Antiproton at CRYRING

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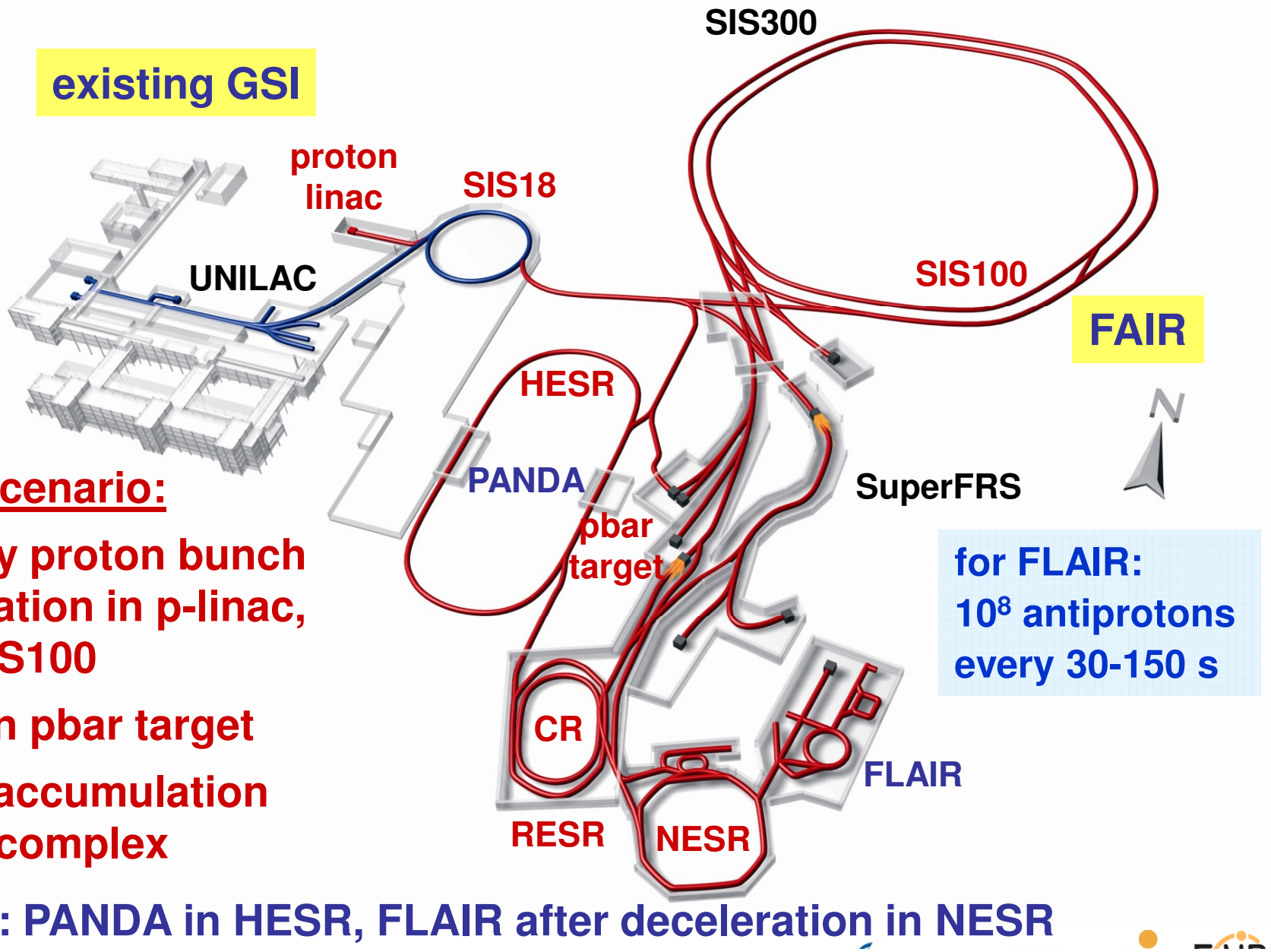
Outline

1. Antiproton Accumulation & Deceleration in HESR
2. Deceleration and Cooling in ESR
3. Low Energy Antiprotons at CRYRING
4. Summary and Conclusion

Full Version of FAIR Accelerator Facility



Antiproton Scenario:

high intensity proton bunch after acceleration in p-linac, SIS18 and SIS100

conversion in pbar target

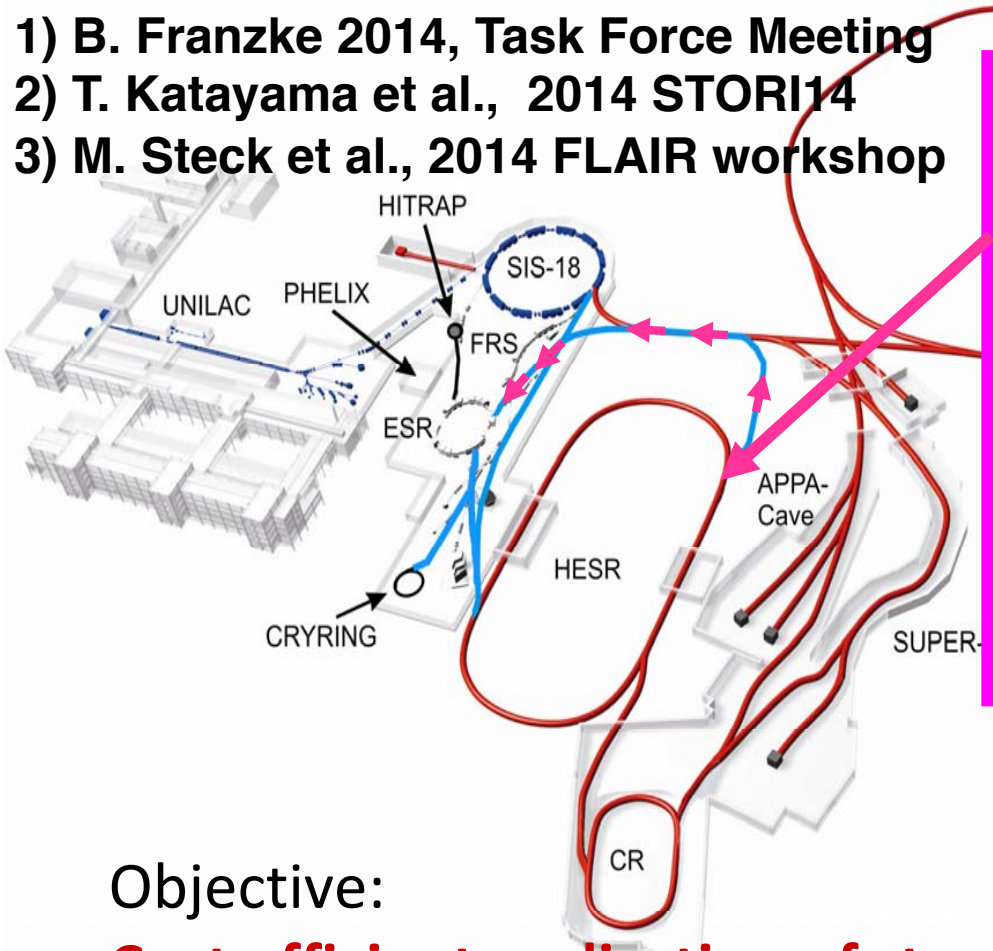
cooling and accumulation in CR/RESR complex

Experiments: PANDA in HESR, FLAIR after deceleration in NESR

Modularized Version : RESR, NESR and FLAIR are dropped out.

Medium-term option: 6 Tm beam line from HESR to ESR

1) B. Franzke 2014, Task Force Meeting
2) T. Katayama et al., 2014 STORI14
3) M. Steck et al., 2014 FLAIR workshop



The beam line would enable:

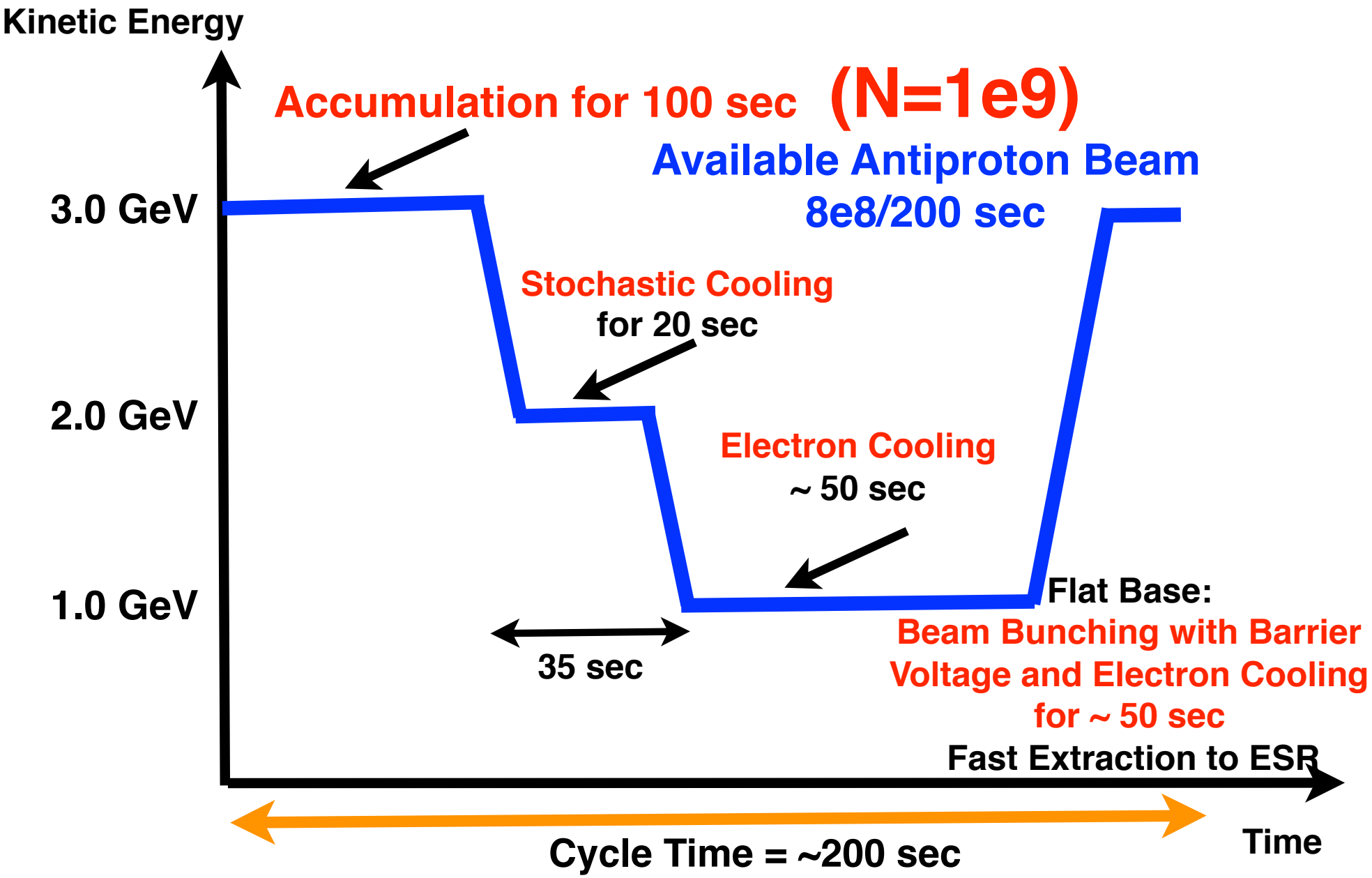
1. Deceleration of pbar beams to lowest energies:
   - in HESR to 1 GeV
   - in ESR to 30 MeV
   - in CRYRING to 300 keV
2. Storage ring experiments in the ESR (e.g. EXL) with exotic nuclei from the Super-FRS, CR, HESR chain.

Objective:

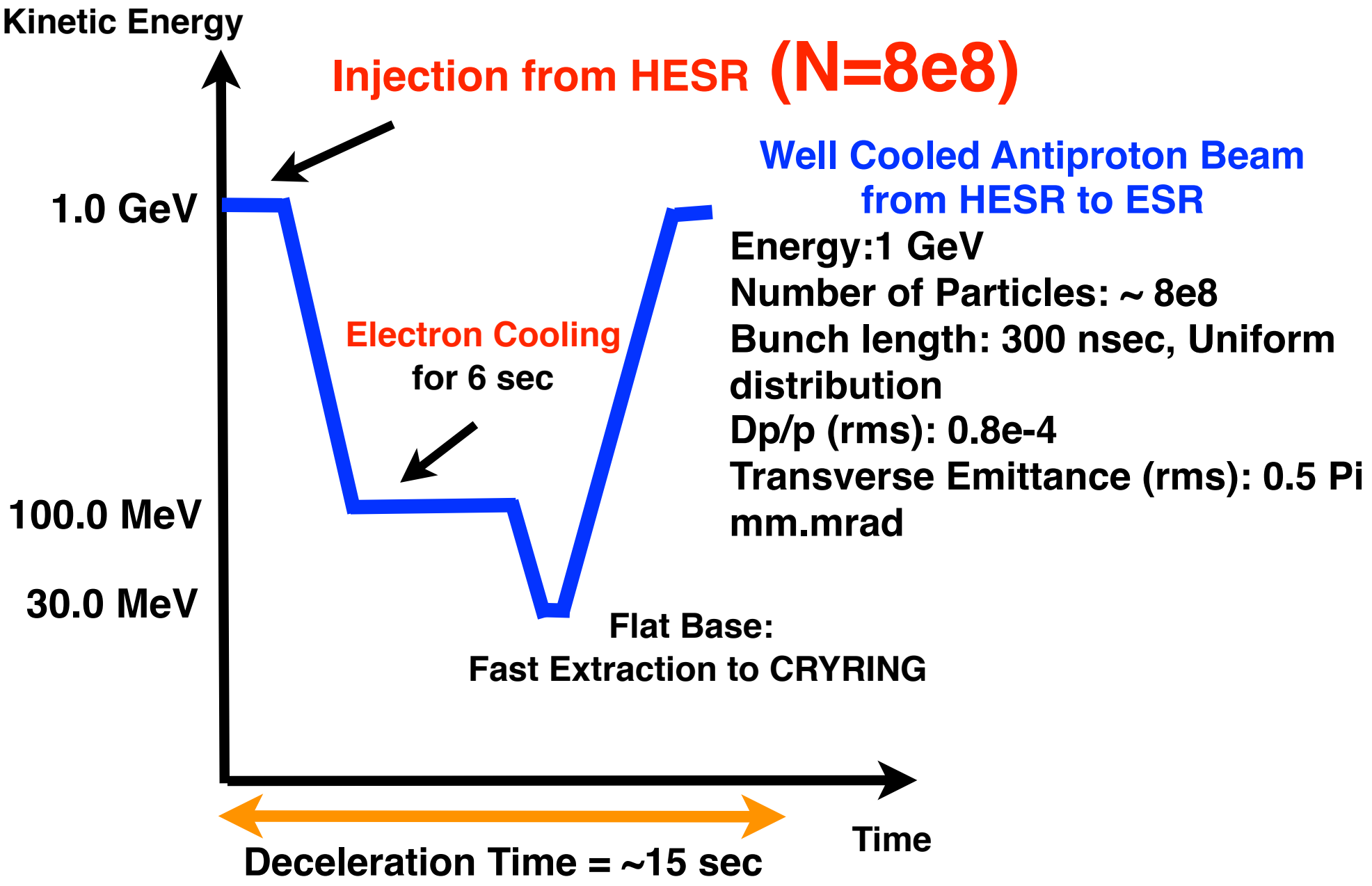
Cost efficient realization of storage ring experiments as proposed in the FAIR CDR will be achieved this way!!

Stepwise improvement of ESR should take place simultaneously!

Operation Scheme of HESR Deceleration for Antiproton Flux to ESR/CRYRING



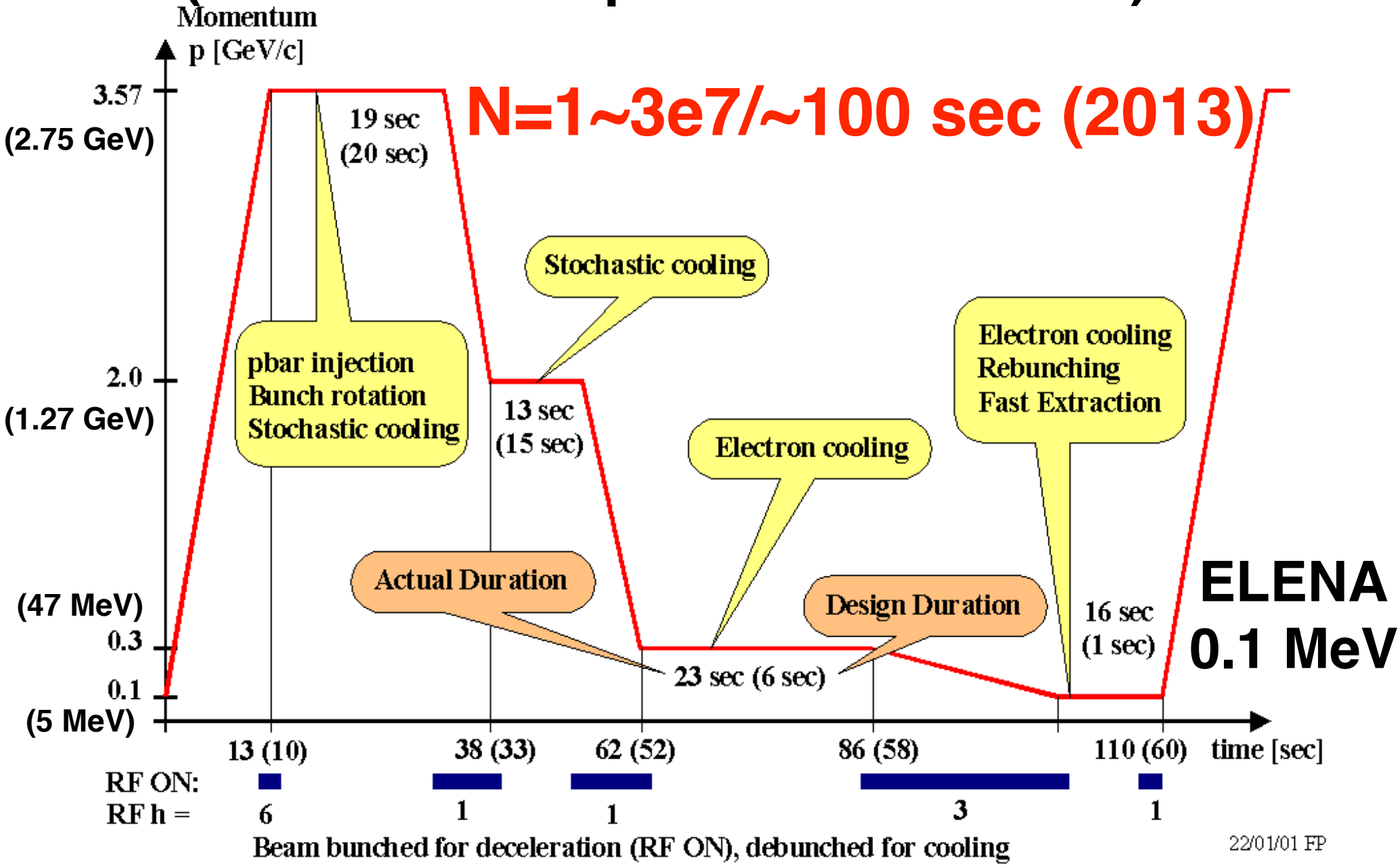
Operation Scheme of ESR for CRYRING



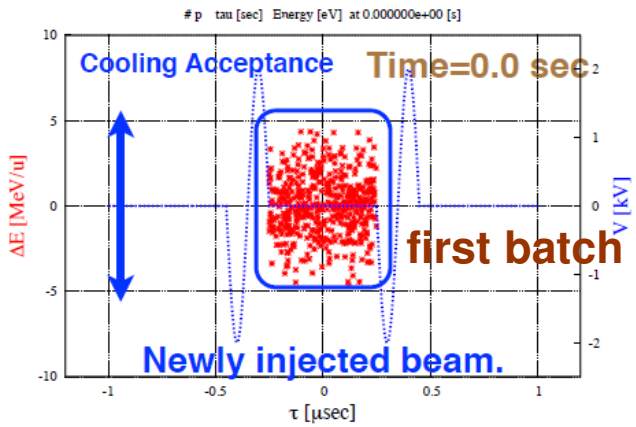
Well Cooled Antiproton Beam from HESR to ESR

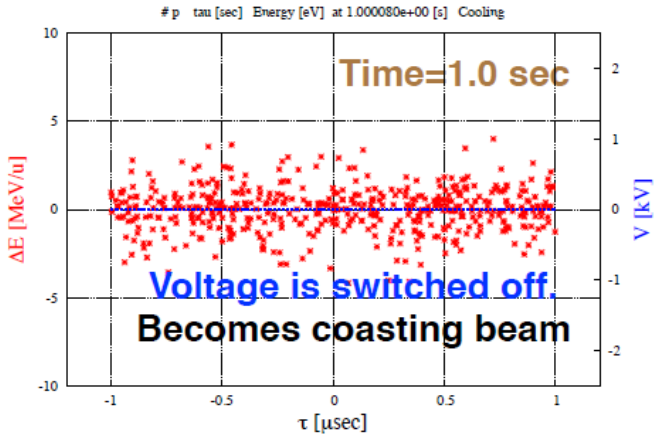
Energy:1 GeV
Number of Particles: ~ 8e8
Bunch length: 300 nsec, Uniform distribution
Dp/p (rms): 0.8e-4
Transverse Emittance (rms): 0.5 Pi mm.mrad

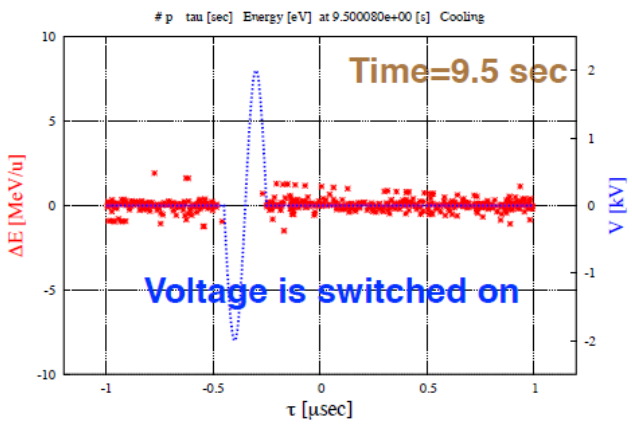
Reference: CERN AD Operation Scheme (All in One Antiproton Decelerator)



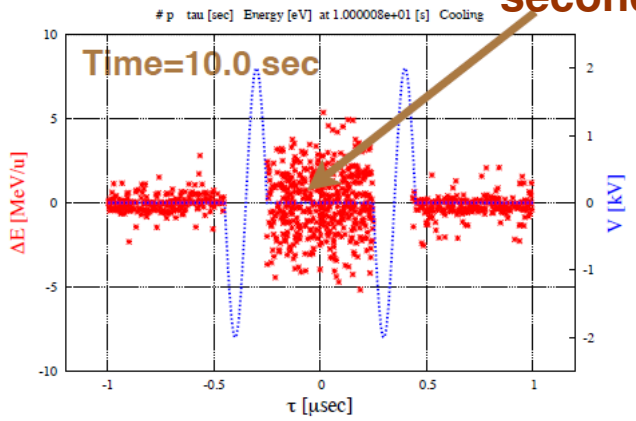
Accumulation of Antiproton Beam in HESR

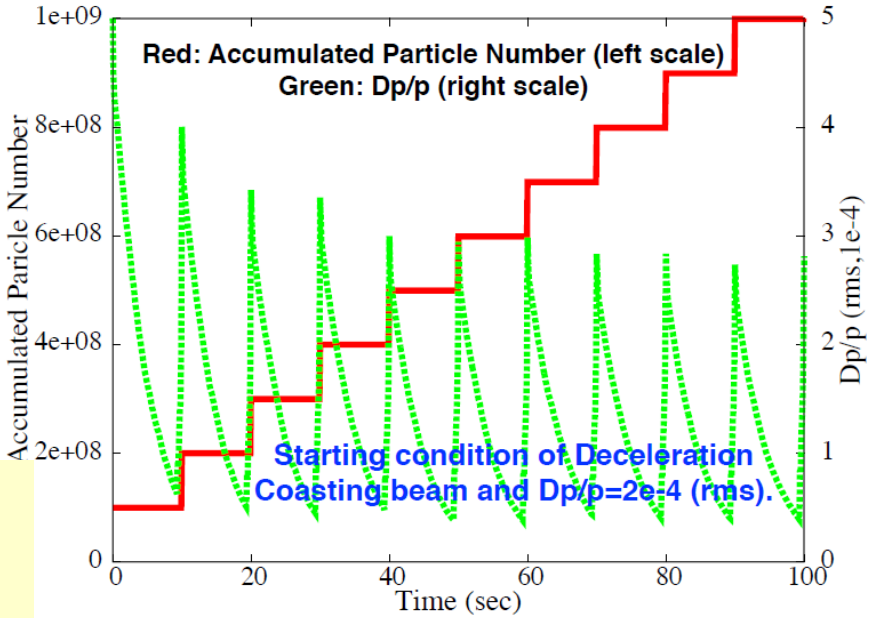






injection of second batch





accumulation (in 100 s) of 1 × 10^9 antiprotons in parallel to deceleration in the ESR

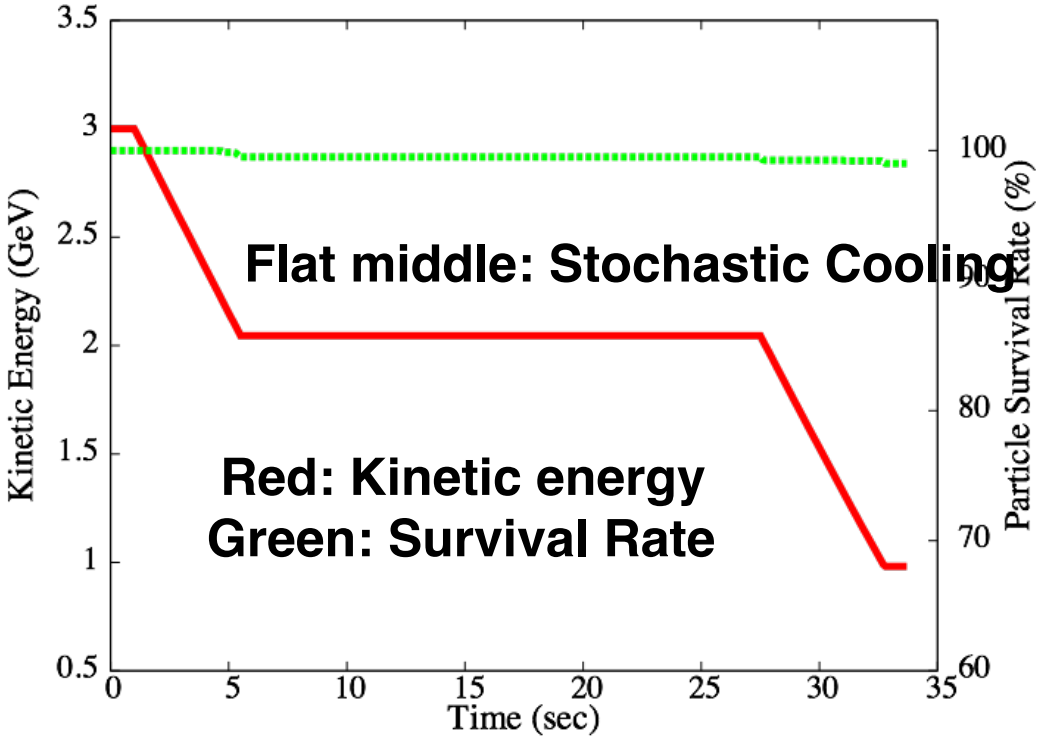
same scheme is used for PANDA experiments

Deceleration from 3 GeV to 1 GeV, Npbar=1e9 with Stochastic Cooling at Middle Flat of 2 GeV to surpress the Anti-damping

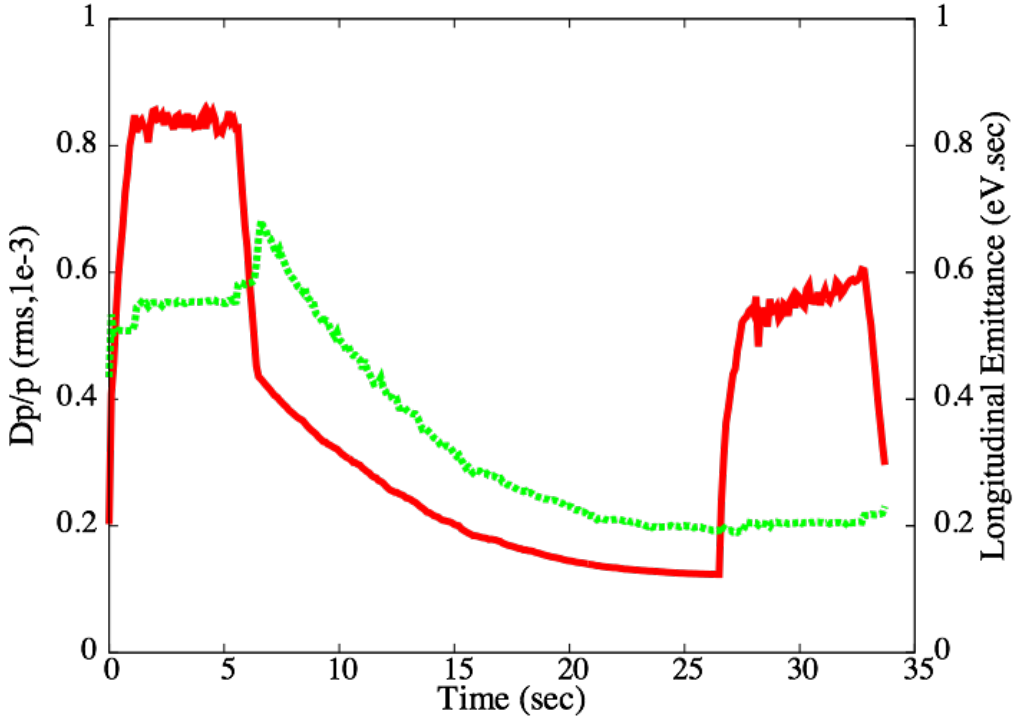
dB/dt=-0.025 Tesla/sec

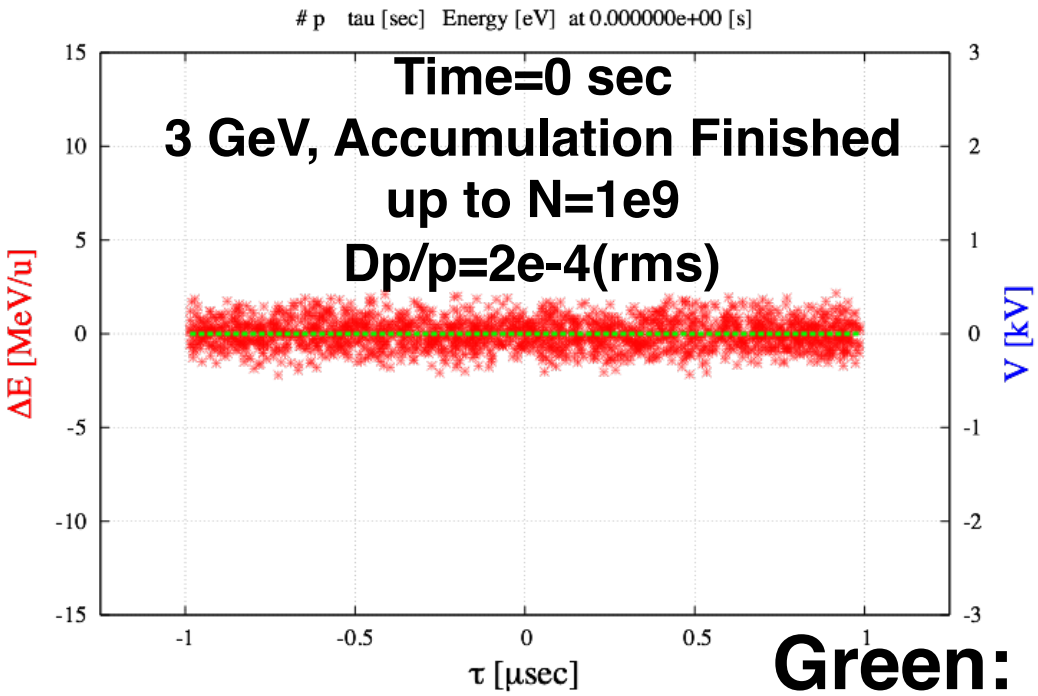
Vrf=2kV

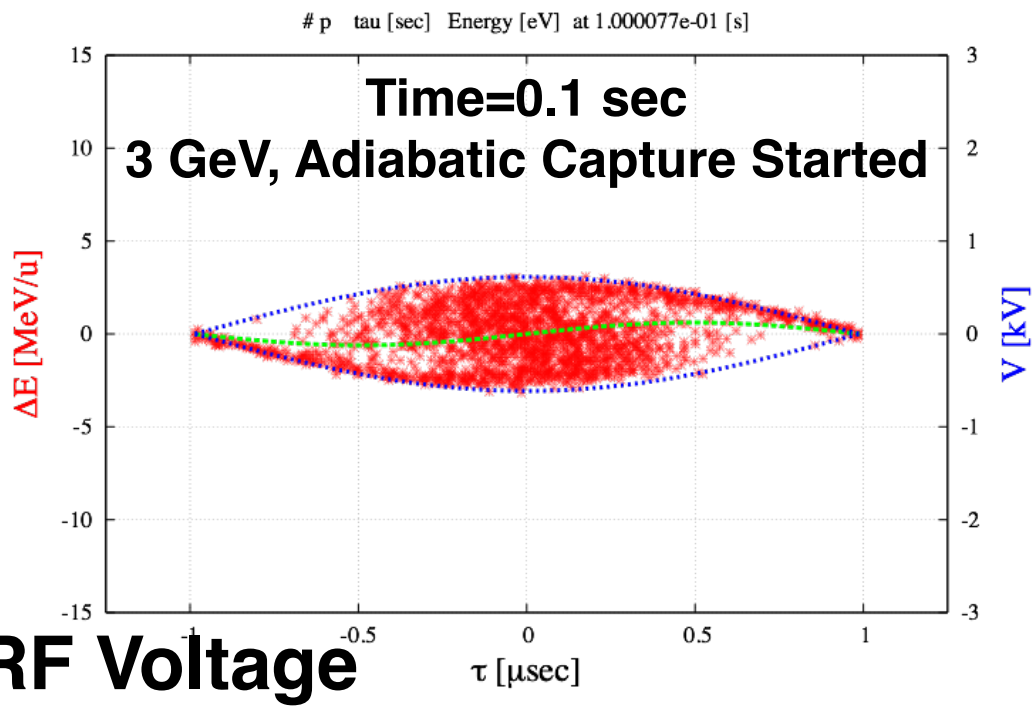
Flat top: Adiabatic bunching



Red: Dp/p
Green: Longitudinal Emittance

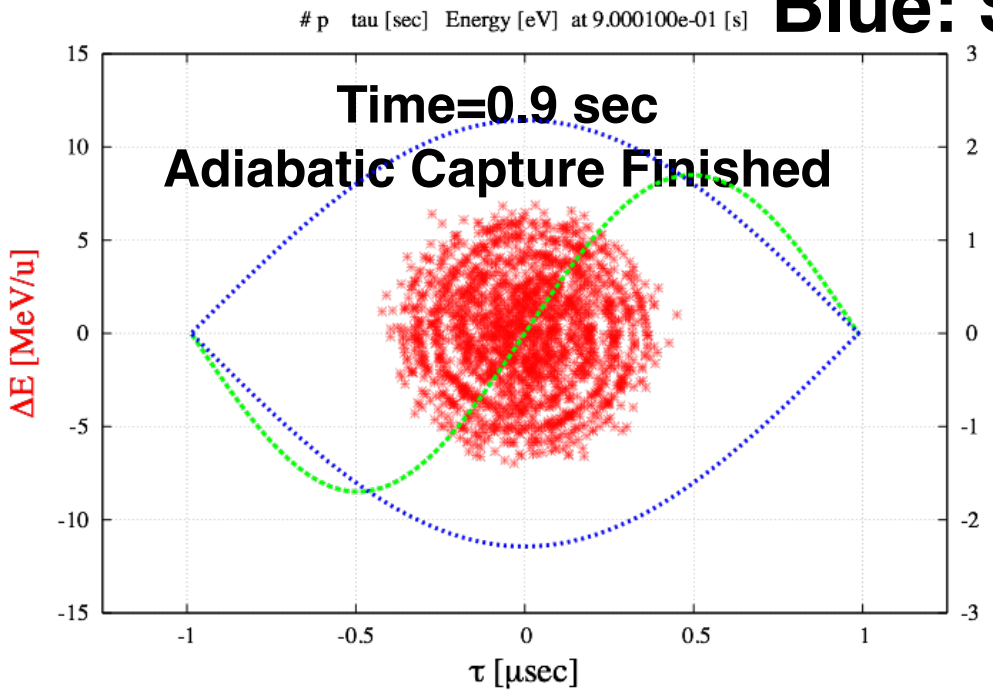


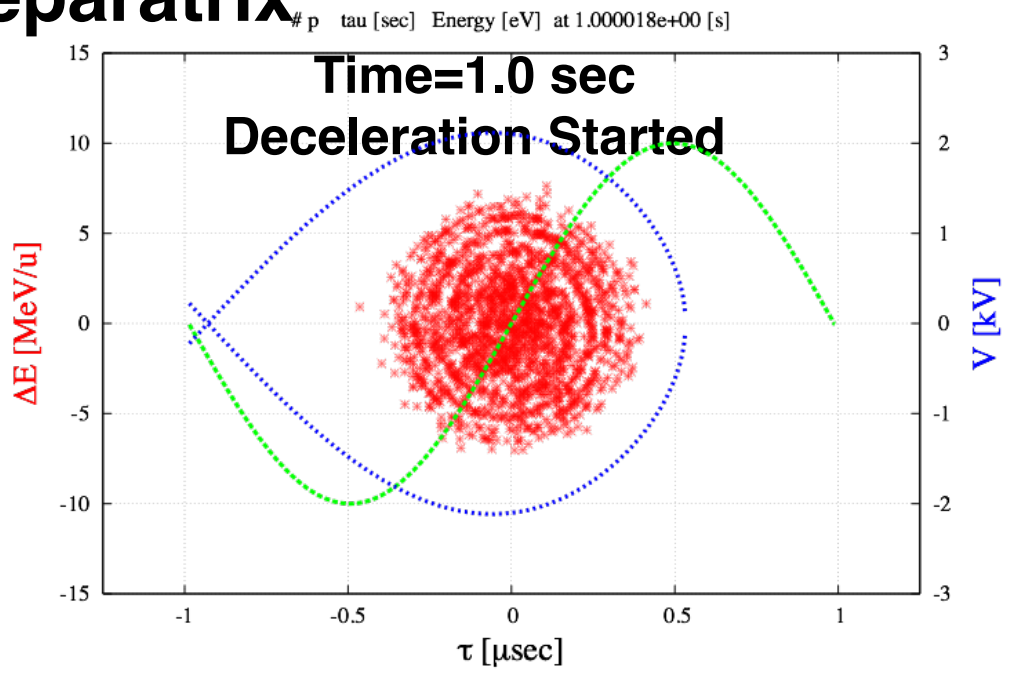


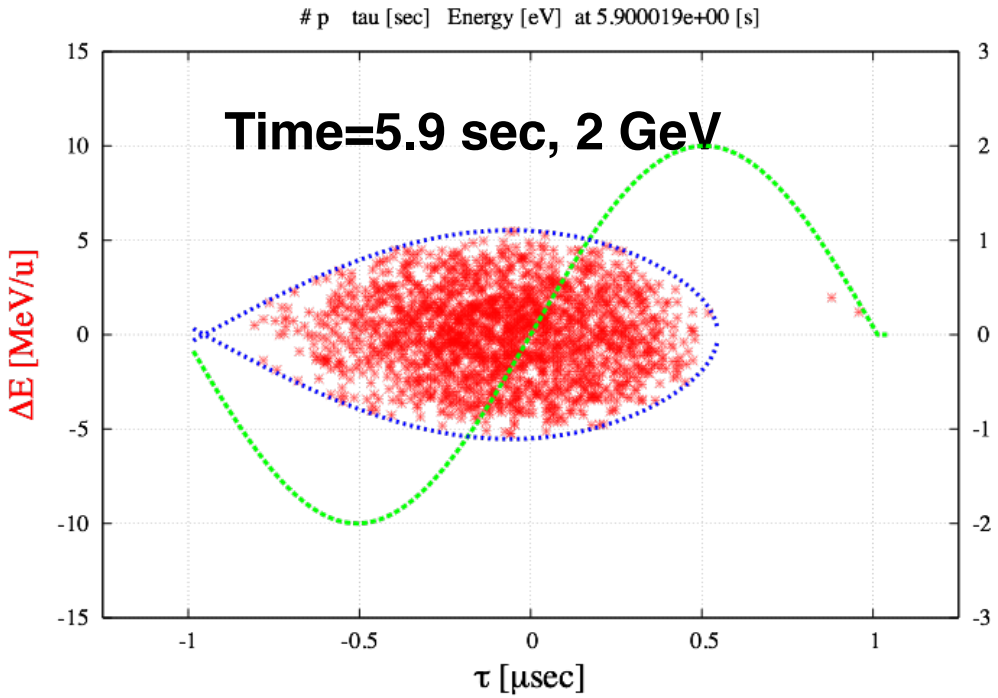


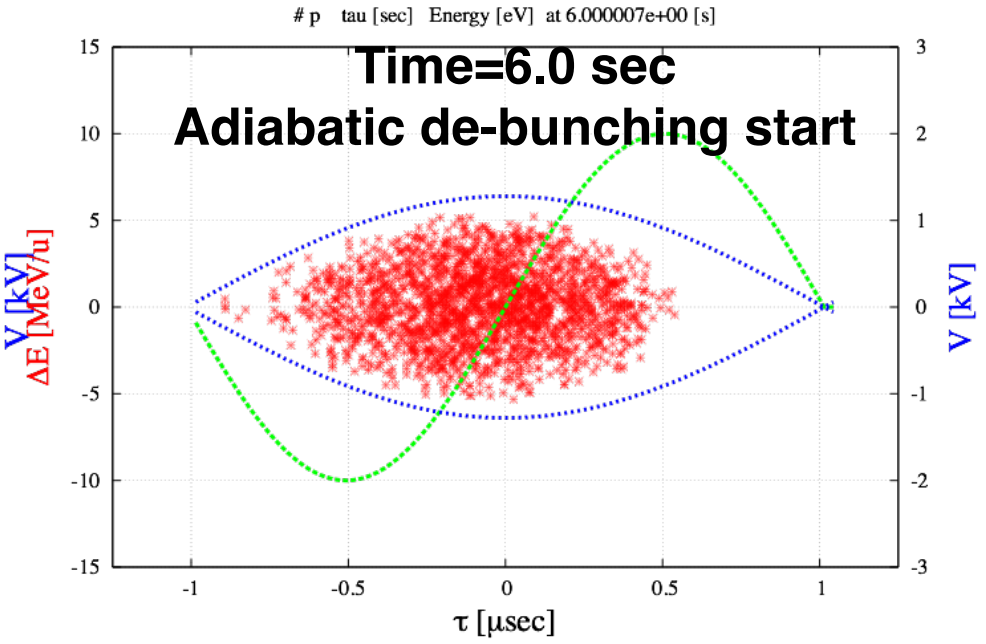
Green: RF Voltage

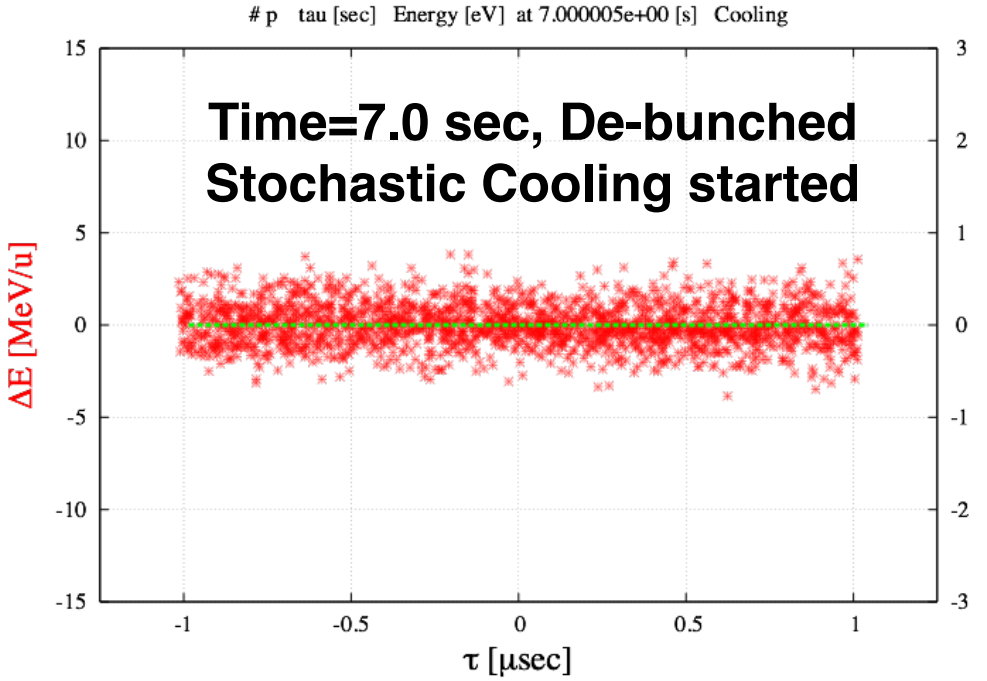
Blue: Separatrix

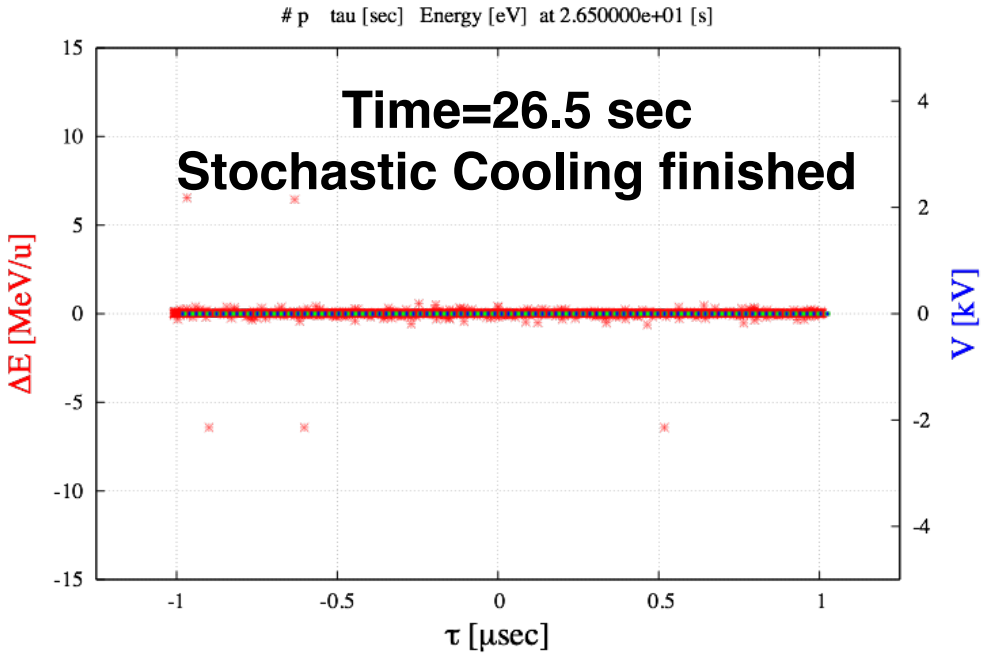




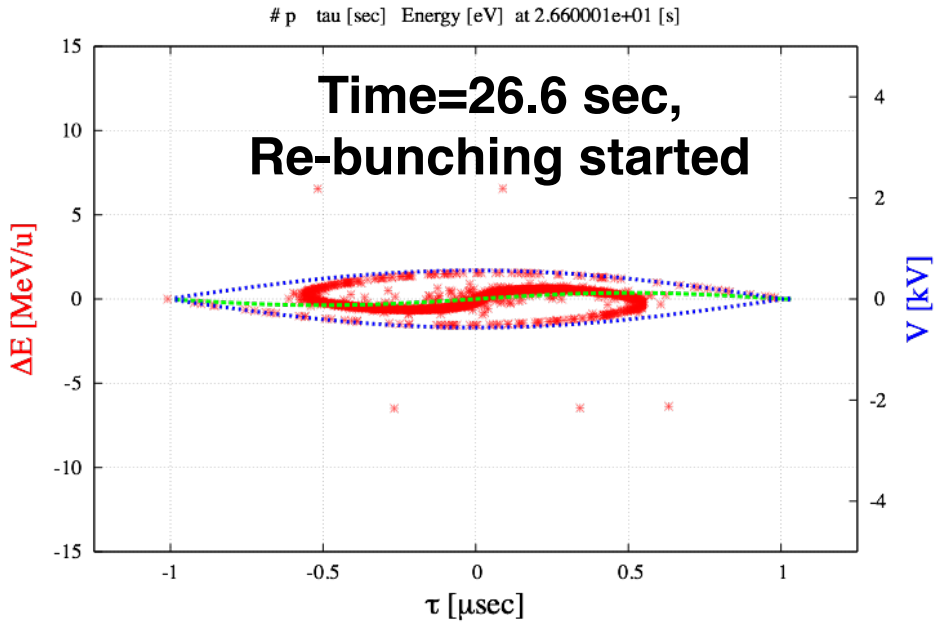


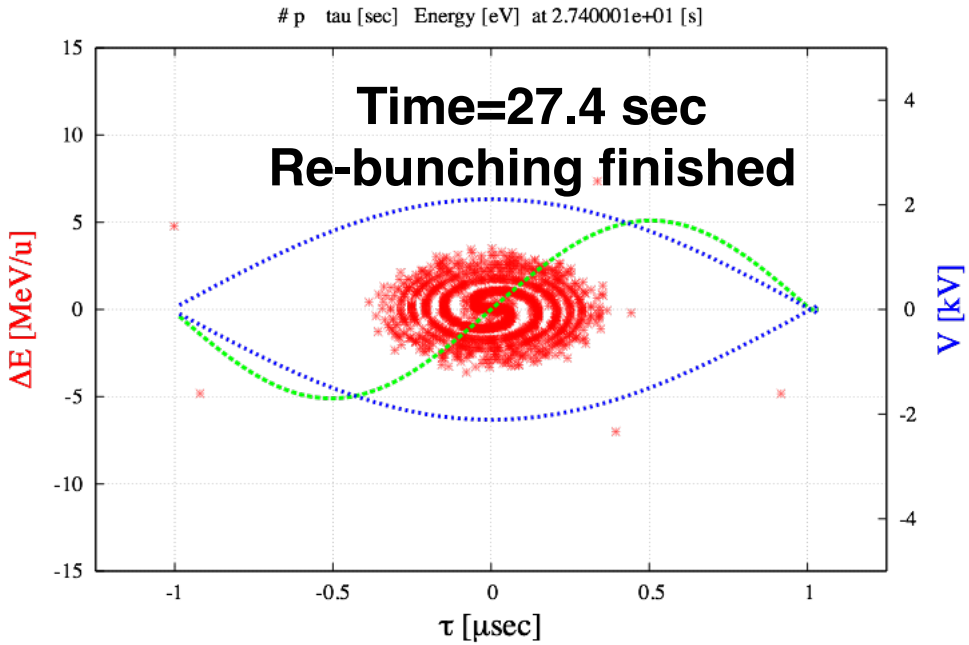


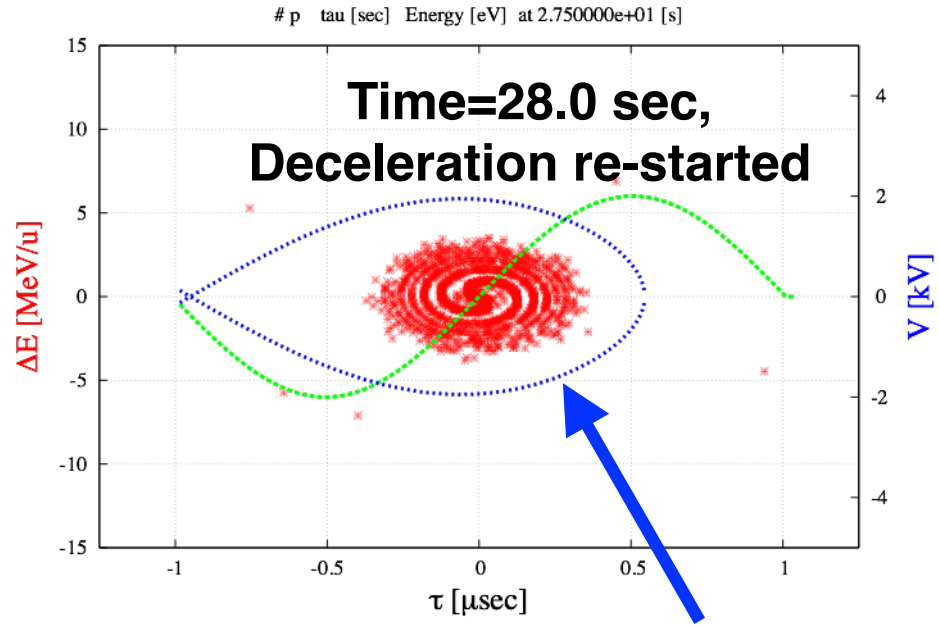


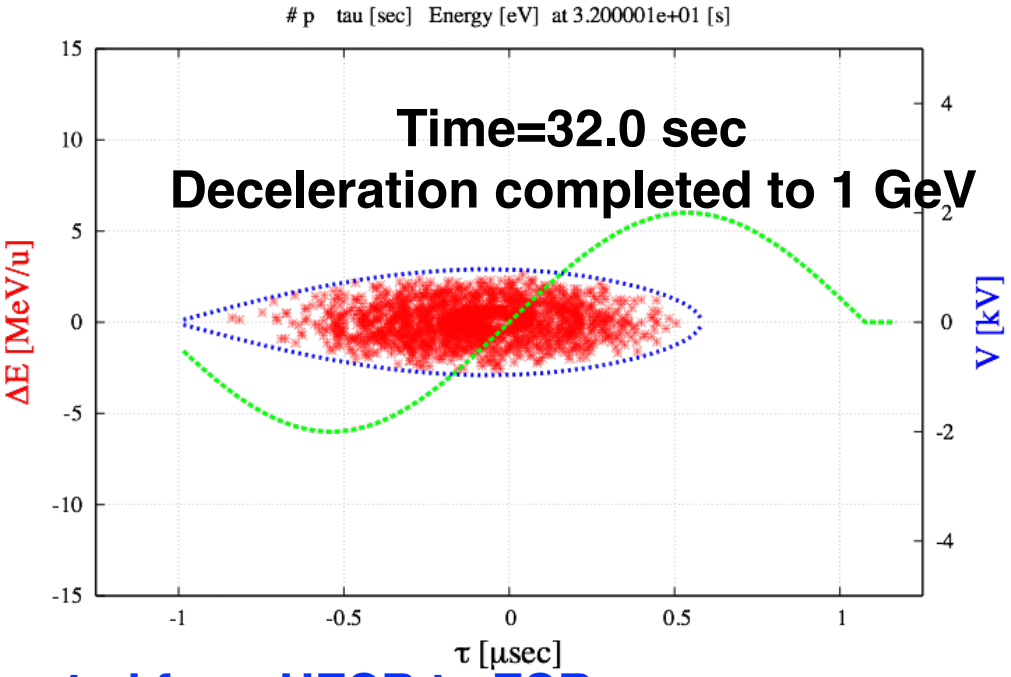


Or Bunched Beam Stochastic Cooling could be applied.

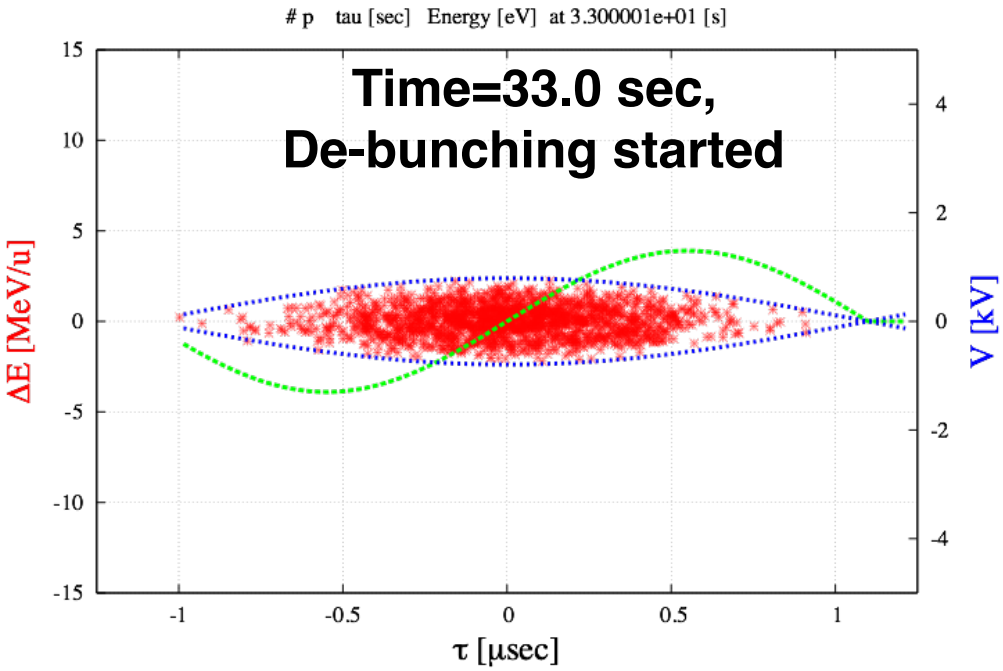


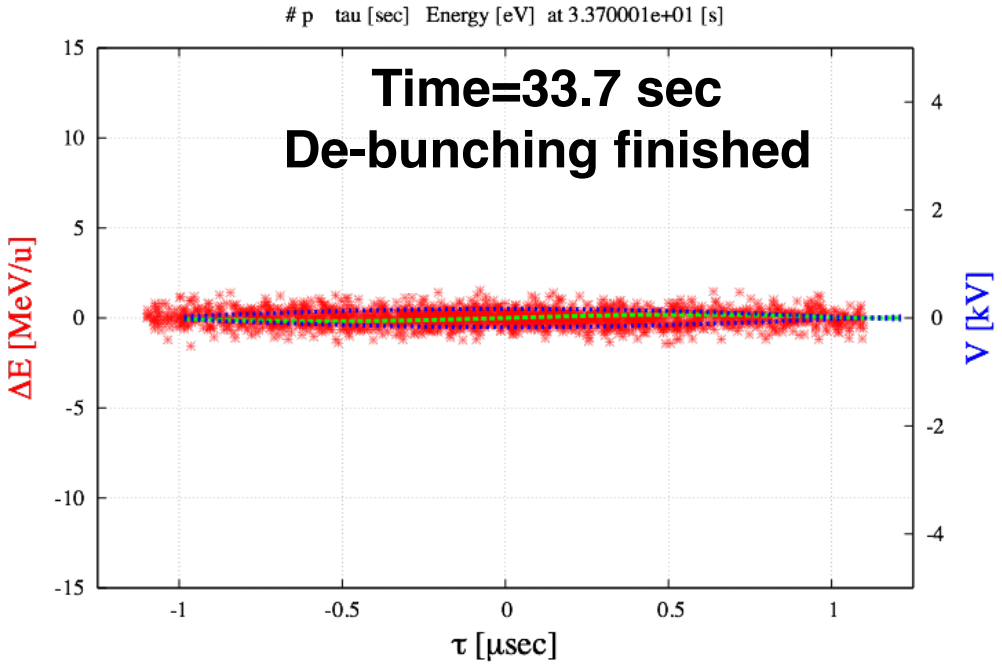




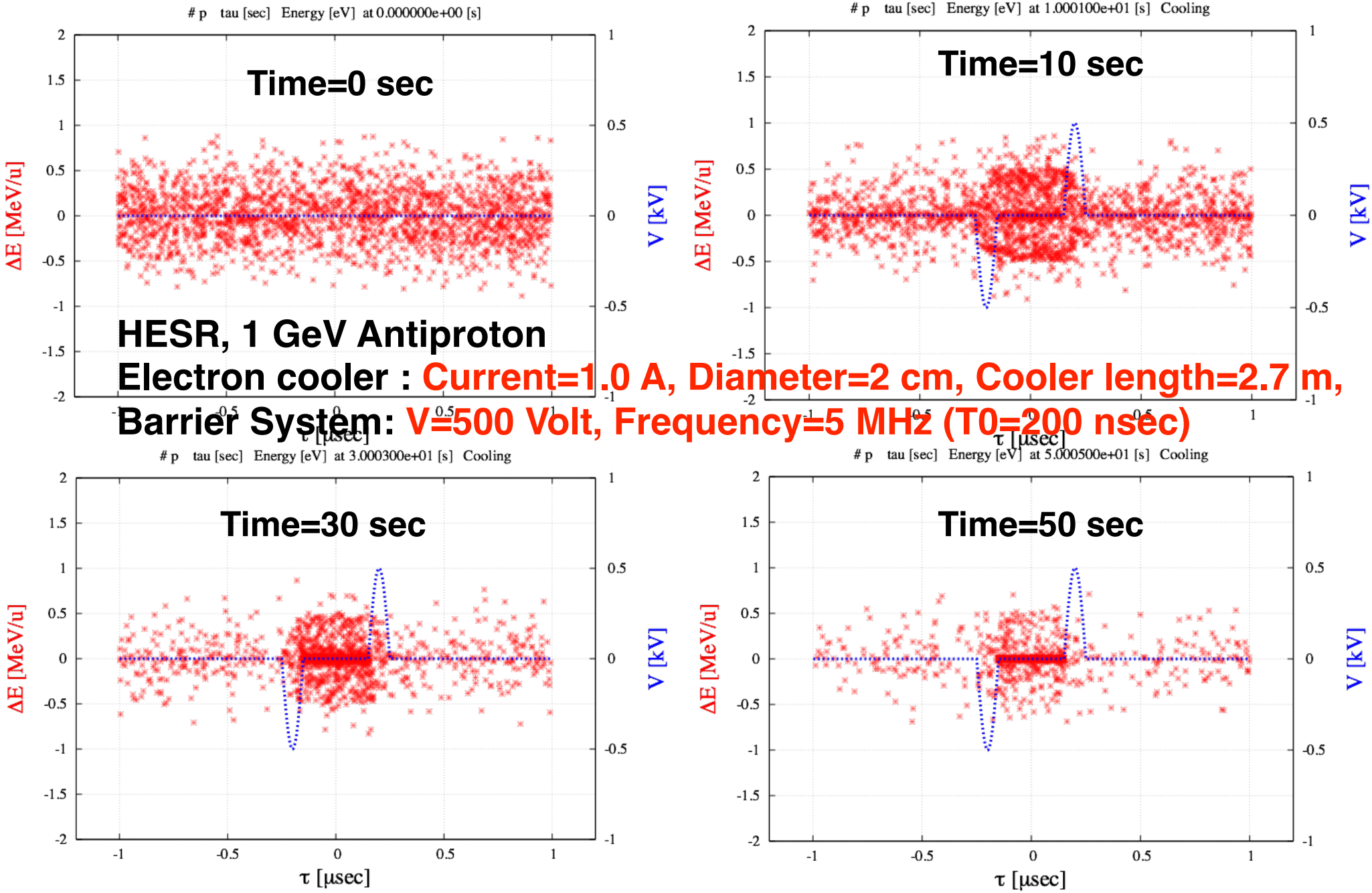


Or this bunched beam could be fast extracted from HESR to ESR


# 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
4
2
0
-2
-4
-1
-0.5
0
0.5
1


# 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
4
2
0
-2
-4
-1
-0.5
0
0.5
1

Short Bunch Formation of 1 GeV Anti-protons with Electron Cooling (One example !)



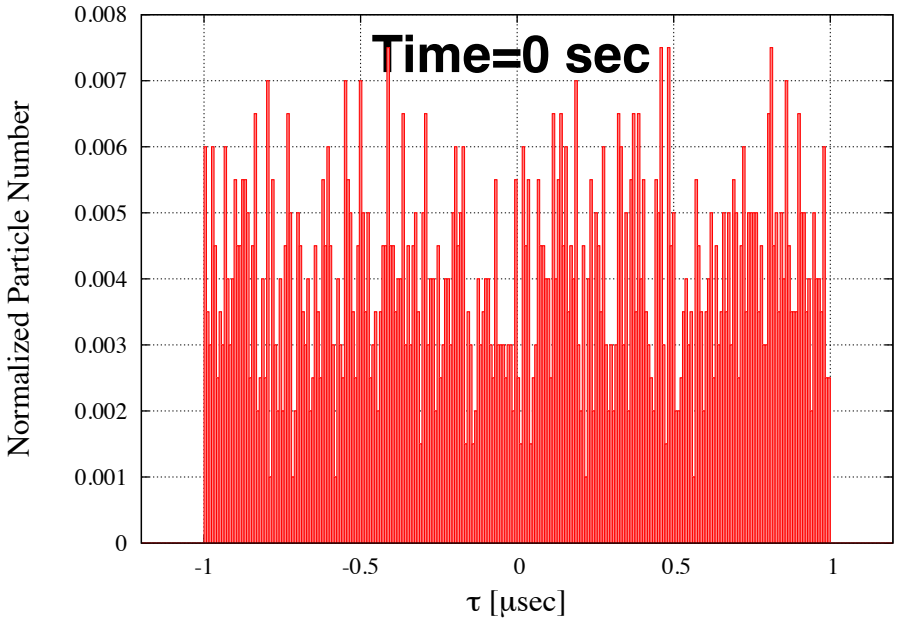
HESR, 1 GeV Antiproton
Electron cooler : Current=1.0 A, Diameter=2 cm, Cooler length=2.7 m,
Barrier System: V=500 Volt, Frequency=5 MHz (T0=200 nsec)

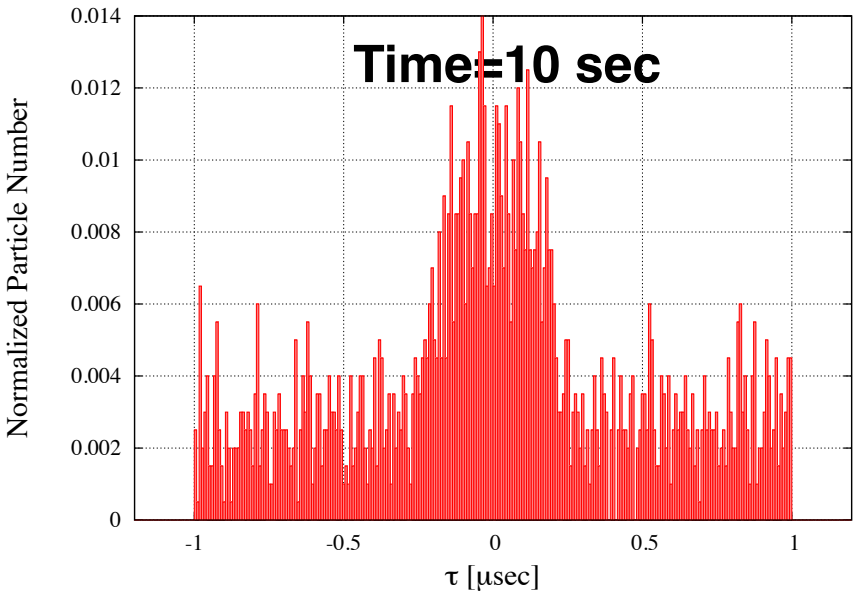
Evolution of Particle Distribution along Ring Orbit

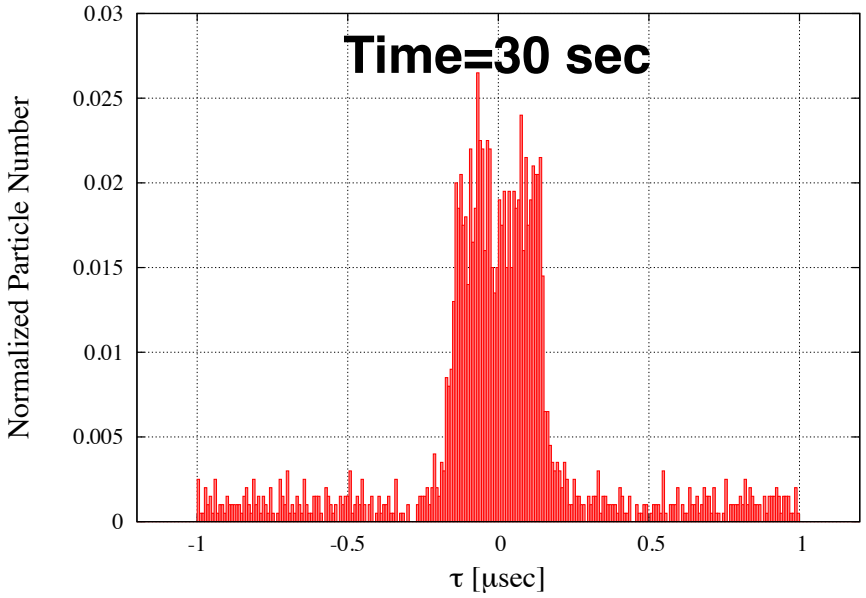
HESR, 1 GeV Antiproton

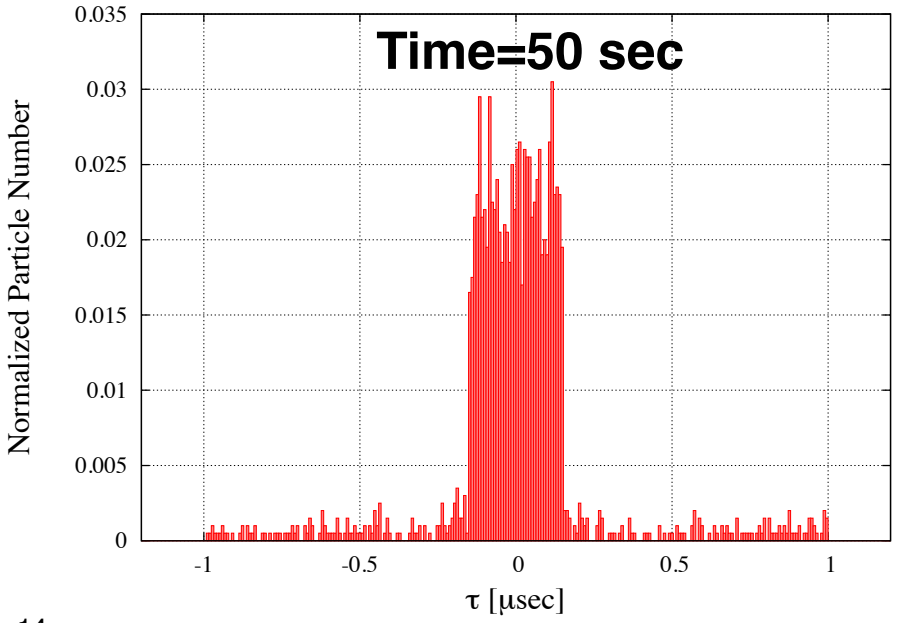
Electron cooler : Current=1.0 A, Diameter=2 cm, Cooler length=2.7 m,

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









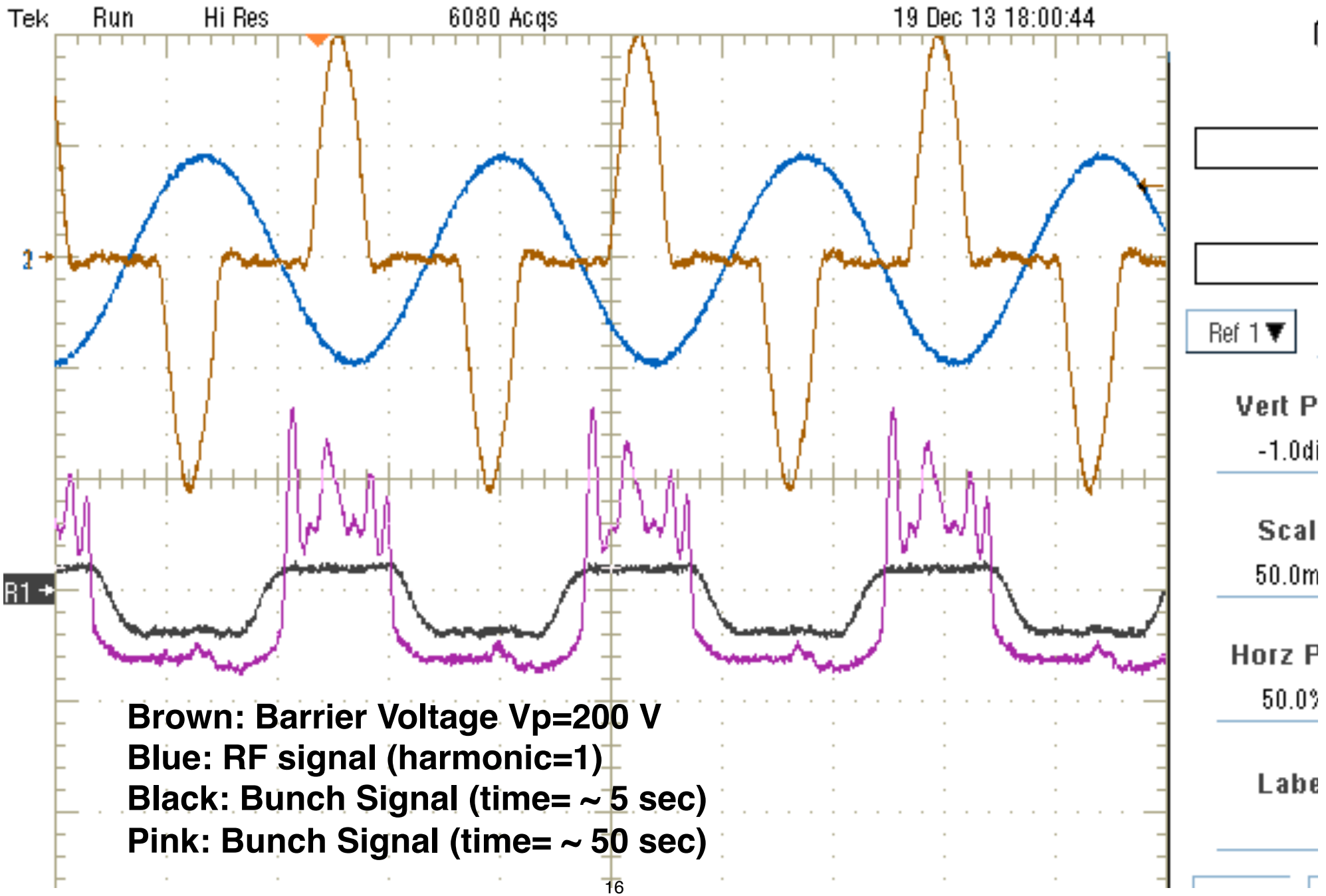
COSY Experiment of Short Bunch Formation
Parameters of Proton Beam and Electron Cooler

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

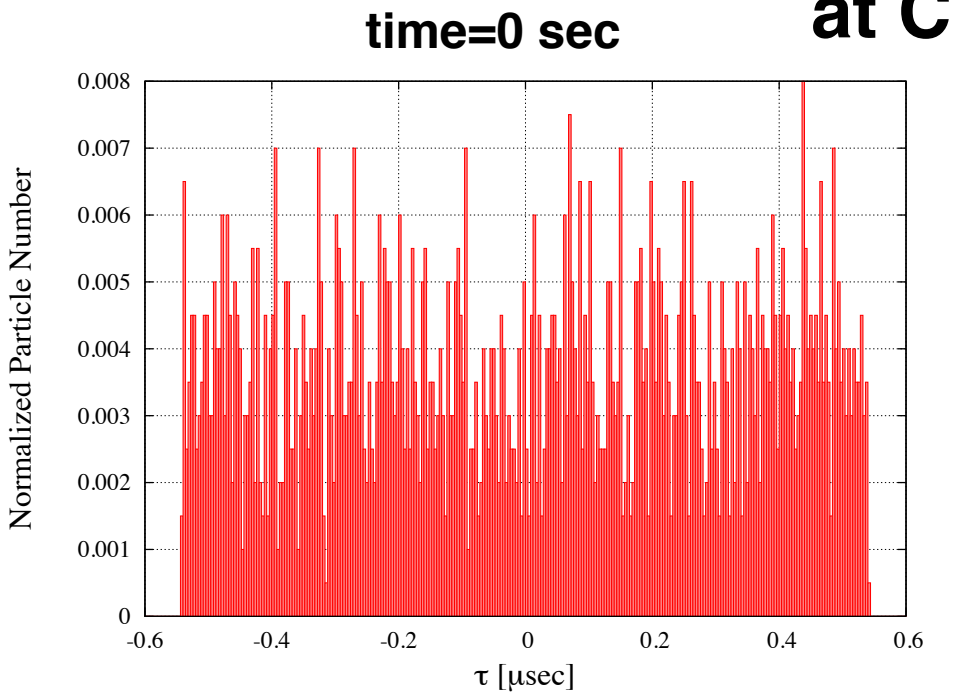
Electron cooler length: 2.7 m
Electron current: 200 mA
Electron diameter: 2 cm
Effective electron temperature: 5e-3 eV
Transverse electron temperature: 0.2 eV
Solenoid magnetic field strength : 0.1 Tesla

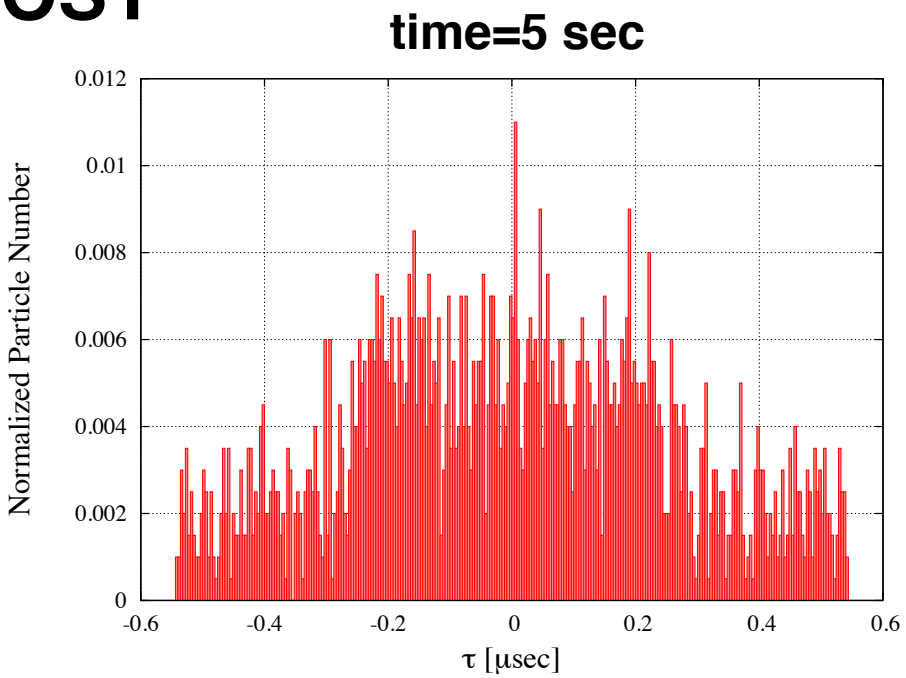
Short Bunch Formation Experiment with Electron Cooler at COSY

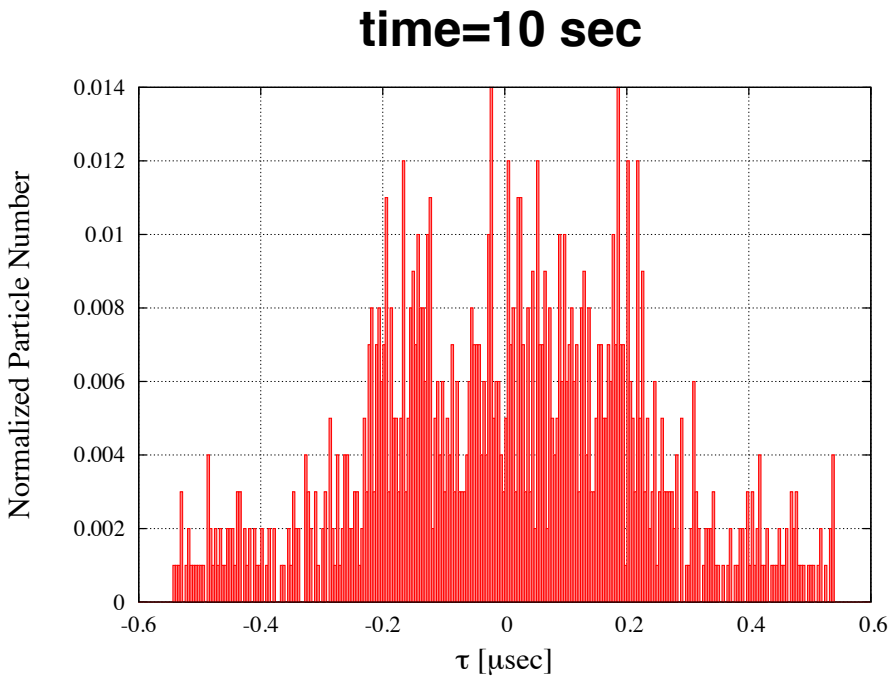


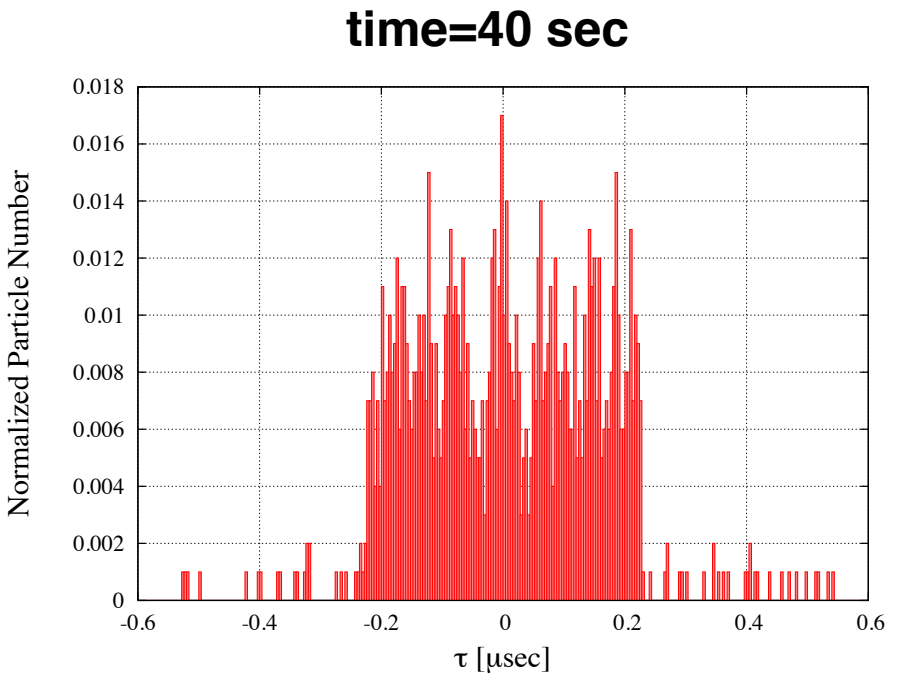
Brown: Barrier Voltage Vp=200 V
Blue: RF signal (harmonic=1)
Black: Bunch Signal (time= ~ 5 sec)
Pink: Bunch Signal (time= ~ 50 sec)

Short Bunch Formation Simulation with Electron Cooler at COSY



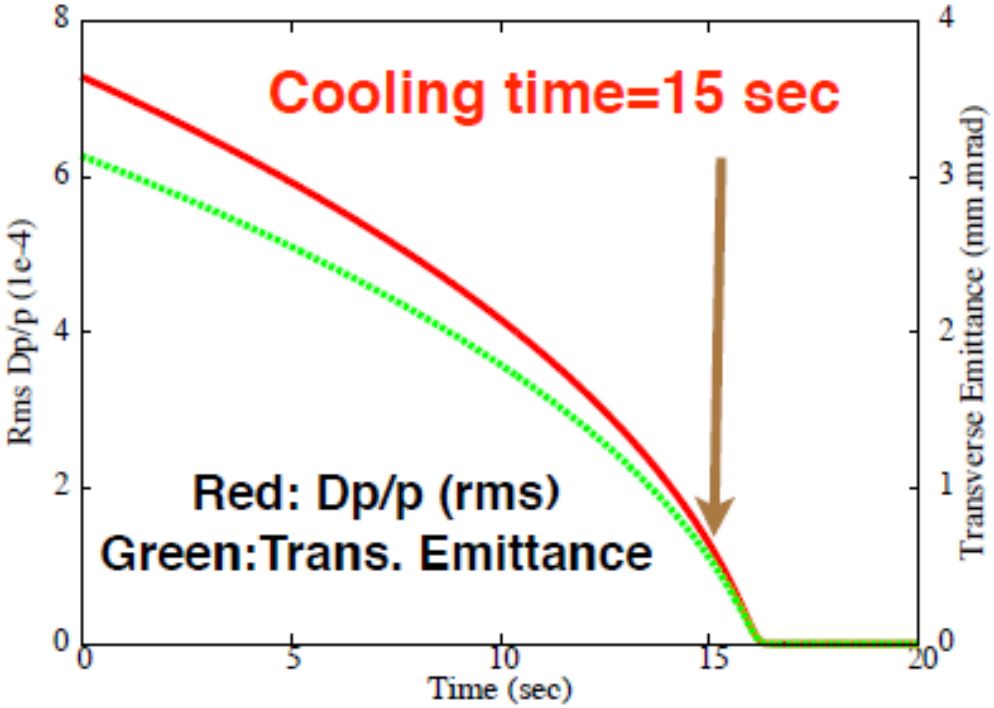




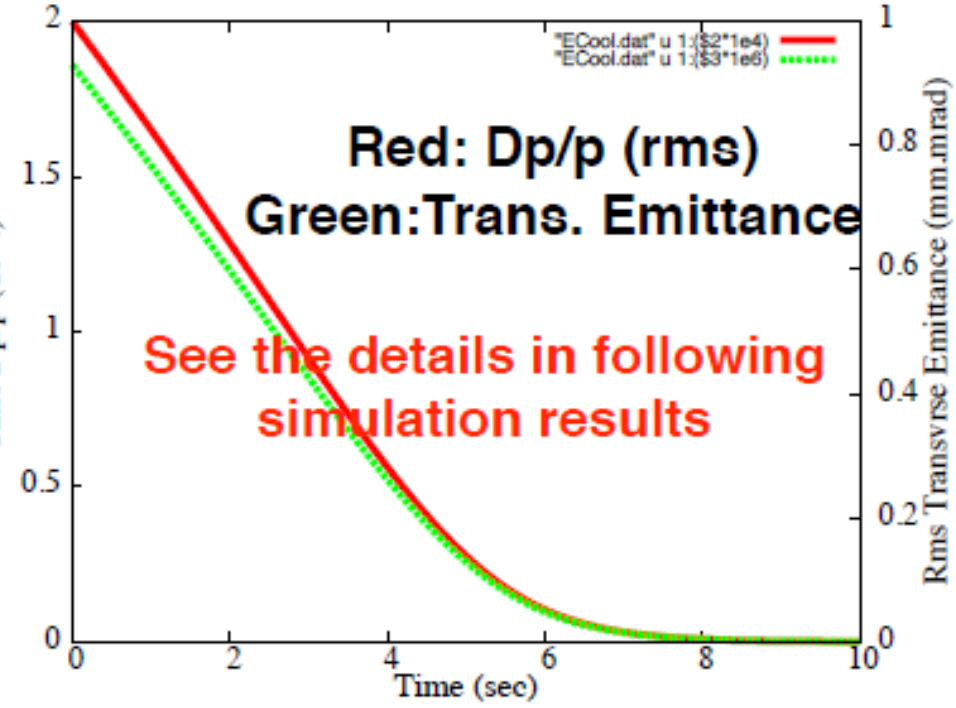


Electron Cooling in the ESR at Low Energy

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



T=30 MeV
Initial Dp/p=2.0e-4
Initial Transverse emittance=0.93 Pi mm.mrad
Diameter of electron beam=5 cm
Current of electron=0.05 A



Antiproton Deceleration in ESR & CRYRING

1 GeV: Less than transition energy of ESR

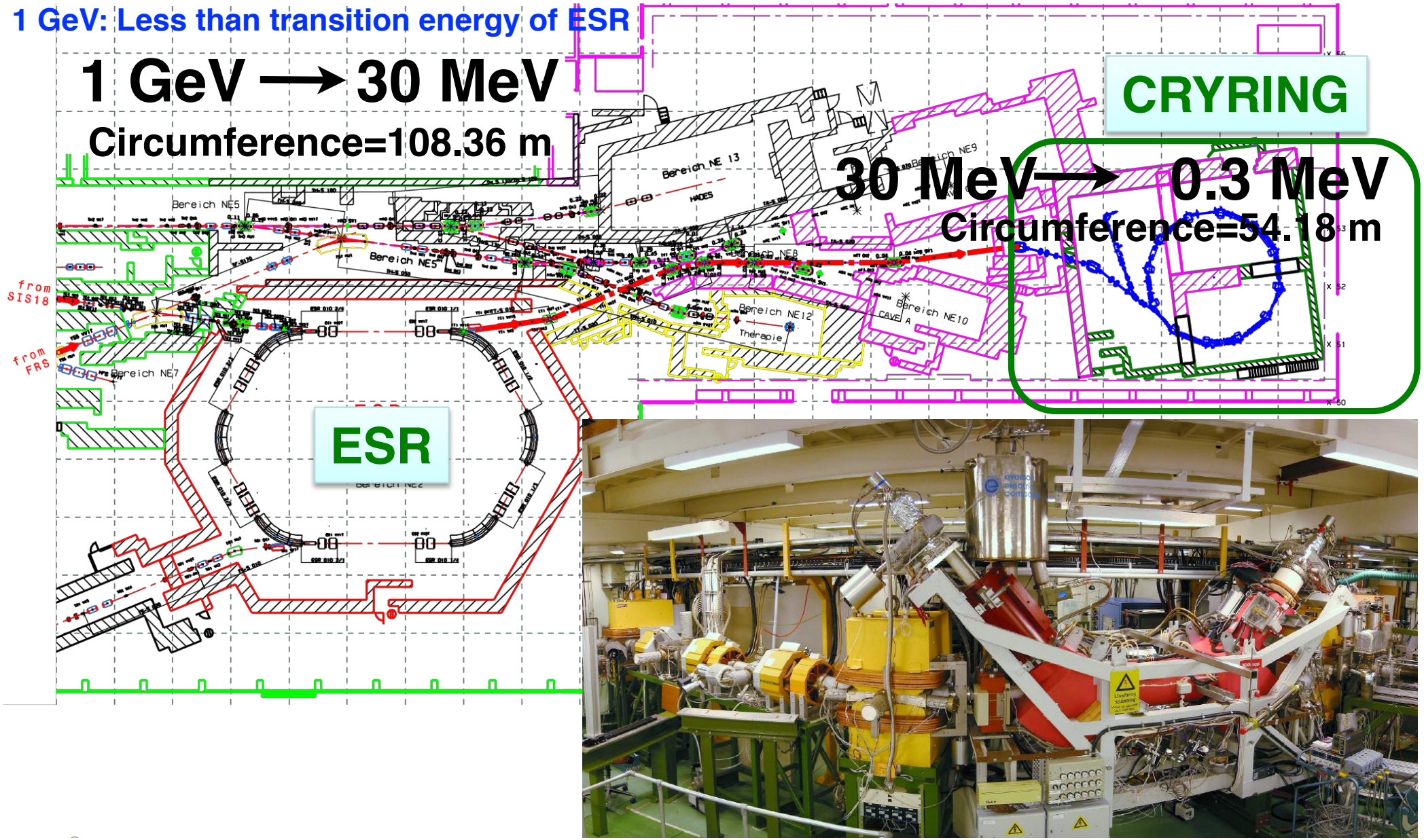
1 GeV ⟶ 30 MeV

Circumference=108.36 m

CRYRING

30 MeV⟶ 0.3 MeV

Circumference=54.18 m



CRYRING: Low Temperature Ecooler and Wide Band RF system.(0.14~1.4 MHz, 0.5kV)

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

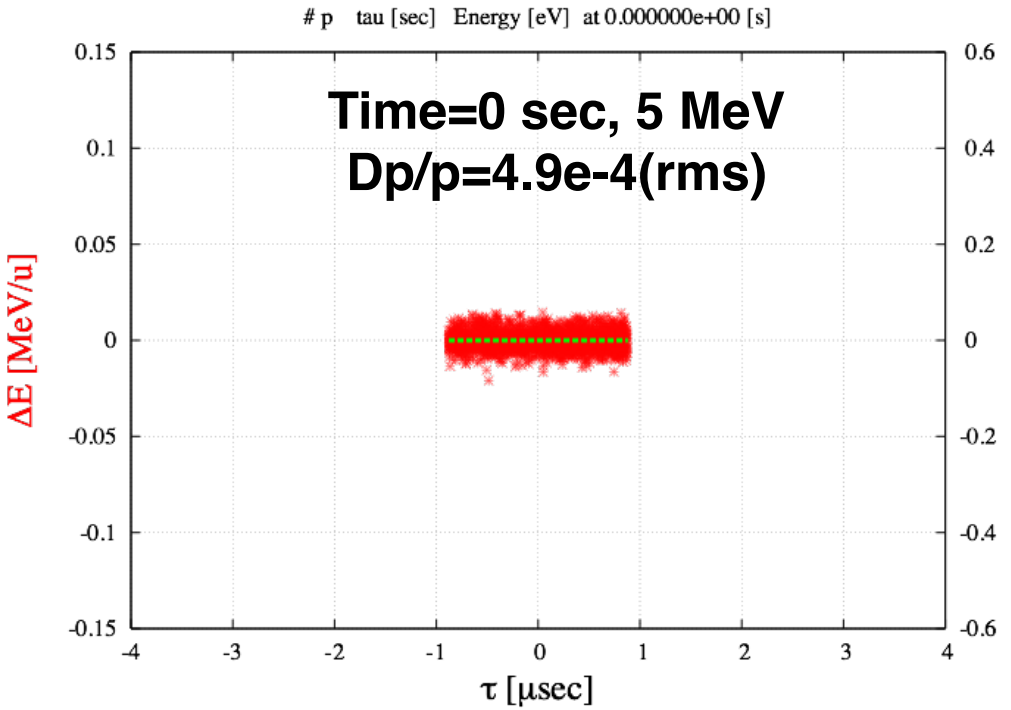
Electron Cooler Parameters

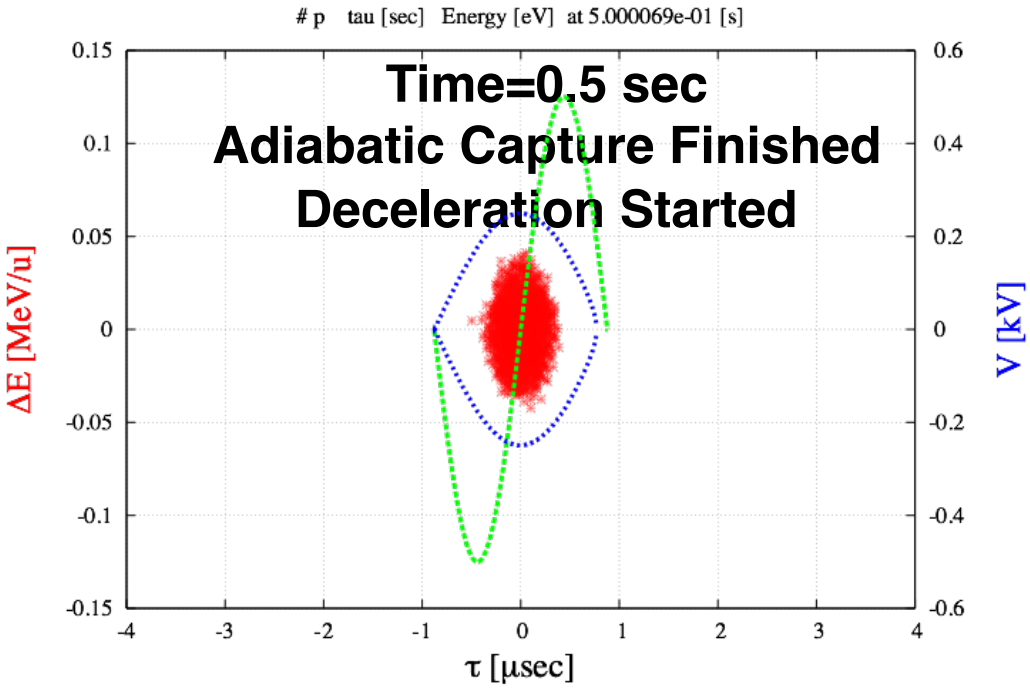
Cooler Length	1.1 m
Electron current	0.11 A
Electron beam diameter	5 cm
Solenoid field strength	0.1 (0.05) Tesla
Effective electron temperature	5e-3 eV
Transverse electron temperature	2e-1 eV

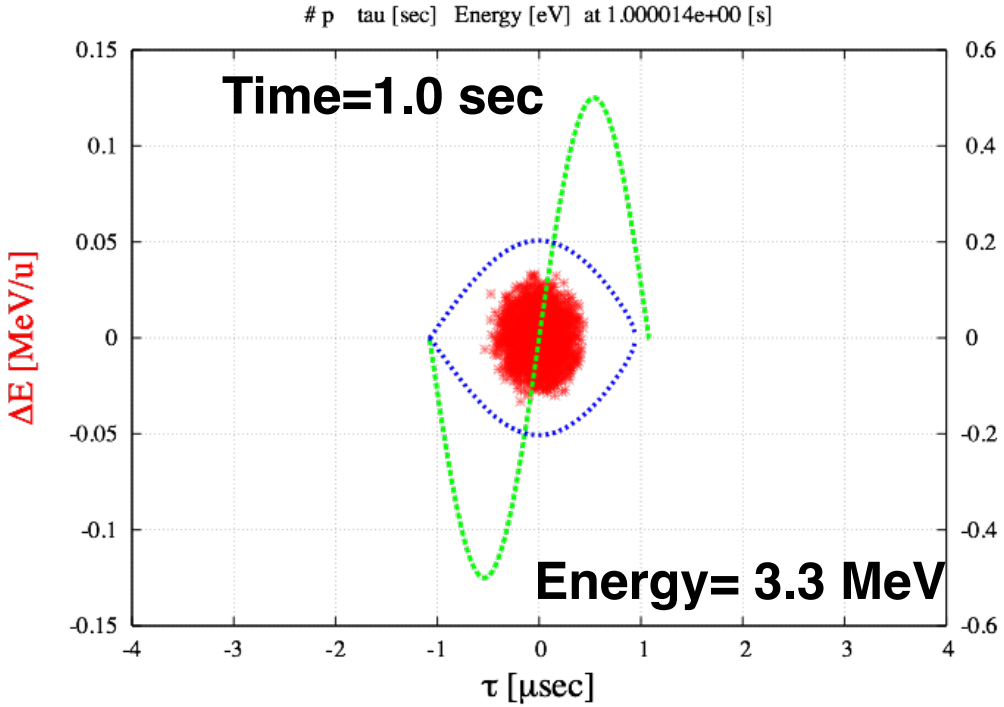
Deceleration of Antiproton Beam in CRYRING from 30 MeV to 0.3 MeV

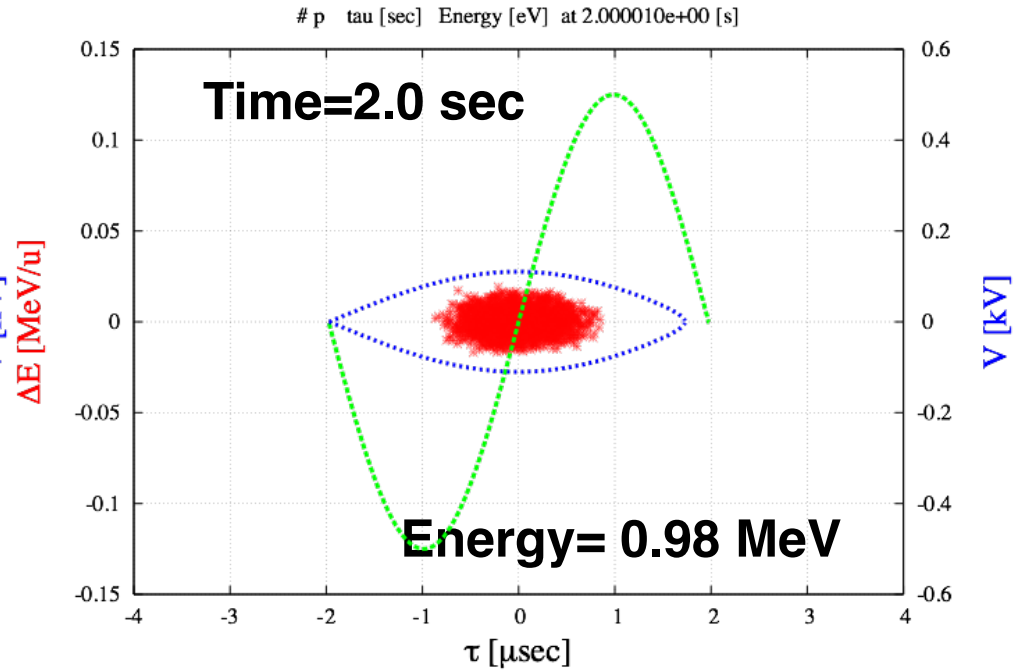
Injected Antiproton Energy: 30 MeV
Particle Number: 8e8
Pulse Length: +/-350 nsec
Dp/p (rms): 6e-4
Transverse Emittance (rms): 0.6 Pi mm.mrad

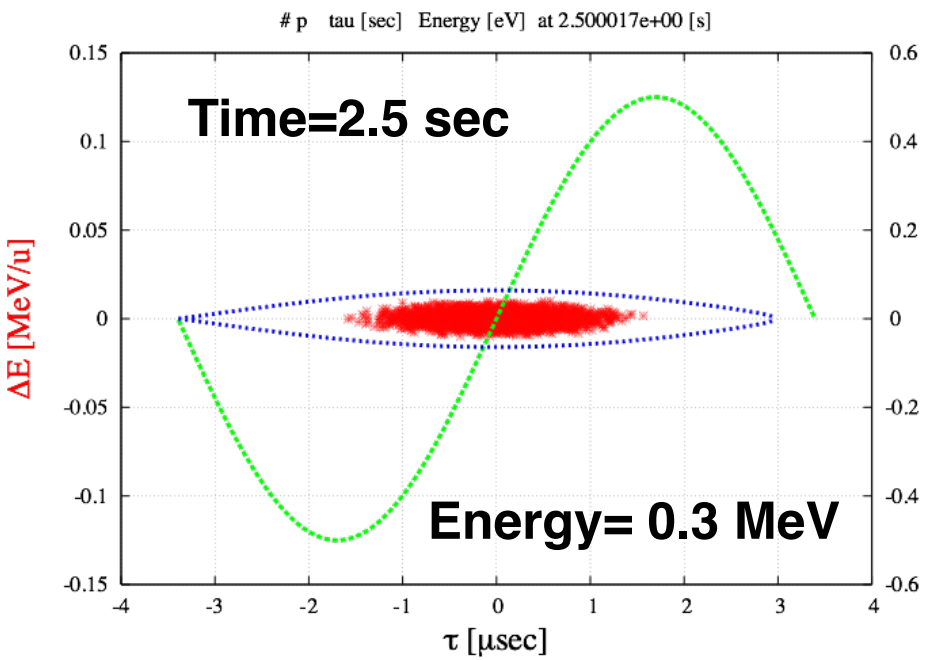
At 5 MeV Electron cooling will be applied to avoid the beam loss at ~ 1MeV.

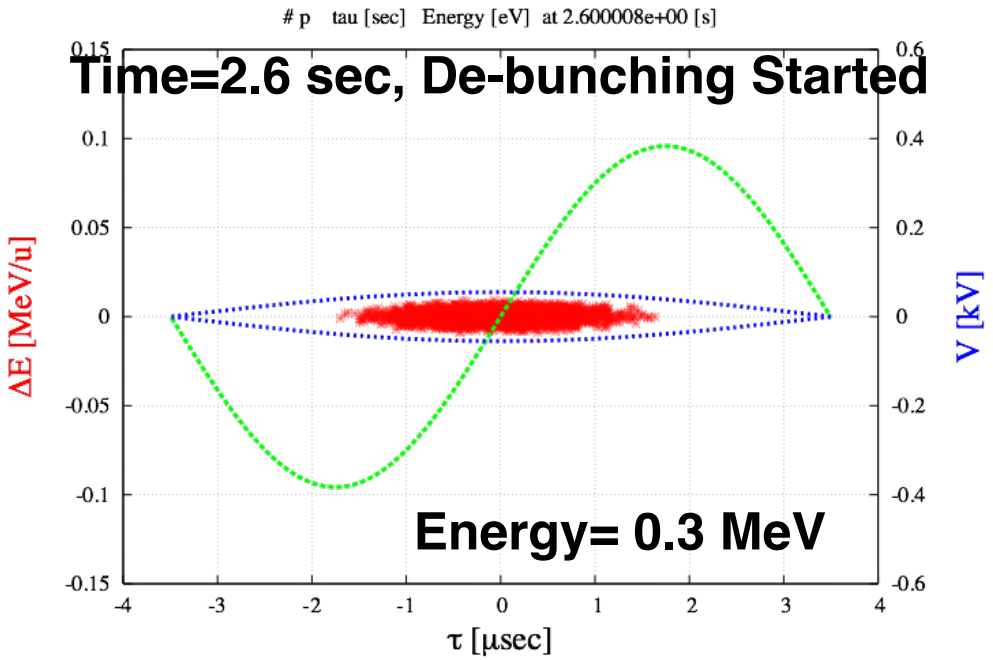

# p tau [sec] Energy [eV] at 0.000000e+00 [s]
Time=0 sec, 5 MeV
Dp/p=4.9e-4(rms)
ΔE [MeV/u]
V [kV]
τ [μsec]

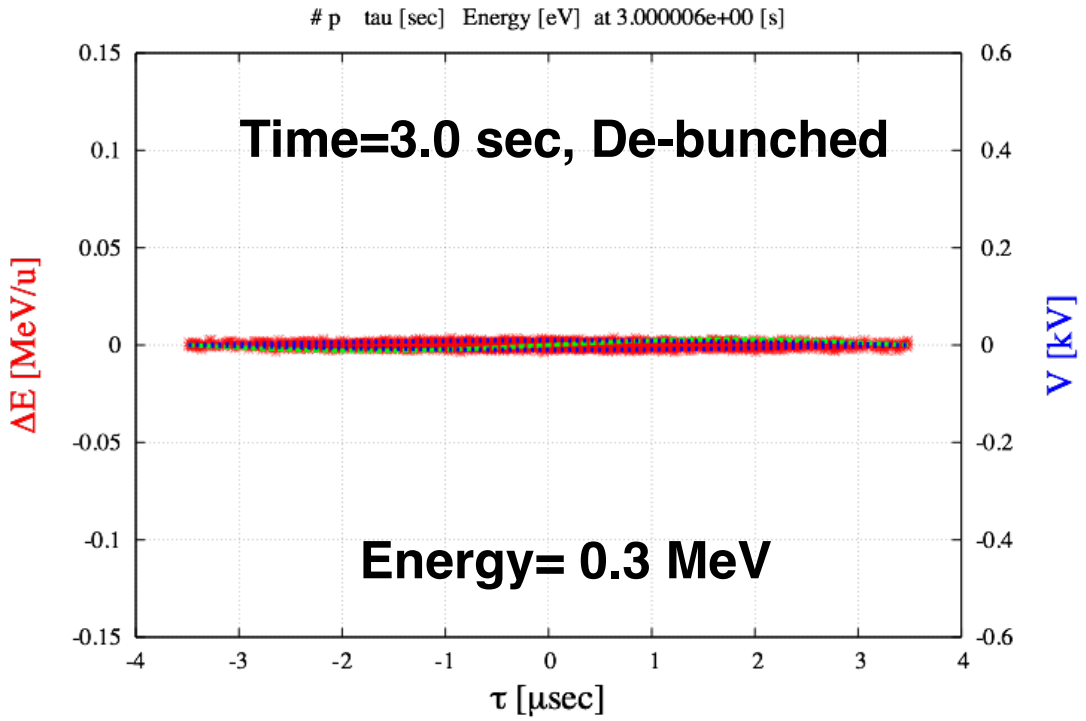

# p tau [sec] Energy [eV] at 5.000069e-01 [s]
Time=0.5 sec
Adiabatic Capture Finished
Deceleration Started
ΔE [MeV/u]
V [kV]
τ [μsec]


# 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]

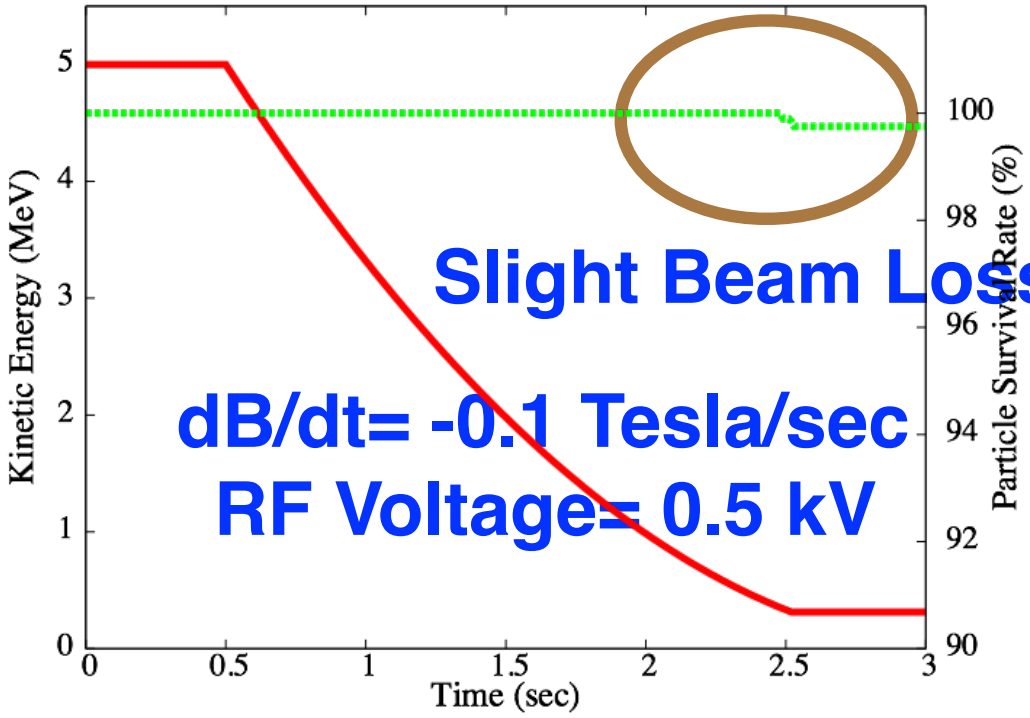

# p tau [sec] Energy [eV] at 2.500017e+00 [s]
Time=2.5 sec
Energy= 0.3 MeV
ΔE [MeV/u]
V [kV]
τ [μsec]


# 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]

Deceleration from 5 MeV to 0.3 MeV

Energy and Particle Survival Rate

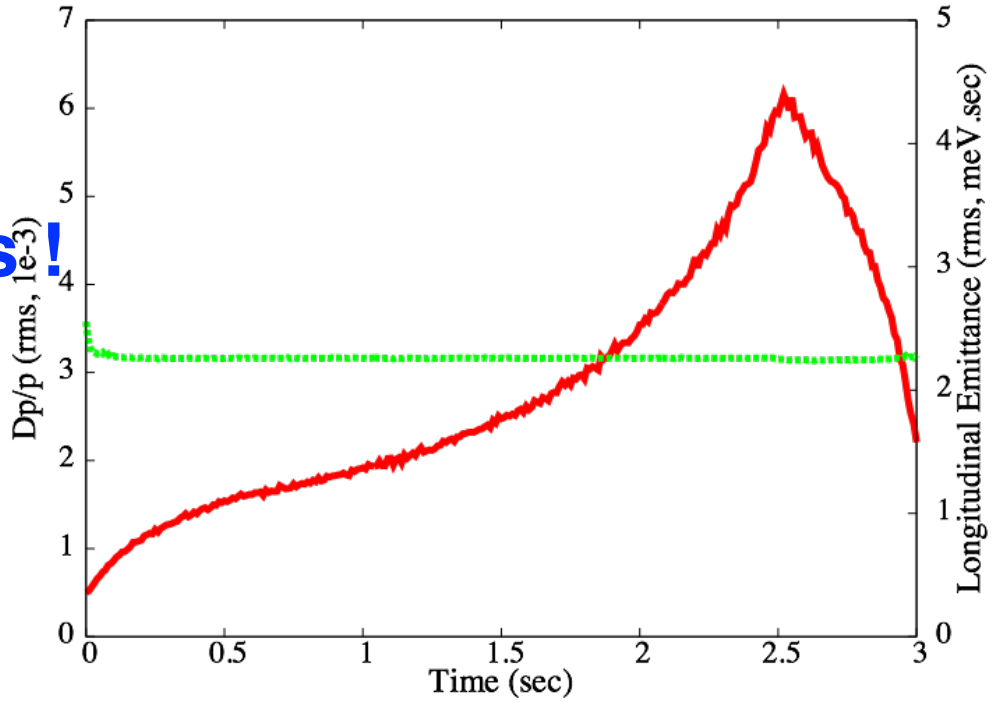


Slight Beam Loss!

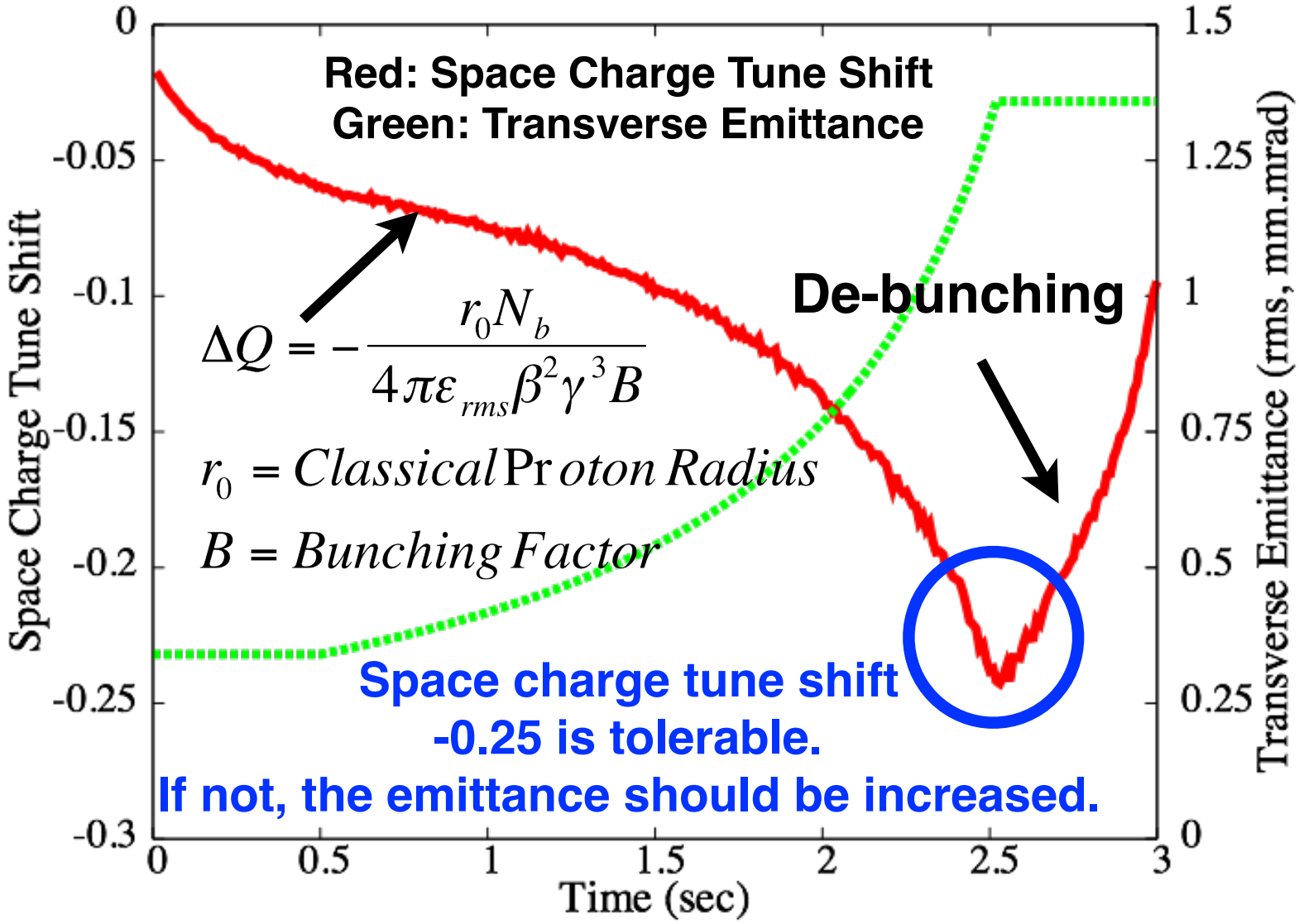
dB/dt= -0.1 Tesla/sec

RF Voltage= 0.5 kV

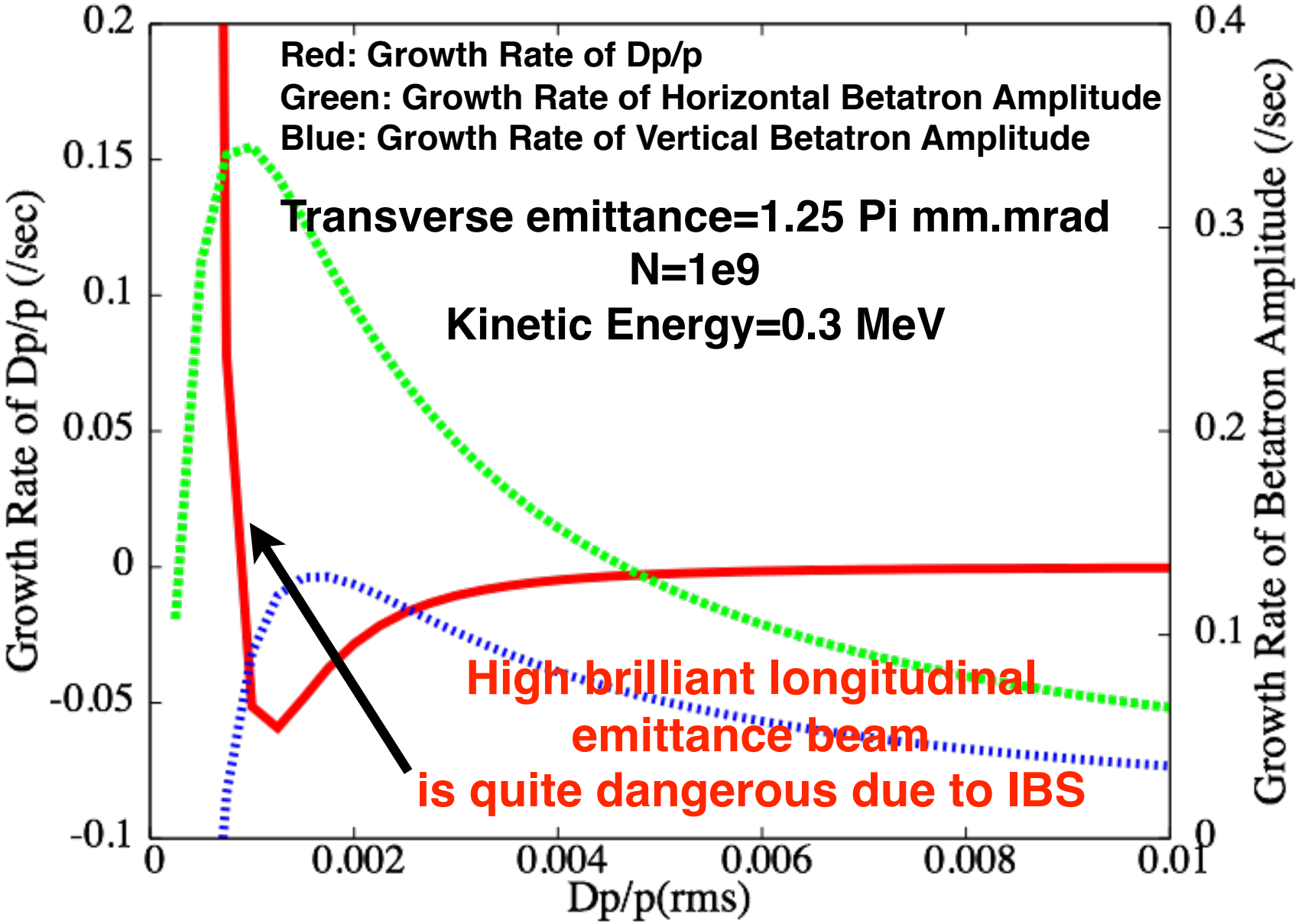
Red: Dp/p
Green: Longitudinal Emittance



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



Intra Beam Scattering Growth Rate



Summary of Antiproton Beam Parameters from CRYRING

Antiproton Energy: 0.3 MeV

Particle Number: 8e8 /220sec (No beam loss during the deceleration) Note: CERN AD 1~3e7/~100 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 (fast extraction case). Much improved for the slow extraction.

The space charge tune shift is -0.25 at the maximal at the lowest energy. Careful adjustment of transverse emittance is required. The IBS growth rate is 0.1~0.3/sec at 0.3 MeV which could be comparable to the period of lowest energy operation.

27

Summary and Conclusion

1. Stochastic cooling system at HESR could well support the 3 GeV antiproton beam accumulation up to N=1e9 with barrier bucket system within the period 100 sec. Also it support the deceleration down to 1 GeV. The short bunch could be formed by electron cooler in the HESR and thus short bunch beam could be transferred to ESR.
2. The transition energy of ESR is 1.24 GeV and injected beam is below the transition energy. Antiproton beam is decelerated down to 30 MeV with electron beam cooling at 100 MeV.
3. Low energy 0.3 MeV antiproton beam is available from CRYRING with the intensity N=8e8 in the period of 100 sec. Detailed technical design work is required including possible beam line from HESR to ESR.
4. Further low energy antiproton beam could be planned with the concept of Ultra Slow Antiproton Ring originally proposed in FLAIR proposal.

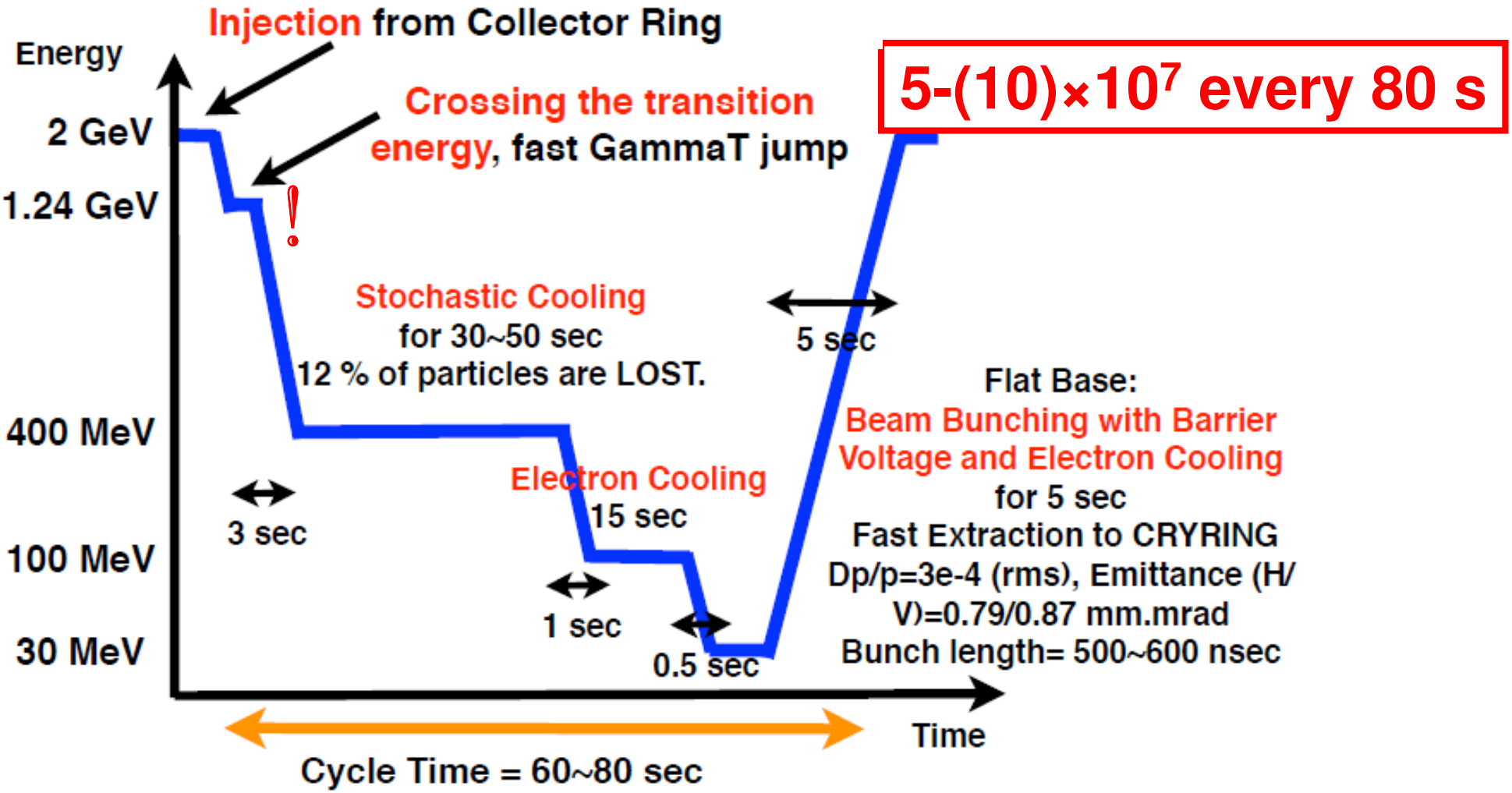
Tasks and Difficulties

1. **Beam transport line from HESR to ESR of 1 GeV antiproton beam. New beam line directly (short cut) from HESR to ESR could be realized ? Or other long beam line of north part could be used ?**
2. **Magnetic field of ESR and CRYRING could be reversed ?**
3. **Or anti-clock wise rotating antiproton beam in the ESR ?**
4. **In that case the new electron cooler for 100 MeV antiproton is necessary .**
5. **New fast kicker magnet for beam injection and extraction to/from ESR will be necessary.**
6. **Beam time sharing of RI and antiproton is feasible ?**
7. **Buget, manpower and schedule are reliably planned ? How may years it would take for the realization ?**
8. **What is the long range operation plan of AD/ELENA at CERN, as mentor and competitor ?**

Another concept ESR Antiproton Deceleration

Deceleration of Antiprotons in the Modularized Start Version of FAIR Employing the ESR Storage Ring

M. Steck
F. Herfurth, M. Lestinsky, Y. Litvinov, T. Stöhlker (GSI),
R. Maier, D. Prasuhn (FZJ), T. Katayama (Nihon University)

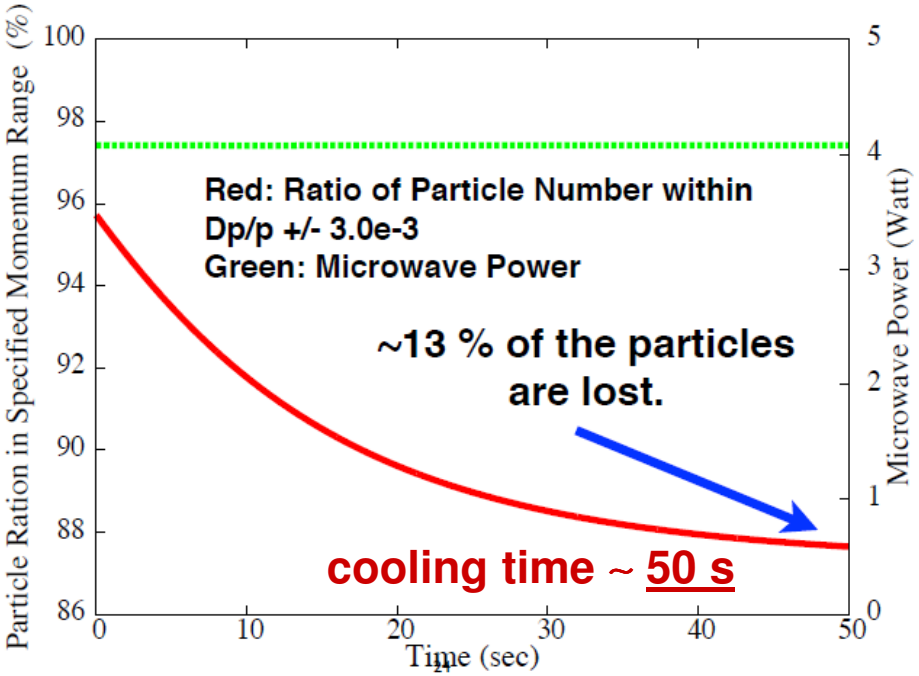


benefits from availability of stochastic and electron cooling in the ESR

Beam Cooling in the ESR at 400 MeV

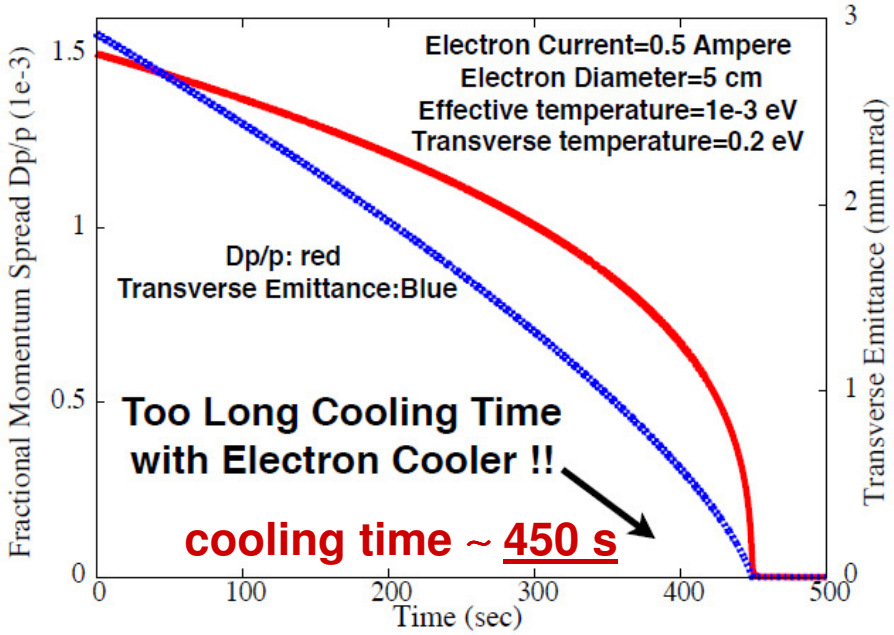
stochastic cooling

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



electron cooling

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



stochastic cooling is much better suited for antiproton beam parameters

Antiproton Cooling Parameters

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)

(rms values of coasting beam)

ELENA (Extra Low ENergy Antiproton) at CERN

Scheduled completion: in 2017

Circumference: 30.4 m (1/6 the size of AD)

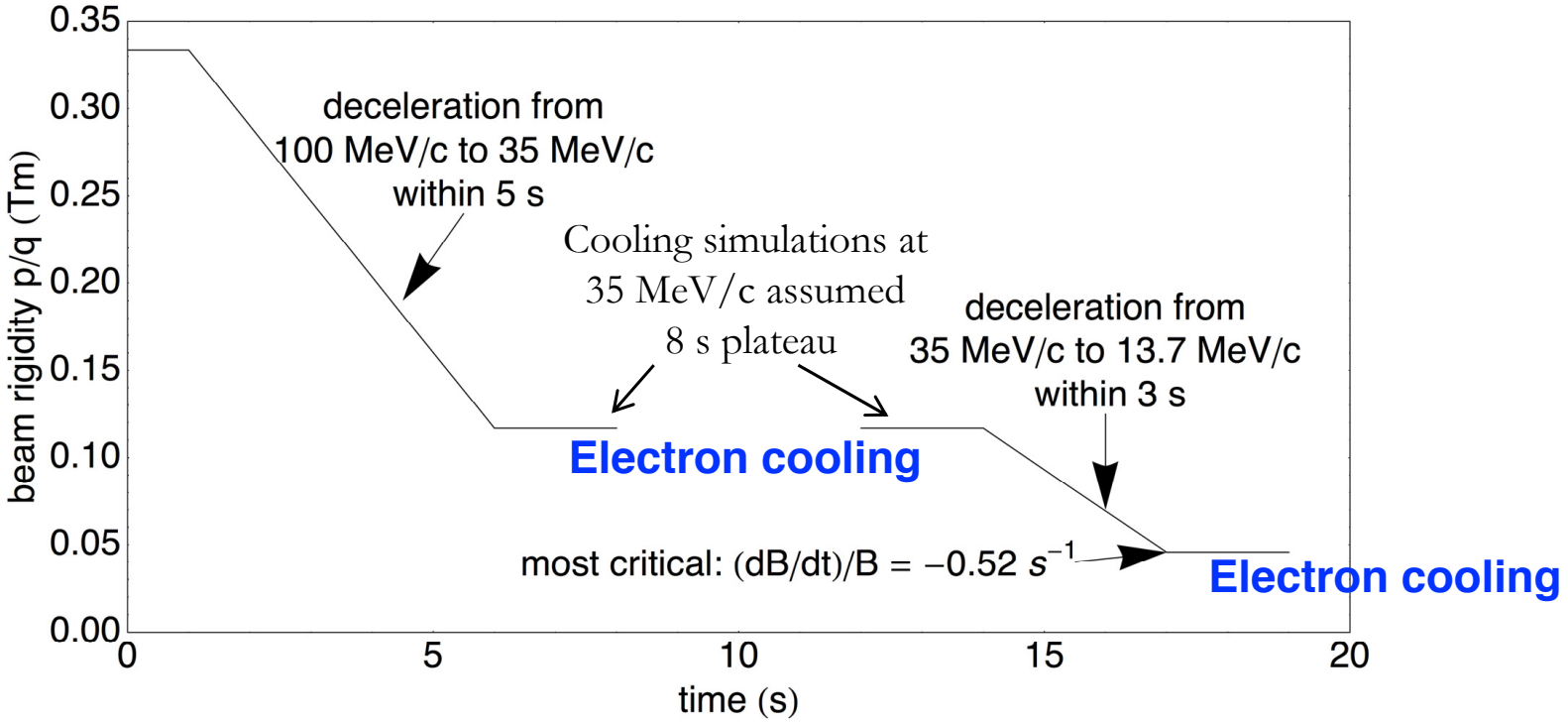
Injection Energy from AD: 5.3 MeV, Decelerated energy:100 keV

Intensity: 1.8e7/100sec (4 bunches),

Bunch length: 300 nsec (fast extraction)

Electron cooler: Energy= 355~55 eV, Current= 10~2 mA

Limit: Space charge tune shift= -0.4 (for 1 bunch), IBS blow up.



Courtesy of G. Tranquille