The Tevatron Years

A Retrospective

Accelerator Complex, Recycler Scheme, Beam Separation, State of the Art of Antiproton Production

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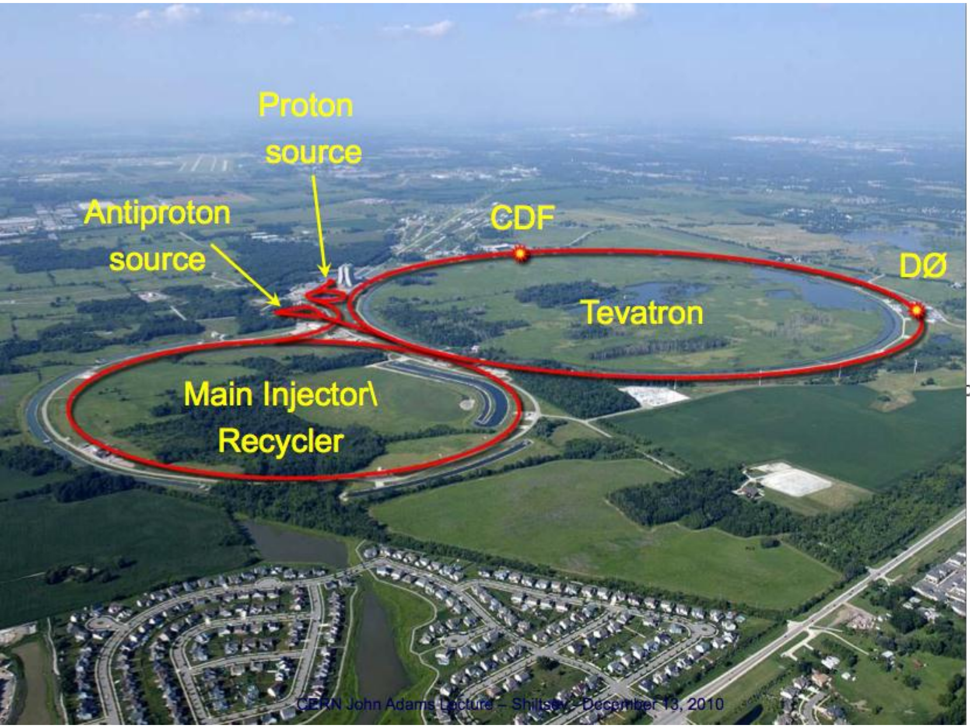
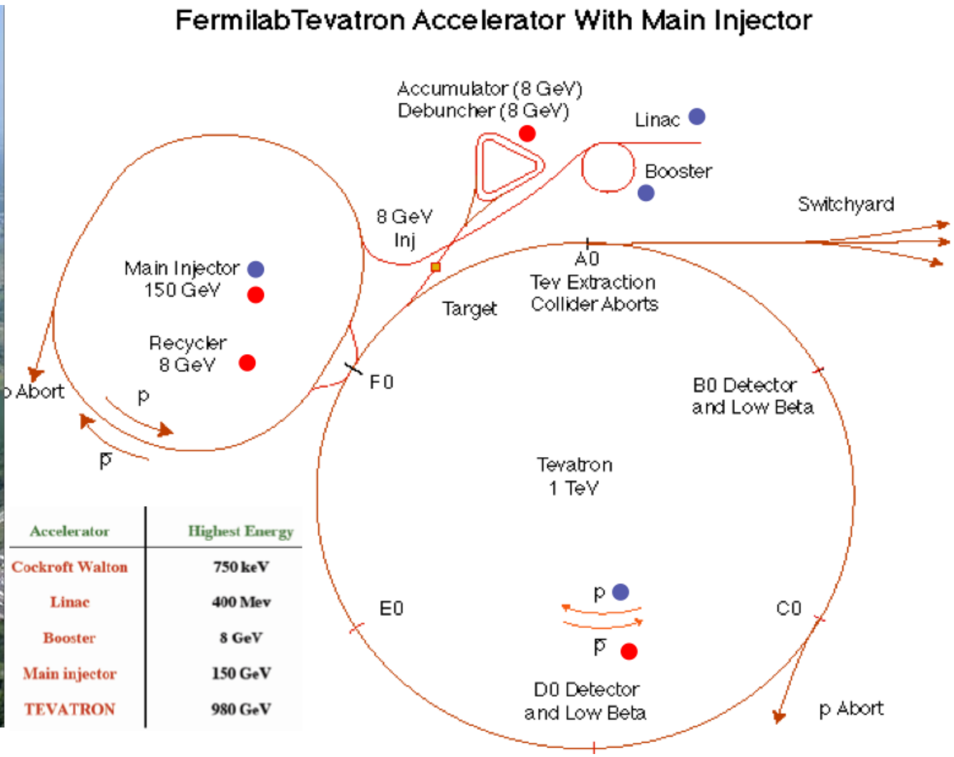
The Tevatron

- The Tevatron was located at Fermilab near Chicago, Illinois, USA
- The Tevatron
  - Had an energy of 978 GeV (almost 1 TeV)
  - A radius of 1km
- The Tevatron was the first large scale synchrotron to use superconducting magnets
- The Tevatron was the first superconducting collider.

The Fermilab Collider Complex



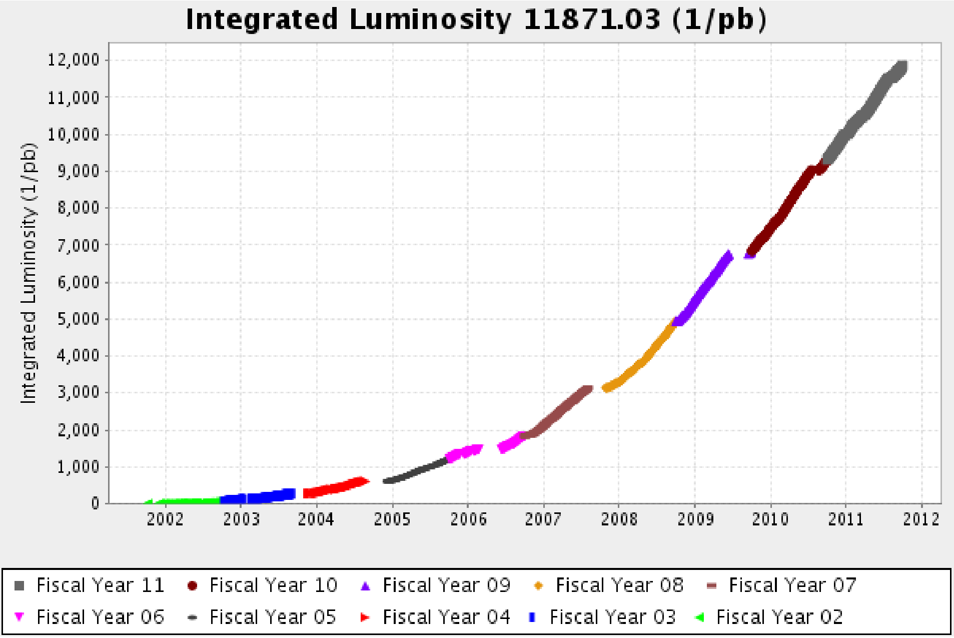

FermilabTevatron Accelerator With Main Injector

Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 Mev
Booster	8 GeV
Main injector	150 GeV
TEVATRON	980 GeV

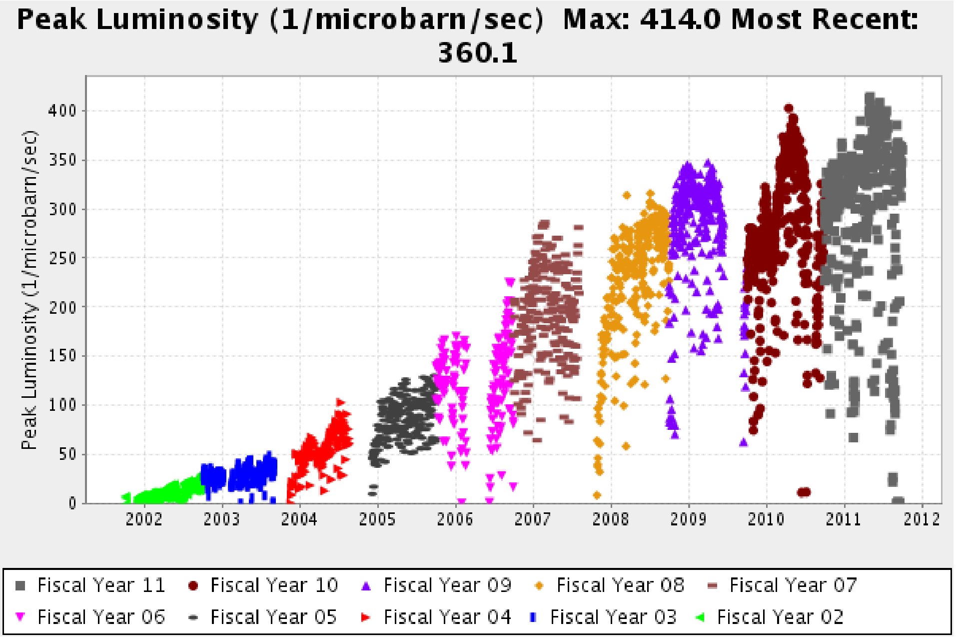
Tevatron Milestones

- Commissioned in 1983 as a Fixed Target Accelerator
- First proton-antiproton collisions - 1985
- Operation collider - 1987
- End of Run I – 1997
- Beginning of Run II – 2001
- End of Run II and the Tevatron - 2011

Tevatron Run II Luminosity



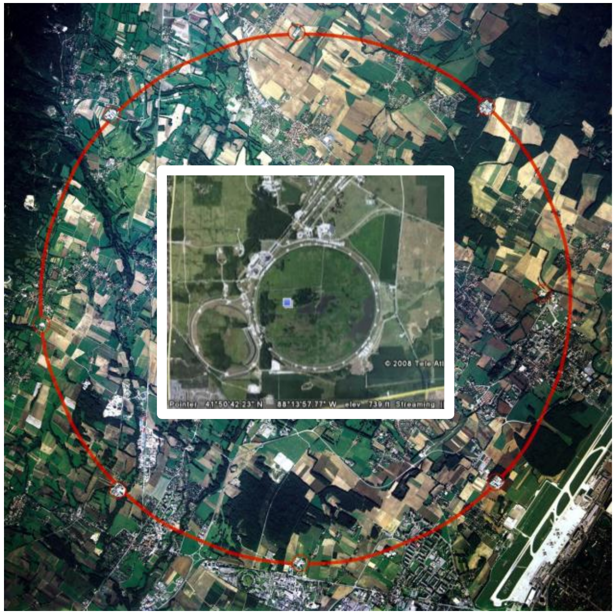
Integrated Luminosity 11871.03 (1/pb)

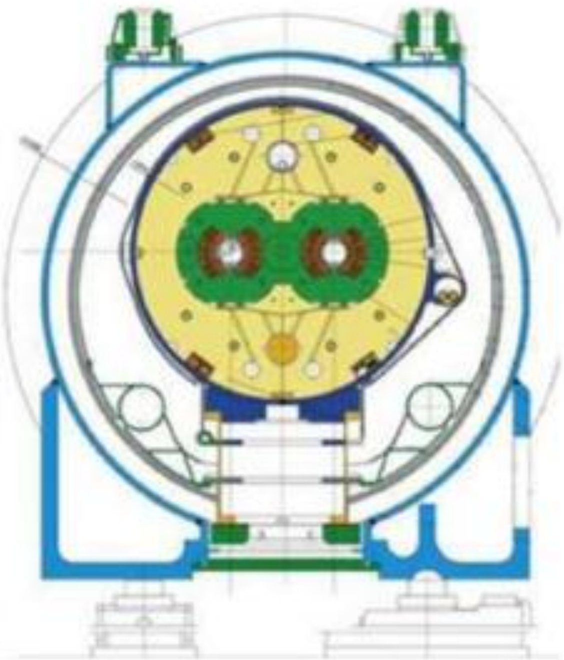


Peak Luminosity (1/microbarn/sec) Max: 414.0 Most Recent: 360.1

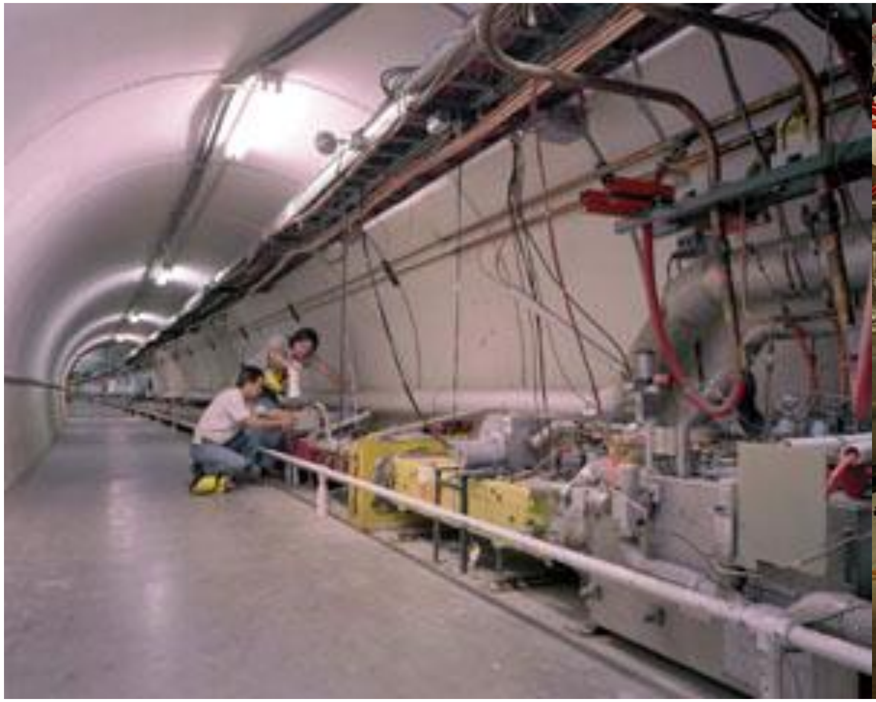
Tevatron Configuration

- The Tevatron was a proton – antiproton (p-pbar) collider
  - At its inception, 4 Tesla superconducting magnets was a risky technology
  - Minimize risk by making one ring with protons and antiprotons counter-rotating
- In contrast, the LHC has 8 Tesla magnets in two rings





The Tevatron and The LHC

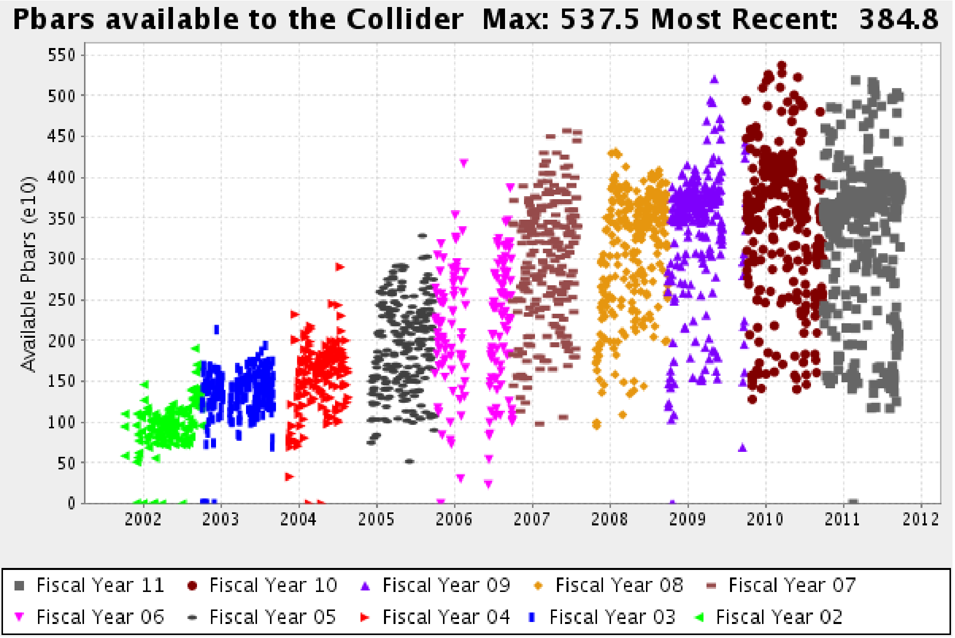


Luminosity

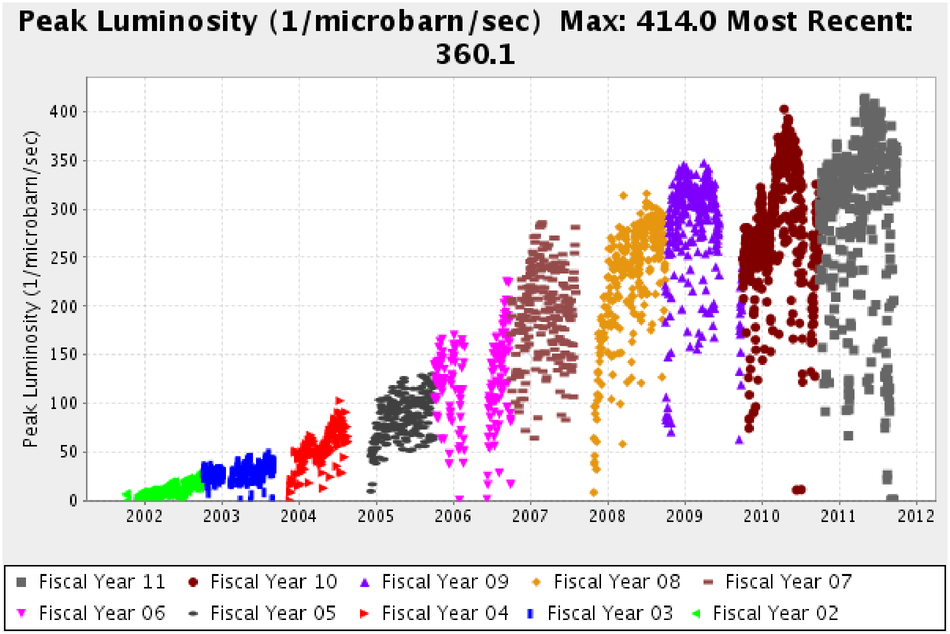
$$L = \frac{3\gamma f_o}{\beta^*} B N_{\bar{p}} \frac{N_p}{\varepsilon_p} \frac{F\left(\beta^*, \theta_{x,y}, \sigma^L_{p,\bar{p}}, \varepsilon_{p,\bar{p}}\right)}{\left(1 + {}^{\varepsilon_{\bar{p}}}\!/_{\varepsilon_p}\right)}$$

- The major luminosity limitations are
  - The number of antiprotons (BN_{pbar})
  - The proton beam brightness (N_p/ε_p)
    - Beam-Beam effects
  - Antiproton emittance
  - $F<1$

Peak Luminosity vs Pbars



Pbars available to the Collider Max: 537.5 Most Recent: 384.8

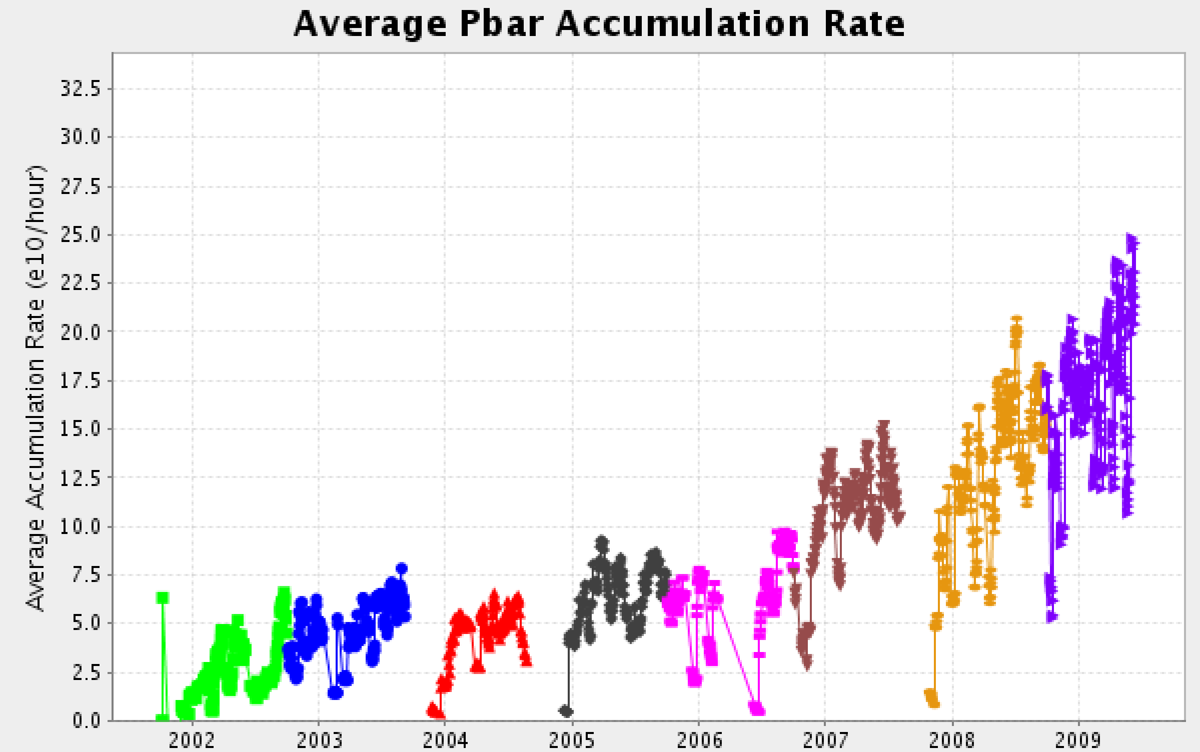


Peak Luminosity (1/microbarn/sec) Max: 414.0 Most Recent: 360.1

Antiproton Economics (Pbar Burn Rate)

$$\Phi_{\bar{p}}^{(\mathrm{min})} = n_c \sigma_a L$$

- $n_c = 2$
- $\sigma_a = 70$ mb
- $L = 3.0\times10^{32}$ cm^{-2}-sec^{-1}
- $\Phi_{burn} = 15\times10^{10}$ hr^{-1}



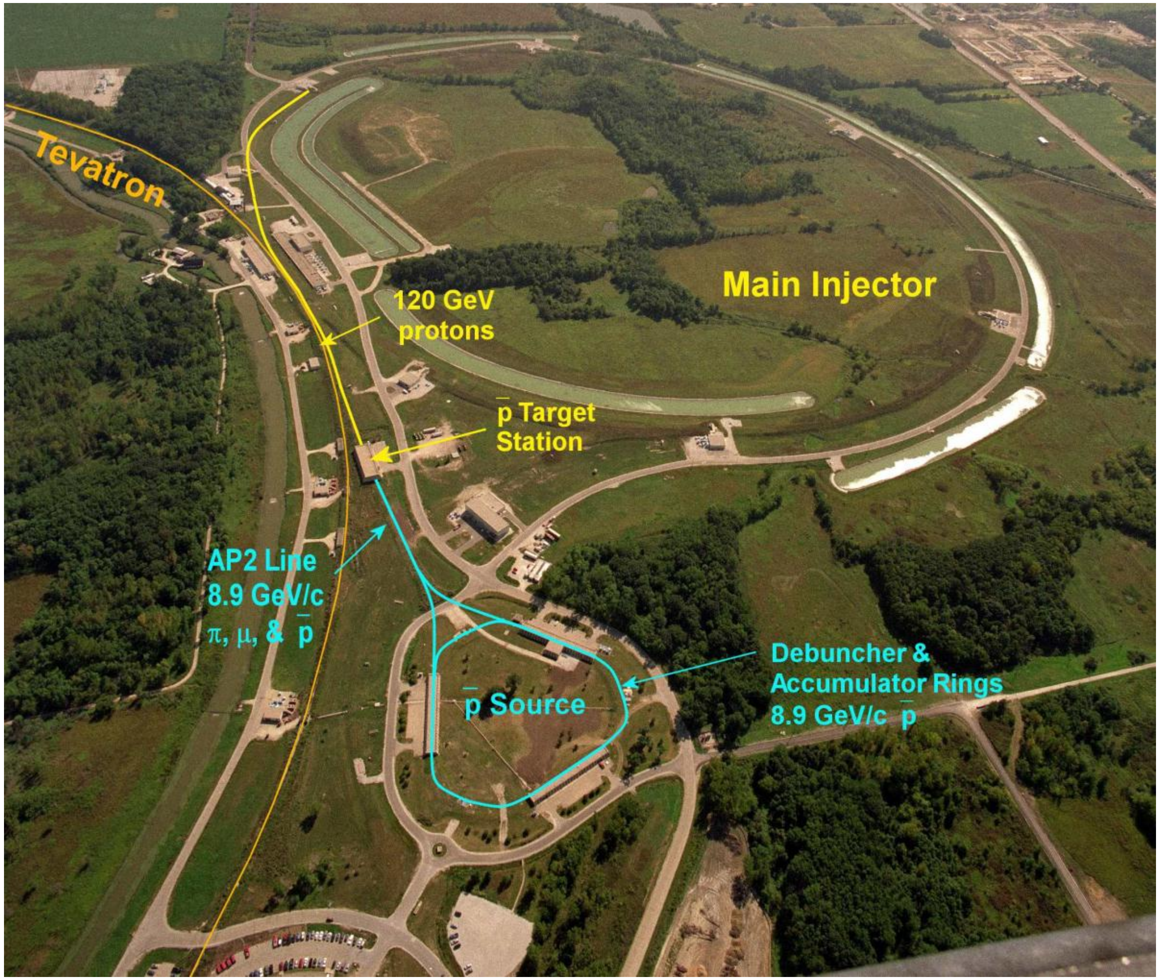
Stacking Rate

$$\Phi = \frac{N_p P}{T_{rep}}$$

- N_p is the number of protons on target
- P is the production ratio of the number of antiprotons produced to N_p
  - Typically about 20×10^{-6}
  - Mostly a function of the collection aperture
- T_{rep} is the cycle time
  - Mostly a function of the cooling rate

Antiproton Production

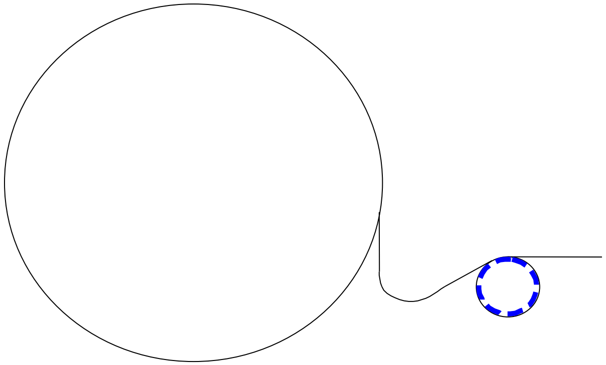
- 1.6×10^8 8 GeV pbars are collected every 2 seconds by striking 8×10^{12} 120 GeV protons on a Nickel target
- 8 GeV Pbars are focused with a lithium lens operating at a gradient of 760 Tesla/meter
- 30,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator 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



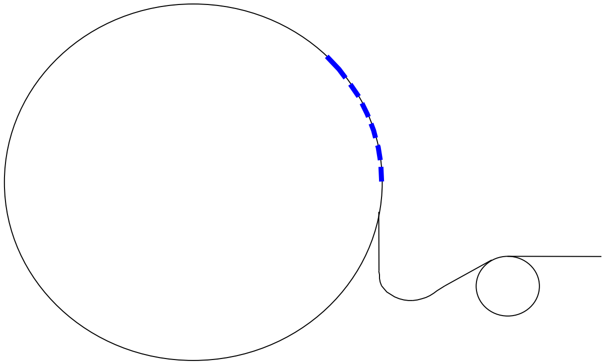
(Some) Key Pbar Technologies

- Slip Stacking
- Inconel Targets and Lithium Lens
- Wideband Stochastic Cooling
  - Slotted Waveguides
  - Optical Notch Filters
- 8 GeV electron cooling
- Recycler Momentum Mining
- Main Injector Coalescing

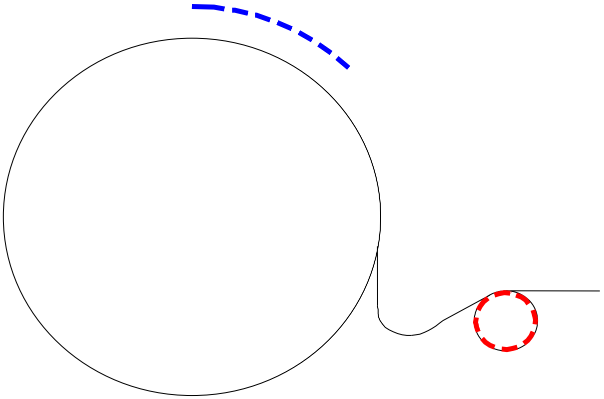
Slip Stacking



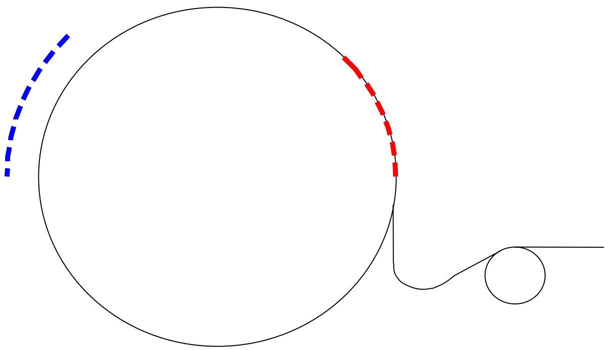
1. First Booster Batch accelerated in Booster



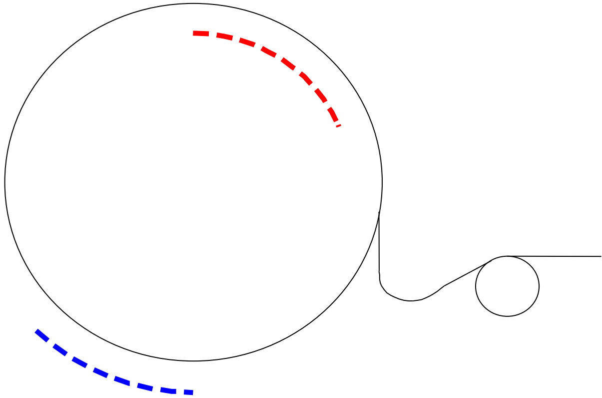
2. First Booster Batch injected onto MI central orbit with RF system A



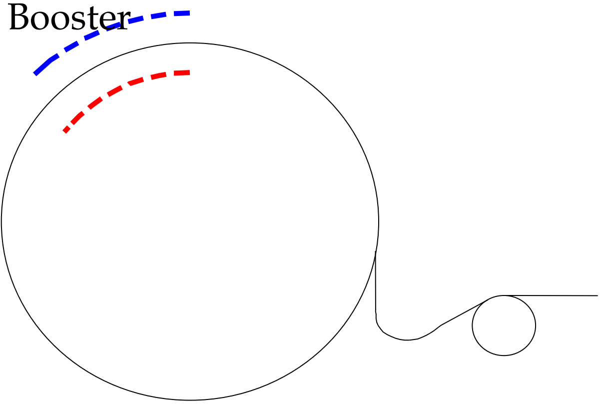
3. First Booster Batch slightly accelerated in MI with RF System **A.** Second Booster Batch accelerated in Booster



4. Second Booster Batch injected onto MI central orbit with RF system B

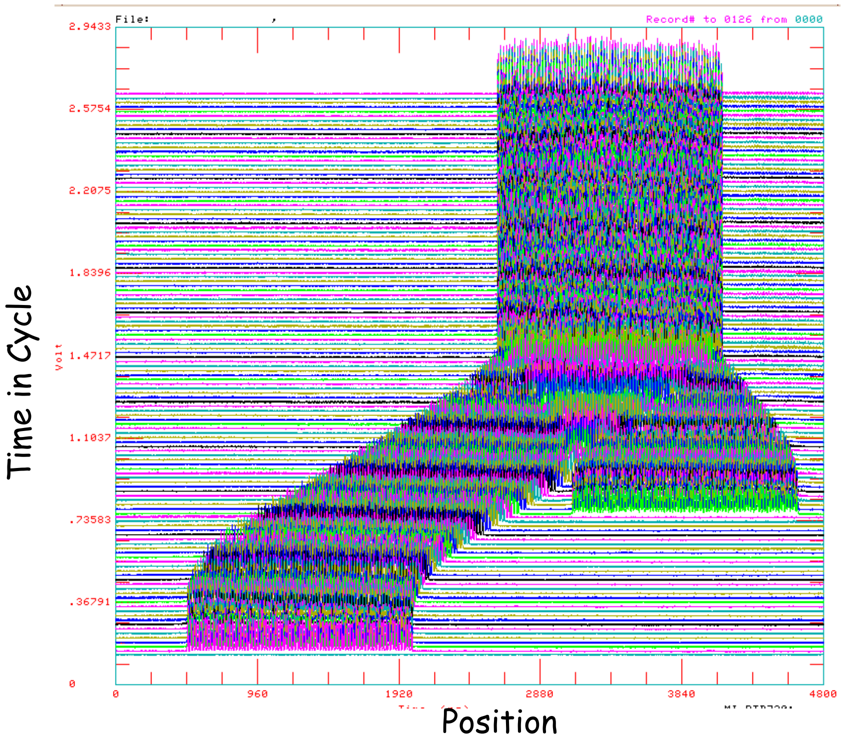


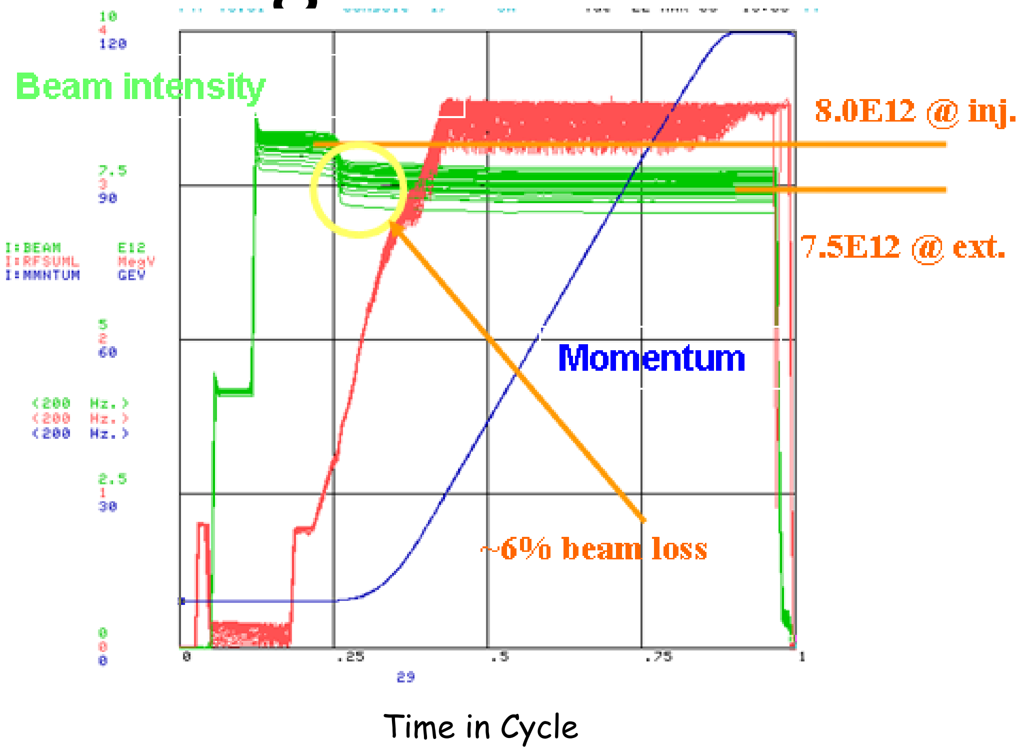
5. Second Booster Batch slightly decelerated in MI with RF System B



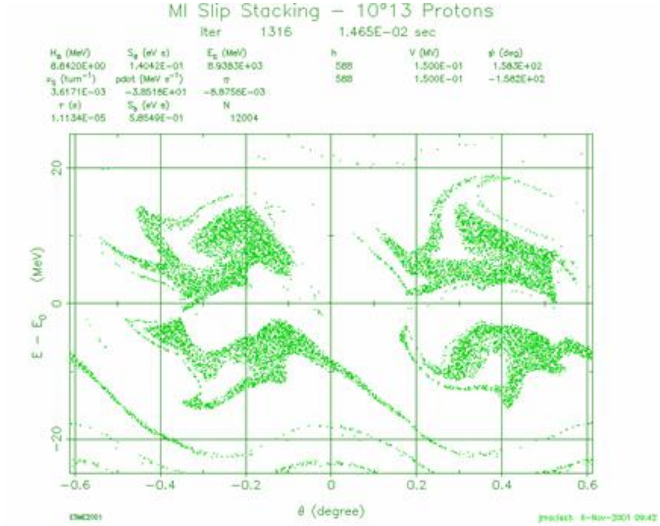
6. Wait till batches line up and snap on RF system C while turning of RF systems A & B

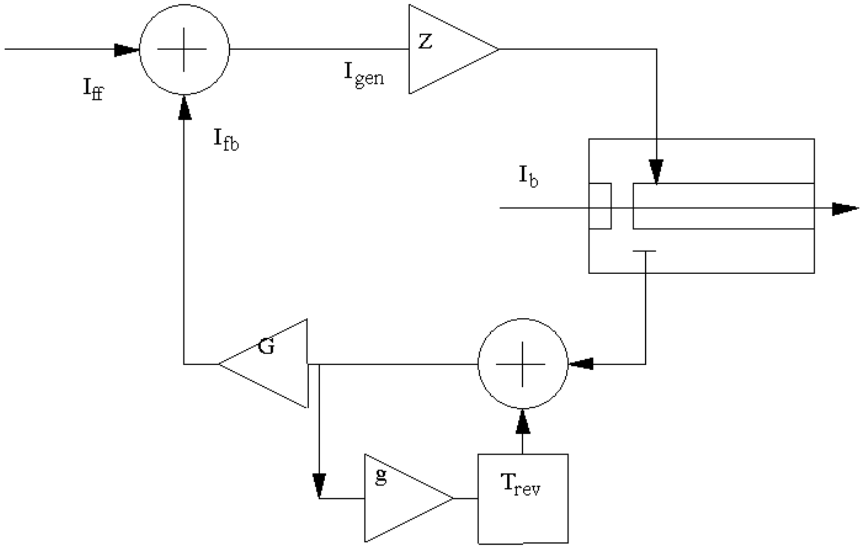
Antiproton Production – Slip Stacking



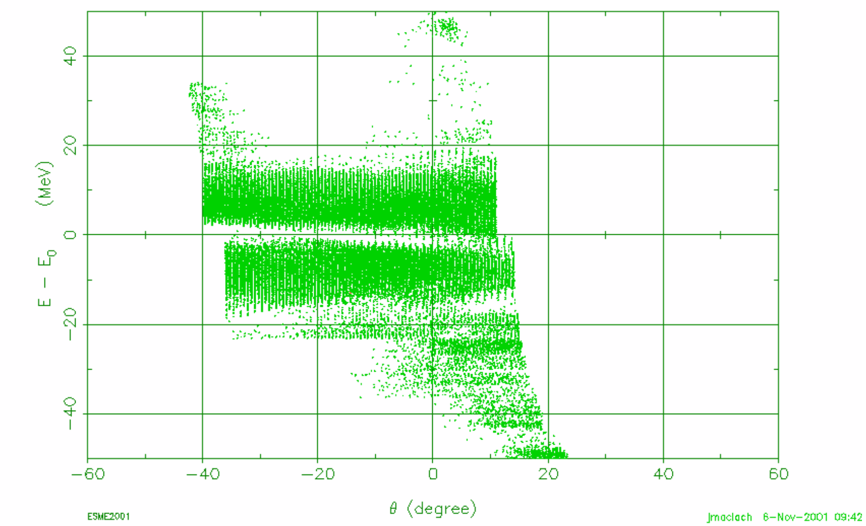


Beam Loading Compensation

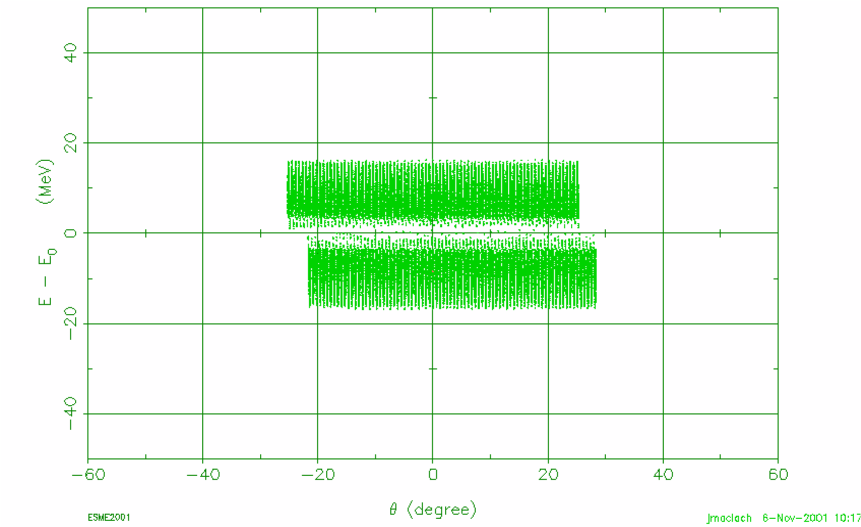




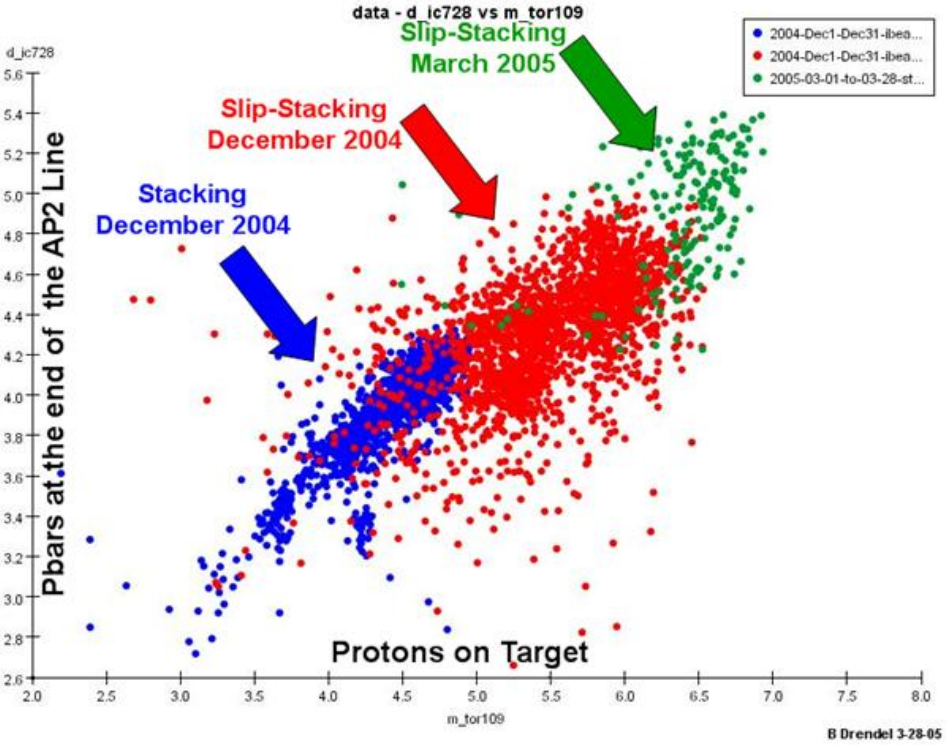
Batch phase space without compensation

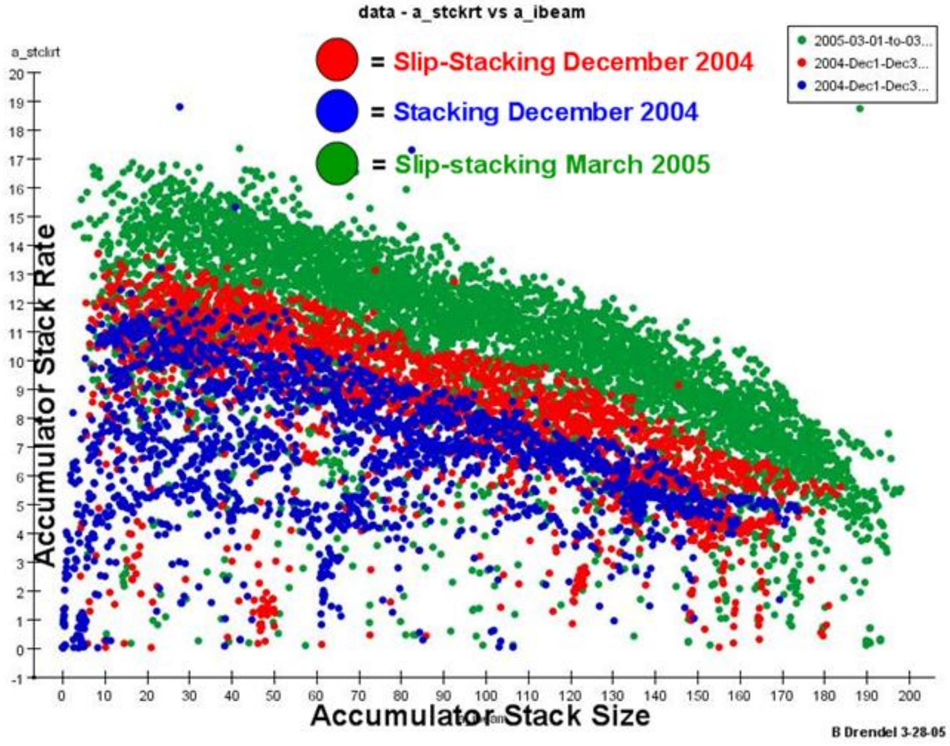


Batch phase space with compensation

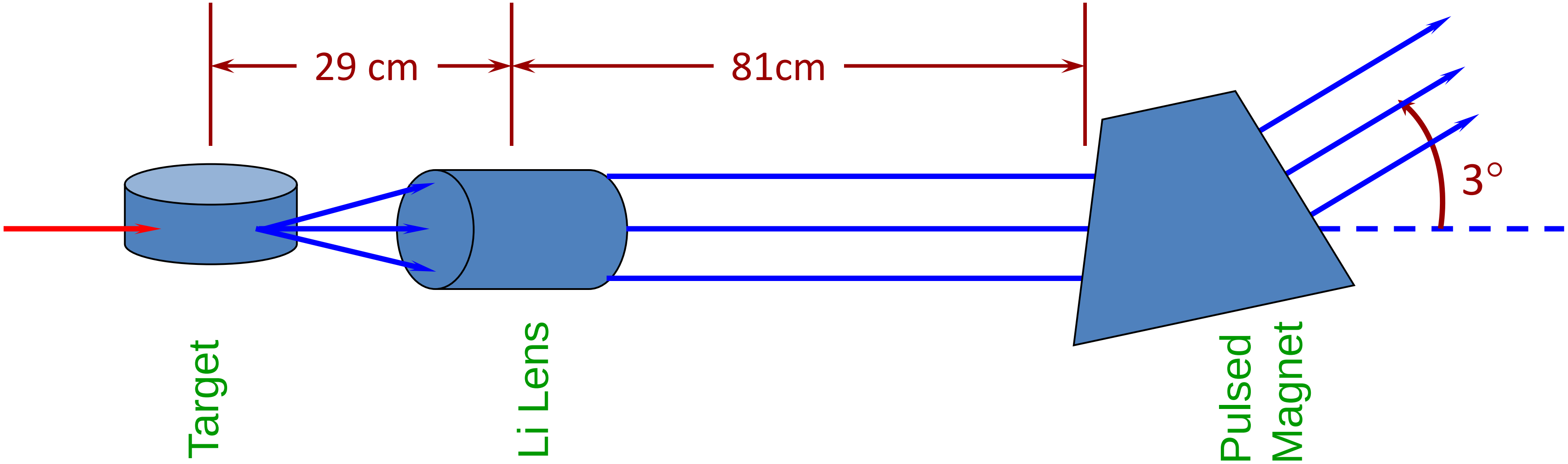


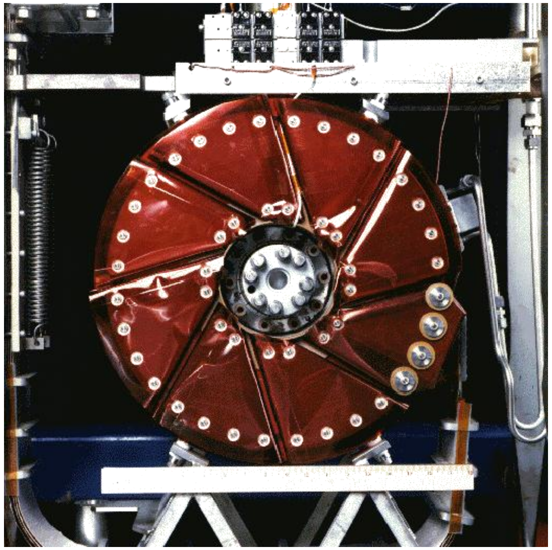
Slip Stacking Performance

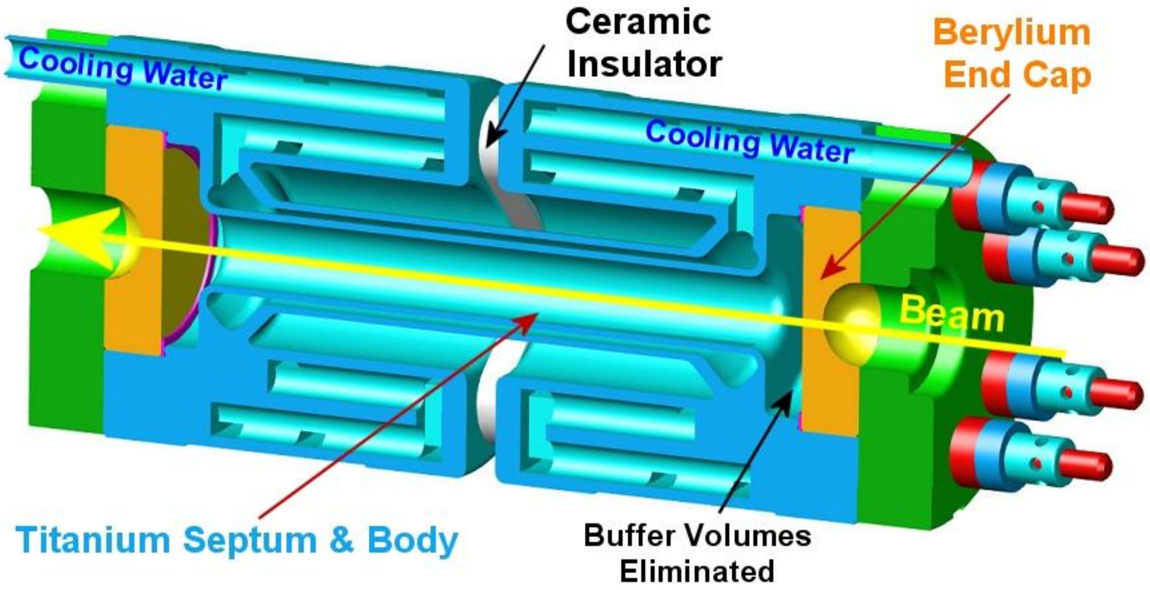




Pbar Target and Lens Technology

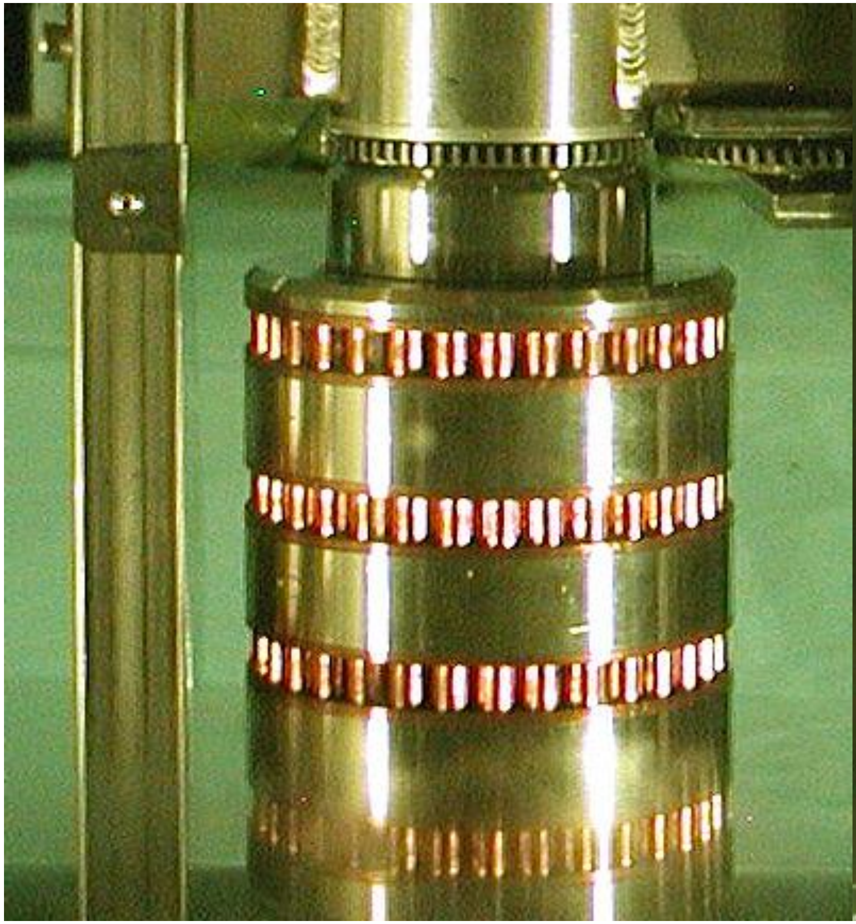




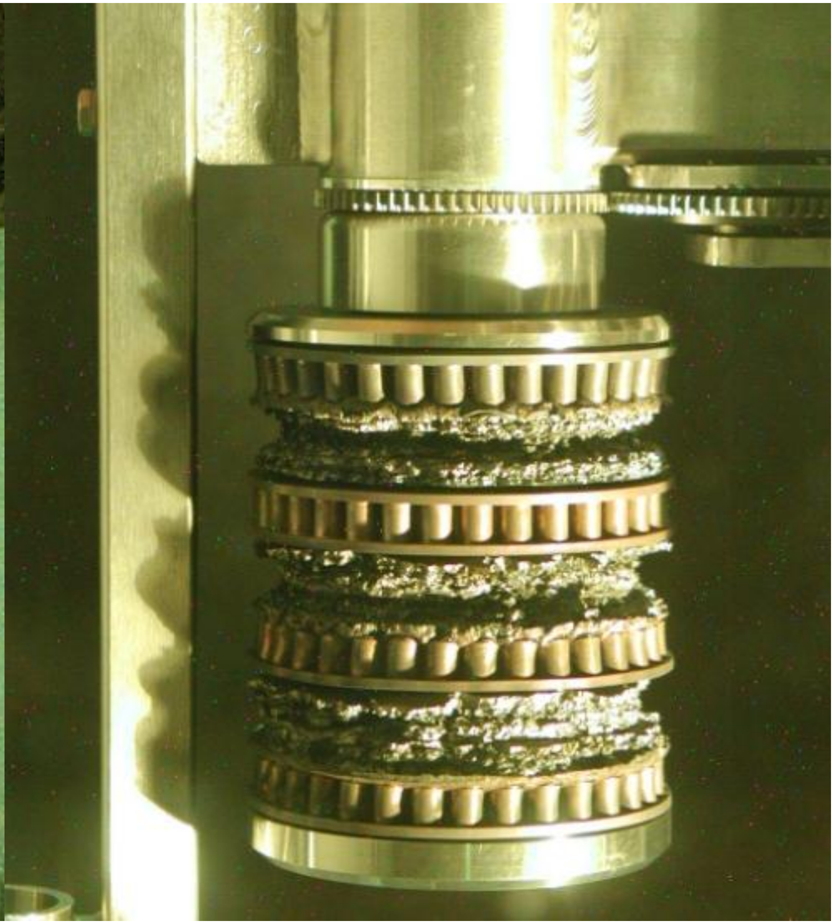


Pbar Targets

Unused Target

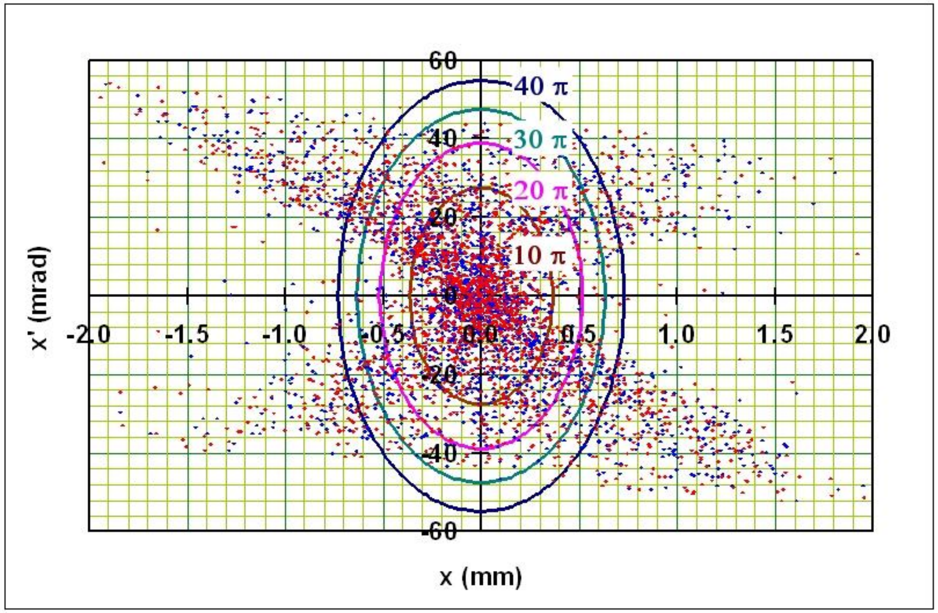


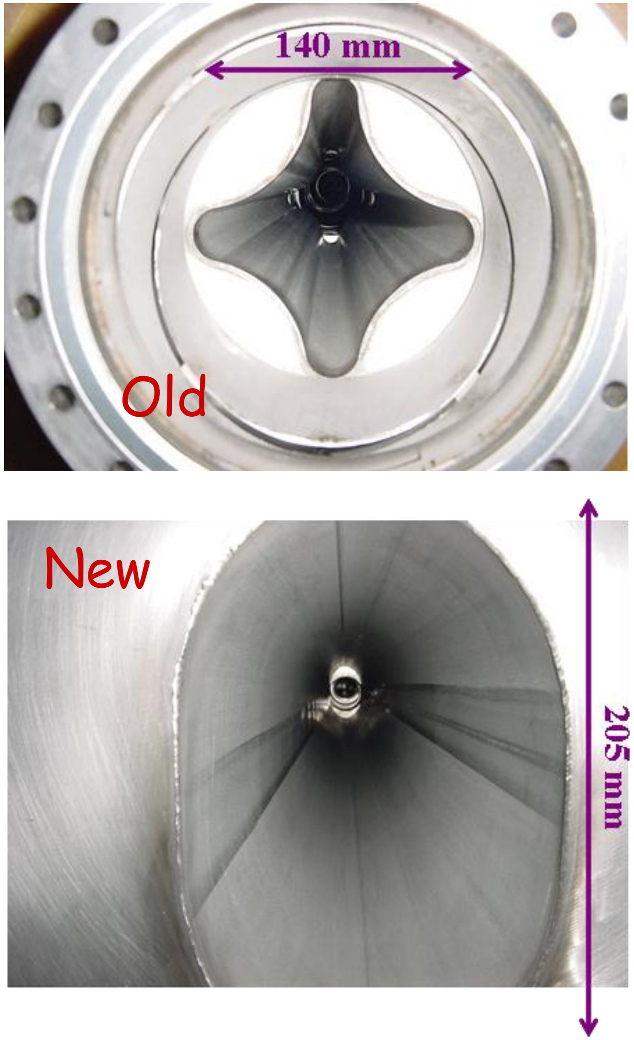
Used Target



Antiproton Aperture

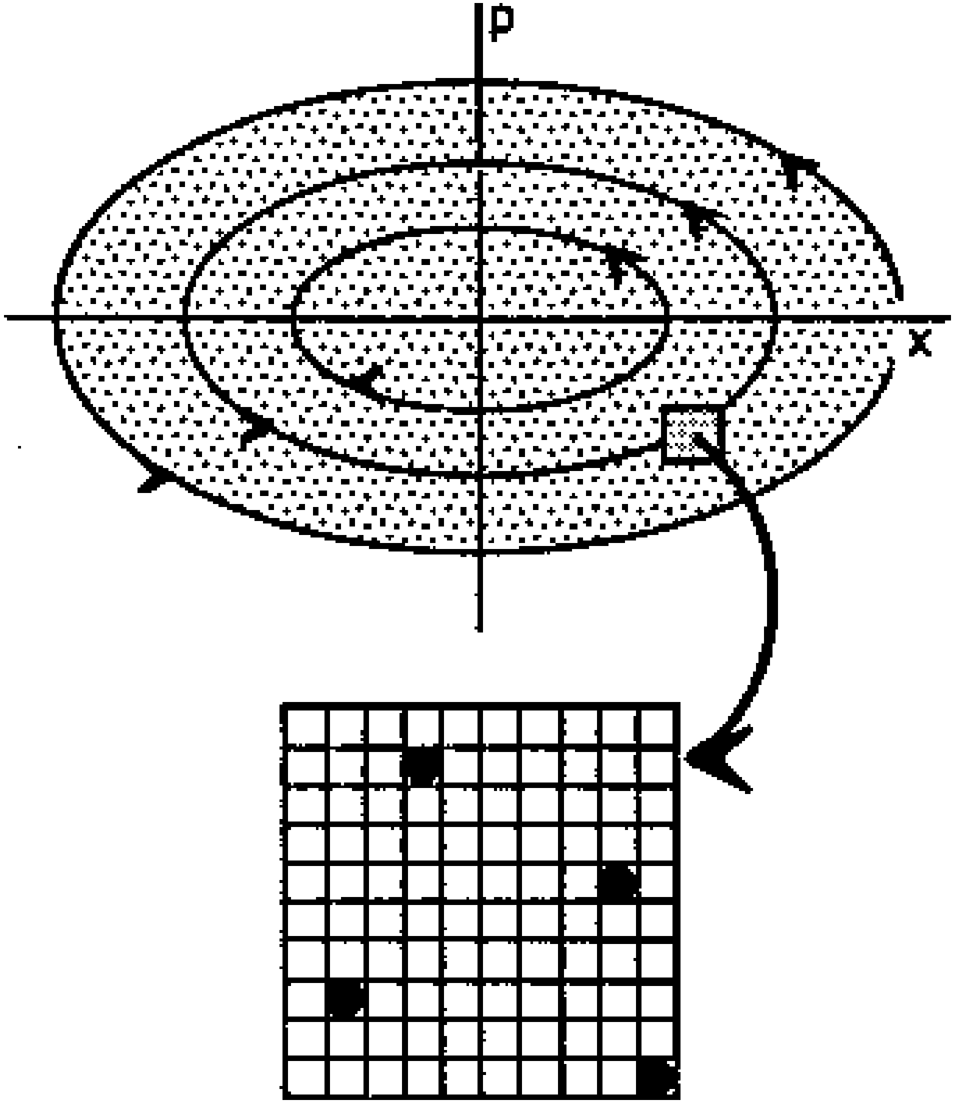
Transverse Phase Space of the target





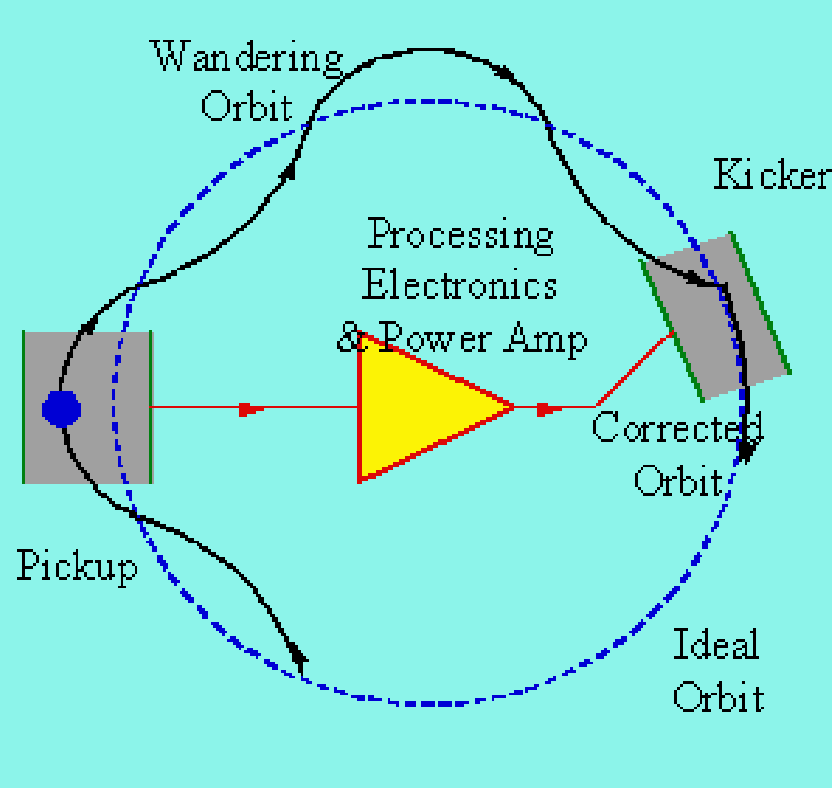
Stochastic Cooling

- Electron Cooling works well for narrow, intense beams
- Stochastic Cooling works well for wide, diffuse beams
- Stochastic cooling re-arranges phase space by placing particles into the "empty holes" in phase space.



Stochastic Cooling

- Stochastic cooling uses feedback
- A pickup electrode measures an “error” signal for a given pbar.
  - This error signal could be the pbar’s position or energy
  - The pickup signal can be extremely small, on the order of 1 pW
  - The Debuncher pickups are cooled to 4 Kelvin to reduce the effect of thermal noise and 300 Kelvin “shine”
- This signal is processed and amplified
  - The gain of the Debuncher systems is about 150 dB (a factor of 10^{15})
- The opposite of the error signal is applied to the pbar at the kicker
  - The kicker signal can be as large as 2 kW

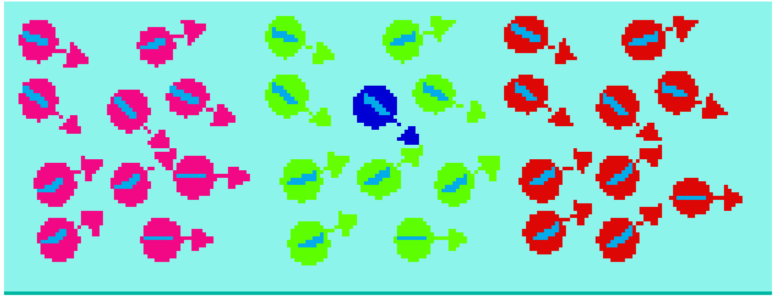


Stochastic Cooling Bandwidth

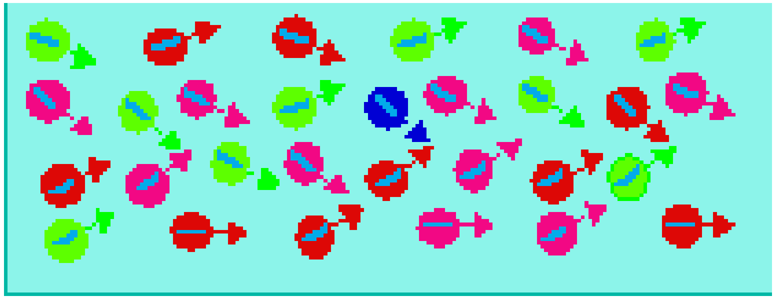
- The ability of a pickup to resolve a single pbar is proportional to the bandwidth of the pickup
- To resolve a single pbar in the Accumulator, the pickup bandwidth would have to be greater than $6\mathrm{x}10^{17}$ Hertz
- The maximum bandwidth of the cooling systems we have built so far is 4 GHz (f_{max} =8 GHz), so on average there are $2\mathrm{x}10^{8}$ pbars underneath a pickup in the Accumulator at any given time
- But these other pbars are sources of noise for a given pbar that needs to be cooled…

Stochastic Cooling Mixing

- Since each pbar has a slightly different energy than any other pbar, every pbar will take a different time to travel around the accelerator
- This causes the pbars to continually mix up so that the noise contribution of the other pbars underneath the pickup averages to zero in the long run.
- This effect is caused Mixing. The mixing factor is given as how many turns around the accelerator does it take for the beam to randomize its sample underneath the pickup
  - Proportional to momentum spread
  - Proportional to the maximum frequency of the cooling system



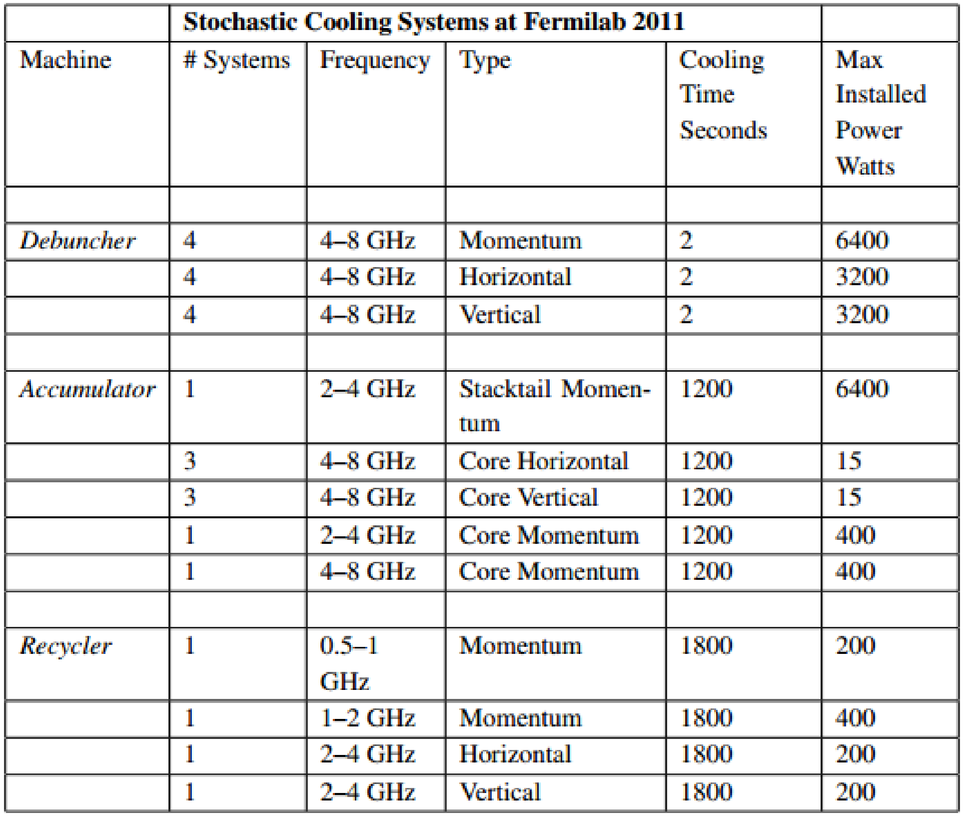
Before Mixing



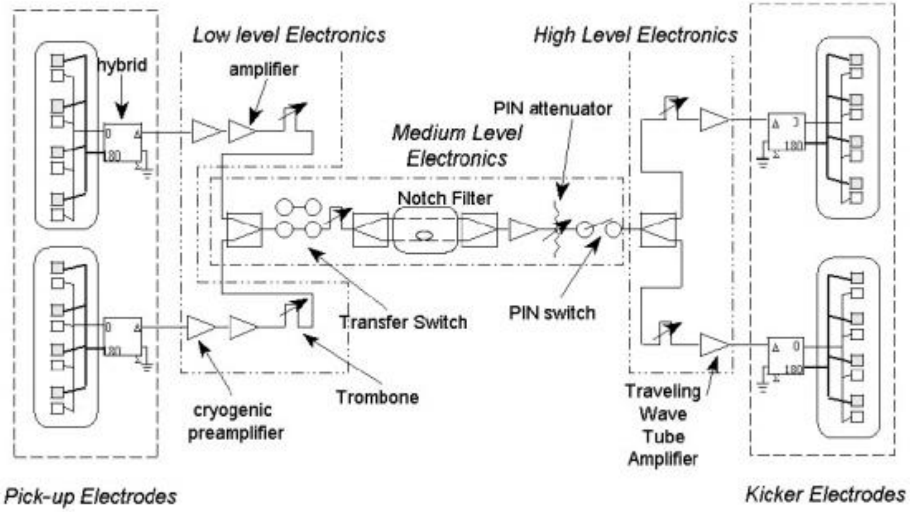
After Mixing

$$\frac{1}{\tau_{\mathrm{cool}}} = \frac{W}{N_p M}$$

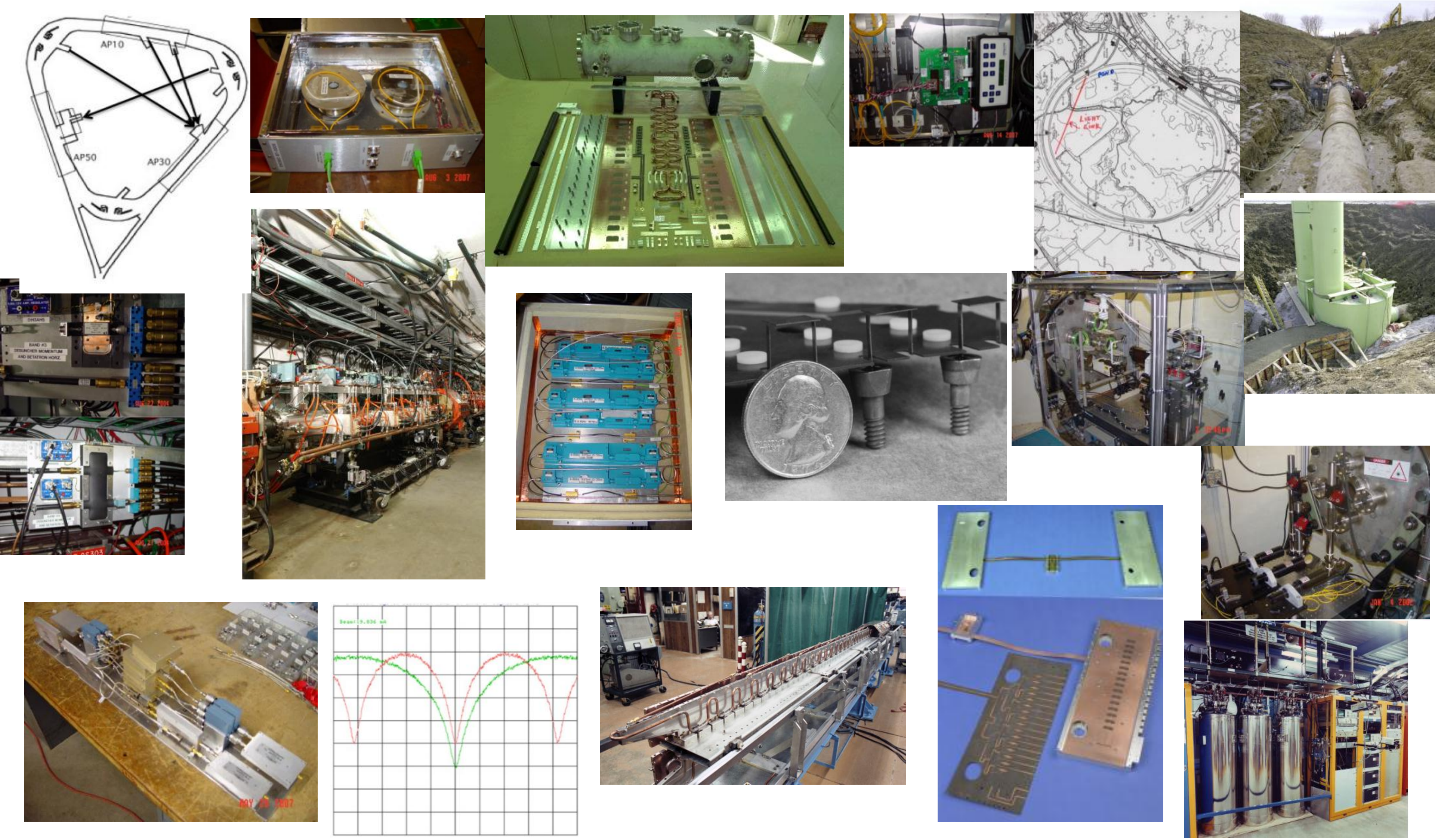
Stochastic Sooling Systems



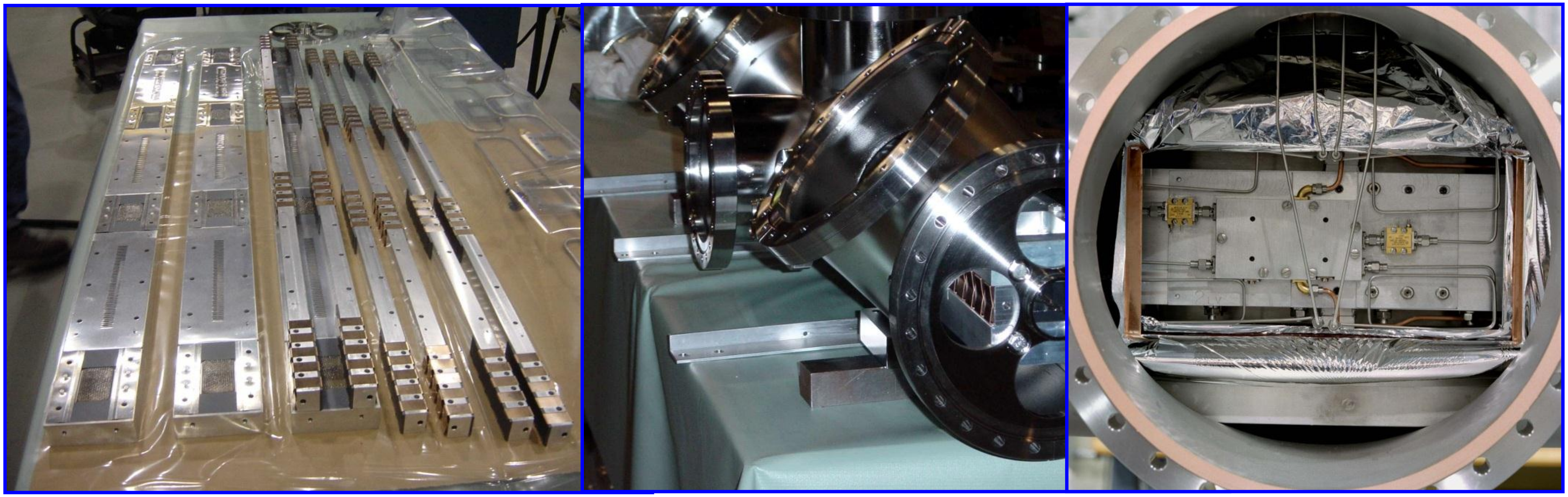
	Stochastic Cooling Systems at Fermilab 2011				
Machine	# Systems	Frequency	Type	Cooling Time Seconds	Max Installed Power Watts
Debuncher	4	4–8 GHz	Momentum	2	6400
	4	4–8 GHz	Horizontal	2	3200
	4	4–8 GHz	Vertical	2	3200
Accumulator	1	2–4 GHz	Stacktail Momentum	1200	6400
	3	4–8 GHz	Core Horizontal	1200	15
	3	4–8 GHz	Core Vertical	1200	15
	1	2–4 GHz	Core Momentum	1200	400
	1	4–8 GHz	Core Momentum	1200	400
Recycler	1	0.5–1 GHz	Momentum	1800	200
	1	1–2 GHz	Momentum	1800	400
	1	2–4 GHz	Horizontal	1800	200
	1	2–4 GHz	Vertical	1800	200

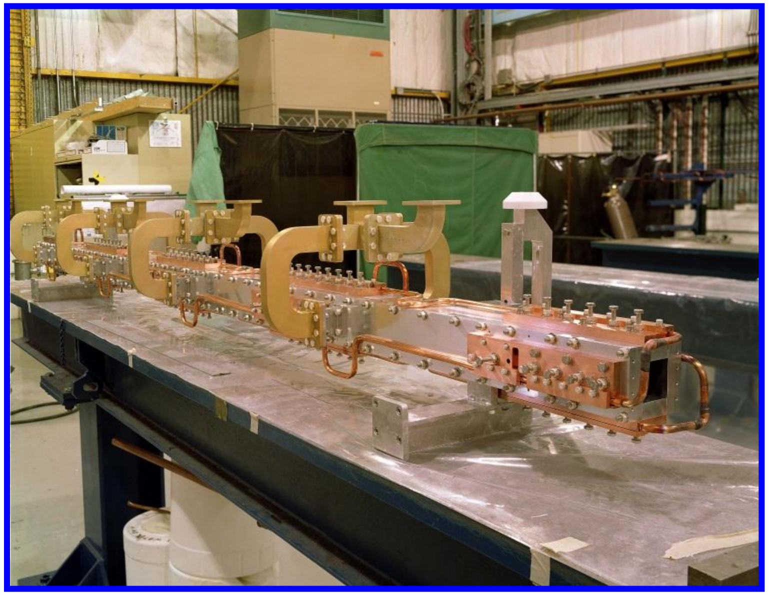


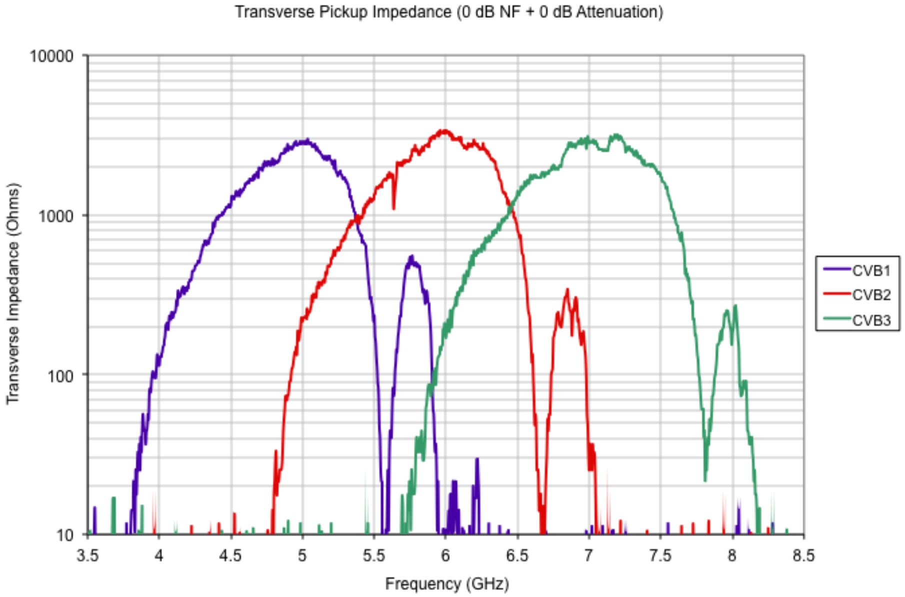
Stochastic Cooling Hardware



Slotted Waveguide Arrays

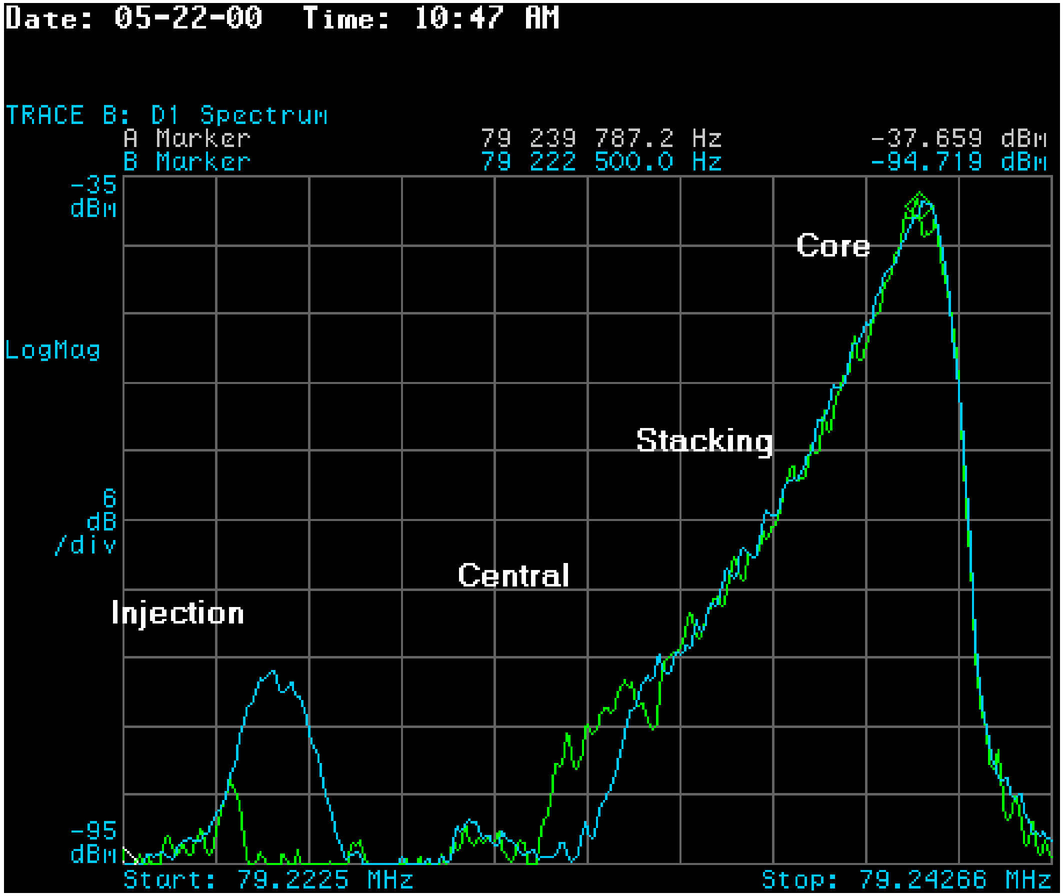






Antiproton Momentum Stacking

- Beam is injected onto the Injection Orbit
- Beam is
  - Bunched with RF
  - Moved with RF to the Stacking Orbit
  - Debunched on Stacking orbit
- Stacktail pushes and compresses beam to the Core orbit
- Core Momentum system gathers beam from the Stacktail
- Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core



Antiproton Momentum Stacking

- The time evolution of the antiproton phase space during cooling is best described by the Fokker-Plank Equation

$$\frac{\partial \psi}{\partial t} = -\frac{\partial \phi}{\partial E}$$

$$\phi_c = \frac{\Delta E_c}{T_o}\psi = eV_o f_o \psi \sum_n \mathrm{Re}\{G_n(E)\}$$

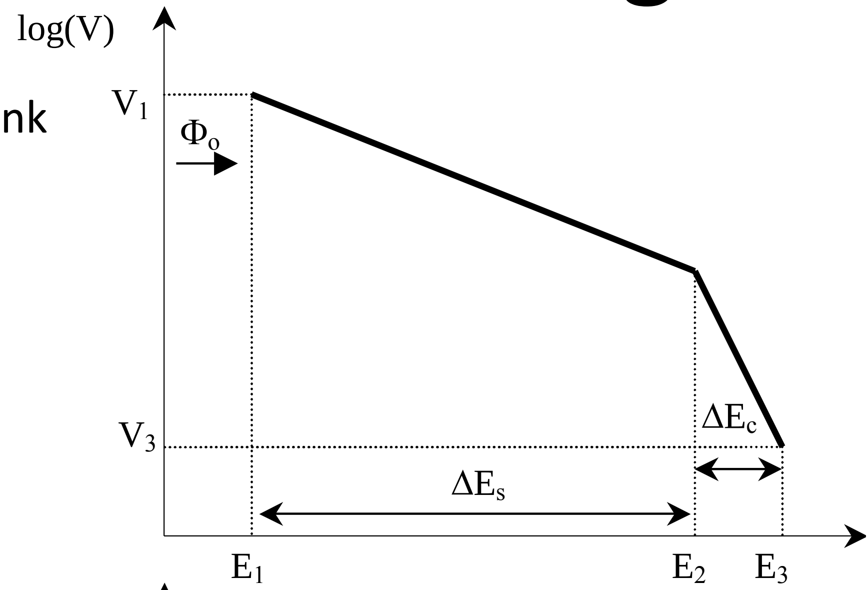
$$\phi_h = \frac{1}{2}\frac{\Delta E_h{}^2}{T_o}\frac{\partial \psi}{\partial E} = \frac{1}{4}(eV_o f_o)^2 \frac{E_o}{\eta f_o}\psi\frac{\partial \psi}{\partial E}\sum_n |G_n(E)|^2$$

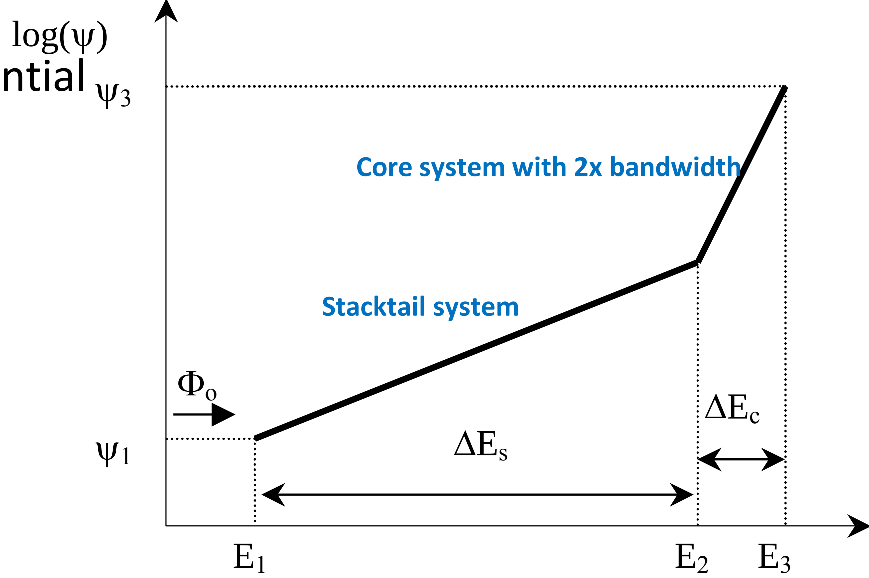
- Optimum profile that maximizes dψ/dE is exponential

$$\psi(E) = \psi_o e^{E/E_d}$$

$$G_n(E) = g_o e^{-E/E_d}$$

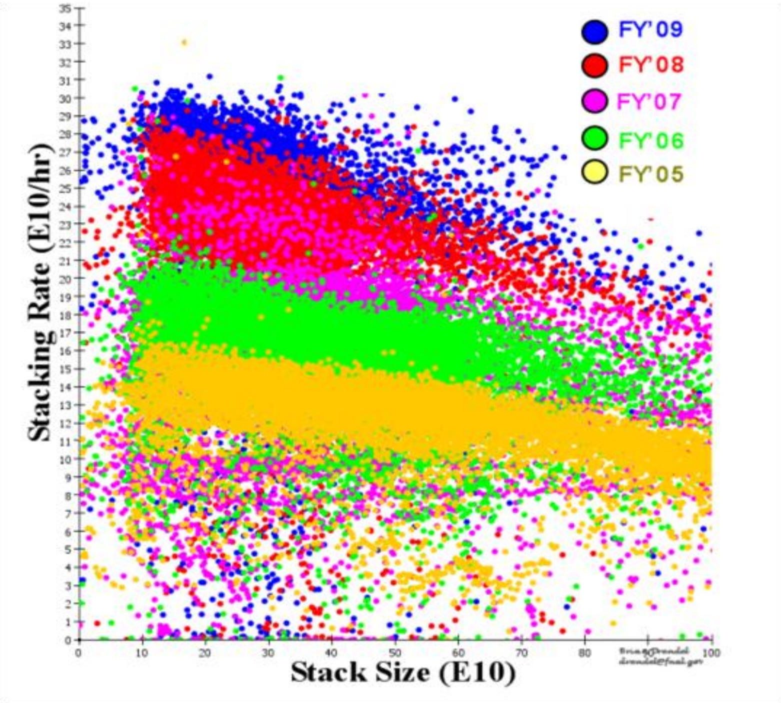
$$\phi_m = \eta f_o \frac{E_d}{E_o}\frac{\left(W/f_o\right)^2}{\ln\left(f_{max}/f_{min}\right)}$$





Stack Rate vs Stack Size

- Once the core fills, the core pushes back on the stacktail and the stacking rate drops
- The stack needs to be removed and cooled in another stage



The Recycler Ring

- Enables the ultimate compression in antiproton phase space with a 3rd ring of antiproton accumulation

- E_kin=8 GeV fixed
- Shares tunnel with 150 GeV fast cycling Main Injector
- C=3.32km
- 344 Permanent magnets (344, 1.45T, Sr-Fe combined function)
- Stores and cools antiprotons
- **Build by the US Congressman**

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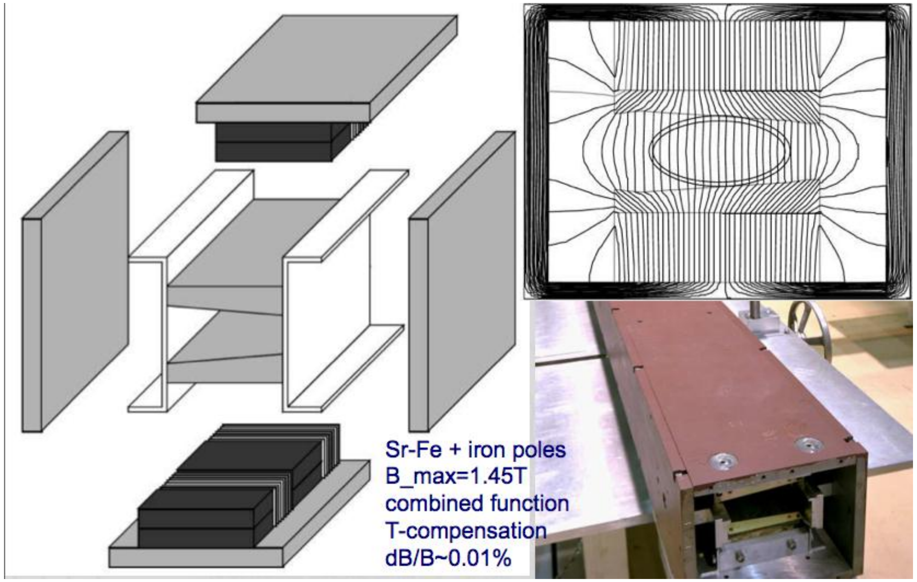
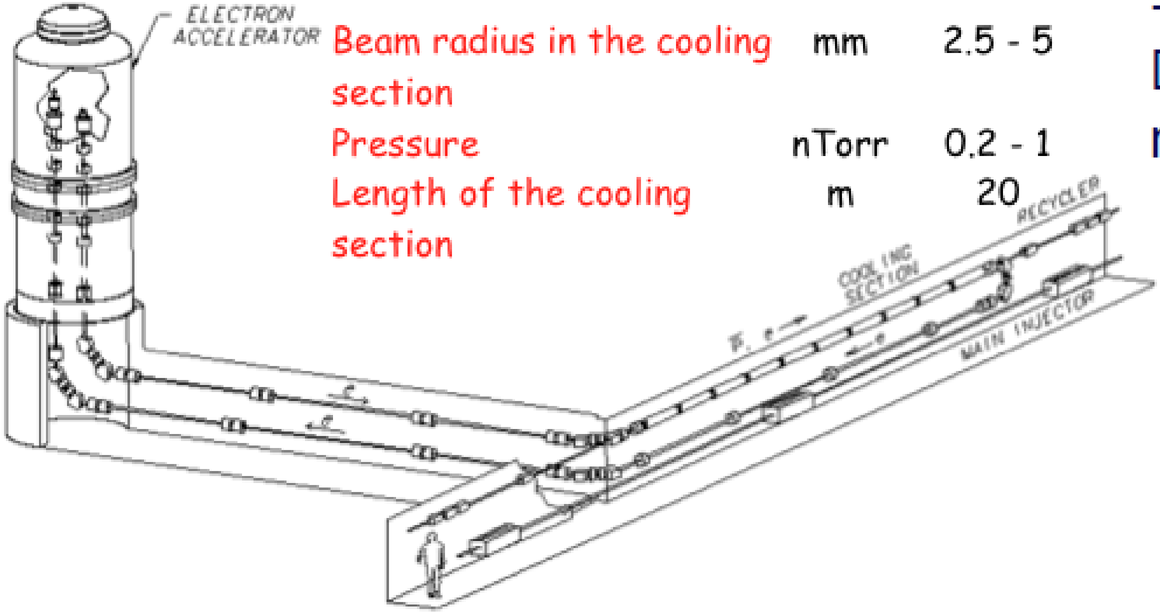


Sr-Fe + iron poles
B_max=1.45T
combined function
T-compensation
dB/B~0.01%

8 GeV Electron Cooling in the Recycler



Electron energy	MeV	4.3
Beam current used for cooling	A	0.05 - 0.5
Beam radius in the cooling section	mm	2.5 - 5
Pressure	nTorr	0.2 - 1
Length of the cooling section	m	20

4.4 MeV x
720 mA (max)
= 3.2 MW
DC beam power
recirculation

- Electrostatic accelerator (Pelletron) working in the energy recovery mode
- DC electron beam
- 100 G longitudinal magnetic field in the cooling section
- Lumped focusing outside the cooling section

8 GeV Electron Cooling in the Recycler

Pelletron

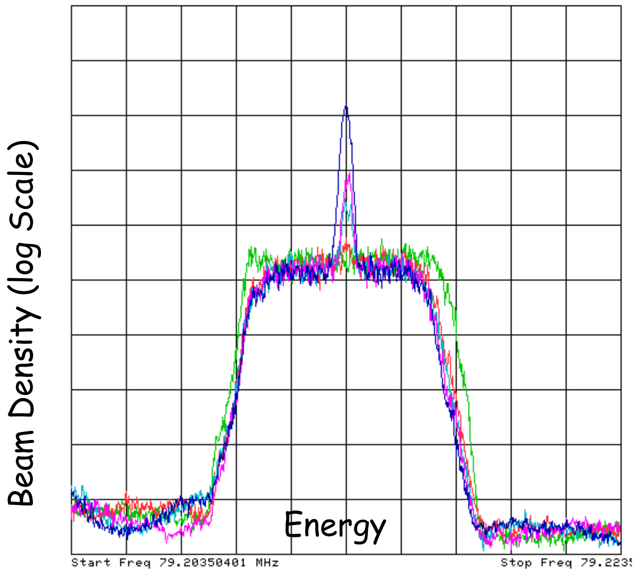
(MI-31 building)

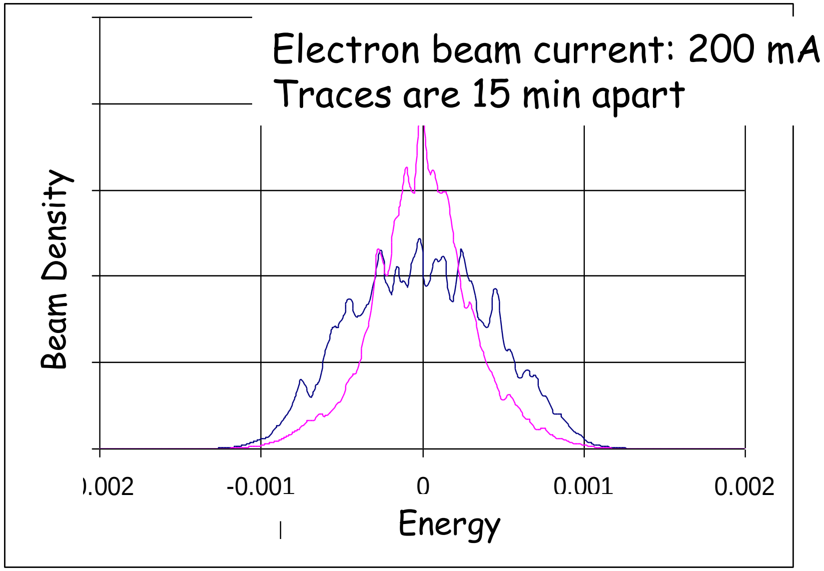
Cooling section solenoids

(MI-30 straight section)

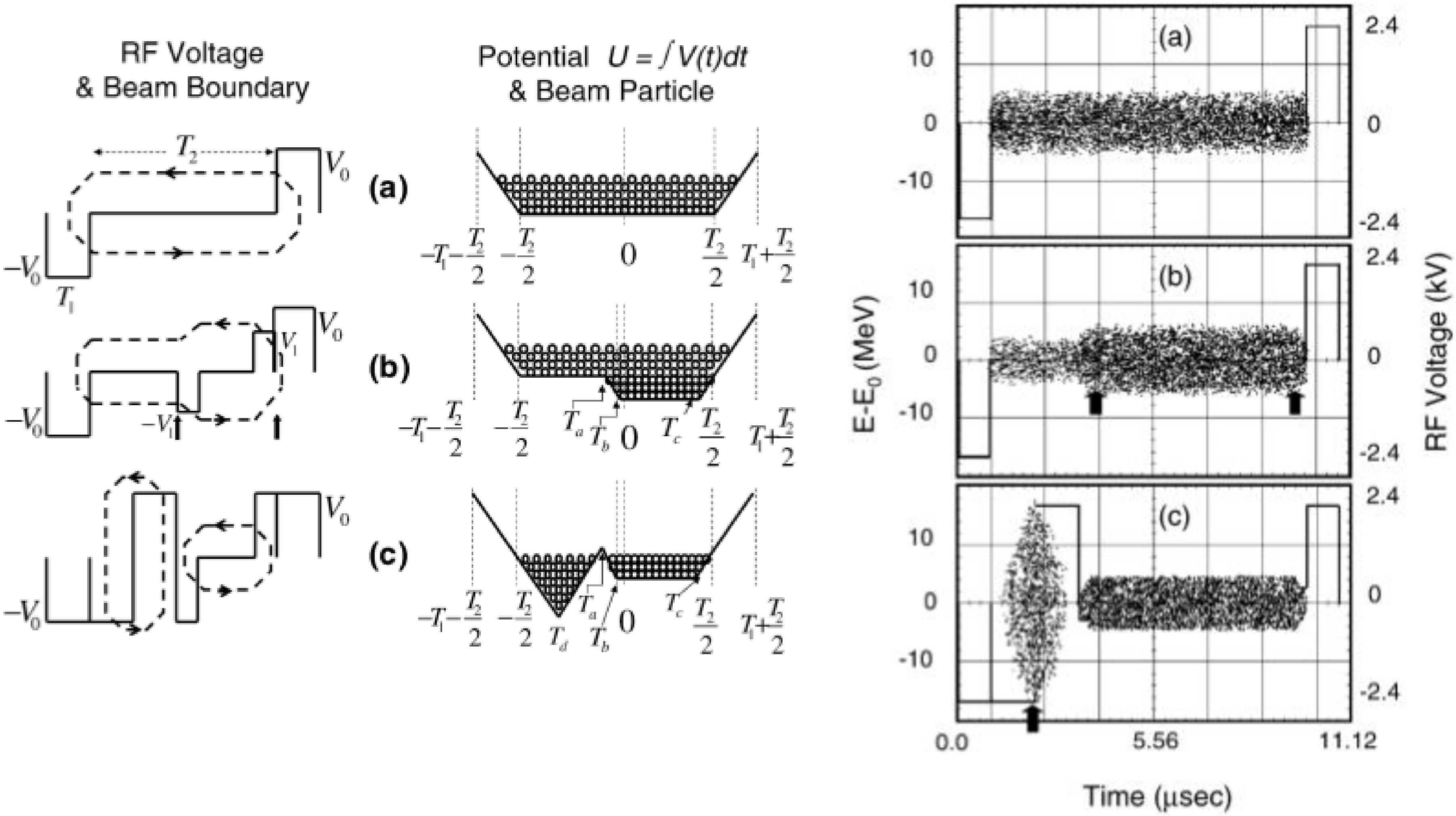
Recycler Electron Cooling

- Electron cooling commissioning
  - 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 goals
  - Supported final design goal of rapid transfers (30eV-Sec/2hrs)
  - Reliably supported stacks of 500x10^{10} (2x FY06 design goal)
  - Achieved 500 mA of electron beam which is the final design goal.



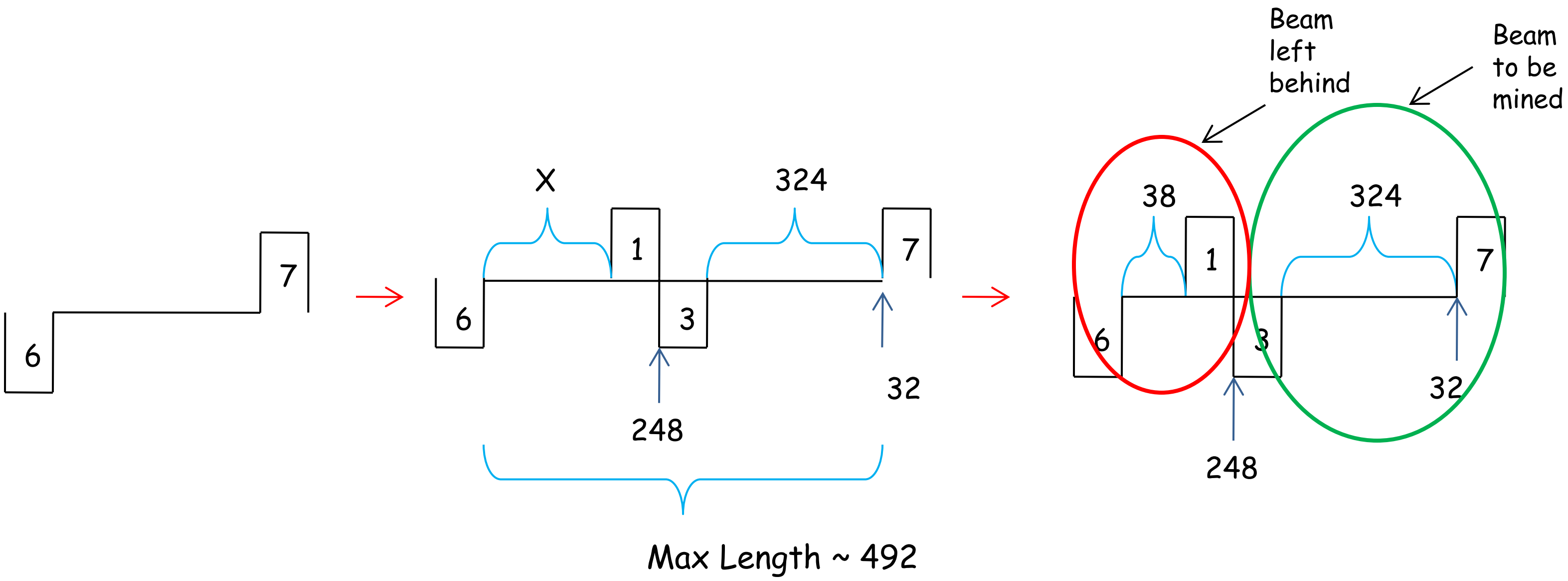


Momentum Mining in The Recycler

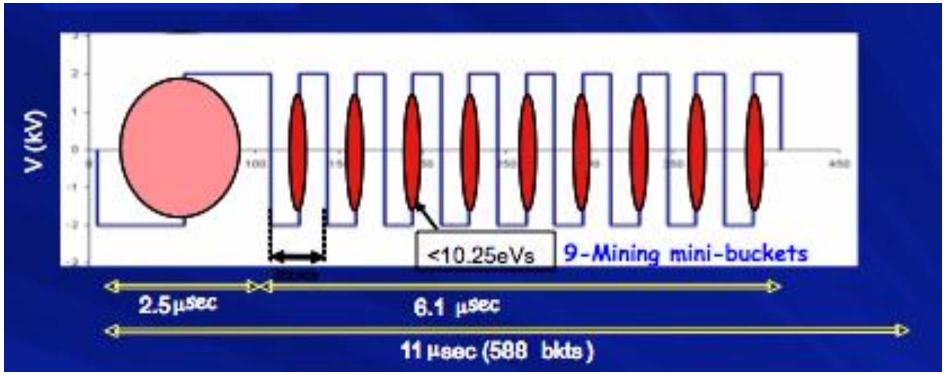


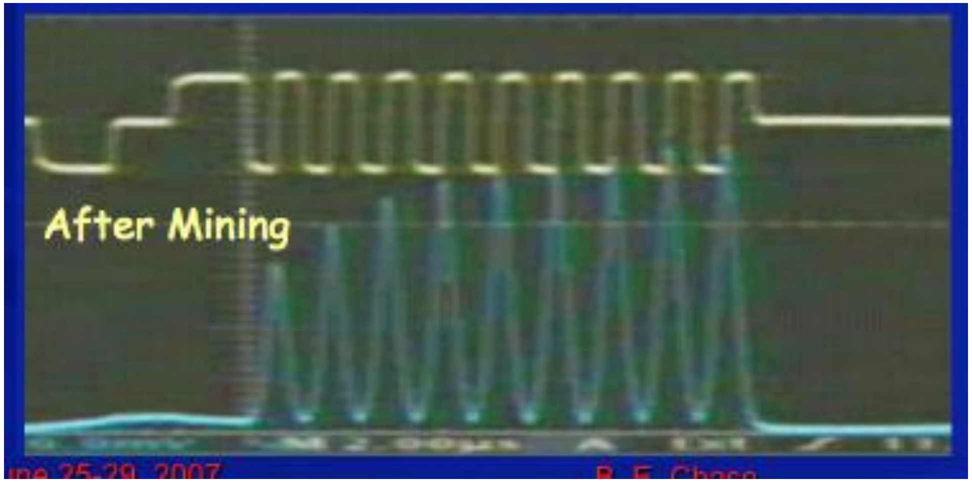
“Partial mining”

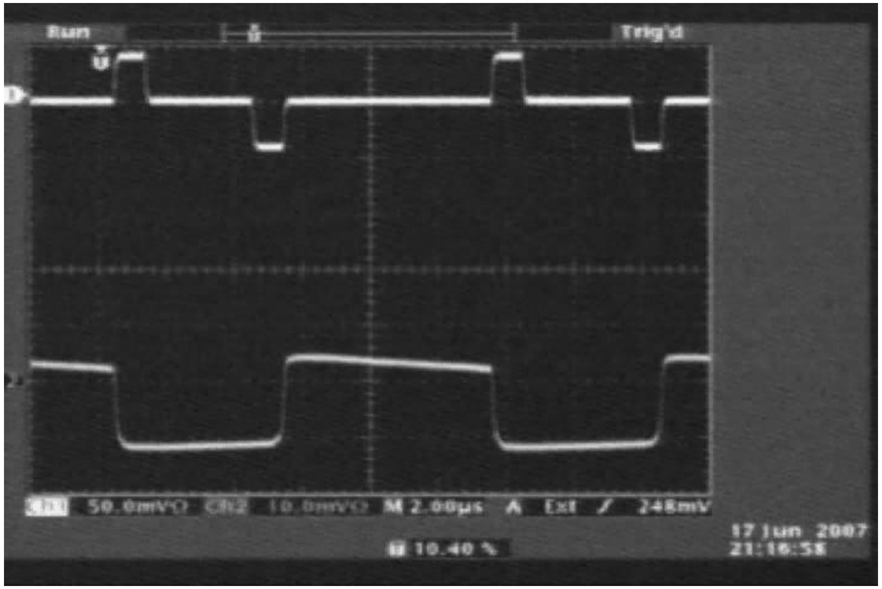
- Ability to extract (“mine”) only a percentage of the Recycler stash without compromise of cooling or lifetime
  - RF manipulations separate beam to be extracted from beam to be left behind
  - Are limitations on amount can extract / leave behind (20%-80%)



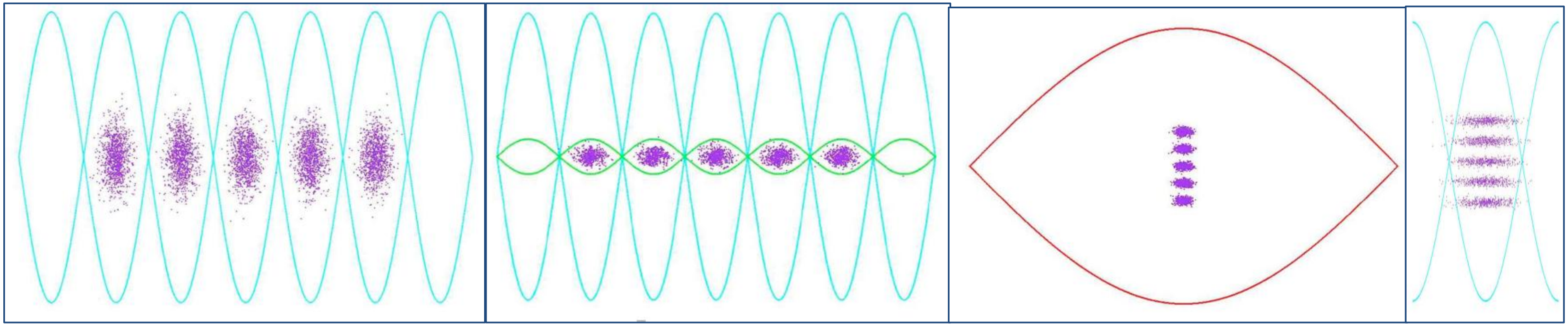
Momentum Mining in The Recycler

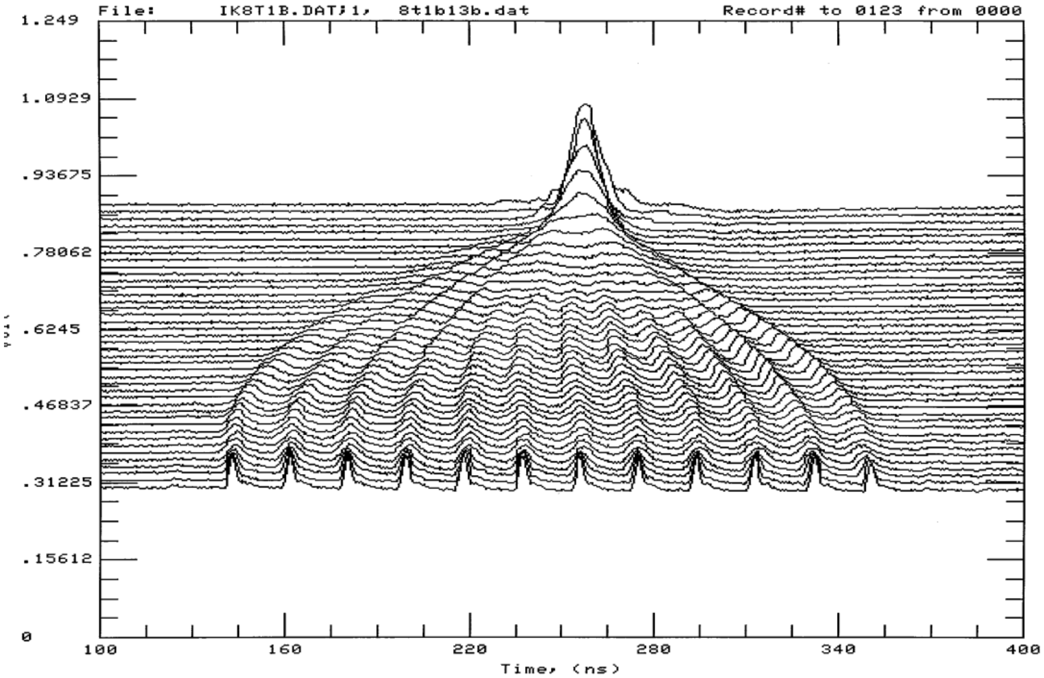






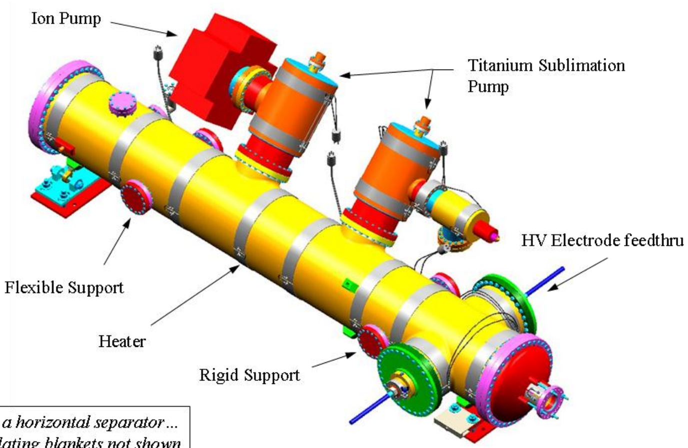
Bunch Coalescing in the Main Injector



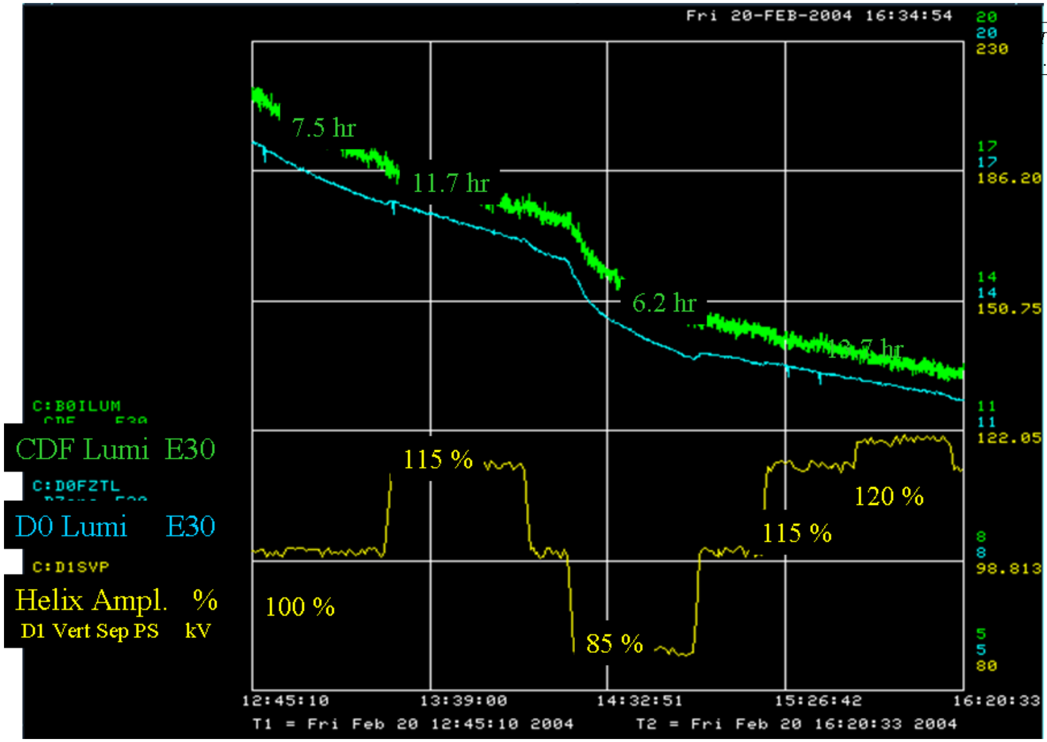


Tevatron Helical Orbit Separation

- More separators
- Higher separator voltage
  - Separator R&D
- Different separator configuration
  - Polarity switches



This is a horizontal separator…
…insulating blankets not shown



Summary

- The luminosity of the Tevatron collider was very dependent on antiproton production.
- Peak antiproton production rates of 30×10^{10} per hour have been achieved using sophisticated and novel technologies
- The ultimate luminosity of any future proton-antiproton collider will be limited by antiproton burn rate, hence antiproton production.

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