Antiproton Cooling in the Fermilab Recycler Ring

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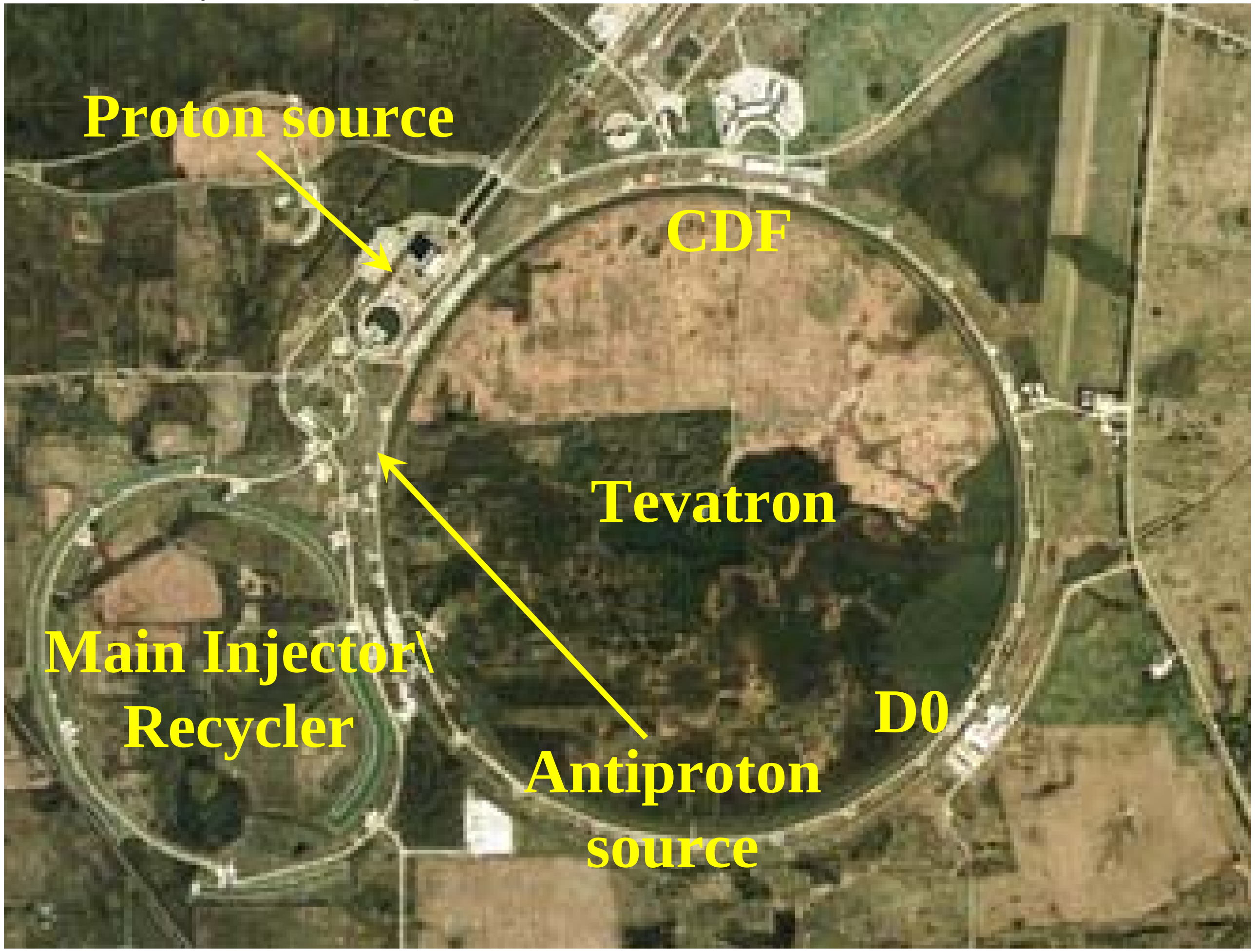
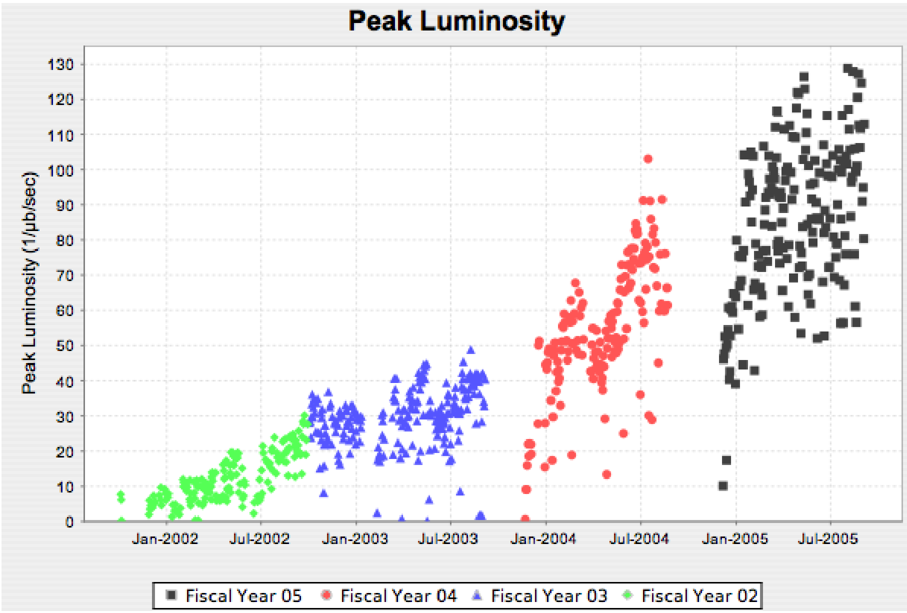
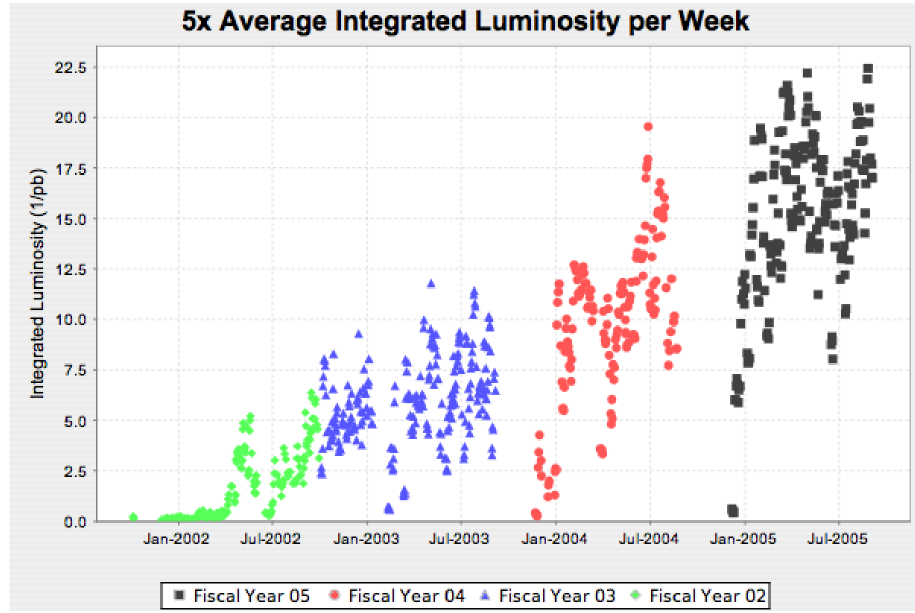
Fermilab Complex

- The Fermilab Collider is a Antiproton-Proton Collider operating at 980 GeV



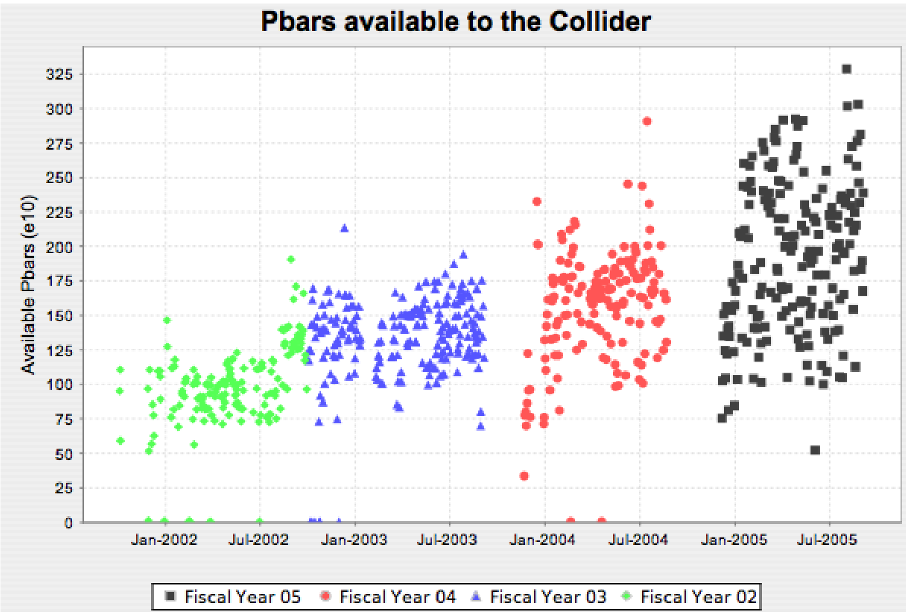
Luminosity History

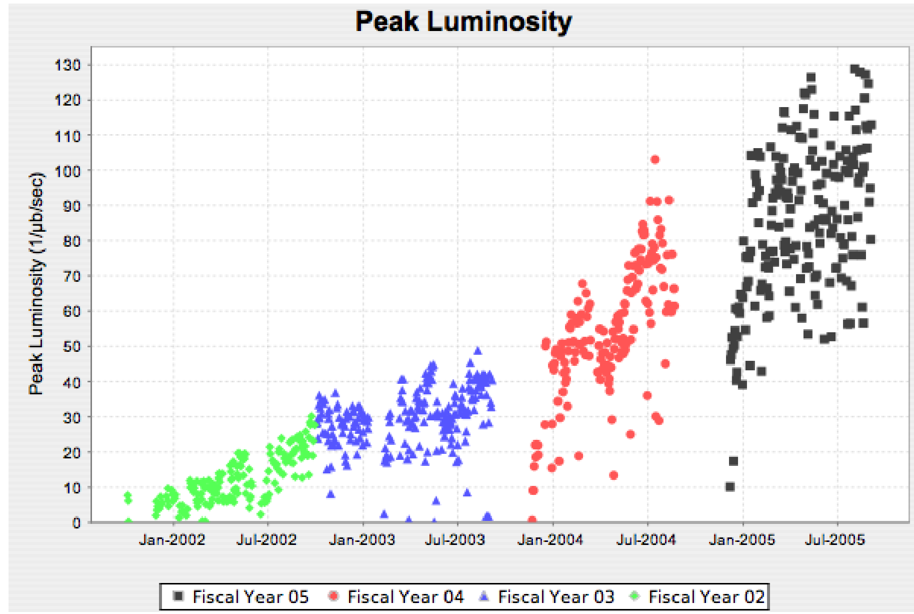




- Luminosity increase is mostly due to:
  - Better performance of the injector chain
  - Introduction of the Recycler into operations
  - Alignment and lattice change in the Tevatron
  - Improved operations, focused studies

Antiprotons and Luminosity



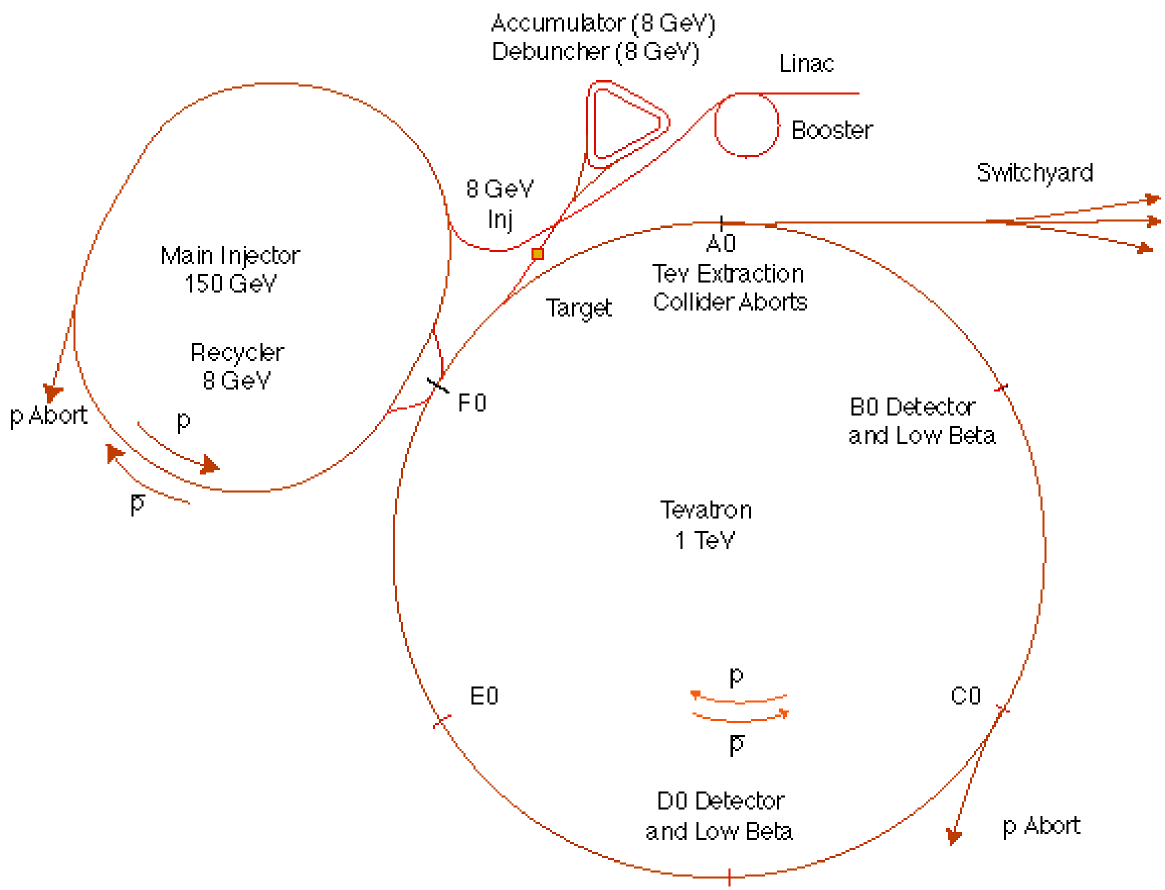


- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

Antiproton Production

- 1×10^8 8-GeV pbars are collected every 2-4 seconds by striking 7×10^{12} 120-GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and cooled in the Debuncher, Accumulator and Recycler Rings
  - The stochastic stacking and cooling increases the 6-D phase space density by a factor of 600×10^6
- 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON

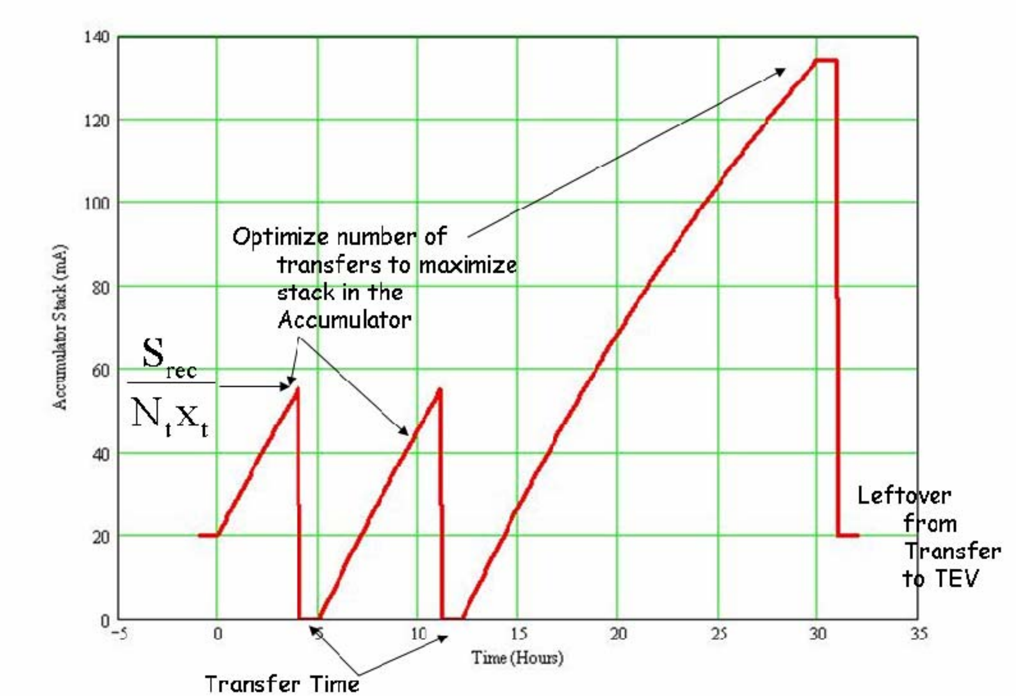
FermilabTevatron Accelerator With Main Injector

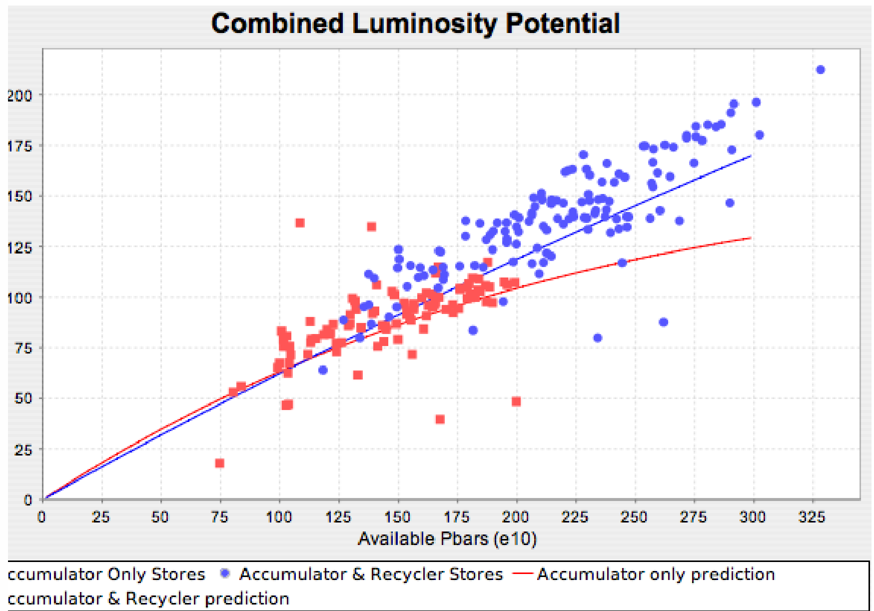


Combined Shots

- Extracting antiprotons from both the Accumulator and the Recycler for the same store eg.
  - Twelve bunches from the Recycler
  - Twenty four bunches from the Accumulator
- Reasons
  - Flexibility in the Run II Upgrade schedule
    - Natural merging of commissioning of electron cooling
  - Push Recycler commissioning progress by plunging it into operations
  - Luminosity enhancement – larger amount of antiprotons for smaller emittances
    - Accumulator stack size limited to <200 mA
      - Stacking Rate
      - Transverse emittance vs Stack Size
- Combined Shot Operation
  - Concept proposed in February '04
  - Dual energy ramps in the MI completed and tested by May '04
  - First Attempt 6/13/04
  - Record Luminosity
    - $103 \times 10^{30} cm^{-2} sec^{-1}$ recorded 7/16/04
    - $129 \times 10^{30} cm^{-2} sec^{-1}$ recorded August 2005
  - Routine Operations - January 2005
- Obstacles
  - Stacking Rate
  - Injector Complex 8 GeV energy alignment
  - Longitudinal emittance in both the Accumulator and Recycler
  - Transfer time between Accumulator to Recycler

Combined Shots





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  - Accumulator stack size limited to <200 mA
    - Stacking Rate
    - Transverse emittance vs Stack Size

Recycler – 8.9 GeV/c storage ring

- At the end of August 2003
  - The Recycler was "on the ropes"
    - Lifetime was < 60hrs
    - Transverse emittance growth was 12π-mm-mrad/hr
  - Took drastic measures
    - Lengthened the Fall 03 shutdown to bake the entire Recycler
    - Instituted the Pbar Tax (Investment) to guarantee the Recycler adequate study time and access to the tunnel

- Recycler bake-out was extremely successful
  - Transverse emittance growth reduced by a factor of 10-20
  - Lifetime > 600 hours
- Recycler commissioning has progressed rapidly
  - Using the Recycler in "Combined Shots" operations makes it a luminosity enhancement
    - Operational January 2005
  - Transverse Damper commissioned August 2005
    - Stacks larger than 150×10^{10} pbars now possible
  - Stand alone Recycler shots to the Tevatron (Sept 2005)
    - Stack of 190×10^{10} pbars in the Recycler
    - $92 \times 10^{30} cm^{-2} sec^{-1}$ Luminosity
- Electron Cooling commissioned July 2005
  - By the end of August 2005, electron cooling is used on every Tevatron shot

Beam Cooling in the Recycler

The missions for cooling systems in the Recycler are:

- The multiple Coulomb scattering (IBS and residual gas) needs to be neutralized.
- The emittances of stacked antiprotons need to be reduced between transfers from the Accumulator to the Recycler.
- The effects of heating because of the Main Injector ramping (stray magnetic fields) need to be neutralized.
- Transverse and longitudinal emittances of the recycled antiprotons need to be reduced by roughly 1/e in the 8-10 hour store length. (Presently not part of the mission; May be in the future)

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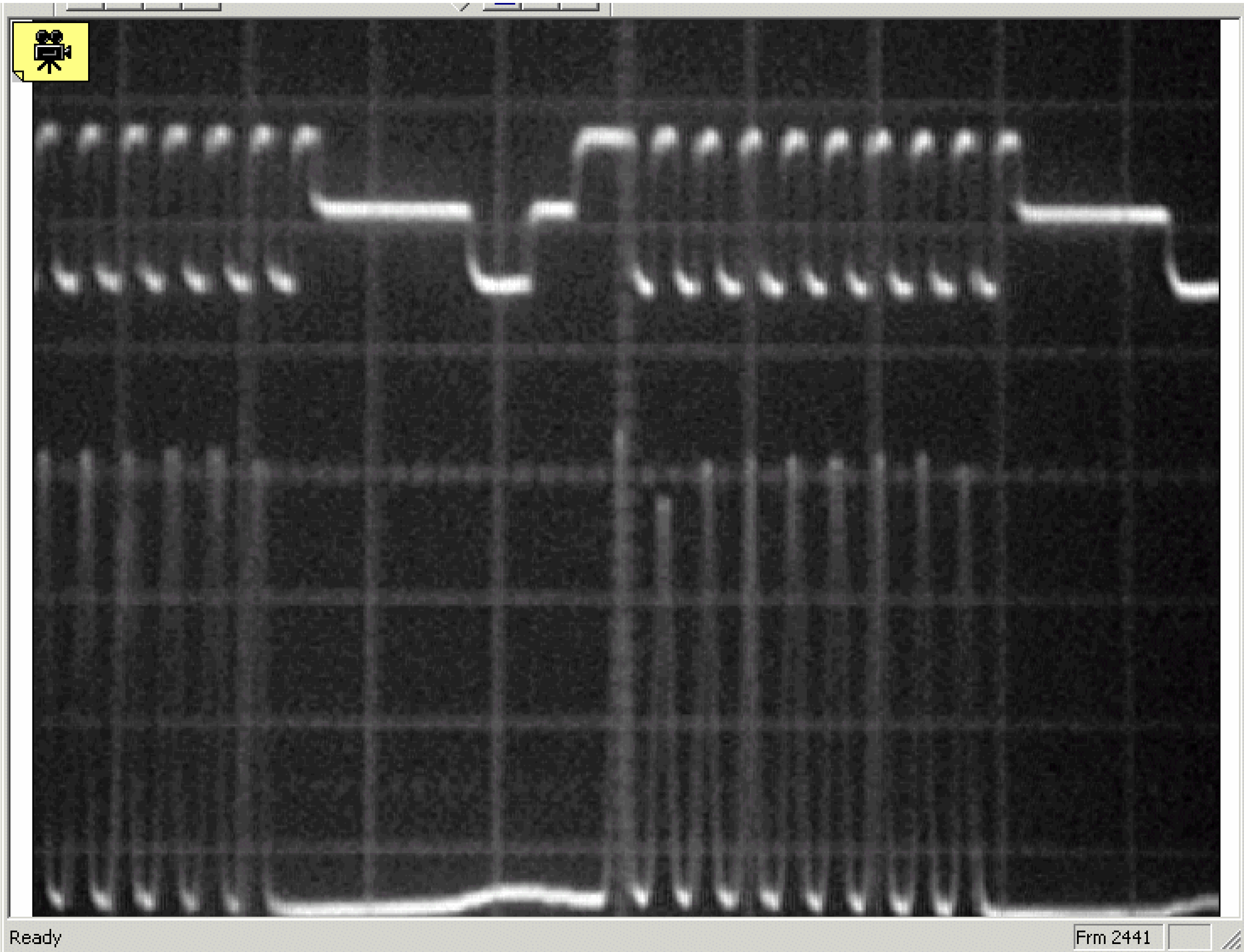
Final goal for Recycler: Prepare 9 (6 eV-s each) bunches for extraction



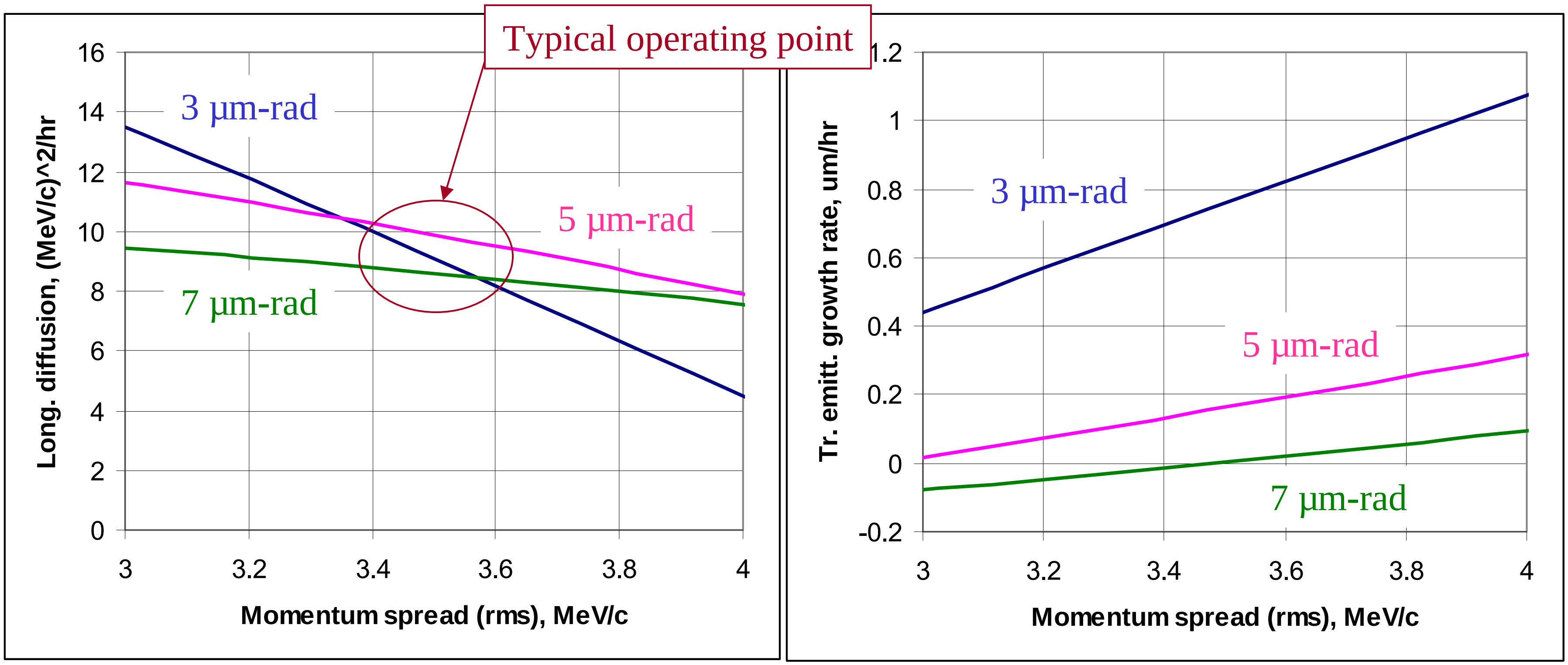
Final Recycler beam parameters

- Short term goals:
  - Recycler provides all Tevatron pbars
  - 250×10^{10} pbars → delivers $5e10^{10}$ pbars per bunch in the Tevatron (75% efficiency to collisions, 36 bunches)
  - Long. emittance (95%): 54 eV-s
  - Transverse emittances (n, 95%): 5 μm-rad
  - Supports peak luminosities above 130×10^{30} $1/(cm^2 s)$
- End of Run II:
  - Up to 600×10^{10} pbars
  - Same emittances

Recycler heating rates

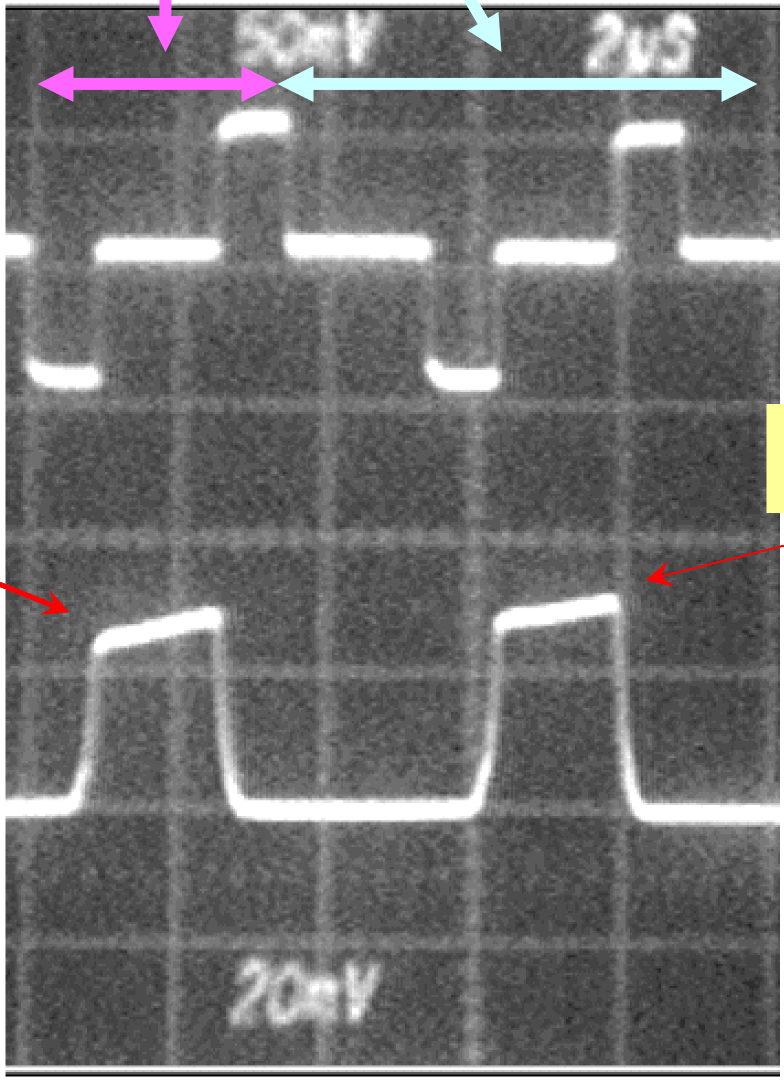
- Residual gas scattering: 0.5 μm-rad/hr (n, 95%)
- Transverse damper: < 0.2 μm-rad/hr (n, 95%)
- IBS rates (B-M model) for 250x10[10] pbars,

54 eV-s as a function of transverse emittances:



Recycler transfers with gated cooling

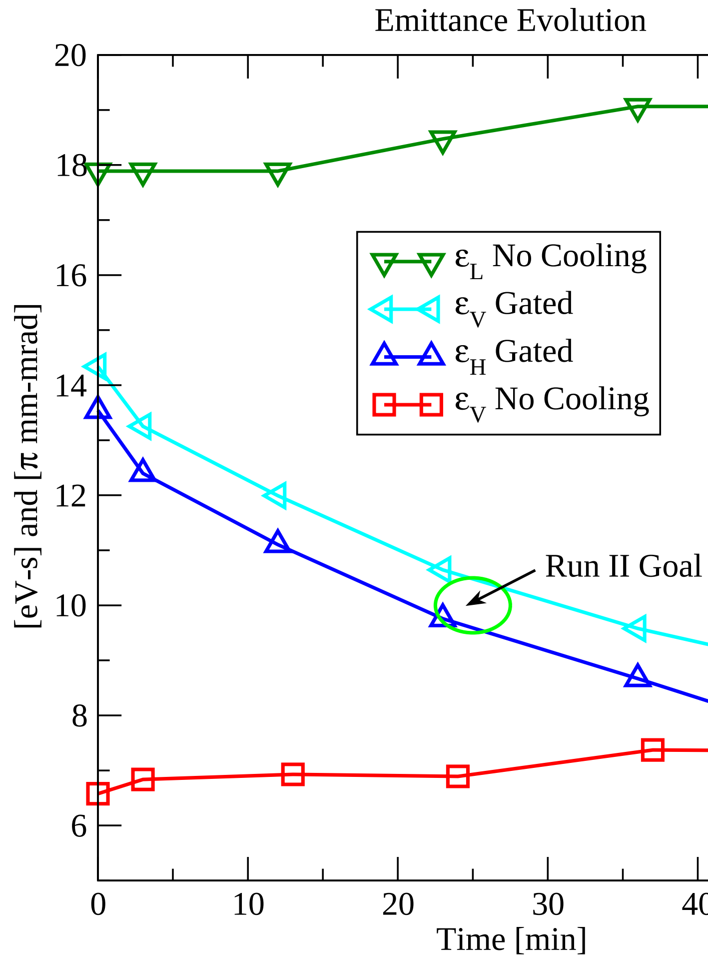
Gated cooling: ON OFF



New batch

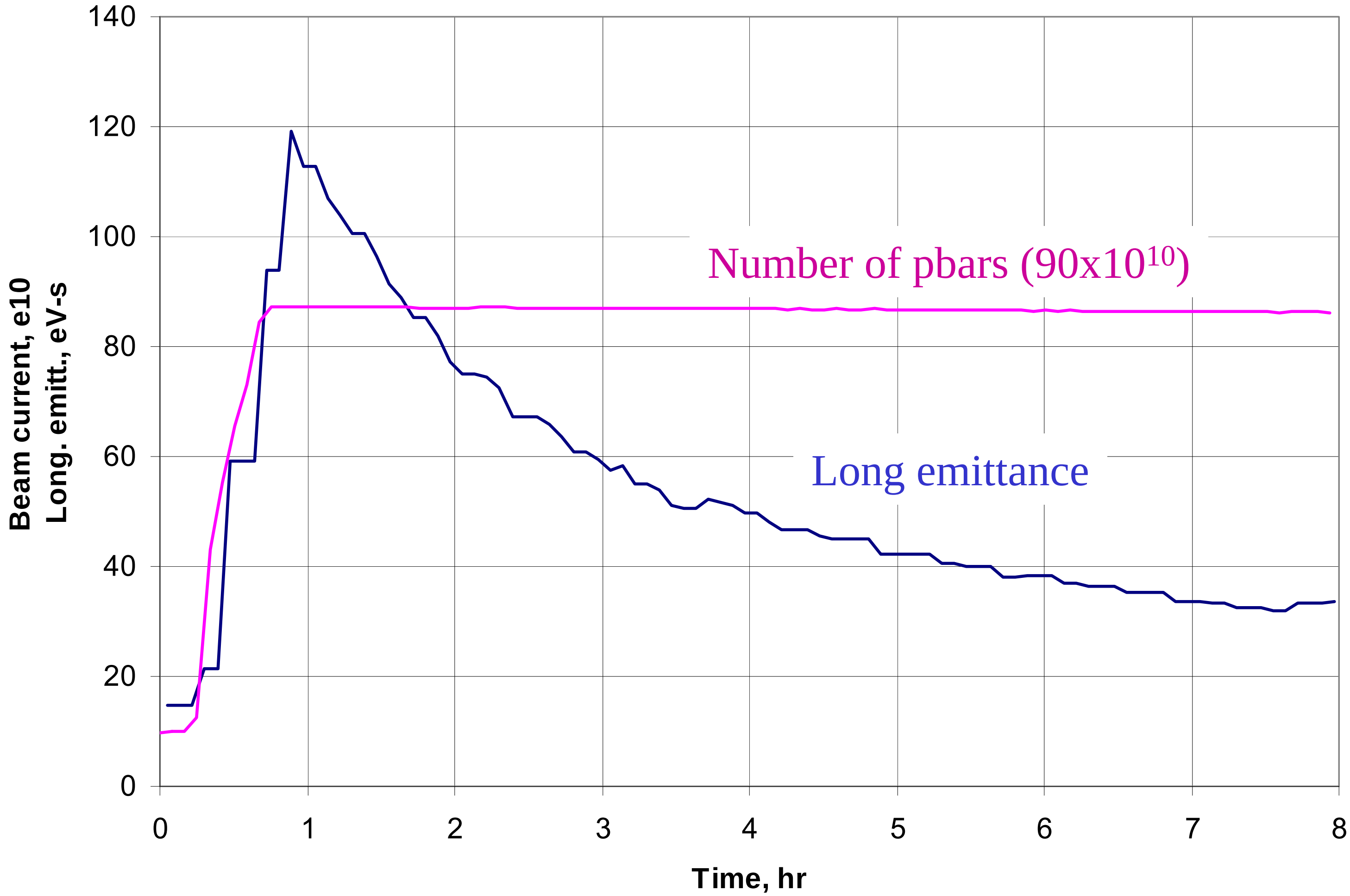
Cold Stack

Gated Cooling Experiment

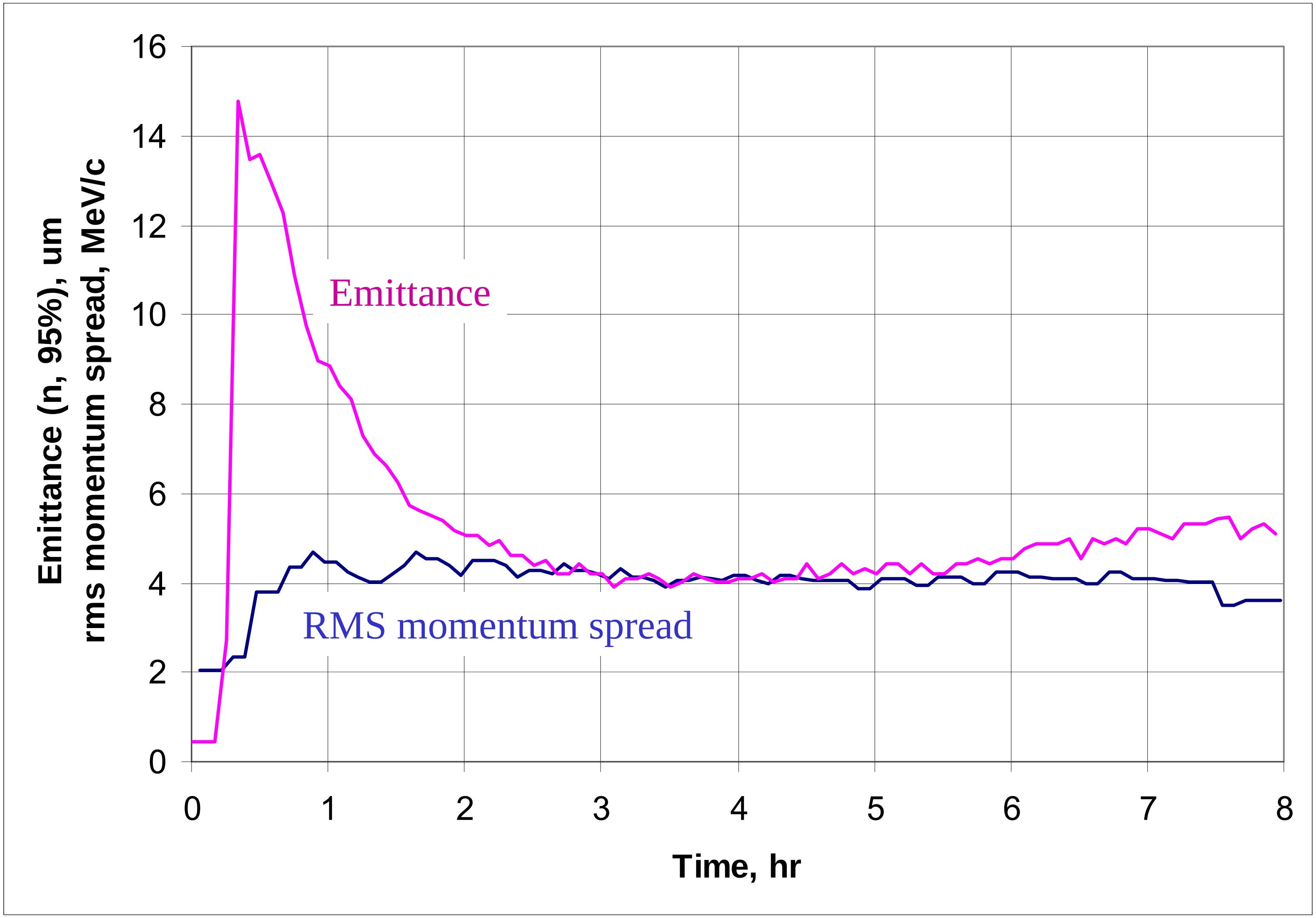


Two segments of beam (25e10 pbars each): one cooled/gated and one not. The uncooled bunch shows natural emittance growth due to IBS and coulomb scattering.

Recycler stochastic cooling system



Present stochastic cooling system



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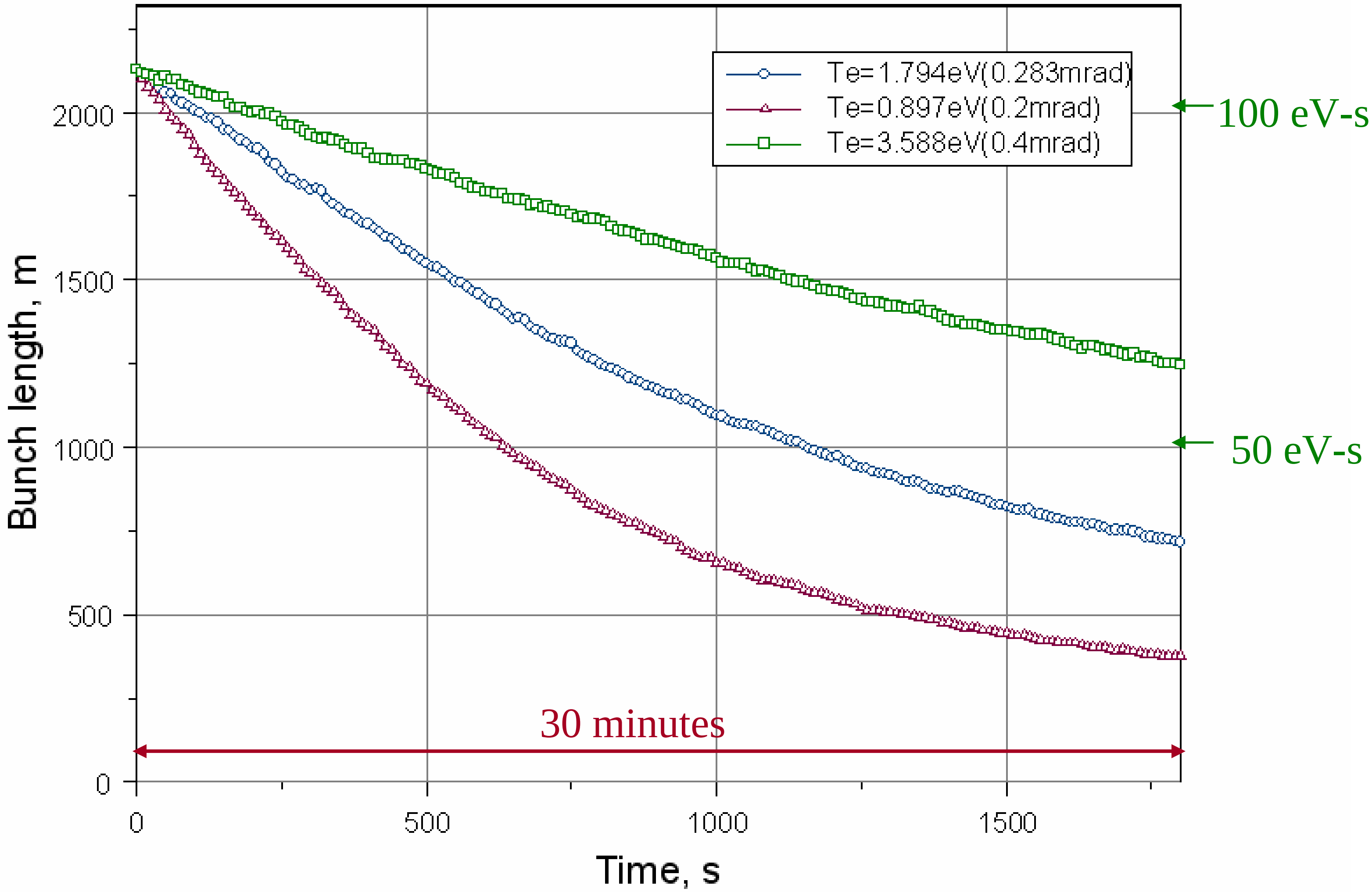
Cooling in barrier buckets

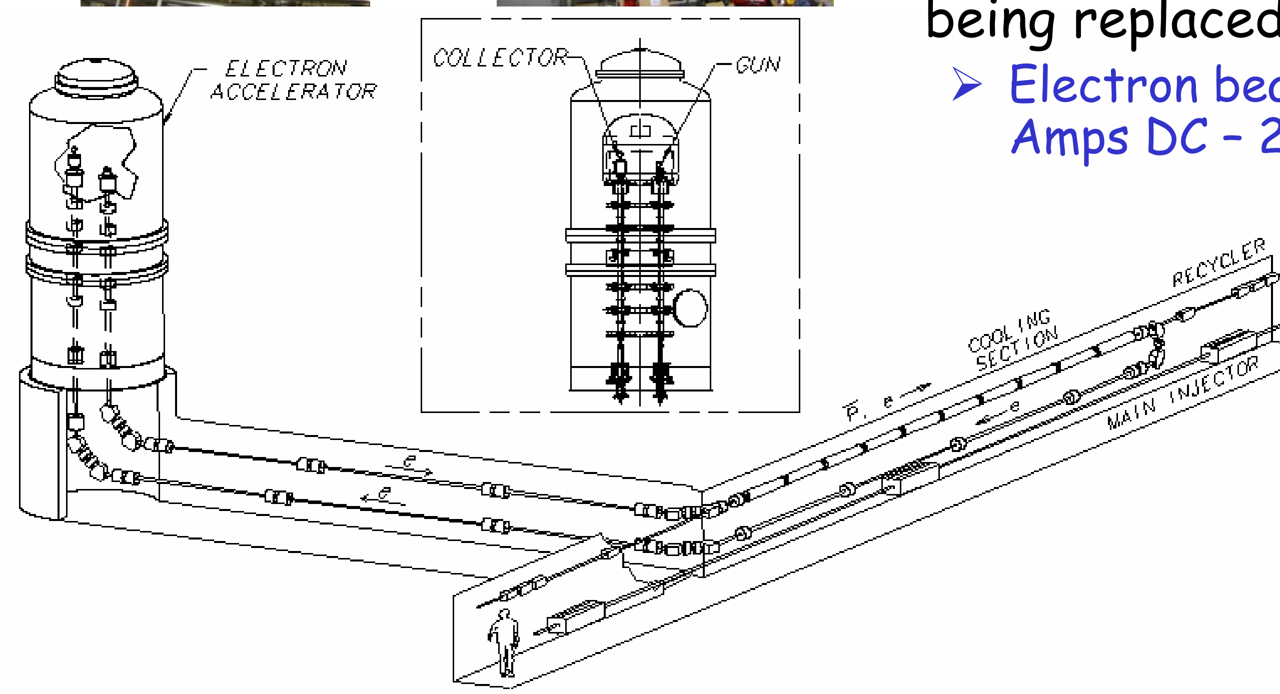
Keep momentum spread constant, compress the bunch length by moving the rf barrier

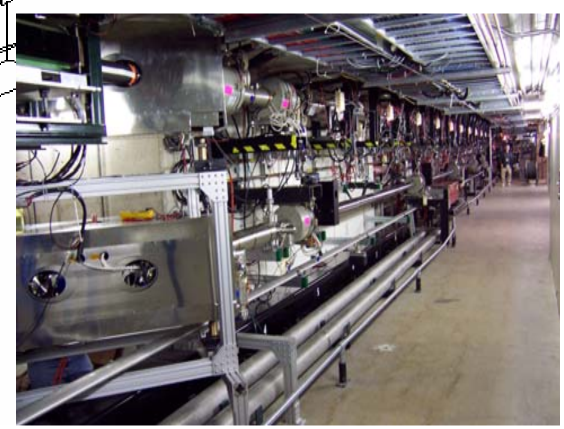
Simulation (MOCAC) of electron cooling + IBS, 500 mA e-beam, 600×10^{10} pbars



Recycler Electron Cooling

- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad angular spread



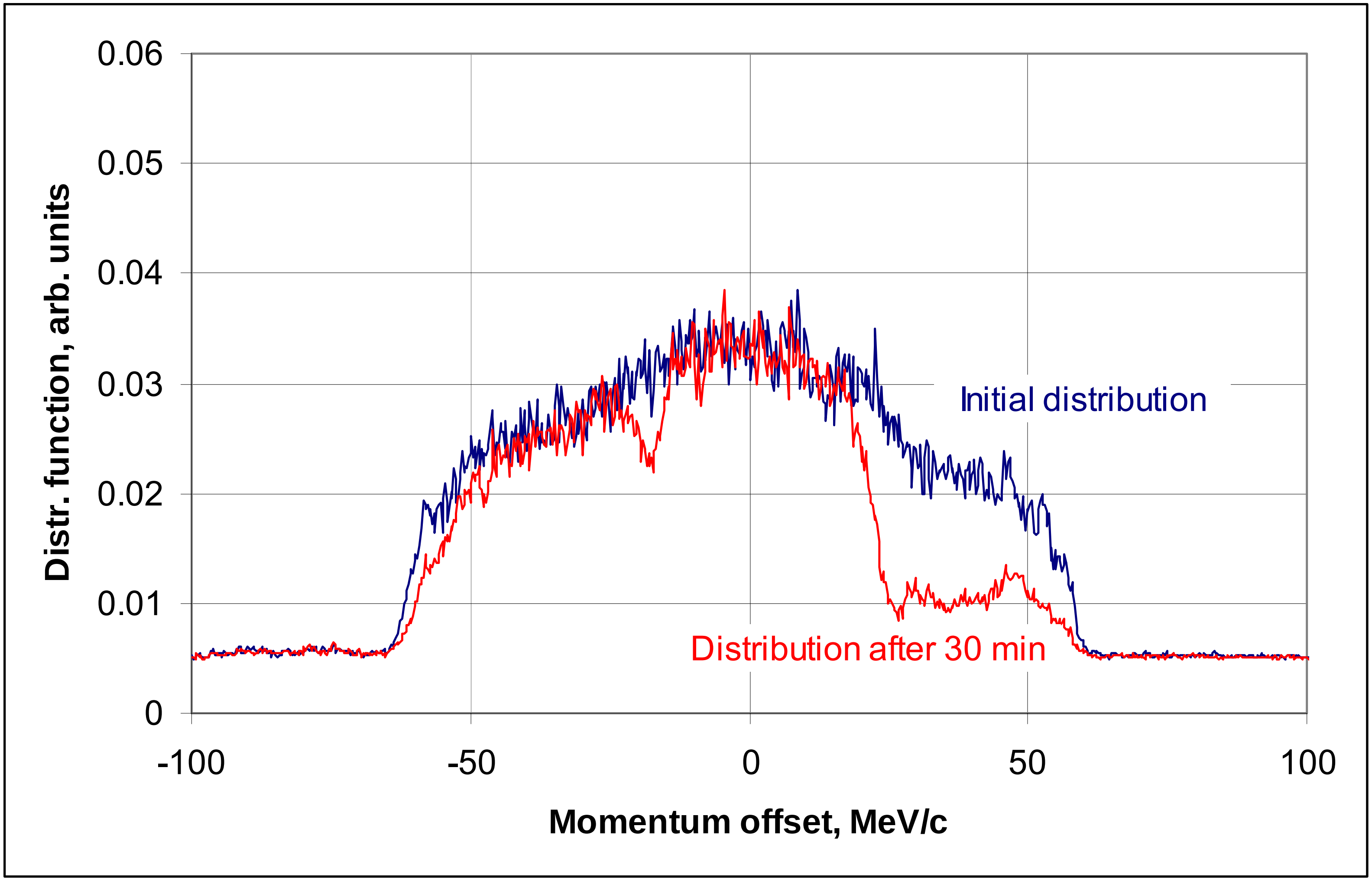


Electron beam parameters

Electron kinetic energy	4.34 MeV
Uncertainty in electron beam energy	0.3 %
Energy ripple	$\leq 10^{-4}$
Beam current (max)	0.5 A DC
Duty factor (averaged over 8 h)	95 %
Electron angles in the cooling section (averaged over time, beam cross section, and cooling section length), rms	$\leq$ 0.2 mrad

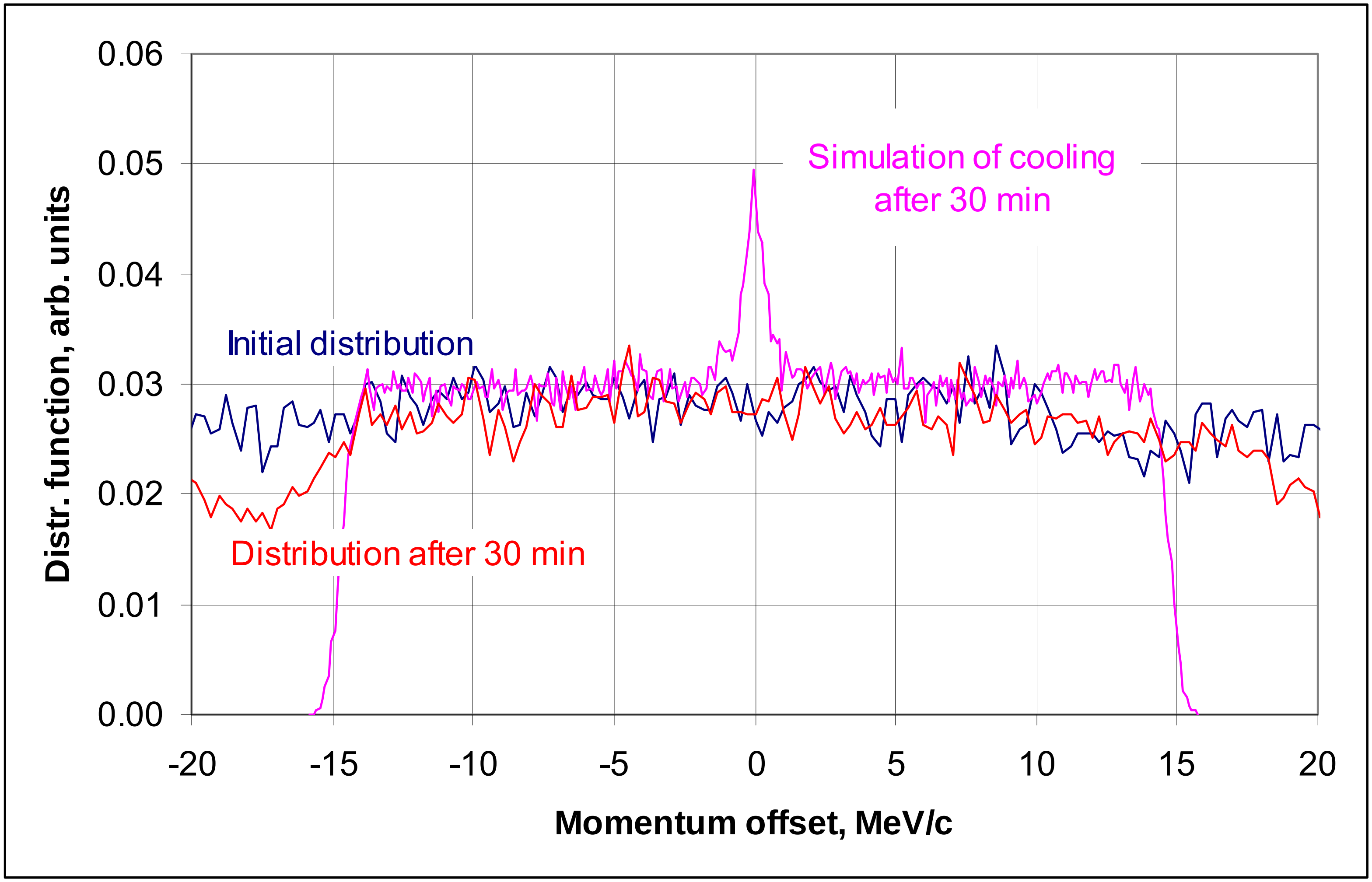
Recycler measured momentum distribution using Schottky

- 1.5e11 pbars, ε_n = 2 μm
- Momentum acceptance (flat central part): about 0.5% (+/- 22 MeV/c)

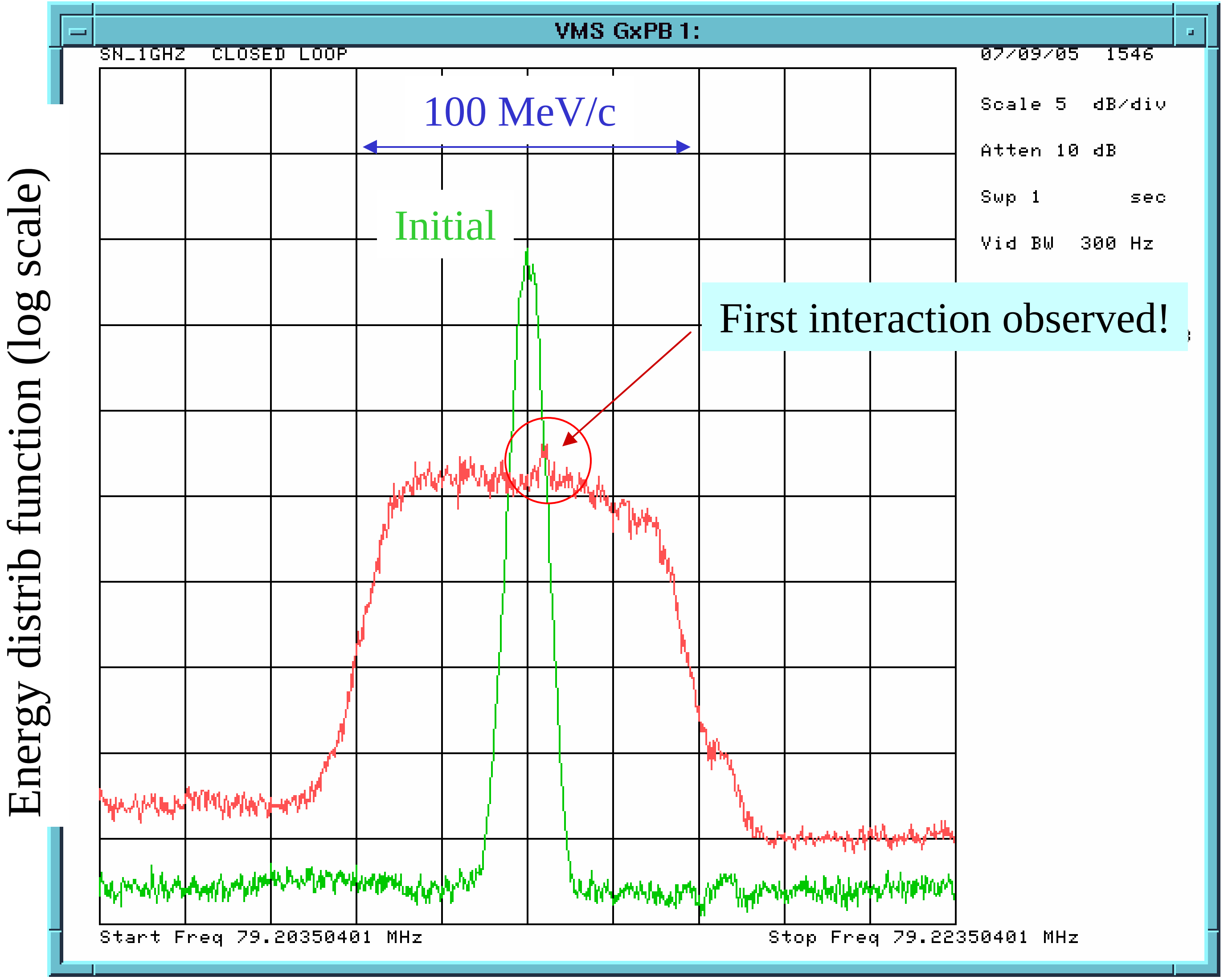


Simulation of cooling demonstration

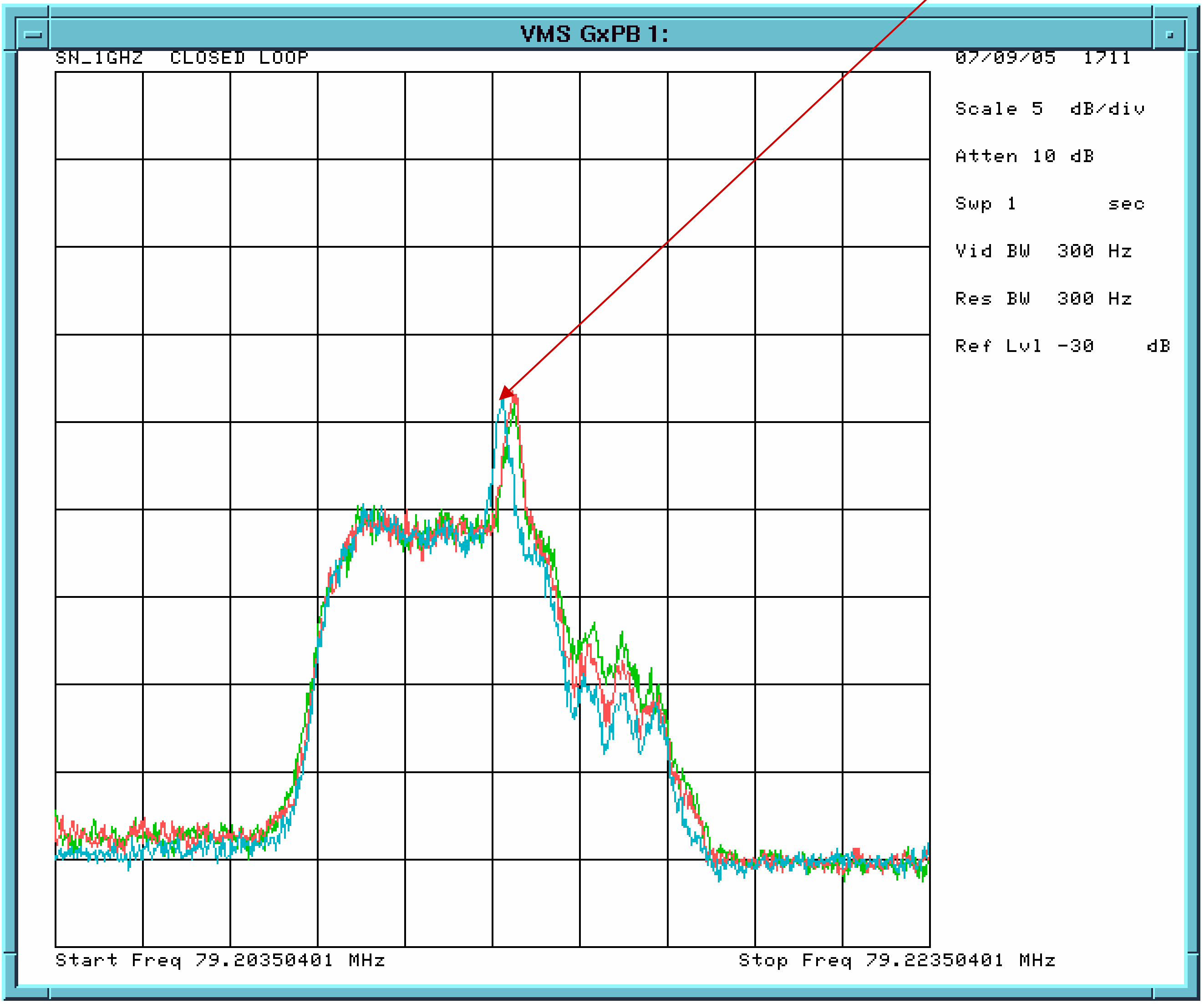
- Without cooling -- the momentum distribution remains flat over 0.3% span for 30 minutes
- Coasting beam, IBS+ECOOL simulation, ε_n = 2 μm-rad, Ie=0.1 A, rms angular spread = 0.5 mrad



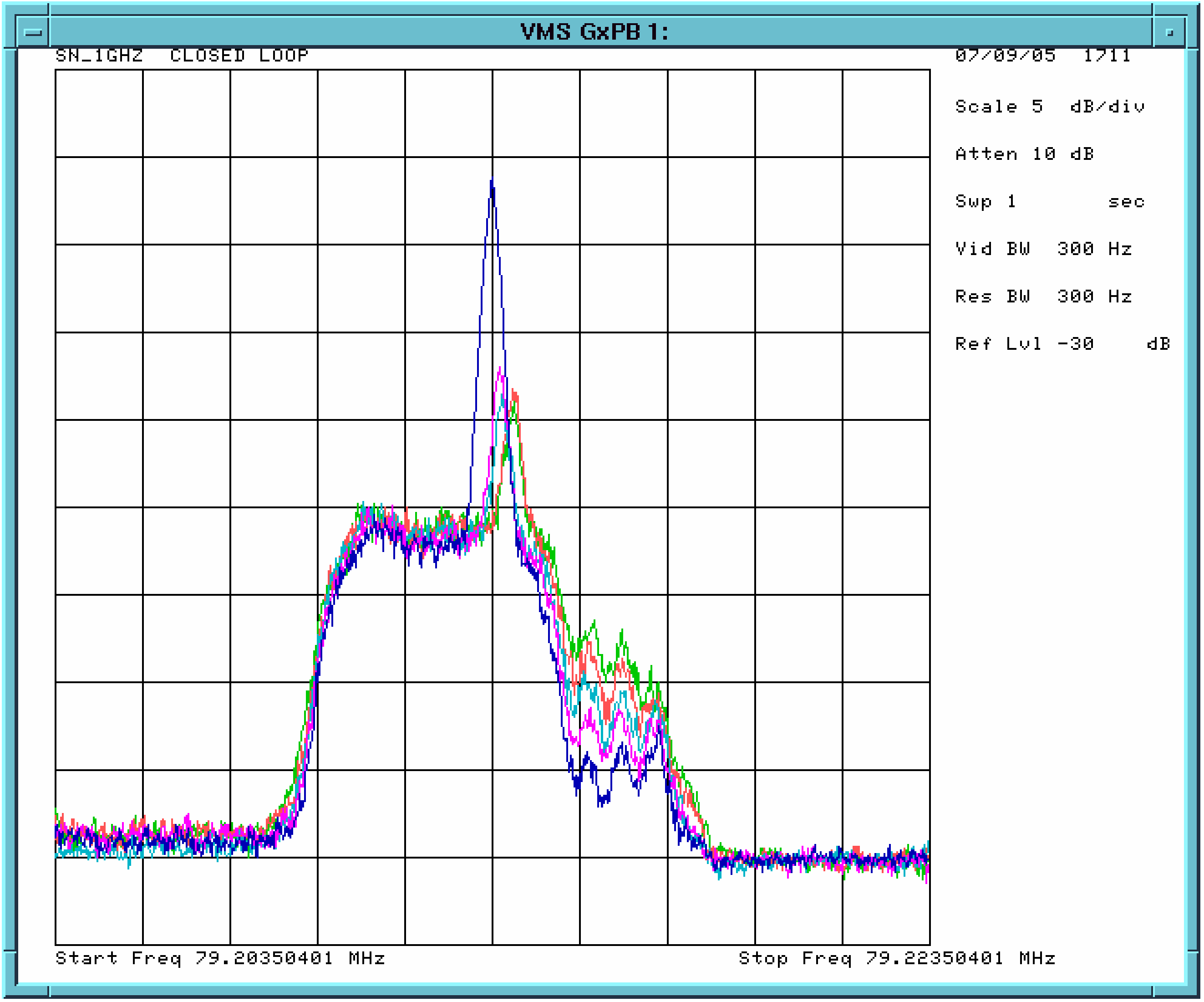
First interaction – July 09, 2005



Electron energy adjusted down by 2 keV

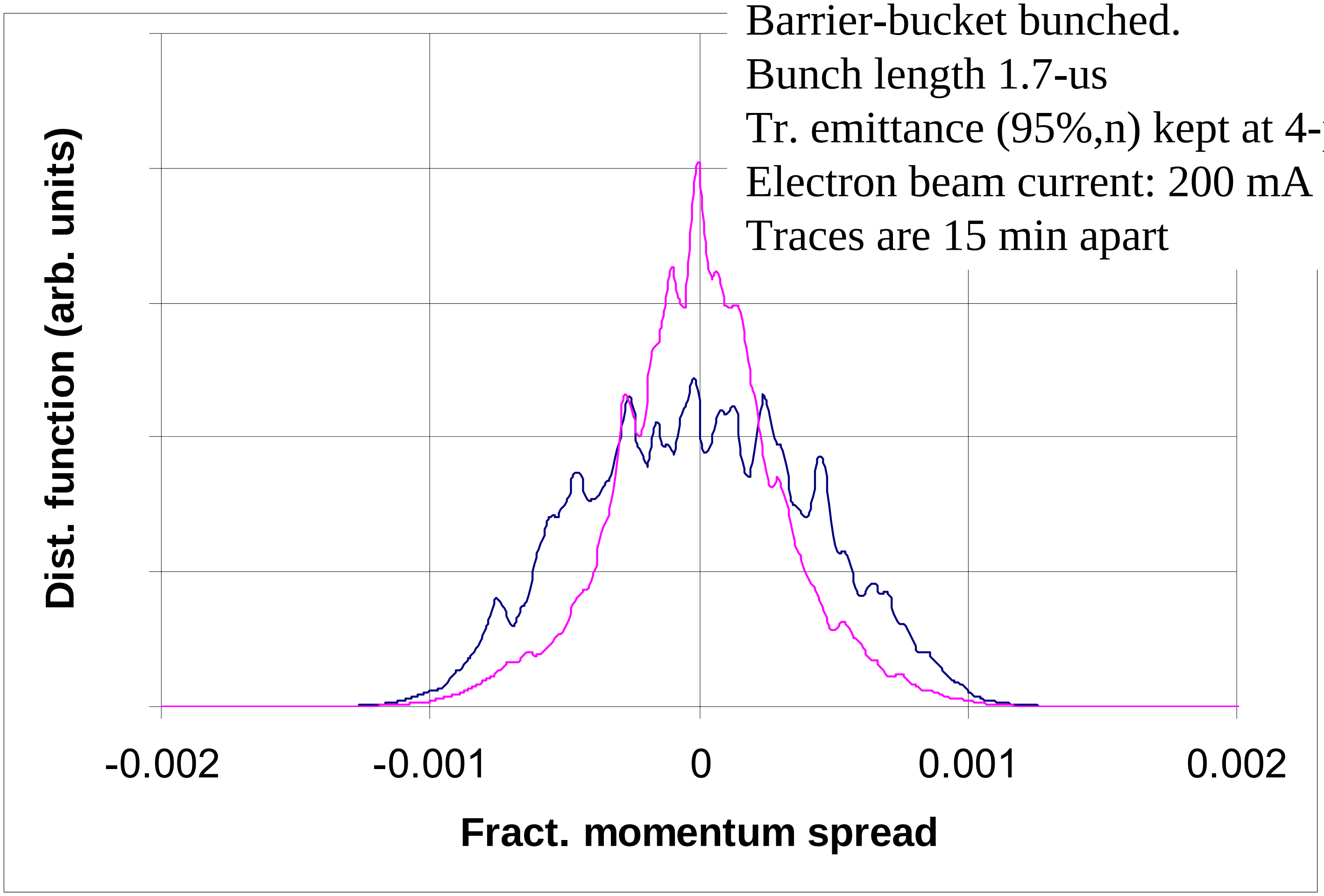


Energies aligned – we were within 3 kV!



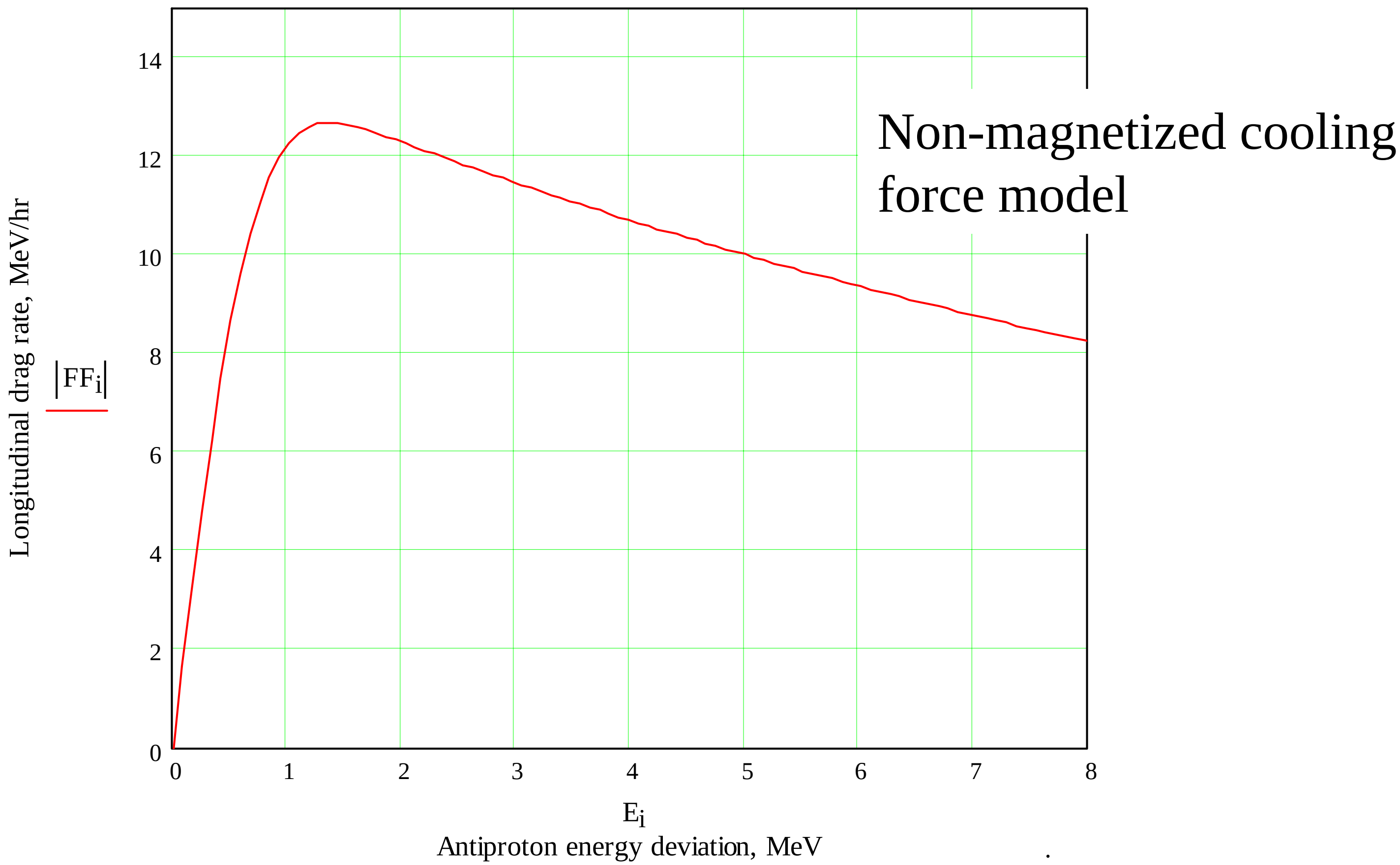
First e-cooling demonstration – 07/15/05

Pbar beam: 63.5e10
Barrier-bucket bunched.
Bunch length 1.7-us
Tr. emittance (95%,n) kept at 4-pi mm-mrad
Electron beam current: 200 mA
Traces are 15 min apart



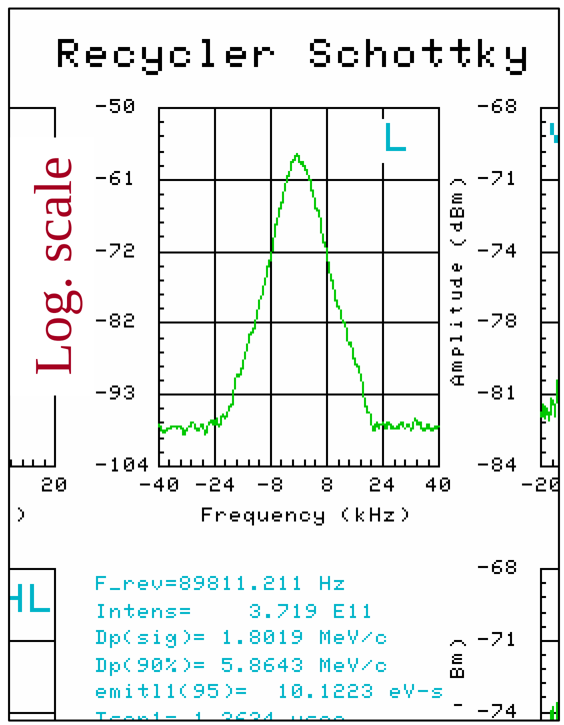
Electron cooling drag rate

- For an antiproton with zero transverse velocity, electron beam: 200 mA, 3-mm radius, 300 eV rms energy spread and 200 μrad angular spread



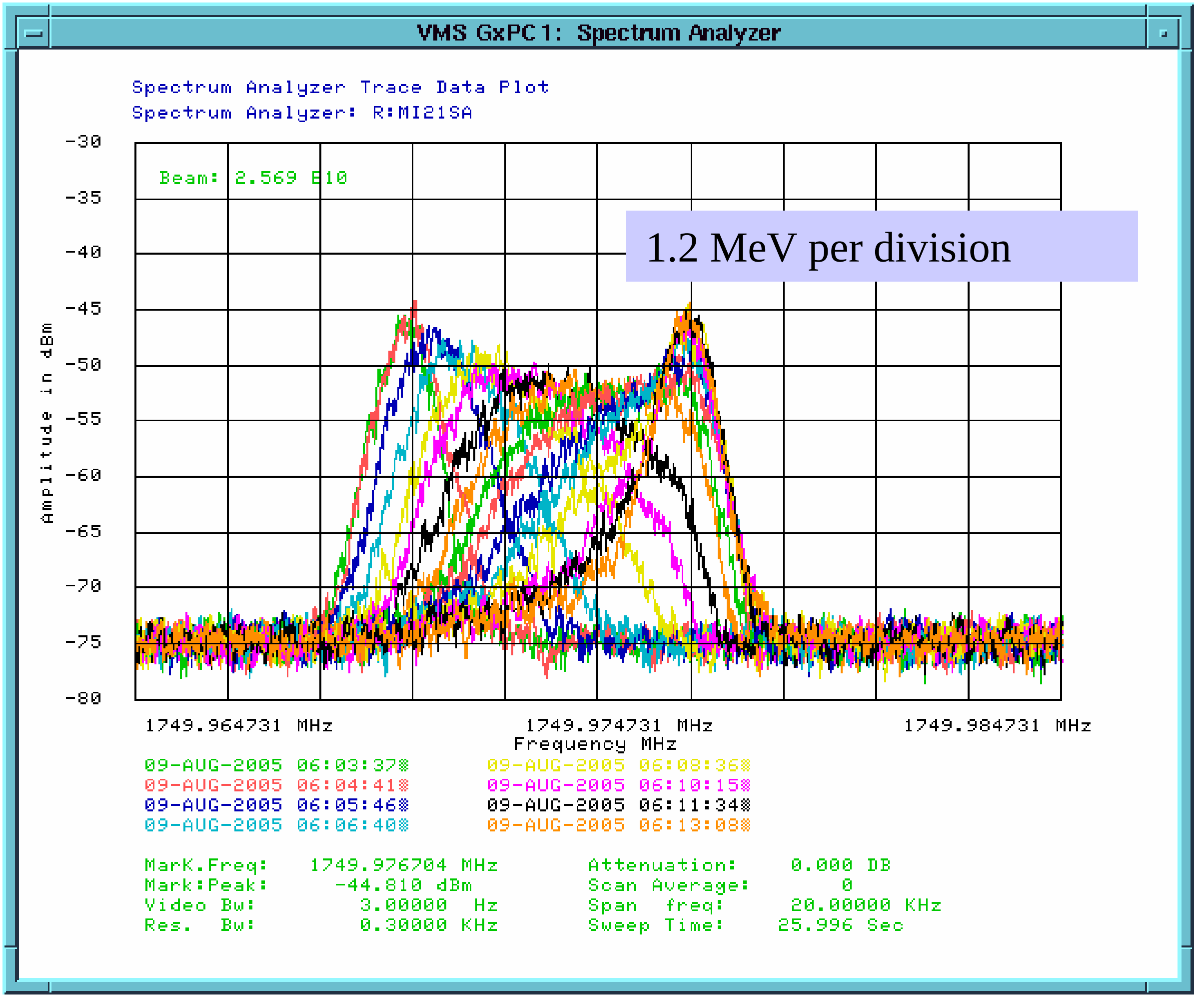
Equilibrium long. emittance

- For a nearly constant drag force, F_0 , the equilibrium momentum distribution is not gaussian but exponential: $f(p) \sim \exp(-|p|/p_0)$, where $p_0 = D/(2F_0)$ and D is the diffusion rate.
- The diffusion rate is mostly determined by the intra-beam scattering.
- The rms momentum spread is $\sqrt{2}\, p_0$ (keep at 3.5 MeV/c)
- For IBS: $D \approx 25$ MeV^2/hr
- Need $F_0 \approx 5$ MeV/hr



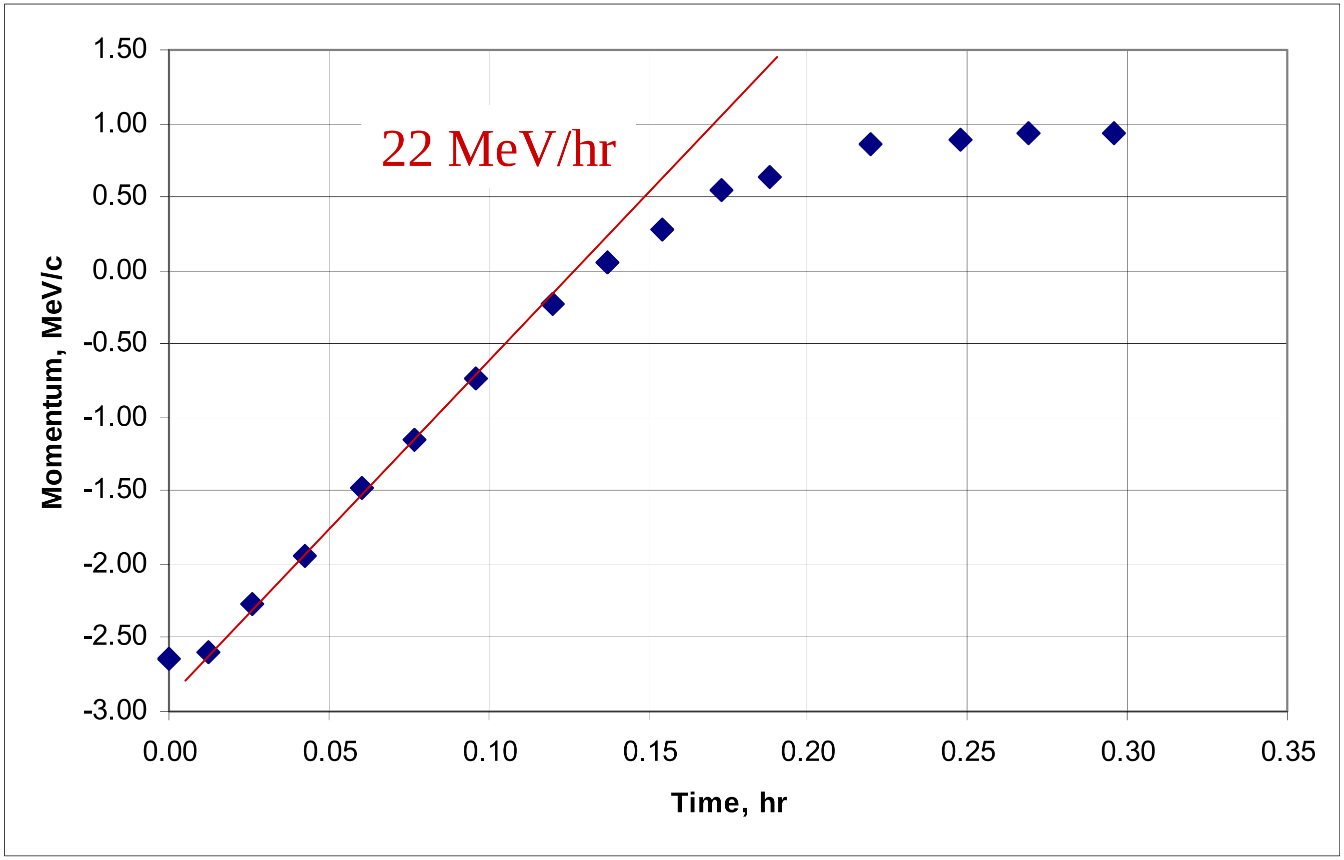
Drag force measurements: electron energy jump by +2 keV

Momentum distribution (log scale)



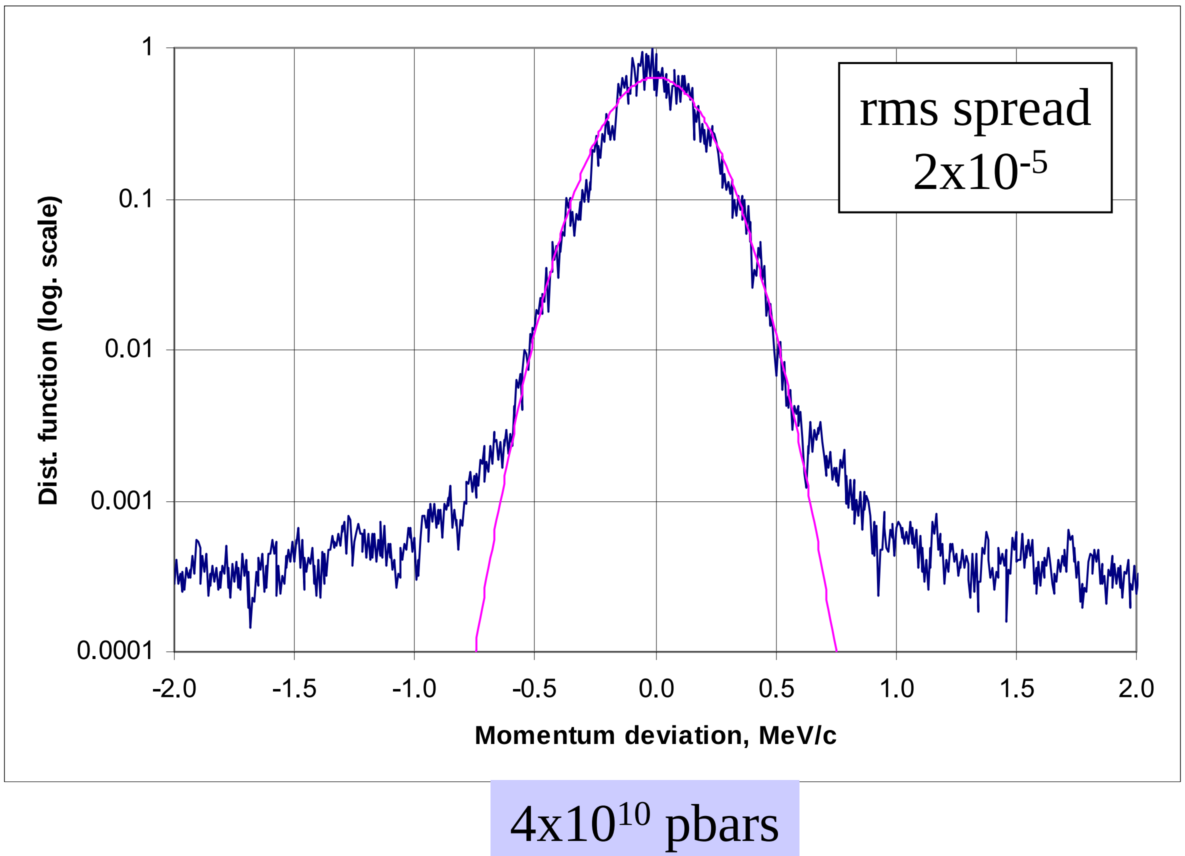
Beam emittance was measured by Schottky: 1.5 µm (n, 95%).
In the cooling section this corresponds to a 0.9 mm radius (rms), electron current 200 mA

Drag force – voltage jump +2 kV



Cooling rate for small amplitudes

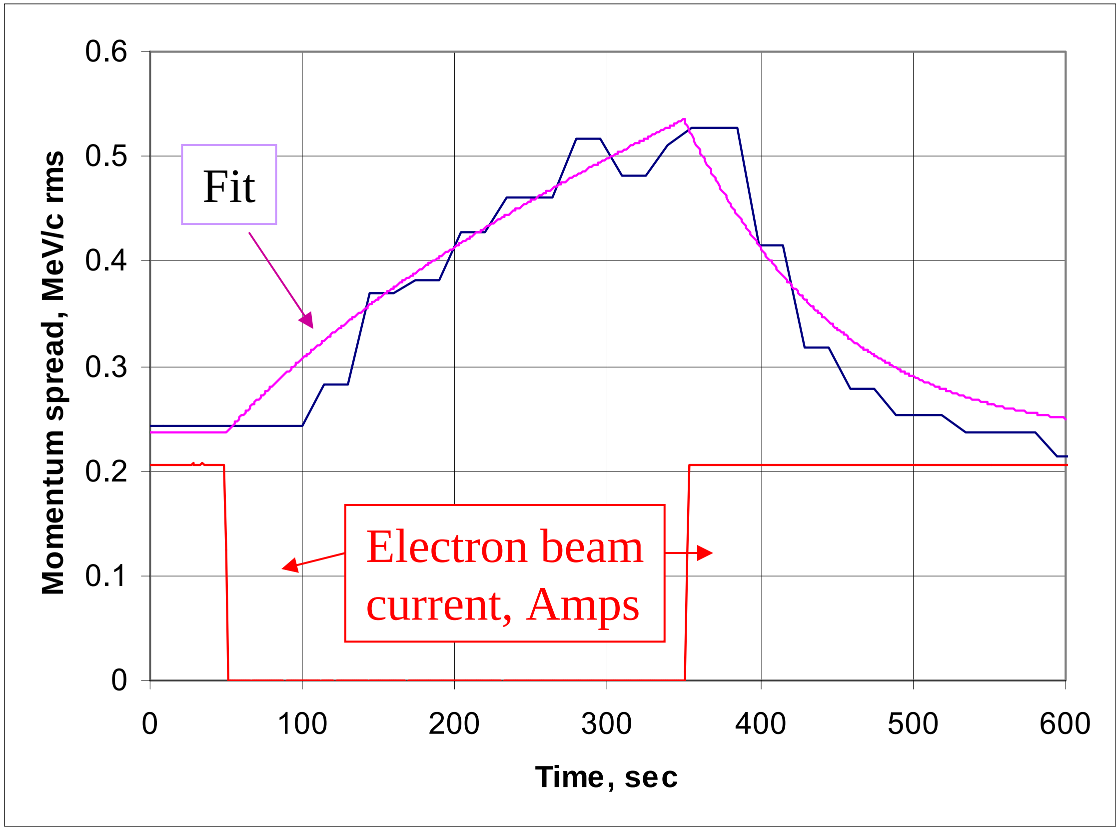
- For small momentum deviations (< 1 MeV) the cooling force is linear: $F \approx -\lambda p$. The distribution function in momentum is close to being gaussian.



$$\sigma_{rms}^2 = \frac{D}{2\lambda}$$

Cooling OFF-ON

- By turning the electron cooling OFF and ON again one can determine both the diffusion and cooling rates



Cooling OFF:

$$\sigma(t) = \sqrt{\sigma_0^2 + Dt}$$

Cooling ON:

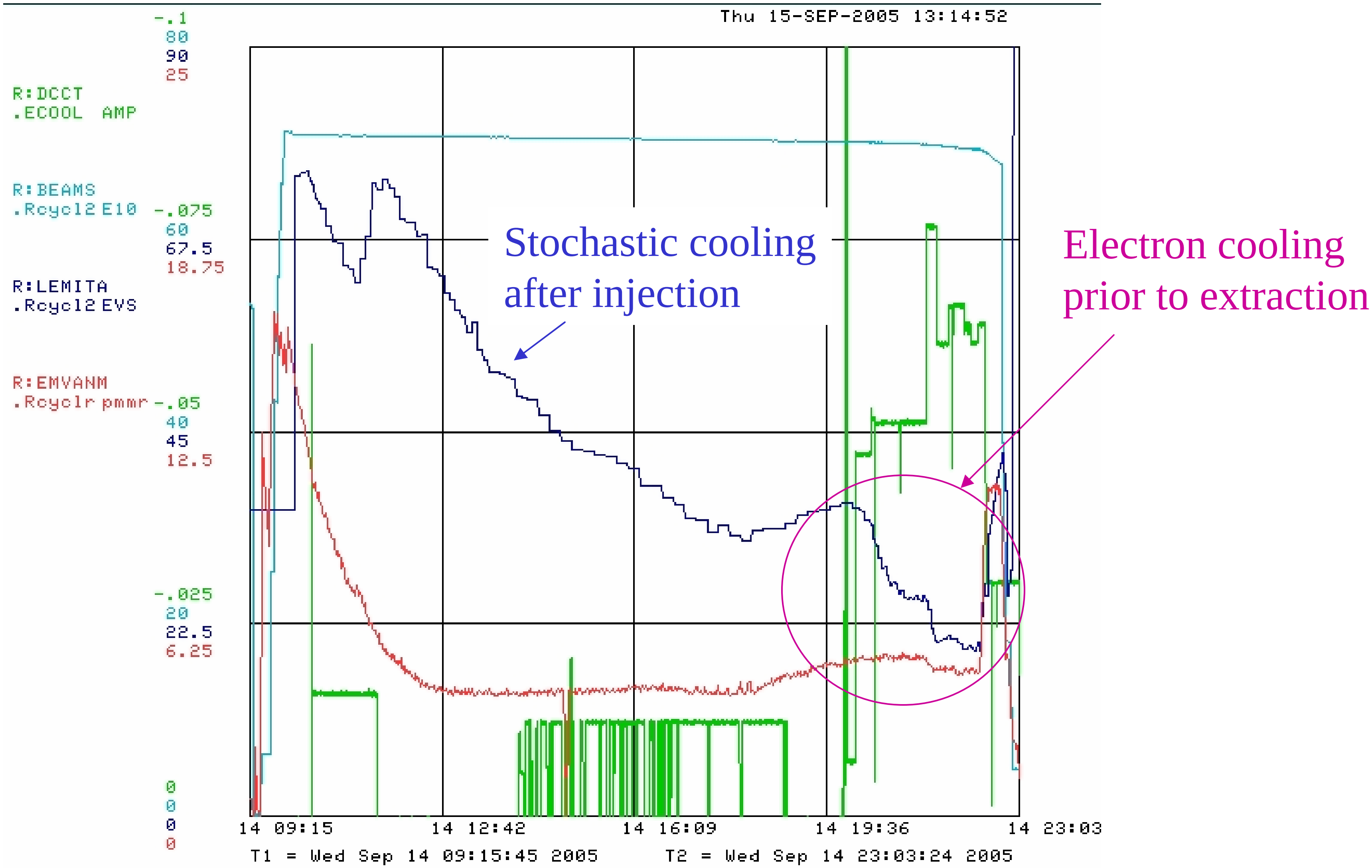
$$\sigma(t) = \sqrt{\left(\sigma_0^2 - \frac{D}{2\lambda}\right)\exp(-2\lambda t) + \frac{D}{2\lambda}}$$

$D \approx 2.8$ MeV^2/hr

$\lambda \approx 25$ hr $^{-1}$

(electron current 200 mA)

Electron cooling in operation



Recycler-Only Operations

- Recycler has been participating in Collider Operations in the Combined Shot mode because the Recycler Stack size has been limited to ~120x10^{10} pbars
  - Longitudinal Cooling
  - Transverse Stability
- With Electron Cooling operational and the transverse dampers commissioned, the Recycler stack size can now be increased to over 200x10^{10} pbars
- The Collider complex is now transitioning from Combined Shot mode to Recycler-Only mode
  - Faster average stacking.
  - Smaller pbar emittances in the TEV

Recycler Electron Cooling Summary

- Electron cooling commisioning
  - Electron cooling was demonstrated in July 2005 two months ahead of schedule.
  - By the end of August 2005, electron cooling was being used on every Tevatron shot
- Electron cooling rates
  - Drag rate: 20 MeV/hr for particles at 4 MeV
  - Cooling rate: 25 hr^{-1} for small amplitude particle
  - Can presently support final design goal of rapid transfers (30eV-sec every hour)
  - Have achieved 500 mA of electron beam which is the final design goal.