Numerical Investigation of Stochastic Cooling at NICA Collider

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Contents

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	Operation energy
Injected intensity	1e9/10sec.cycle	Emittance	0.5 Pi mm.mrad (?)
Momentum spread	3.0E-04 (rms)	Bunch length (h=1)	300 nsec (uniform)

Fundamental questions 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

Max BetaX Function=176.06m

Max BetaY Function=145.43

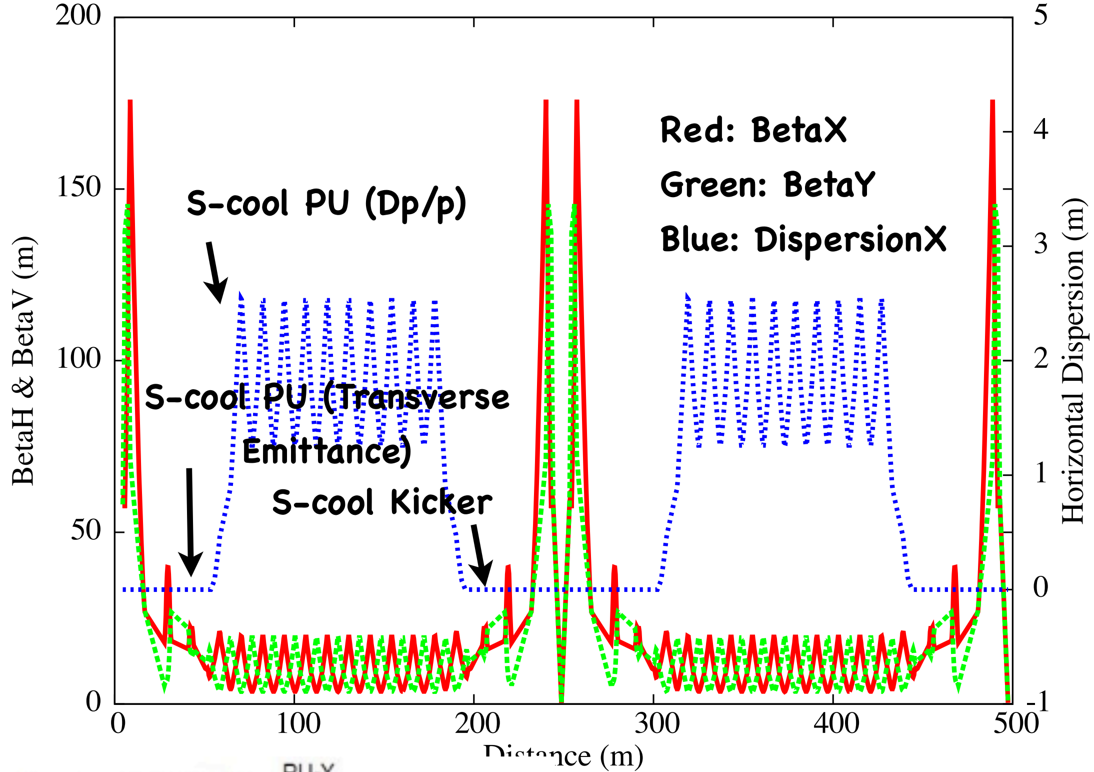
Min BetaX Function=0.35 m

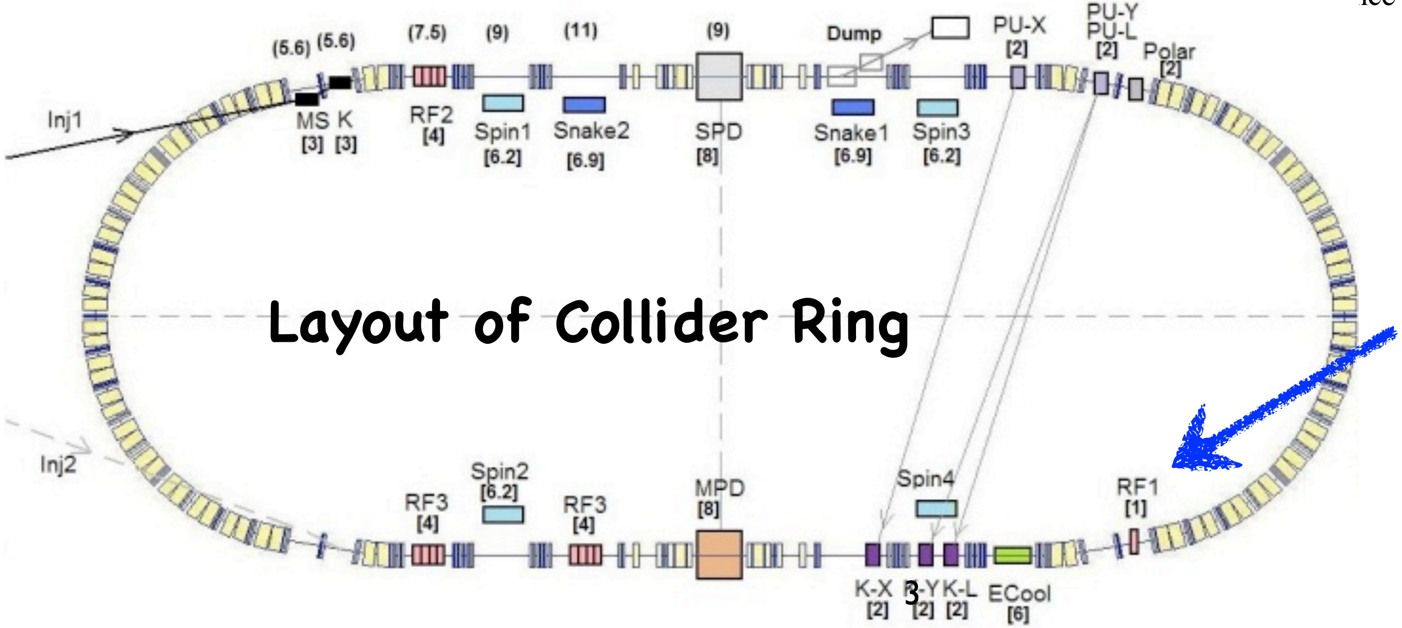
Min BetaY Function=0.35 m

Max DispersionX=2.50 m

Max DispersionY=0.145 m

NICA Collider FODO Lattice





This RF cavity should be moved out.

Intra Beam Scattering (IBS) effect

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

(i=x, y, s)

NICA collider

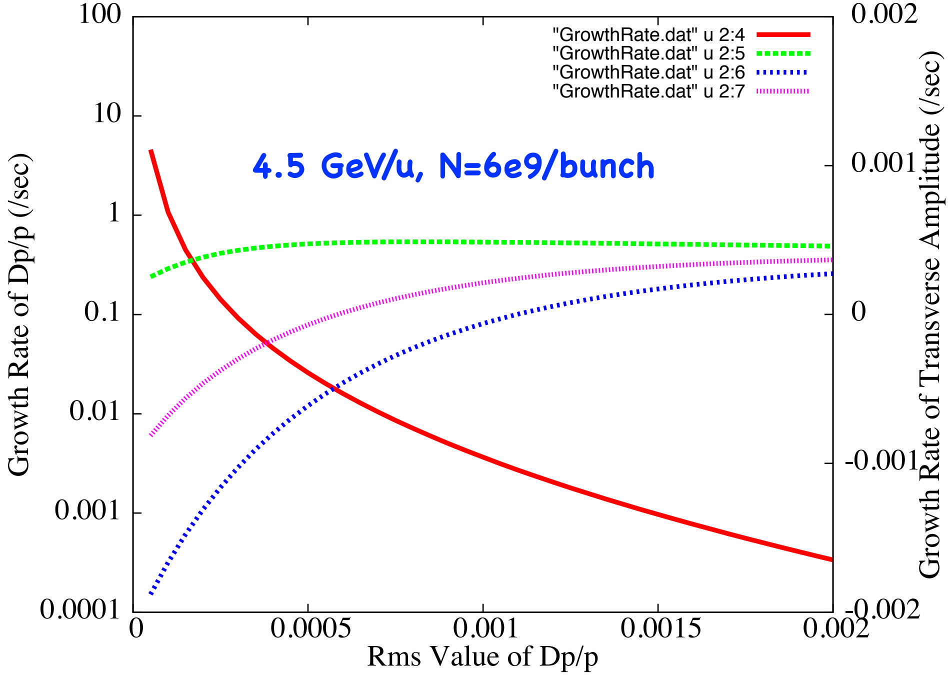
1. Low energy 1.0 - 4.5 GeV/u
2. High charge state 197Au79 +
3. Small emittance 0.6-1.0 Pi mm.mrad

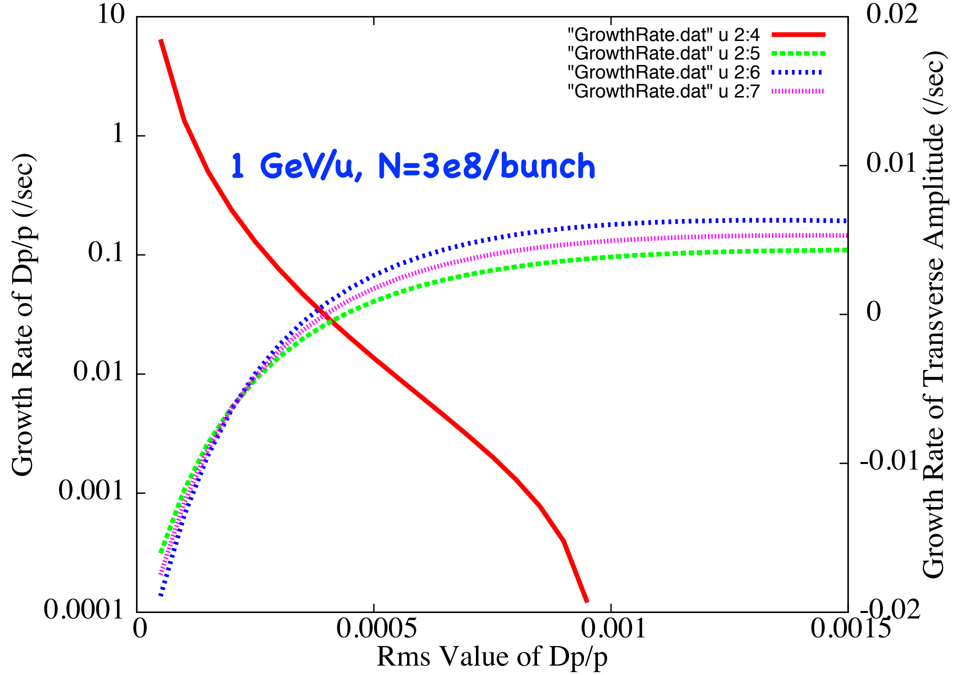
Growth rate are easily large value, and beam emittance and momentum spread gradually large. IBS is most dangerous factor to deteriorate the beam quality and luminosity. To attain high average luminosity value, IBS effect has to be compensated by cooling system.

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

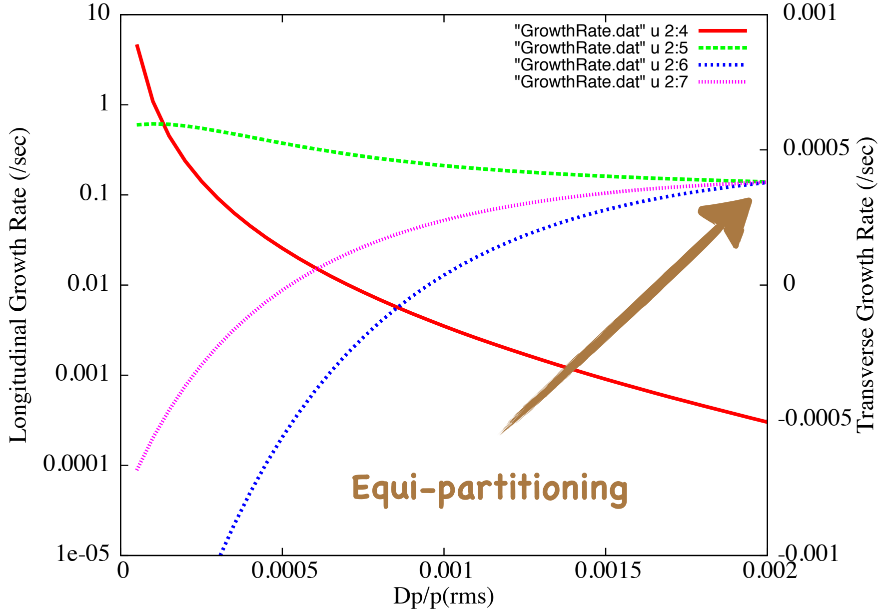




1/tauP (dp/p=1e-3)= 3.65E-03 (tau=270 sec)
1/tauH (dp/p=1e-3)= 4.86E-04 (tau=2050 sec)
1/tauV (dp/p=1e-3)= -6.1E-05 (tau=-16000 sec)

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)

NICA Collider IBS Growth Rate 4.5 GeV/u 197Au79+
Transverse Emittance=1.1 (H), 0.78 (V) Pi mm.mrad



Bunch Length=0.6 m (rms)
Particle Number=5.1e9/bunch
Transverse Emittance=1.1(H), 0.78(V) Pi mm.mrad (rms)

Red: Rate of Dp/p
Green: Rate of Horizontal Betatron Motion
Blue: Rate of Vertical Betatron Motion
Pink: Rate at H&V Coupling

This parameter set is the case for the equi-partitioning of longitudinal, horizontal and vertical IBS effects. Three growth rates have the same growth rates of 3.5e-4/sec. Dp/p=2e-3, Horizontal emittance=1.1 Pi mm.mrad and Vertical emittance=0.78 Pi mm.mrad.

Beam Parameters for Various Energies for NICA Collider

Circumference=503.04 m, Ring Momentum Compaction=0.0199,

Gamma-t=7.09, Initial 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

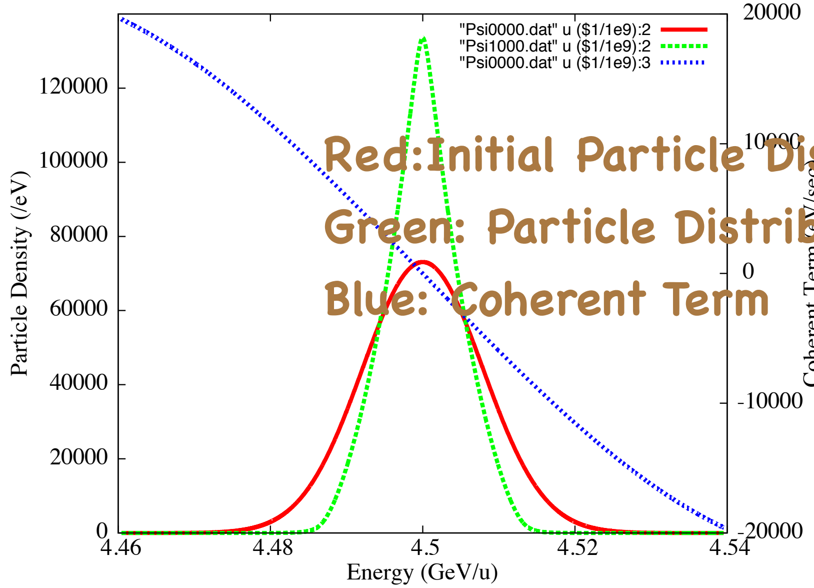
Nequivalent=BunchNumber*IonNumber/Bunch*BunchingFactor

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

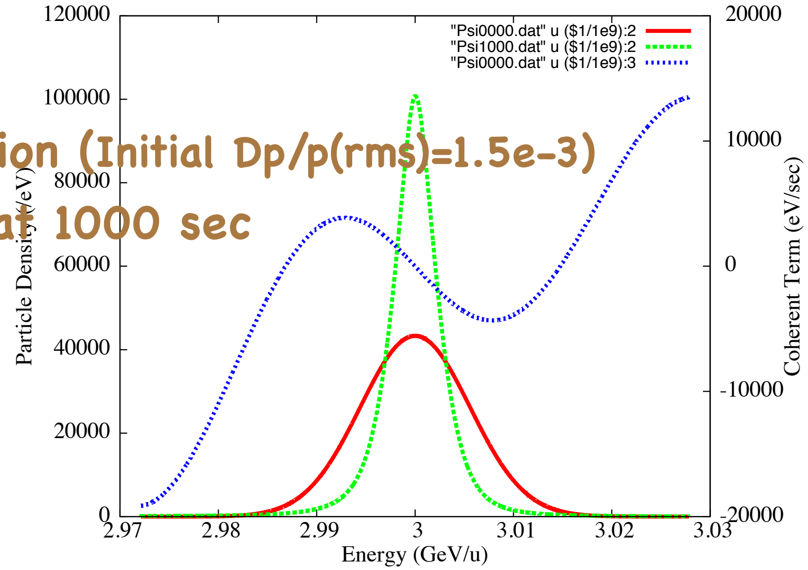
Frequency Band=3-6 GHz (Without IBS effects)

Red:Initial Particle Distribution (Initial Dp/p(rms)=1.5e-3)
Green: Particle Distribution at 1000 sec
Blue: Coherent Term

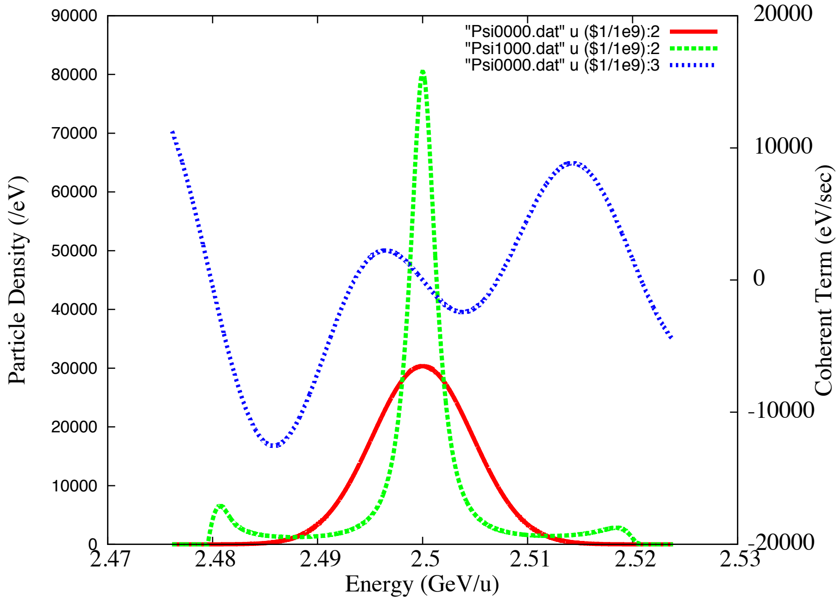
Energy=4.5 GeV/u, Gain=50 dB



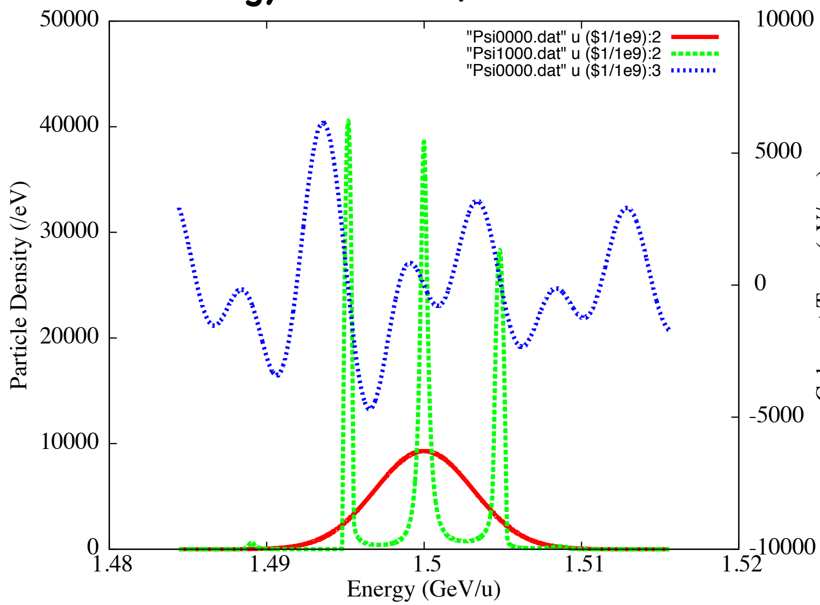
Energy=3.0 GeV/u, Gain=50 dB



Energy=2.5 GeV/u, Gain=50 dB



Energy=1.5 GeV/u, Gain=50 dB



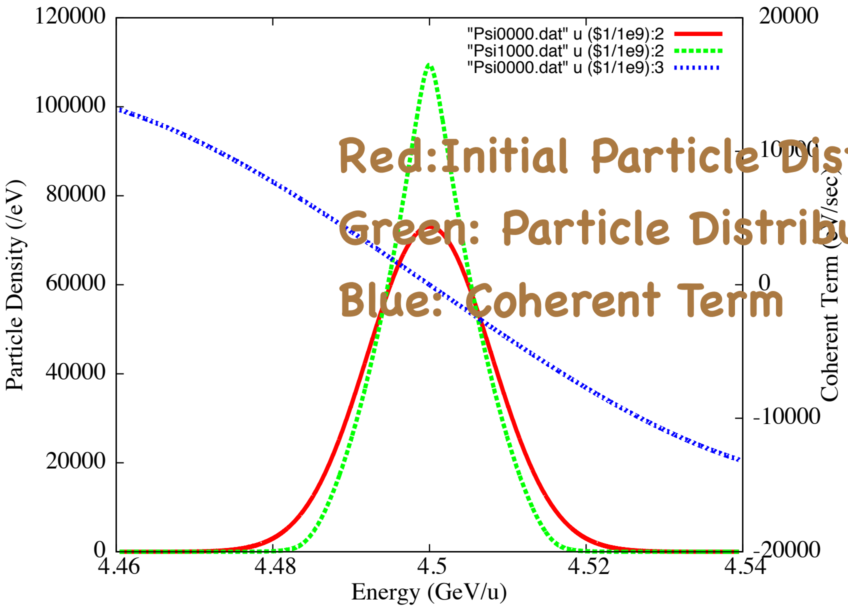
Frequency Band=2-4 GHz (Without IBS effects)

Red:Initial Particle Distribution (Initial Dp/p(rms)=1.5e-3)

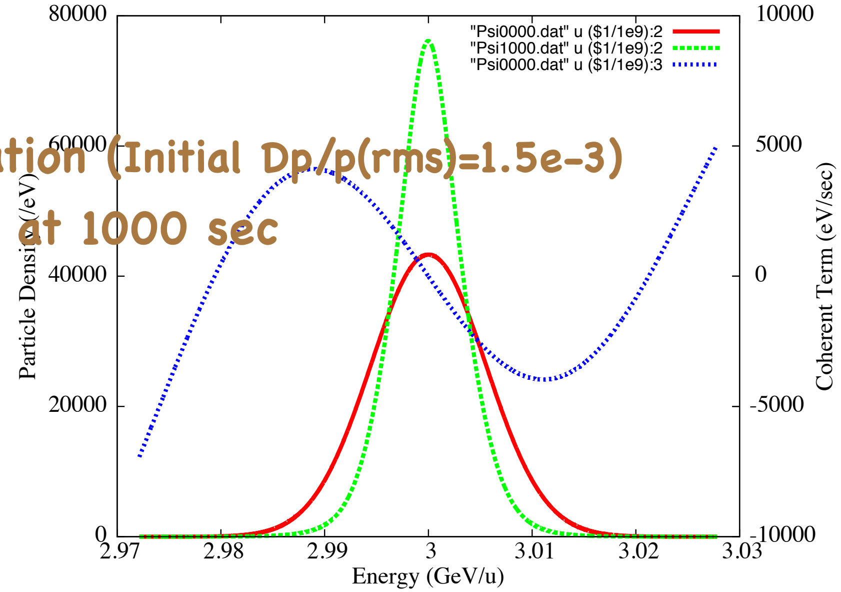
Green: Particle Distribution at 1000 sec

Blue: Coherent Term

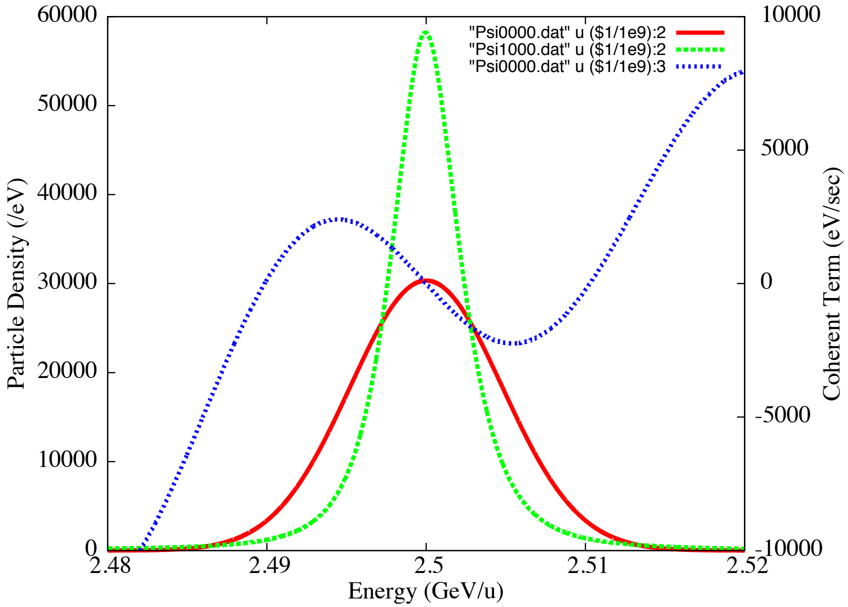
Energy=4.5 GeV/u, Gain=50 dB



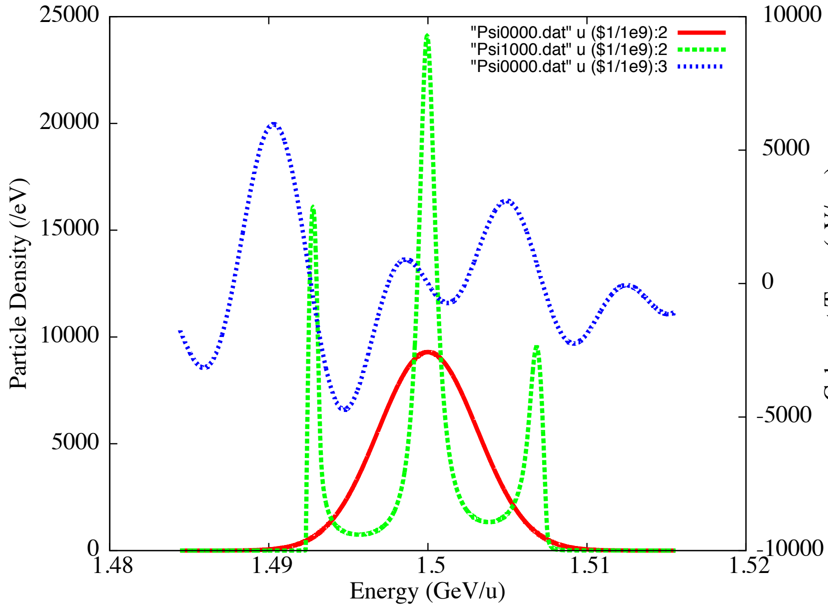
Energy=3.0 GeV/u, Gain=50 dB



Energy=2.5 GeV/u, Gain=50 dB



Energy=1.5 GeV/u, Gain=50 dB

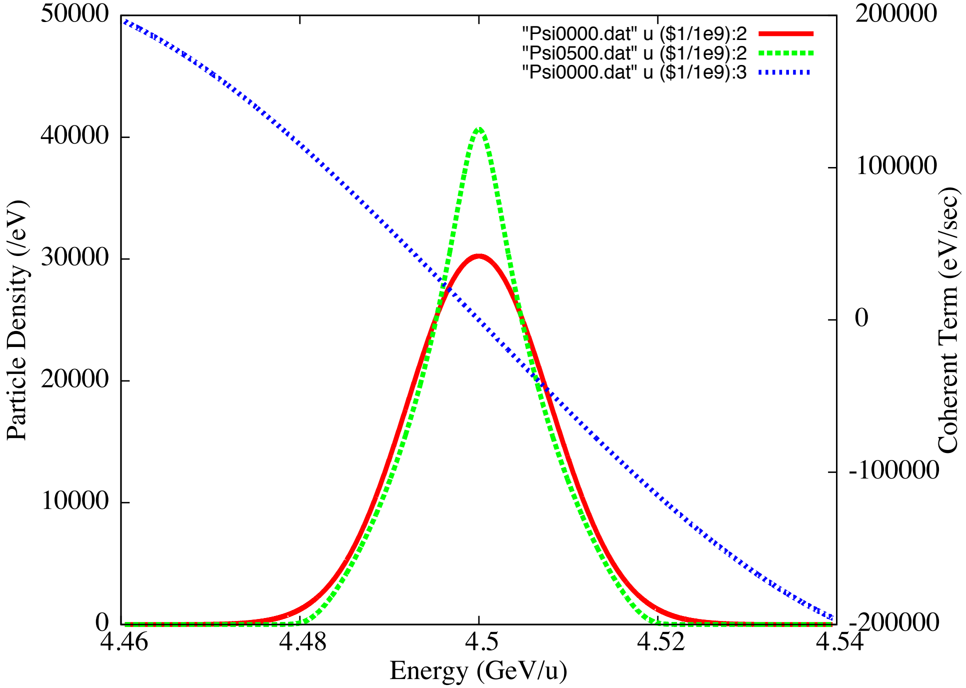


Example of Fokker Planck Solution with Coasting Beam Approximation

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

Band=3-6GHz, Gain=70dB, Eta=0.00927, LocalEta=-0.0018

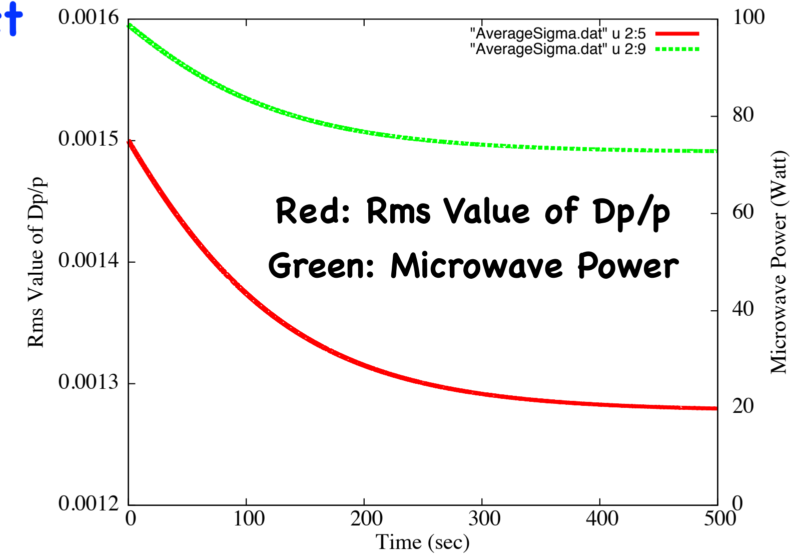
With IBS Effect

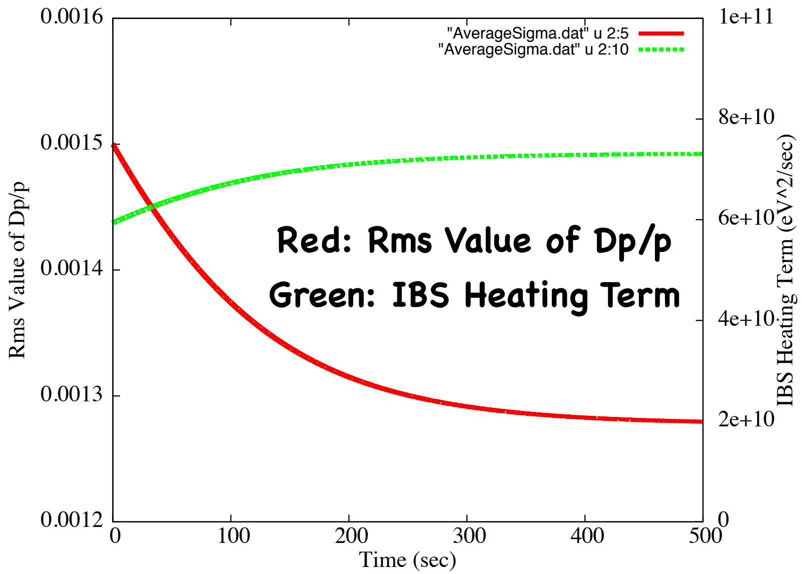


Red: Initial Particle Distribution

Green: Particle Distribution at 500 sec

Blue: Coherent Term



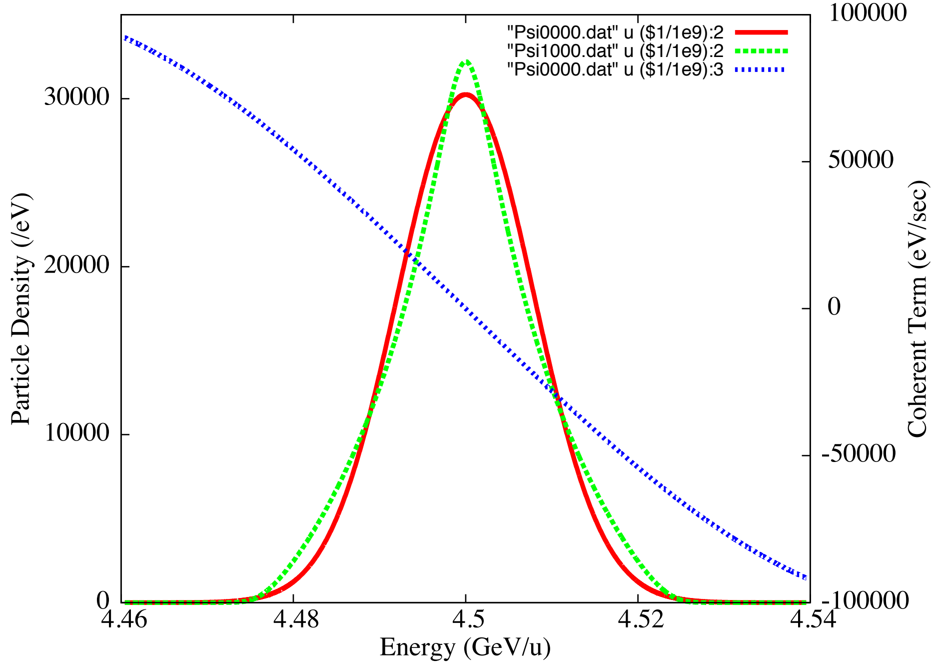


Example of Fokker Planck Solution with Coasting Beam Approximation

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

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

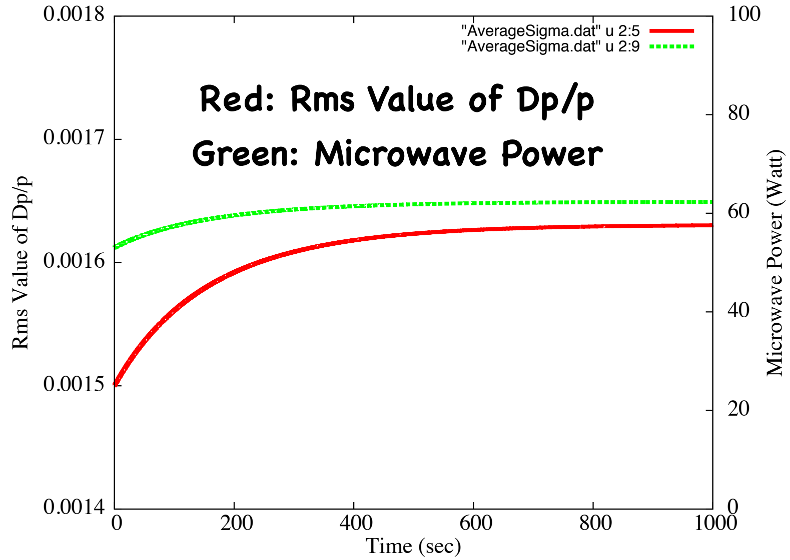
With IBS Effect

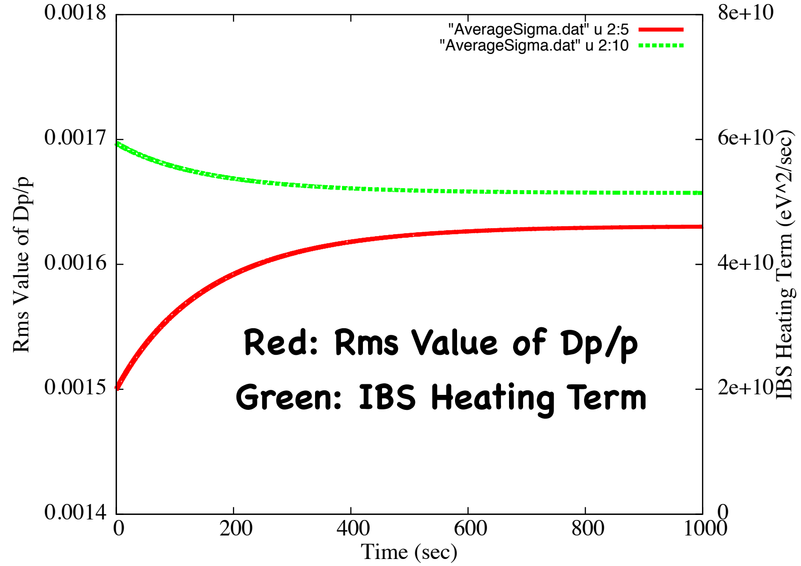


Red: Initial Particle Distribution

Green: Particle Distribution at 1000 sec

Blue: Coherent Term



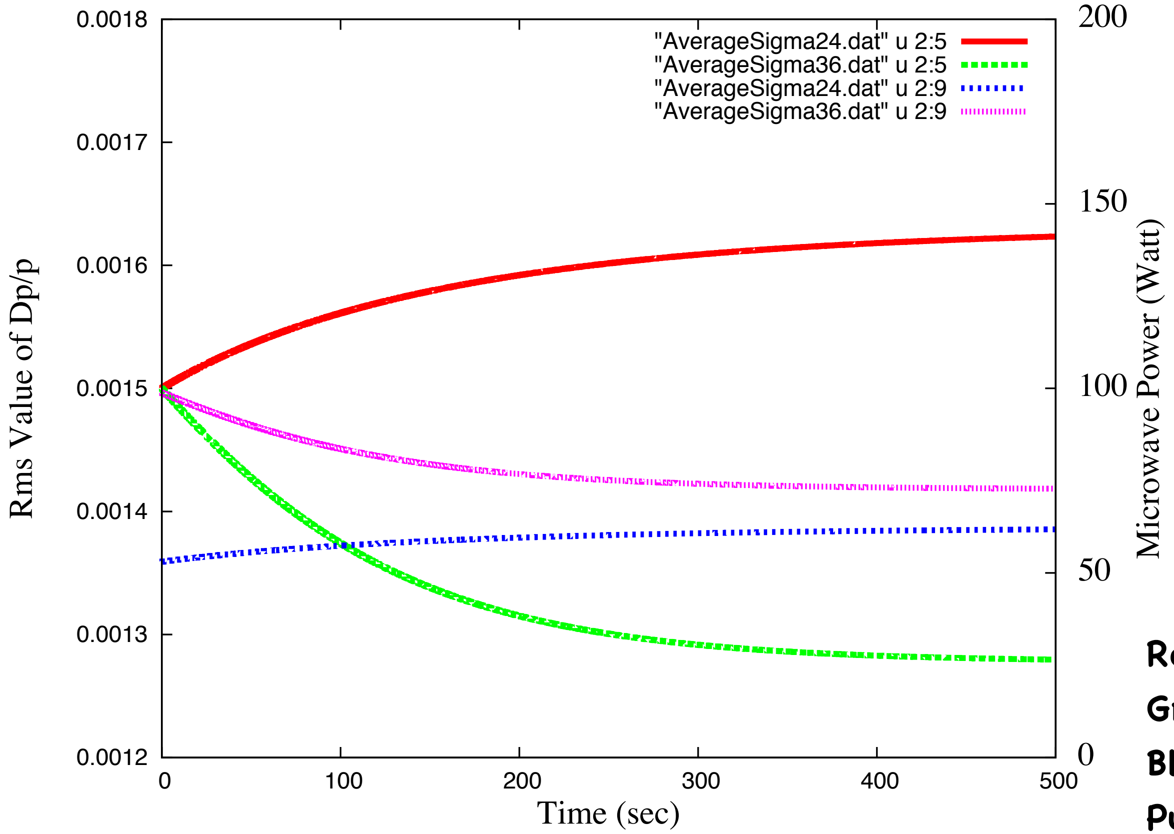


Comparison of Band Width

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

Band=2-4GHz & 3-6GHz, Gain=70dB, Eta=0.00927, LocalEta=-0.0018

With IBS Effect



Red: Rms Value of Dp/p (2-4 GHz)

Green: Rms Value of Dp/p (3-6 GHz)

Blue : RF power (2-4 GHz)

Purple: RF power (3-6 GHz)

Momentum Cooling and Synchrotron Motion in Barrier Bucket System

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

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

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*

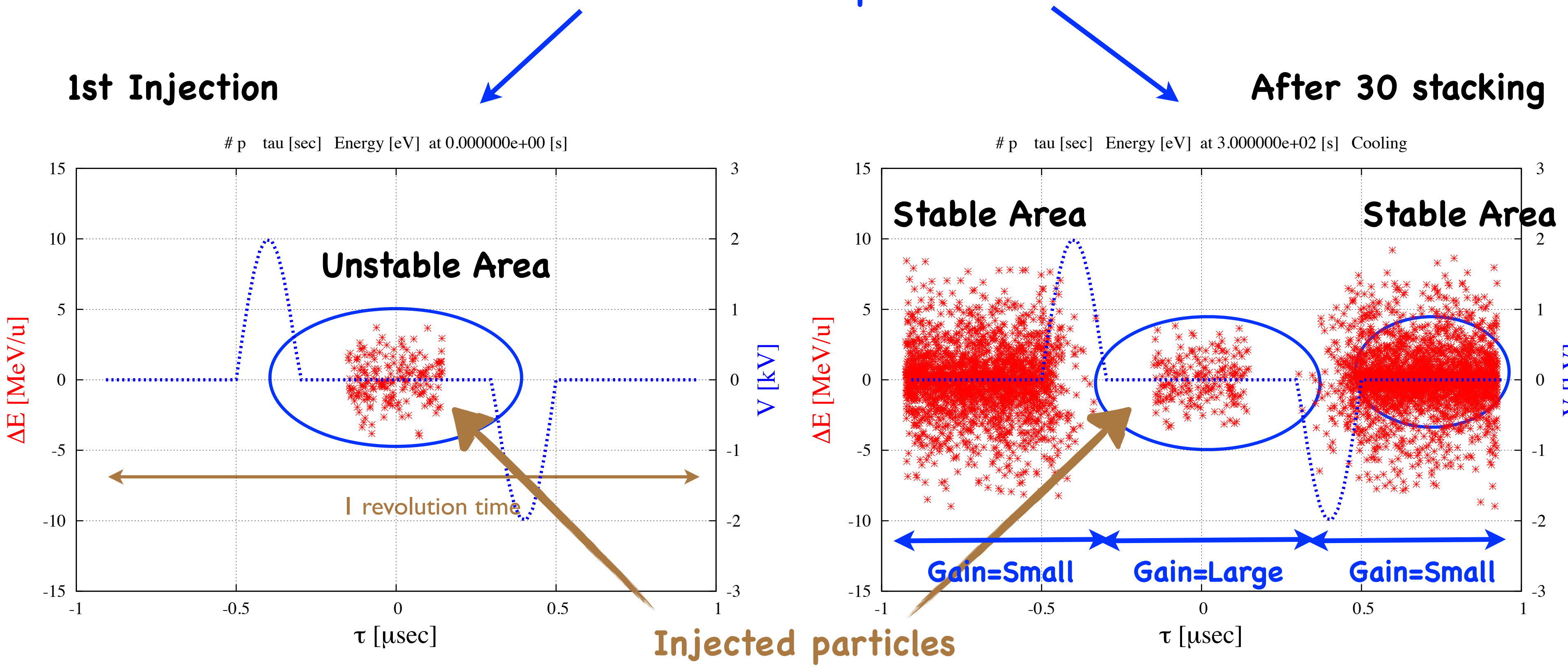
ξ_{IBS} : *IBS Diffusion*

Random energy kick leads to diffusion in phase space

Cooling can move particles from unstable to stable area

Fixed Barrier Case

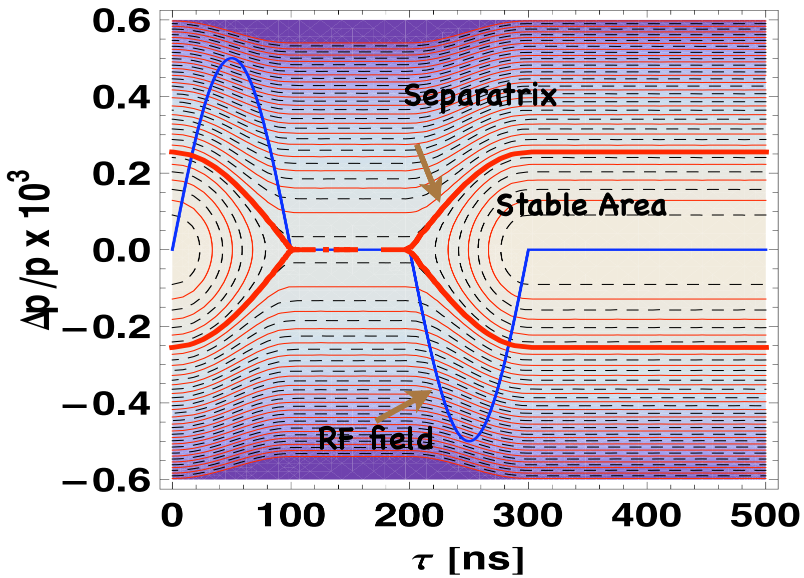
Stochastic Cooling is applied to injected and stacked particles.

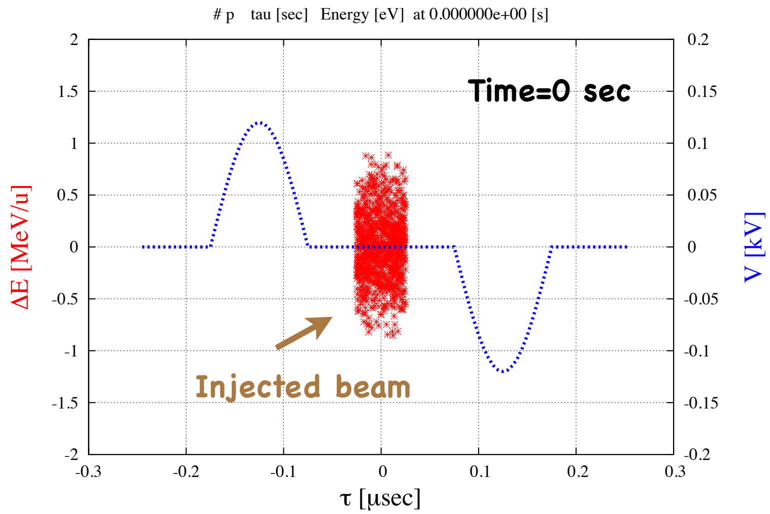


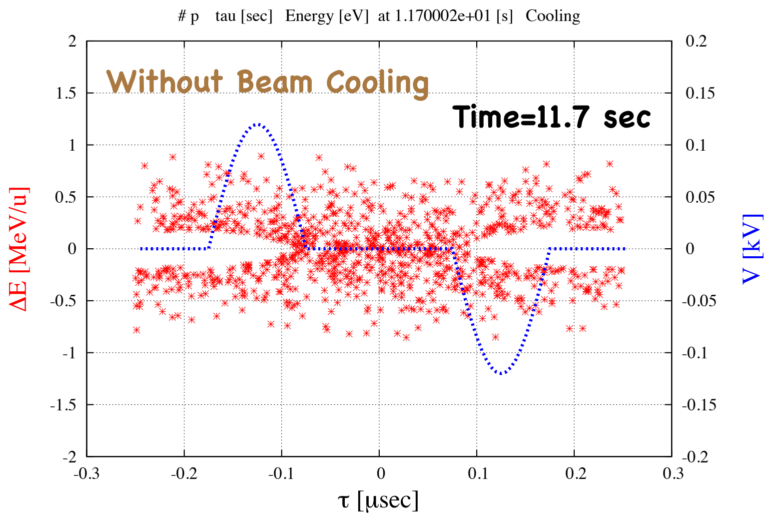
Red: Particles (energy left scale)

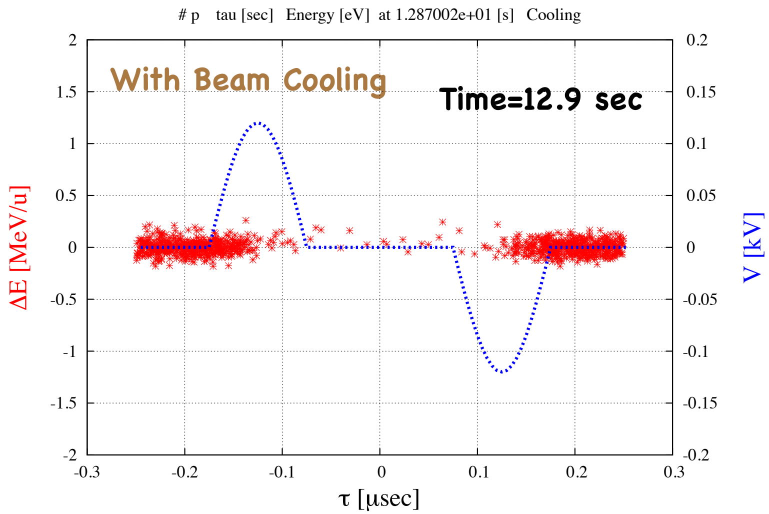
Blue: Barrier voltage (right scale)

Separatrix and Beam Trajectory at Barrier Bucket System









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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: 546.852 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
10. Number of PU, and Kicker=128
11. Pickup Impedance=50 Ohm
12. Gain=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
17. Transverse emittance = 0.3 Pi mm.mrad (constant)

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NICA BB parameters

Beam energy=4.5 GeV/u

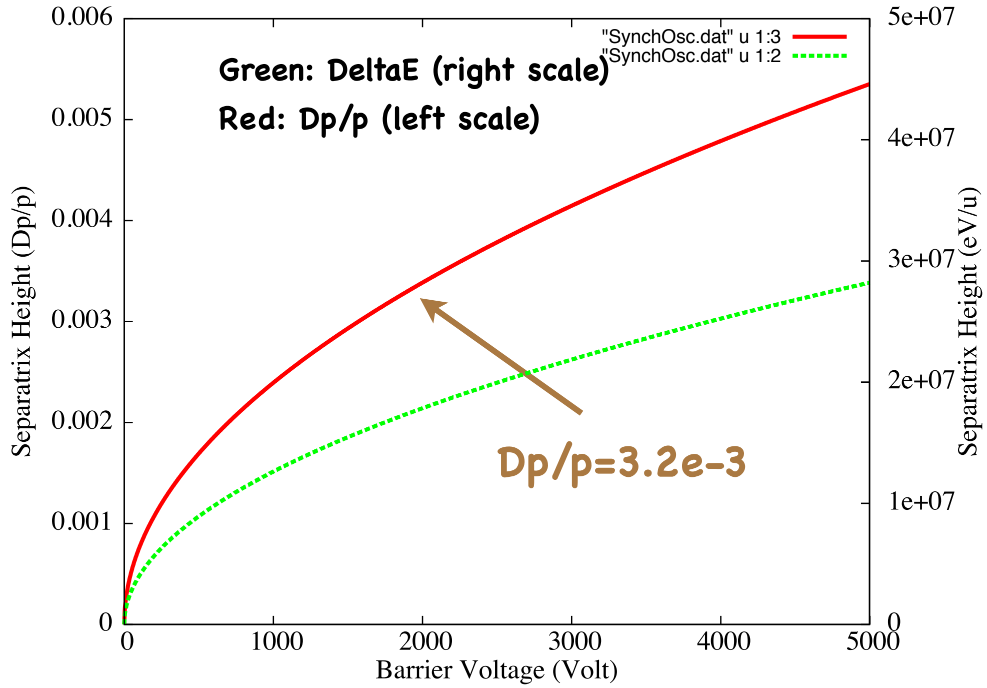
BB Voltage = 2 kV

BB frequency= 2.5 MHz (T=400 nsec)

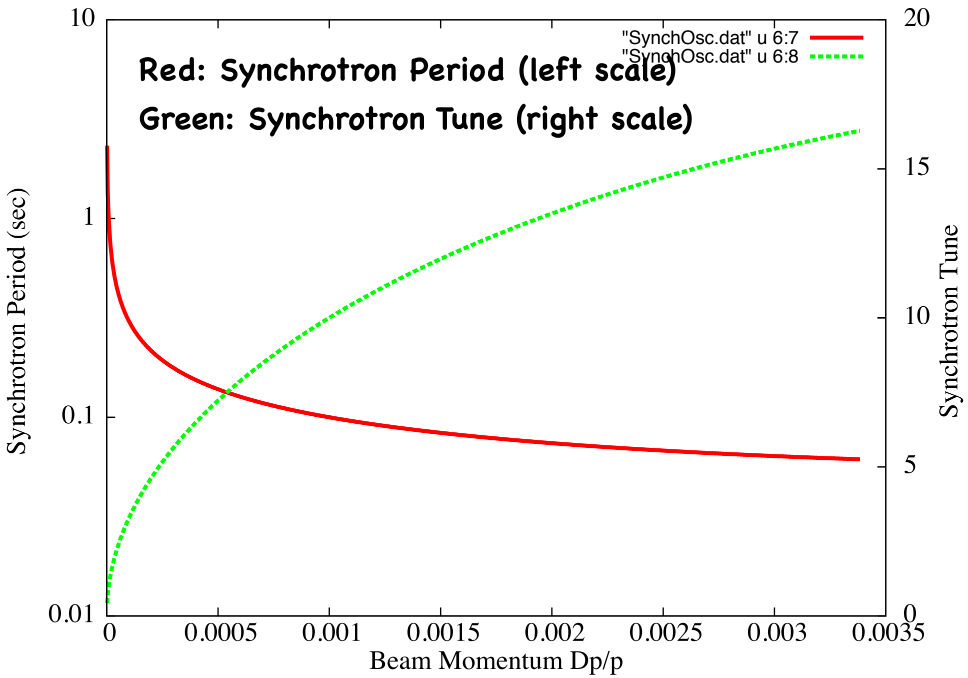
Ring slipping factor: 0.00845

Revolution Period=1.8515e-6 sec

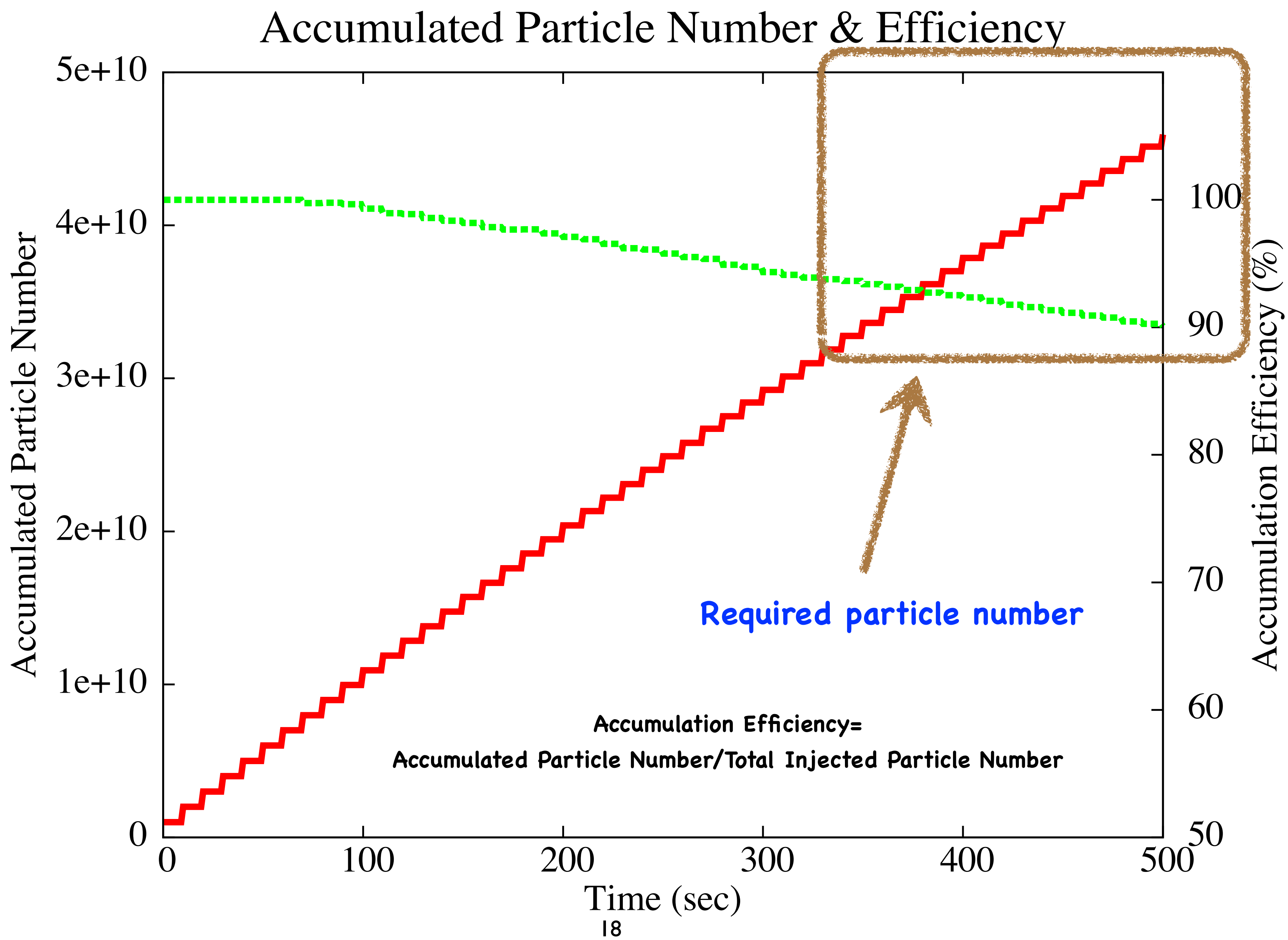
Separatrix Height vs Barrier Voltage



Synchrotron Period & Tune vs Particle Momentum

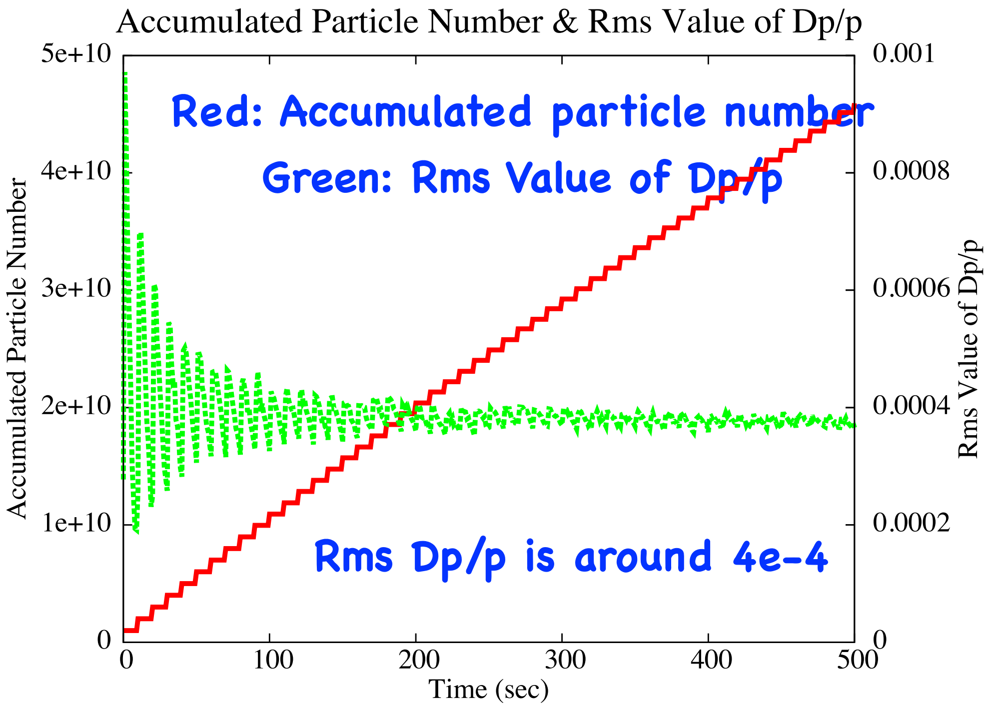


Accumulated Particle Number & Efficiency (Initial Gain=115dB)

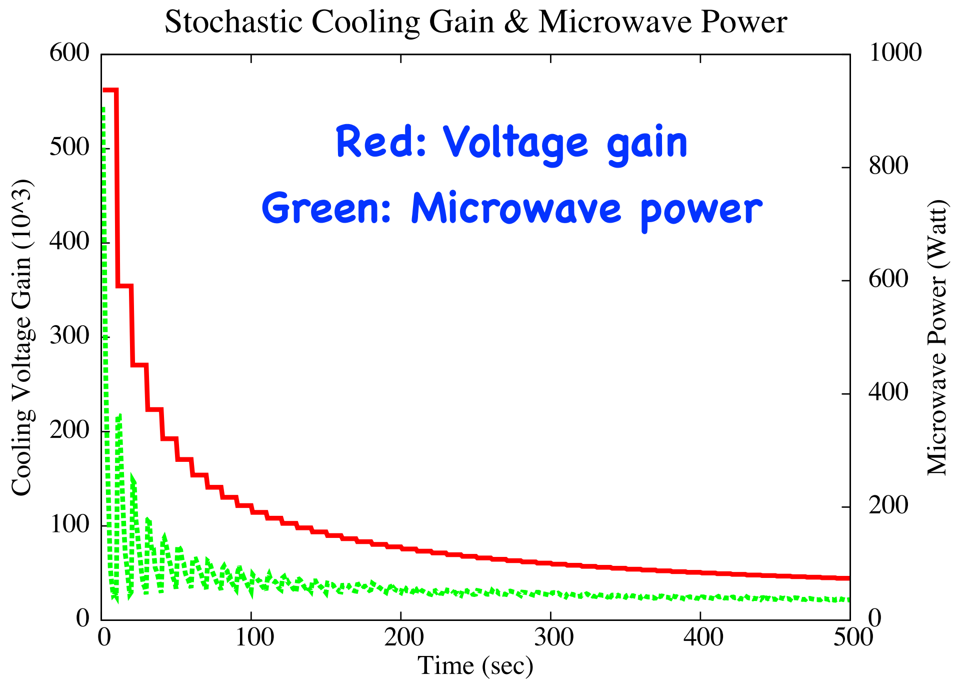


Initial Gain=115 dB

Accumulated particle number & Rms Value of Dp/p during the accumulation



Gain Reduction of Cooling System & Microwav power

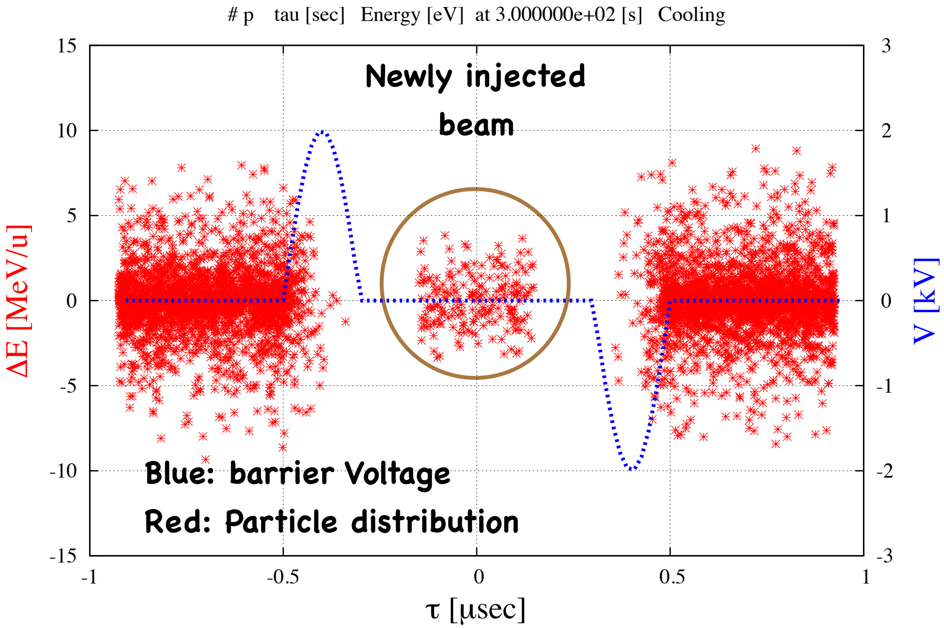


This gain reduction as the increase of stacked particle number is critically important to achieve the high efficiency stacking. This is due to the fact that the Schottky noise- power becomes dominant if the gain is kept constant when the particle number is increased. Namely optimum gain is smaller for the larger number of particles.

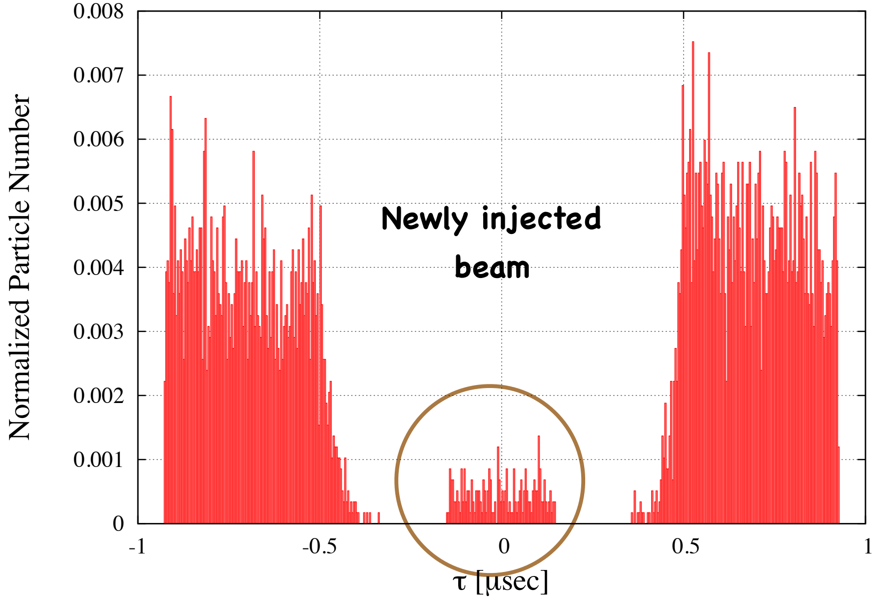
Initial Gain=115 dB

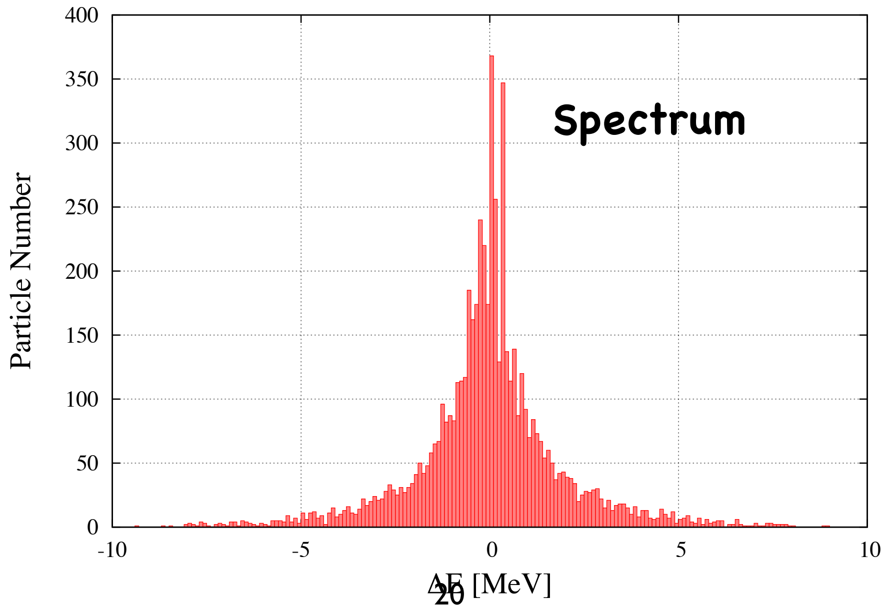
Phase Space Mapping

Time=300.0 sec



Particle distribution along the Ring Circumference

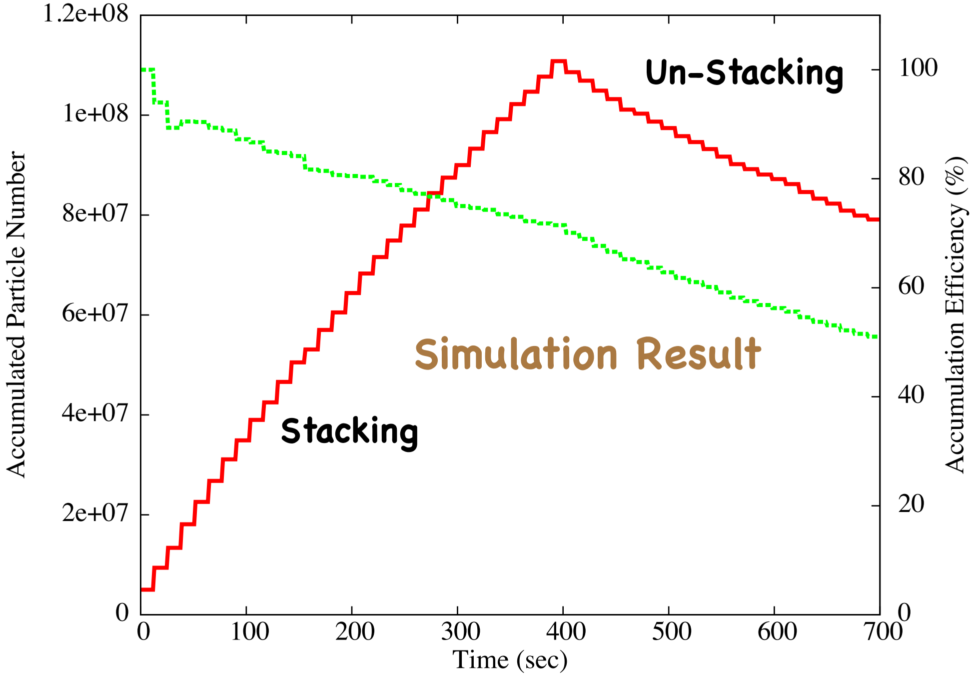


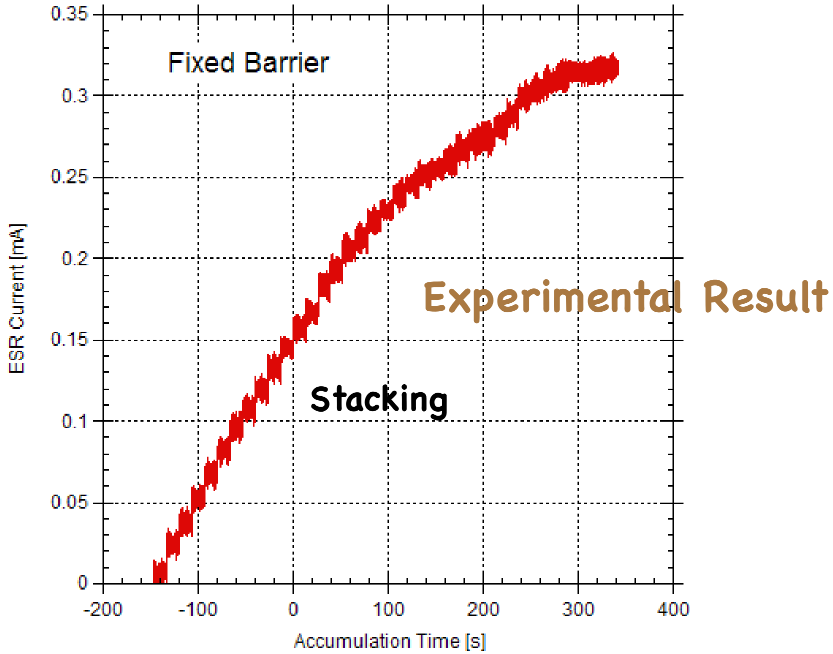


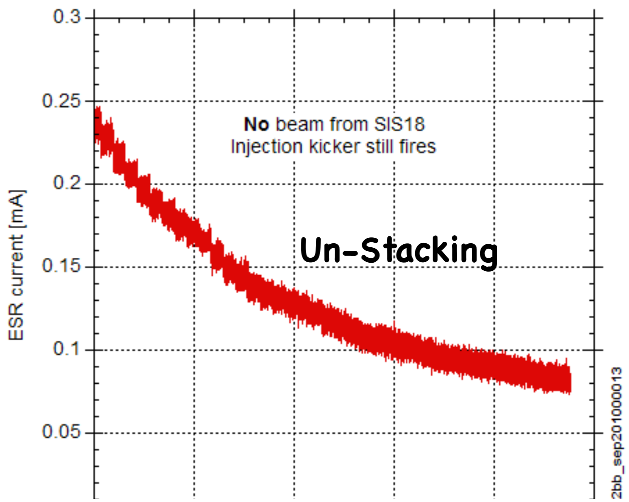
ESR POP Experiment

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

Accumulated Particle Number & Efficiency







Un-Stacking

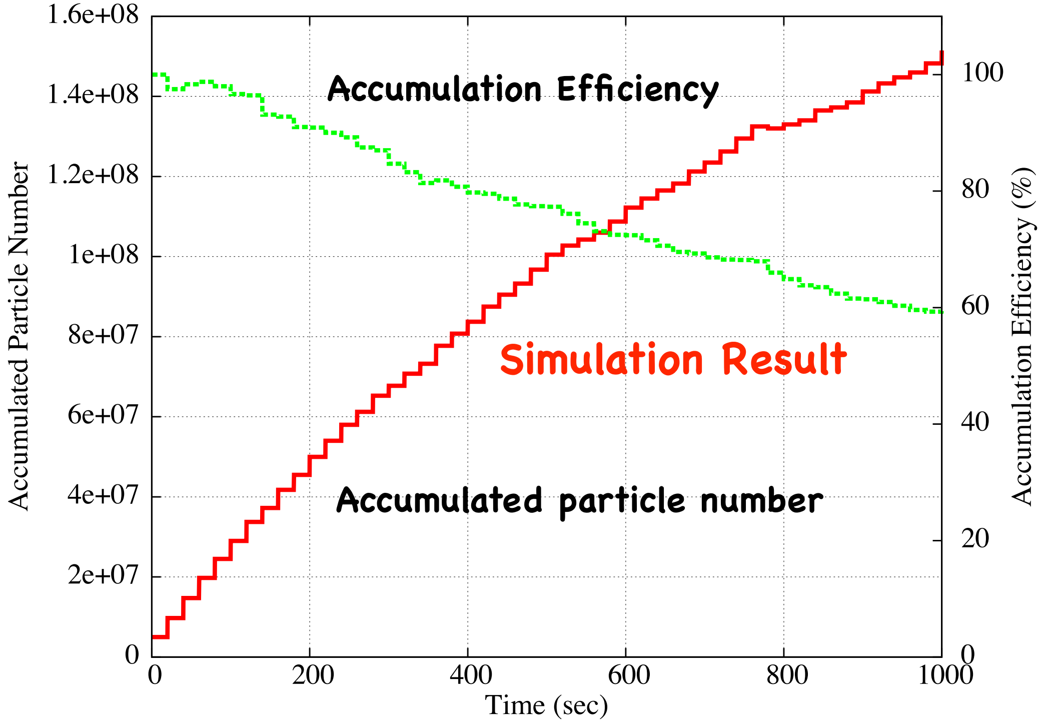
- No Beam injection but Kicker is fired -

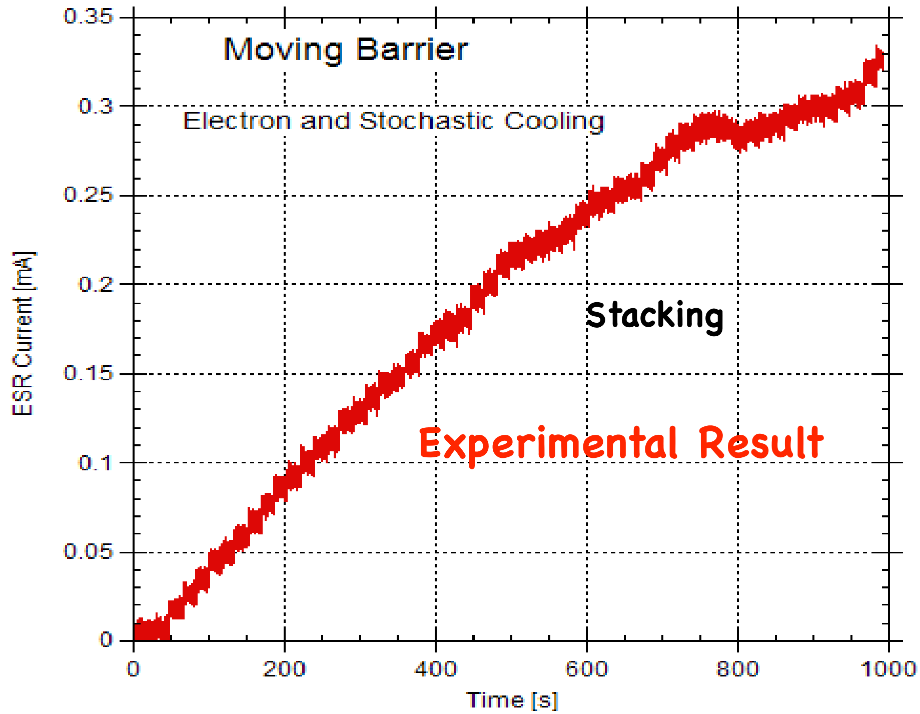
Accumulation Efficiency=

Accumulated Particle Number/Total Injected Particle Number

POP Experiment at ESR
Moving Barrier Case, Gain=120 dB
Vbb=120V, Ie=0.3A, Cycle time=20 sec, Kicker period=200 nsec

Accumulated Particle Number & Efficiency





Accumulation Efficiency=
Accumulated Particle Number/Total Injected Particle Number

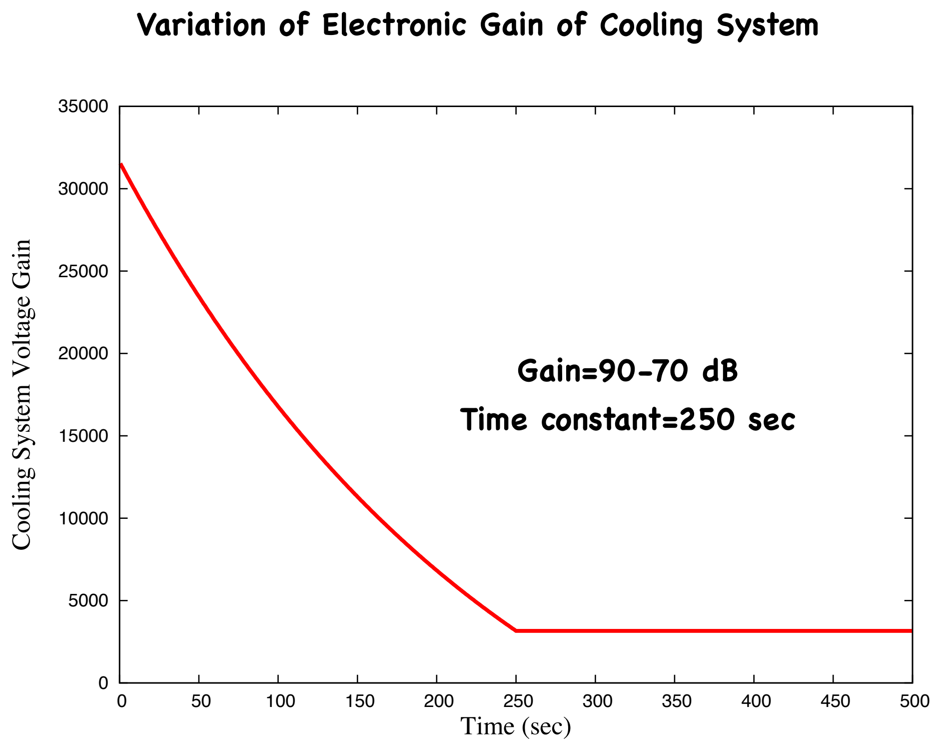
Reference: M. Steck et al. Poster contribution to this meeting (Experimental results)
T. Katayama et al., Poster contribution to this meeting. (Simulation results)

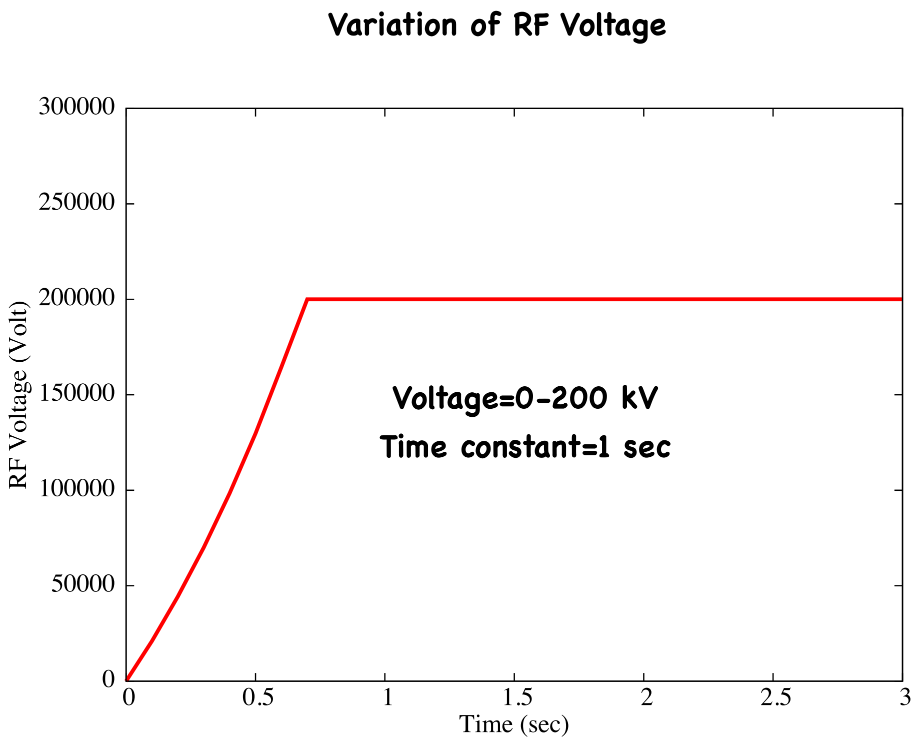
“ How do we make short bunches from the coasting beam in the Collider ?”

Part 1 Beam bunching from the coasting beam
Operation scheme

1. Gain of stochastic cooling system is reduced from the initial value 90dB to 80 (75)dB within time constant 250 sec.
2. RF voltage is increased from 0 to 200 kV (harmonic=24) with time constant 1 sec for the adiabatic bunching.

Short Bunch Formation





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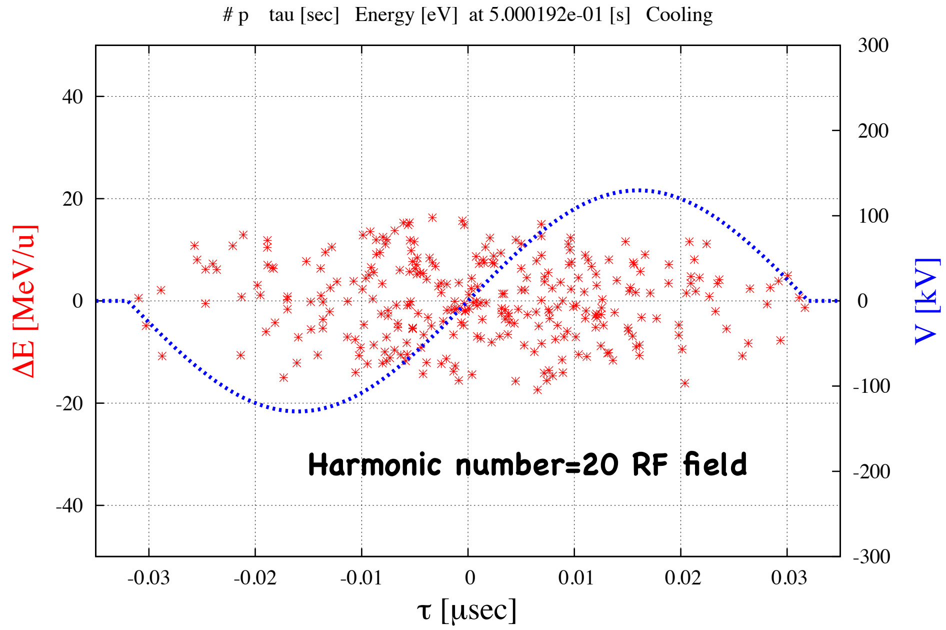
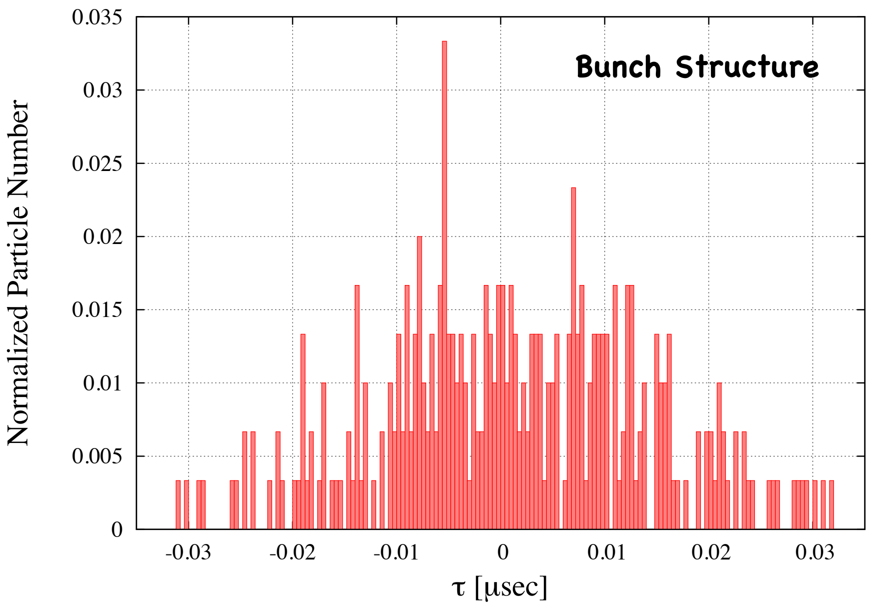
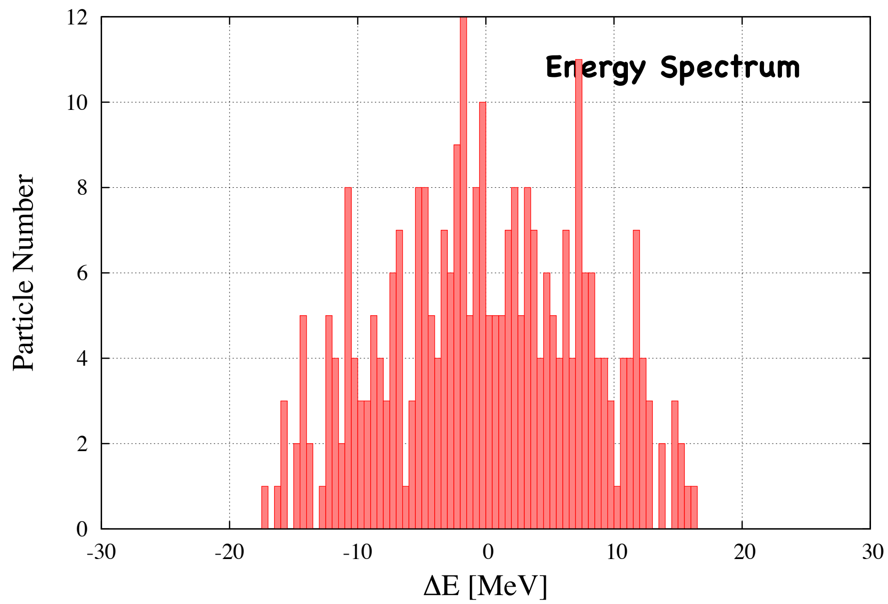
Vrf=0-200 kV (Adiabatic increase within 1 sec)

Phase space mapping



Time=0.5 sec





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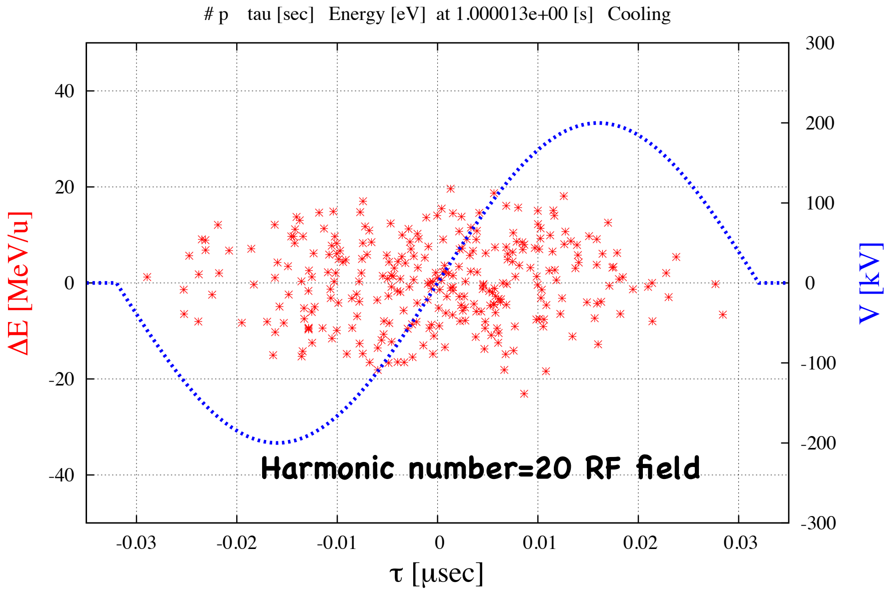
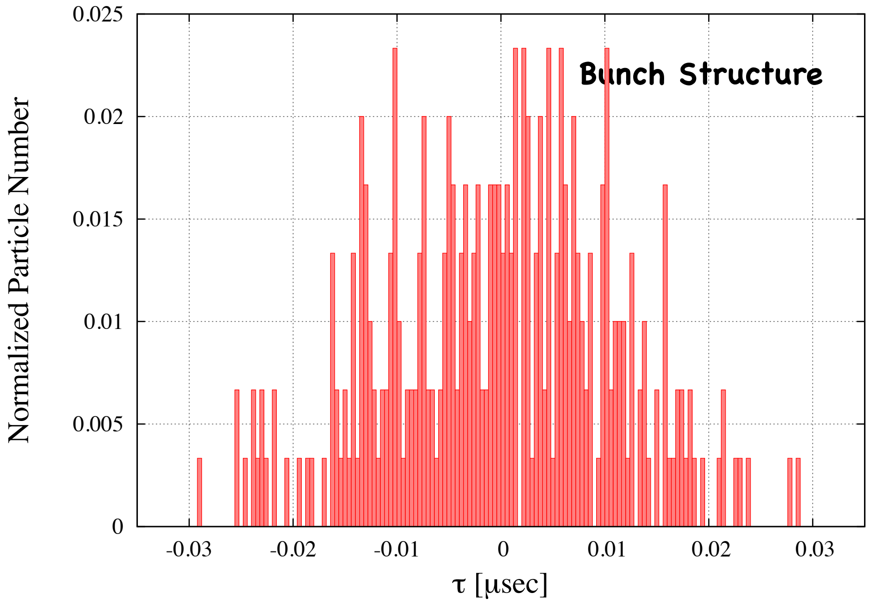
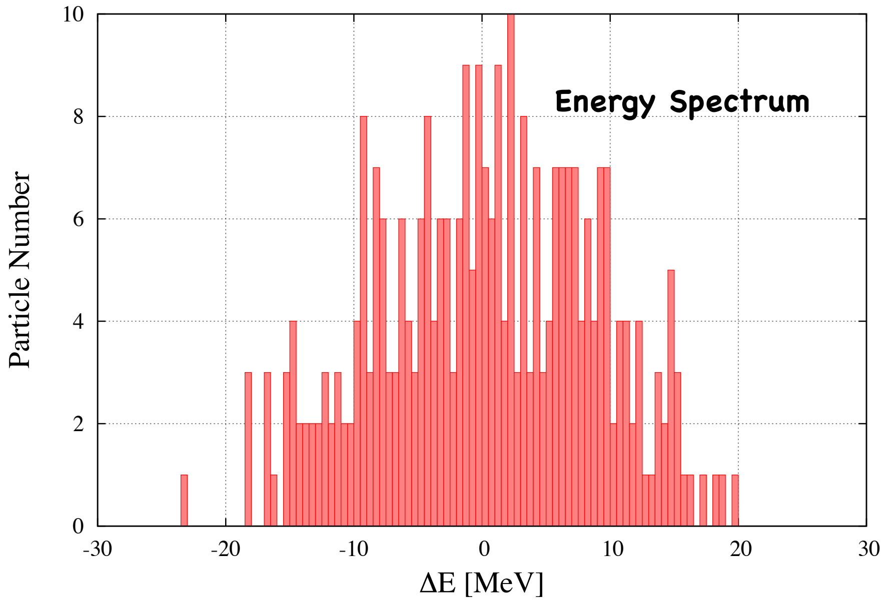
Vrf=0-200 kV (Adiabatic increase within 1 sec)

Phase space mapping



Time=1.0 sec





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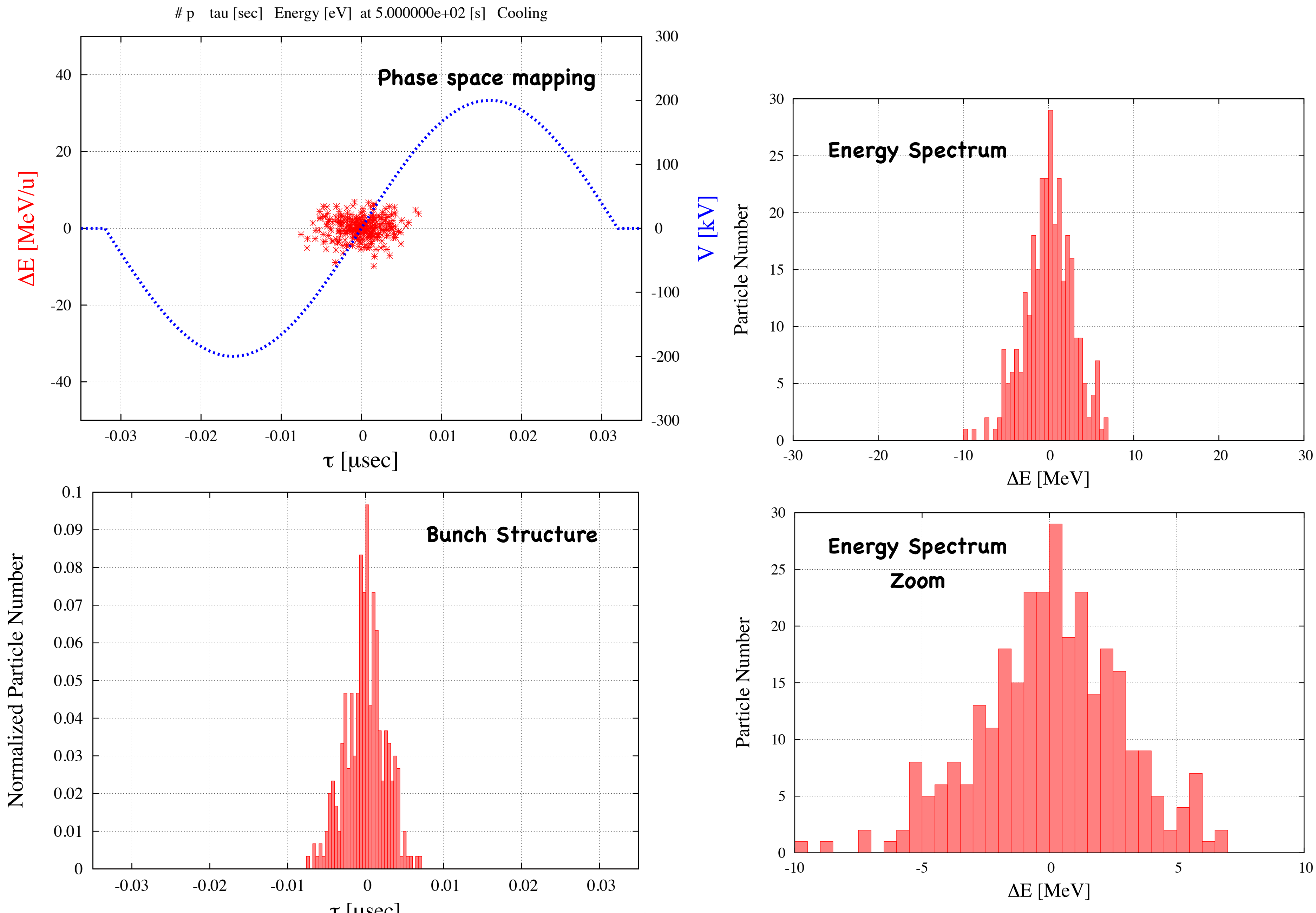
Time=500 sec, Equilibrium condition



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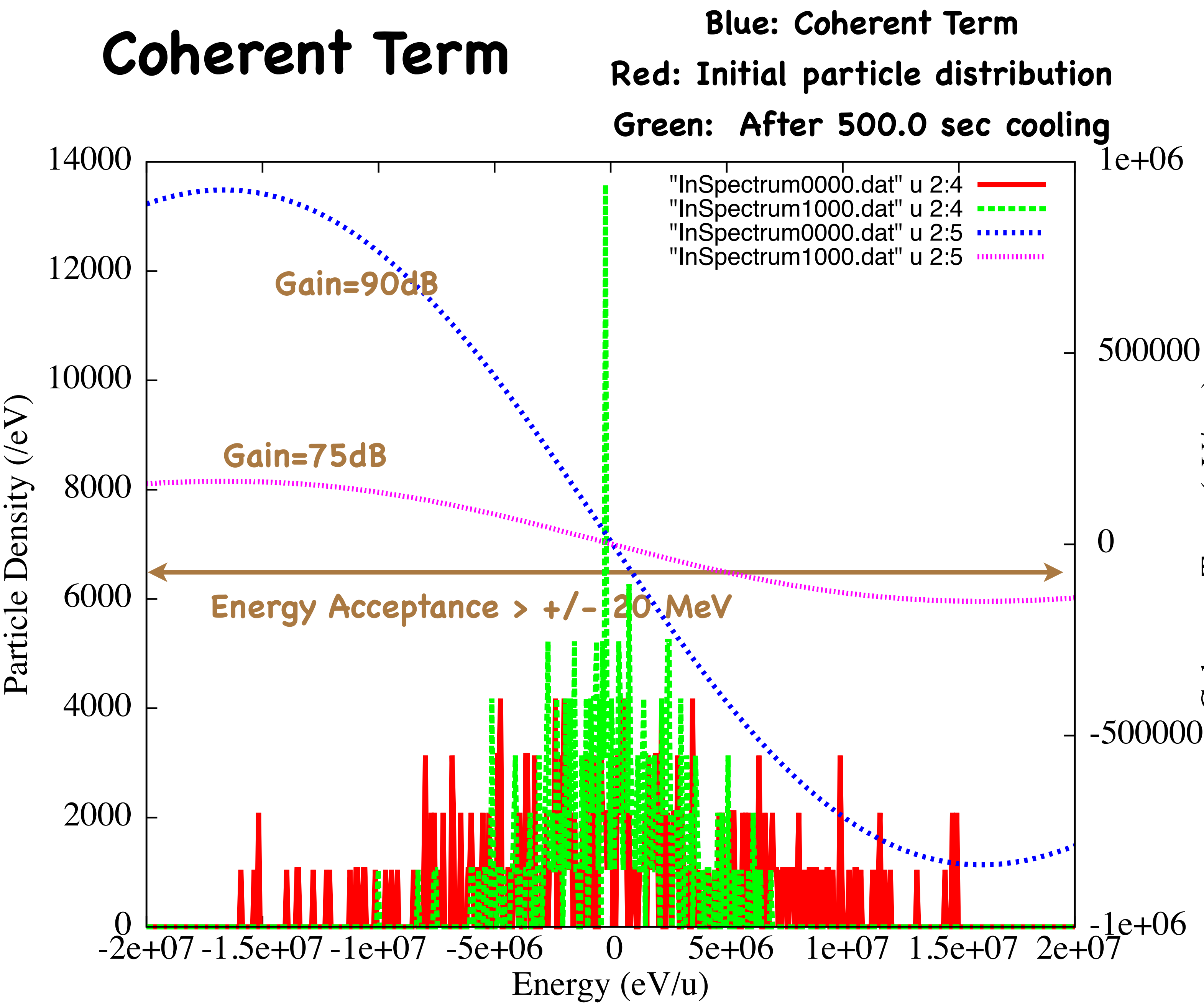
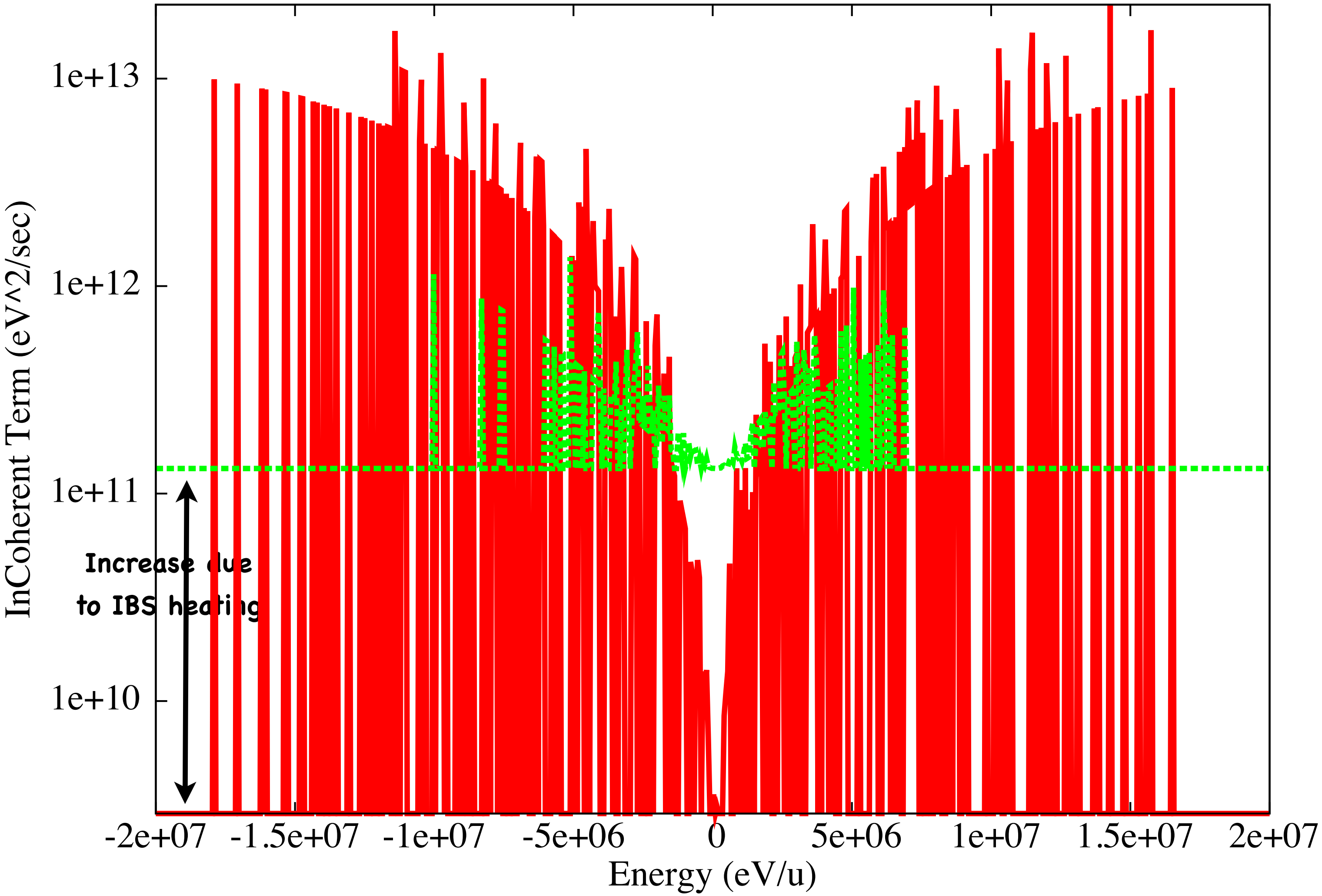
Coherent Term



28

InCoherent Term

Red: Initial InCoherent Term
Green: After 500 sec cooling InCoherent term



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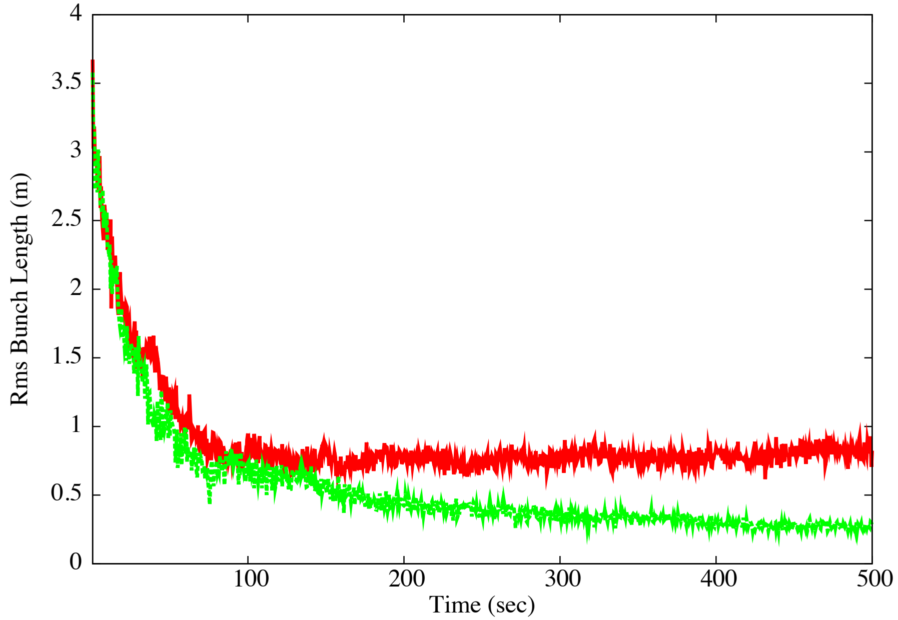
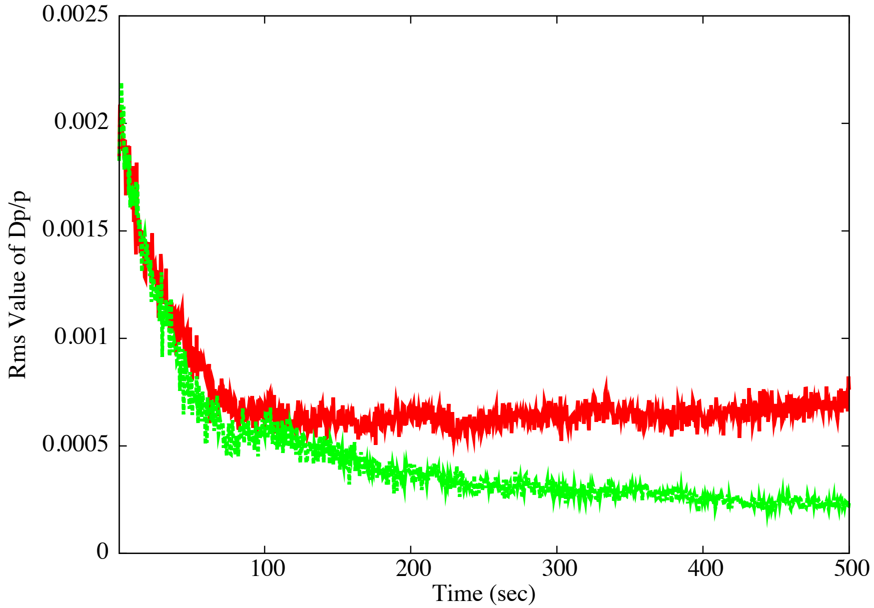
Evolution of Rms Bunch Length (m)
Vrf=200 kV



Evolution of Rms Dp/p
Vrf=200 kV



Gain=90-70 dB, With IBS effect (Red)

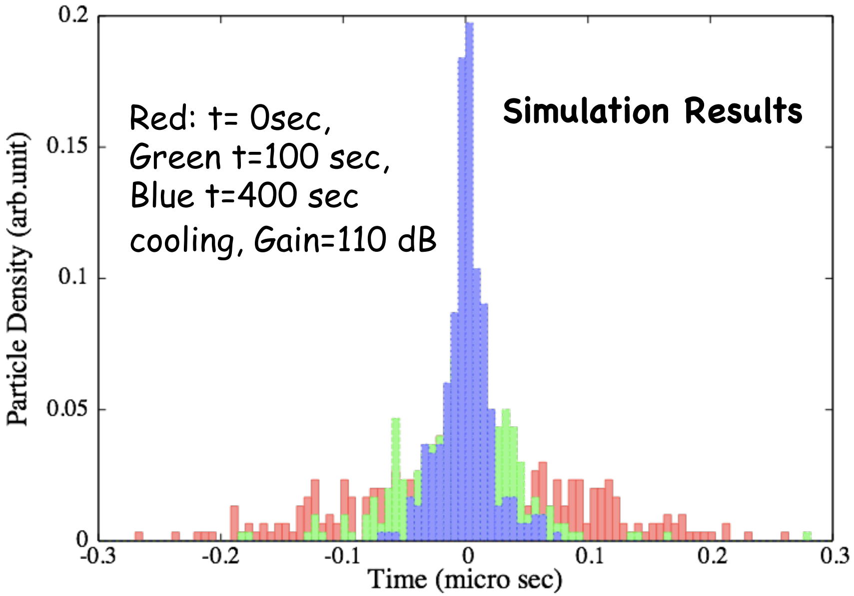
Gain=90-70 dB, Without IBS Effects(Green)

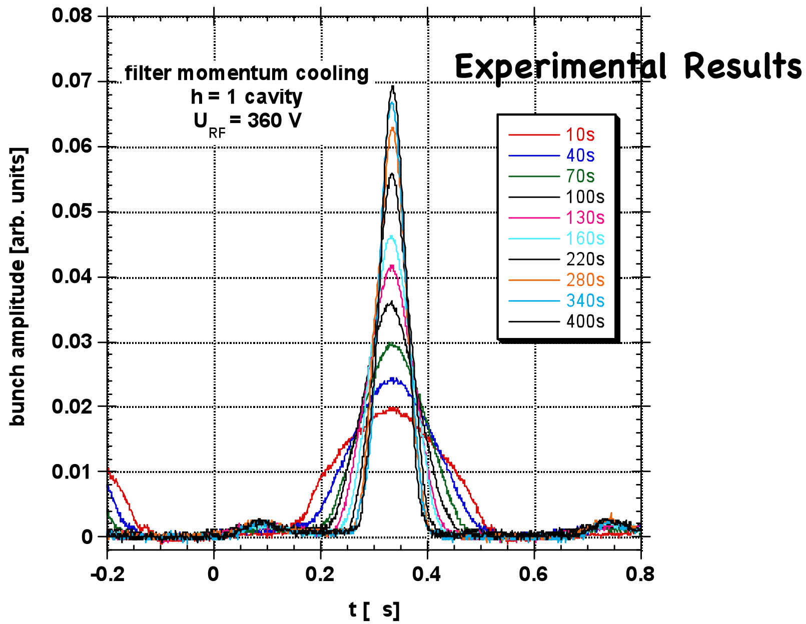
30

Beam Bunching with Stochastic Cooling

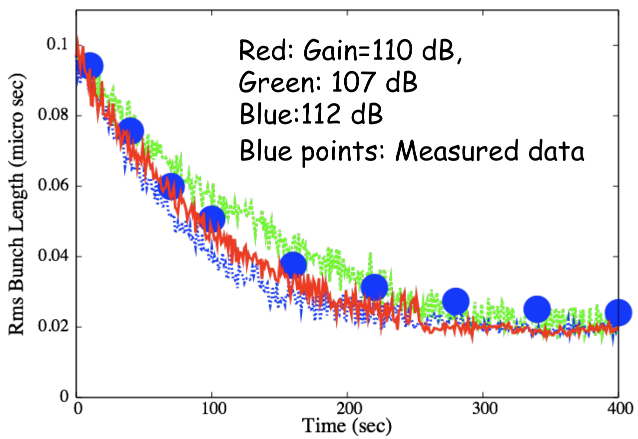
T. Katayama, GSI, Darmstadt, Germany
H. Stockhorst, R. Stassen, D. Prasuhn and R. Maier,
Forschungszentrum, Jülich, Germany
T. Kikuchi, Nagaoka Univ. of Technology, Japan, I. Meshkov, JINR, Russia

COSY Bunched Beam Cooling
IPAC10 in Kyoto

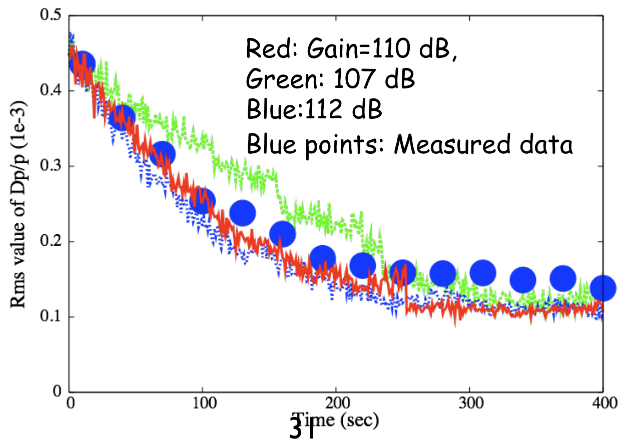




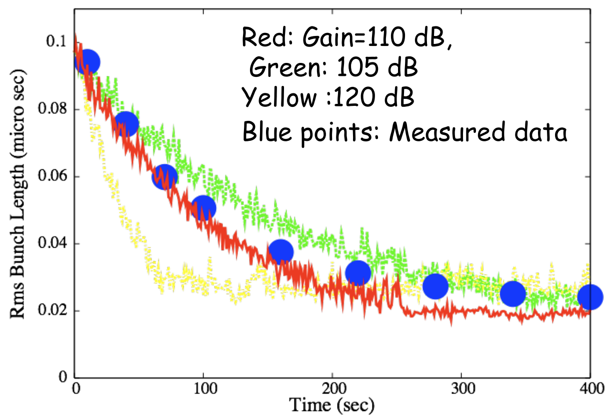
Evolution of Bunch Length



Evolution of Dp/p



Evolution of Bunch Length



Re-capturing of the pre-bunched beam and further bunching

1. Pre-bunched beam has the bunch length = 3 ns (rms) and Dp/p= 6e-4 (rms). (Gaussian distribution in both dimension). This bunch is re-captured by the RF field of harmonic=100. Again the RF voltage is increased from 0 to 500 kV (harmonic=100) with time constant 1 sec for the adiabatic capturing.

2. Gain of stochastic cooling system is kept constant as 80 dB and wait further cooling and bunching.

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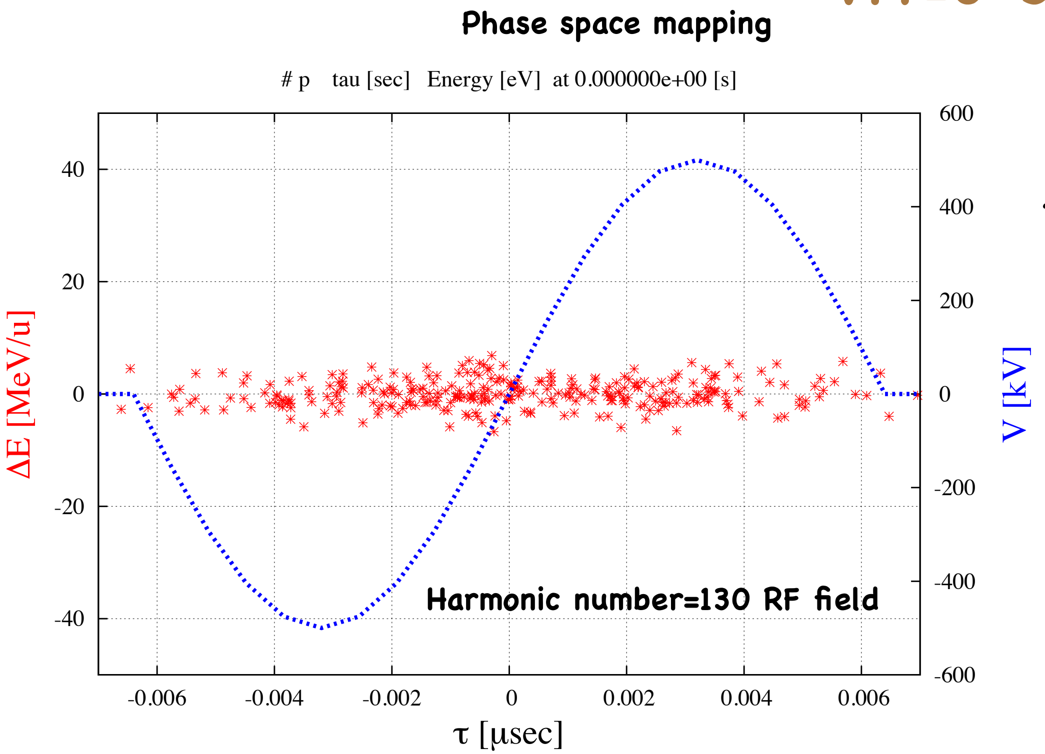
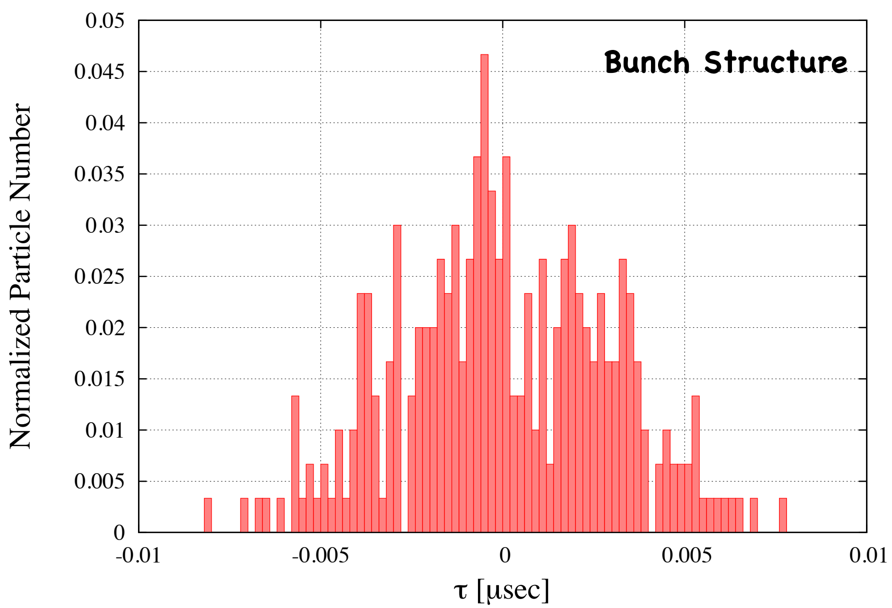
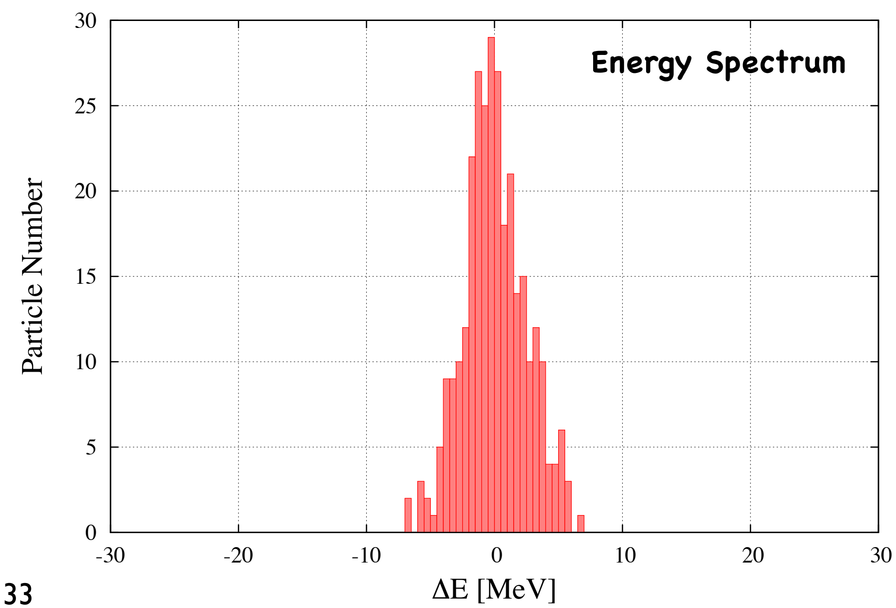
Vrf=0-500 kV (Adiabatic increase within 1 sec)

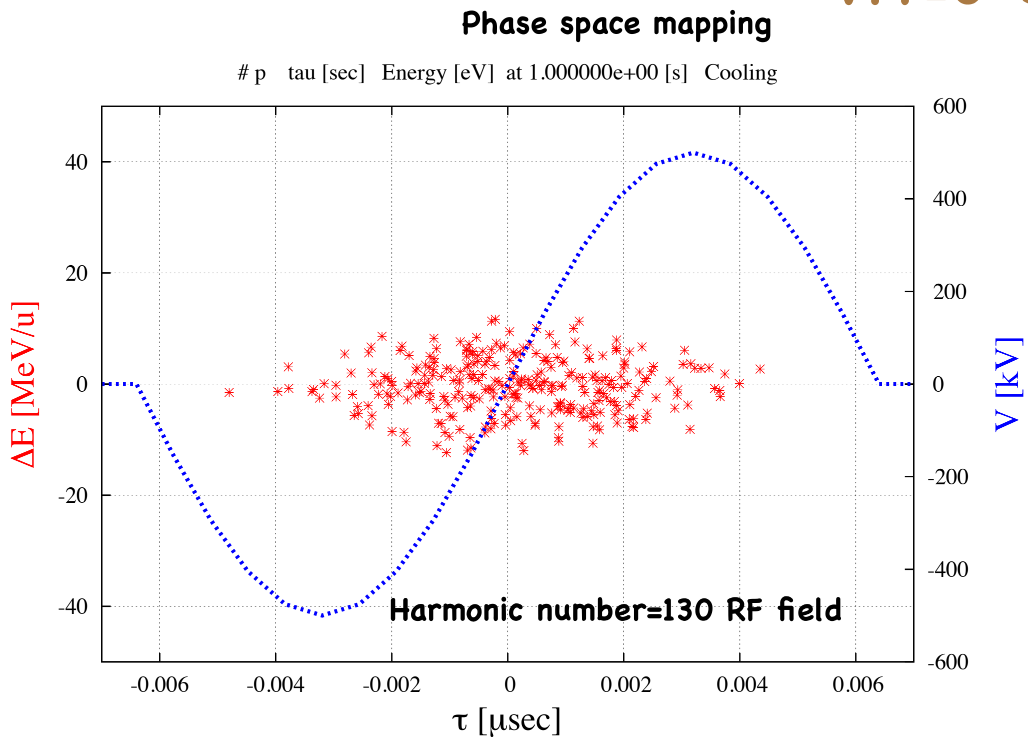


Time=0.0 sec

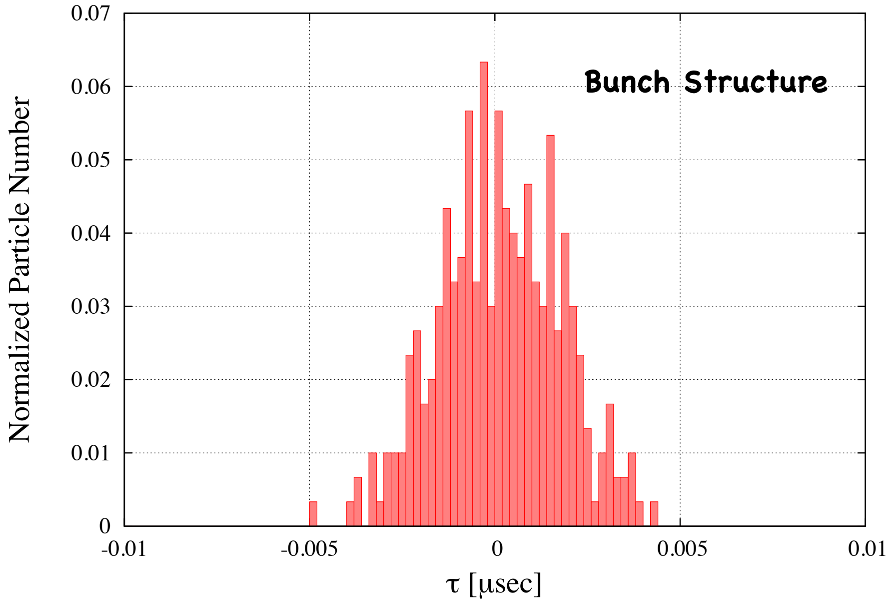


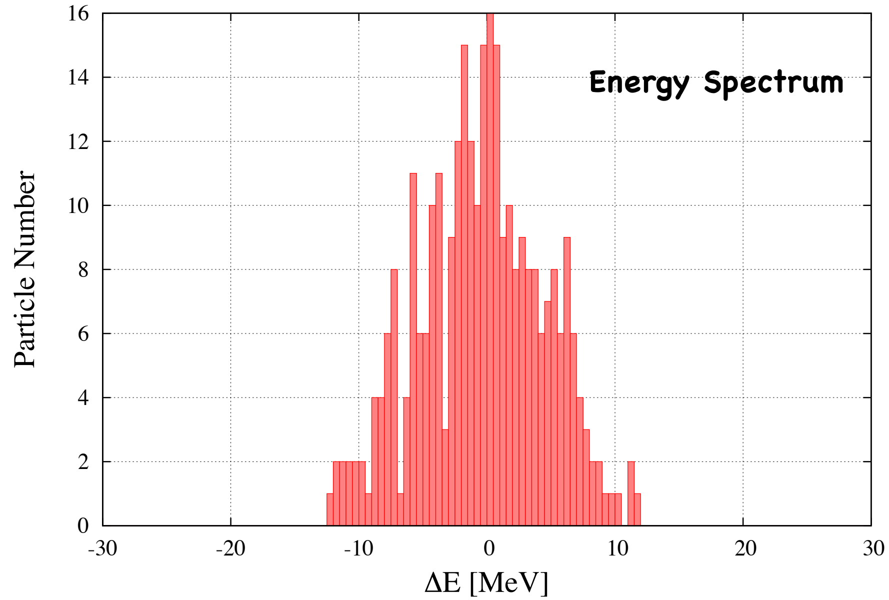


Vrf=0-500 kV (Adiabatic increase within 1 sec)



Time=1.0 sec





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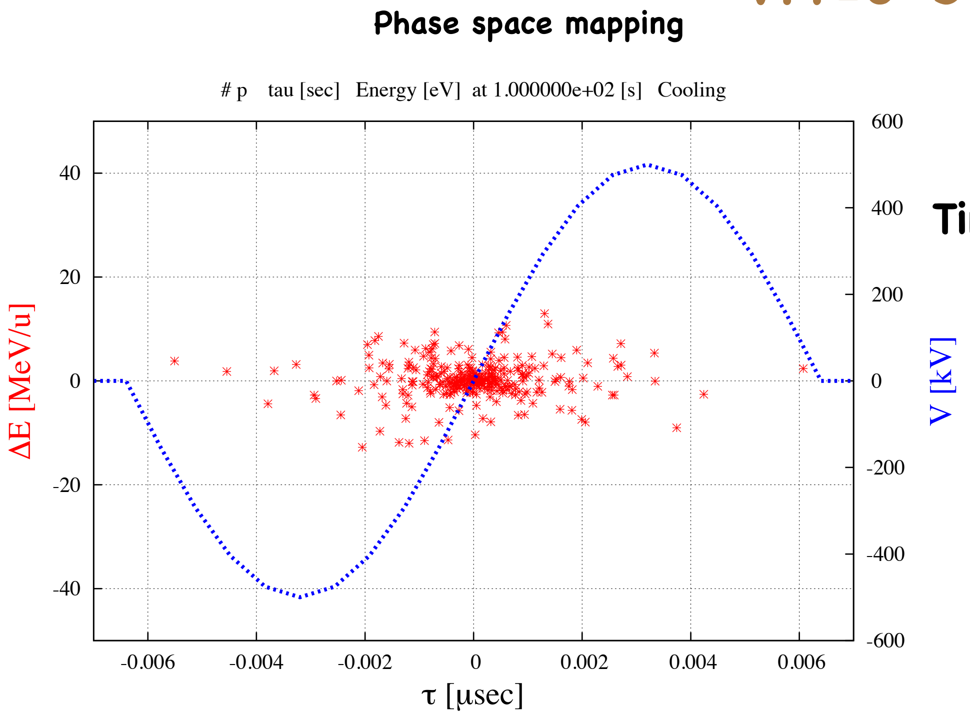
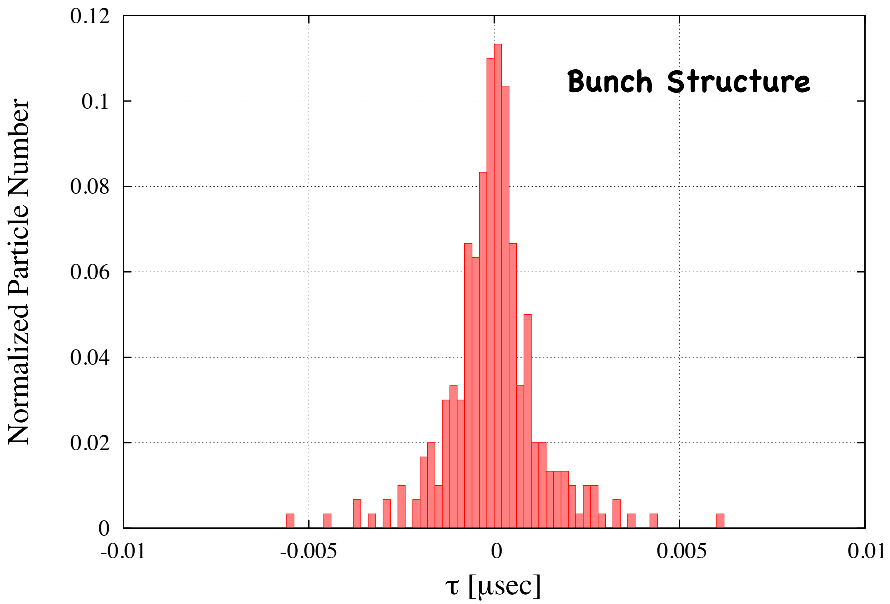
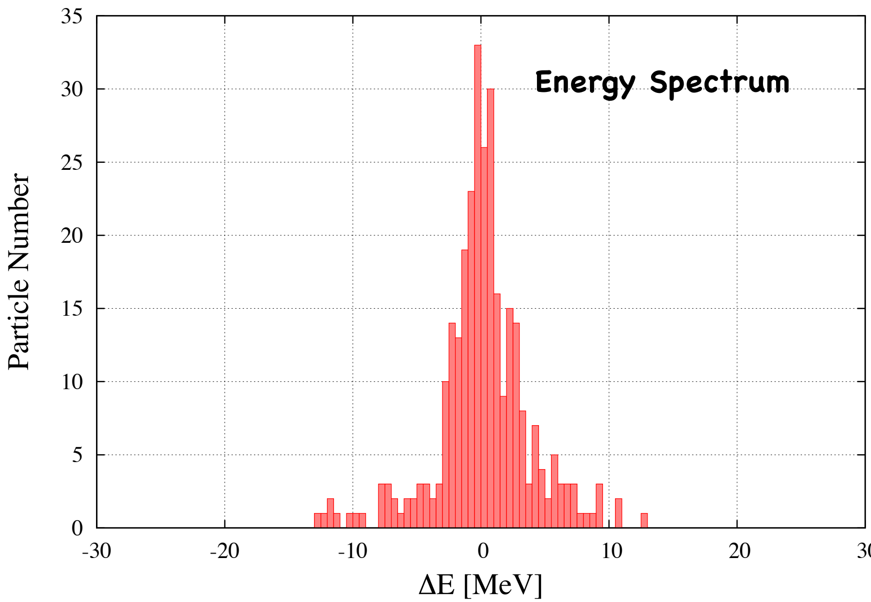
Vrf=0-500 kV (Adiabatic increase within 1 sec)

Time=100.0 sec







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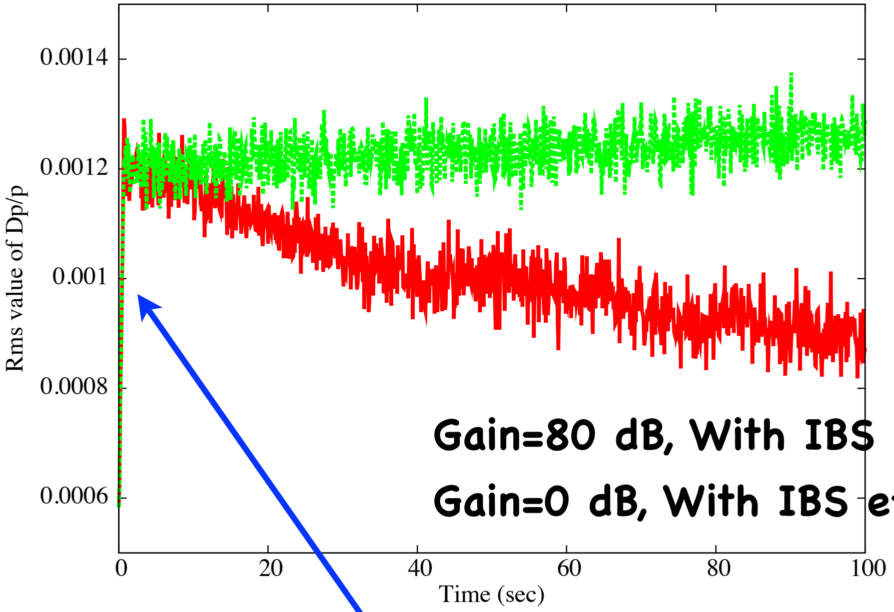
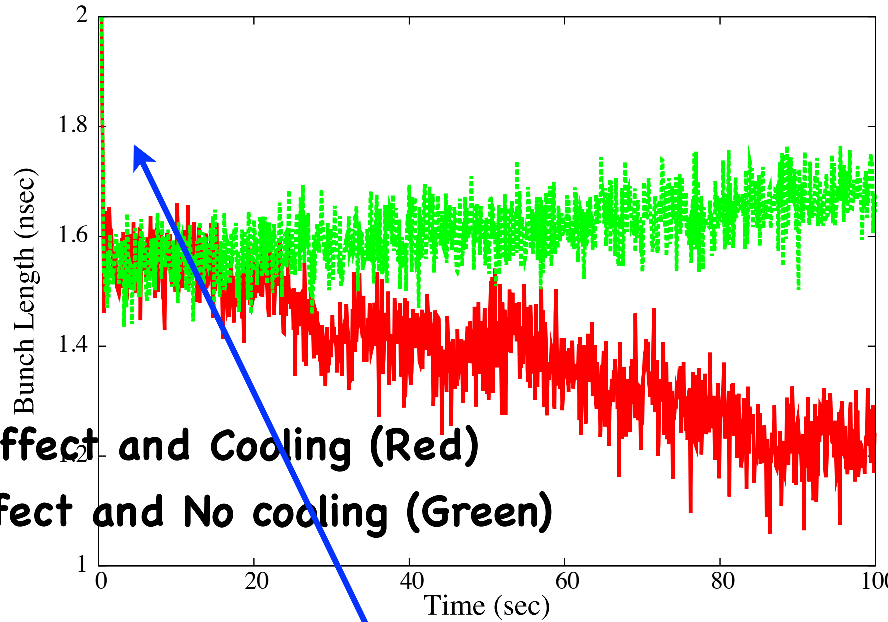
Evolution of Rms Dp/p
Vrf=500 kV



Evolution of Rms Bunch Length
Vrf=500 kV



Gain=80 dB, With IBS effect and Cooling (Red)

Gain=0 dB, With IBS effect and No cooling (Green)

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

L. Thorndahl: Time domain analysis of bunched beam cooling (Vrf=200 kV) Private communication

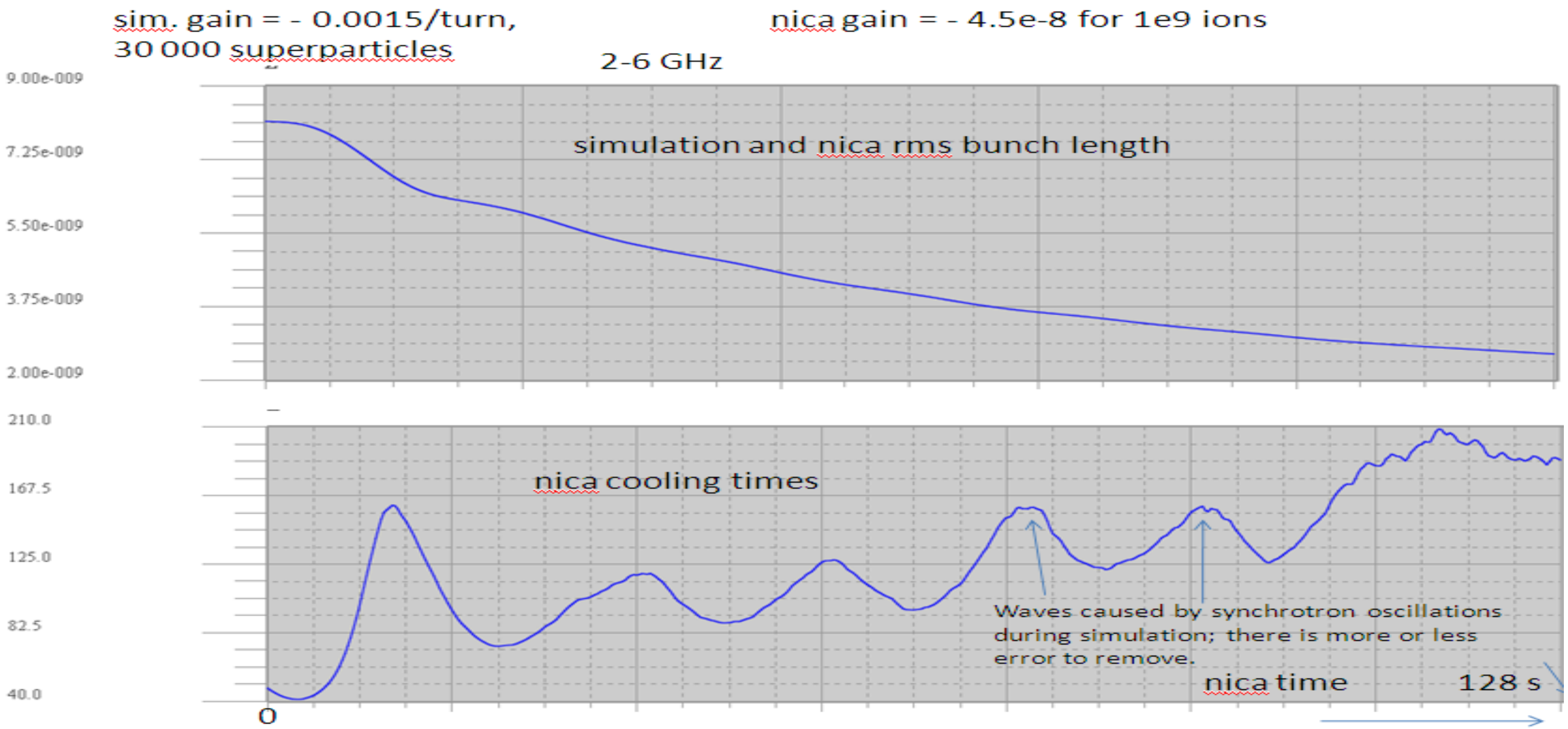


Fig. 4 Reduced gain leads to a lower bunch length and somewhat faster cooling.

Parameters of simulation of bunch rotation at NICA collider

Energy=4.5 GeV/u, 197Au79+, Ring eta value=0.013

Revolution period=1.809e-6 sec

Harmonic number=26 and 130

Initial particle distribution=Uniform random coasting beam (Time domain),
 Dp/p(rms)=3e-4 Gaussian

RF voltage 1 : Harmonic=26, 0-200 kV (Exponentially increase with time constant 0.1 sec for the adiabatic capture)

RF voltage 2: Harmonic=130, V=500kV or 1000kV

Ta: Adiabatic capture time=0.1 sec

Tp: Phase change time=1e-5 sec

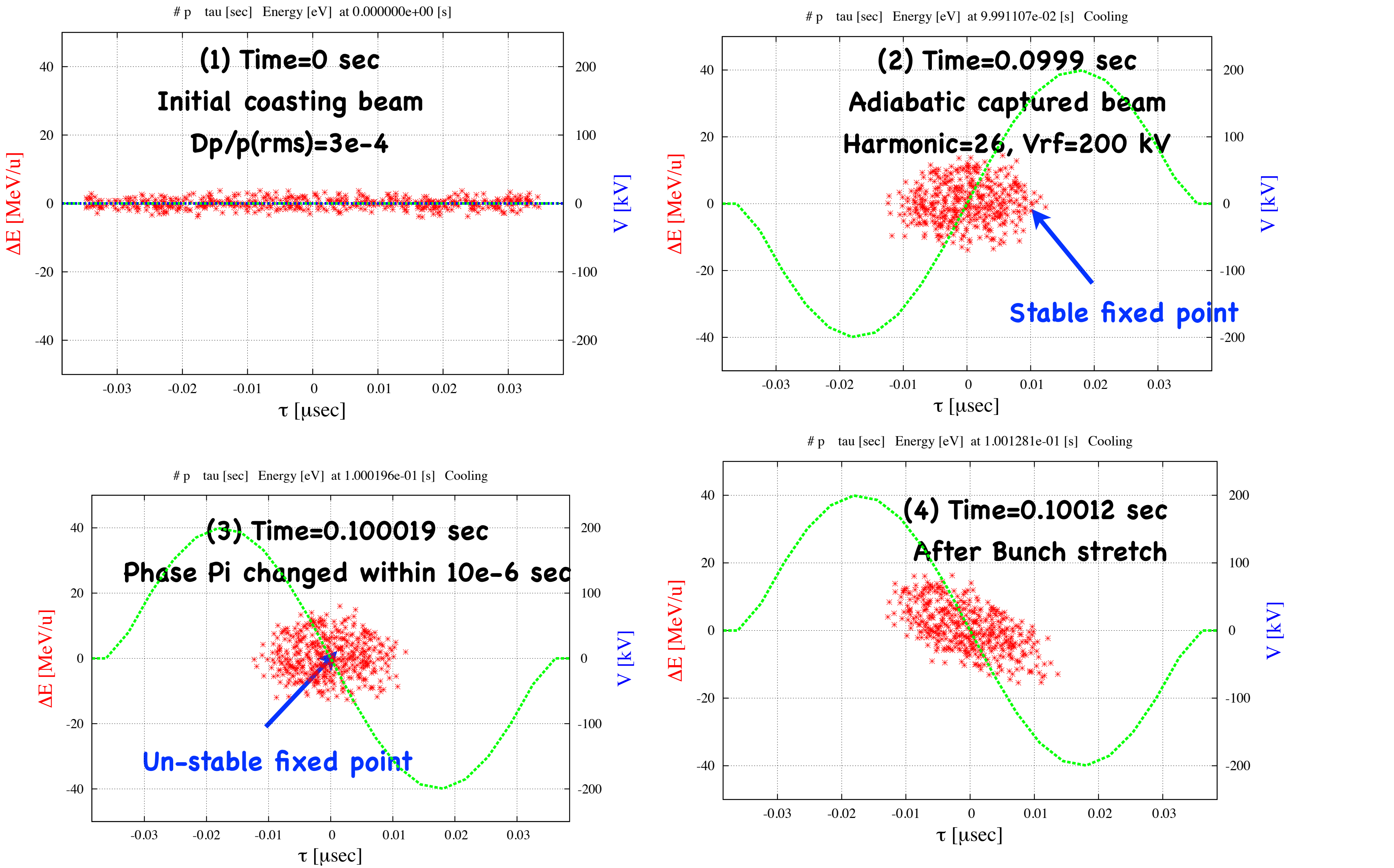
Ts: Bunch stretching time=2e-4 sec

Tr: Bunch rotation time=8e-4 sec

T5: Harmonic=130 RF application period=0.1 sec

Phase Jump Bunch Rotation Method

Phase Space Mapping
Harmonic=26, Vrf=200 kV



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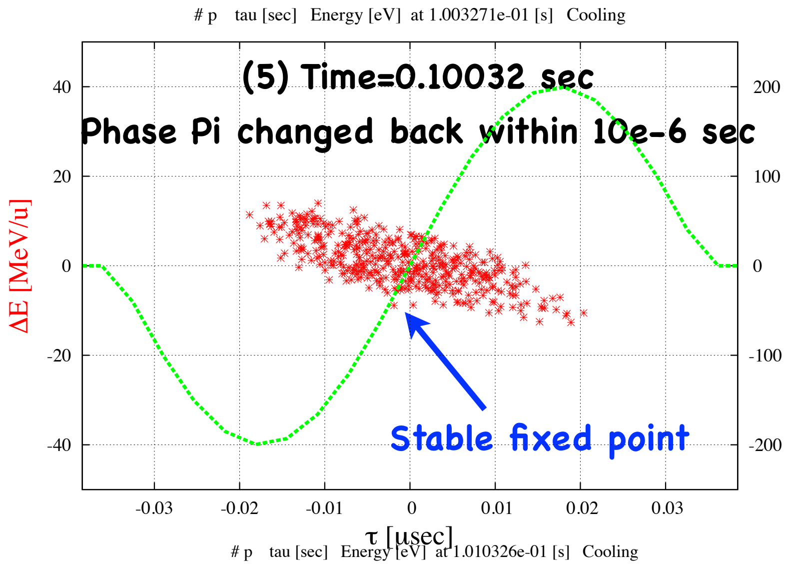
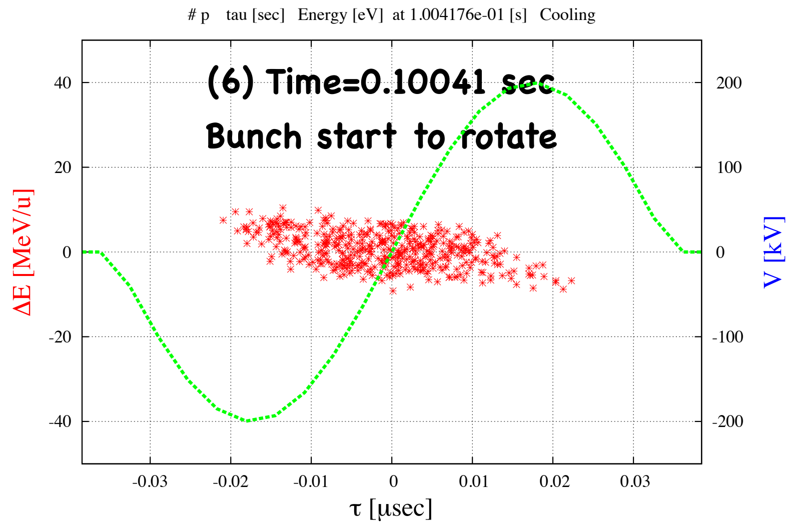
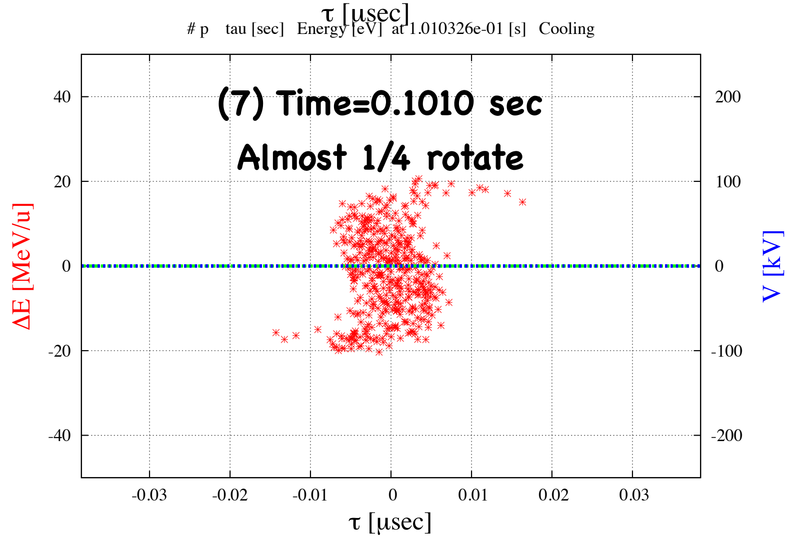


p tau [sec] Energy [eV] at 1.003271e-01 [s] Cooling
(5) Time=0.10032 sec
Phase Pi changed back within 10e-6 sec
Stable fixed point
ΔE [MeV/u]
V [kV]
τ [μsec]



p tau [sec] Energy [eV] at 1.004176e-01 [s] Cooling
(6) Time=0.10041 sec
Bunch start to rotate
ΔE [MeV/u]
V [kV]
τ [μsec]



p tau [sec] Energy [eV] at 1.010326e-01 [s] Cooling
(7) Time=0.1010 sec
Almost 1/4 rotate
ΔE [MeV/u]
V [kV]
τ [μsec]

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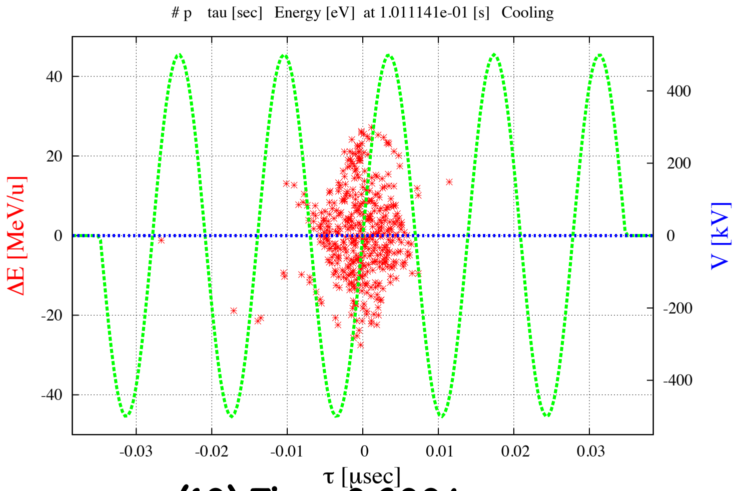
Phase Space Mapping

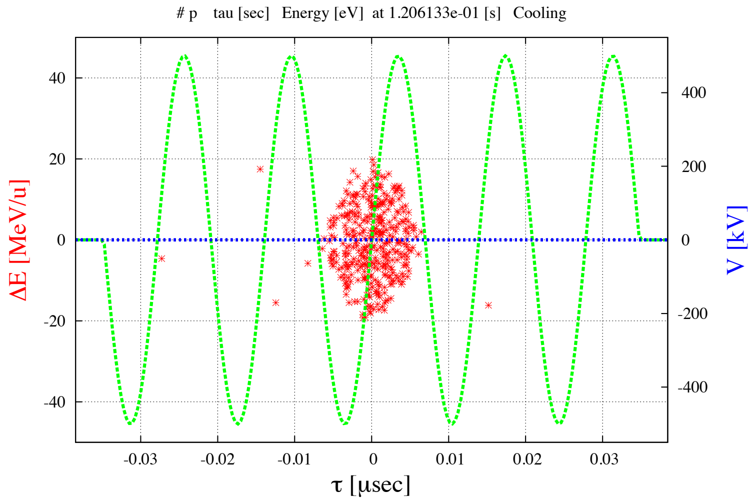
Harmonic=130, Vrf=500 kV

(8) Time=0.1011 sec

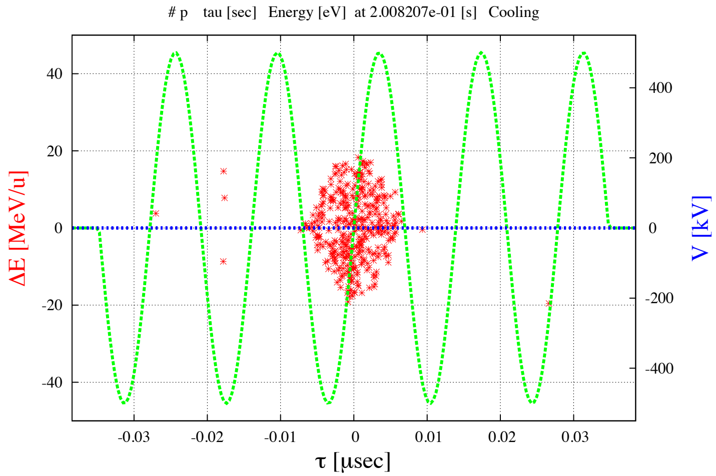


(9) Time=0.1206 sec

Bunch is fixed condition



(10) Time=0.2004 sec



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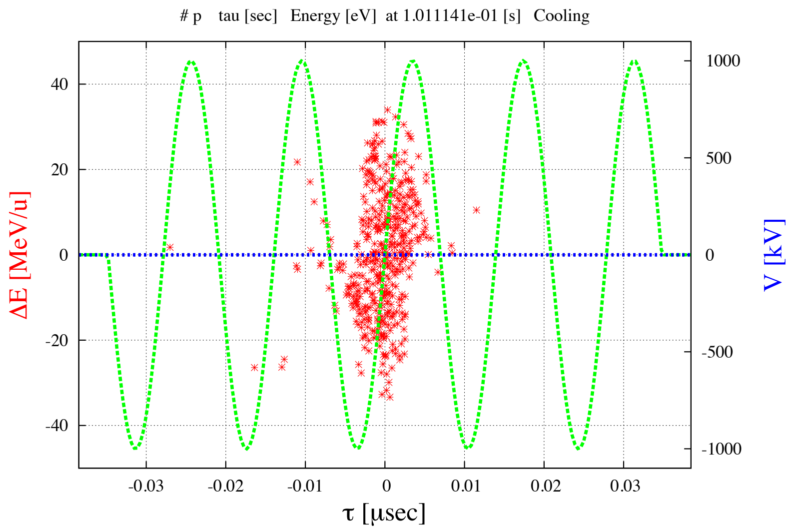
Phase Space Mapping

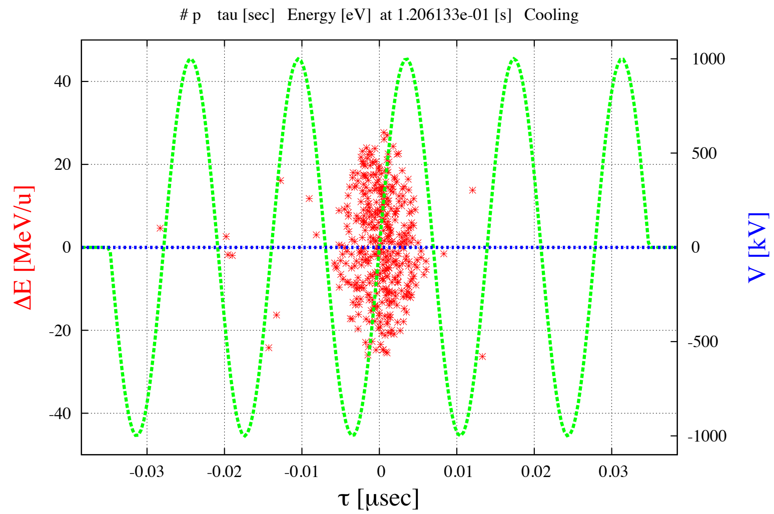
Harmonic=130, Vrf=1000 kV

(8) Time=0.1011 sec

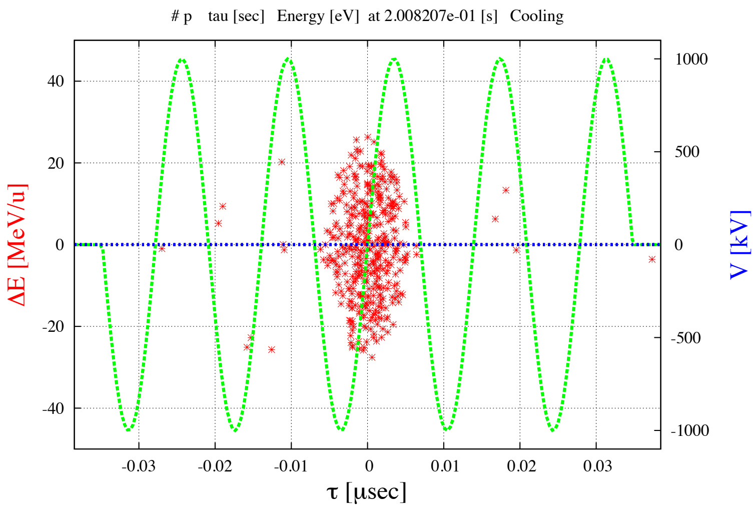


(9) Time=0.1206 sec

Bunch is fixed condition



(10) Time=0.2004 sec



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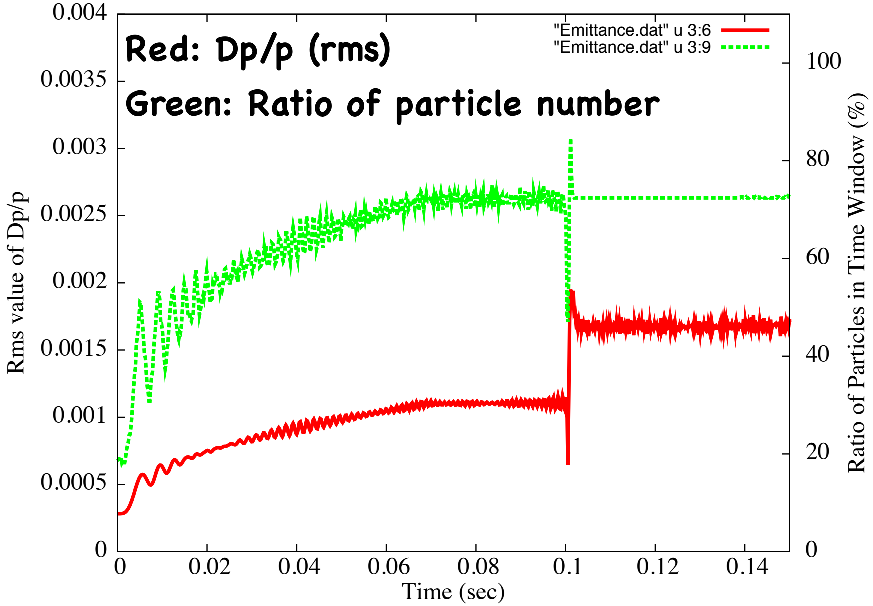
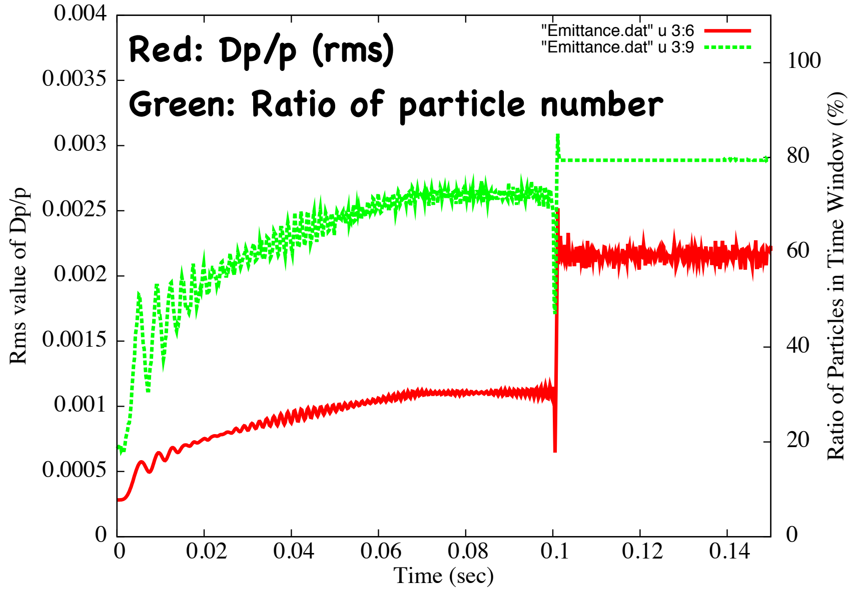
Ratio of particle number in the time width +/- 6.95 ns (+/- Trevolution/130/2)

H=130, Vrf=500 kV case



Dp/p increases up to 0.0017
The ratio of particle number is 73 %.

H=130, Vrf=1000 kV case



Dp/p increases up to 0.0022
The ratio of particle number is 80 %.

Electron Cooling is applicable to the BB ACCUMULATION of NICA collider ?

Electron Cooling at NICA Collider

Specifications of Electron Cooler

Ion: 197Au79+, 1.0 GeV/u, 1.5 GeV/u, 2.0 GeV/u

Cooler Length= 6m

Electron current= 1A

Electron Diameter= 2cm

Effective Electron Temperature= 1meV

Transverse Temperature=1 eV

Longitudinal magnetic field= 0.1 Tesla

Beta function at Cooler= 15m

Cooling force: Parkhomchuk empirical formulae

Coasting Beam approximation (Synchrotron motion is not taken account).

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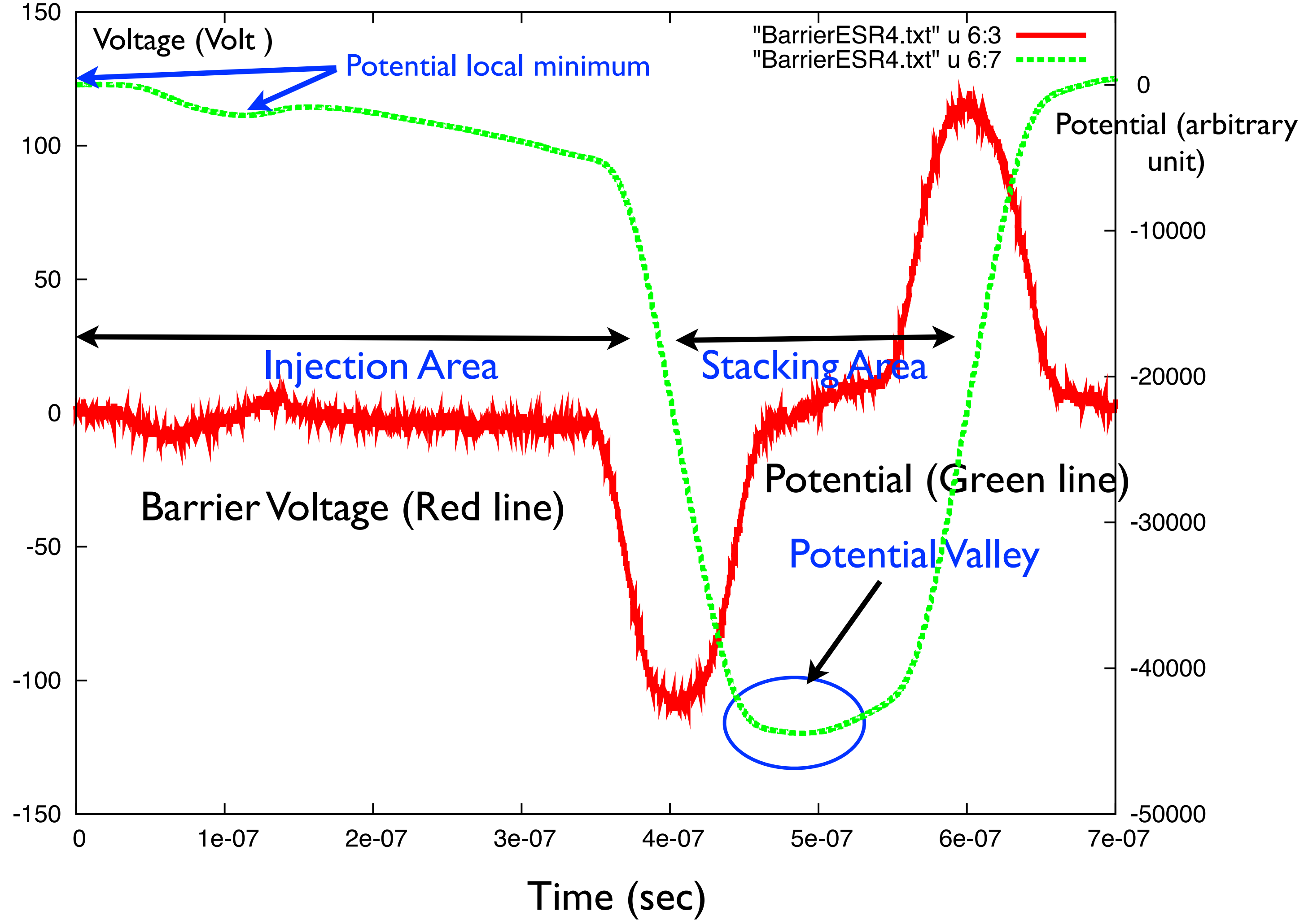
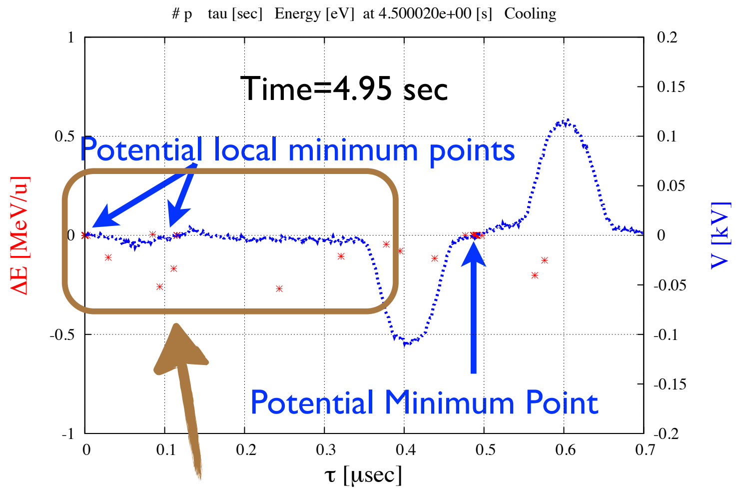
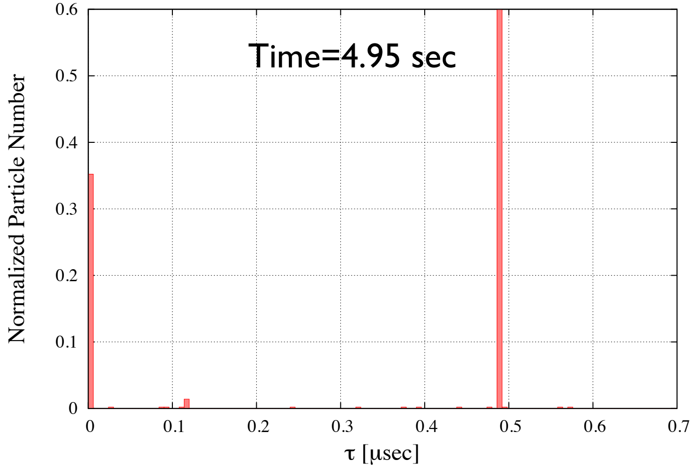
ESR Experiment on BB Accumulation with Electron Cooling, 124Xe54+, 154MeV/u (2008)

Measured Barrier Bucket Voltage and Potential

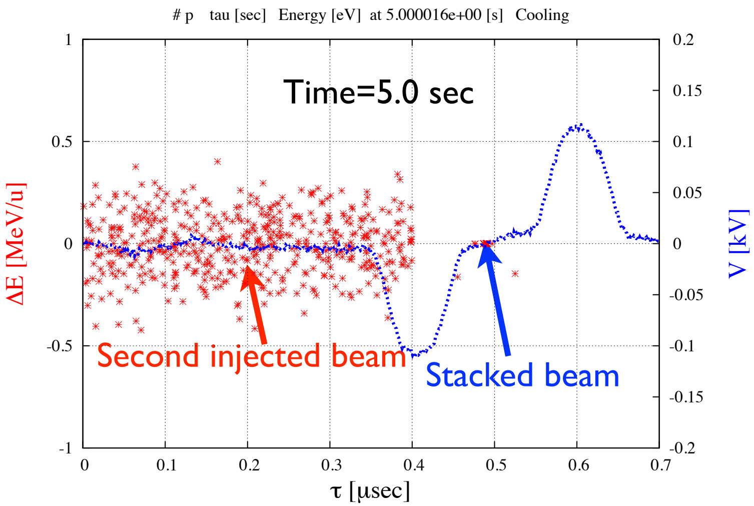


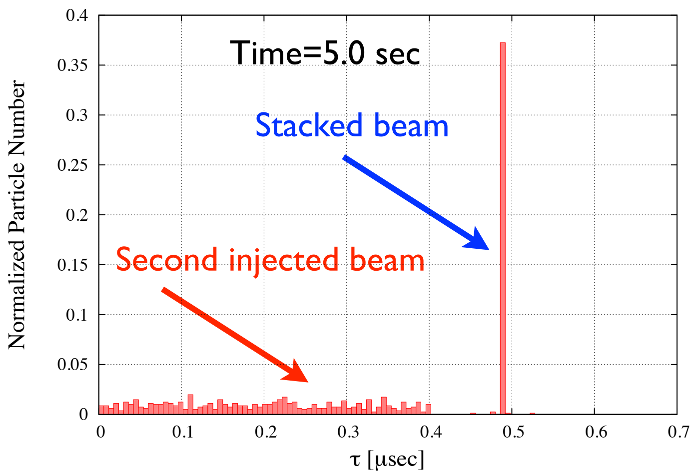
Simulation Ie=0.3 A



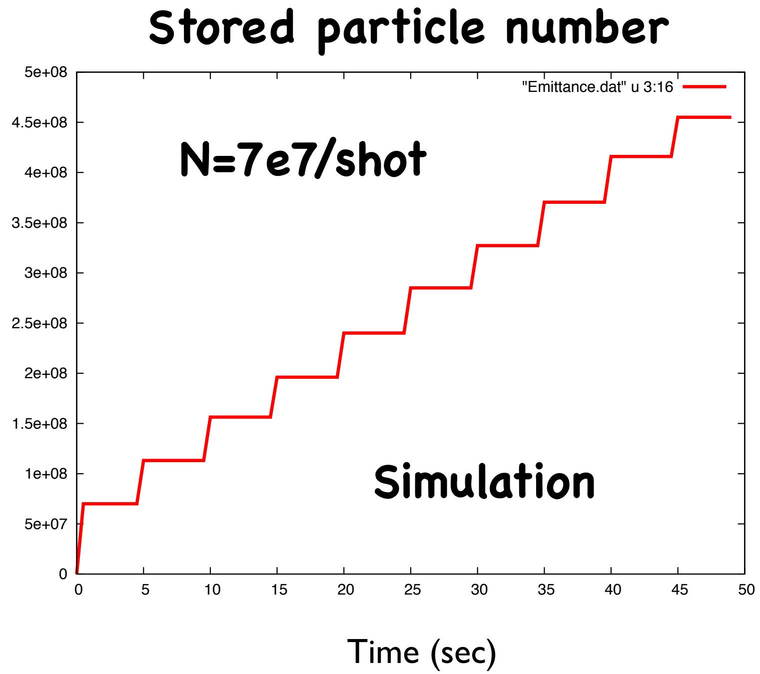


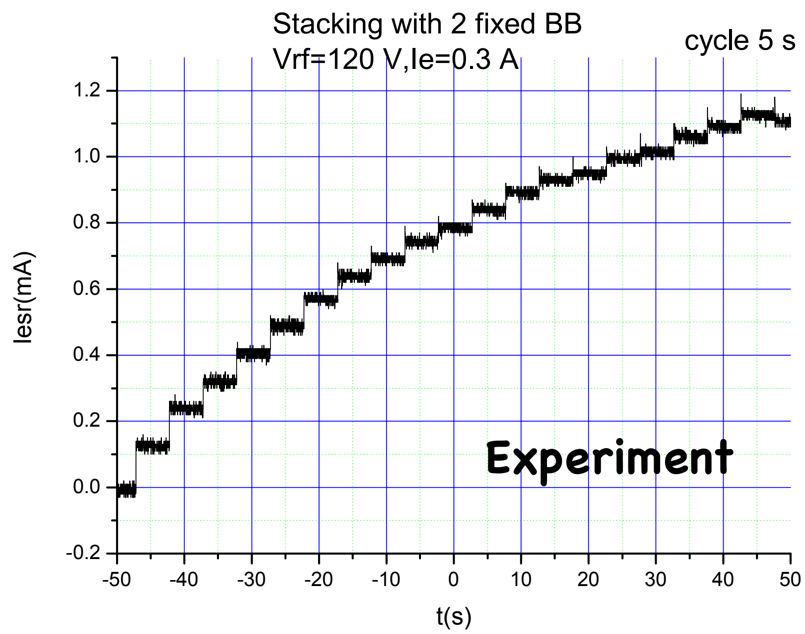
Those particles are kicked out !





Typical example of particle accumulation Ie=0.3 A





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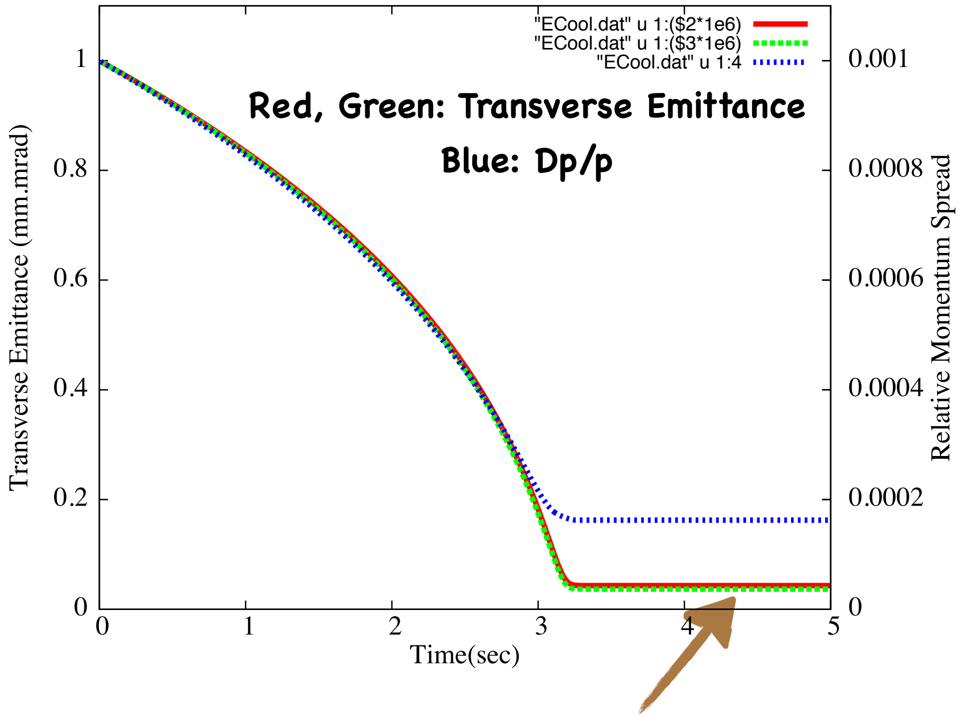
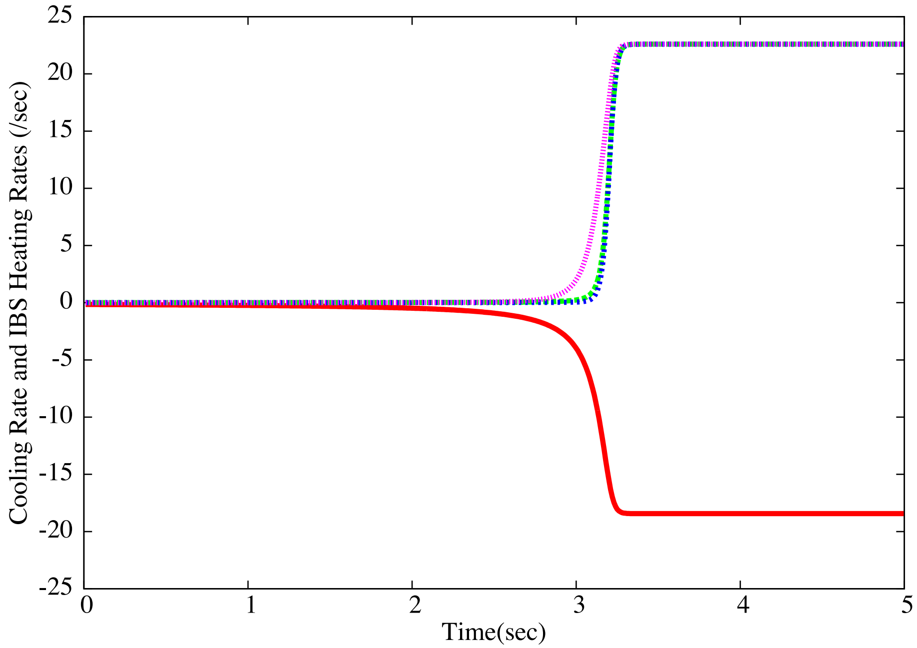
NICA 1.0 GeV/u,
Initial Value: 1 Pi mm.mrad, Dp/p=1e-3
N=7e10, Coasting beam

With IBS



Equilibrium values
Emittance=0.043 (H), 0.037(V) mm.mrad
Dp/p=1.6e-4



Red: Electron Cooling Rate
Green, Blue: IBS Growth Rate of Emittance
Purple: IBS Growth Rate of Dp/p

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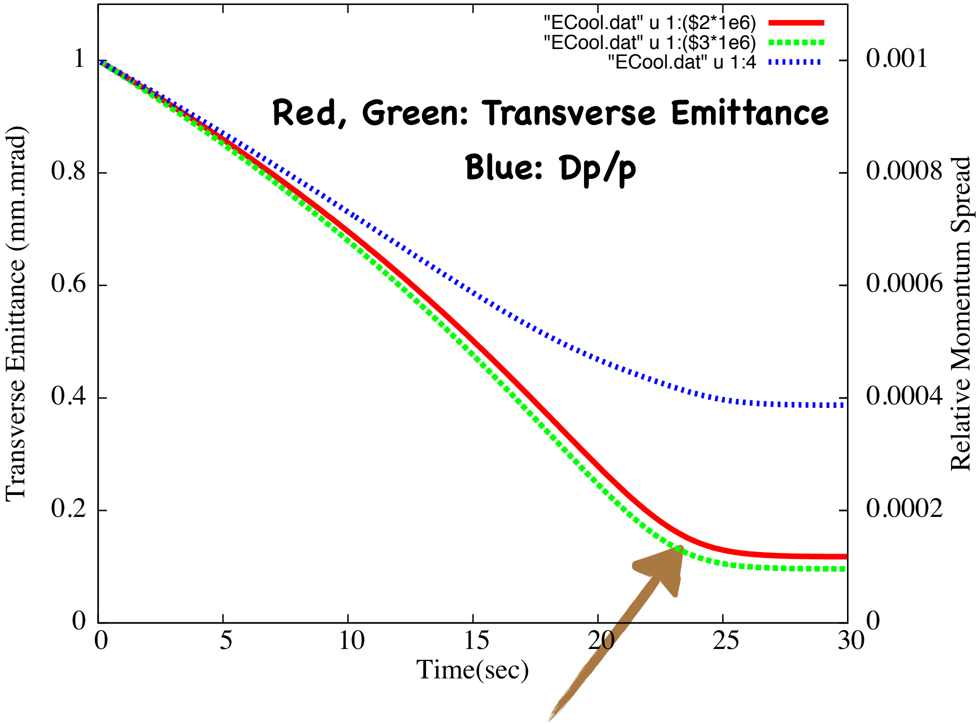
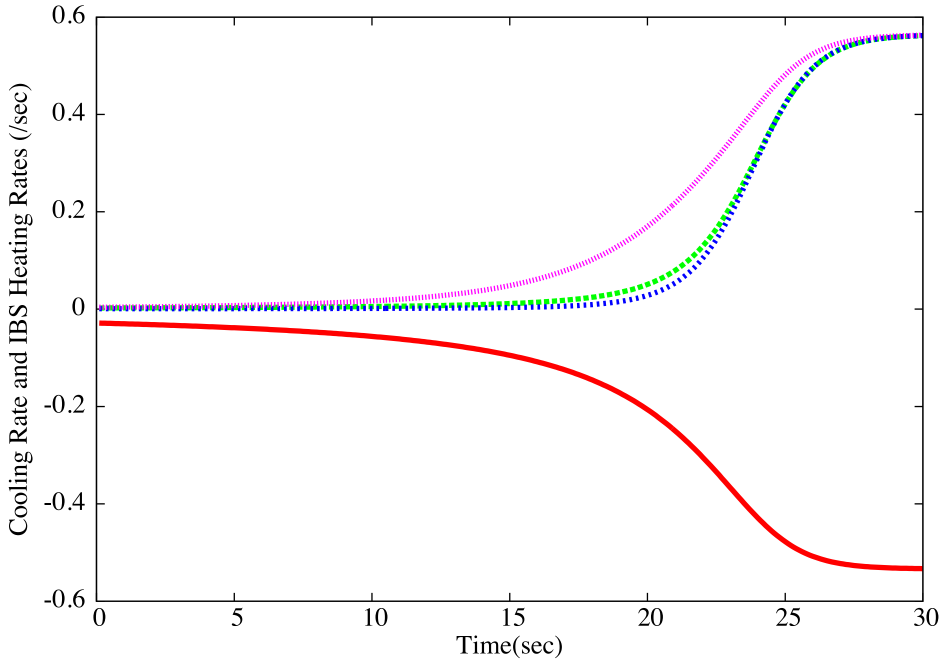
NICA 2.0 GeV/u

Initial Value: 1 Pi mm.mrad, Dp/p=1.0e-3

N=3e11, Coasting beam

With IBS





Equilibrium values

Emittance=0.12(H), 0.09 (V) mm.mrad

Dp/p=3.7e-4

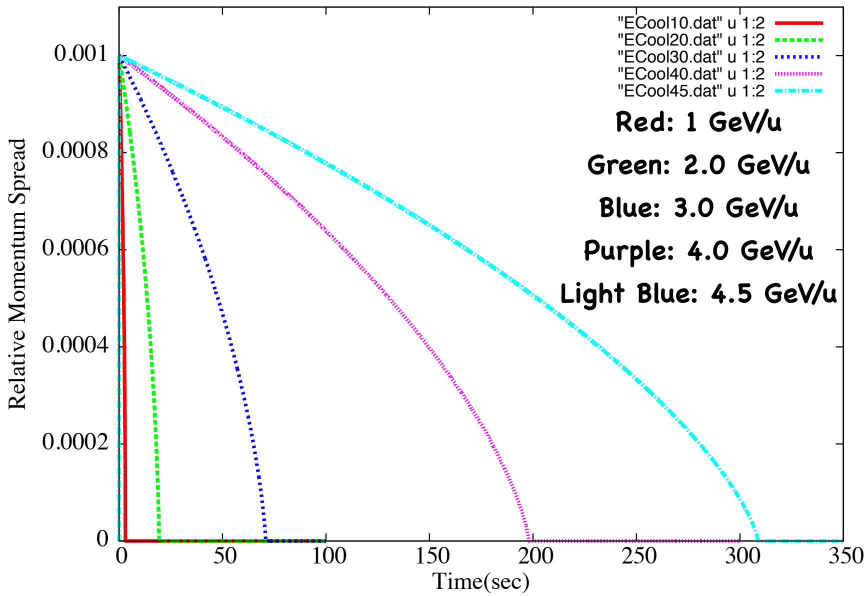
Red: Electron Cooling Rate

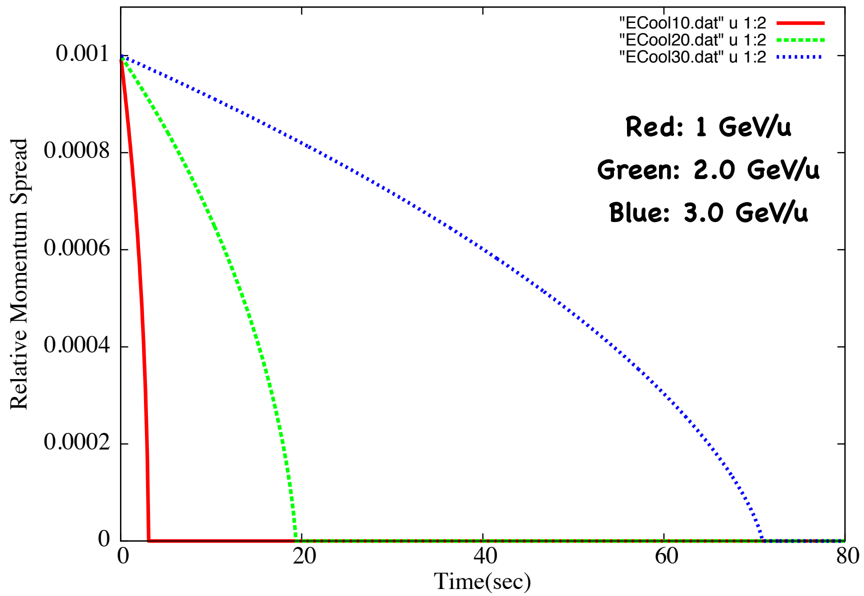
Green, Blue: IBS Growth Rate of Emittance

Purple: IBS Growth Rate of Dp/p

Initial Value: 1 Pi mm.mrad, Dp/p=1.0e-3 Without IBS

Evolution of Momentum Spread





2 GeV/u might be Ok, but for 3 GeV/u might be Not.

Simulation study of BB stacking with electron cooling is urgent !

Conclusion

1. NICA collider is the low variable energy (1-4.5 GeV/u), high intensity (3e8-6e9/ bunch) heavy ion collider which requires much careful designed bunched 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 stochastic cooling 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 stochastic cooling.
5. The wider band width 3-6 GHz is favorable for the fast cooling but it limits the momentum cooling acceptance. From this point of view, the 2-4 GHz is better selection.
6. The electron cooling would work well below the energy 2.0 GeV/u.
7. The serious engineering problem of stochastic cooling is to reject the strong coherent signal of the synchrotron motion in the short bunch.