Beam Accumulation and Bunching with Cooling

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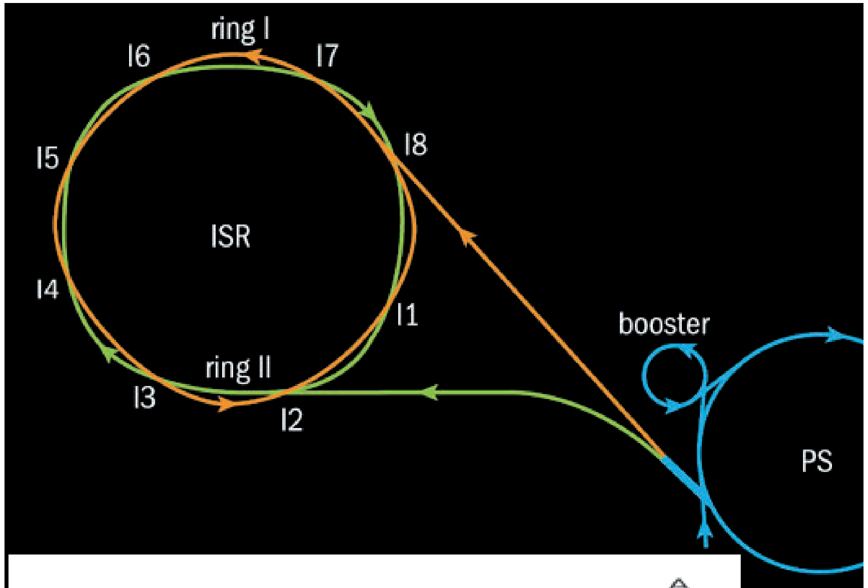
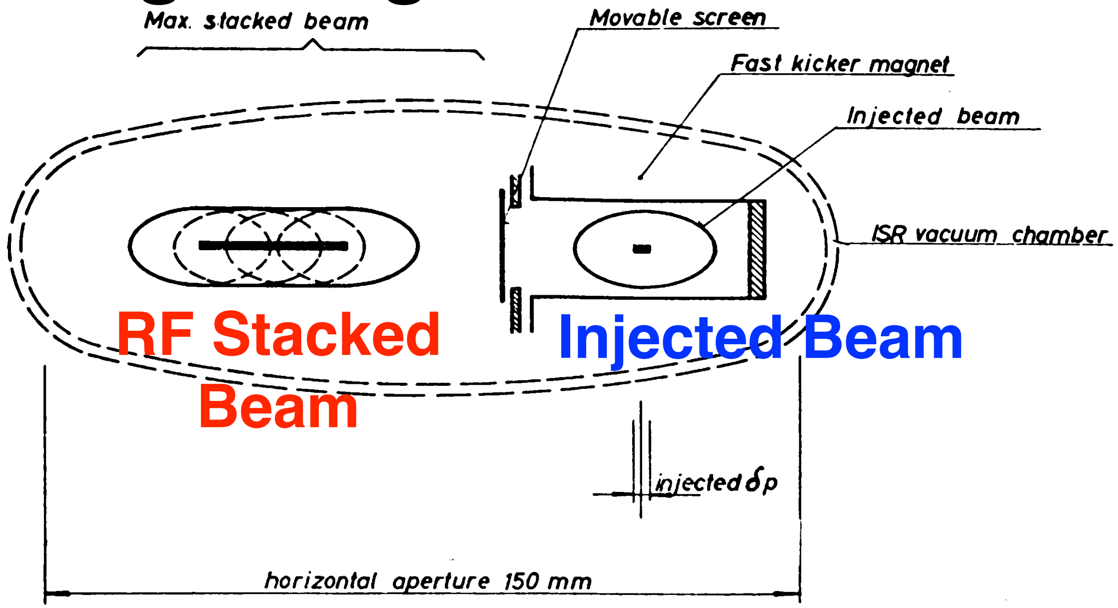
Outline

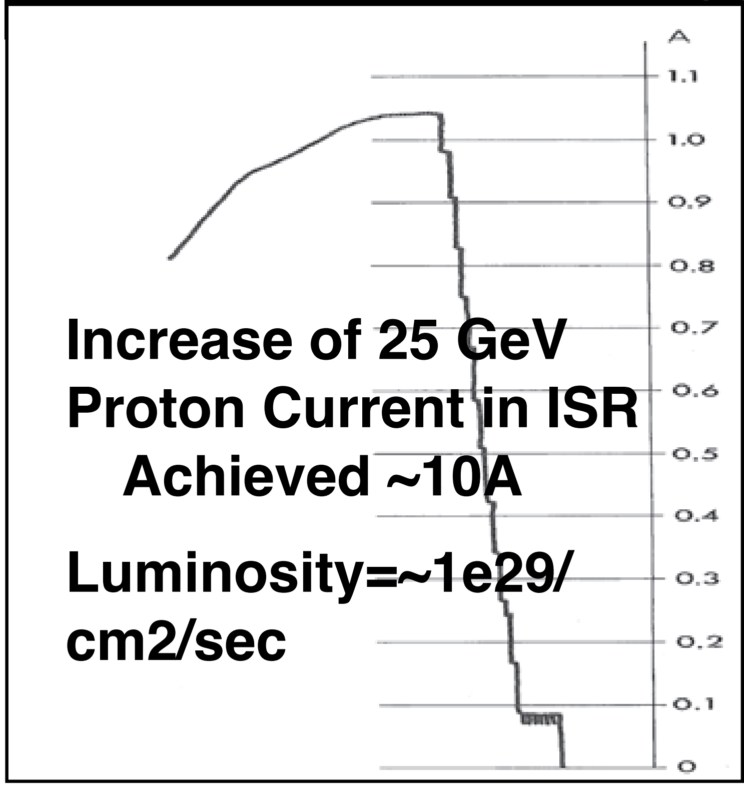
1. RF Stacking & Cooling, ISR and TARN
2. Stochastic Stacking, AA & RESR
3. Barrier Bucket Accumulation, ESR, HESR & NICA
4. Bunching, COSY & NICA
5. Summary & Outlook

ISR: Intersecting Storage Ring 1971-1983





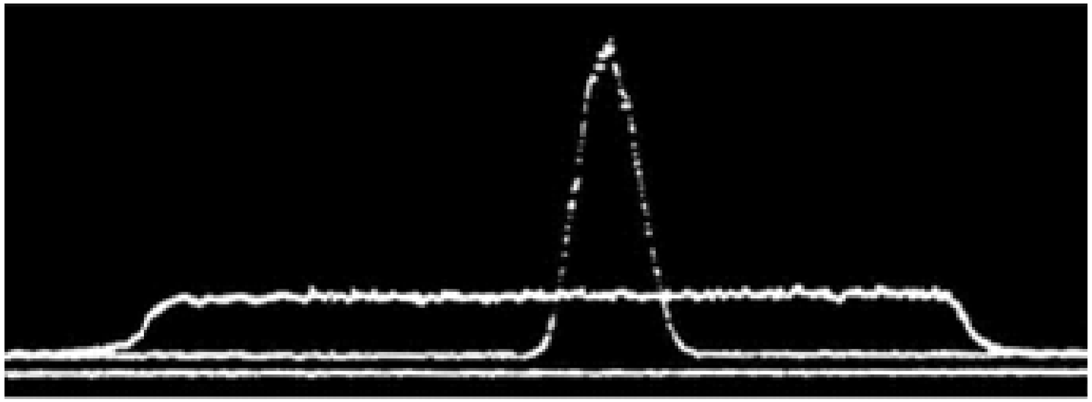
Cross Sectional View of
ISR Vaccum Chamber



Increase of 25 GeV
Proton Current in ISR
Achieved ~10A

Luminosity=~1e29/
cm2/sec

← Time



1.7 GeV/c Proton Beam, Momentum
Stochastic Cooling at ICE (1977-78)

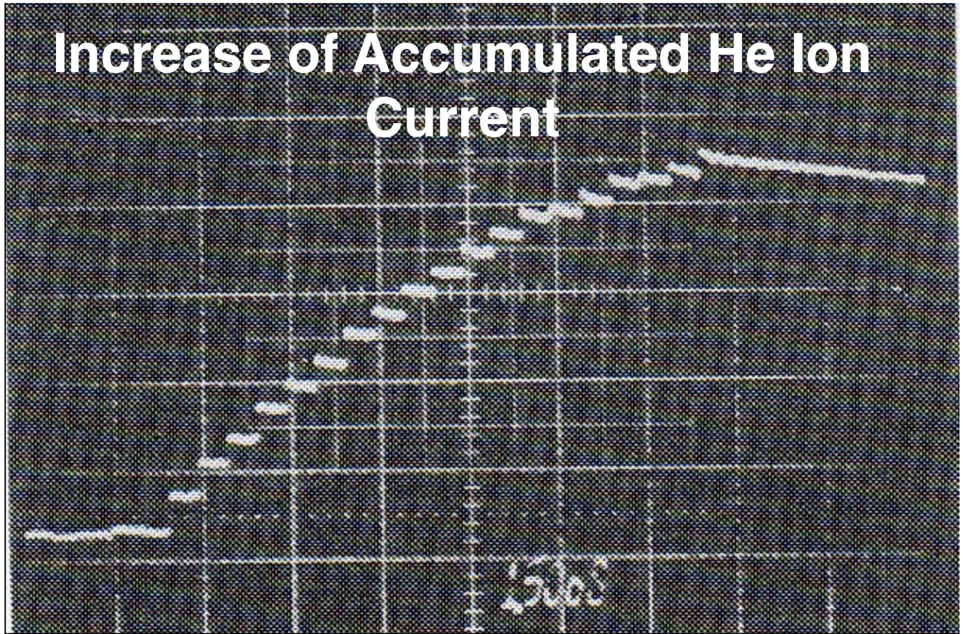
TARN (Test Accumulation Ring for NUMATRON) 1978-1985

Circumference : 31.7m

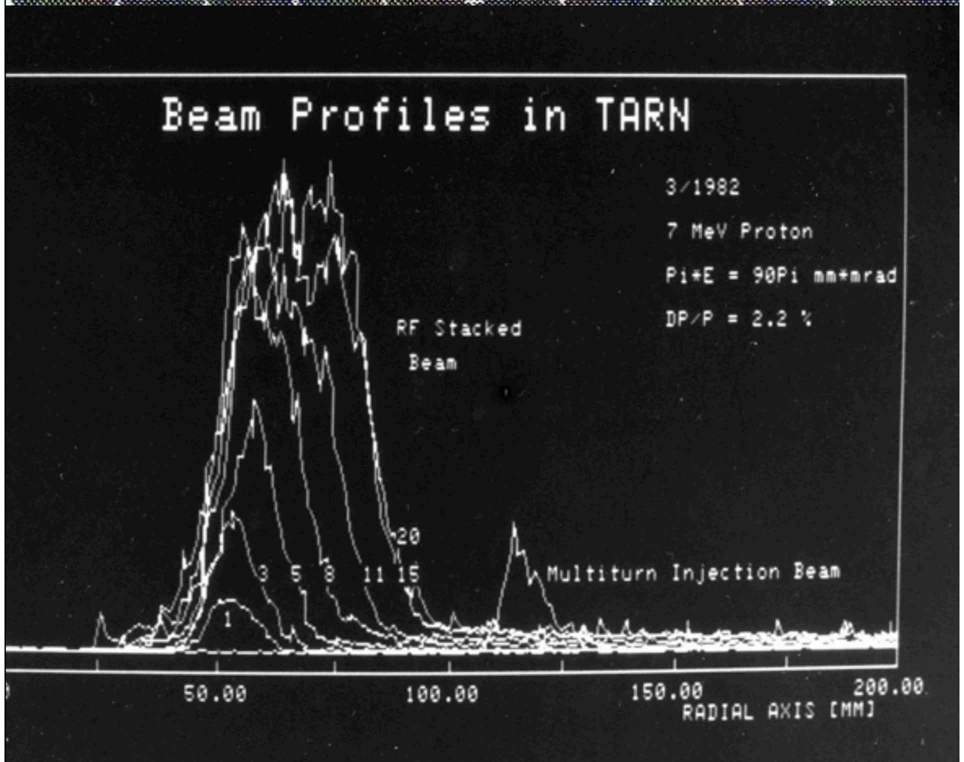
Ion energy : 7 MeV/u

Injector: SF cyclotron

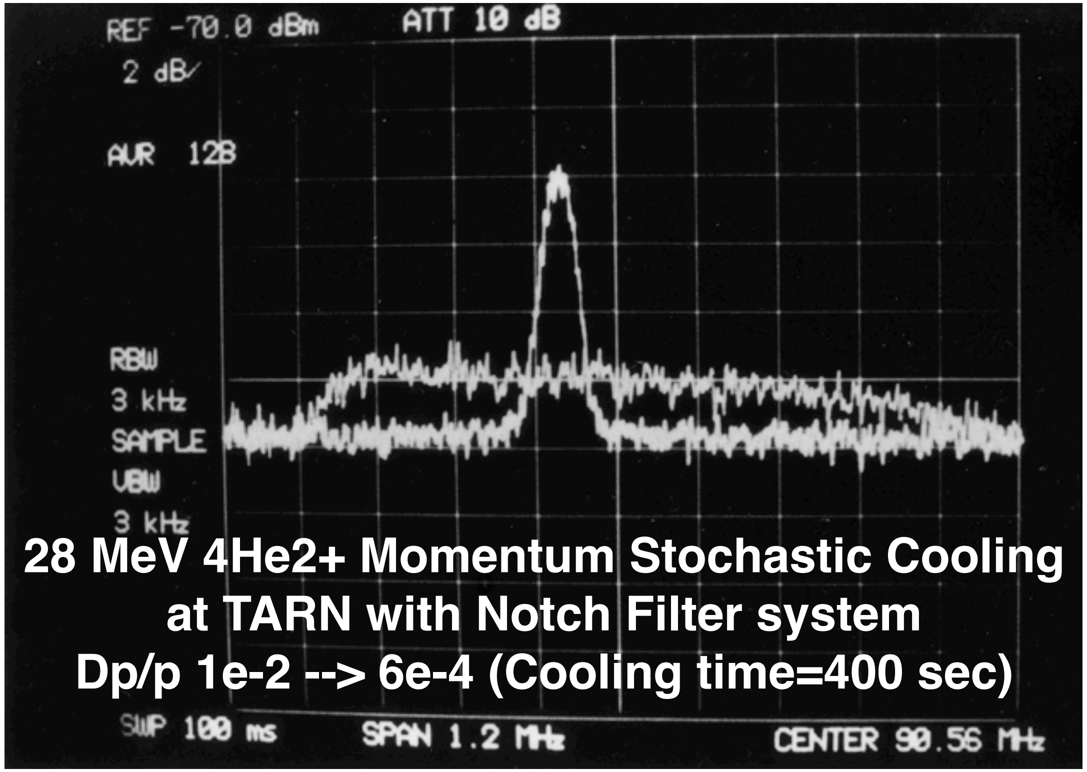
Multiturn injection+RF stacking & Stochastic Momentum cooling



Increase of Accumulated He Ion Current



Beam Profile of Accumulated Ion Beam

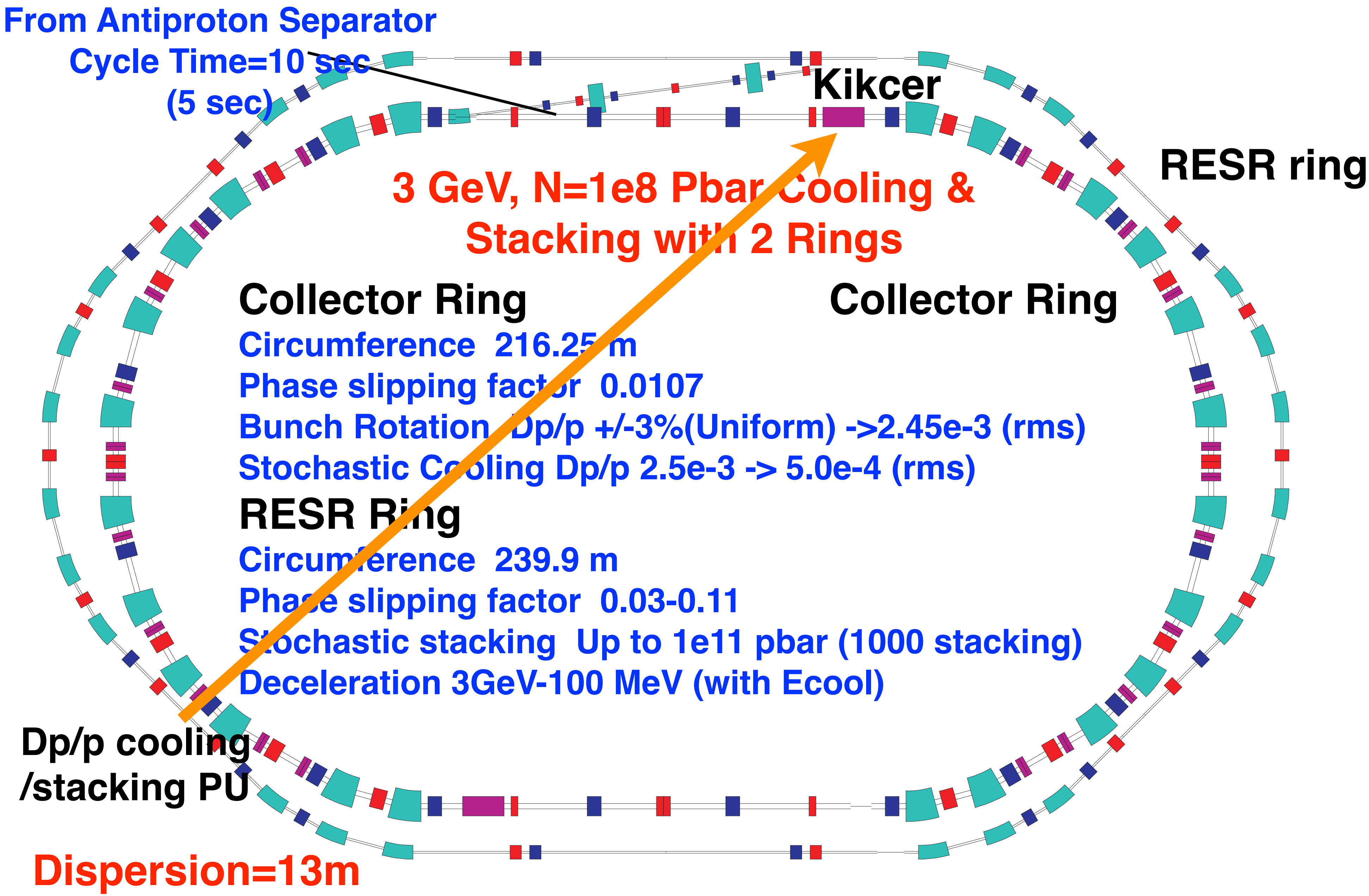


28 MeV 4He2+ Momentum Stochastic Cooling at TARN with Notch Filter system

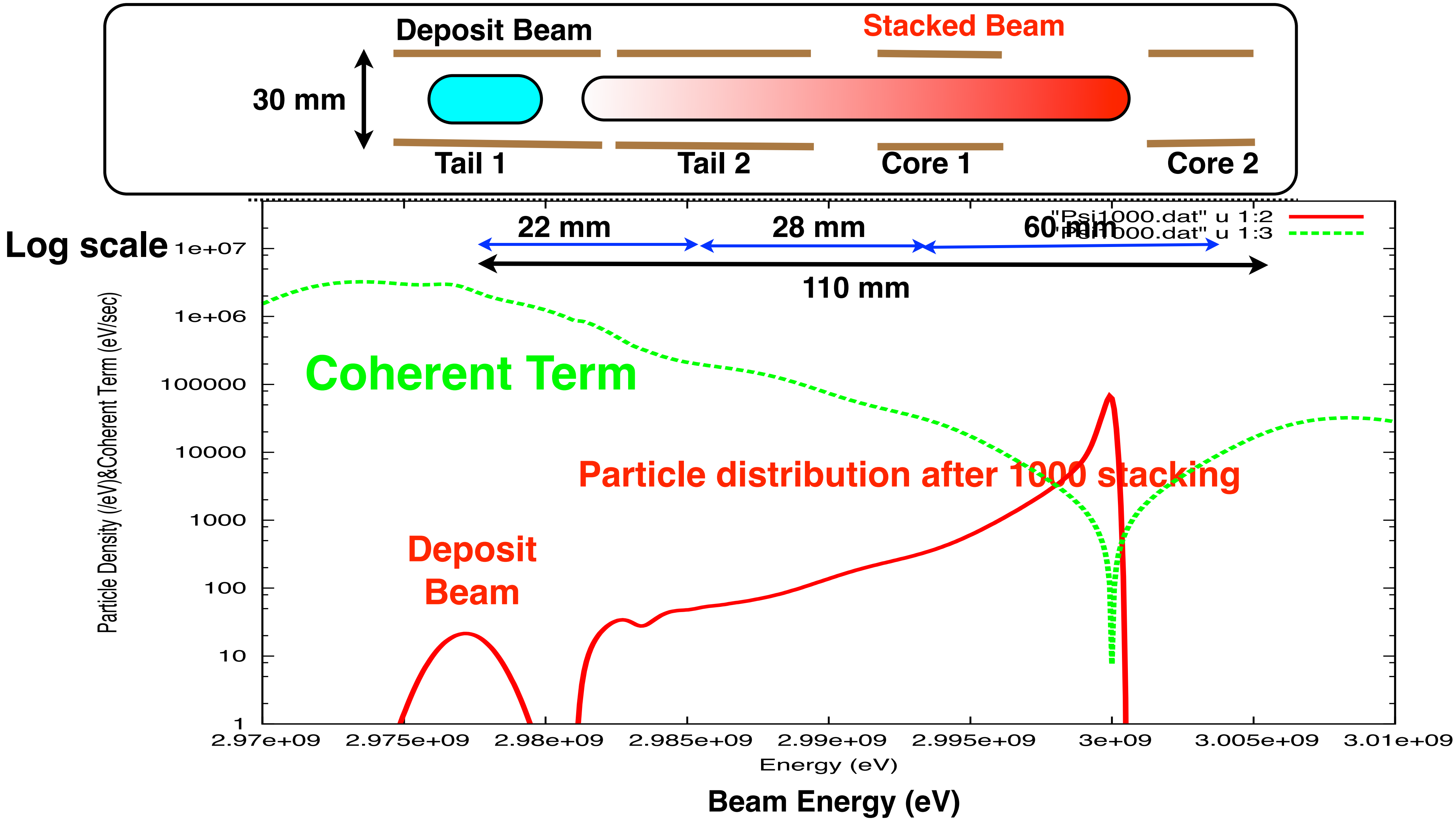
Dp/p 1e-2 --> 6e-4 (Cooling time=400 sec)

Stochastic Stacking

Collector Ring & RESR Ring of FAIR Project



Schematic Layout of Tail and Core System at RESR



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**

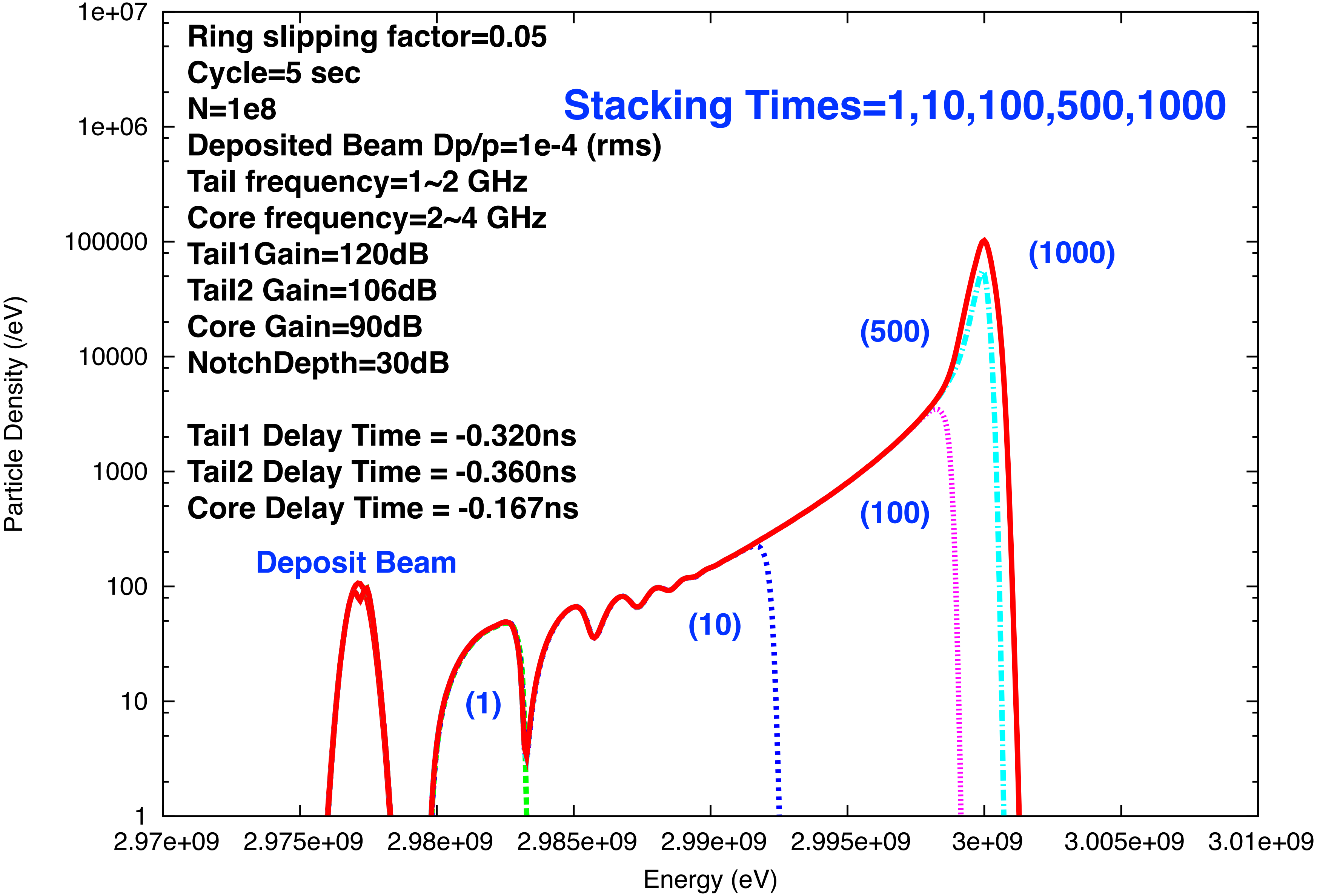
$$F(E) : Cooling\ Force$$

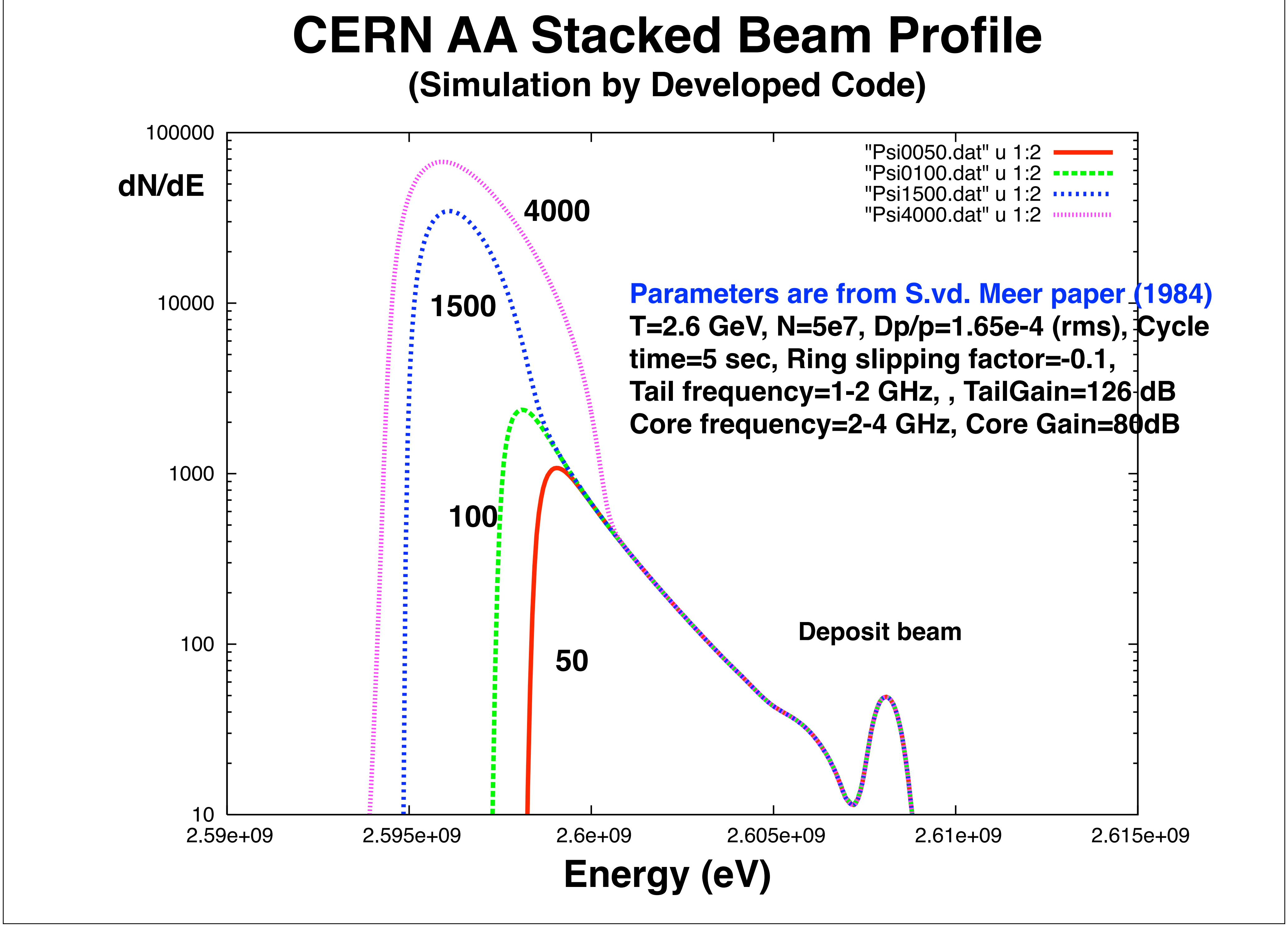
$$D(E,t) : Diffusion\ Force$$

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

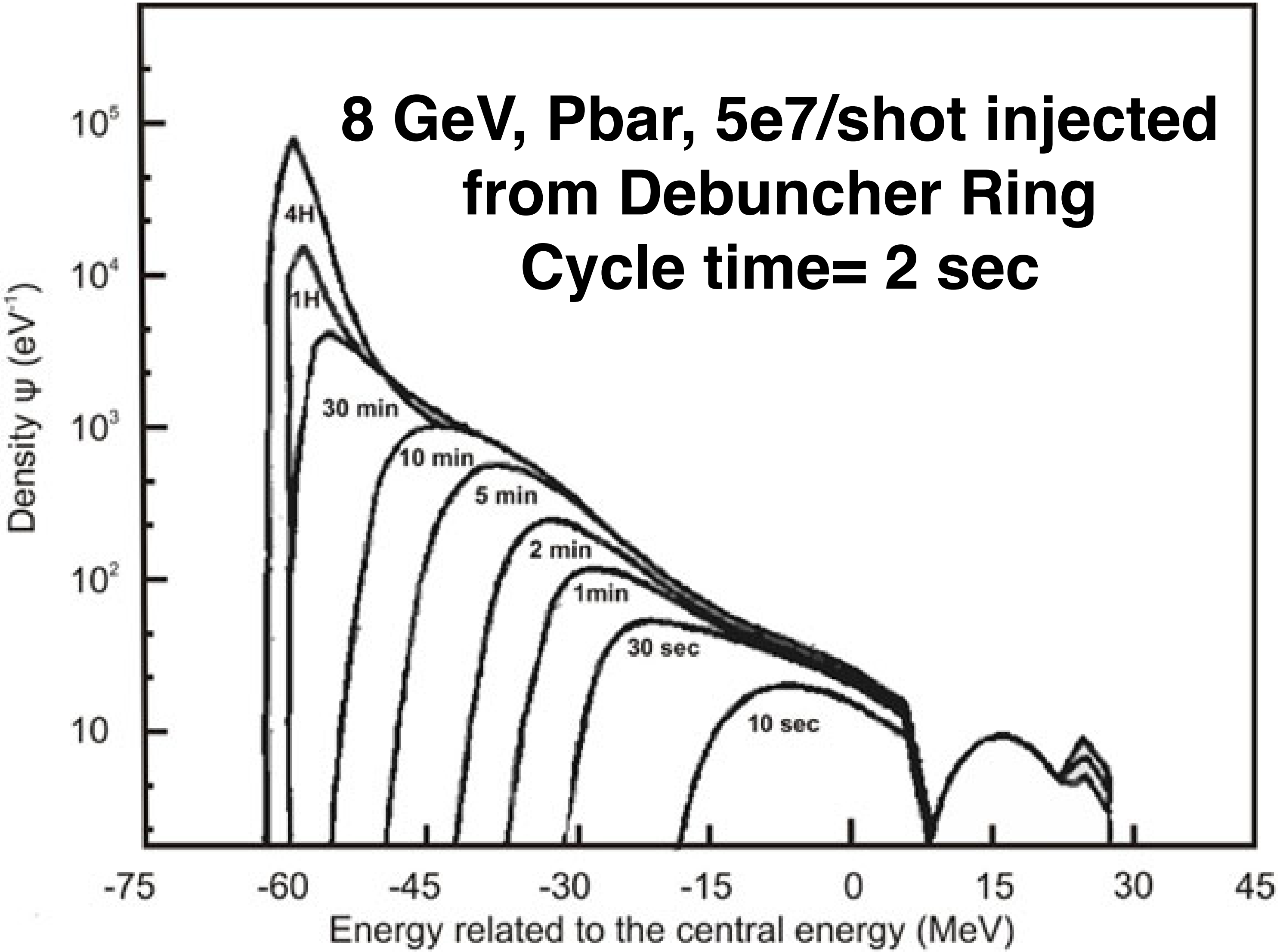
***Diffusion Force*: Function of Particle density, Band width, Gain, PU temperature, IBS diffusion force.**

RESR 3 GeV Antiproton
Stacked Beam Profile during Stacking




CERN AA Stacked Beam Profile
(Simulation by Developed Code)
dN/dE
100000
10000
1000
100
10
"Psi0050.dat" u 1:2
"Psi0100.dat" u 1:2
"Psi1500.dat" u 1:2
"Psi4000.dat" u 1:2
4000
1500
100
50
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=80dB
Deposit beam
2.59e+09
2.595e+09
2.6e+09
2.605e+09
2.61e+09
2.615e+09
Energy (eV)

Fermi Lab. Accumulator Ring (Calculated)



(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

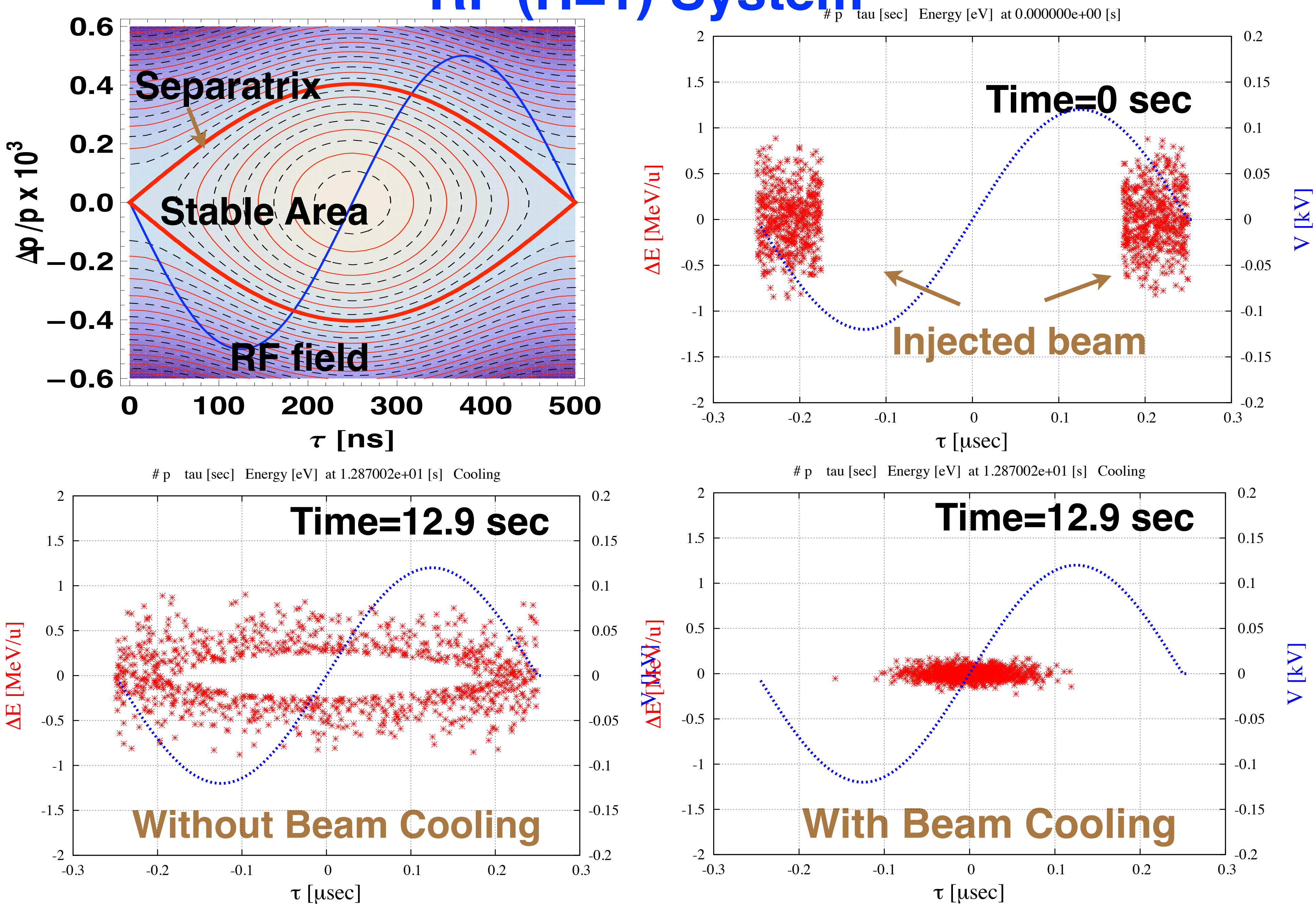
1. **Beam momentum spread should be within the momentum acceptance of cooling system.**

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

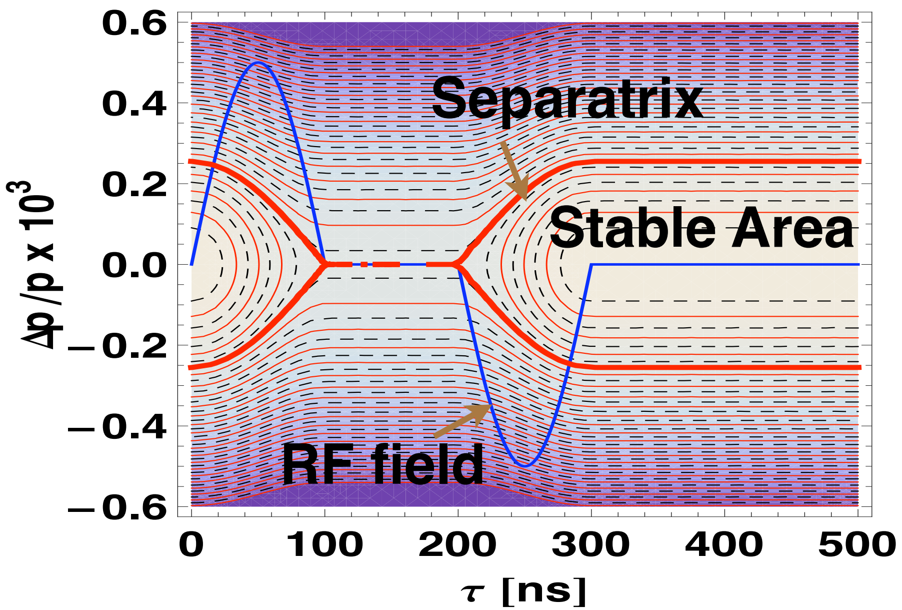
3. **Cooled and stacked beam should not be disturbed by the injection kicker field.**

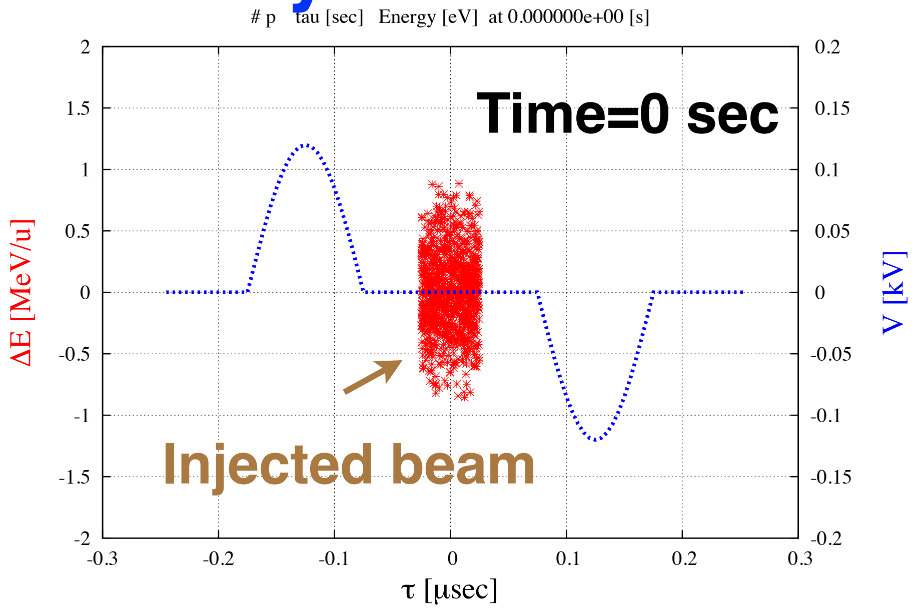
B. Franzke invited one of authors T.K in 2005 to GSI and suggested to investigate the possibility of Barrier Bucket Stacking Scheme of Antiproton beam.

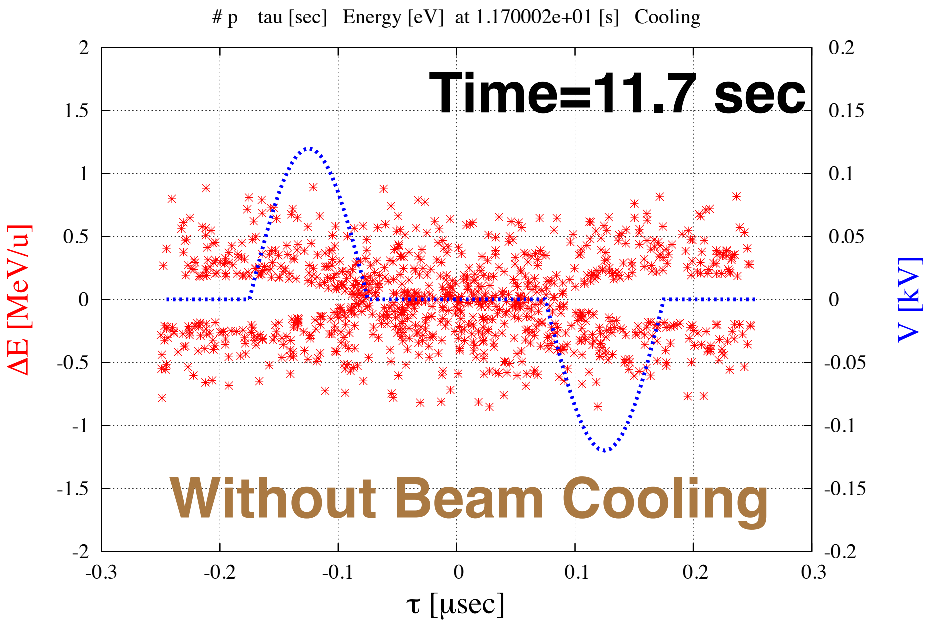
Separatrix and Beam Trajectry at RF (H=1) System

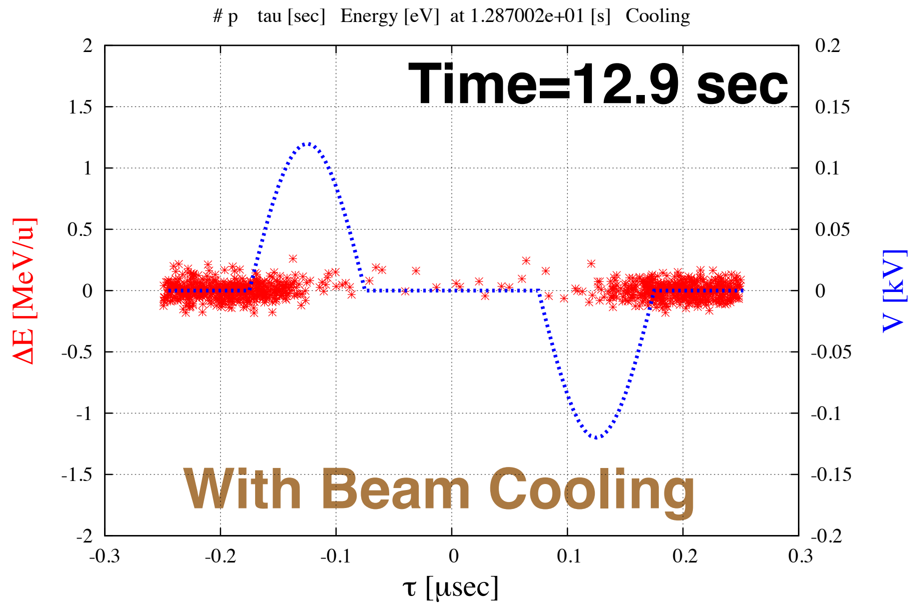


Separatrix and Beam Trajectory at Fixed Barrier Bucket System







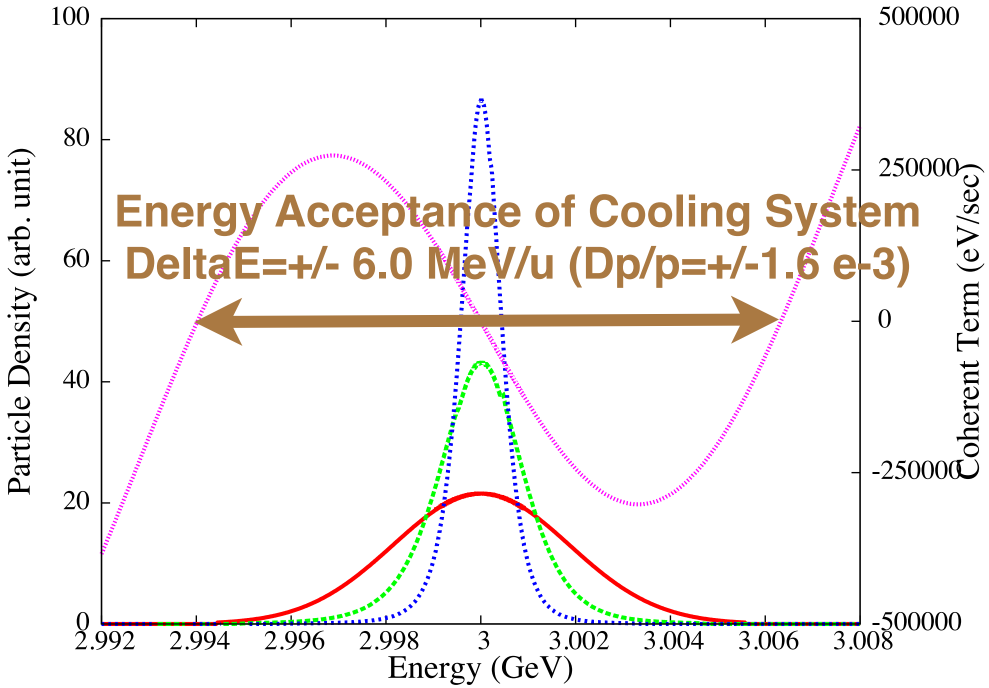


Accumulation & Cooling Parameters for HESR

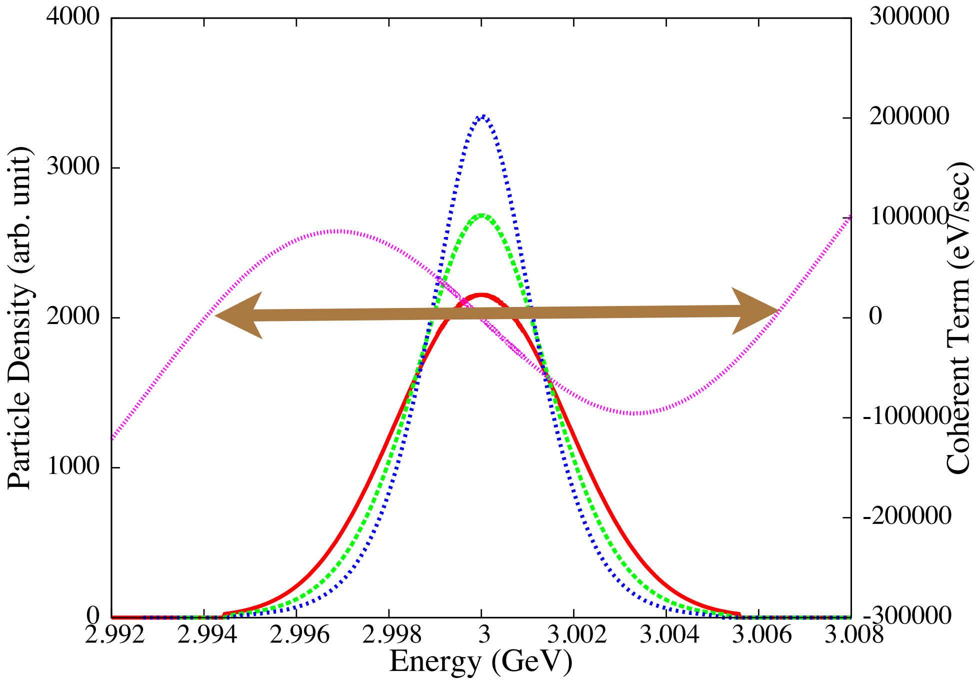
Injected Beam	3 GeV, Antiproton
Intensity	1e8
Injected Momentum Spread	5e-4 (rms)
Ring Slipping Factor	0.03
Cooling System	Notch Filter, 2-4 GHz
Injected Beam Width	~ 500 nsec
Revolution Period	~2000 nsec
Injection Kicker magnet	1000 nsec (250 nsec Falling/ Rising time)
Cycle Time	10 sec
Barrier Voltage	+/- 2 kV
Barrier Voltage Frequency	5 MHz (T=200 nsec)
Barrier Voltage Rising/Falling Time	0.2 sec
Barrier Voltage Moving Time	0.5 sec

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

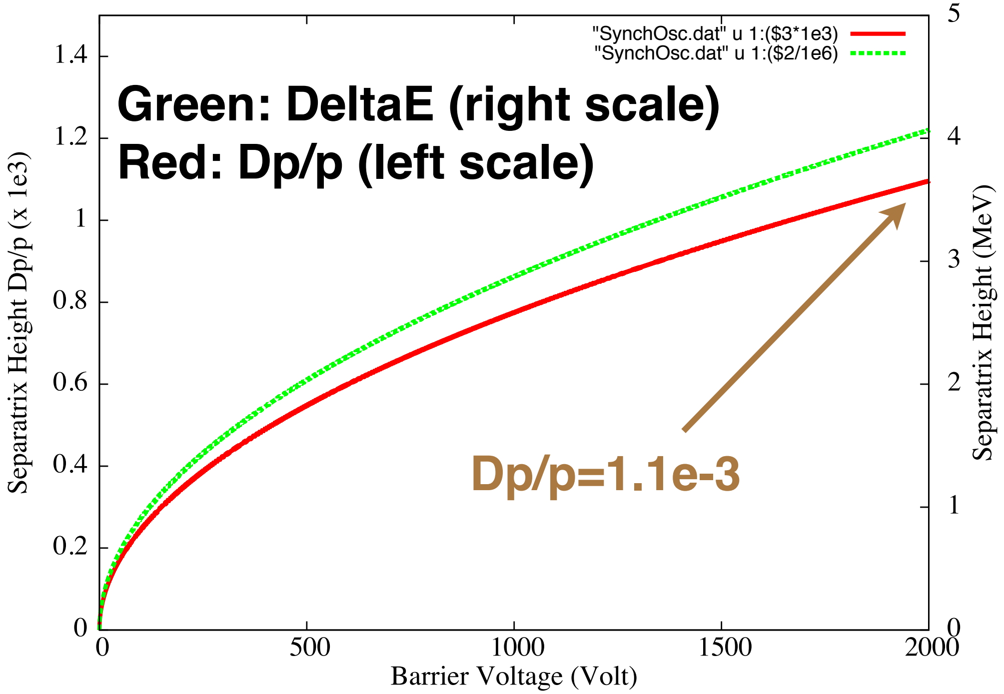


Time=0 sec (red), 5 sec (Green), 10 sec (Blue). Cooling Term (Pink)

HESR BB parameters

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

Separatrix Height of BB System



$$\Delta E_b = \left(\frac{2\beta^2 E_0 \varepsilon e V_0 T_1}{\pi \eta T_0} \right)^{1/2}$$

$$\varepsilon = Q / A$$

$$E_0 = Total\ Energy / nucleon$$

Particle Tracking Code for Momentum Cooling and Synchrotron Motion in Barrier RF System

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

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

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

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

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*

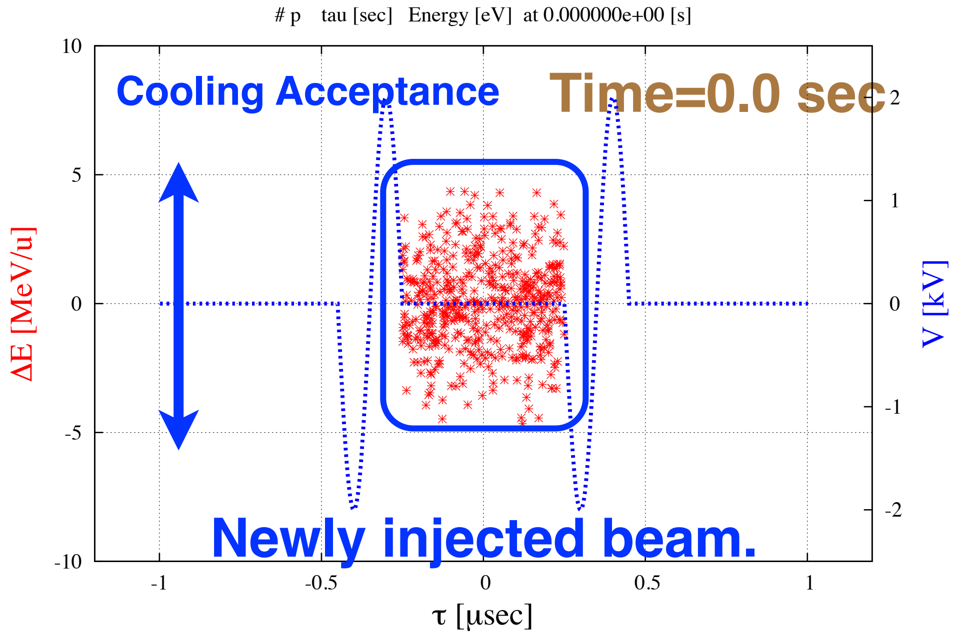
Random energy kick leads to diffusion in phase space.

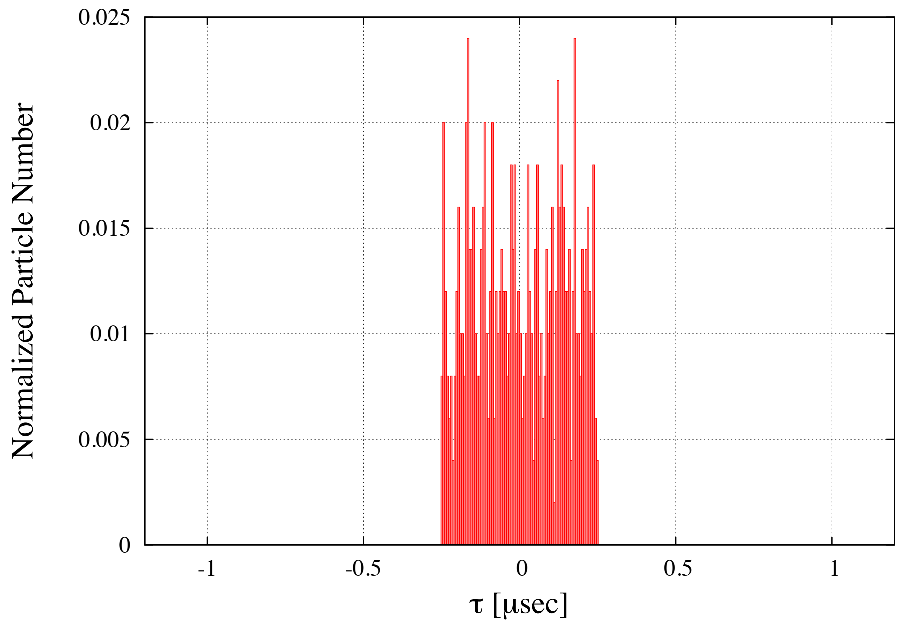
Moving Barrier Bucket System, Voltage=2000 Volt

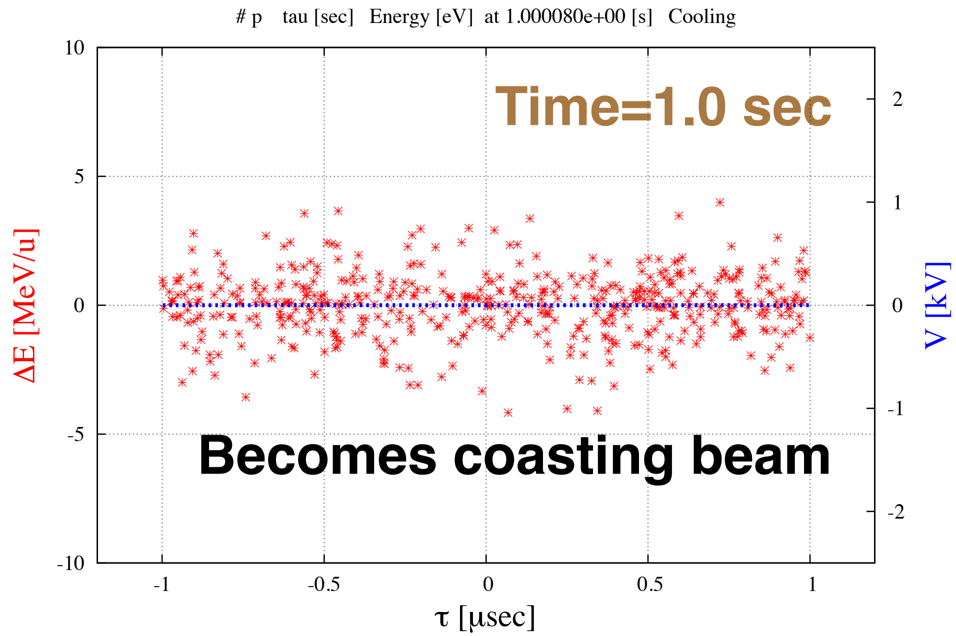
Phase Space Mapping

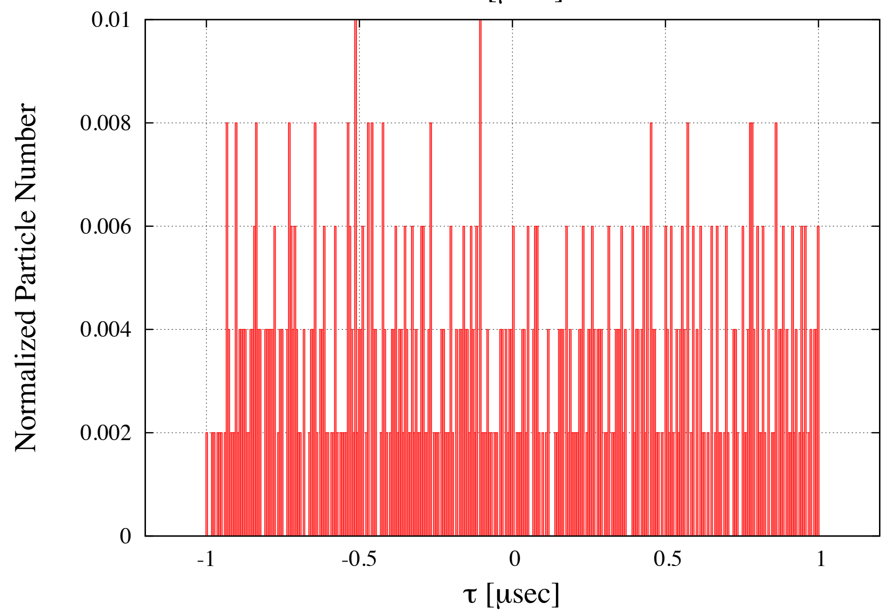
Blue: barrier Voltage
Red: Particle distribution

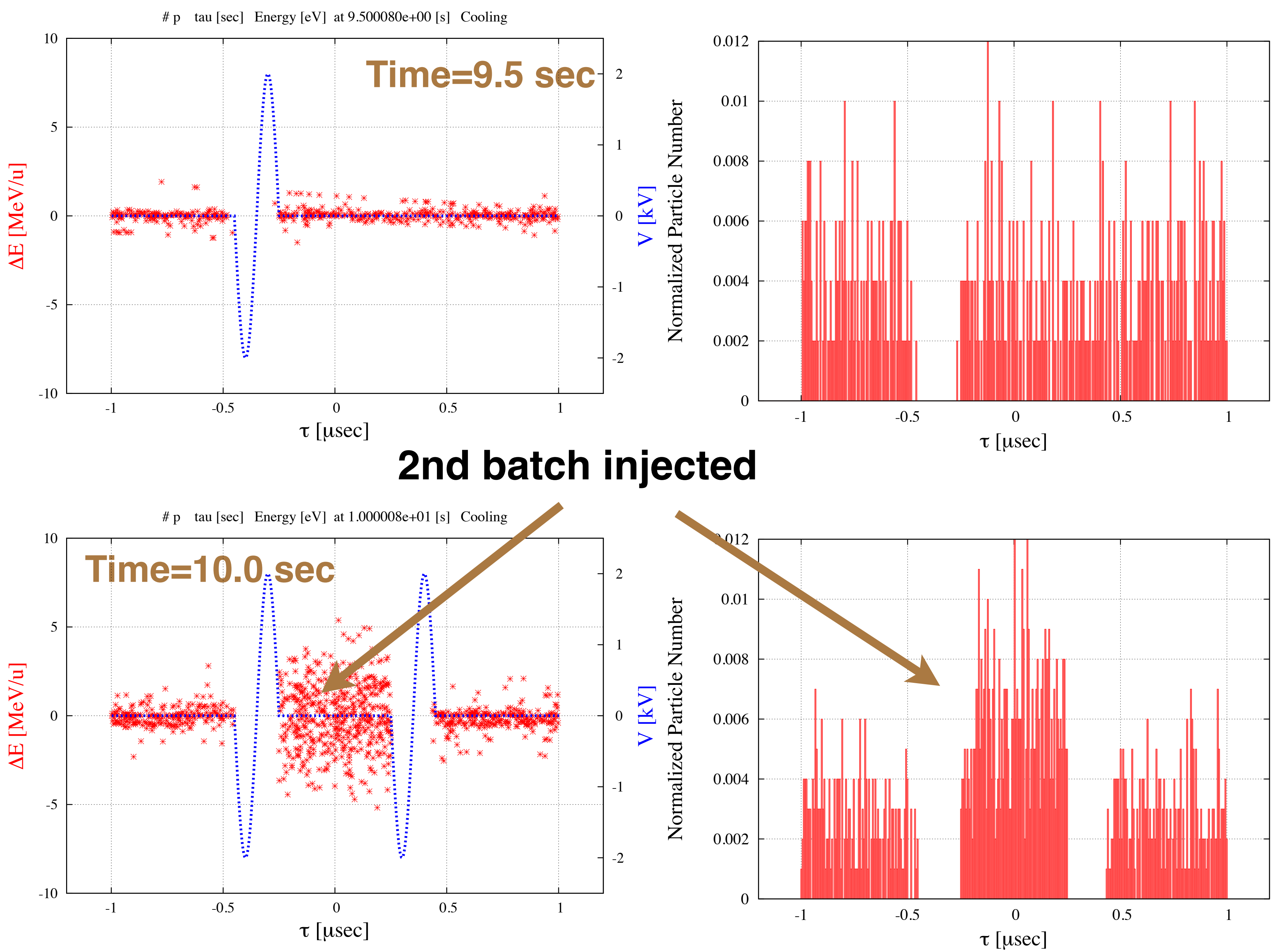
Particle distribution along the Ring Circumference









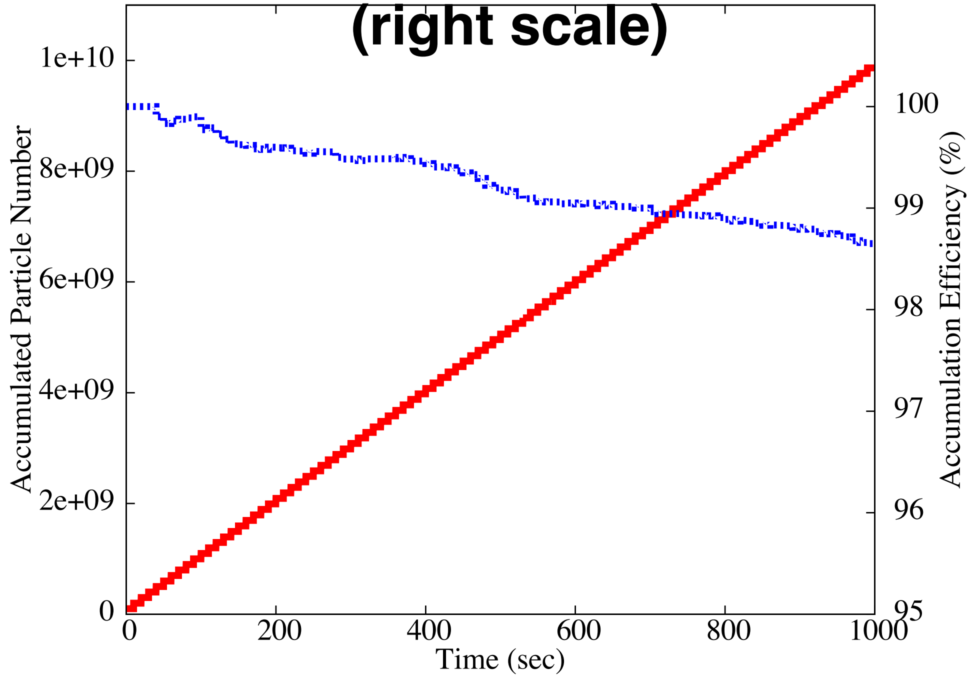


# p tau [sec] Energy [eV] at 9.500080e+00 [s] Cooling
Time=9.5 sec
ΔE [MeV/u]
V [kV]
τ [μsec]
Normalized Particle Number
τ [μsec]
2nd batch injected
# p tau [sec] Energy [eV] at 1.000008e+01 [s] Cooling
Time=10.0 sec
ΔE [MeV/u]
V [kV]
τ [μsec]
Normalized Particle Number
τ [μsec]

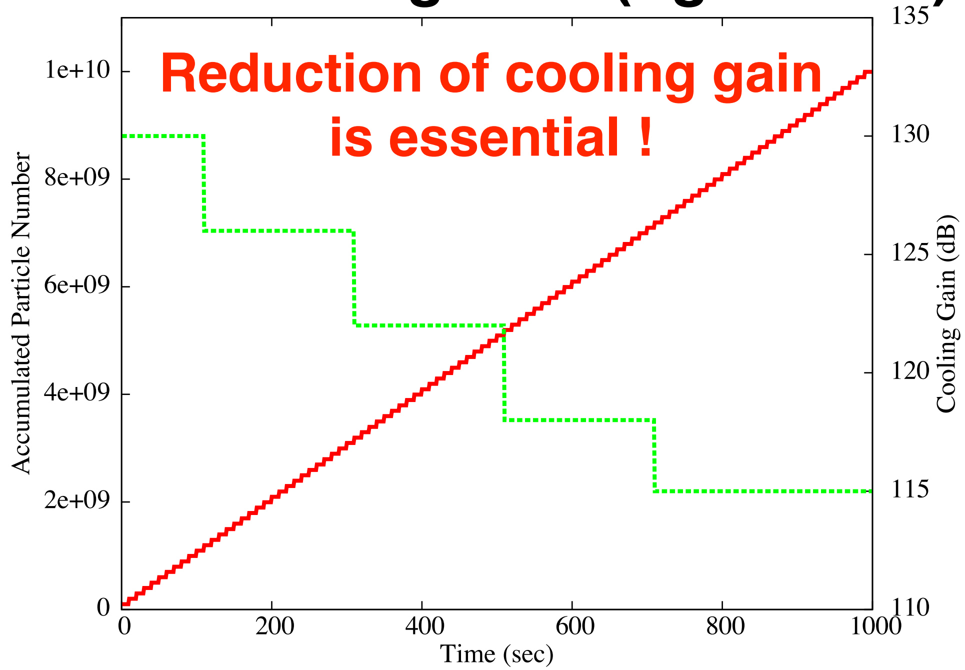
HESR Moving Barrier Bucket System, Voltage=2000 Volt

Cycle time= 10 sec

Blue: Accumulation Efficiency (right scale)

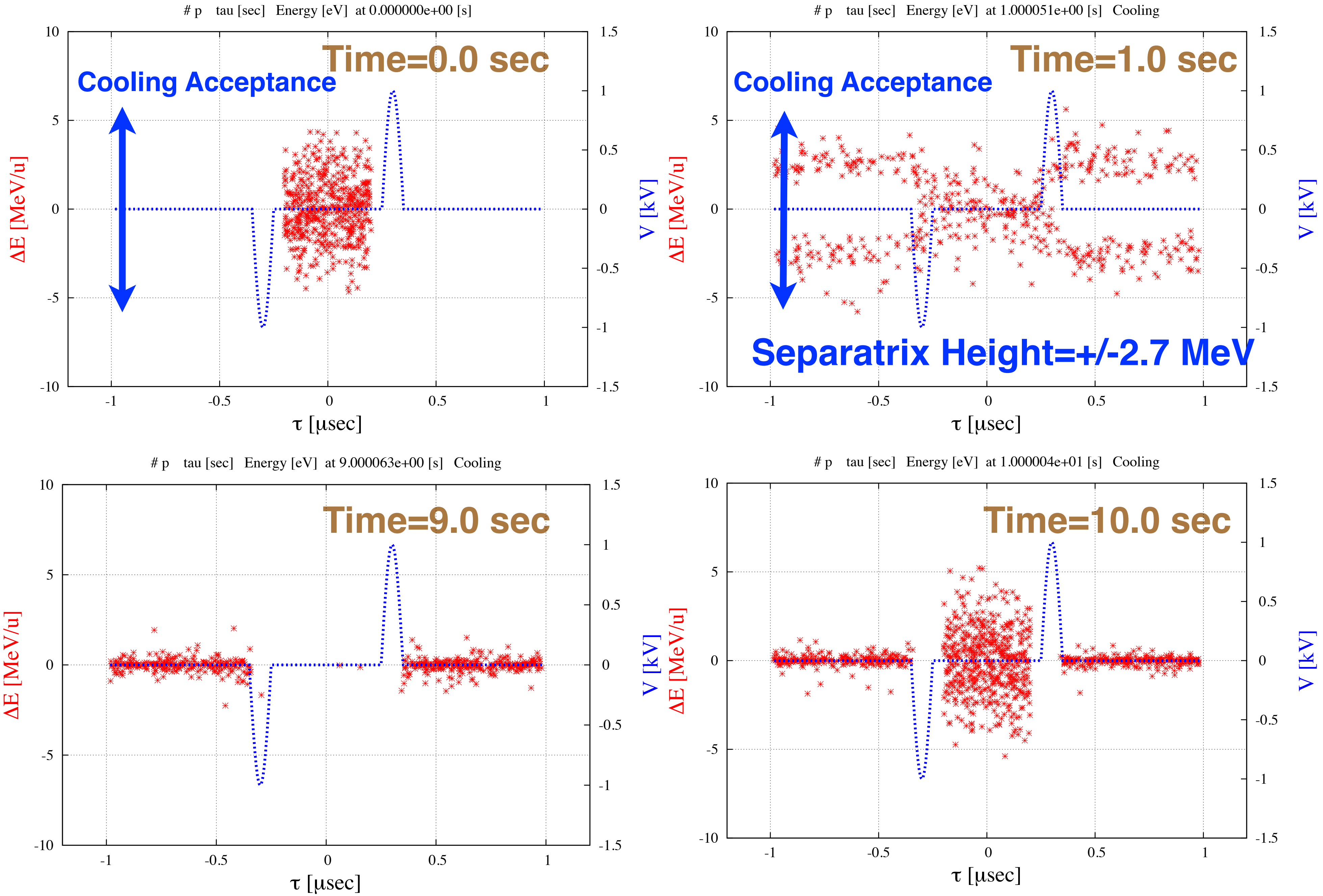


Green:Cooling Gain (right scale)



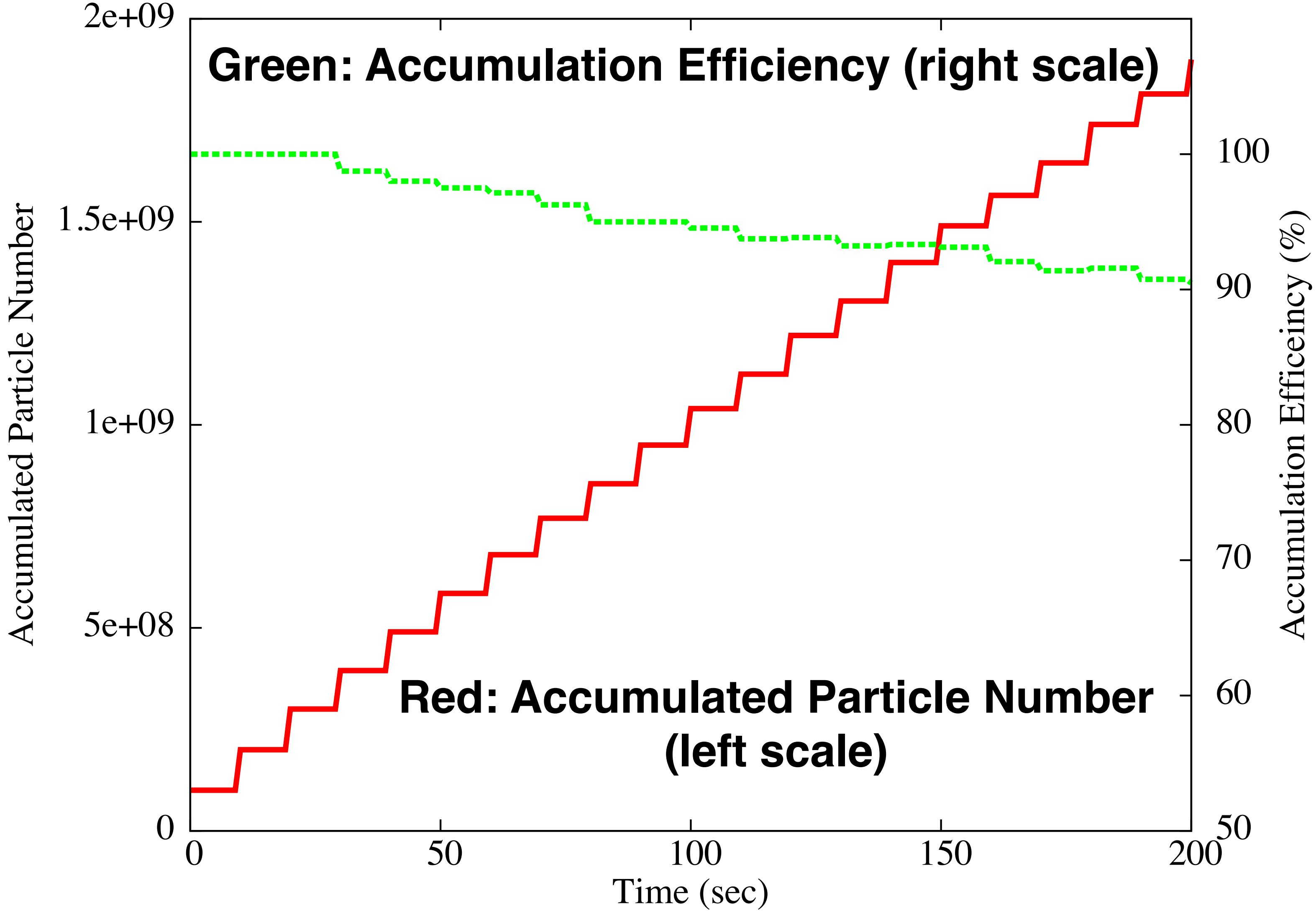
Red: Accumulated Particle Number (left scale)

Fixed Barrier 1000 Volt (Phase mapping)



Fixed Barrier Bucket System, Voltage=1000 Volt

Accumulation efficiency
=Accumulated Particle Number
/Total Injected Particle Number



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

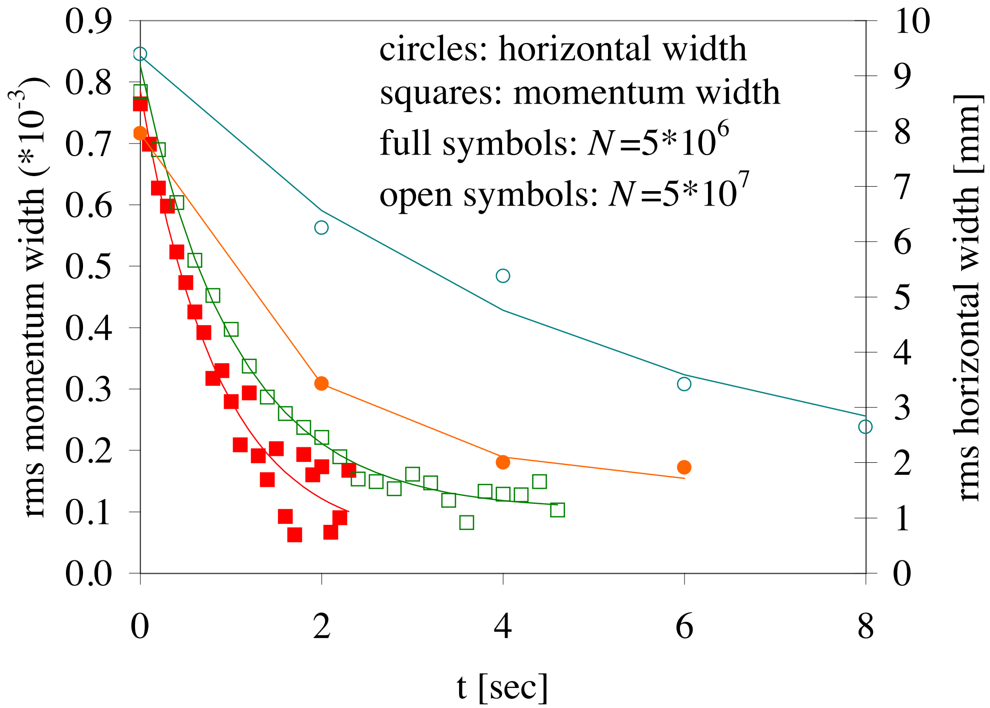
Spokesman of POP Experiment: M. Steck

Parameters of Stochastic Cooling and Barrier Voltage at POP Exepriment at ESR

1. Particle: 40Ar18+, 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)

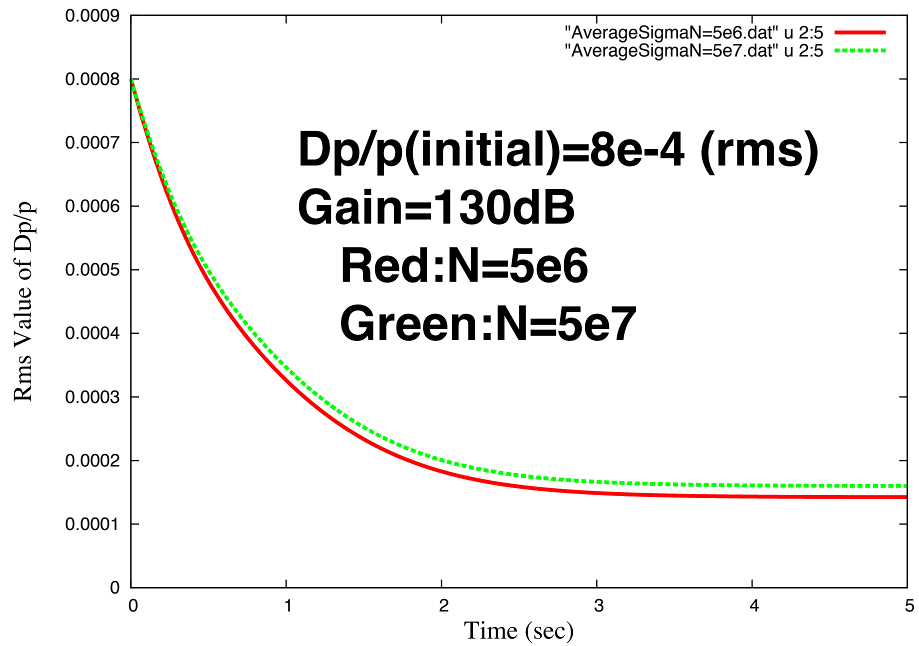
Comparison of Experimental and Simulation Results of Momentum Cooling at ESR

Experimental Results
36Ar18+ 390 MeV/u

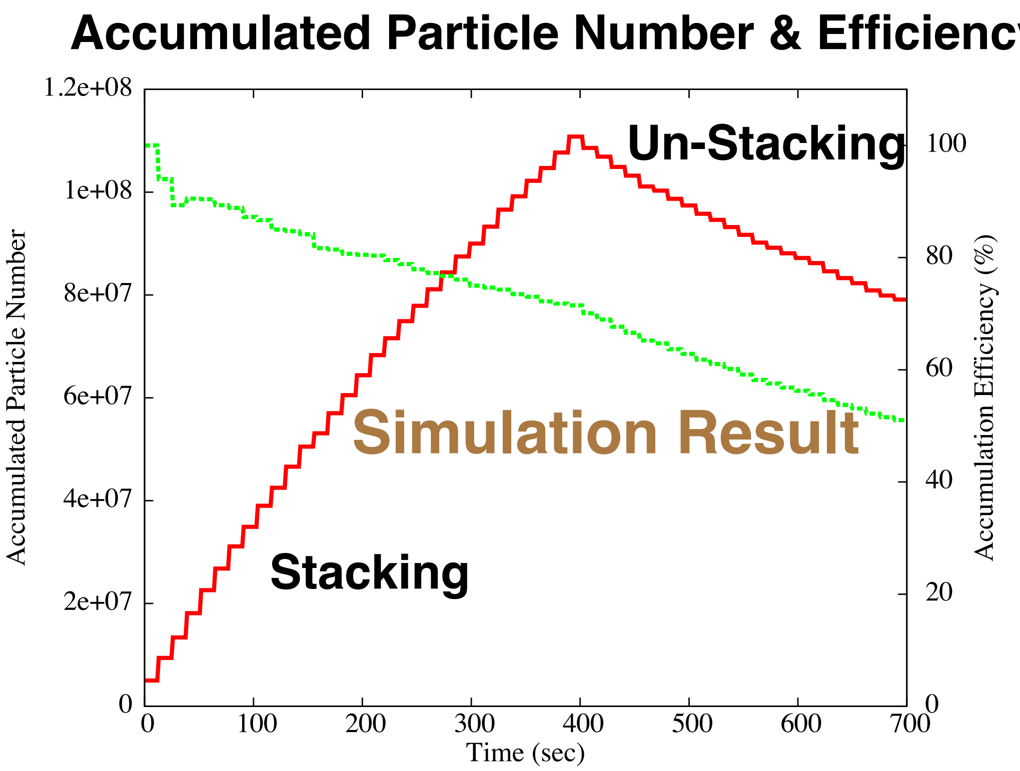


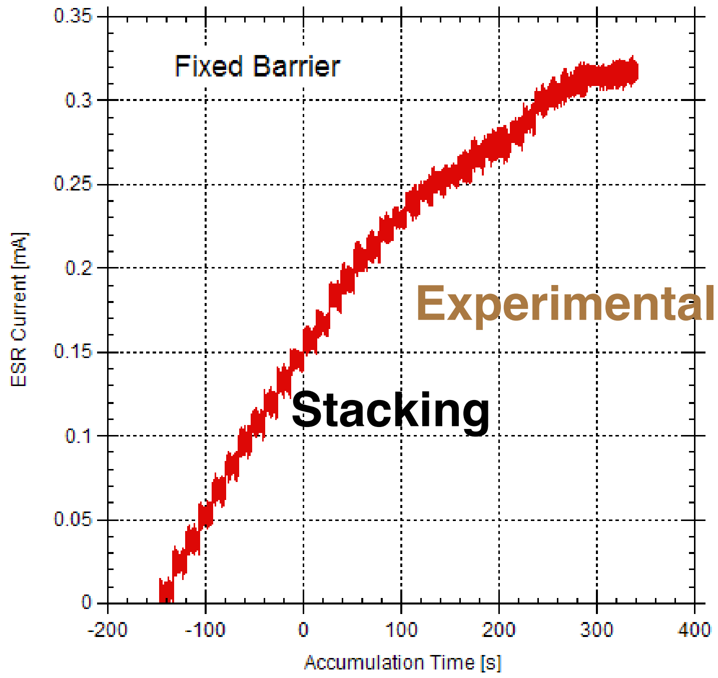
(Ref) F. Nolden et al., EPAC 2000

Simulation Results
with Fokker Planck code

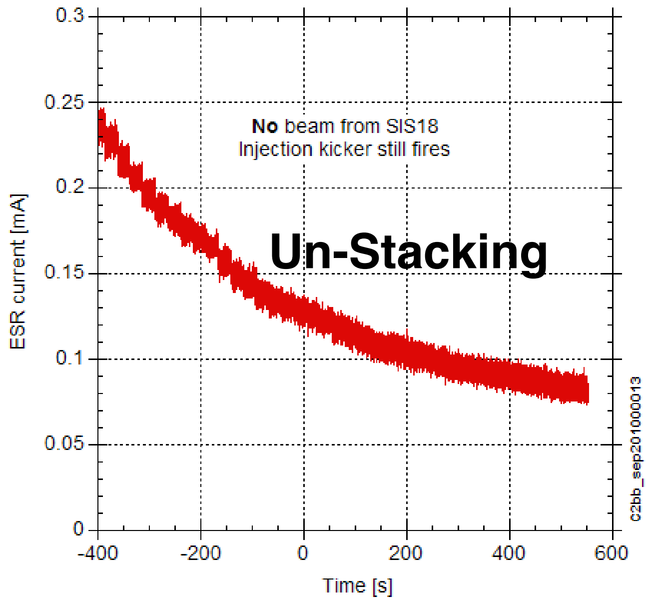


Fixed Barrier Case Vbb=120 V, Stochastic Cooling Gain=120dB





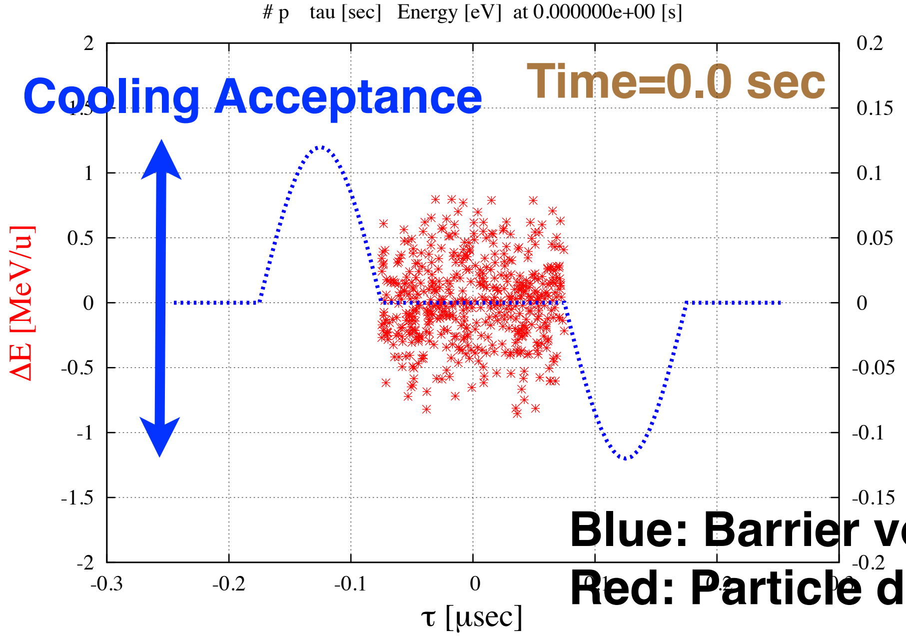
Un-Stacking
- No Beam injection but Kicker is fired -

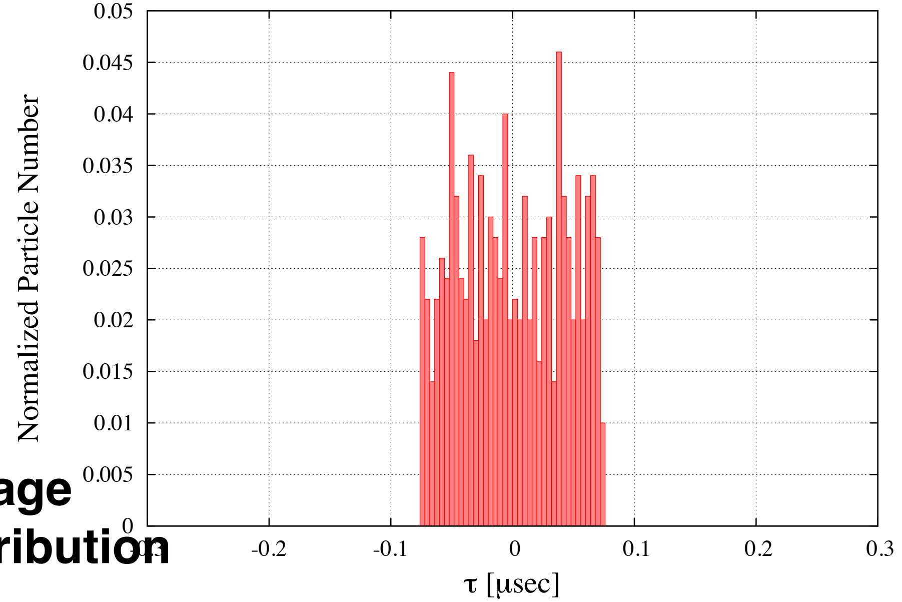


Accumulation Efficiency= Accumulated Particle Number/Total Injected Particle Number

Phase Space Mapping

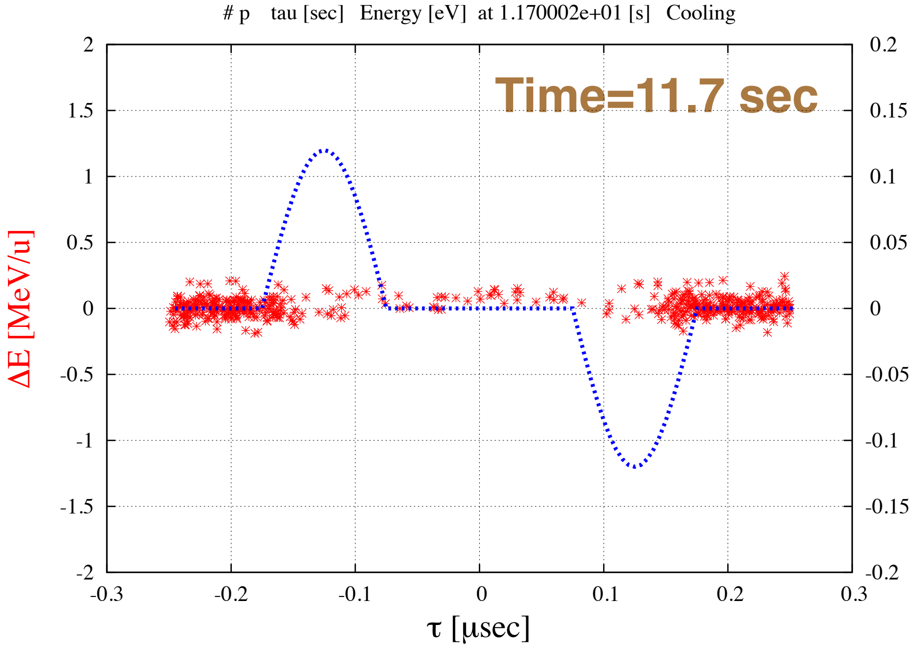
Particle distribution along the Ring Circumference

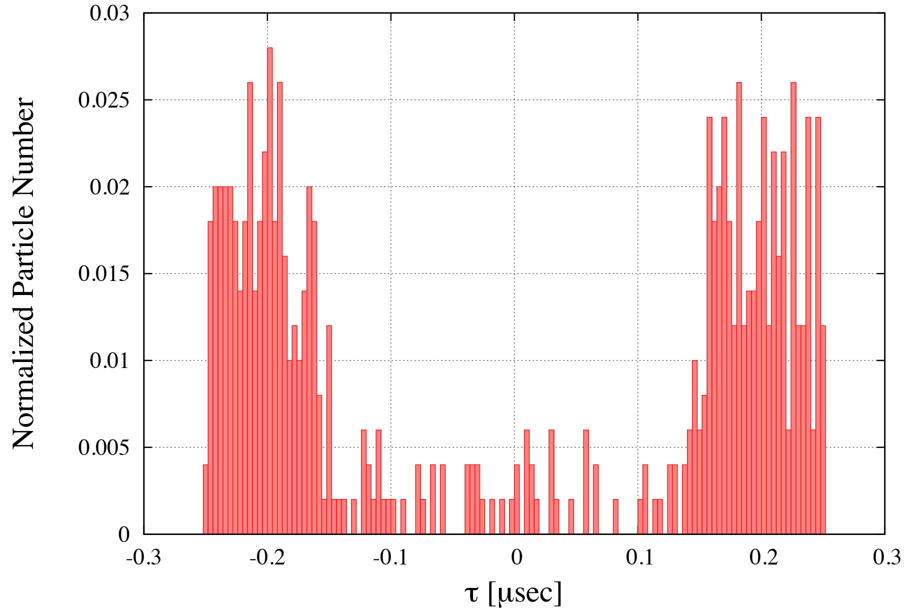




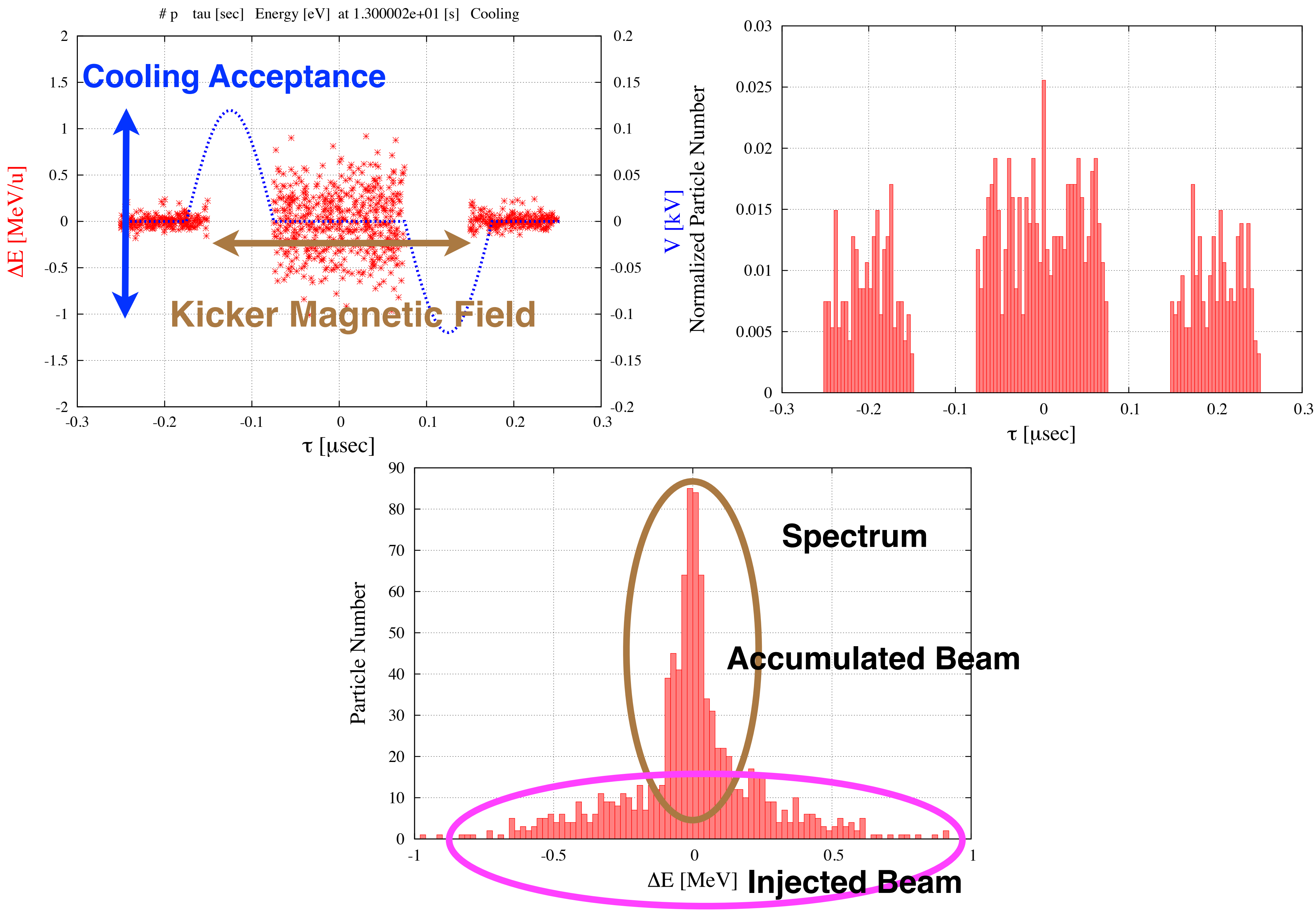
Blue: Barrier voltage

Red: Particle distribution

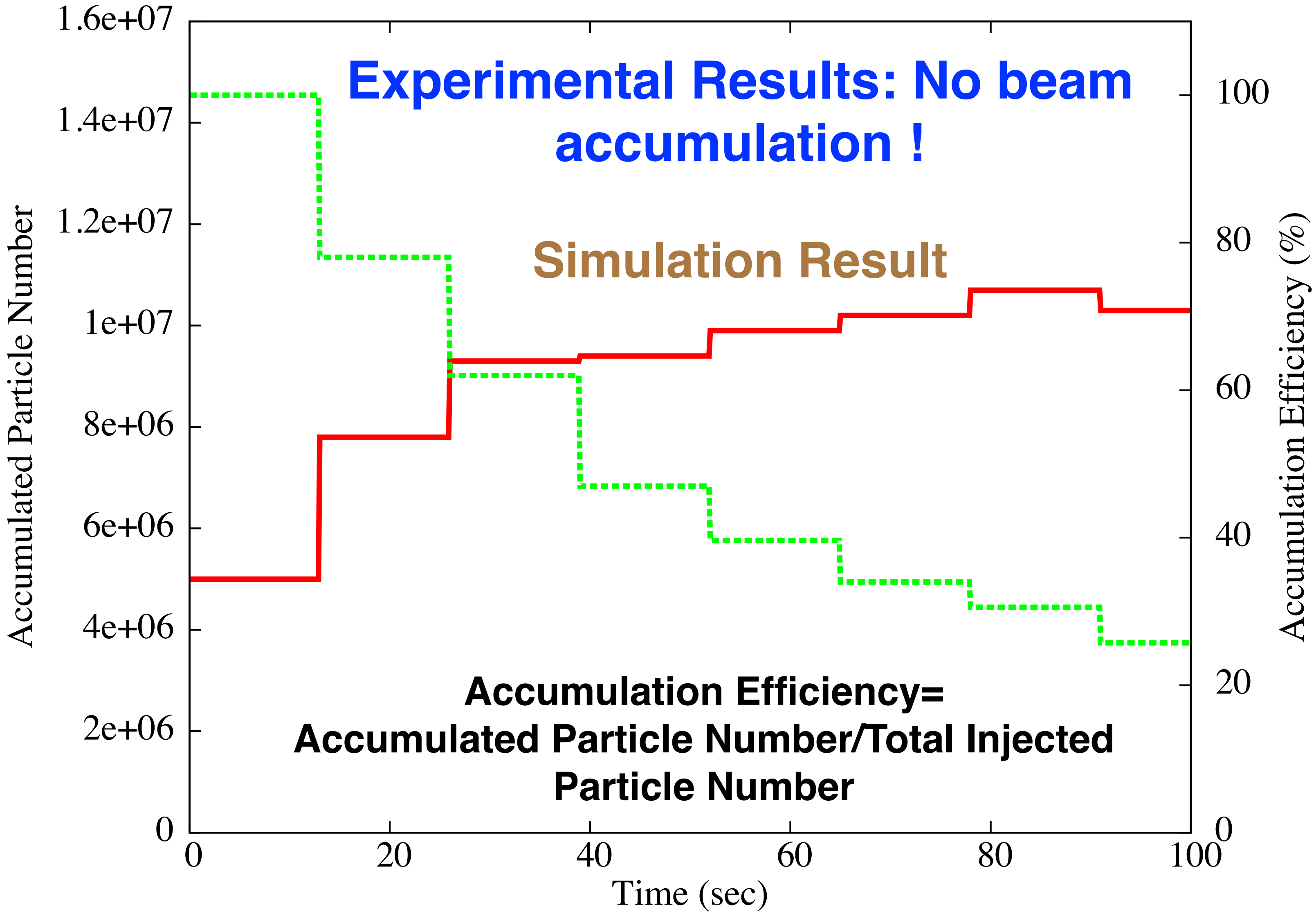




Time=13.0 sec **2nd bunch injected**

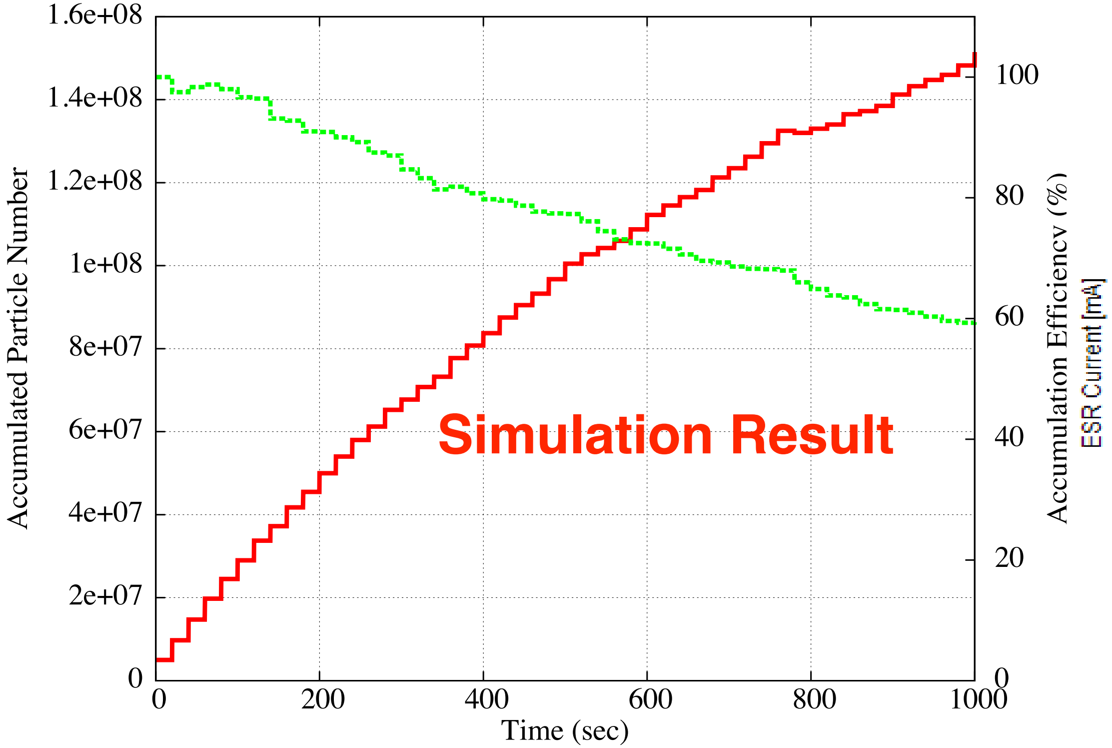


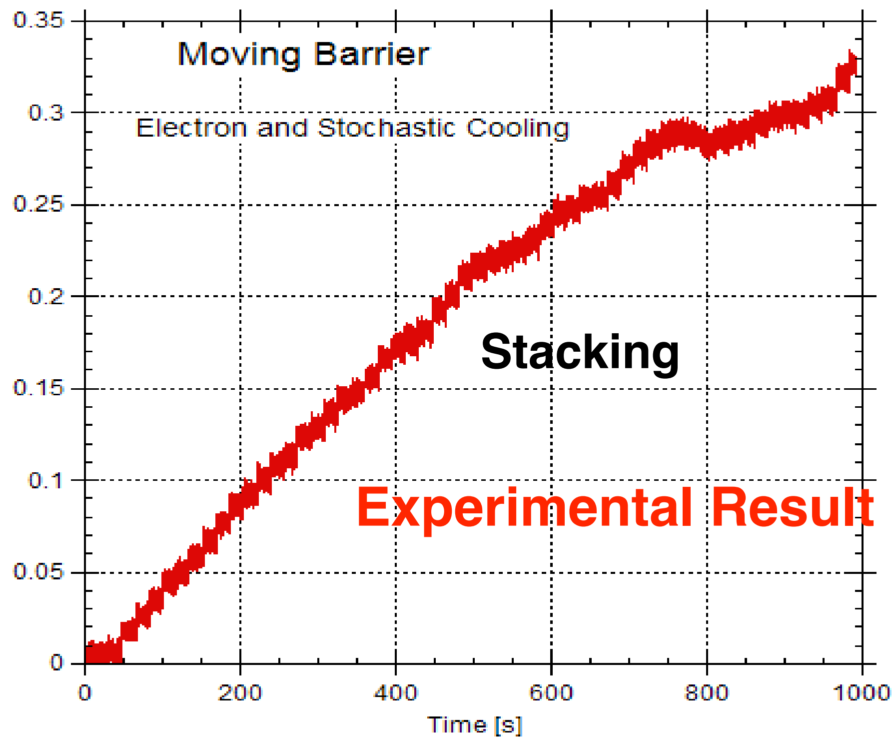
Moving Barrier Case, Gain=120dB
Vbb=120V, Ie=0A



Moving Barrier Case, Gain=120 dB Vbb=120V, Cycle time=20 sec, Kicker period=200 nsec, with Electron Cooler Ie=0.3 A

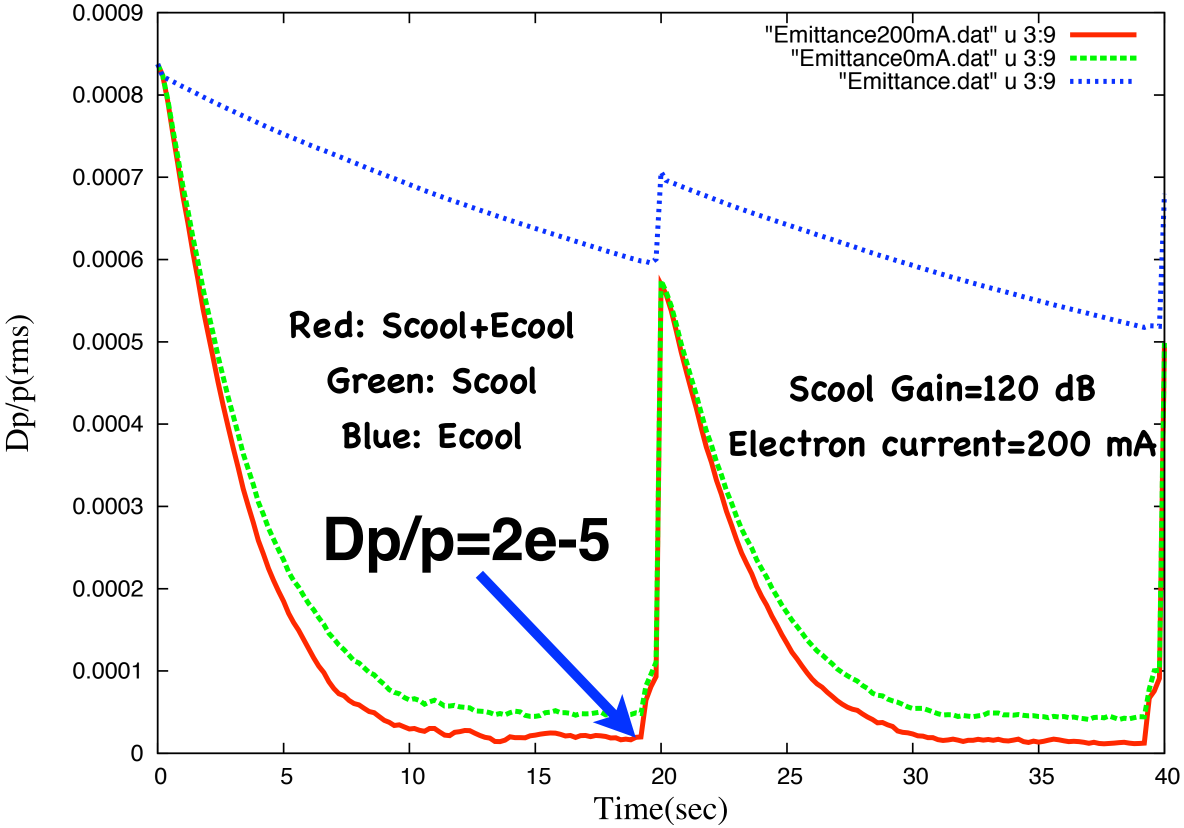
Accumulated Particle Number & Efficiency





Accumulation Efficiency (green)
Accumulated particle number (red)

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



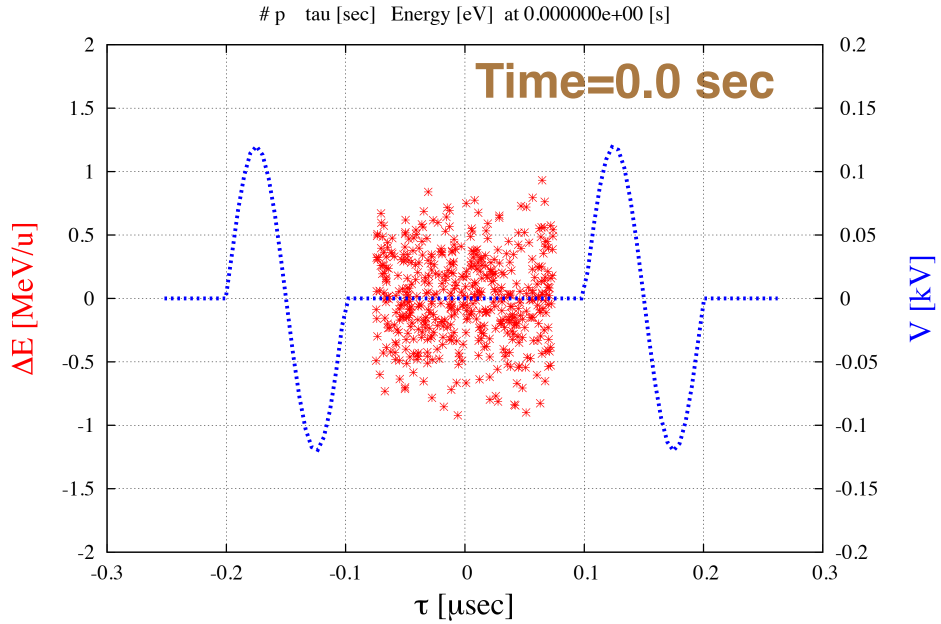
Electron Cooler at ESR

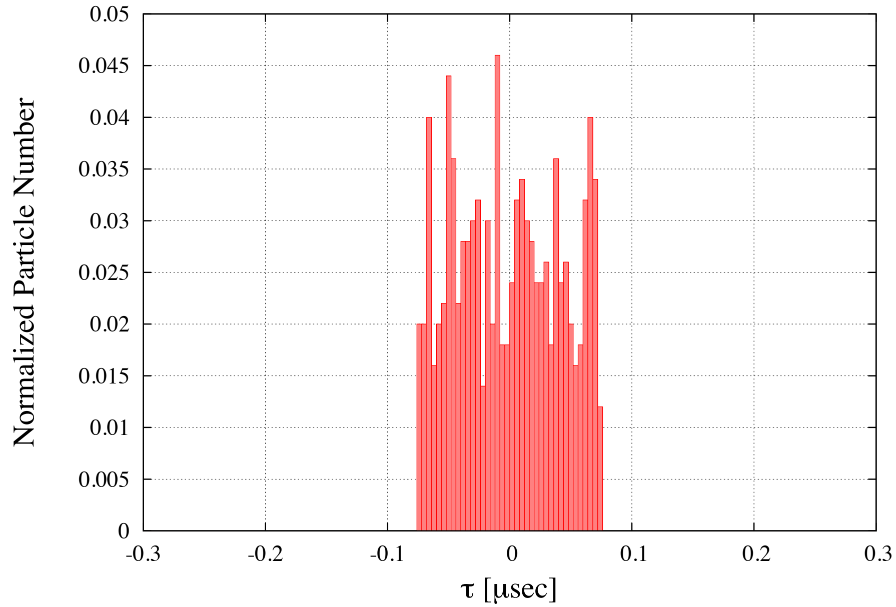
Length	2 m
Electron Diameter	5 cm
Electron Current	0.2 A
Effective Electron Temperature	1e-3 eV
Beta Function at Cooler	16 m

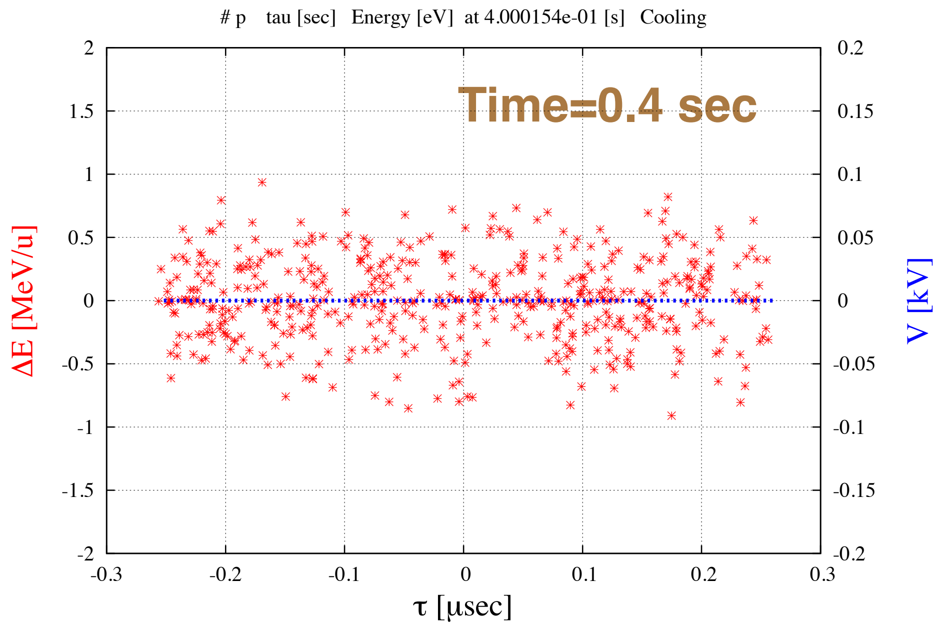
Moving Barrier Case

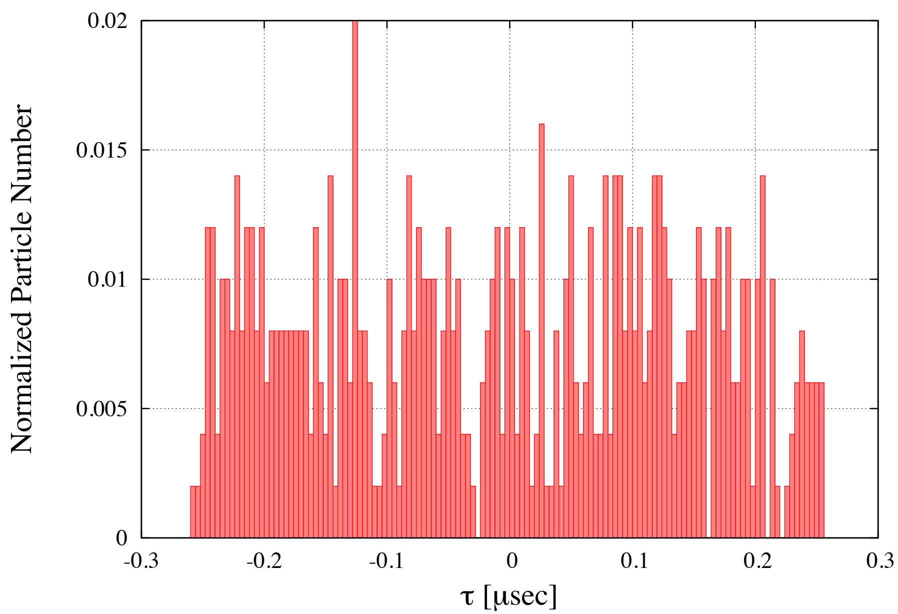
Phase Space Mapping

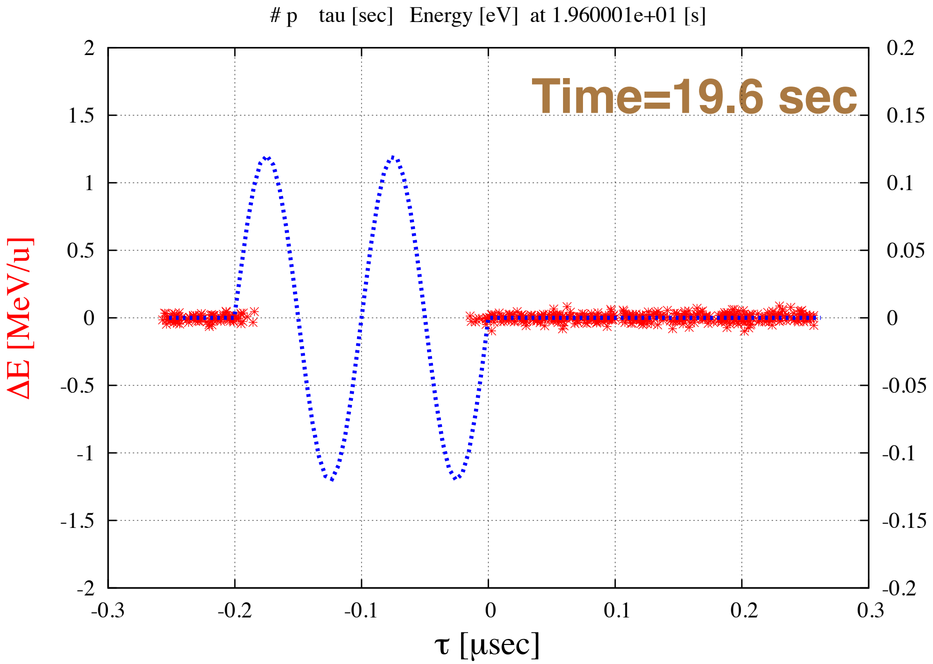
Particle distribution along the Ring Circumference



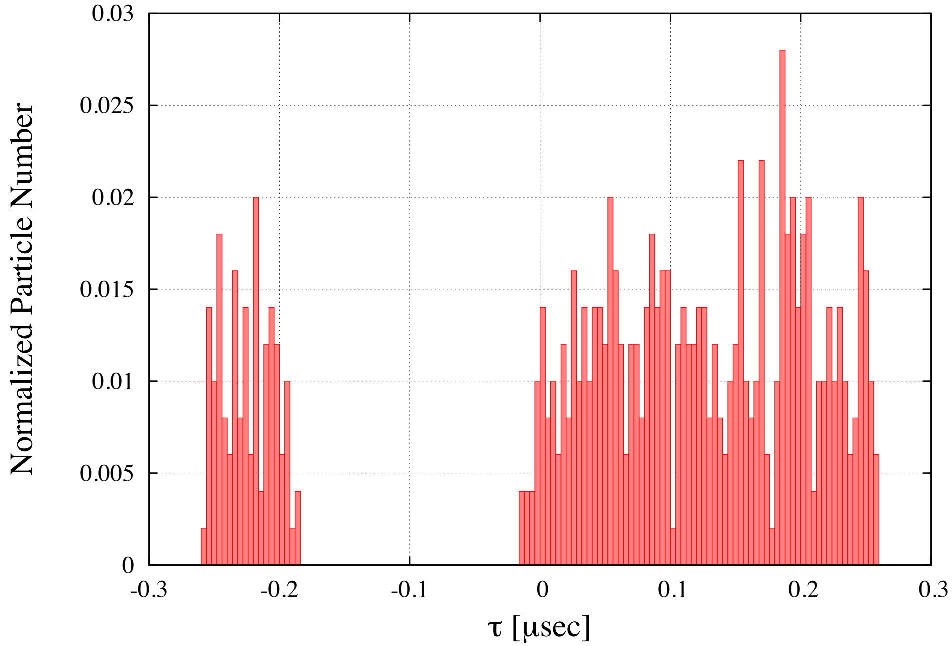




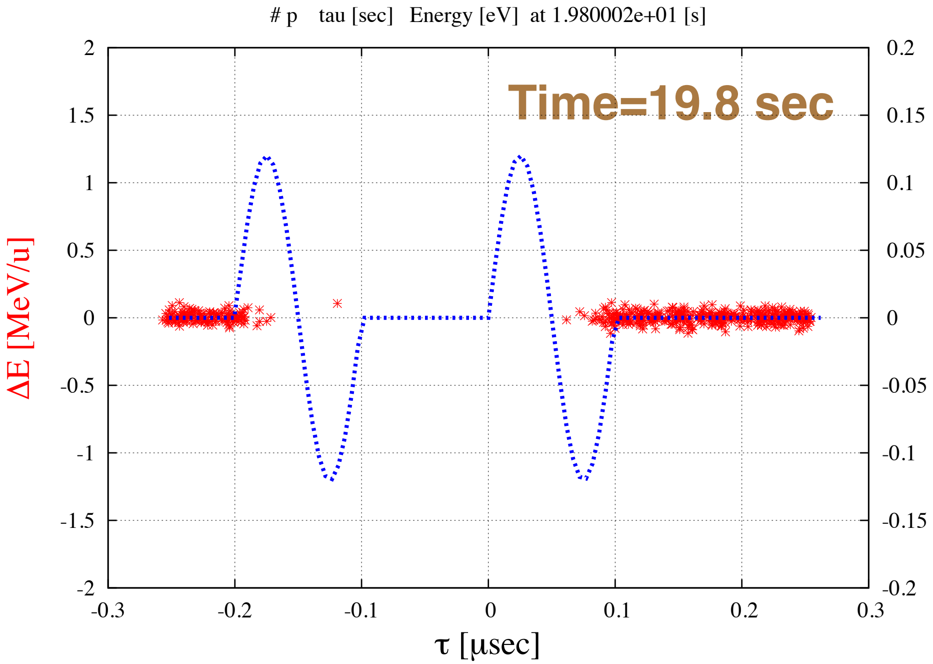




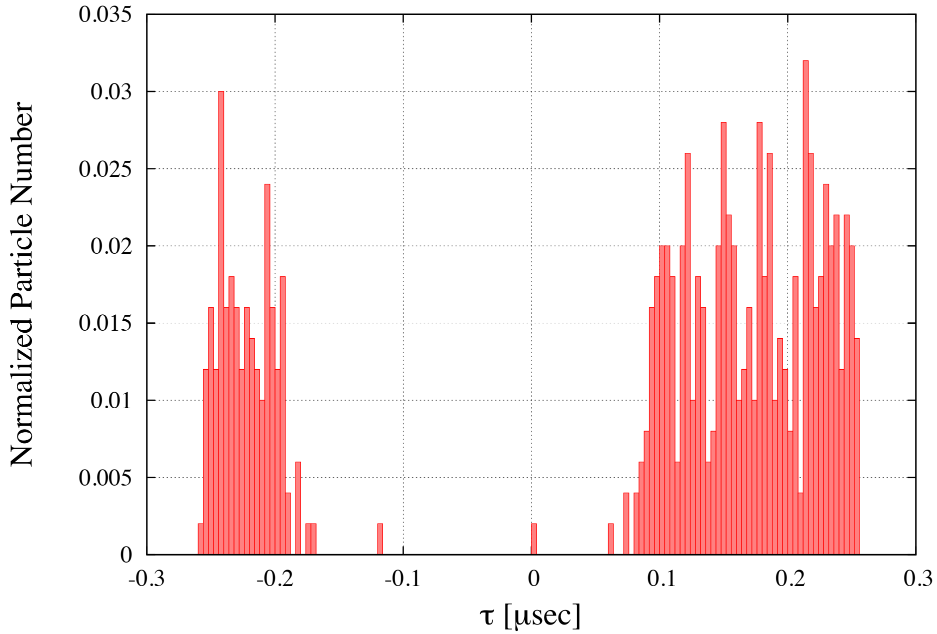
# p tau [sec] Energy [eV] at 1.960001e+01 [s]
Time=19.6 sec
ΔE [MeV/u]
V [kV]
τ [μsec]



Normalized Particle Number
τ [μsec]

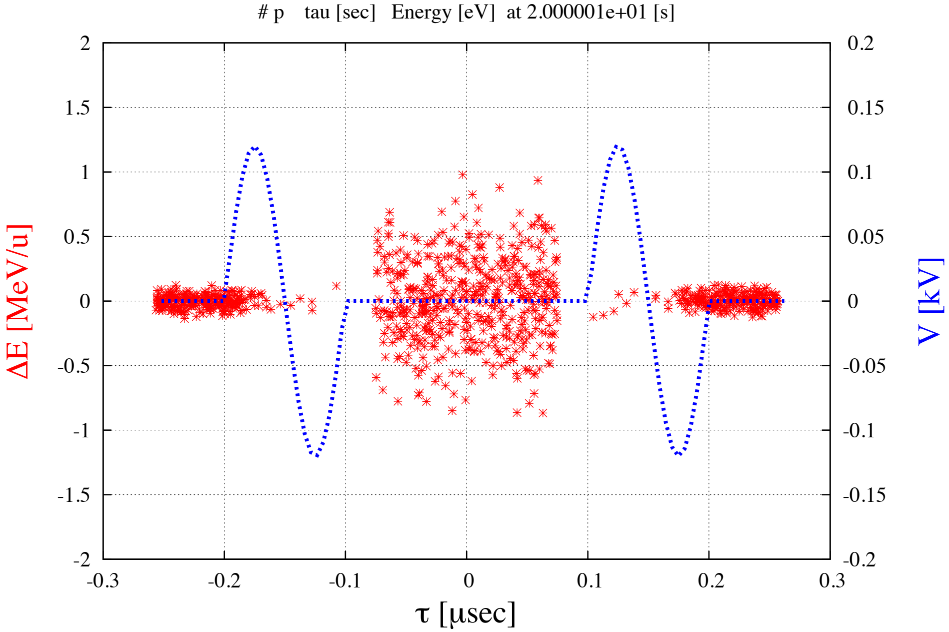


# p tau [sec] Energy [eV] at 1.980002e+01 [s]
Time=19.8 sec
ΔE [MeV/u]
V [kV]
τ [μsec]

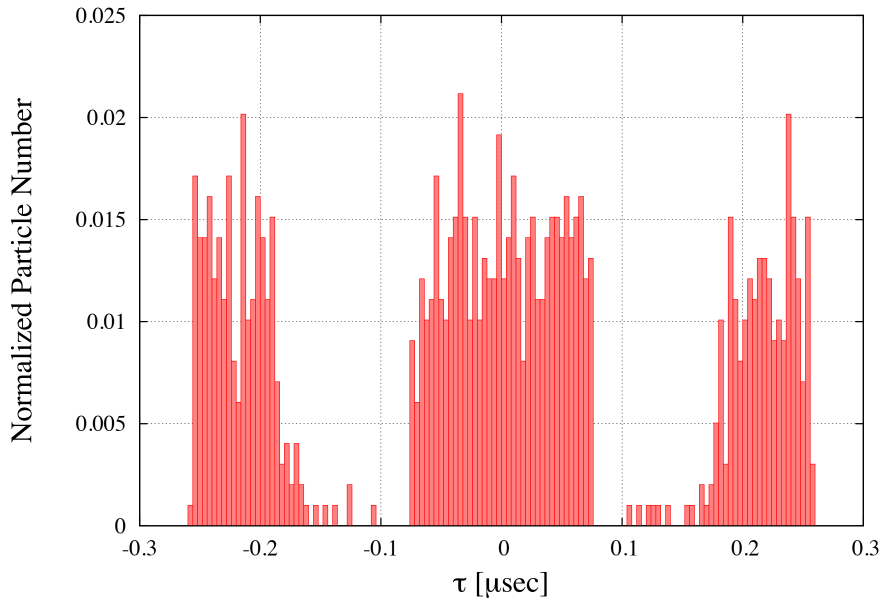


Normalized Particle Number
τ [μsec]

Time=20.0 sec



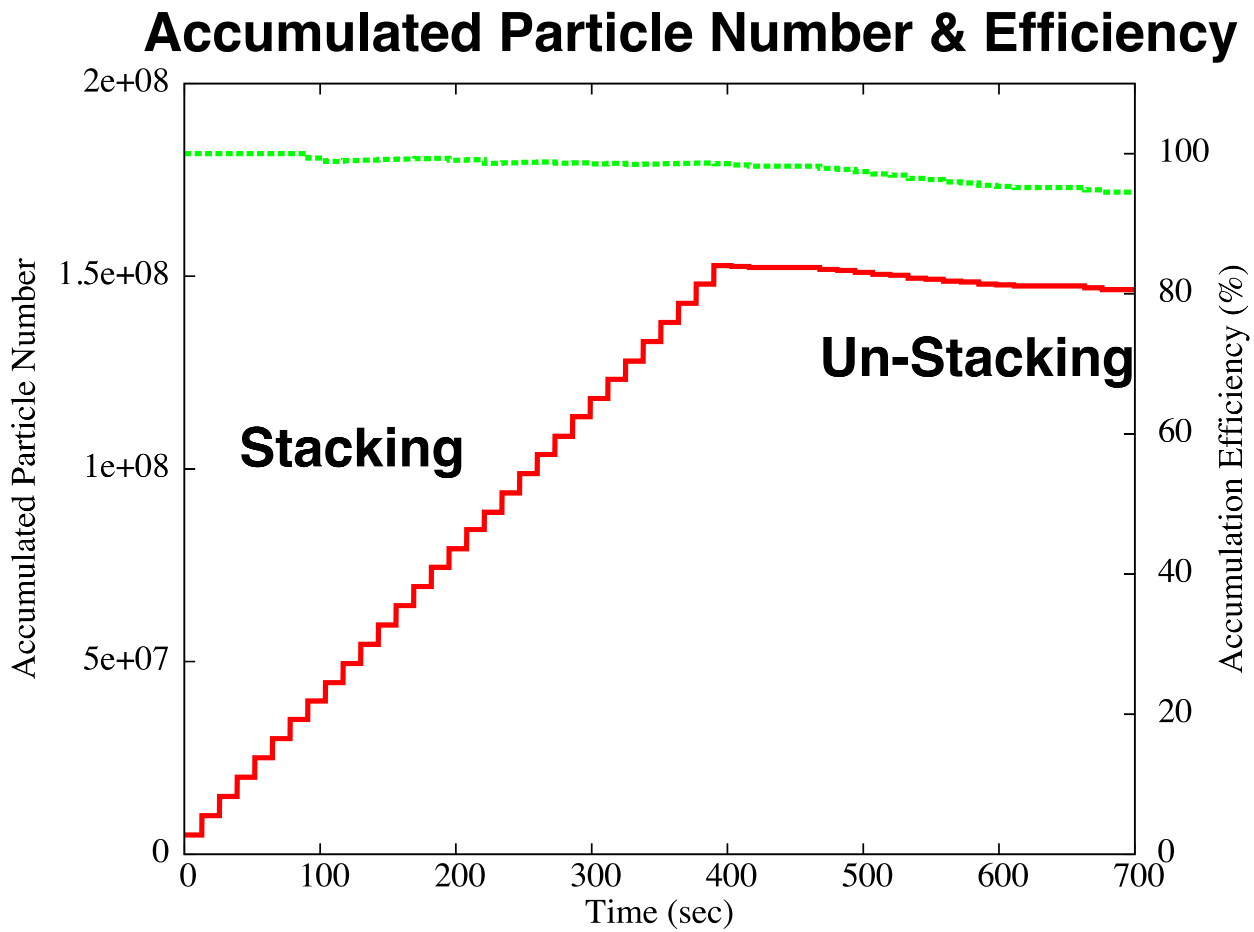
p tau [sec] Energy [eV] at 2.000001e+01 [s]
ΔE [MeV/u]
V [kV]
τ [μsec]
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.3
-0.2
-0.1
0
0.1
0.2
0.3



Normalized Particle Number
τ [μsec]
0.025
0.02
0.015
0.01
0.005
0
-0.3
-0.2
-0.1
0
0.1
0.2
0.3

ESR Moving Barrier Case, Gain=120 dB
Vbb=2kV, Ie=0 A

(2 kV BB system is under construction & Experiment could be in 2014)



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 batchs). 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).

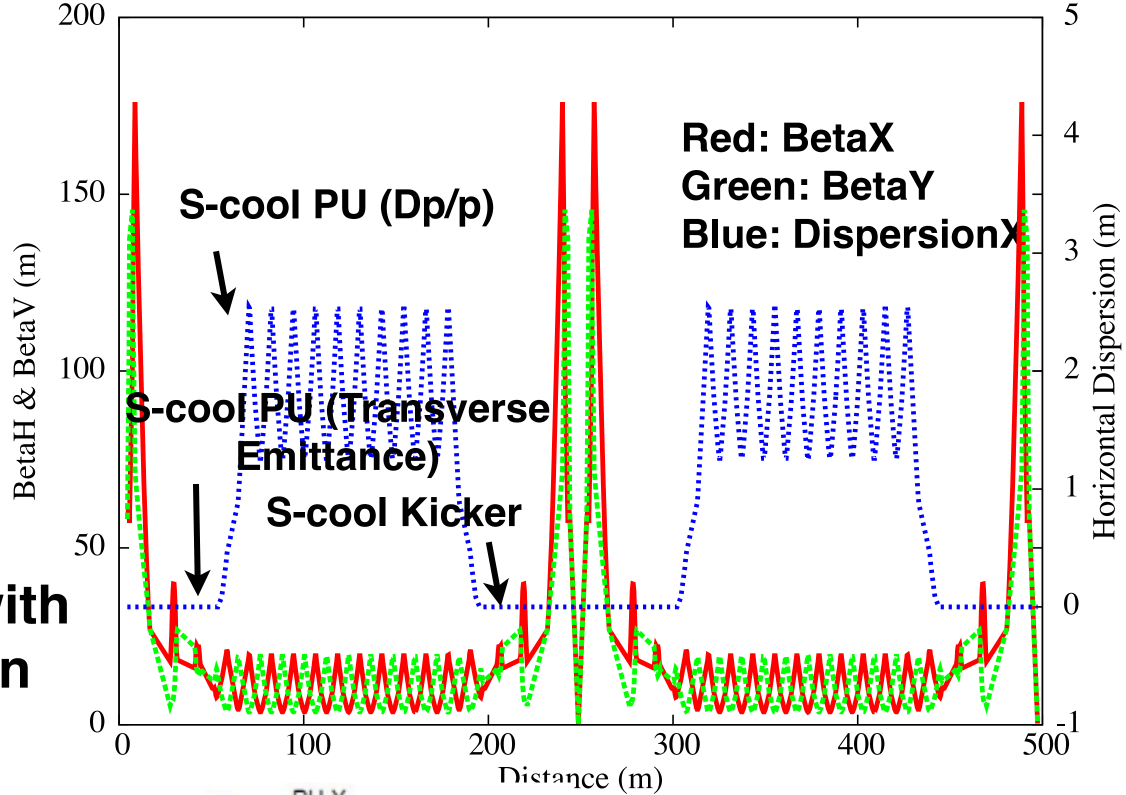
3. Compensation of IBS Diffusion

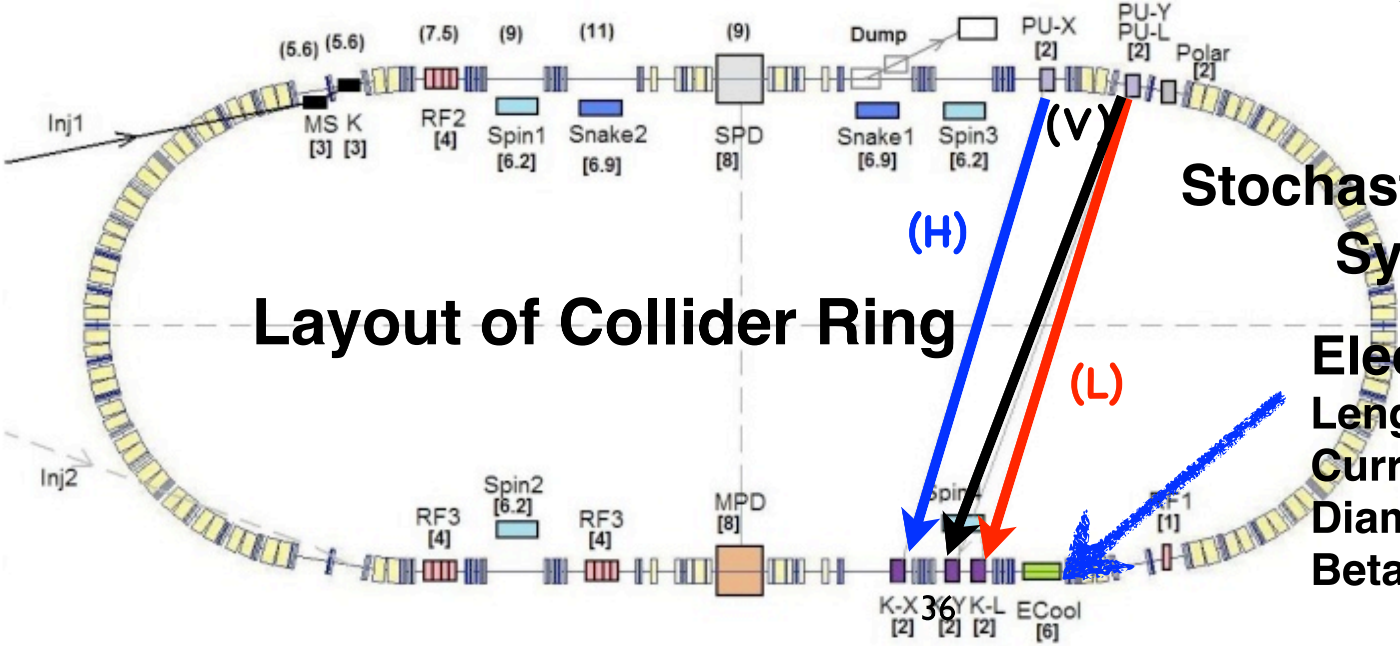
At the collider mode, the Intra Beam Scattering diffusion effects have to be compensated by beam cooling.

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



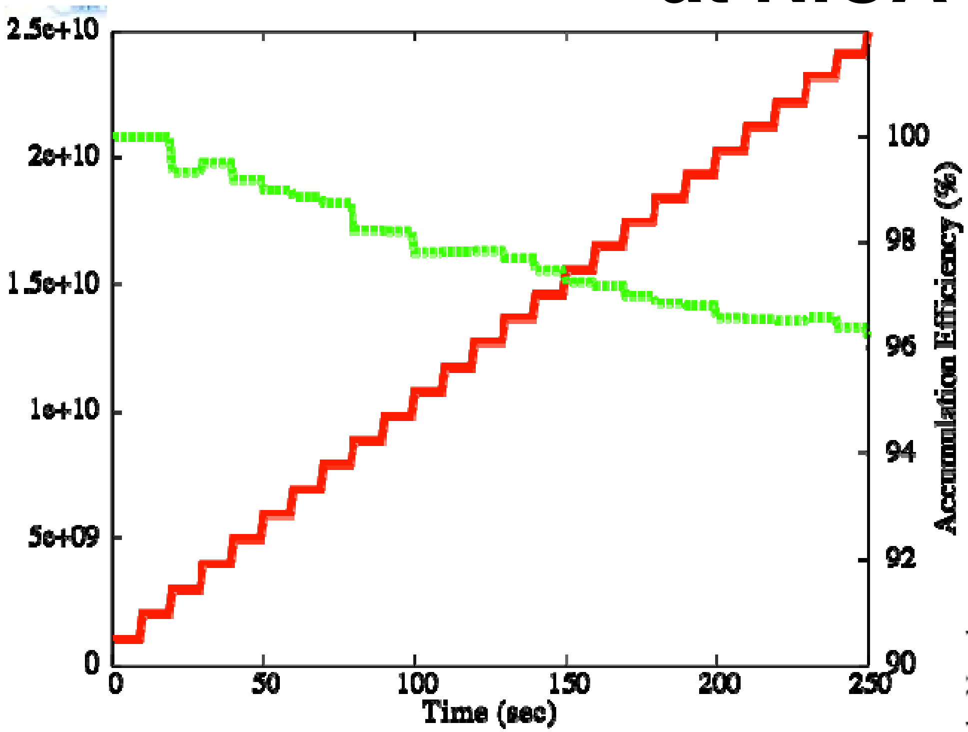


Stochastic Cooling System

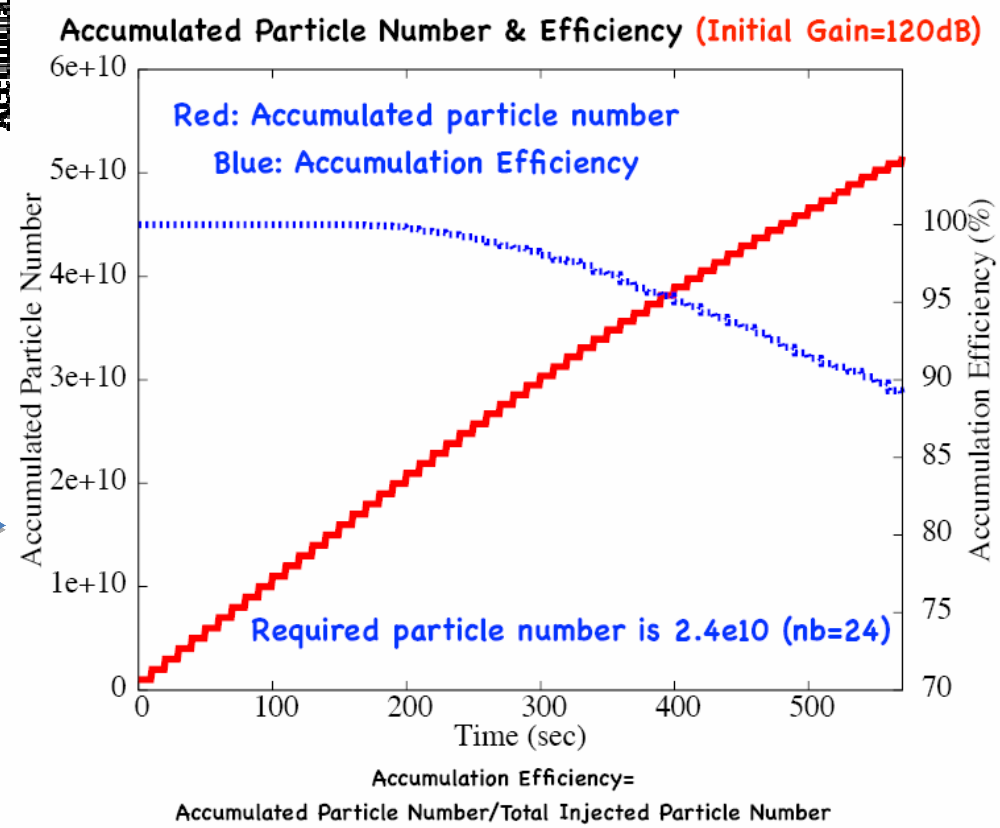
Electron Cooler

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

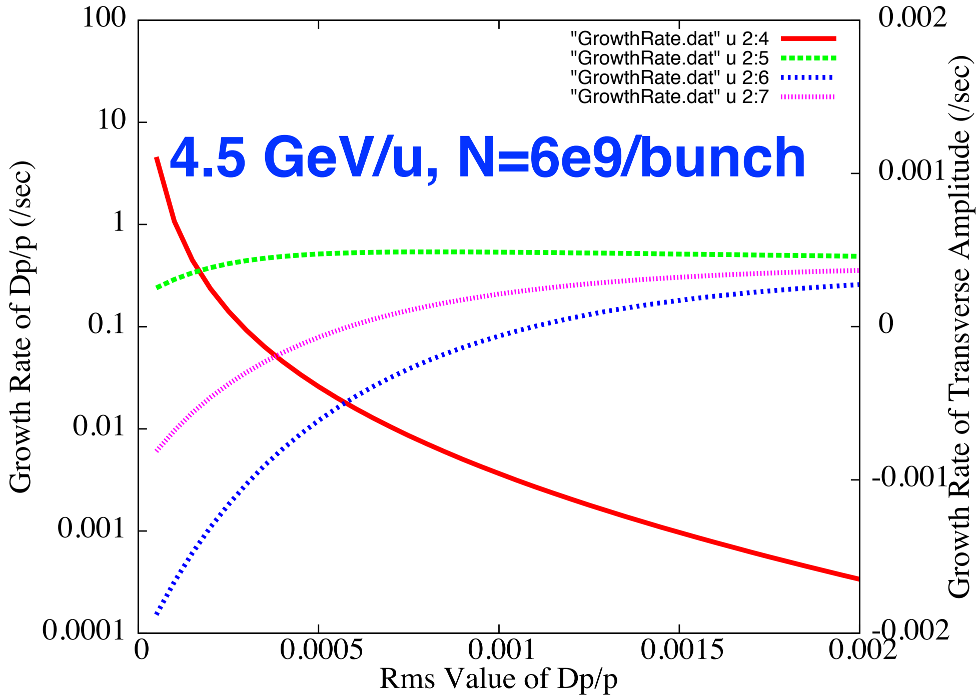


Beam stacking with stochastic cooling @3.5 GeV/u

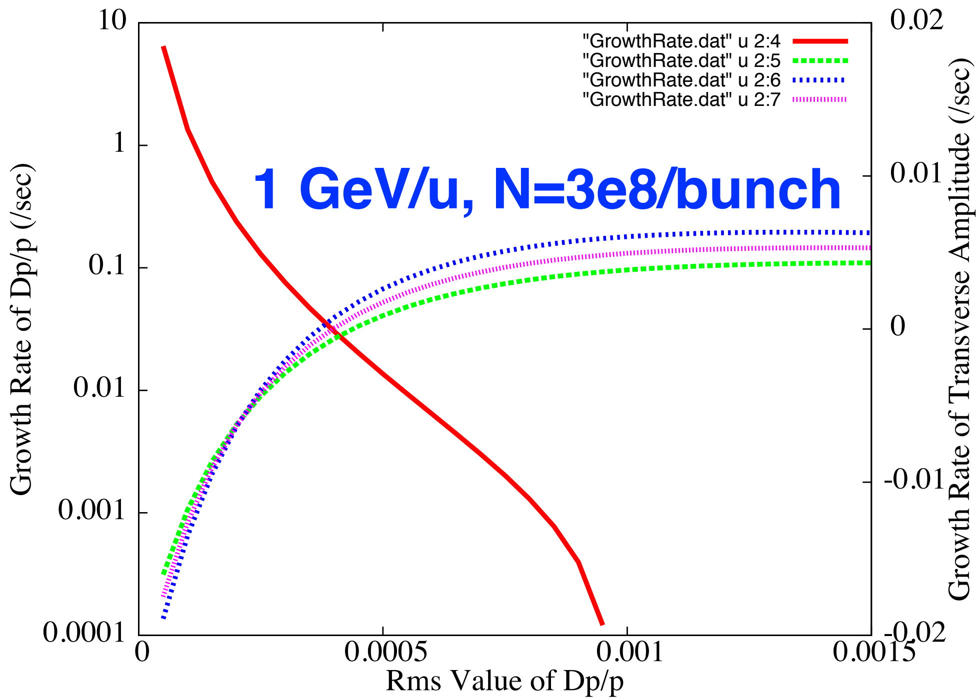
Intra Beam Scattering (IBS) effect

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

Bunched Beam IBS Growth Rates (Calculated with Martini/Parzen Formulae)
EmittanceH=1.2 Pi mm.mrad, EmittanceV=0.9 Pi mm.mrad
Bunch length (rms)=0.6 m



Red: 1/tauP, Green: 1/tauH, Blue: 1/tauV
Pink: (1/tauH+1/tauV)/2.0
1/tauP (dp/p=1e-3)= 3.65E-03 (tau=270 sec)
1/tauH (dp/p=1e-3)= 4.86E-04 (tau=2050 sec)
1/tauV (dp/p=1e-3)= -6.1E-05 (tau=-16000 sec)



Red: 1/tauP, Green: 1/tauH, Blue: 1/tauV
Pink: (1/tauH+1/tauV)/2.0
1/tauP (dp/p=1e-3)= -7.95E-05 (tau=-12000 sec)
1/tauH (dp/p=1e-3)= 3.86E-03 (tau=260 sec)
1/tauV (dp/p=1e-3)= 6.03E-03 (tau=166 sec)

Short Bunch Formation from the Accumulated Coasting Beam at 3.5 GeV/u

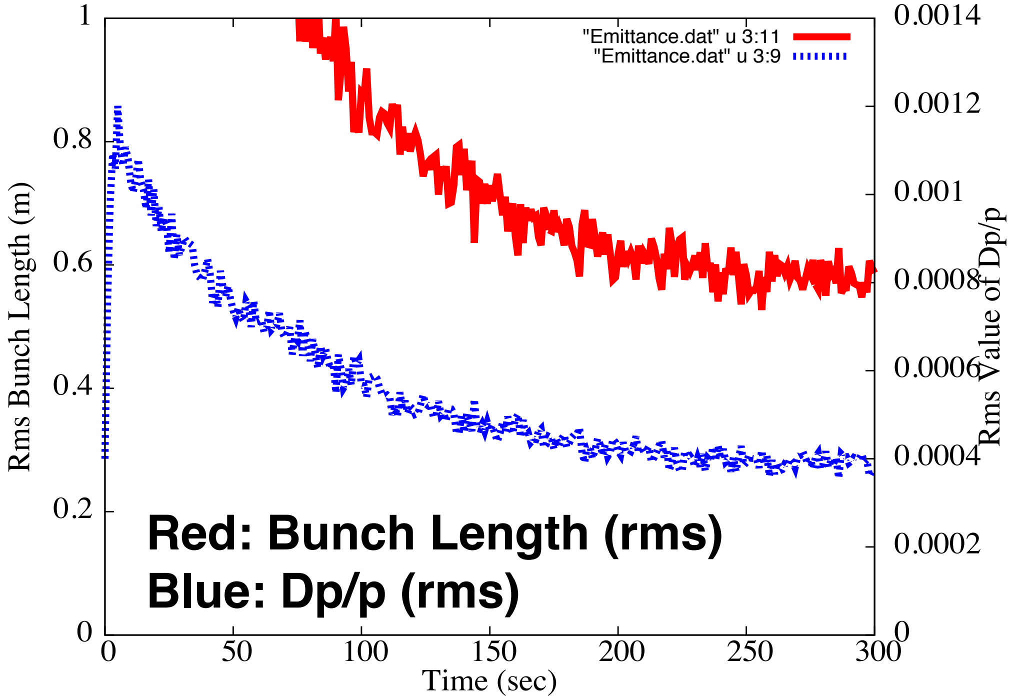
(First Step Harmonic=24)

Initial beam parameters after Barrier Bucket Accumulation

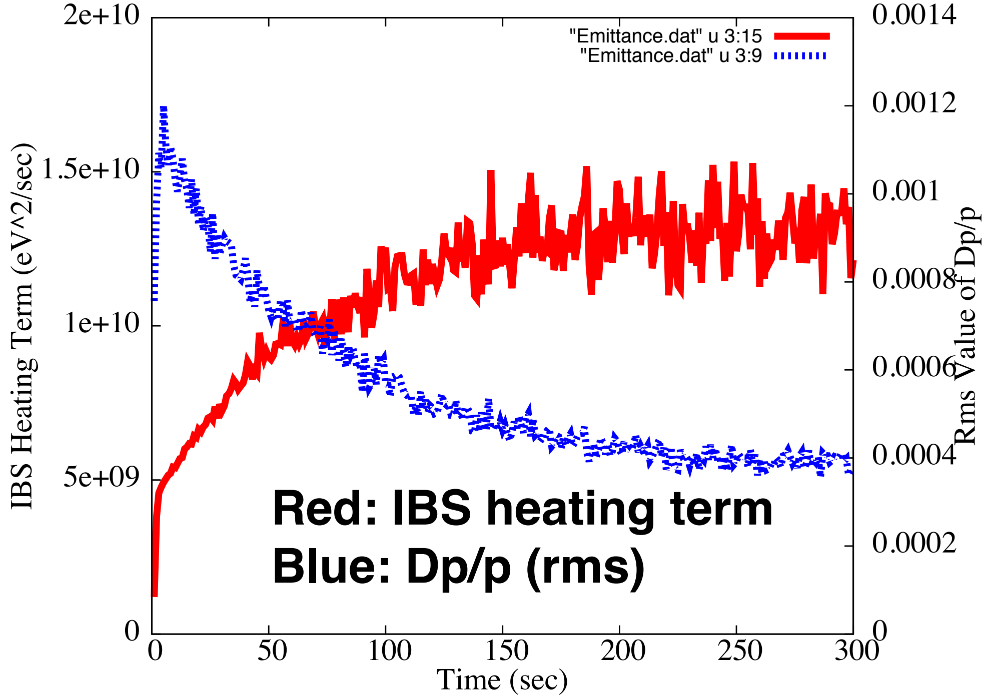
- **Dp/p (rms)=4e-4 (Gaussian)**
- **Bunch shape=Coasting beam (Uniform Random)**

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



Evolution of IBS Heating Term & Dp/p



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

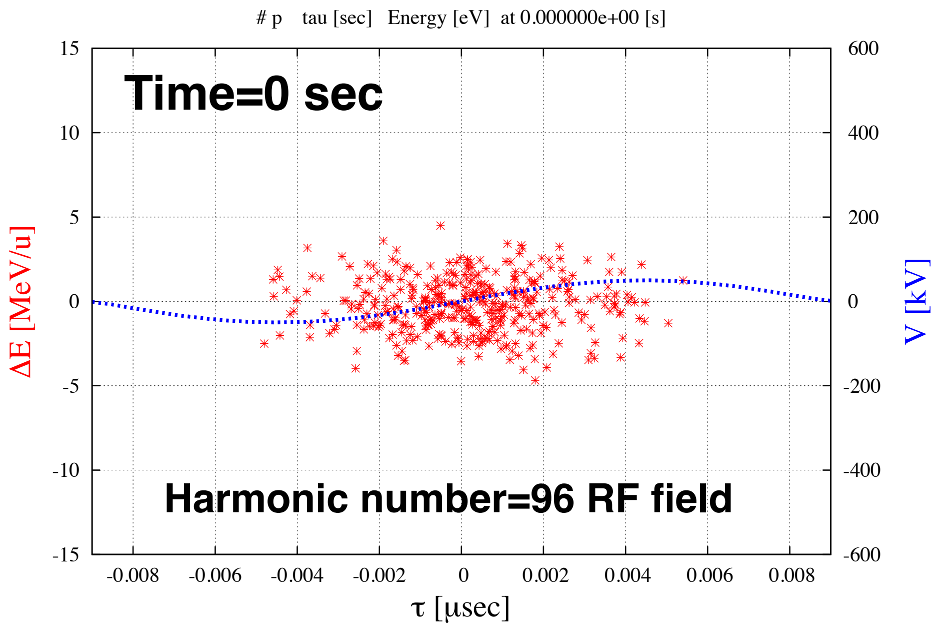
Dp/p (rms)=4.01e-4 (rms)

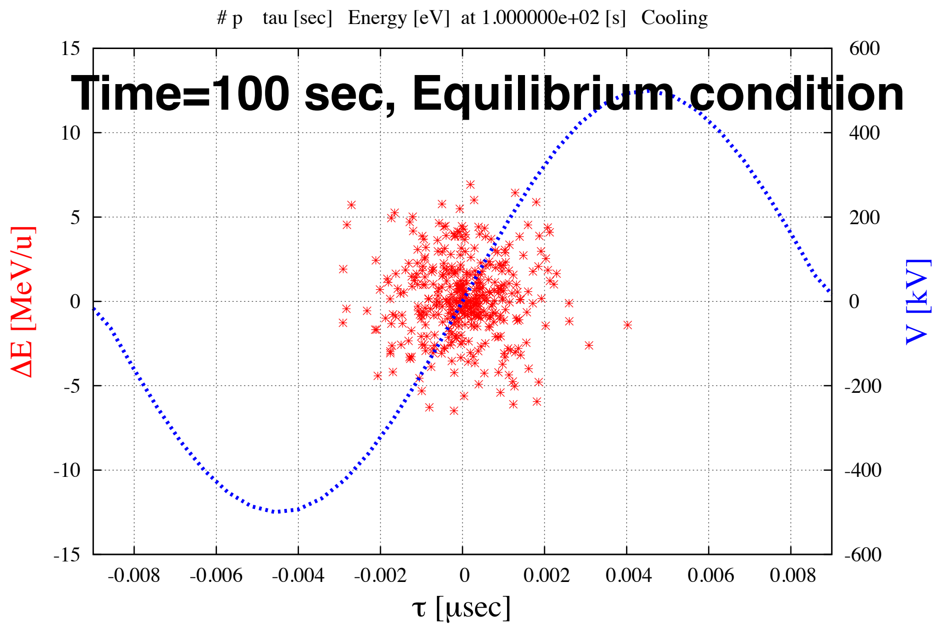
Bunch length=0.56m (rms)

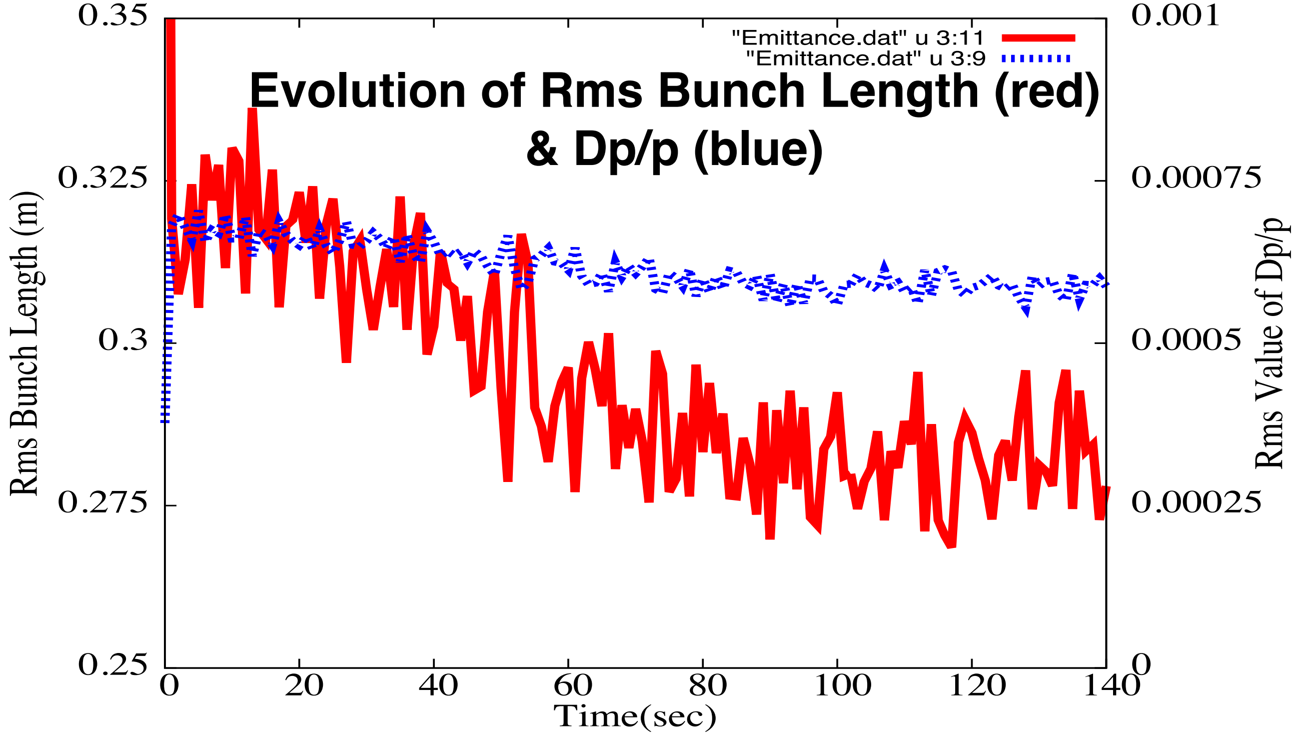
1. Gain of stochastic cooling system is kept constant as 80 dB.
2. RF voltage is increased from 50 kV to 500 kV (harmonic=96) with time constant 1 sec for the adiabatic bunching.

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)

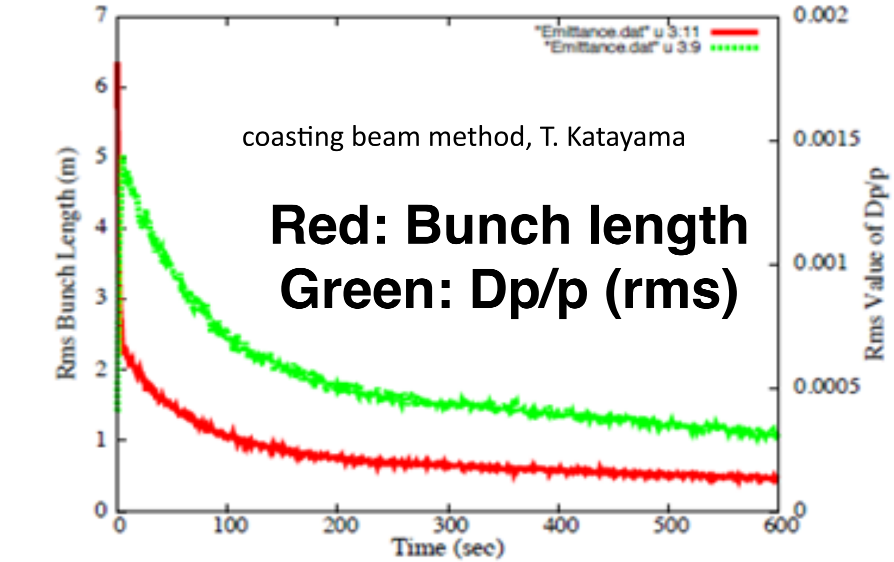




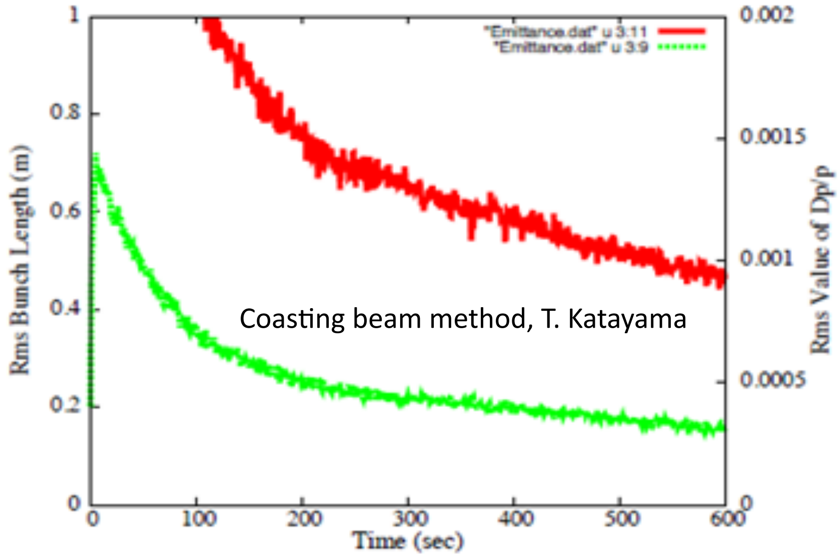


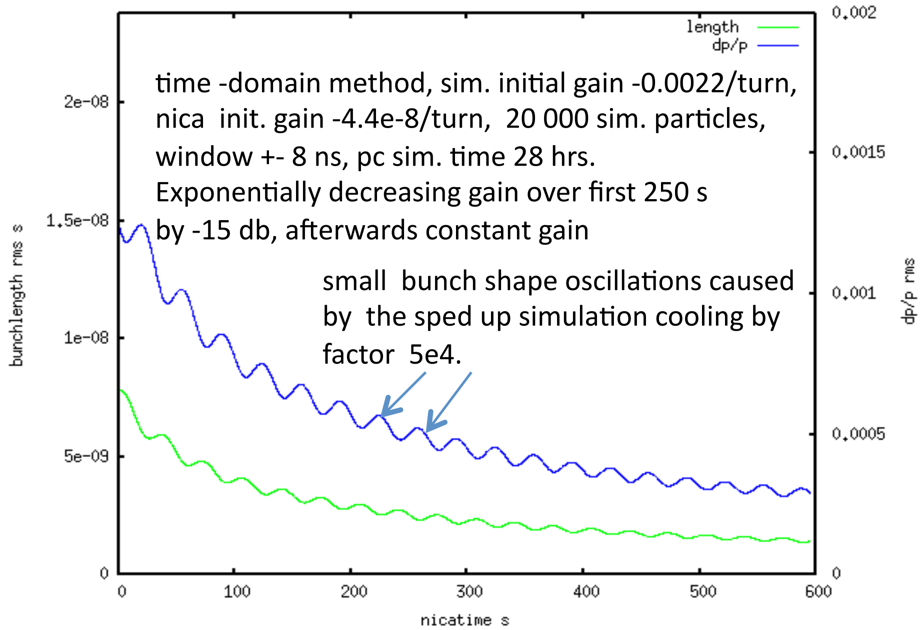
Comparison of Results by Lars and Takeshi

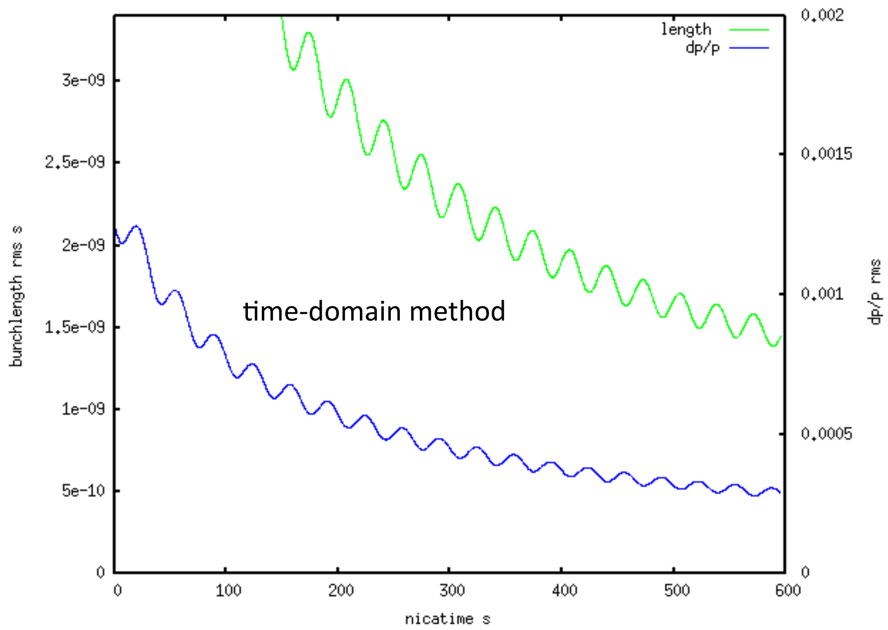
L. Thorndahl: Contribution to this workshop



Bunch length scale enlarged

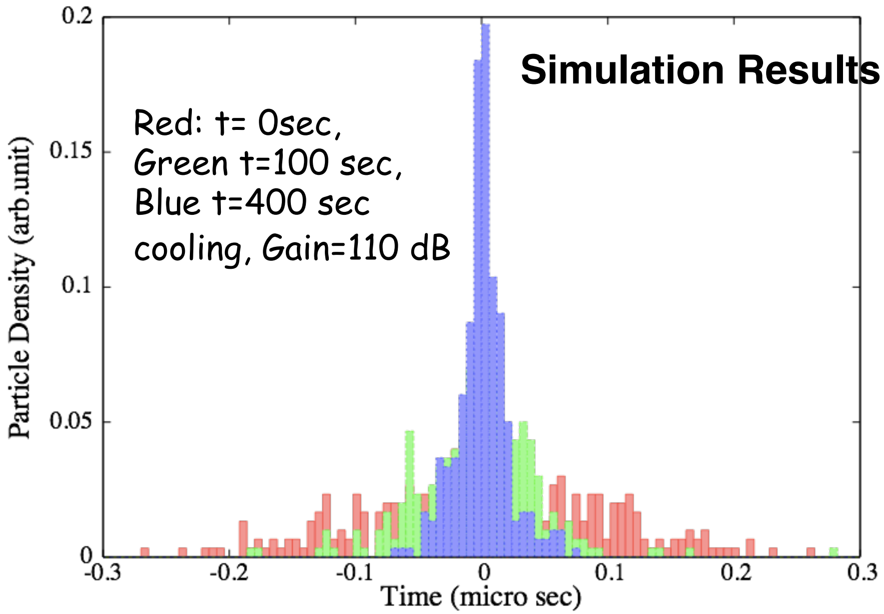




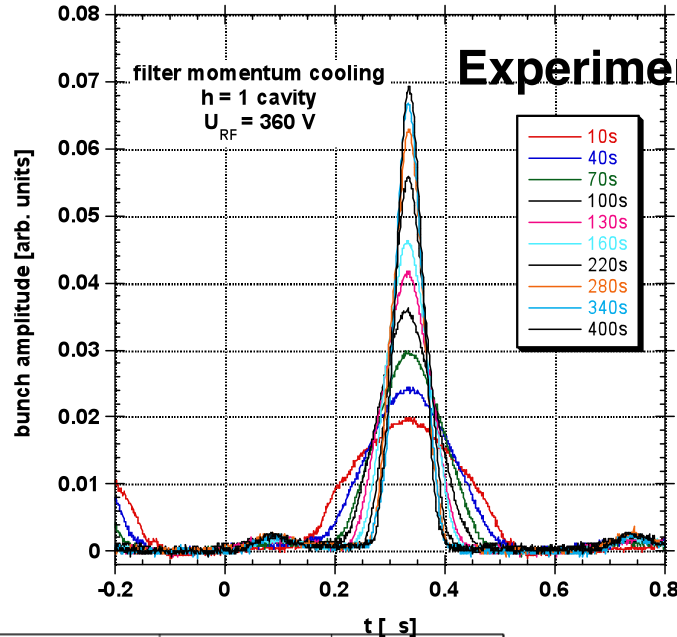


Beam Bunching Experiment with Stochastic Cooling at COSY

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

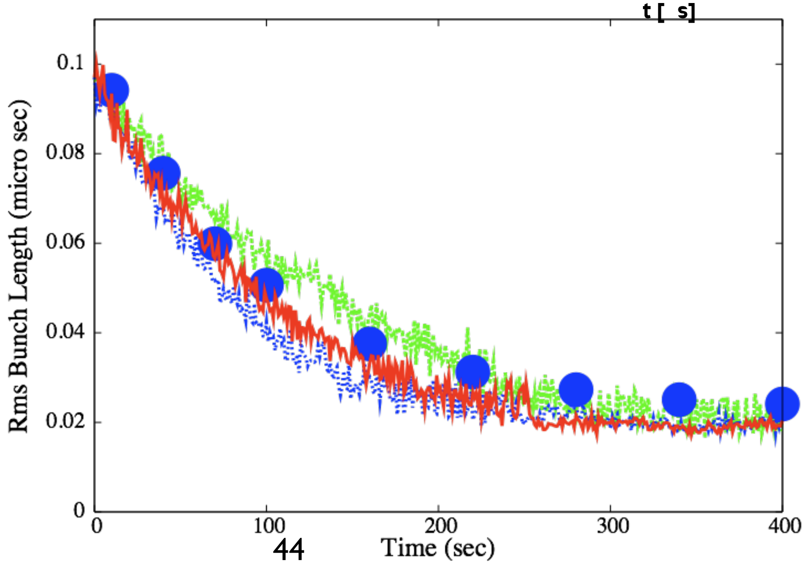


Experimental Results



Evolution of Bunch Length

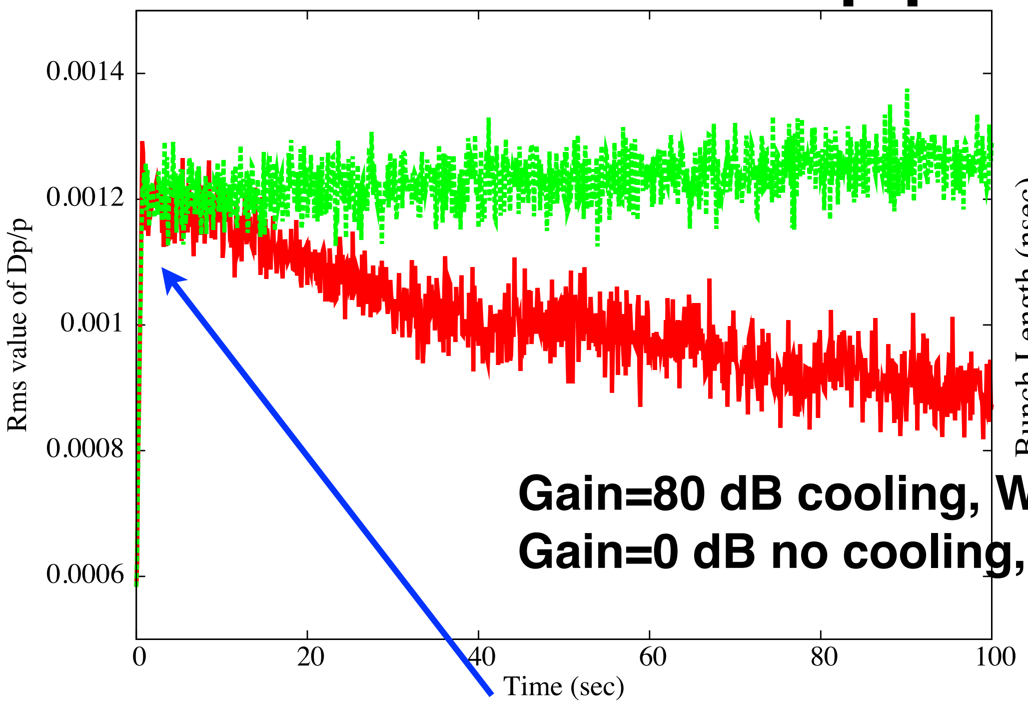
Red: Gain=110 dB,
Green: 107 dB
Blue:112 dB
Blue points: Measured data



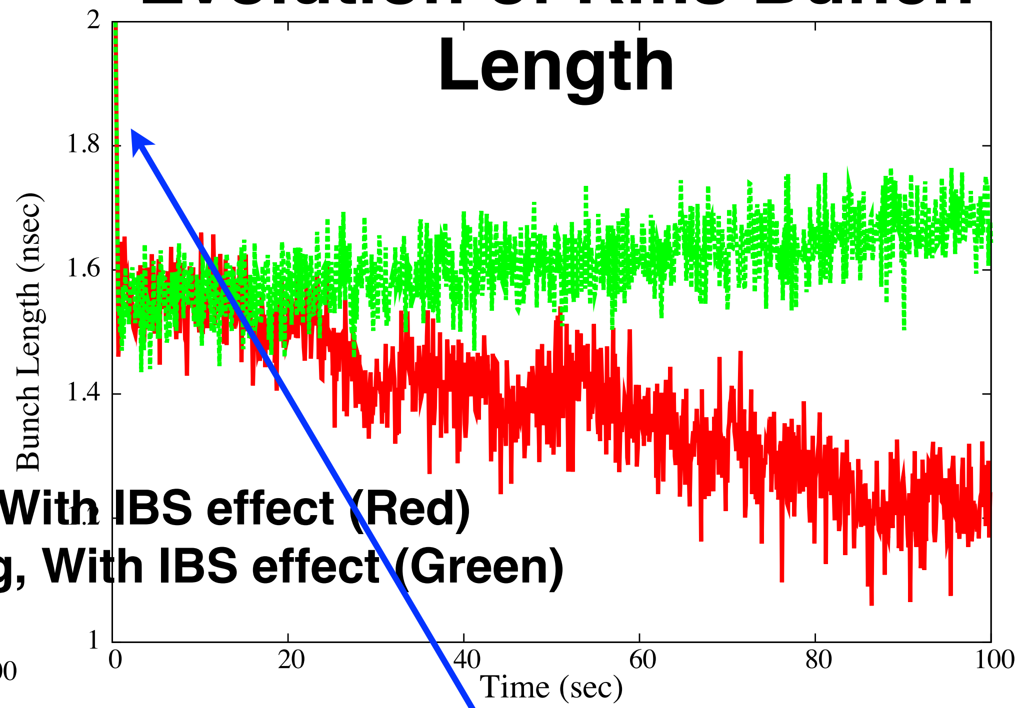
Suppression of Beam Heating due to IBS with Stochastic Cooling (Vrf=500 kV)

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

Evolution of Rms Dp/p



Evolution of Rms Bunch Length



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.

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.

Space charge electric field and potential

In the Laboratory Reference Frame, the longitudinal electric field due to the space charge is given by

$$E_z(z) = -\frac{g}{4\pi\varepsilon_0\gamma^2}\frac{\partial\rho(z)}{\partial z} \qquad g = 1 + 2.0\ln(b/a)$$

where g is the geometric factor. From this electric field the energy variation of ions per unit time is derived and the synchrotron motion is represented by following equation.

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

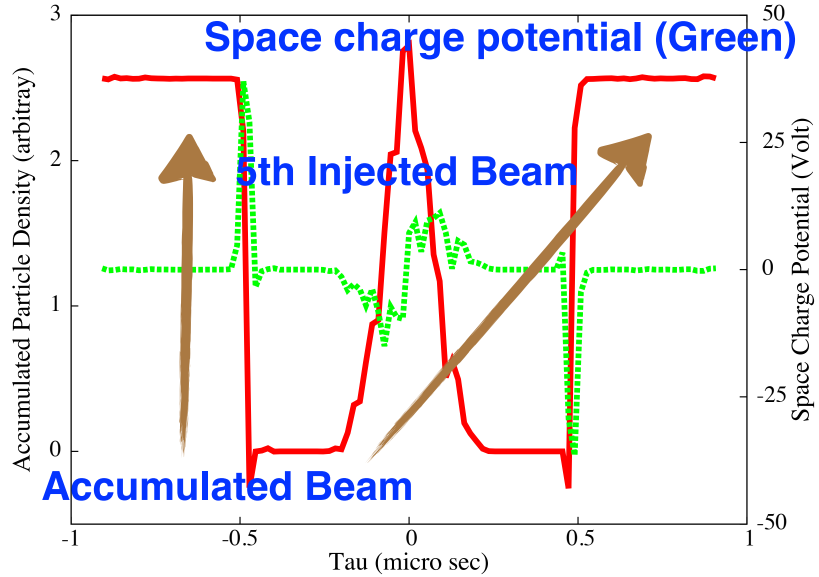
$$\frac{d\tau}{dt} = \frac{\eta}{\beta^2}\frac{\Delta E}{E_0}$$

Here the Vrf means the external RF field, Ecool 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.

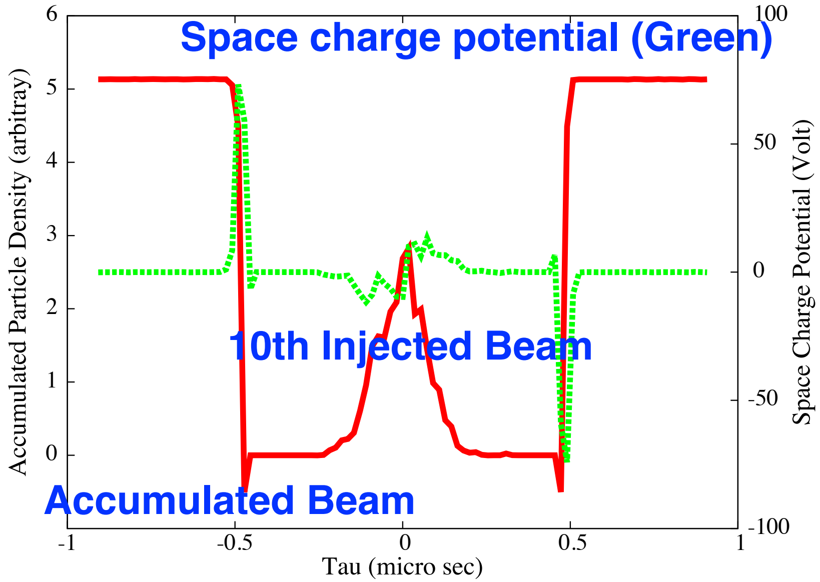
Particle tracking has been done with Particle-In-Cell method.

Space Charge Effects during BB stacking of 1.5 GeV/u 197Au79+ ion in NICA Collider

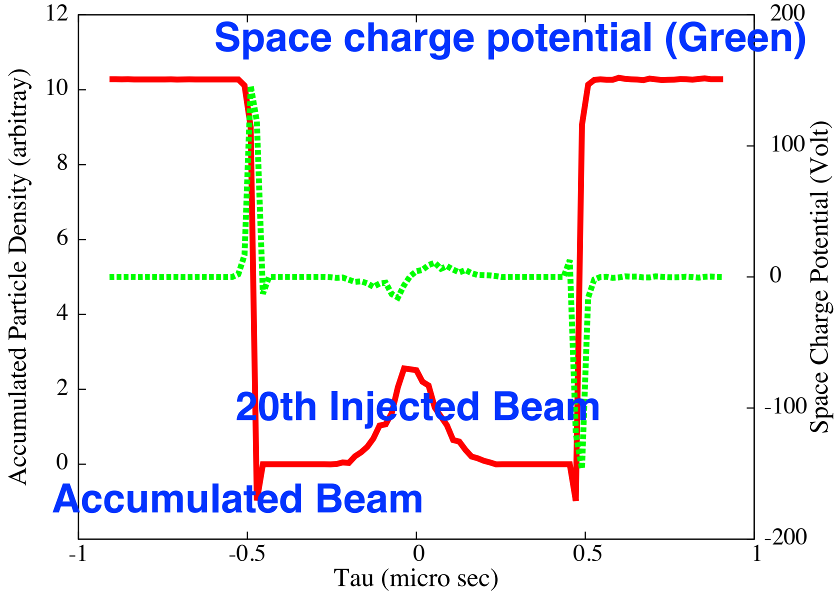
Time=50 sec (5 times injection)



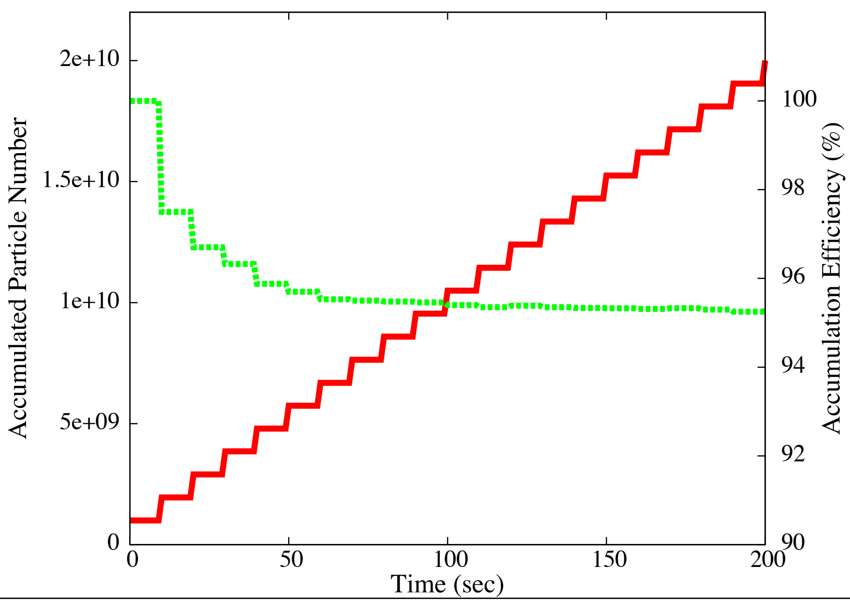
Time=100 sec (10 times injection)



Time=200 sec (20 times injection)

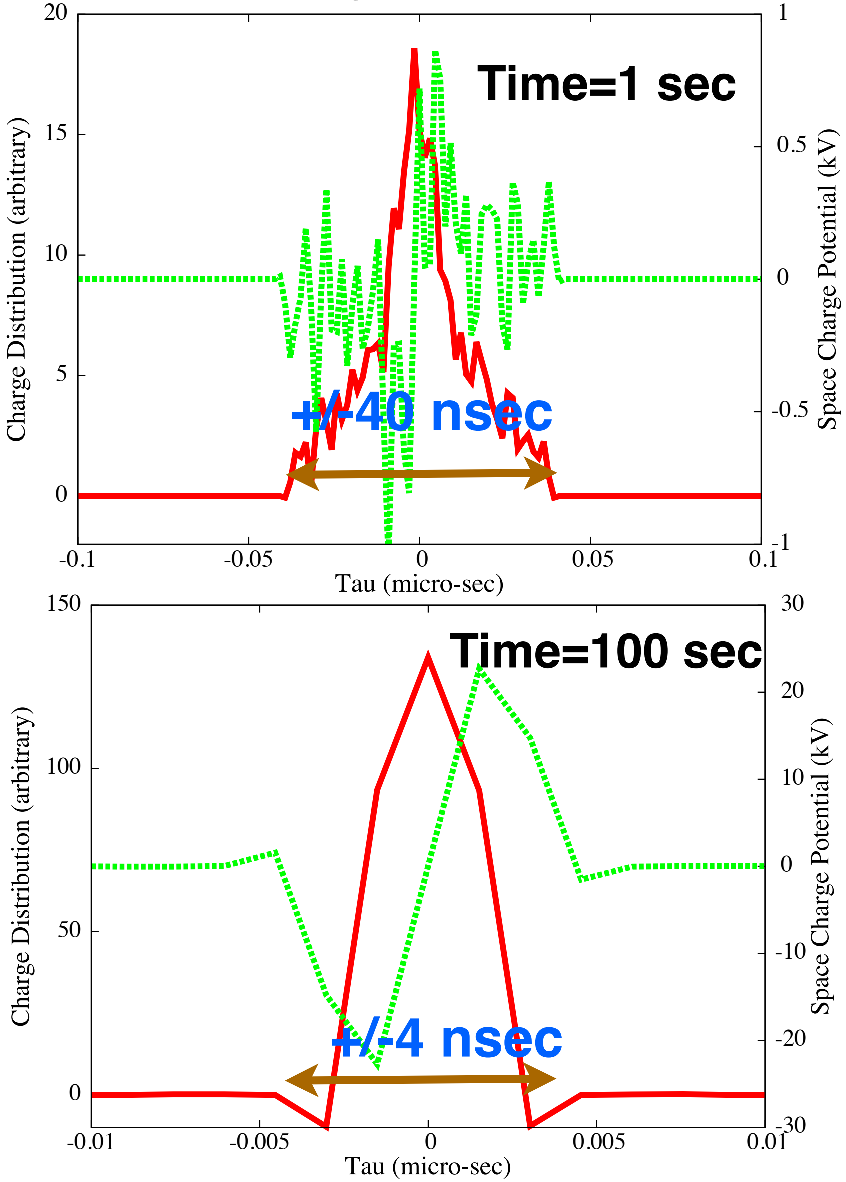


Accumulated Particle Number & Efficiency

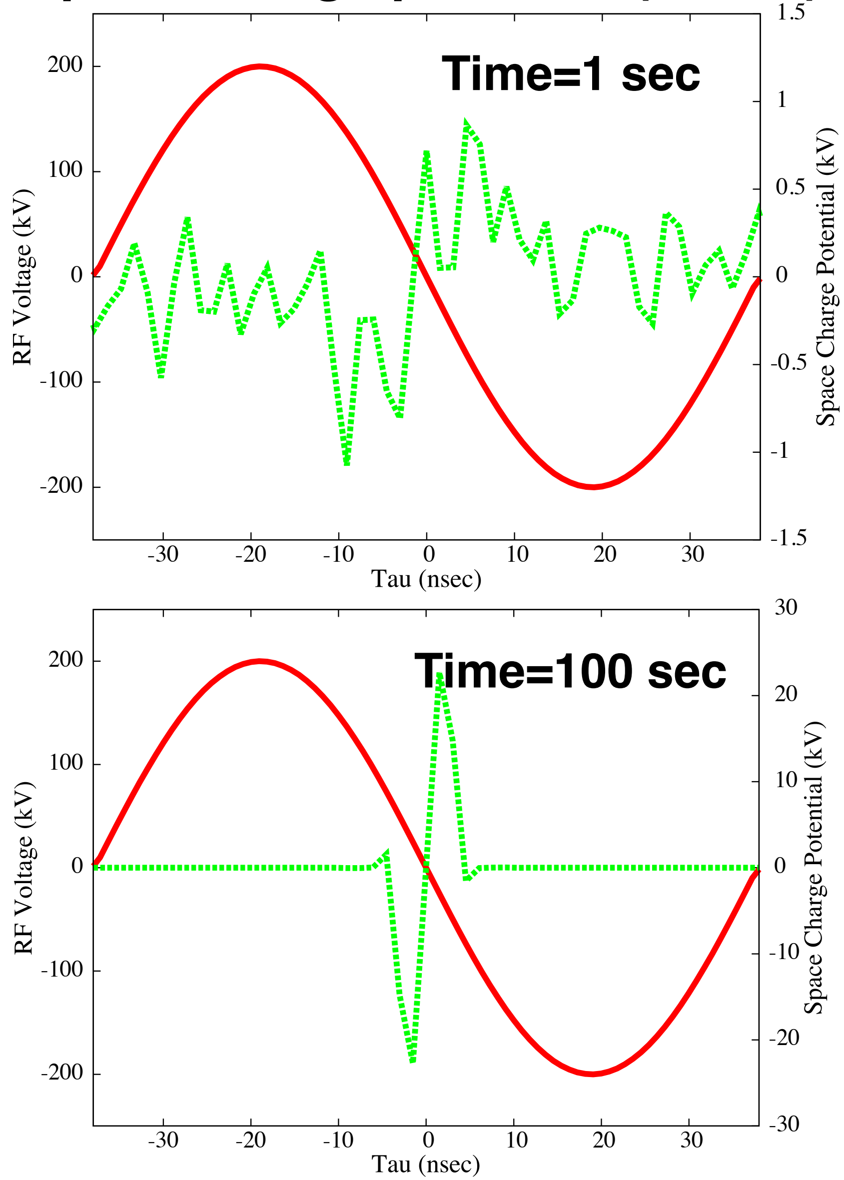


Space Charge Effects during Short Bunch Formation of 1.5 GeV/u 197Au79+ ion in NICA Collider

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



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



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).