Accelerator Status and Performance Projections

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Luminosity

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

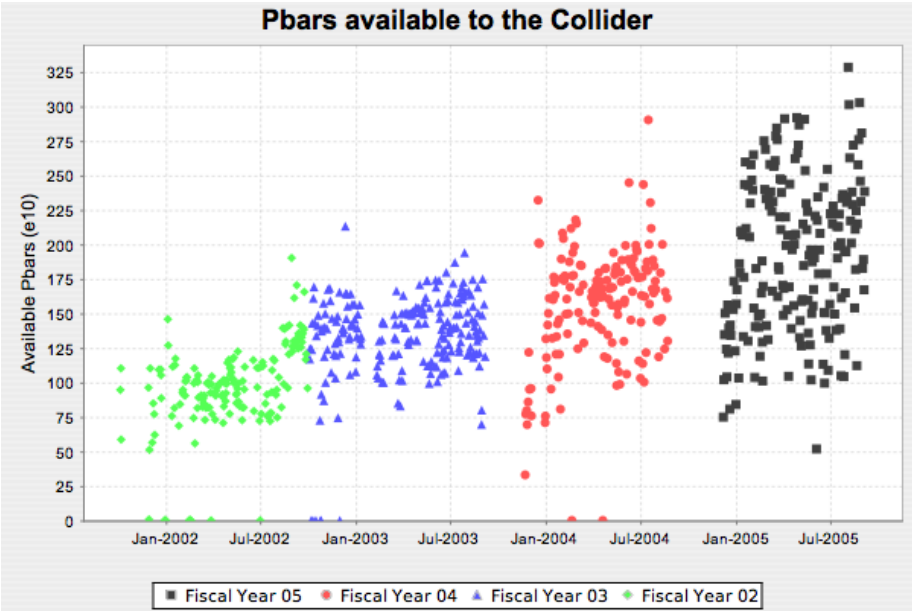
- The major luminosity limitations are
  - The number of antiprotons (BN_{pbar})
  - The proton beam brightness (N_p/ε_p)
    - Beam-Beam effects
  - Antiproton emittance
  - F<1

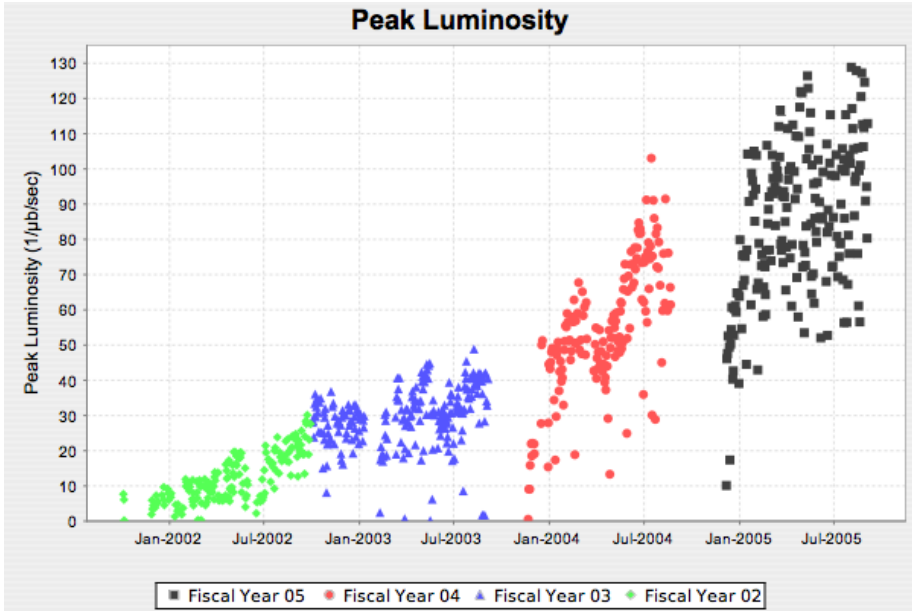
Antiproton Economics

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

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

Antiprotons and Luminosity





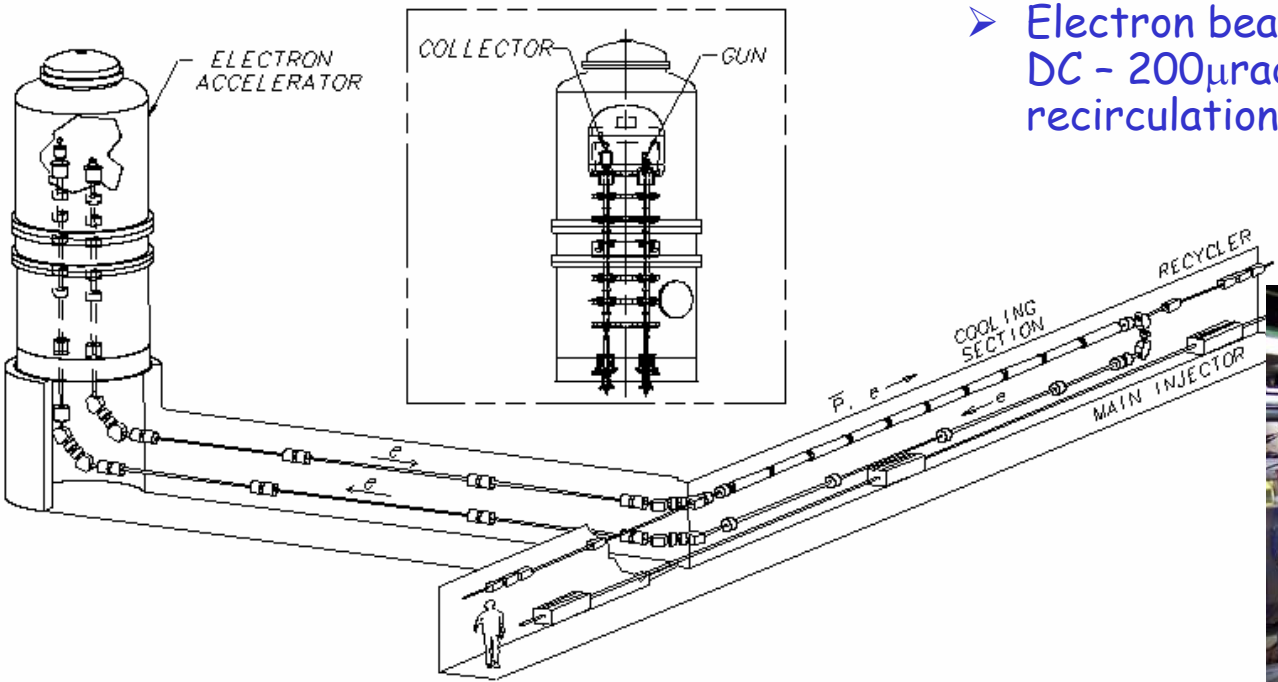
- The strategy for increasing luminosity in the Tevatron is to increase the number of antiprotons
  - Increase the antiproton production rate (Run 2 Upgrades)
  - Provide a third stage of antiproton cooling with the Recycler
  - Increase the transfer efficiency of antiprotons to low beta in the Tevatron

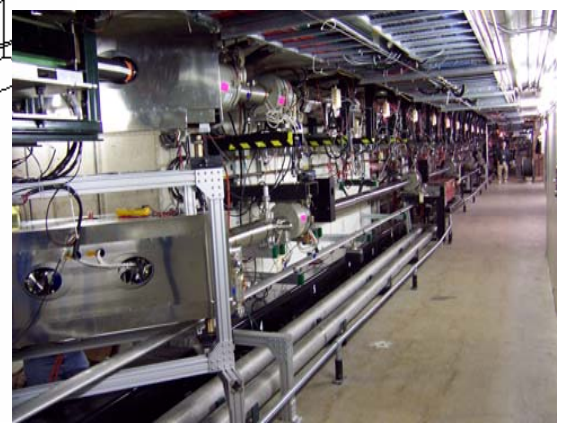
Run II Upgrades

- More protons on the antiproton target
  - Slip stacking
    - MI Beam loading compensation
    - Booster Cogging
  - Intensity Goals:
    - Base: 6.5×10^{12}
    - Design: 8.0×10^{12}
- Better antiproton collection efficiency
  - Lithium lens gradient upgrade
  - AP2-Debuncher aperture increases
    - Physical aperture increases
    - Beam based alignment
  - Production Goals at a 2 second cycle time:
    - Base: 15×10^{-6}
    - Design: 21×10^{-6}
- Better cooling
  - Accumulator Stacktail
  - Electron cooling in the Recycler
  - Average Stacking Rate Goals:
    - Base: 9.7×10^{10}/hour
    - Design: 21.7×10^{10}/hour
- Rapid Antiproton Transfers
  - Transfer Time Goals
    - Base: 45 minutes
    - Design: 15 minutes

Recycler Electron Cooling

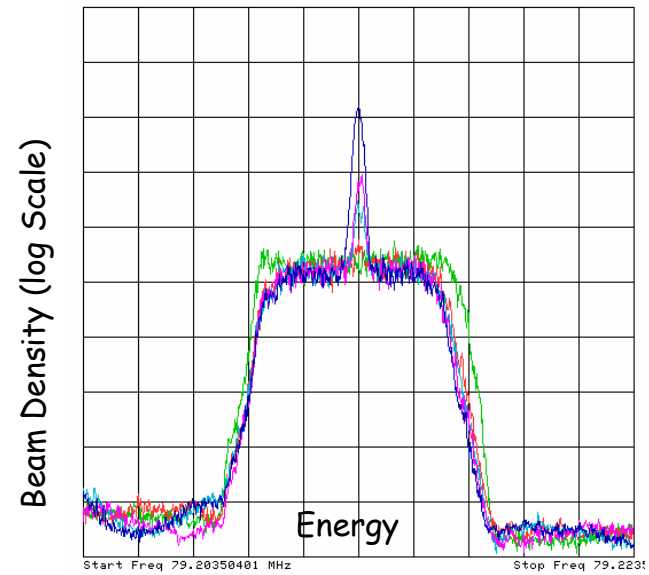
- The maximum antiproton stack size in the Recycler is limited by
  - Stacking Rate in the Debuncher-Accumulator at large stacks
  - Longitudinal cooling in the Recycler
- Longitudinal stochastic cooling of 8 GeV antiprotons in the Recycler is being replaced by Electron Cooling
  - Electron beam: 4.34 MeV – 0.5 Amps DC – 200μrad beam spread – 99% recirculation efficiency

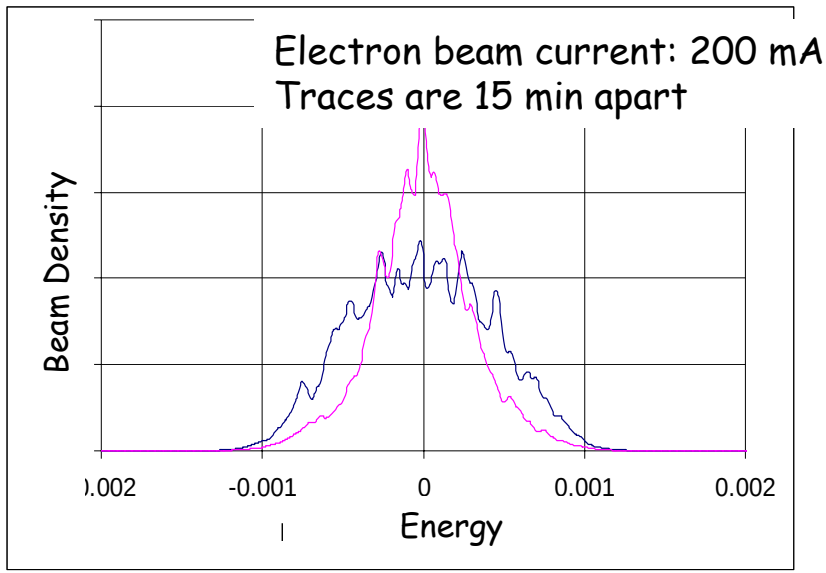




Recycler Electron Cooling

- 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 goals
  - Can presently support final design goal of rapid transfers (30eV-Sec/2hrs)
  - Can presently reliably support stacks of 250×10^{10} (FY06 design goal)
  - Have achieved 500 mA of electron beam which is the final design goal.





Recycler-Only Operations

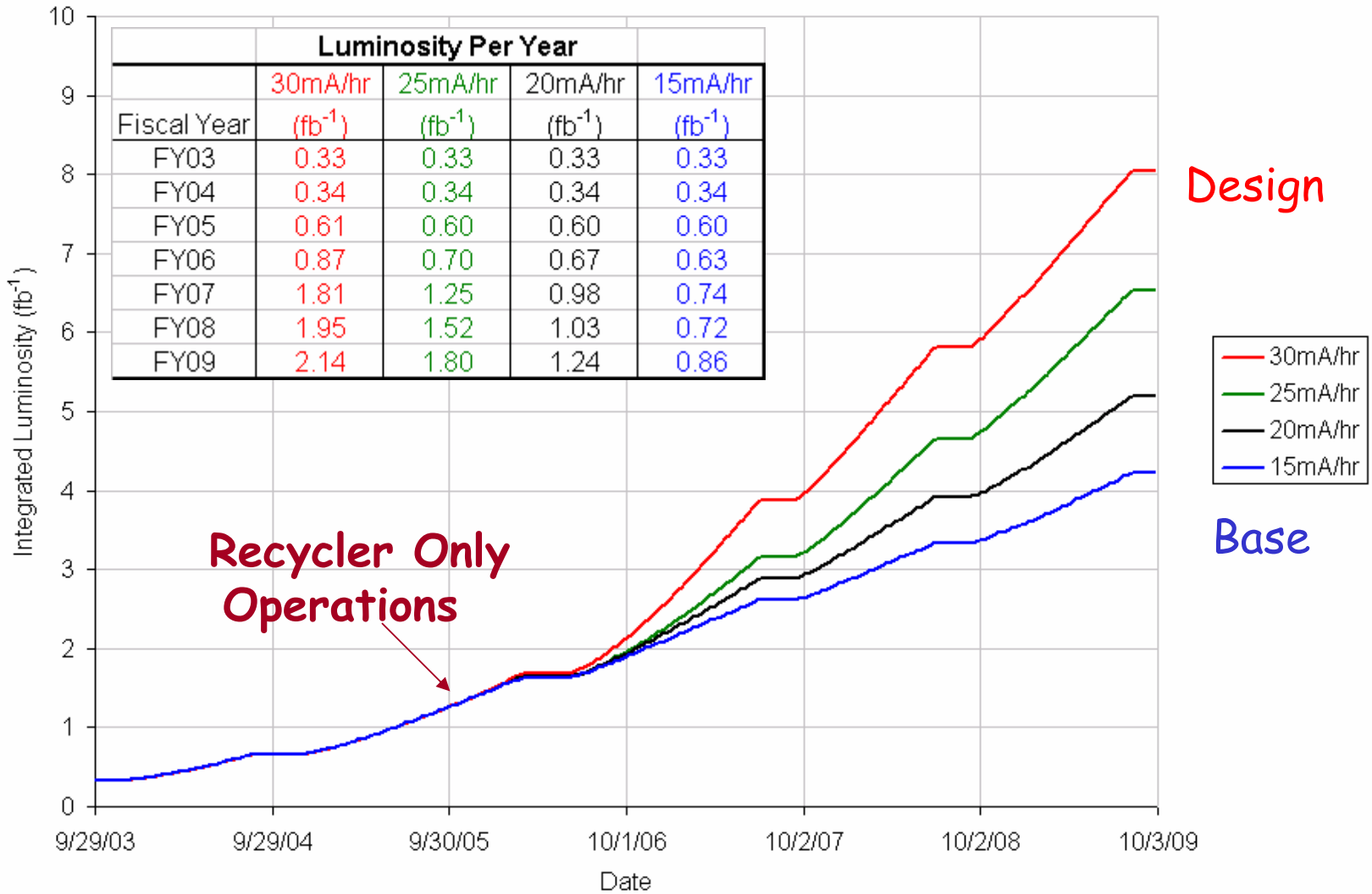
- Recycler has been participating in Collider Operations in the Combined Shot mode because the Recycler Stack size has been limited to ~120x10^{10} pbars
  - Longitudinal Cooling
  - Transverse Stability
- With Electron Cooling operational and the transverse dampers commissioned, the Recycler stack size 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
  - In Recycler-Only mode we will no longer need
    - The Accumulator shot lattice
    - Pbar-Tev shot setup
    - Dual energy ramps in the Main Injector
    - Complicated RF states
  - In addition, the Neutrino program will benefit because the Accumulator will spend most of the time with small stacks, hence fast cycle times.
- Transition should be complete by November 1, 2005

Luminosity Projections

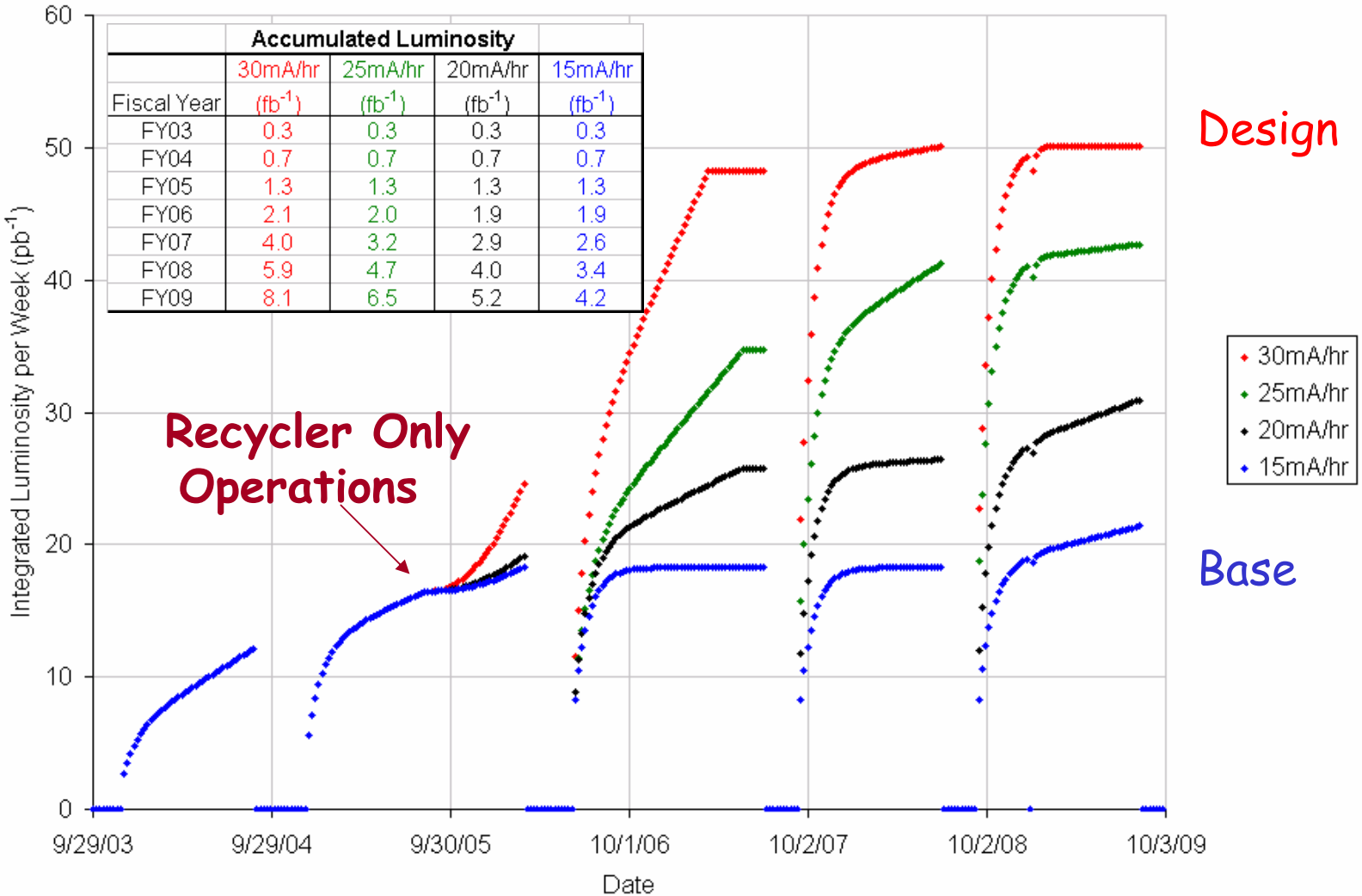
- Our plan is to deliver the design projection,
  - but, develop an understanding of fallback scenarios
  - With electron cooling commissioning going well, the major uncertainty is the stacking rate
- Luminosity Scenarios
  - Design Projection:
    - Electron cooling
    - 15 minute Accumulator to Recycler transfers
    - Peak Stack rates of 30 mA/hr
  - Fall-back Projection:
    - Electron cooling
    - $\frac{1}{2}$ hour Accumulator to Recycler transfers
    - Peak Stack rates of 20-25 mA/hr
  - Base Projection:
    - Electron cooling
    - 3/4 hour Accumulator to Recycler transfers
    - Peak Stack rates of 15 mA/hr

Integrated Luminosity

Luminosity Per Year				
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.33	0.33	0.33	0.33
FY04	0.34	0.34	0.34	0.34
FY05	0.61	0.60	0.60	0.60
FY06	0.87	0.70	0.67	0.63
FY07	1.81	1.25	0.98	0.74
FY08	1.95	1.52	1.03	0.72
FY09	2.14	1.80	1.24	0.86

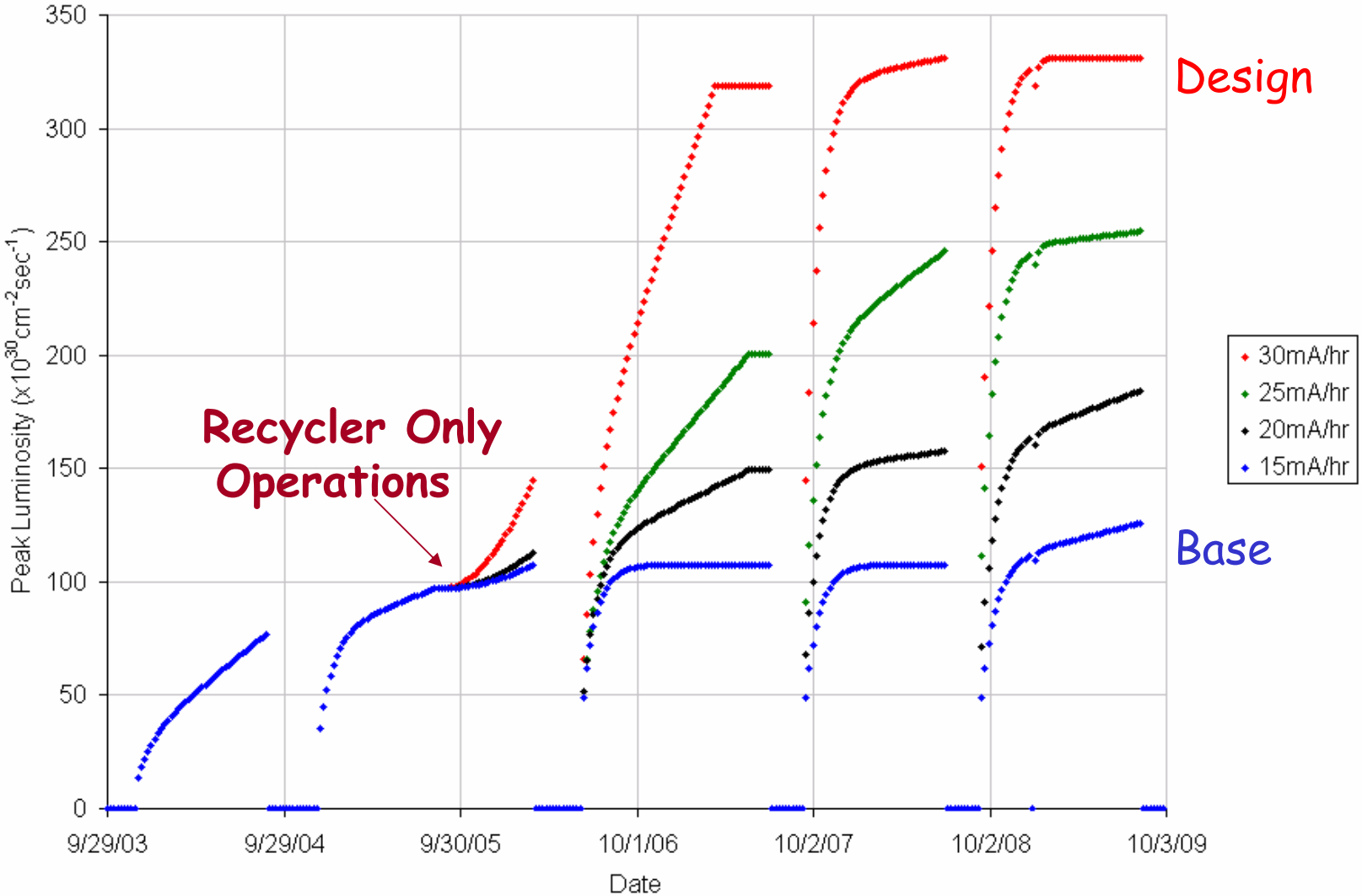


Weekly Luminosity Projection



Accumulated Luminosity				
	30mA/hr	25mA/hr	20mA/hr	15mA/hr
Fiscal Year	(fb^{-1})	(fb^{-1})	(fb^{-1})	(fb^{-1})
FY03	0.3	0.3	0.3	0.3
FY04	0.7	0.7	0.7	0.7
FY05	1.3	1.3	1.3	1.3
FY06	2.1	2.0	1.9	1.9
FY07	4.0	3.2	2.9	2.6
FY08	5.9	4.7	4.0	3.4
FY09	8.1	6.5	5.2	4.2

Peak Luminosity Projection

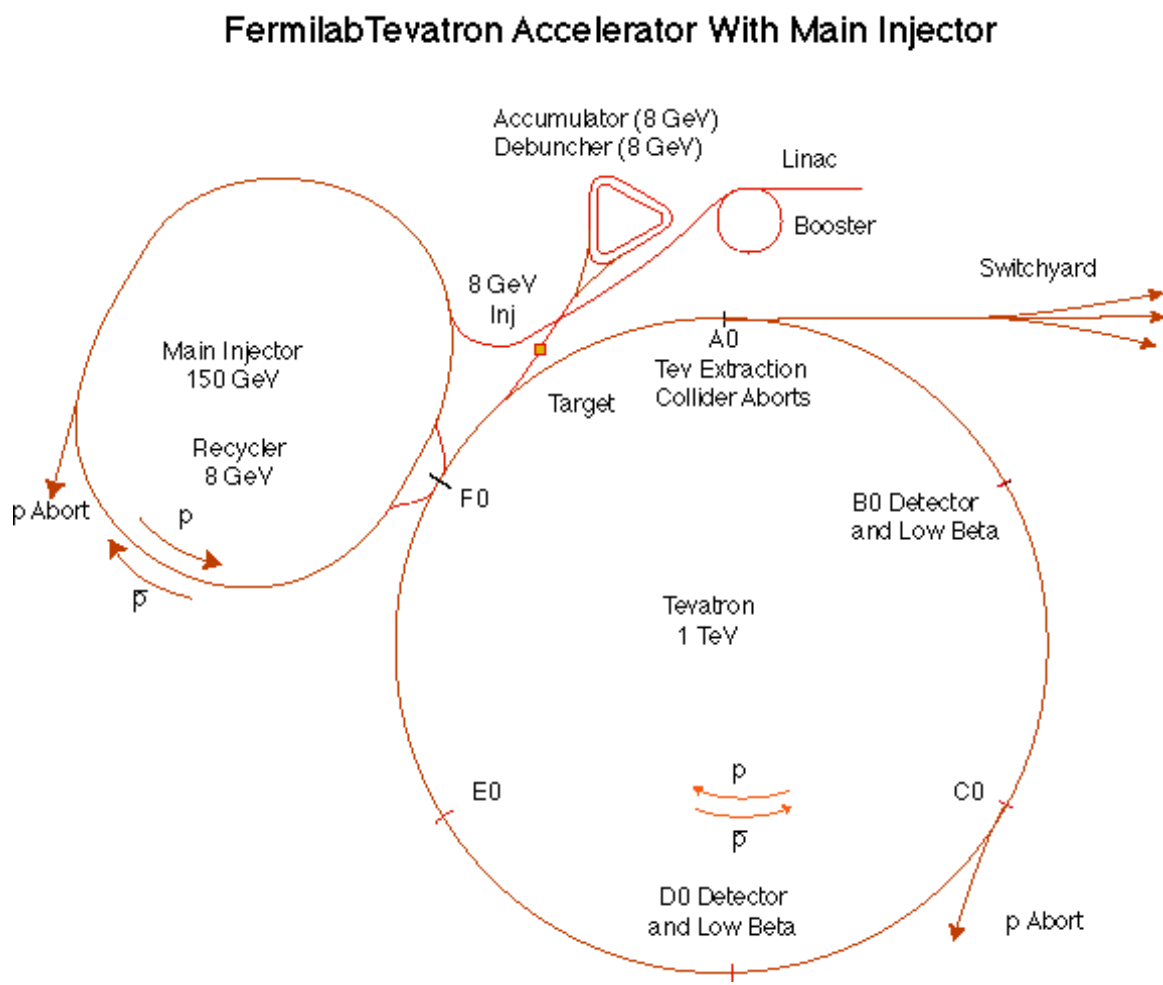


Stacking Progress

- The cornerstone of the Run II upgrades is antiproton production.
- The Phase 3 goal for the zero-stack stack rate is 20×10^{10} pbars/hour.
- Our best value to date is 17×10^{10} pbars/hour
- We have formed a special team of 20 people, dedicated 100%, to focus on antiproton production
  - Booster Extraction
  - Main Injector Slip Stacking
  - Antiproton Source
  - Instrumentation
- The goal of the stacking team is to:
  - Document the current state of the complex for antiproton stacking.
  - Formulate a study plan and needed instrumentation to reach 20×10^{10} pbars/hour
  - Successfully execute the plan by March 2006.
- The team meets twice a week at Tuesdays and Thursdays at 9 am in the Huddle to discuss overall progress and integration with collider operations.

Antiproton Production

- $1x10^8$ 8 GeV pbars are collected every 2-4 seconds by striking $7x10^{12}$ 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 $600x10^6$
- 8 GeV Pbars are accelerated to 150 GeV in the Main Injector and to 980 GeV in the TEVATRON



Stacking Rate

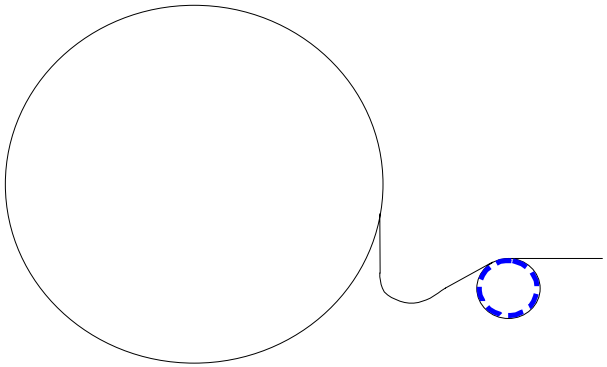
$$\Phi = \frac{N_p P}{T_{rep}}$$

- 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 15-20x10^{-6}
  - Mostly a function of the collection aperture
- T_{rep} is the cycle time
  - Mostly a function of the cooling rate

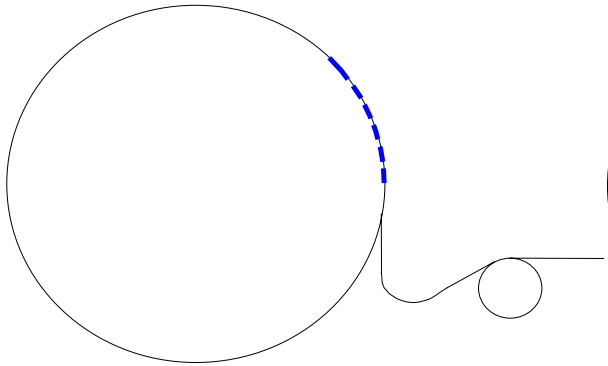
Number of Protons on Target

- The beam current in the Linac is limited by how much power the Klystrons can source to the beam
  - $P=I \times V$
- The beam in the Booster is limited by space charge tune shift
  - Moving particles produce a magnetic field on the other particles which act as a de-focusing lens
  - De-focusing force is proportional to the beam current
- Slip-stacking is a technique to double the number of particles
  - Done at relatively high energy so space charge is n ot a problem
  - Takes advantage of the enormous amount longitudinal "room" available in the Main Injector
    - Big circumference
    - Big momentum aperture

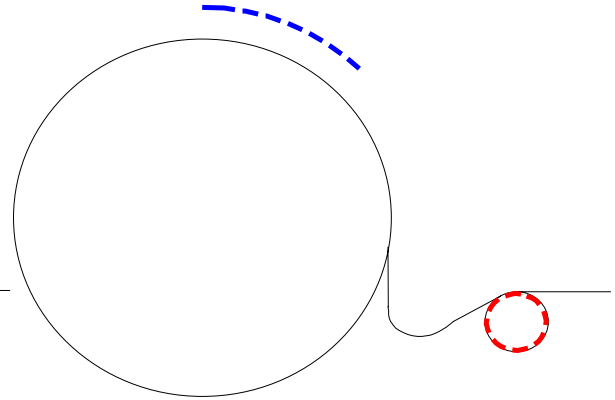
Slip Stacking



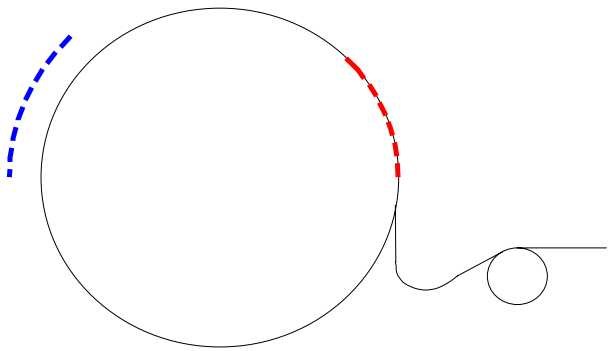
1. First Booster Batch accelerated in Booster



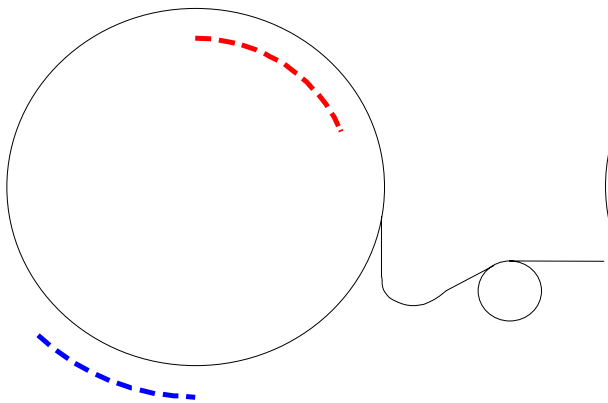
2. First Booster Batch injected onto MI central orbit with RF system A



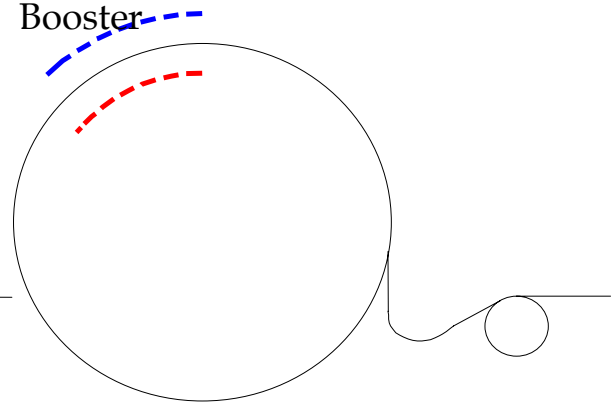
3. First Booster Batch slightly accelerated in MI with RF System A. Second Booster Batch accelerated in Booster



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

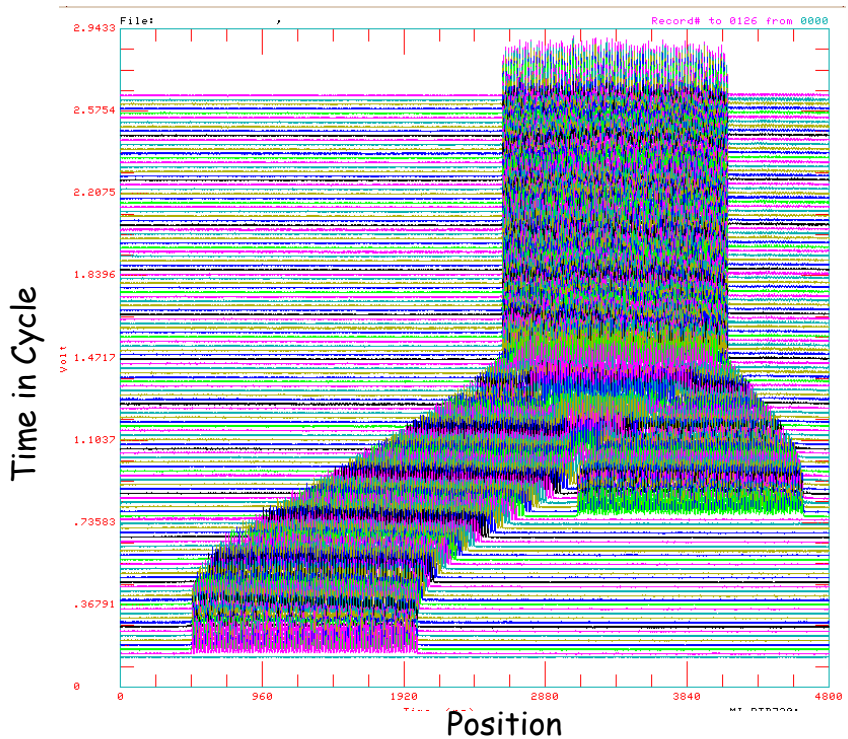


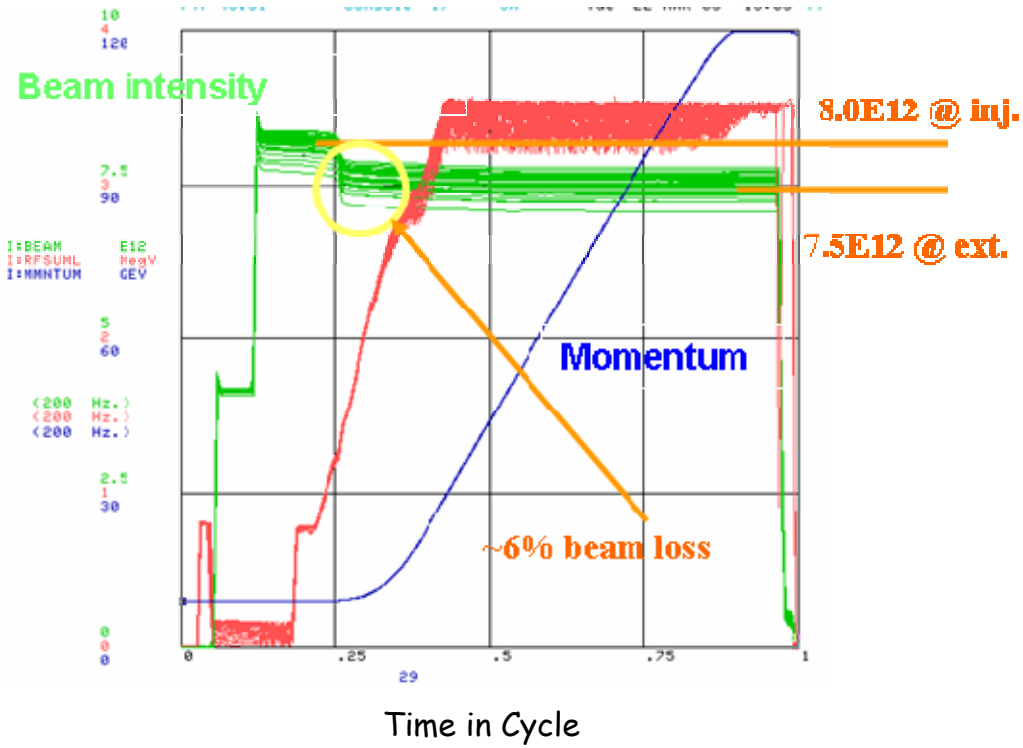
5. Second Booster Batch slightly decelerated in MI with RF System B



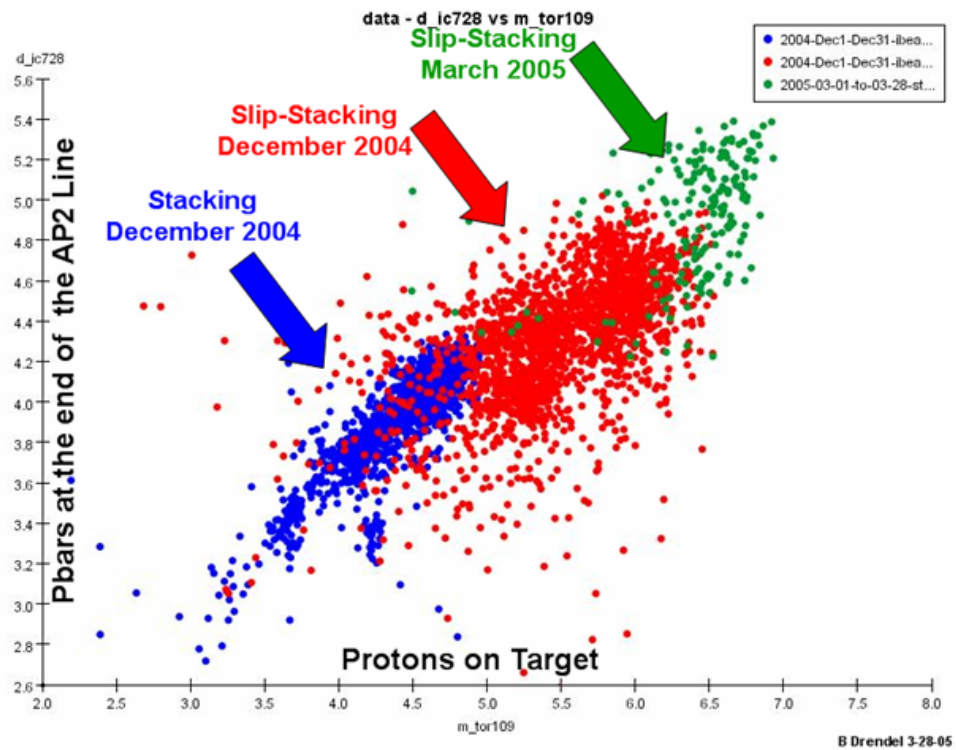
6. Wait till batches line up and snap on RF system C while turning of RF systems A & B

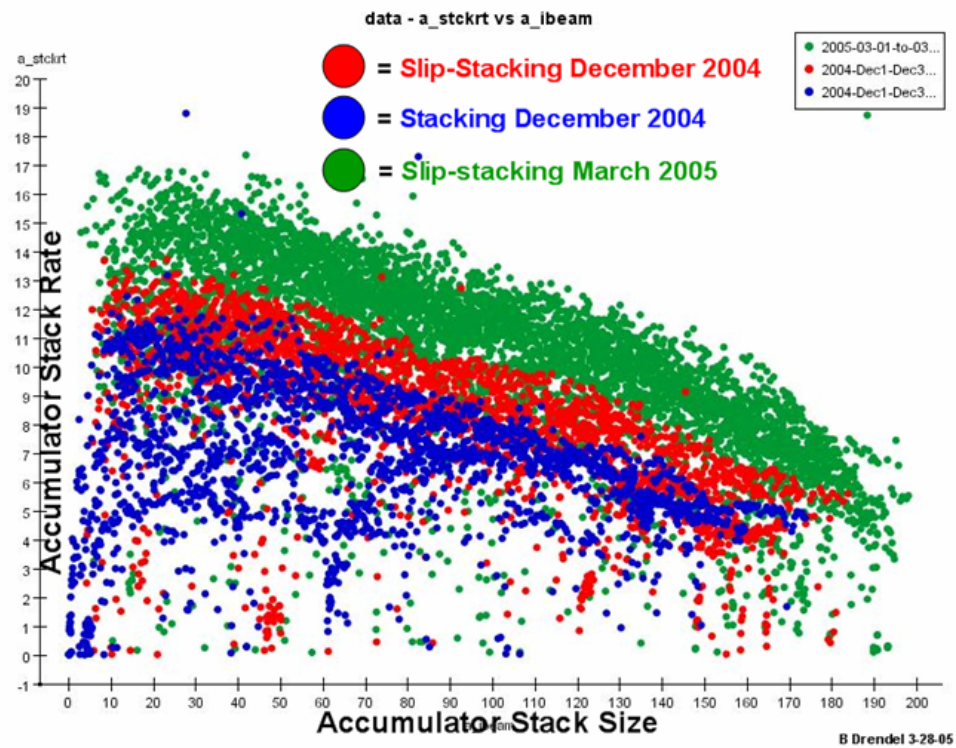
Antiproton Production – Slip Stacking





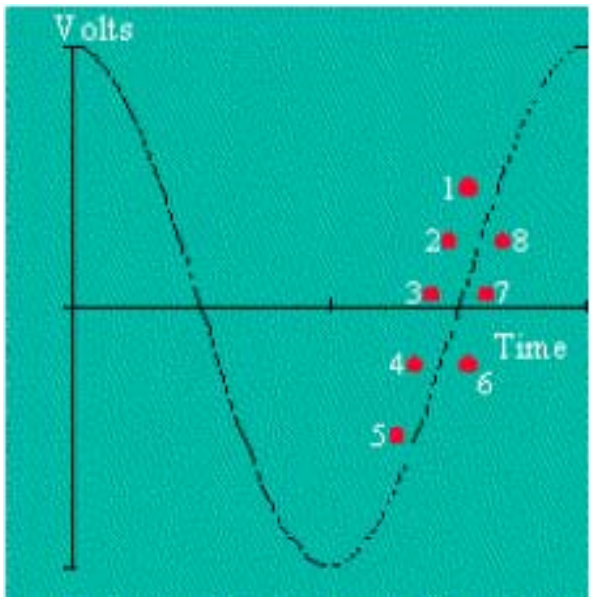
Antiproton Production – Slip Stacking



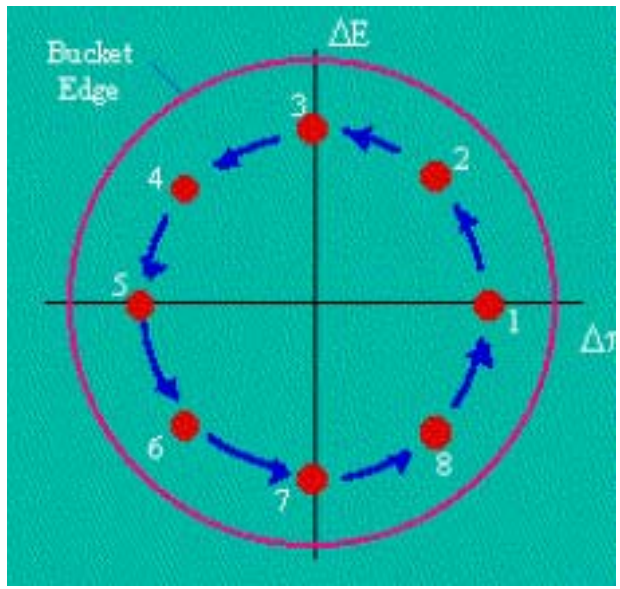


RF Basics

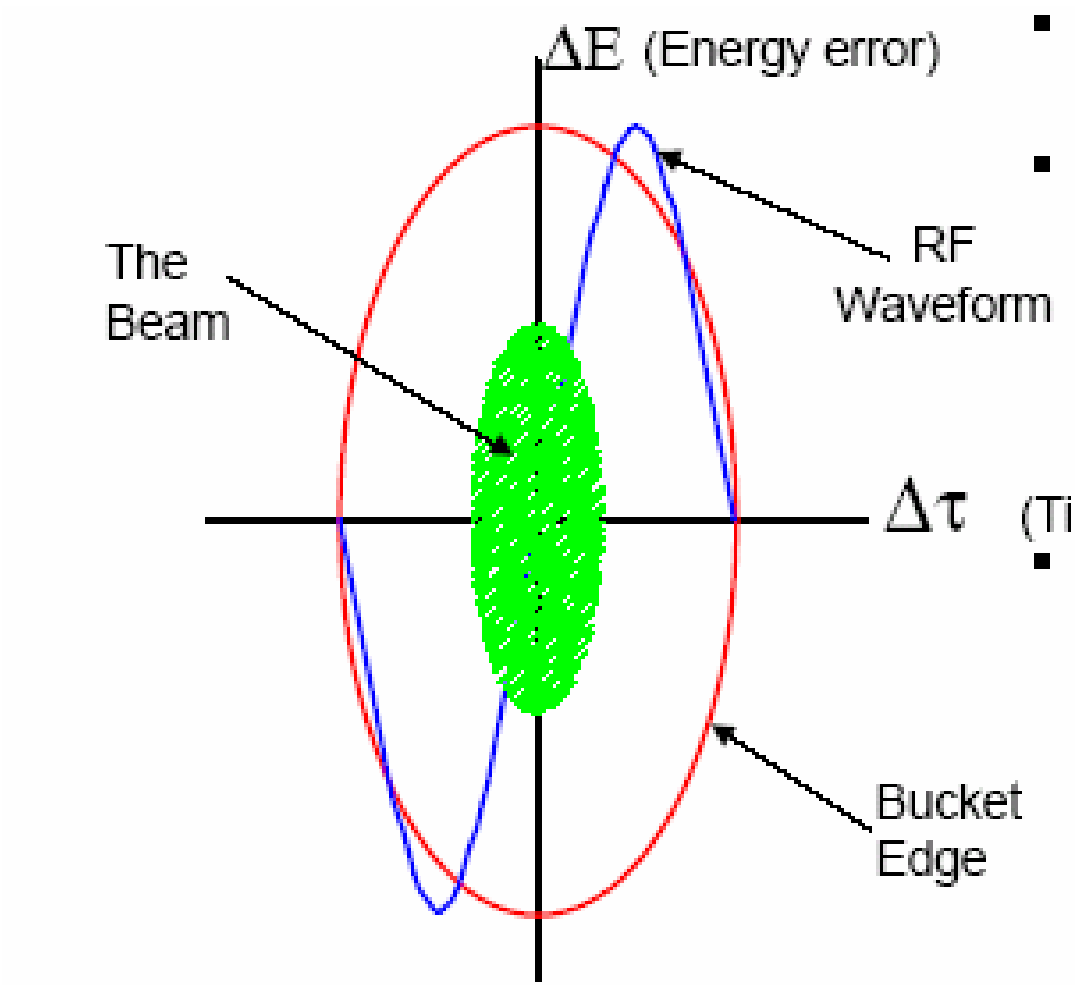
- The RF Voltage not only accelerates the beam but forms a barrier to keep particles from wandering away in time.
- The magnitude of the RF Voltage determines the size of this barrier or "bucket"



- A particle's energy error and time (phase) error are plotted on a "phase space" plot.
- The RF bucket causes a particle with a phase space error to wander about phase space in an ellipse. The shape of the ellipse is determined by the strength of the RF voltage.

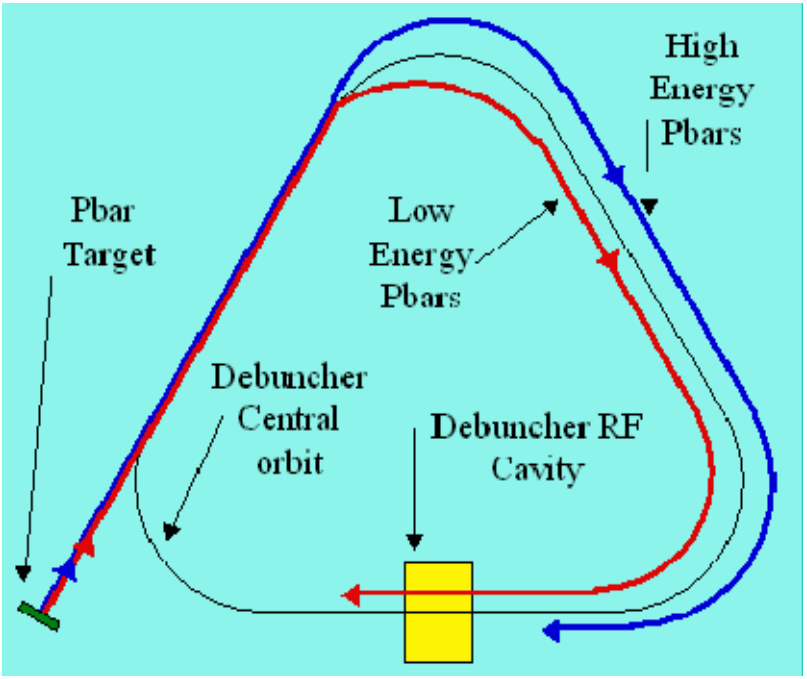


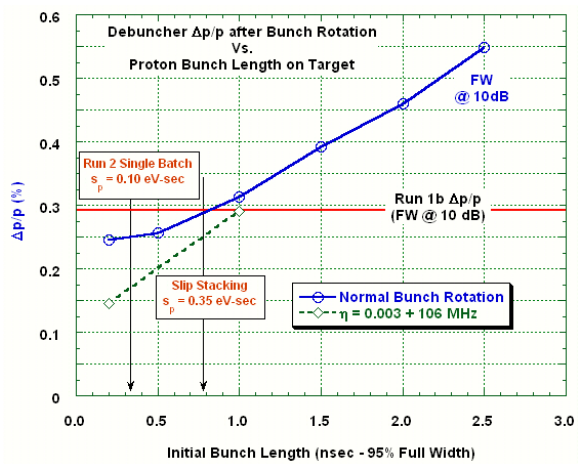
RF Basics

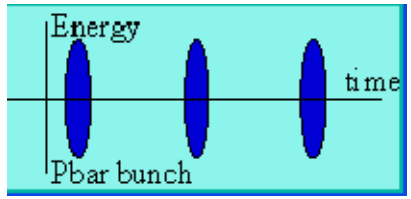


- The beam consists of many particles.
- Each particle has its own energy and phase error. The area in phase space that contains all the particles is called the "emittance".
- The emittance of the beam can never shrink. It can only increase.

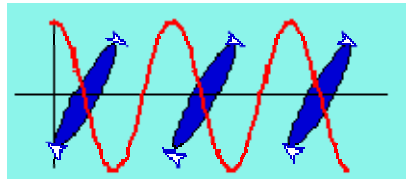
Pbar Debunching



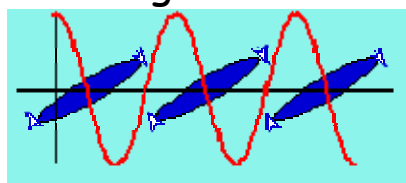




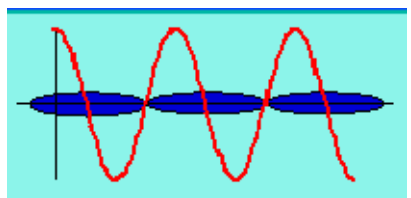
Pbars right after the target



Pbars arriving at the RF Cavity



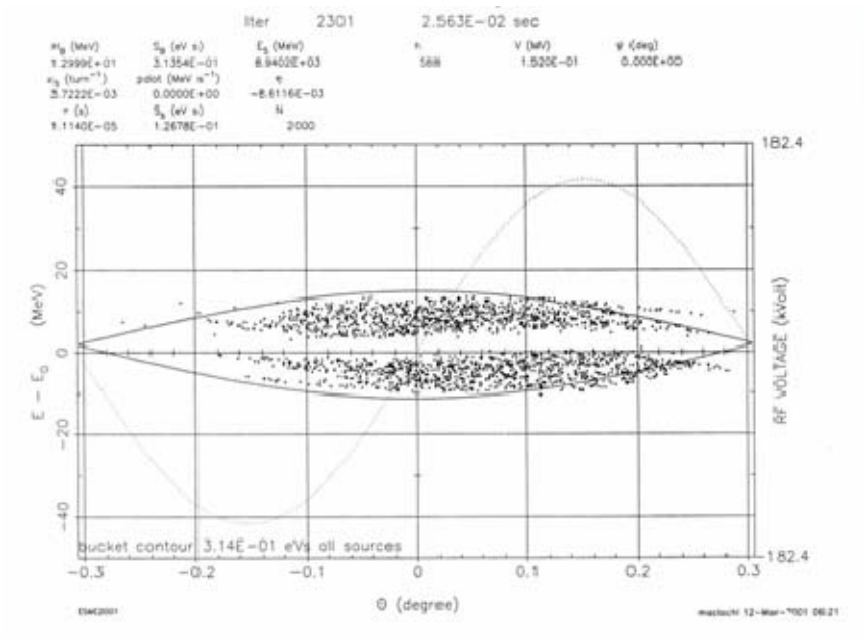
Pbars after many turns

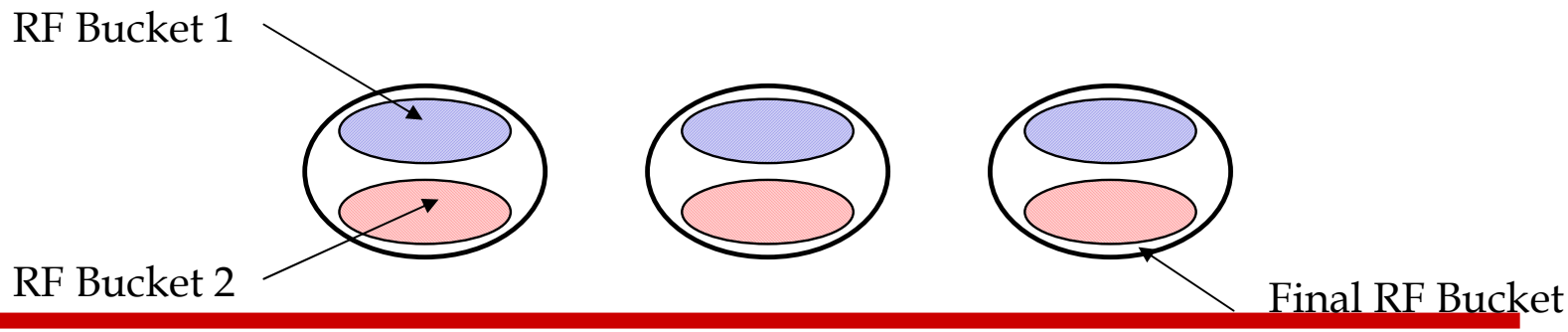


Pbars at the end of Debunching

Longitudinal Emittance and Slip Stacking

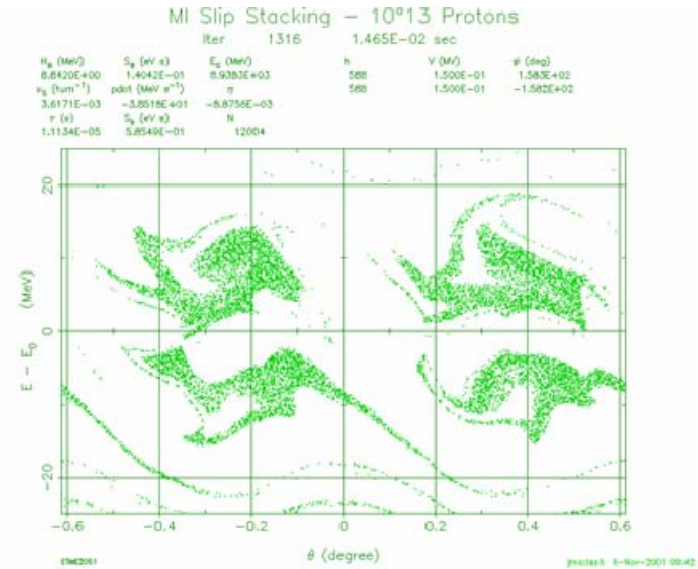
- To obtain a short bunch length, the longitudinal emittance of the proton bunches should be small as possible.
- A small longitudinal emittance requires that energy separation between the A & B batches be as small as possible during the final capture.
- The small energy separation requires that the RF buckets of the A & B batches not overlap
- The bucket heights which is proportional to the RF voltage must be very small.

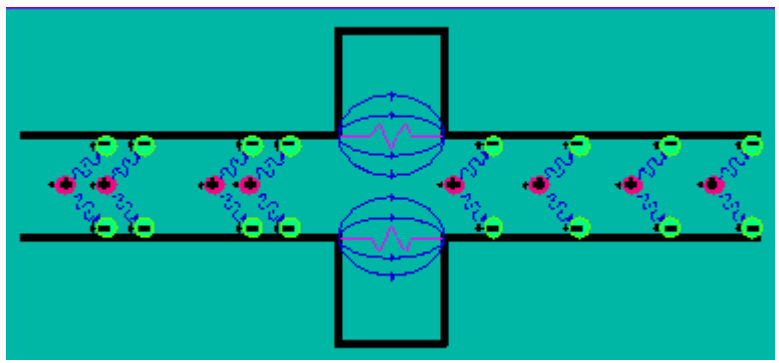


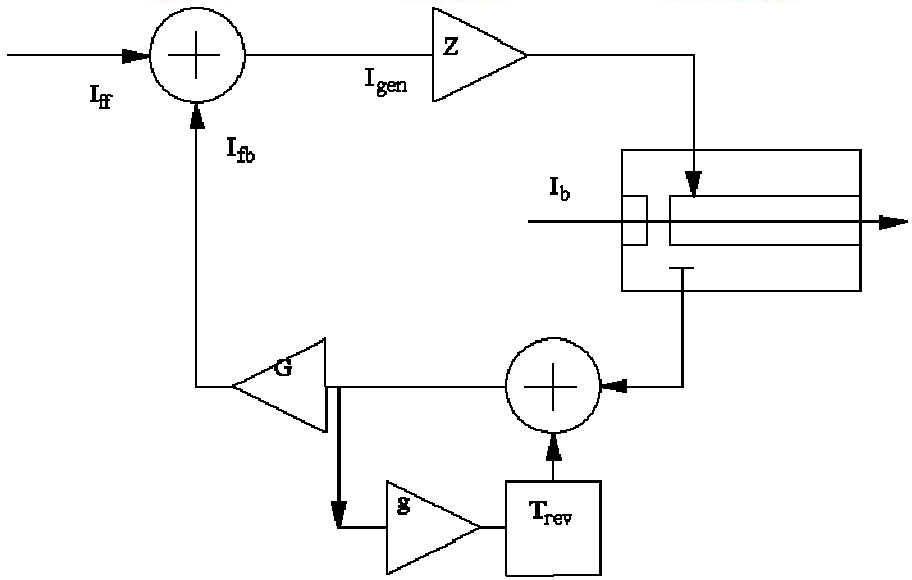


Beam Loading

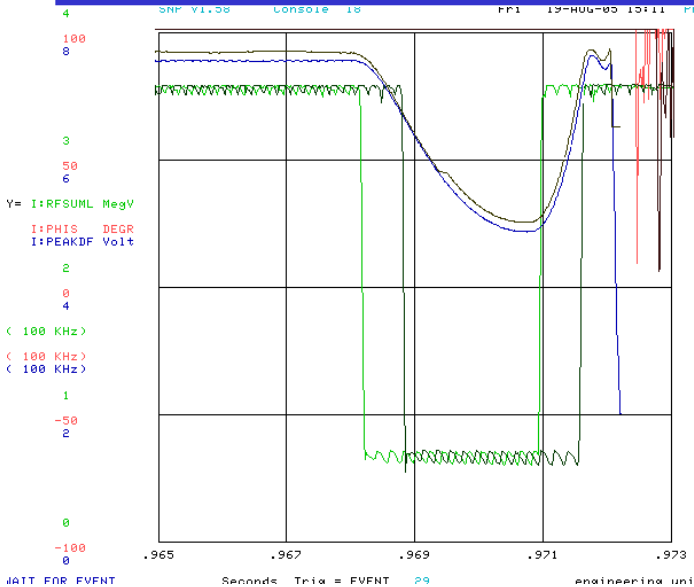
- Low Frequency (< 100 MHz) RF power sources, such as tetrodes, are typically current sources.
- The particle beam is accelerated with an electric field or a "voltage" gradient.
- An RF cavity can be thought of as a narrow band transformer that converts current to voltage.
  - The larger the cavity impedance, the more voltage that can be obtained for the same RF power.
- The particle beam travelling through the RF cavity is also a "current" source (especially at these energies).

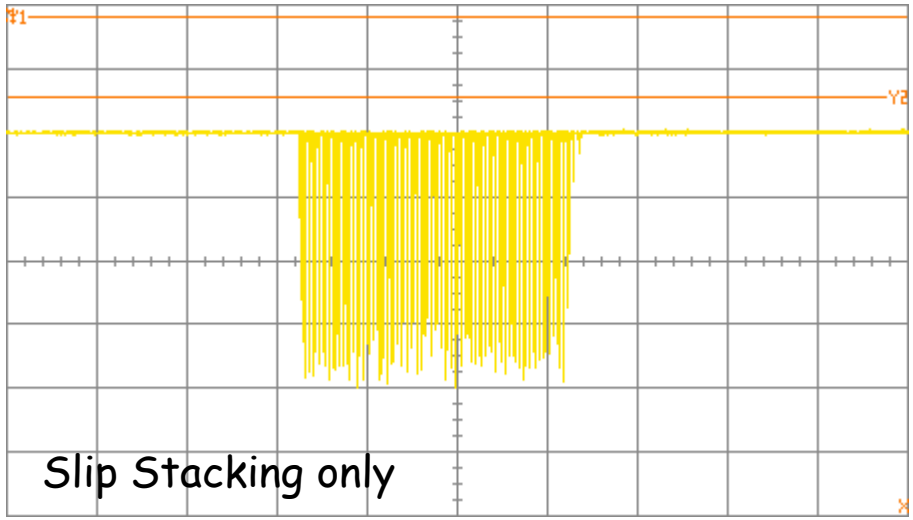


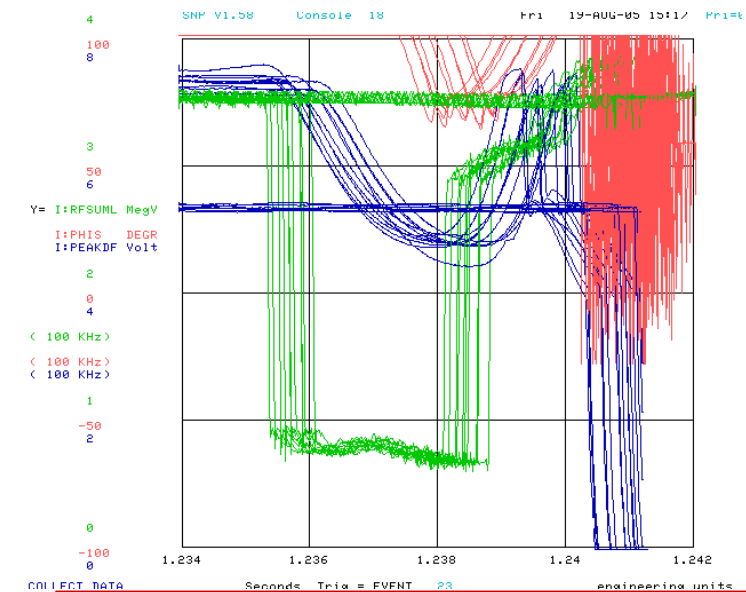


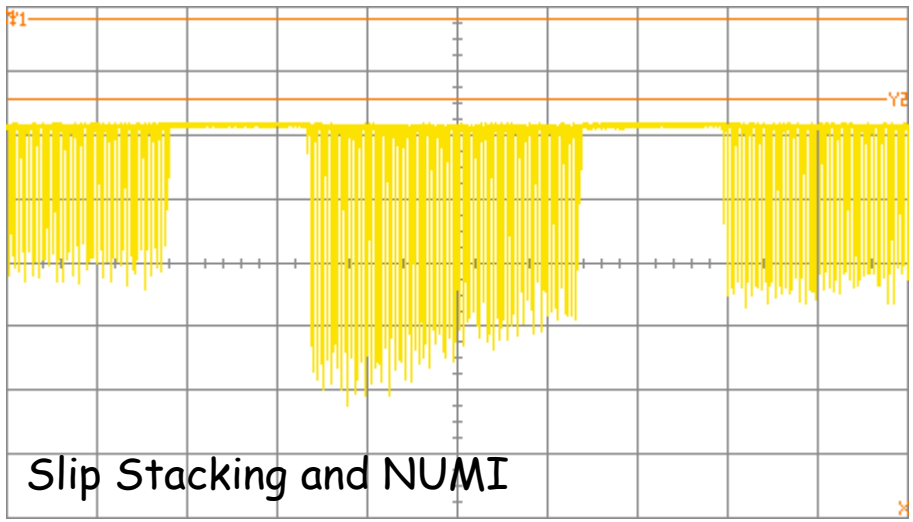


Main Injector 120 GeV Bunch Rotation







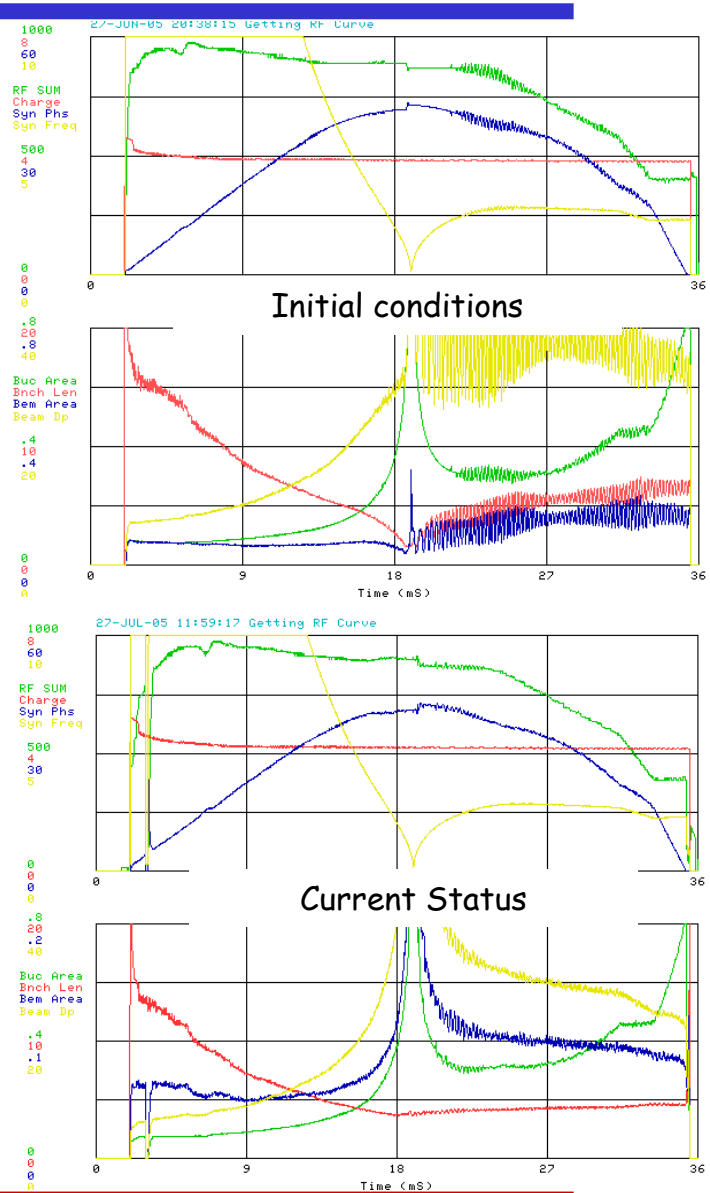


Stacking Team - Booster Extraction

Goals

	Initial	3/1/2006	Final	Status	
Intensity	3.9	4.2	4.5	4.2	$x10^{12}$
Emittance	0.2	0.12	0.12	0.08	eV-Sec
Momentum Spread	18	18	18	12	MeV

- Remaining Tasks
  - Stronger Mode 1 damping
  - Transverse Damper
  - 8 GeV Bunch Rotation Reliability
  - RF Step at Transition
  - Operational Streamlining
    - Instrumentation
    - App. Programs



Stacking Team - Main Injector Slip Stacking

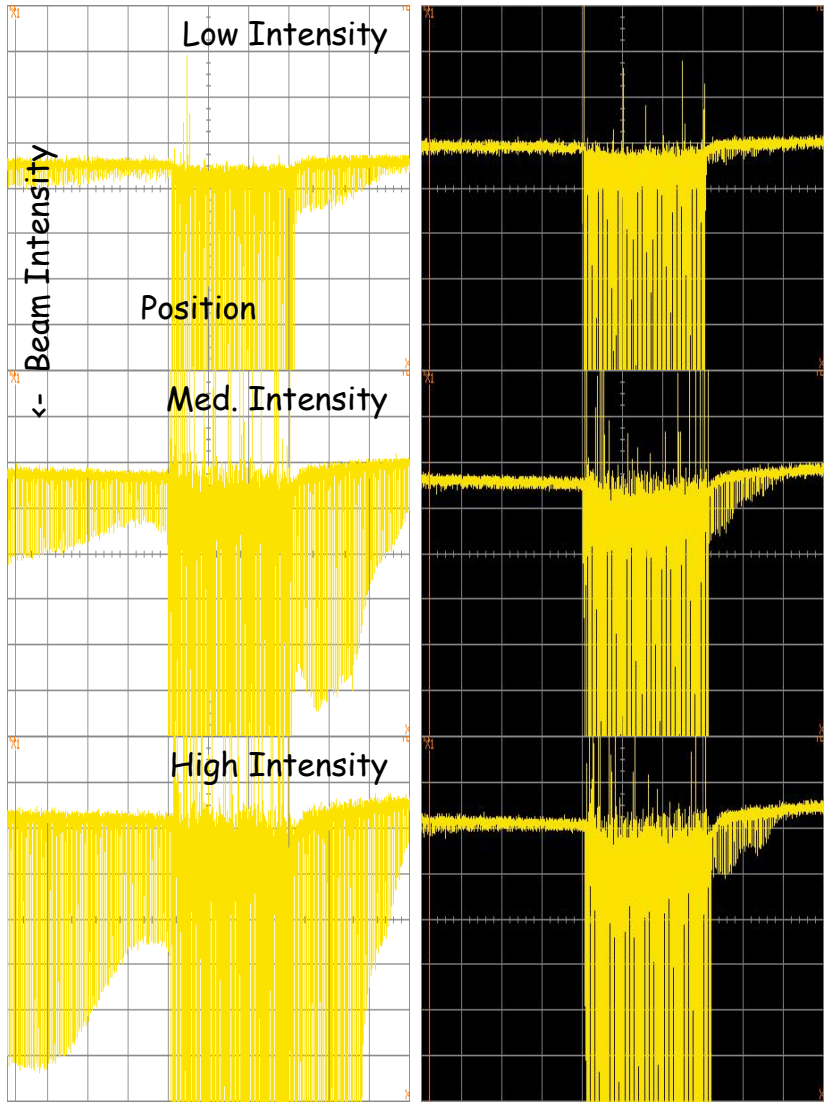
Goals

	Initial	3/1/2006	Final	Status	
Intensity	6.2	7.2	8	7.4	$x10^{12}$
Bunch Length	2	1.5	1.5	1.8*	nS
Efficiency	75	95	95	90	%

*Effective Bunch length on Mixed Mode Cycles

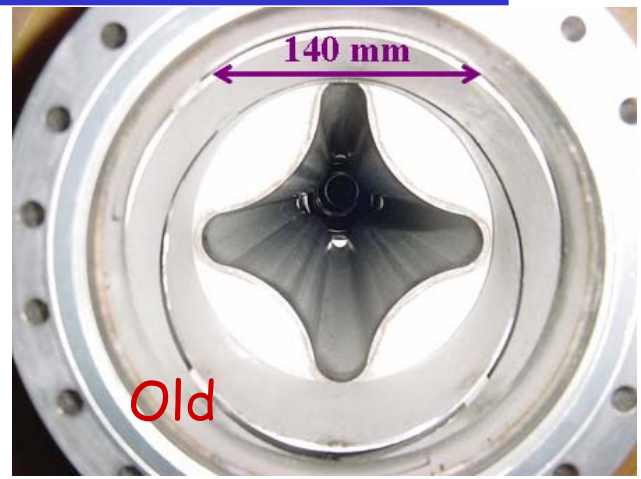
- Remaining Tasks
  - Reduce effective bunch length on target
    - Beam loading during Mixed-Mode 120 GeV Bunch Rotation
    - Elimination of difference between Pbar-Production-Only cycle and Mixed-Mode cycle
  - Operational Streamlining

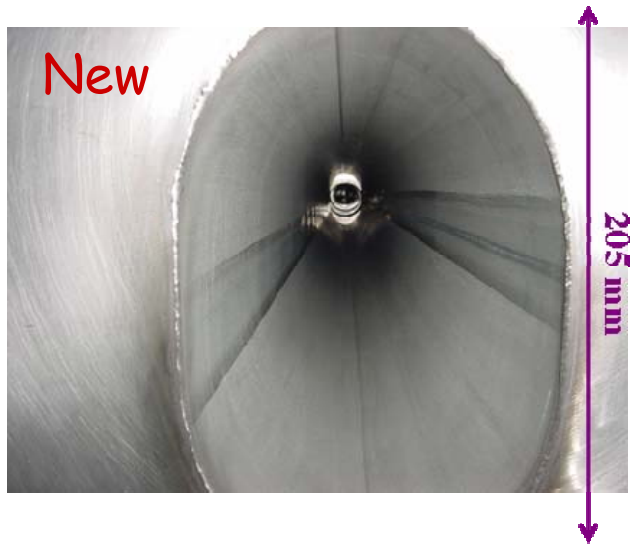
Initial conditions | Current Status



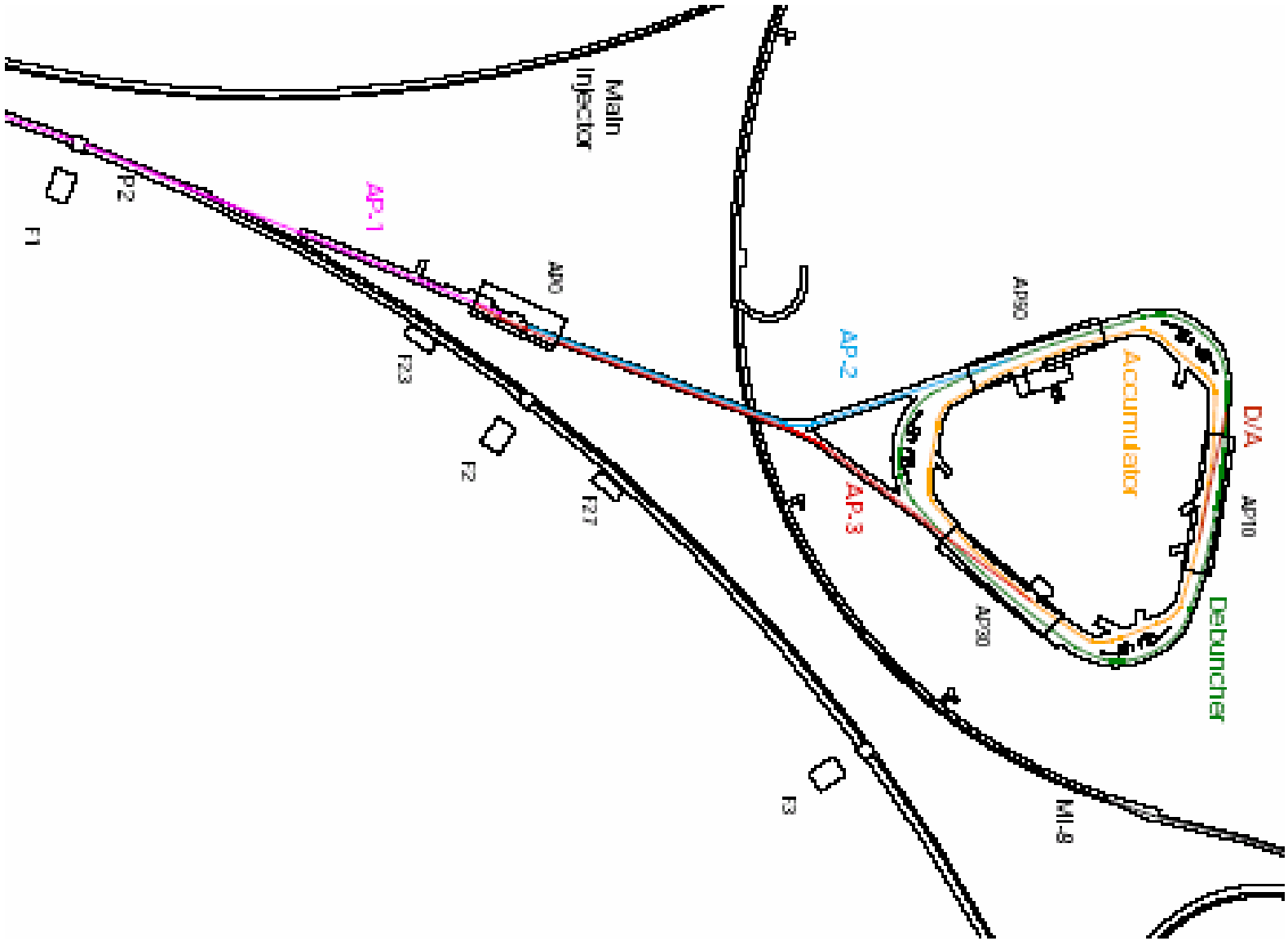
Antiproton Aperture - Pbar Production

- The measured aperture of the initial stages of the antiproton production chain is about 65% of the available physical aperture.
- An aggressive beam-based alignment program is under development to bring the measured aperture to the physical aperture.
  - Would increase the stacking rate by over a factor of 2
  - The final design goal is to achieve 77% of the physical aperture which will increase in stacking rate by 40%
- The beam based alignment scheme consists of 5 major components
  - Independent control of the quad gradients (done)
  - Beam position measurement system to measure orbit distortion due to varying quad gradients (in- progress)
  - Orbit control devices to center the beam through the quads (done)
  - Moveable control of tight apertures (stochastic cooling arrays) (in progress)
  - Loss monitor system to measure losses at tight apertures (done)
- Most of the recent focus has been to complete the instrumentation upgrade
  - Extremely small beam currents ~10μAmps
- The goal for this year is to increase the aperture for each plane from 65% to 72% of the available physical aperture which would result in a 20% increase in antiproton production rate





AP2 Line and the Debuncher

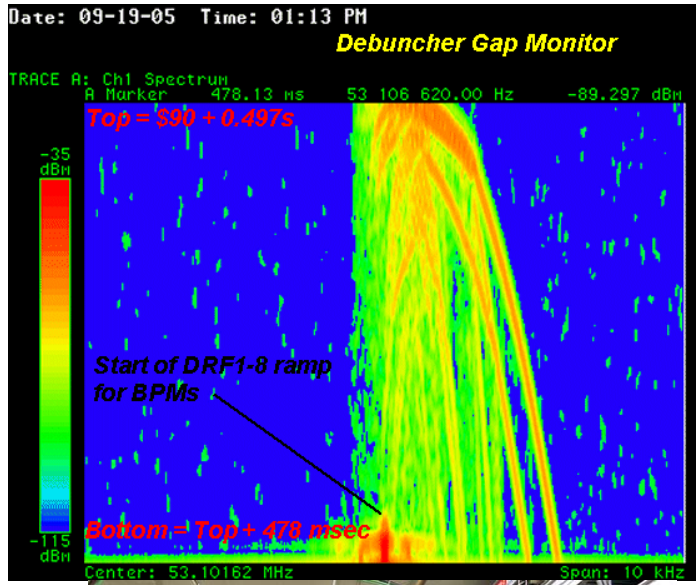


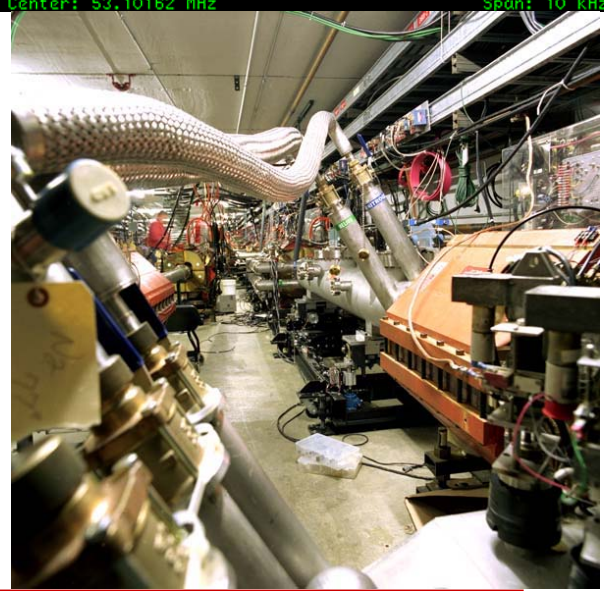
Beam Based Alignment

- For maximum aperture, we would like the beam to go through the center of the quadrupoles
- You cannot trust the absolute position of beam position monitors.
- If the beam goes off center through a quadrupole, it gets a kick. The kick is proportional to
  - strength of the quad
  - the offset of the transverse beam position with respect to the center of the quad.
- To measure how far off center the beam is in the quad
  - Measure the beam trajectory downstream of the quad with BPMs
  - Change the Quad current (strength)
  - Measure the difference in beam position
    - If the beam goes though the center of the quad, the trajectories will be the same
  - Change the position of the beam through the quad with an upstream trim magnet until the quad does not steer the beam.

Beam Based Alignment

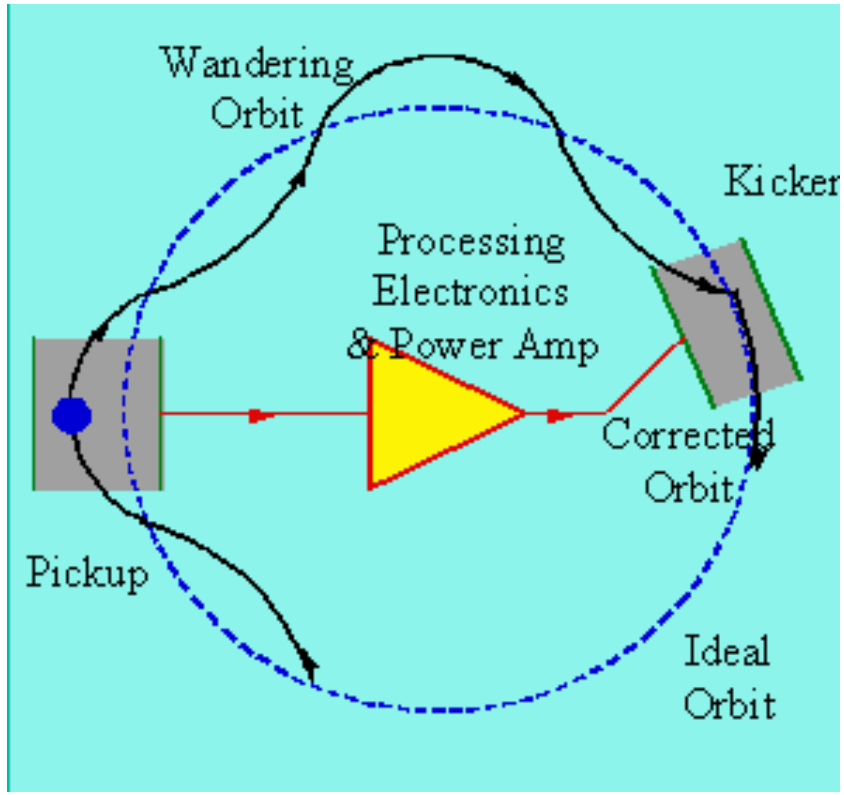
- Necessary components
  - Beam position system
  - Individual control of quad strength
  - Trim magnets to control the orbit
- Problems in the Debuncher
  - Beam position system
    - Pbar current extremely low
    - Secondary spray
    - Reverse proton beam loading
  - Quad strength
    - Quads are on busses – had to add lots of shunts
  - Trim magnets
    - There is no space in the Debuncher to add trim magnets
    - Orbit correction is done by placing quads on remote control stands
  - Overall
    - Align with reverse protons
      - Large setup overhead
    - Stack with forward pars
    - Just isn't the same!





Stochastic Cooling

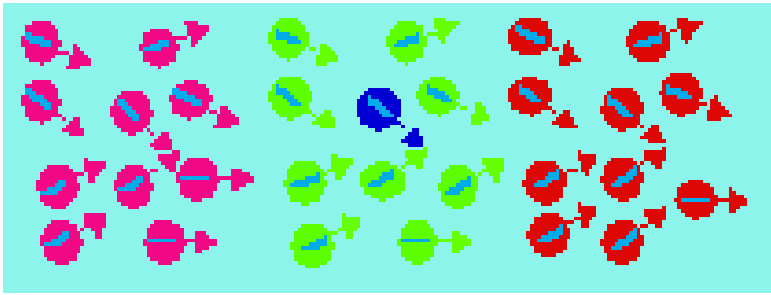
- Electron Cooling works well for narrow, intense beams
- Stochastic Cooling works well for wide, diffuse beams
  - Stochastic cooling uses feedback
  - A pickup electrode measures an "error" signal for a given pbar.
    - This error signal could be the pbar's position or energy
    - The pickup signal 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



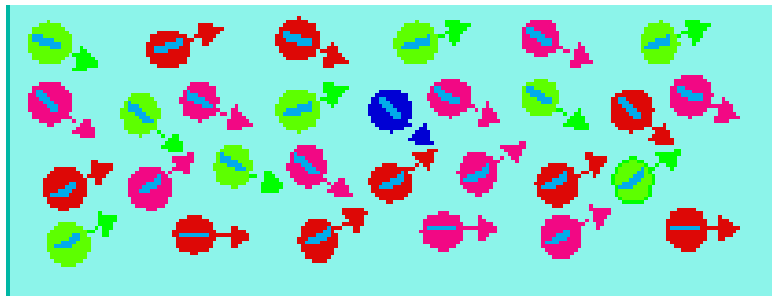
Stochastic Cooling

- 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 6×10^{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 2×10^{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. But:
  - 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

Stochastic Cooling



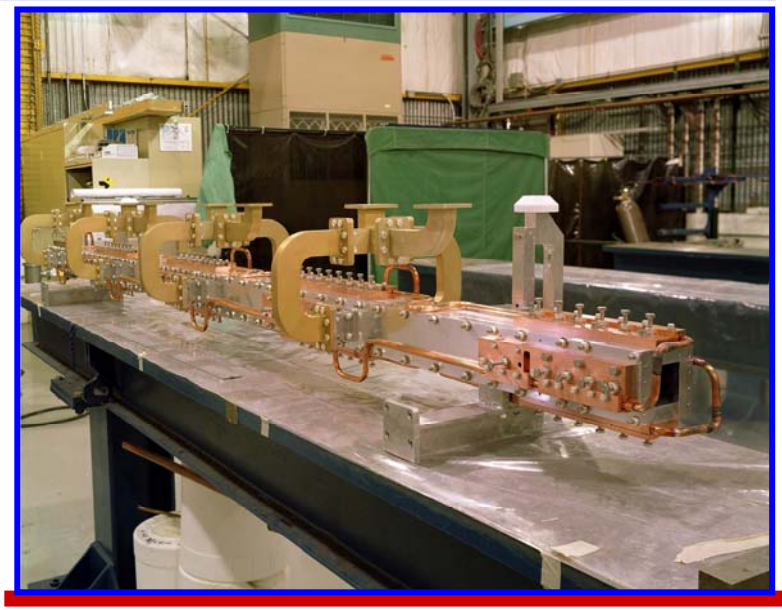
Before Mixing

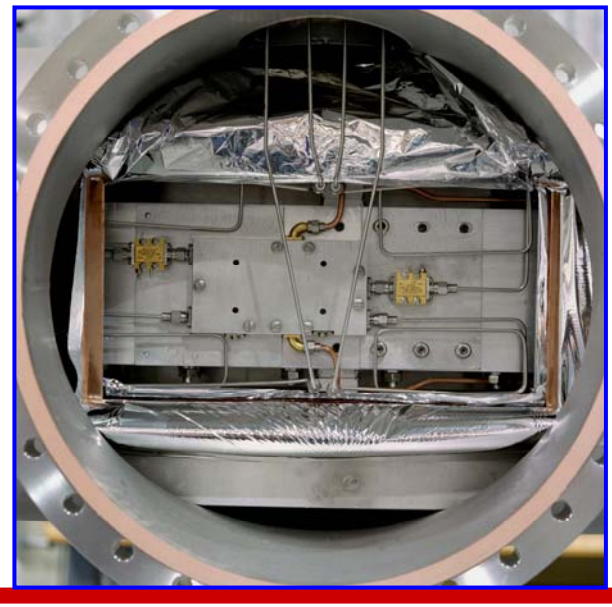


After Mixing

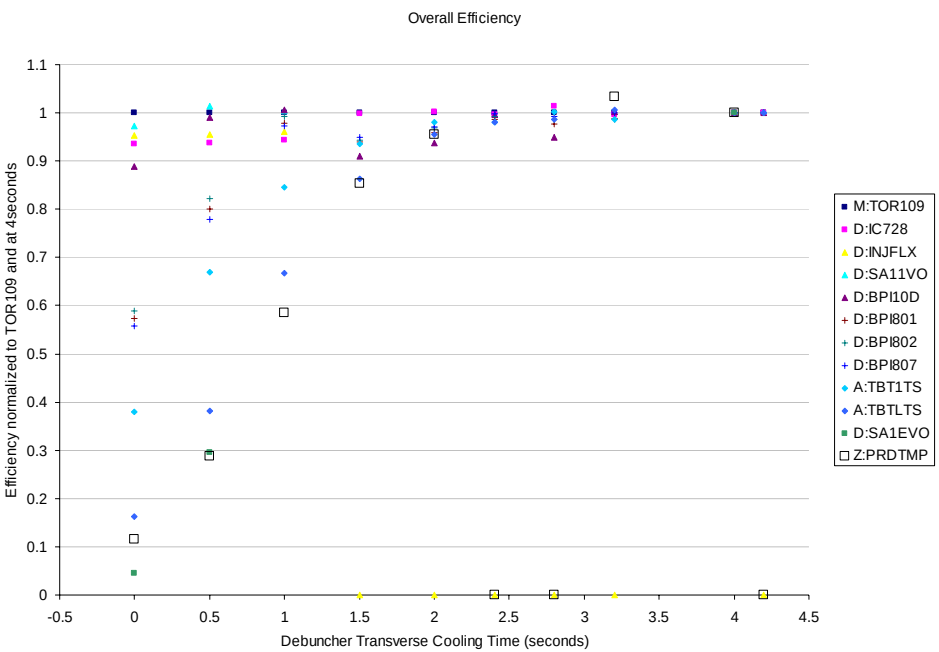
$$\frac{1}{\tau_{cool}} = \frac{W}{N_p M}$$

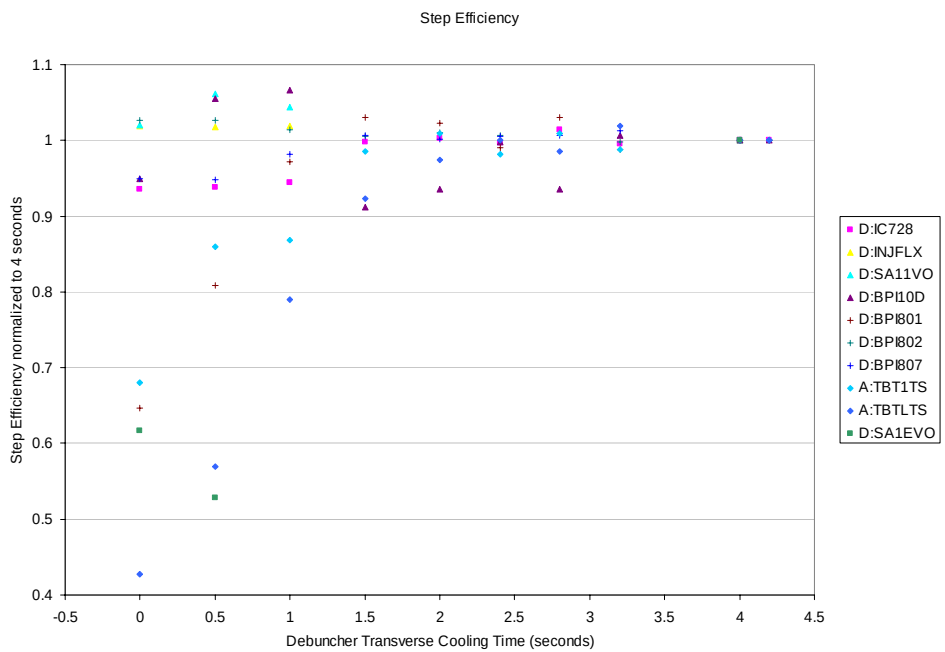
Stochastic Cooling Pickups

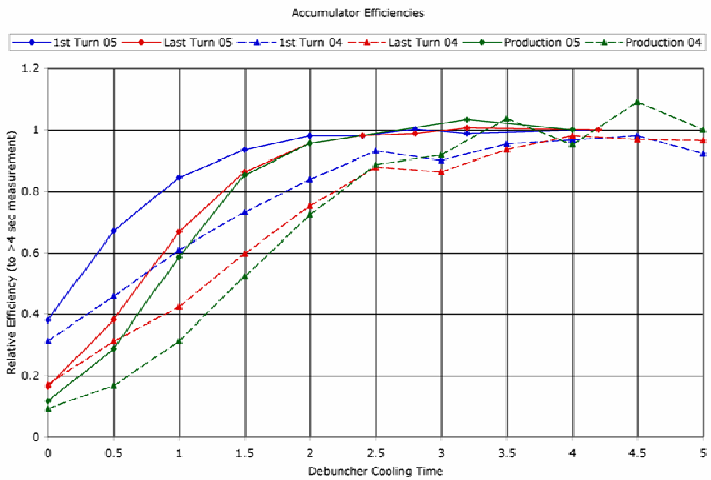




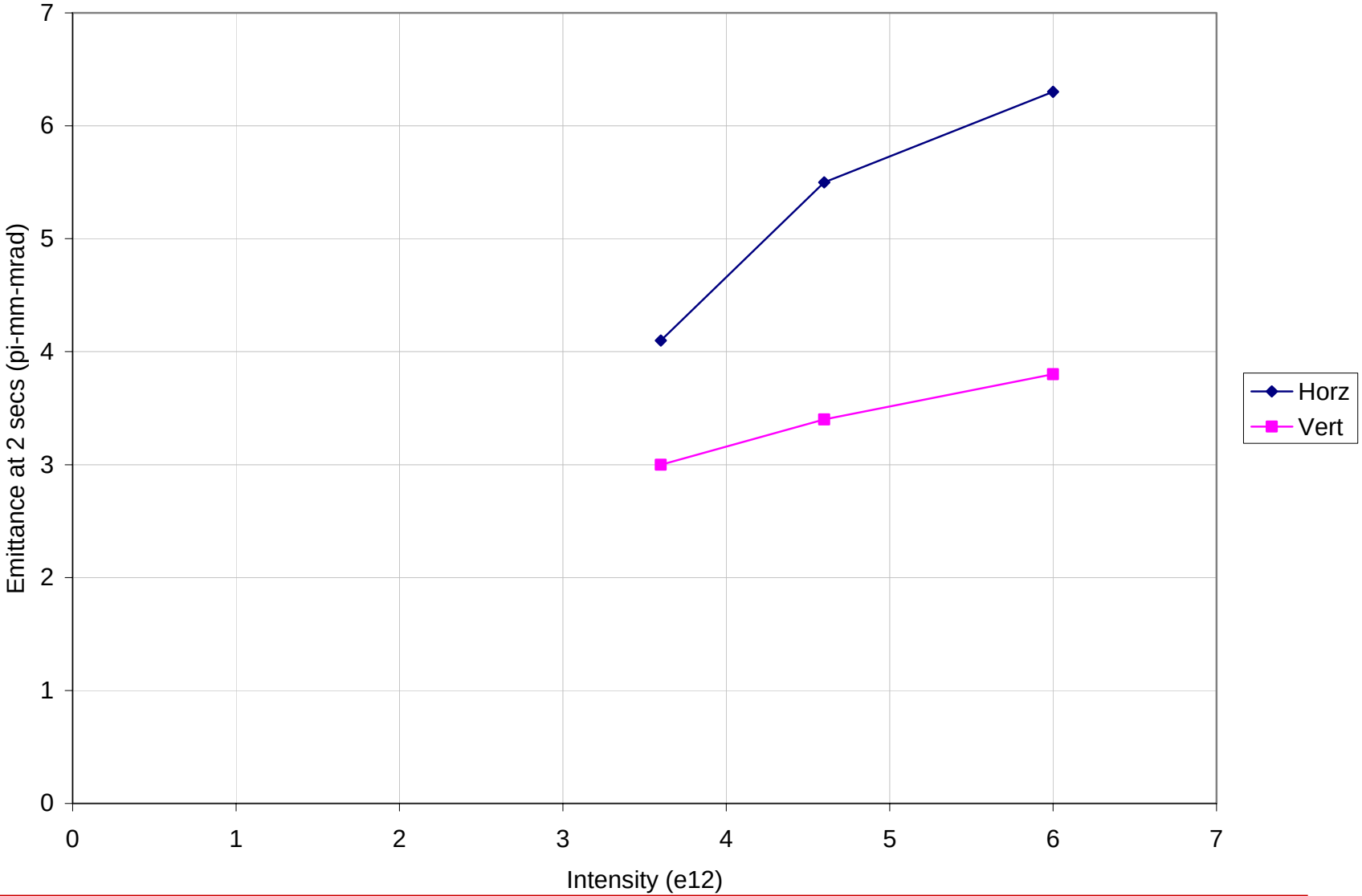
PBar Production Chain Efficiency







Debuncher Transverse Cooling Characterization



Antiproton Stacking – Stacktail System

- The time evolution of antiprotons during cooling is best described by the Fokker-Plank Equation

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

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

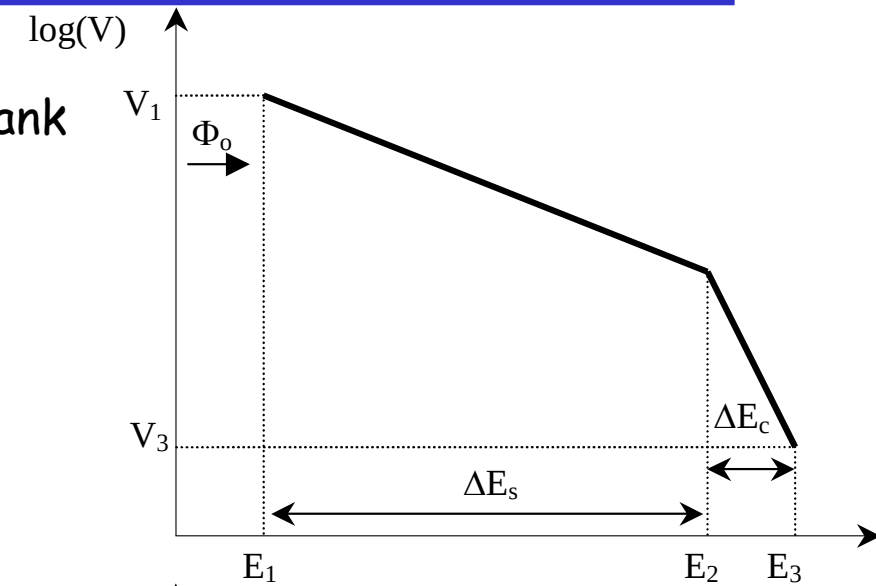
$$\phi_h = \frac{1}{2}\frac{\Delta E_h{}^2}{T_o}\frac{\partial\psi}{\partial E} = \frac{1}{4}(eV_o f_o)^2 \frac{E_o}{\eta f_o}\psi\frac{\partial\psi}{\partial E}\sum_n |G_n(E)|^2$$

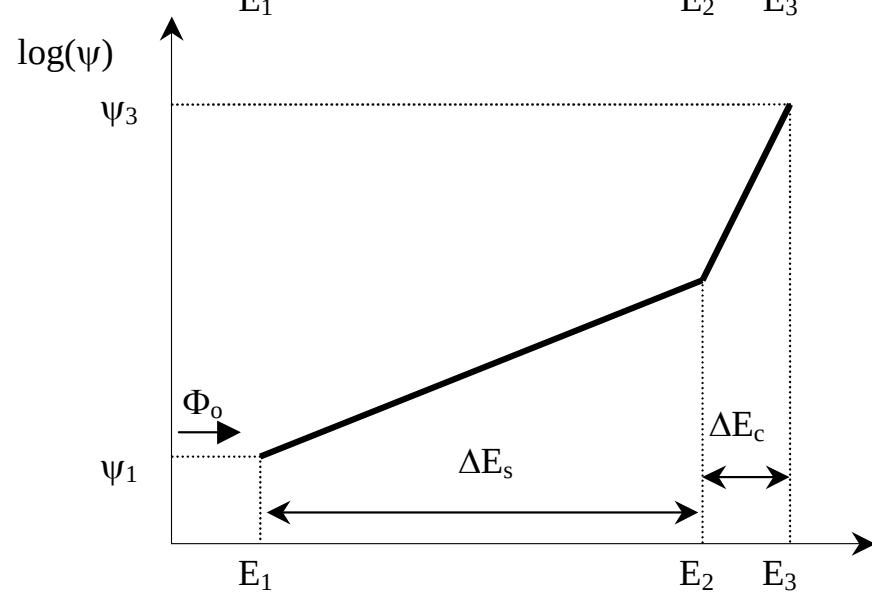
- Optimum profile that maximizes dψ/dE is exponential

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

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

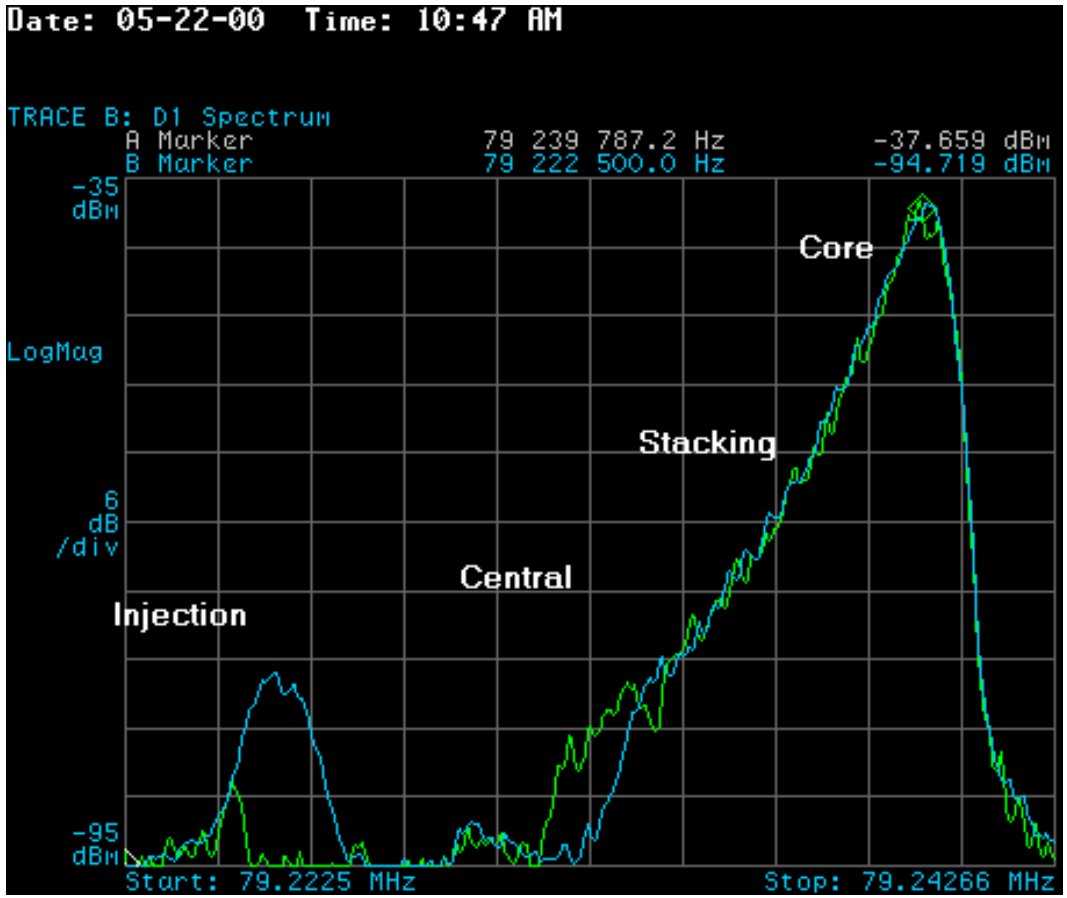
$$\phi_m = \eta f_o \frac{E_d}{E_o}\frac{\left(W/f_o\right)^2}{\ln\left(f_{max}/f_{min}\right)}$$



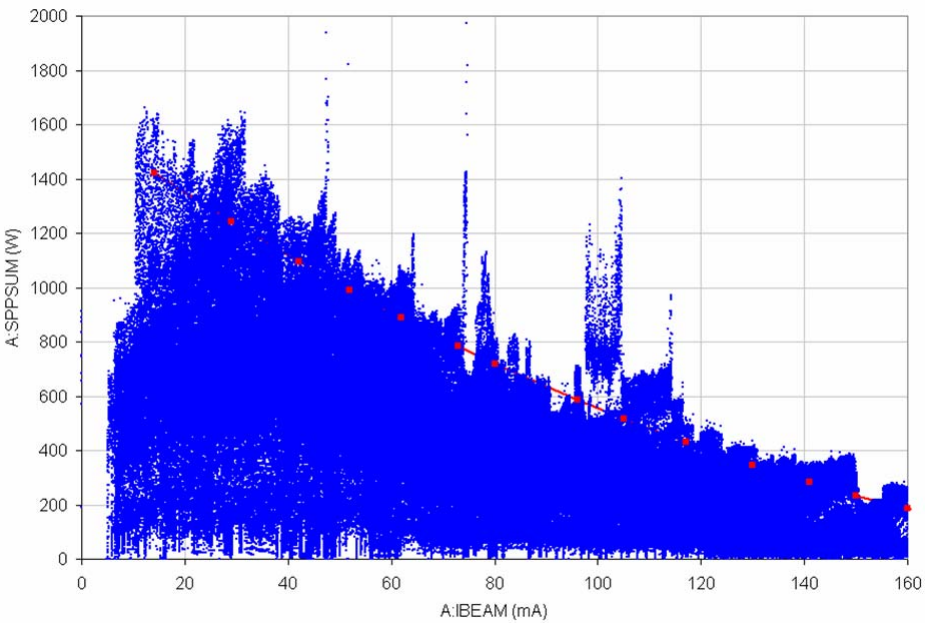


Antiproton Stacking – Stacktail System

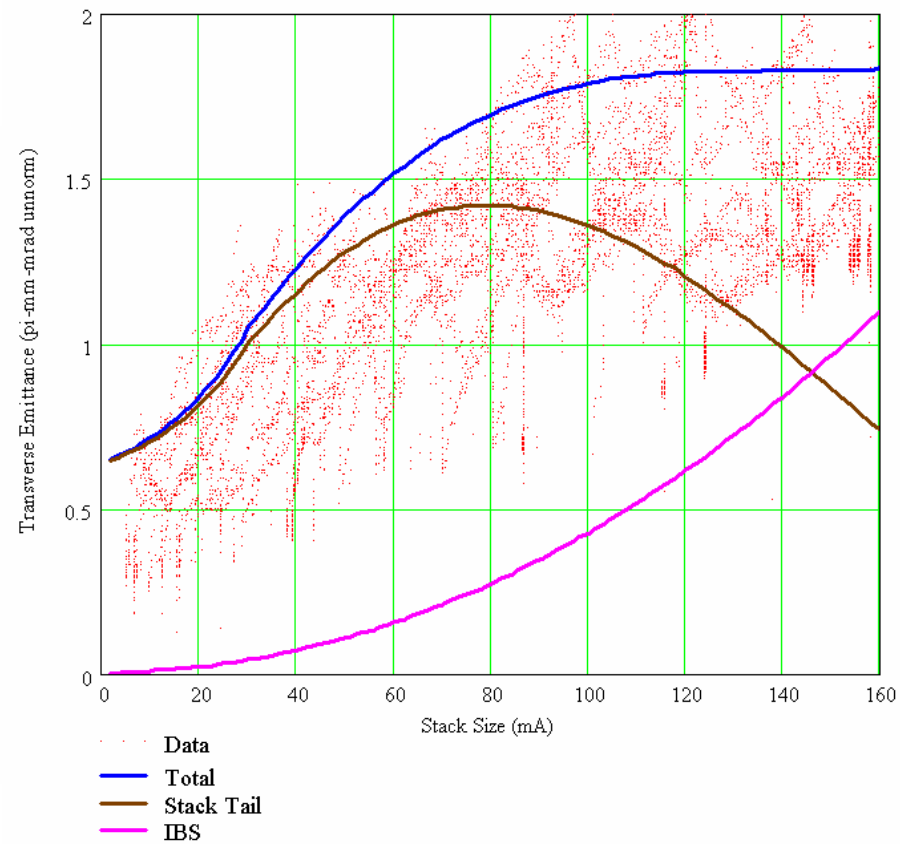
- Beam is injected onto the Injection Orbit
- Beam is
  - Bunched with RF
  - Moved with RF to the Stacking Orbit
  - Debunched on Stacking orbit
- Stacktail pushes and compresses beam to the Core orbit
- Core Momentum system gathers beam from the Stacktail
- Accumulator Transverse Core Cooling system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



StackTail Heating



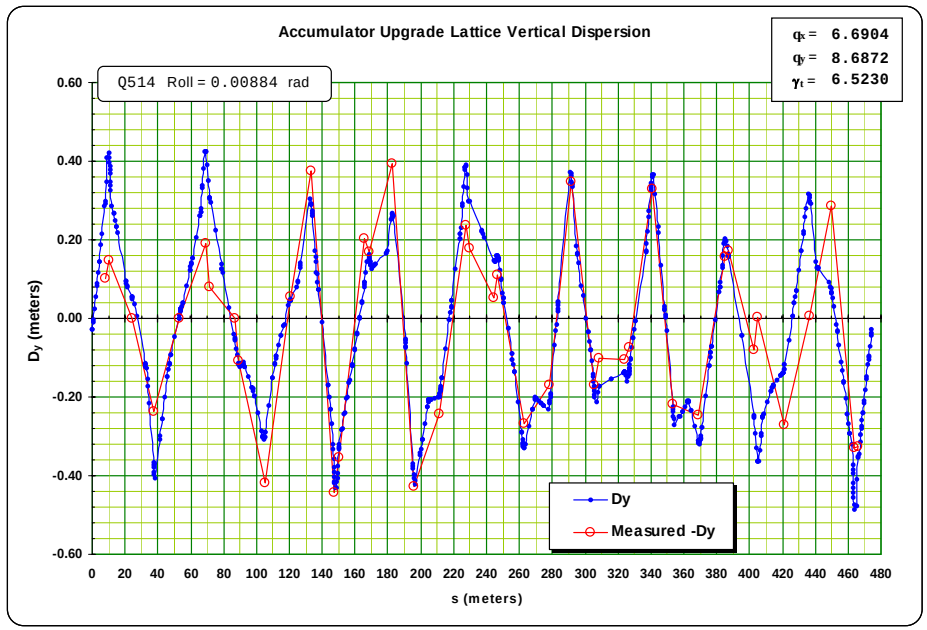
Stacktail Power vs.
Stack Size



Core Emittance vs.
Stack Size

Stacktail Heating

- To push fast cycle times the gain of the stacktail is increased
- More power in the stacktail can transversely heat the core beam
  - Longitudinal tanks transversely misaligned give transverse kicks
  - Residual dispersion gives transverse kick
    - Longitudinal kick in dispersion changes local reference orbit which results in a betatron oscillation
    - Dispersion in A30 where stacktail tanks are located should have a dispersion function < 0.01 meters!
  - When implementing the "Shot Lattice" (over 3 years ago), a dispersion wave was created by the hysterisis of the magnet ramps
    - This wave was not removed because we typically ran with long cycle times and stacktail heating was not as big as issue as it is today



Antiproton Source Tasks

	Initial	3/1/2006	Final	Status	
Beam on Target	6.2	7.2	8	7.4	$x10^{12}$
Production	15	17	21	13*	$x10^{-6}$
Cycle Time	2.2	2.2	2	2.2	Sec.

*During Mixed Mode Cycles

- Remaining Tasks
  - Beam base alignment effort of the AP2 and Debuncher
    - AP2 BPMs complete
    - Ready to upgrade Debuncher BPMs to see 53 MHz pbars
    - Differential Orbits for the AP2
    - Magnetic measurement of the upstream aperture of AP2
  - Correct the intensity dependence of Debuncher transverse cooling
    - Optimize transverse gain ramping
    - Optimize A10 straight section aperture
    - Correct of matching of D/A line
  - Optimize the flux through the Stacktail for Recycler-Only operations
    - Reduce StackTail Heating
      - Eliminate Vertical Dispersion in the Accumulator
      - Center Stacktail tanks
    - Implement 4-8 GHz momentum cooling during stacking
    - Speed up ARF1 curves
    - Lower the energy of the Stacktail deposition orbit
  - Rapid Transfers
    - Optimize P1-AP3 line and Main Injector to Recycler line for large $\Delta p/p$
    - Commission Pbar Injection Damper
    - Attempt transfers without reverse proton tune-up

Summary

- The Run II Upgrades are on track to provide over $8fb^{-1}$ by the end of 2009
  - The Recycler is operational
  - Electron cooling is commissioned and operational!
  - Slip Stacking is operational
- The major challenge left in Run II is the increasing the antiproton production rate
  - AP2- Debuncher aperture upgrade
  - Debuncher to accumulator transfers
  - Rapid transfers between the Accumulator and Recycler