The Fermilab Antiproton Source

Keith Gollwitzer

Antiproton Source Department
Accelerator Division
Fermilab

15 December 2006

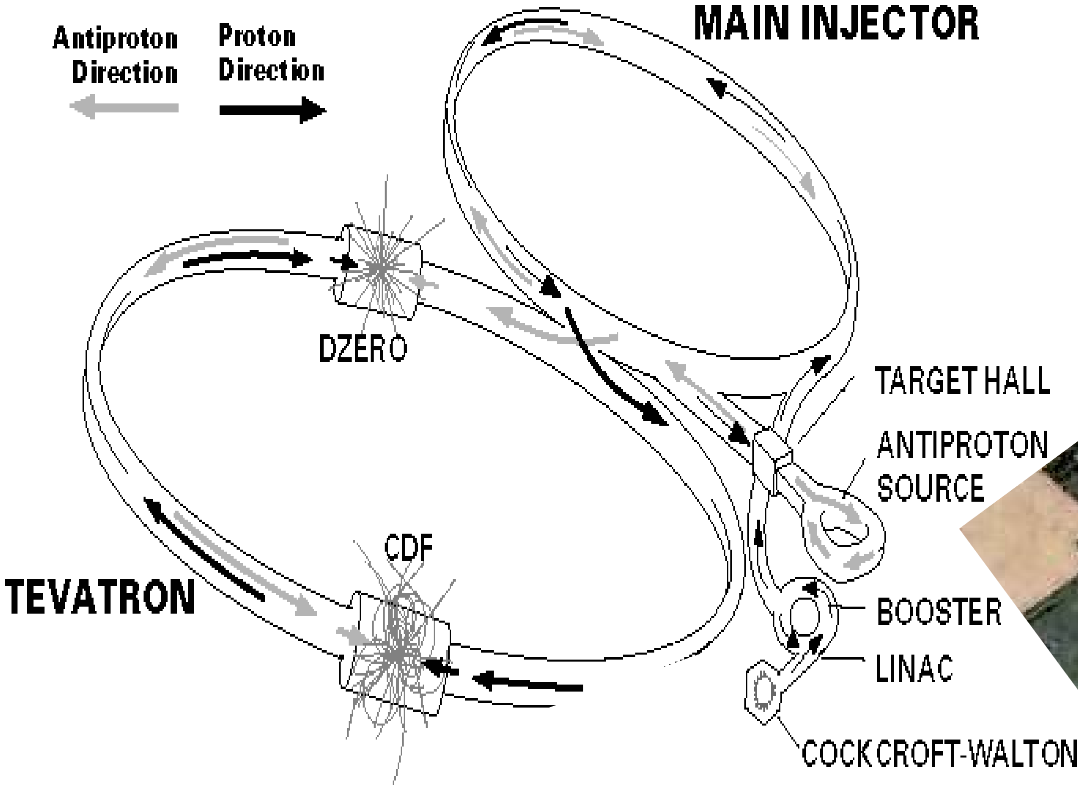
History, Disclaimers and Notes

- The Fermilab Antiproton Source was designed-built-commissioned in the early to mid 1980's
- My first interaction with Fermilab was doing the E760/E835/E862 experiments in the Antiproton Source (1989-1997)
- Became a member of the Antiproton Source Department in 1998 (while still participating in E835)
- In most cases, I know how we have made things work; but not necessarily the original concept
- Today, I will focus on recent Antiproton Source operations and changes
  - I am not the person to talk about the Recycler
- Notes:
  - Pbar == Antiproton
  - 1mA of pbars == 10^{10} pbars in the Accumulator

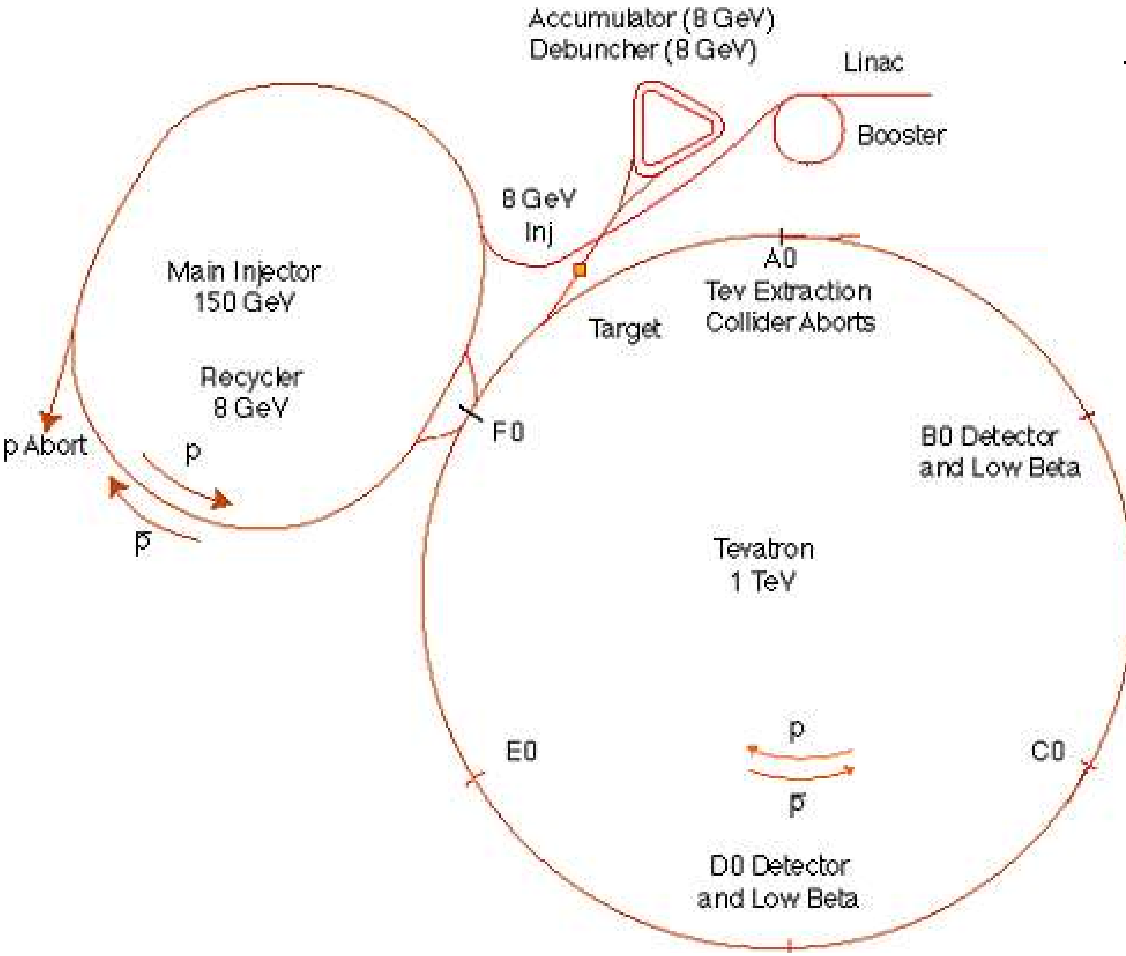
Basic Outline

- Purpose
  - Provide cold/dense pbars to collider program (via Recycler)
- Operation
  - Stacking
    - Protons on Target from Main Injector
    - Target Station
      - Target
      - Lens
      - Momentum selection
    - Transport of Secondaries
    - Debuncher
      - Bunch Rotation
      - Stochastic Cooling
    - Transfer
    - Accumulator
      - RF deceleration
      - Stochastic Cooling
        - » Stacktail
  - Unstacking
    - Cool Core
    - Capture beam
    - RF accelerate
    - Extract beam to MI
  - Reverse protons
    - Studies
      - All except cooling
      - Cheaper than pbars
- Studies
  - Year ago TeVatron failures
- Performance
- Current Focus

Fermilab Overview



Fermilab Overview

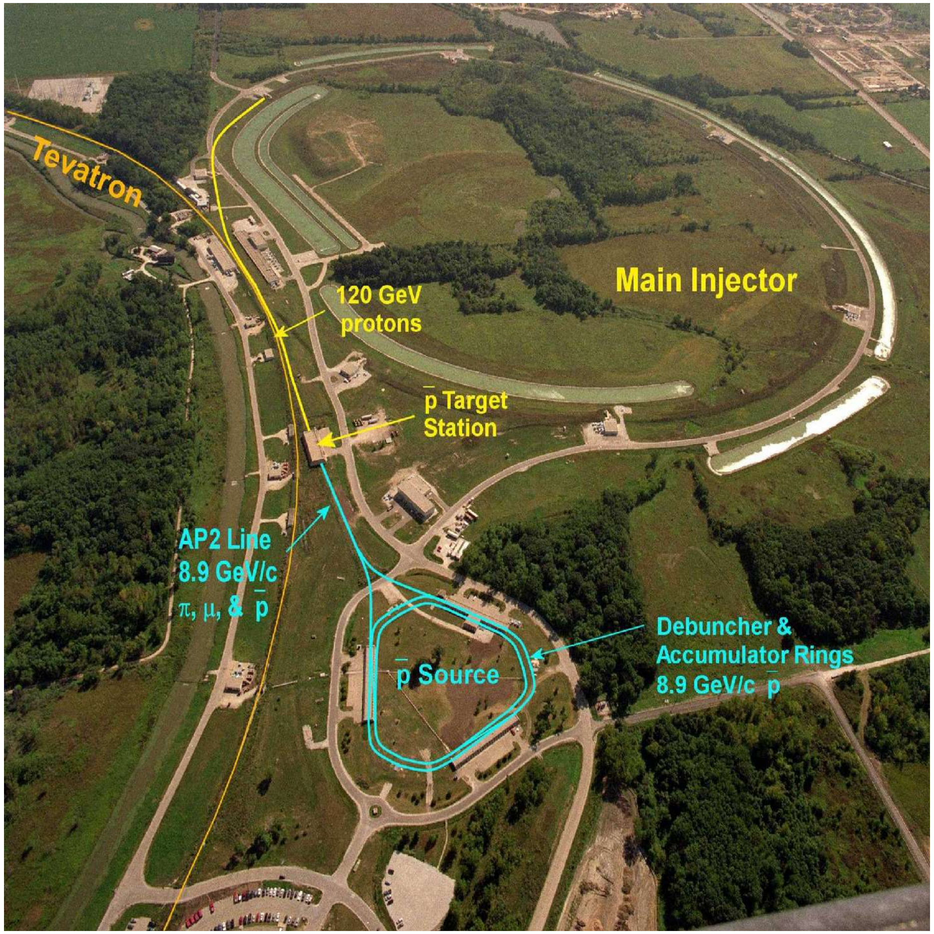


Accelerator	Highest Energy
Cockroft Walton	750 keV
Linac	400 MeV
Booster Debuncher Accumulator Recycler	8 GeV
Main Injector	150 GeV
TEVATRON	980 GeV

Antiprotons at Fermilab

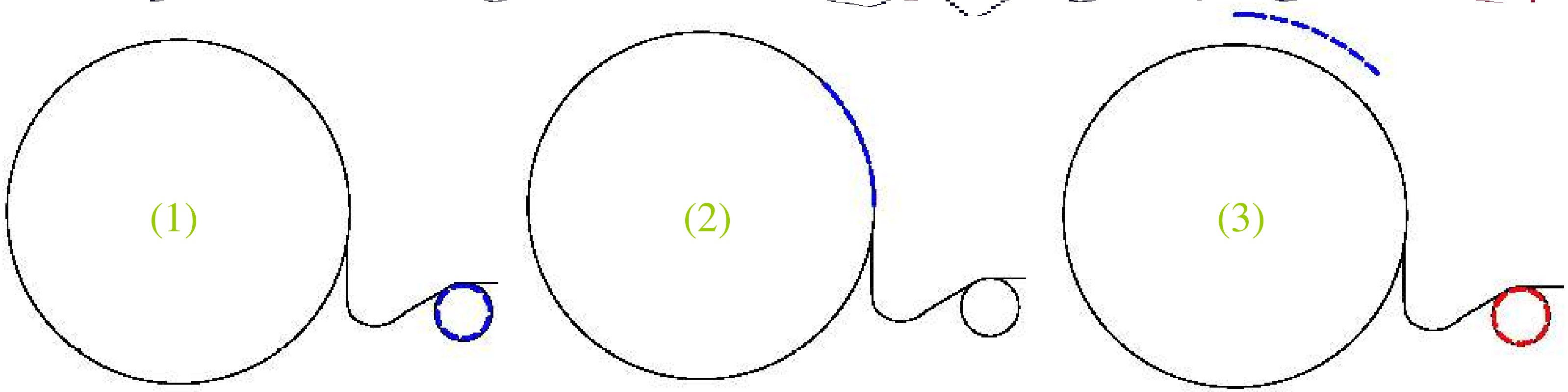
- Collider Operations
  - Prior to 2005, stack 60-200x10^{10} pbars and then transfer to TeVatron (via Main Ring/Injector) for acceleration with protons and then beams brought into collision.
  - Since Oct 2005, stack 50-100x10^{10} pbars and then transfer to Recycler Ring (where up to 100x10^{10} pbars are collected before injection into the TeVatron)
  - Tradeoff: stacking rate and maximum stack size
- Other Experiments
  - Decelerate to Charmonia formation energies
    - Not easy to decelerate due to stacking done with magnets in saturation for stability.

Protons on Target

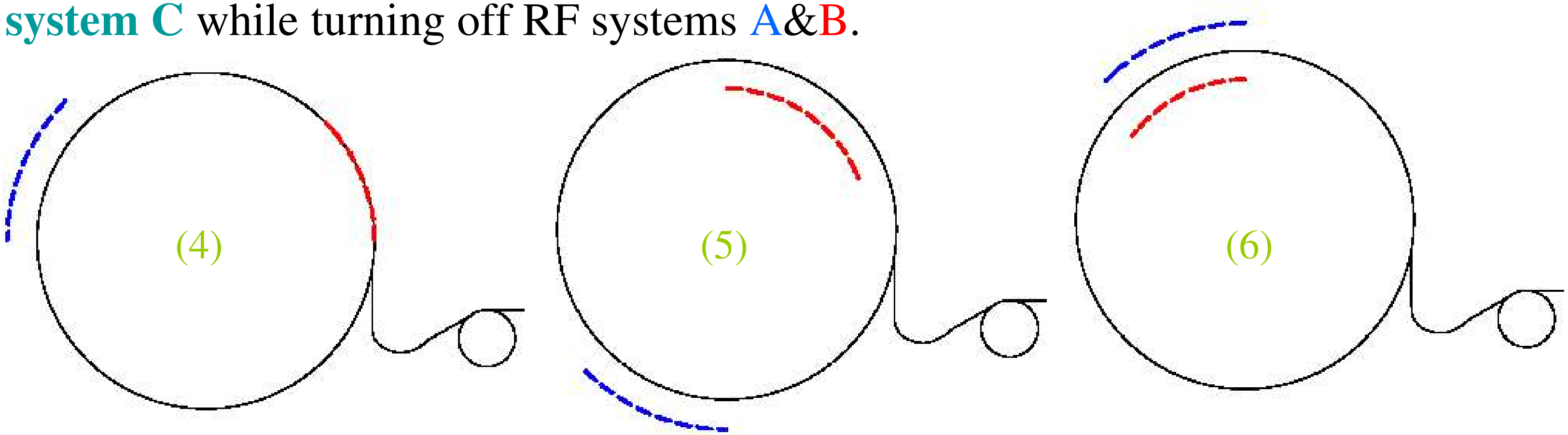


- 81 Bunches at 53MHz per Booster batch
- 2 Batches are Slip Stacked in the Main Injector

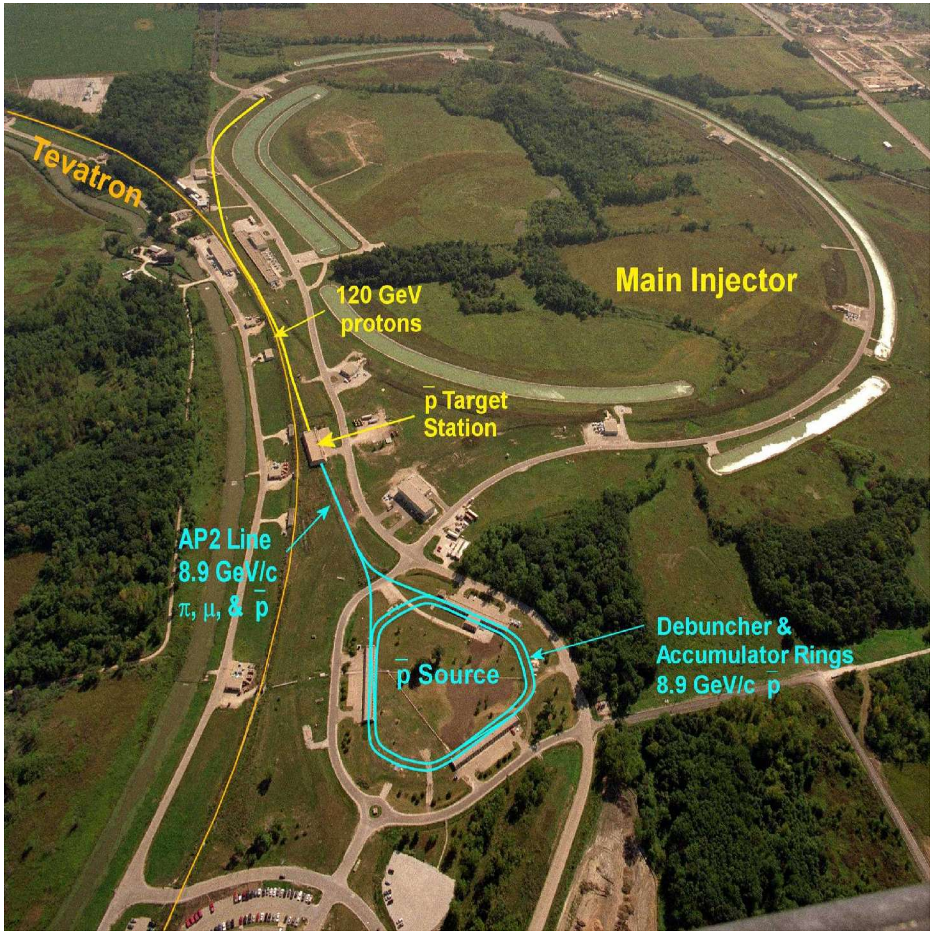
Slip Stacking Cartoon



(1) Booster batch 1. (2) Batch 1 in MI. (3) RF system A accelerates beam while Booster batch 2 is prepared. (4) Inject batch 2 into MI. (5) Decelerate batch 2 with RF system B. (6) Allow batches to ***slip*** until lined up; capture both batches with **RF system C** while turning off RF systems A&B.

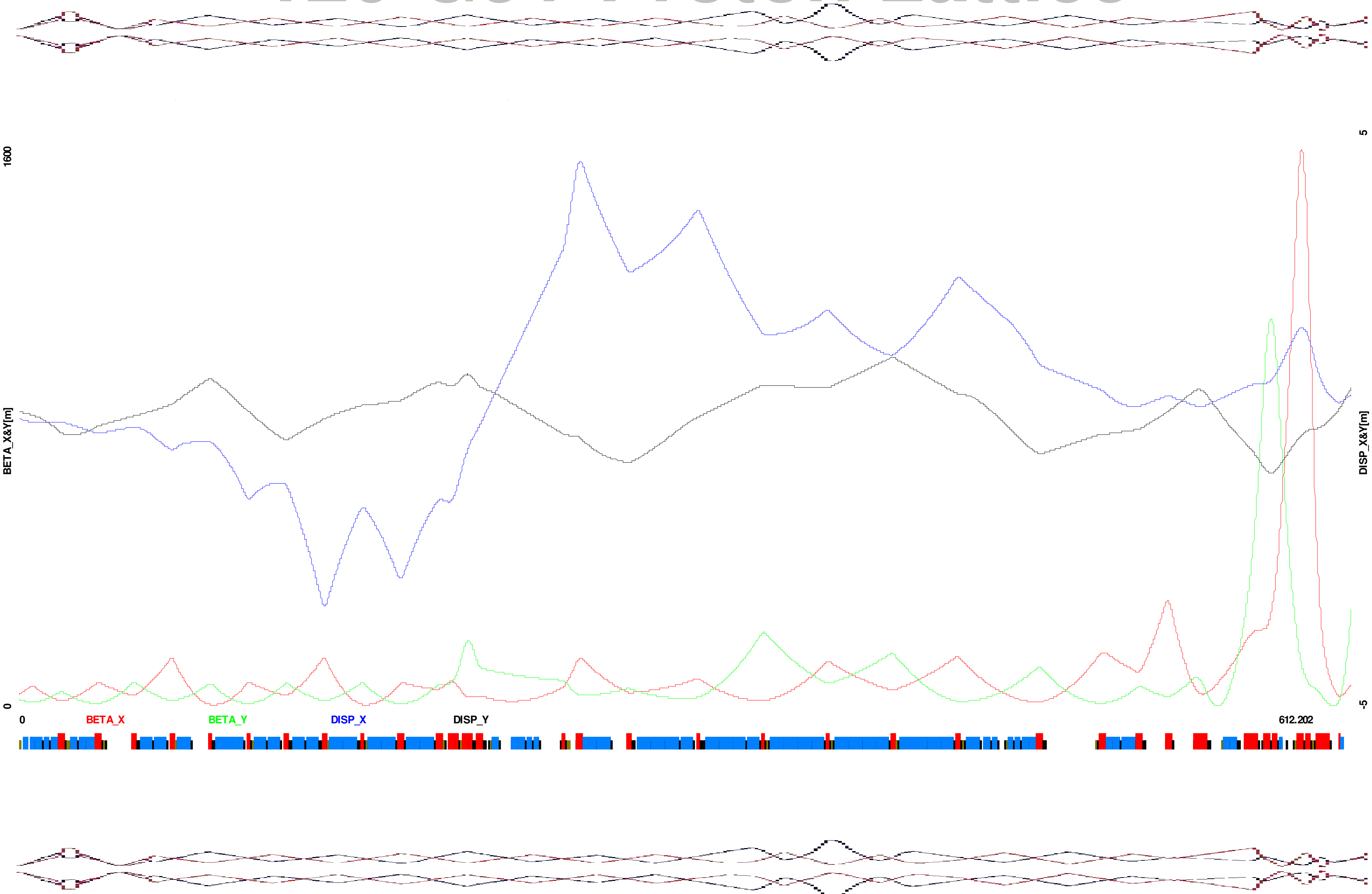


Protons on Target



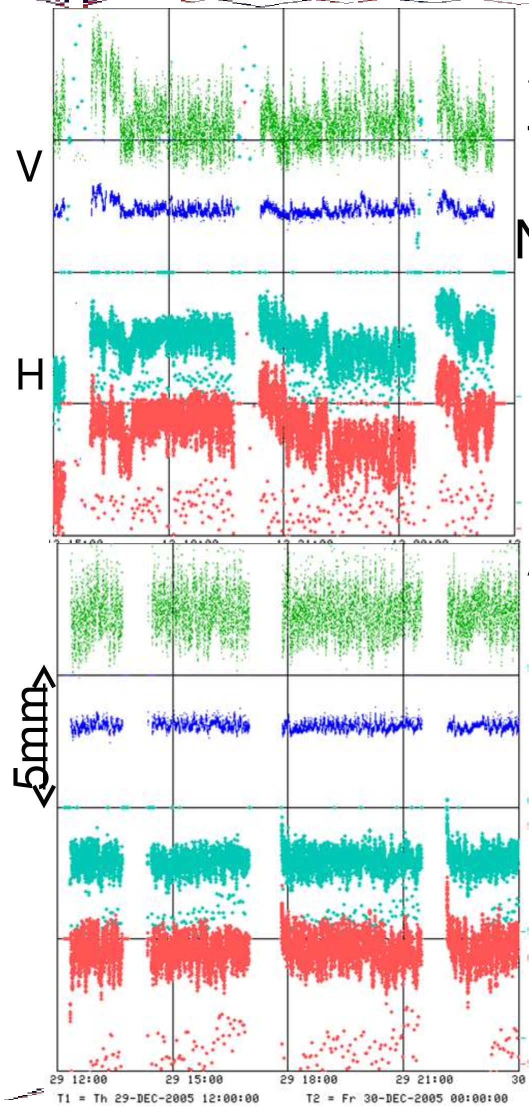
- 81 Bunches at 53MHz per Booster batch
- 2 Batches are Slip Stacked in the Main Injector
- Accelerate to 120 GeV
- Bunch Rotate in Main Injector to reduce bunch length to ~2ns
- Extract into ~600m beam line to target

120 GeV Proton Lattice



Orbit Control

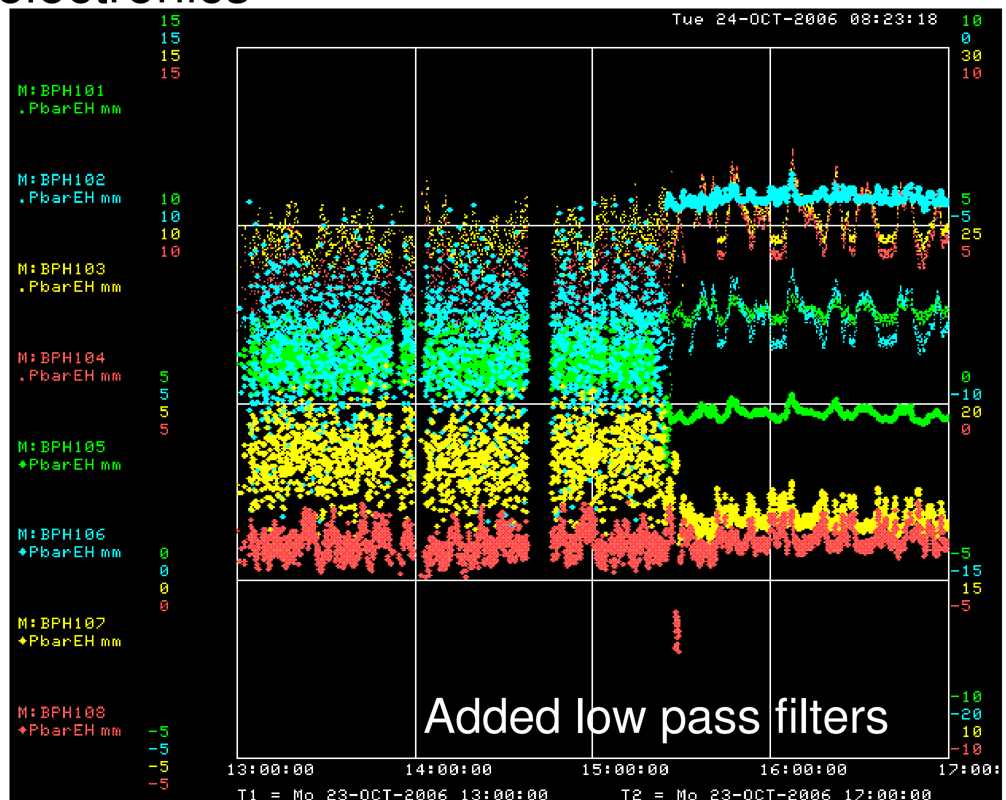
Autotune/Feedback has been implemented to compensate for power supply drift.



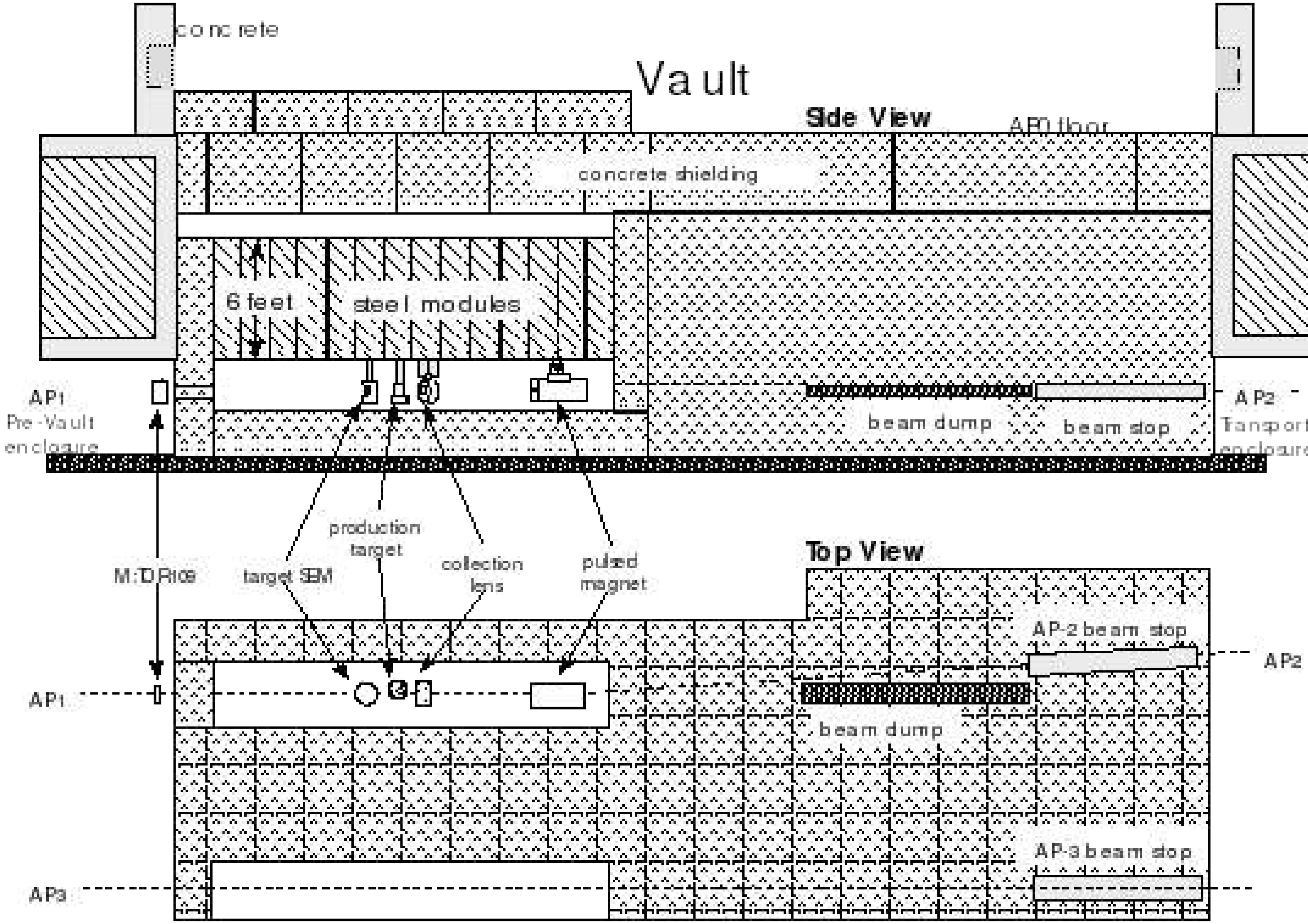
Before

After

New BPM electronics

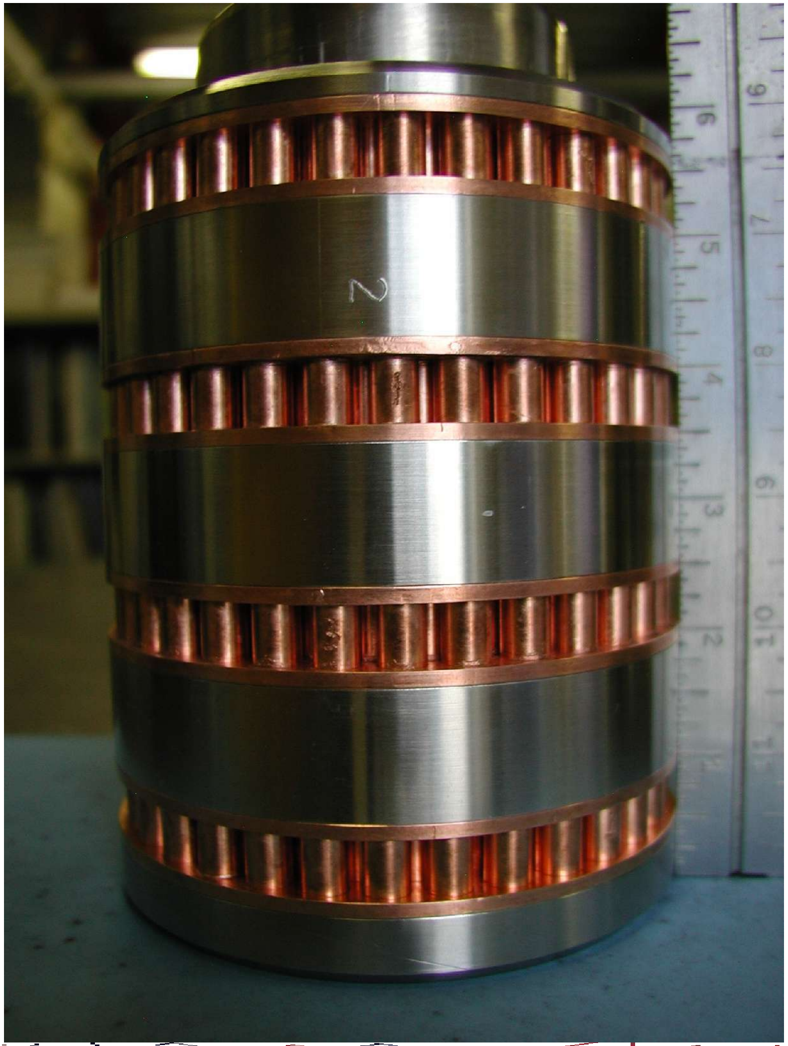


Target Station

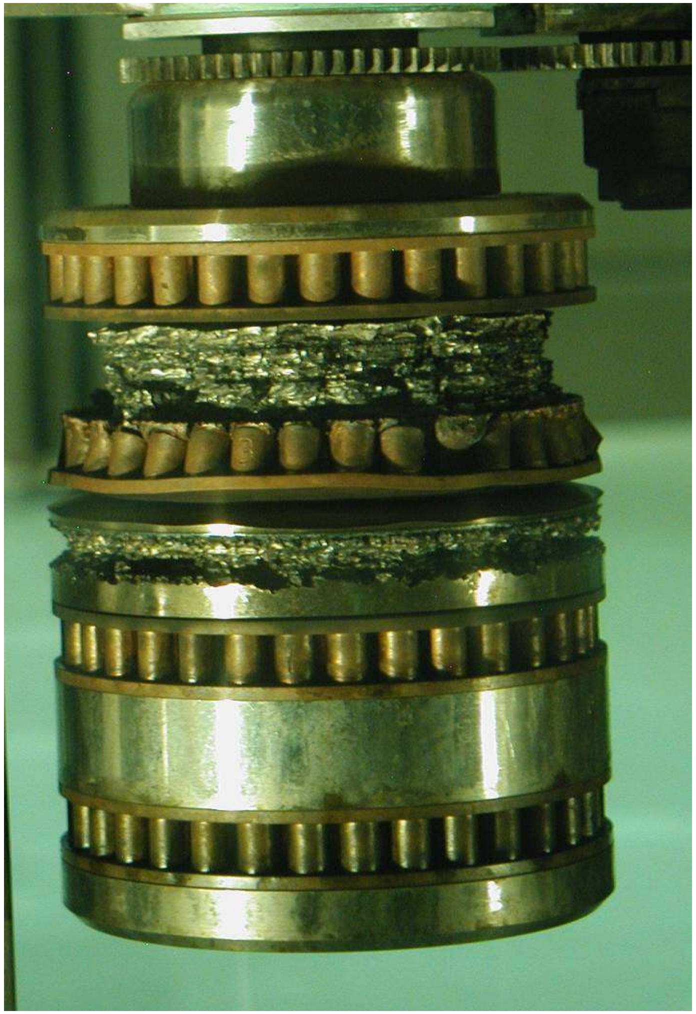


Production Target

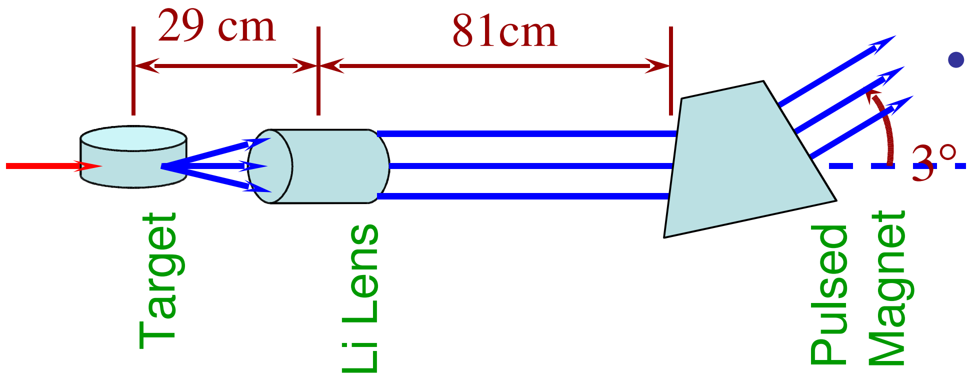
- Shown is the latest target design
  - Nickel alloy
  - Copper heat sink with air cooling
- Beam hits off center of cylinder
- Beam optics are set to minimize beam size but not cause single pulse damage of target
  - ~200 microns
- Cylinder rotates every production cycle to allow for cooling
  - Several pulses on same chord causes production degradation
- Target moved vertically to sample different (parts of) disks
  - Once a week after yield decreases~5%
- Target moves horizontally to lengthen chord once depletion occurs

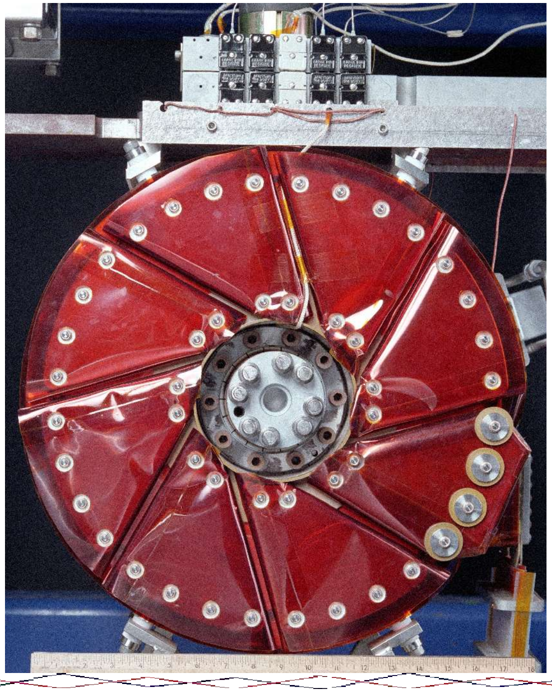


Targets are Consumables



Collection Lens

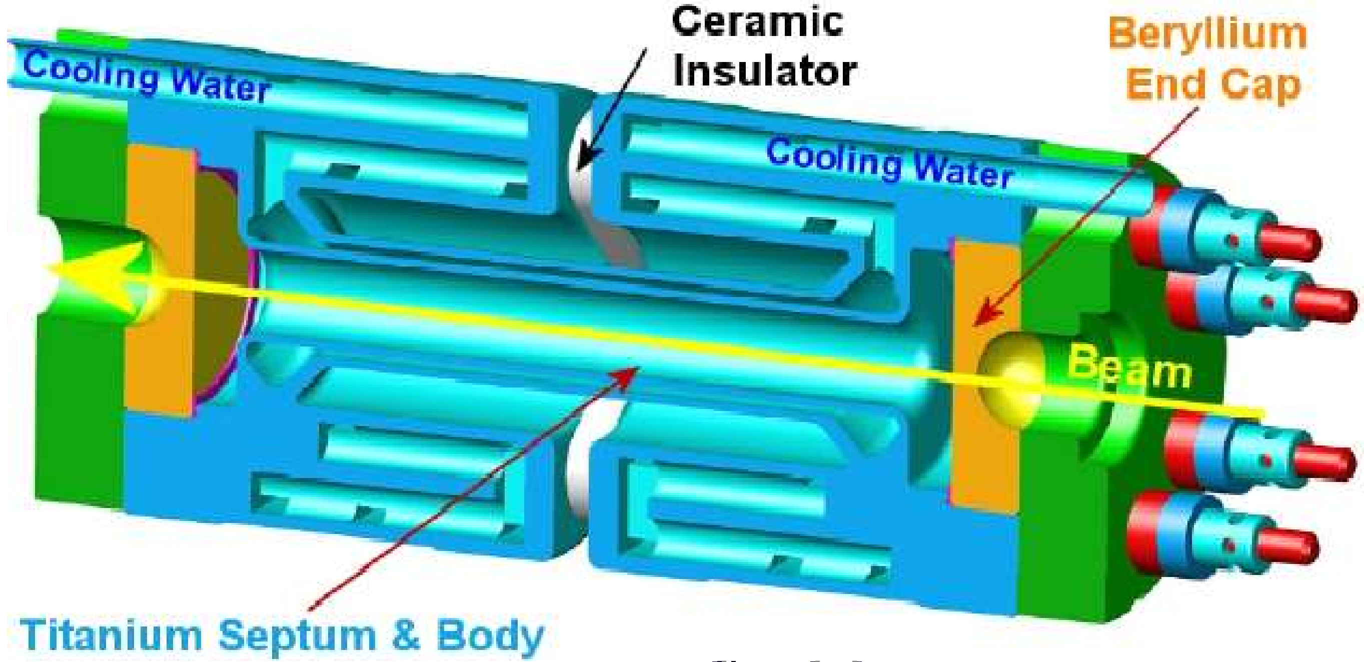




- Solid Lithium
  - Cylinder
    - 1cm radius
    - 15cm long
      - Optimized for multiple scattering
  - Current flows in beam direction
    - Axial Focusing
- Lifetime vs Production time
  - Typically last 4-9x10^6 pulses
    - Gradient also determines lifetime
  - Production takes >4months

Upgraded Lens Design

- Change of production process
  - Stainless Steel to Titanium
  - Electron welding to diffusion bonded
- Most failures are lithium getting into cooling water
  - Weaken welds seen doing autopsies on old failures

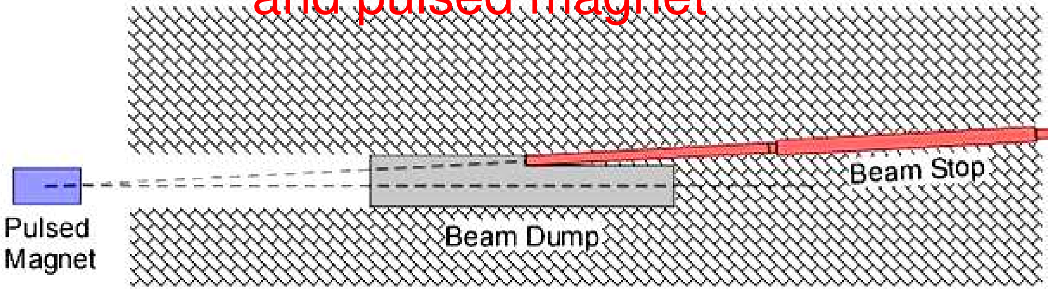


Upgrade Lens in Operation

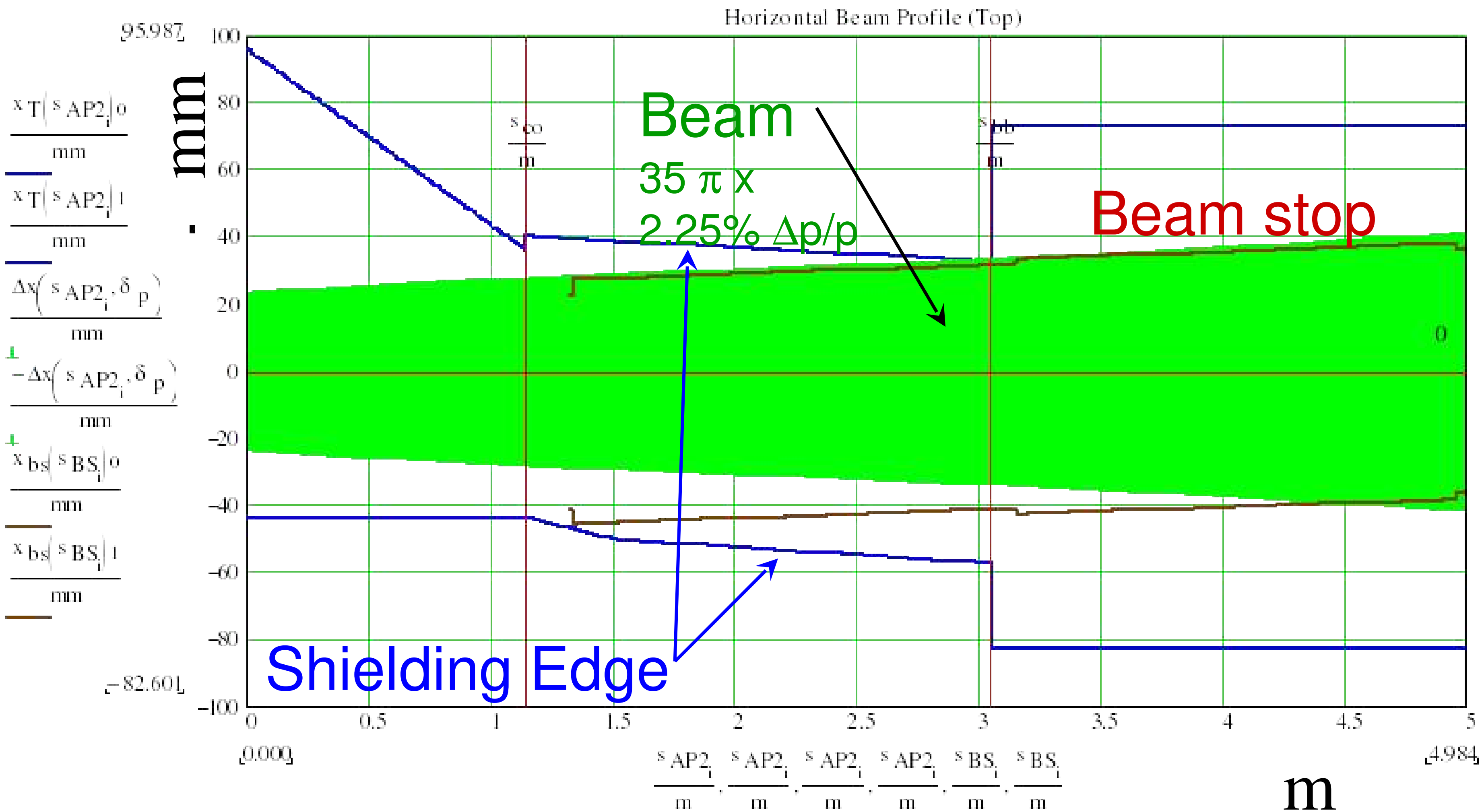
- Prototype lens of 8mm radius was made, pulsed and put into operation
  - 2million pulses before lens overheated
    - Partially caused by high gradient and short focal length needed to compensate for smaller radius
      - Target was adjusted longitudinally for minimum separation of target station modules (focal length)
      - Proton beam size became too small causing target material to be sputtered onto lens/transformer
- First 1cm lens in operation since October
  - Started at old gradient (640T/m)
  - This month, start increasing the gradient in steps
    - 700T/m had a ~3% increase in yield
    - 50T/m steps up to 850T/m
  - Goal is higher gradient and to last 10million pulses

Pulsed Magnet

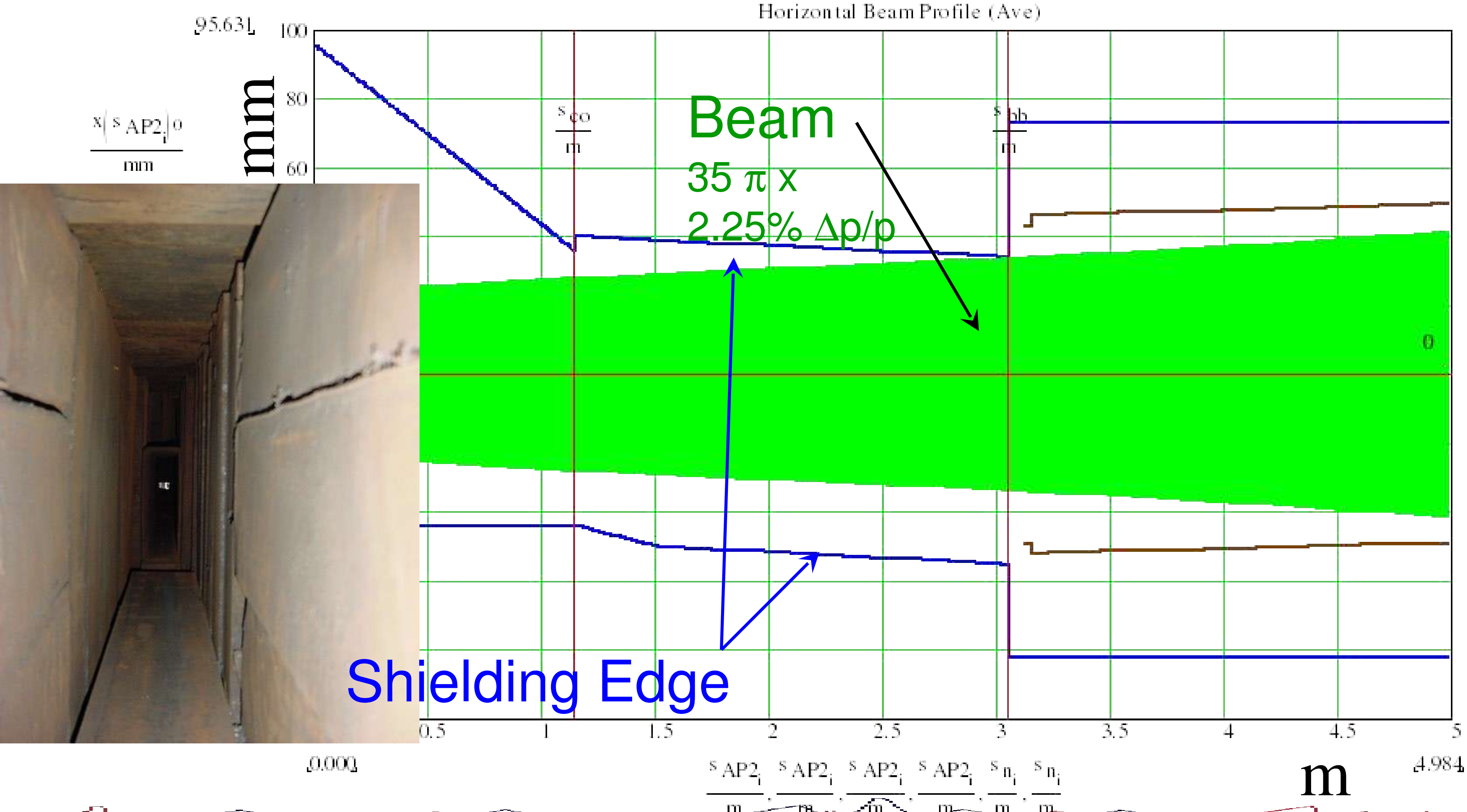
- Pulsed Magnet sends 8GeV negative secondaries into transport line
  - Must allow non-interacted 120GeV proton beam through to beam dump
  - Must survive in environment of secondary spray
    - Collimator added between lens and pulsed magnet



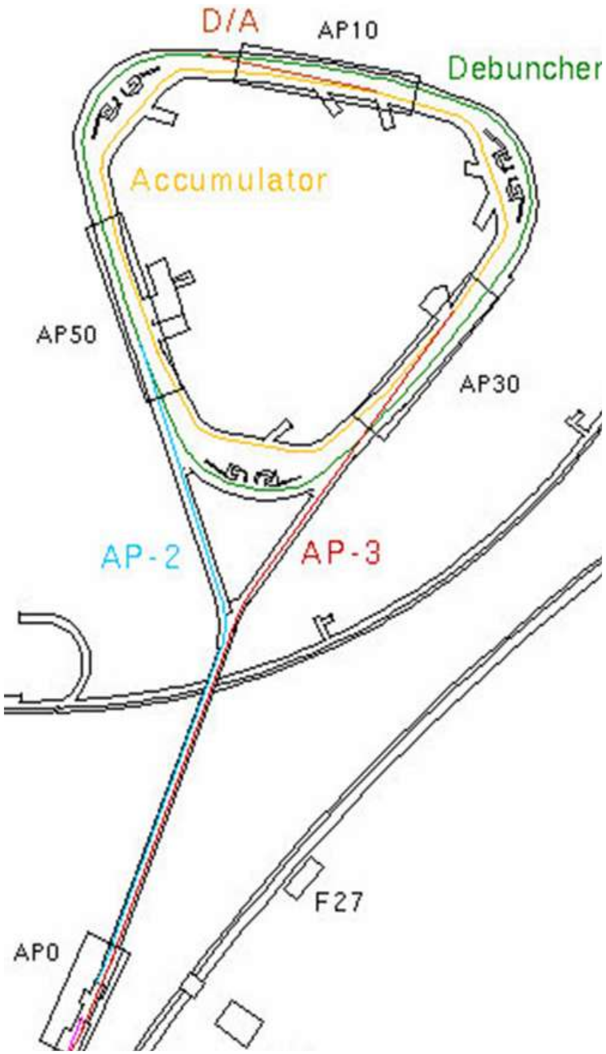
Mis-Alignment of Beam Stop & Pipe with Shielding



Relocation of Beam Stop and New Beam Pipe

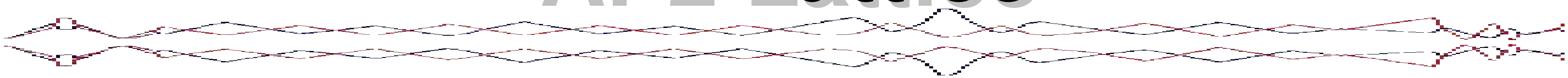


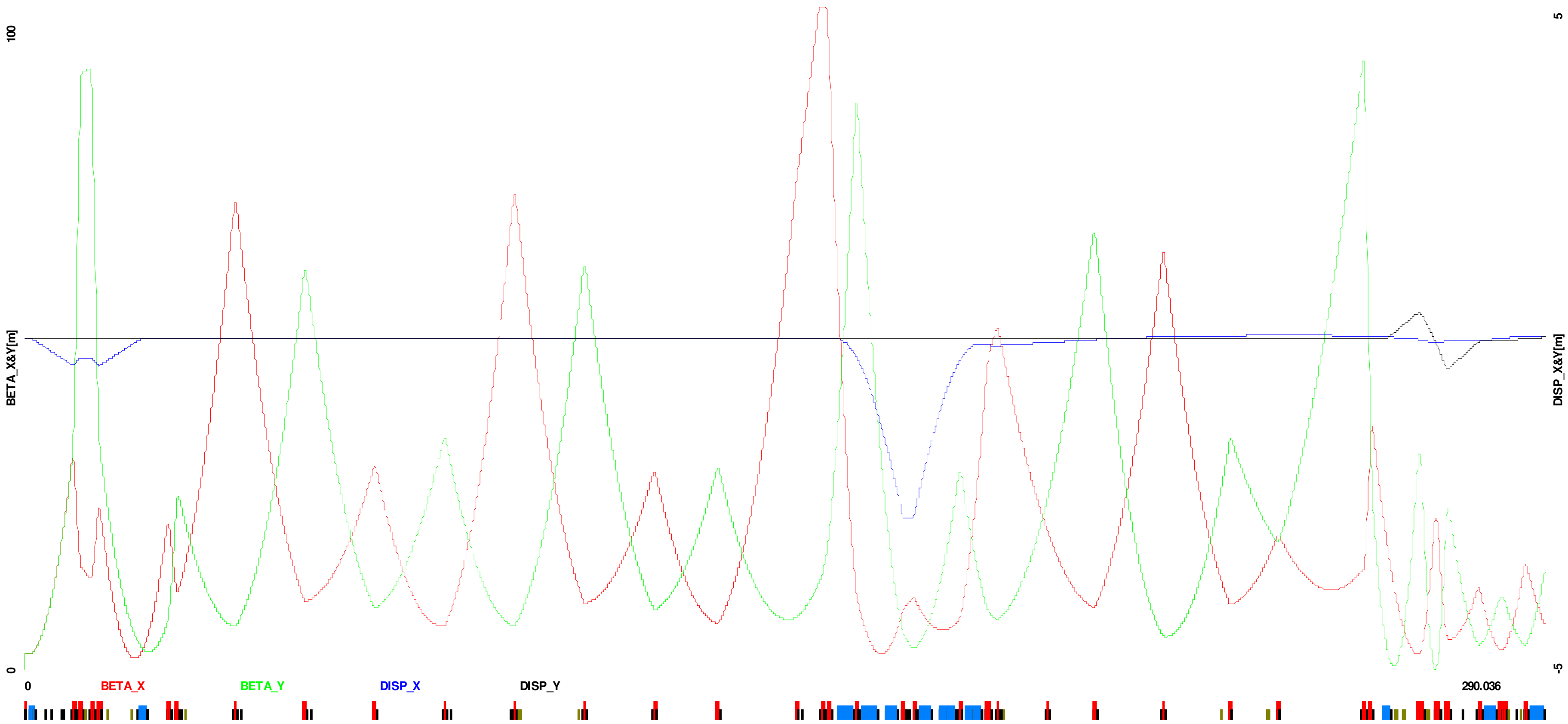
Transport of 8GeV Secondaries

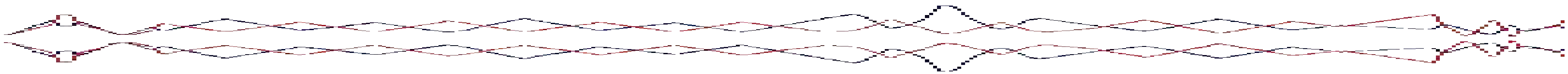


- AP2 transports secondaries to Debuncher
  - Designed admittance >35π mm-mrad
    - Accepted beam emittance: >330π mm-mrad
  - “Left bend” momentum selects ~5%
  - ~1% of the secondaries are antiprotons at the end of AP2
  - Recent upgrade of BPM electronics to allow measurements of beam
    - Orbit work is on-going

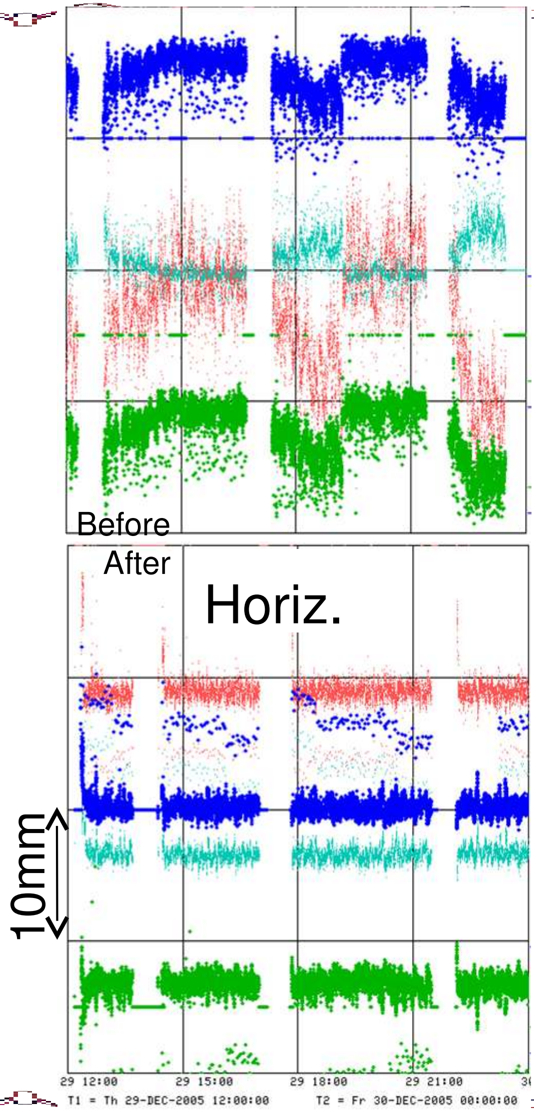
AP2 Lattice





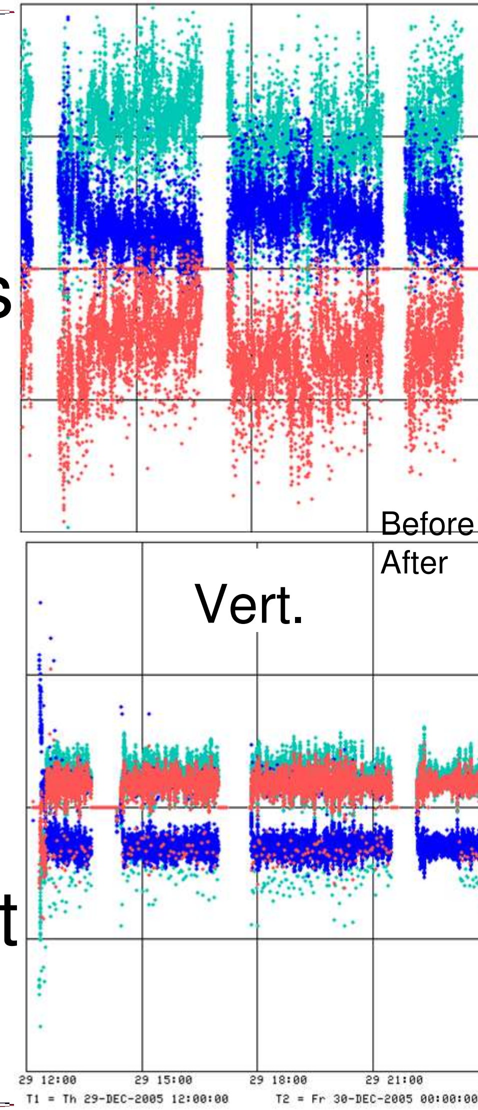


AP2 Orbit Control



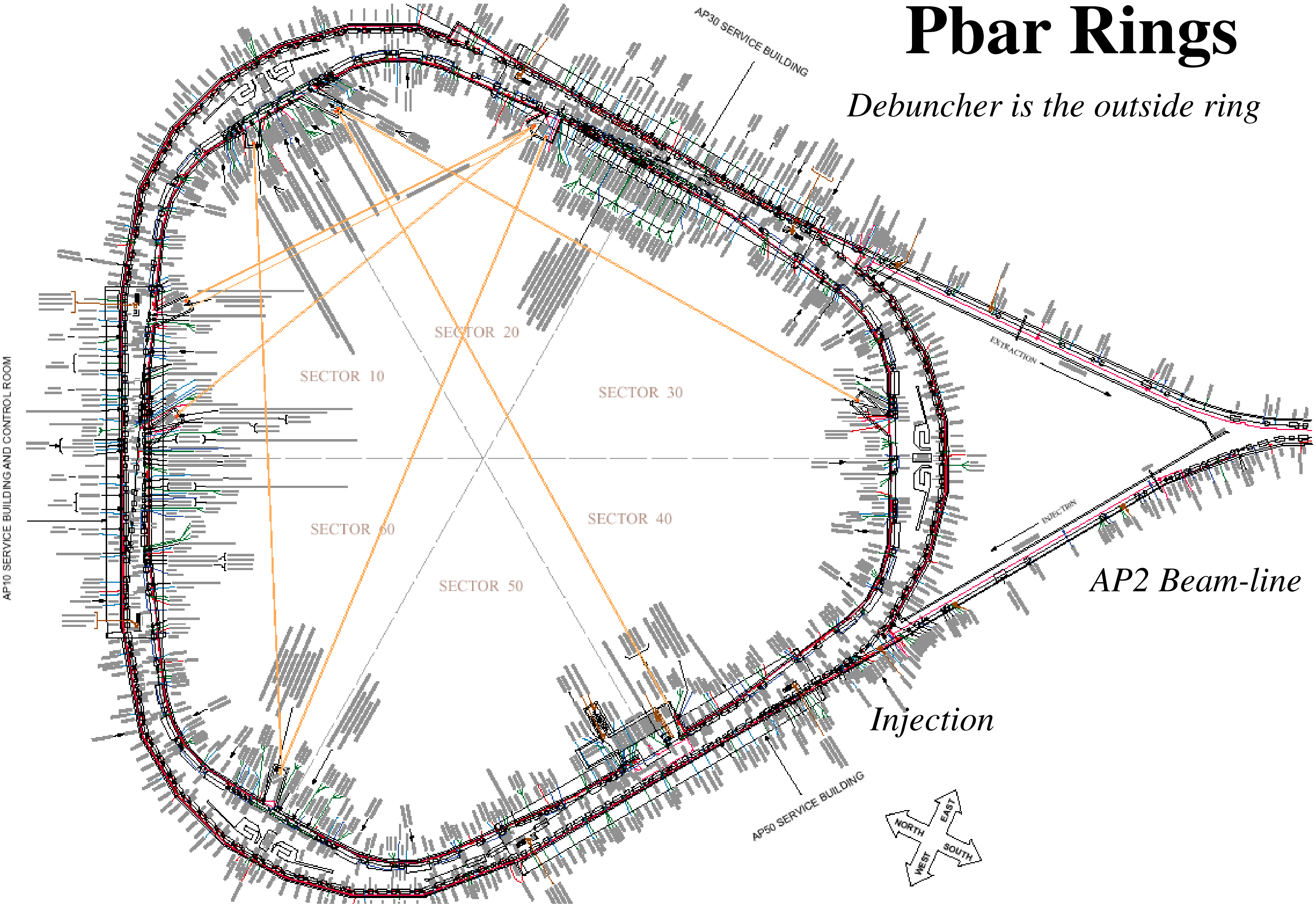
Autotune/Feedback has been implemented on this beam line as well.

Compensation for power supply drift and thermal effects of the pulsed devices of the target station



Pbar Rings

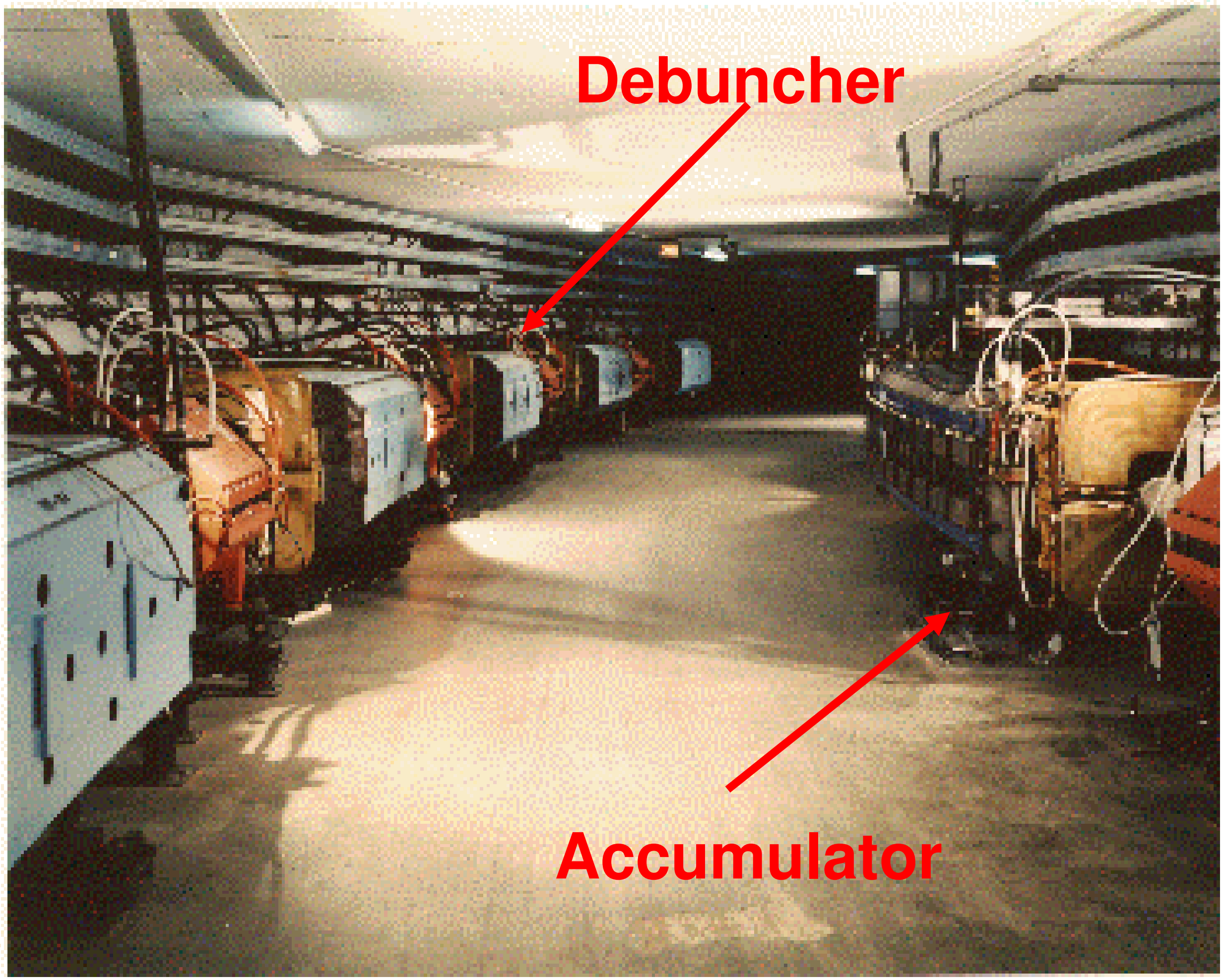
Debuncher is the outside ring



AP2 Beam-line

Injection

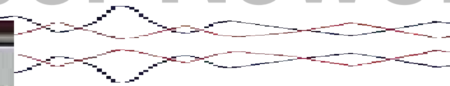
Antiproton Source Storage Rings

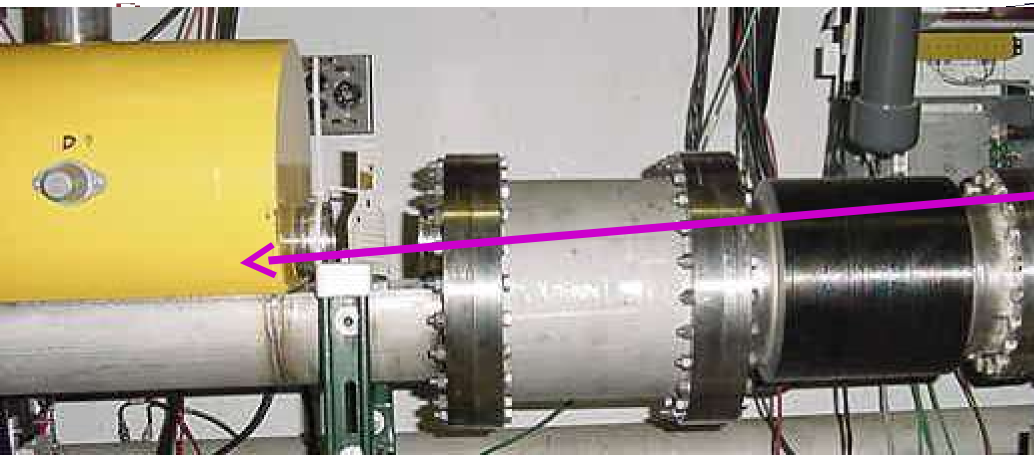


Debuncher First Turns

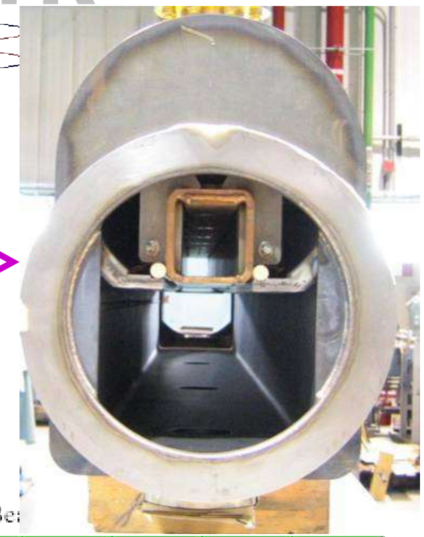
- Arriving Secondaries are $\Delta p/p = \pm 2.25\%$
  - Pions and muons decay within ~30 turns
  - Electrons do not survive first turn
- Designed admittance is 35π mm-mrad
  - Required removing limiting apertures
    - Transverse Schottkys
      - Now use Damper plates and Stochastic Cooling pickups to perform measurements
  - Rework of beam tubes
    - Injection Septum
    - Replaced single small quad with two large aperture quads in injection region
    - Extraction Kicker
  - Added motorized stands
    - Center components about beam
      - Kickers, septa, pickups
    - Use quadrupoles for orbit steering
      - 30% of quads available to correct orbit
- Bunch Rotation in 50 turns reduces the momentum spread

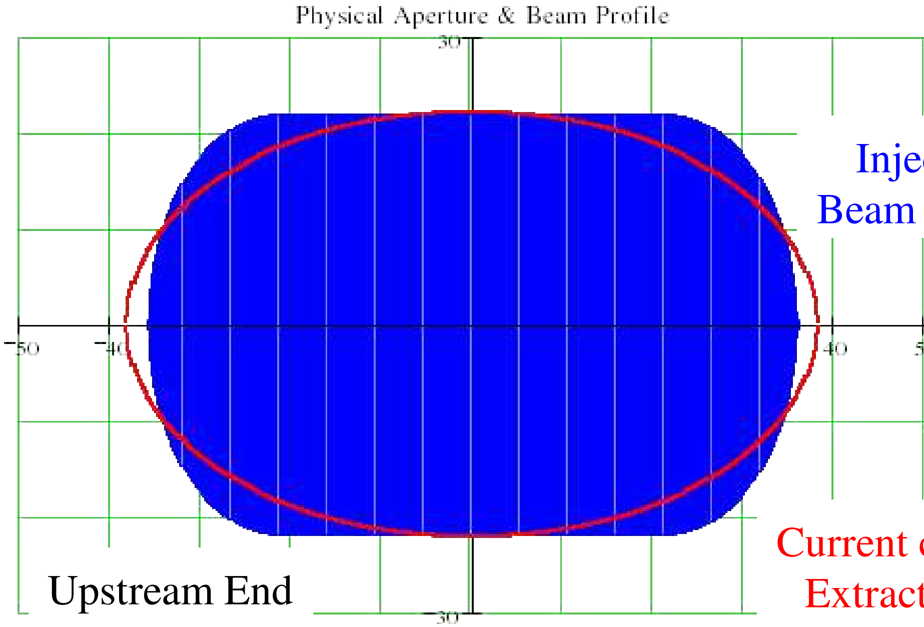
Beam Chamber Rework



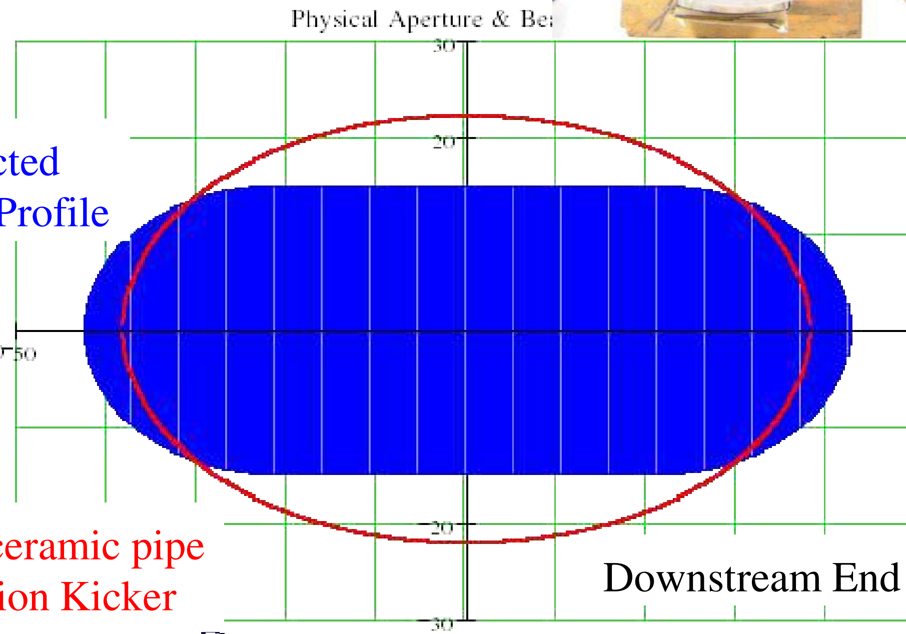


Injection Septum
Before
After





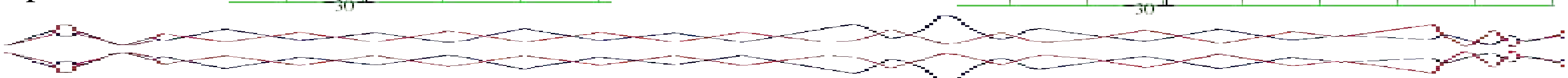
Injected
Beam Profile



Upstream End

Current ceramic pipe
Extraction Kicker

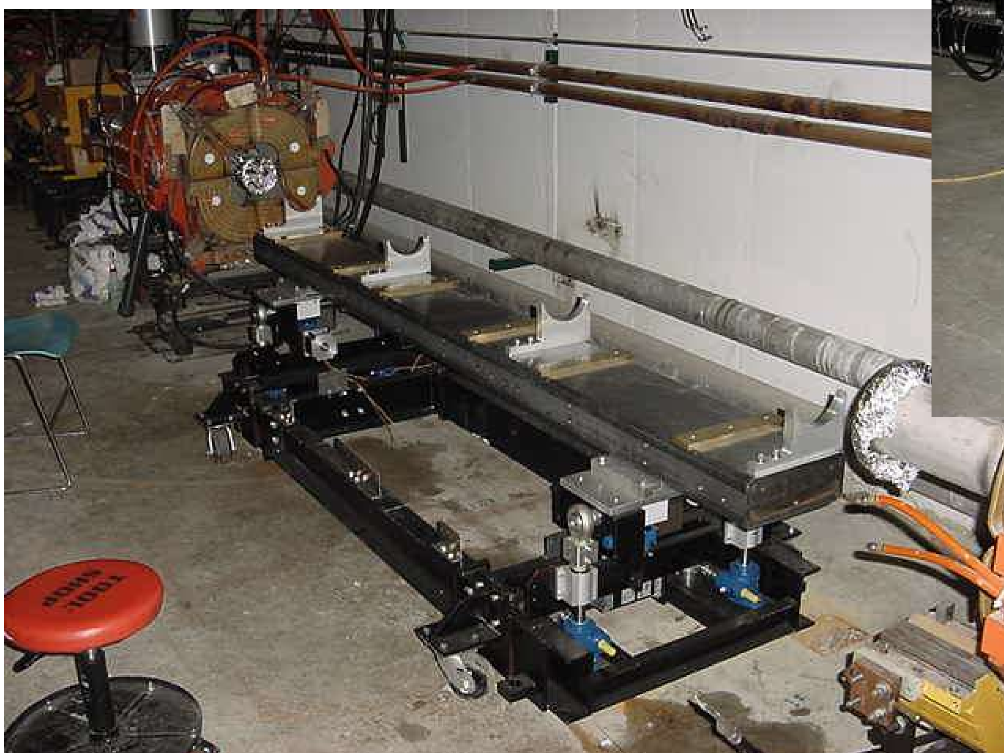
Downstream End



Motorized Stands

Stochastic Cooling Tank

Quadrupole for
orbit correction

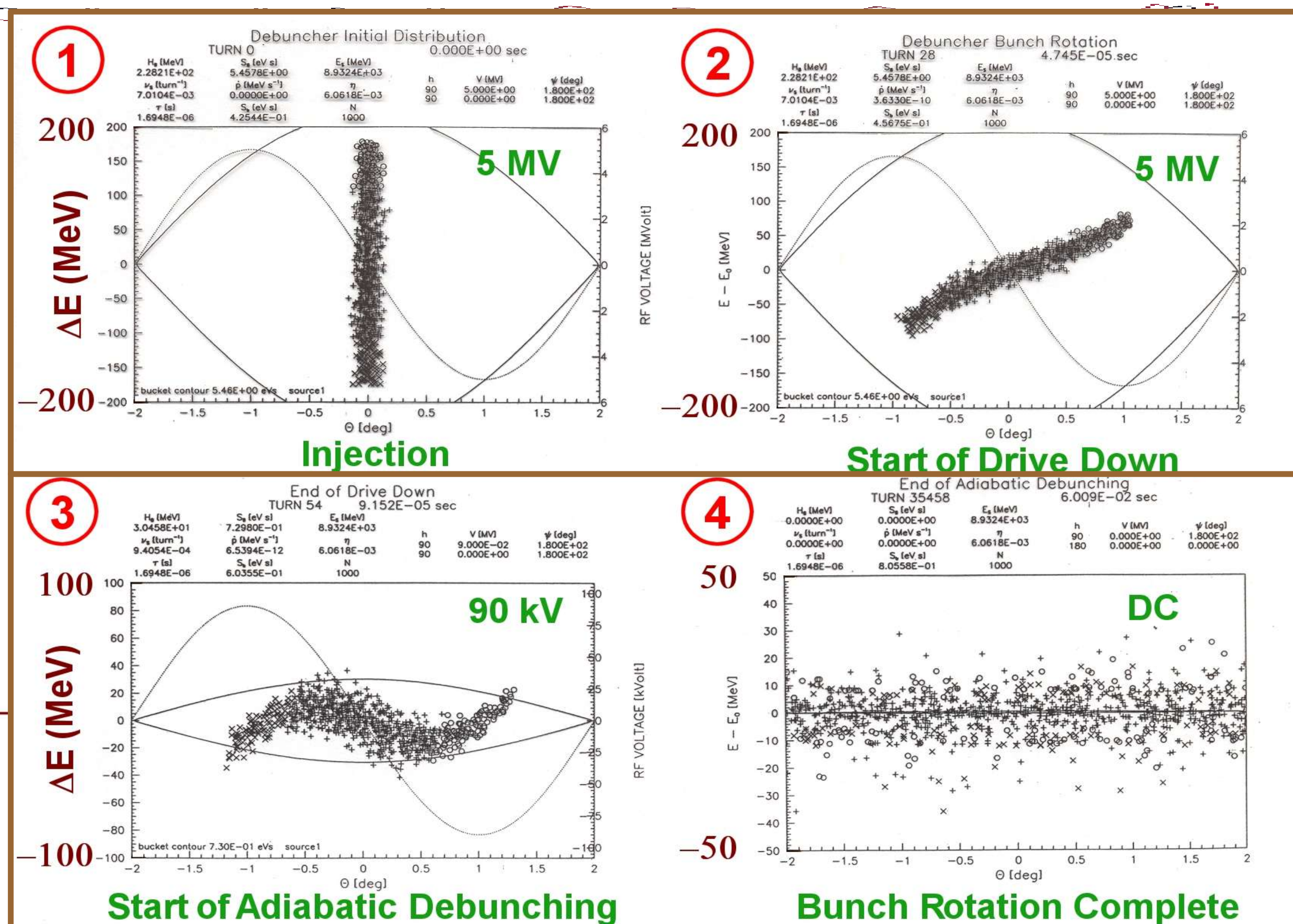


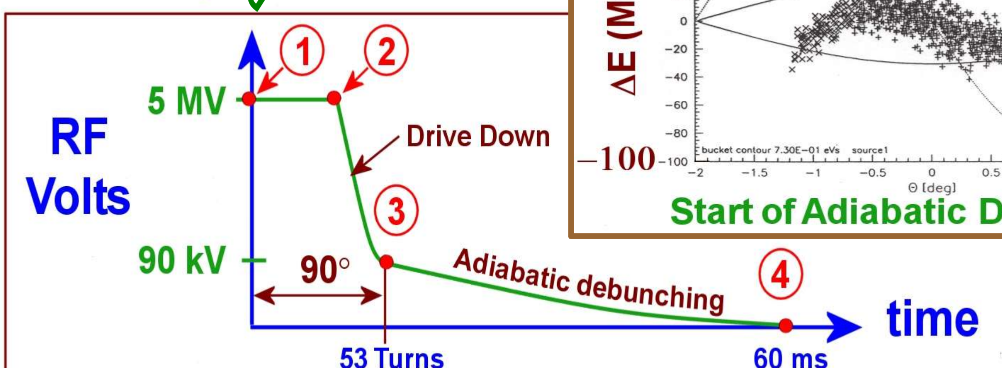
Extraction Kicker

Bunch Rotation

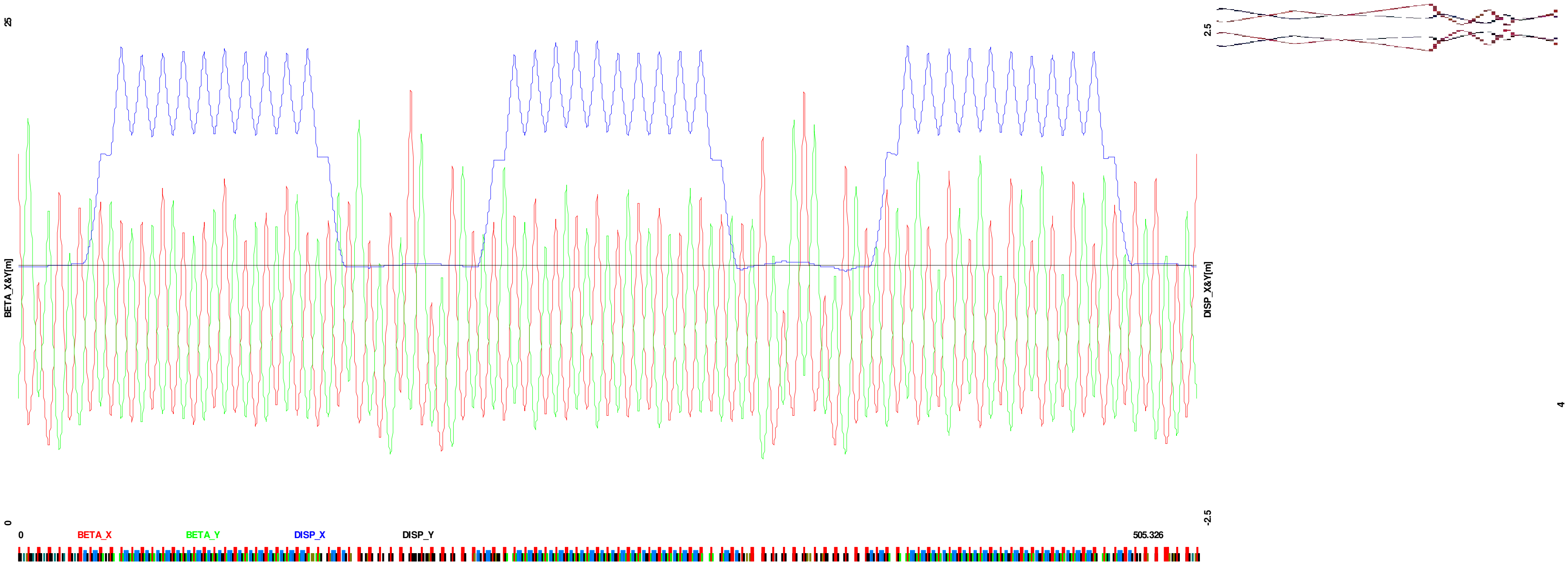
6 Cavities for Drive Down

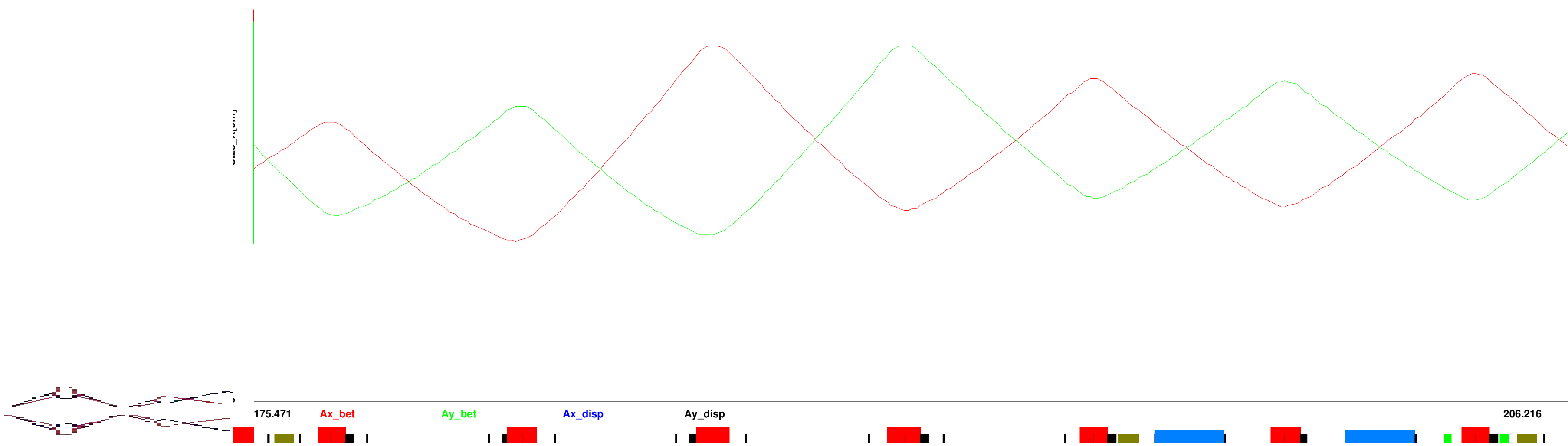
2 Adiabatic cavities





Debuncher Lattice

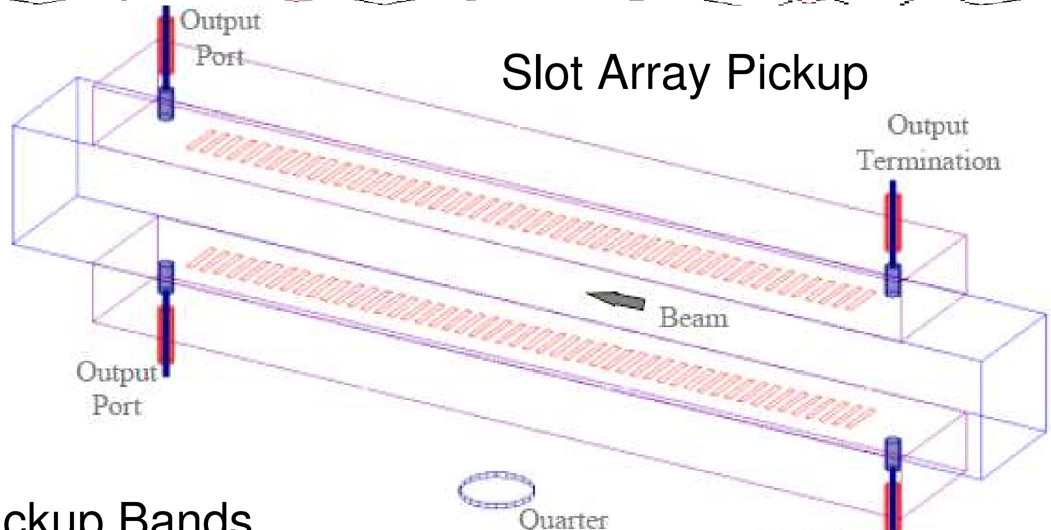




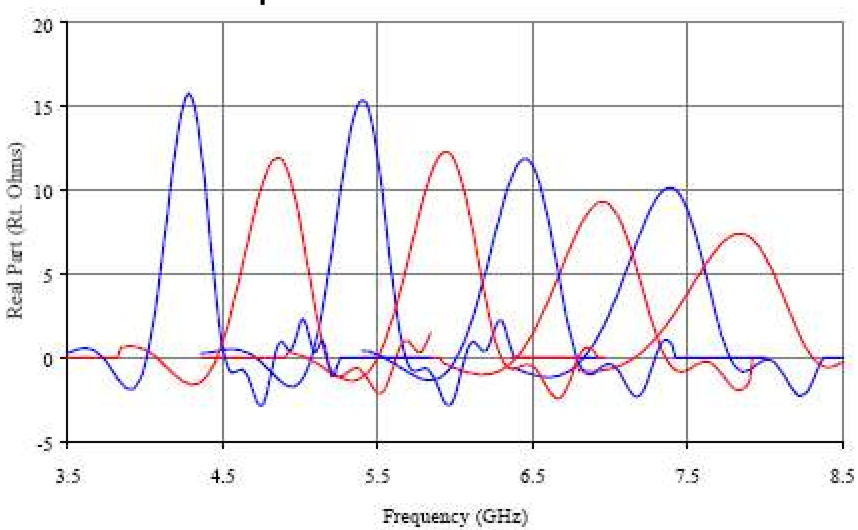
Debuncher Cooling

- 4-8 GHz of Bandwidth
  - 8 Narrowband Pickup channels
  - 4 Narrowband Kicker Channels
- Physical front end temperature = 10K
  - Front end microwave noise temperature ~ 30K
- Pickup and kicker antenna arrays
  - Fixed 35 π mm-mrad, slot coupled, slow wave, waveguide arrays
    - Pickups are narrowband (<1GHz) tuned to separate frequencies
- Kicker Power
  - Transverse - 4 TWT's per kicker band at 150 Watts/ TWT
  - Momentum - 8 TWT's per kicker band at 150 Watts/ TWT
  - Total Power = 9600 Watts
- Phase Space reduction in 2seconds
  - Factor of 10 in longitudinal phase space
  - Factor of 7-10 in both transverse phase space dimensions

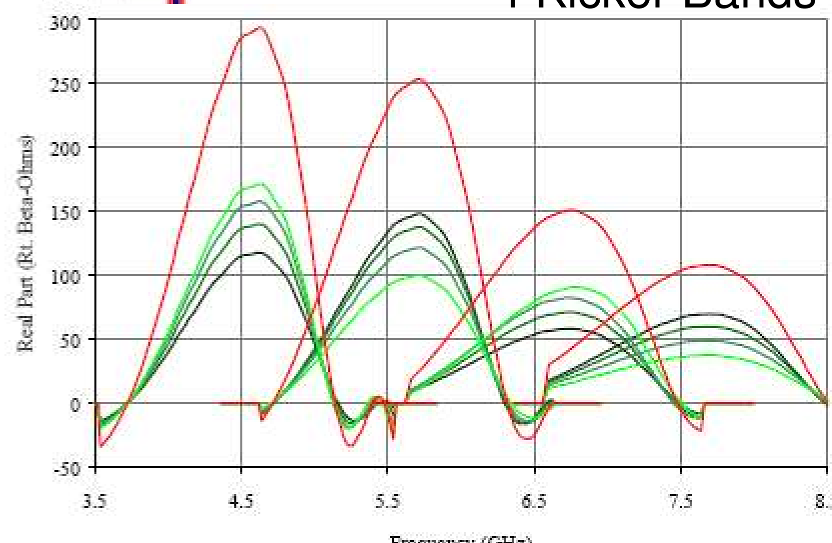
Debuncher Cooling



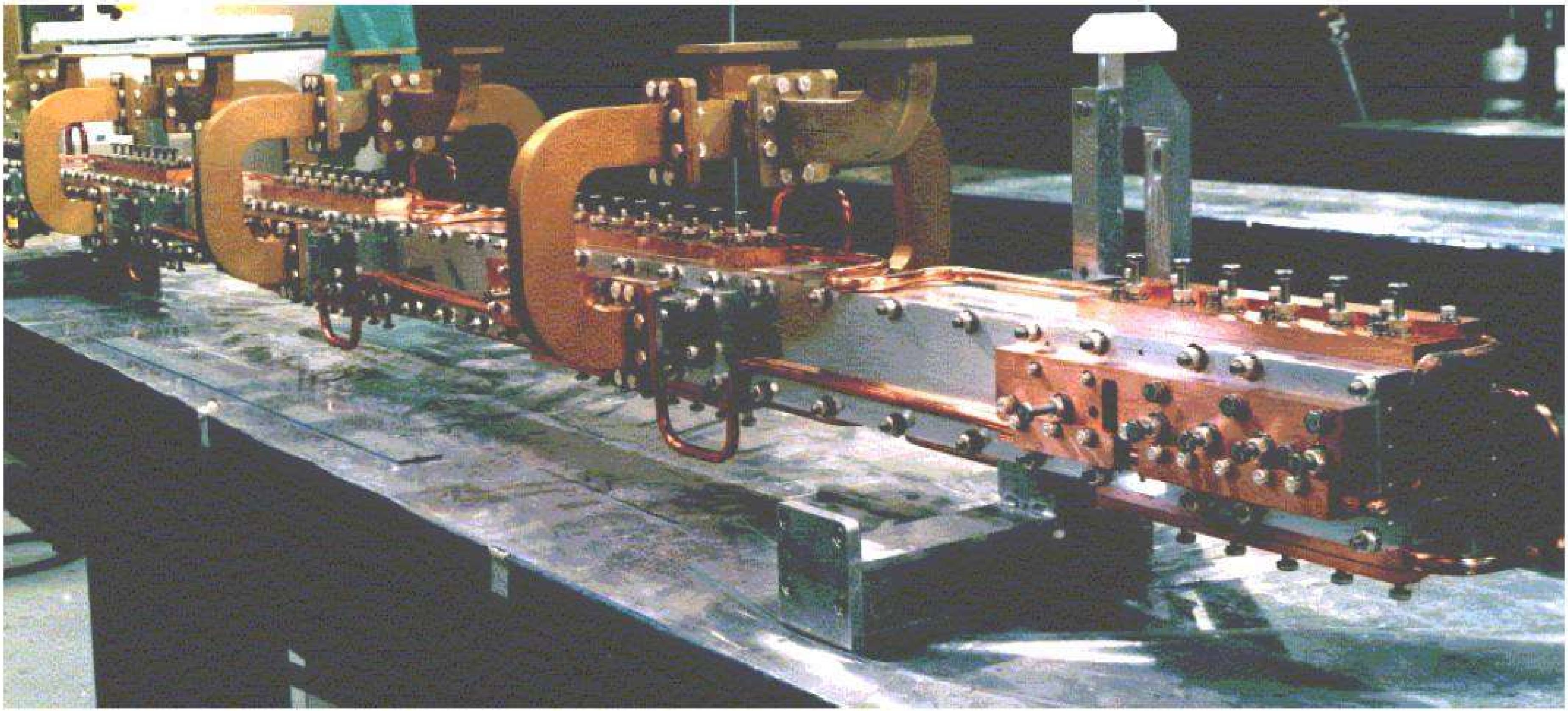
8 Pickup Bands



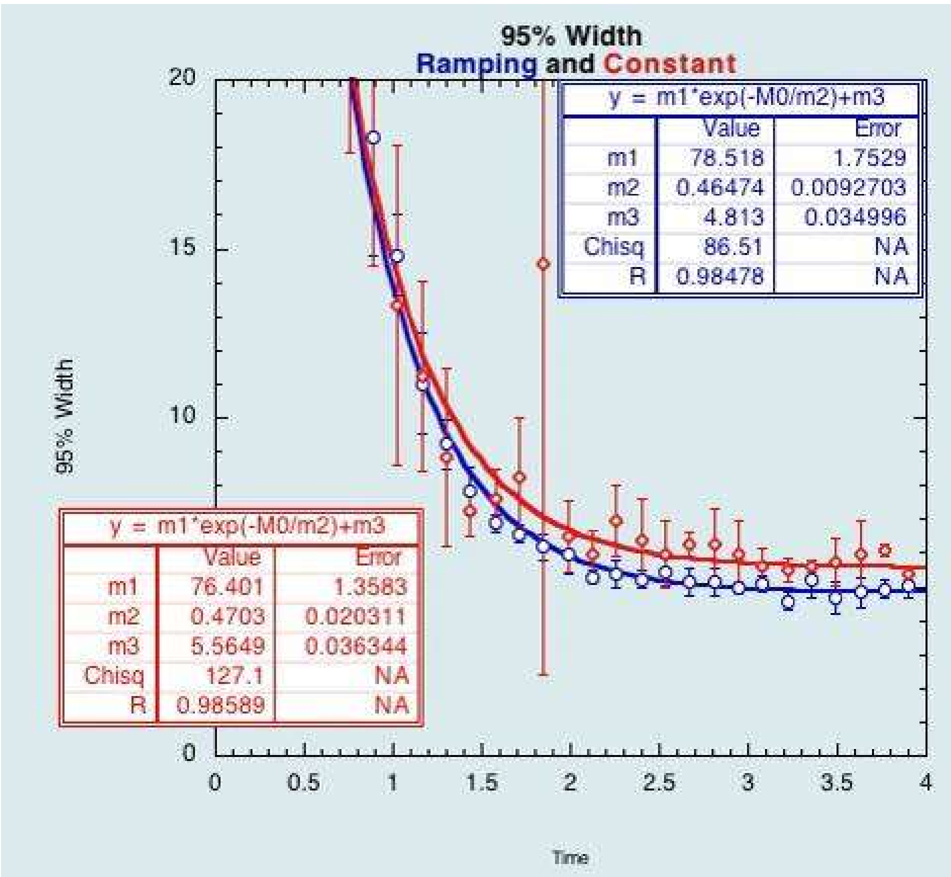
4 Kicker Bands



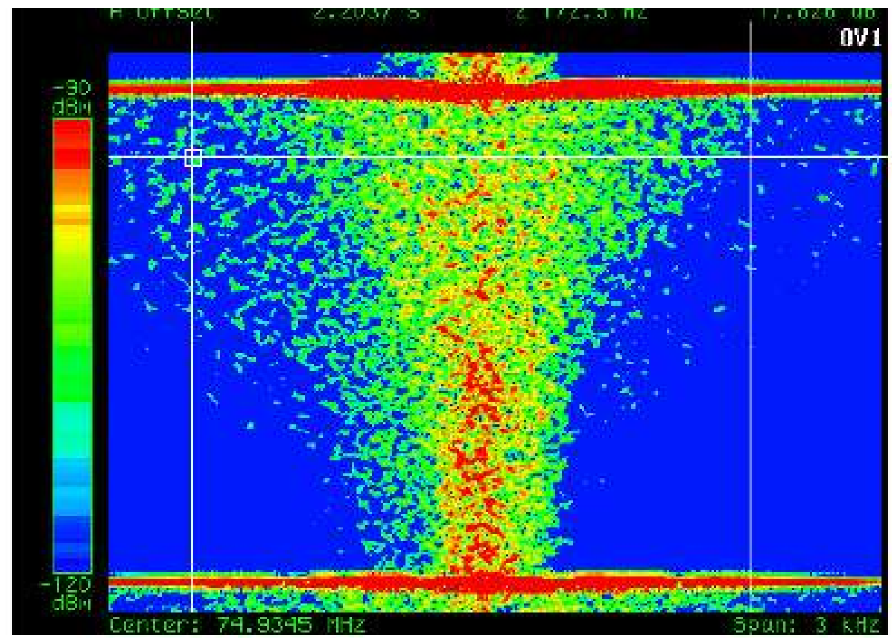
Slow Wave Array



Debuncher Momentum Cooling

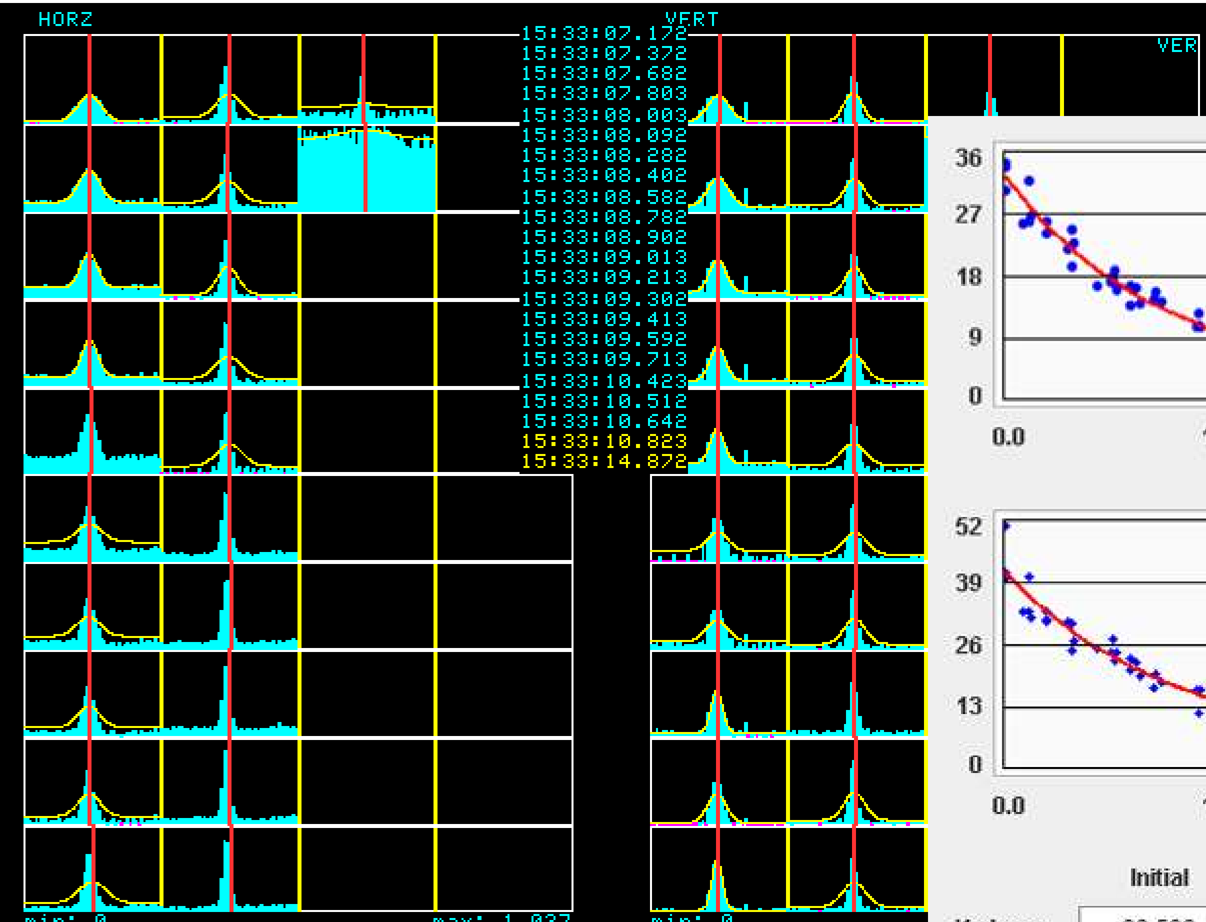


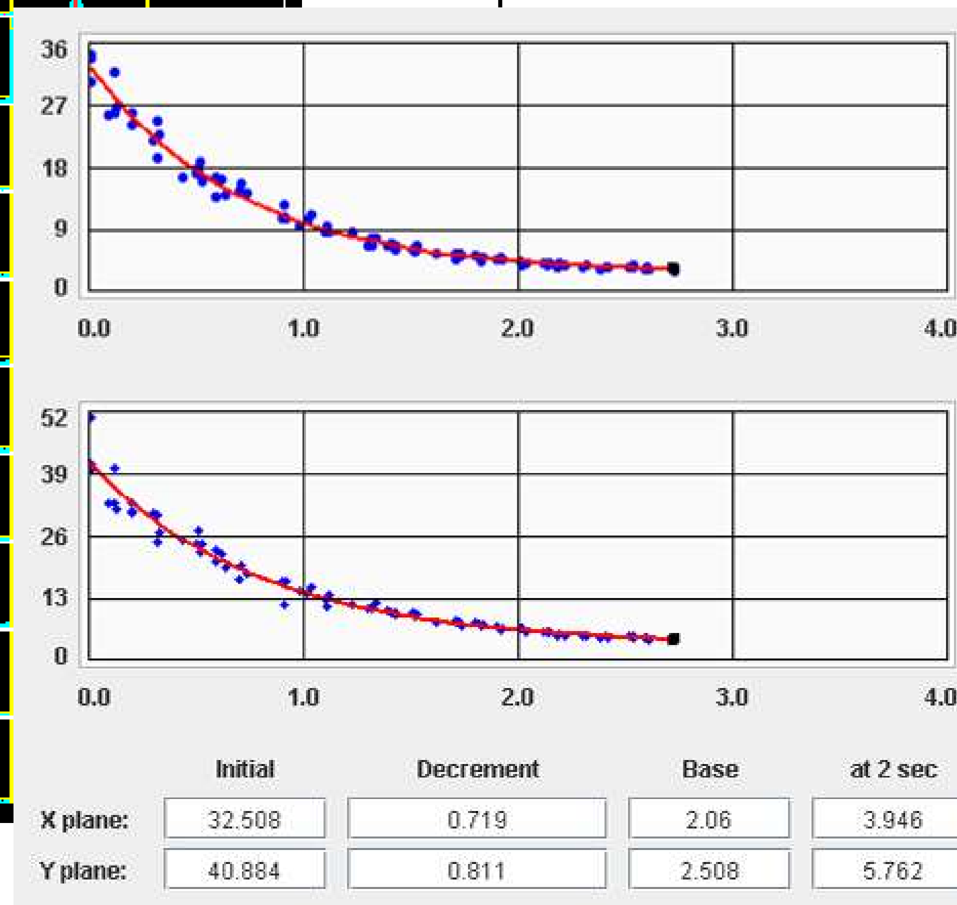
- Reaches design in 2seconds
- Gain ramping to keep TWT near maximum



Debuncher Transverse Cooling

Ion Profile Monitor
Samples ~100ms

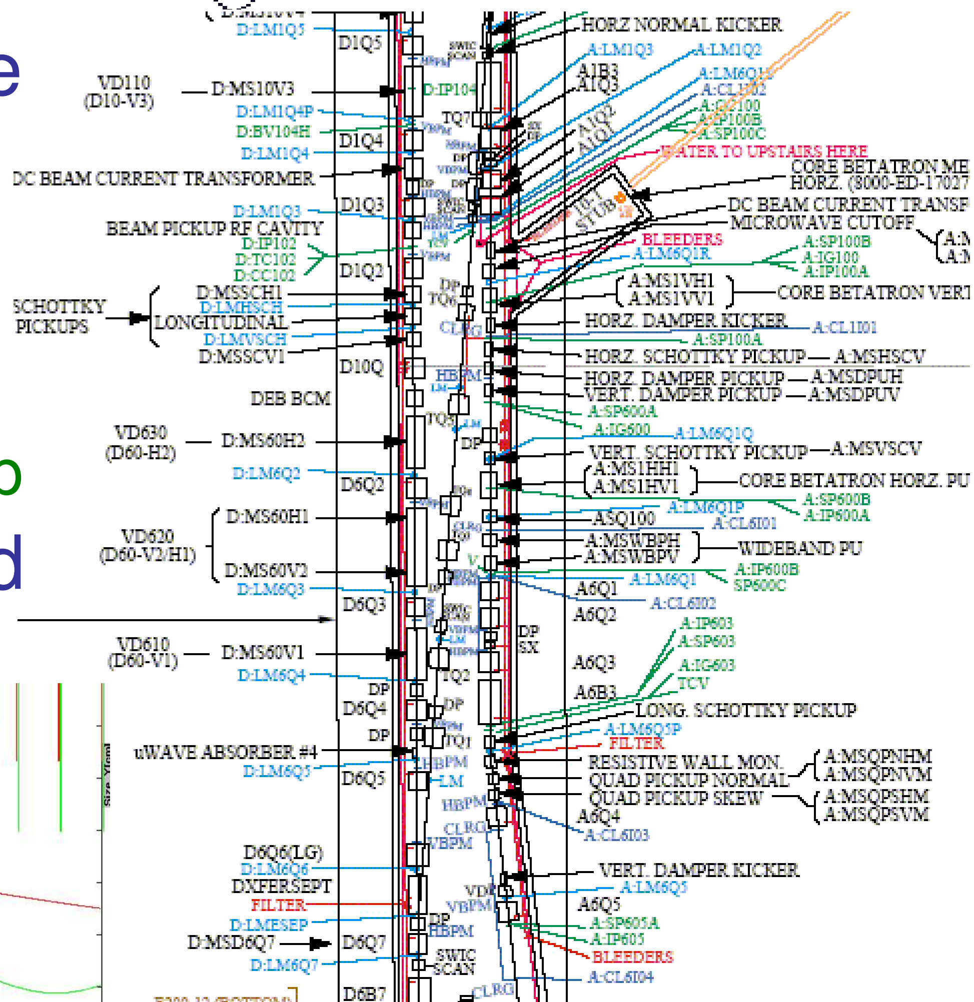


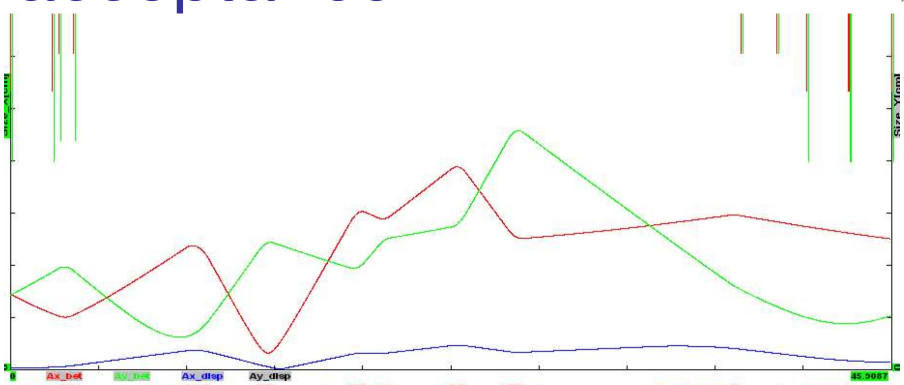


	Initial	Decrement	Base	at 2 sec
X plane:	32.508	0.719	2.06	3.946
Y plane:	40.884	0.811	2.508	5.762

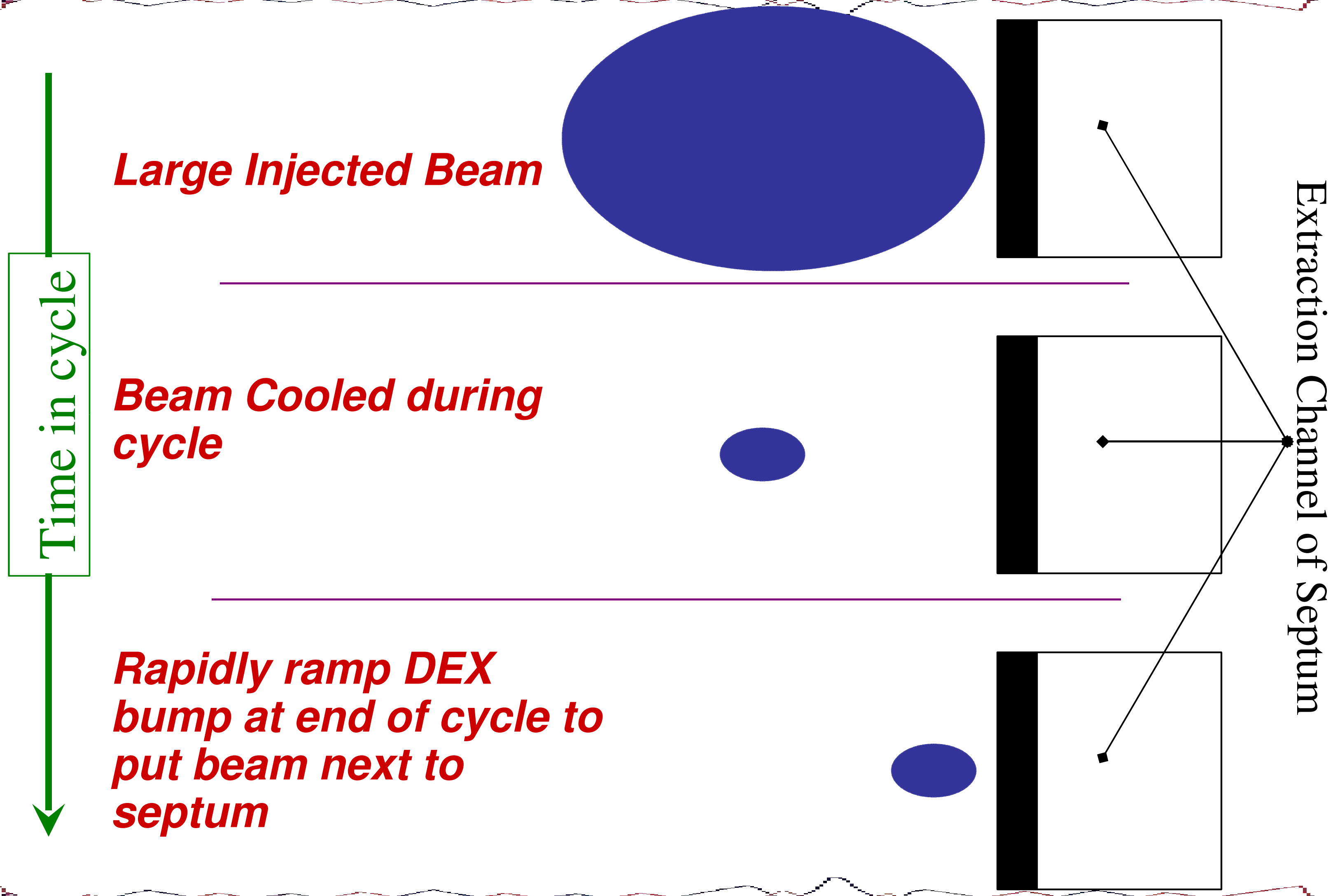
D/A Beam Line

- Short transfer beam line between Debuncher and Accumulator
  - Involves two kickers and three septa
  - Ramped extraction bump
- Designed 10π mm-mrad acceptance

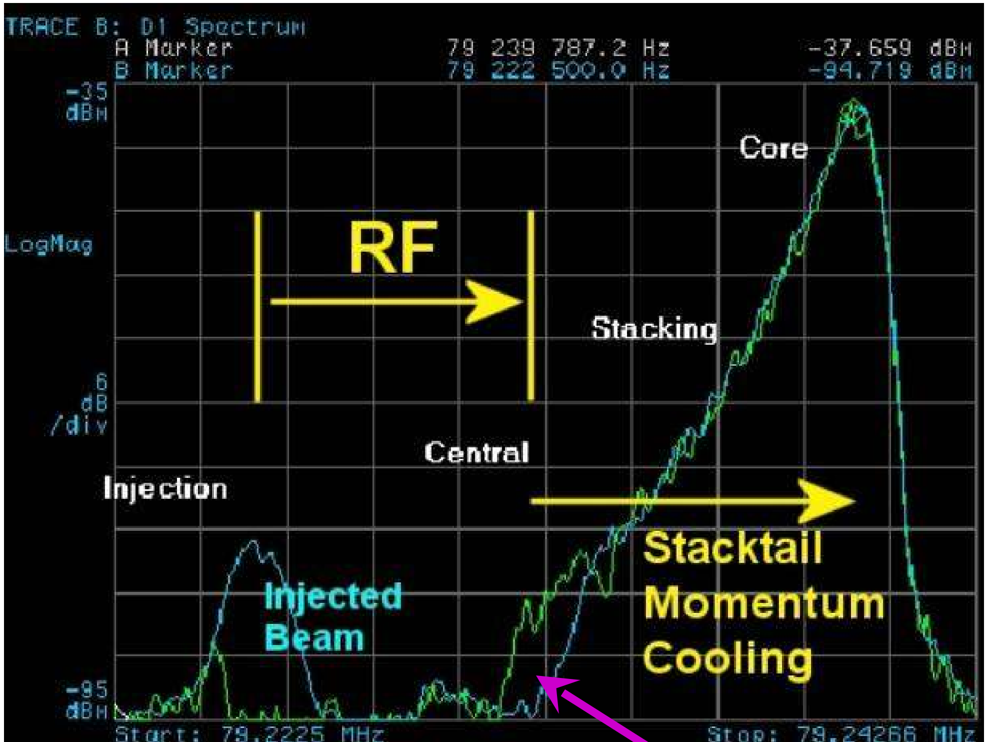




Ramped Extraction Bump



Accumulator

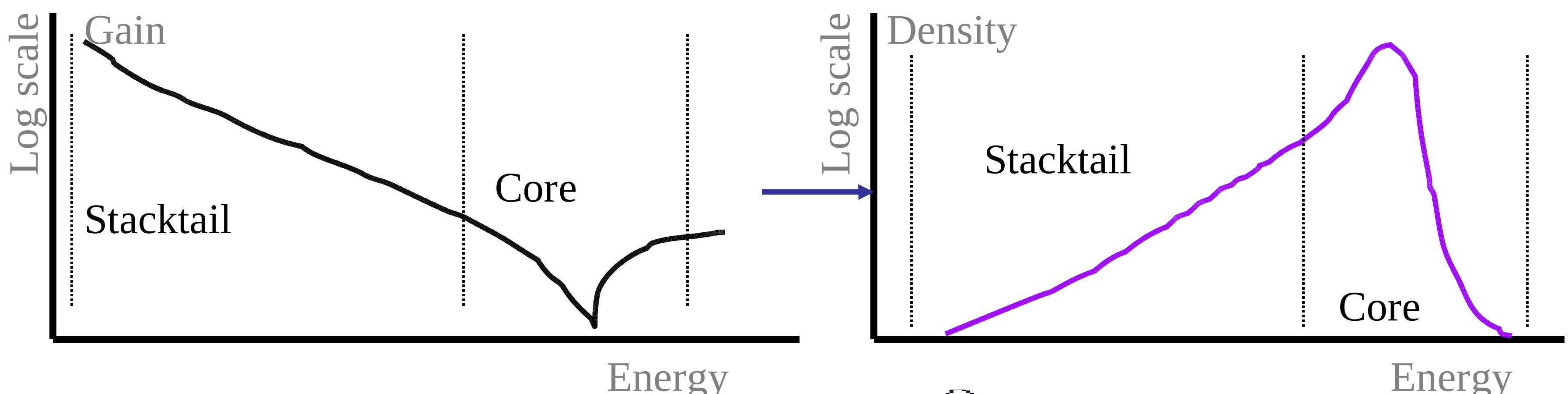


Cyan = After injection before RF capture
Green = After RF is turned off

- RF system decelerates from injection to deposition orbit
- Stochastic Cooling
    - 2-4 GHz stacktail
    - 2-4 & 4-8 GHz core momentum
    - 4-8 GHz transverse slotted waveguide pickups
  - Increase particle density by factor of 5000
  - Factor of 3-5 decrease in both transverse phase space dimensions
- Cycle Limit is clearing Deposition orbit

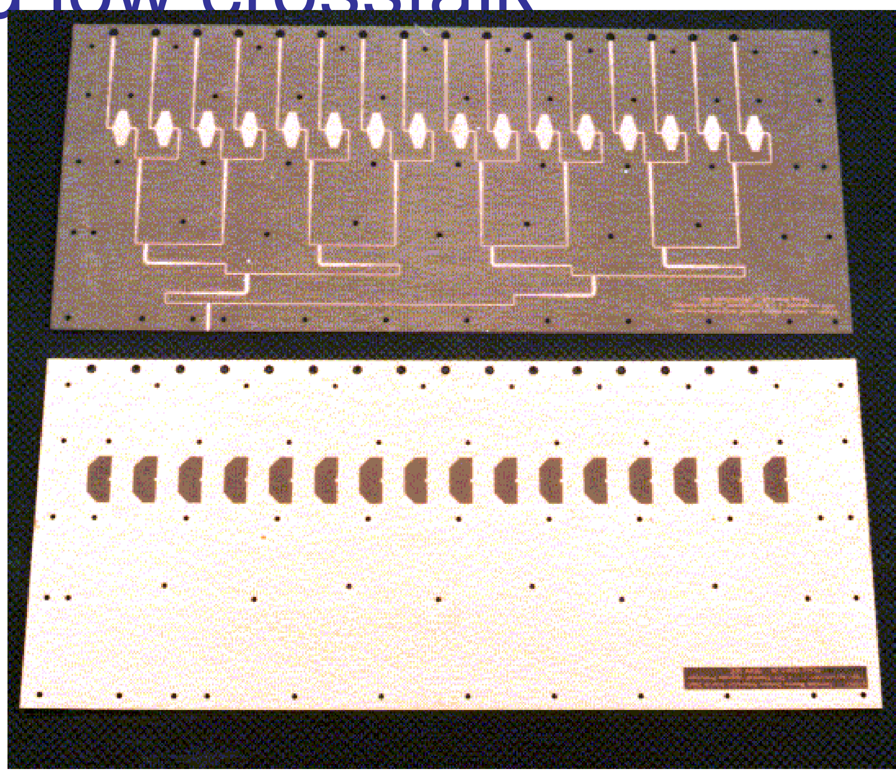
Stochastic Stacking

- Simon van Der Meer solution:
  - Constant Flux: $\frac{\P y}{\P t} = \text{constant}$
  - Solution: $\frac{\P y}{\P E} = \frac{y}{E_d}$, where E_d characteristic of design $y = y_0 \exp\left[\frac{(E - E_i)}{E_d}\right]$
  - Exponential Density Distribution generated by Exponential Gain Distribution
  - Max Flux = $(W^2|\eta|E_d)/(f_0 p \ln(2))$



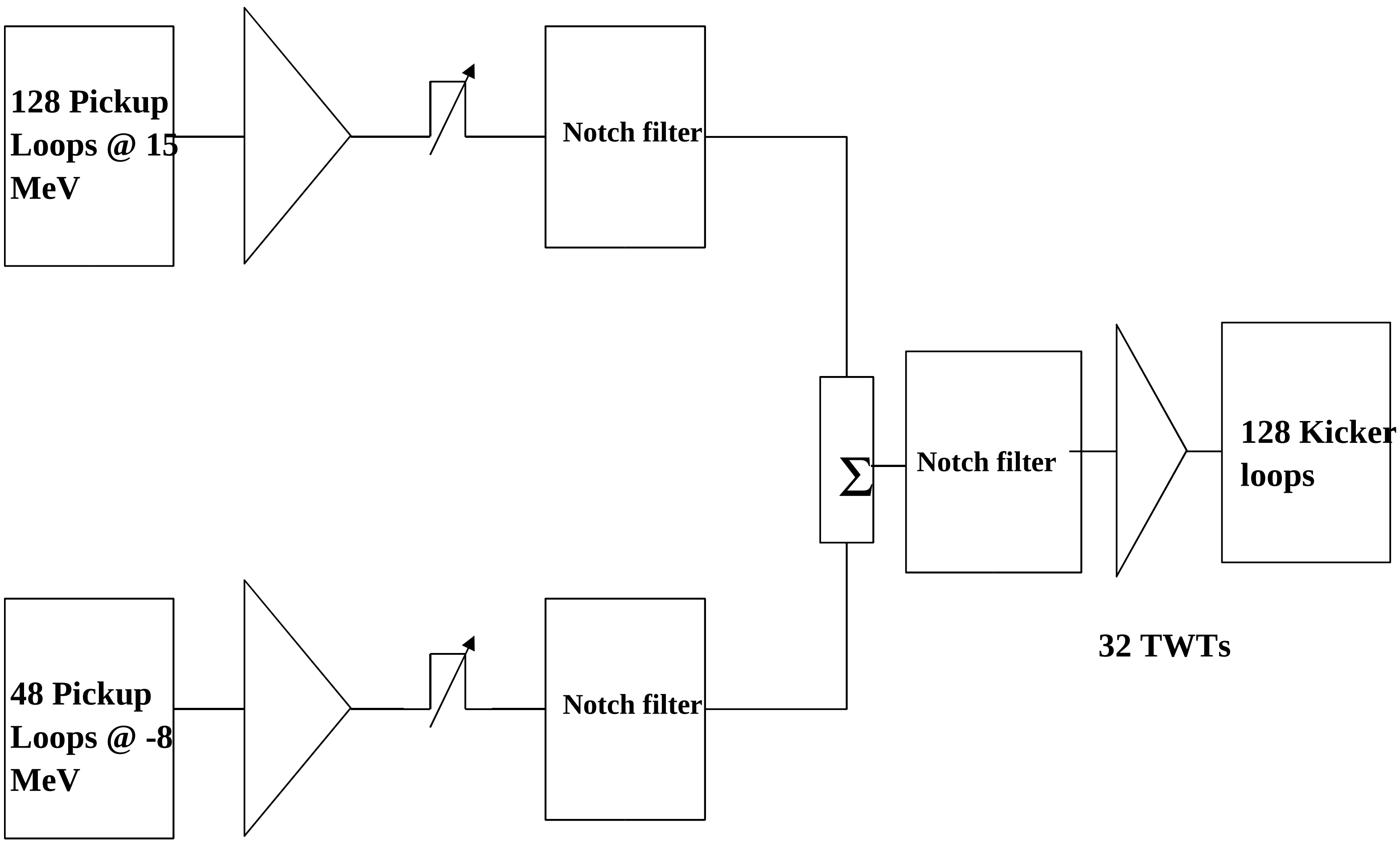
Stacktail Pickups

Planar loops with stripline combiner boards for low loss and low crosstalk



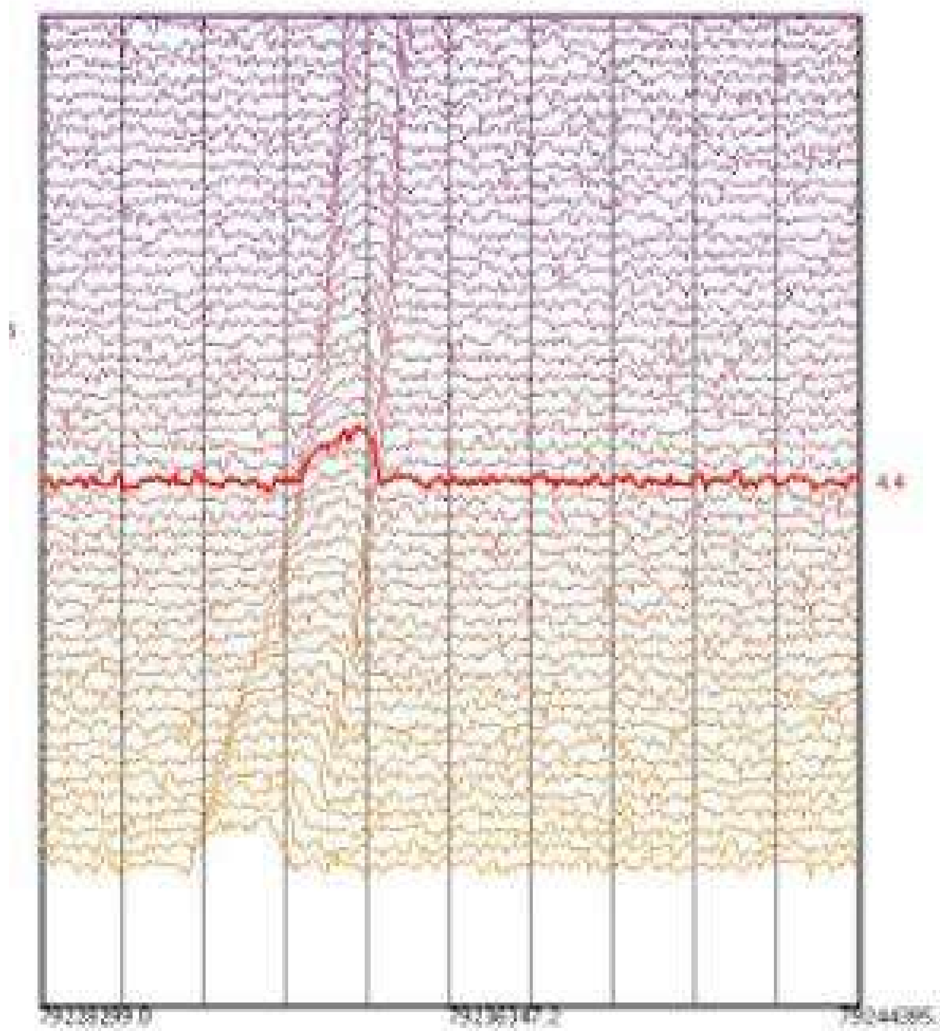
Pickups cooled by Liquid Nitrogen

Stacktail Electronics



Single Pulse Evolution

- ~10^8 antiprotons
- The narrowing of the pulse is the exponential gain

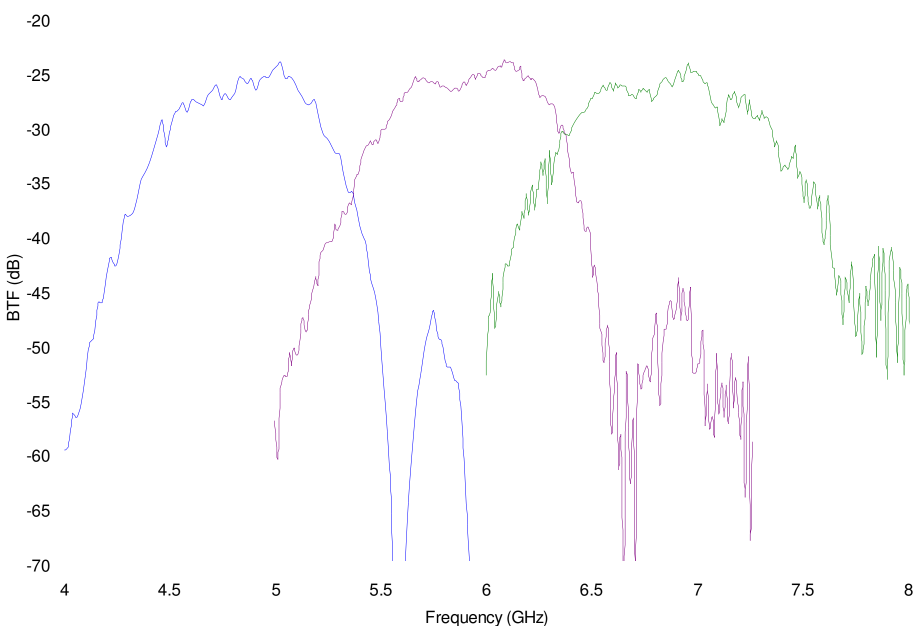


Core Cooling Systems

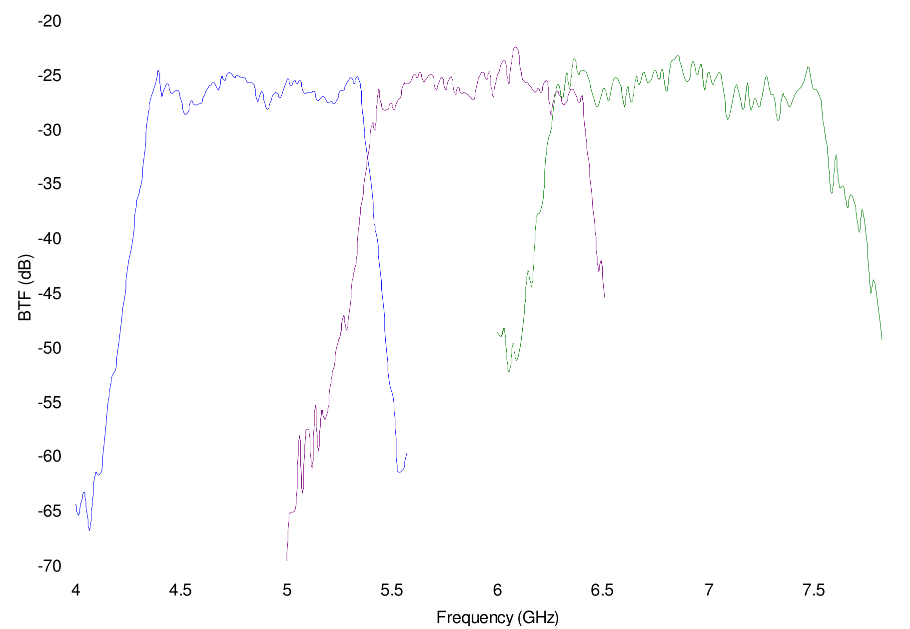
- Had been using 4-8 GHz system as a helper for the 2-4 GHz core system. Decided it was time to move to 4-8 GHz.
  - Because the 4-8 GHz core system runs at twice the frequency, the electrodes are ½ the size so the system has a factor of two smaller momentum reach.
  - However, 1 GHz of bandwidth at 7 GHz is ~3x more powerful than 1 GHz of bandwidth at 2.5 GHz
  - Moving the core closer to Stacktail to accommodate the smaller reach resulted in system instabilities at moderate stacks.
    - Several attempts were made and we learned from each
- We now
  - Use the 2-4 GHz core momentum system to augment the hand-off between the Stacktail and the 4-8 GHz core momentum system
  - Run the 4-8 GHz core momentum system at MUCH larger gain.
    - By replacing the trunk coaxial cable with optical fiber, the 4-8 GHz system is > 5.7 more powerful than the 2-4 GHz system
  - Run the Stacktail during deposition debunching to pre-form the distribution to match the Stacktail profile
    - Tradeoff is more stacktail "on" time with "back-streaming" of pbars knocked out of RF bucket and do not stack but provide a large signal

Core Transverse Systems

- Each plane has three bands to give a bandwidth of 4-8GHz

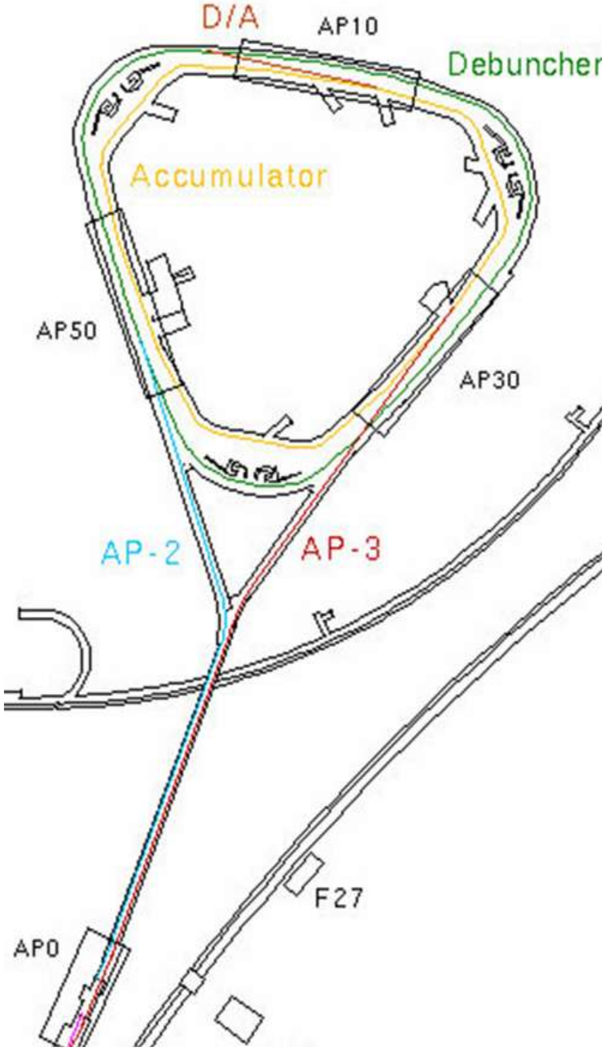


Before Equalizers



After Equalizers

Unstacking

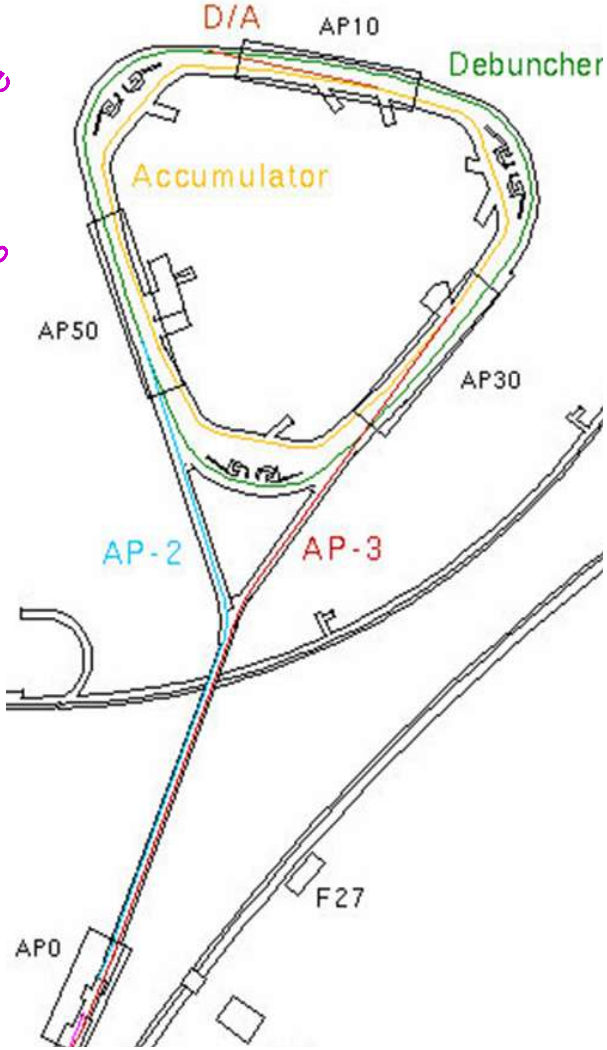


- Current operations is to perform 4-5 transfers when the stack reaches 50×10^{10} pbars.
  - Recycler sets longitudinal emittance
- RF system accelerates beam from core to extraction orbit
- Extracted into beam line to send beam to MI
  - Goes around target station

8 GeV Reverse Protons

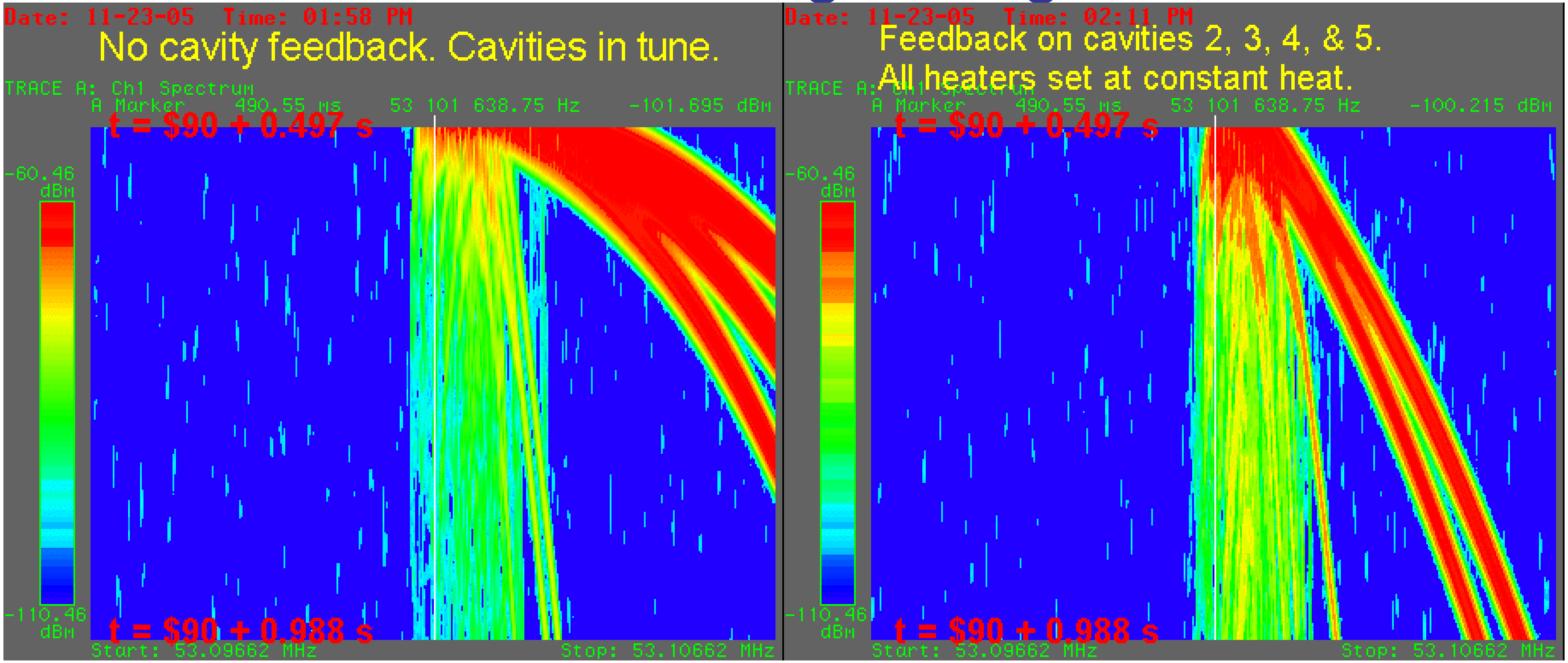
- Studies: Orbit, Lattice Measurements, Aperture
- 8GeV protons from MI
  - Transfer Line
  - Accumulator
    - Studies; or
    - D/A transfer
      - Studies; or
      - Debuncher
        - » Studies; or
        - » Extract up AP2 for studies

The pbar core is unaffected during reverse proton studies with the exception of Accumulator and some D/A studies



Reverse Protons Headache

- Debuncher RF cavities decelerate beam
- Overhead in de-tuning/tuning RF cavities



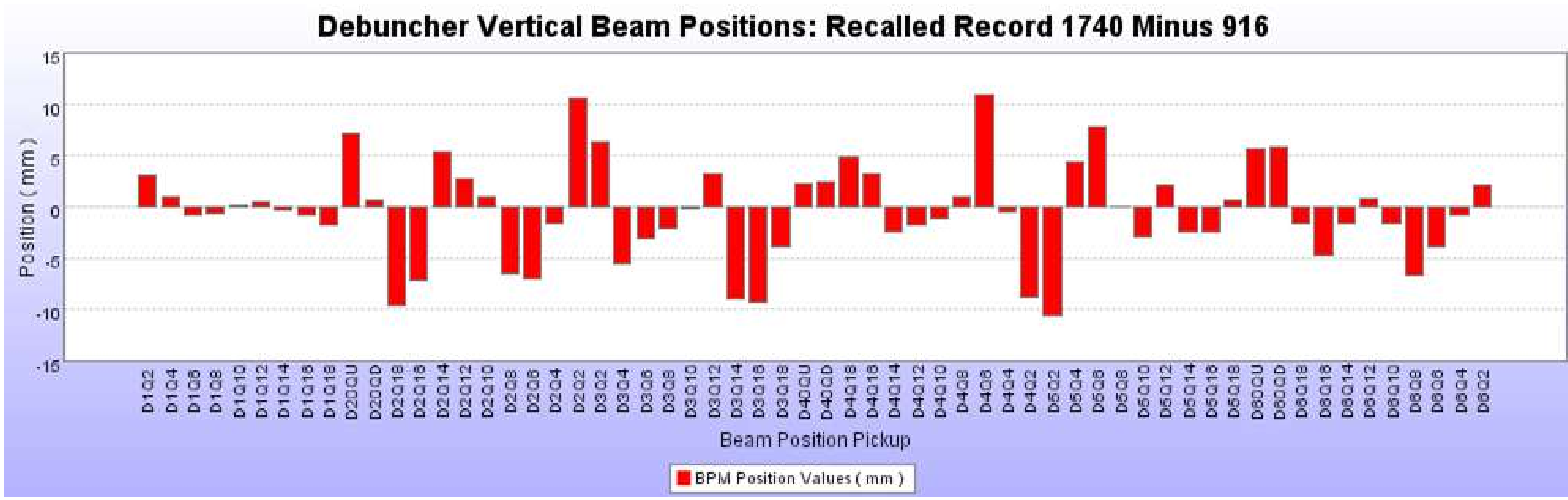
Studies

- The history of the Fermilab Antiproton Source focus has been cooling systems
  - At different times it has been the different systems
  - It is apparent to me that orbits, aperture and diagnostics were made to work well enough to get enough beam to overwhelm a cooling system(s).
- Four years of operations with opportunistic studies or short interruption to stacking
  - TeVatron failures allow for several shifts of studies
- About a year ago it was determined that the cooling systems were handling the flux
  - Several weeks were spent increasing the AP2 beam line and Debuncher admittance from ~20π to ~32π mm-mrad

Debuncher Work - 1

- Determination of orbit-quad center offset
  - Change quad excitation and look for orbit change
  - 68 quads have shunts
    - 10 quads have ability to control excitation alone
    - The rest are paired symmetrically about mid-point of straight section
  - Concern about excitation of two quads at one time and determining offsets for each quad
    - Did quad excitation orbits for nominal orbits as well as for two 1-bumps per plane
      - Checked for consistency of change in offset determination with the change of orbit due to the 1-bumps
- Vertical Orbit Correction
  - Attempted global fit to minimize orbit-quad center offsets
    - Re-checked orbit-quad center offsets: no improvement
      - Use of motorized quad stands as correction devices
  - Local orbit corrections to minimize orbit-quad center offsets
    - Re-check while working around the ring: all <1mm offset

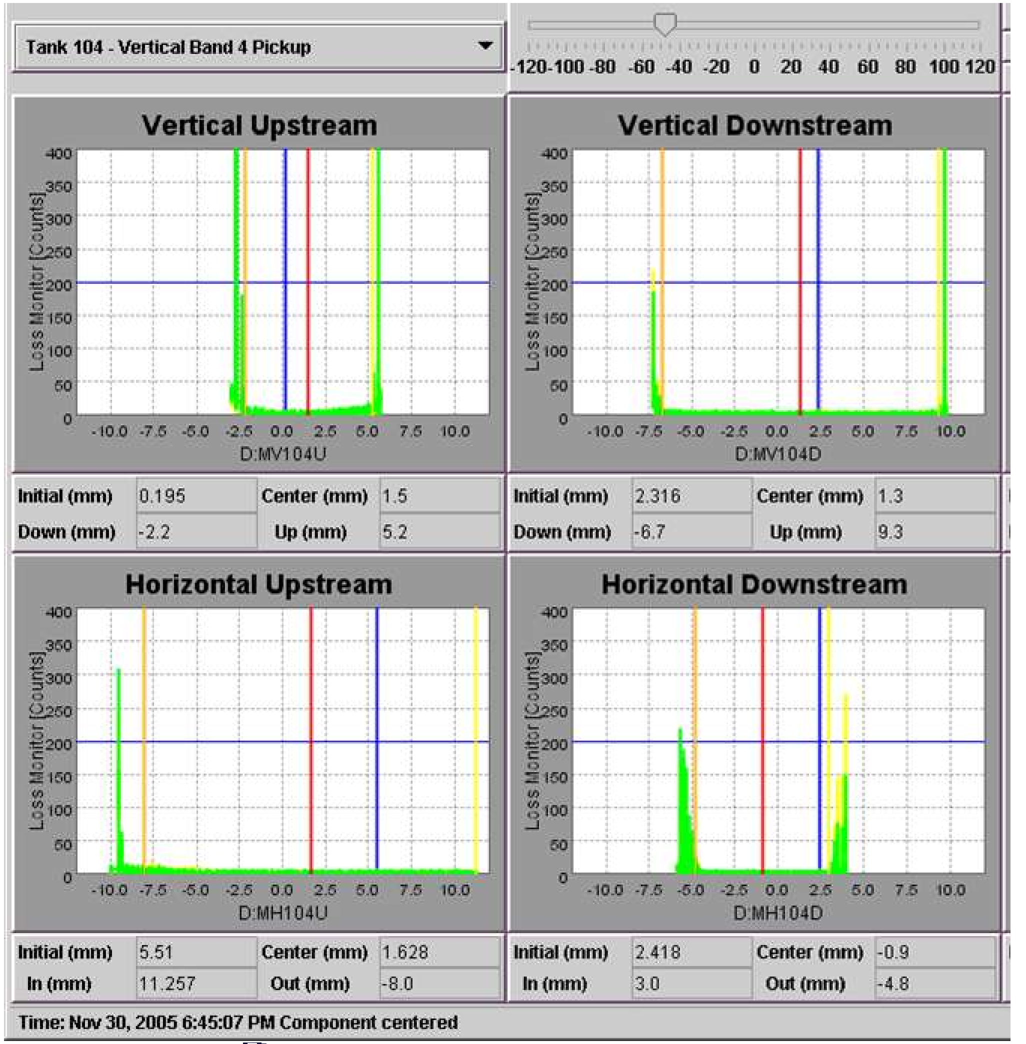
Debuncher Vertical Orbit Change



- Several places the orbit changed by ~1cm
- Angle change at injection area
- All vertical trims and a majority of the motorized quad stands were used to perform the correction

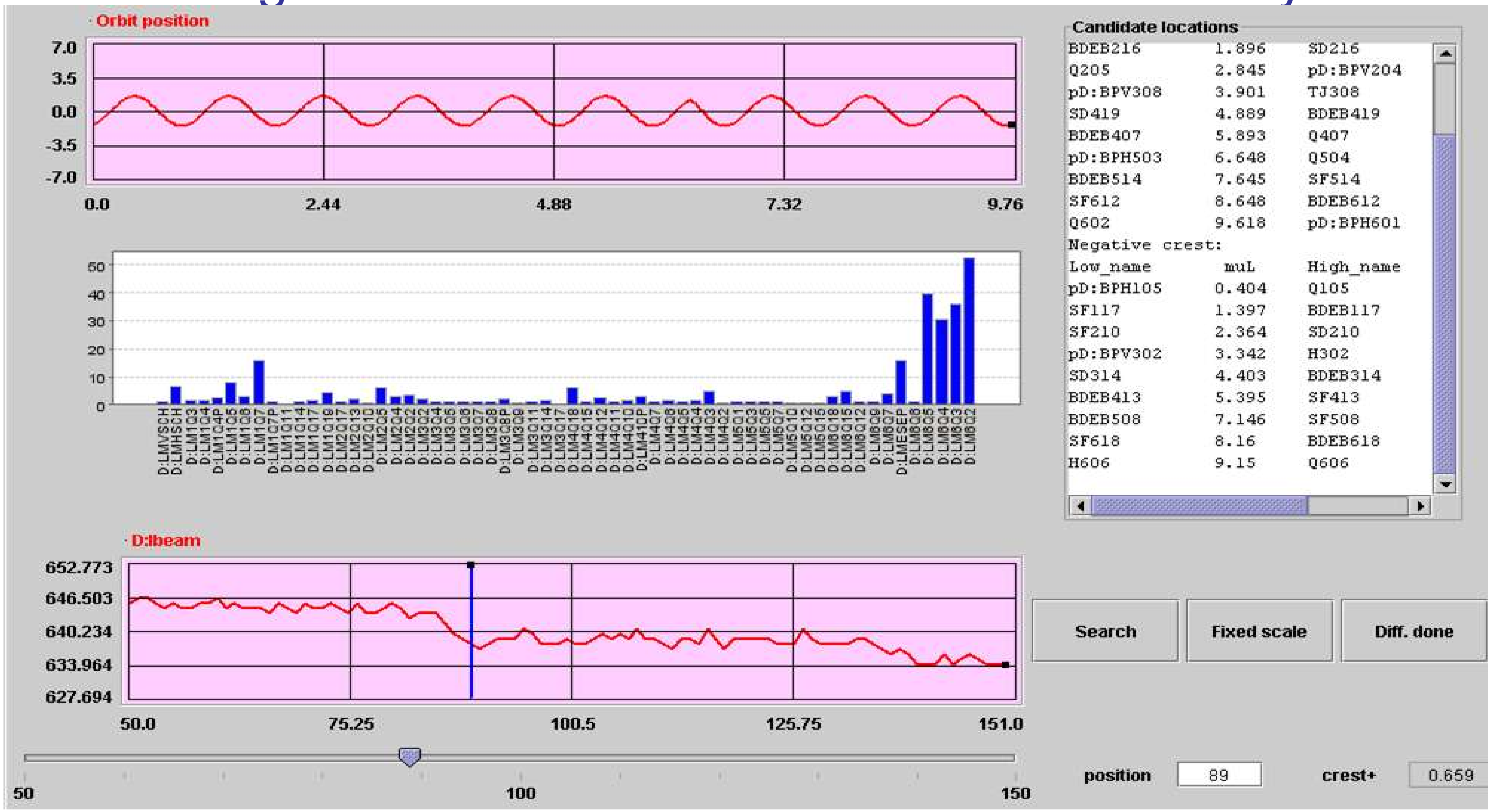
Debuncher Work - 2

- Horizontal Orbit Correction
  - Injection Region was only done
  - Horizontal orbit-quad center offsets determined
- Centered motorized devices about orbit
  - Total of 72 motors
- Lattice measurements were performed



Debuncher Limiting Aperture

- Running Wave → Debuncher transverse Schottkys



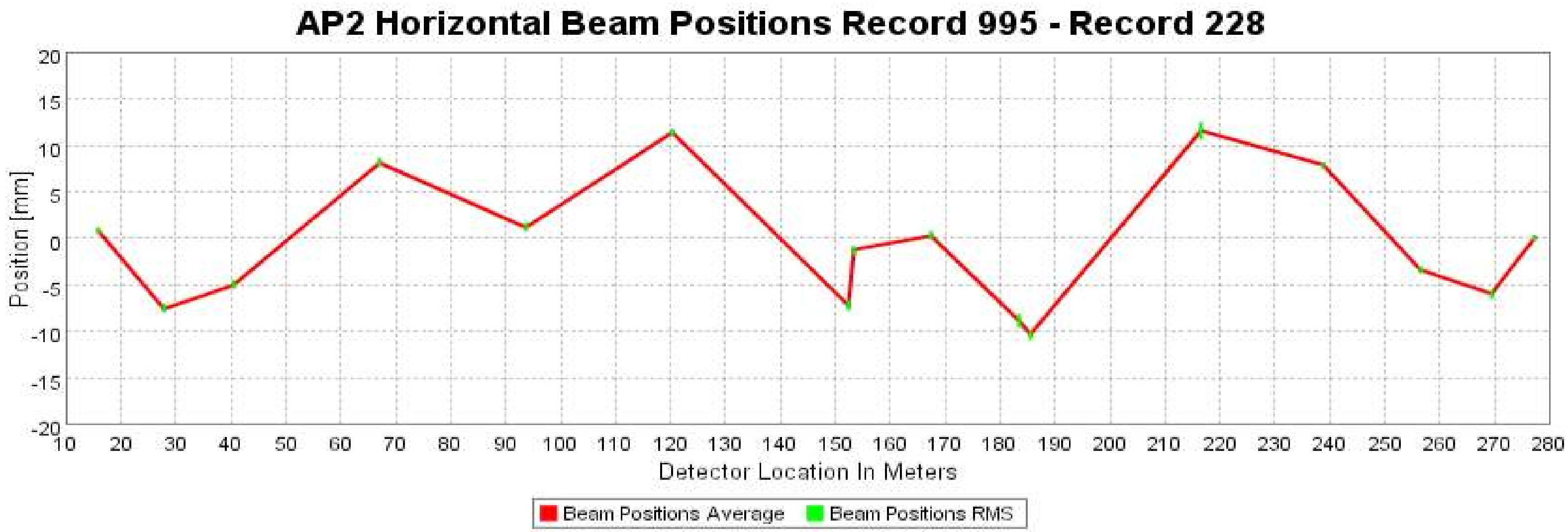
Setting Injection Region

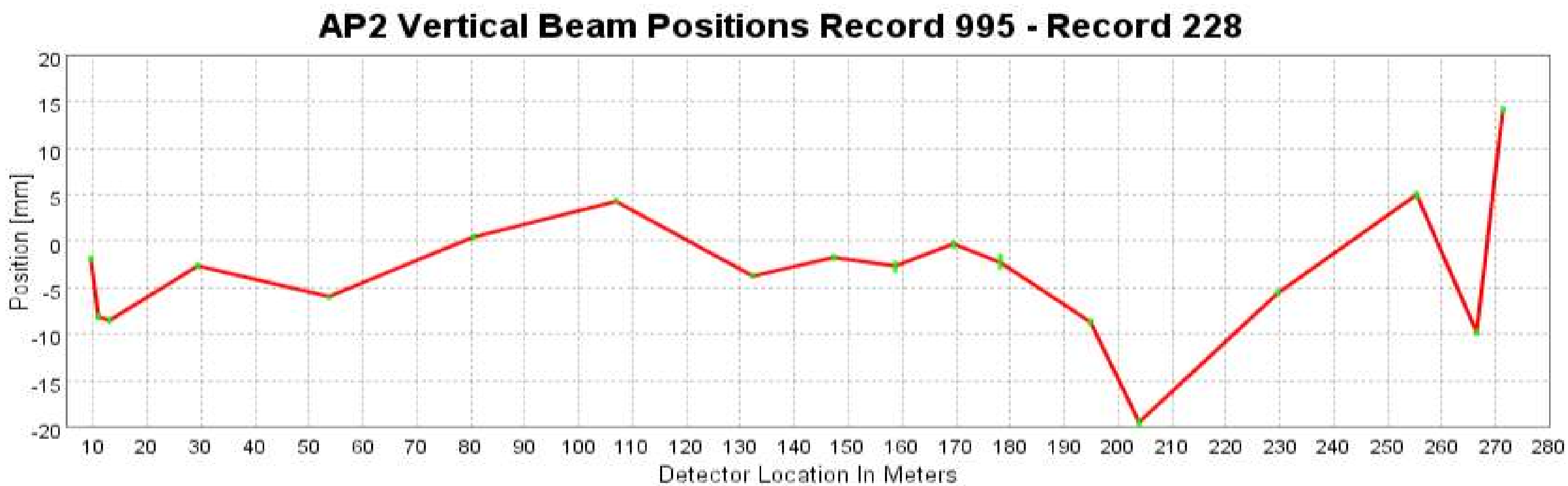
- Extracted beam up AP2 from Debuncher and determine orbit-quad center for the three down-stream most quads
  - Determined horizontal closed orbit and AP2 orbit are centered in quads.
- Set vertical closed orbit to nestle under the septum
- Determine kicker strength to center beam in septum
- Determine septum strength to put beam in the center of the three AP2 quads

AP2 Work

- Able to have reverse protons every 15 seconds
- Determine downstream AP2 orbit-quad center offsets
  - Not able to do upstream due to bussed quads and few BPMs to make offset determination
- Corrected orbit to minimize offset
- Summary of orbit changes for reverse protons
  - Several places big changes, largest 2cm
  - Large vertical angle at the end of AP2
- Lattice measurements
- Installed new lattice which believed to better match Debuncher

AP2 Orbit Change

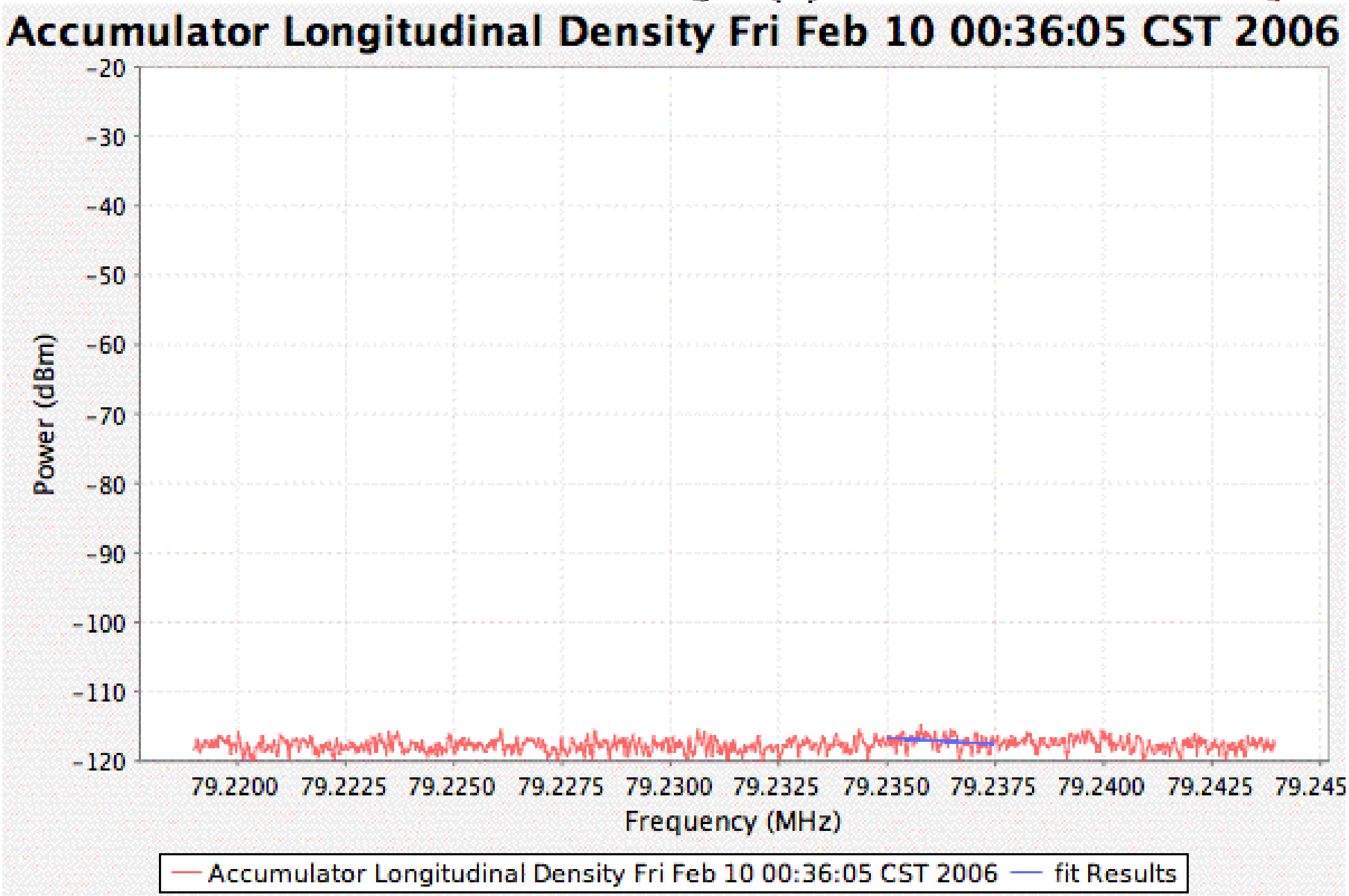




Stacking Studies

- Steered secondaries to the vertical BPM positions found during the reverse proton studies
- Steered to horizontal downstream BPM positions
  - Upstream, the momentum distribution affects the horizontal position
- Problems with AP2 orbit “wandering”
  - Traced to 120GeV protons starting with Main Injector
  - Associated with amount of time between cycles
    - Consistent cycle time is best
  - Developed auto orbit correction program
    - Does 120GeV proton correction
    - Then does AP2 secondaries correction
    - Identified need for additional AP2 trims
- Centered Debuncher pickups
- Exchange 2-4GHz and 4-8GHz core momentum cooling roles

10% Increase of the Stack Rate



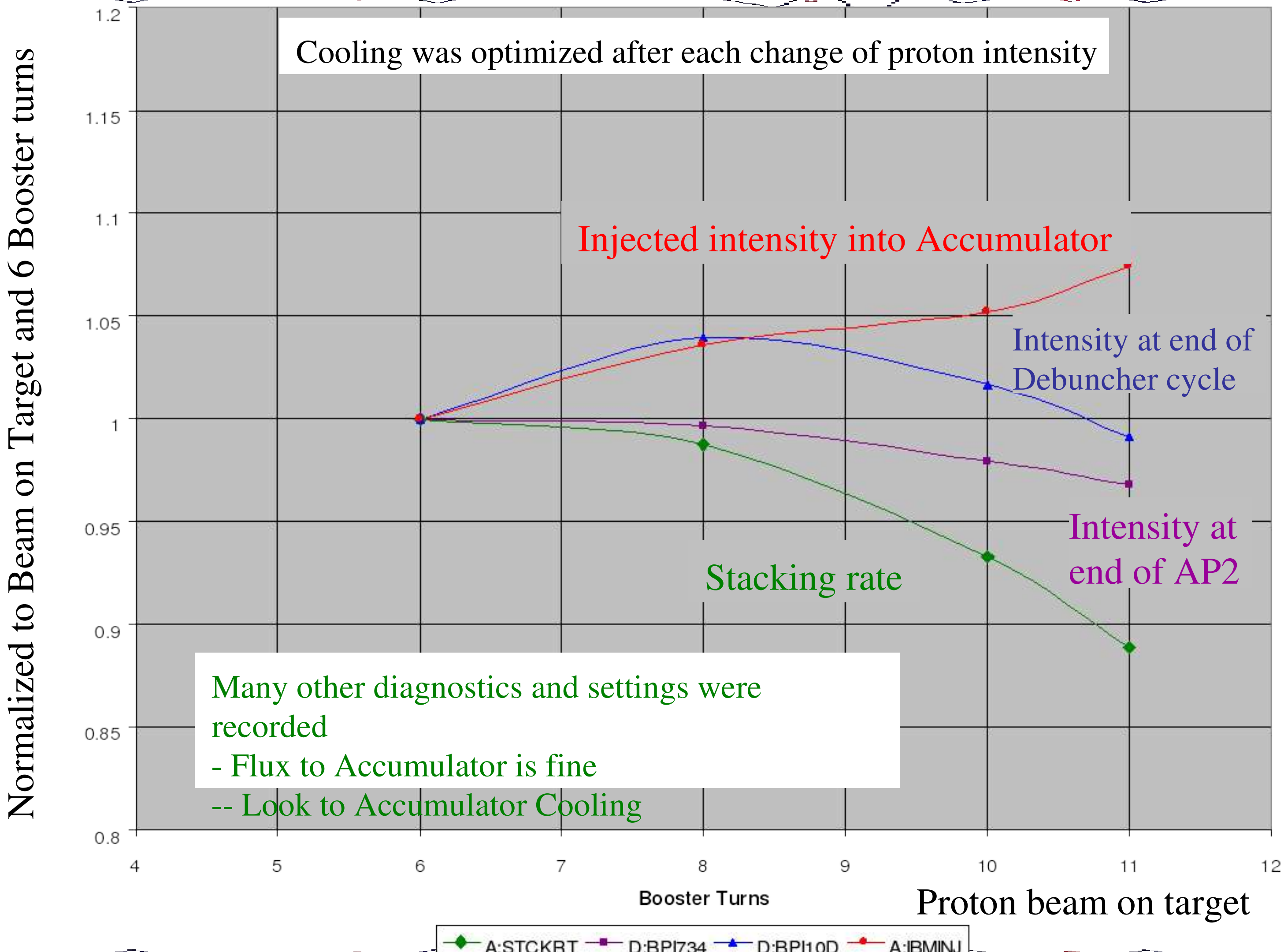
Numbers

- Best Hour of stacking: 20.63×10^{10}/hr
  - Typical daily best hour is 19×10^{10}/hr
- Stack cycle time: 2.4s
  - Design to be 2.0s
- Protons on target: 8×10^{12} (design)
  - Ranges from 7 to 8.5×10^{12}
- Production ranges from 12 to 22 pbars per million protons dependent upon cycle time and amount of beam on target
- In the Debuncher each stacking cycle has 1.8 to 2.2×10^{8} pbars

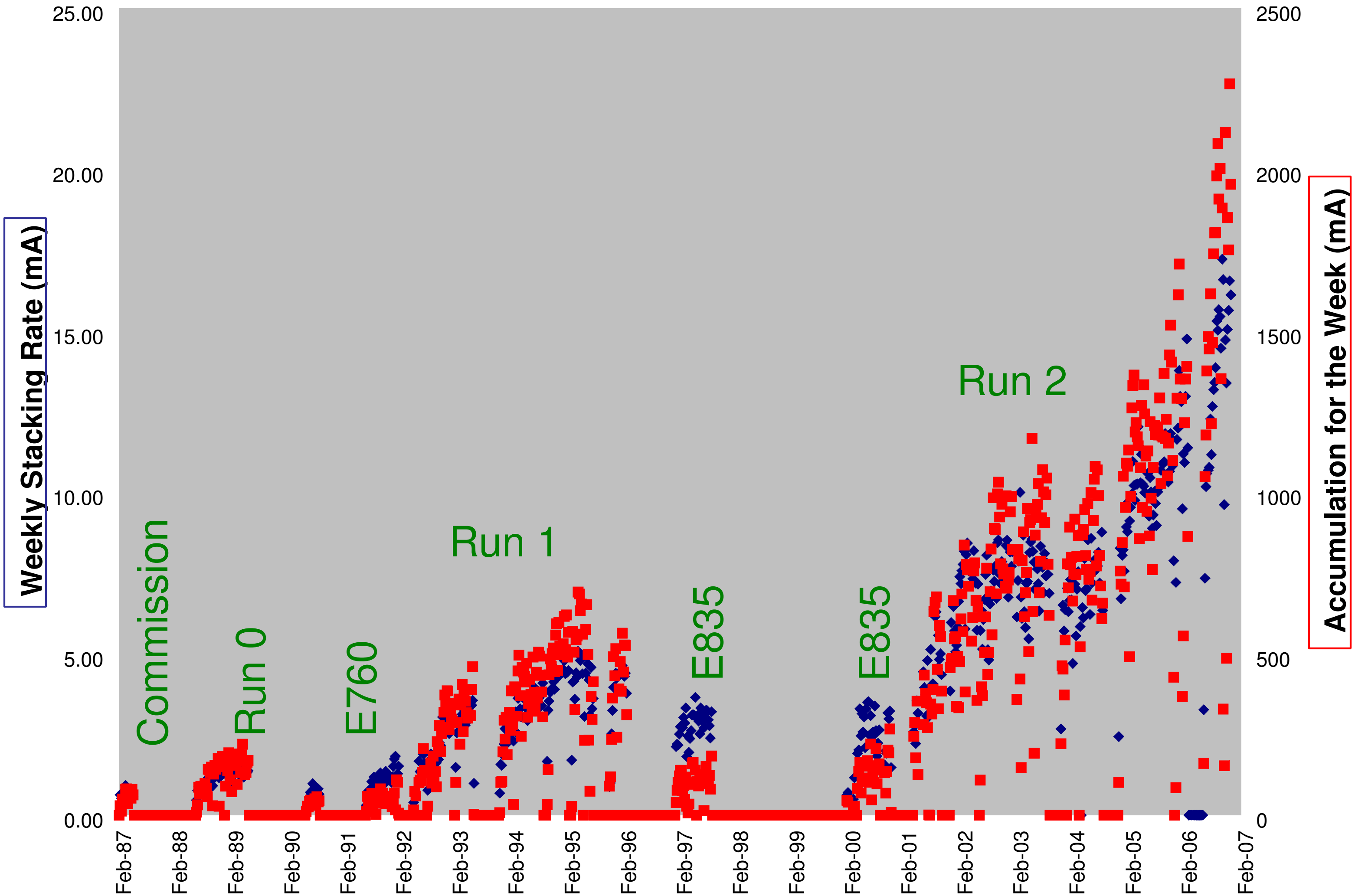
Limitations ?!?!

- 8×10^{12} protons at 2.4s means that the Debuncher throughput is 30×10^{10}/hr
  - If 2.0s…36×10^{10}/hr
    - Another 10%(?) from lens gradient and admittance would mean 40×10^{10}/hr
- Cooling systems
  - Shorten cycle time and production falls
    - 2.4s gives the maximum stacking rate
  - Studies with long cycle times and controlling the amount of time each system cools have been done
    - Stacktail is the problem

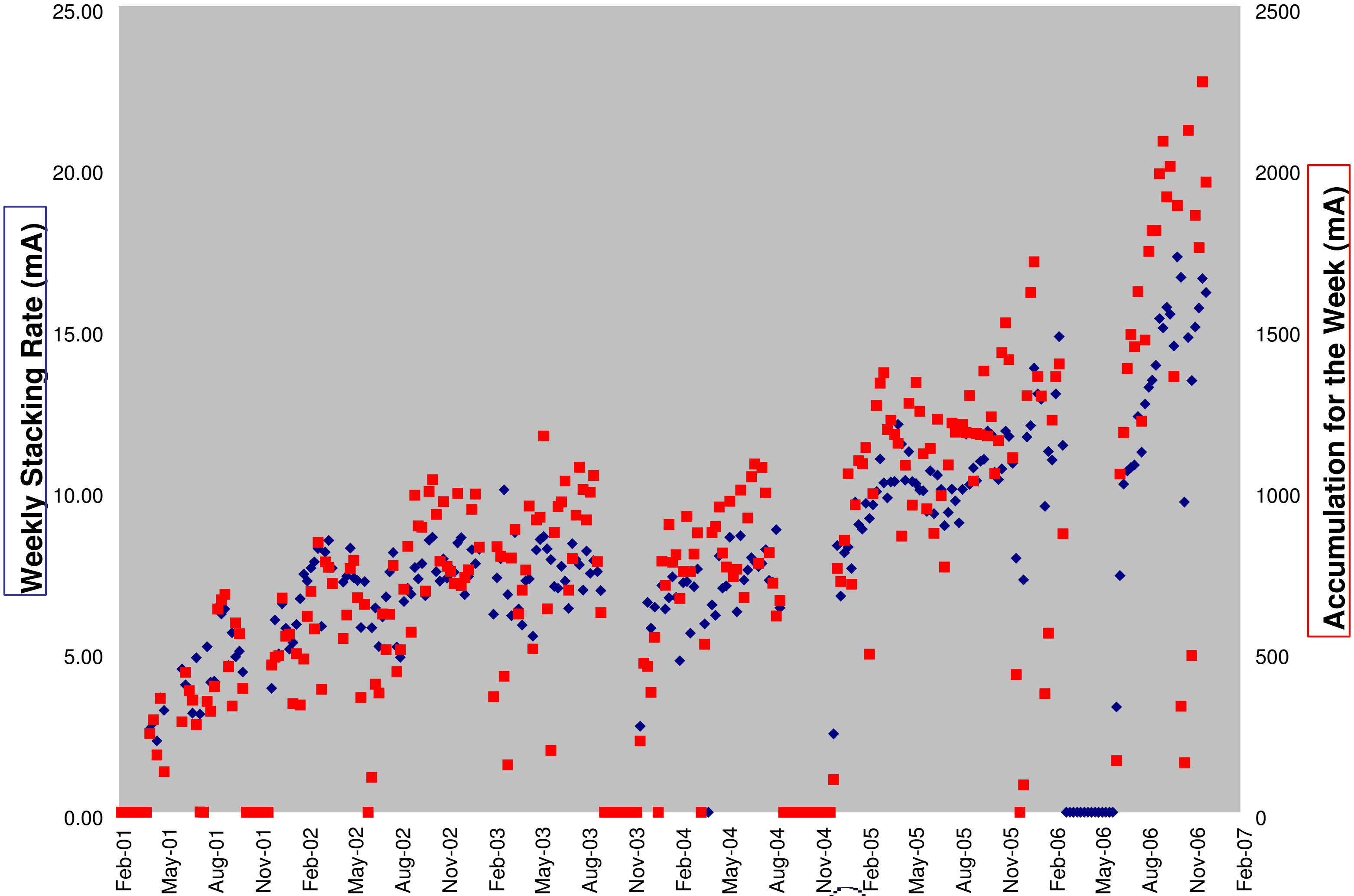
Intensity Study – 4s Cycle Period



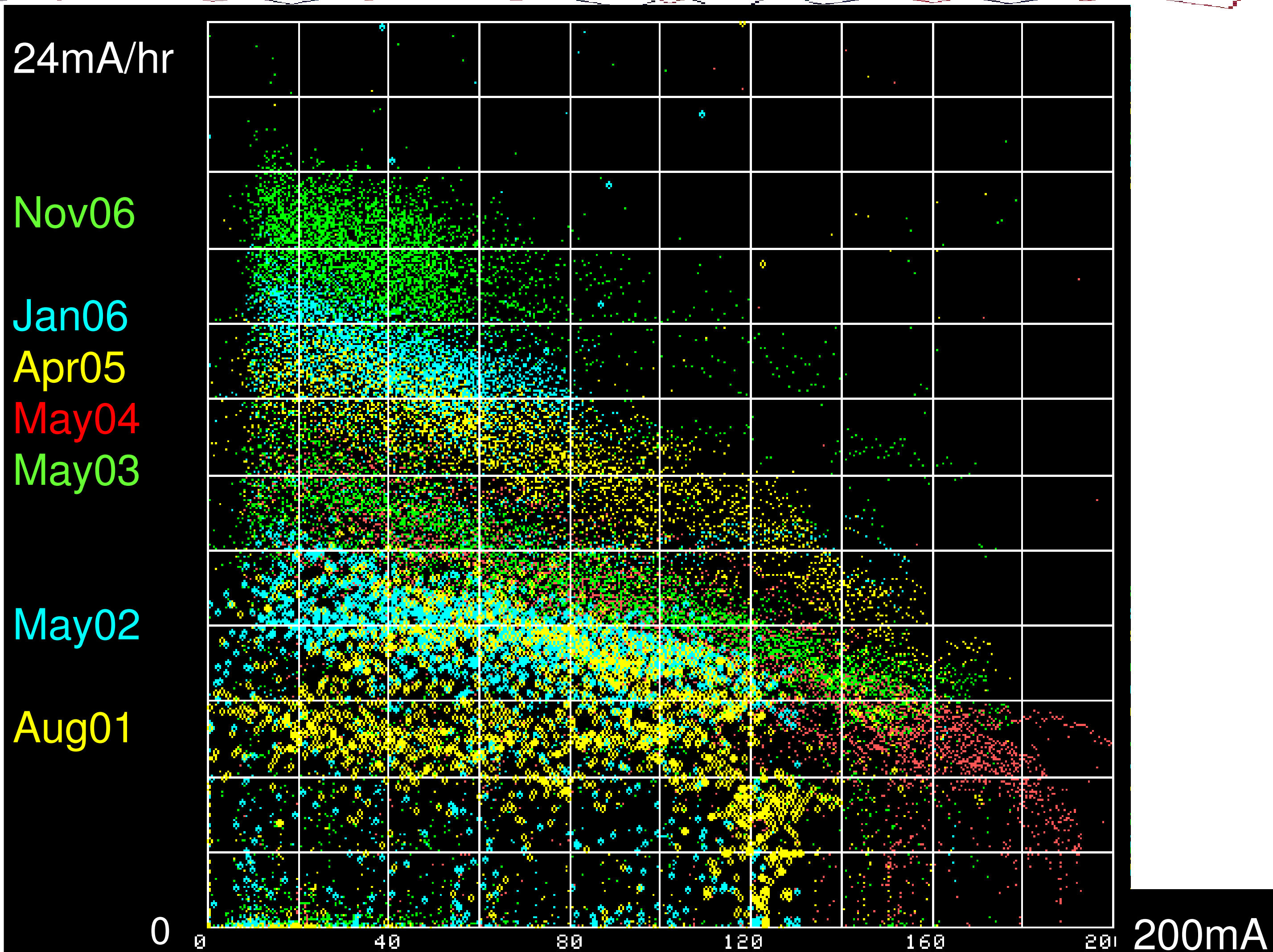
Stacking History



Run II Stacking History



Stack Rate function of Stack Size

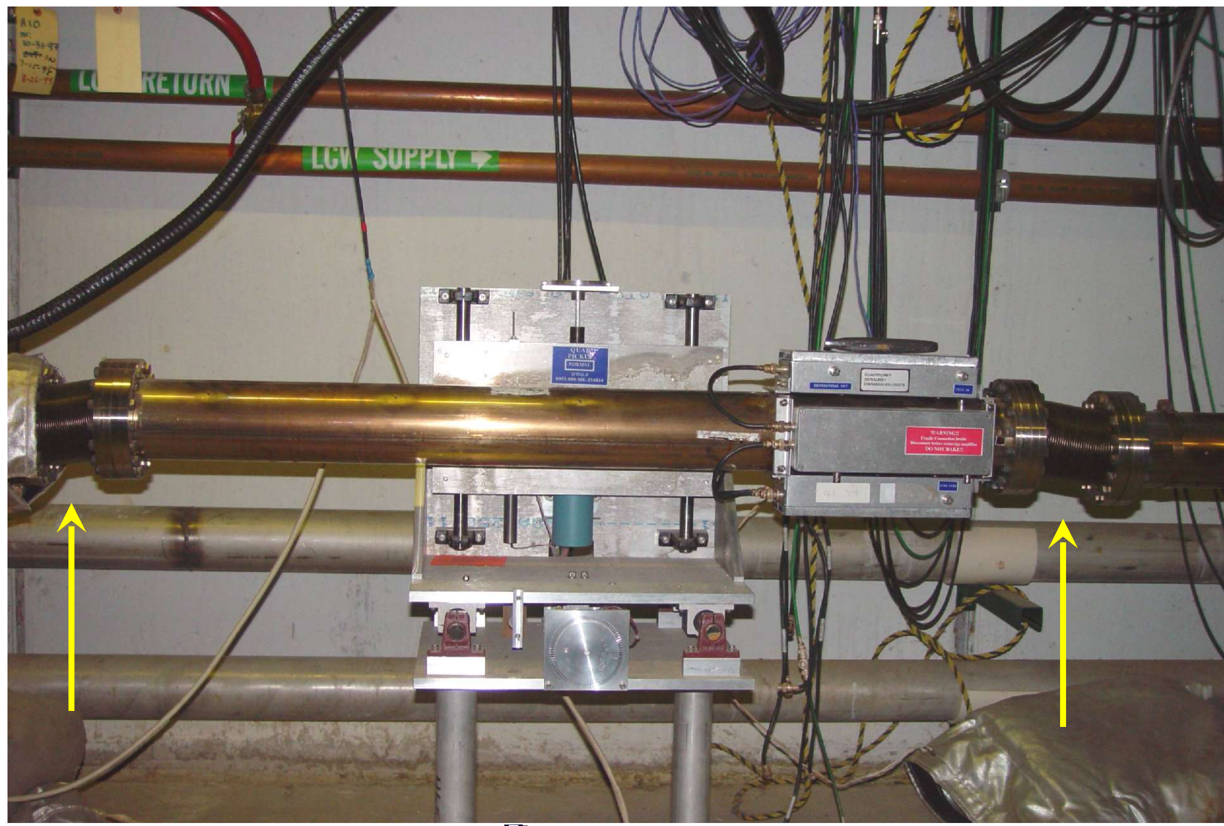


Accumulator Work

- Continued studies of cooling systems
  - Continued development of model/simulation
    - Many measurements performed to help set model parameters
    - Other measurements to test model predictions
      - Not as successful as one would like
- Accumulator Aperture
  - Not the best it has ever been
  - Concerned about injection channel

Accumulator Aperture

- Spent 4½ shifts of beam study time to improve the Accumulator aperture.
  - Identified an aperture restriction
    - Quad pickup has been removed
  - Scanned all moveable devices



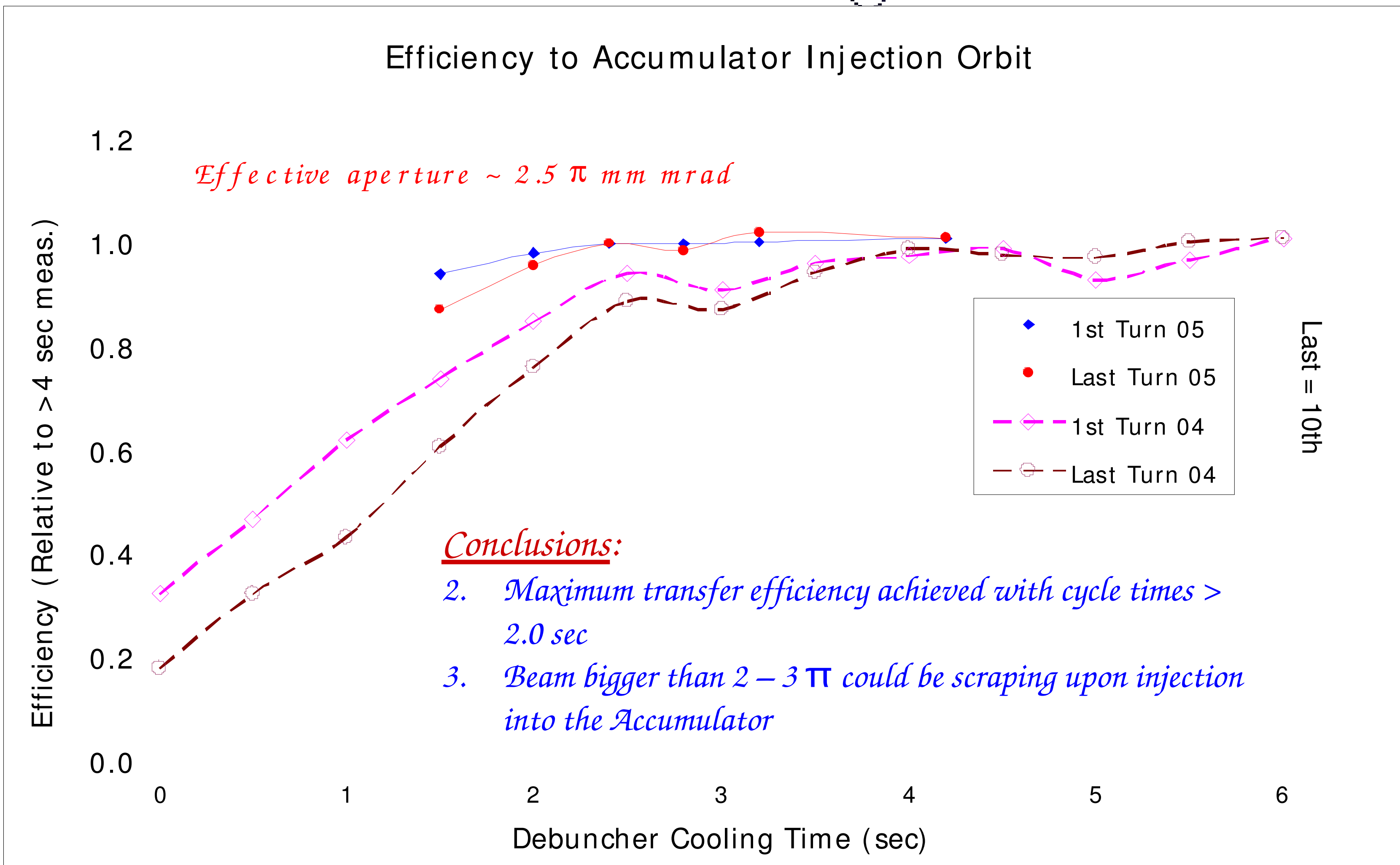
Accumulator Admittance

Date		Injection	Central	Core
8/25/1999	H	8.3 π	10.0 π	8.2 π
	V	9.6 π	9.4 π	7.7 π
2/15/2006 Start of studies	H		6.3 π	
	V		7.4 π	
2/17/2006 End of studies	H	6.3 π	7.0 π	6.6 π
	V	9.2 π	7.9 π	6.6 π

Improvement: Horizontal – 11%, Vertical – 7%

Apertures remain substantially smaller than they were in 1999.

Stacking Cycle Time Study



Conclusions:

2. *Maximum transfer efficiency achieved with cycle times > 2.0 sec*
3. *Beam bigger than 2 – 3 π could be scraping upon injection into the Accumulator*

Current Focus

- **STACKTAIL**
  - Optimize optics
  - Optimize control of electronics path
  - Change E_d
    - Leg 1 has two tanks; split by moving a tank
  - New equalizers to increase bandwidth by ~20%
  - More Bandwidth

Summary

- The Fermilab Antiproton Source continues to provide pbars for the TeVatron collider program
- Improvement in the stacking rate has occurred over the course of Run II
- Improvement to come will be from increasing the flux that the Stacktail stochastic cooling system can handle