Antiproton accumulation and cooling at Fermilab's Recycler ring

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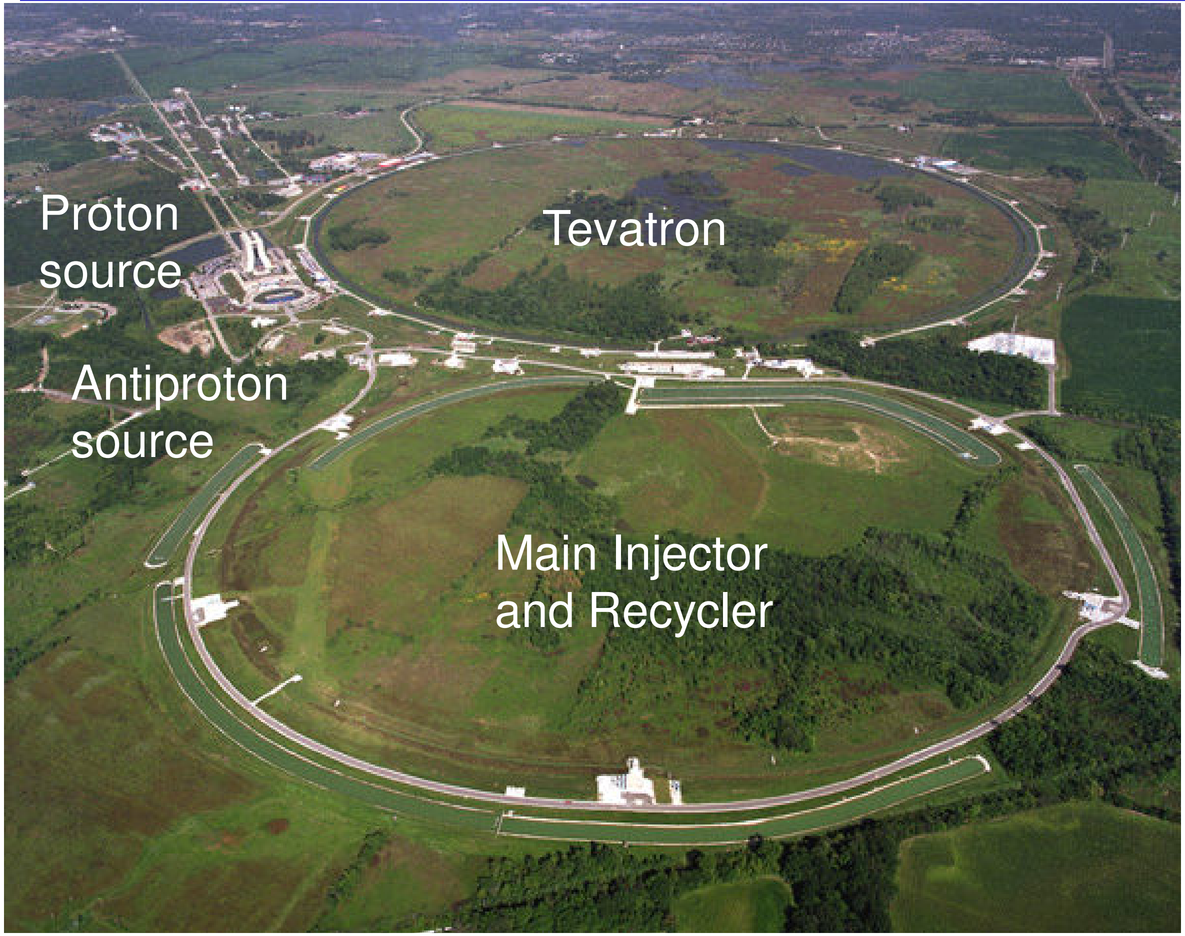
Outline

- Introduction
- Recycler and its elements
- Recycler accumulation cycle
- Performance
- Plans and conclusion

Fermilab Tevatron complex

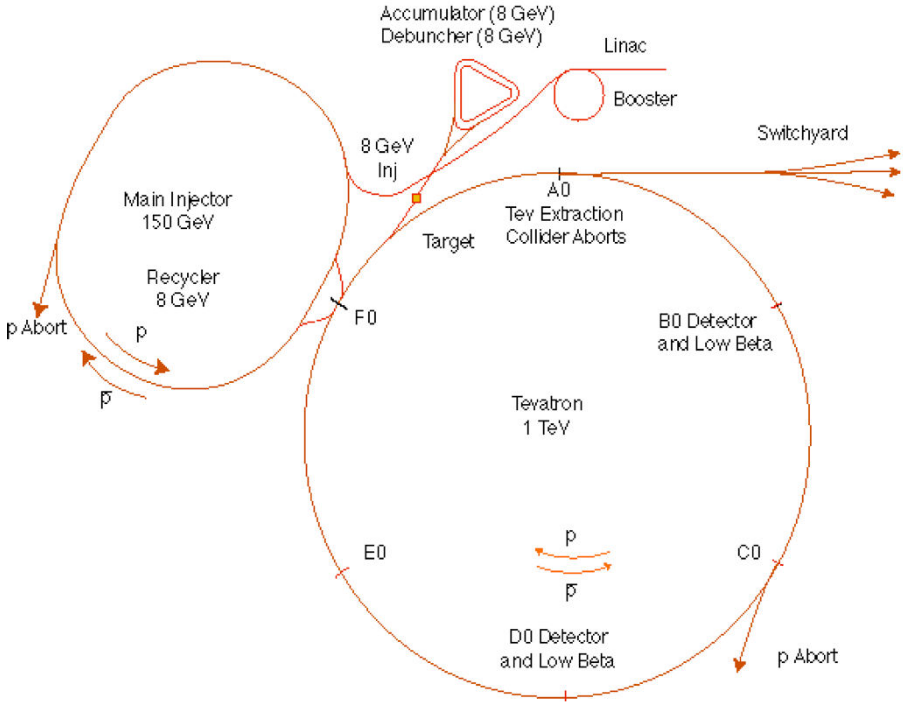


- Tevatron is 980 GeV proton – antiproton collider
- The complex includes 9 accelerators and storage rings
- See M.Convery's report for details of complex's operation

The Recycler ring is an important part of the complex, helping to improve the production rate of antiprotons and the quality of antiproton bunches coming to the Tevatron.

Antiproton production

- Three storage rings are involved
- Every 2.2 seconds
  - ~$8\cdot10^{12}$ 120 GeV protons strike an Inconel target
  - ~$2\cdot10^{8}$ antiprotons are captured into the Debuncher ring, cooled, and transferred into the Accumulator ring
- Every 40 -50 min
  - $(15 – 20)\cdot10^{10}$ antiprotons are sent from Accumulator to the Recycler ring
    - Accumulator can store up to ~$200\cdot10^{10}$
- Once in 15 – 20 hours
  - ~ $400\cdot10^{10}$ antiprotons are extracted from Recycler, accelerated in Main Injector, and transferred to Tevatron



Details of the antiproton production are in V. Nagaslaev’s talk on July 30

Why so long chain of production?

- The figure of merit is the phase density of antiprotons

  $$\rho_{6D} = \frac{N_{\bar{p}}}{\varepsilon_x \varepsilon_y \varepsilon_z}$$

  where $N_{\bar{p}}$ is the number of antiprotons and $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are the normalized beam emittances.

  - The phase density stays constant during acceleration or beam manipulation if there is no heating or cooling terms
    - Strong cooling is needed to create the density required for Tevatron
  - The phase density increases from the injection into the Debuncher to exits of Debuncher, Accumulator, and Recycler by factors of 10^3, 10^7, and $5 \cdot 10^8$, correspondingly
- Cooling in Debuncher and Accumulator is provided by stochastic cooling
  - The rate of the stochastic cooling is inversely proportional to the number of antiprotons
    - To cool fast, one needs to keep the number of particles in the machine low
    - Three - ring chain provides optimum cooling conditions in each storage ring
- The role of the Recycler is to provide the final increase by a factor ~50 of the phase density

Recycler ring

- 8 GeV antiproton storage ring
  - Located in the Main Injector tunnel
  - The name came from the original intention to reuse antiprotons left after the end of Tevatron stores
    - Deceleration and transferring antiprotons was found too complicated and not efficient to apply

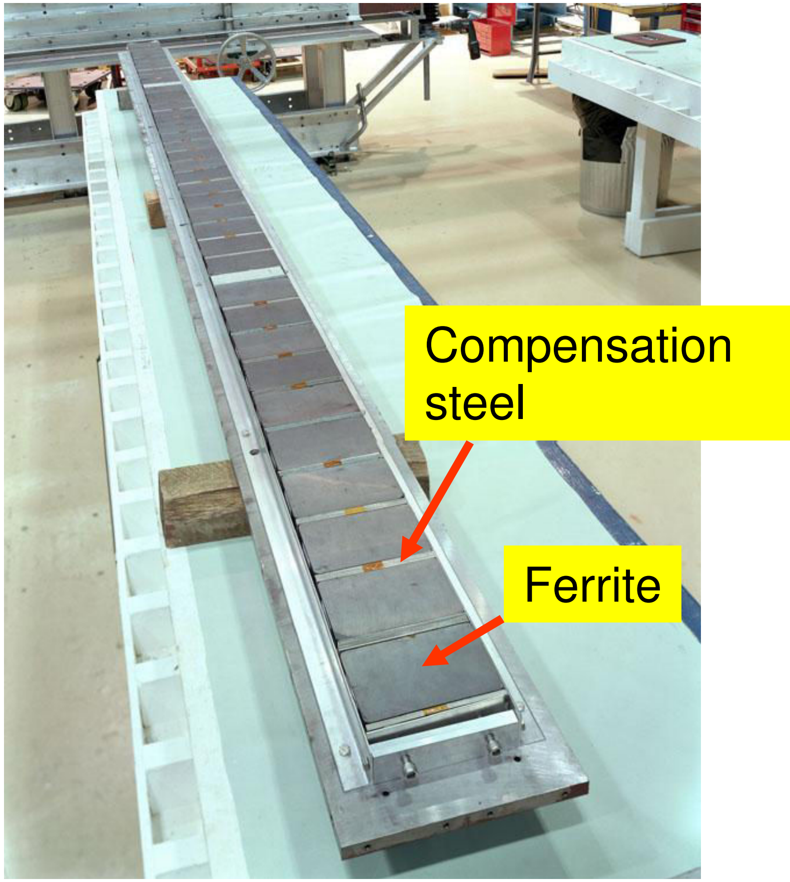
Circumference		3310.4	m
Momentum		8.889	GeV/c
Vacuum		$< 5\cdot10^{-10}$	Torr
Life time	up to	1000	hour
Maximum number of stored antiprotons		$526\cdot10^{10}$	
Tunes (H/V)		25.464/24.468	

Equipped with stochastic and electron cooling

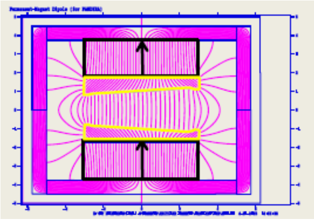
Gerry Jackson and Bill Foster in the Main Injector tunnel

Elements of the Recycler: Magnets

- FODO structure, combined functions magnets
- Most of focusing and bending is provided by strontium ferrite permanent magnets
  - Typical field ~ 0.1 T
  - Electromagnets are only for orbit and tune correction
- Compensated temperature dependence
  - Specially designed compensation scheme provides ~ $7 \cdot 10^{-5}$ change in the field strength over a 5C interval
  - The temperature drift is by 100 times higher without the compensation



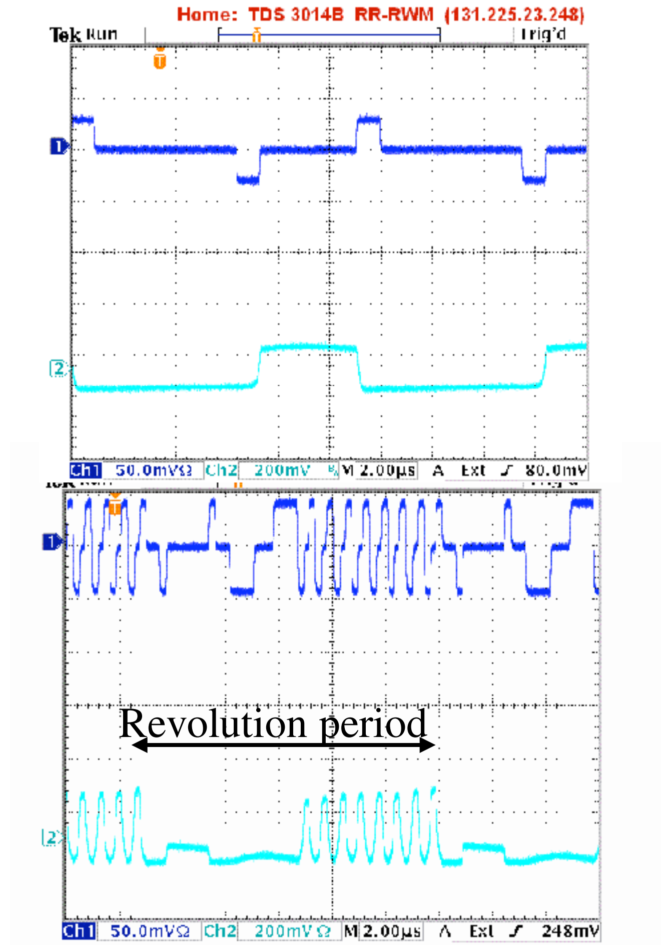
Bottom plate of a Recycler magnet with permanent magnets and compensation inserts. Courtesy of J.Volk

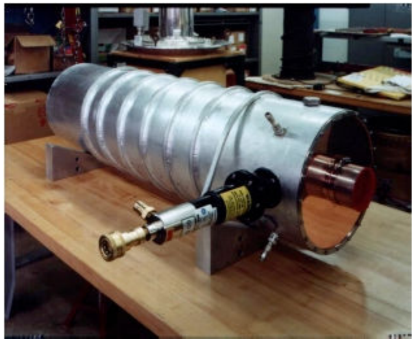


Model of one of the Recycler magnets

Elements of the Recycler: RF

- A wide – band RF system
  - 10 kHz – 100 MHz, 4 broad – band, 3.5 kW solid state amplifiers
- Variety of wave forms
  - A rectangular barrier bucket to contain the main bunch
  - 2.5 MHz (4 periods) for injection and extraction
  - A set of 2 X 9 rectangular barriers to cut the beam into 9 identical portion in preparation for extraction
  - Forms for studies…

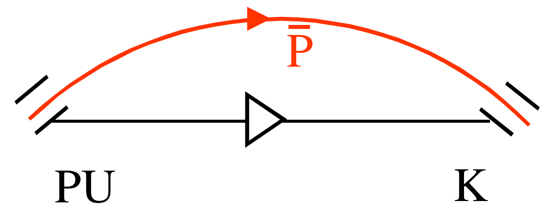




Examples of RF forms and corresponding beam profiles. Top: cooling between transfers; bottom: preparation of bunches for extraction.

Elements of the Recycler: Stochastic cooling

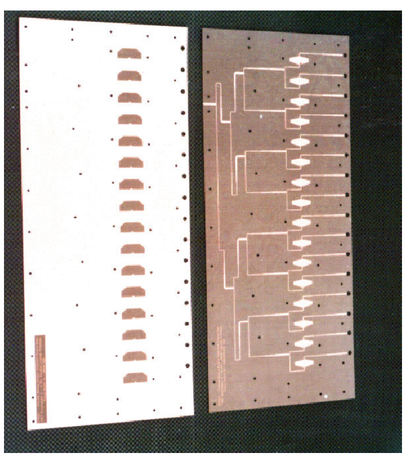
- 4 systems
  - 2 longitudinal
    - 0.5 -1 GHz and 1- 2 GHz
    - Notch filter cooling
  - Horizontal and Vertical
    - 2 – 4 GHz each
- 1/6 of the ring from pickup to kicker
  - All signals are transferred by laser beams through the same vacuum pipe



Schematic of stochastic cooling.

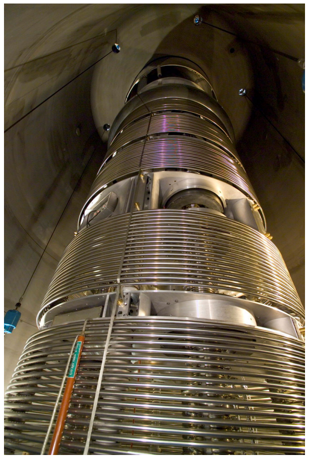
For a sample of particles, a deviation from an equilibrium trajectory is detected by the pickup; the signal is amplified and transmitted via a chord to arrive to the kicker at the same time as the sample; the kick partially corrects the deviation. The cooling rate is determined mainly by the number of particles *N* and the bandwidth of the cooling system *W*

$$\frac{1}{\tau_{SC}} \sim \frac{W}{N_p}$$

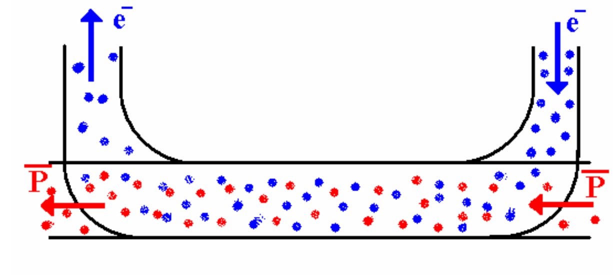


Planar pickups and kickers of the RR SC system

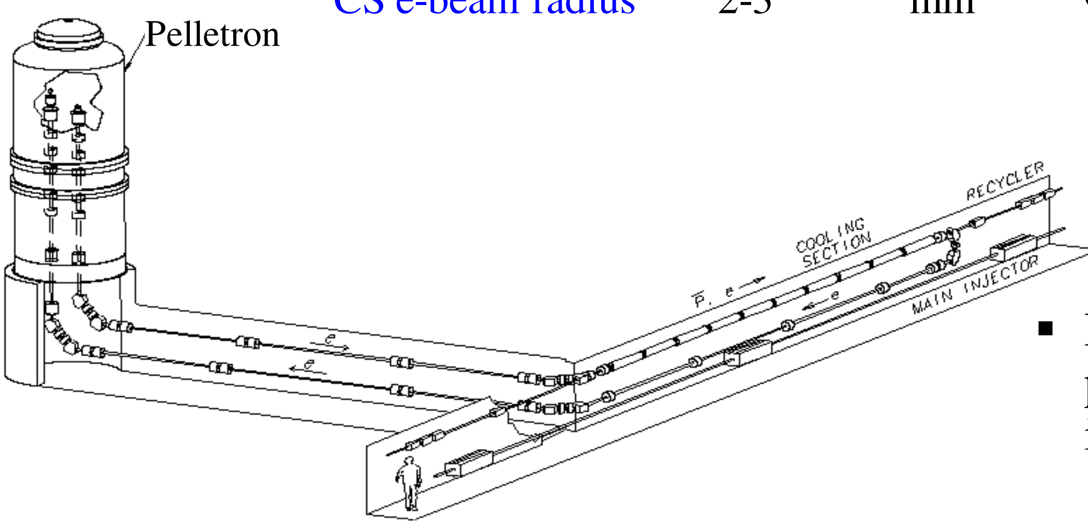
Elements of the Recycler: Electron cooling



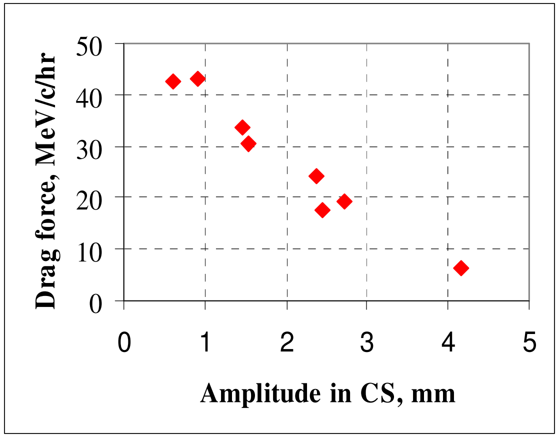
Parameter	Value	Unit
Electron energy	4.35	MeV
Beam current	0.1-0.5	A
HV ripple, rms	300	V
Cooling section		
(CS) length	20	m
CS solenoid field	105	G
CS e-beam radius	2-3	mm



- Electron cooling is a process of a thermal exchange through Coulomb scattering between hot heavy particles (antiprotons) and cold electrons
  - ➢ For cooling to be effective,
    - the electron beam has to be cold
    - average velocities of both beams should be precisely matched
- Recycler e-cooler uses a powerful DC electron beam in the energy recovery mode
    - Kinetic energy in the collector is 3 keV

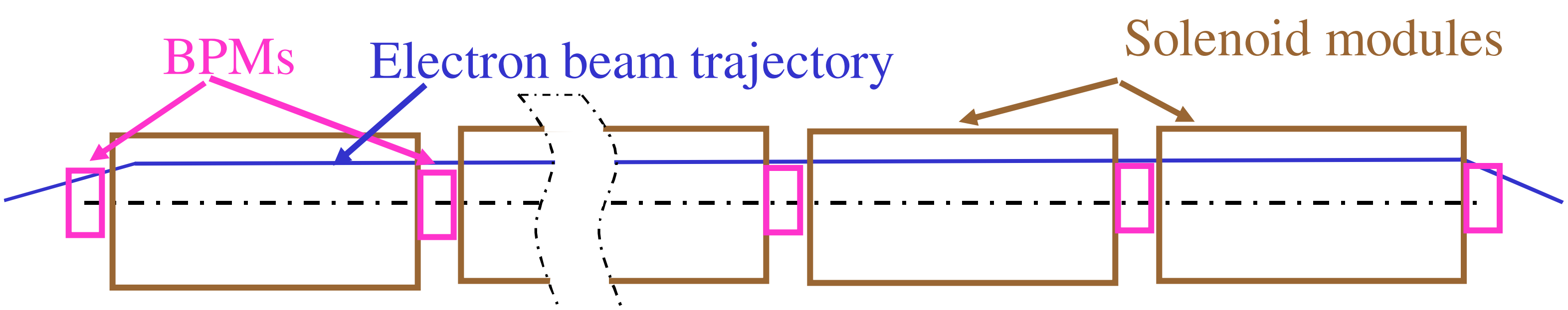


Electron cooling with an offset between beams



Measured longitudinal force as a function of antiproton betatron amplitude in the cooling section. Ie = 0.1A.

- Antiproton with large betatron amplitudes are not cooled effectively
  - Most of the time, they are outside of the electron beam
- When electron and antiproton beams propagate through the cooling section being aligned, electron cooling results in a too cold core and hot tails
  - It deteriorates the life time and may cause an instability
- In operation, the electron beam is always at I_e = 0.1A and is kept shifted vertically
  - Parallel shift in the cooling section
    - Because of coupling in the Recycler, all antiprotons are cooled

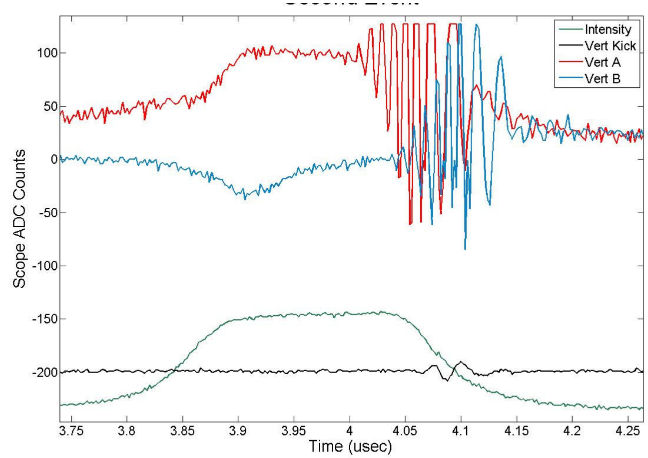


Two cooling systems work together

- Two cooling systems are complimentary
  - Stochastic cooling system is effective for hot beams with low density
  - Electron cooling works best for already cold antiprotons and does not depend on their density
    - Also, it cools primarily longitudinally
- Both systems are on all the time
  - For the initial injection, when the incoming antiprotons are hot, SC is the main tool
  - For dense beams, ECool provides most of cooling, while SC helps preserving the life time

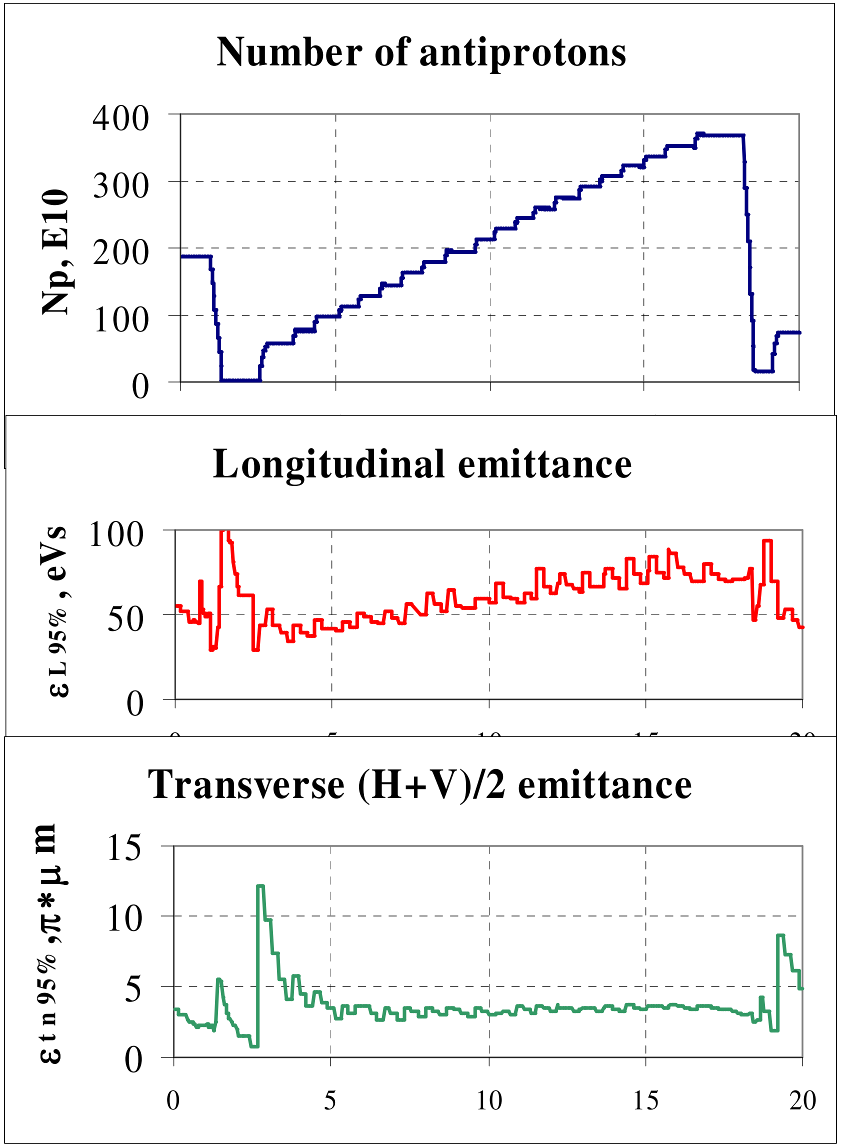
Elements of the Recycler: dampers

- A resistive wall instability puts a limit to the maximum phase density in the Recycler
  - Numerically [A.Burov]: $$\frac{N_p[10^{10}]}{\varepsilon_L[95\%, eV \cdot s] \cdot \varepsilon_\perp[95\%, norm., \pi \cdot mm \cdot mrad]} \approx 0.8$$
  - Occurs on the trailing edge of the bunch at $(n - \nu_v)$ frequencies
- Two transverse (H&V) dampers have been installed
  - 70 MHz bandwidth (35 MHz in the first version); digital
  - The instability threshold is increased by a factor of ~3.5
- After full commissioning of the dampers, instabilities still happened
  - When the dampers were malfunctioning
  - If density was too high
    - Only during extraction or studies
    - To avoid, in routine operation the electron beam is never moved on axis



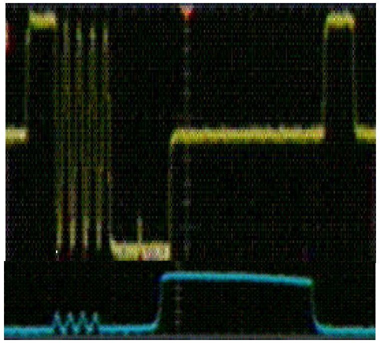
An example of instability during extraction. Oscillation frequency is ~100MHz. Courtesy of N. Eddy

Typical Recycler accumulation cycle



- Every 40-50 min, (15 – 20)·10^{10} antiprotons are transferred from Accumulator through MI in two parcels
  - Each transfer increases the longitudinal emittance by 15 – 20 eVs
- At Np ~ (350 – 400)·10^{10}, antiprotons are transferred to MI for acceleration and injection into Tevatron

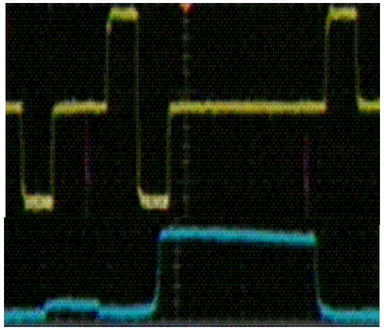
Recycler cycle -injection



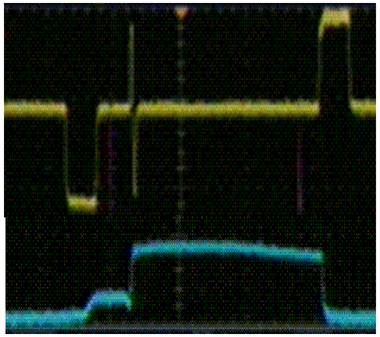
Four antiproton bunches are injected into matching 2.5 MHz buckets

- Longitudinal injection
  - The main beam is kept between two rectangular barriers at 6 μs
  - Antiprotons arriving from Accumulator are injected into a free part of the same orbit
  - After merging, the final bunch has an increased longitudinal emittance
  - Typical efficiency of the transfer is ~ 95% (from Acc. to RR)

2.5 MHz structure is adiabatically removed; the injected beam is in a rectangular bucket

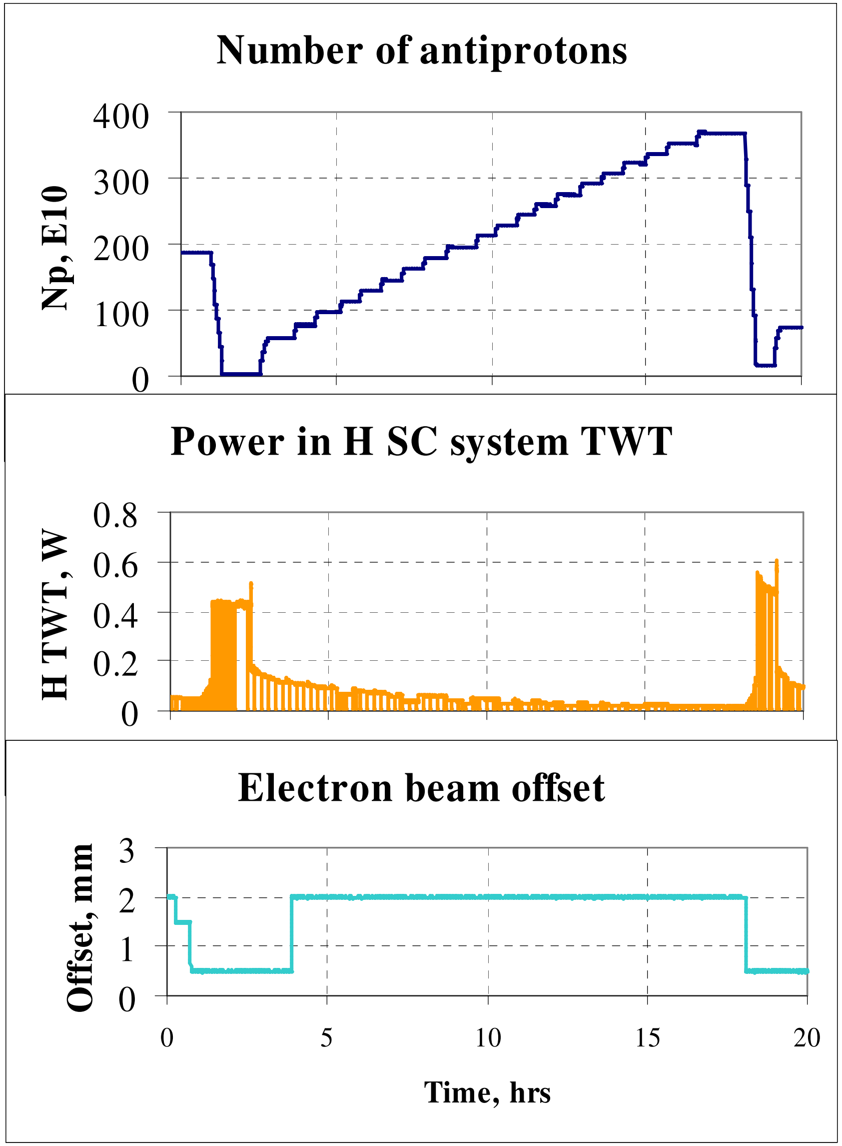


Oscillograms of RF voltage and beam profile during injection. The horizontal span is one revolution period, 11μs.



The injected beam is merged with the main bunch

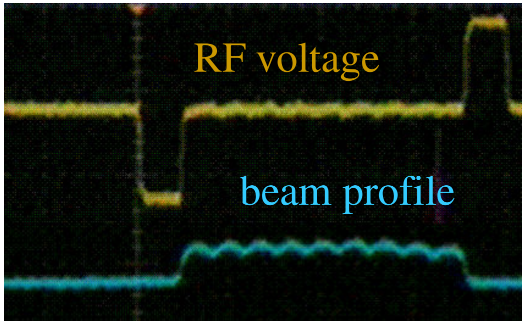
Recycler cycle - cooling



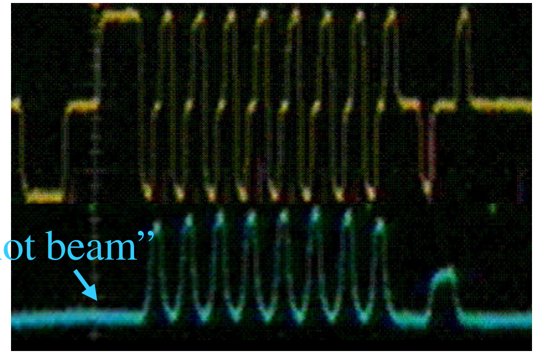
- Stochastic cooling systems are adjusted according to the number of antiprotons
  - The output power decreases with the increase of the antiproton density
- The strength of electron cooling is regulated by the parallel shift of the electron beam in the cooling section
  - 2 mm offset at regular cooling and 0.5 mm while preparing for extraction
    - Typical rms size of the antiproton beam in the cooling section is 1 – 2 mm
  - Balance between the cooling rate, life time, and instability threshold

Recycler cycle - extraction

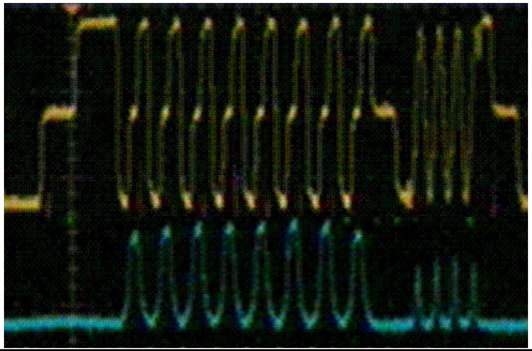
The beam is at the final position and length. Cutting into 9 identical bunches (“mining”) begins.



9 bunches are prepared. The first is moved to the position of extraction.



The first bunch is captured into four 2.5 MHz buckets and is ready for the transfer to Main Injector



The horizontal span of the oscillograms is one revolution period, 11μs.

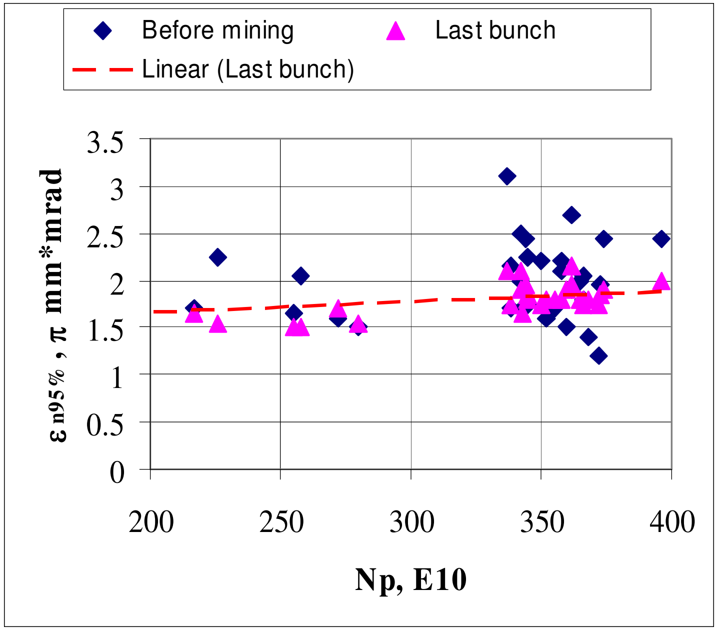
- The goal is to prepare 36 bunches with the same number of antiprotons and the same emittances
  - The beam is divided into 9 portions (“mining”)
  - One portion at a time is sent to MI as four bunches, accelerated, and injected into the Tevatron
  - Takes ~20 min
- Typically, only 2 – 5% of antiprotons are left in the Recycler
  - 1-2% are lost during extraction
  - Recently, a “partial mining” procedure was developed to extract only a portion of the beam (see M.Convery’s report)

Parameters of extracted bunches

- Typical parameters of an extracted bunch (one out of 36)
  - Longitudinal emittance (95%) , eV*s ~ 1
  - Transverse emittance (95%, normalized, measured with Flying Wire), $\pi \cdot$mm$\cdot$mrad ~ 2
  - Number of antiprotons, $\sim 10 \cdot 10^{10}$
- At a given RF structure, the final emittances depends weakly on the pre-history or number of particles
  - At these parameters, the intra beam scattering (IBS) makes the distribution of average velocities in the beam frame "spherical", i.e.

$$\upsilon_L \approx \upsilon_H \approx \upsilon_V$$

  - Emittances can be decreased only together



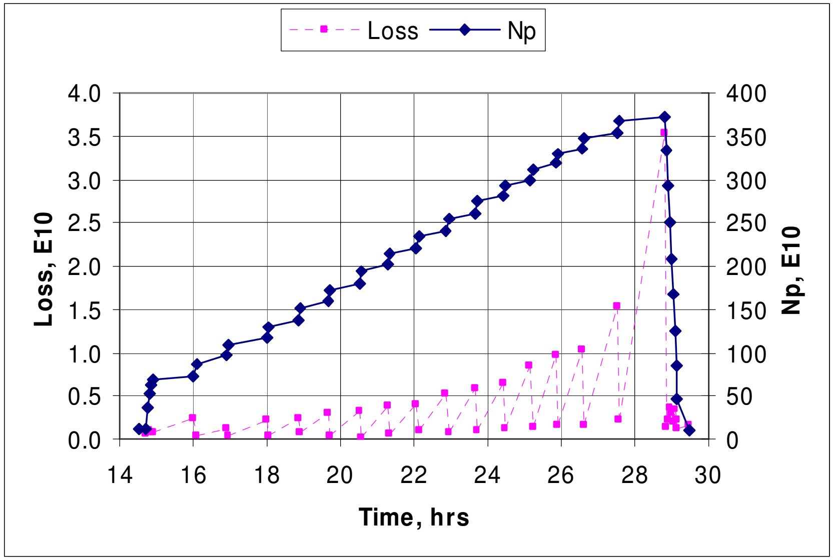
Emittance (H+V)/2 of antiprotons immediately before "mining" and before extraction of the last portion. Summer 2008. At that time, the electron beam position varied by operators that increased the scatter in the initial beam emittance. Note that the final scatter is significantly lower.

Storage efficiency

- The goal of the Recycler is to accumulate particles coming from Accumulator and transfer them into Tevatron with minimum losses
  - Efficiency of accumulation for a specific shot is characterized by *Storage Efficiency*

$$Storage\ Efficiency = \frac{N_p\ extracted\ to\ MI + N_p\ left\ in\ RR}{N_p\ transferred\ from\ MI\ to\ RR + N_p\ left\ from\ previous\ shot}$$

    - Both injection and extraction go through Main Injector, and intensity is measured by the same device
  - Typical storage efficiency is ~ 93%
    - ~3.5% is lost during transfers and ~3.5% in the Recycler

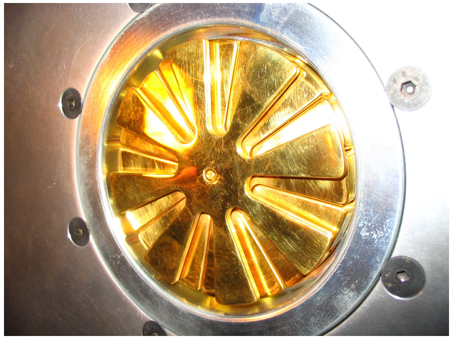


Beam intensity and beam loss between injections/extractions during one cycle of accumulation. April 20 -21, 2009. Upper points on the loss curve correspond to time between two – parcel transfers, and the lower points are the loss between parcels.

The life time drops with intensity from ~ 700 hrs to ~150 hrs

Reliability

- Recycler
  - An accidental beam loss about once in a month
    - High stray magnetic fields from Main Injector; malfunctioning of corrector power supplies; lightning; …
    - Typically, only a portion of the antiproton beam is lost
  - Several instances of instabilities during last year
  - A couple of lost parcels from Accumulator in a month
    - Software, kickers, human errors…
- Electron cooler
  - The electron beam is on > 90% of time outside of planned shutdowns
    - Cooler is ready at ~97%
    - About half of the down time is caused by unplanned Pelletron accesses for repairs
      - 17 since installation in 2005
      - Typical length of an access is 30 hrs
      - Longest time without an access is 7 months (2008 – 2009)
    - Other reasons are software, water cooling, ..



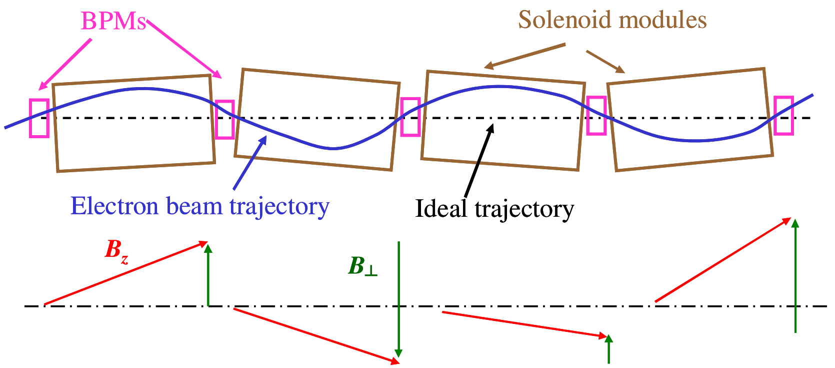
Failures of the Generating Voltmeter caused three Pelletron accesses

What has been done in the last year or so

- Improved stability of operation
  - Lower number of accidental losses
    - Improved procedures; modified corrector power supplies; magnet moves to decrease the corrector currents
    - 70 MHz dampers were fully commissioned
- Better electron cooling (see the next slides)
  - Allowed to keep the electron beam at 2 mm offset during accumulation
    - Improved the life time and simplified procedures
  - Efficient cooling between more frequent transfers
- Better transfer procedures
  - Fast and frequent transfers from Accumulator
  - Faster Tevatron loading
- "Partial mining" (capability to extract effectively only a portion of the Recycler antiprotons)
- A record number of antiprotons in the Recycler, $525 \cdot 10^{10}$

Electron cooling improvements

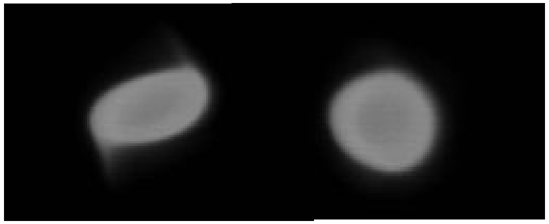
- Stable electron beam recirculation
  - ~ 1 full discharge in the Pelletron per year (~ 2 hrs recovery time)
  - Several beam interruptions per week (20 sec recovery time)
  - Result of operation at low current (0.1A) and at stable conditions, and of improvements in the protection system
- Energy stability of 0.01%
  - Pelletron temperature stabilization to 0.2 C
  - Beam – based feedback loop
- Adjustment of dipole beam oscillations in the cooling section
  - Needs to be done periodically because of mechanical drifts
    - A special procedure based on measuring beam cooling properties



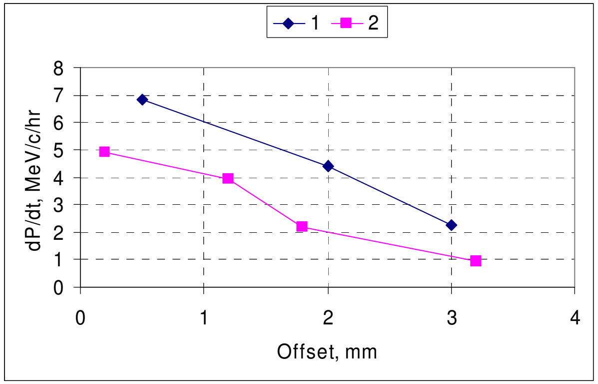
Mechanical tilt of a solenoidal module results in an additional transverse field in the cooling section, which excites dipole beam oscillations.

ECool: beam envelope angles

- For optimum cooling, the electron beam envelope in the cooling section needs to be a round cylinder.
  - Any deviations mean additional angles that decrease the cooling force
- Because of indications of poor cooling at the beam periphery, a set of dedicated measurement was made
  - Images of the beam at he exit of the cooling section were recorded in a pulse mode
    - Showed strong quadrupole oscillations
    - Oscillations were corrected by adjusting quadrupoles upstream
    - Cooling became only worse
      - Interpreted as a strong contribution to optics from residual gas ionization
  - Successfully tuned the quadrupole based on cooling measurements



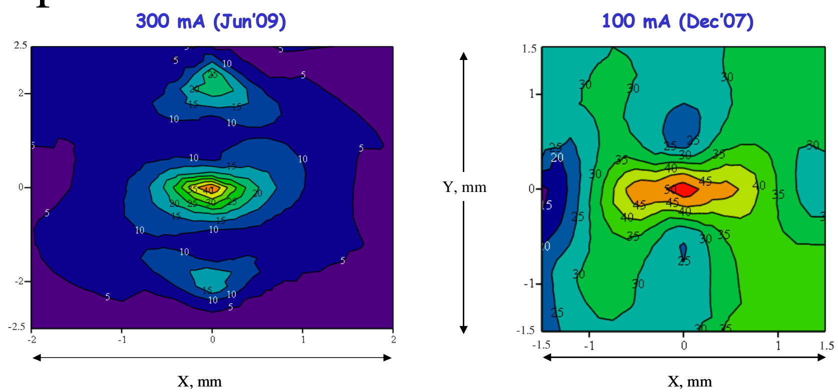
Beam image at the exit of the cooling section before (left) and after (right) quadrupole correction. 100 ns gate of 2 μs pulse; YAG scintillator.



Longitudinal cooling rates at various vertical offsets of electron beam before (set 2) and after (set 1) adjustments of quadrupoles.

A couple of unanswered questions

- What determines the life time of an intense, cold antiproton beam?
  - Depends on the number of particles, emittances, distributions, speed of cooling, working point…
    - No dominant parameter has been found
      - For example, in steady state with $525 \cdot 10^{10}$ and phase density right under instability threshold, the life time was 500 hrs, while at normal transfer frequency it drops below 200 hrs at $Np > 350 \cdot 10^{10}$.
    - Do not have a good model
      - Likely, the life time is determined by higher order resonances and tails of distributions
- Why cooling efficiency doesn't improve with the electron beam current?
  - The cooler is capable of providing 0.5A electron beam, but cooling is the best at 0.1A
    - Theory predicts a linear dependence
    - Scans with a "pencil" antiproton beam showed only "islands" of good cooling force in the high-current electron beam



Cooling force across electron beam at Ie = 0.3A (left) and 0.1A (right). Interpolation of measurements in discrete points.

Future

- We plan to run Recycler/Ecool in FY 2010-2011 with no major changes
  - Performance satisfies the present needs of the Tevatron complex
  - Not much room for improvements
    - The storage efficiency is 93%
    - Minimum beam emittances are limited by the damper capabilities
  - No upgrades are being made in 2009 shutdown
  - Most of personnel devote a major portion of time to future projects
- After the end of Run-II in 2011, the Recycler will be used as a proton machine to improve the proton flux in the Main Injector
  - Necessary modifications are under preparation
  - Electron cooler will be removed
    - A possibility to use the cooler at BNL for the low-energy run is being discussed

Conclusion

- Recycler is an essential and reliable part of the antiproton production chain in the Tevatron complex
- Improvements in the Recycler and Electron cooler contributed to the increase of the of integrated luminosity rate in FY2009
- We hope for a stable running in FY 2010 - 2011