# Stochastic Cooling of RI Beam in the Collector Ring of FAIR

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## Outline

1. Cooling Objective
2. Characteristics of RI Beam & Bunch Rotation
3. TOF & Palmer Cooling
4. Combination of TOF, Palmer and Filter Cooling
5. Adiabatic Bunching for Fast Extraction
6. Matching to HESR Acceptance & Conclusion

**Ackowledgement: to the late D. Moehl (CERN) , H. Stockhorst, R. Stassen (FZJulich) and B. Franzke (GSI) for valuable discussions.**

# Collector Ring Objectives

**Objective1: 3 GeV Antiproton Beam Cooling**

- Full cooling time < 10 sec with Filter cooling
- Transition gamma=3.85, Ring slipping factor=-0.011
- Injection into HESR and Accumulation

**Objective 2: 740 MeV/u Heavy Ion Beam Cooling**

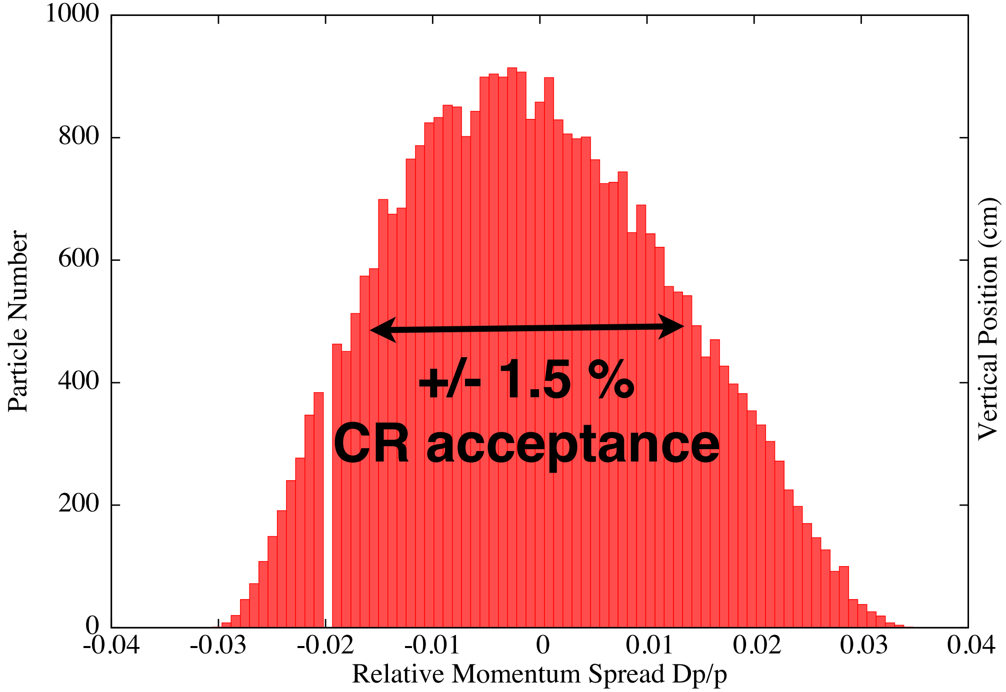
- Full cooling time < 5~10 sec, Transition gamma=2.73
- Slipping factor=0.178 results in small Dp/p accepatance of Filter cooling system.
- Injection into HESR, might be accumulated.

**Limitation**

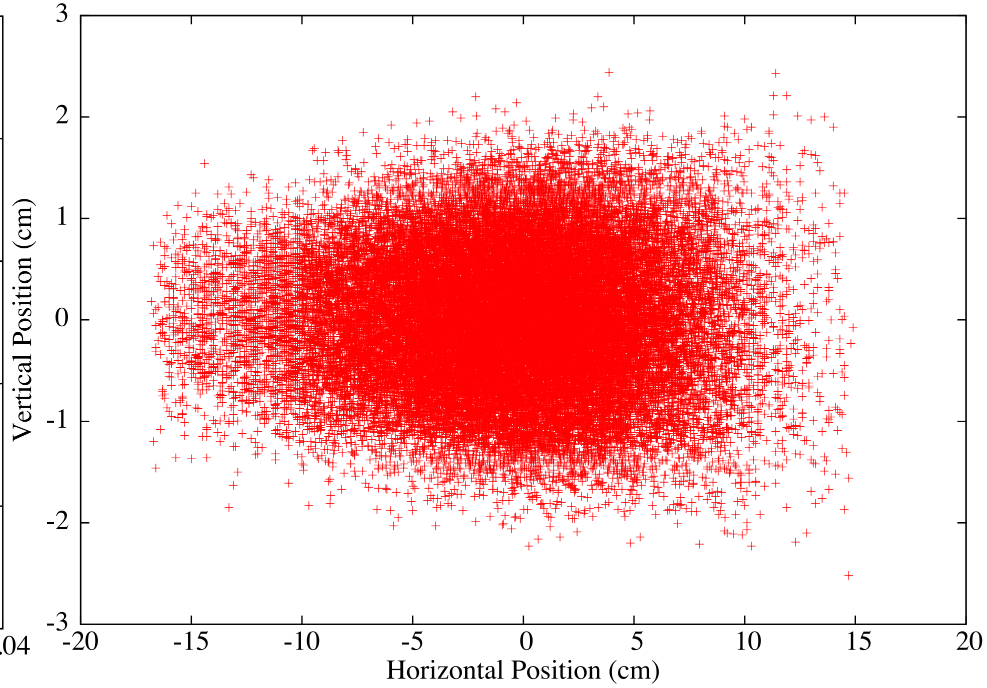
- Available Microwave power < 4.8 kW (for Long. and Transverse)
- Longitudinal < ~1.6 kW (Effective), Gain is limited.

# Momentum Spread & Transverse Emittance of 132Sn50+ Beam after Super Fragment Separator

## Momentum Spectrum




## Real Space (Horizontal/Vertical)




**Momentum spread:**

Rms Dp/p=1.25e-2

**Collector Ring Acceptance**
**Dp/p= +/- 1.5 %**

**Beam Emittance (rms):**

90.65 Pi mm.mrad (Horizontal)

44.26 Pi mm.mrad (Vertical)

**Collector Ring Acceptance =**
**45 Pi mm.mrad (rms)**

# Bunch Rotation of Heavy Ion Beam in CR

| | |
|---|---|
| Ion | 132Sn50+ |
| Kinetic energy | 740 MeV/u |
| Number of bunch | 1 |
| Total number of RI | 1e8 |
| Momentum width (full width) | +/- 1.5 % |

Gaussian (rms value=1.25% and truncated at +/-1.2 rms value)

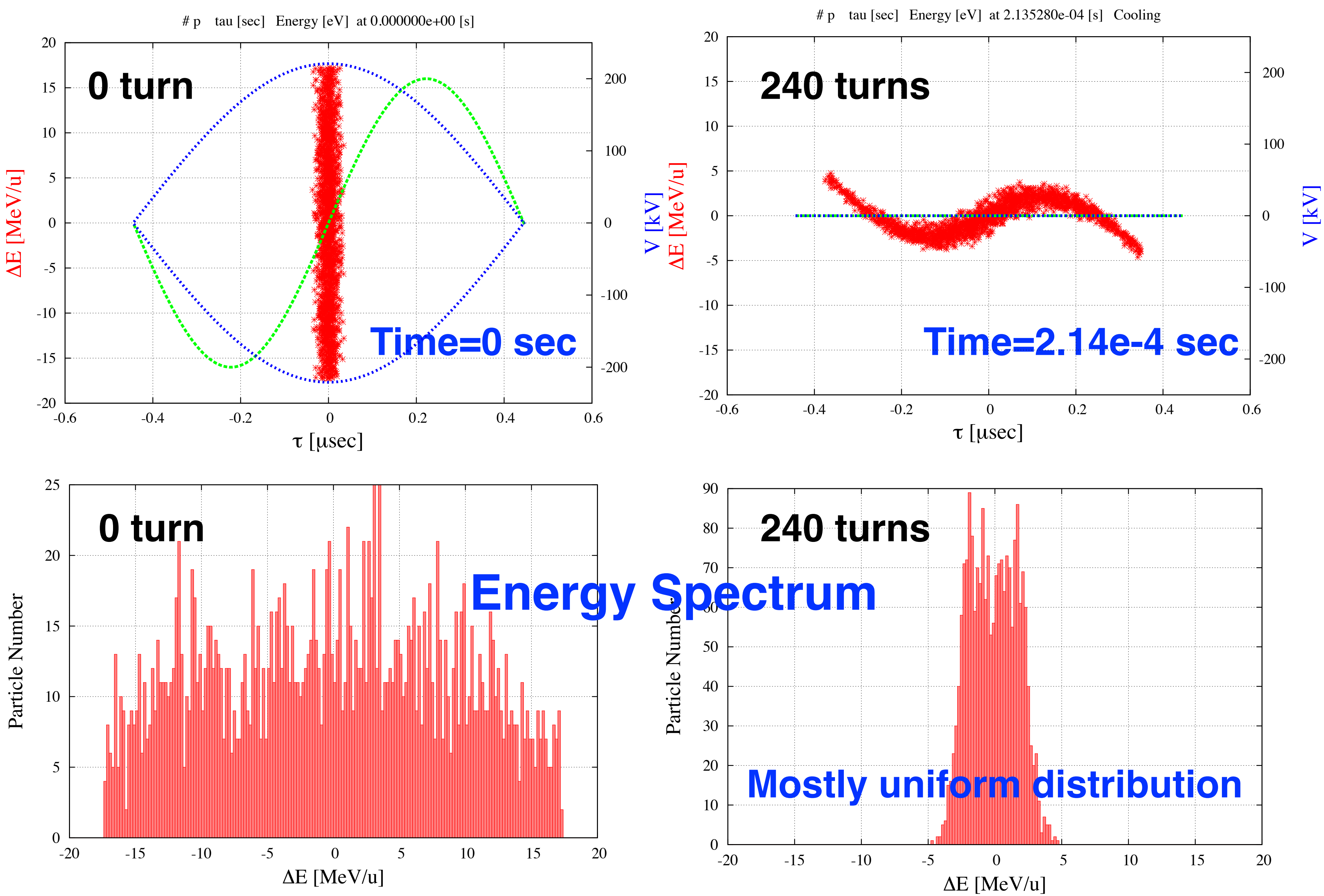
| | |
|---|---|
| Bunch width (full) | +/- 37.5 nsec |

Gaussian (rms value =12.5 nsec and truncated at +/- 3.0 rms value)

Determined by the bunch length of primary beam from SIS100.

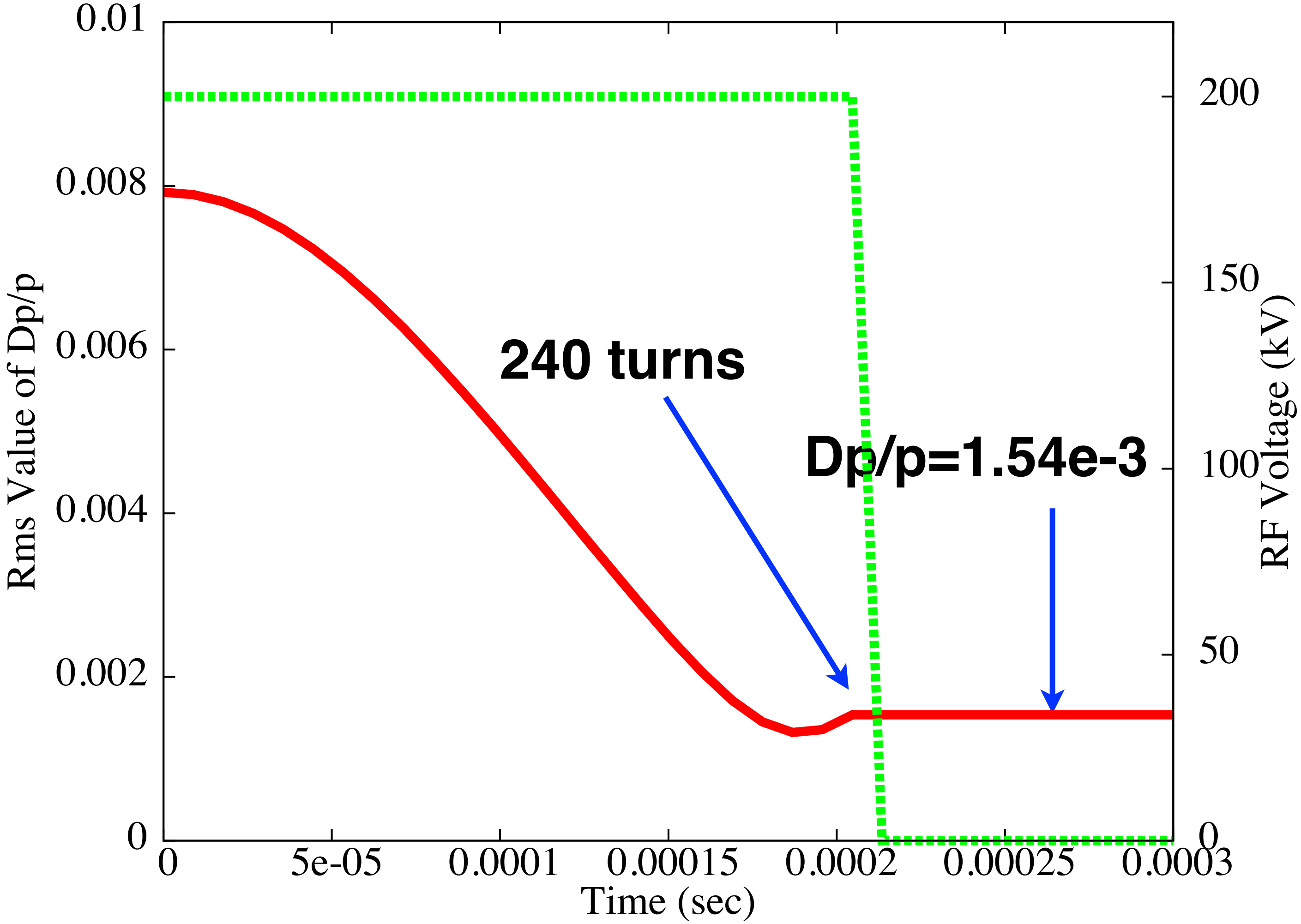
| | |
|---|---|
| Ring slipping factor | 0.178 |
| Revolution frequency | 1.148 MHz |
| RF harmonic number | 1 |
| Maximum RF voltage | 200 kV |

# Particle distribution and RF voltage

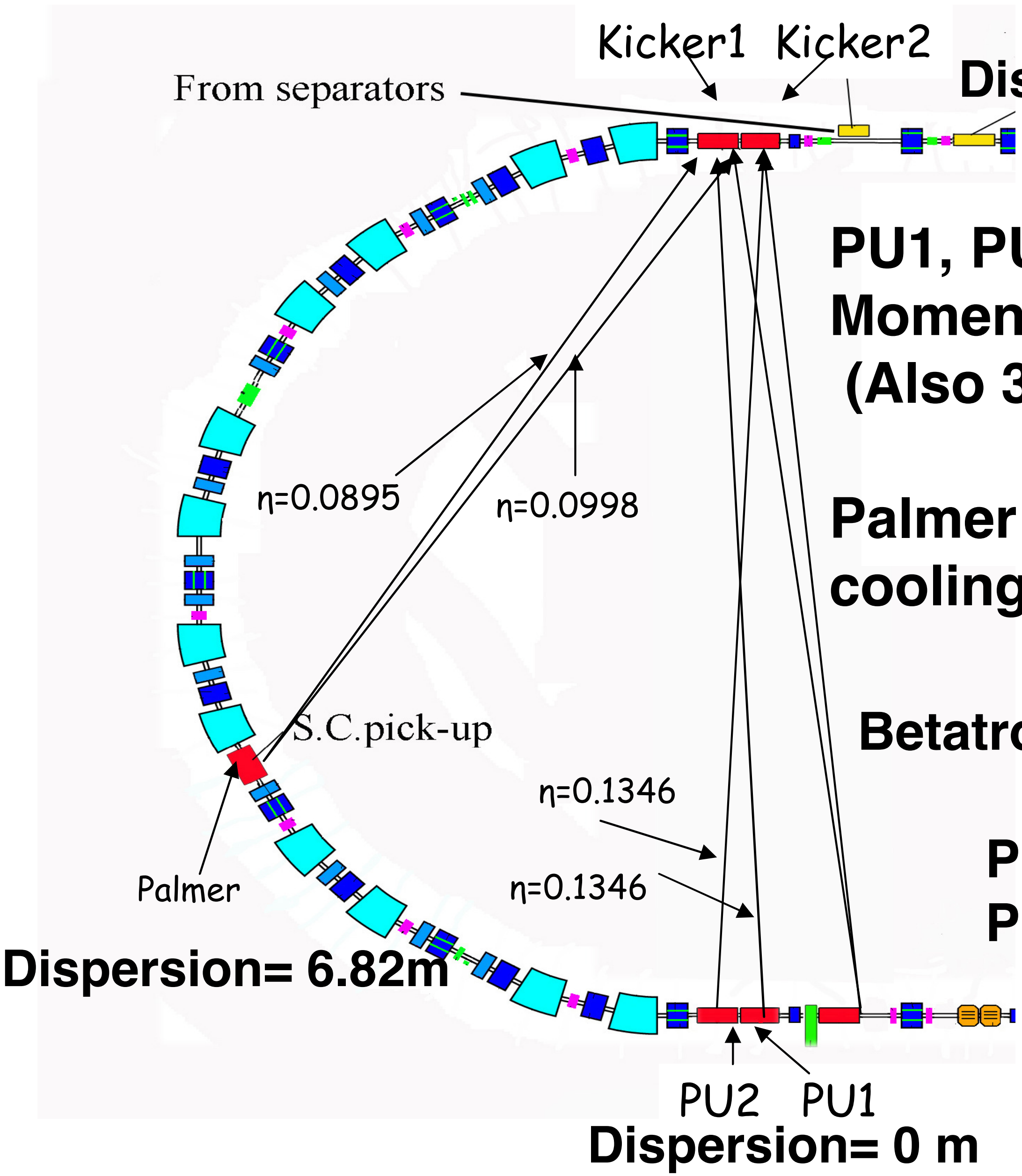


# RF Voltage Pattern: Apply 200 kV during quarter synchrotron oscillation period and switched off.

**Rms Dp/p (red)　　RF Voltage pattern (Green)**



# Layout of PU and Kicker of Stochastic Cooling in the Collector Ring, Band Width=1~2 GHz




**PU1, PU2, K1, K2 : Filter & TOF Momentum cooling + Betatron Cooling (Also 3 GeV Antiproton Beam Cooling)**

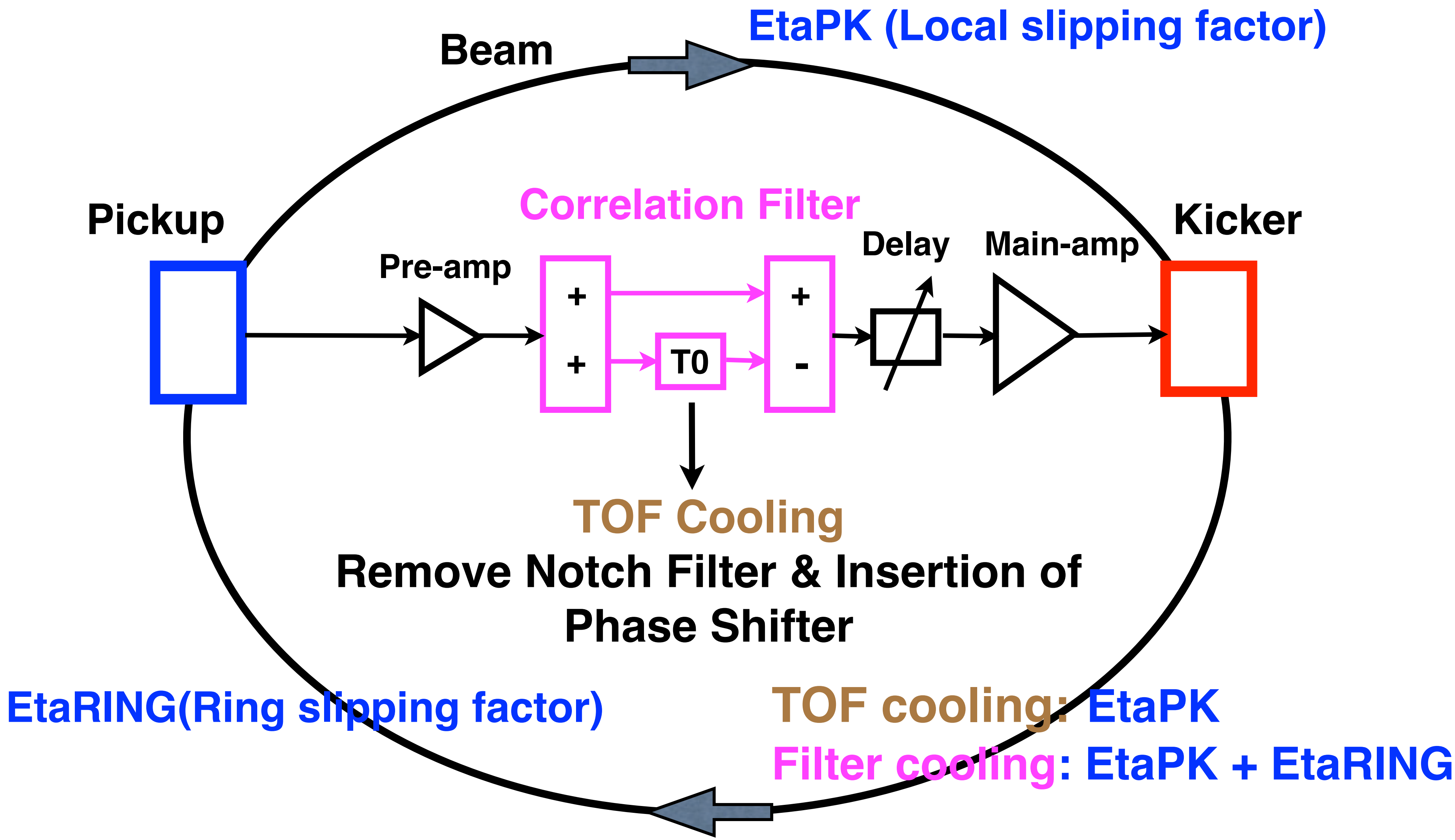
**Palmer PU, K1,K2: Palmer Momentum cooling**

**Betatron Phase advance from PU1, PU2 to Kicker**

**PUI --> K : 4.41/4.61 rad (H/V)**

**PU2--> K : 4.55/4.71 rsd (H/V)**

# SetUp of Filter and TOF Cooling




(Ref.) W. Kells, "Filterless Fast Momentum Cooling", 11th Int. Conf. on High Energy Acc. (1980)

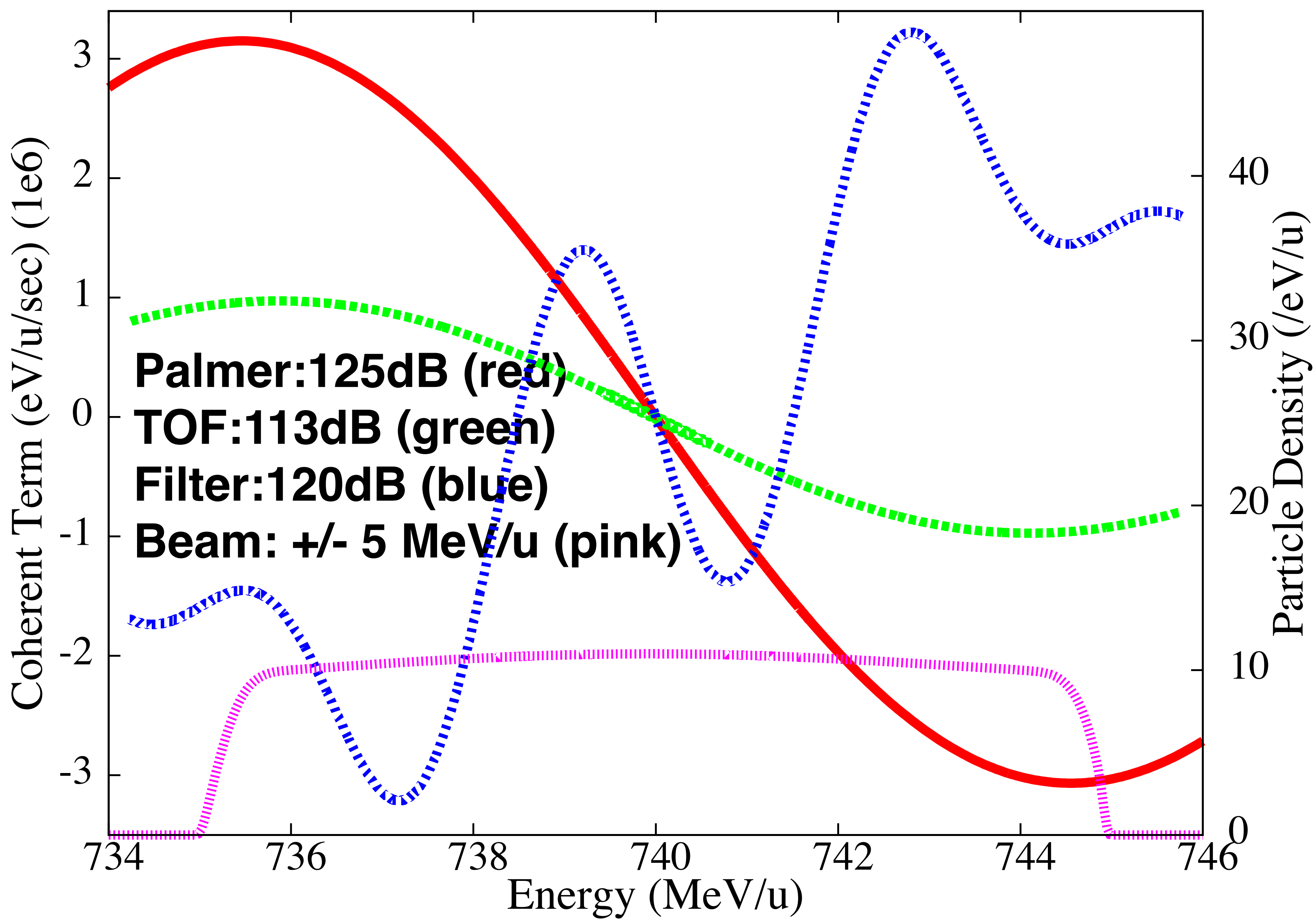
# Three Methods of Momentum Cooling

| | Signal PU | Hardware | Advantage | Disadvantage |
|---|---|---|---|---|
| Palmer | Difference Signal of Two Horizontal Electrodes | PU has to be set at Dispersion section | Wider Momentum Acceptance | Straight section with Large Dispersion |
| TOF | Sum Signal of Two Electrodes | PU set at Dispersion Free section | Wider Momentum Acceptance | Long cooling time/Large eq Dp/p |
| Notch Filter | Sum Signal of Two Electrodes | PU set at Dispersion Free section Notch Filter | Short cooling time/Small eq Dp/p | Small Momentum Acceptance |

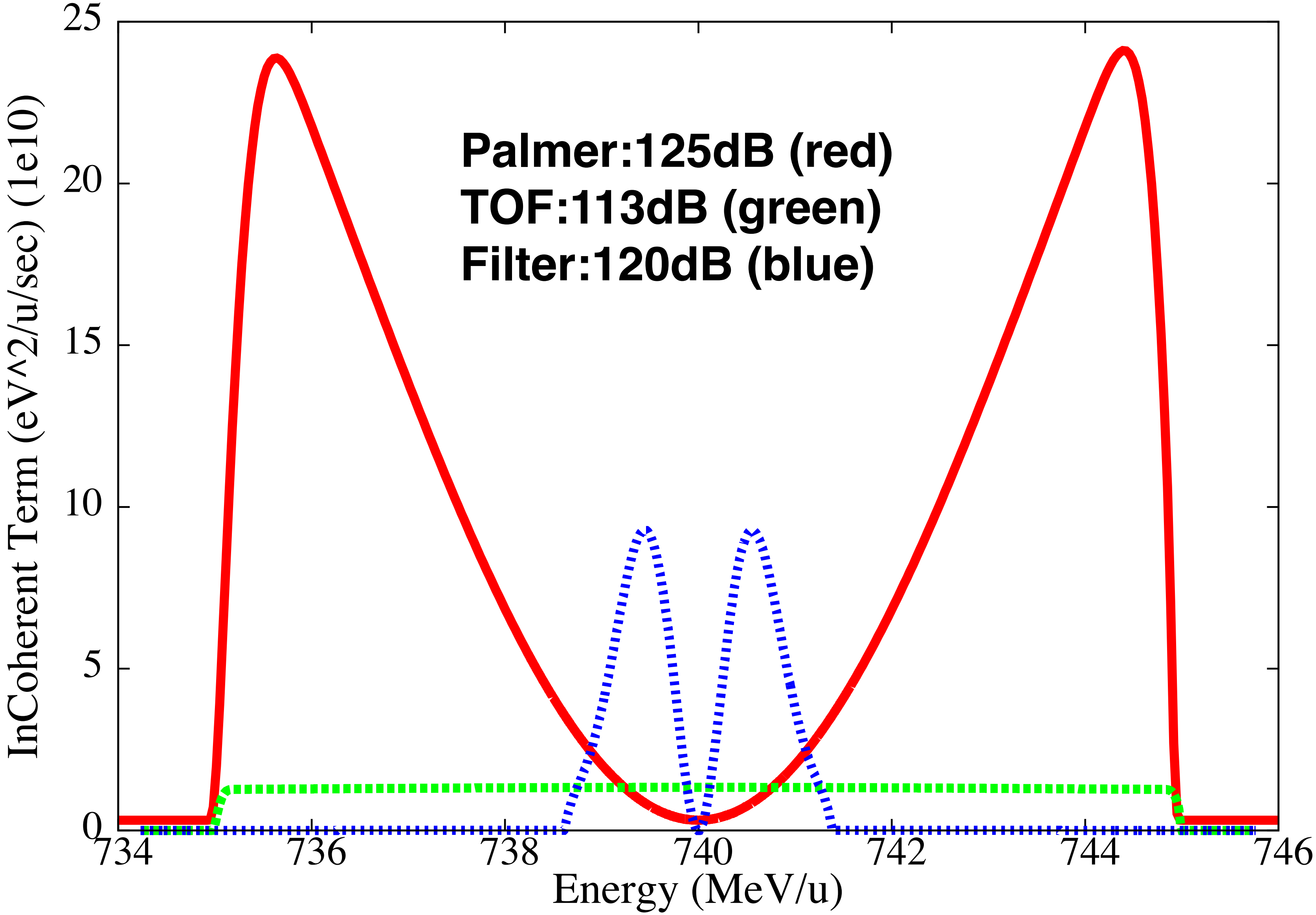
# Stochastic Cooling System of Collector Ring
## (TOF, Palmer & Filter System)

| | |
|---|---|
| Beam kinetic energy | 740 MeV/u |
| Number of particles | 1e8 |
| Initial energy spread | +/- 5 MeV/u (Dp/p=+/-4.38e-3) Uniform distribution (TOF/Palmer Cooling) |
| Transition Gamma | 2.73 |
| Ring slipping factor | 0.178 !! (Note 3 GeV Pbar case, 0.01) |
| | |
| Slipping factor from PU to K | 0.1346 (TOF & Filter), 0.0998 (Palmer) |
| Type of Pickup and Kicker | Lambda/4 loop coupler (As a 1st approximation) |
| Cooling method | Palmer, TOF & Filter method |
| Temperature at PU | Atmospehric 300 K (Palmer), 40K (Filter &TOF), 40 K (Noise) |
| TOF from PU to Kicker | 0.336e-6 sec (TOF & Filter), 0.208e-6 sec (Palmer) |
| | |
| Dispersion at PU | 0.0 m (TOF & Filter), 6.82 m (Palmer) |
| Dispersion at Kicker | 0.0 m |
| | |
| Number of PU and Kicker | 48/48 (PU & kicker) for TOF and Filter, 24/48 (Palmer) |
| Loop height, width | 126e-3 m, 50e-3m (Plunging is not considered in the present calculation) |
| Coupling impedance | 50 Ohm |
| Band | 1-2 GHz |
| Gain | 100~125 dB (Adjusted according to the particle number) |
| Microwave power | Should be less than around 500 Watt. |

# Comparison of Coherent Term of Palmer, TOF and Filter Cooling System



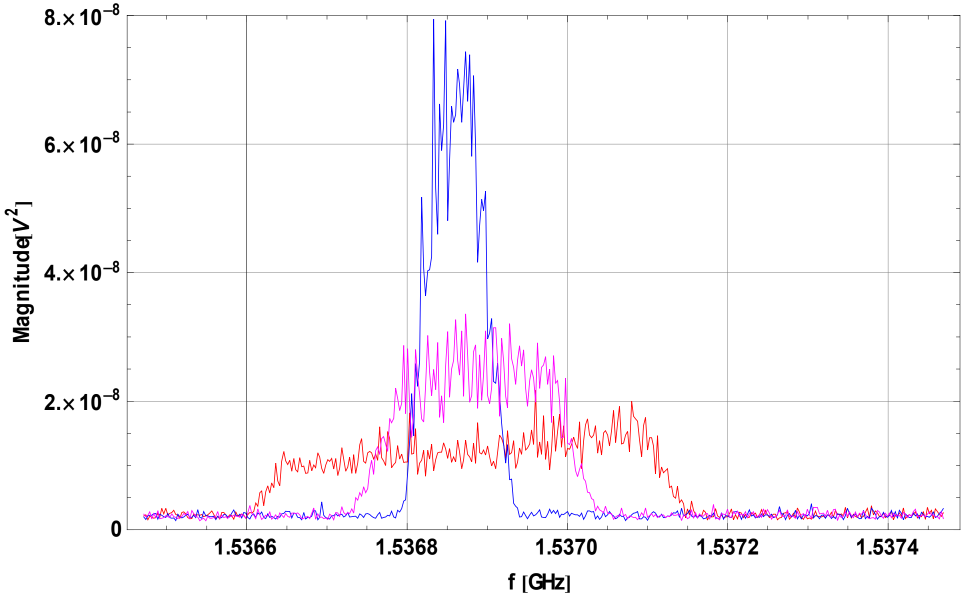
# Comparison of InCoherent Term of Palmer, TOF and Filter Cooling System



# TOF Cooling Experiment and Simulation at COSY

## Proton, Momentum=2.6 GeV/c, Gain=95dB, N=1e9, Dp/p(initial)=+/-1.63e-3, Band width=1.8-3 GHz

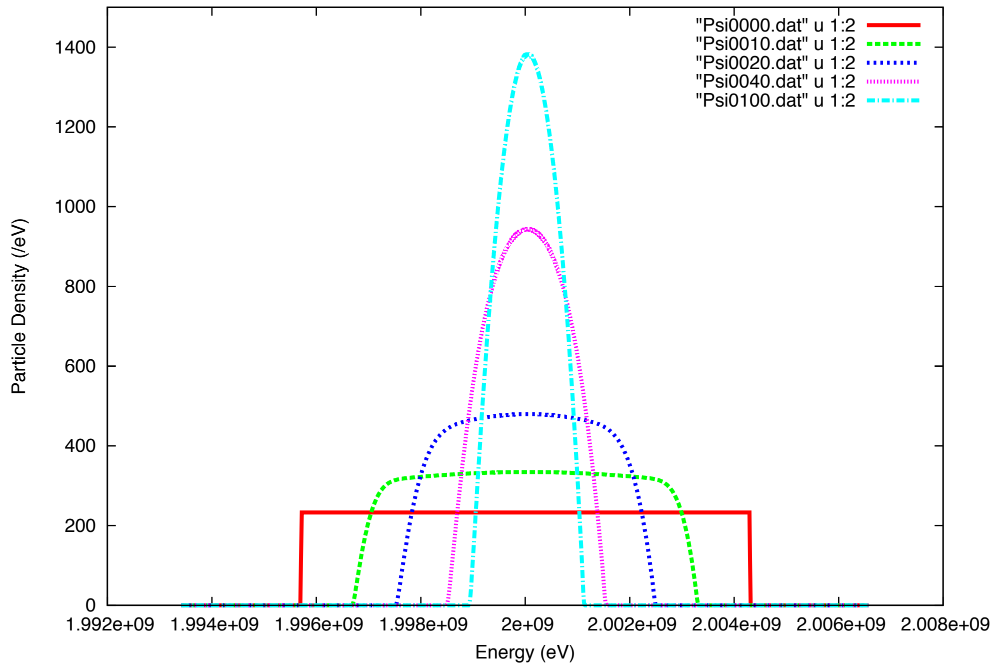
### 1st Experimental Result (June 17, 2009)




Red:Initial, Pink 200 sec, Blue 900 sec

(Ref.) H. Stockhorst et al., “COOL09, TUM2MCI01”

### Simulation Results




Time=0 (red), 100 (Green), 200(Blue), 400(Pink) & 1000 (Light blue) sec

# Fokker-Planck Equation (Longitudinal cooling process)

$$\frac{\partial \Psi}{\partial t} + \frac{\partial}{\partial E}\left(F(E)\Psi - D(E,t)\frac{\partial \Psi}{\partial E}\right) = 0$$

$$\Psi(E,t) = \frac{dN}{dE}$$ **Distribution Function of Particles**

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

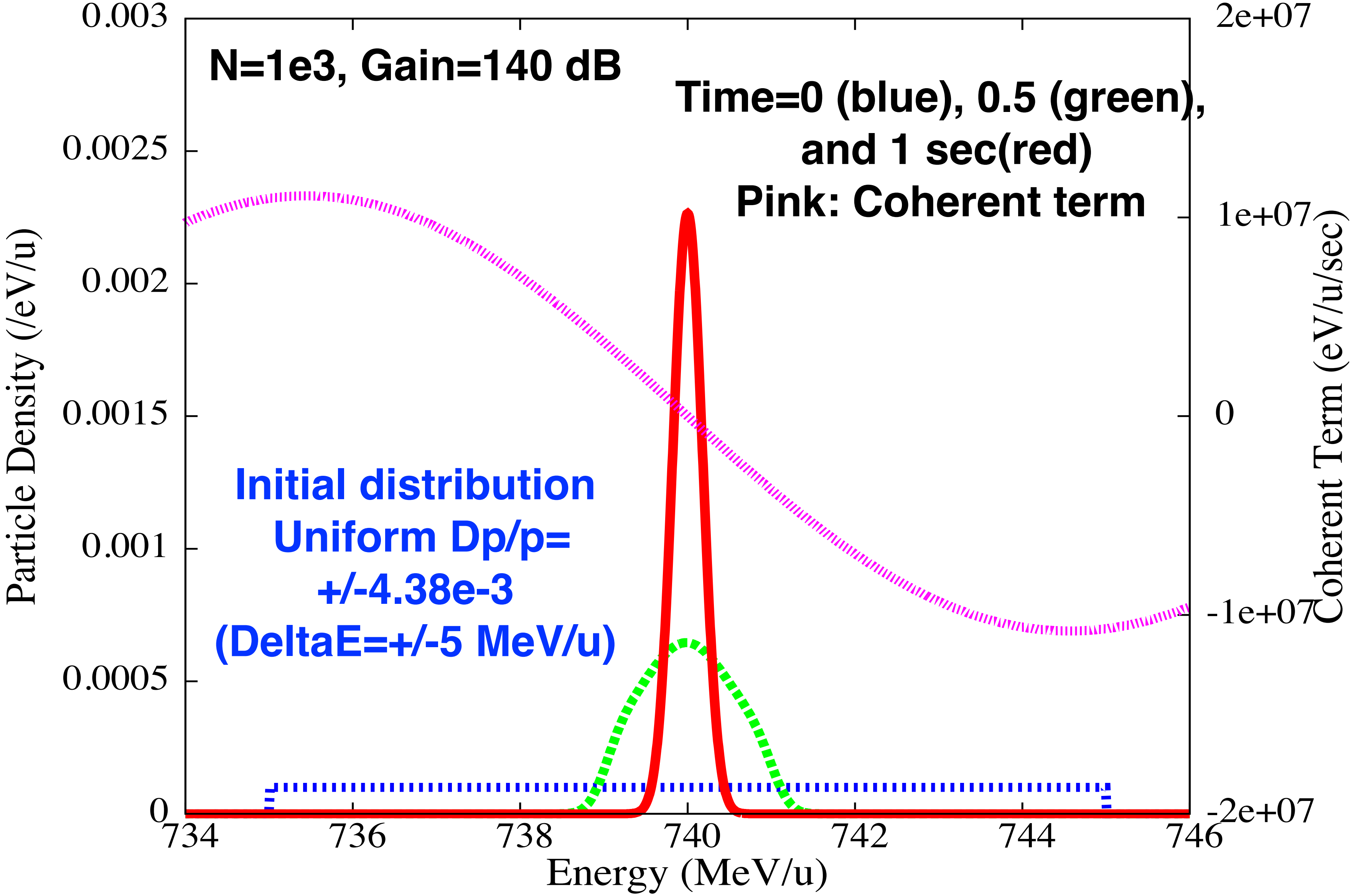
$$D(E,t) : Diffusion\ Force$$

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

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

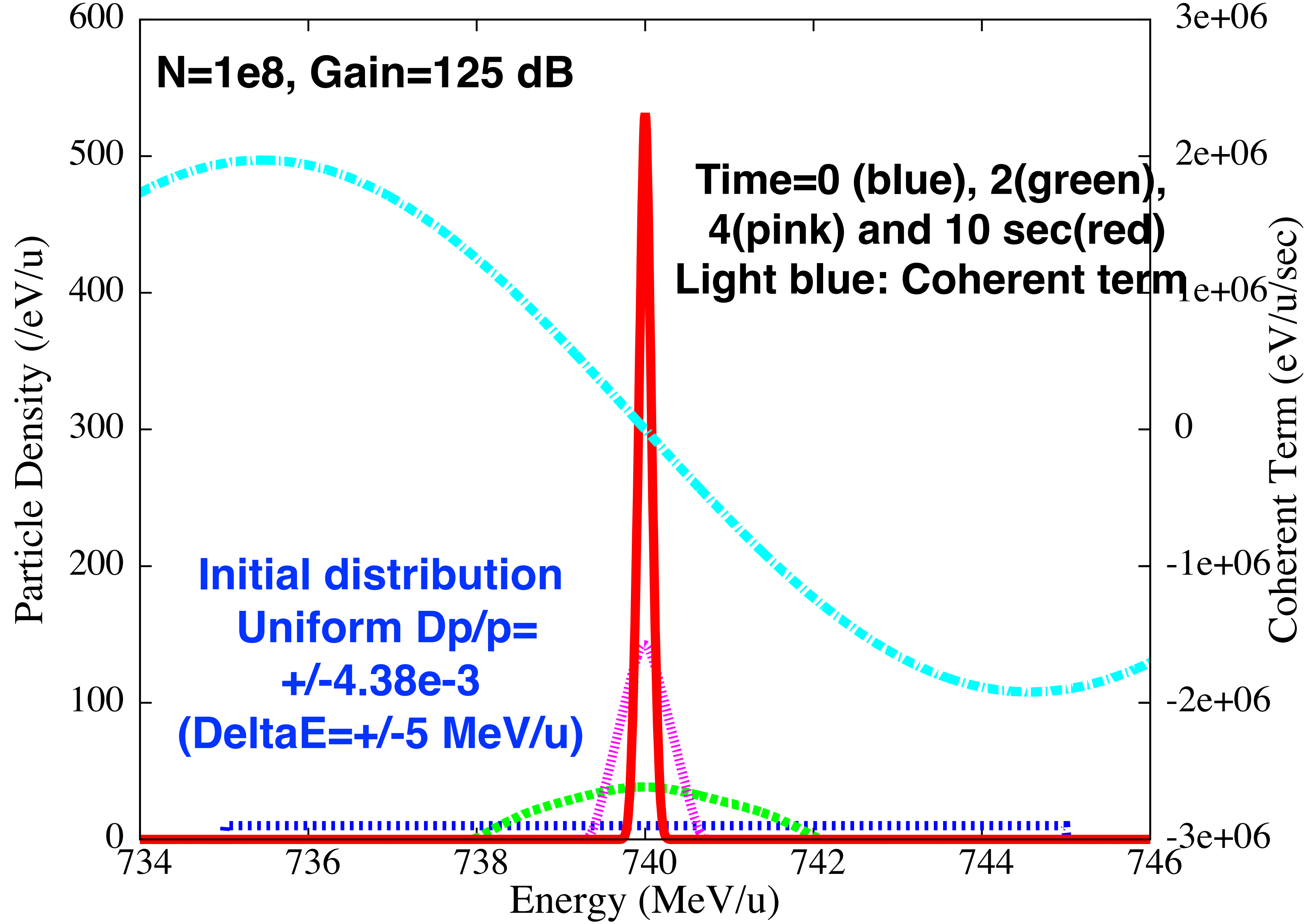
# Palmer Cooling

## Particle Distribution Function Psi=dN/dE

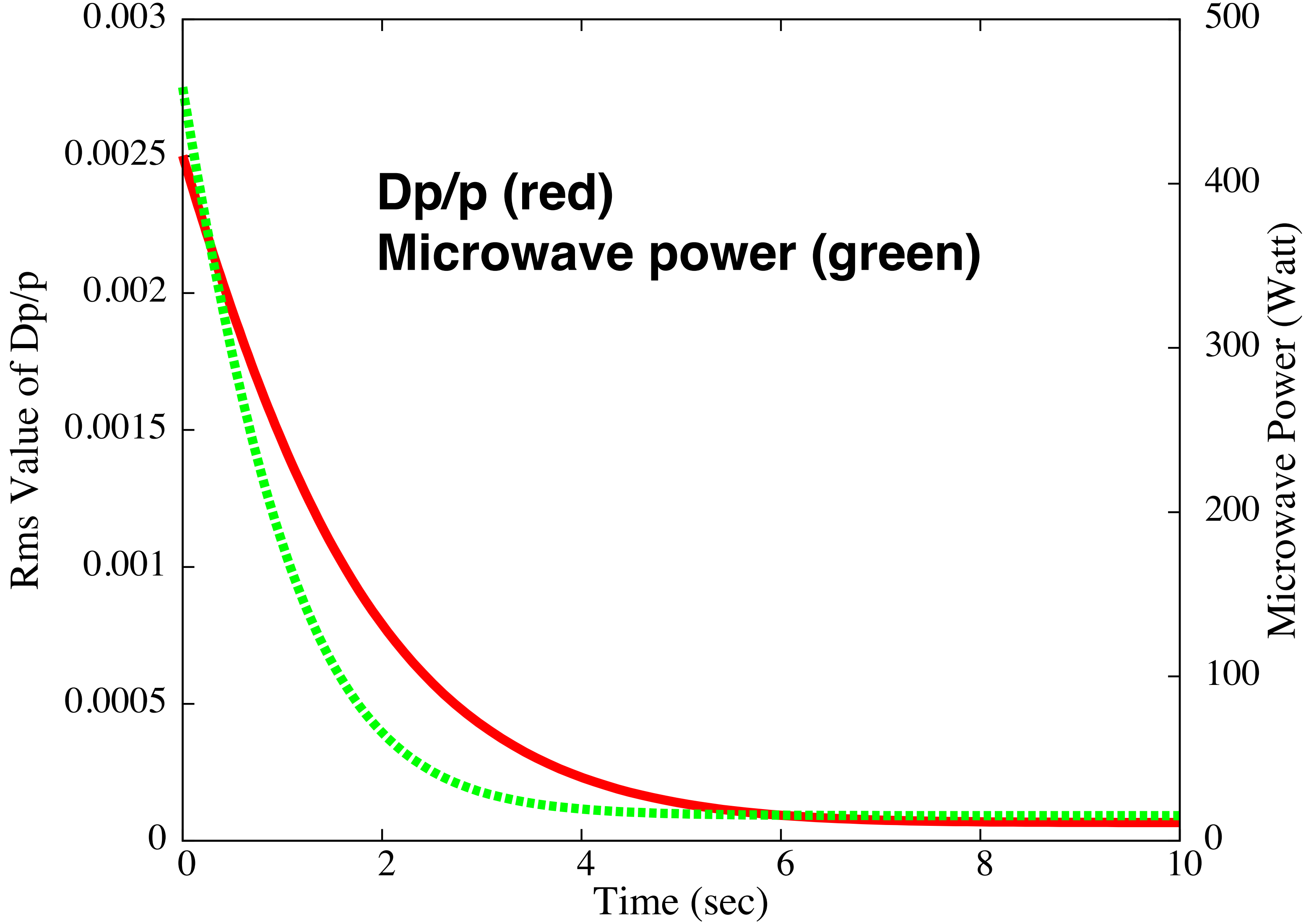


# Palmer Cooling

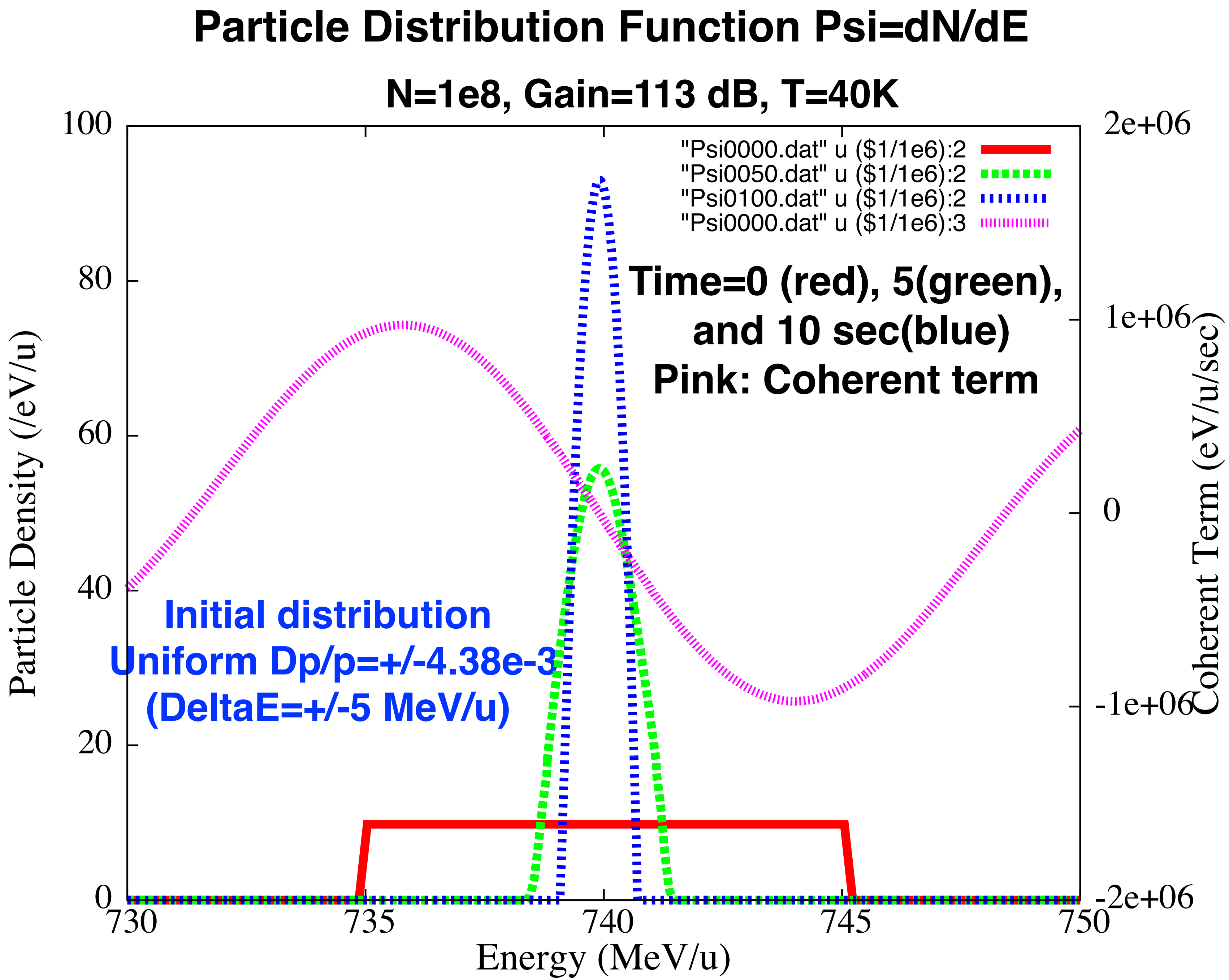
## Particle Distribution Function Psi=dN/dE



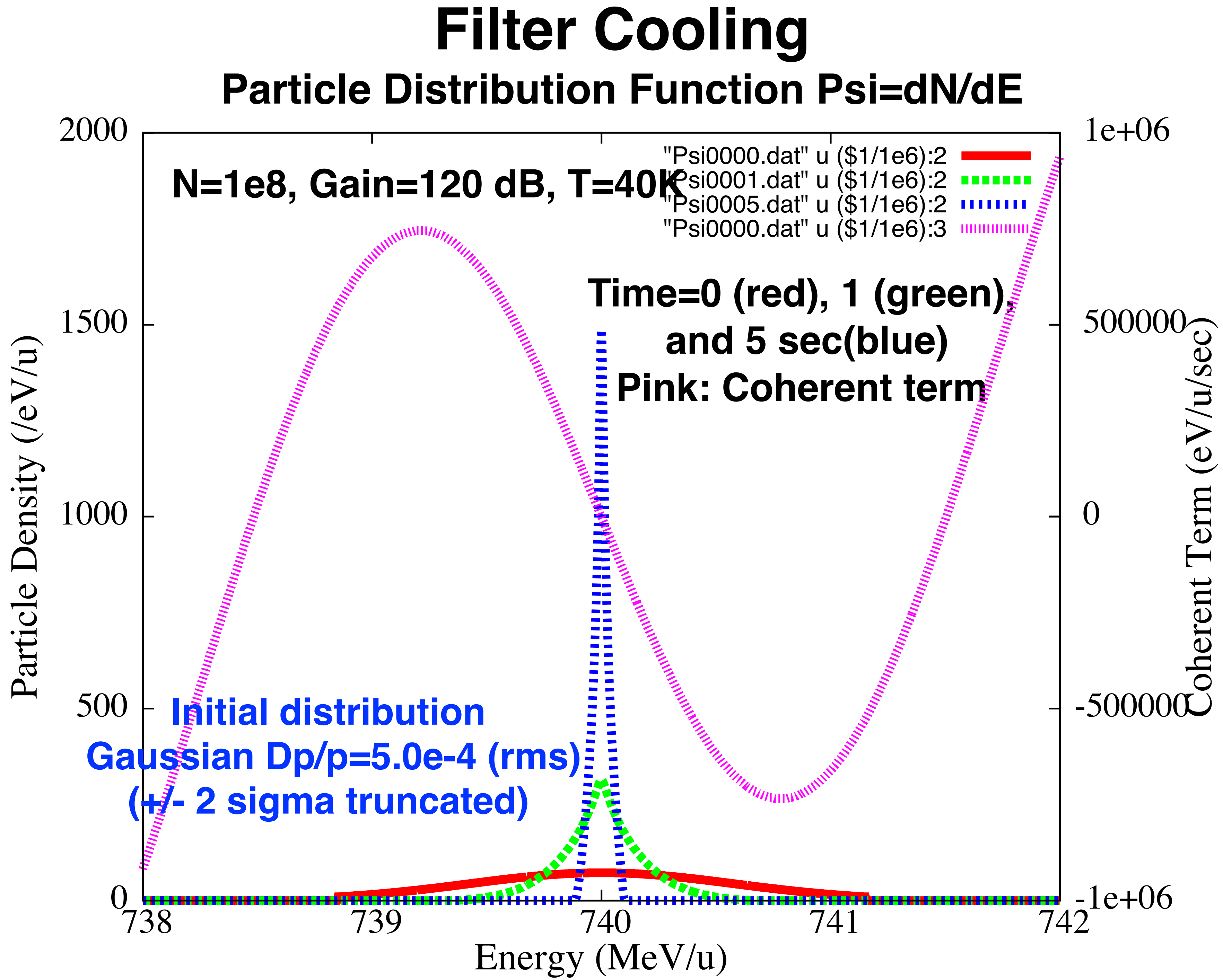
# Palmer Cooling
## Evolution of rms value of Dp/p & Microwave Power
## N=1e8, Gain=125 dB



# TOF Cooling



Particle Distribution Function Psi=dN/dE
N=1e8, Gain=113 dB, T=40K
"Psi0000.dat" u ($1/1e6):2
"Psi0050.dat" u ($1/1e6):2
"Psi0100.dat" u ($1/1e6):2
"Psi0000.dat" u ($1/1e6):3
Time=0 (red), 5(green),
and 10 sec(blue)
Pink: Coherent term
Initial distribution
Uniform Dp/p=+/-4.38e-3
(DeltaE=+/-5 MeV/u)
Particle Density (/eV/u)
Coherent Term (eV/u/sec)
Energy (MeV/u)
100
80
60
40
20
0
2e+06
1e+06
0
-1e+06
-2e+06
730
735
740
745
750



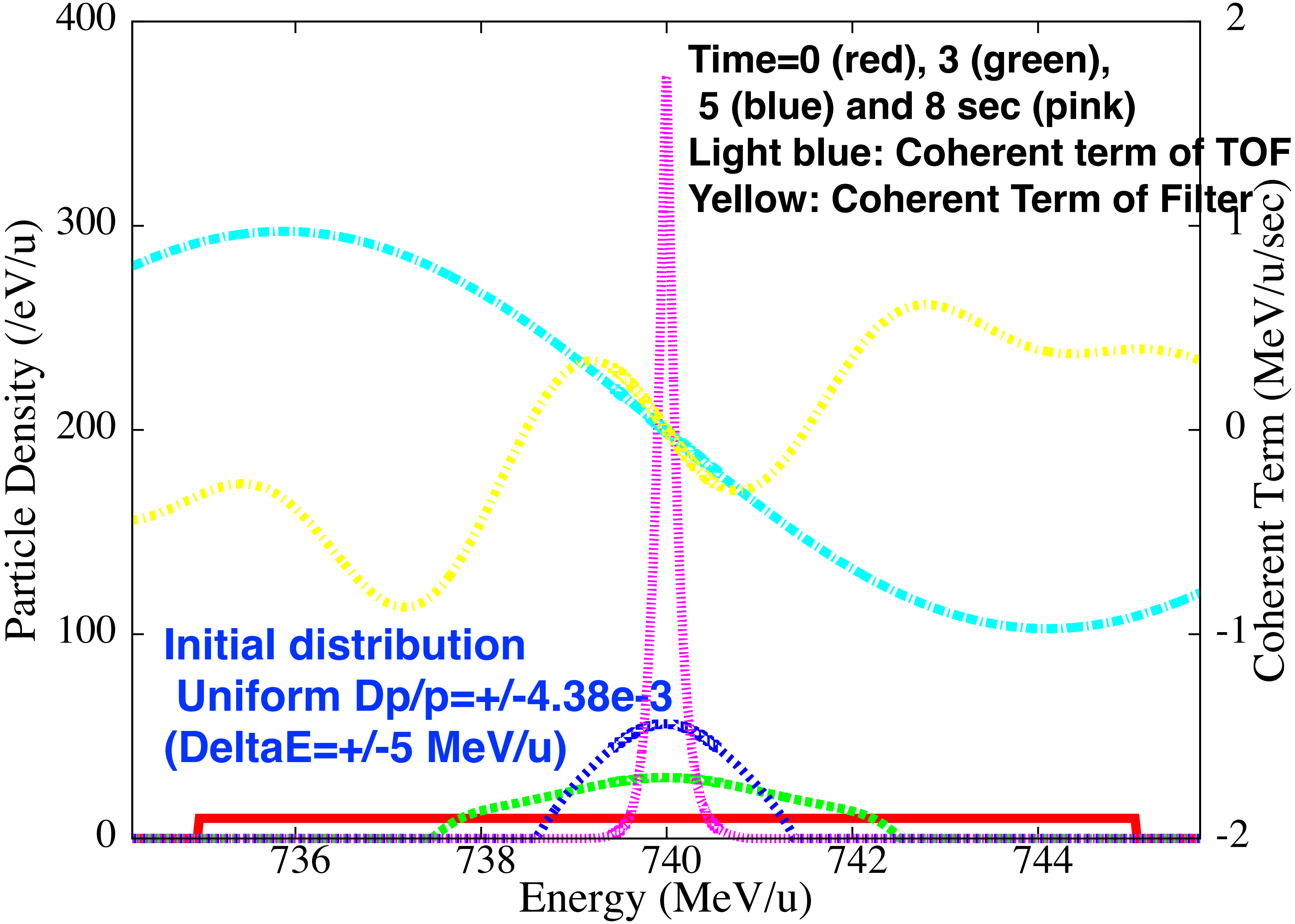
Filter Cooling
Particle Distribution Function Psi=dN/dE
N=1e8, Gain=120 dB, T=40K
"Psi0000.dat" u ($1/1e6):2
"Psi0001.dat" u ($1/1e6):2
"Psi0005.dat" u ($1/1e6):2
"Psi0000.dat" u ($1/1e6):3
Time=0 (red), 1 (green), and 5 sec(blue)
Pink: Coherent term
Initial distribution
Gaussian Dp/p=5.0e-4 (rms)
(+/- 2 sigma truncated)
Particle Density (/eV/u)
Coherent Term (eV/u/sec)
Energy (MeV/u)
2000
1500
1000
500
0
1e+06
500000
0
-500000
-1e+06
738
739
740
741
742

# TOF + Filter Cooling

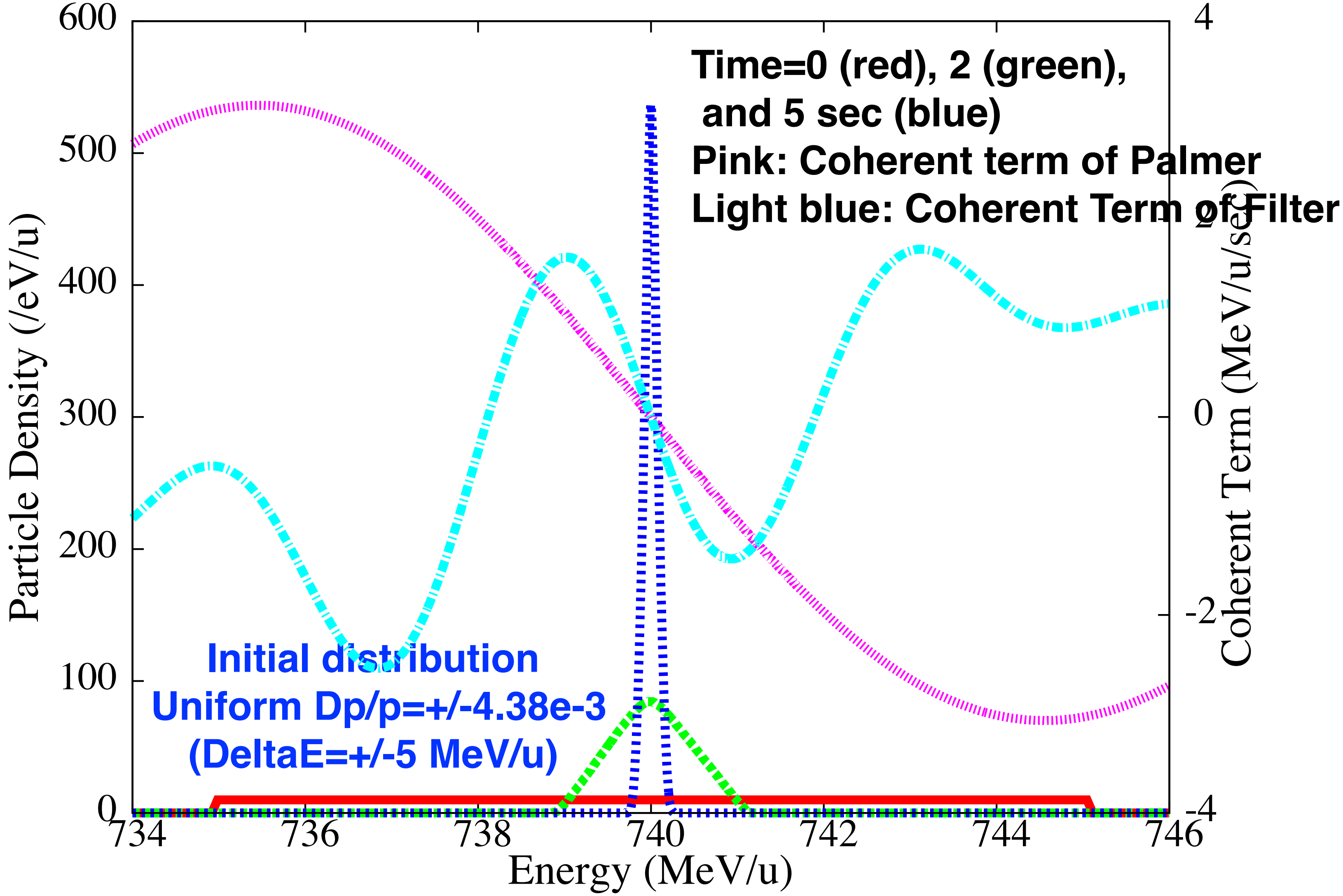
## Particle Distribution Function Psi=dN/dE

**N=1e8, TOF Gain=113 dB, Filter Gain=113dB, T=40K**

**Switch over Time from TOF to Filter= 5 sec**

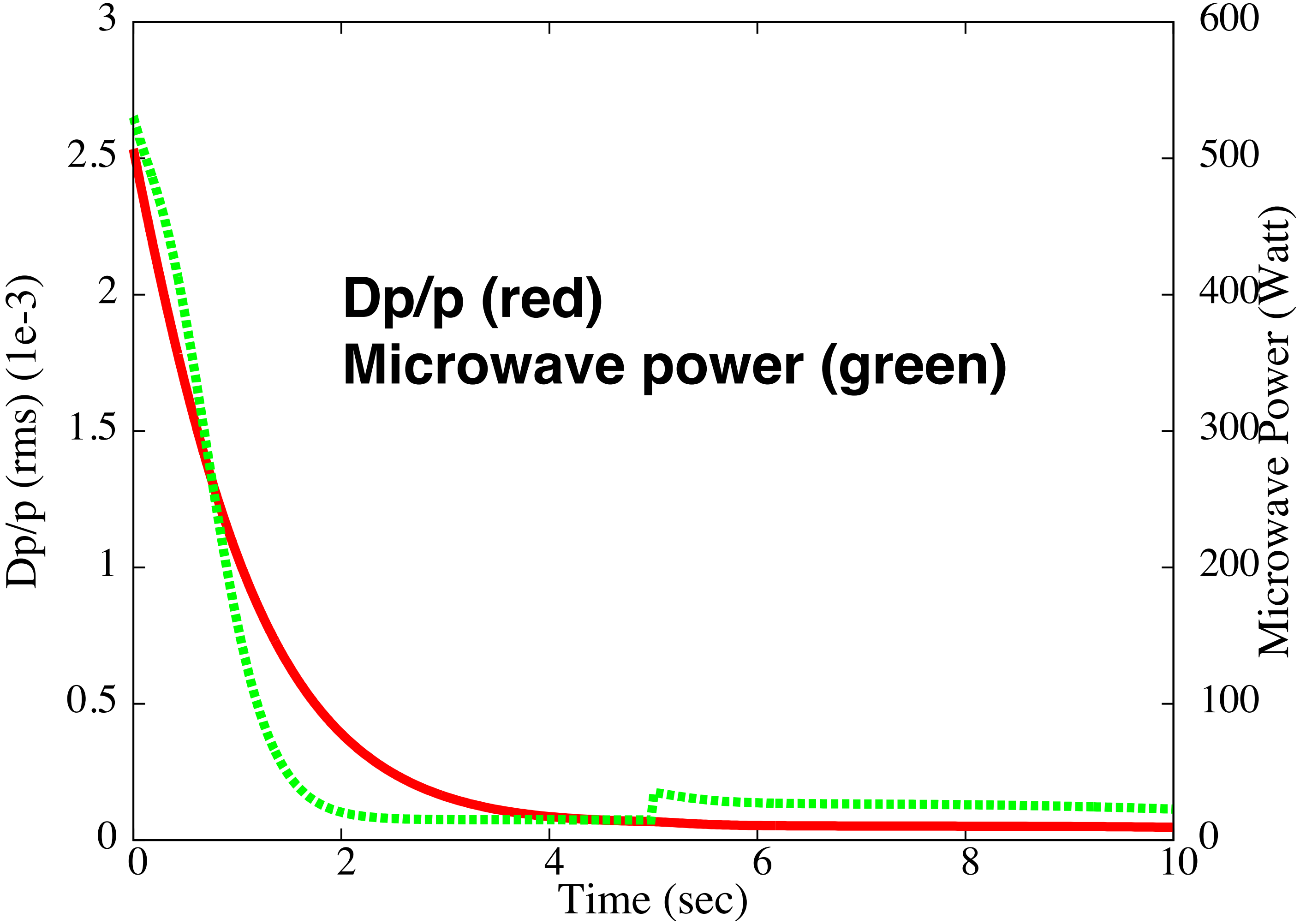


# Palmer + Filter Cooling
# Particle Distribution Function Psi=dN/dE
## N=1e8, Palmer Gain=125 dB, Filter Gain=125dB, T=300K
## Switch over Time from Palmer to Filter= 5 sec



# Evolution of rms value of Dp/p & Microwave Power

## N=1e8, Palmer Gain=125 dB, Filter Gain=125dB, T=40K
## Switch over Time from Palmer to Filter= 5 sec



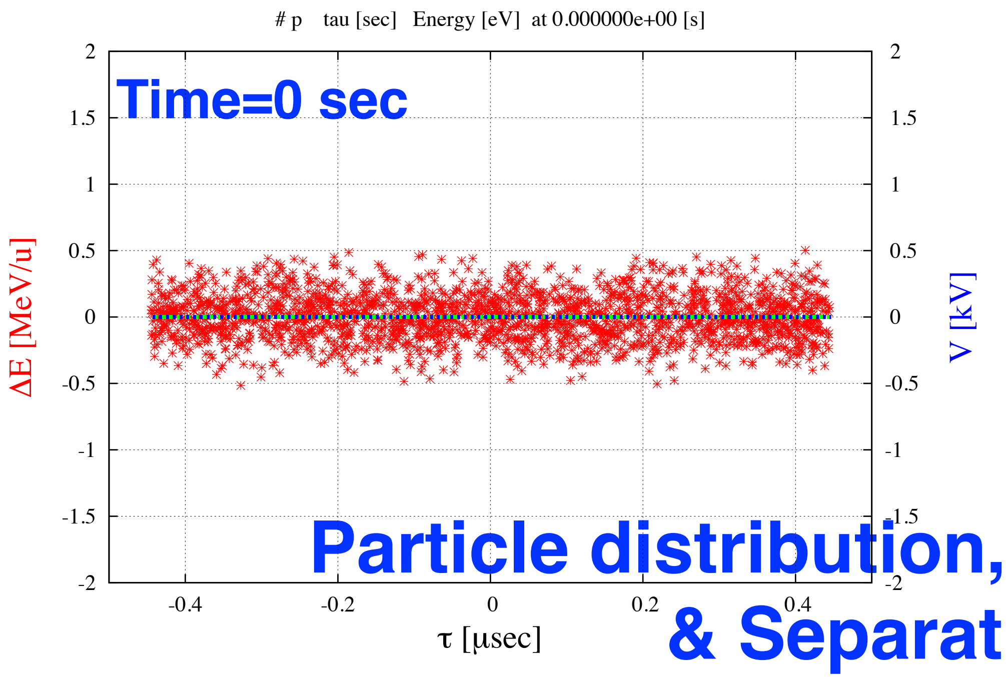
# Summary of TOF, Palmer & Filter Cooling

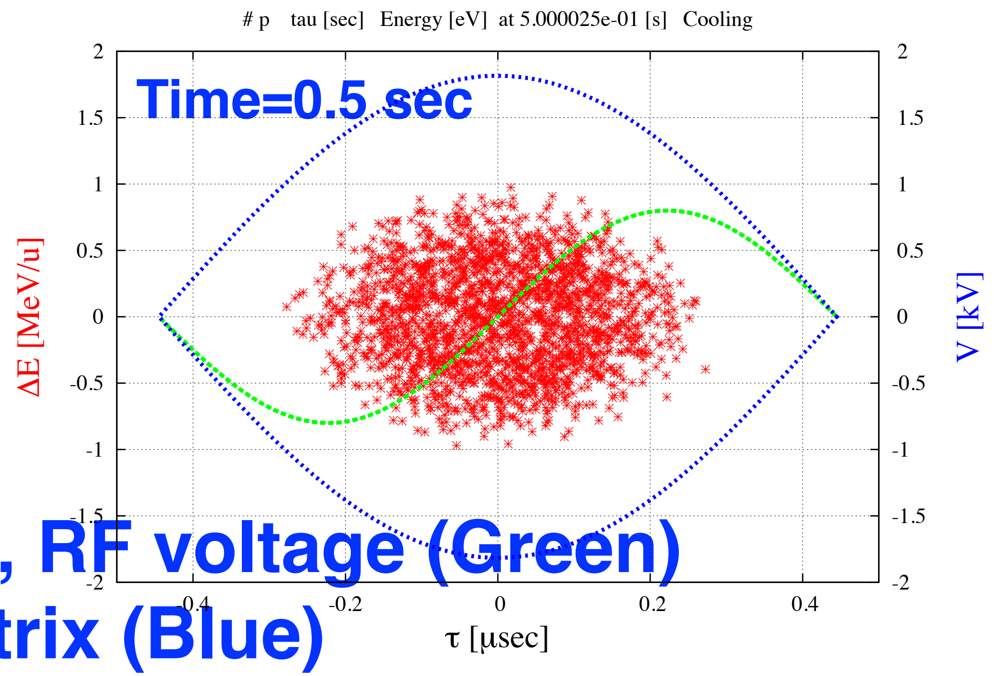
| Cooling Type | Particle Number | TOF or Palmer Gain (dB) | Filter Gain (dB) | Hand Over Time (sec) | Equi. Dp/p (rms) at 10 sec |
|---|---|---|---|---|---|
| TOF & Filter | 1.00E+08 | 113 | 120 | 5 | 2.80E-05 |
| TOF & Filter | 1.00E+09 | 113 | 113 | 5 | 1.20E-03 |
| Palmer & Filter | 1.00E+08 | 125 | 120 | 5 | 3.22E-05 |
| Palmer & Filter | 1.00E+09 | 117 | 113 | 5 | 1.49E-04 |

1. Initial momentum spread is +/-4.38e-3 (DeltaE=+/- 5 MeV/u) uniform distribution.
2. At the handover time (in column 5), the cooling method is switched from TOF/Palmer to Filter cooling.

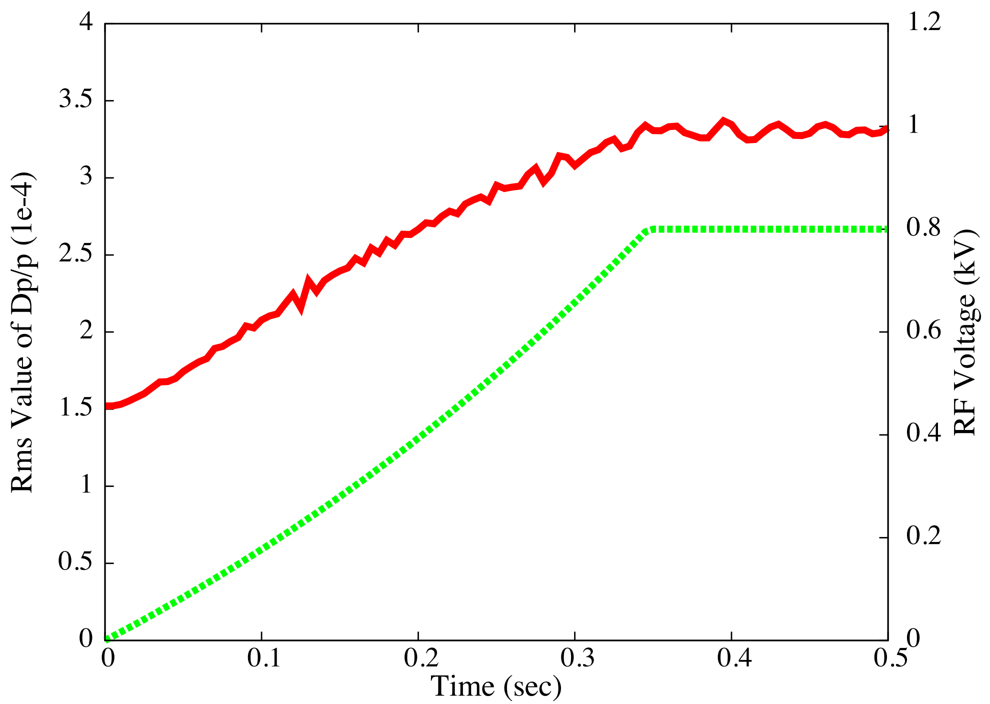
# Adiabatic Bunching of Heavy Ion Beam in CR
# Ion 238U92+

| | |
|---|---|
| Kinetic energy | 740 MeV/u |
| Number of bunch | 1 |
| Total number of ions | 1e9 |
| Initial momentum spread | |
| Gaussian (rms value=1.5e-4 and truncated at +/- 3 rms value) | |
| Initial Bunch length (Uniform random) (Coasting) | 0.8897e-6 sec |
| Ring slipping factor | 0.178 |
| Revolution frequency | 1.148 MHz |
| RF harmonic number | 1 |
| Maximum RF voltage | 0.8 kV |




## Particle distribution, RF voltage (Green) & Separatrix (Blue)

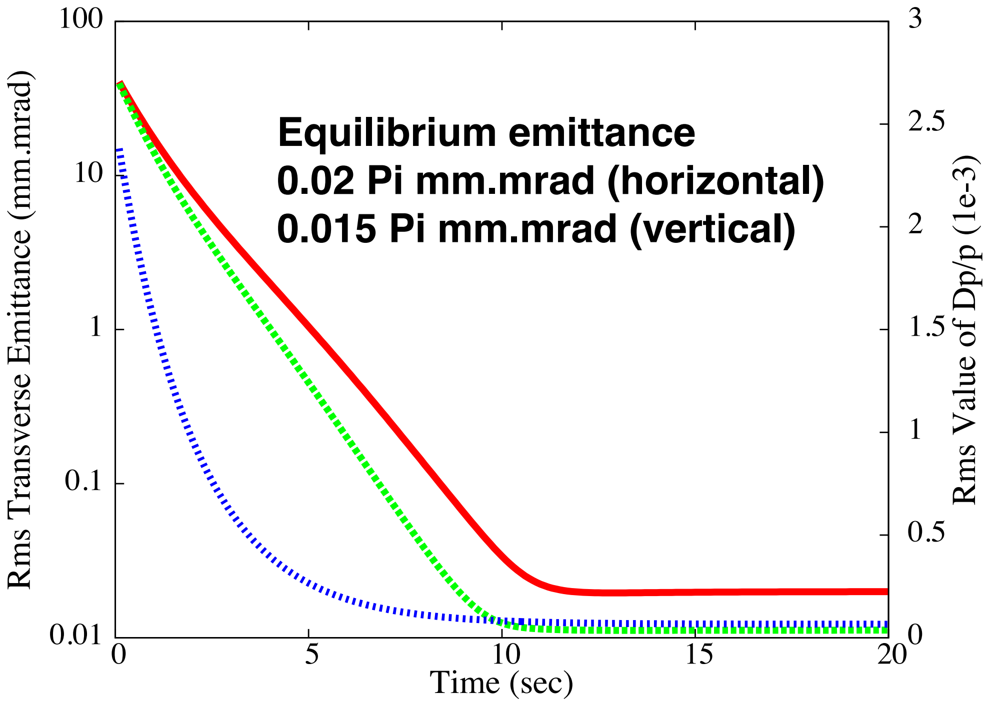


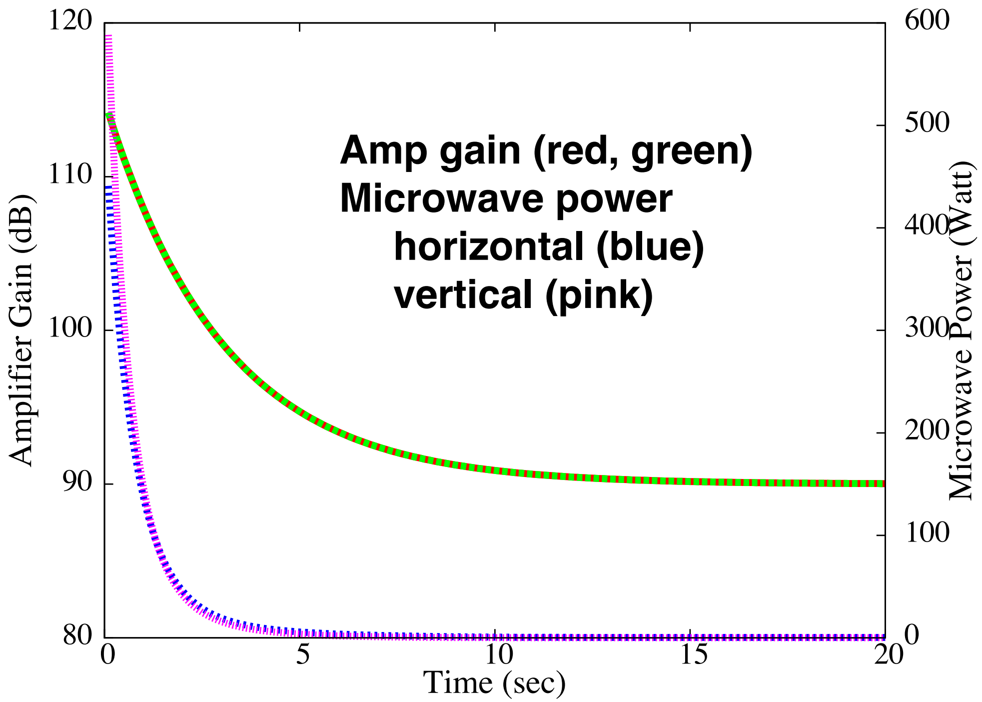

**RF Voltage pattern (Green):**
**Increase from 0 to 0.8 kV within 0.35 sec.**
**Rms Value of Dp/p (Red).**

**After adiabatic bunching**
**Increase of Dp/p = Factor 2.2**

# Transverse Cooling
# with Plunging & Variable Gain including BFE

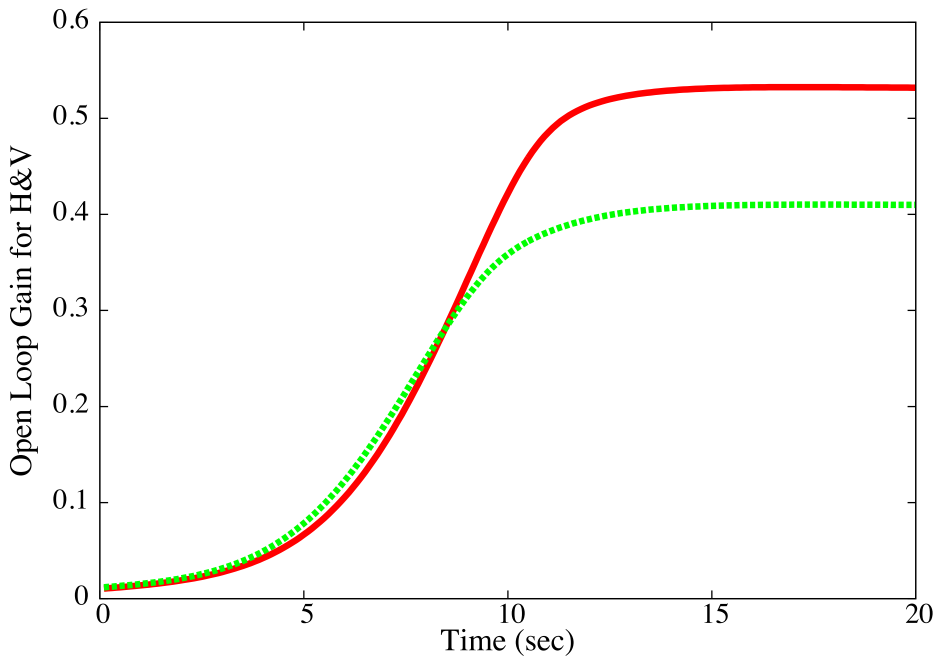
**Plunging: Electrode gap=2*sqrt(6*rmsEmittance)+0.01 (m)**



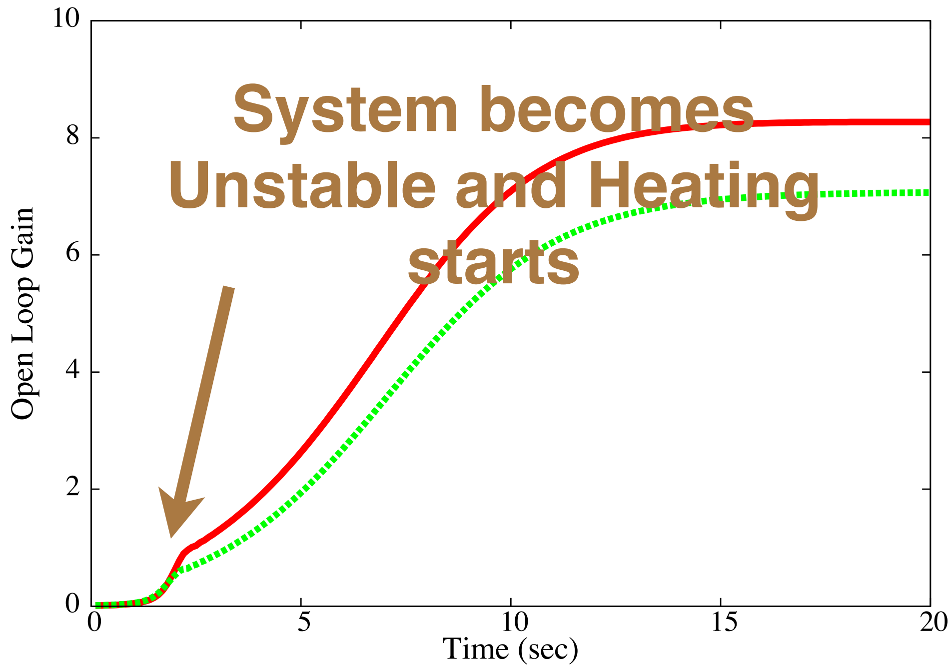



# Open Loop Gain of Transverse Cooling System

**Gain: 113 dB --> 90dB**




**Gain: 113 dB constant**




**Open Loop Gain; Horizontal (red) and Vertical (Green)**

# Matching of RI Beam Parameters between CR and HESR

## 1. HESR Acceptance (Gamma transition=6.2 Lattice) and Required Beam Parameters

Transverse Acceptance=7 Pi mm.mrad, Dp/p=+/- 2e-3

Transverse Emittance < 1.1 Pi mm.mrad, Dp/p(rms) < 7e-4

## 2. CR Beam Qualities Dp/p (rms) after Stochastic Cooling (Coasting beam condition)

| Particle Number | 1e6 (at 5 sec) | 1e8 (at 10 sec) | 1e9 (at 10 sec) |
|---|---|---|---|
| Palmer | 1.35e-4 | 6.6e-5 | 2.7e-4 |
| TOF | 1.13e-4 | 3.2e-4 | 1.0e-3 |
| Palmer+Filter | | 3.2e-5 | 1.5e-4 |
| TOF+Filter | | 2.8e-5 | 1.2e-3 |

## 3. Conclusion

When the RI beam experiment is performed at the HESR and the role of CR is just to cool the RI beam (N=1e8) to match to the injection into HESR, we only need the TOF + Filter cooling system. It can cool the beam, N=1e8, to the enough smaller momentum (< 7e-4) spread than the acceptance of HESR after the adiabatic bunching for the fast extraction from the Collector Ring. However to assure the high intensity RIB, say N=1e9, the Palmer system is preferable. The transverse cooling will reduce the emittance from 45 Pi mm.mrad to less than 1 Pi mm.mrad within 5 sec.