Overview of Run II Upgrades Beyond FY03

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DOE Review

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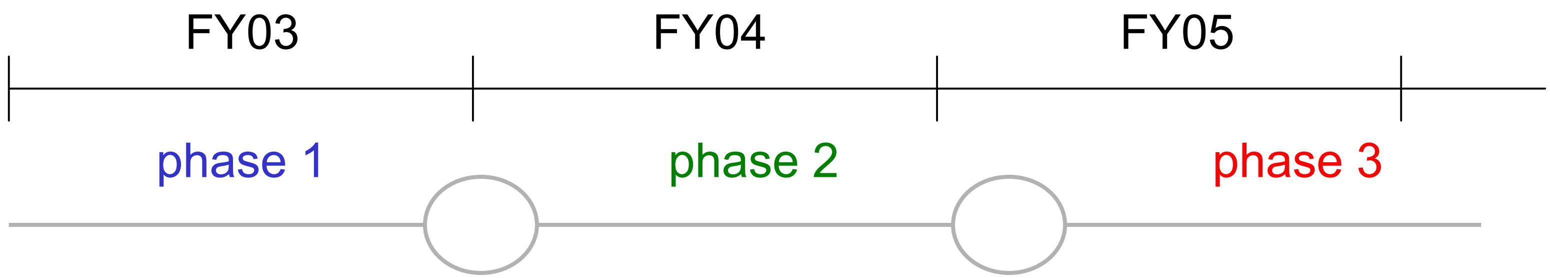
Upgrades Beyond FY03 (a.k.a Run IIb)

- Run IIb includes a specific set of projects, documented for the Dec 01 AAC meeting*, to extend the luminosity to 2-4 x 10^{32} $cm^{-2}sec^{-1}$
- Jeff Spalding is the project manager. Dave McGinnis is the technical coordinator
- Work with Mike Church to develop an integrated plan for Run IIa and IIb
  - Define the scope and resources needed
  - Integrate resource loaded schedule with the RLS for FY03
  - Phased approach as resources roll-off "Run IIa", and as the subprojects go through development and commissioning
- The components of the plan are:
  - Proton accumulation (slip stacking) in Main Injector
  - Antiproton yield improvements
    - Lithium Lens gradient upgrade
    - AP2-Debuncher Aperture upgrade
  - Antiproton stochastic cooling improvements
  - Electron cooling in the Recycler
  - Rapid antiproton transfers between the Accumulator to the Recycler
  - Tevatron beam-beam compensation

* http://www-bd.fnal.gov/doereview02/RunIIBTDR.pdf

Run II Timeline



- accumulator stacking - increase to 18 E10/hr and 200 E10
- commission RR late FY03

RR in Tevatron operation

- stack size increases to >200
- slip stacking commissioned
- first phase for rapid transfers (few hours)
- initial stacktail cooling changes for increased stack rate
- e-cooling installed and commissioned in MI

slip stacking, e-cooling and rapid transfers (<1 hr)

- e-cooling in operation
- rapid pbar transfers
- stacktail cooling optimized for rate

- Recycling from Tevatron
- beam-beam compensation
- Luminosity leveling

Run II Luminosity Goals

- Goal for early Run II
  - Accumulate 0.7 – 1.0 fb^{-1} by the end of FY04
  - Peak luminosity between 6.0-8.0x10^{31} $cm^{-2}sec^{-1}$ with the present complex
  - Peak luminosity between 8.0-10.0x10^{31} $cm^{-2}sec^{-1}$ with the Recycler
- Goal for Run II
  - Accumulate ~10 fb^{-1} before the LHC physics startup
  - Peak luminosity between 2.0-4.0x10^{32} $cm^{-2}sec^{-1}$
    - Increase antiproton intensity by a factor of 2-3
    - The Recycler is a prerequisite
  - Base plan for Run II
    - continue operating with 36 bunches and no crossing angle
    - 103 bunch operation with crossing angle is maintained as an option if required by the experiments

Luminosity Formula

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

The major luminosity limitations are

- The number of antiprotons ($BN_{\bar{p}}$)
- The proton beam brightness (N_p/ε_p)
- $F<1$

Antiproton Economics

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

- $n_c = 2$
- $\sigma_a = 70$ mb
- $L = 4.0 \times 10^{32}$ cm^{-2}-sec^{-1}
- $\Phi = 20 \times 10^{10}$ hr^{-1}

Run II Parameters

Run	Run Ib (Final)	Run II (now)	Run II FY04	Run II (Final)	
Typical Luminosity	1.6	3.6	8.0	39.2	$x10^{31}cm^{-2}sec^{-1}$
Integrated Luminosity	3.1	4.2	14.6	87.9	pb^{-1}/wk
Interactions/crossing	2.5	0.9	2.1	10.2	
Pbar Bunches	6	36	36	36	
Form Factor	0.59	0.63	0.70	0.70	
Protons/bunch	23.0	17.3	27.0	27.0	$x10^{10}$
Pbars/bunch	5.6	2.4	3.0	14.8	$x10^{10}$
Pbars lost in collisions	8.4	15.5	28.0	142.4	$x10^{10}$
Total pbars	33.6	85.2	108.2	531.3	$x10^{10}$
Stack Size	67.2	131.1	132.0	625.1	$x10^{10}$
Peak Pbar Prod. Rate	7.0	11.5	20.0	45.0	$x10^{10}$/hr
Avg. Pbar Prod.Rate	4.2	6.9	12.0	39.2	$x10^{10}$/hr

Run	Run Ib (Final)	Run II (now)	Run II FY04	Run II (Final)	
Store Hours	84	72	80	95	per week
Pbar Transmission Eff.	50	65	82	85	%
Recycling efficiency	0	0	0	50	%
Pbar Utilization	12	12	21	33	%
β^*	35	35	35	35	cm
Bunch Length (rms)	0.6	0.54	0.43	0.43	m
Energy	900	980	980	980	GeV
Bunch Spacing	3500	396	396	396	nS
Proton Emittance	23	20	20	20	π-mm-mrad
Pbar Emittance	13	15	15	15	π-mm-mrad
Luminosity lifetime	17	10	11	12	hr
Store Length	16	19	11	11	hr

- Consistent with Steve's "stretch goals" ($3fb^{-1}$/yr FY07 & FY08)
- The Run II Final luminosity represents the complex's inherent capability
  - If the experiments limit the number of interactions per crossing, we may utilize luminosity leveling to a peak of $2x10^{32}cm^{-2}\ sec^{-1}$ with an integrated luminosity of ~75 pb^{-1}/week (http://www-bd.fnal.gov/doereview02/Team132Report.pdf)

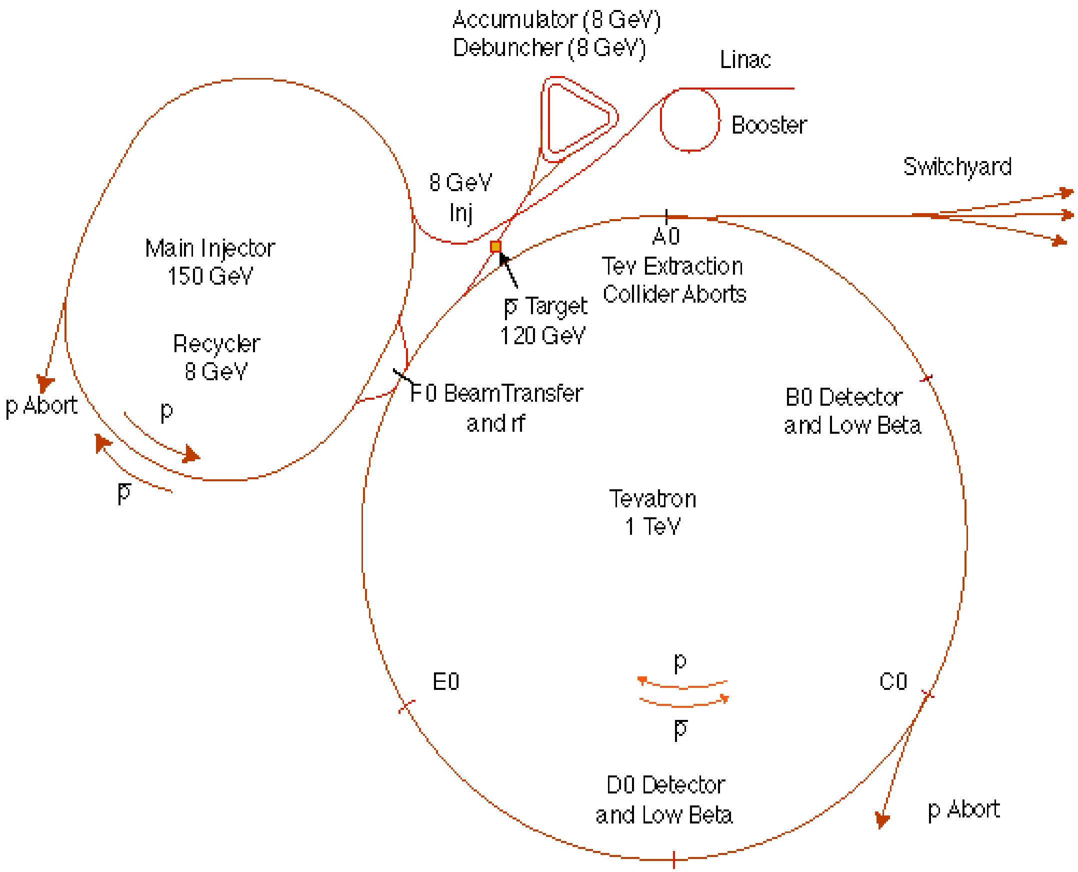
The Upgrade Plan

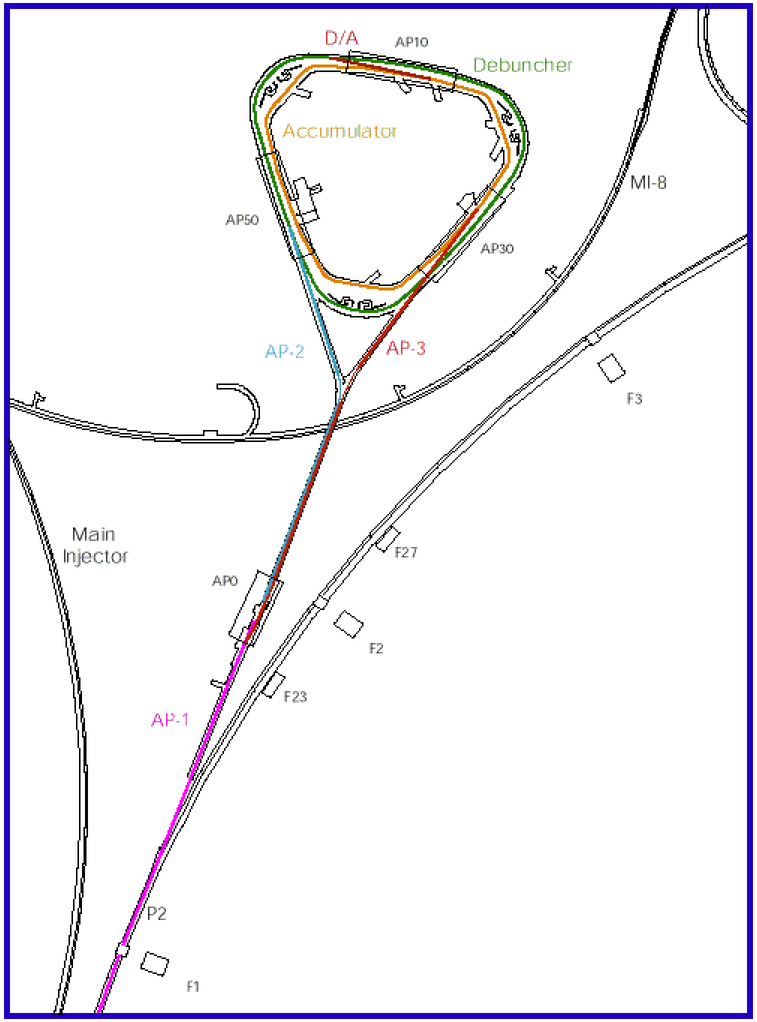
- To reach $4x10^{32} cm^{-2} sec^{-1}$ we need to increase the number of antiprotons in the collider by a factor of five over the initial Run II goal.
- The Recycler is designed to provide a factor of two increase in the number of antiprotons
  - Third stage of cooling (1.4x)
  - Recycling (1.4x)
- An additional 2-3x increase in the number of antiprotons in the collider will result from the upgrades outlined in this talk.
- These upgrades must occur.
  - without major interruption to Run II
  - within a period of 2-3 years
  - with a budget of about ~$30 M

The Upgrade Plan

- Design Strategy
  - Increase the Antiproton Flux
    - Increase the number of protons on the antiproton production target by slip-stacking (1.5x, operational FY04)
    - Increase the antiproton collection efficiency by:
      - Increasing the gradient of the antiproton collection lens (1.3x, operational late FY04)
      - Increasing the aperture of the antiproton collection transfer line and Debuncher ring (2.3 x, operational FY03 – FY05)
  - Cool the increased antiproton flux
    - Increase the antiproton flux capability of the Accumulator Stacktail momentum cooling system. (Gradual integration starting mid FY04 thru mid FY05)
    - Implement electron cooling in the Recycler Ring. (operational early FY05)
    - Streamline and improve antiproton transfers between the Accumulator and the Recycler. (Stage 1 operational early FY04 with Recycler integration. Stage 2 operational in early FY05)
    - Compensate bunch-by-bunch tune-shifts in the TEVATRON with a pulsed electron lens. (operational mid FY06)

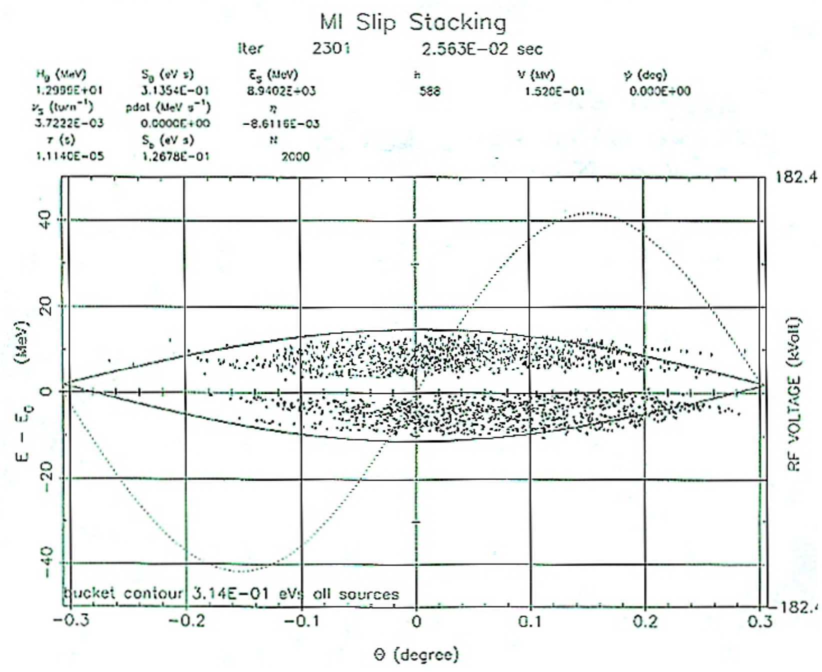
The Fermilab Accelerator Complex

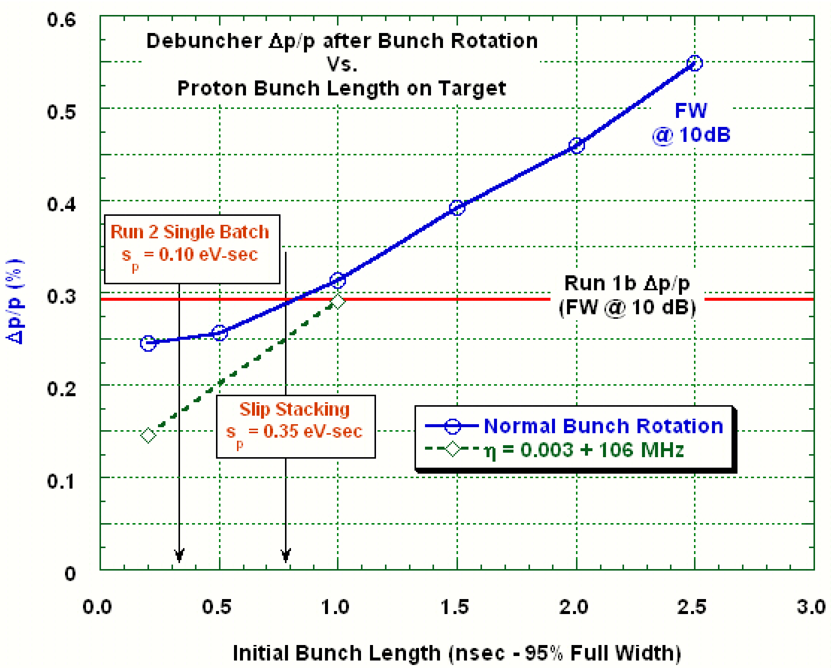




More Antiproton Flux – Slip Stacking

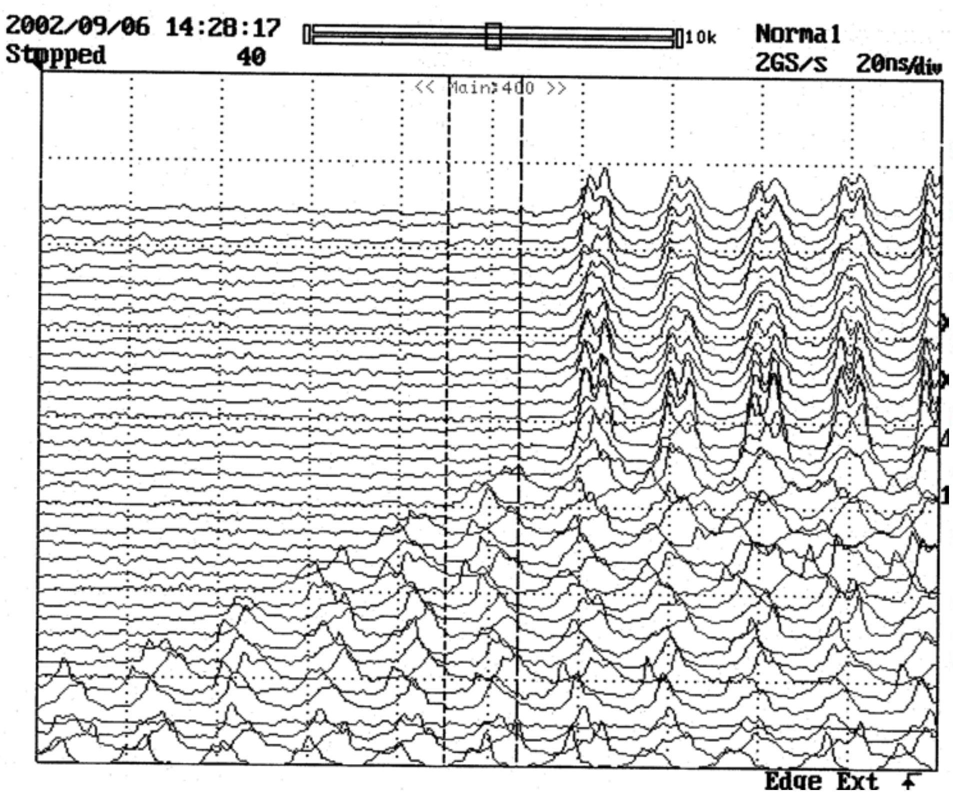
- Increase the number of protons on the antiproton production target by a factor of 1.8 by slip stacking two Booster batches in the Main Injector. (The extra Main Injector cycle time required for NUMI will reduce this factor to 1.5)
- The increase in longitudinal emittance is not an issue because of non-linearities in the antiproton debunching process

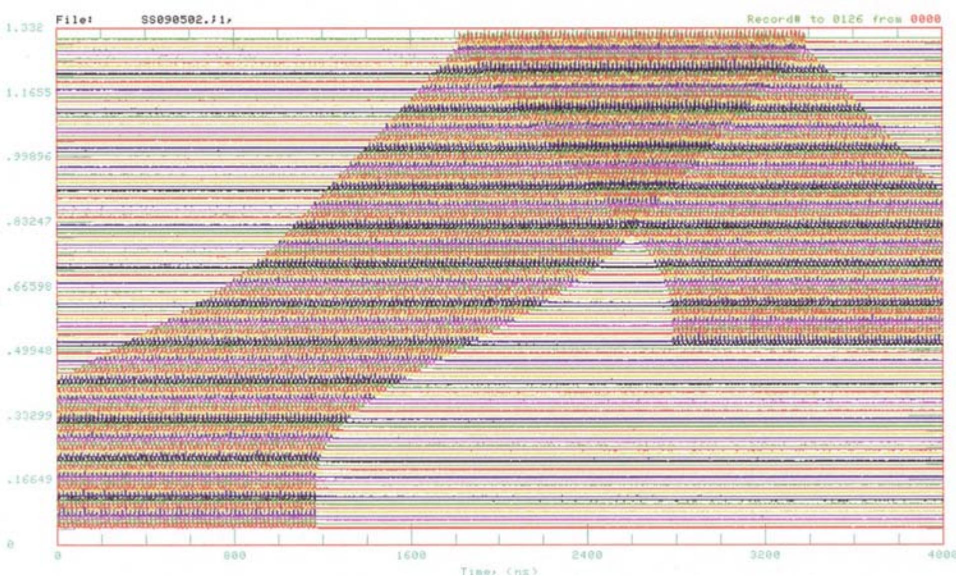




Slip Stacking Progress

- Slip Stacking has been demonstrated in the Main Injector
  - All the low level RF hardware needed for slip stacking is operational.

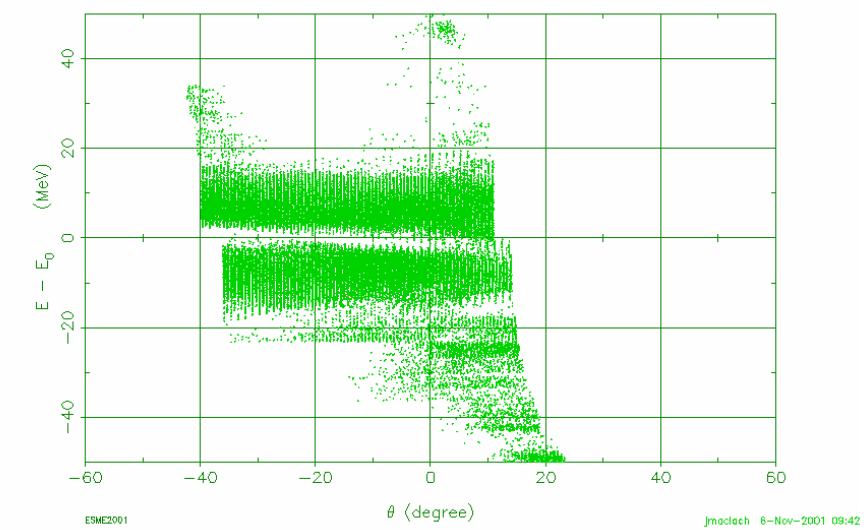




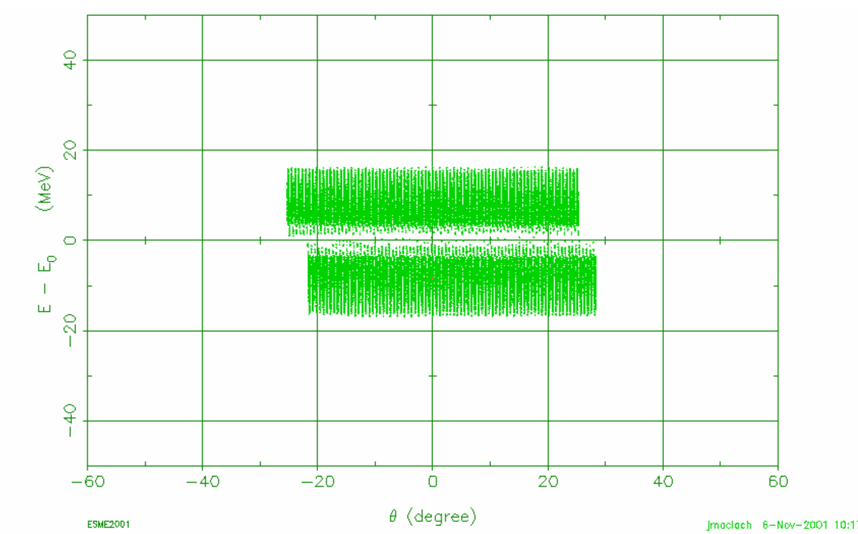
Slip Stacking Progress

- Effects of high intensity beamloading have been simulated
  - 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
  - Initial beamloading compensation systems are operational in the Main Injector
    - Direct RF feedback with no IIR filter with ~23dB of gain is installed on each of the eighteen 53 MHz Cavities
    - Proton and Pbar feed-forward systems are operational.
      - 20 dB of rejection is obtained on the mode 1 lines

Batch phase space without compensation

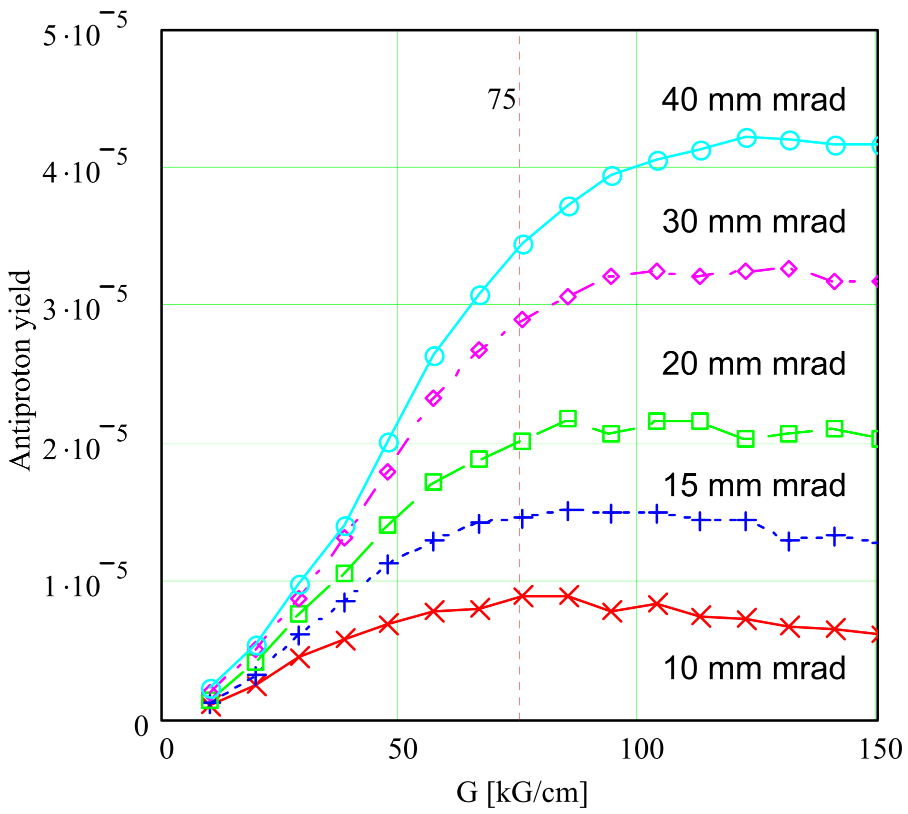


Batch phase space with compensation



More Antiproton Flux – Antiproton Collection

- Increase the antiproton collection efficiency by a factor of 2.0 –2.7 by:
  - increasing the gradient of the antiproton collection lens by 30%
  - Increasing the aperture of the antiproton collection transfer line and Debuncher ring by a factor of 2.7
    - Beam based alignment
    - There are only a few small aperture components that need to be replaced



Antiproton Target Station Progress

- New Target Optics
  - 1st pass Lattice Design complete
- Target Material Study
  - Inconel 600 study complete
  - Inconel 625 study in progress
- Target Sweeping
  - Rebuild complete
  - Pulse testing in progress
  - Installation during January '03 shutdown
- Lithium Lens Upgrade
  - Assembly process upgrade
    - Chemical processing
    - Pre-load studies
    - DAQ
  - Diffusion Bonded Lens Prototype
    - Prototype #1 to be filled within next month and tested to failure
    - Prototype #2 fabrication in process.

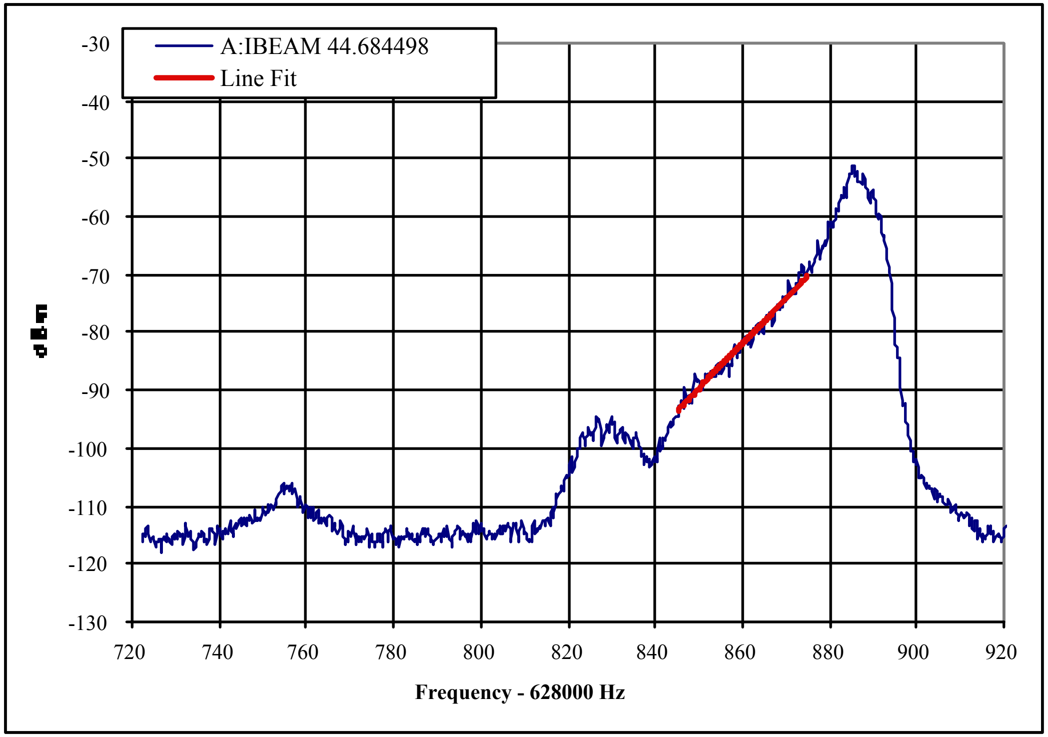
AP2-Debuncher Aperture Progress

- New trims in the AP2 line
  - To be installed in January 03 shutdown
- Moveable Debuncher Quad stands
  - 10 of thirty fabricated – to be installed in January '03 shutdown
- Debuncher BPM Upgrade
  - Prototype testing completed.
  - Full system to be installed in Spring of '03.
- AP2 Debuncher Aperture Upgrade
  - Largest single component of future upgrades – possible increase in production efficiency 2.3x
  - Three accelerator physicists are assigned (Gollwitzer, Werkema, Derwent)
  - Three engineering physicists are assigned (Vander Meulen, Sondgeroth, Budlong)
  - Beam Study plan has been developed.
  - Collaboration with Technical Division forming.

Handling More Antiprotons

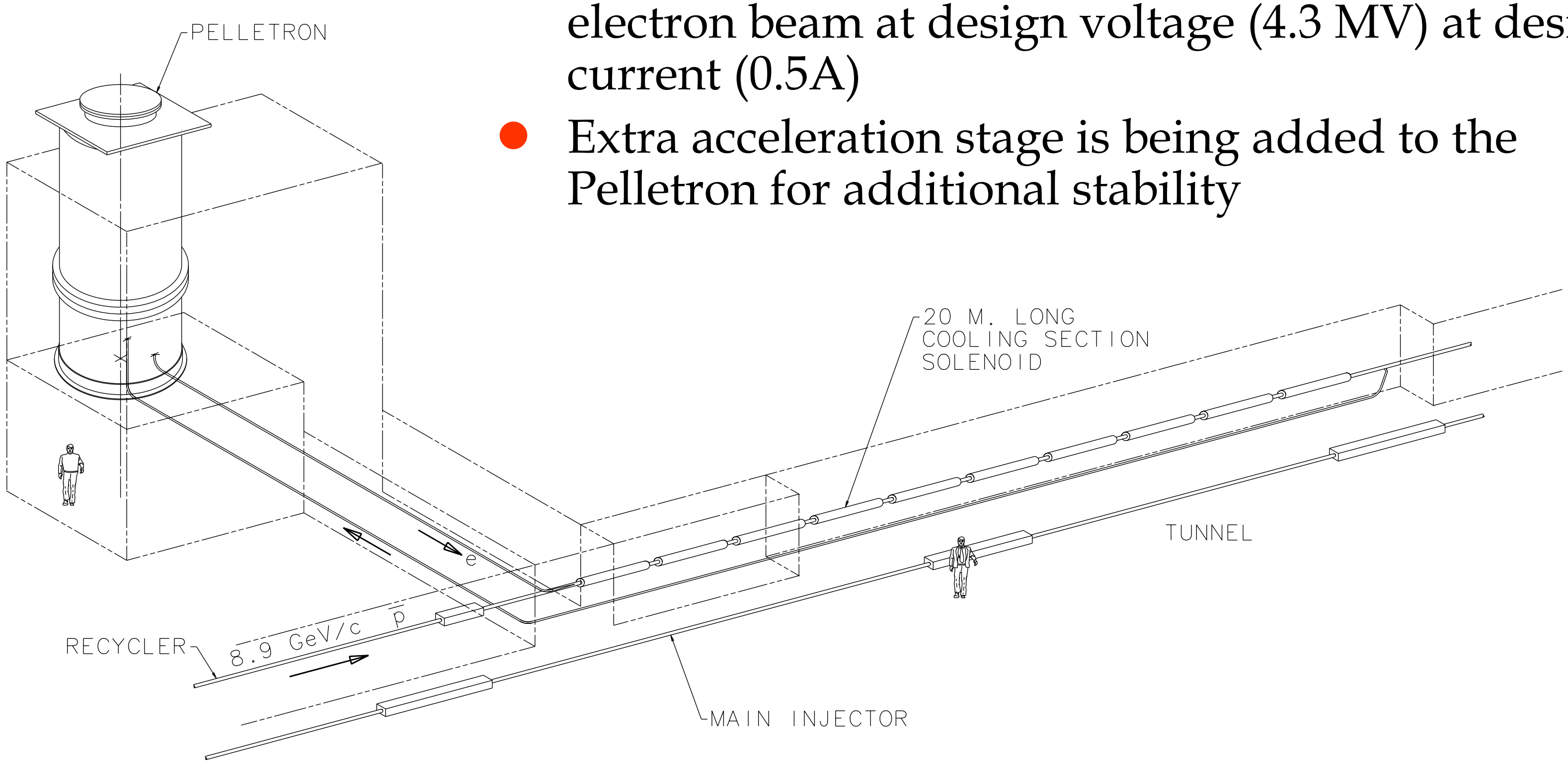
- The Debuncher 4-8 GHz Cooling systems were designed to handle large Run 2 pbar fluxes
- Increase the antiproton flux capability of the Accumulator Stacktail momentum stochastic cooling system
  - Increase E_d (decrease gain slope)
    - More Flux
    - Less Cooling
    - Smaller Stacks
    - Transfers often
  - Design has been simulated to stack above 90×10^{10} pbars/hour
  - Design requires no new tunnel hardware
    - Can be implemented in a "graded" approach
  - Increased system bandwidth to 6 GHz currently being investigated

$$\Phi = \frac{W^2 \eta E_d}{f_0 p \ln\left({}^{F_{\min}}\!/_{F_{\max}}\right)}$$



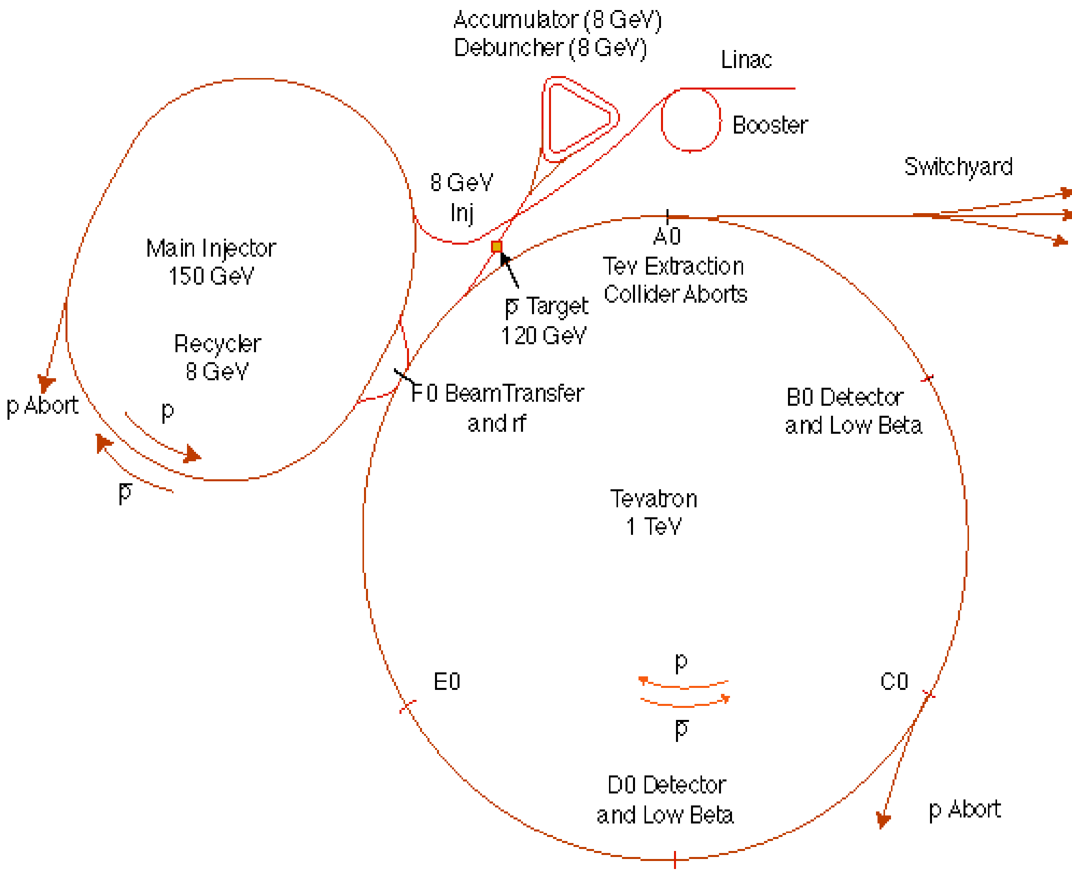
Cooling Large Antiproton Stacks

- 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
- The Electron Cooling Project has re-circulated electron beam at design voltage (4.3 MV) at design current (0.5A)
- Extra acceleration stage is being added to the Pelletron for additional stability



Handling More Antiprotons

- Accumulator Stacktail reconfiguration will require transfers between Accumulator and Recycler every 15 minutes
- Construction project undesirable for Run II
- Streamline and improve antiproton transfers between the Accumulator and the Recycler
  - Optimize optics
  - Optimize controls
  - Implement better hysterisis protocols
  - Pbar Injection dampers



Tevatron Beam-Beam Compensation

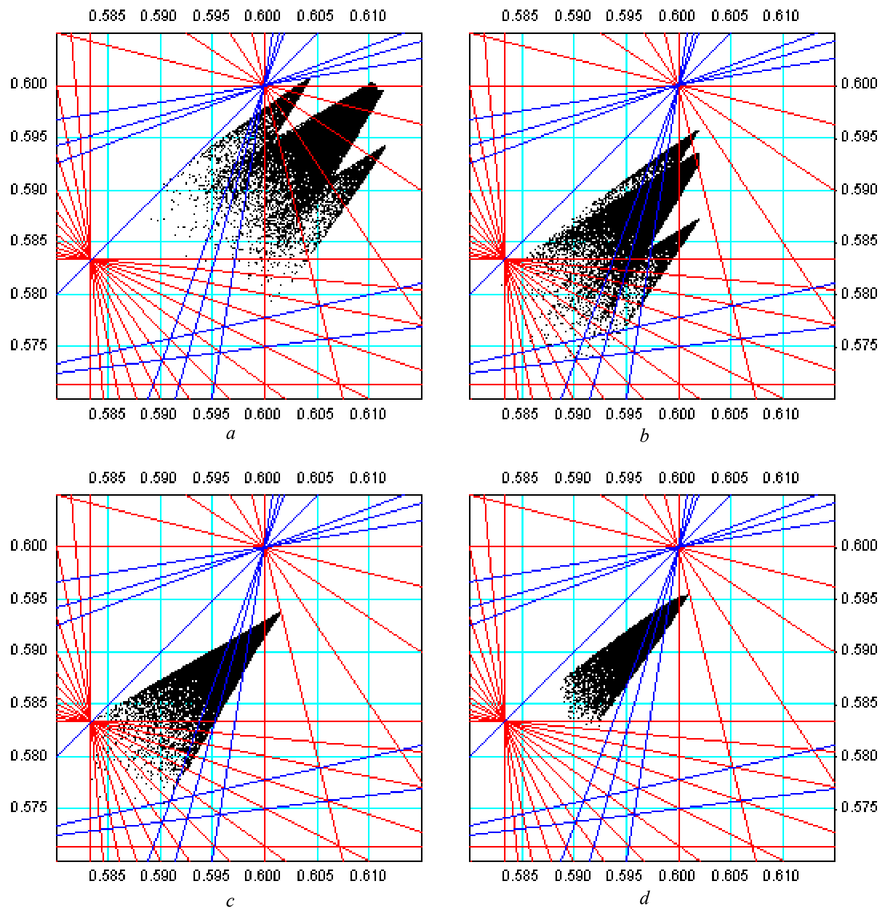
- Current experience with Run II has emphasized the need for beam-beam compensation in the TEVATRON
- Final Run II bunch intensities @ 396 nS spacing will require compensation of beam-beam effects.

No Lens

One linear Lens

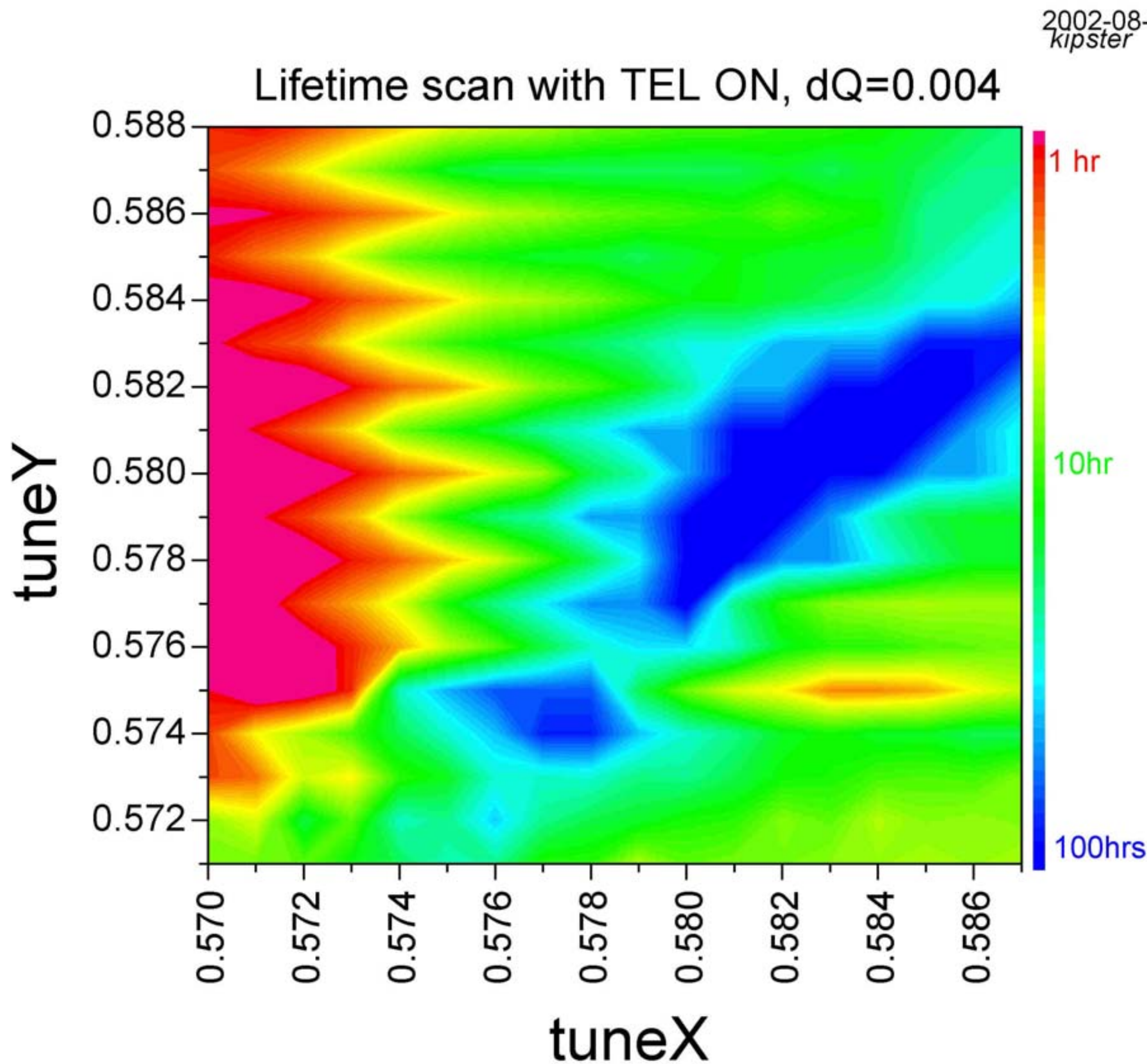
Two Linear Lenses

Two non-Linear Lenses



Tevatron Beam-Beam Compensation Progress

- TEL e-current noises are small
- p(pbar) lifetime reduction due to TEL comes from non-linear beam-beam effects - "donut collimator"
- Lifetime at good working points is about 100 hrs
- e-beam positioning is important
- Smoother edge e-beam is needed → Gaussian gun
- Gun and magnets to be modified in Jan'03 shutdown



Uncertainties

- Proton accumulation (slip stacking) in Main Injector
  - Stability of 40 dB of loop gain in RF feedback beamloading compensation
  - Longitudinal emittance dilution budget
- Antiproton yield improvements
  - Lithium Lens Gradient Upgrade
    - Lifetime of lenses vs. construction rate of lenses
  - AP2-Debuncher aperture upgrade
    - Rate of aperture improvement vs. amount of effort expended
- Antiproton stochastic cooling improvements
  - Stability of the system
  - System design margin
- Rapid Antiproton Transfers
  - Reliability of the process
- Electron cooling in the Recycler
  - Operational environment of the Main Injector Tunnel
- Tevatron beam-beam compensation
  - Beam lifetime
  - Operation in the strong-strong regime

Summary

- A number of improvements have been identified with a goal of pushing luminosity into the range 2-4x10^{32} $cm^{-2}sec^{-1}$.
- Published Run II Upgrade "Plan" in December 2001. Major elements:
  - Proton accumulation (slip stacking) in Main Injector
  - Antiproton yield improvements
    - Lithium Lens gradient upgrade
    - AP2-Debuncher Aperture upgrade
  - Antiproton stochastic cooling improvements
  - Electron cooling in the Recycler
  - Rapid antiproton transfers between the Accumulator to the Recycler
  - Tevatron beam-beam compensation
- Progress has been made on all fronts. Project resources will ramp up as effort on "Run 2a" rolls off.
- We are developing an integrated plan for Run IIa and IIb