Run 2 Upgrades Technical Strategy

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Director's Review

May 5, 2003

Run II Luminosity Goals

- The peak luminosity goal for the Run 2Upgrades is 2.9×10^{32} $cm^{-2}sec^{-1}$

$$L = \frac{3\gamma f_0}{\beta^*}\left(BN_{\bar{p}}\right)\left(\frac{N_p}{\varepsilon_p}\right)\frac{F\left(\beta^*, \theta_{x,y}, \varepsilon_{p,\bar{p}}, \sigma^L_{p,\bar{p}}\right)}{\left(1+\varepsilon_{\bar{p}}/\varepsilon_p\right)}$$

- The major luminosity limitations are
  - The number of antiprotons (BN_{pbar})
  - The proton beam brightness (N_p/ε_p)
  - $F < 1$
- The pbar "burn" rate $\Phi_{\bar{p}}^{(\min)} = n_c \sigma_a L$
  - $n_c = 2$
  - $\sigma_a = 70$ mb
  - $L = 2.9\times10^{32}$ cm^{-2}-sec^{-1}
  - $\Phi = 15\times10^{10}$ hr^{-1}

Run II Parameters

- The major increase in luminosity will result from a 4x increase in the <u>average</u> pbar production rate

	Typical Run Ib	Store 2328	Goal: FY03	Run II Target	
Peak Luminosity	1.6	4.1	6.6	29.0	$x10^{31}cm^{-2}sec^{-1}$
Integrated Luminosity	3.1	6(1)	12.0	60.0	pb^{-1}/wk
Store hours per week	84	86(3)	81(3)	106	
Interactions/crossing	2.5	1.0	1.7	8.0	
Pbar Bunches	6	36	36	36	
Form Factor	0.59	0.60	0.63	0.63	
Protons/bunch	23.0	20.5	24.0	27.0	$x10^{10}$
Pbars/bunch	5.6	2.5	3.1	13.5	$x10^{10}$
Peak Pbar Prod. Rate	7.0	12(2)	18.0	45.0	$x10^{10}$/hr
Avg. Pbar Prod.Rate	4.2	7.0	11.0	40.0	$x10^{10}$/hr
Pbar Transmission Eff.	50	60	80	80%	%
Stack Used	67	152	141(4)	610	$x10^{10}$
MI extraction Long.Emit.		3.5	2.5	2.5	eV s
Bunch Length (rms)	0.6	0.6	0.54	0.54	m
Proton Emittance (at coll)	23	19	20	20	π-mm-mrad
Pbar Emittance (at coll)	13	14	15	14	π-mm-mrad
Store Length	16	22	15	15	hr

(1) typical April 03 (other numbers in this column are for store 2328)
(2) best stacking rate achieved $13.1x10^{10}$/hr for one hour (peak ~14.5)
(3) excluding studies
(4) additional pBar stack used for RR commissioning

Design Strategy

- Increase the Antiproton Flux
  - Increase the number of protons on the antiproton production target by slip-stacking
    - (Slip Stacking (1.9x) X NUMI (0.8x) = 1.5x)
  - Increase the antiproton collection efficiency by:
    - Increasing the gradient of the antiproton collection lens (1.3x)
    - Increasing the aperture of the antiproton collection transfer line and Debuncher ring (2.3x)

Design Strategy

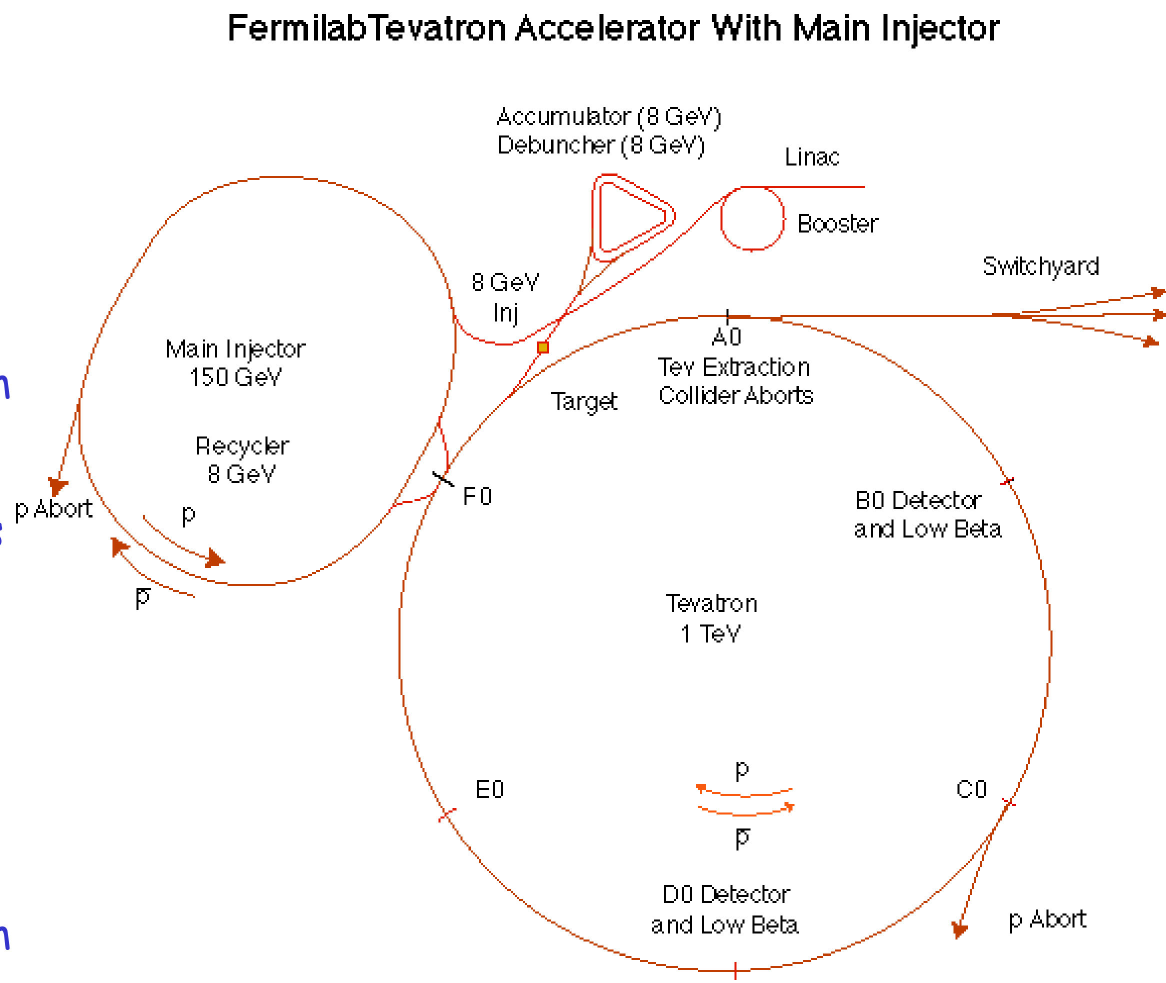
- Cool the increased antiproton flux
  - Increase the antiproton flux capability of the Accumulator Stacktail momentum cooling system.
  - Electron cooling in the Recycler Ring.
    - Cool large stacks (~600×10^{10} pbars)
    - Increase the ratio of the average to peak stacking rate (1.5x)
  - Streamline and improve antiproton transfers between the Accumulator and the Recycler.

Design Strategy

- TEVATRON Beam-Beam compensation
  - Beam-Beam modeling
  - Larger Separation
    - Improved Ramp Helices
    - More Separator Strength at 980 GeV
  - Active Compensation Research
    - Electron Lens
    - Wires

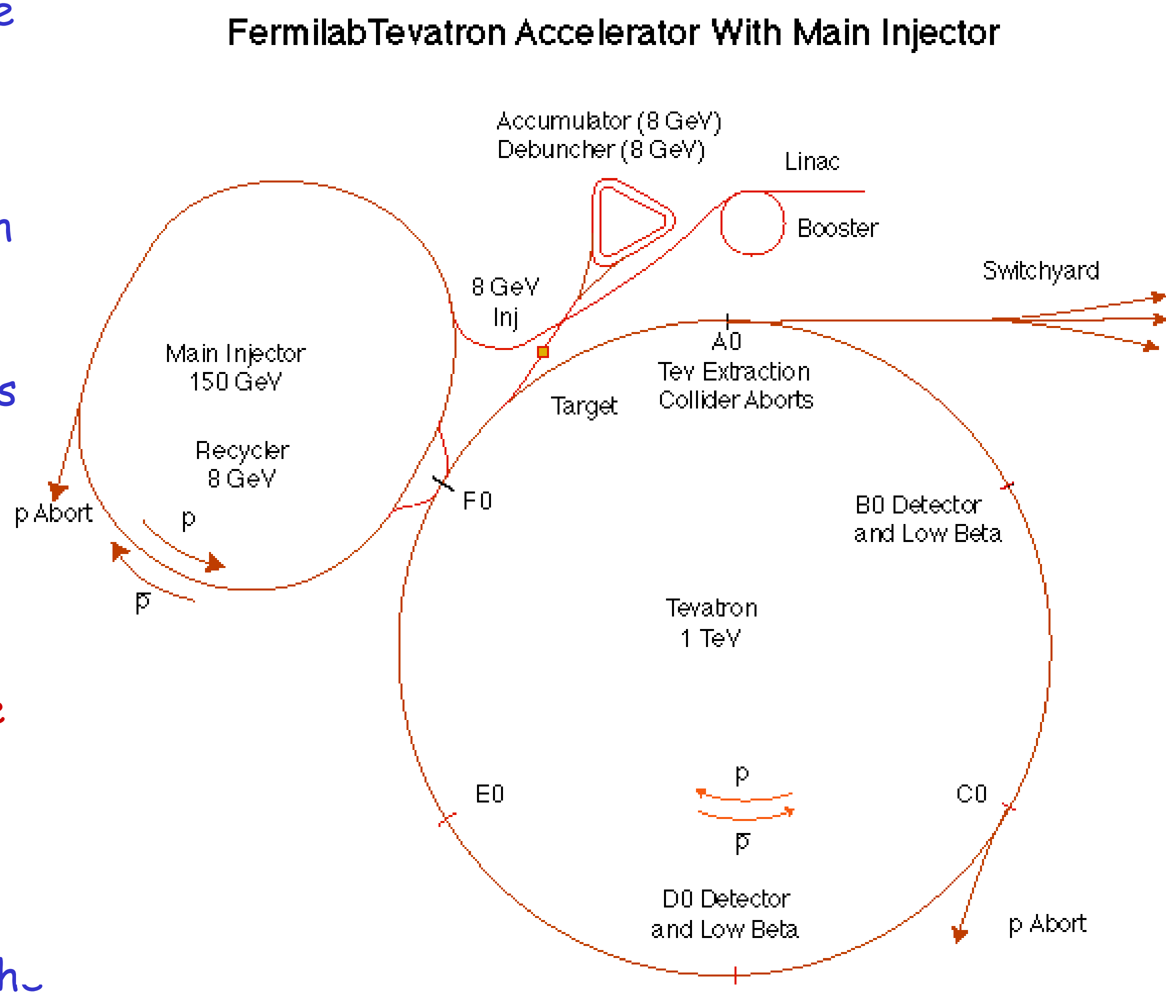
The Fermilab Accelerator Complex

- Proton Production
  - H- ions are accelerated to 750 keV in the Crockoft-Walton
  - H- ions are accelerated to 400 MeV in the Linac
  - H- ions are stripped and multi-turn injected onto the Booster
  - Protons are accelerated from 400 MeV to 8 GeV in 33 mS in the Booster
  - In the Main Injector Protons are accelerated from 8 GeV
    - to 120 GeV for pbar production in 1.5-2.4 seconds
    - to 150 GeV for TEVATRON filling in 3.0 seconds
  - Protons are accelerated from 150 GeV to 980 GeV in the TEV



The Fermilab Accelerator Complex

- Present Antiproton Production
  - 85x10^6 8 GeV pbars are made every 2 seconds by smashing 5x10^{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
  - 18,000 pulses of 8 GeV Pbars are collected, stored and stochastically cooled in the Debuncher and Accumulator 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

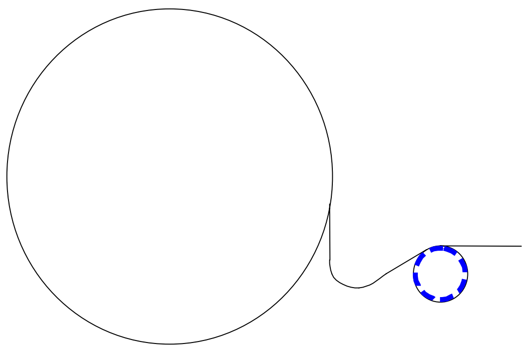


More Protons on Target - Slip Stacking

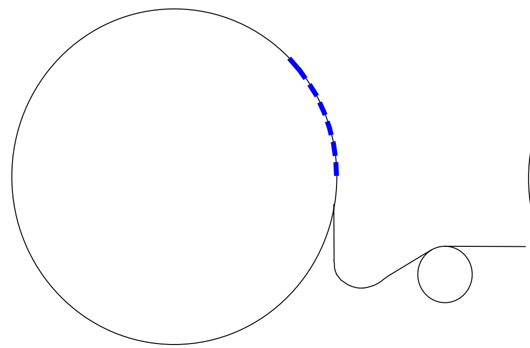
- The intensity of the Proton Source is limited by space charge tune shift at 400 MeV (and other things)
- The available longitudinal phase space in the Main Injector is enormous.
  - Momentum aperture
  - Circumference

Slip Stacking

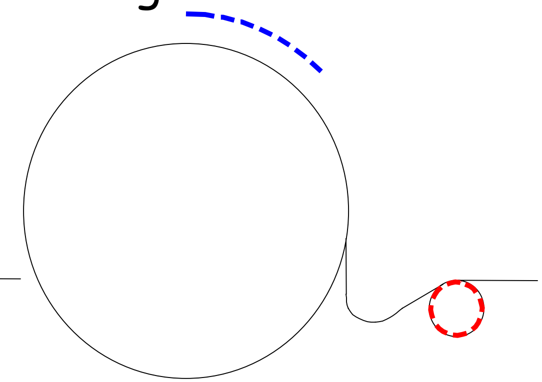
- Slip stacking combines two booster batches into a single batch.



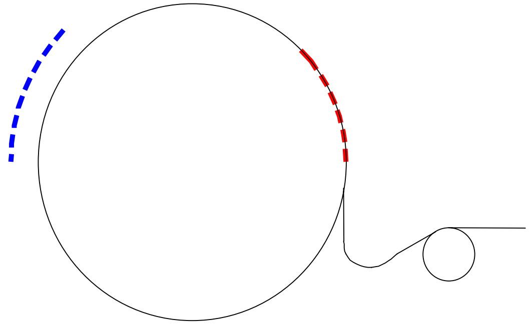
1. First Booster Batch accelerated in Booster



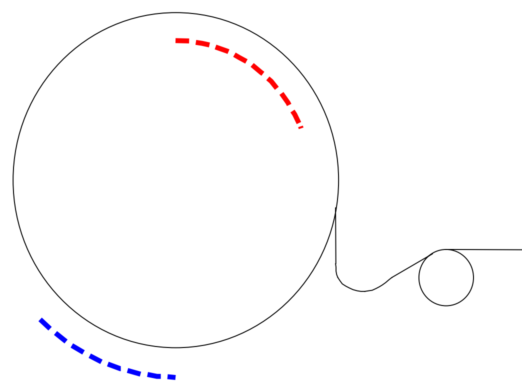
2. First Booster Batch injected onto MI central orbit with RF system *A*



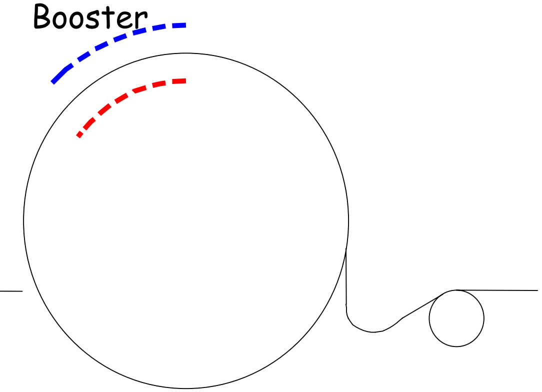
3. First Booster Batch slightly accelerated in MI with RF System *A*. Second Booster Batch accelerated in Booster



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

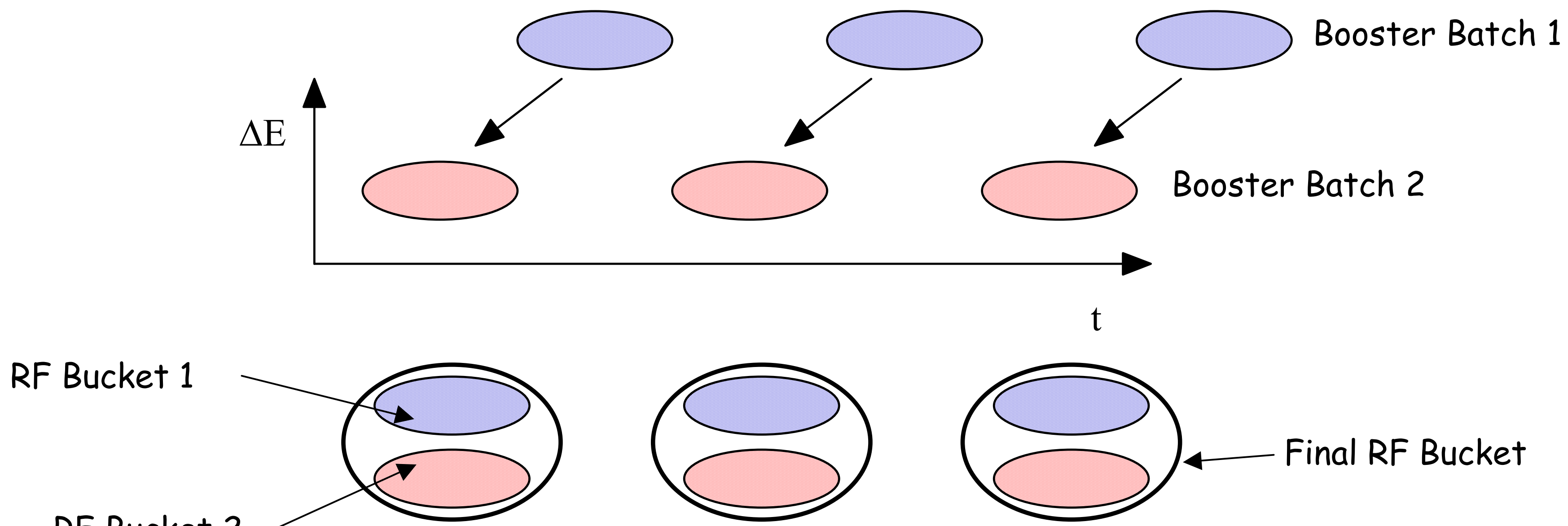


5. Second Booster Batch slightly decelerated in MI with RF System B



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

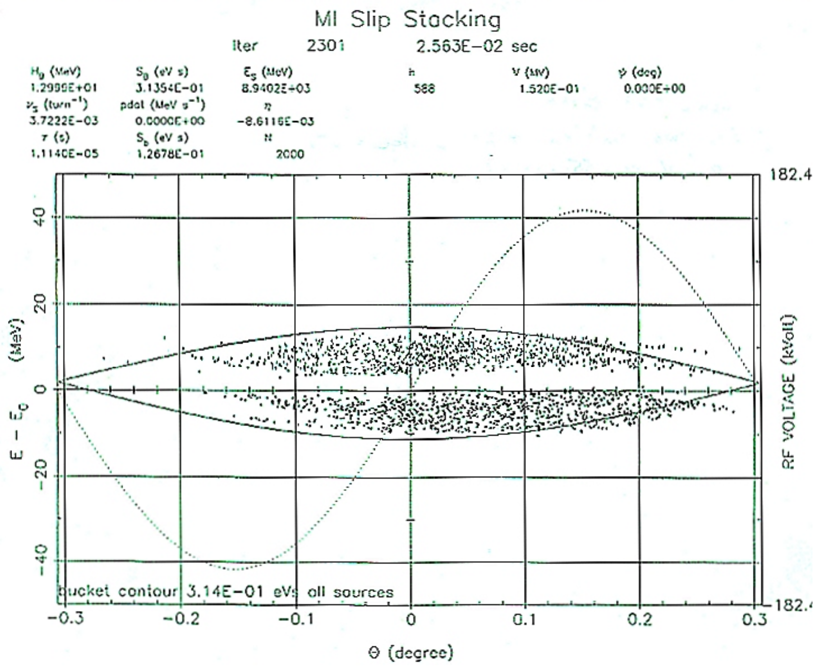
Slip Stacking

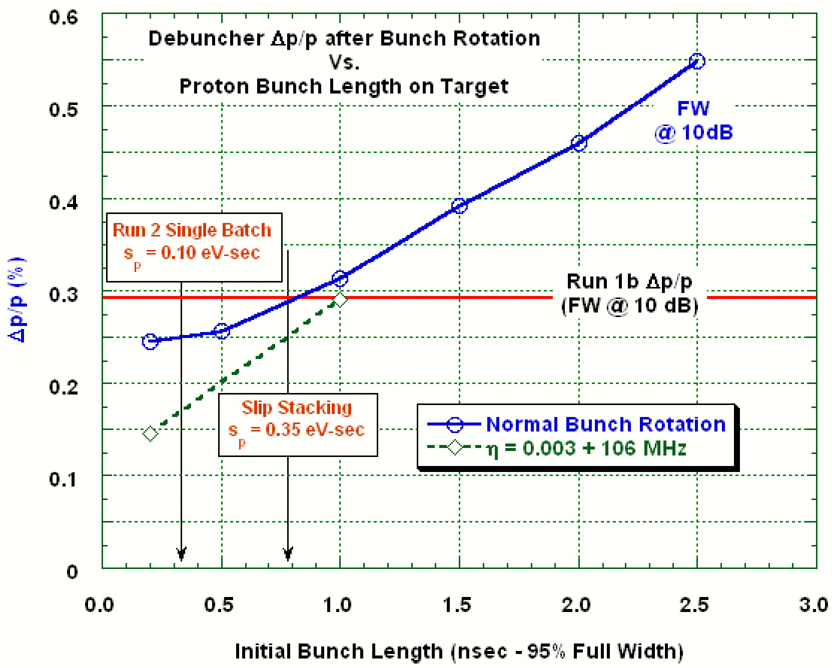


RF Phase Space Cartoon

Slip Stacking

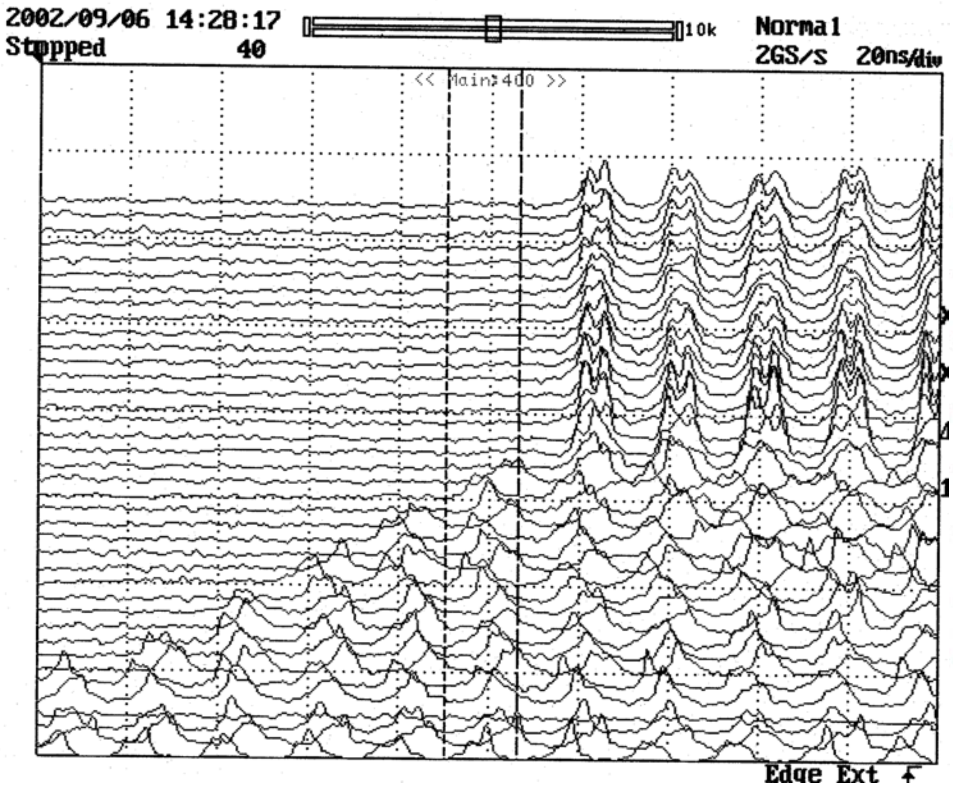
- The increase in longitudinal emittance of the proton beam is "obscured" by non-linearites in the pbar Debuncher bunch rotation.

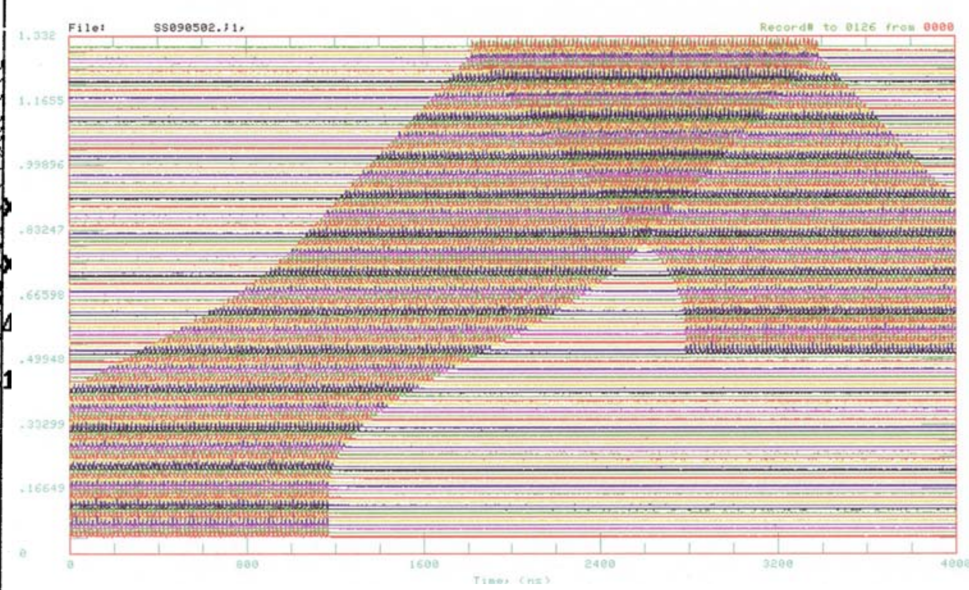




Slip Stacking

- Low intensity slip stacking has been demonstrated in the Main Injector

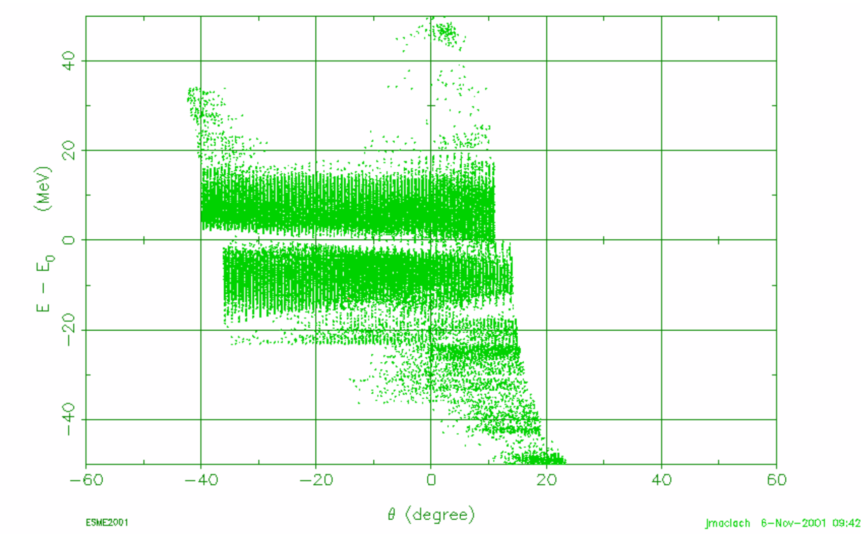




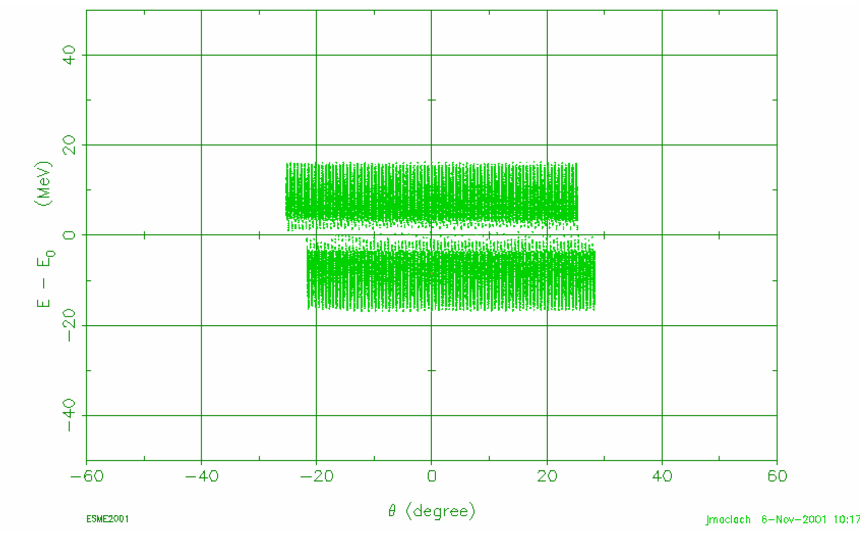
Beam Loading in Slip Stacking

- The ratio of beam-induced voltage to accelerating voltage during slip-stacking will be somewhere between 3-10.
- Effects of high intensity beam-loading have been simulated

Batch phase space without compensation

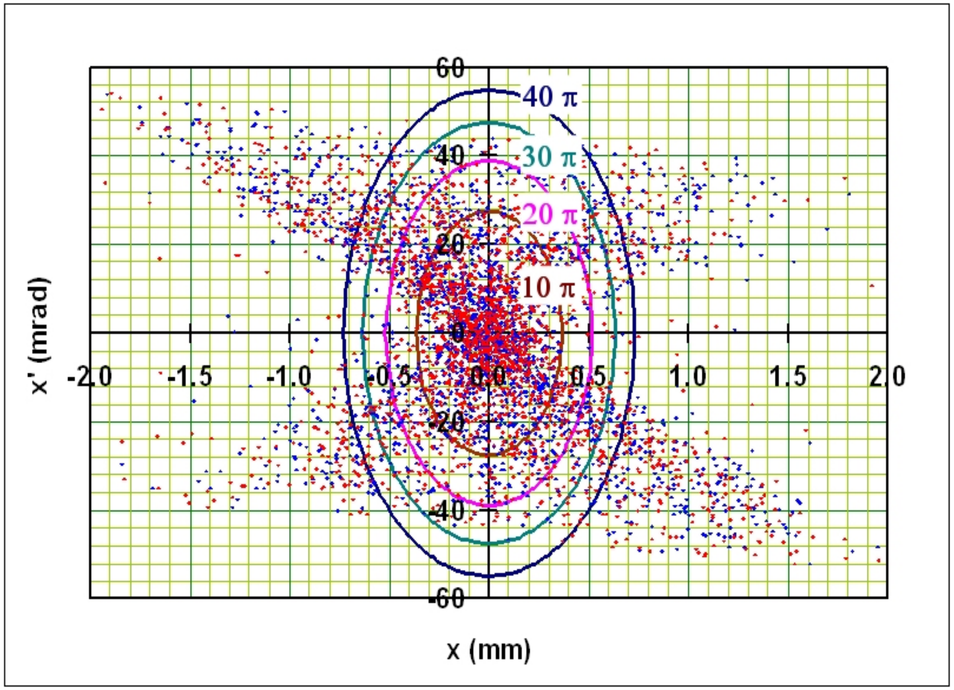


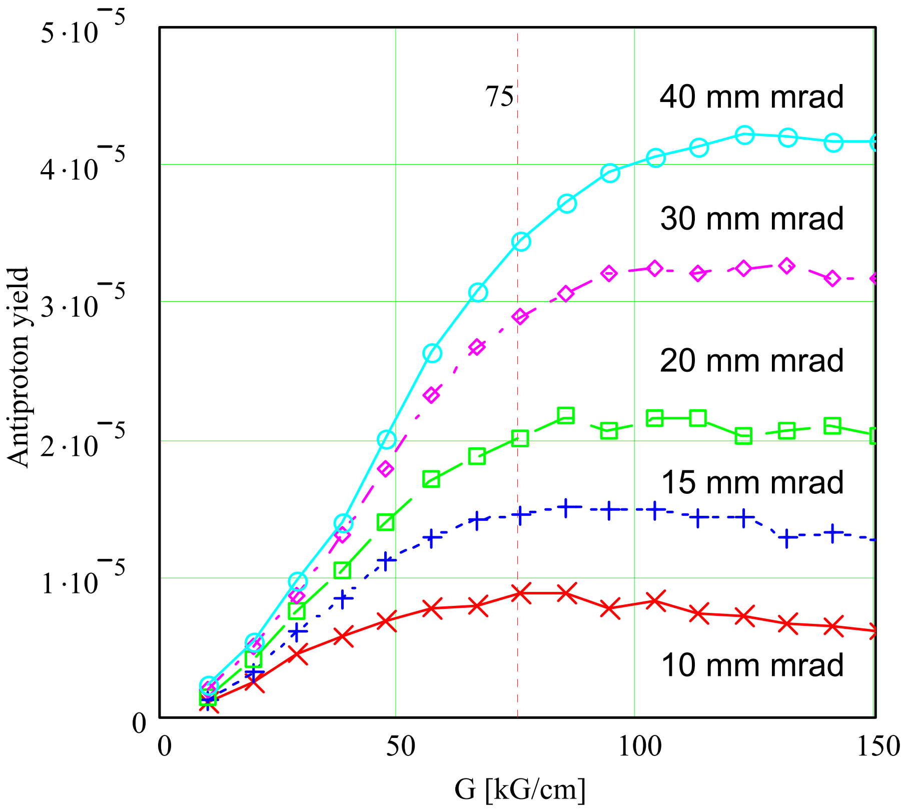
Batch phase space with compensation



- Beamloading compensation using direct RF feedback is necessary
  - 40 dB of loop gain is needed at the fundamental
  - IIR filter is necessary in feedback path for stability

More Antiproton Flux – Antiproton Collection

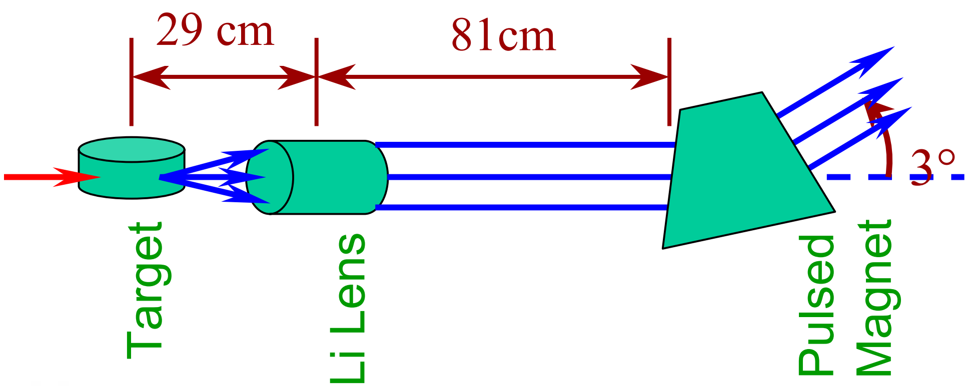


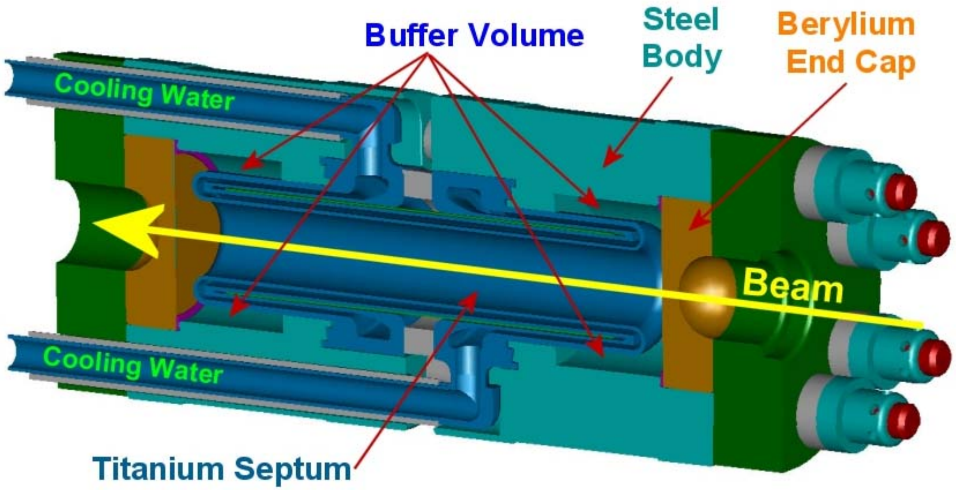


MARS model of `p phase space distribution at the center of the target. D*p*/*p* < 2.25%, contains only `*p*'s within acceptance of Li Lens

More Antiproton Flux - Lithium Lens Upgrade

- TEV 1 design gradient was 1000 T / m
- Catastrophic failures due to component fatigue limits the present gradient to 760 T / m
- Upgrade present lens design to obtain 1000 T / m
  - New fabrication techniques
    - Diffusion bonding, etc.
  - New materials
  - Package re-design
    - better cooling, etc.
  - Lens parameter changes
    - radius, etc. –





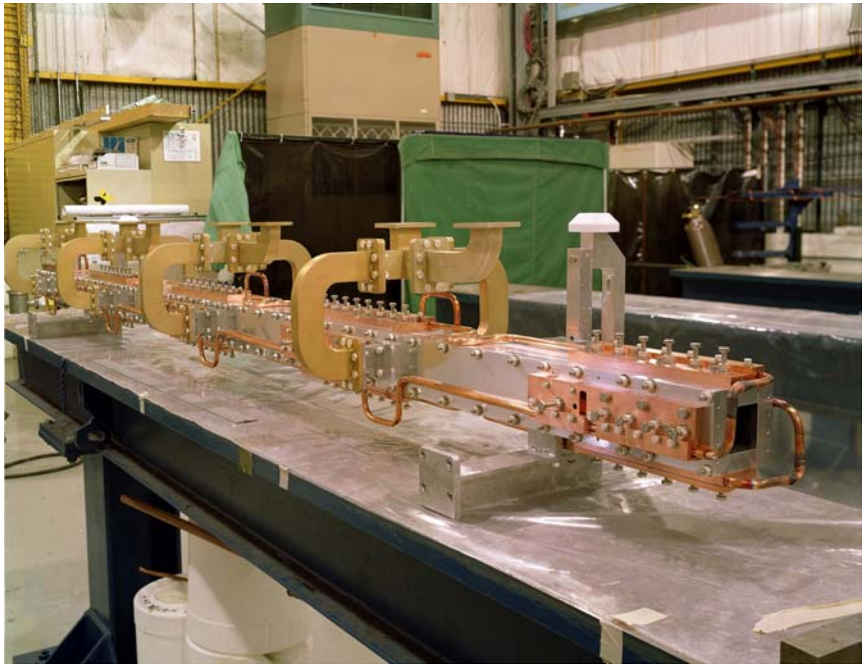
More Antiproton Flux – Antiproton Collection

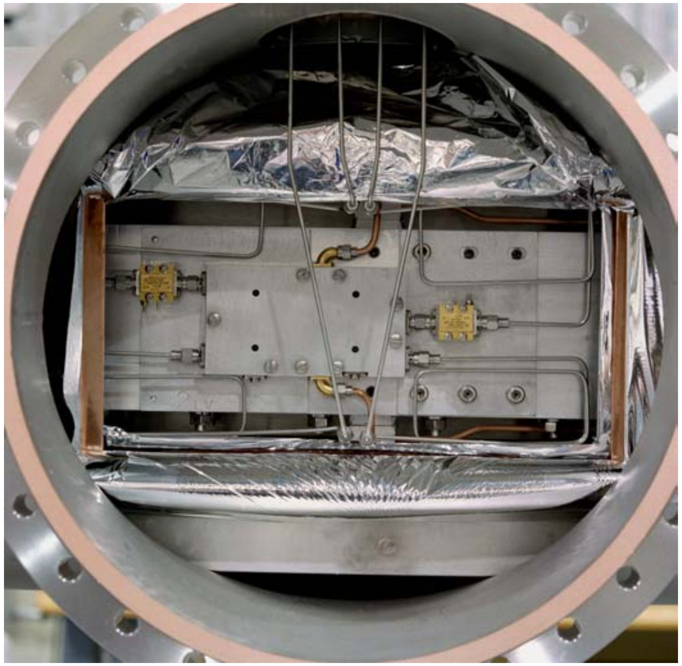
- Increasing the aperture of the antiproton collection transfer line and Debuncher ring by a factor of 2.3
  - Beam based alignment
  - There are only a few small aperture components that need to be replaced
- Identify and correct limiting apertures
  - Alignment
  - Orbit control
    - More AP2 trim dipoles
    - Debuncher moveable quad stands
  - Element redesign
    - Document apertures (existing drawings, survey data, inspection) (FNAL:TD)
    - Review optics and design of AP2→ Debuncher injection region (LBNL)

	Recent Measurements	Nom. Phys. Aperture
Horizontal (mm-mrad)	$20 \pm 1.5\ \pi$	$40\ \pi$
Vertical (π mm-mrad)	$12 \pm 1.5\ \pi$	$40\ \pi$
Momentum	±2.25%	±2.25%

Antiproton Cooling - Debuncher

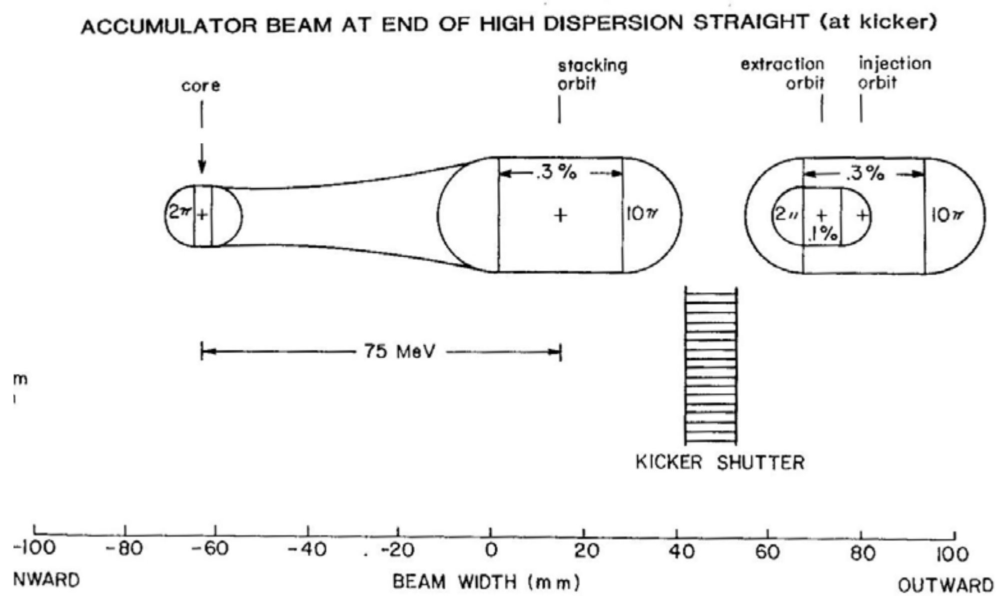
- Debuncher Stochastic Cooling System was designed for very high flux
  - System Configuration
    - Liquid Helium front end (T_{eff}=30K)
    - Bandwidth = 4-8 GHz Subdivided into 4 bands
    - Large available kicker power
  - Dispersion in notch filters limit momentum width
  - Common mode rejection limits transverse cooling gain

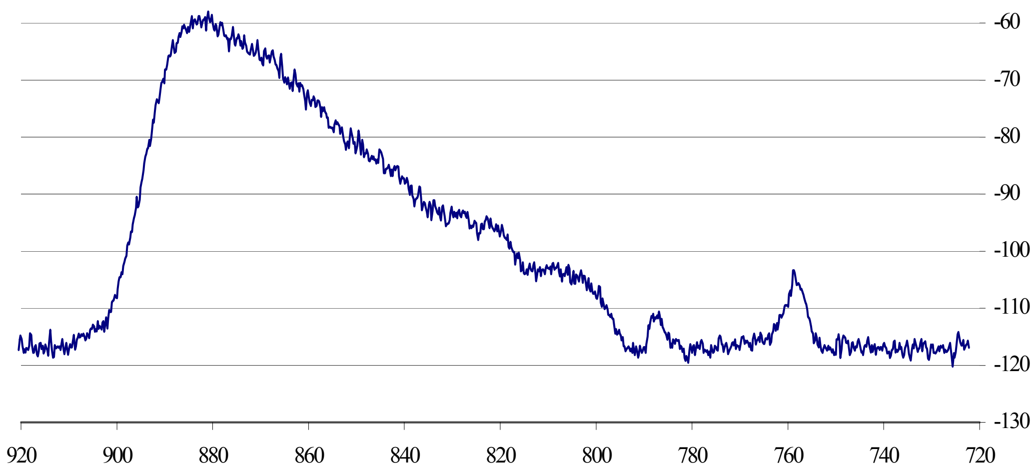




Antiproton Stacking - Stacktail System

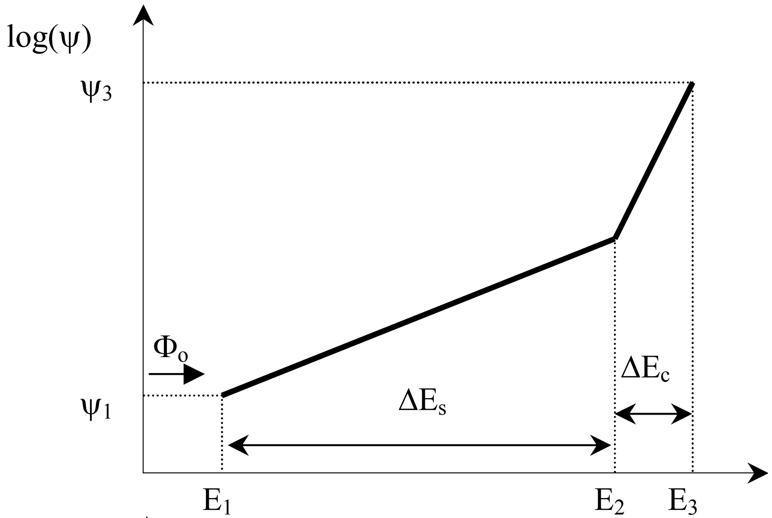
- Beam is injected onto the Injection Orbit
- Beam is
  - Bunched with RF
  - Moved with RF to the Stacking Orbit
  - Debunched on Stacking orbit
- Stacktail pushes and compresses beam to the Core orbit
- Core Momentum system gathers beam from the Stacktail
- Accumulator Transverse Core Cooling system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

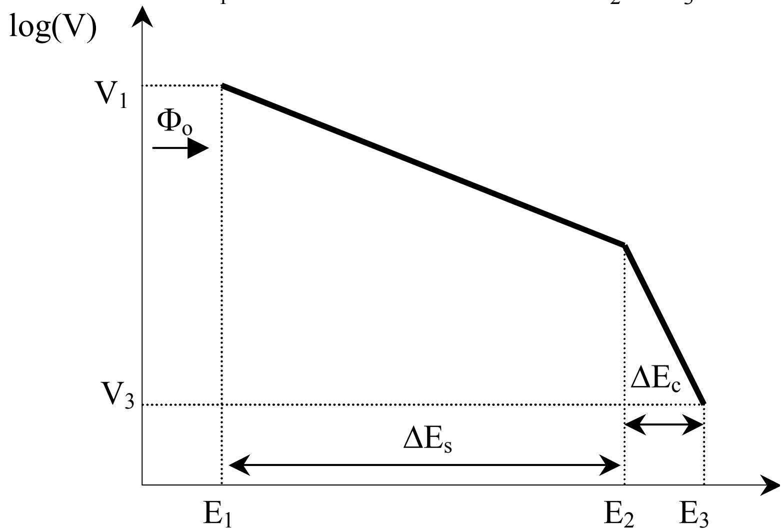




Antiproton Stacking - Stacktail System

- Optimum profile that maximizes $d\psi/dE$ is exponential





$$\psi(E) = -\frac{2\Phi_o}{f_o V(E)} = -\frac{2\Phi_o}{f_o V_i} e^{-\frac{E_i - E}{E_d}} = \psi_i e^{-\frac{E_i - E}{E_d}}$$

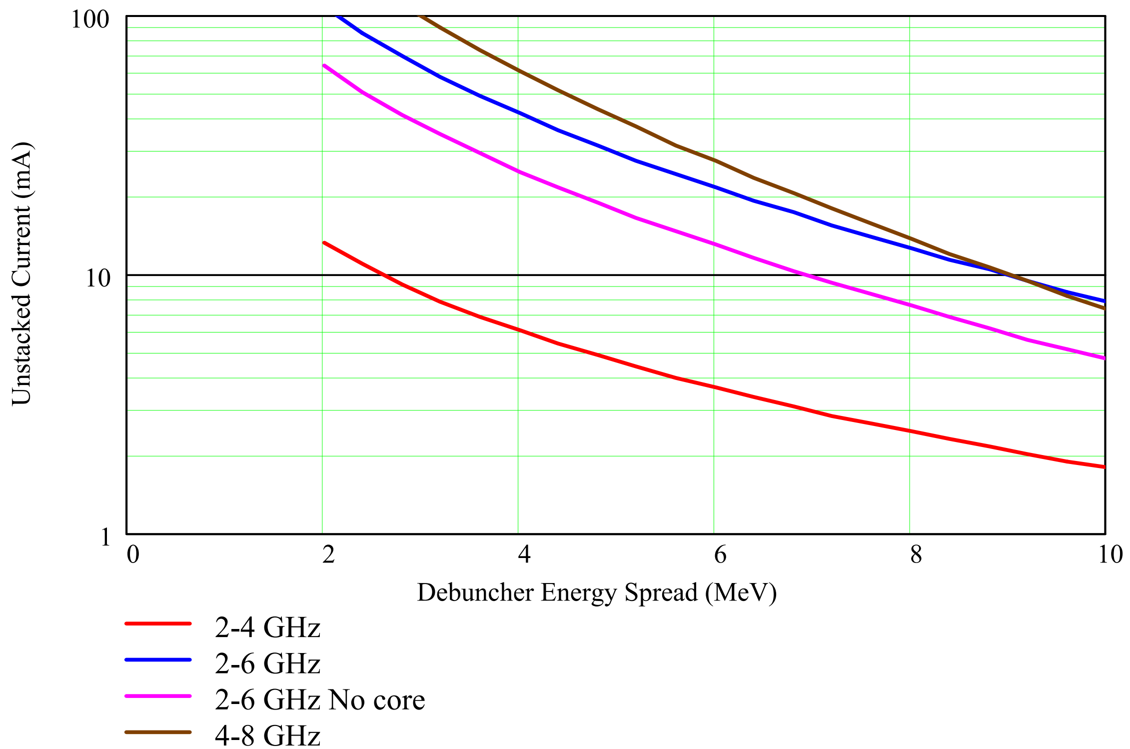
$$\Phi_o = \frac{|\eta| W^2 E_d}{f_o \beta p c \ln\left(f_{max} / f_{min} \right)}$$

Antiproton Stacking - Stacktail System

- The best way to increase flux is to increase the bandwidth

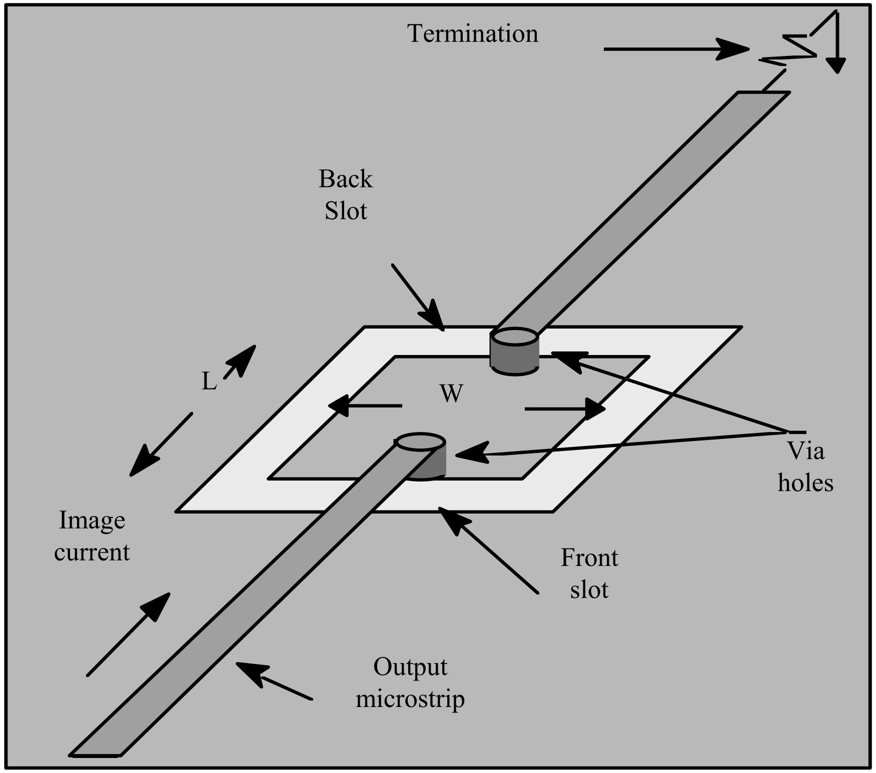
$$\Phi_o = \frac{|\eta| W^2 E_d}{f_o \beta p c \ln\left(f_{max} / f_{min} \right)}$$

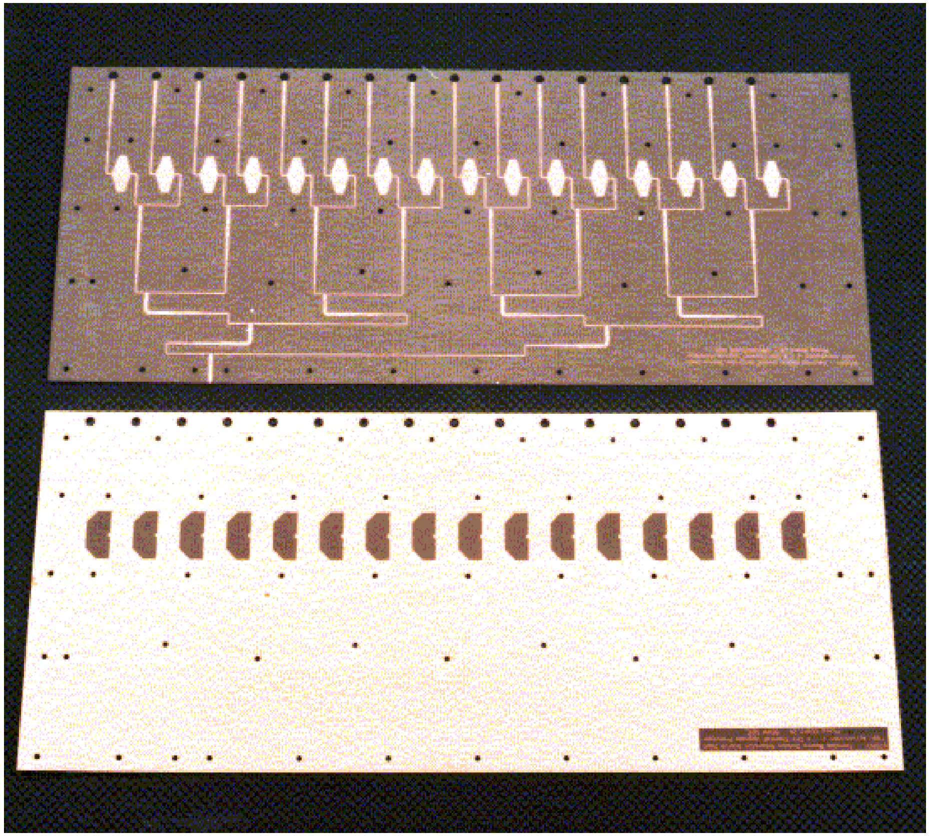
- Increase E_d (decrease gain slope)
  - More Flux
  - Less Cooling
  - Smaller Stacks
  - Transfers often



Antiproton Stacking – Stacktail System

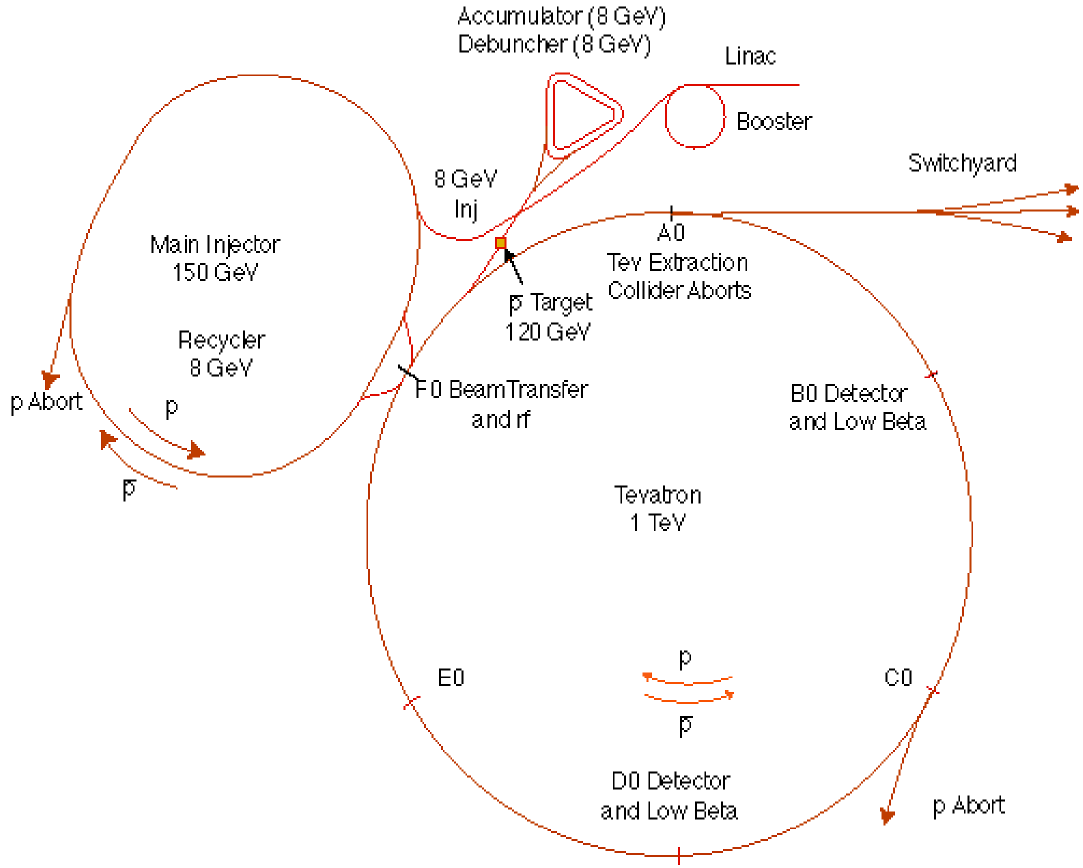
- Will increase Stacktail bandwidth from 2-4 GHz to 2-6 GHz
  - Adding a 4-6 GHz Planar Loop System
  - Design has been simulated to stack above 70×10^{10} pbars/hour
- Will transfer 22×10^{10} pbars to the Recycler every 30 minutes for 10 hours





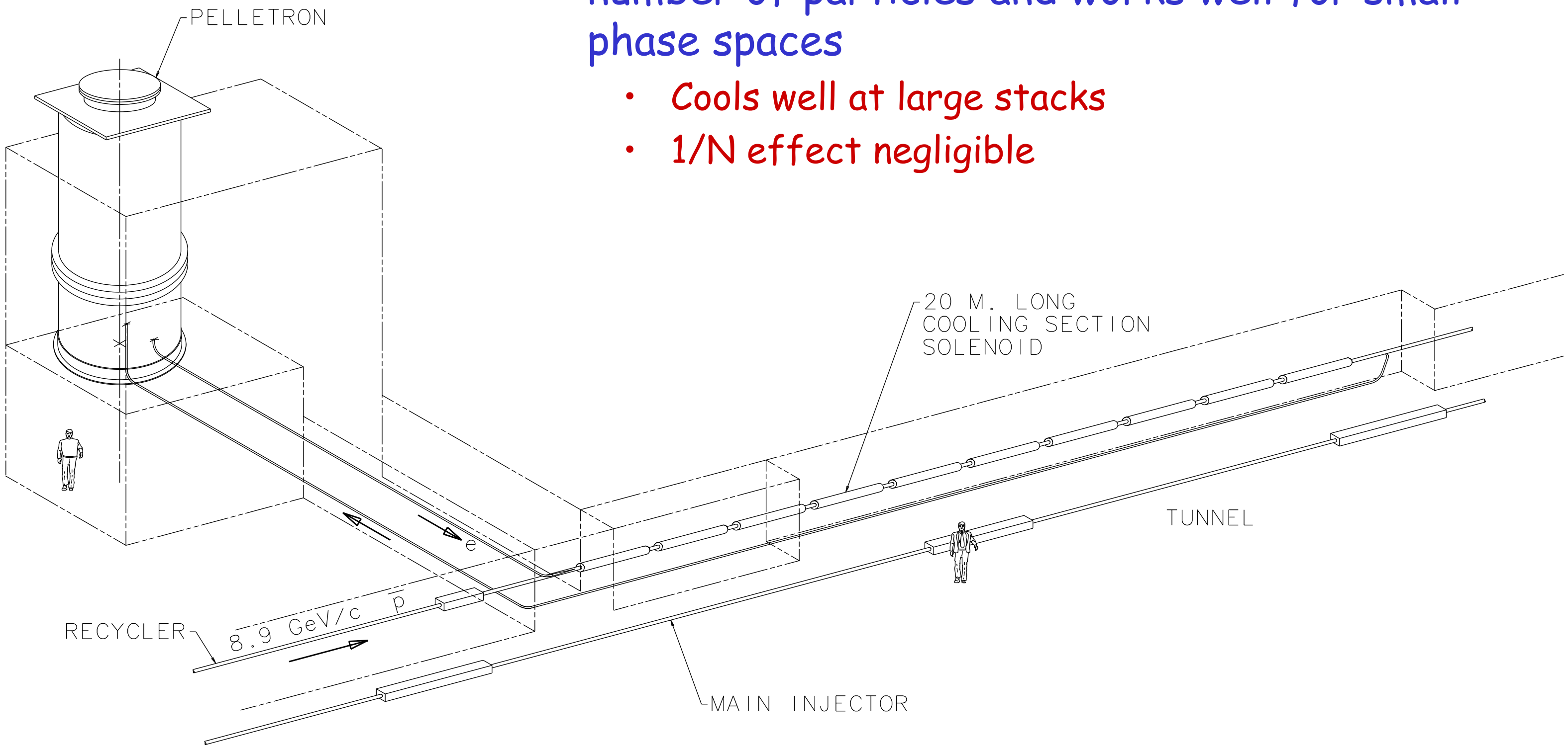
Handling More Antiprotons

- Streamline and improve antiproton transfers between the Accumulator and the Recycler
  - Construction project undesirable for Run II
  - Optimize optics
  - Optimize controls
  - Implement better hysterisis protocols
  - Pbar Injection dampers



Cooling Large Antiproton Stacks

- Implement high energy electron cooling in the Recycler Ring
  - Stochastic cooling works well for small numbers of particles and large phase spaces
  - Electron cooling is fairly independent of the number of particles and works well for small phase spaces
    - Cools well at large stacks
    - 1/N effect negligible



Cooling Large Antiproton Stacks

- Completed Pelletron tests with U-bend
  - Meet specs except for recirculating stability:
    - @500mA spec<5min recovery per hour
    - actual~20sec per 4min @ design energy 4.3MeV, per 20 min @3.5MeV
    - →at spec, but trips too frequent
  - Additional 1MeV stage for Pelletron ordered to reduce field and improve operating stability

- Building beamline at wideband
- MI-31 construction underway
- Move to MI-31 in one year,add 6th stage to the Pelletron and commission with U-bend
- Install beamline in MI tunnel summer 04

Cooling section: nine 2m long solenoids supported from the tunnel ceiling

TEVATRON Beam-Beam compensation

- TEVATRON modeling
  - Parametric
  - Beam-Beam
  - Optics
  - Instabilities
- Larger Separation
  - Improved Ramp Helices
  - Adding new separators to correct the betatron phase imbalances along the machine
  - More Separator Strength at 980 GeV
    - Increasing voltage on the near IP separators in 1.4 times
      - Increasing voltage
      - Increasing length
        - We can use the space where non-powered Q1 quads are presently located

TEVATRON Active Beam-Beam compensation

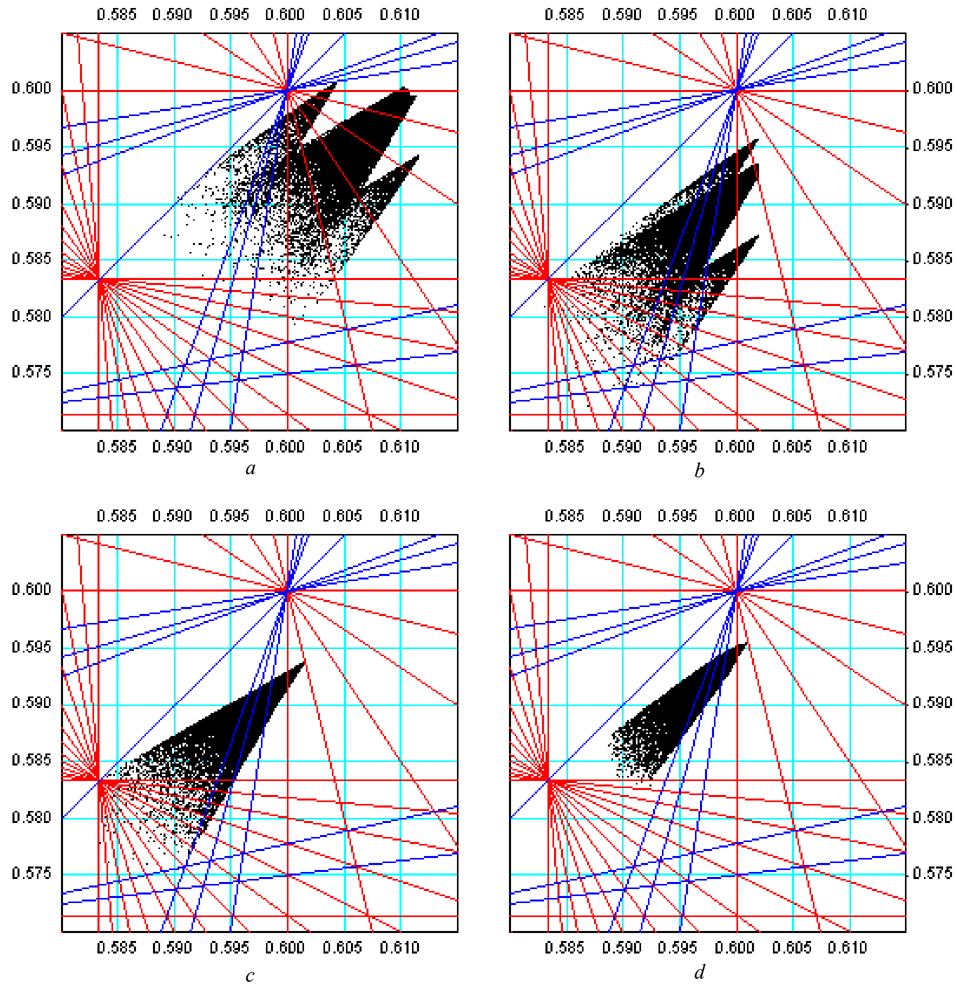
- Tevatron electron lens can reduce both long range and head-on tune shifts

No Lens

One linear Lens

Two Linear Lenses

Two non-Linear Lenses



TEVATRON Active Beam-Beam compensation

- Recently we achieved electron lens operation without degradation of the beam lifetime
- One TEL installed and used operationally to clean the abort gaps
- Gun and magnets upgraded in Jan shutdown
- Studies of proton tune shifts:
  - p lifetime at good WP ~160 hrs and tuneshift ~ 0.005
- Next:
  - Explore use of TEL for 150, ramp and squeeze
  - Study pbar tune shift and lifetime
  - → decision on building second TEL
- Also investigating use of wire compensation (as proposed for LHC)

Summary

- Key to Luminosity Upgrades is Pbar Production
  - Pbar Burn Rate
  - Beam-Beam Issues in the TEVATRON
- Pbar Production needs to be increased to 40×10^{10} per hour
  - More protons on target
  - Bigger Pbar Collection Aperture
  - High flux stochastic cooling
  - Electron Cooling
- Detailed Talks on
  - Slip Stacking
  - Antiproton Collection
    - Lithium Lens Upgrade
    - AP2 & Debuncher Aperture
  - Cooling Issues
    - Debuncher Stochastic Cooling
    - Accumulator Stochastic Cooling
    - Electron Cooling
  - TEVATRON Issues