Beam Cooling at NICA Collider

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Outline

1. Goals & Fundamental Parameters
2. Barrier Bucket Accumulation
3. Short Bunch Formation
4. Space Charge Problem
5. Conclusion

Fundamental Parameters of Collider

Ion species	197Au79+	Transverse Emittance	1.0 Pi mm.mrad
Operation Energy	1-4.5 GeV/u	Momentum spread	1.5E-03 (rms)
Circumference	503.04 m	Beta function at colliding point	0.35 m
Number of Ion/bunch	3e8-3e9	Expected luminosity	~1e27/cm2.sec
Number of bunch/ring	24	Bunch length (rms)	0.6
Injector	NUCLOTRON	Injection energy	1.0~4.5 GeV/u
Injected intensity	1e9/5sec.cycle	Emittance	0.5 Pi mm.mrad (?)
Momentum spread	3.0E-04 (rms)	Bunch length (h=1)	300 nsec

Fundamental issues to be solved.

1. How do we make such short bunch with required ion number ?
2. How do we keep the luminosity during the experimental period against the diffusion effects such as IBS ?

Circumference=503.04 m

Tune Values (Qx/Qy)=9.440/9.44

Transition Gamma=7.091 (fixed)

Max BetaX Function=176.06m

Max BetaY Function=145.43

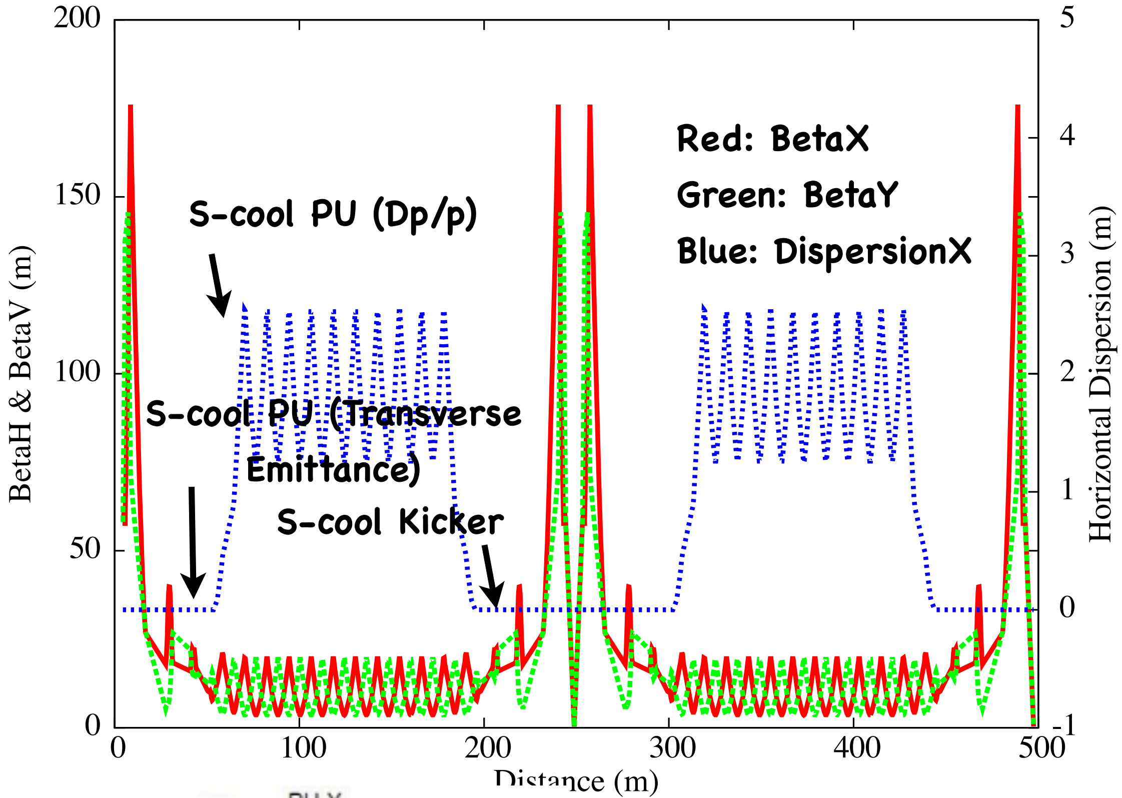
Min BetaX Function=0.35 m

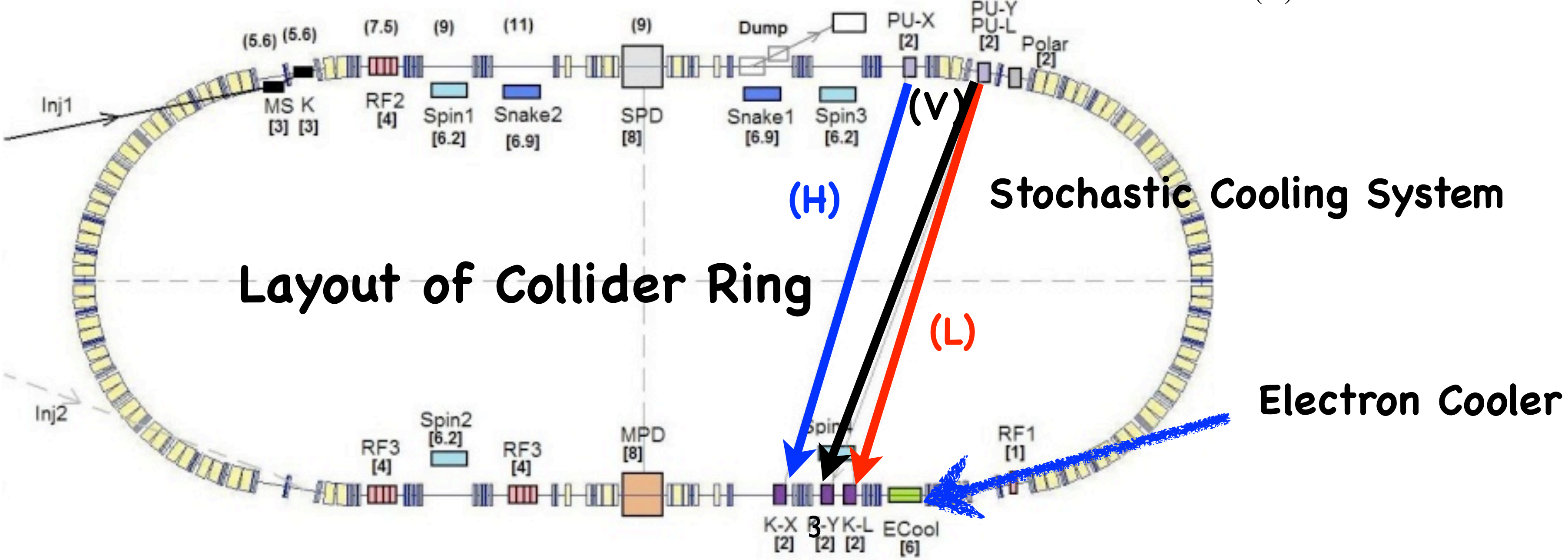
Min BetaY Function=0.35 m

Max DispersionX=2.50 m

Max DispersionY=0.145 m

NICA Collider FODO Lattice





Beam Parameters for Various Energies for NICA Collider

Circumference=503.04 m, Ring Momentum Compaction=0.0199,

Gamma-t=7.09, Dp/p(rms)=1.5e-3

Path Length from PU to Kicker=170m

Energy (GeV/u)	1.5	2.5	3.0	4.5
Ring Slipping Factor	0.1268	0.0537	0.0350	0.00949
Local slipping Factor (from PU to Kicker)	0.1173	0.0442	0.02546	-5.40E-05
Particle Number/ bunch	3.00E+08	1.50E+09	2.50E+09	6.00E+09
Coasting Equivalent Particle Number	7.26E+10	3.63E+11	6.05E+11	1.45E+12

Bunching Factor=Circumference/2sqrt(Pi)/SigmaS/BunchNumber=10.2

Nequivalent=BunchNumber*IonNumber/Bunch*BunchingFactor

Coasting Equivalent Particle Number is used for estimation of momentum cooling with use of Fokker Planck solver.

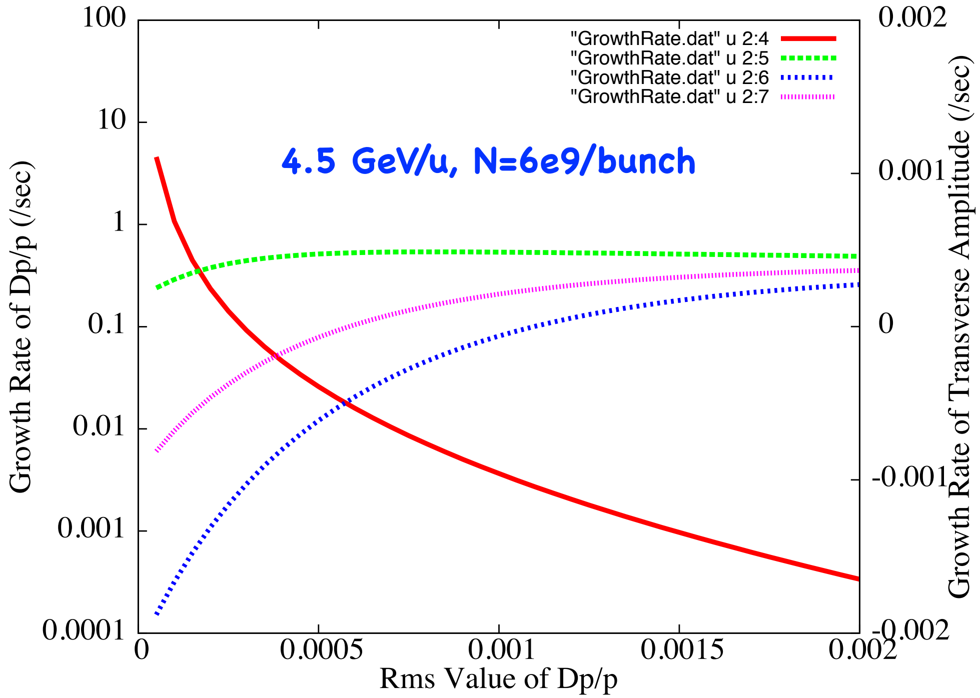
Intra Beam Scattering (IBS) effect

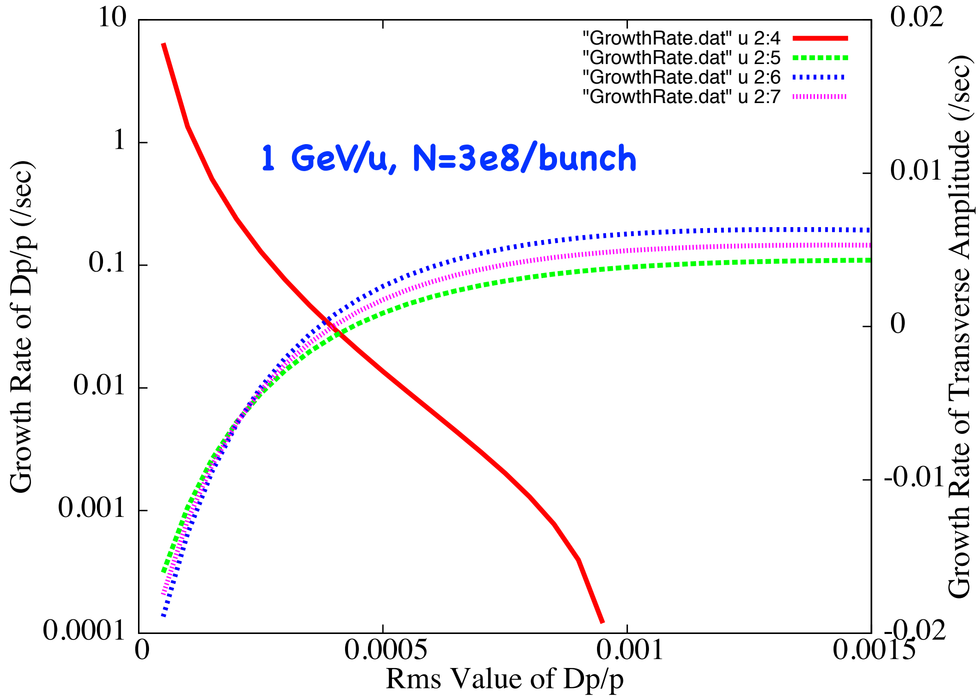
$$\frac{1}{\sigma_i}\frac{d\sigma_i}{dt} \propto \frac{NQ^4}{A^2\varepsilon_x\varepsilon_y\sigma_p\sigma_s\beta^3\gamma^4} F_i(\sigma_x,\sigma_y,\sigma_p,Lattice\ Function)$$

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

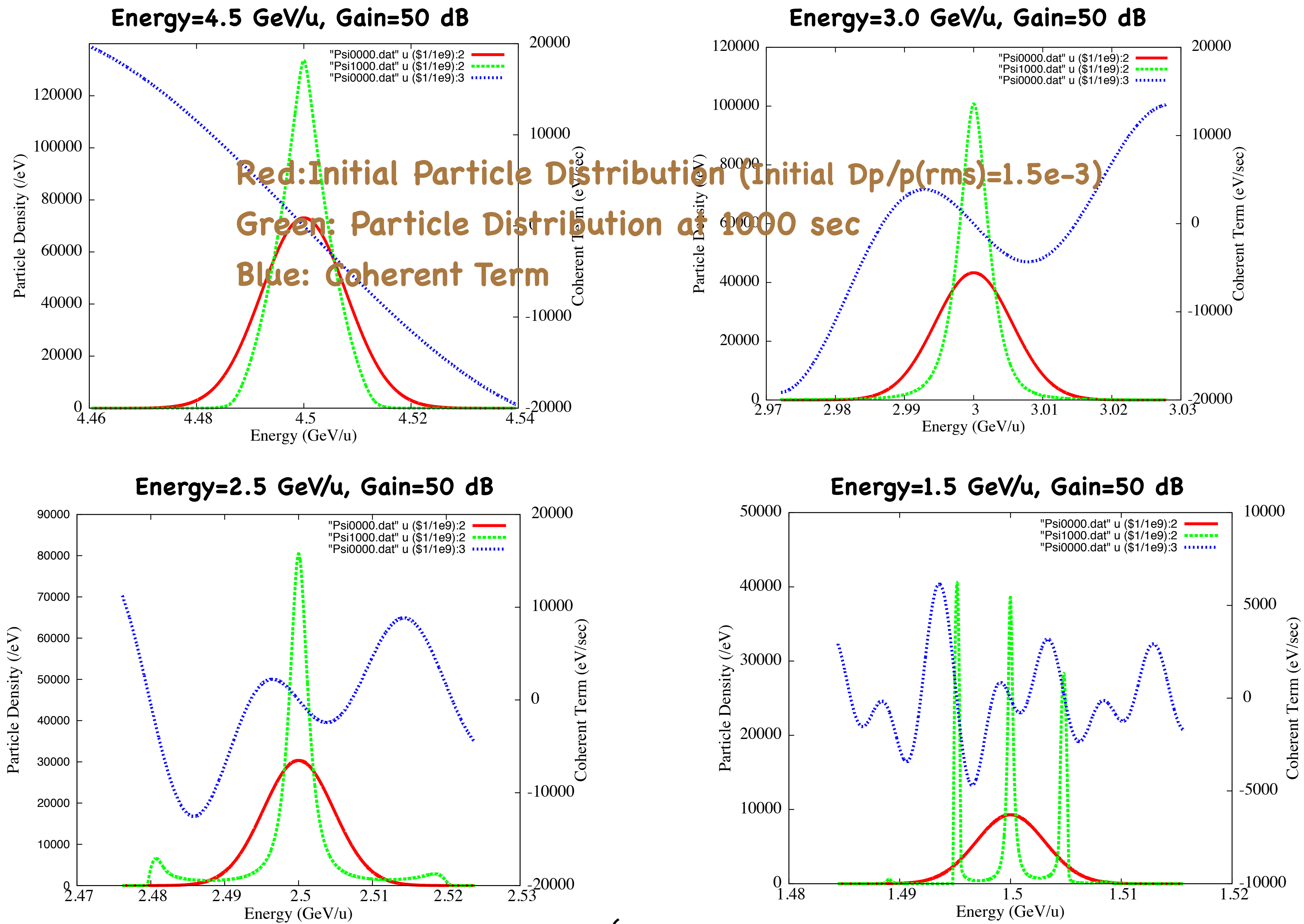




1/tauP (dp/p=1e-3)= 3.65E-03 (tau=270 sec)
1/tauH (dp/p=1e-3)= 4.86E-04 (tau=2050 sec)
1/tauV (dp/p=1e-3)= -6.1E-05 (tau=-16000 sec)

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)

Stochastic Cooling, Frequency Band=3-6 GHz



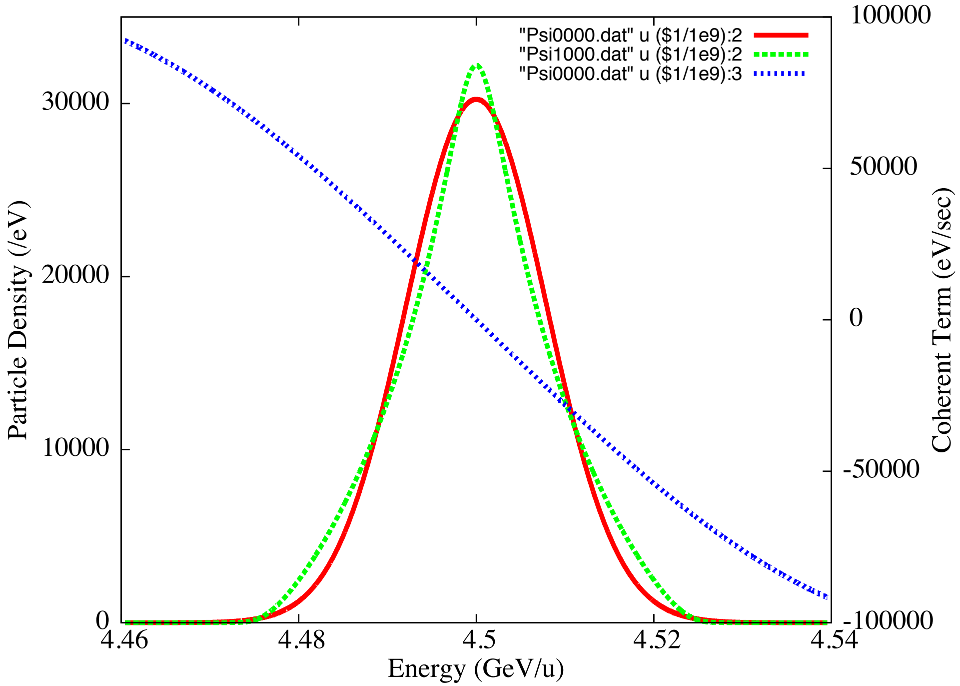
How do we compensate the IBS diffusion efffects ?

Fokker Planck Solution with Coasting Beam Approximation

4.5 GeV/u, N=3e11, Dp/p=1.5e-3 (Initial)

Band=2-4GHz, Gain=70dB, Eta=0.00927, LocalEta=-0.0018

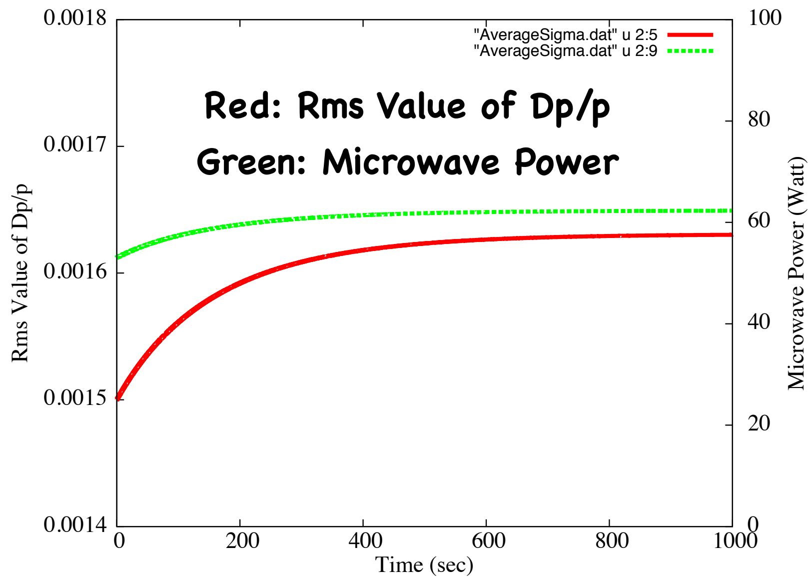
With IBS Effect

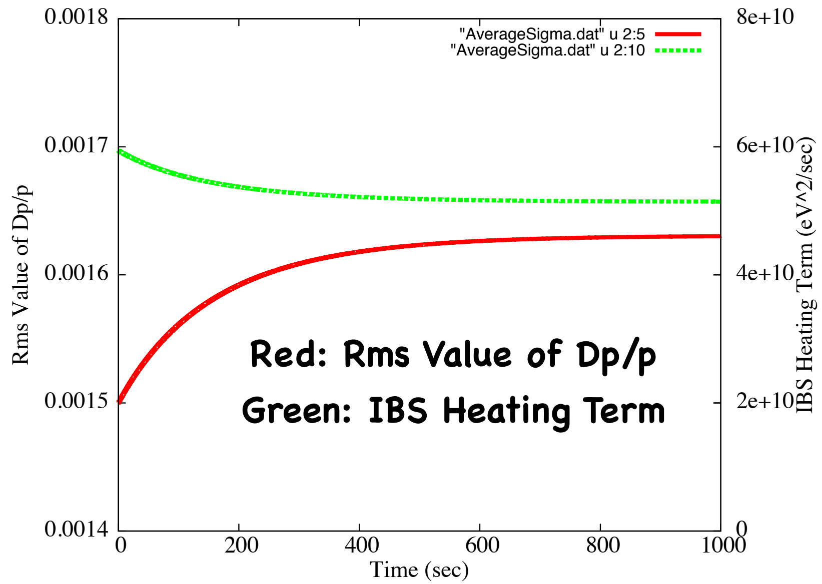


Red: Initial Particle Distribution

Green: Particle Distribution at 1000 sec

Blue: Coherent Term





The beam cooling system could not only compenasates the IBS diffusion but also could be useful for the accumulation and short bunch formation. Particle tracking method.

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 Schottky, Thermal and IBS diffusion

q : *Chrage State of Ion*
η : *Ring Slipping Factor*
$V(\tau)$: *Barrier Voltage*
$F(\Delta E)$: *Cooling Force*

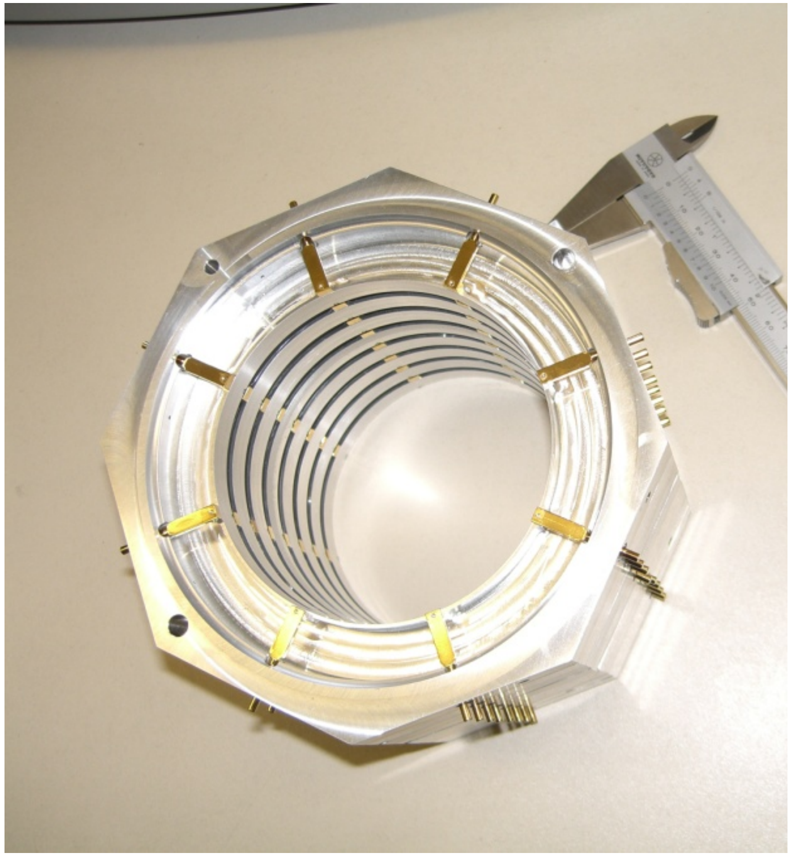
ξ_s : *Schottky Diffusion*
ξ_{th} : *Thermal Diffusion*
ξ_{IBS} : *IBS Diffusion*

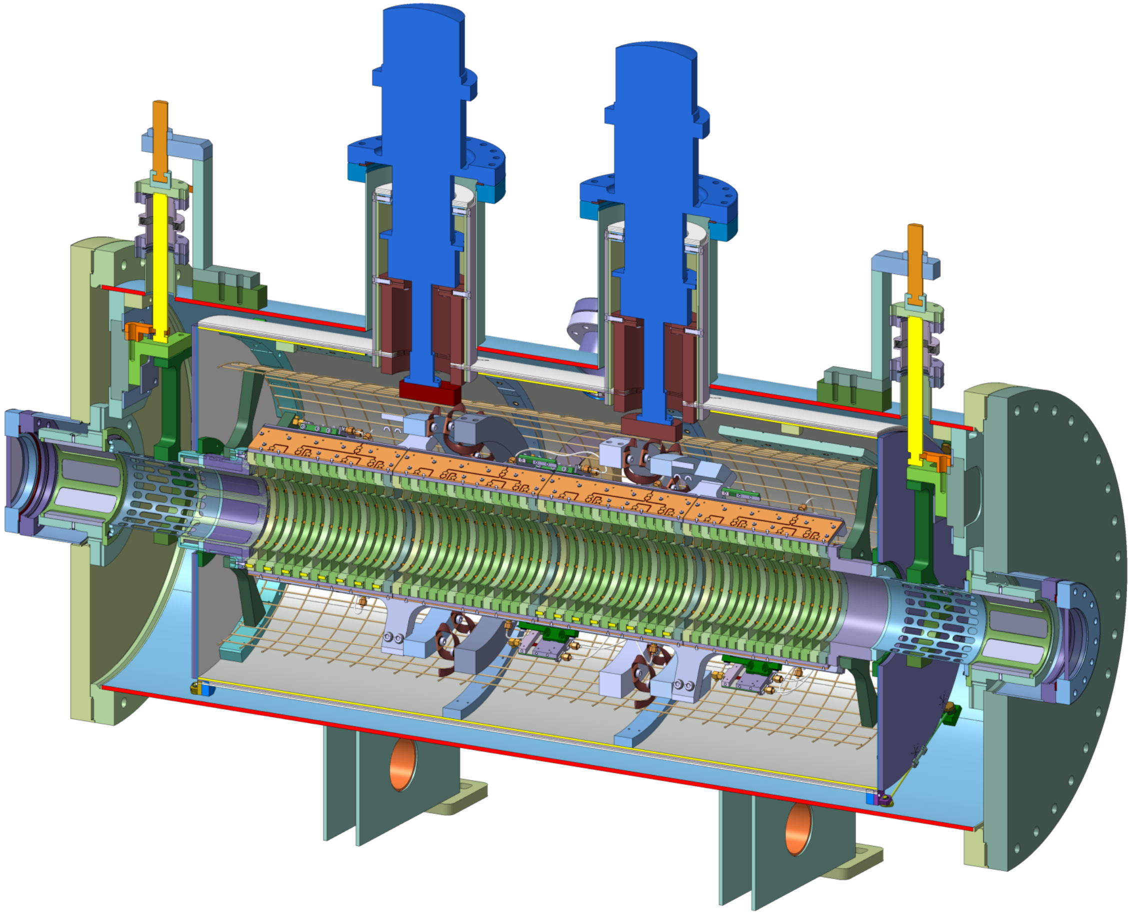
Random energy kick leads to diffusion in phase space

Parameters of Stochastic Cooling and Barrier Pulse at NICA Collider

1. Particle: 197Au79+, 4.5 GeV/u, Gamma=5.833, Beta=0.985
2. Ring circumference: 503.04 m
3. Number of injected particles from Nuclotron: 1e9 ions/bunch.
4. Injected momentum spread : 3.0e-4 (1 sigma)
5. Injected bunch length : 300 nsec (Uniform)
6. Ring slipping factor: 0.00845
7. Time of flight from PU to Kicker: 0.617 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 or 3-6 GHz
10. Number of PU, and Kicker=128 (Could be reduced with use of better electrode)
11. Pickup Impedance=50 Ohm
12. Gain=80~120 dB.
13. Atmospheric Temperature: 300 K, Noise Temperature=40 K
14. BB Voltage = 2 kV
15. BB frequency= 2.5 MHz (T=400 nsec)
16. Injection Kicker Pulse Width=500 nsec

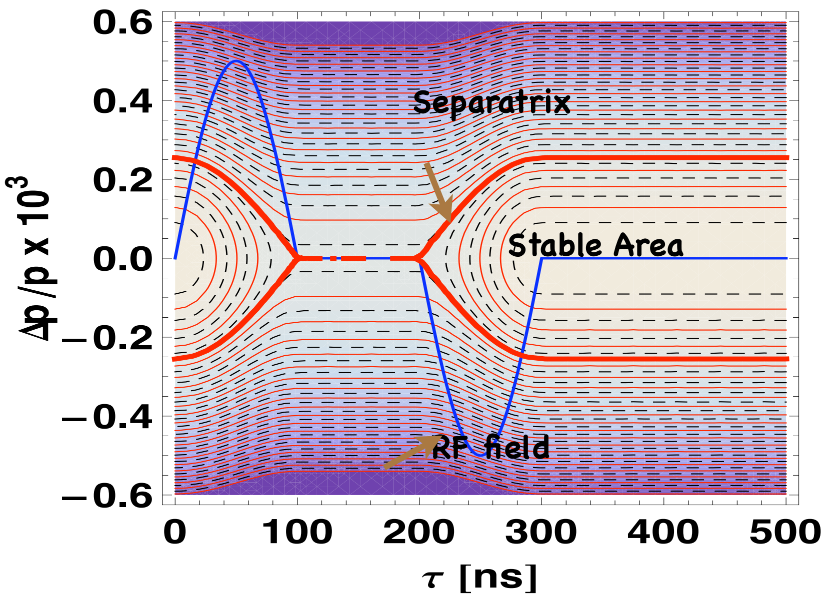
PickUp Structure for HESR Stochastic Cooling 2-4 GHz, (Similar electrode is used for Nuclotron and NICA collider)

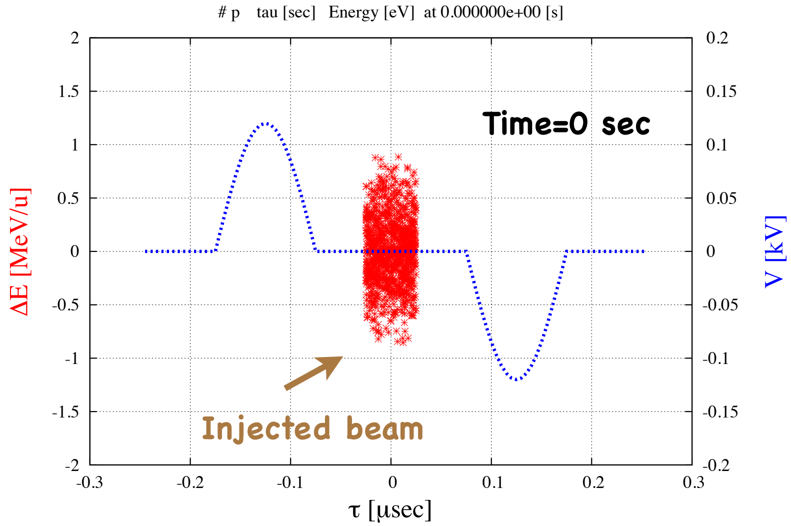


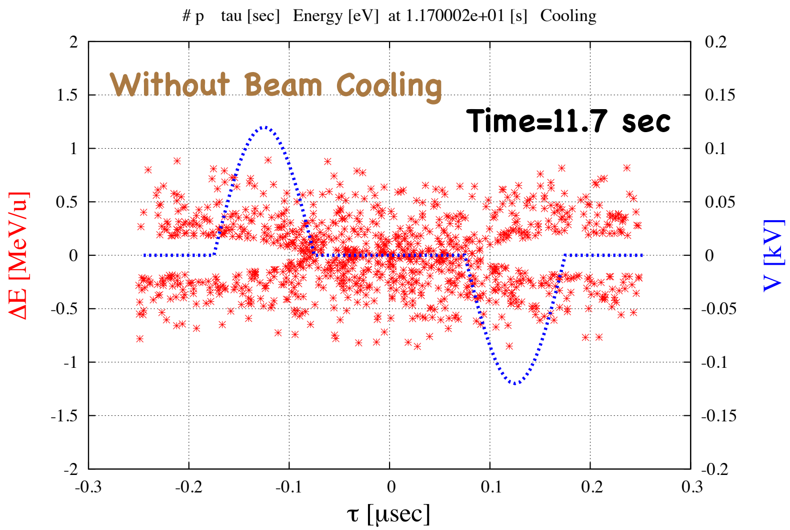


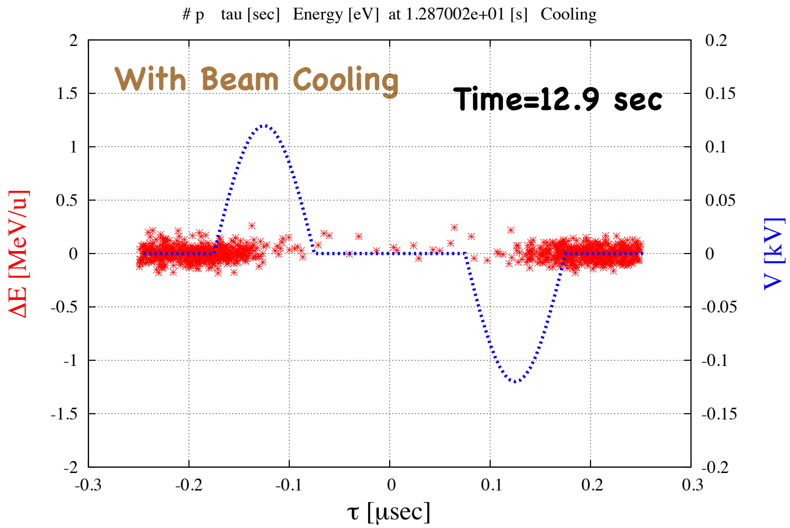
from Rolf Stassen, Julich

Principle of Barrier Bucket Accumulation Separatrix and Beam Trajectory with/without Cooling



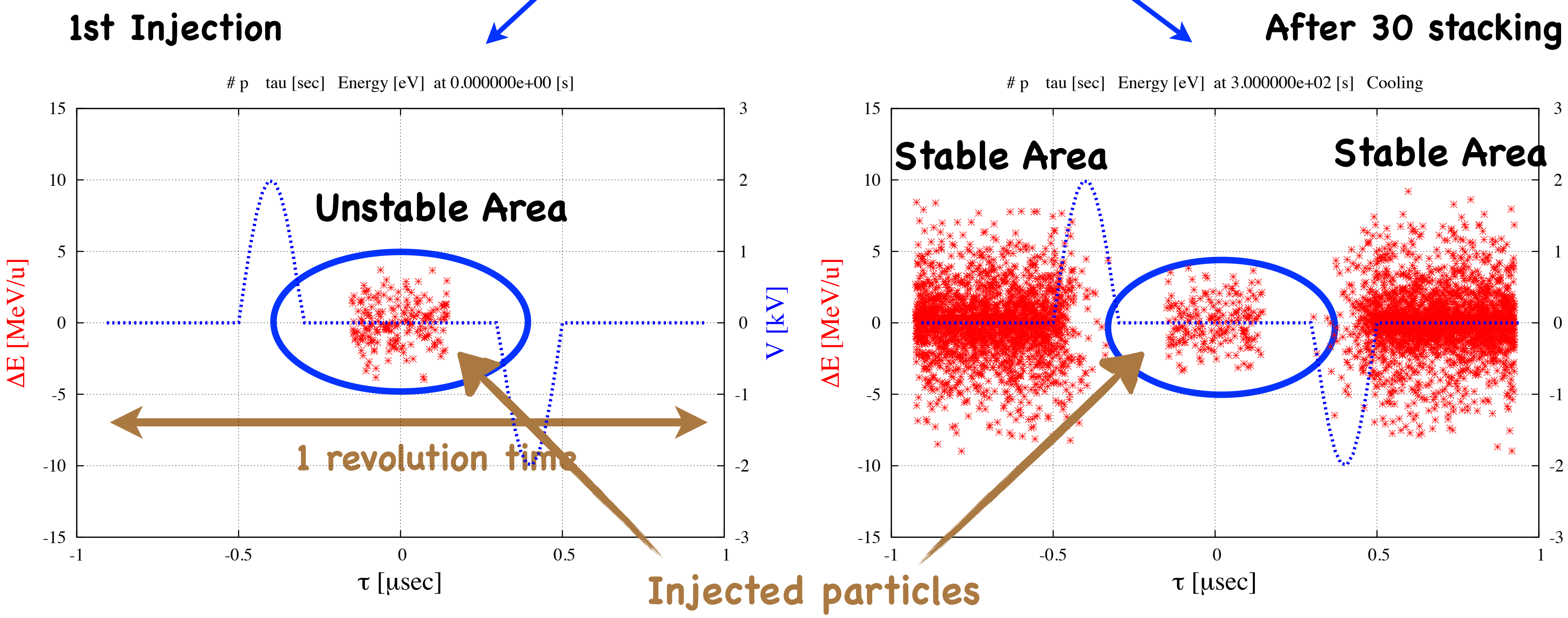






Barrier Bucket Accumulation with Stochastic Cooling and Fixed Barrier at NICA Collider

Stochastic Cooling is applied to injected and stacked particles.

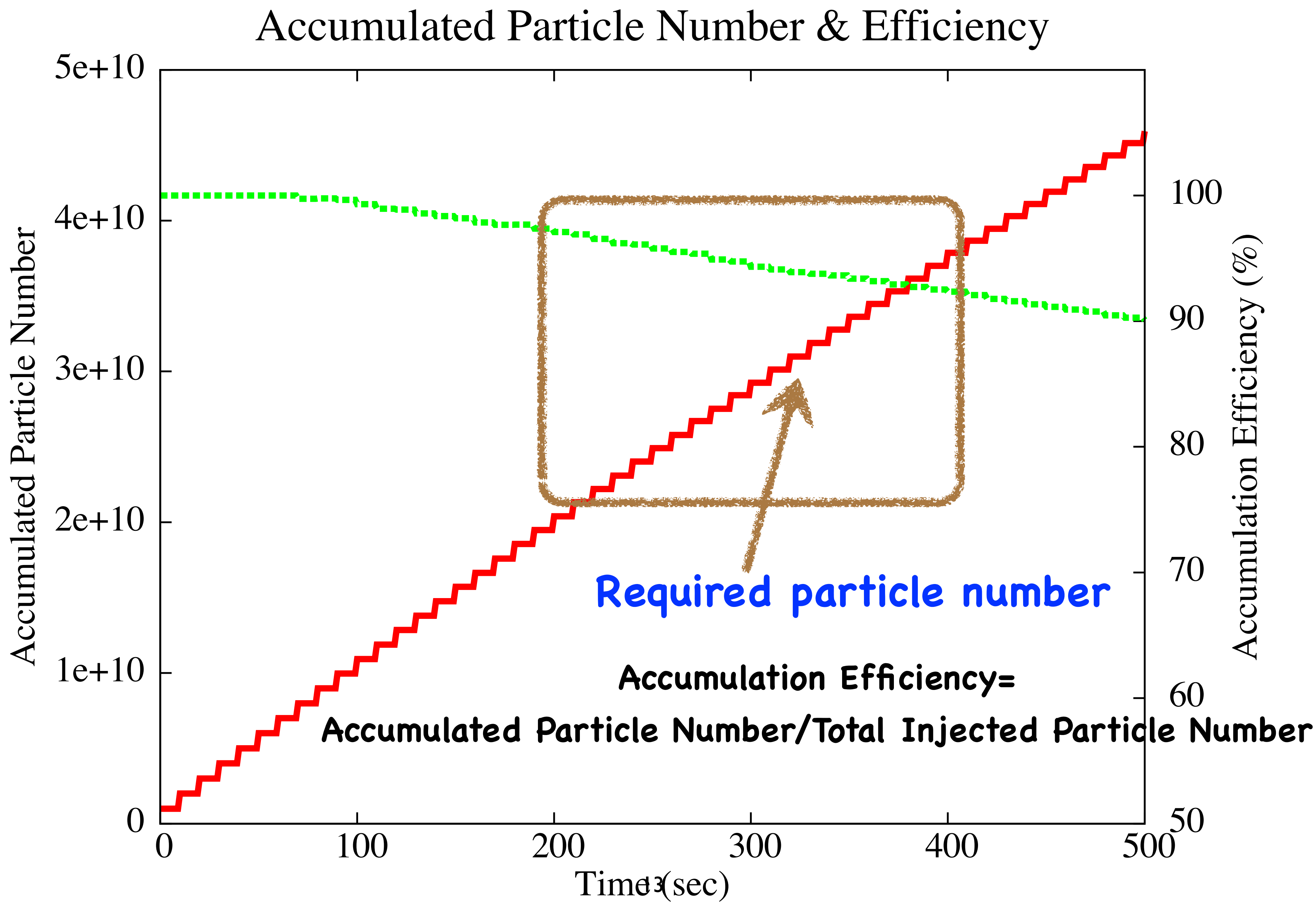


Red: Particles (energy left scale)

Blue: Barrier voltage (right scale)

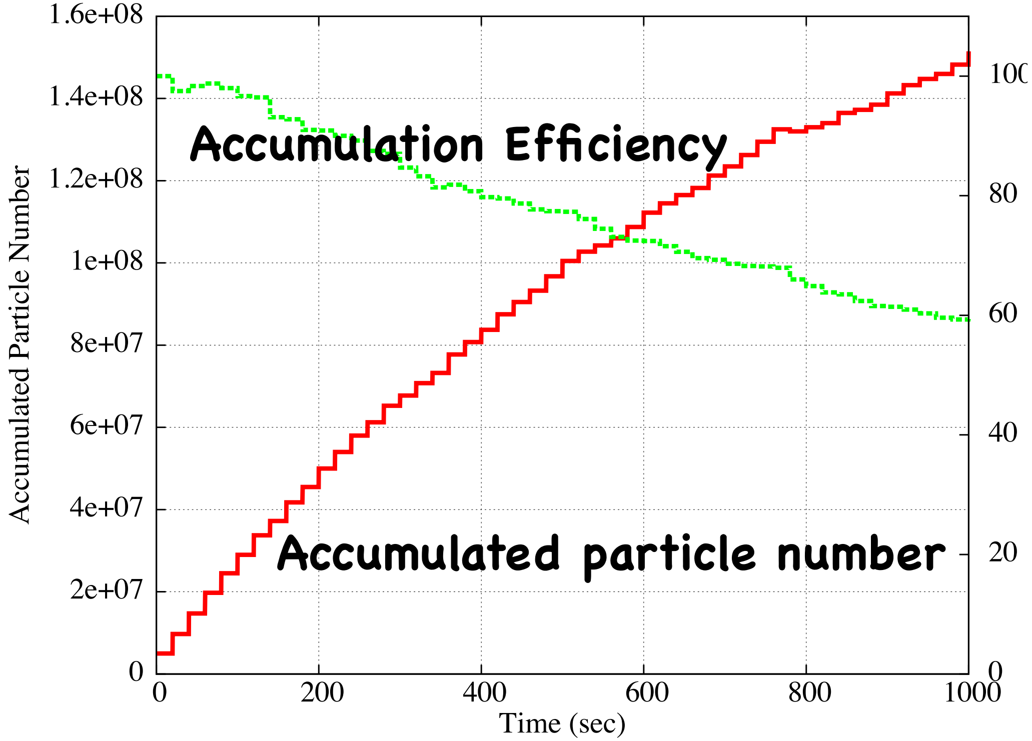
Accumulated Particle Number & Efficiency (Initial Gain=115dB)

4.5 GeV/u

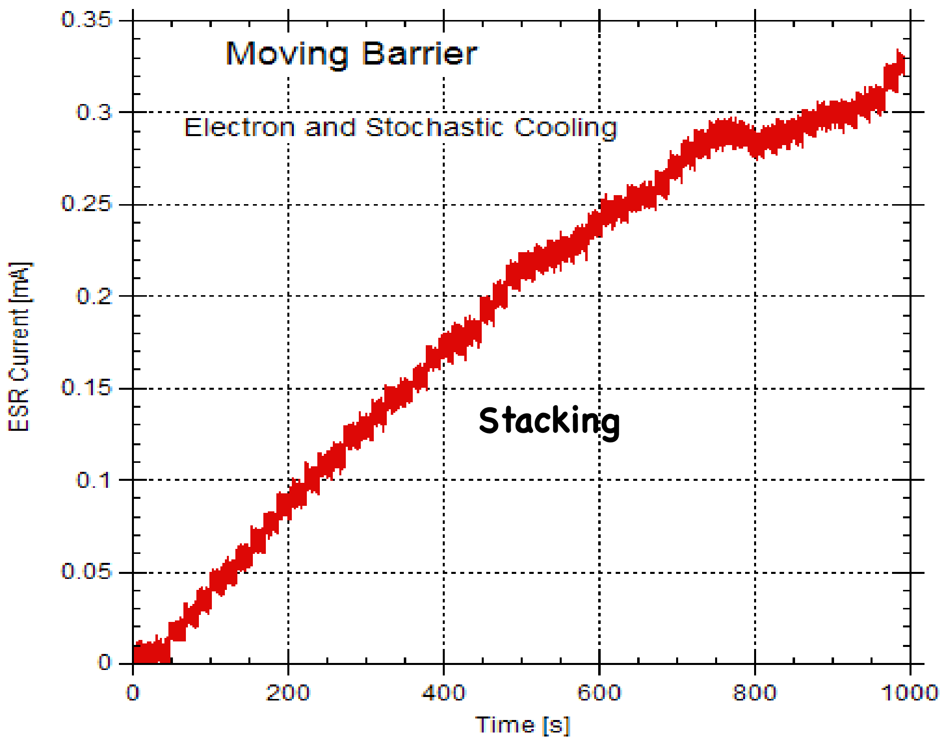


GSI POP Experiment at ESR, 40Ar18+, 400 MeV/u
Moving Barrier Case, Gain=120 dB, Vbb=120V, Electron Cooler Ie=0.3A
Cycle time=20 sec, Kicker period=200 nsec

Simulation Result



Experimental Result



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)

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

(First Step Harmonic=24)

Initial beam parameters after Barrier Bucket Accumulation

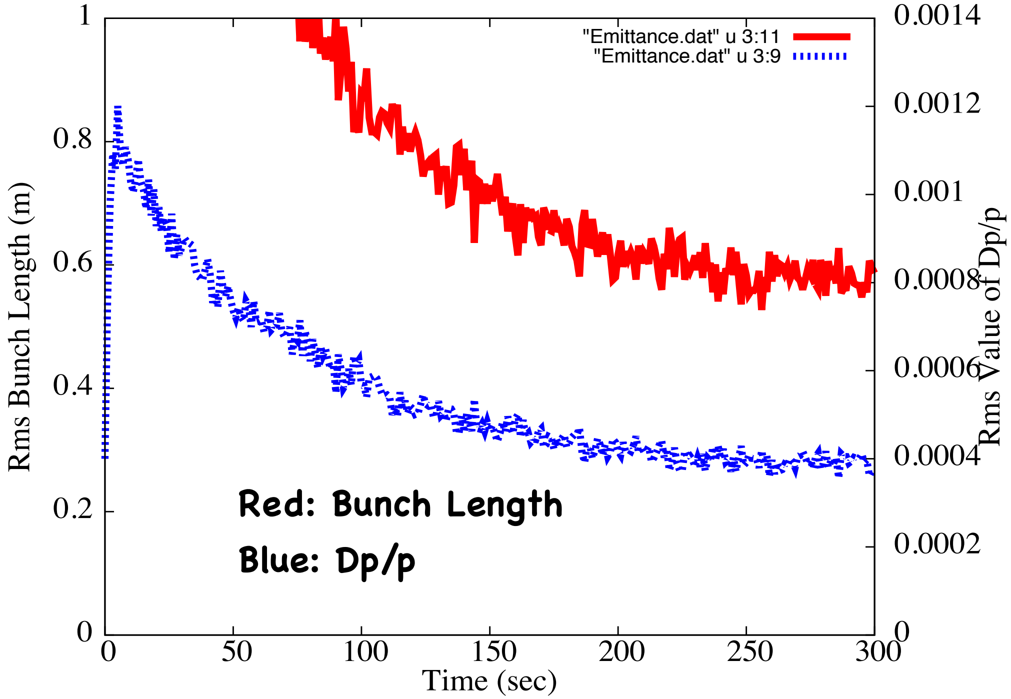
Dp/p (rms)=4e-4 (Gaussian)

Bunch shape=Coasting beam (Uniform Random)

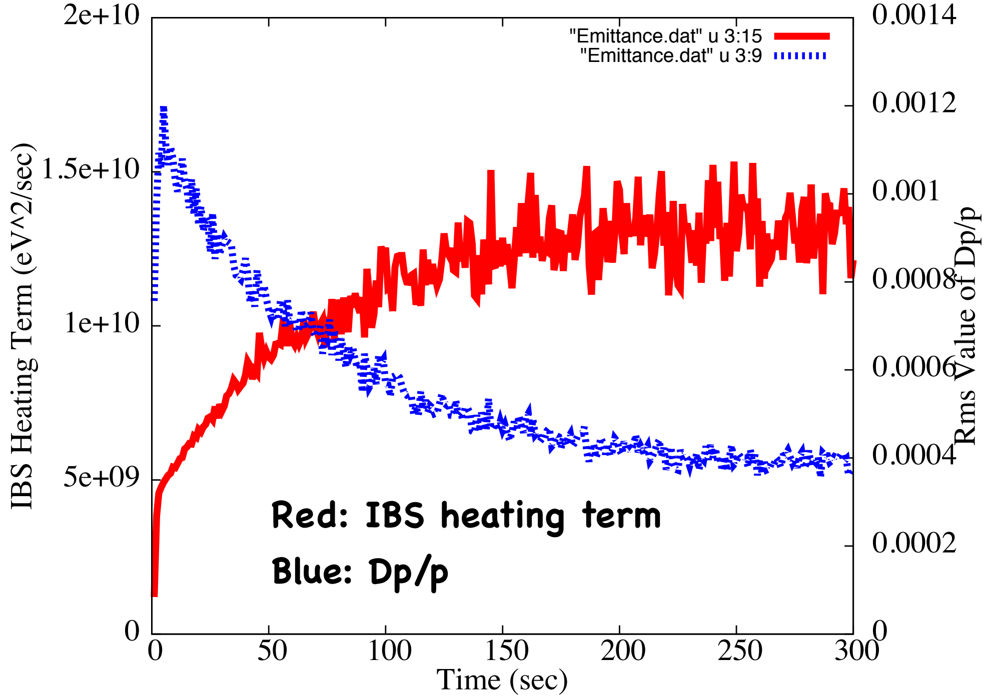
1. Gain of stochastic cooling system is reduced from the initial value 90dB to 75 dB within time constant 250 sec.

2. RF voltage is increased from 0 to 200 kV (harmonic=24) with time constant 5 sec for the adiabatic bunching.

Evolution of Rms Bunch Length & Dp/p

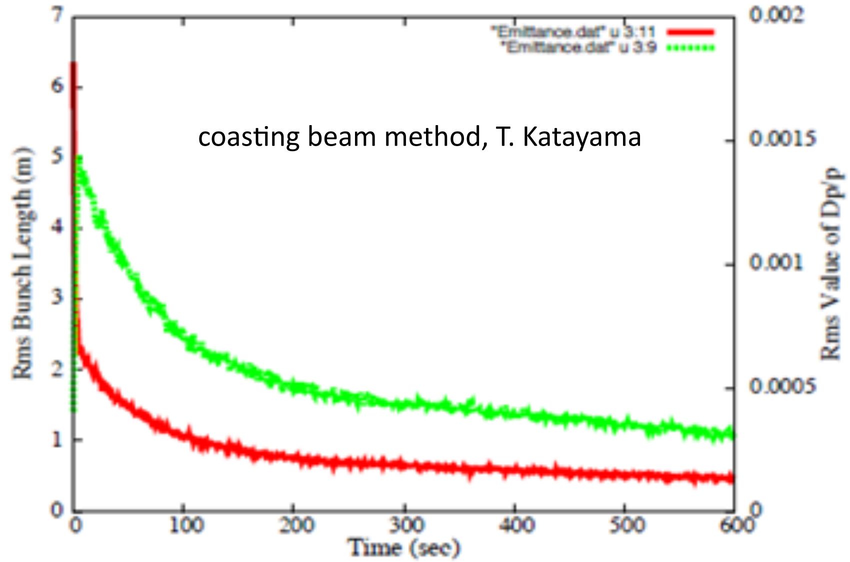


Evolution of IBS Heating Term & Dp/p

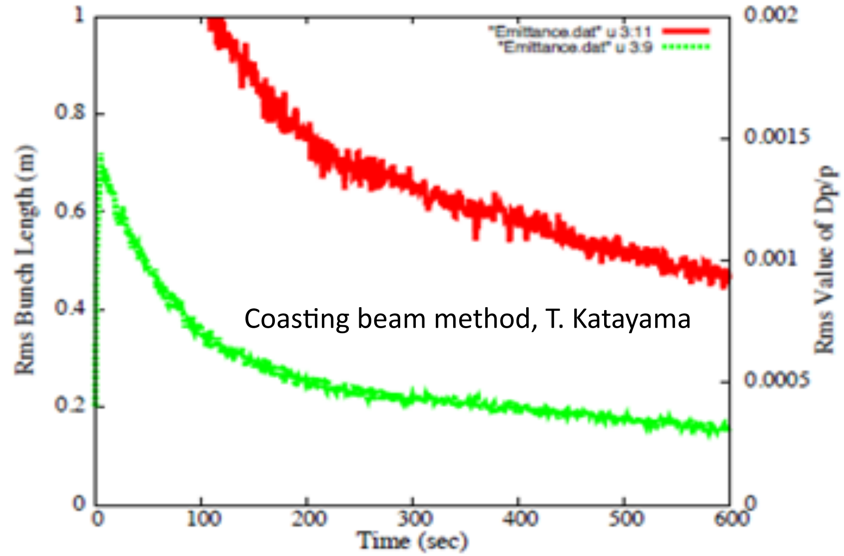


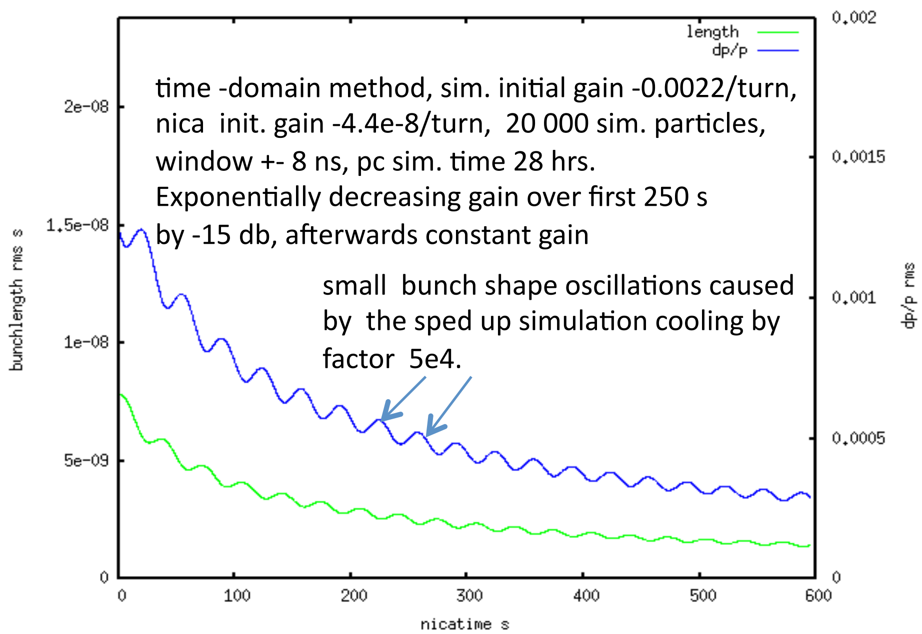
Comparison of Results by Lars and Takeshi

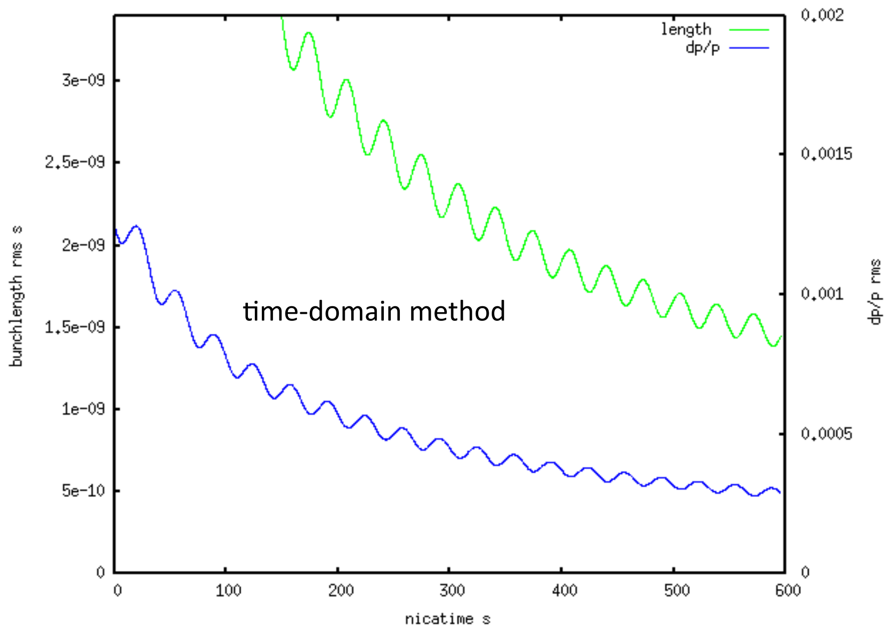
Red: Bunch Length
Green: Rms Dp/p



Bunch length scale enlarged







Beam Bunching with Stochastic Cooling

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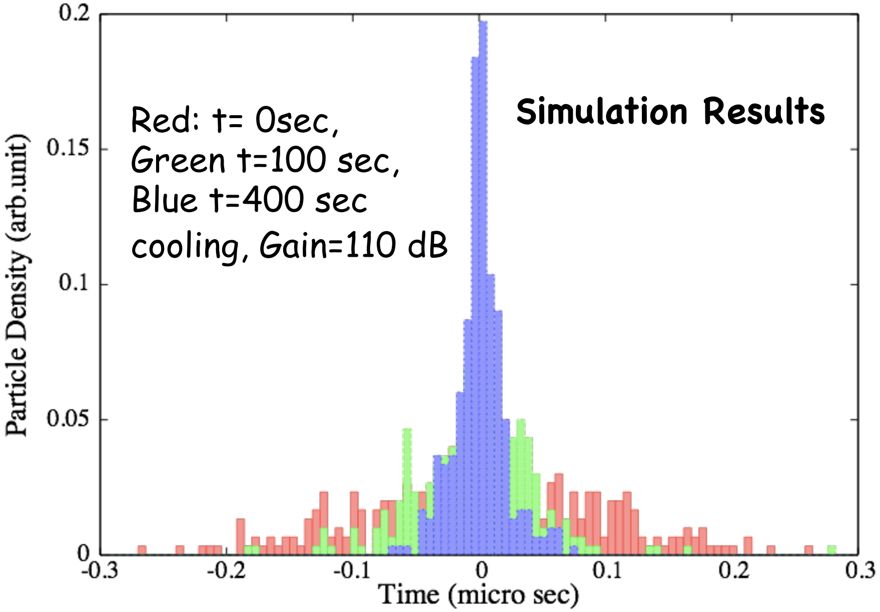
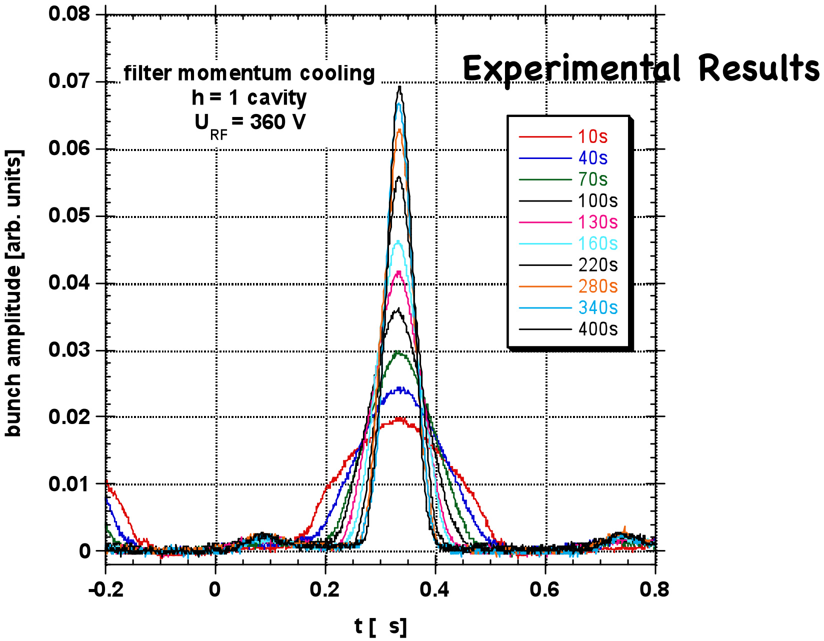
H. Stockhorst, R. Stassen, D. Prasuhn and R. Maier,
Forschungszentrum, Jülich, Germany
T. Kikuchi, Nagaoka Univ. of Technology, Japan, I. Meshkov, JINR, Russia

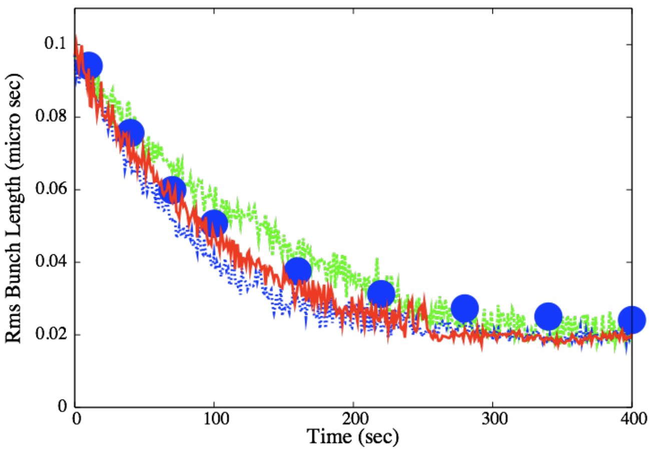
COSY Bunched Beam Cooling
IPAC10 in Kyoto





Evolution of Bunch Length

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



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)

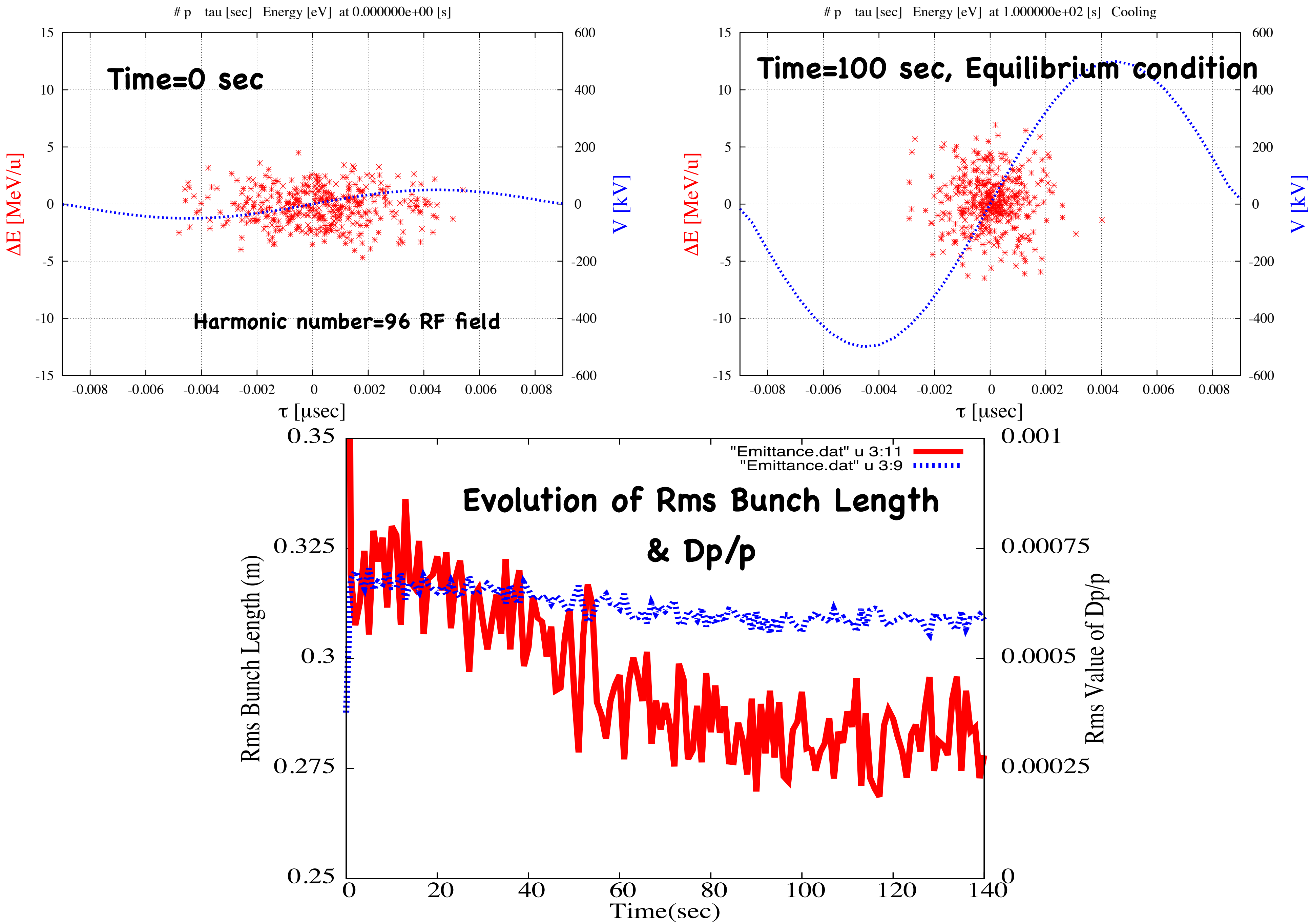
Bunch length=0.56m (rms)

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

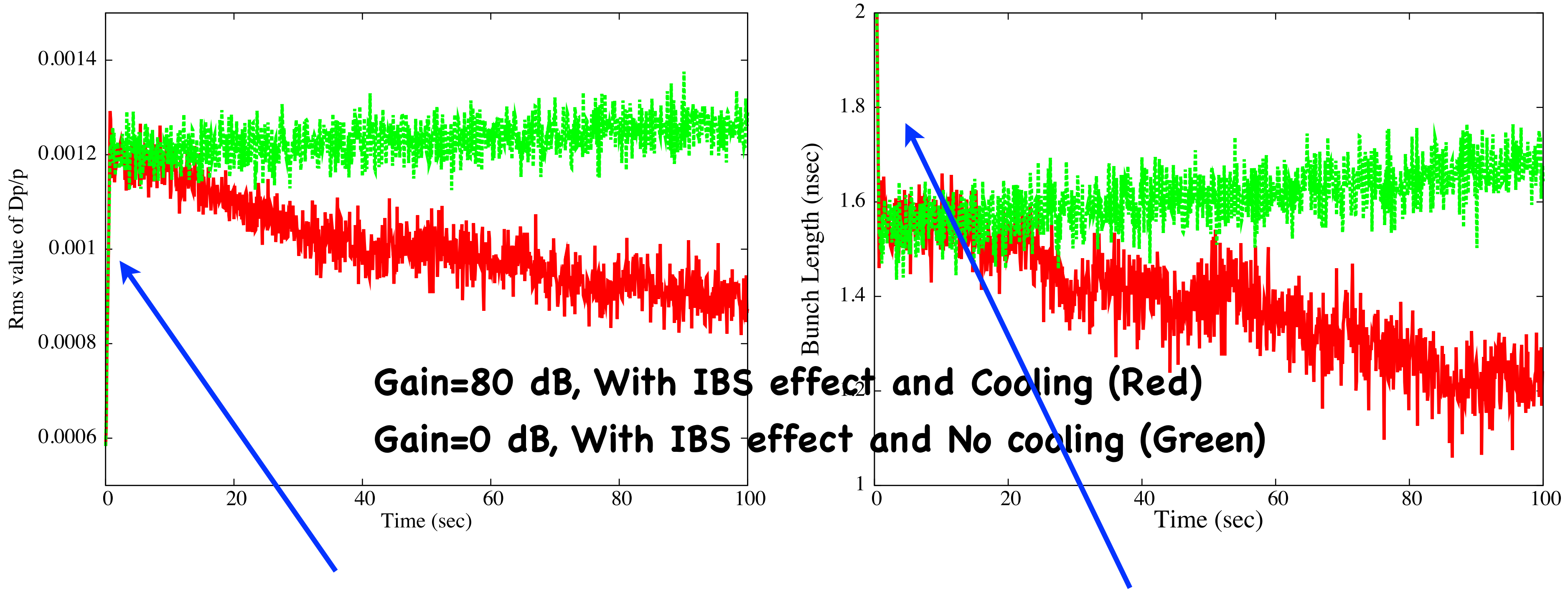
1. Bunch length=0.275 m (rms), 0.94 nsec (rms)
2. Dp/p=5.9e-4 (rms)

Vrf=50-500 kV (Adiabatic increase within 1 sec)



Evolution of Rms Dp/p
Vrf=500 kV

Evolution of Rms Bunch Length
Vrf=500 kV



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.

Specifications of Electron Cooler at NICA Collider

Ion: 197Au79+, 1.5 GeV/u, Eta=0.1268

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

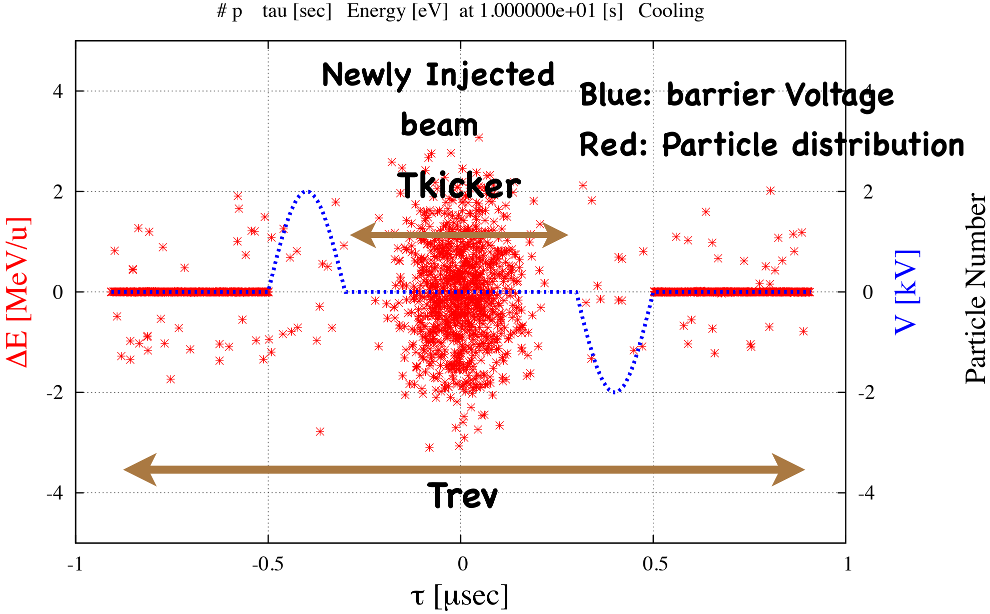
Beta function at Cooler= 16 m

Cooling Force: Parkomchuk empirical formulae

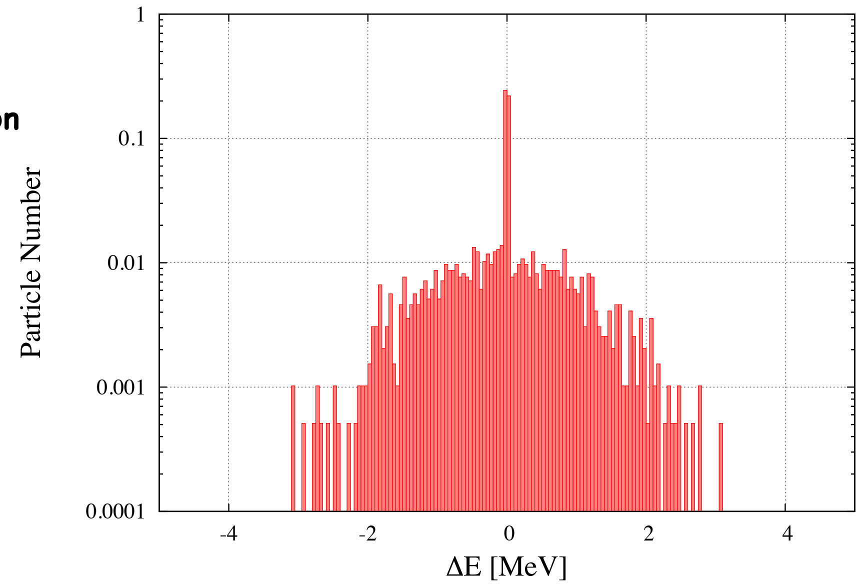
Energy=1.5 GeV/u, Ring Slipping Factor=0.1268

Time=10 sec

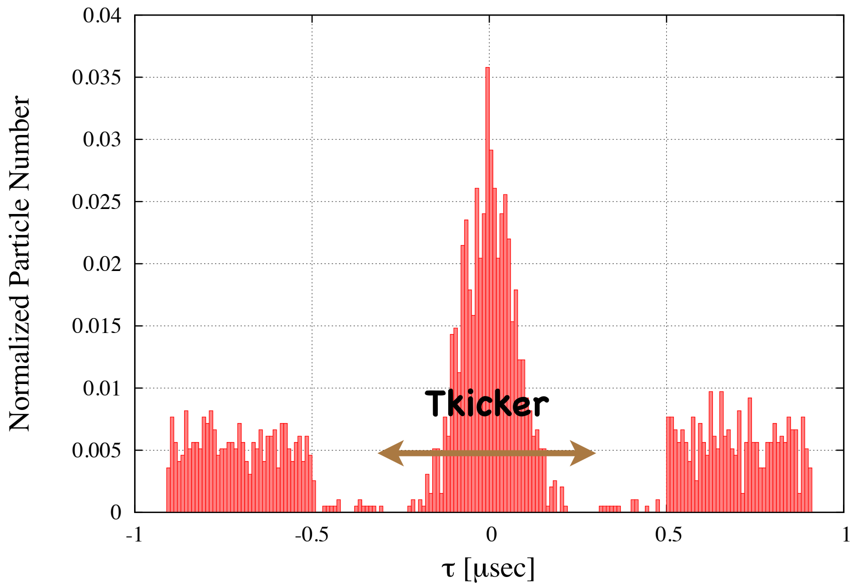
Barrier voltage & Particle distribution



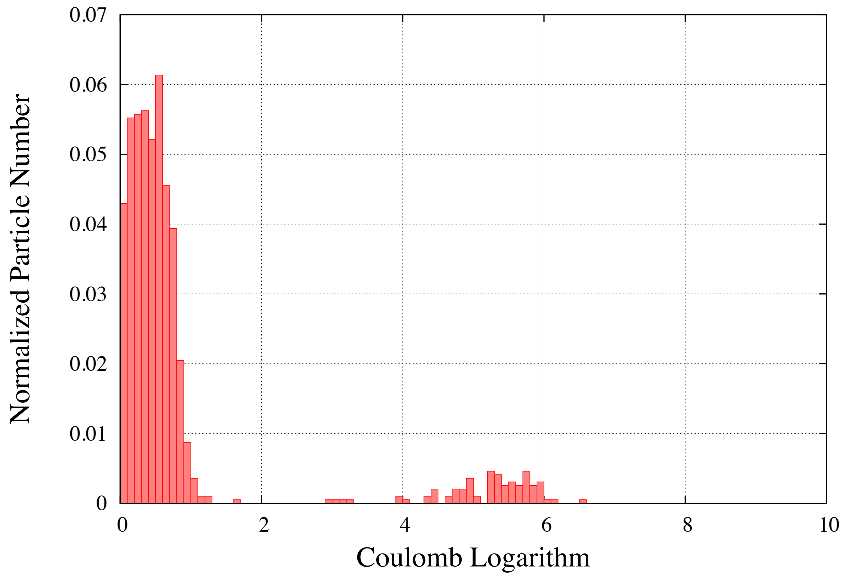
Energy spectrum



Particle distribution along the circumference



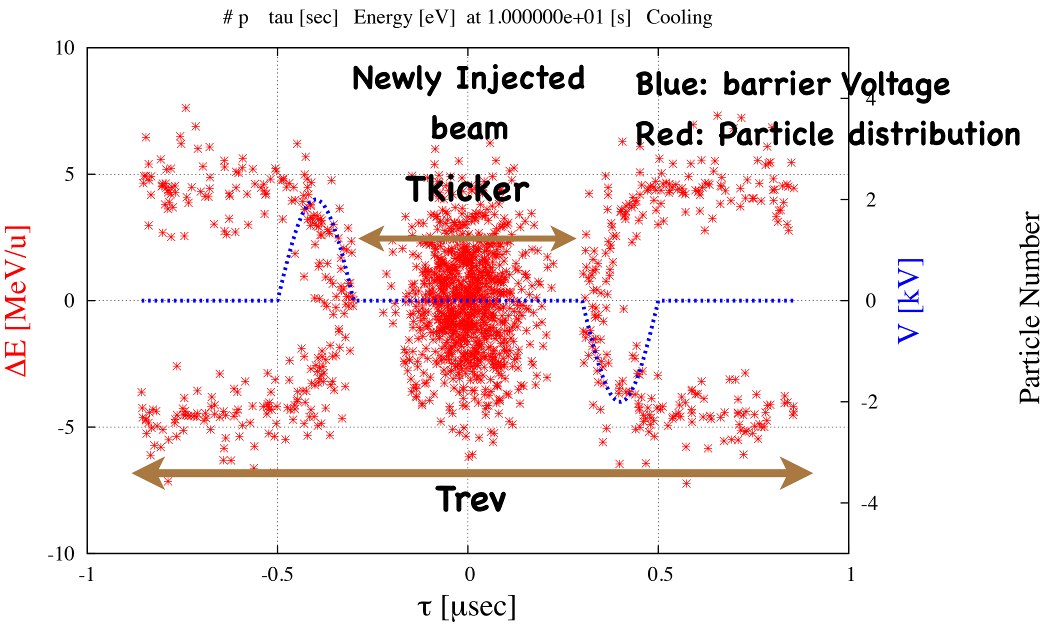
Coulomb log distribution



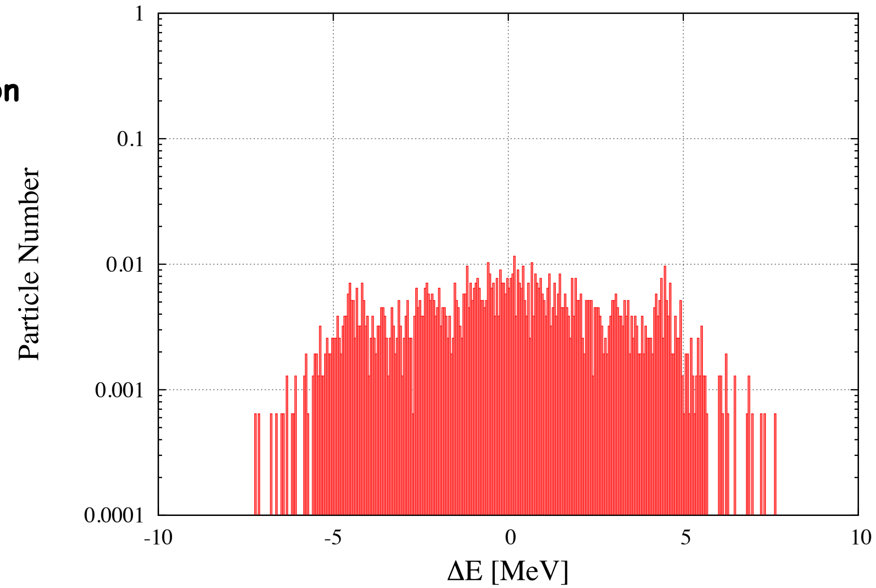
Energy=3.5 GeV/u, RingSlippingFactor=0.0243

Time=10 sec

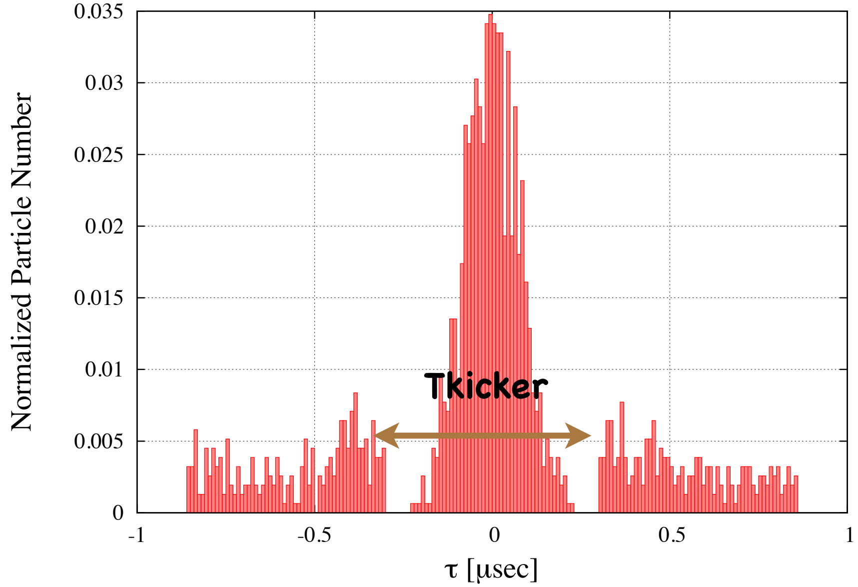
Barrier voltage & Particle distribution



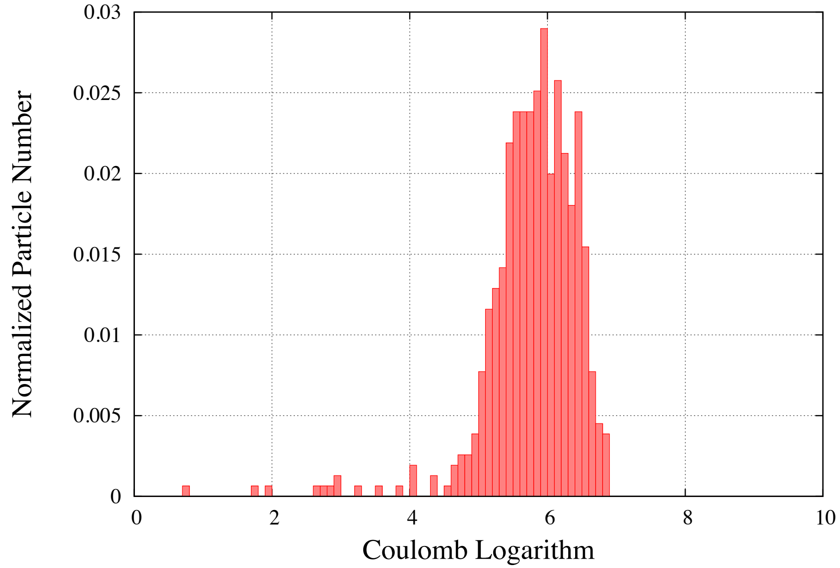
Energy spectrum



Particle distribution along the circumference

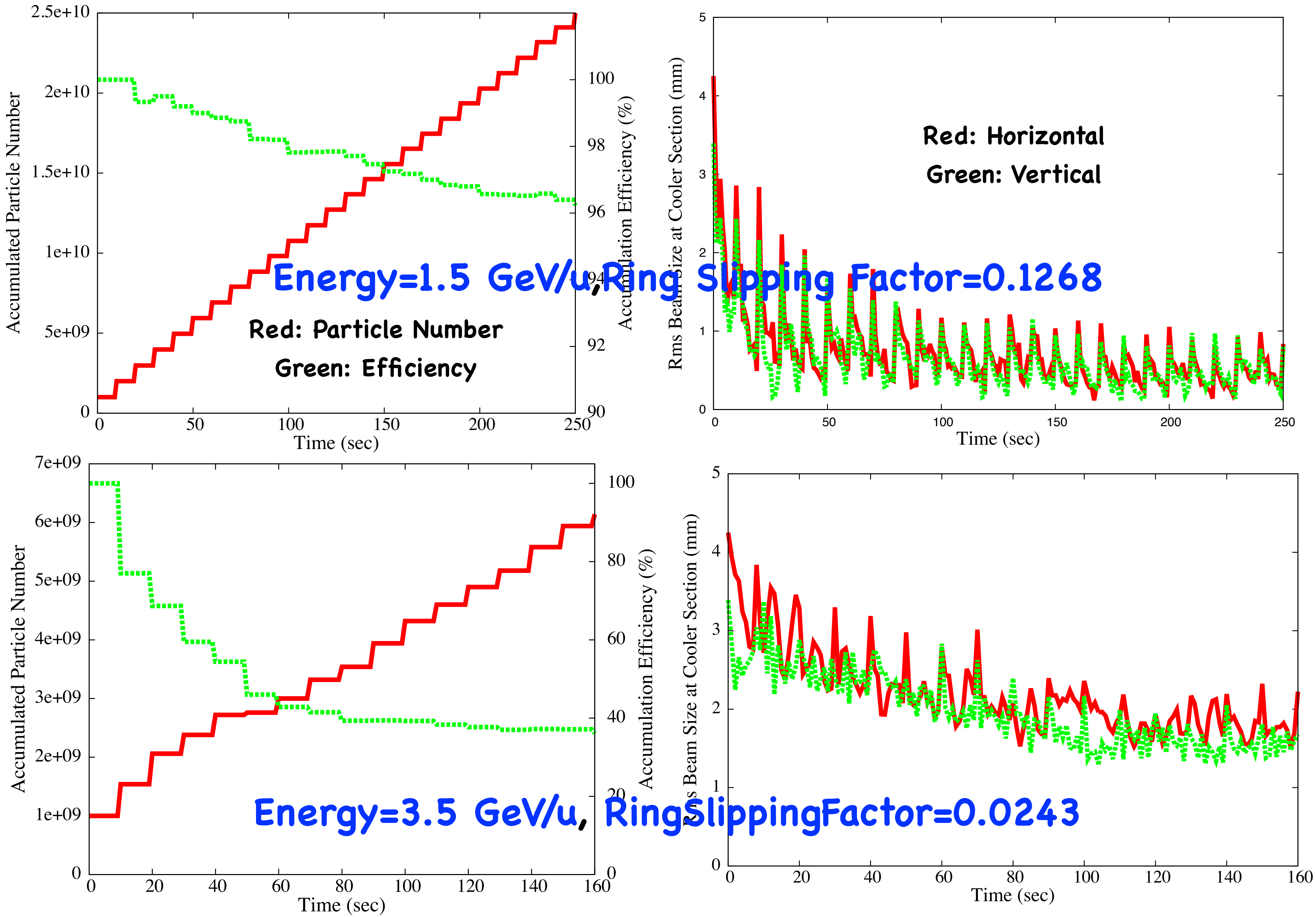


Coulomb log distribution



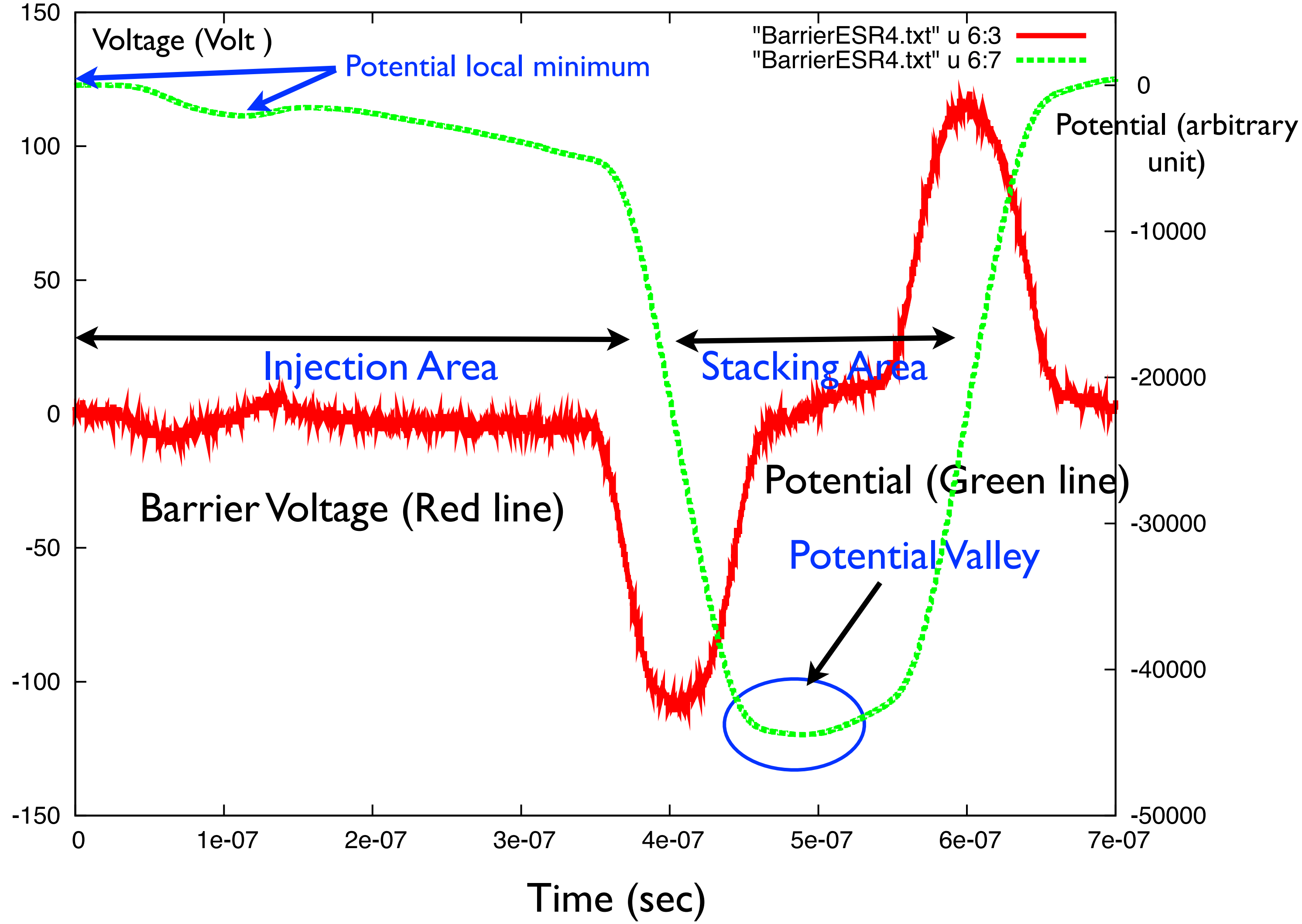
Accumulated Particle Number & Accumulation Efficiency

Rms Beam Size at Cooler Section



ESR Experiment on BB Accumulation with Electron Cooling, 124Xe54+, 154MeV/u (2008)

Measured Barrier Bucket Voltage and Potential



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.

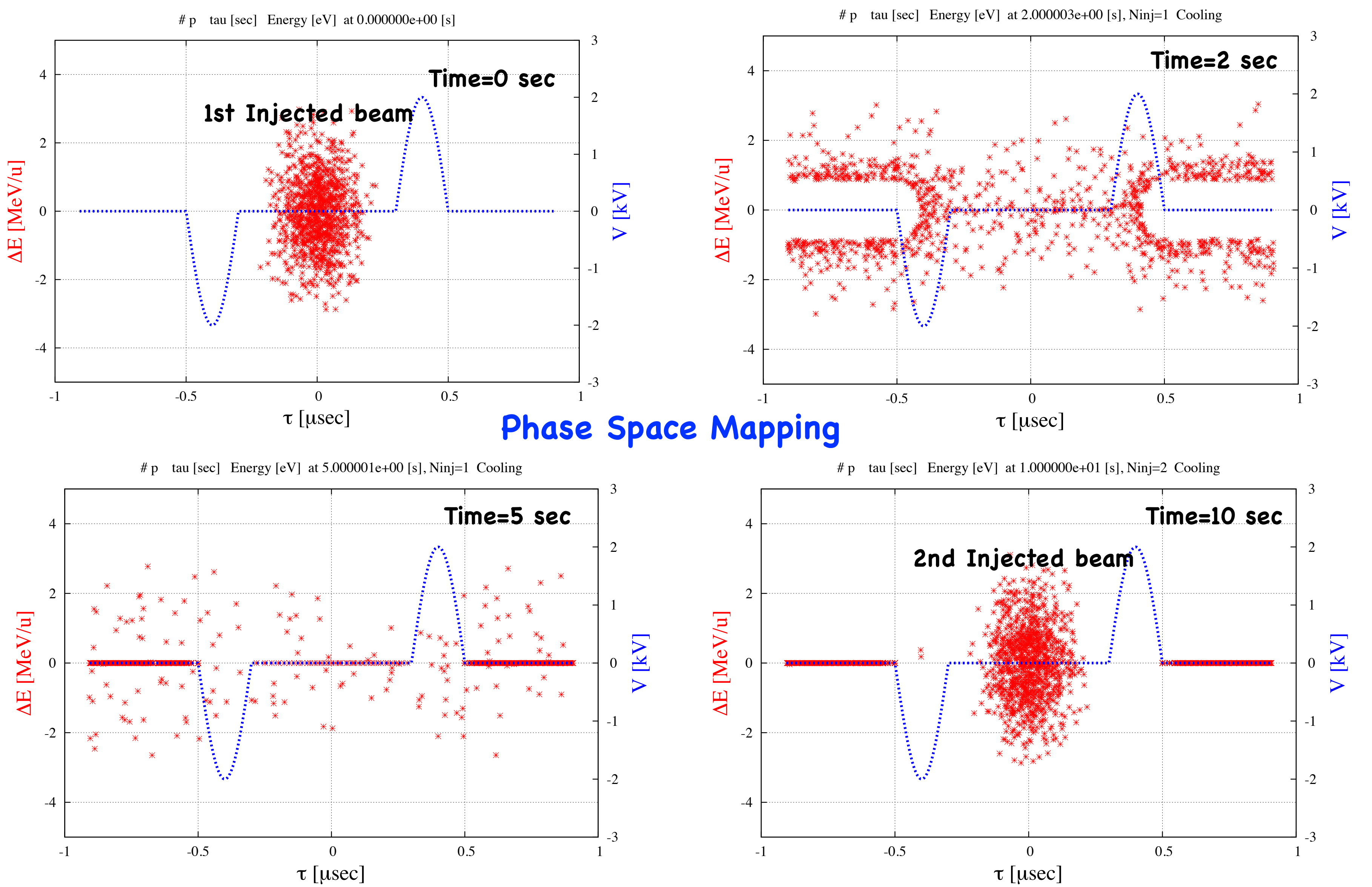
$$\frac{d\Delta E}{dt} = \frac{Z}{A}\frac{V_{rf}}{T_0} - E_{cool} - \frac{Z}{A}\frac{g}{4\pi\varepsilon_0\gamma^2}\frac{d\rho}{d\tau}$$

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

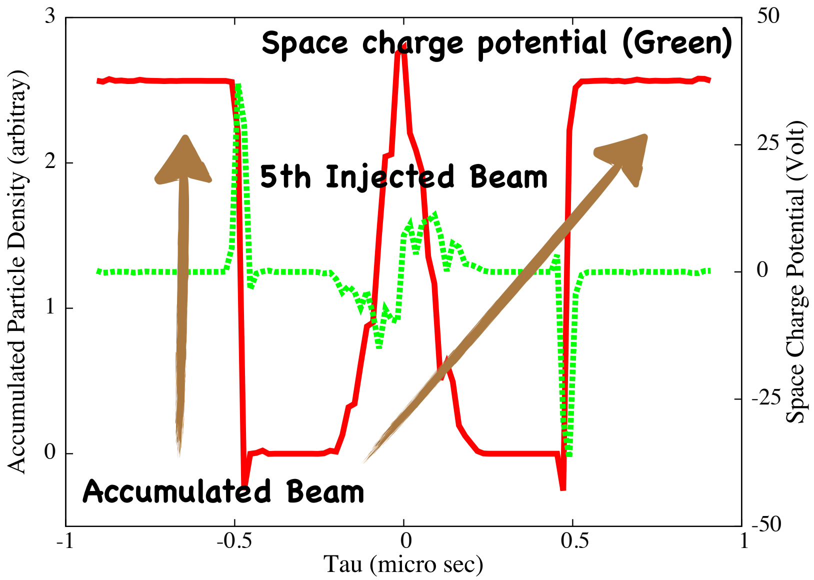
Here the Vrf means the external RF field, Ecool the cooling effects and the 3rd term in the right hand side shows the space charge effects. Z is the charge state of ion and A the mass number.

Particle tracking has been done with Particle In Cell method.

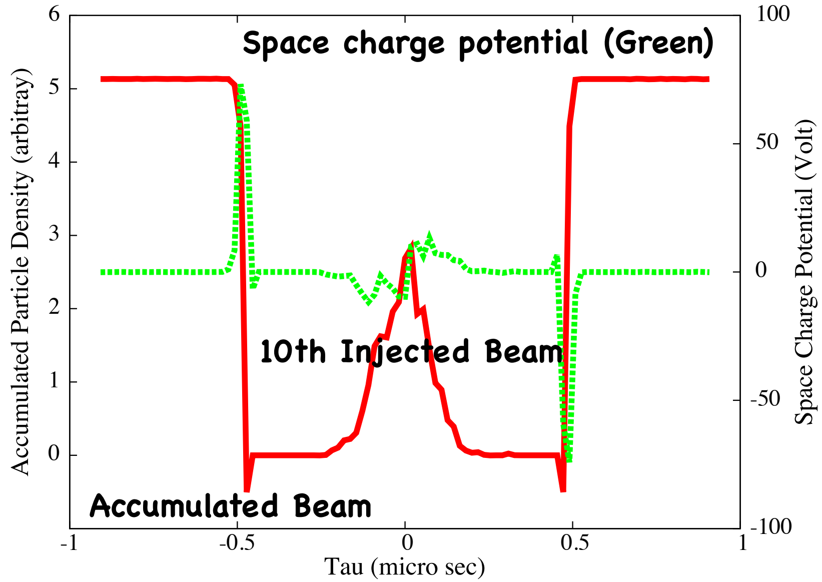
Ion=197Au79+, Energy=1.5 GeV/u, N=1e9/shot, Cycle time=10 sec, Ring Slipping Factor=0.1268, Dp/p(initial)=5e-4(rms) (Gaussian)



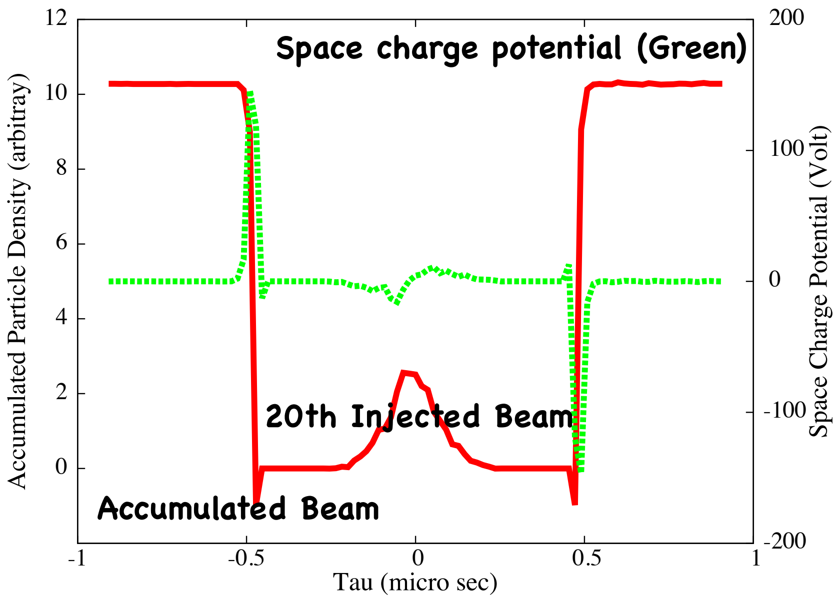
Time=50 sec (5 times injection)



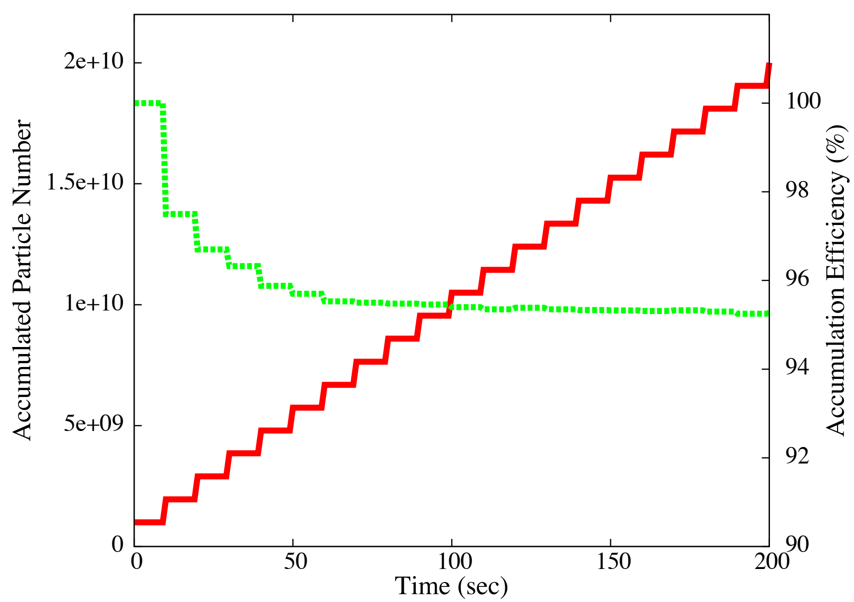
Time=100 sec (10 times injection)



Time=200 sec (20 times injection)

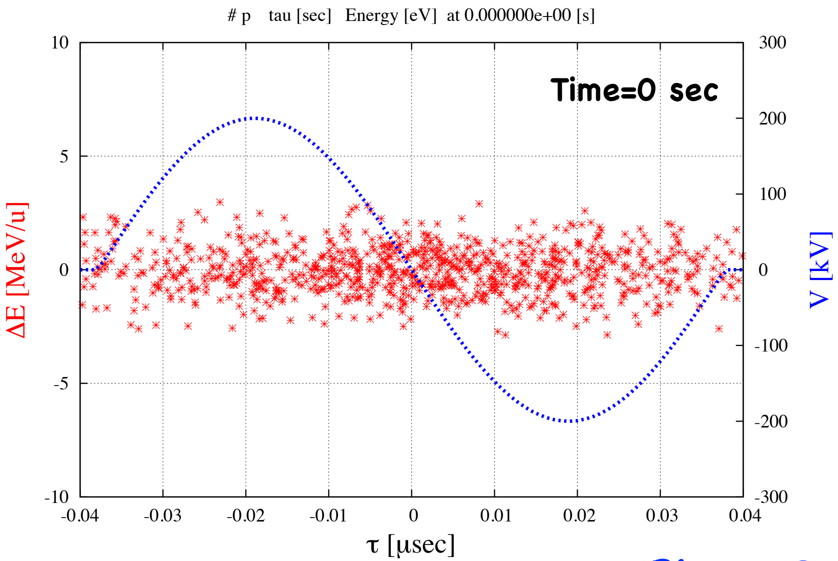


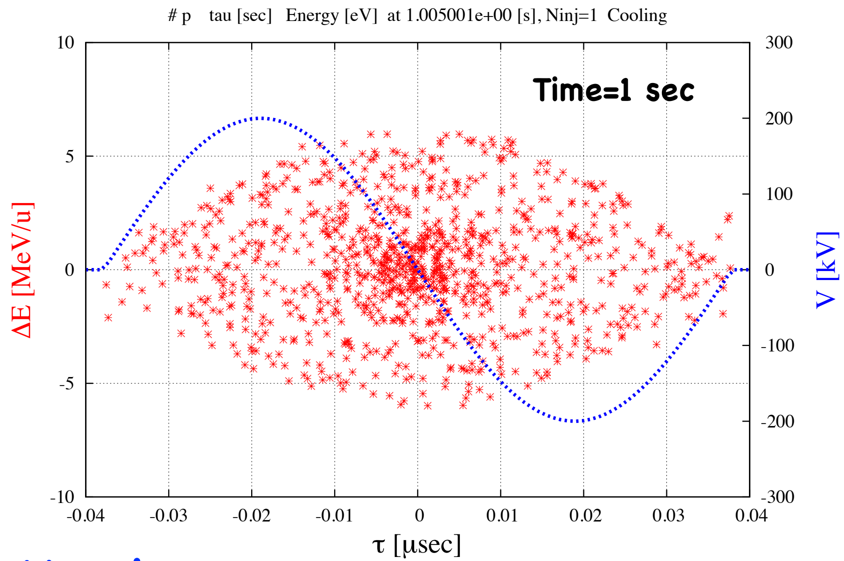
Accumulated Particle Number & Efficiency



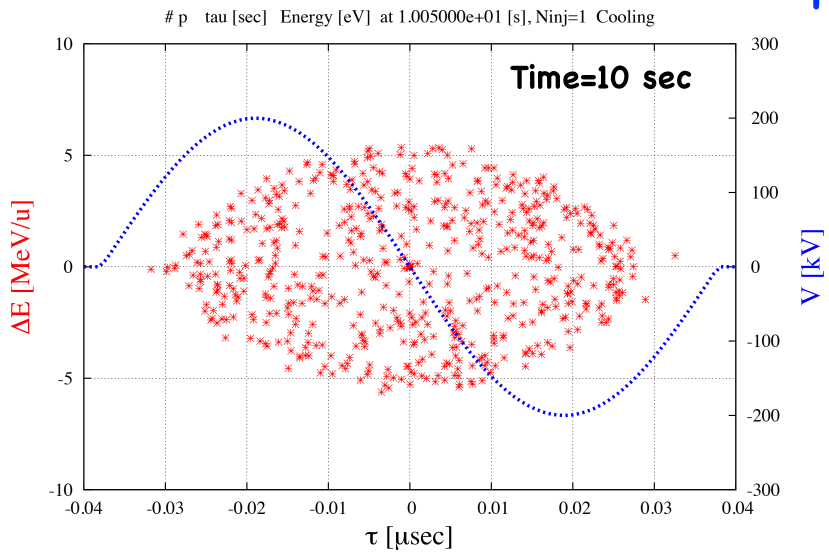
Short Bunch Formation.

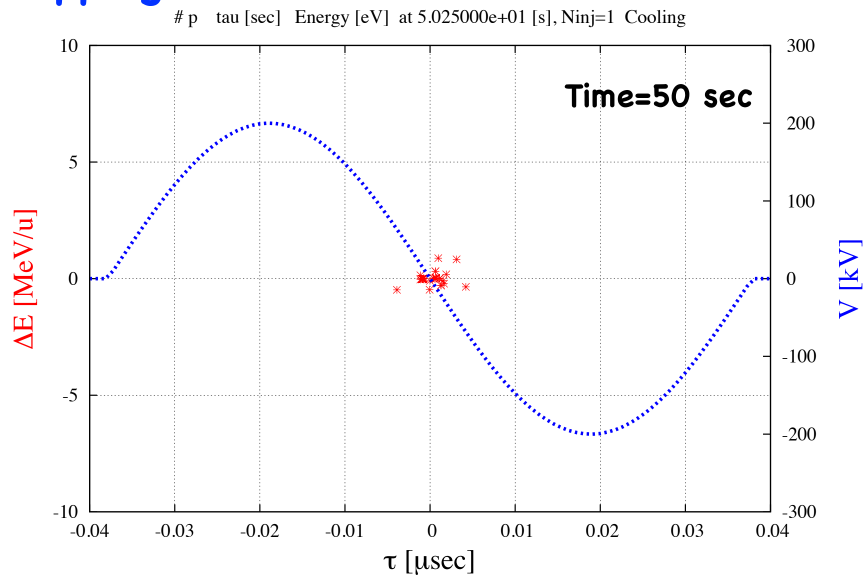
Ion=197Au79+, Energy=1.5 GeV/u, N=1e9, RF voltage=200kV, Ring Slipping Factor=0.1268, Dp/p(initial)=5e-4(rms) (Gaussian)



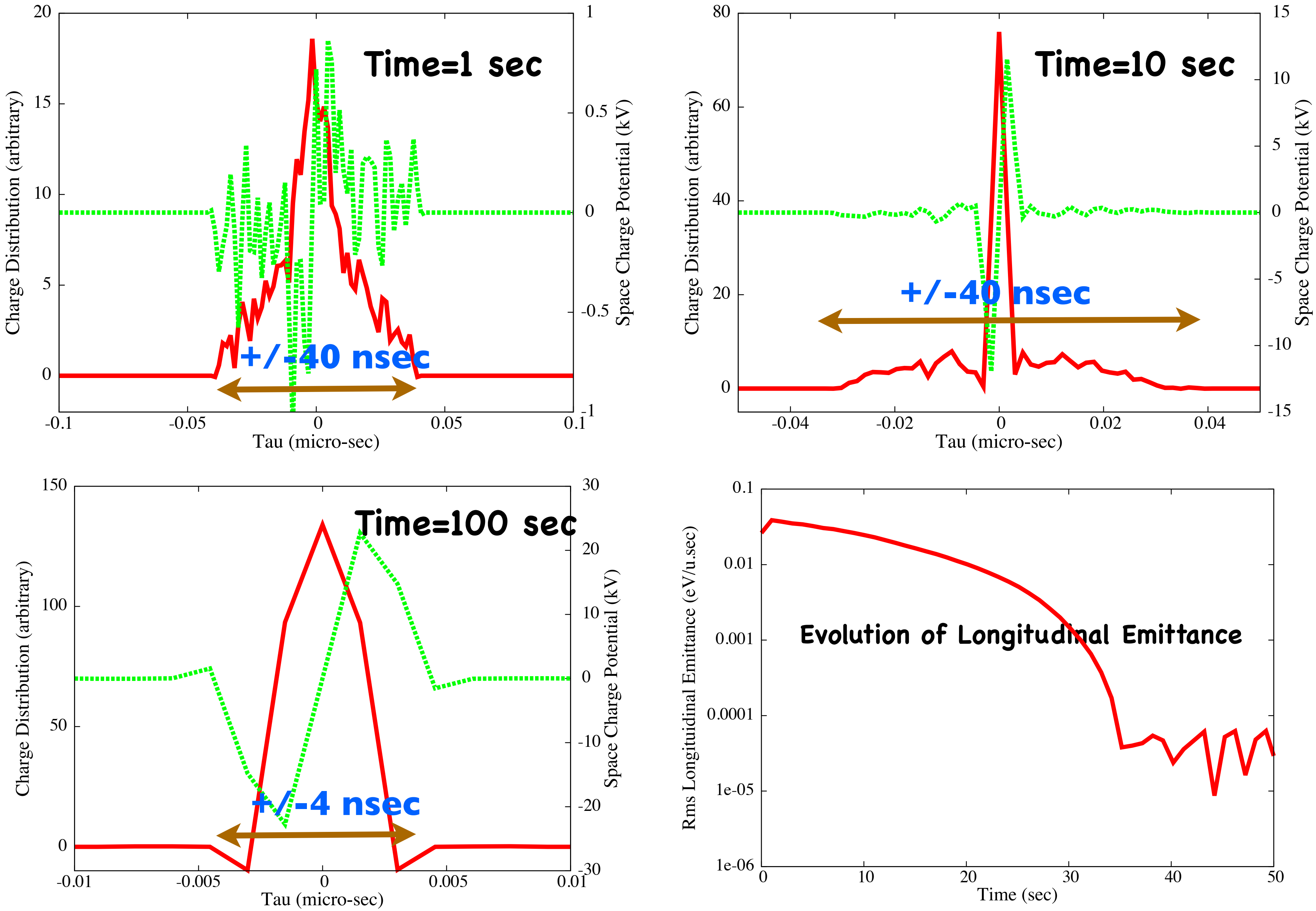


Phase Space Mapping

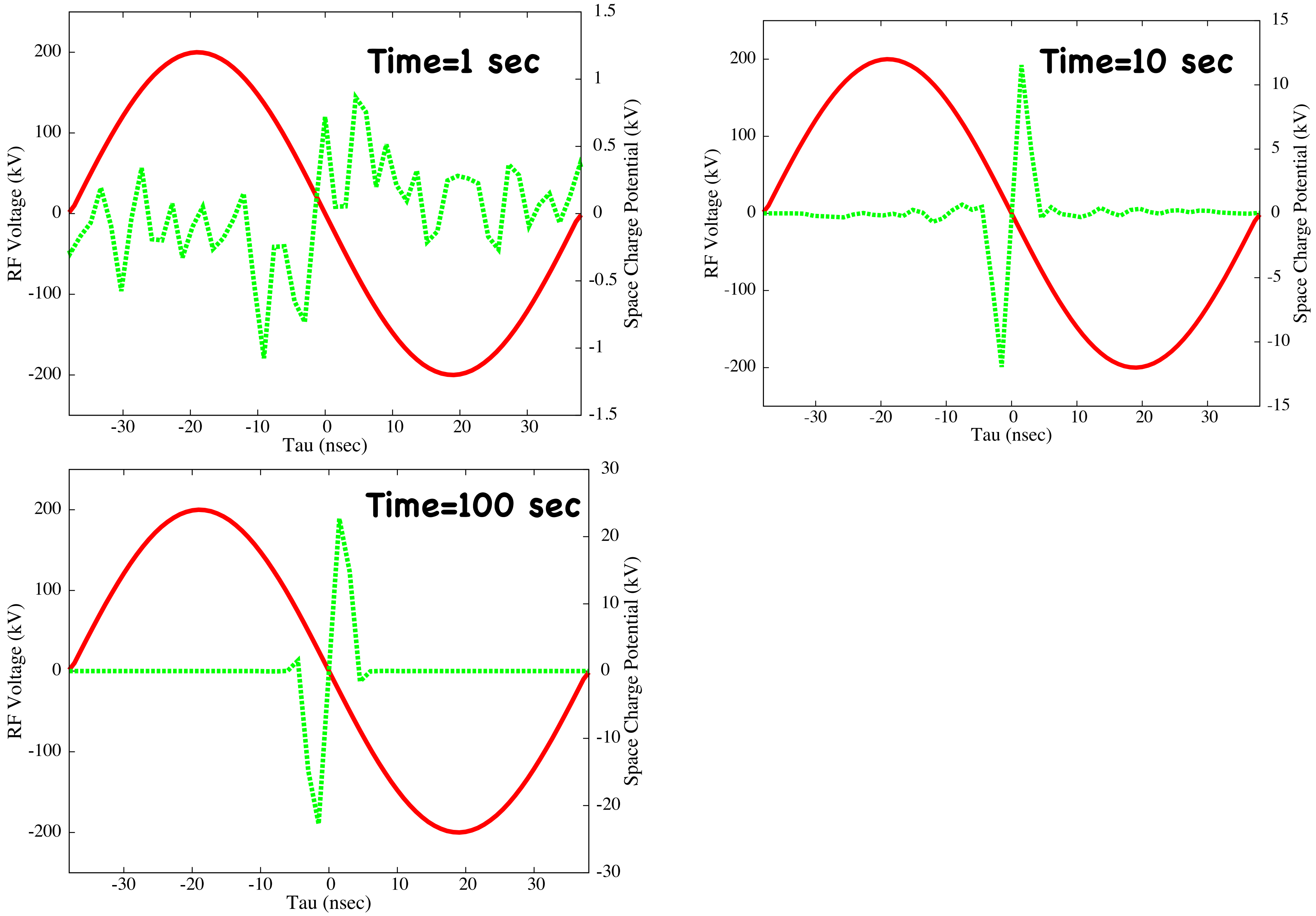




Evolution of Bunch Shape (red) & Space charge potential (Green)



Evolution of Space charge potential (Green) and RF potential (red)



Summary

1. NICA collider is a low and variable energy (1-4.5 GeV/u), high intensity (3e8-6e9/bunch) heavy ion collider which requires much careful designed beam cooling devices.

2 We have investigated the momentum cooling process with Fokker-Planck approach of coasting beam approximation, and with the particle tracking of bunched beam. Both simulation methods are experimentally bench-marked at the storage rings. (ESR/COSY)

3. The beam cooling devices could be useful not only for the suppression of the IBS heating effects but also for the beam accumulation with barrier bucket method and for the short bunch formation.

4. The present designed lattice is a FODO structure of the fixed transition gamma, (7.09) and then the ring slipping factor is not adequate (too large) for the low energy region, less than 2.5 GeV/u for the stochastic cooling.

5. The wider band width 3-6 GHz is favorable for the fast stochastic cooling but it limits the momentum cooling acceptance. From this point of view, the 2-4 GHz is better selection.

6. The electron cooler (6m length, 1A current, 2cm diameter) can be effectively used for the beam accumulation and short bunch formation below the beam energy of 2.5 GeV/u while for higher energy the stochastic cooling is inevitable.

7. The electron cooling and stochastic cooling are quite complementary for the beam accumulation with barrier voltage method and short bunch formation.

8. At the energy 1.5 GeV/u, the space charge potential during the beam accumulation reaches to 150-200 Volt after 20 batch accumulation (N=2e10) at the edge of beam profile. However this value is enough small comparing with the barrier voltage of 2 kV, and we could not find any deterioration of beam accumulation efficiency in the barrier bucket scheme.

9. In the short bunch formation, the bunch length becomes as short as +/- 3~5 nsec (full width), and the maximal space charge potential reaches to +/- 20 kV. The external RF voltage is assumed as 200~500 kV and it is +/- 60~130 kV at +/- 3 nsec. The slight deformation (bunch lengthening) of bunch shape could be anticipated. But it could be managed.