120 V, Stochastic Cooling Gain=120dB



The accumulated particle number and accumulation efficiency at the moving barrier operation. The barrier voltage is 120 Volt.

The accumulation efficiency was quite low. This is because of the fact that the barrier voltage is so small 120 Volt and the stochastic cooling force is not enough for the moving barrier method.

Momentum Cooling of Ar18+ 400 MeV/u Beam at ESR at Moving Barrier Case with Electron Cooling and Stochastic Cooling (Simulation)



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

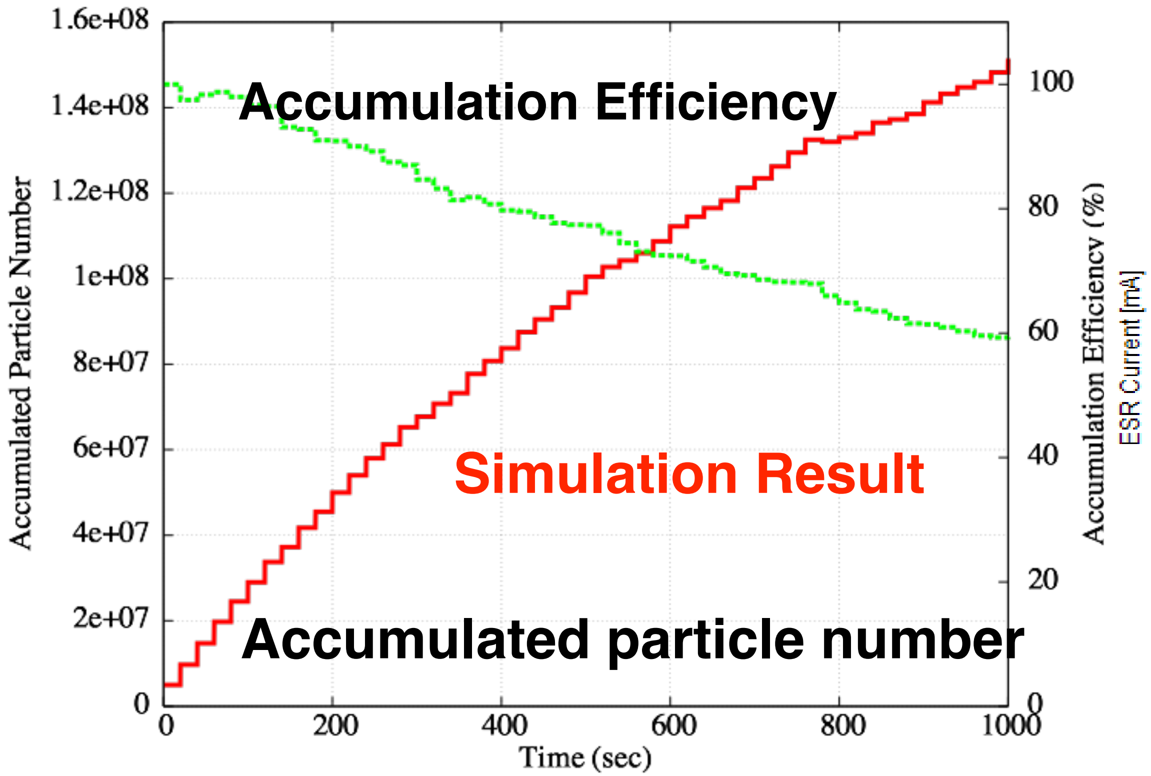
The evolution of Dp/p (rms) value during two cycles operation of moving barrier. The blue line shows the case of electron cooler alone, the green line the case of stochastic cooling alone and the red line the case of simultaneous use of electron cooler and the stochastic cooler.

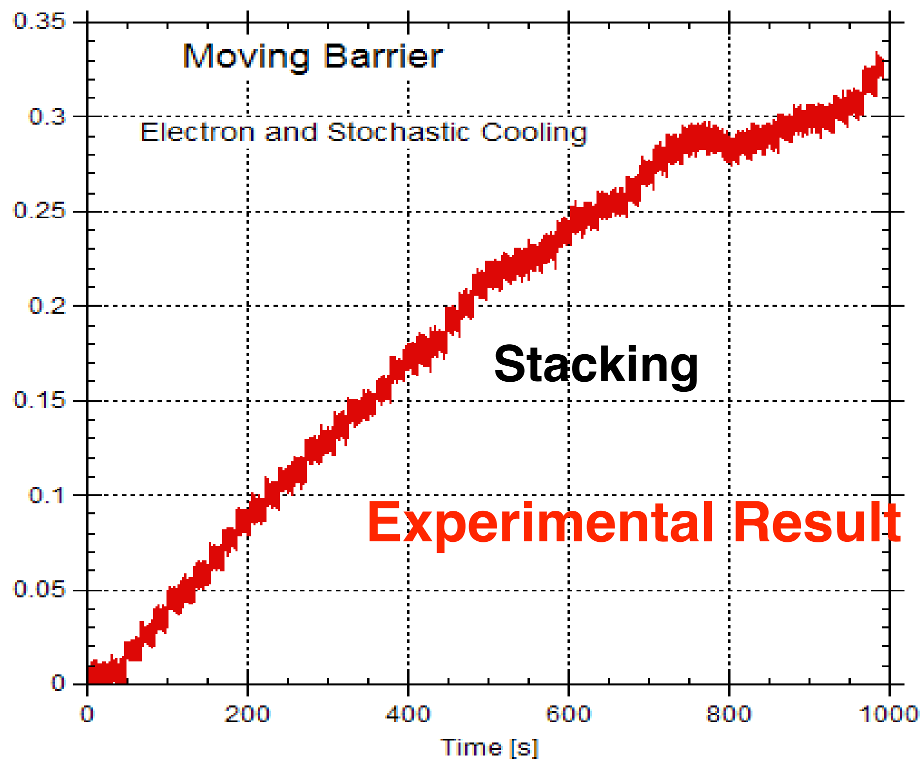
Proof Of Principle (POP) Experiment at ESR

400 MeV/u, Ar18+ from SIS18

Moving Barrier Case, Stochastic Cooling Gain=120dB

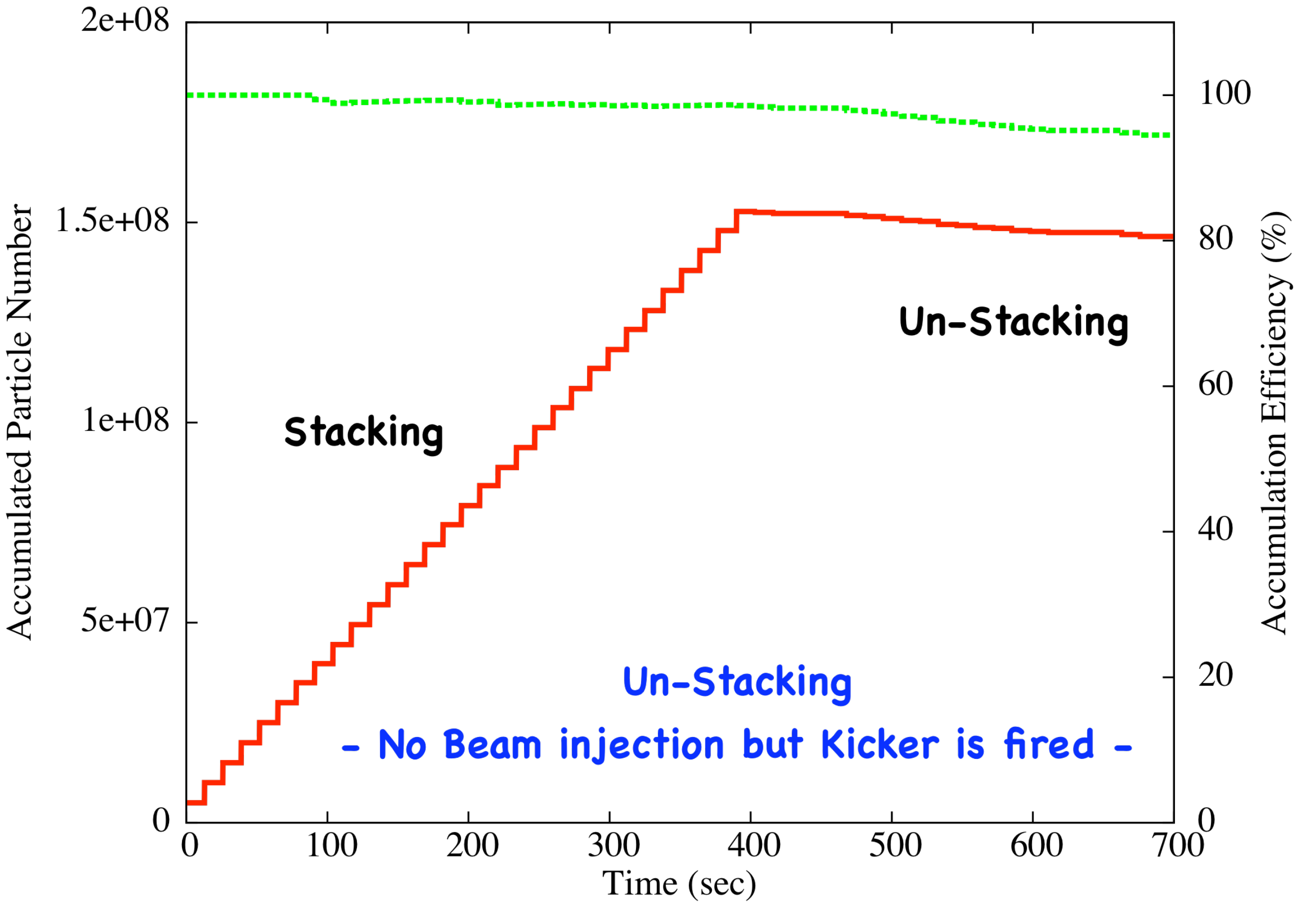
Vbb=120V, Ie=0.3A, Cycle time=20 sec





Accumulation Efficiency=Accumulated Particle Number/Total Injected Particle Number

Moving Barrier Accumulation with only stochastic cooling with BB voltage 2 kV at the ESR



Celebration of Success of POP Experiment
2010 September 9th at ESR Control Room
GSI, FZJ, JINR & CERN Collaboration

Spokesman: M. Steck

Beam Accumulation with Barrier Bucket and Stochastic Cooling System at NICA Collider

January 12, 2009

One solution to the question on
“ How do we inject and accumulate 2e10 ion beams in the Collider from the Nuclotron ?”
Injection Cycle= 10 sec (5 sec each for 1 Collider Ring)

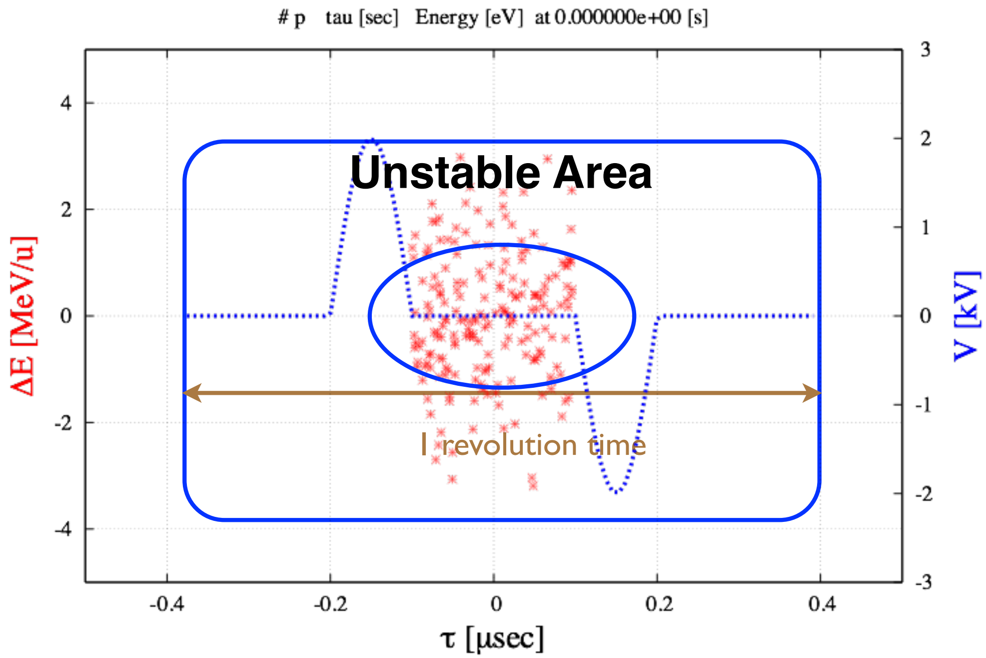
Parameters of Stochastic Cooling and Barrier Pulse at NICA Collider

1. Particle: 197Au79+, 3.5 GeV/u, Gamma=4.76, Beta=0.978
2. Ring circumference: 375 m
3. Number of injected particles from Nuclotron: 1e8 ions/bunch.
4. Injected momentum spread : 3.0e-4 (1 sigma)
5. Injected bunch length : 200 nsec (Uniform)
6. Ring slipping factor: 0.0232
7. Time of flight from PU to Kicker: 0.4 e-6 sec
8. Dispersion at PU: 5.0m, Dispersion at Kicker=0.0 m (Palmer stochastic cooling method)
9. Band width: 2-4 GHz
10. Number of PU, and Kicker=128
11. Pickup Impedance=50 Ohm
12. Gain=90 dB.
13. Atmospheric Temperature: 300 K, Noise Temperature=40 K
14. BB Voltage = 5 kV
15. BB frequency= 5 MHz (T=200 nsec)
16. Injection Kicker Pulse Width=400 nsec
17. Transverse emittance = 0.3 Pi mm.mrad (constant)

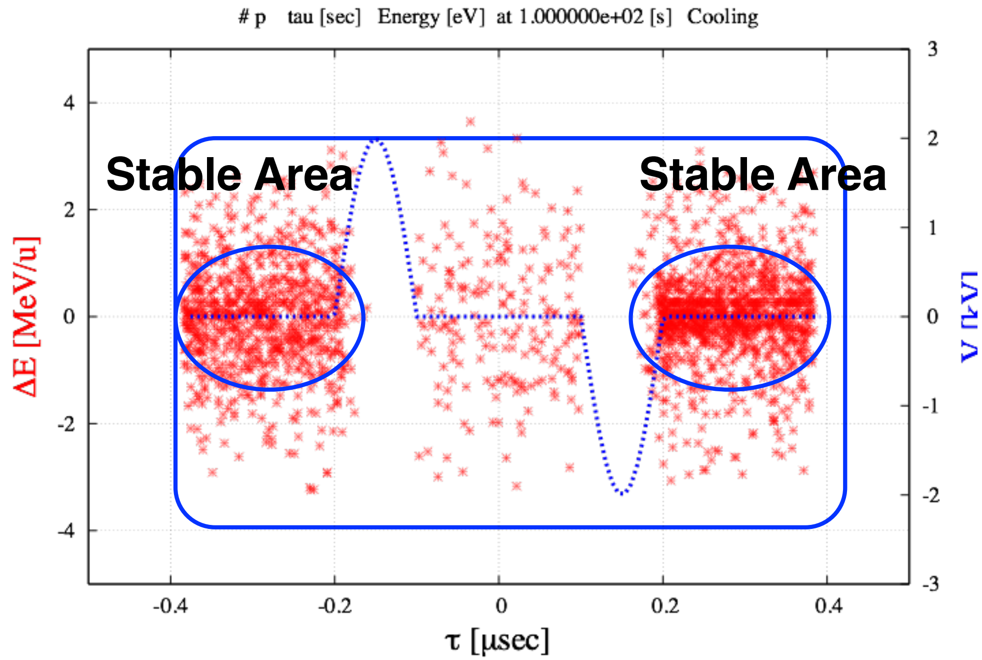
Fixed Barrier Case

Stochastic Cooling is applied to injected and stacked particles.

1st Injection

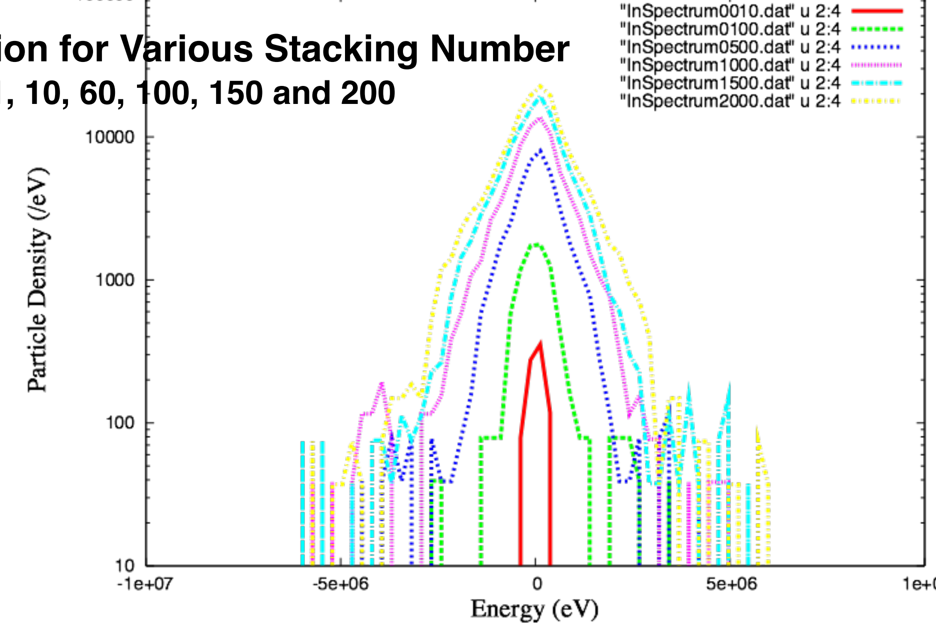


After 10 stacking

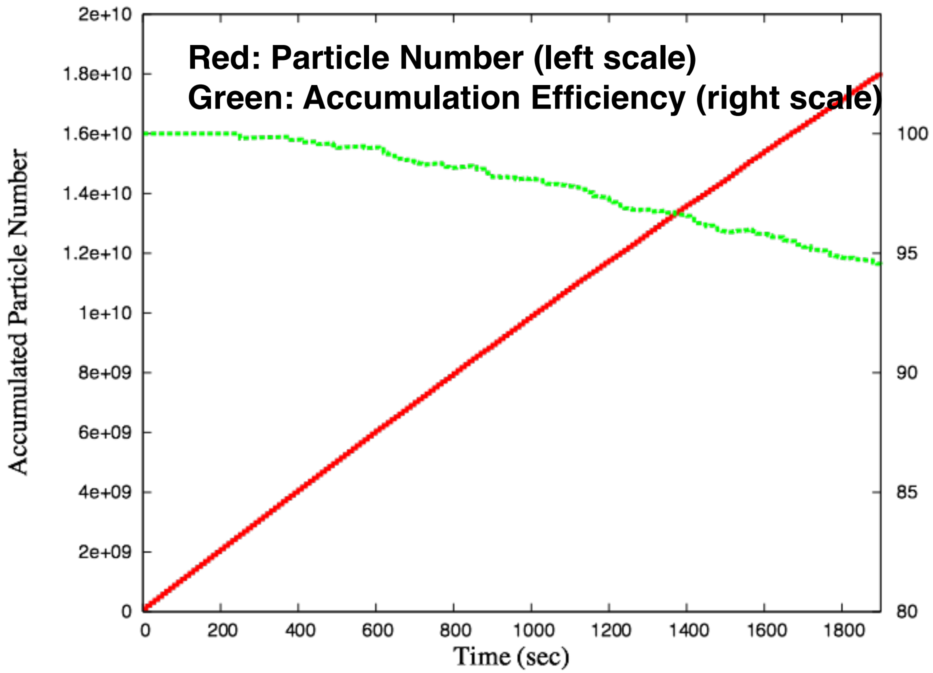


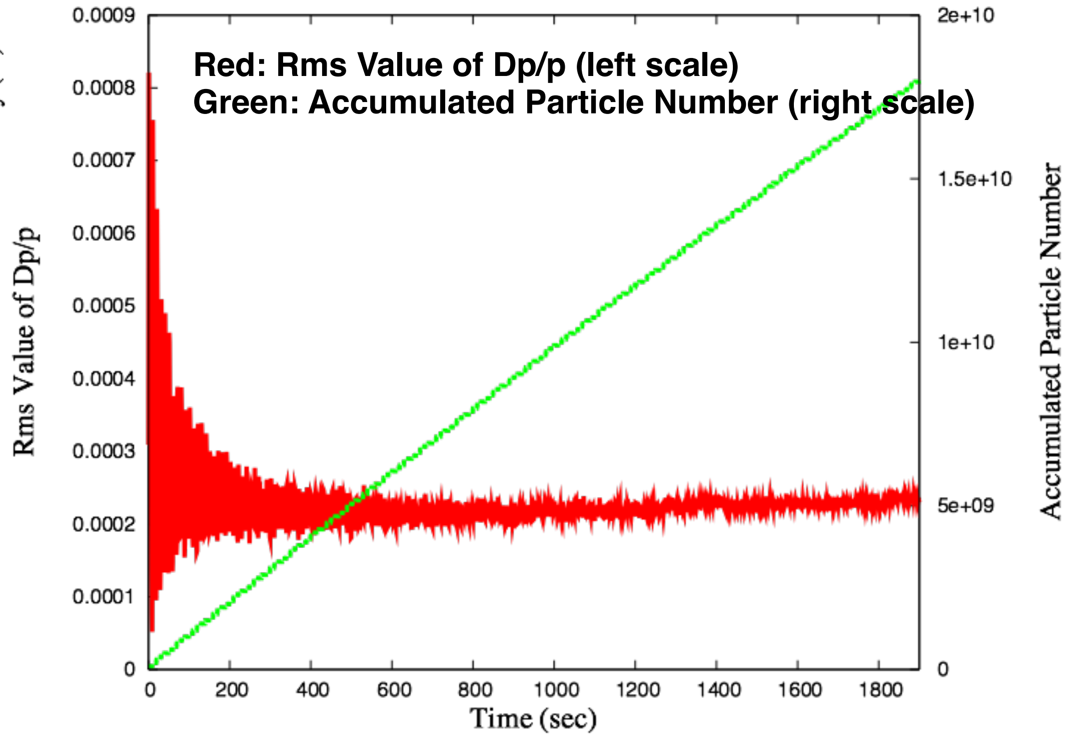
Red: Particles (energy left scale)
Blue: Barrier voltage (right scale)

Particle Distribution for Various Stacking Number
Stacking Number: 1, 10, 60, 100, 150 and 200



Accumulated Particle Number & Efficiency

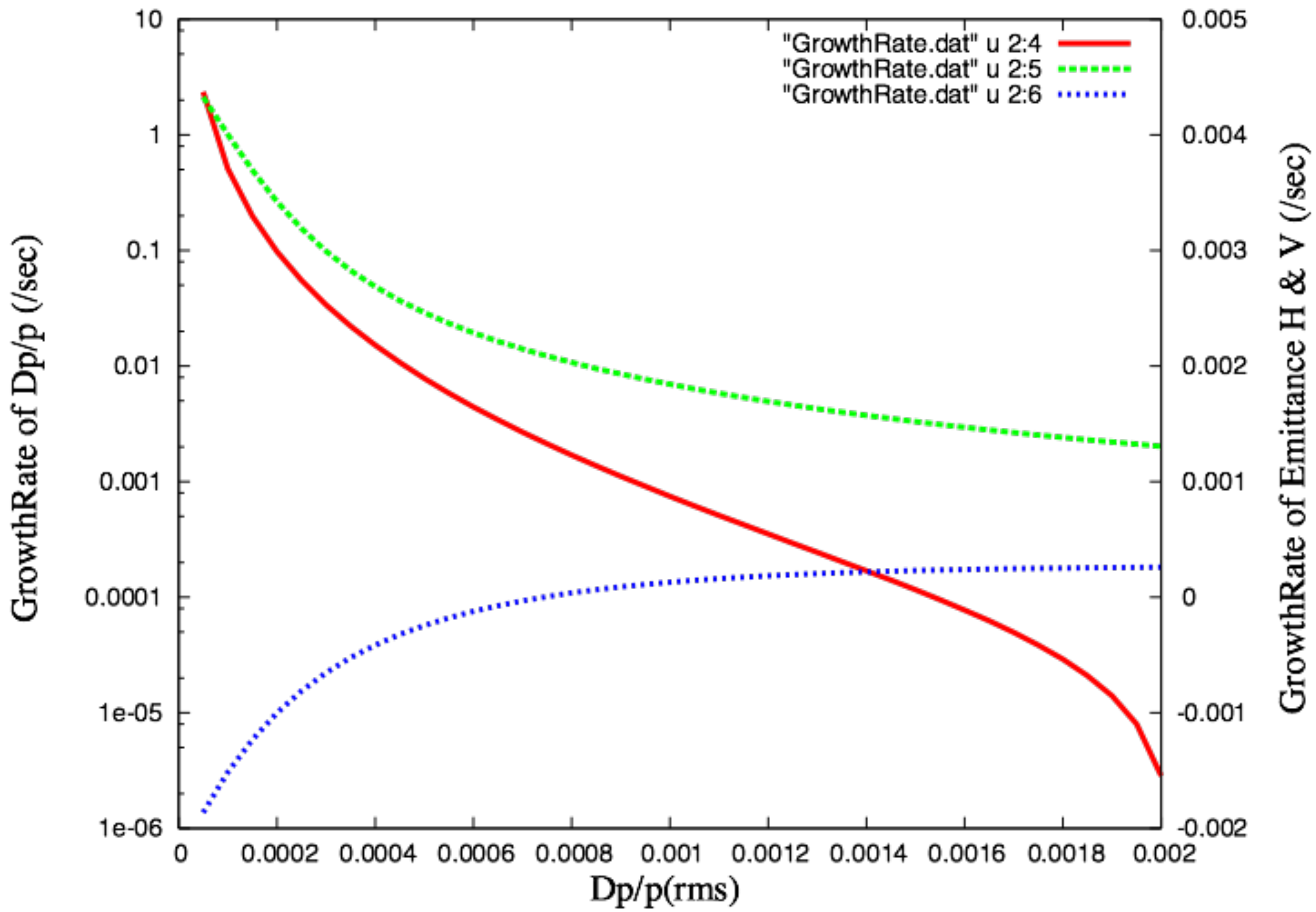




Accumulation Efficiency= Accumulated Particle Number/Total Injected Particle Number

IBS Growth Rates

IBS Growth Rate of Dp/p is calculated with Martini formulae and the result can be represented with the following curves. In the stochastic cooling/stacking calculation, IBS heating term is calculated at every computing cycle with use of these curve.



Dp/p (red, left scale)
Horizontal Emittance (green, right scale)
Vertical Emittance (blue, right scale)

Dp/p (rms value)

3.5 GeV/u, 197Au79+, N=2e10/ring, Coasting beam, Emittance=0.3 Pi e-6 m. rad. GrowthRate is inversely proportional to the bunch length and proportional to the number of particles in the bunch.

Heavy Ion Beam Accumulation in NICA Collider with Barrier Voltage and Electron Cooling

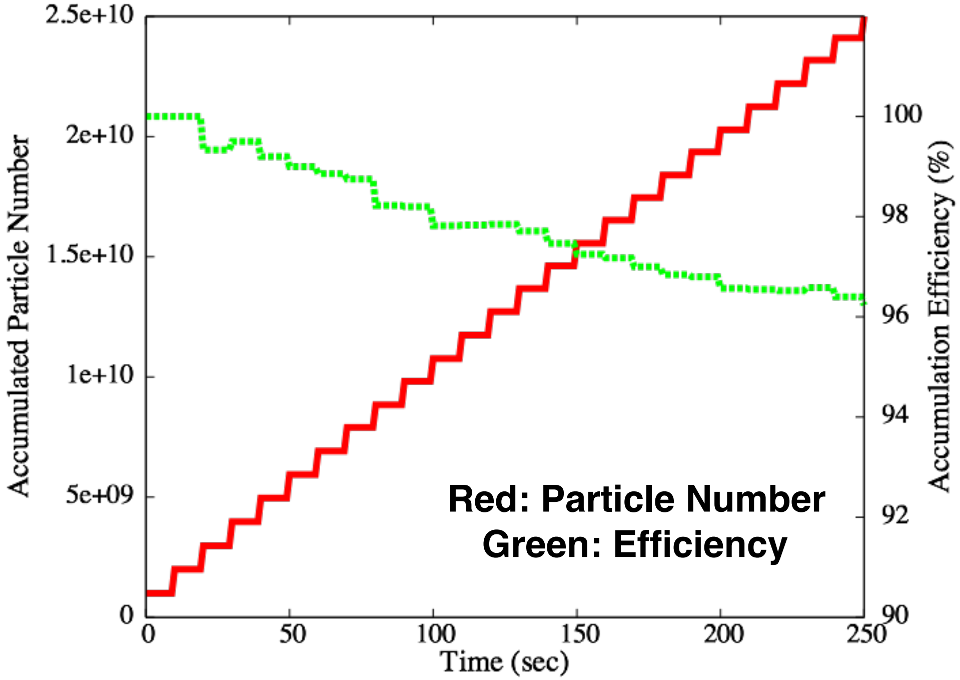
Ion: 197Au79+, 1.5 GeV/u, 2.5 GeV/u, 3.5 GeV/u
Cooler Length= 6 m
Electron current= 1 A
Electron Diameter= 2 cm
Effective Electron Temperature= 1 meV
Transverse Temperature= 1 eV
Longitudinal Magnetic Filed Strength= 1 kG
Beta function at Cooler= 16 m

Cooling Force: Parkomchuk empirical formulae

Case 1

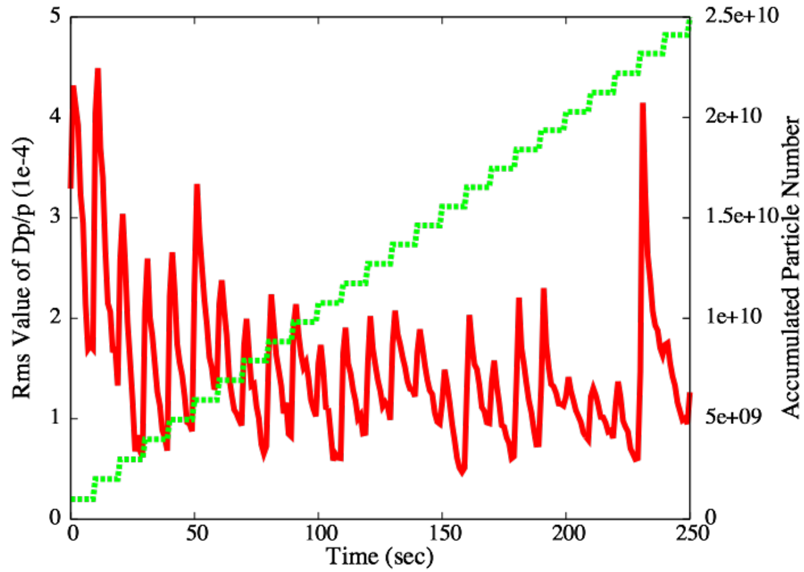
Ion=197Au79+, Energy=1.5 GeV/u, N=1e9/shot, Cycle time=10 sec
Ring Slipping Factor=0.1268, Dp/p(initial)=5e-4(rms) (Gaussian)

Accumulated Particle Number & Accumulation Efficiency

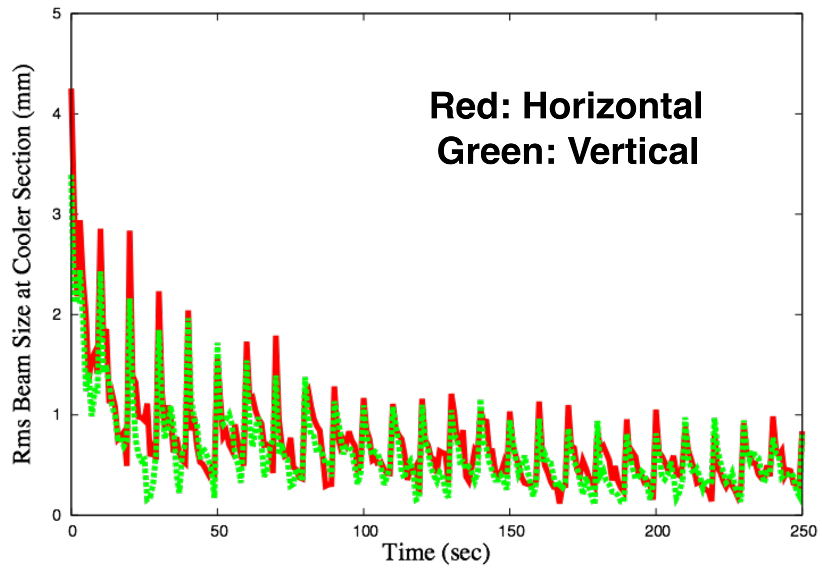


Accumulation Efficiency= Accumulated Particle Number/Total Injected Particle Number

Rms Dp/p & Particle Number



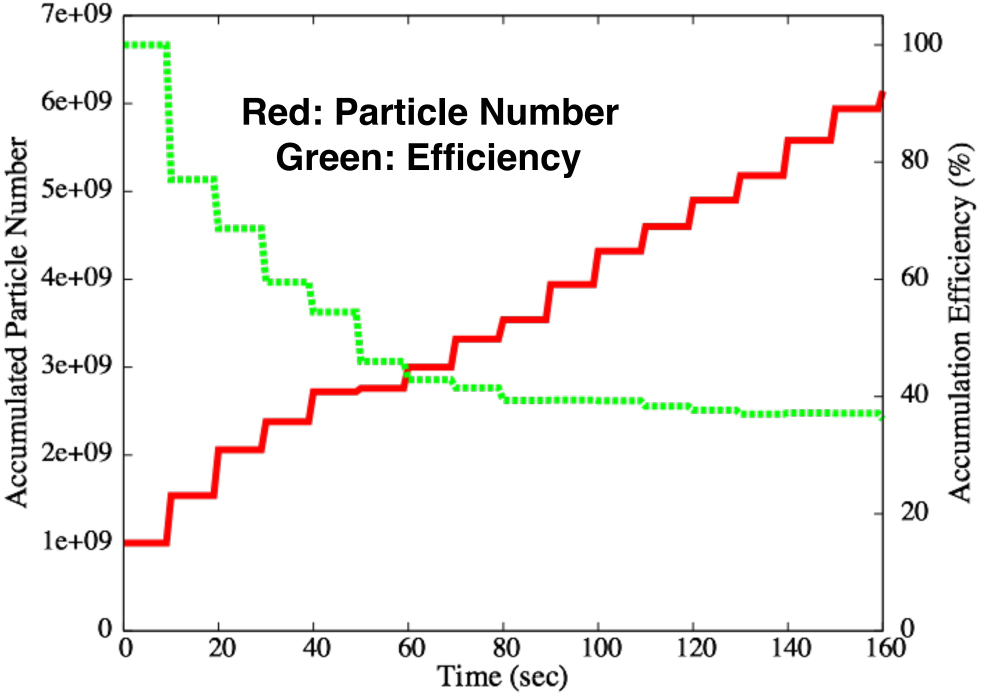
Rms Beam Size at Cooler Section



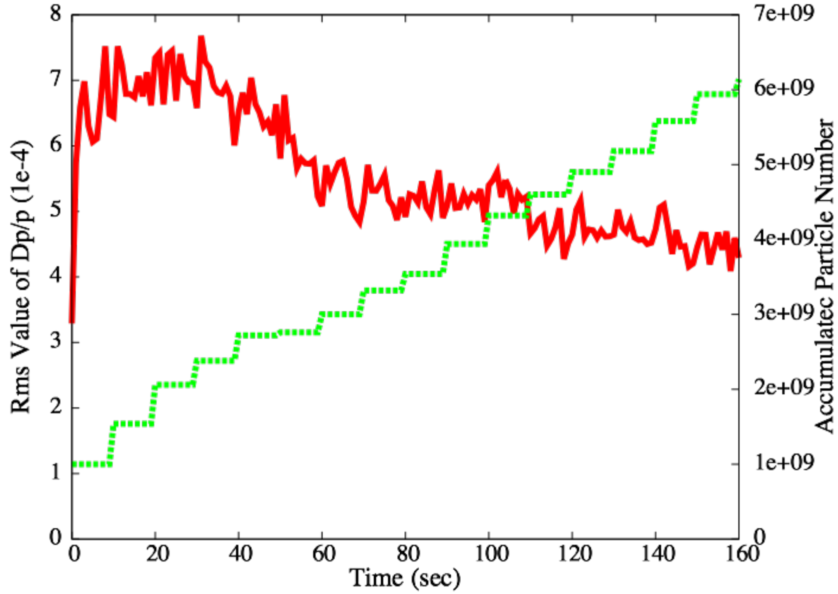
Case 2

Ion=197Au79+, Energy=3.5 GeV/u, N=1e9/shot, Cycle time=10 sec
RingSlippingFactor=0.0243, Dp/p(initial)=5e-4(rms) (Gaussian)

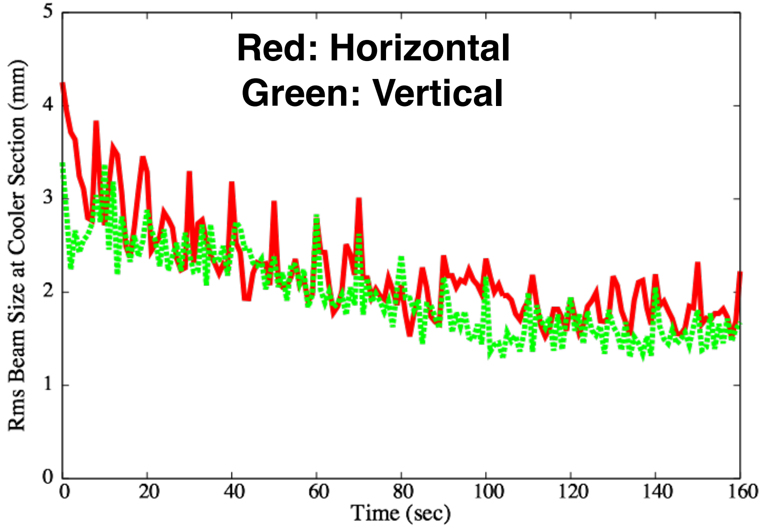
Accumulated Particle Number & Accumulation Efficiency



Rms Dp/p & Particle Number



Rms Beam Size at Cooler Section



Conclusion

1. It was proposed to use the method of moving barrier voltage combined with stochastic cooling for the 3 GeV antiproton beam accumulation in the HESR. The simulation shows that it is quite effective way to accumulate the antiproton beam up to N=1e10 with the cycle of 10 sec from the Collector Ring with high stacking efficiency more than 90 %.

2. This concept was confirmed by the POP experiment at the ESR of which the results were well reproduced by the simulation with multi-particle tracking code including the IBS diffusion effects.

3. At the NICA collider at JINR the fixed barrier method could be used for the accumulation of 2e10 Au ions from the injector synchrotron Nuclotron, with the stochastic cooling at the energy of 3.5 GeV/u and the electron cooling at the lower energy 1.5 ~ 2.0 GeV/u.

4. In the NICA collider, the accumulated ions have to be made of short bunches, say 20 bunches with rms bunch length of ~ 1 ns. The strong bunched beam cooling will be applied with large RF field voltage ~ 200 kV to produce such short bunch beam. During the colliding experiments, the diffusion effects due to the IBS should be compensated by the bunched beam stochastic cooling.