Beam Physics Issues of Low Energy Antiproton Production at Modularized Start Version of FAIR

May 13, 2014

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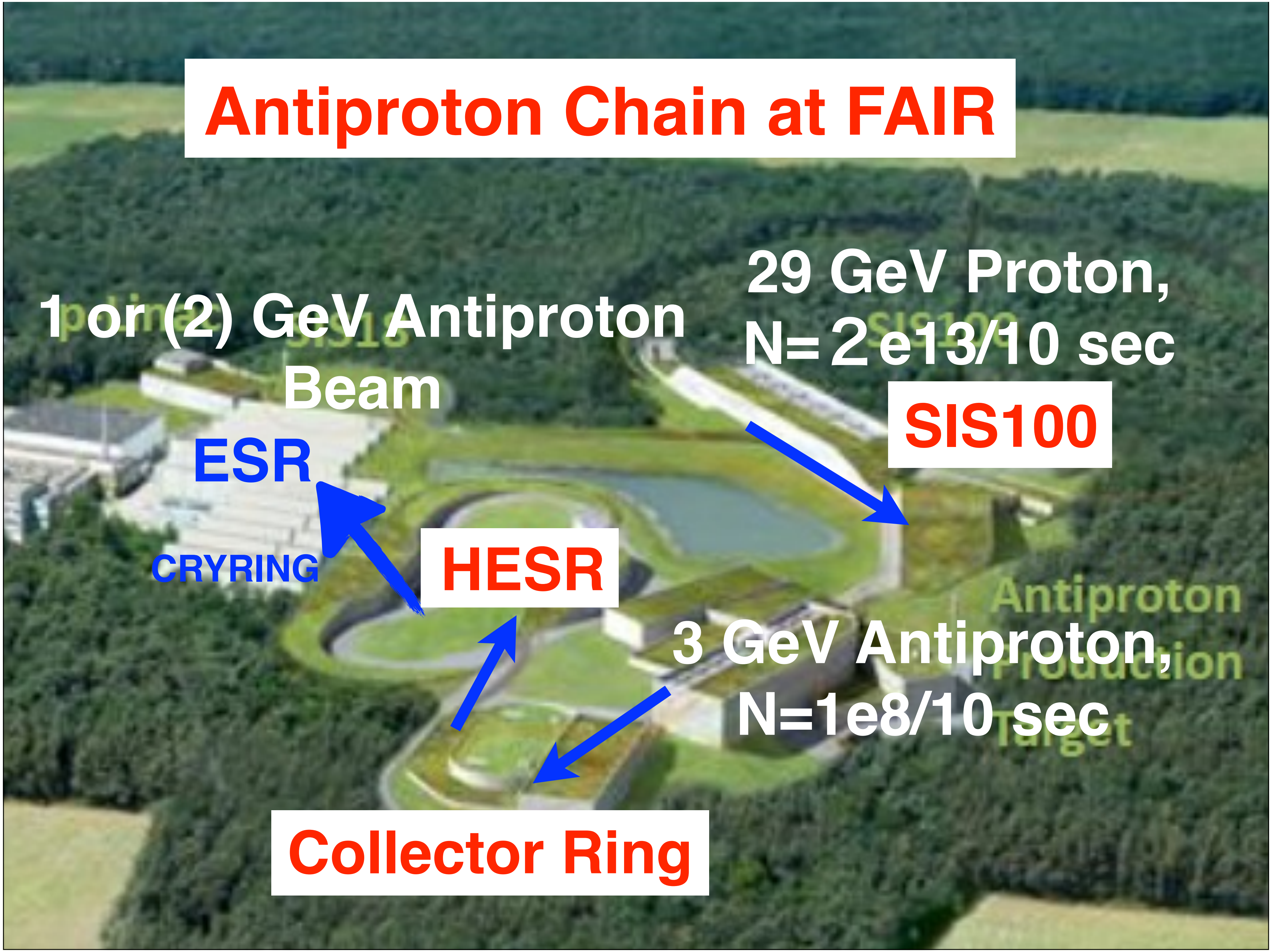
Outline

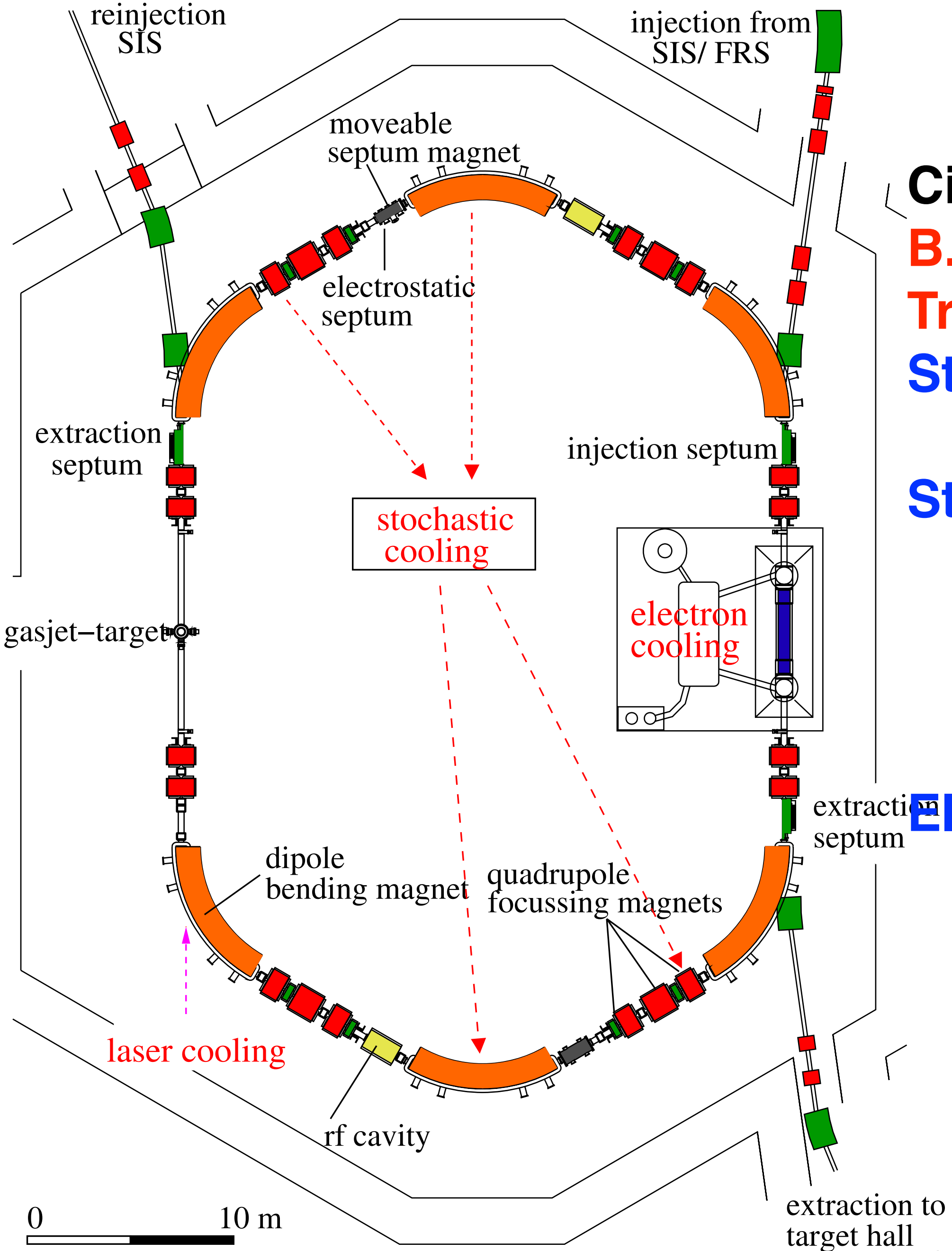
1. Two Scenarios of Low Energy Antiproton Production.
2. Description of Scenario 1.
3. Beam Accumulation and Deceleration in HESR
4. Deceleration in ESR
5. Low Energy Antiprotons from CRYRING

Collaboration with H. Stockhorst, R. Stassen, V. Kamerdzhiev, D. Prasuhn, R. Maier (FZJ) and M. Steck (GSI)

Antiproton Chain at FAIR



Experimental Storage Ring (ESR) at GSI

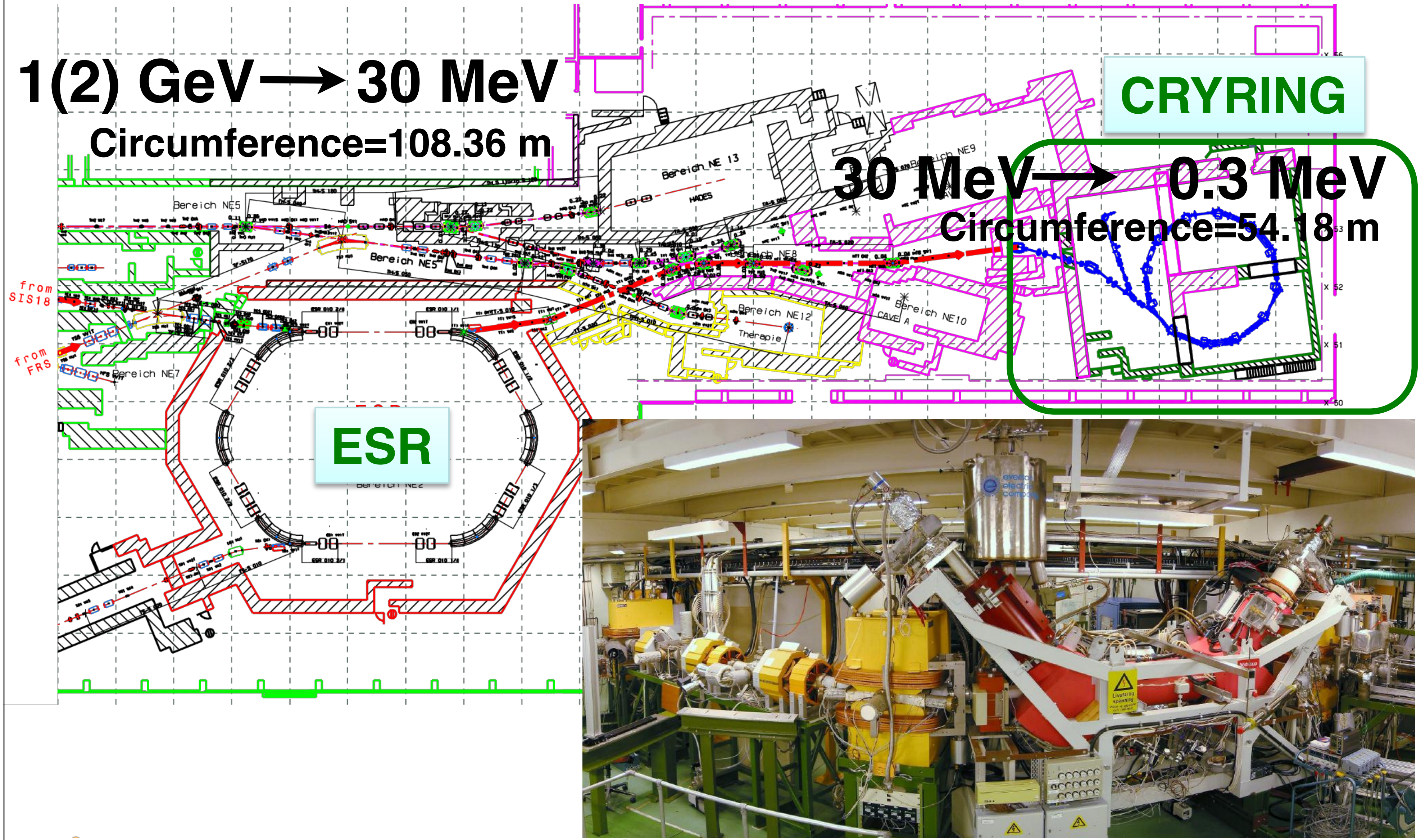


Circumference: 108.36 m
B.rho:10 Tesla.m, 2 GeV Pbar
Transition energy: 1.254 GeV, Pbar
Stochastic & Electron Cooling Devices

Stochastic Cooling:
- **Band width: 0.8 GHz (0.9-1.7 GHz),**
- **Palmer method (Momentum Cooling)**
- **Operation energy: 400 MeV/u**

Electron cooler
- **Cooler length: 1.8m**
- **Max. electron current: 0.5 A**
- **Electron diameter: 5 cm**
- **Solenoid field: 0.5 Tesla**

Anti-proton Deceleration in ESR & CRYRING



CRYRING: Low Temperature Ecooler and Wide Band RF system.

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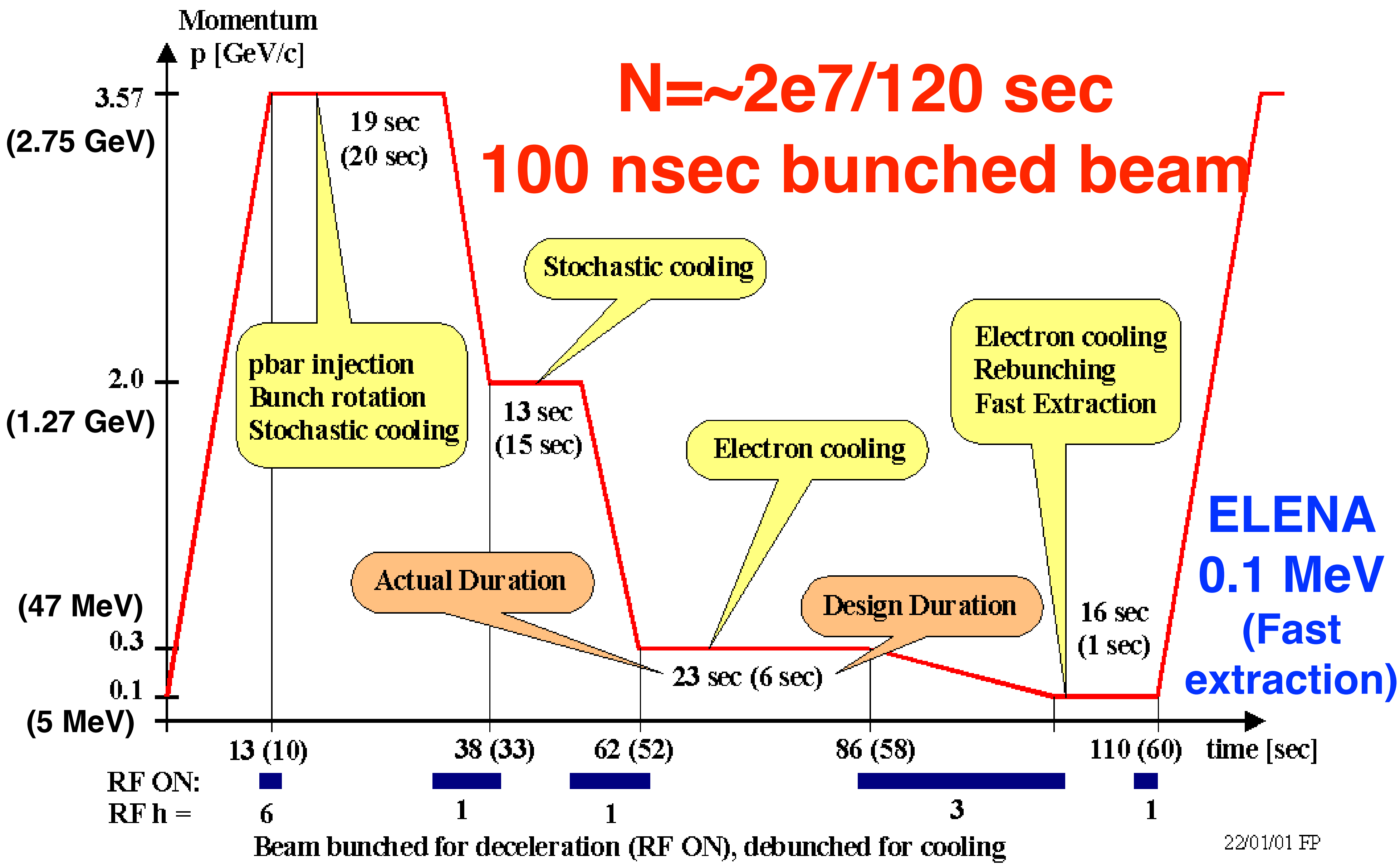
Parameters of CRYRING

Circumference	54.18 m
Periodicity	6
Dipole bending radius	1.2 m
Transition Gamma	2.30
Max Beta Function (Horizontal/Vertical)	7.35/8.36 m
Max Horizontal Dispersion	2.06 m
RF frequency	0.14-1.4 MHz
RF Voltage	0.5 kV
dB/dt (In the present simulation)	-0.1 Tesla/sec

CERN AD Operation (~2000)



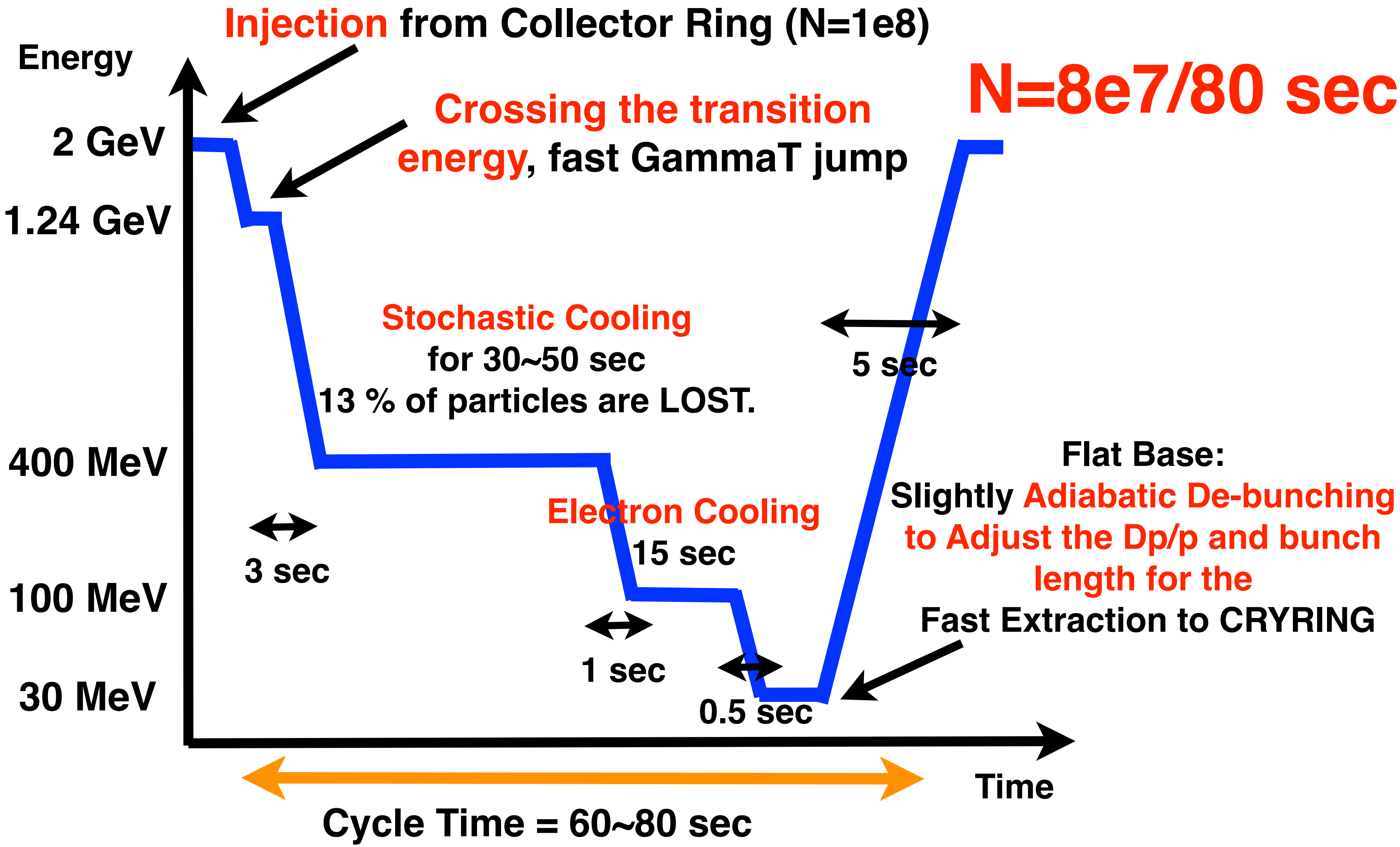
Possible two scenarios for low energy antiproton production at MSV of FAIR

Key limitation factors: ESR Brho=10 Tm (2 GeV), Transition energy=1.254 GeV. No deceleration function in CR.

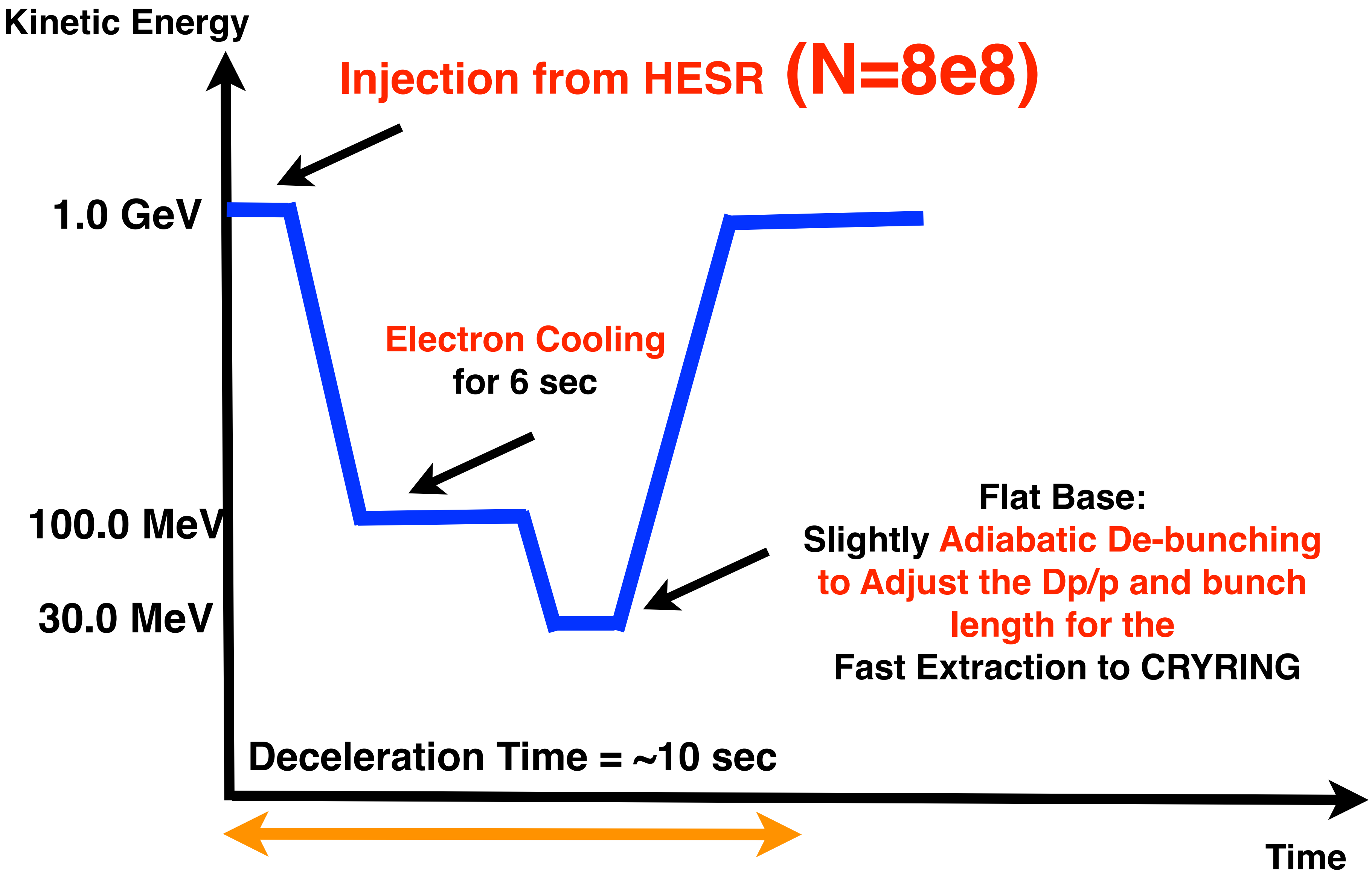
Scenario 1. Stochastic cooling and re-bunching of 2 GeV Pbar, N=~5e7 in Collector Ring. Transfer to ESR and Deceleration in ESR. Crossing the transition energy, stochastic cooling at 0.4 GeV and electron cooling at 100 MeV. Deceleration to 30 MeV. Deceleration in CRYRING to 0.3 MeV.

Scenario 2. Accumulation to N=1e9 in HESR at 3 GeV from CR. Deceleration to 1 GeV (Stochastic cooling at 2 GeV) and Transfer to ESR. Deceleration in ESR to 30 MeV (Electron cooling at 100 MeV). Deceleration in CRYRING to 0.3 MeV.

Operation Scheme of Anti-proton at ESR (Scenario 1)



Operation Scheme of ESR (Scenario 2)



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Part 1
Short Description of Scenario 1

Antiproton production yield for CERN case

1. 26 GeV/c Proton
2. Max. production at 3.7 GeV/c
3. Sharp fall off of production cross section outside peak

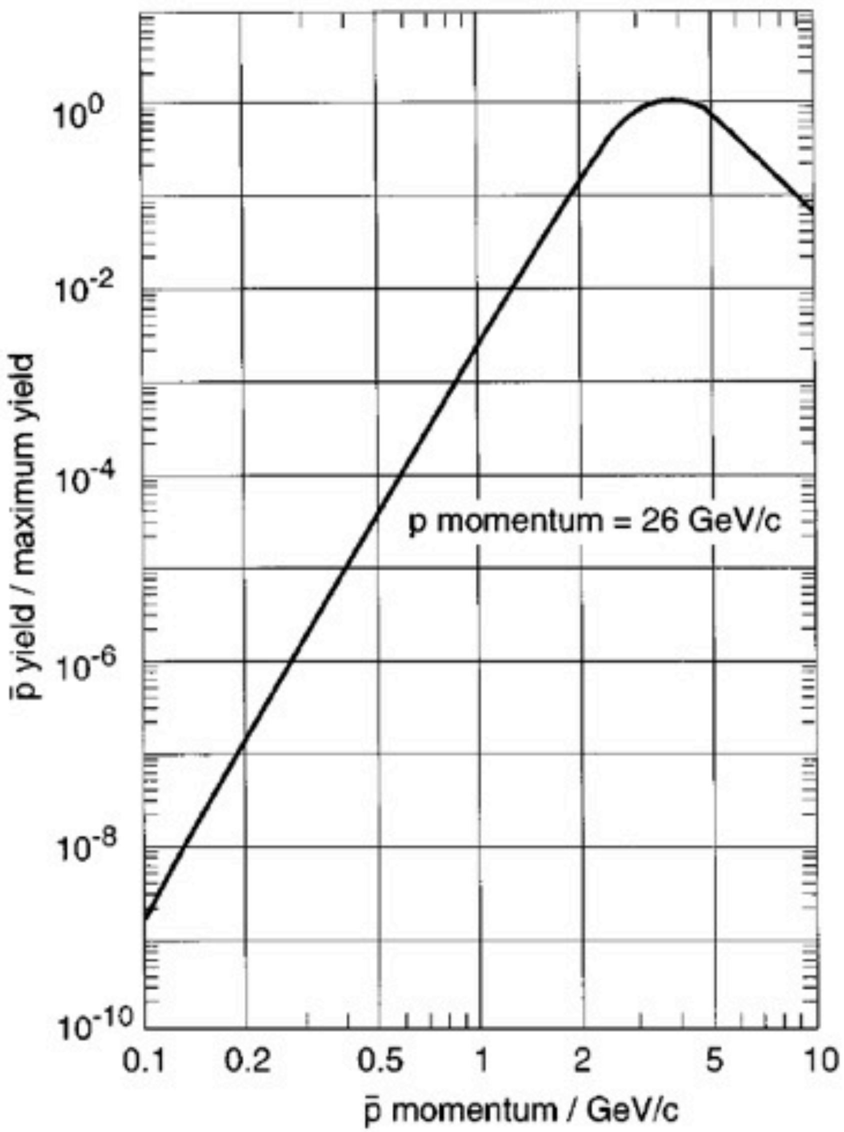
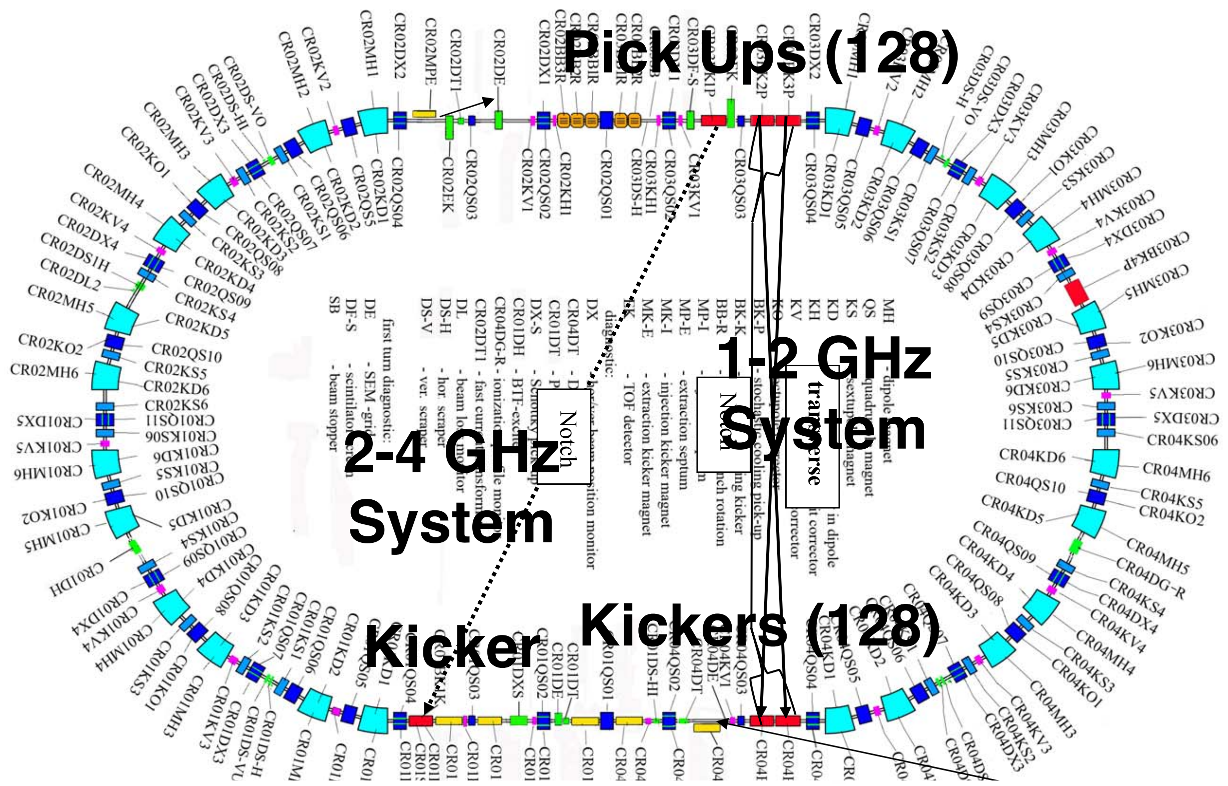


FIG. 1. Normalized antiproton yield (antiprotons per proton) at 26 GeV/*c* proton-beam momentum. The normalization is chosen so that the yield is one at the maximum.

Stochastic Cooling System of Collector Ring

2 GeV, N=1e8, Notch Filter System

Ring slipping factor	0.0275
Slipping factor from PU to K	0.00373 (1- 2GHz)
TOF from PU to Kicker	0.294e-6 sec (1-2 GHz)



1-2 GHz: Pbar 3D cooling, PH, PV, KH, KV.

2-4 GHz Pbar longitudinal cooling; pickup P2-4, kicker K2-4.

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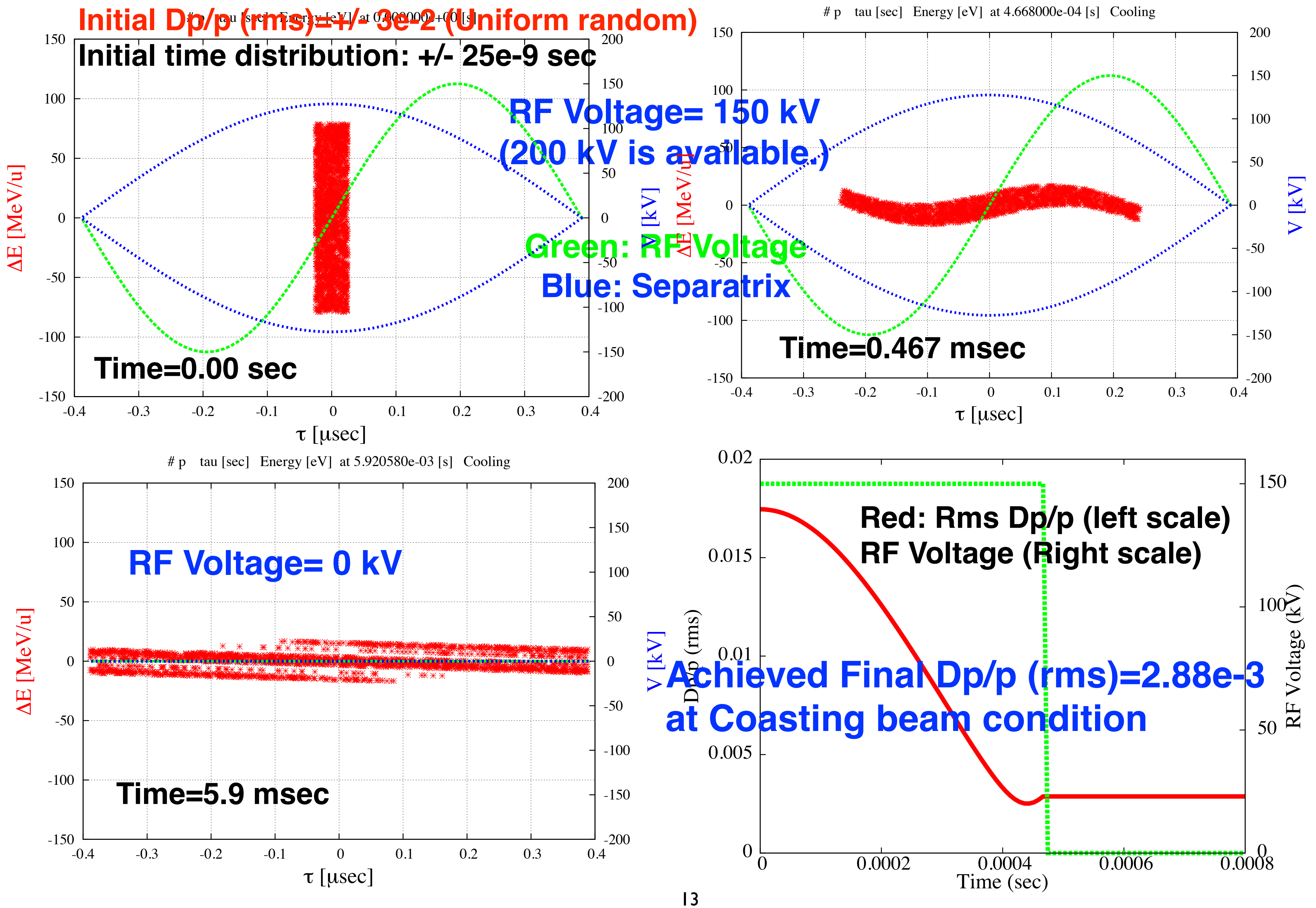
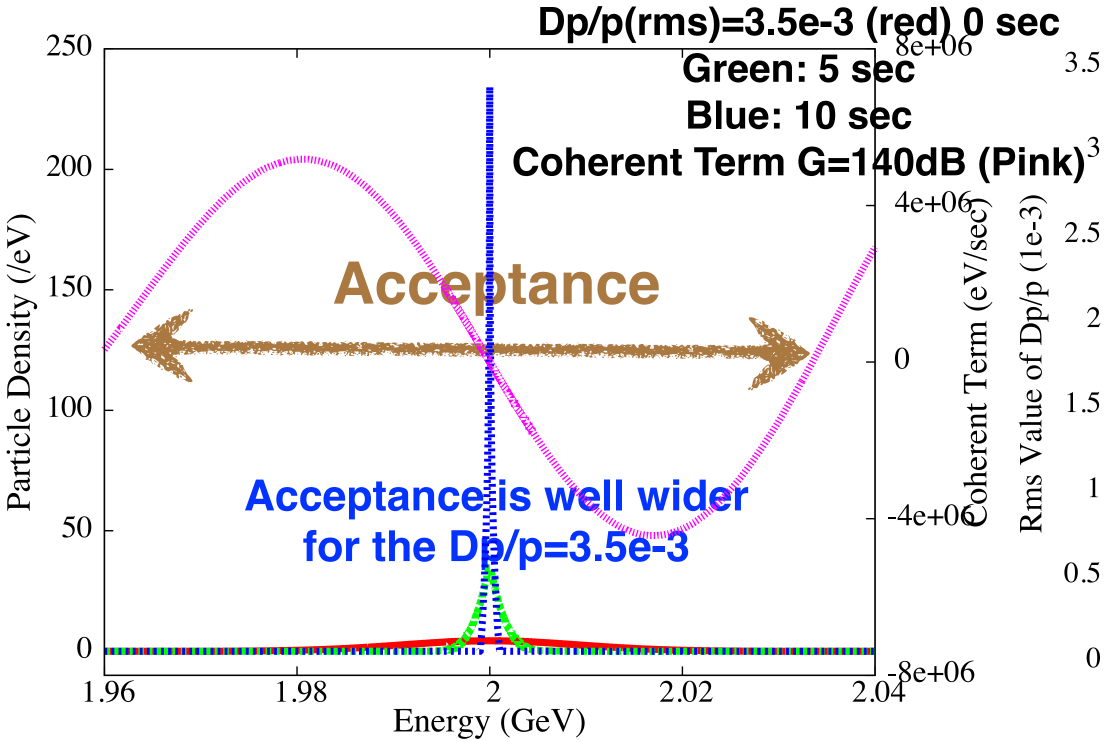
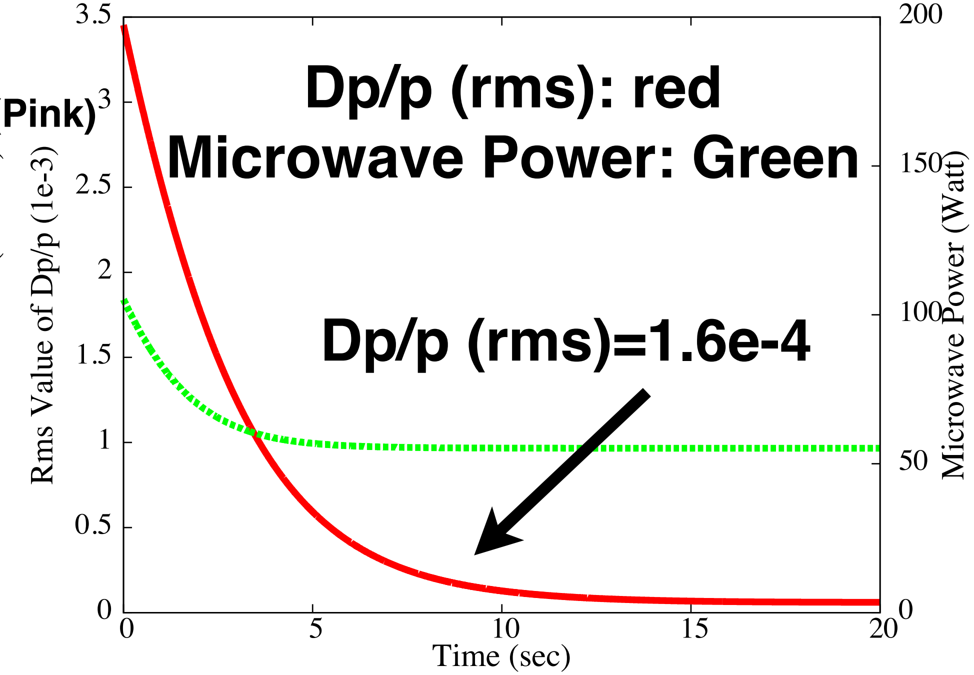
Bunch Rotation in the Collector Ring



Evolution of Particle Distribution, rms value of Dp/p and Microwave Power for Stochastic Cooling in CR
Band=1-2 GHz, Gain=140dB, Dp/p(initial)=3.5e-3

Case: 45 Ohm (Kicker), 11.25 Ohm(PickUp)





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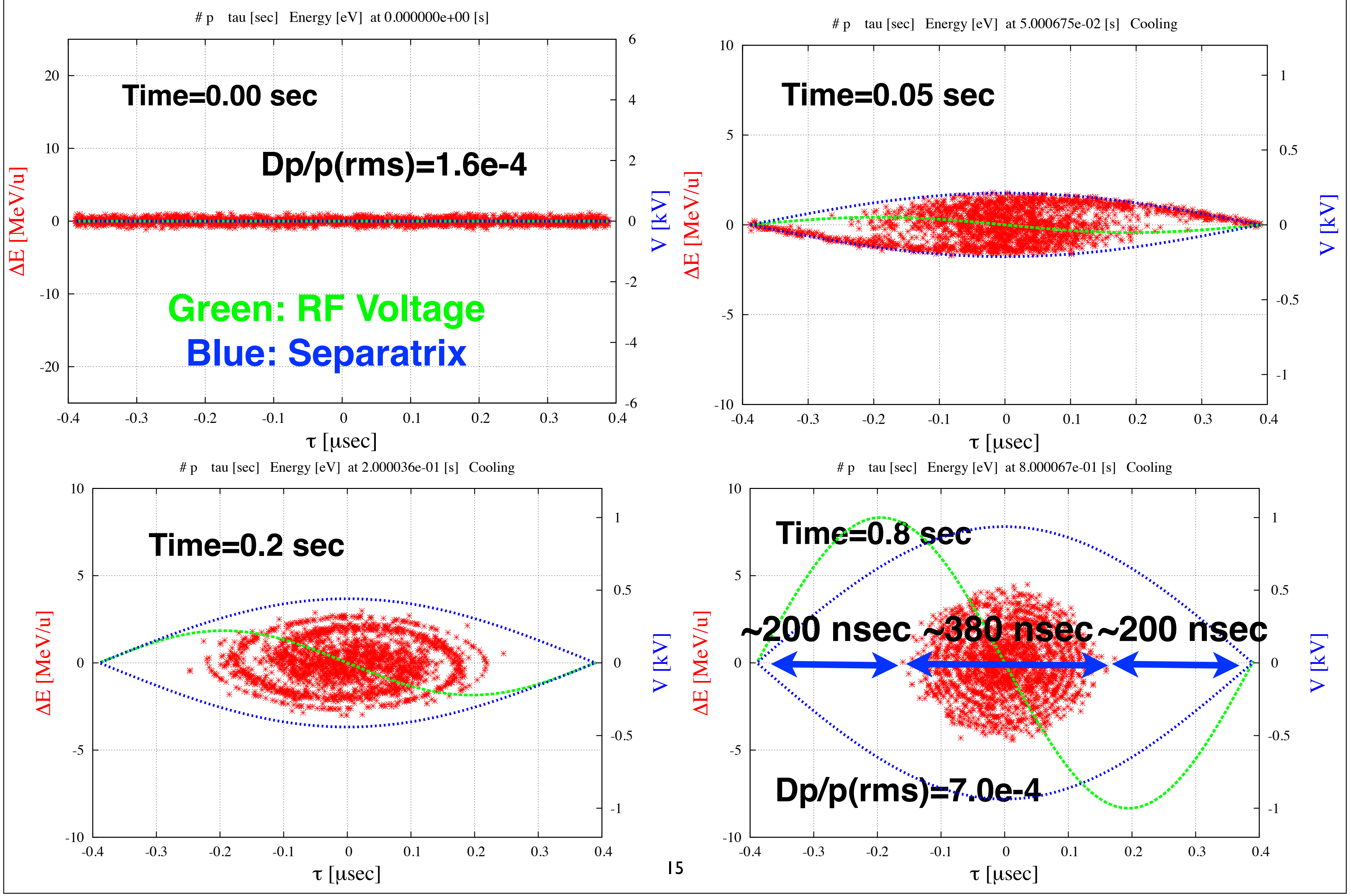
Beam Re-Bunching in the Collector Ring

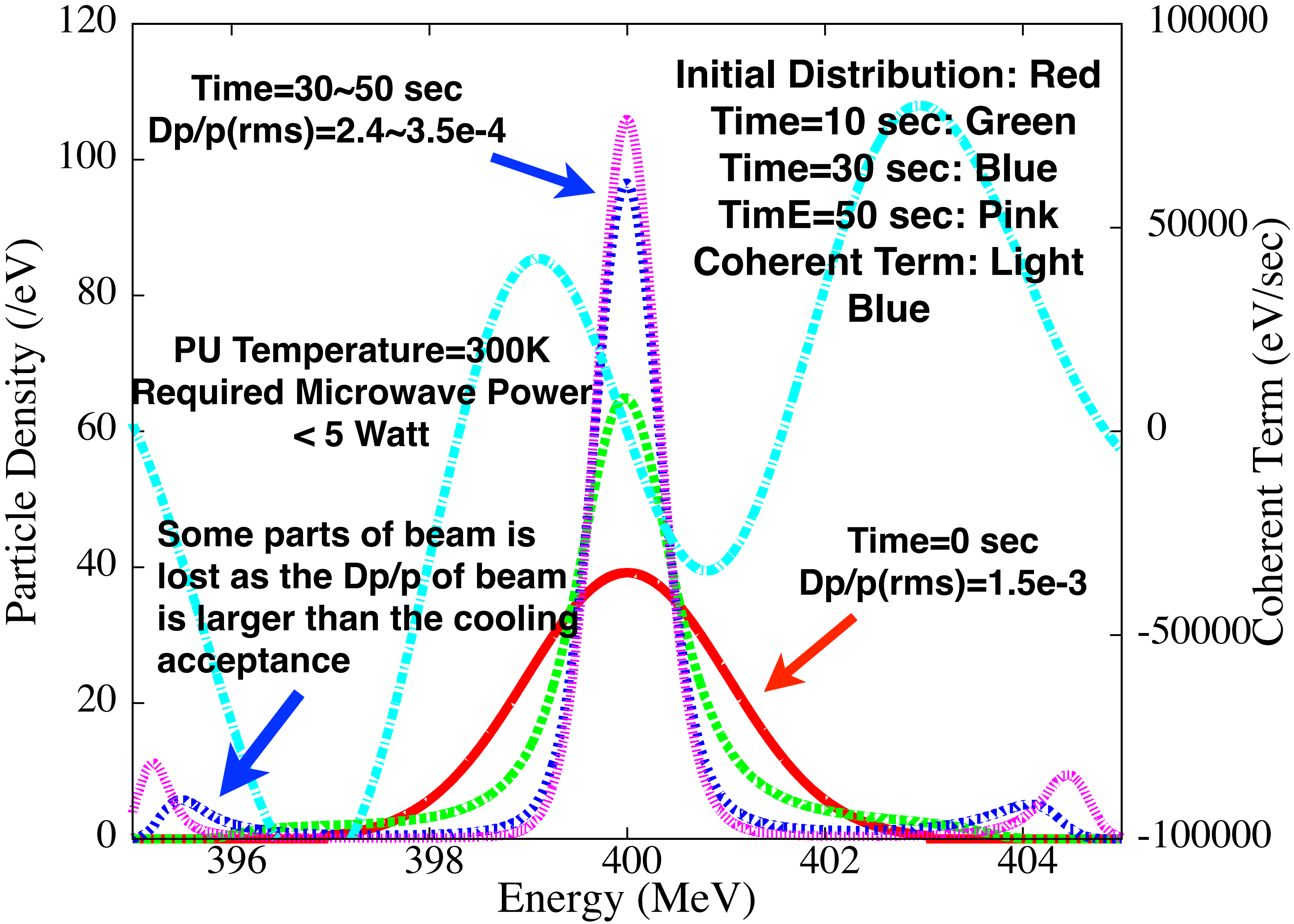


Stochastic Cooling of 0.4 GeV Pbar at ESR

Evolution of Dp/p, Particle Distribution.

Gain=120dB, Dp/p(initial, rms)=1.5e-3

Particle Number=1e8



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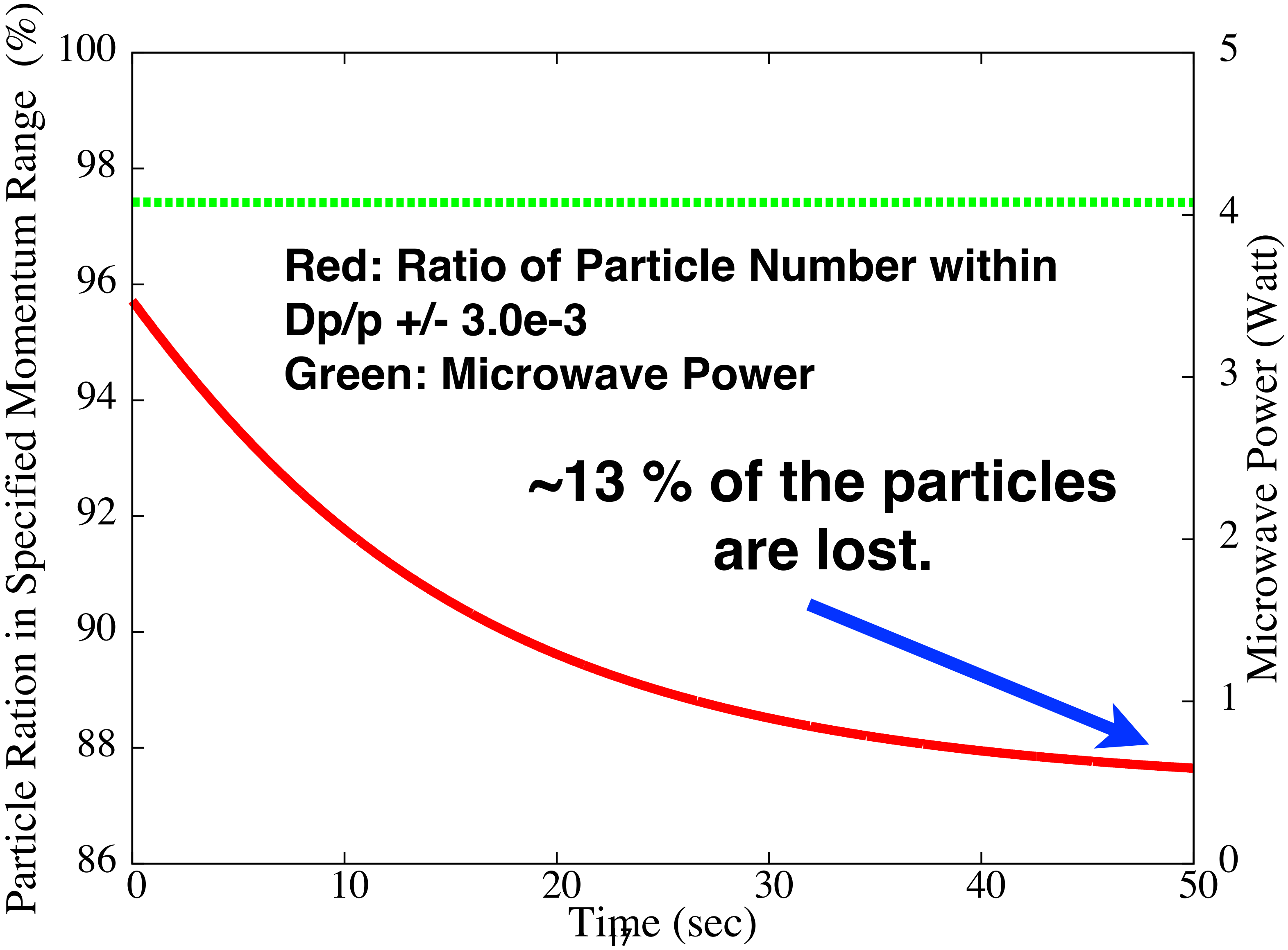
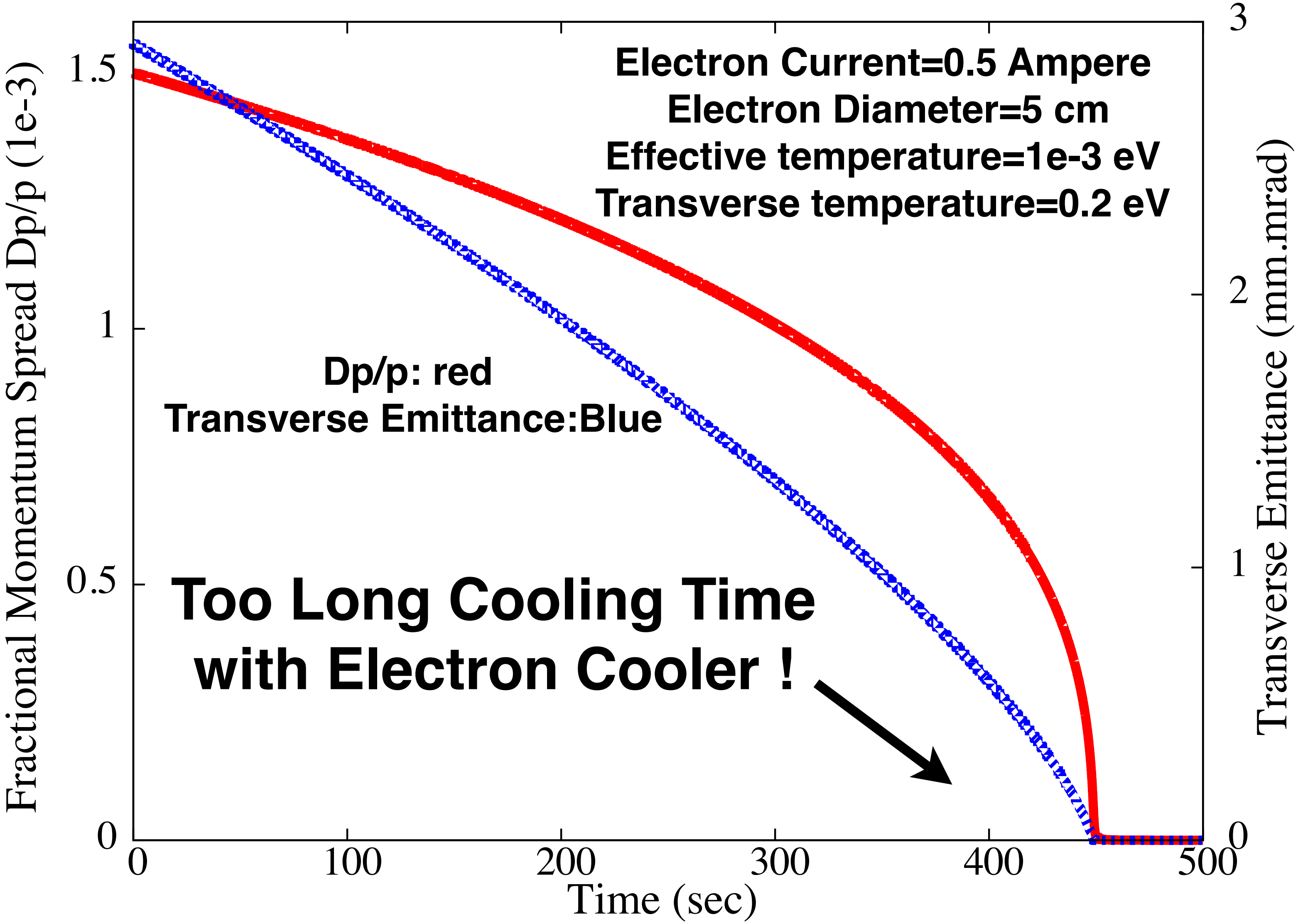
Evolution of Fraction of Particle Number in the Dp/p window less than +/- 3.0e-3 and Microwave Power during the 400 MeV stochastic cooling

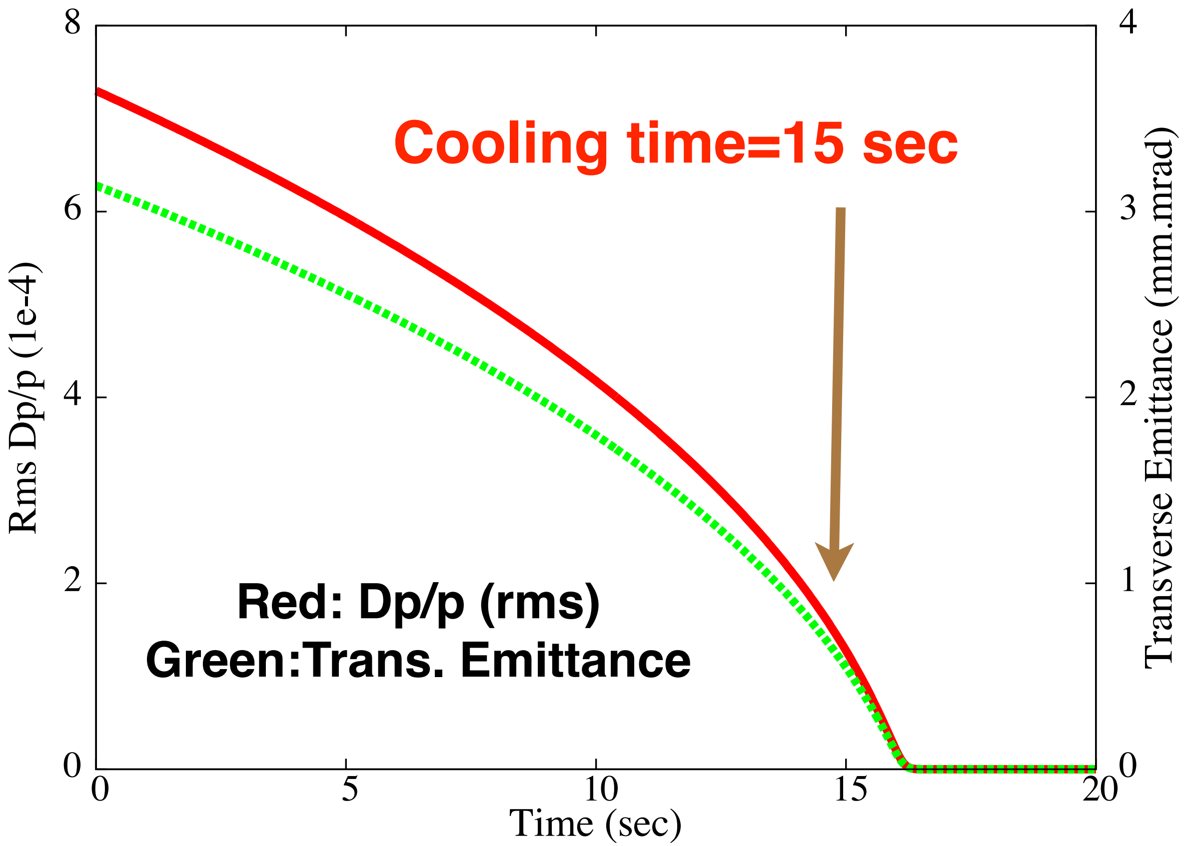


If we use the Electron Cooling for 400 MeV, Emittance (Initial)= 2.92 Pi mm.mrad Dp/p(initial, rms)=1.5e-3



Electron Cooling at ESR without IBS effects

T=100 MeV
Initial Dp/p=7.30e-4
Initial Transverse emittance=3.14 Pi mm.mrad
Diameter of electron beam=5.0 cm
Current of electron=1.0 A (Challenging !)



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Anti-proton Cooling Parameters (Scenario 1)

(all values are rms values at the coasting beam condition)

Energy (MeV)	Transverse Emittance before Cooling (Pi mm.mrad)	Transverse Emittance after Cooling (Pi mm.mrad)	Dp/p before Cooling	Dp/p after Cooling	Cooling Time (sec)	Ring
2000	45	1	2.9e-3 (After bunch rotation)	1.60E-04	10	Collector Ring (Stochastic Cooling)
400	2.92	1.46 (pessimistic assumption)	1.50E-03	5.10E-04	50	ESR (Stochastic Cooling)
100	3.15	0.5	7.30E-04	1.00E-04	15	ESR (Electron Cooling)
30	0.94	0.8	2.00E-04	3.0e-4 (After Bunching)	5	ESR (Electron Cooling)

Part 2

Stacking of 3 GeV Antiproton Beam in HESR with Use of Barrier Bucket and Stochastic Cooling System

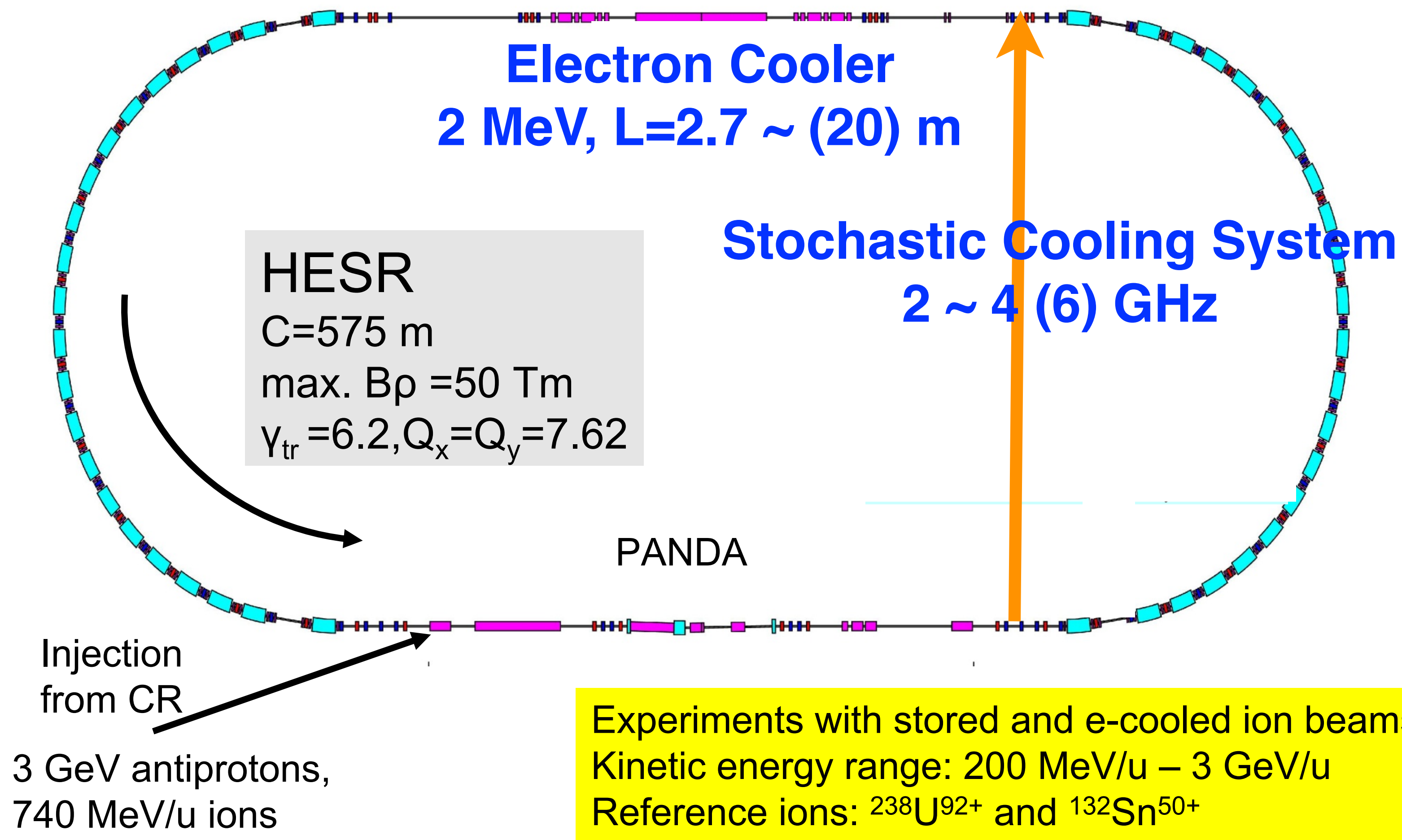
High Energy Storage Ring (HESR)
1-14 GeV Antiproton & 0.7~3 GeV/u Heavy Ions

Fundamental requirement to HESR antiproton beam performance

High resolution mode: N=1e10, Dp/p < 5e-5 (rms)

(High luminosity mode: N=1e11, Dp/p < 1e-4 (rms))

with Hydrogen target density of 4e15 atoms/cm2

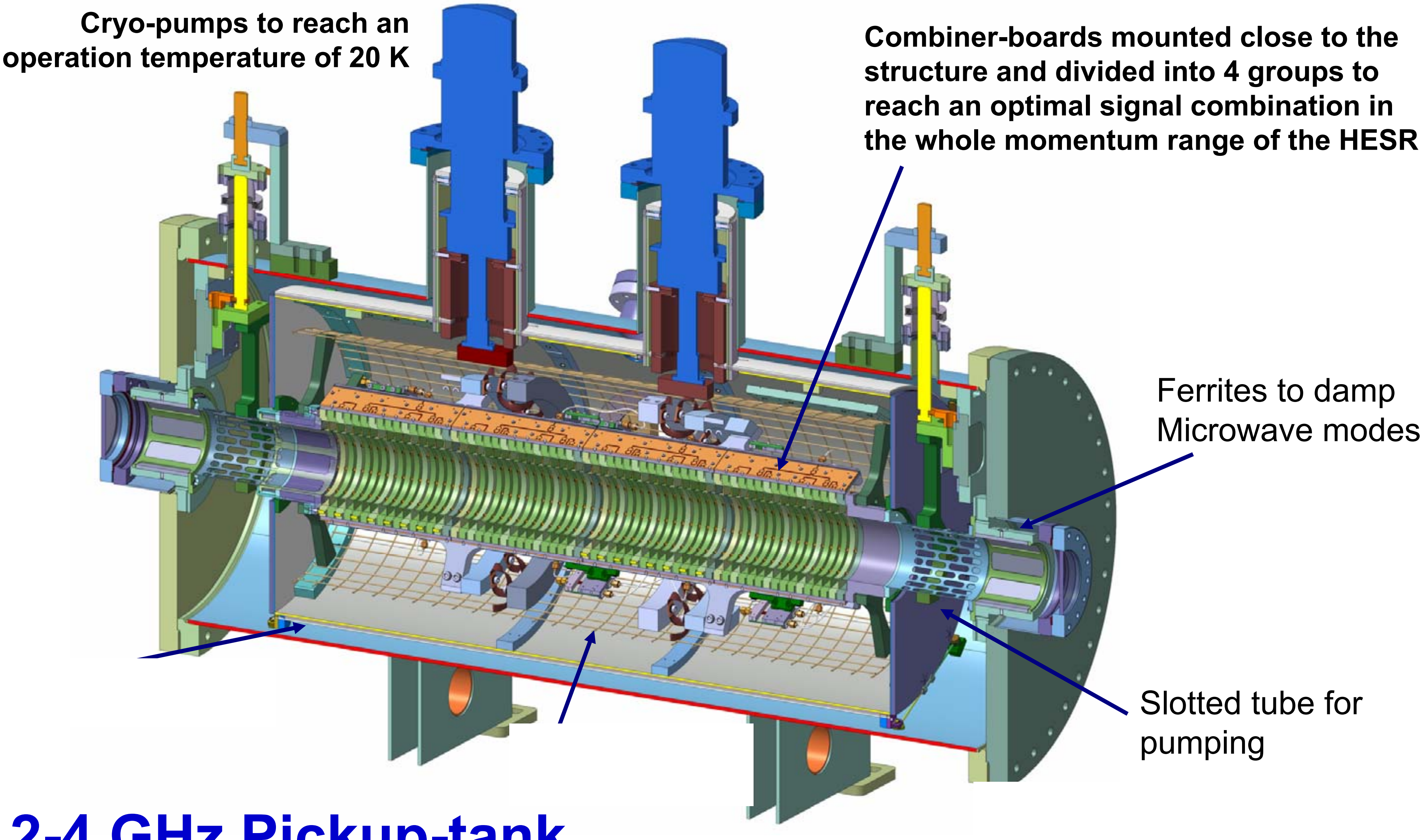


Experiments with stored and e-cooled ion beams
Kinetic energy range: 200 MeV/u – 3 GeV/u
Reference ions: $^{238}U^{92+}$ and $^{132}Sn^{50+}$

HESR Stochastic Cooling Parameters

Beam kinetic energy	3.0 GeV (Pbar)
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	New PU Structure Developed at Julich
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	130-115 dB (Varied during stacking cycle)

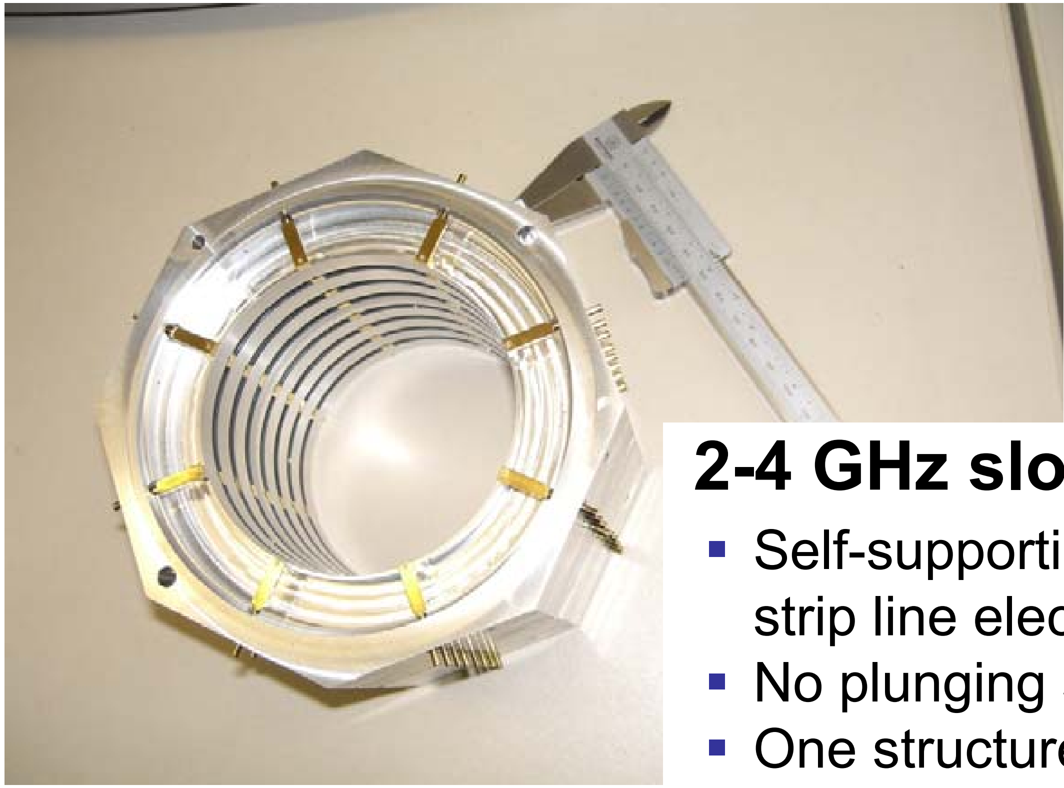
64 Slot couplers/tank, Cooling energy range > 0.8 GeV



2-4 GHz Pickup-tank

from R. Stassen

PickUp and Kicker Structure for HESR Stochastic Cooling

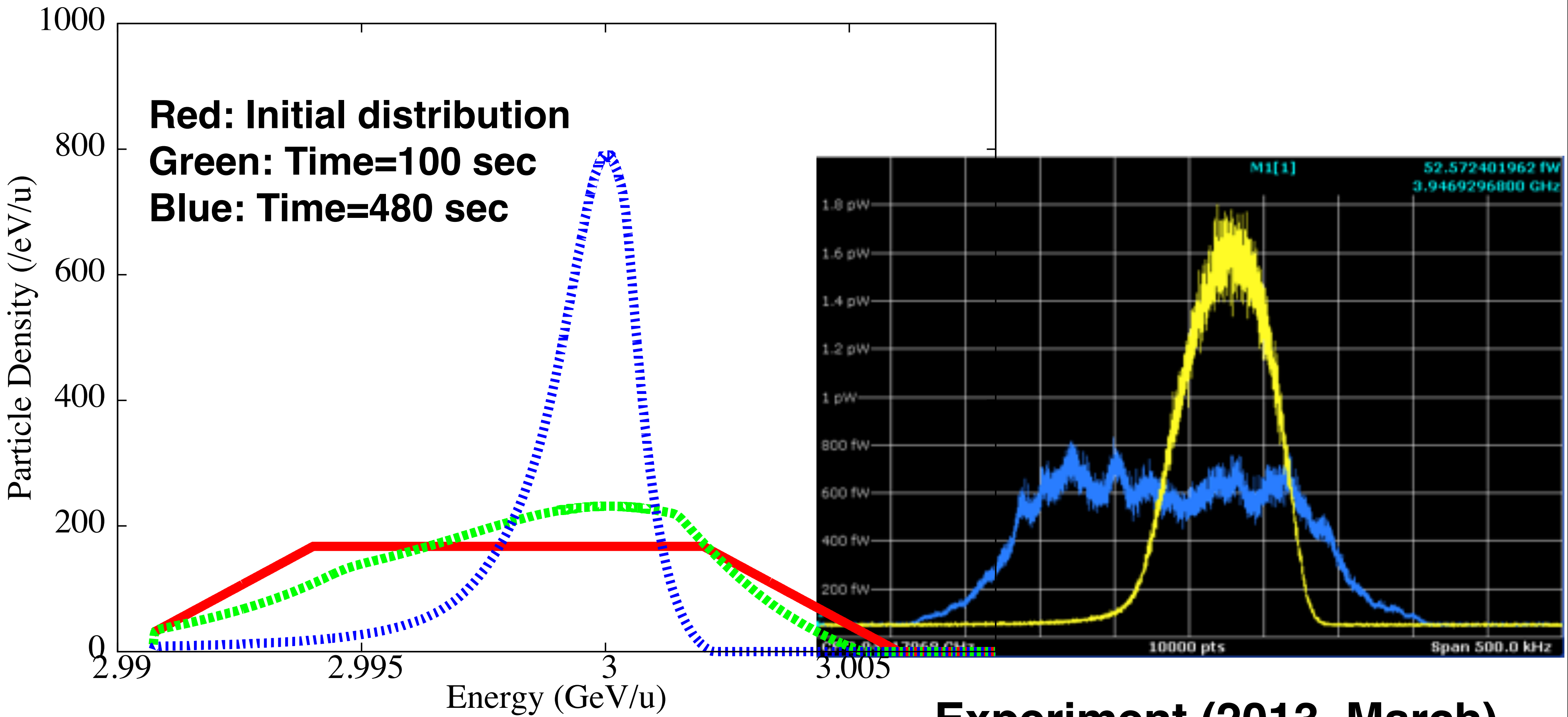


2-4 GHz slot ring couplers:

- Self-supporting and robust structure with 8 50Ω strip line electrodes
- No plunging system
- One structure for all three cooling planes
- Structure tested in small cryogenic test-tank with real COSY beam. The measured sensitivity was higher than the plunging COSY-lambda/4 structures

Nuclotron Deuteron Beam,
Stochastic Momentum Cooling with FZJ PU/Kicker

Energy=3 GeV/u,N=2e9, Gain=113dB
(JINR & FZJ IKP Collaboration)



Simulation with FP solver

Experiment (2013, March)

Blue: Initial

Yellow: 480 sec

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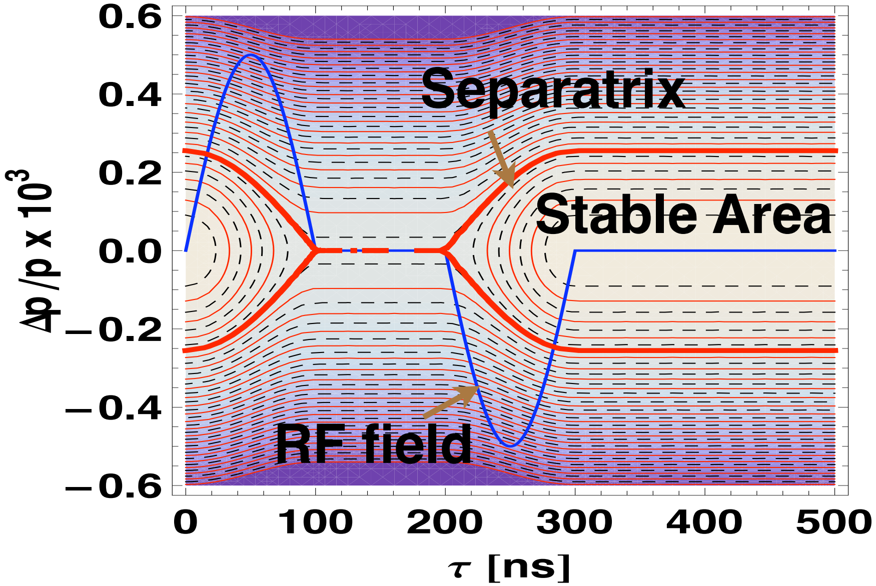
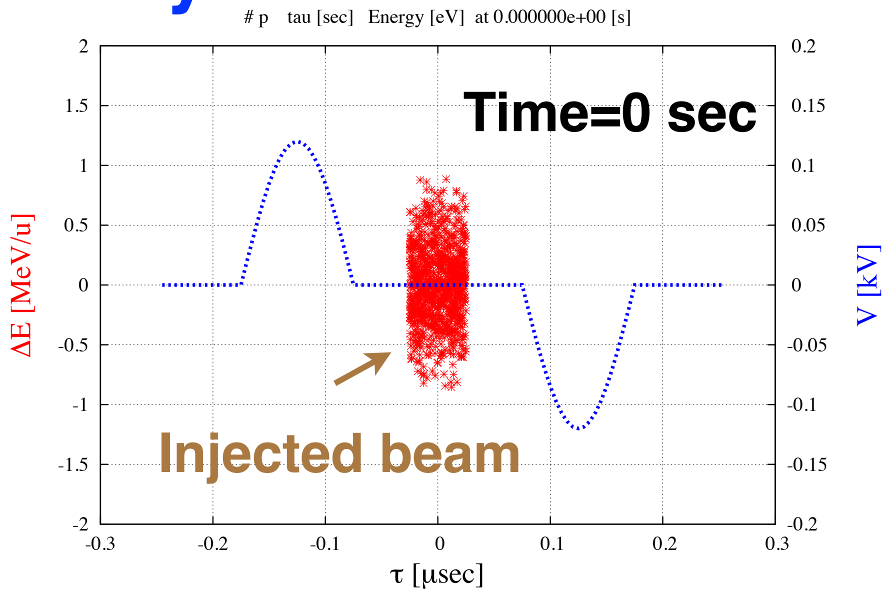
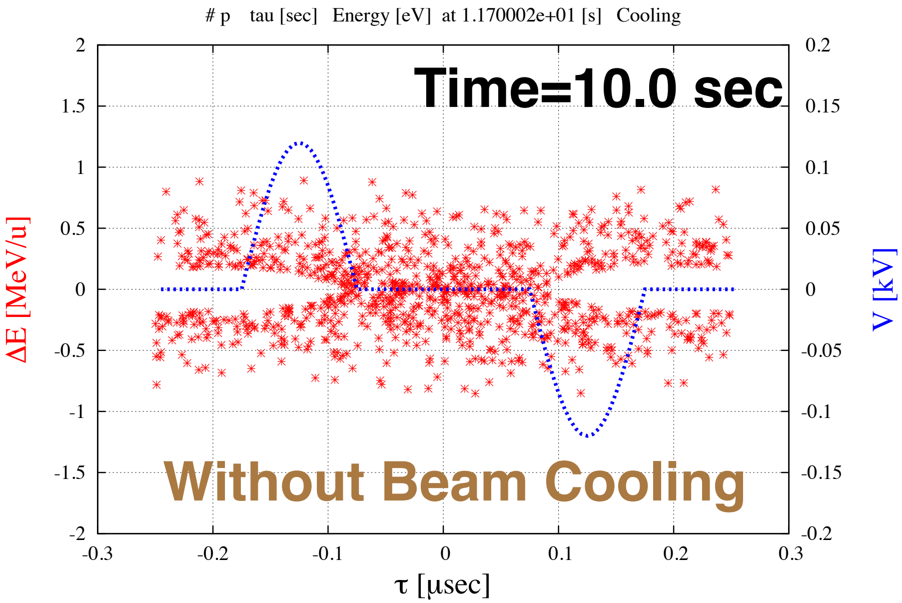
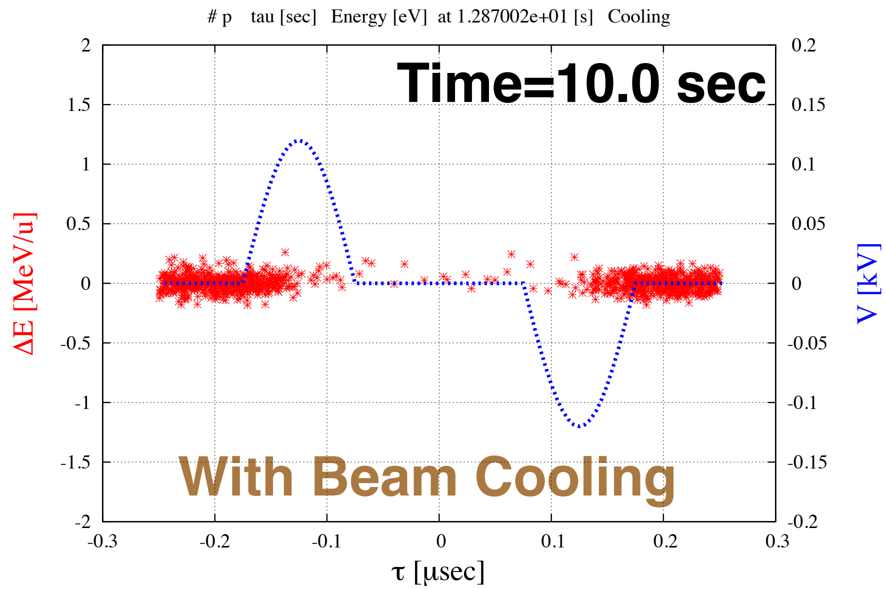
Separatrix and Beam Trajectory at Barrier Bucket System





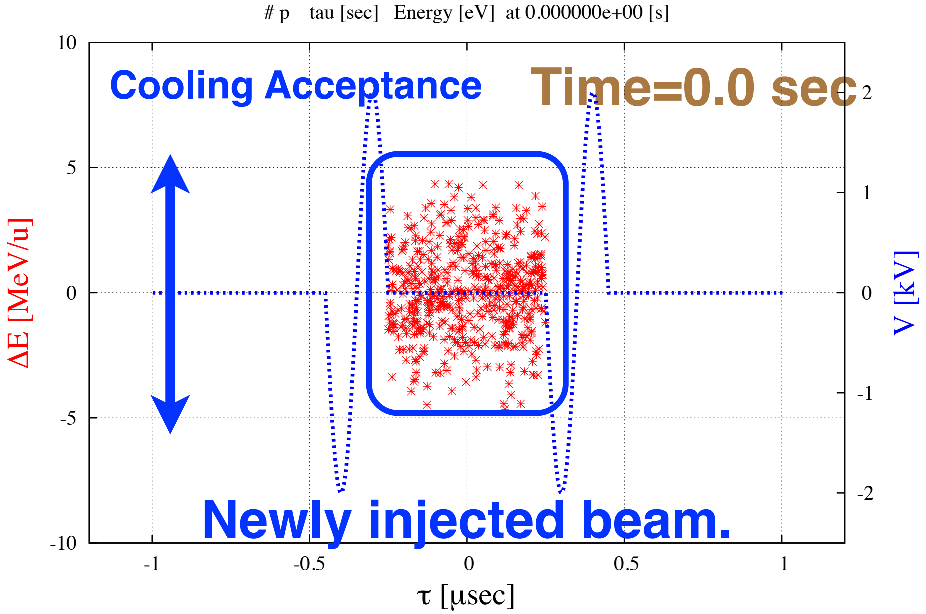


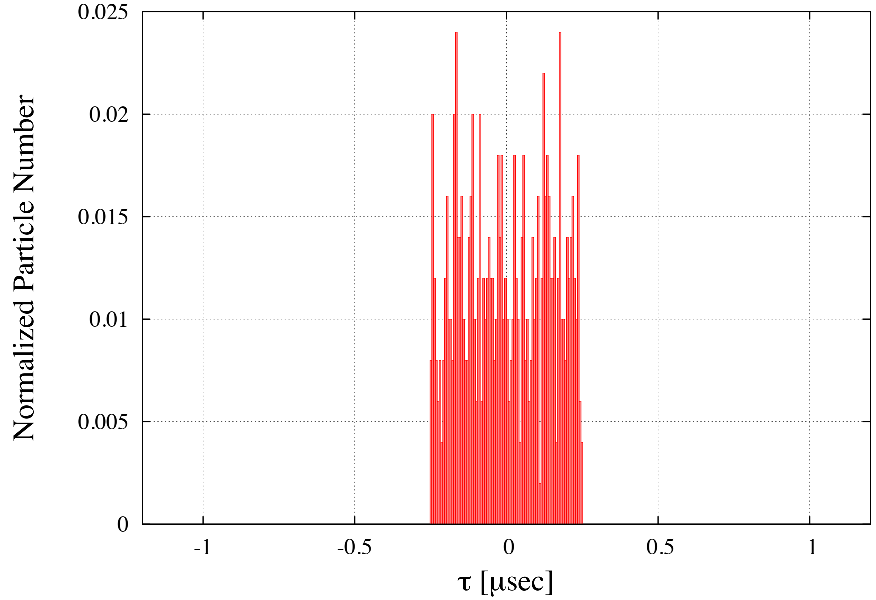


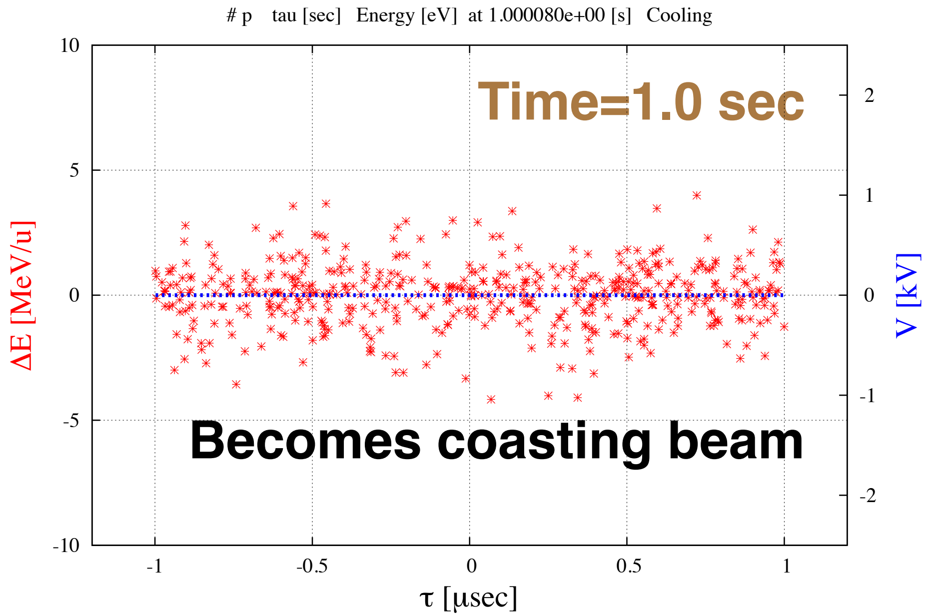
Phase Space Mapping

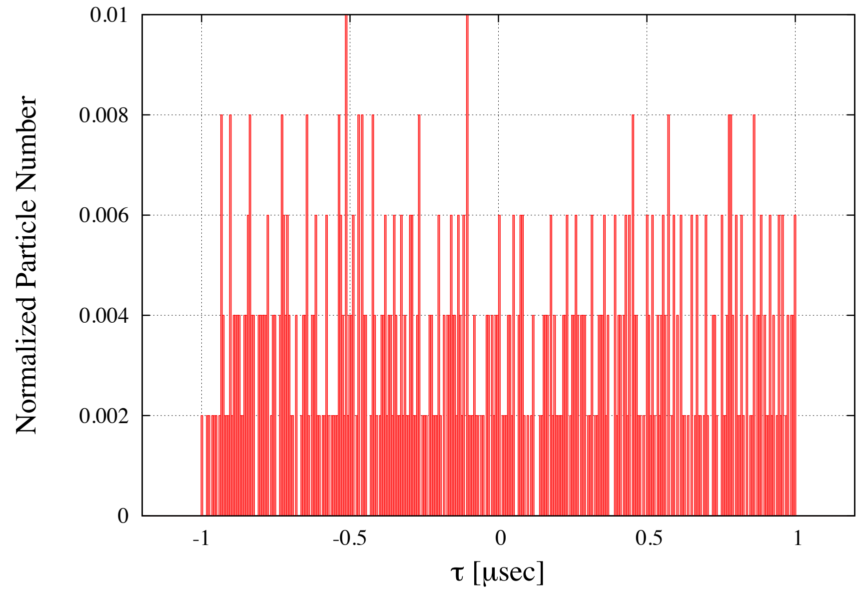
Blue: barrier Voltage
Red: Particle distribution

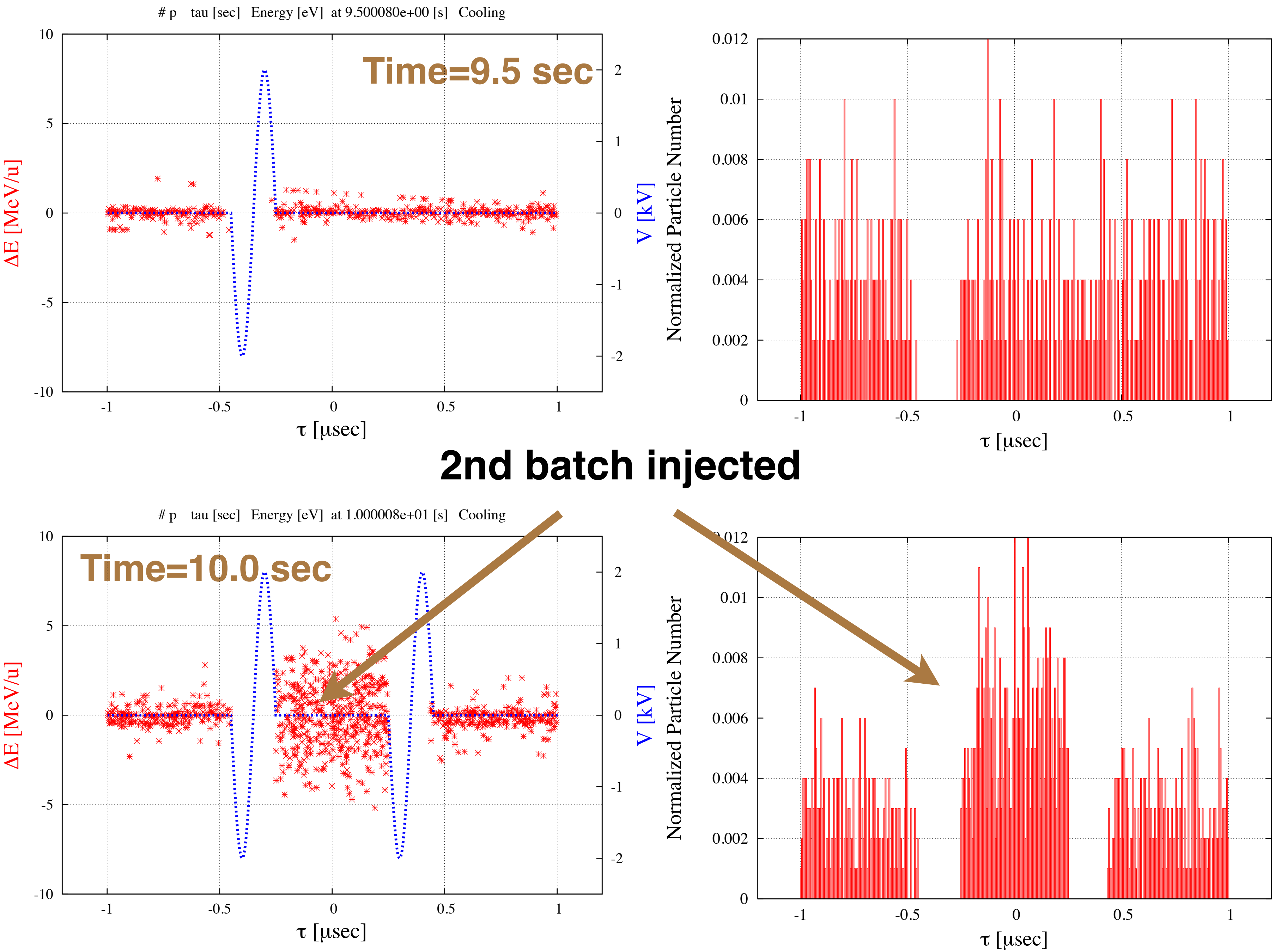
Particle distribution along the Ring Circumference









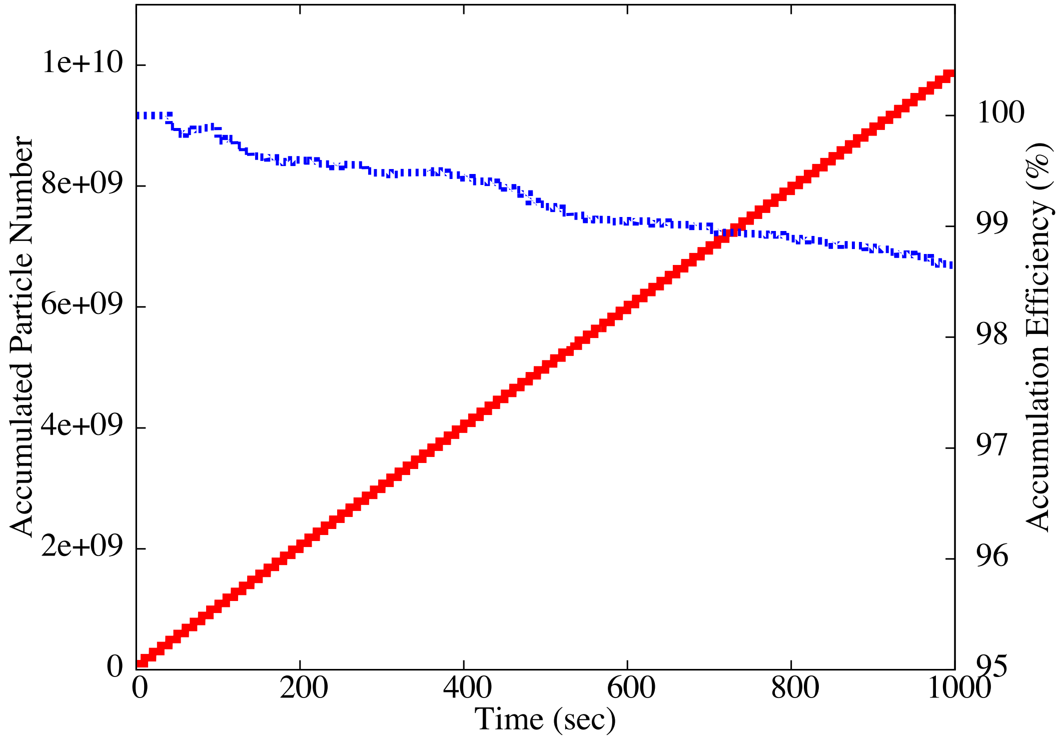


# p tau [sec] Energy [eV] at 9.500080e+00 [s] Cooling
Time=9.5 sec
ΔE [MeV/u]
V [kV]
τ [µsec]
Normalized Particle Number
τ [µsec]
2nd batch injected
# p tau [sec] Energy [eV] at 1.000008e+01 [s] Cooling
Time=10.0 sec
ΔE [MeV/u]
V [kV]
τ [µsec]
Normalized Particle Number
τ [µsec]

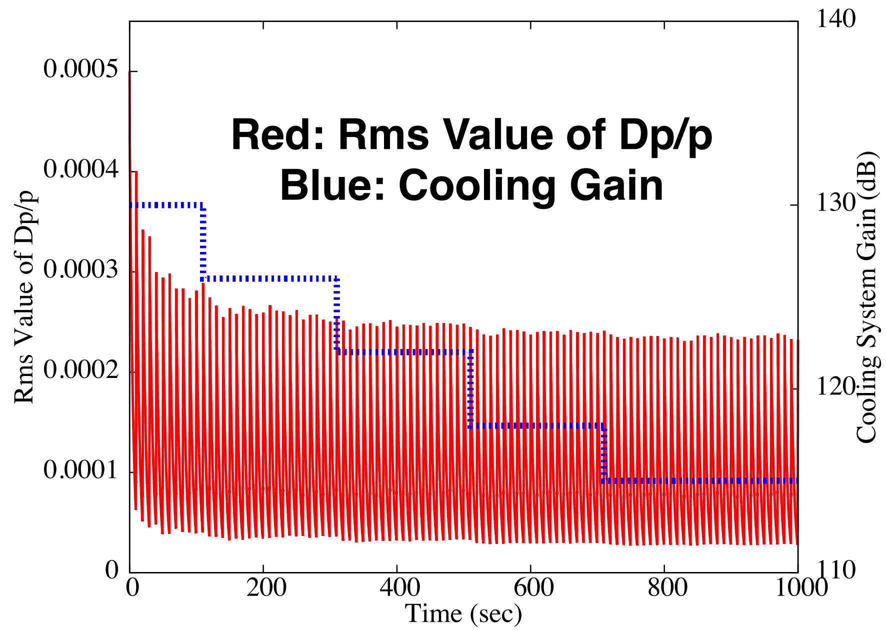
HESR, Beam Accumulation with Moving Barrier System, Voltage=2000 Volt

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)



Starting condition of Acceleration and Deceleration
Coasting beam Dp/p=2e-4 (rms)

Barrier Voltage Parameters for HESR

Injected Beam Width	**500 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**

HESR BB parameters

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

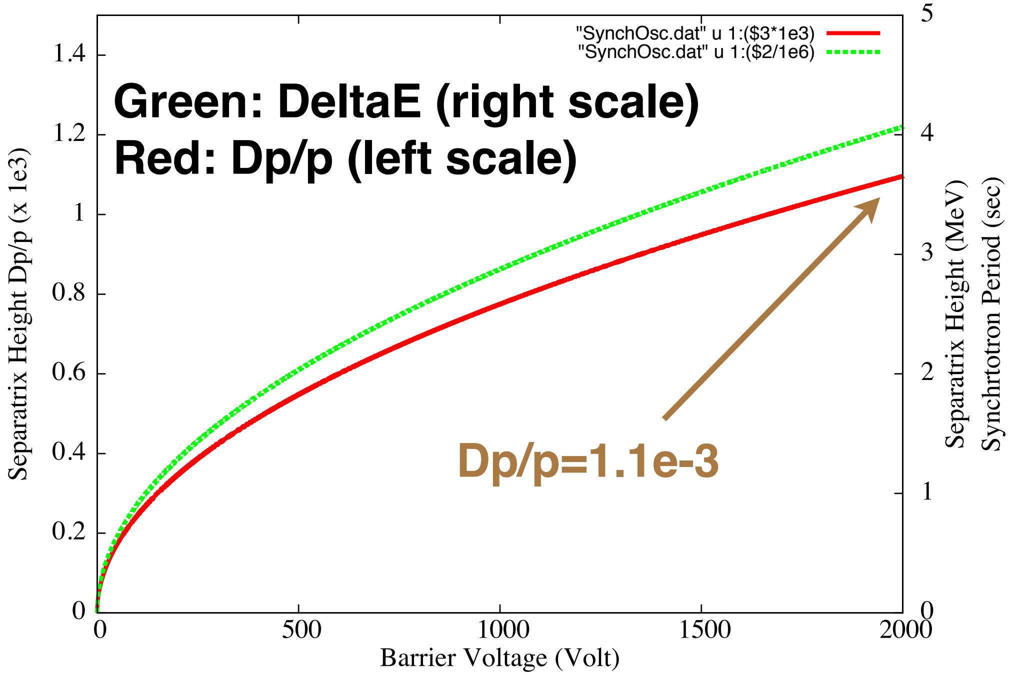
Separatrix Height of BB System

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

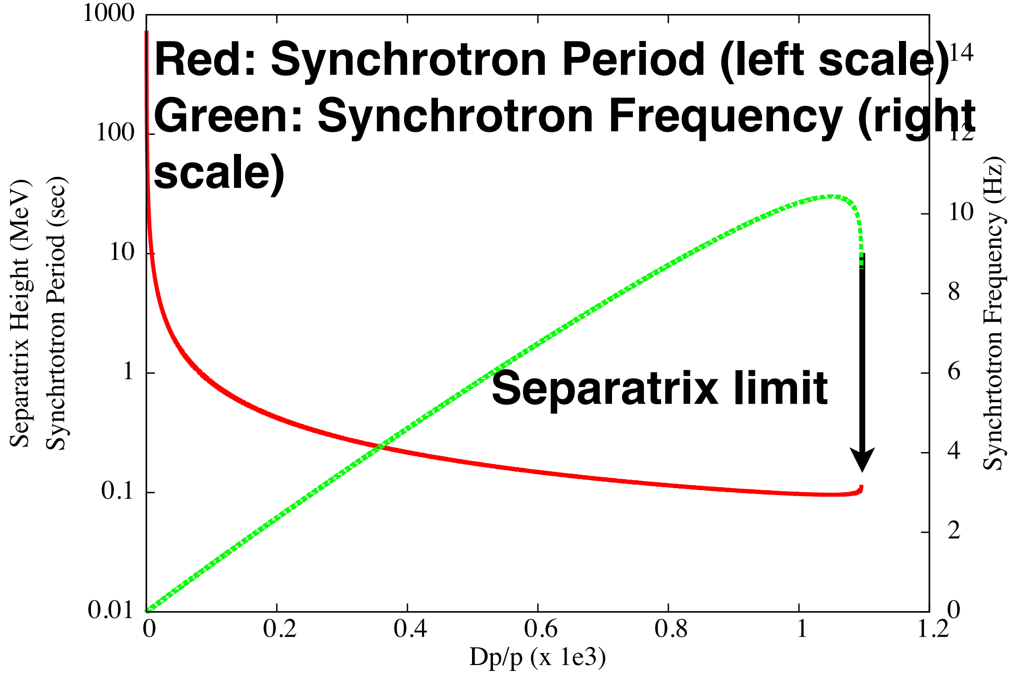
$$\varepsilon = Q / A$$

$$E_0 = Total\ Energy / nucleon$$

Separatrix Height vs Barrier Voltage

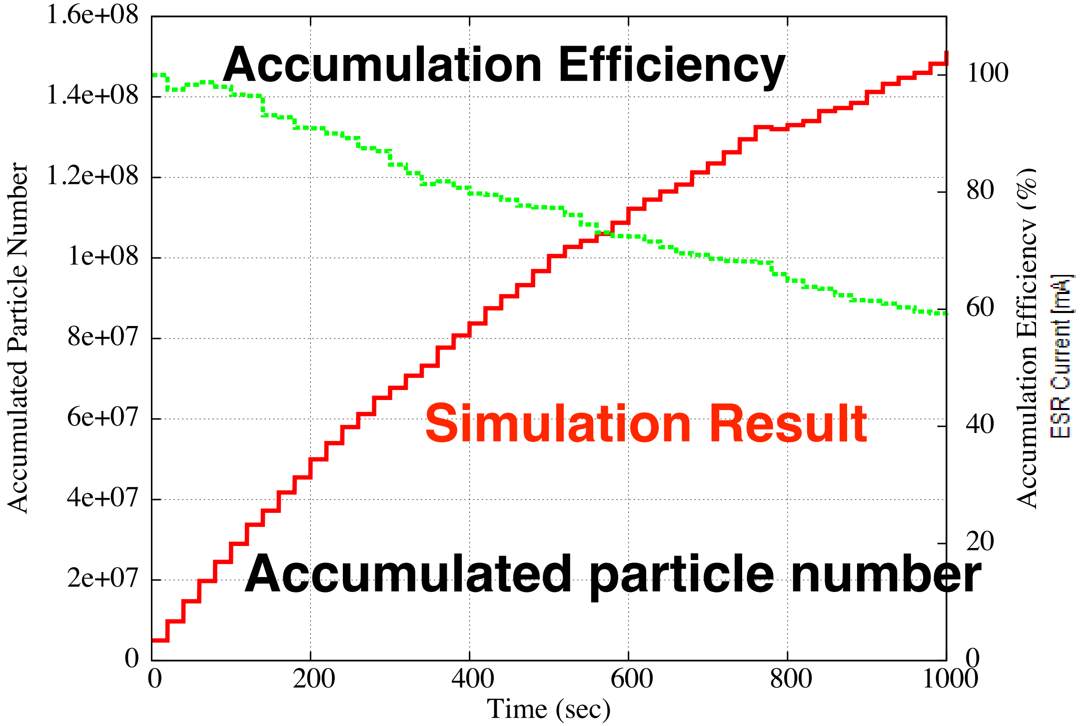


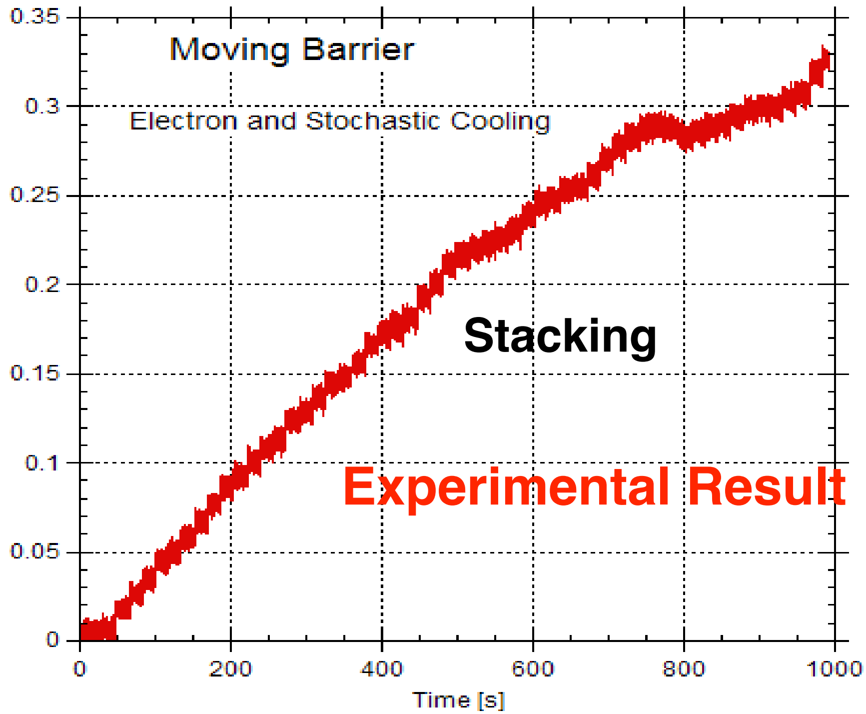
Synchrotron Period & Frequency vs Particle Momentum



PoP Experiment at ESR, 400 MeV/u, Ar18+
Moving Barrier Case, Stochastic Cooling
Gain=120 dB
Vbb=120V, Ie=0.3A, Cycle time=20 sec

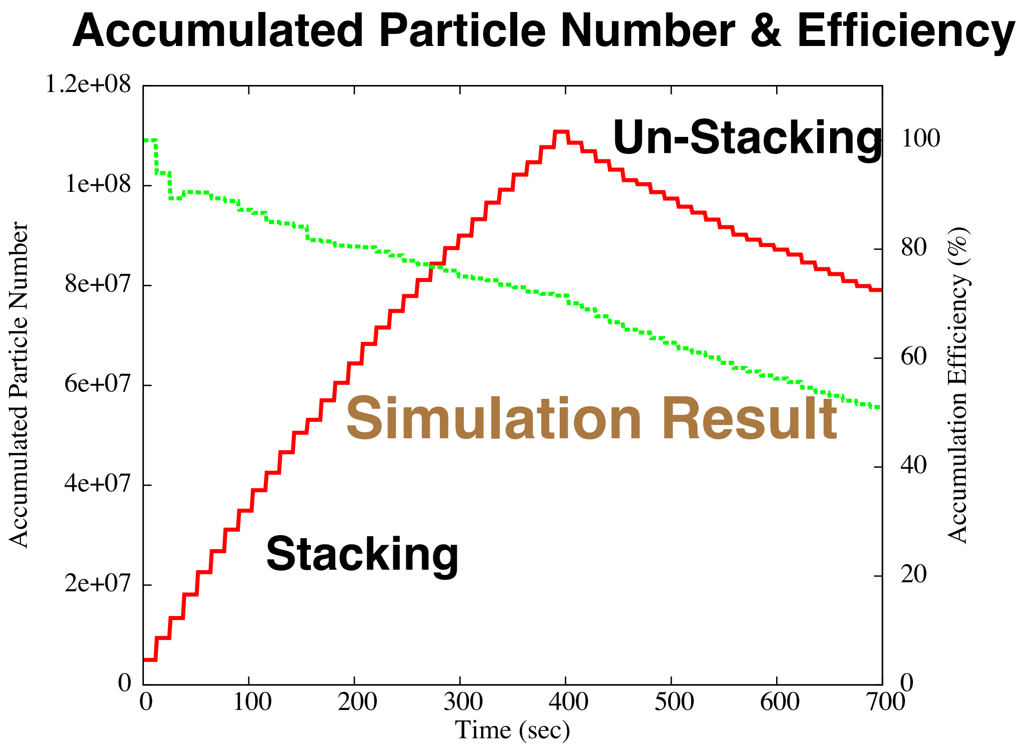
Accumulated Particle Number & Efficiency

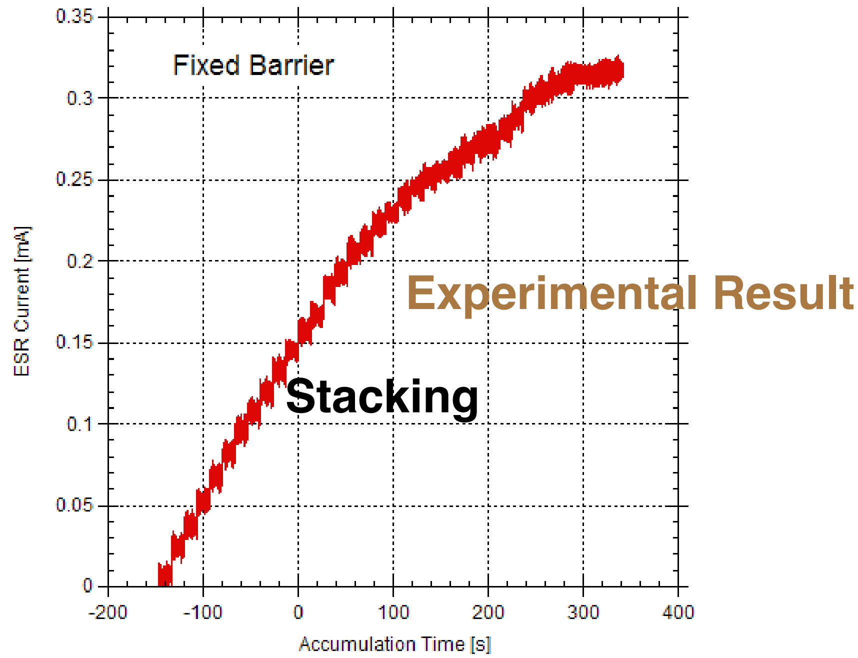




Accumulation Efficiency= Accumulated Particle Number/Total Injected Particle Number

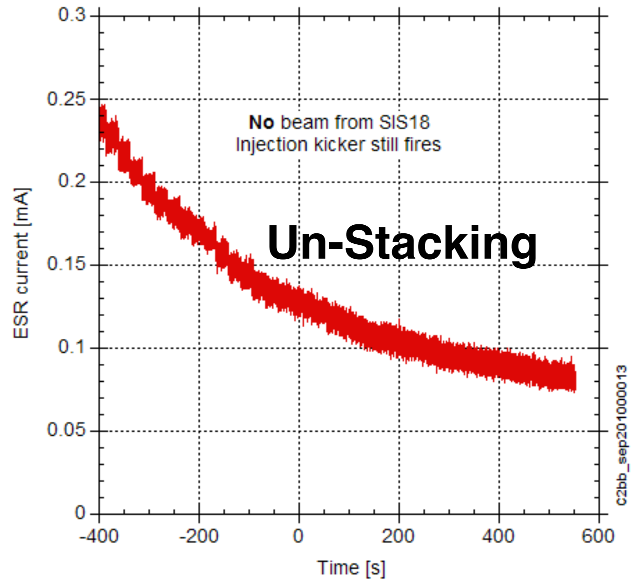
Fixed Barrier Case Vbb=120 V, Stochastic Cooling Gain=120dB





Un-Stacking

- No Beam injection but Kicker is fired -



Accumulation Efficiency=
Accumulated Particle Number/Total Injected Particle Number

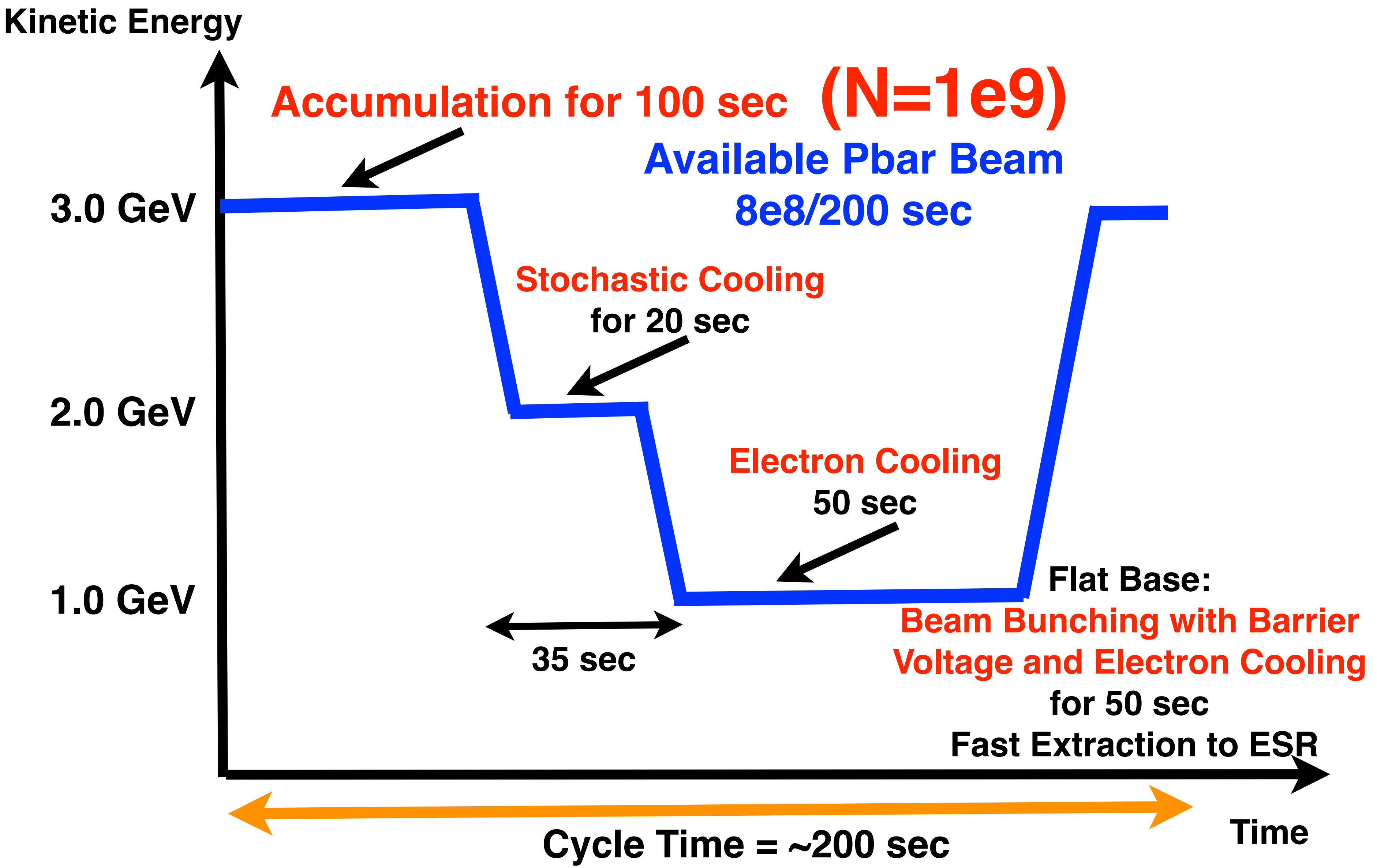
Celebration of Success of POP Experiment 2010 September 9th, at ESR Control Room

GSI, FZJ, JINR & CERN Collaboration

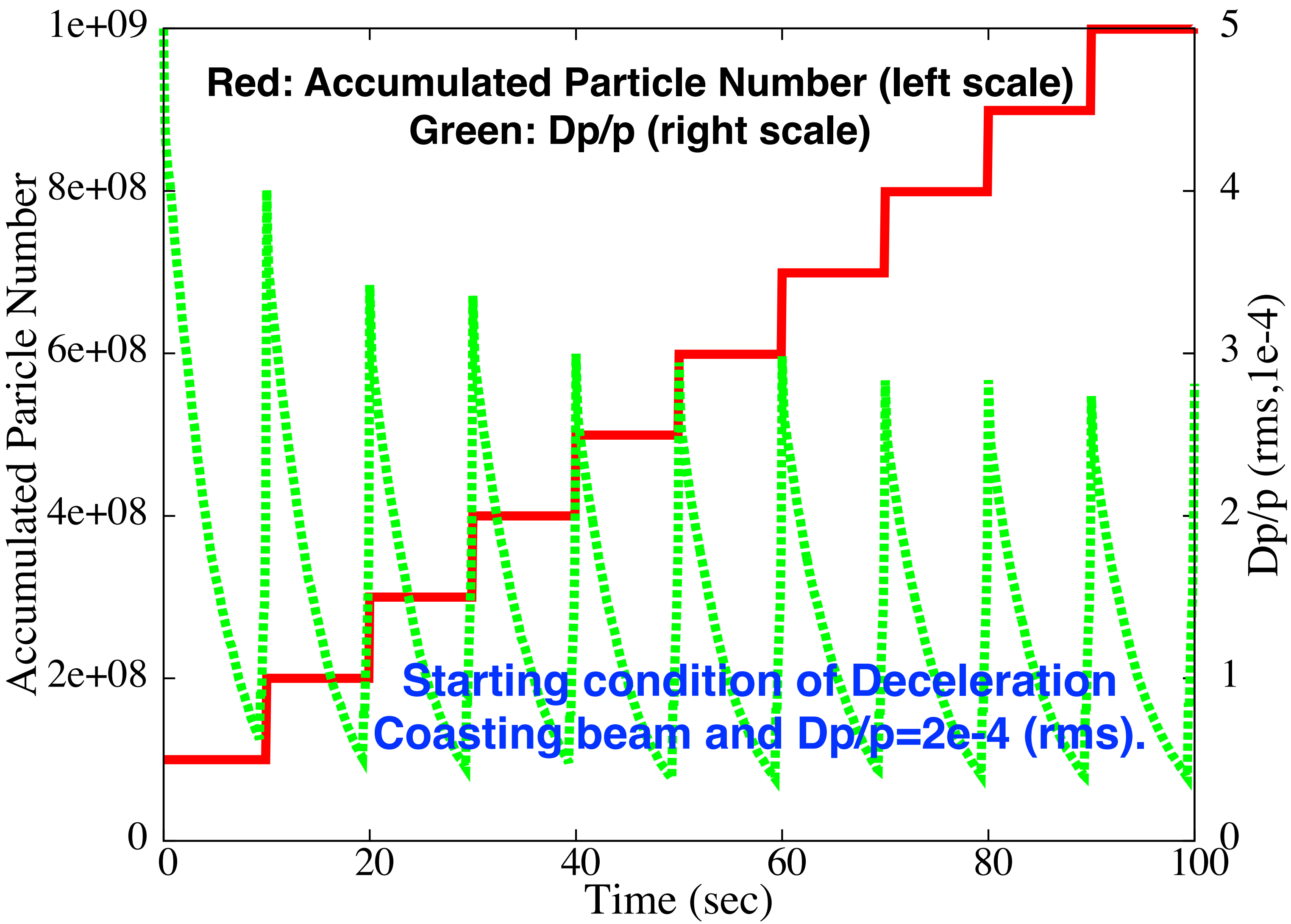
Spokesman: M. Steck

Part 3
Deceleration of Antiprotons in HESR

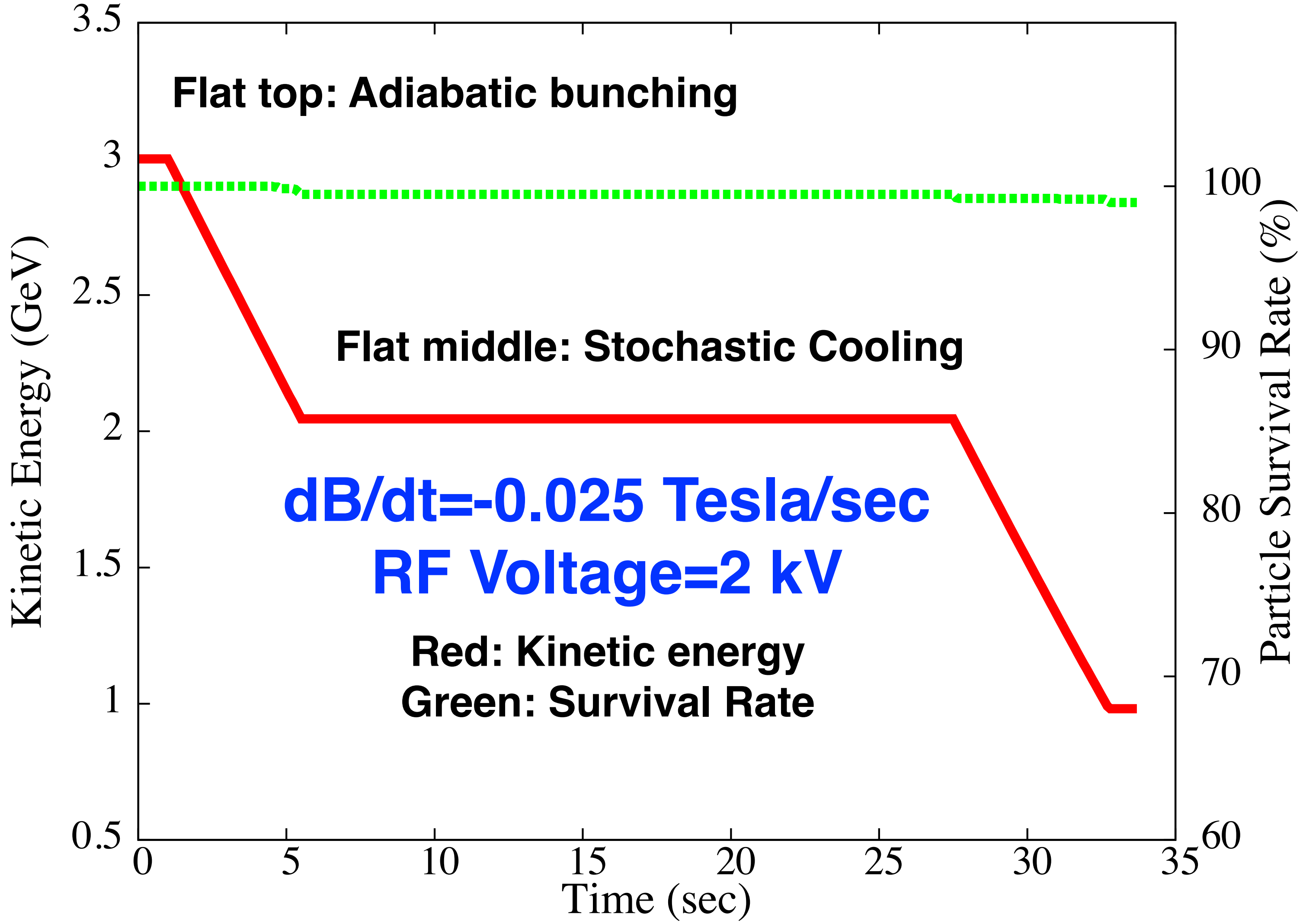
Operation Scheme of HESR for High Dense Antiproton Flux to ESR/CRYRING



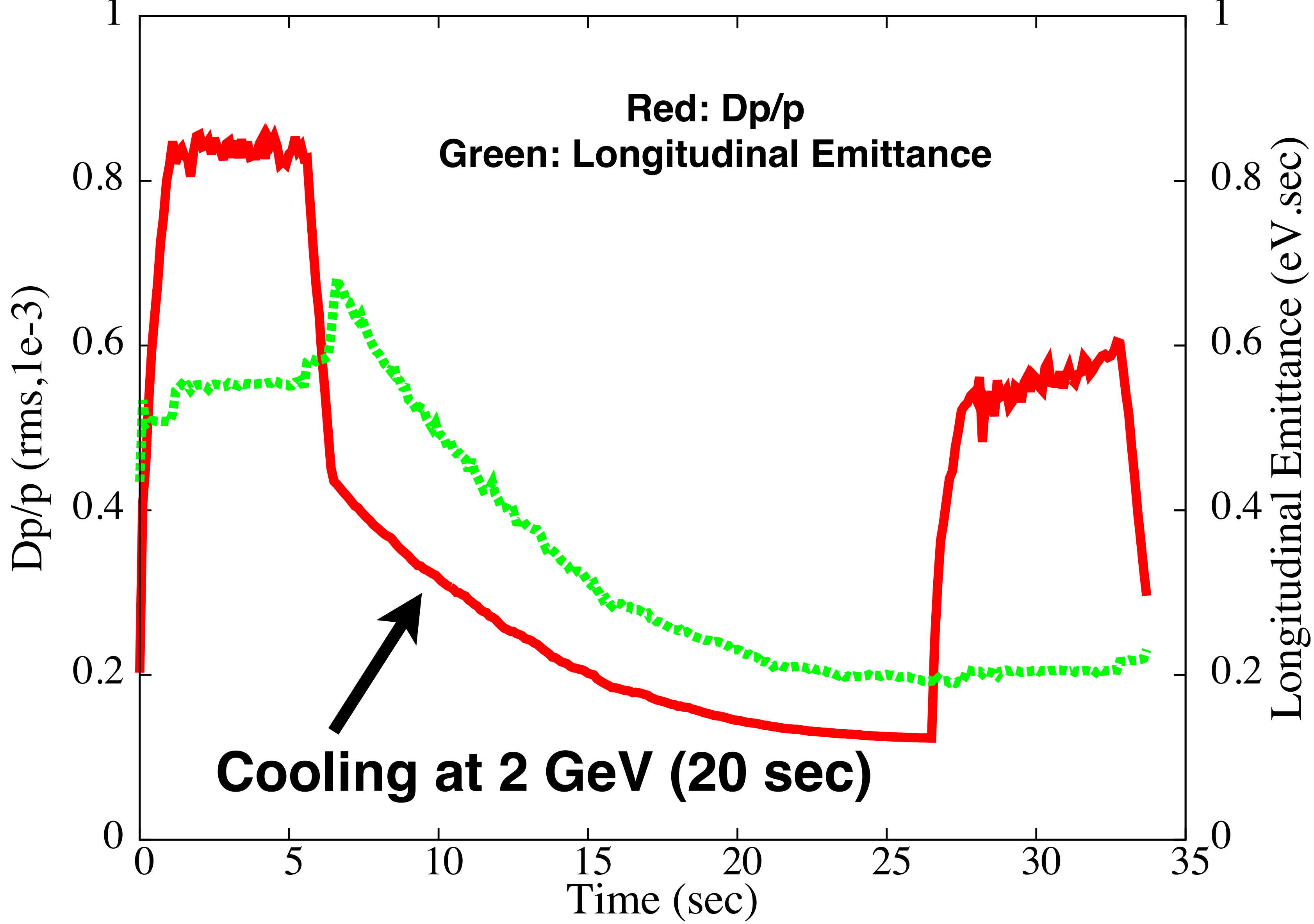
For FLAIR, Accumulation up to 10 times, N=1e9



Deceleration from 3 GeV to 1 GeV, Npbar=1e9 with Stochastic Cooling at Middle Flat of 2 GeV



Evolution of Dp/p and Longitudinal Emittance during Deceleration



Phase Equation

$$\frac{d}{dt}\left(\frac{\Delta E}{\omega_0}\right) = \frac{1}{2\pi}\frac{Q}{A}eV\left(\sin\phi - \sin\phi_s\right)$$

$$\frac{d\phi}{dt} = \frac{h\omega_0\eta}{\beta^2{}_s E_s}\Delta E$$

$$\eta = \frac{1}{\gamma^2{}_t} - \frac{1}{\gamma^2}$$

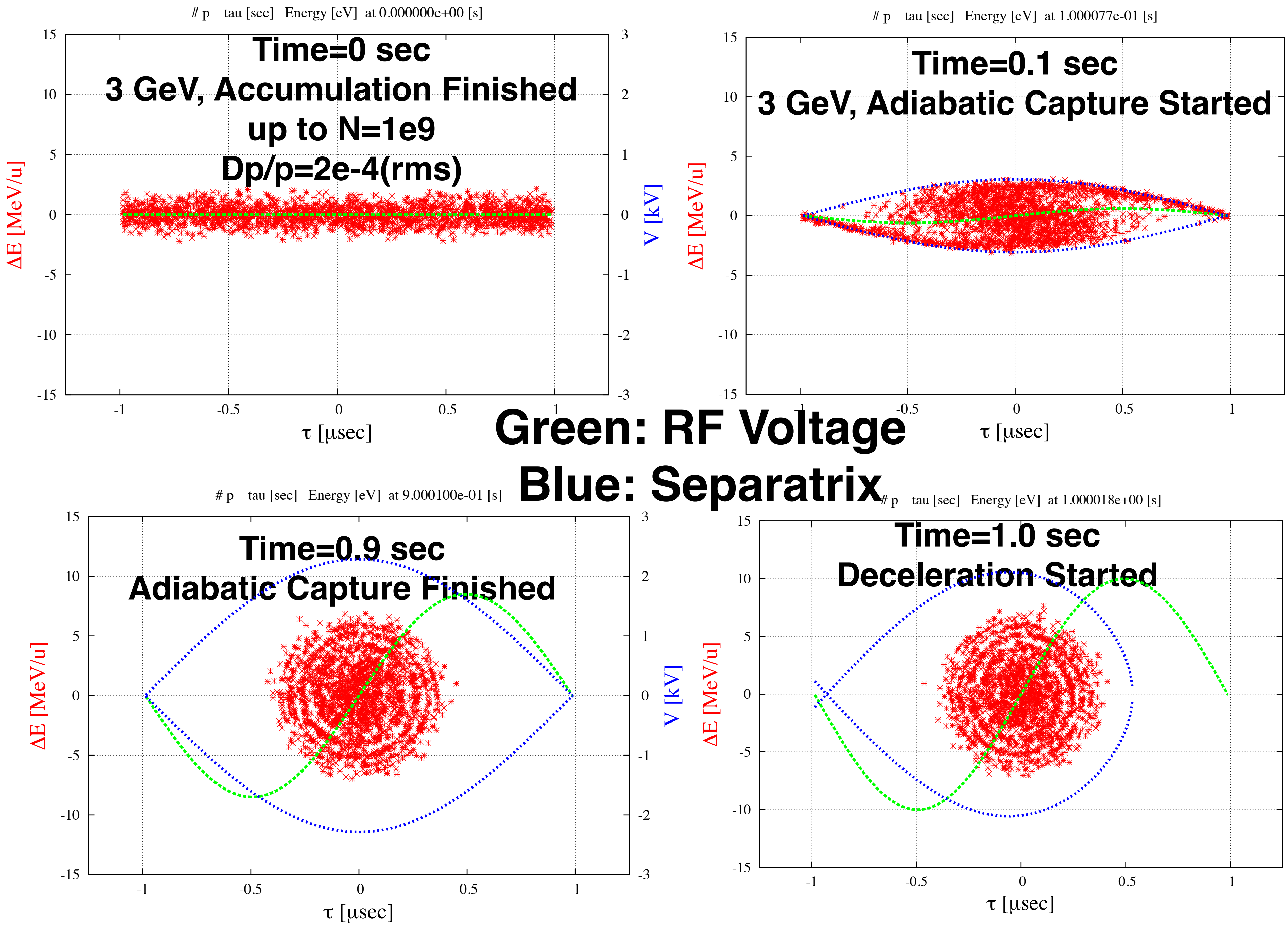
Synchronous Phase

$$V\sin\phi_s = 2\pi\rho R\, dB/dt$$

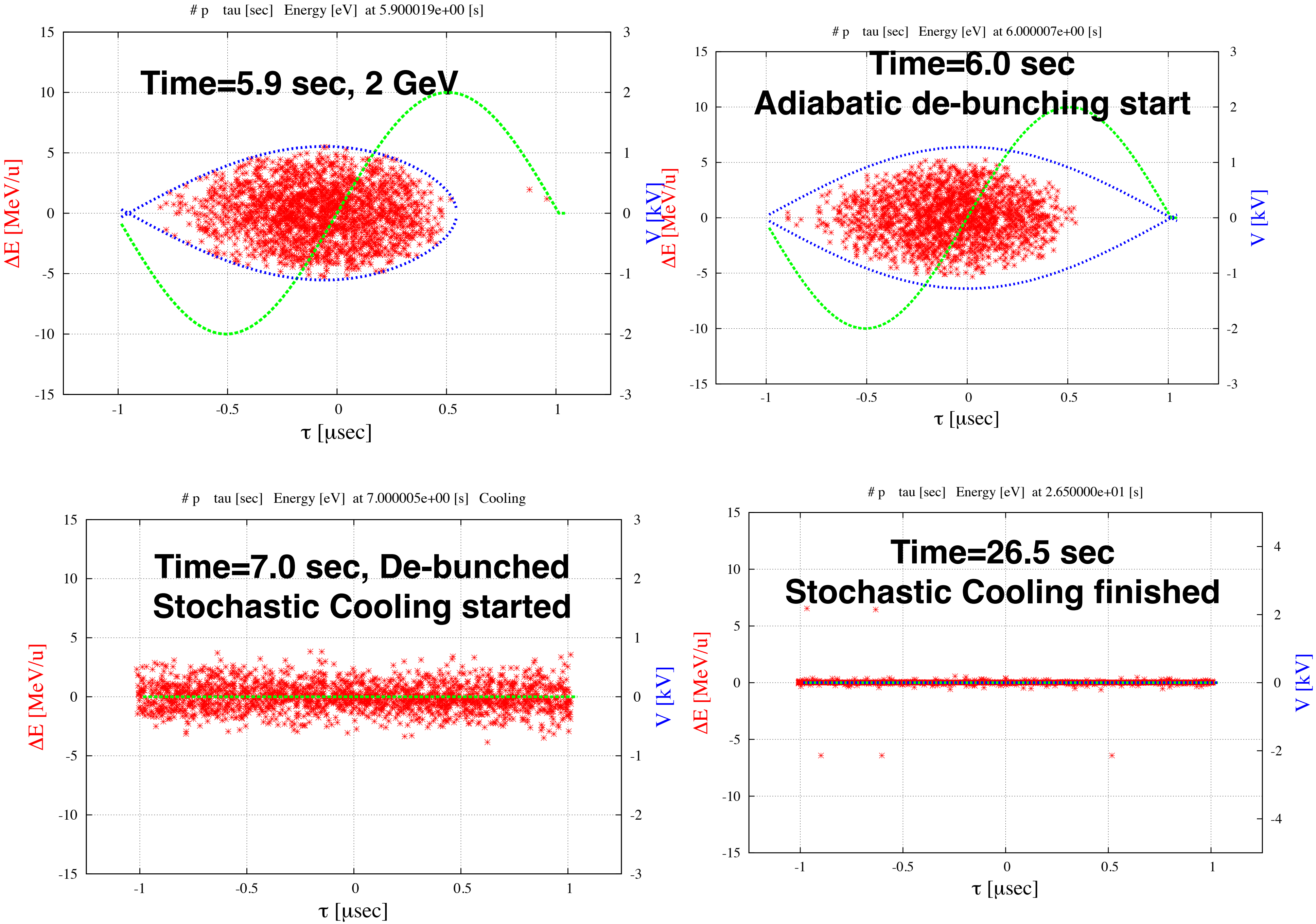
Separatrix Height

$$H = 2\left[\frac{QeV\beta^2 E_s}{2\pi hA|\eta|}\right]^{1/2} Y(\phi_s)$$

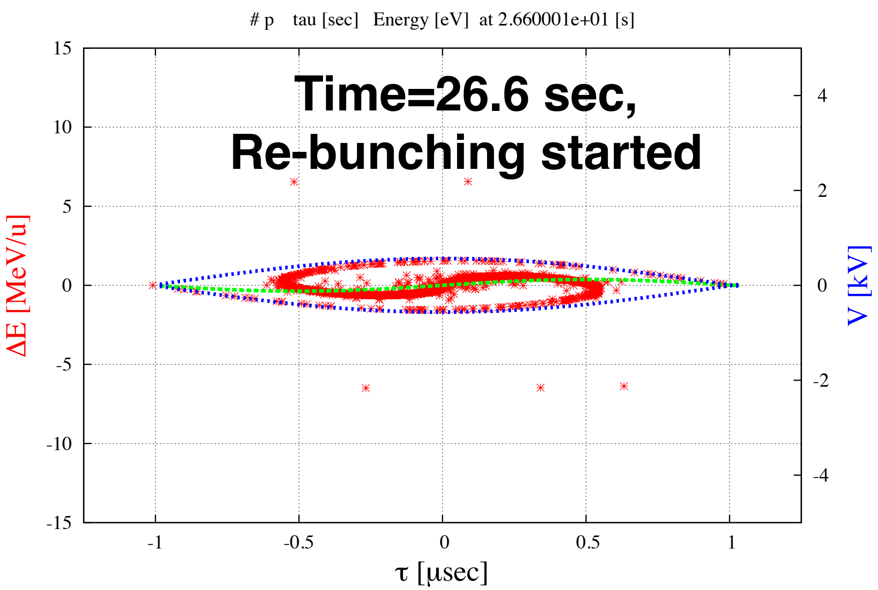
$$Y(\phi_s) = \left[\cos\phi_s - \frac{\pi - 2\phi_s}{2}\sin\phi_s\right]^{1/2}$$

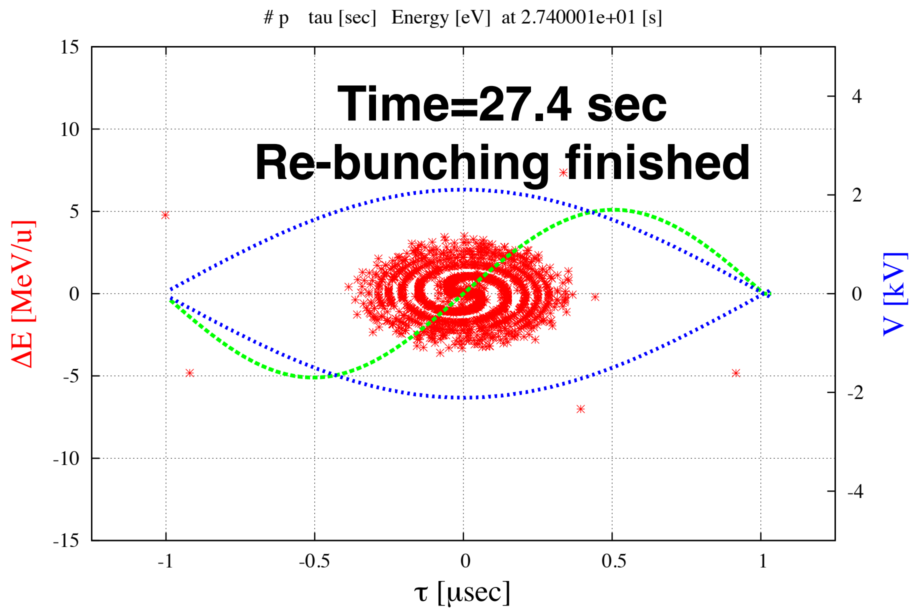


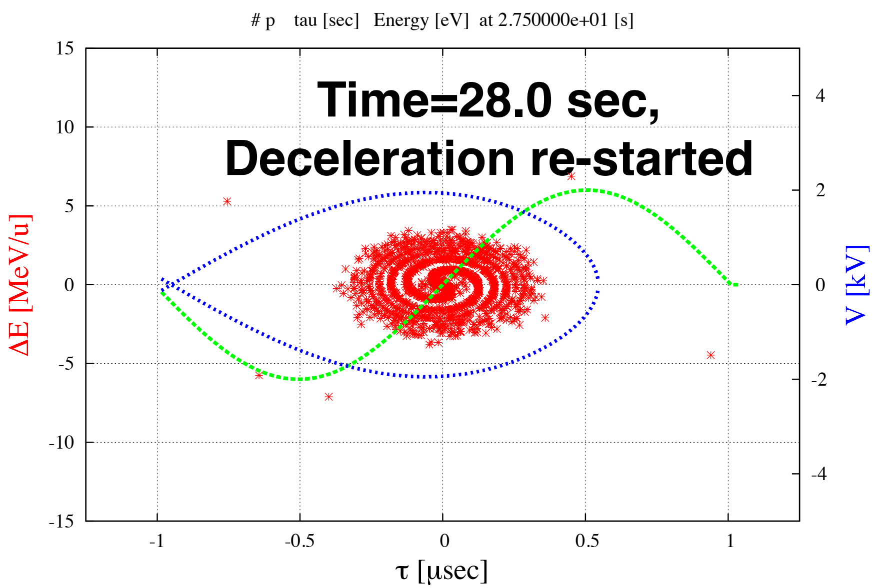
# p tau [sec] Energy [eV] at 0.000000e+00 [s]
Time=0 sec
3 GeV, Accumulation Finished
up to N=1e9
Dp/p=2e-4(rms)
# p tau [sec] Energy [eV] at 1.000077e-01 [s]
Time=0.1 sec
3 GeV, Adiabatic Capture Started
Green: RF Voltage
Blue: Separatrix
# p tau [sec] Energy [eV] at 9.000100e-01 [s]
Time=0.9 sec
Adiabatic Capture Finished
# p tau [sec] Energy [eV] at 1.000018e+00 [s]
Time=1.0 sec
Deceleration Started
ΔE [MeV/u]
V [kV]
τ [μsec]

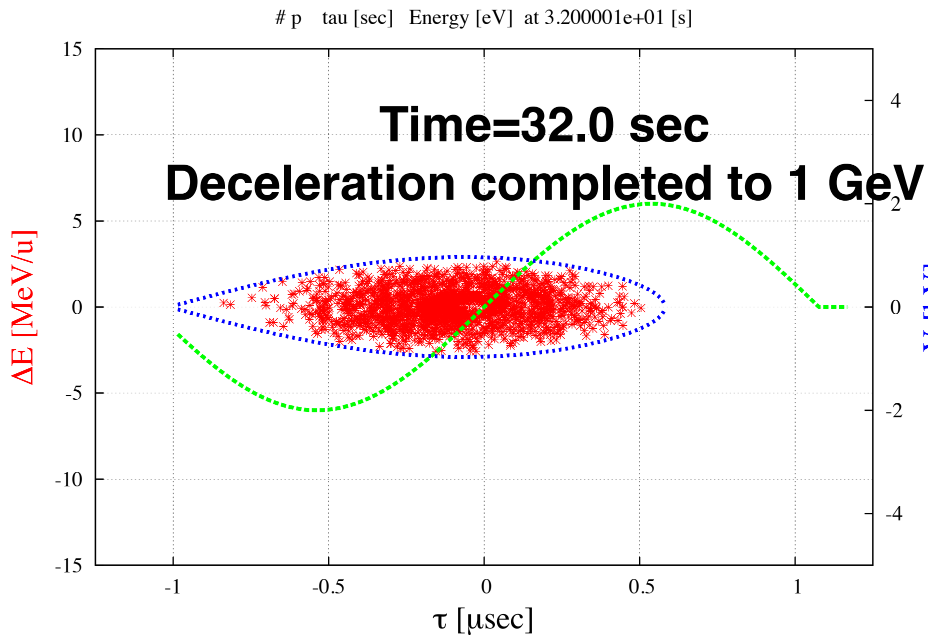


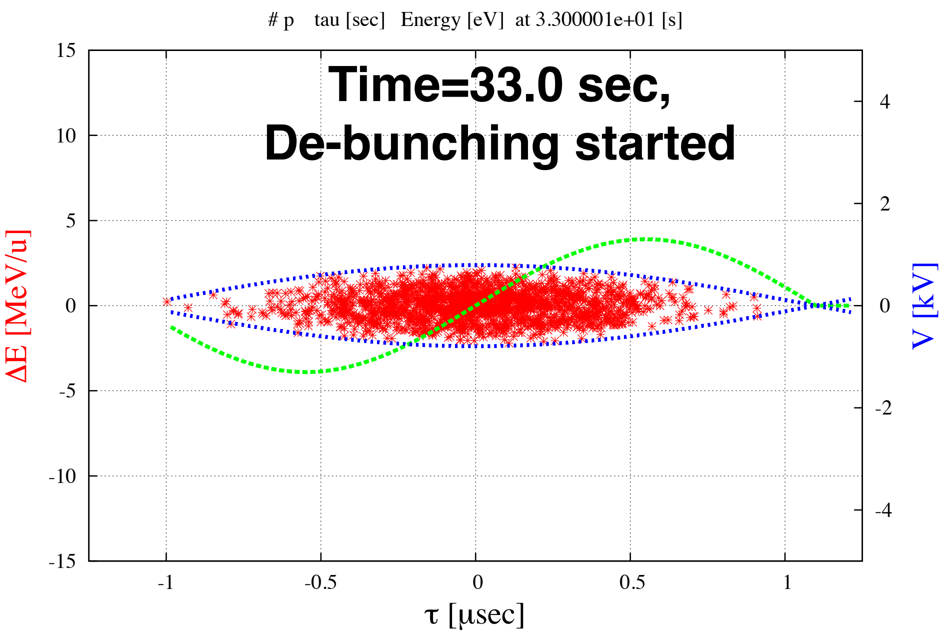
# p tau [sec] Energy [eV] at 5.900019e+00 [s]
Time=5.9 sec, 2 GeV
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 6.000007e+00 [s]
Time=6.0 sec
Adiabatic de-bunching start
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 7.000005e+00 [s] Cooling
Time=7.0 sec, De-bunched
Stochastic Cooling started
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 2.650000e+01 [s]
Time=26.5 sec
Stochastic Cooling finished
ΔE [MeV/u]
V [kV]
τ [μsec]


// p tau [sec] Energy [eV] at 2.660001e+01 [s]
Time=26.6 sec,
Re-bunching started
ΔE [MeV/u]
V [kV]
τ [μsec]

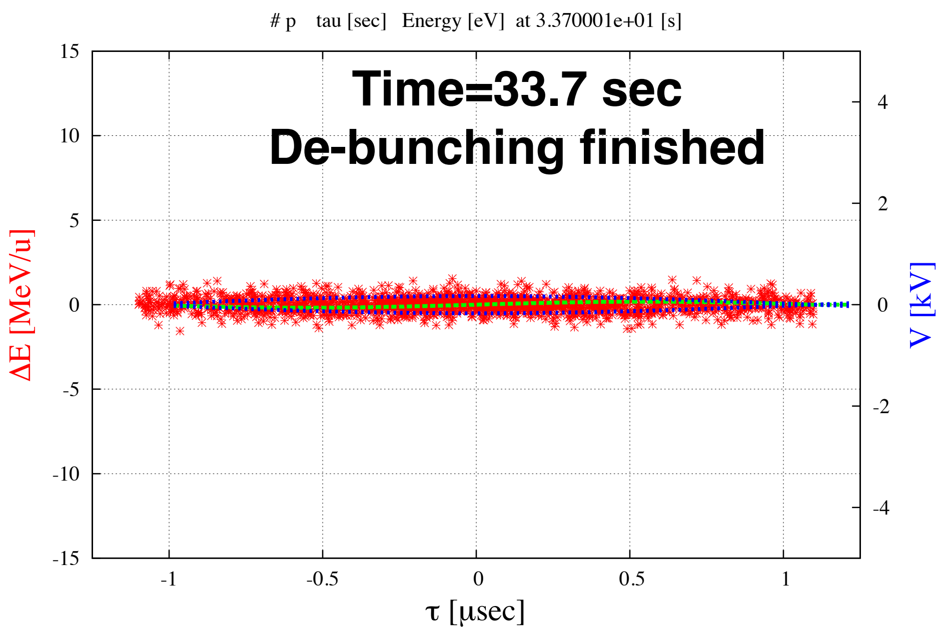

// p tau [sec] Energy [eV] at 2.740001e+01 [s]
Time=27.4 sec
Re-bunching finished
ΔE [MeV/u]
V [kV]
τ [μsec]


// p tau [sec] Energy [eV] at 2.750000e+01 [s]
Time=28.0 sec,
Deceleration re-started
ΔE [MeV/u]
V [kV]
τ [μsec]


// p tau [sec] Energy [eV] at 3.200001e+01 [s]
Time=32.0 sec
Deceleration completed to 1 GeV
ΔE [MeV/u]
V [kV]
τ [μsec]



# p tau [sec] Energy [eV] at 3.300001e+01 [s]
Time=33.0 sec,
De-bunching started
ΔE [MeV/u]
V [kV]
τ [μsec]
15
10
5
0
-5
-10
-15
-1
-0.5
0
0.5
1
4
2
-2
-4



# p tau [sec] Energy [eV] at 3.370001e+01 [s]
Time=33.7 sec
De-bunching finished
ΔE [MeV/u]
V [kV]
τ [μsec]
15
10
5
0
-5
-10
-15
-1
-0.5
0
0.5
1
4
2
-2
-4

Short Bunch Formation at 1 GeV with Electron Cooler

Betatron Tune Qx, Qy: 7.586/7.603
Transition gamma : 6.23
Momentum Slipping Factor : 0.20 (at 1.0 GeV)
Beta Function at Cooler: Horizontal=20 m, Beta Vertical=90 m

Anti-proton Beam Specifications

Kinetic Energy=1GeV, Number of particles=1e9, Transverse emittance (horizontal& vertical)=1.0 Pi mm.mrad (rms). Relative momentum spread Dp p=2.0e-4 (rms) and Gaussian truncated at +/- 3 rms values. The initial time structure of the beam is coasting, uniform random.

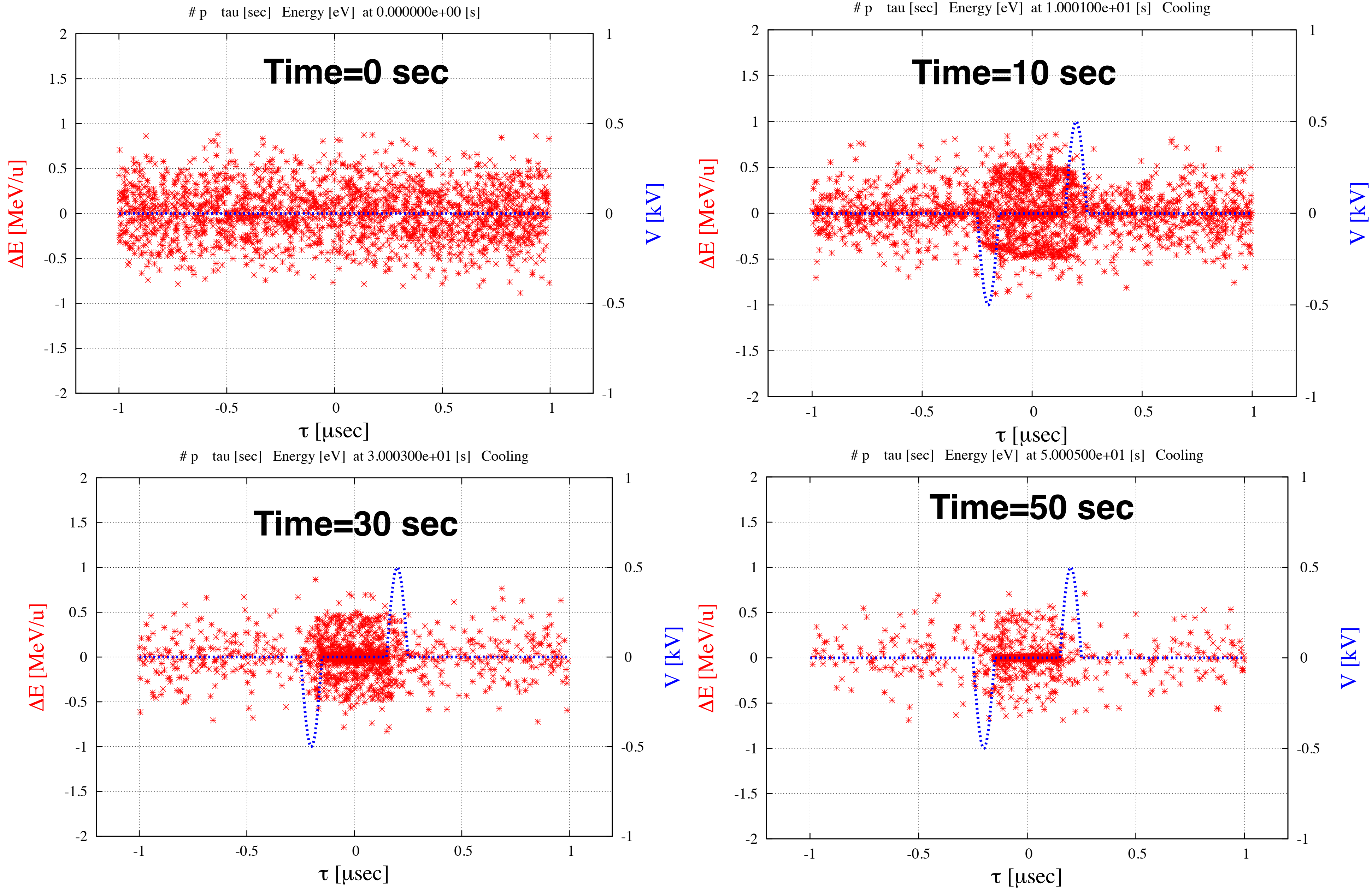
Specification of HESR/COSY electron cooler

Current=1.0 A, Diameter=2 cm, Cooler length=2.7 m, Effective temperature=5e-3 eV, Transverse temperature=0.2 eV, Longitudinal magneti field=0.1 Tesla.

Barrier Bucket System

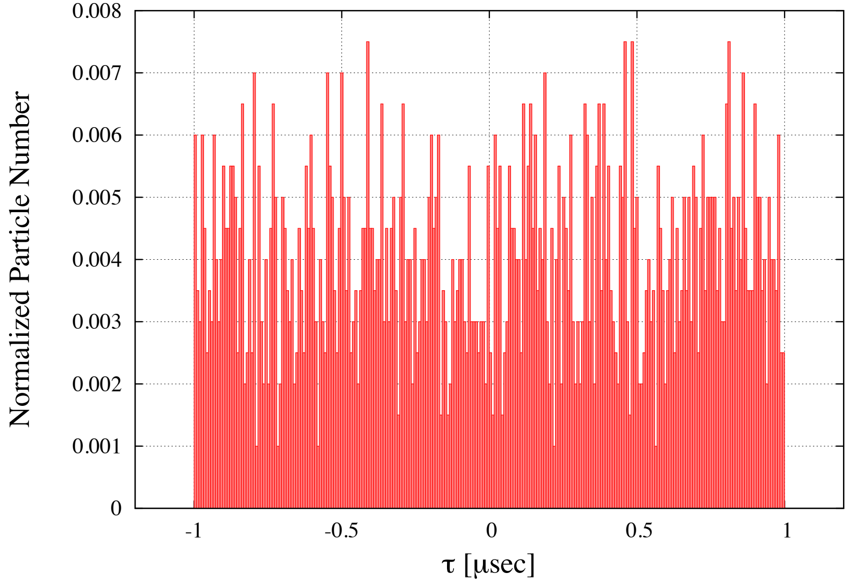
V=500 Volt, Frequency=5 MHz (T0=200 nsec)

Short Bunch Formation of 1 GeV Anti-protons with Electron Cooling

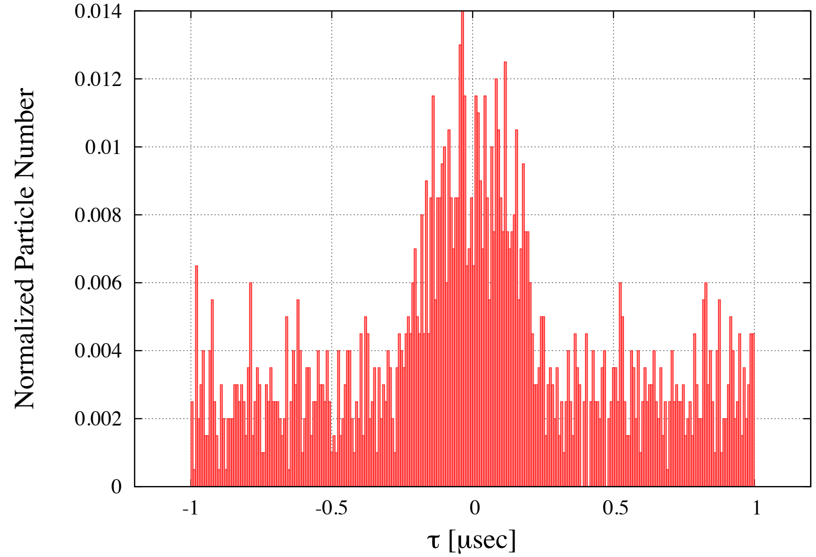


Evolution of Particle Distribution along Ring Orbit

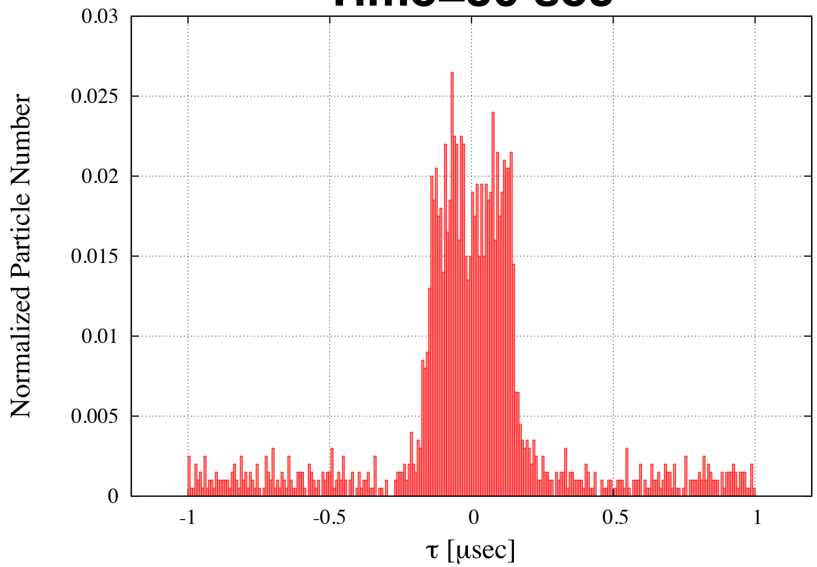
Time=0 sec



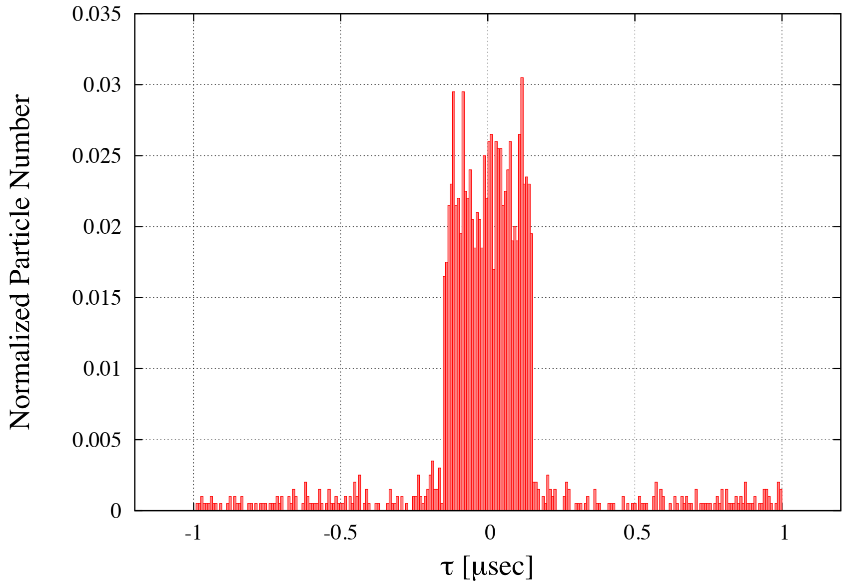
Time=10 sec



Time=30 sec



Time=50 sec



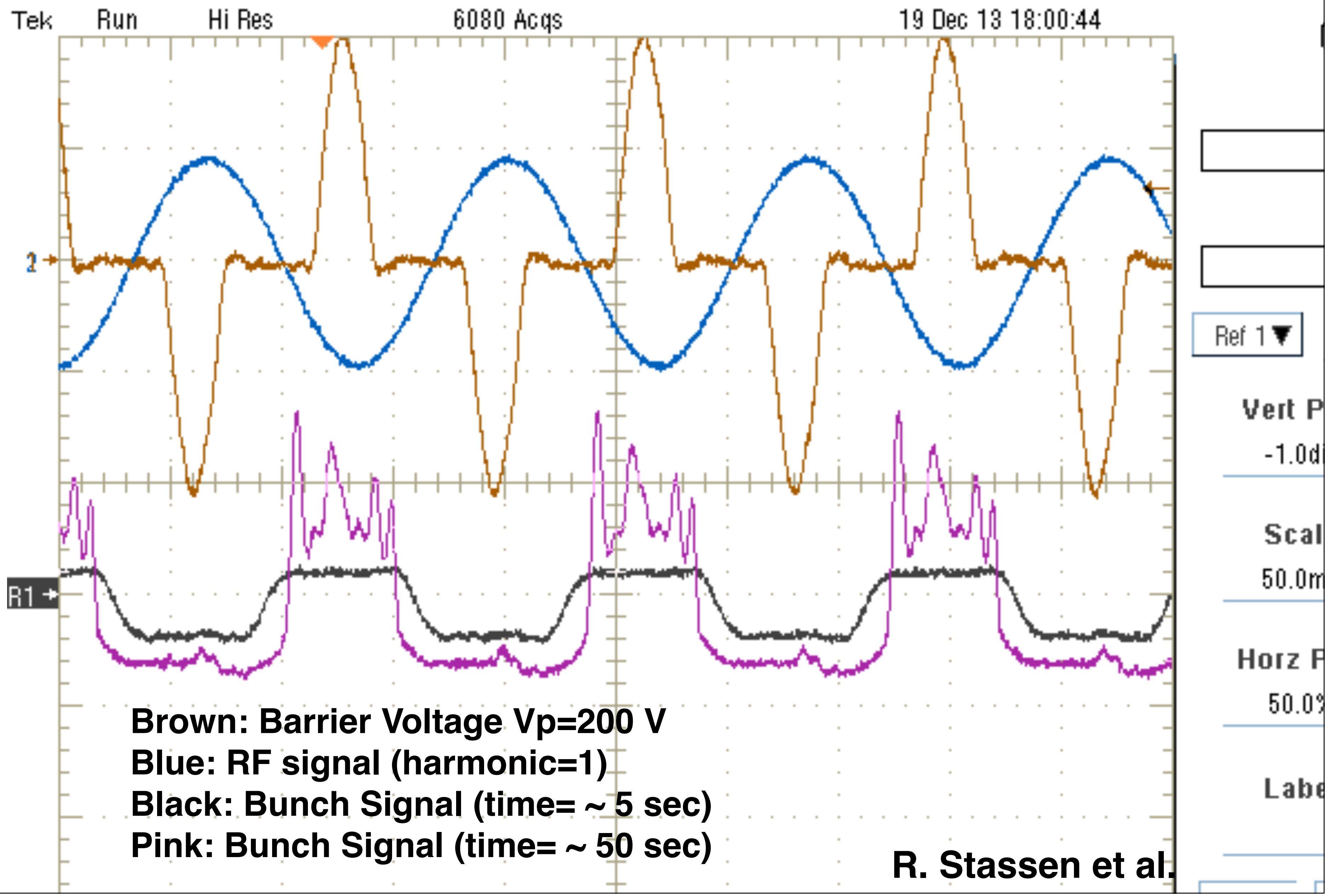
COSY Experiment of Short Bunch Formation
Parameters of Proton Beam and Electron Cooler

Proton kinetic energy: 200 MeV
Beam intensity: 2e9
Initial momentum spread: 3e-4 (rms)
Transverse emittance: 2 Pi mm.mrad

Barrier frequency: 5 MHz
Barrier voltage: 120 Volt

Electron cooler length: 2.7 m
Electron current: 200 mA
Electron diameter: 2 cm
Effective electron temperature: 5e-3 eV
Transverse electron temperature: 0.2 eV
Solenoid magnetic field strength : 0.1 Tesla

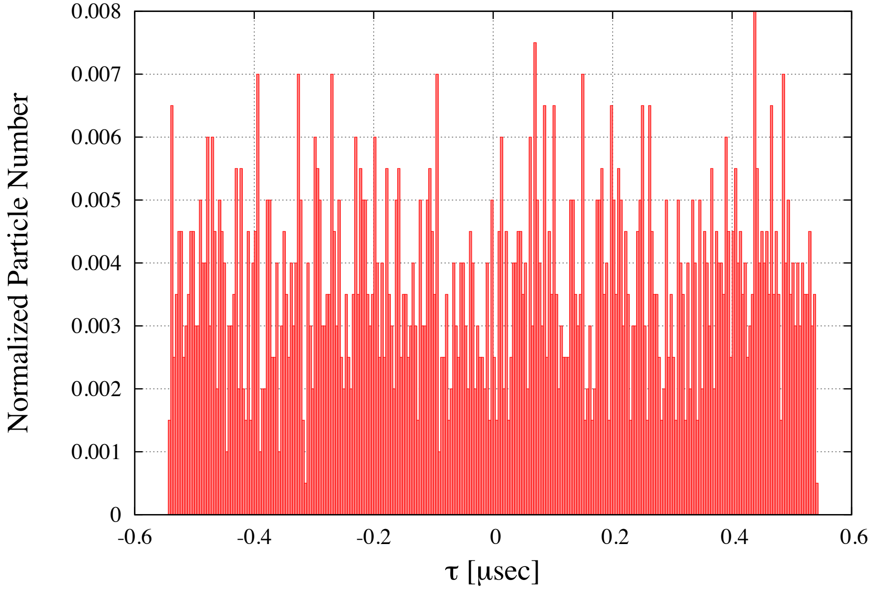
Short Bunch Formation Experiment with Electron Cooler at COSY



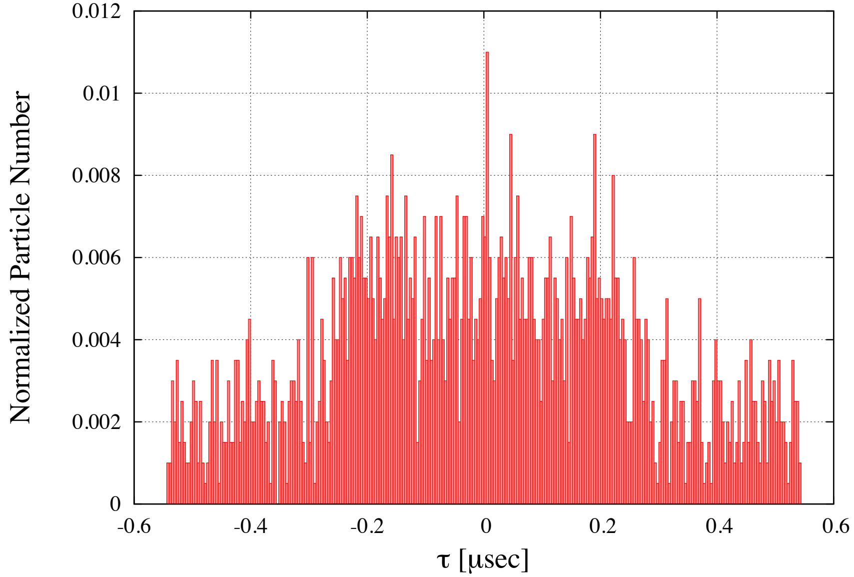
Brown: Barrier Voltage Vp=200 V
Blue: RF signal (harmonic=1)
Black: Bunch Signal (time= ~ 5 sec)
Pink: Bunch Signal (time= ~ 50 sec)

R. Stassen et al.

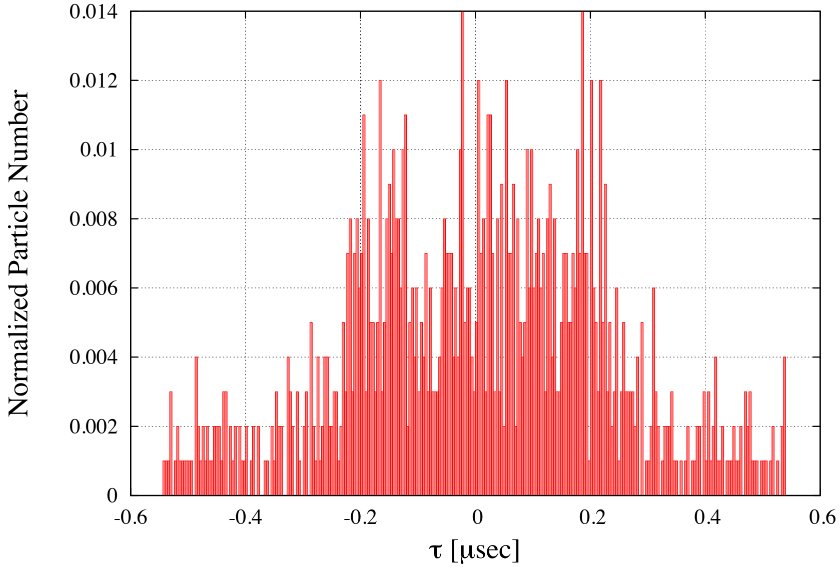
time=0 sec



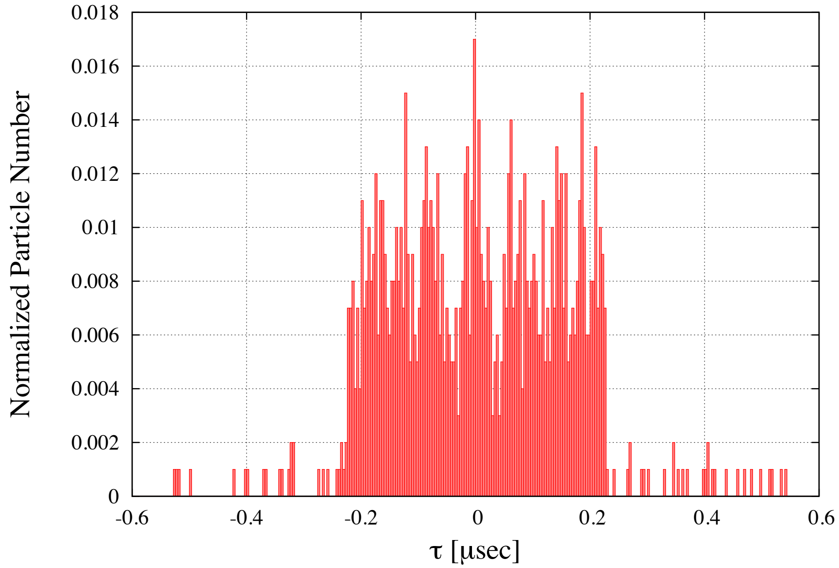
time=5 sec



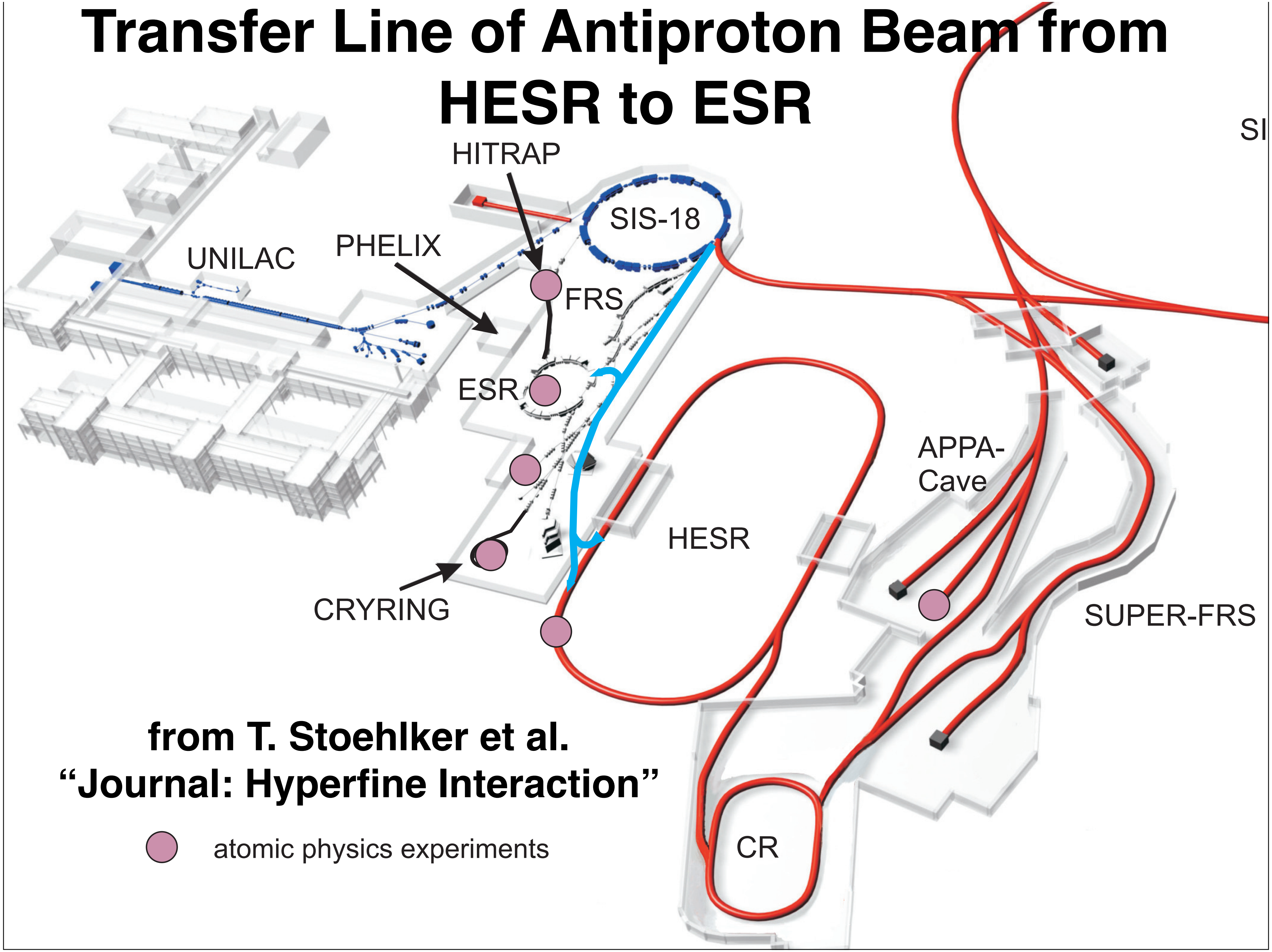
time=10 sec



time=40 sec



Transfer Line of Antiproton Beam from HESR to ESR

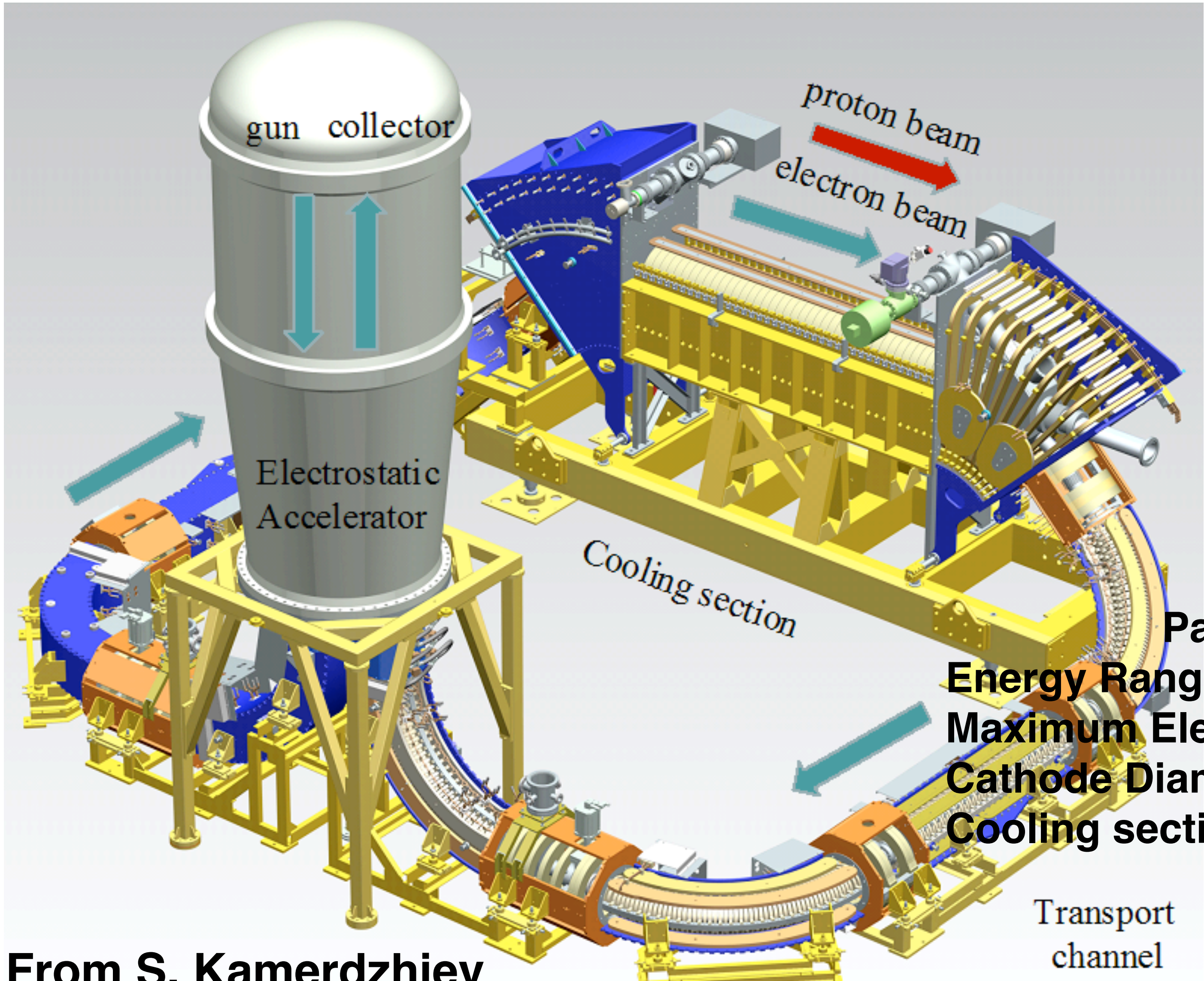


from T. Stoehlker et al.
"Journal: Hyperfine Interaction"

atomic physics experiments

Appendix
Electron Cooling at COSY & HESR

COSY 2 MeV Electron Cooler
under commissioning at COSY



Parameters

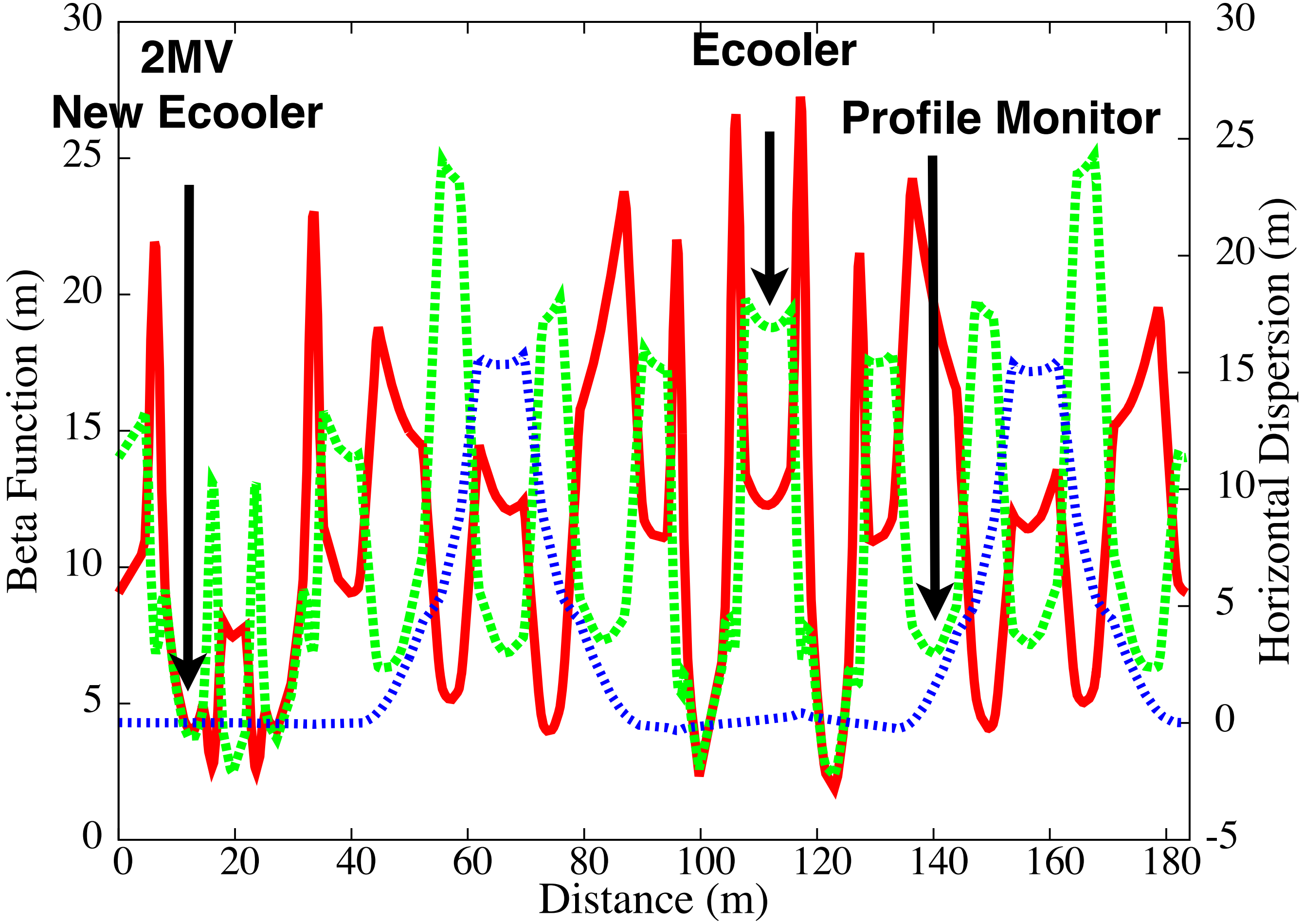
Energy Range: 0.025 ... 2 MeV
Maximum Electron Current: 1-3 A
Cathode Diameter: 30 mm
Cooling section length: 2.69 m

From S. Kamerdzhiev

54

COSY Twiss Function

Red: Horizontal Beta
Green: Vertical Beta
Blue: Horizontal Dispersion



Parameters of 2 MeV Electron Cooling at COSY

1. Ion: Proton, Energy=200 MeV & 2 GeV, Intensity=5e9
   Betatron tune values: Qx=Qy=3.61
   Initial Dp/p=3.0e-4 (0.2 GeV) /1e-4 (2 GeV), Transverse Emittance=5.0 Pi (0.2GeV) / 0.5Pi (2 GeV) mm.mrad

2. Electron cooler, Ie= 0.5A (0.2 GeV) / 2A (2 GeV)
   Effective cooler length= 2.7 m
   Solenoid field= 0.1 Tesla
   Diameter of electron beam= 2.0 cm
   Effective electron temperature=1e-2
   Transverse electron temperature= 0.2 eV

3. COSY lattice
   Transition gamma=2.27
   Beta functions at Cooler: BetaH=6.0 m, BetaV=6.0 m, Dh=0.0 m
   Beta functions at Profile monitor: BetaH=18.9 m, BetaV=7.5 m, Dh=3.28 m

In the present analysis and simulation, following empirical formulae by Vasily are exclusively used.

Cooling Force Formula (PRF)

$$\vec{F} = -\frac{4 r_e^2 c^4 n_e^* m_e Z^2}{(V_\perp^2 + V_\parallel^2 + V_{eff}^2)^{3/2}} \vec{V} \cdot \ln\left(1 + \frac{\rho_{\max}}{\rho_{\min} + \rho_L}\right)$$

Coupled Cooling Equation (LRF)

$$\frac{d\varepsilon}{dt} = -2G\varepsilon$$

$$\frac{d}{dt}(\Delta E) = -G\,\Delta E$$

$$G = \frac{4 r_e r_n c n_e \eta_c}{\gamma^2 \left[\beta^2 \gamma^2 \frac{\varepsilon}{\beta_{cool}} + \left(\frac{\Delta E}{\beta E}\right)^2 + \frac{T_{eff}}{m_e c^2}\right]^{3/2}} \frac{Z^2}{A} \ln \xi$$

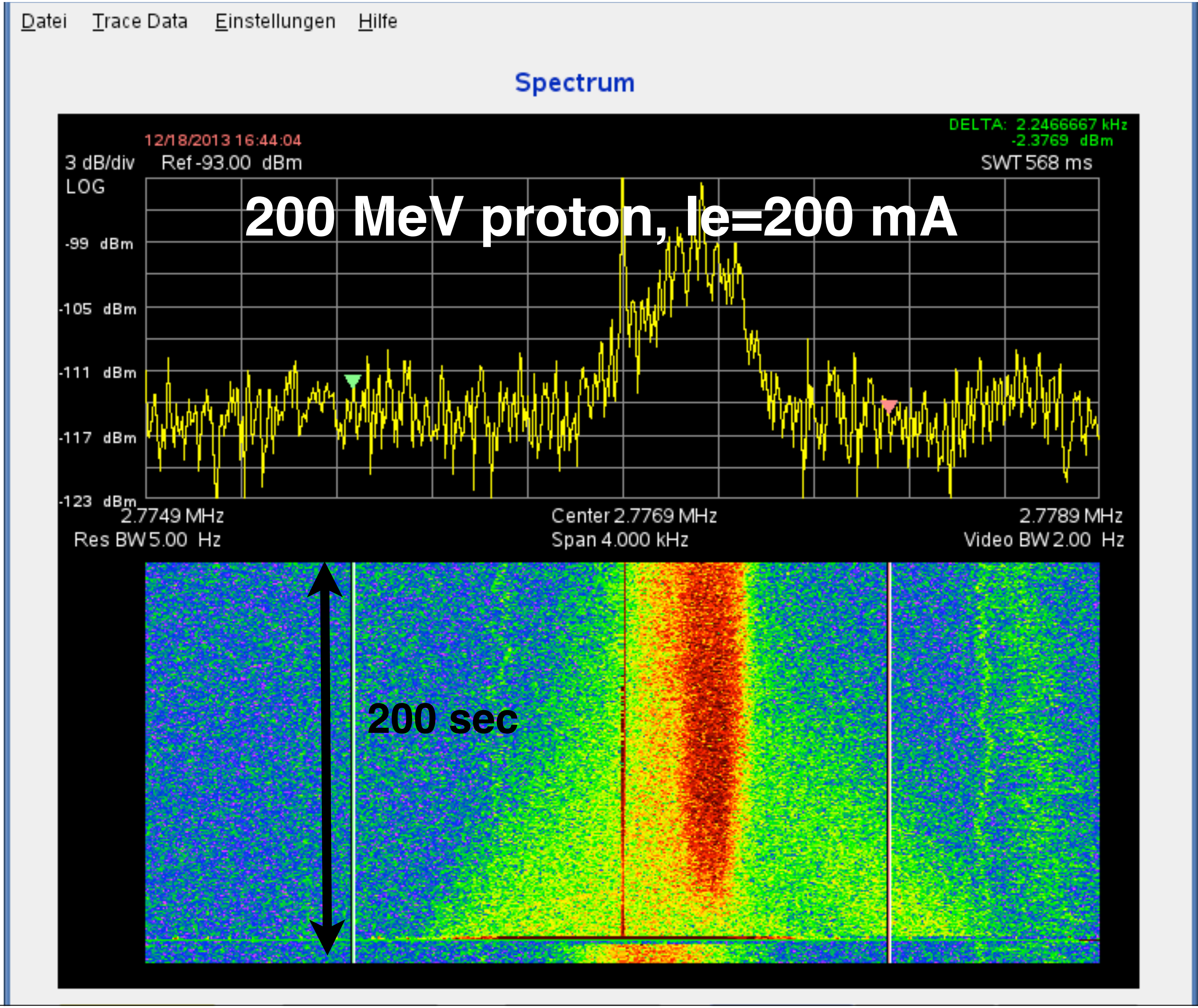
Coulomb Log

$$\ln \xi = \ln\left(1 + \frac{\rho_{\max}}{\rho_{\min} + \rho_L}\right)$$

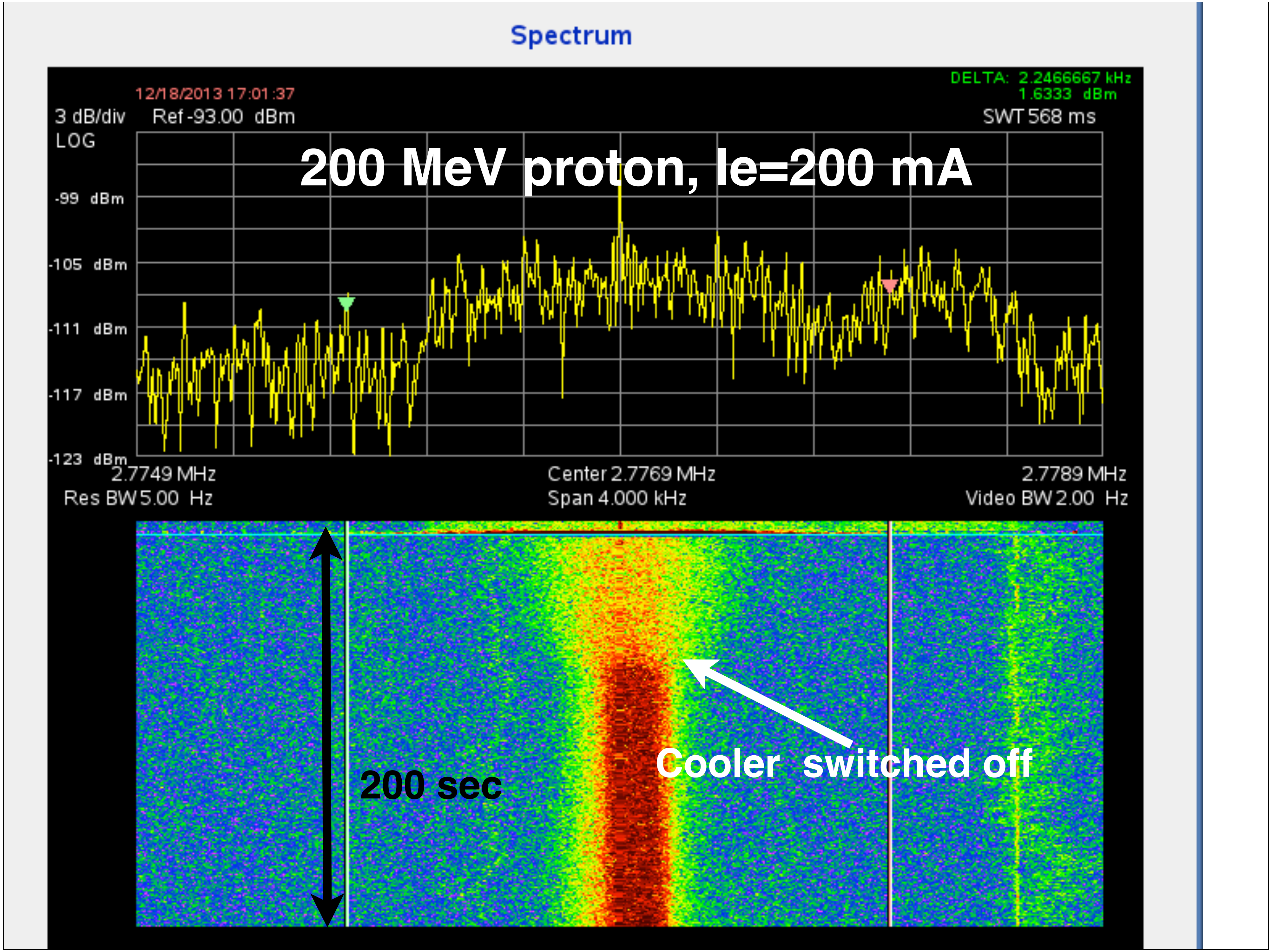
$$\rho_{\max} = \sqrt{\gamma^2 \varepsilon / \beta_{cool} + (\Delta p / p)^2} \cdot CoolerLength$$

$$\rho_{\min} = \frac{r_e}{\beta^2 \gamma^2 \frac{\varepsilon}{\beta_{cool}} + \frac{T_{eff}}{m_e c^2}}$$

$$\rho_L = \frac{m_e}{eB} \sqrt{\frac{2 T_\perp}{m_e}}$$

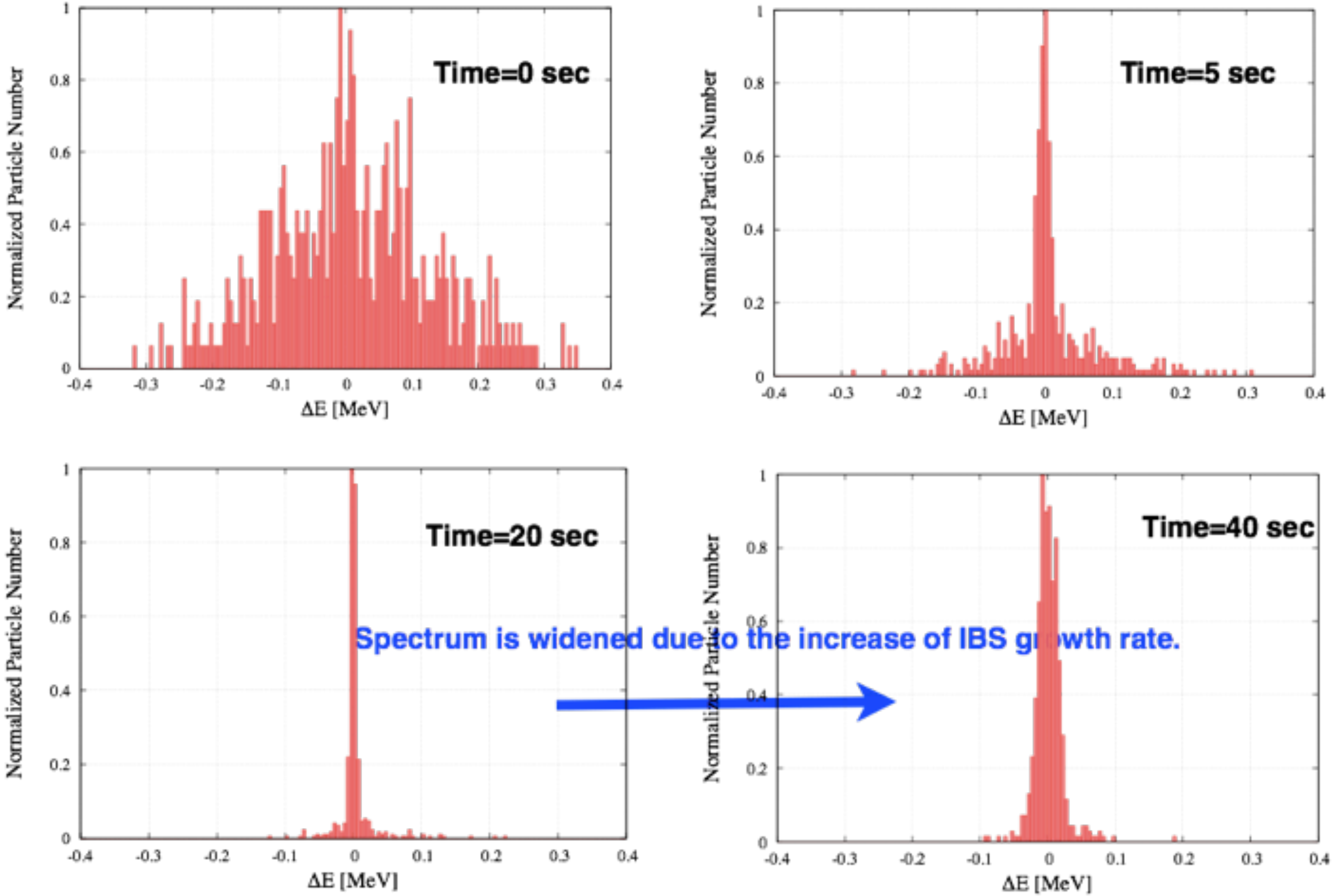


Datei
Trace Data
Einstellungen
Hilfe
Spectrum
12/18/2013 16:44:04
DELTA: 2.2466667 kHz
-2.3769 dBm
3 dB/div
Ref -93.00 dBm
SWT 568 ms
LOG
200 MeV proton, Ie=200 mA
-99 dBm
-105 dBm
-111 dBm
-117 dBm
-123 dBm
2.7749 MHz
Center 2.7769 MHz
2.7789 MHz
Res BW 5.00 Hz
Span 4.000 kHz
Video BW 2.00 Hz
200 sec

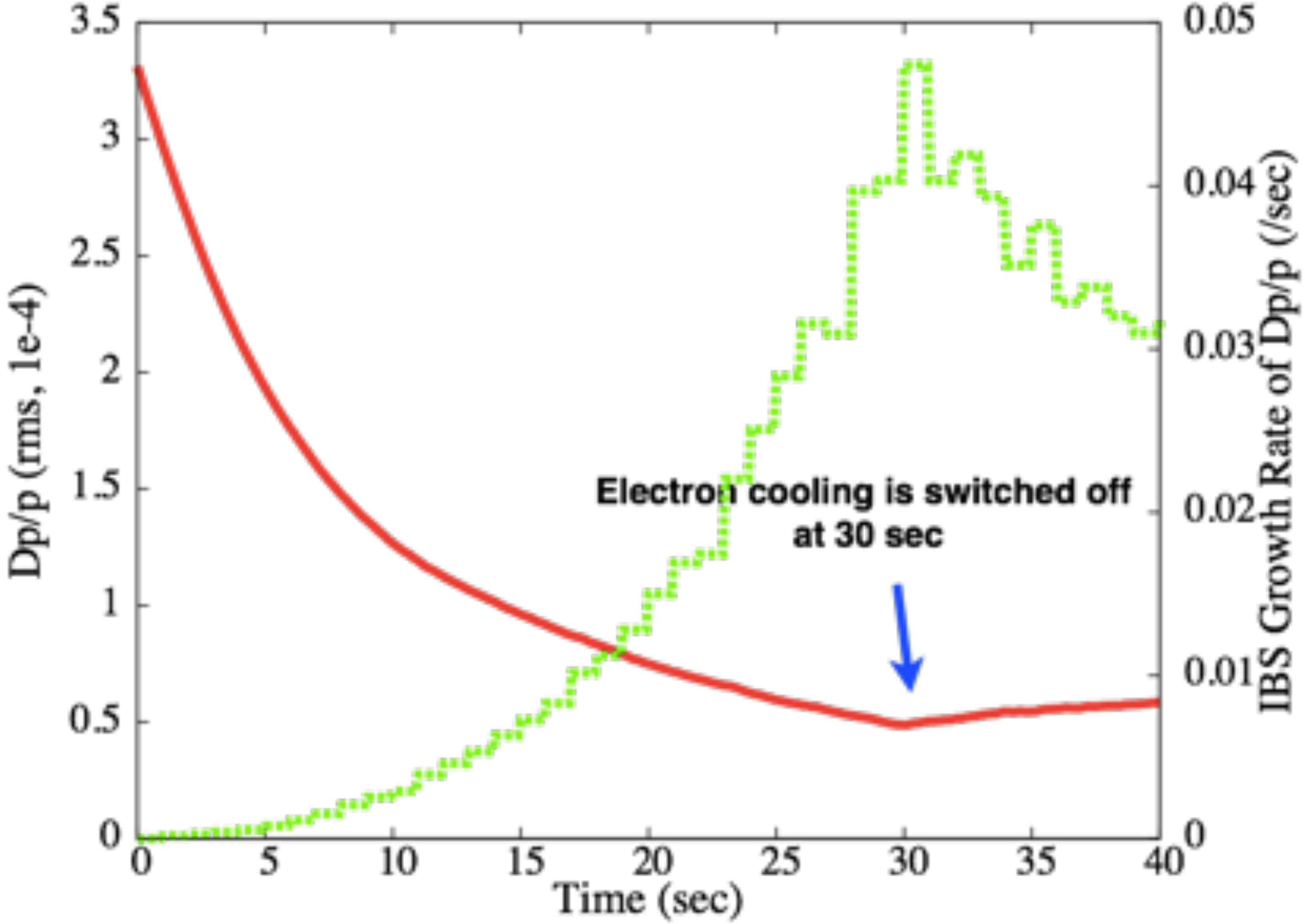


Spectrum
12/18/2013 17:01:37
DELTA: 2.2466667 kHz
1.6333 dBm
3 dB/div
Ref -93.00 dBm
SWT 568 ms
LOG
200 MeV proton, Ie=200 mA
-99 dBm
-105 dBm
-111 dBm
-117 dBm
-123 dBm
2.7749 MHz
Center 2.7769 MHz
2.7789 MHz
Res BW 5.00 Hz
Span 4.000 kHz
Video BW 2.00 Hz
200 sec
Cooler switched off

Energy Spectra during Electron Cooling (Simulation)



Evolution of Dp/p and IBS Growth Rate during Electron Cooling at COSY 200 MeV Proton

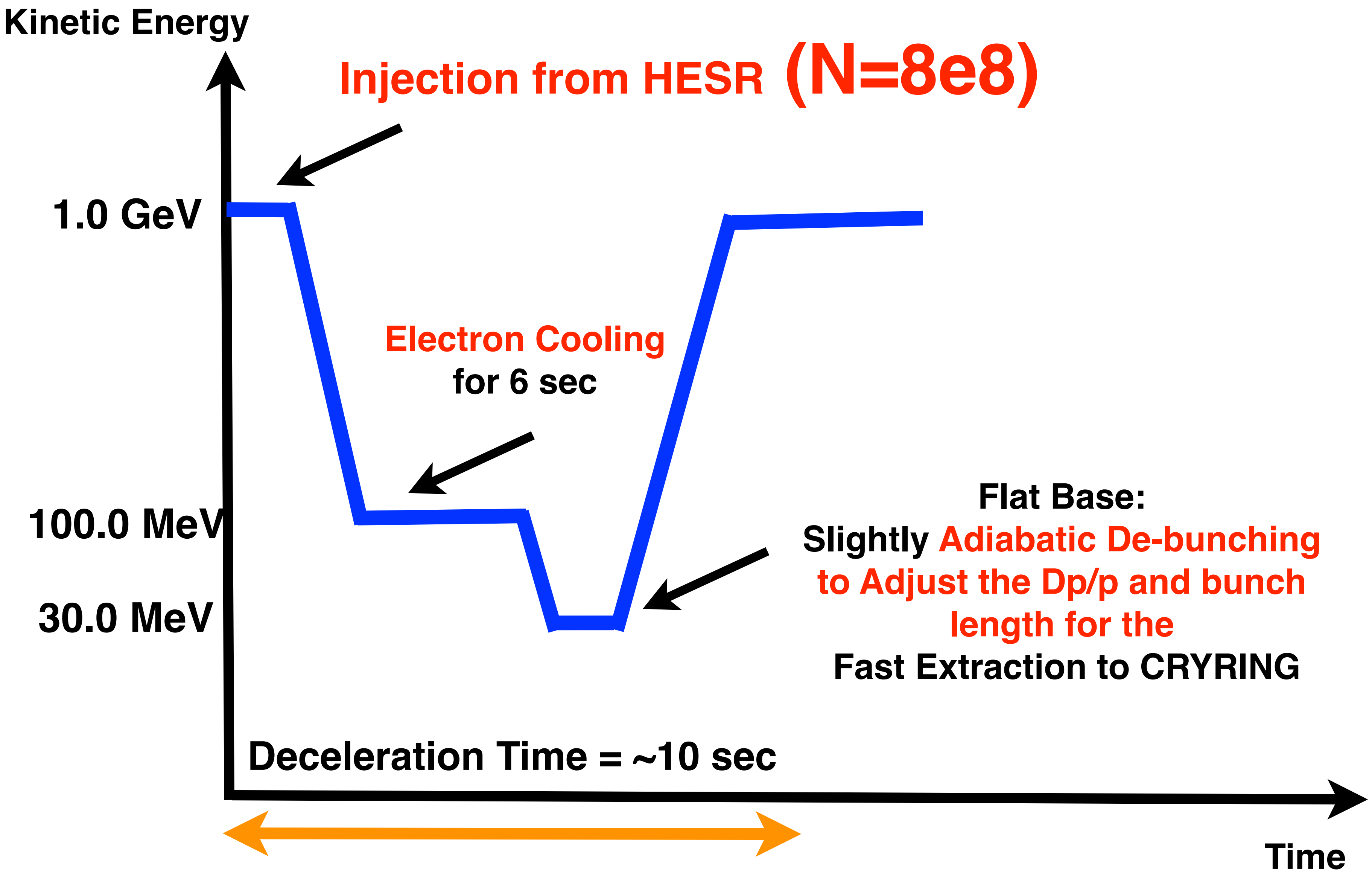


Part 4
Antiproton Deceleration in ESR

Antiproton Beam Parameters from HESR to ESR

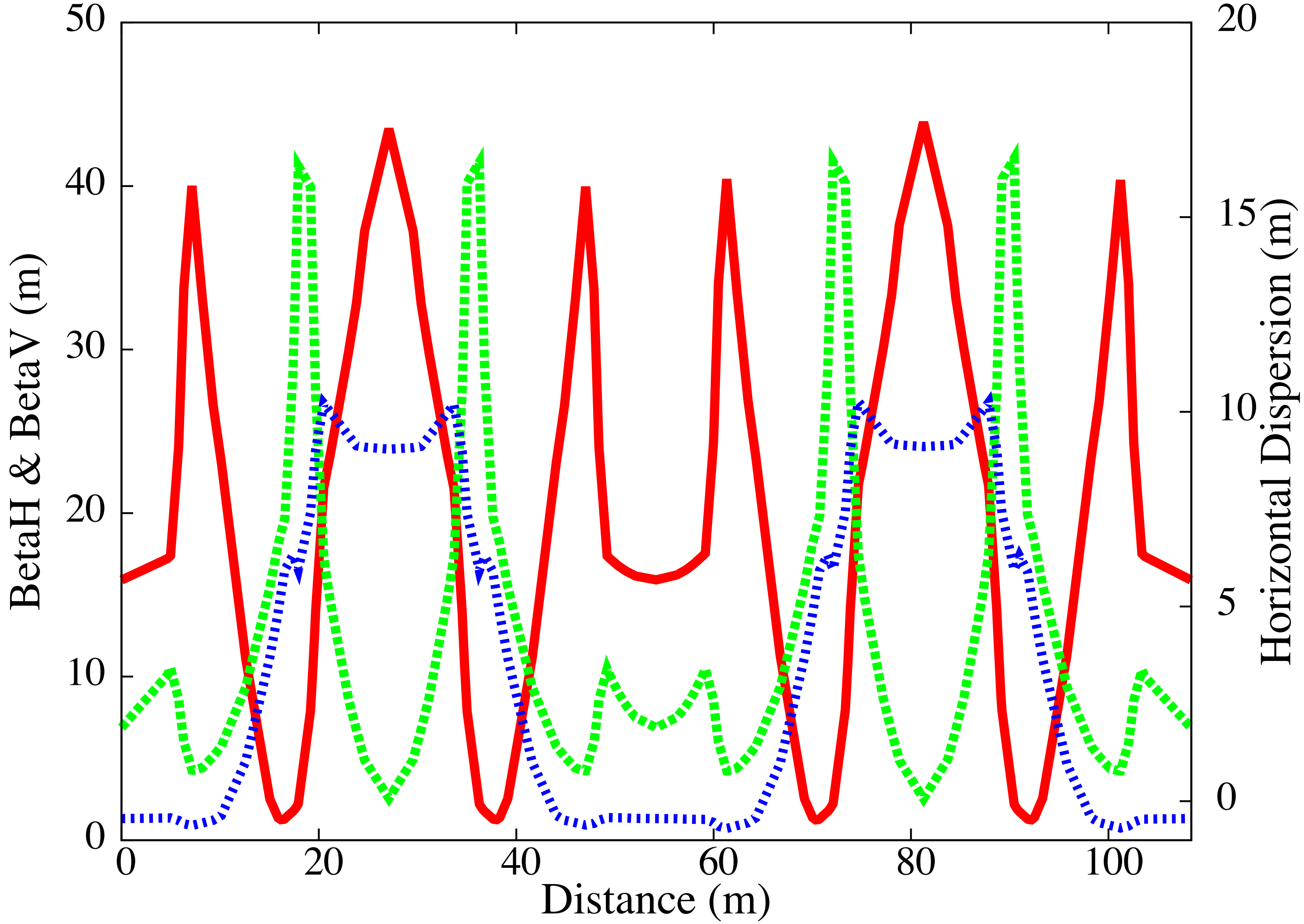
Energy:1 GeV
Number of Particles: ~ 8e8/180sec
Bunch length: 300 nsec, Uniform distribution
Dp/p (rms): 0.8e-4
Transverse Emittance (rms): 0.5 Pi mm.mrad

Operation Scheme of ESR for CRYRING



Lattice of ESR GammaTransition=2.337

Transition Energy=1.254 GeV



Red: Beta H
Green: Beta V
Blue: Horizontal Dispersion

Momentum Acceptance of ESR

Max Horizontal Beta function, BetaH: 42 m
Max Horizontal Dispersion, Dh:10 m
Useful half aperture, r: 80 mm

Max horizontal emittance is 1.9 pi mm.mrad (rms) at 100 MeV.
(from HESR injected 1 GeV beam emittance=0.5 pi mm.mrad
which increases due to adiabatic anti-damping)

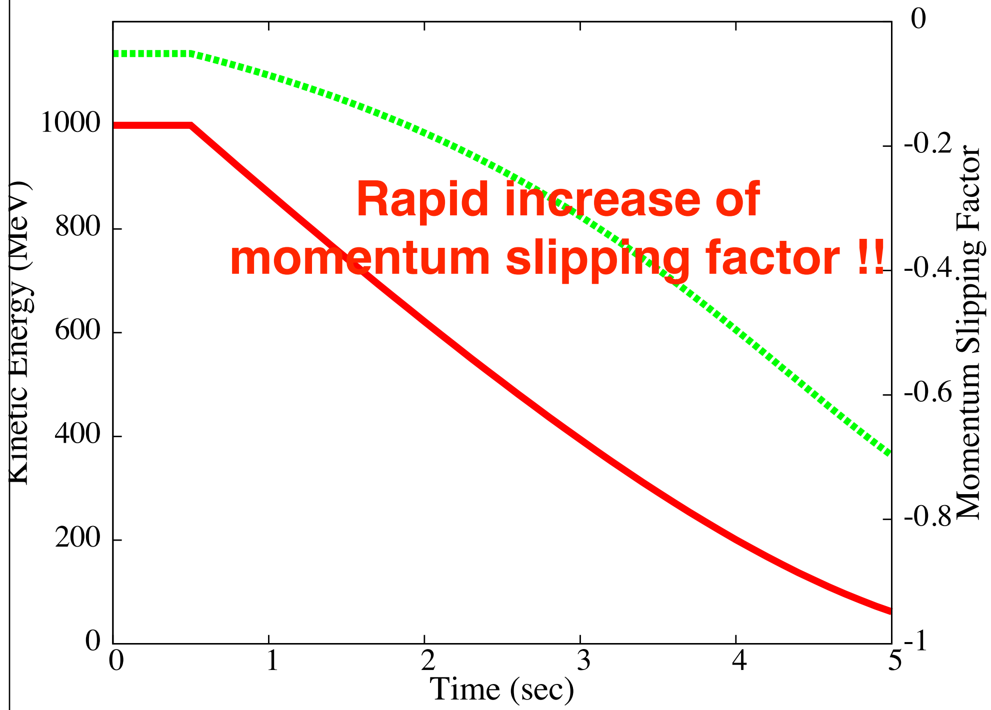
Thus Dp/p=(r-betatron amplitude)/Dh=5.8e-3
where Betatron amplitude =sqrt(6*1.9e-6*BetaH)=22 mm

Momentum acceptance = +/- 5.8e-3 at 100 MeV

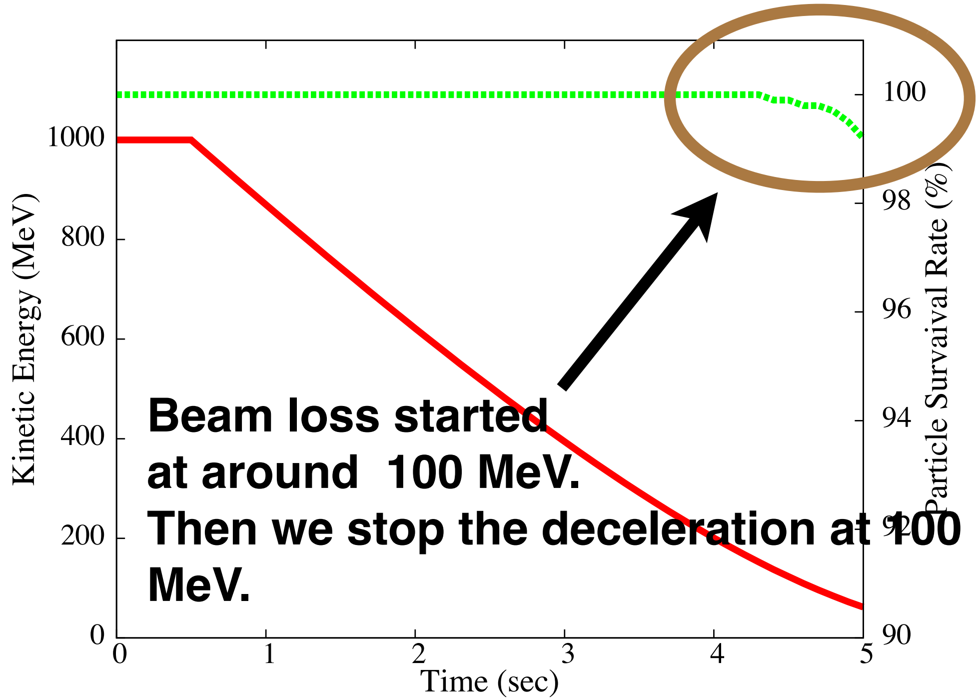
Deceleration from 1 GeV to 100 MeV

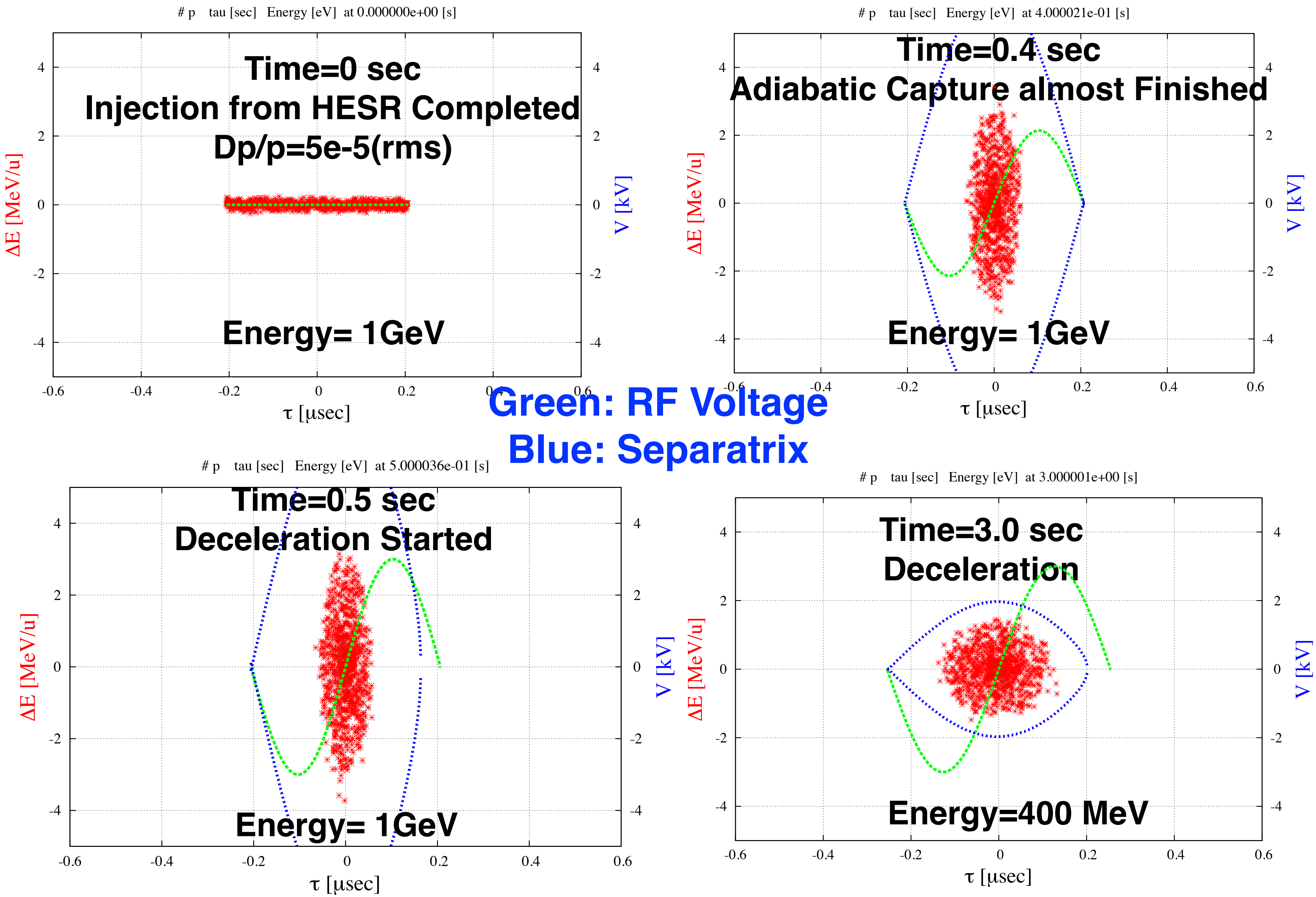
dB/dt= -0.1 Tesla/sec
RF Voltage= 3 kV

Red: Kinetic energy
Green: Momentum slipping factor
Flat top: Adiabatic bunching

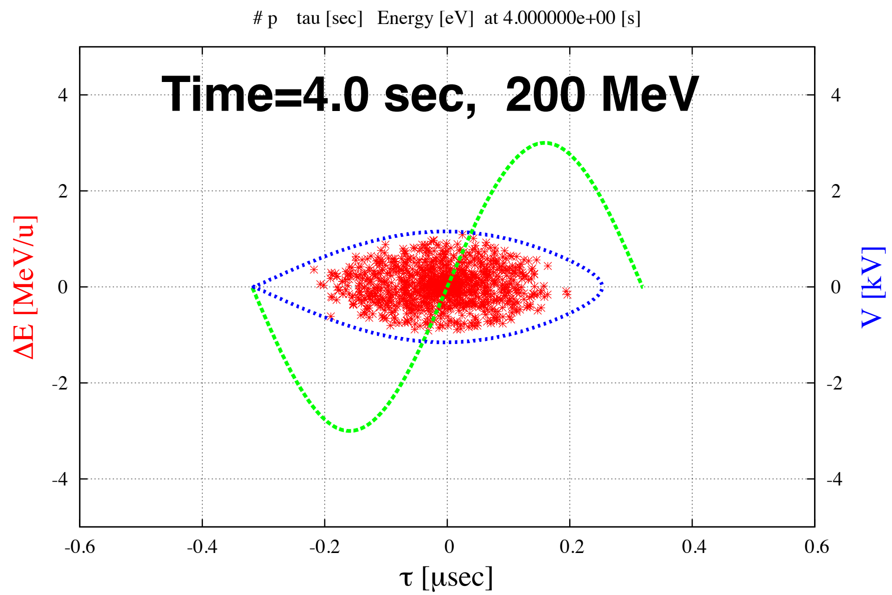


Energy and Particle Survival Rate

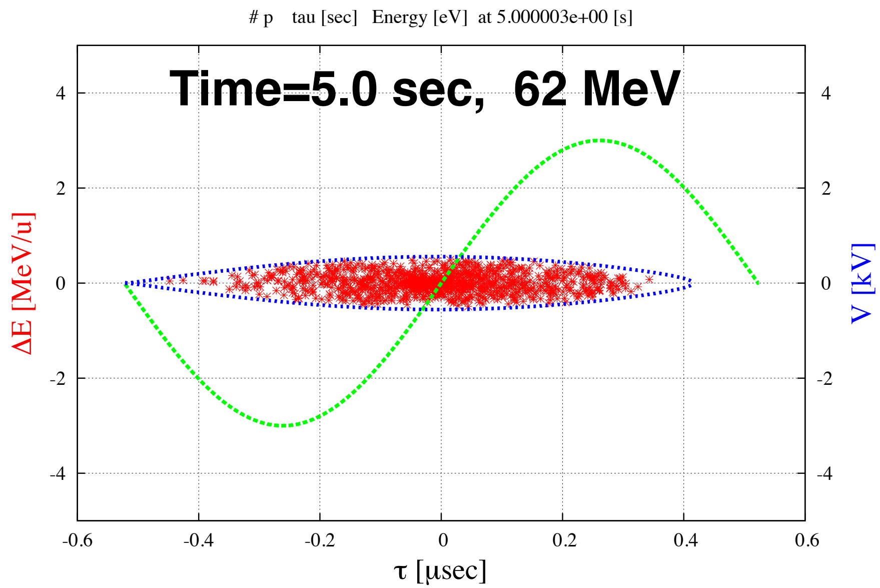




# p tau [sec] Energy [eV] at 0.000000e+00 [s]
Time=0 sec
Injection from HESR Completed
Dp/p=5e-5(rms)
Energy= 1GeV
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 4.000021e-01 [s]
Time=0.4 sec
Adiabatic Capture almost Finished
Energy= 1GeV
Green: RF Voltage
Blue: Separatrix
# p tau [sec] Energy [eV] at 5.000036e-01 [s]
Time=0.5 sec
Deceleration Started
Energy= 1GeV
# p tau [sec] Energy [eV] at 3.000001e+00 [s]
Time=3.0 sec
Deceleration
Energy=400 MeV



Green: RF Voltage
Blue: Separatrix



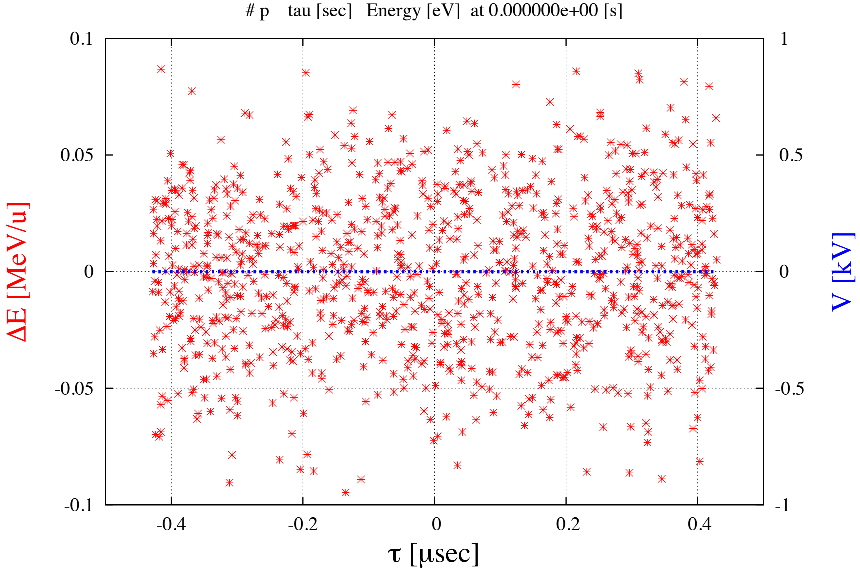
Separatrix becomes too small and beam loss occurred at this 62 MeV energy. Then the deceleration is stopped at 100 MeV.

Electron Cooling at 100 MeV

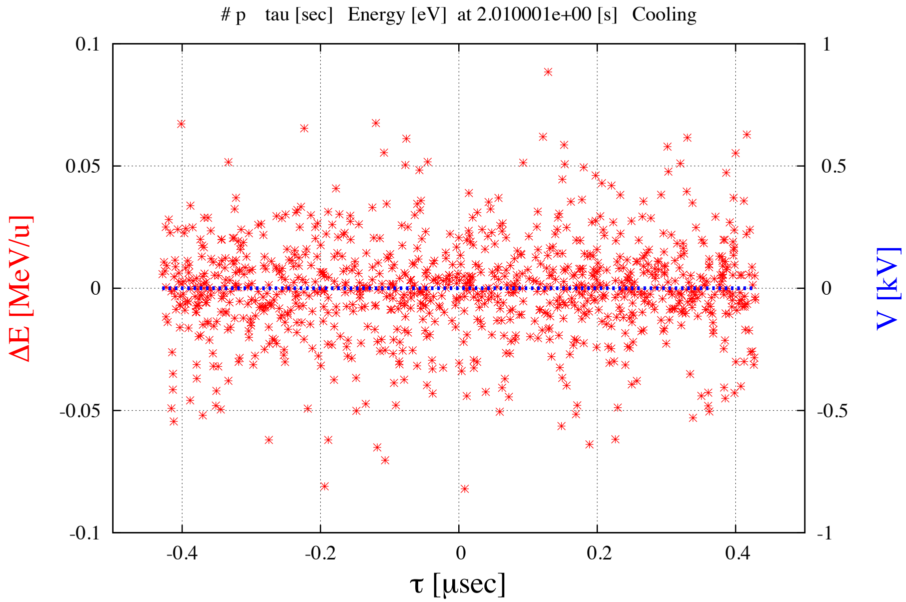
Antiproton Energy: 100 MeV
Electron Energy: 53.5 KeV
Electron Current: 0.5 A
Diameter of Electron Beam: 5 cm
Cooler Length: 1.8 m
Solenoid Magnetic Field: 0.1 Tesla
Effective Electron Temperature: 5e-3 eV
Transverse Electron Temperature: 0.2 eV

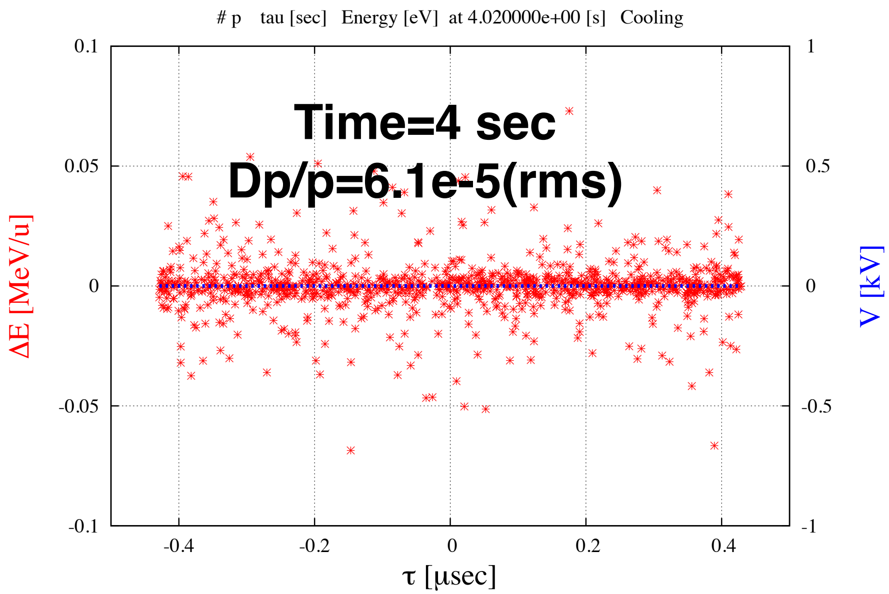
Number of Particles: 8e8
Initial Dp/p (rms): 1.8e-4 (this value is derived from the value of longitudinal emittance and the beam is coasting condition)
Initial Transverse Emittance (rms): 1.94 Pi mm.mrad

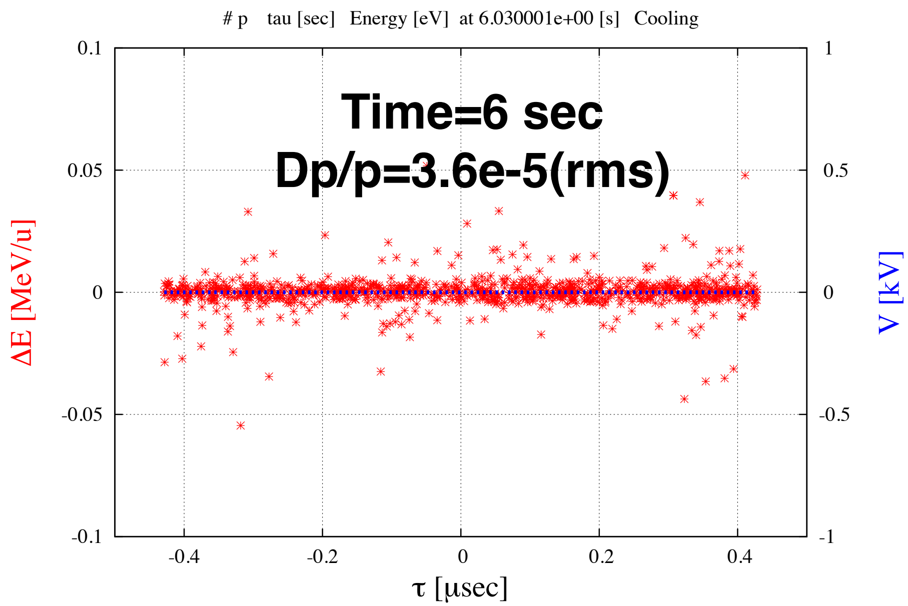
Time=0 sec
Dp/p=1.8e-4(rms)



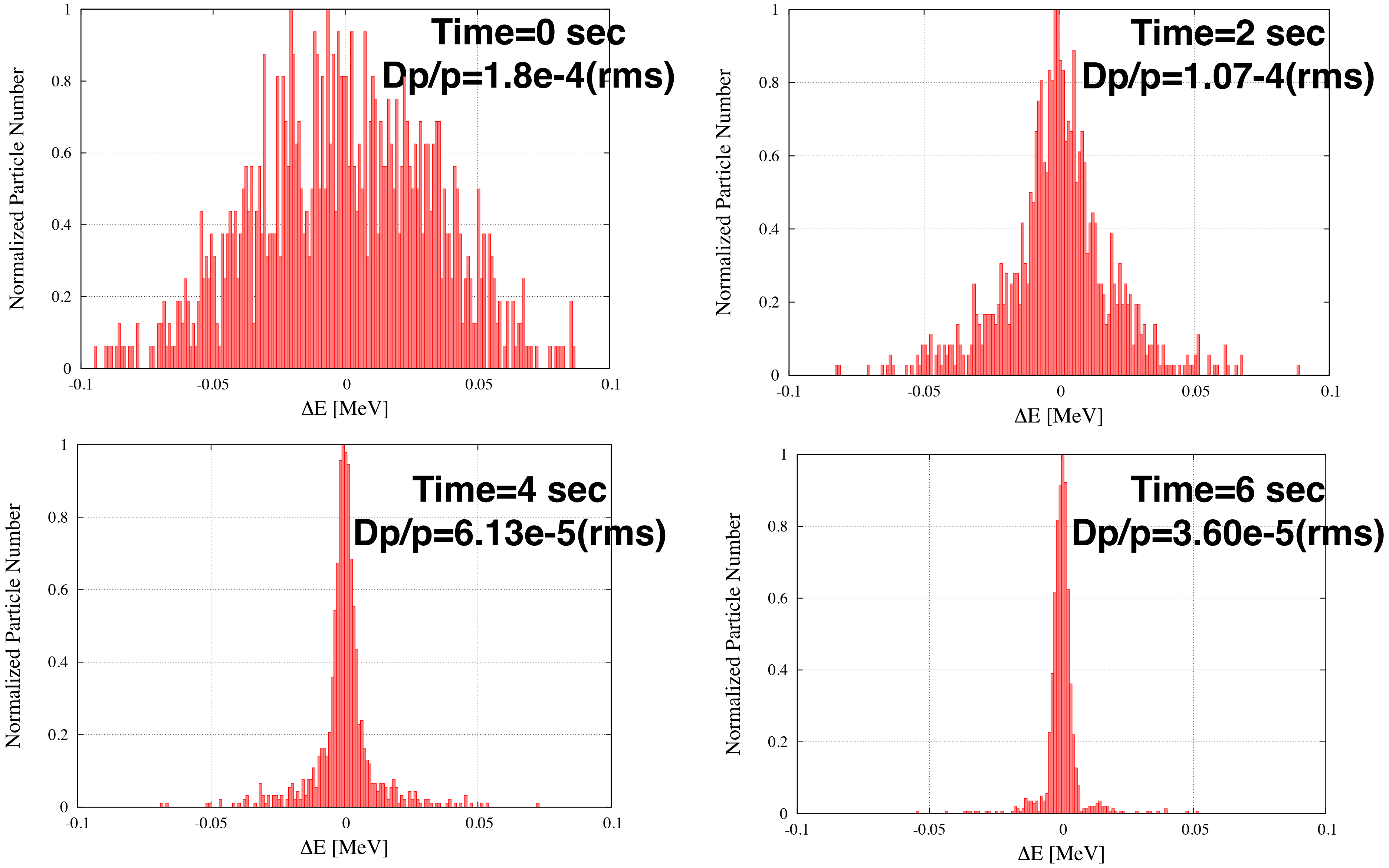
Time=2 sec
Dp/p=1.07e-4(rms)



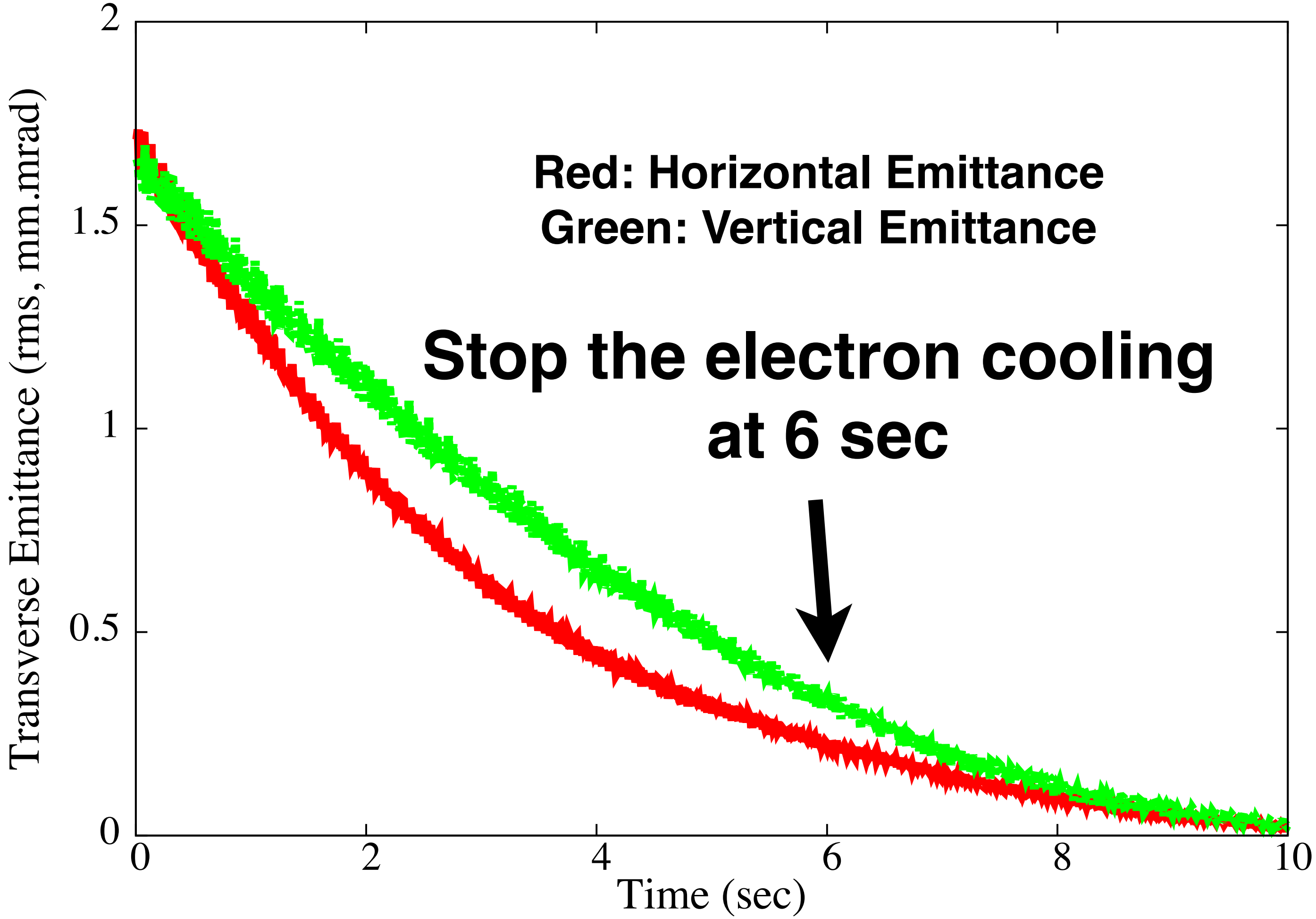




Spectrum of Electron Cooling at 100 MeV



Evolution of Transverse Emittance

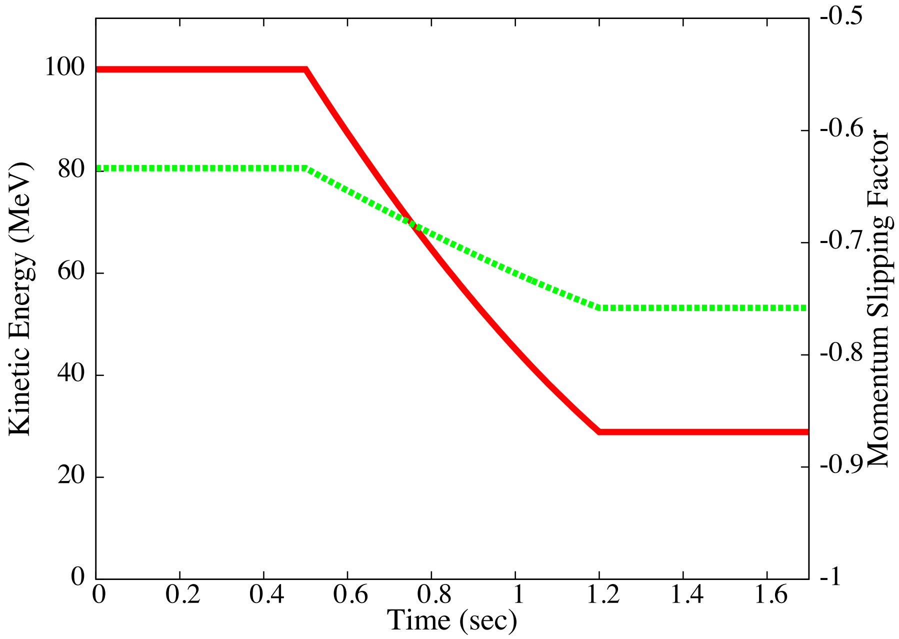


Deceleration from 100 MeV to 30 MeV after Electron Cooling

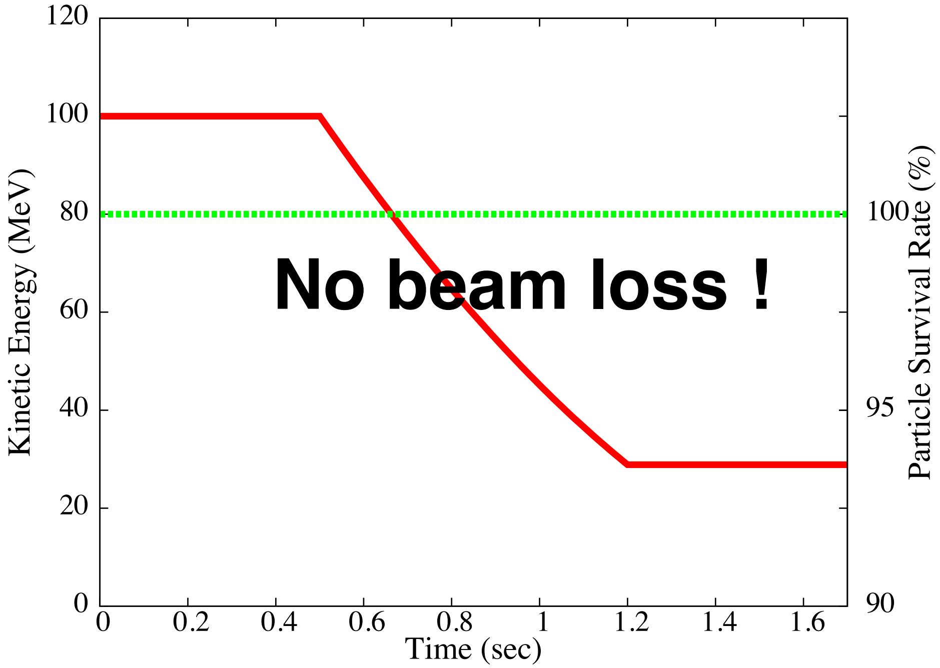
dB/dt= -0.1 Tesla/sec
RF Voltage= 3 kV

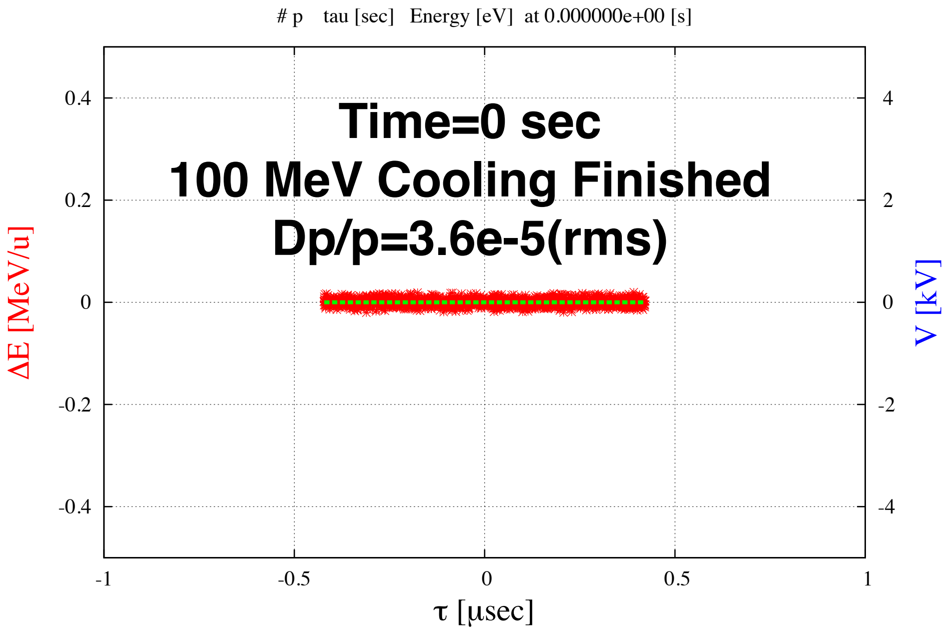
Red: Kinetic energy
Green: Momentum slipping factor

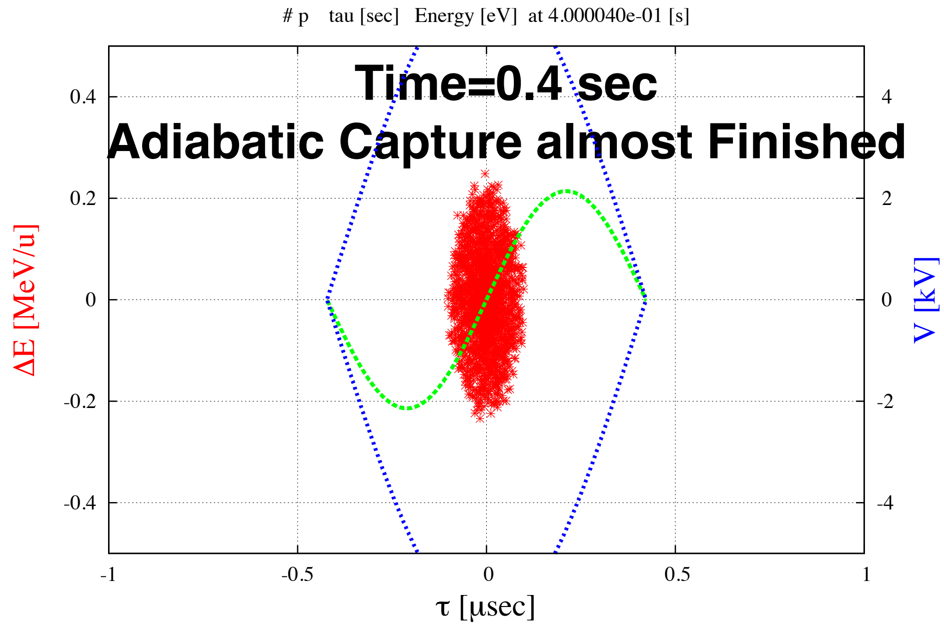
Flat top: Adiabatic bunching

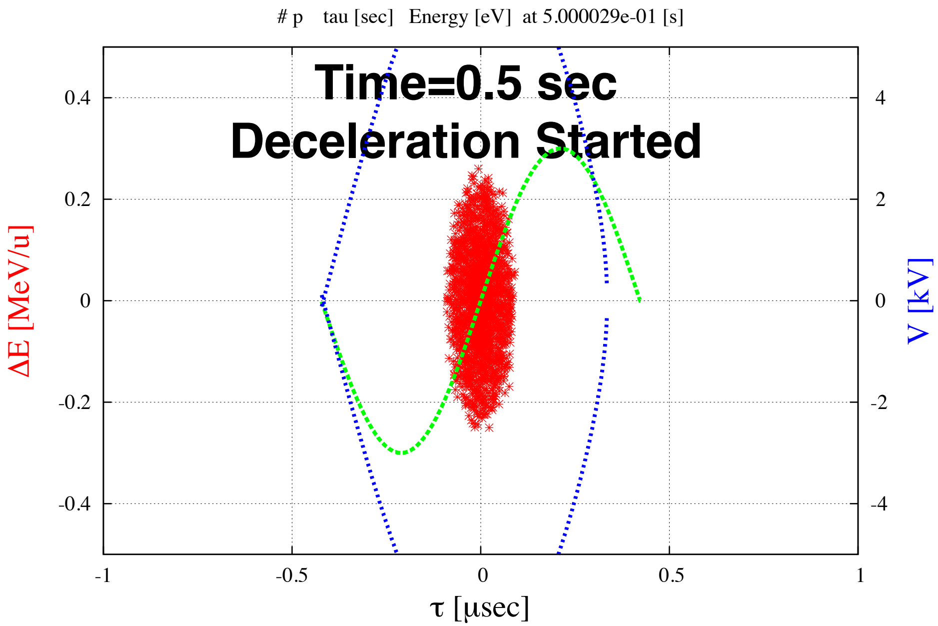


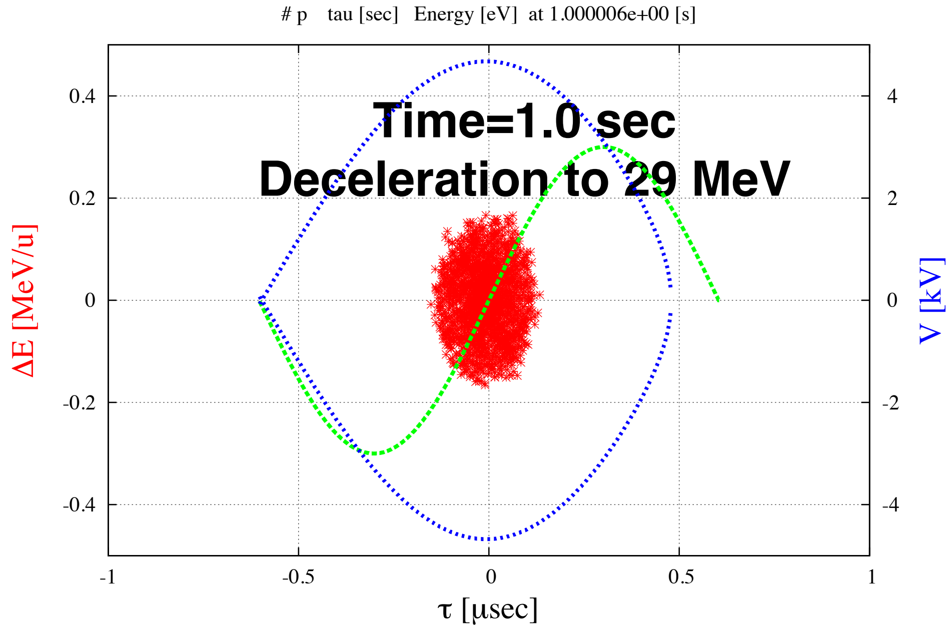
Energy and Particle Survival Rate



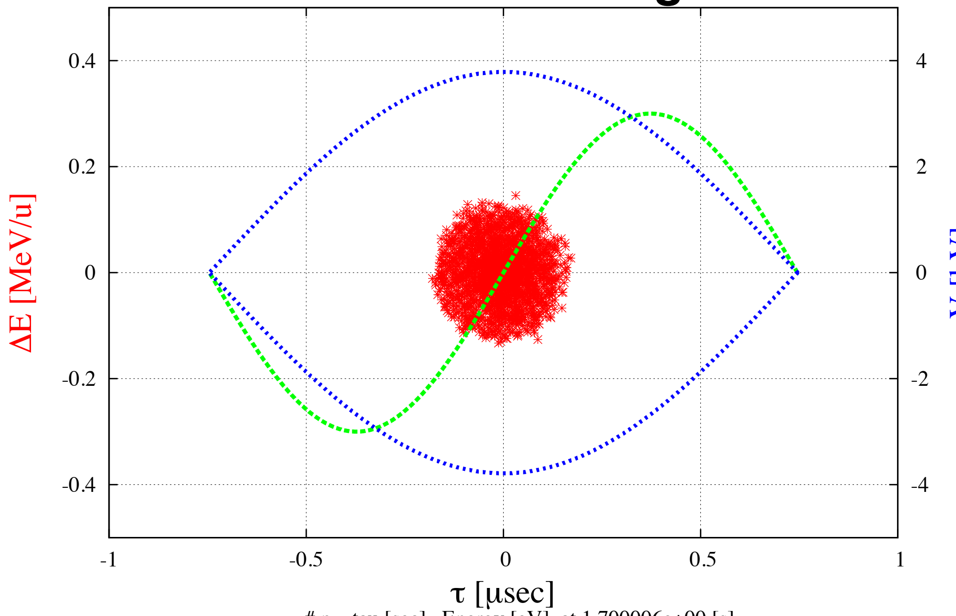

# p tau [sec] Energy [eV] at 0.000000e+00 [s]
Time=0 sec
100 MeV Cooling Finished
Dp/p=3.6e-5(rms)
ΔE [MeV/u]
V [kV]
τ [μsec]
0.4
0.2
0
-0.2
-0.4
4
2
-2
-4
-1
-0.5
0.5
1


# p tau [sec] Energy [eV] at 4.000040e-01 [s]
Time=0.4 sec
Adiabatic Capture almost Finished
ΔE [MeV/u]
V [kV]
τ [μsec]
0.4
0.2
0
-0.2
-0.4
4
2
-2
-4
-1
-0.5
0.5
1

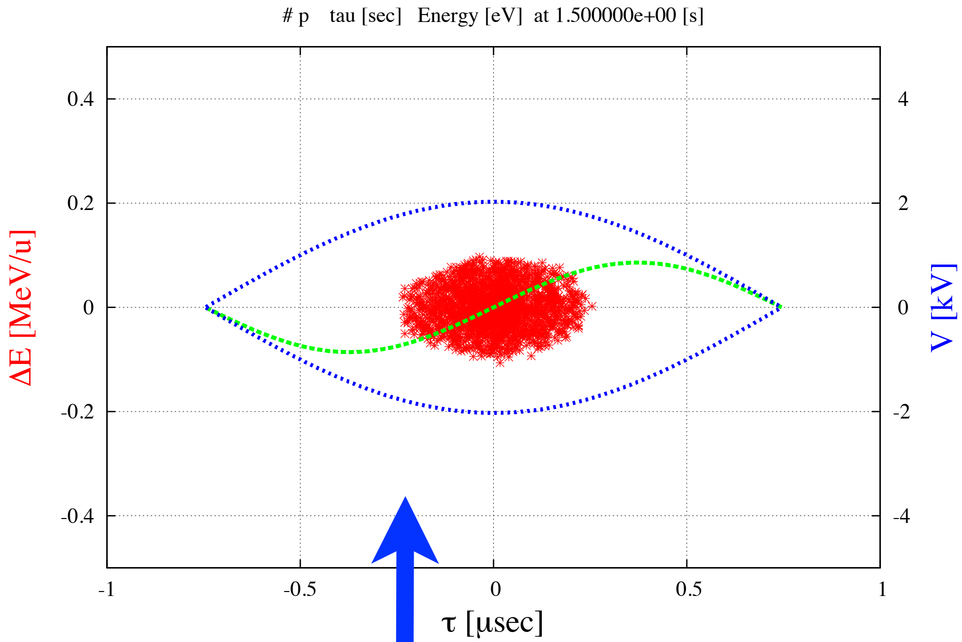

# p tau [sec] Energy [eV] at 5.000029e-01 [s]
Time=0.5 sec
Deceleration Started
ΔE [MeV/u]
V [kV]
τ [μsec]
0.4
0.2
0
-0.2
-0.4
4
2
-2
-4
-1
-0.5
0.5
1

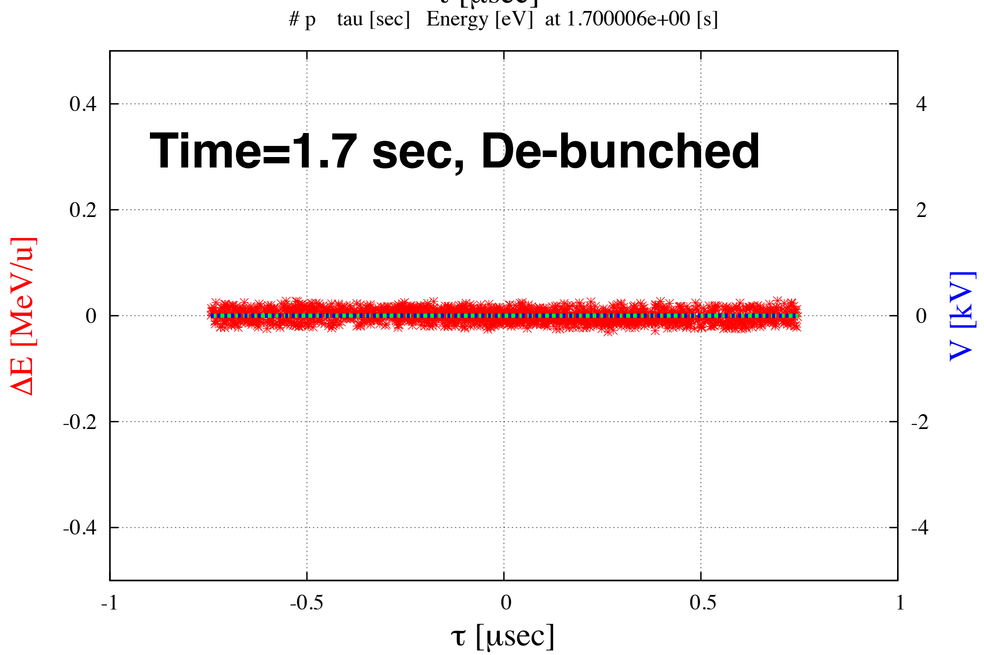

# p tau [sec] Energy [eV] at 1.000006e+00 [s]
Time=1.0 sec
Deceleration to 29 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]
0.4
0.2
0
-0.2
-0.4
4
2
-2
-4
-1
-0.5
0.5
1

Time=1.2 sec, Decelerated to 30 MeV
Adiabatic de-bunching started



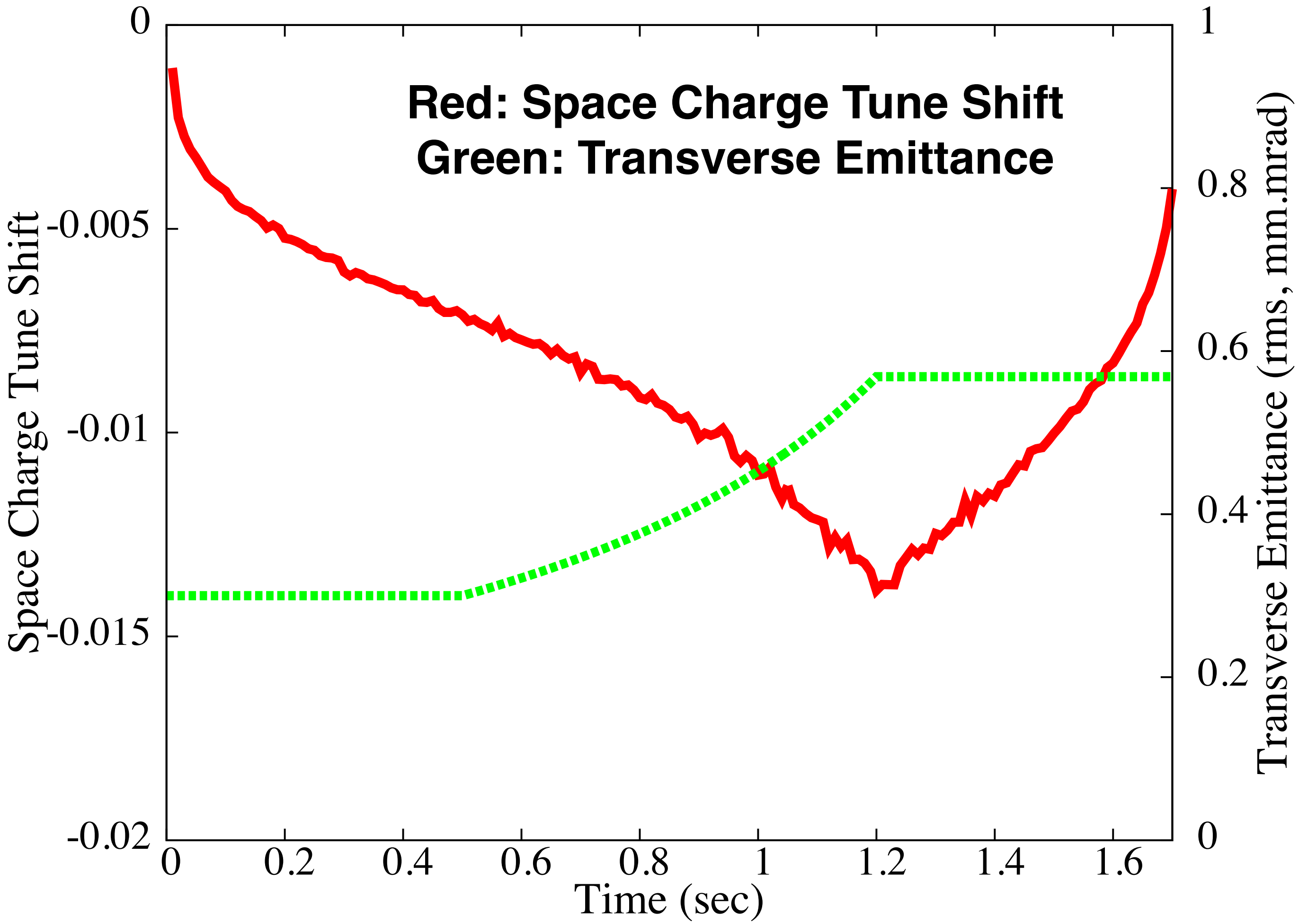
Time=1.5 sec, 30 MeV
Adiabatic de-bunching





FAST EXTRACTION TO CRYRING

Space Charge Tune Shift & Transverse Emittance (100 MeV - 30 MeV)



Part 5
Antiproton Deceleration in CRYRING

Deceleration of Antiproton Beam in CRYRING from 30 MeV to 0.3 MeV

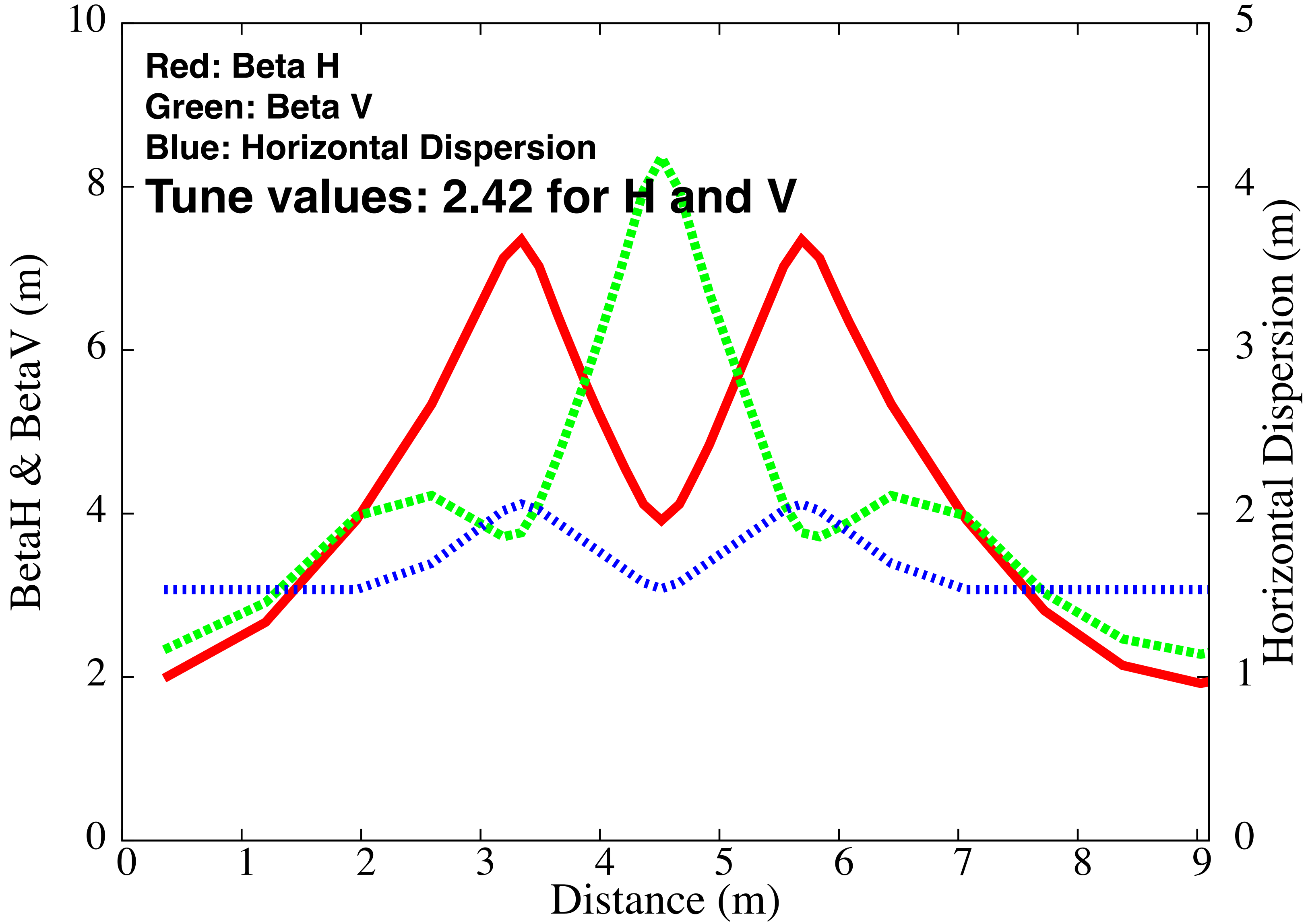
Injected Antiproton Energy: 30 MeV
Particle Number: 8e8
Pulse Length: +/-350 nsec
Dp/p (rms): 6e-4
Transverse Emittance (rms): 0.6 Pi mm.mrad

At 5 MeV Electron cooling will be applied to avoid the beam loss at ~ 1MeV.

Acceptance of Transverse emittance and Dp/p ?

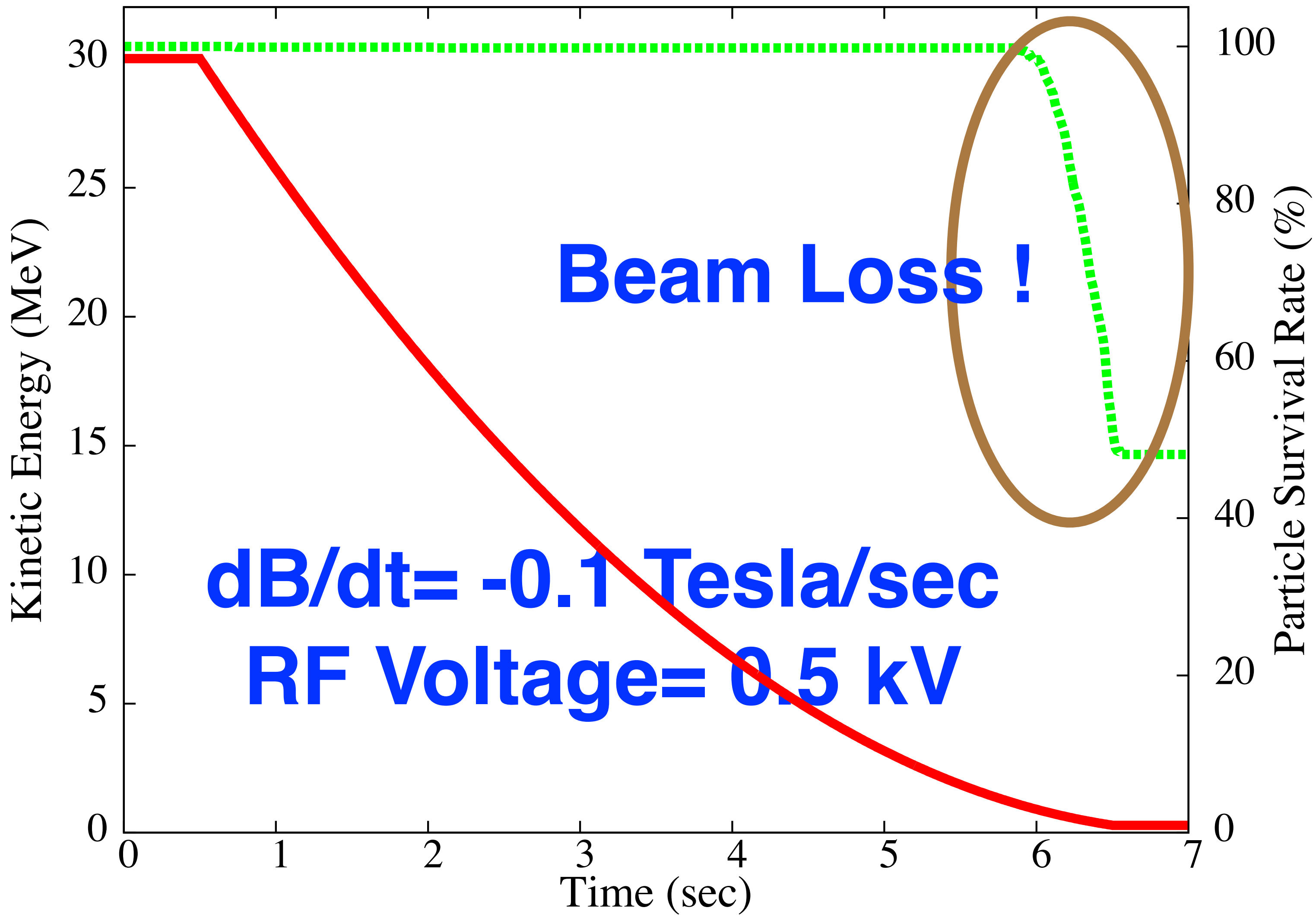
At the lowest energy 0.3 MeV, the transverse emittance is expected as 1.4 Pi mm.mrad (rms) when the injected 30 MeV has the transverse emittance of 1.0 Pi mm.mrad (rms) where the electron cooling is used at the intermediate energy 5 MeV. As the maximal beta function is 7.35 m, the betatron amplitude is 7.9 mm. The useful half aperture is 40 mm and the maximal horizontal dispersion is 2.06 m, and then the Dp/p acceptance is +/-1.56e-2 at 0.3 MeV.

Twiss Parameters of CRYRING (One Sextant)



Deceleration from 30 MeV to 0.3 MeV

Energy and Particle Survival Rate



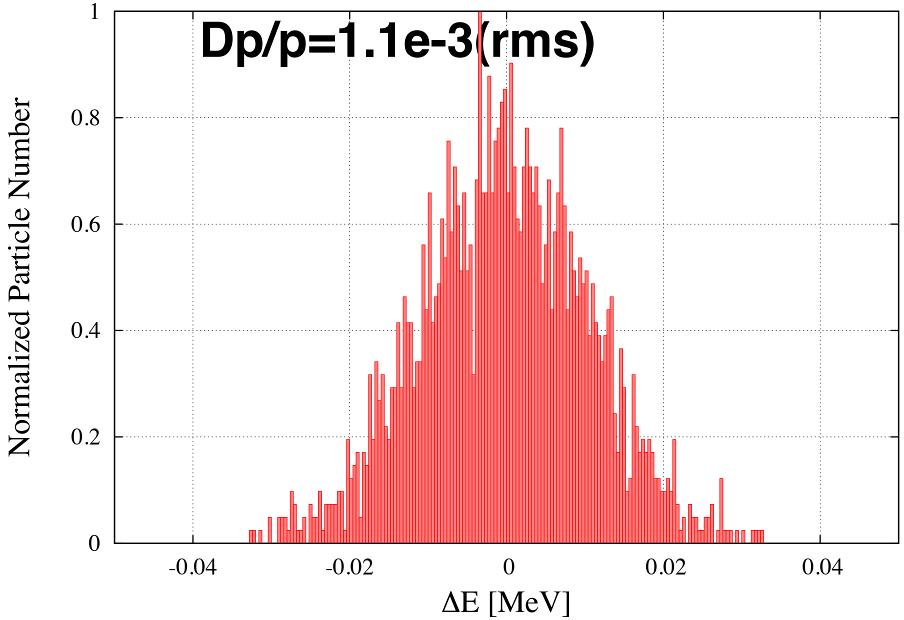
To avoid the beam loss at the energy at 0.5-1.0 MeV we have to use the electron cooling at 5 MeV

Electron Cooler Parameters

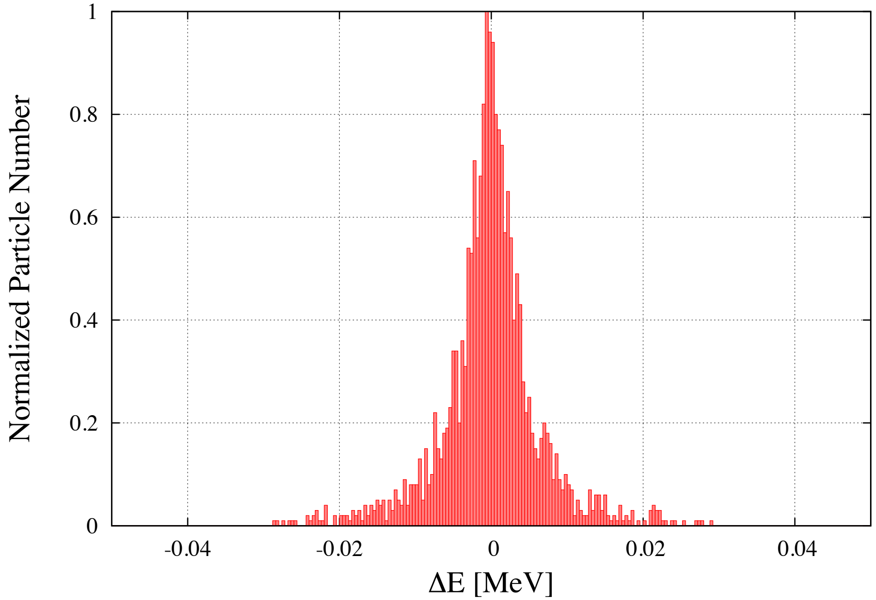
Cooler Length	1.1 m
Electron current	0.11 A
Electron beam diameter	5 cm (4cm)
Solenoid field strength	0.1 (0.05) Tesla
Effective electron temperature	5e-3 eV
Transverse electron temperature	2e-1 eV

Evolution of Spectrum with Electron Cooling

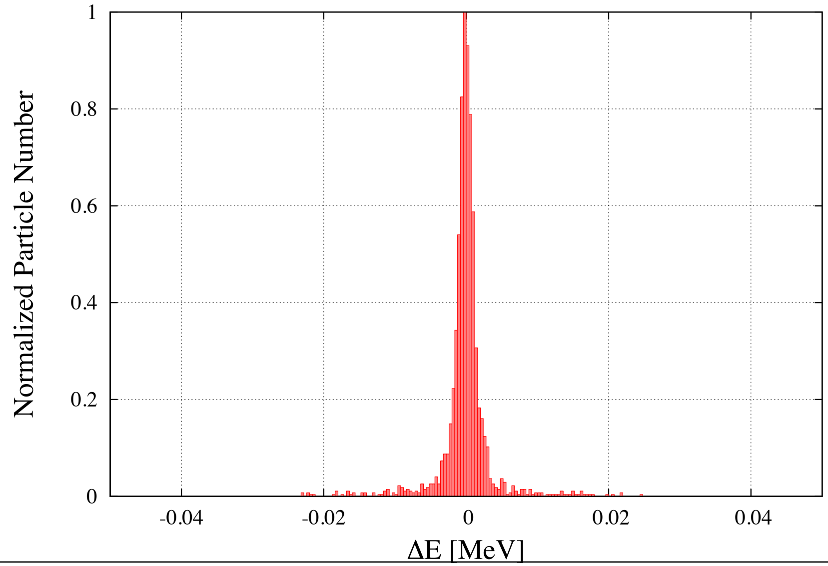
Time=0 sec



Time=1.0 sec

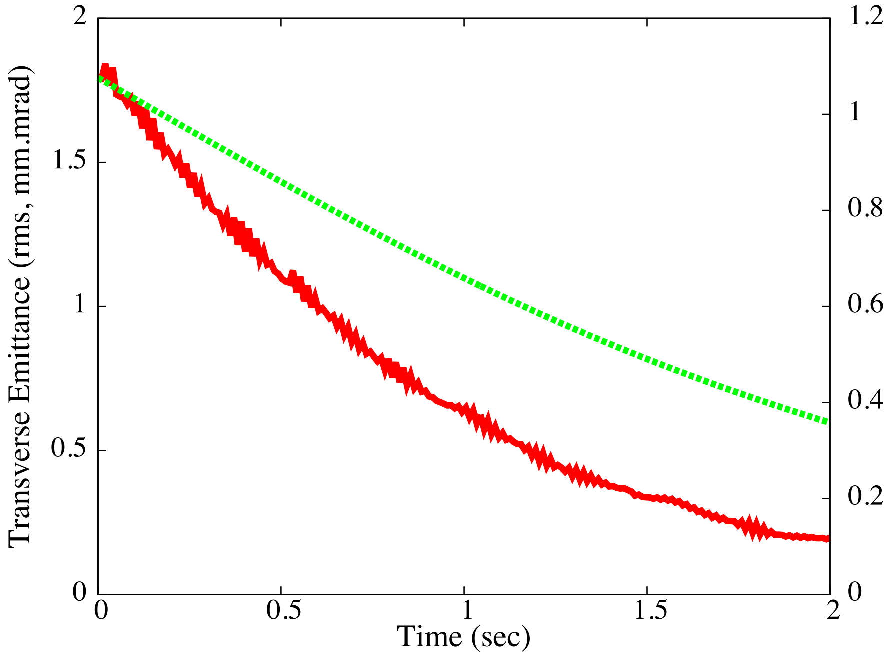


Time=2.0 sec

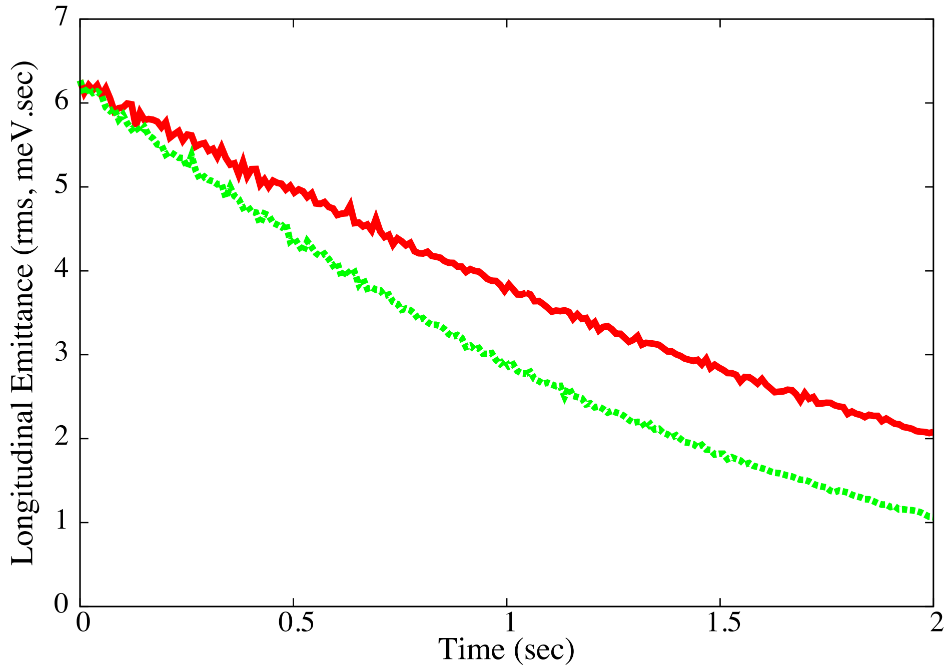


Evolution of Transverse/Longitudinal Emittance and Dp/p with Electron Cooling

Red: Transverse Emittance
Green: Dp/p

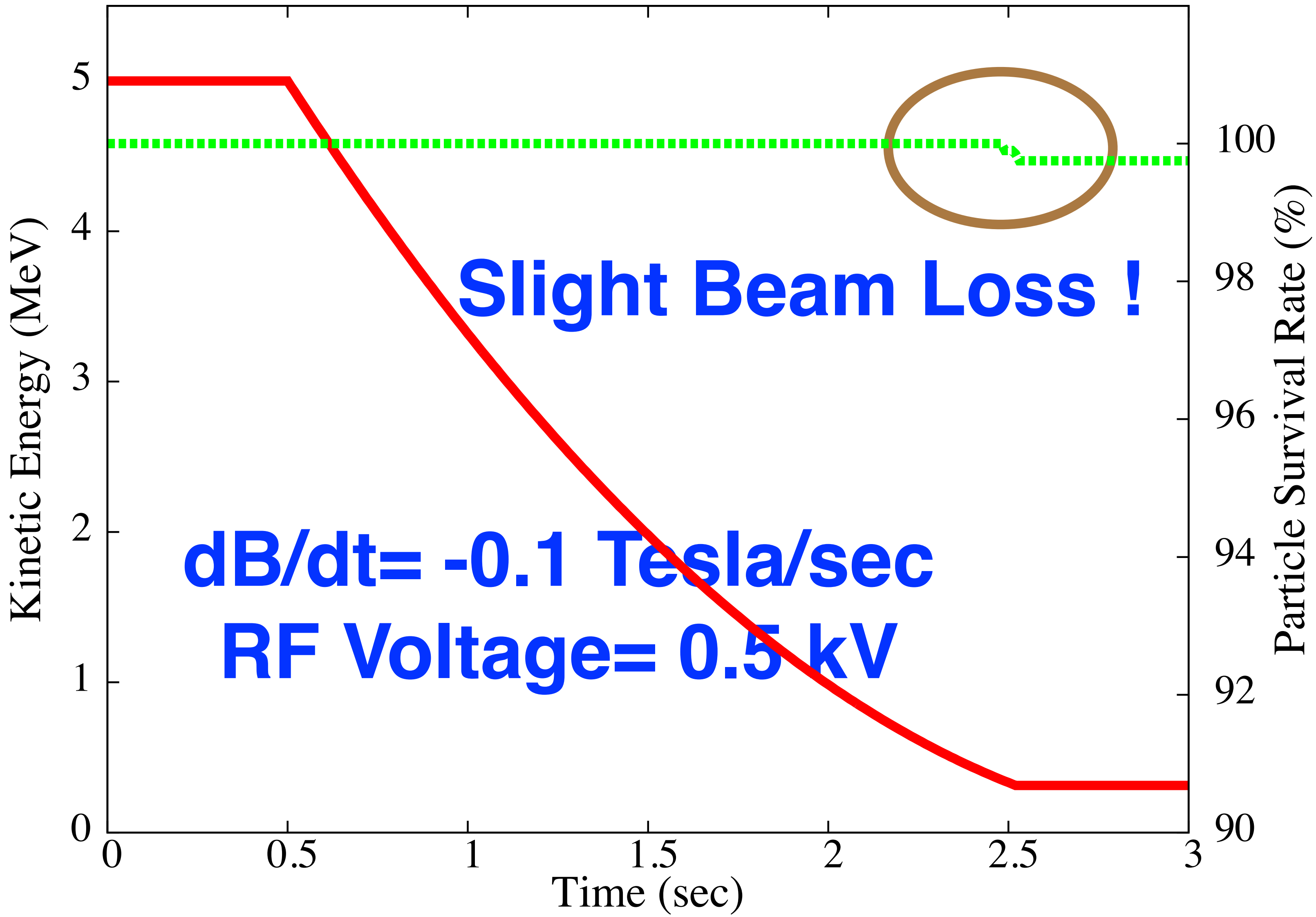


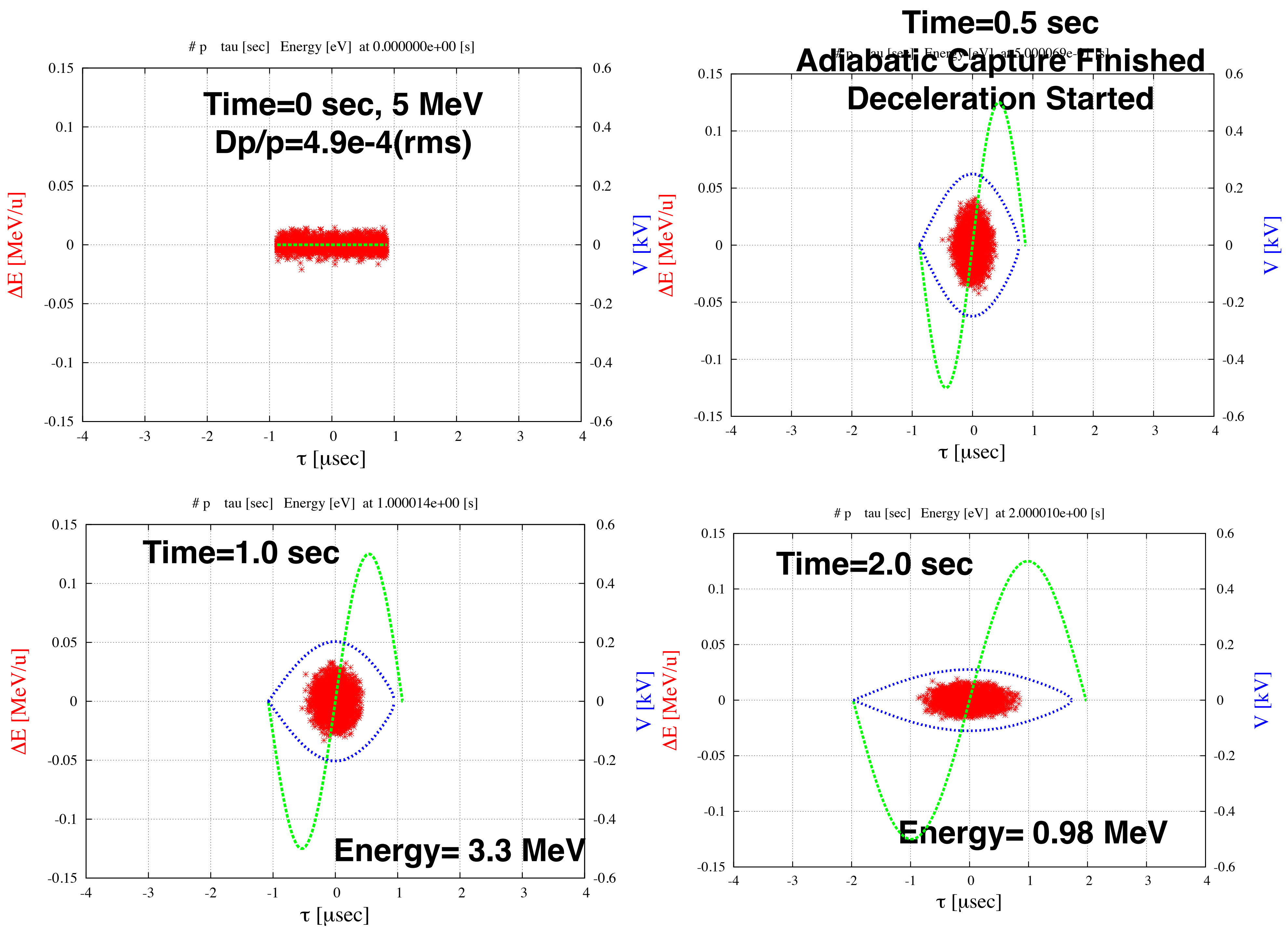
Red: Electron Diameter=5cm, B=0.1 Tesla
Green: Electron Diameter=4cm, B=0.05 Tesla
Both case Ie=0.1 Ampere



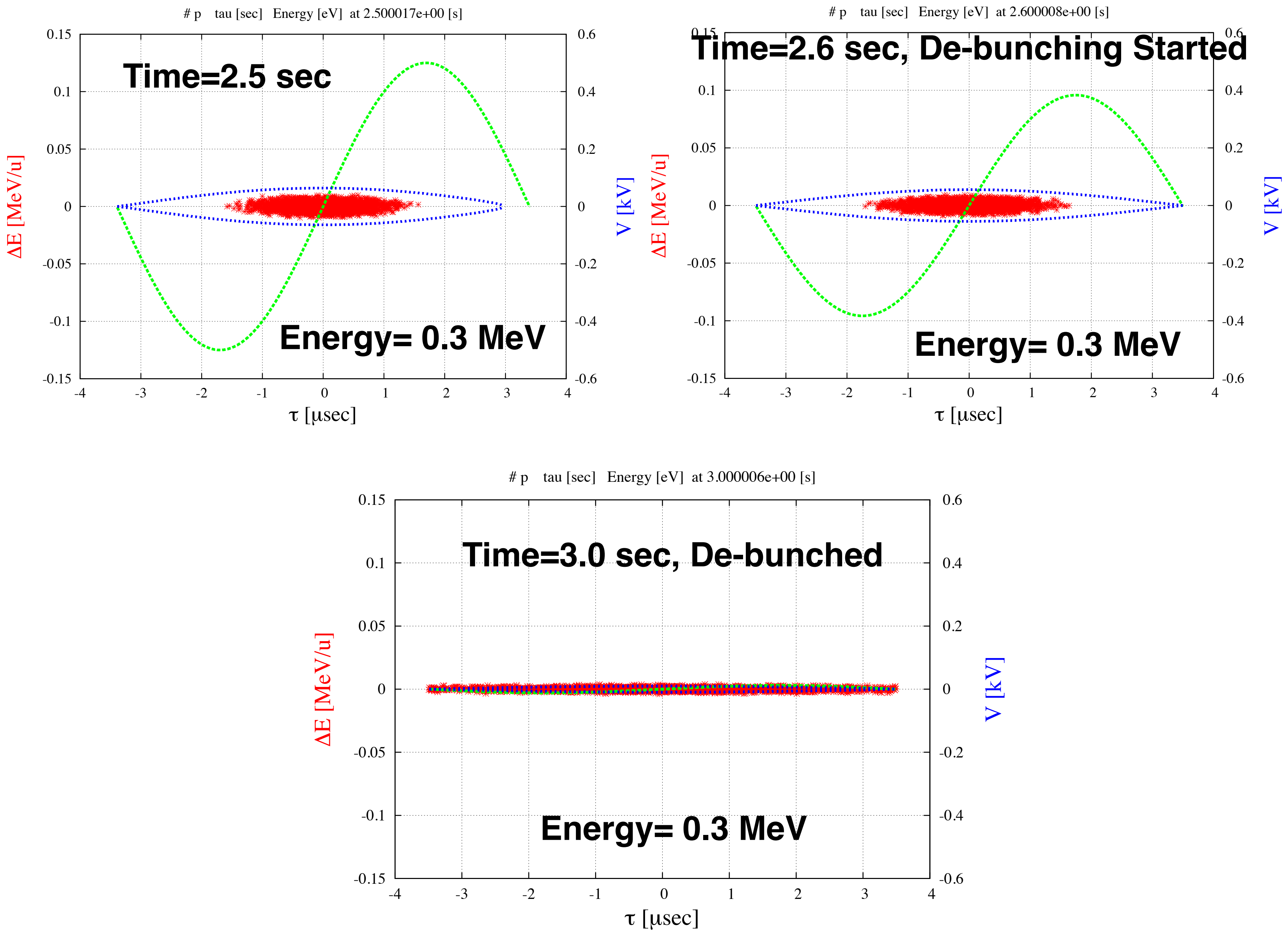
Deceleration from 5 MeV to 0.3 MeV

Energy and Particle Survival Rate





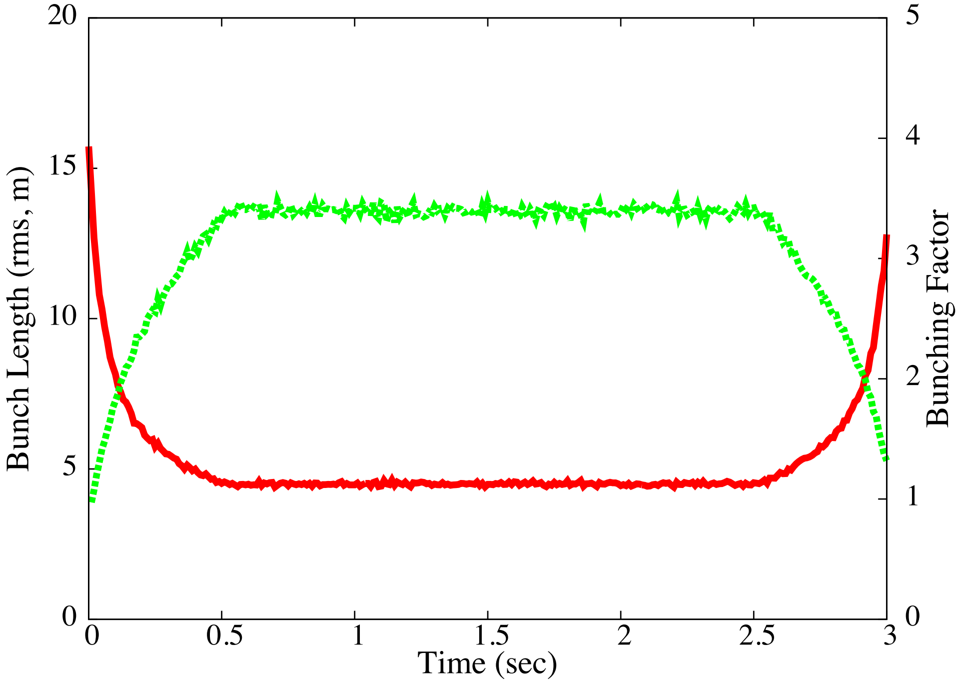
# p tau [sec] Energy [eV] at 0.000000e+00 [s]
Time=0 sec, 5 MeV
Dp/p=4.9e-4(rms)
ΔE [MeV/u]
V [kV]
τ [μsec]
Time=0.5 sec
Adiabatic Capture Finished
Deceleration Started
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 1.000014e+00 [s]
Time=1.0 sec
Energy= 3.3 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 2.000010e+00 [s]
Time=2.0 sec
Energy= 0.98 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]



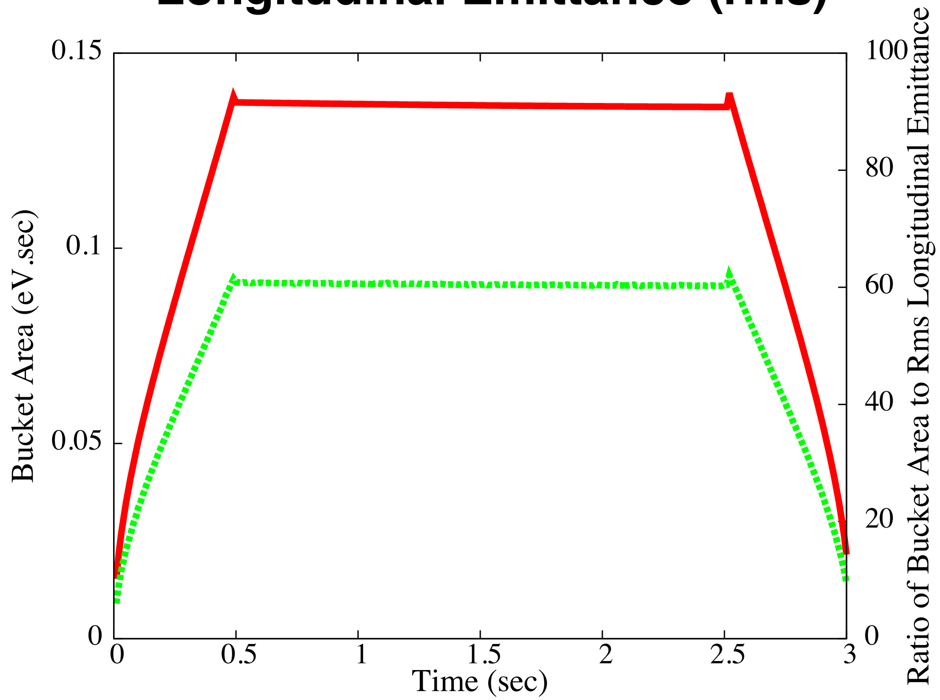
# p tau [sec] Energy [eV] at 2.500017e+00 [s]
Time=2.5 sec
Energy= 0.3 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 2.600008e+00 [s]
Time=2.6 sec, De-bunching Started
Energy= 0.3 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]
# p tau [sec] Energy [eV] at 3.000006e+00 [s]
Time=3.0 sec, De-bunched
Energy= 0.3 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]

Evolution of Longitudinal Parameters during Deceleration from 5 MeV to 0.3 MeV in CRYRING

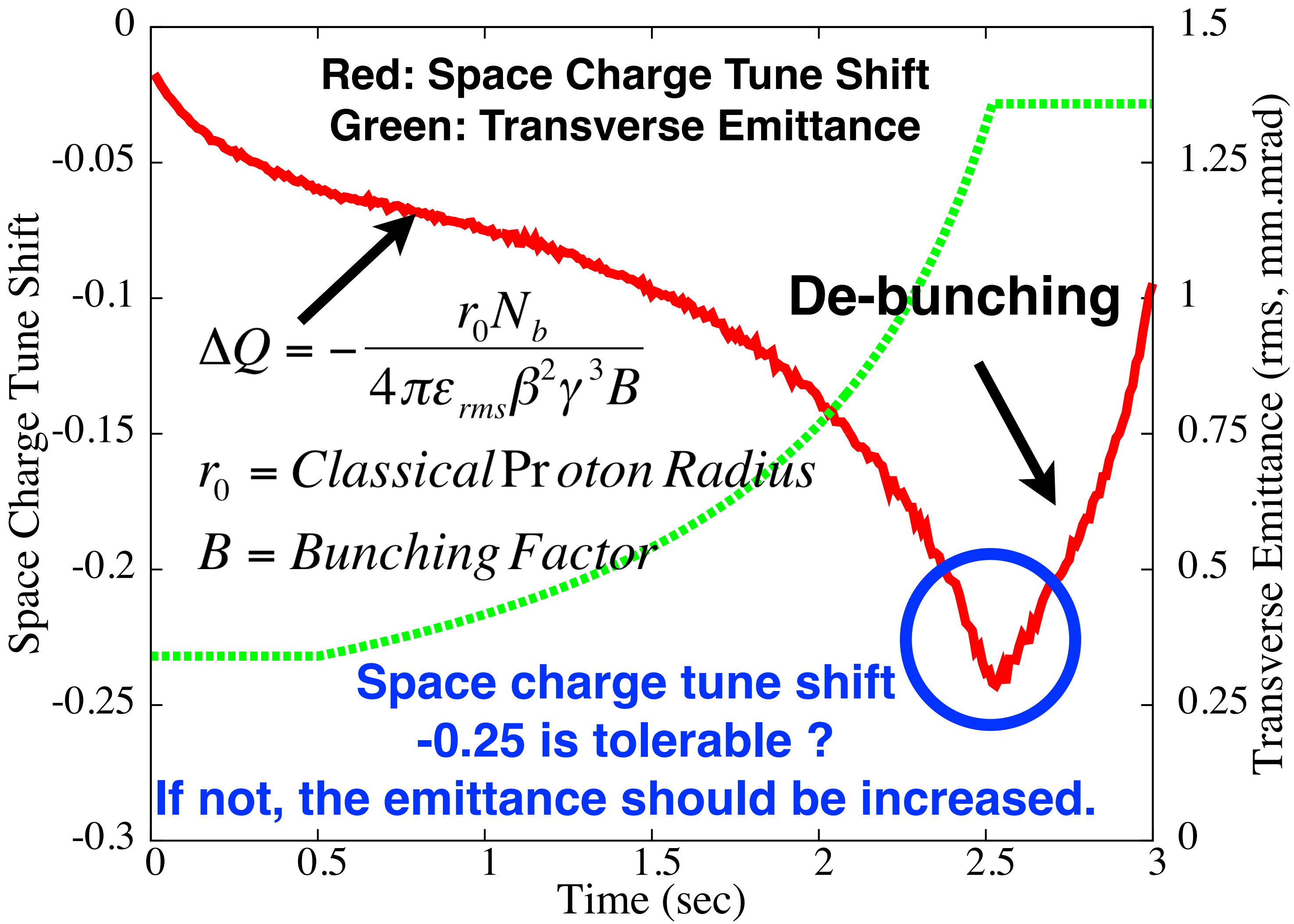
Red: Bunch Length (rms)
Green: Bunching Factor



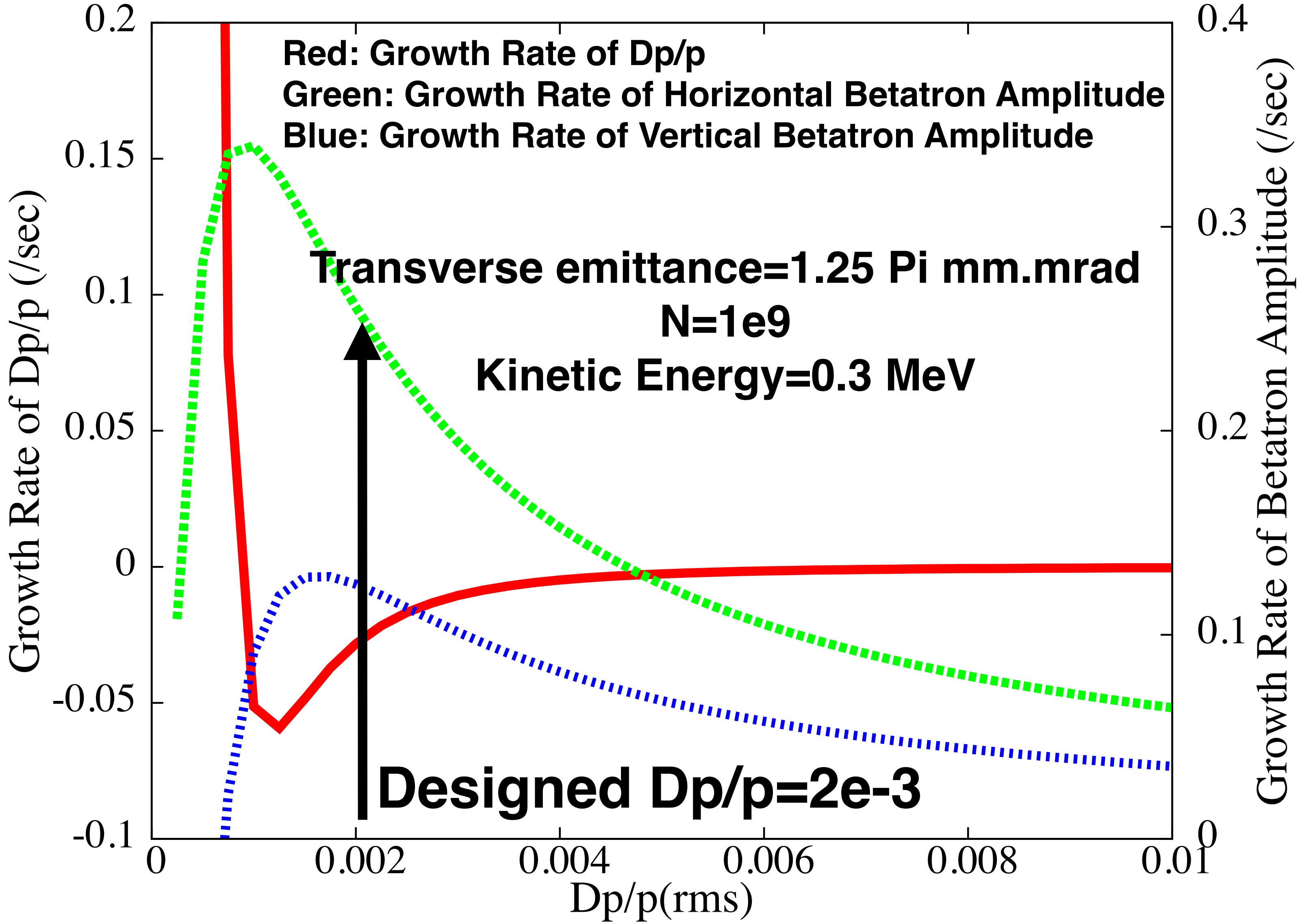
Red: Bucket Area
Green: Ratio of Bucket Area to Longitudinal Emittance (rms)



Transverse Emittance & Space Charge Tune Shift (during deceleration from 5 MeV to 0.3 MeV)



Intra Beam Scattering Growth Rate



Summary of Beam Parameters from CRYRING (Scenario 2)

Antiproton Energy: 0.3 MeV
Particle Number: 8e8 /220sec(No beam loss during the deceleration) Note: CERN AD ~2e7/120 sec
Pulse Length: Coasting for the Slow Extraction or +/-1.5 microsec (full width) for the Fast Extraction
Dp/p (rms): 2e-3 (coasting) or 6e-3 (bunched)
Transverse Emittance (rms): 1.3 Pi mm.mrad

The space charge tune shift is -0.25 at the maximal at the lowest energy. Careful adjustment of transverse emittance is required.
IBS growth could be managed.