Performance of the Accelerator Complex

FNAL Annual User's Meeting

June 2, 2004

Dave McGinnis

Outline

- Goals
- Accomplishments during the Fall 2003 Shutdown
- Performance
- Major Accomplishments
- Machine Issues
- Near Term Future
- Summary

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Goals

Major FY04 Goals

- Operate the Collider at the Main Injector project luminosity design goals
  - 80% Antiproton transform efficiency from the Accumulator to Low Beta
  - 260×10^9 protons per bunch
  - 18×10^{10}/hour antiproton zero stack stacking rate
- Integrate over $300 pb^{-1}$ in 39 weeks
- Prepare the Collider for implementation of the initial stages of the Run II Upgrades
  - Slip Stacking
  - AP2-Debuncher Aperture
- Commission the Recycler for electron cooling

Accomplishments during the Fall 2003 Shutdown

Major Accomplishments of the Fall 2003 Shutdown

- Proton Source
  - Installation of the new dogleg magnets in one of the extraction regions
  - Installation of large aperture magnets in the beginning of the transfer line from Booster to Main Injector
  - Installation of the Booster Collimation System
- Antiproton Source
  - Installation of the motorized Debuncher Quad Stands
  - Installation of the Debuncher BPM System
  - Survey and alignment of the AP2 line
  - Installation of the new equalizers for the Debuncher momentum cooling BAW notch filters
- Main Injector
  - Installation of the NUMI extraction Lambertsons and transfer line
  - Instrumentation relocation for NUMI

Major Accomplishments of the Fall 2003 Shutdown

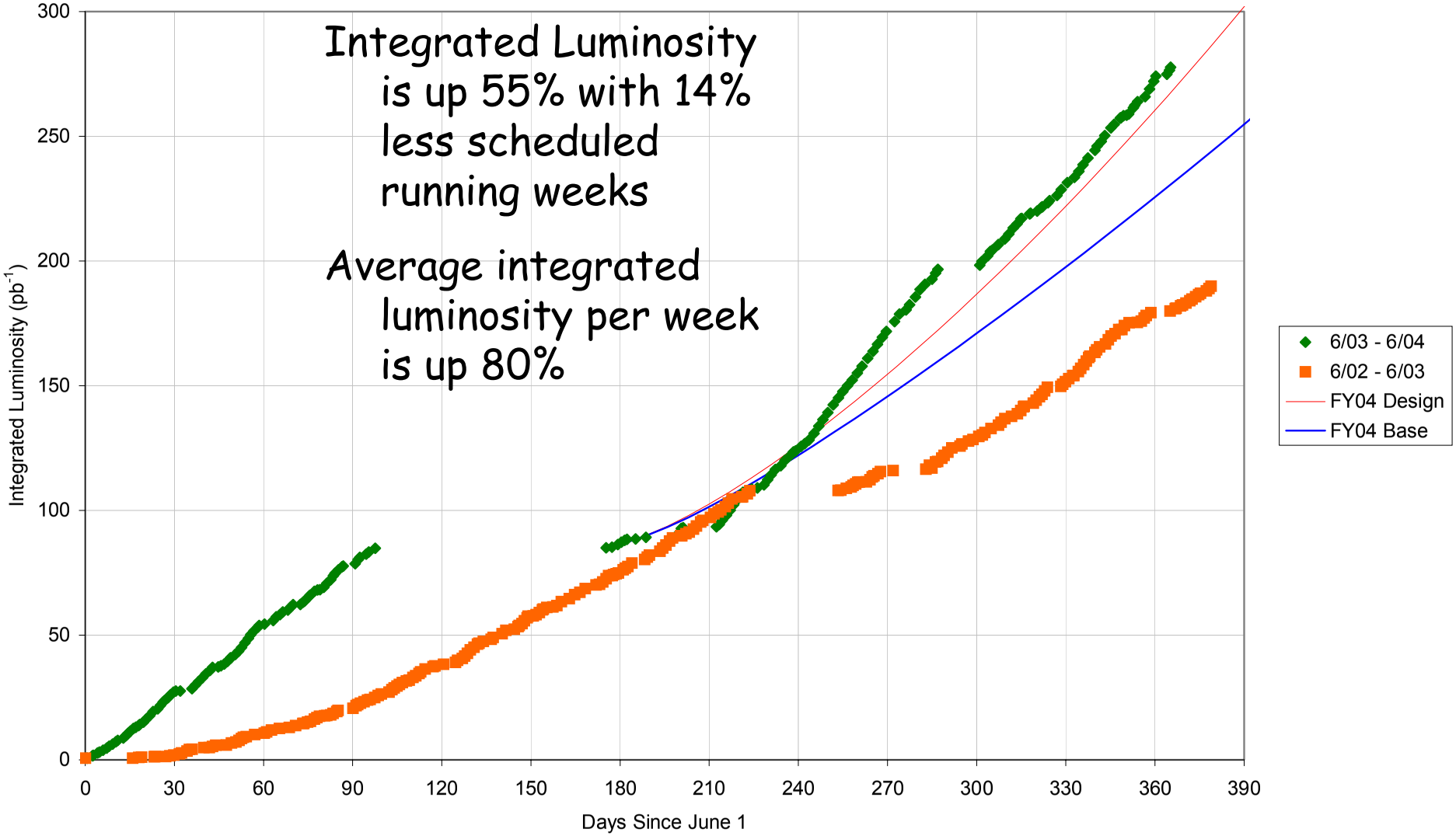
- TEVATRON
  - Installation of a ring-wide laser tracker alignment network
  - Complete survey of all TEV magnets
  - Un-roll dipoles with rolls > 1 mrad
    - Rolls over 4 mrad had to be done warm – 100% complete
    - Rolls under 4 mrad can be done cold – 100% complete
  - Re-alignment of the several devices for aperture increase
  - Alignment of the D0 triplet
  - Smart bolt retrofit
    - Remove sag in magnets that can cause coupling
    - Done in B & D sectors because of the lack of skew correctors in this region
  - Replacement of ~50 aging magnet stand pairs

Major Accomplishments of the Fall 2003 Shutdown

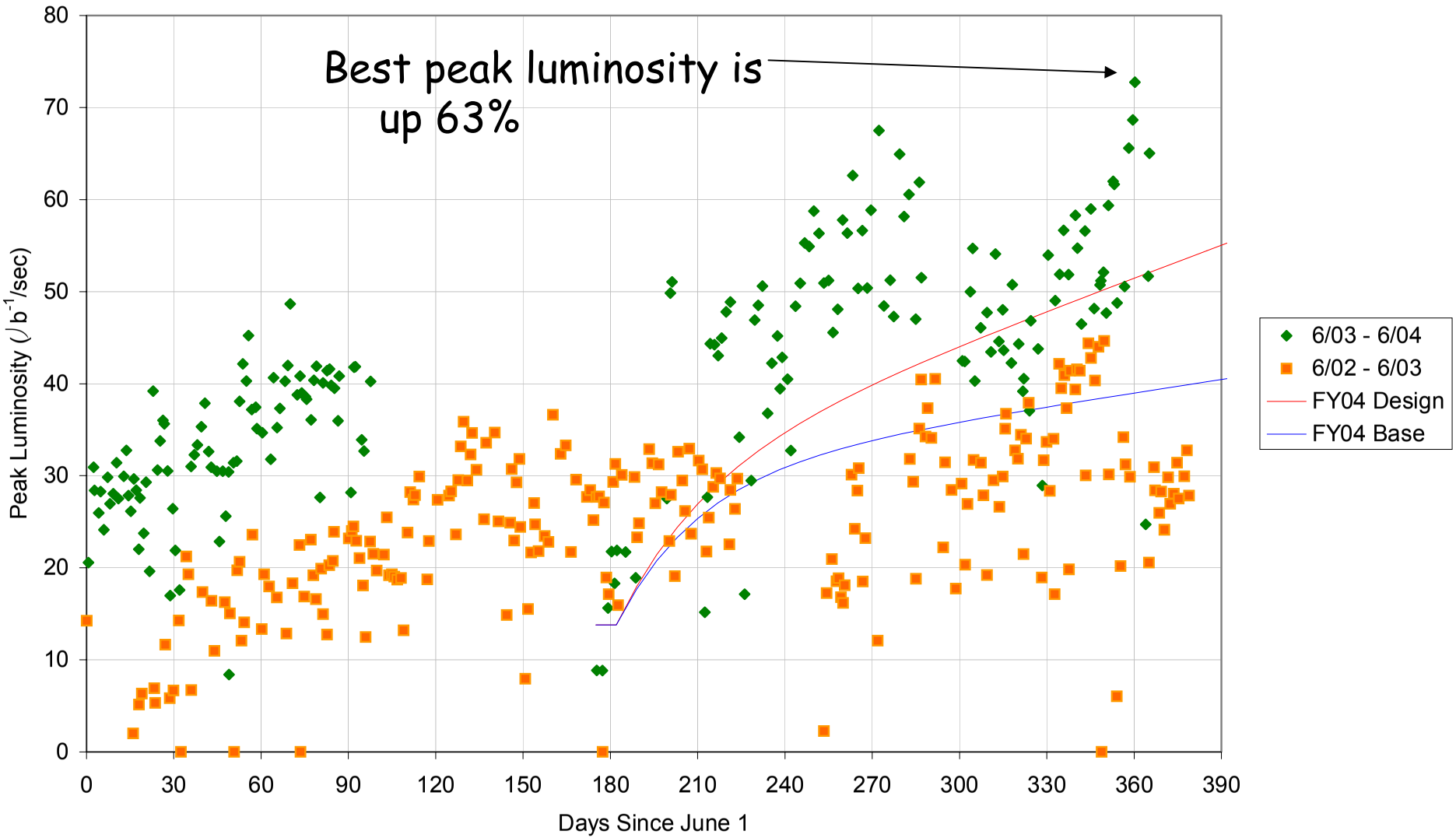
- TEVATRON (continued)
  - Shielding of the F0 Lamberston laminations to reduce the transverse impedance of the TEVATRON
  - Re-wiring of the octupole circuits
    - Differential chromaticity between pbar and proton helices
    - Increase Landau damping
  - New sextupole circuit for decoupling injection helical orbits
- Recycler
  - Complete ring-wide bake
  - Replaced 170 ft of contaminated vacuum pipe
  - Upgraded vacuum instrumentation
  - Finished the ion pump upgrade
  - Additional magnetic shielding added

FY04 Performance

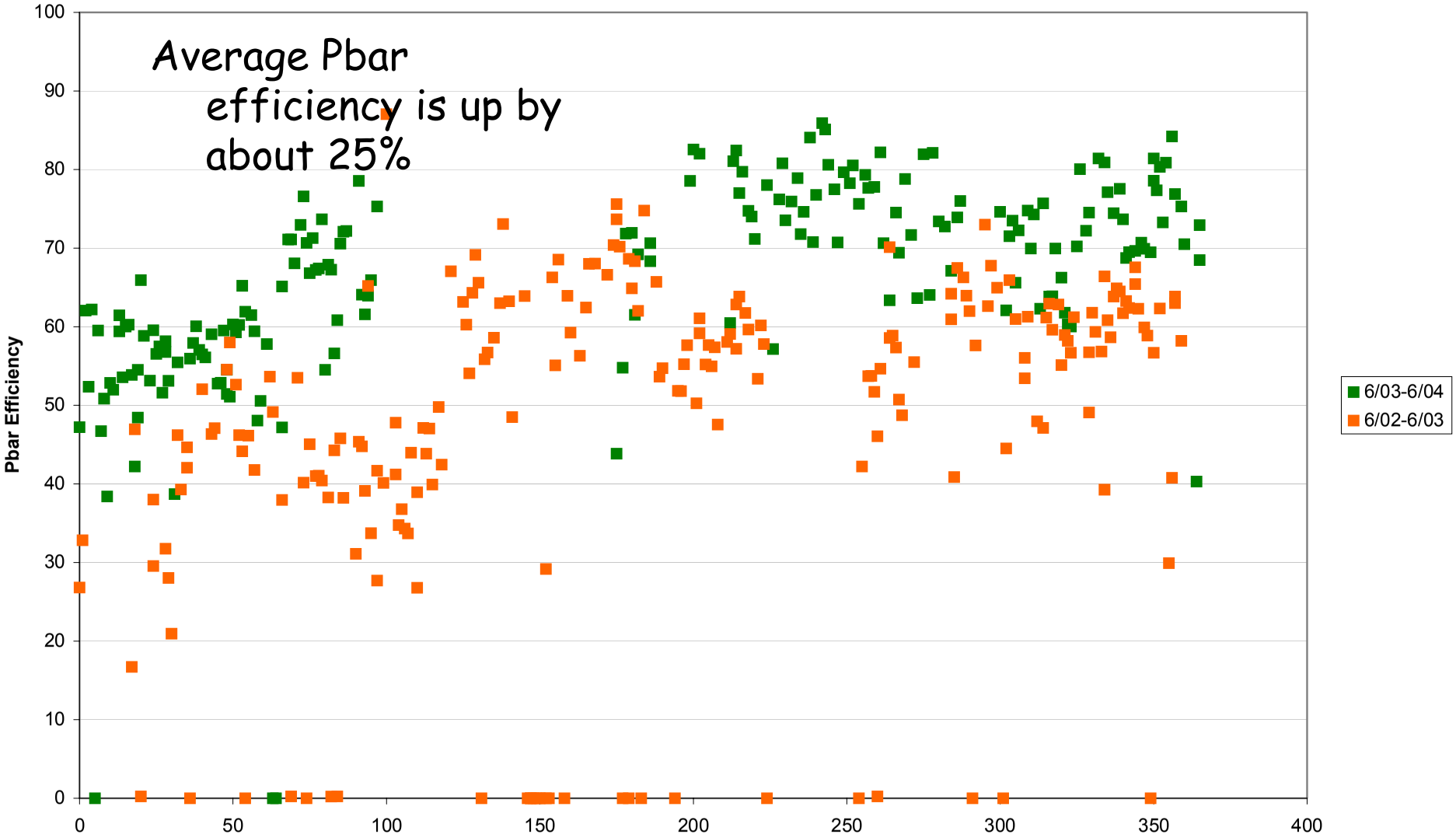
Integrated Luminosity



Peak Luminosity



Antiproton Efficiency to Low Beta



Store Parameters

17% above year-end goal

		Store Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Initial Luminosity (Average)	72.8	57.1	64.8	36.1	61.9	43.3	$x10^{30}cm^{-2}sec^{-1}$
Integrated Luminosity per Store (Averaged)	1939	1796	2494	1089	2000	1300	nb^{-1}
Luminosity per week (Averaged)	-	9.4	-	6.4	11.3	7.4	pb^{-1}
Store Length	12.0	18.2	25.1	14.9	15.0	15.0	Hours
Store Hours per week	-	92	-	88	85	84	Hours
Shot Setup Time	2.2	2.3	2.4	2.3	2.2	2.2	Hours

Within 8% of year-end goal

5% above year-end goal

Store Parameters

Within 3% of year-end goal

		Store Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Initial Luminosity (Average)	72.8	57.1	64.8	36.1	61.9	43.3	$x10^{30}cm^{-2}sec^{-1}$
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Within 10% of year-end goal

25% above year-end goal

Store Parameters

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Initial Luminosity (Average)	72.8	57.1	64.8	36.1	61.9	43.3	$x10^{30}cm^{-2}sec^{-1}$
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Within 17% of year-end goal

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Shot Setup Time	2.2	2.3	2.4	2.3	2.2	2.2	Hours

8% above year-end goal

TEV Parameters

Within 5% of year-end goal

		TEVATRON Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Protons per bunch	248	247	241	237	260	260	$\times 10^9$
Antiprotons per bunch	33	27	33	22	31	25	$\times 10^9$
Proton Efficiency to Low Beta	83	79	79	58	-	-	%
Pbar Transfer efficiency to Low Beta	71	72	75	63	80	77	%
HourGlass Factor	0.72	0.73	0.71	0.70	0.65	0.65	
Initial Luminosity Lifetime	6.7	7.0	7.3	9.5	8.3	7.0	hours
Asymptotic Luminosity Lifetime	23.9	24.6	24.2	25.1	25.0	25.0	hours
Effective Emittance	17.4	18.2	18.8	21.6	21.0	23.0	π-mm-mrad

Within 5% of year-end goal

Within 7% of year-end goal

TEV Parameters

6% above year-end goal

		TEVATRON Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Protons per bunch	248	247	241	237	260	260	$\times 10^9$
Antiprotons per bunch	33	27	33	22	31	25	$\times 10^9$
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Effective Emittance	17.4	18.2	18.8	21.6	21.0	23.0	π-mm-mrad

Within 13% of year-end goal

6% above year-end goal

TEV Parameters

Within 11% of year-end goal

		TEVATRON Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Protons per bunch	248	247	241	237	260	260	$x10^9$
Antiprotons per bunch	33	27	33	22	31	25	$x10^9$
Proton Efficiency to Low Beta	83	79	79	58	-	-	%
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Asymptotic Luminosity Lifetime	23.9	24.6	24.2	25.1	25.0	25.0	hours
Effective Emittance	17.4	18.2	18.8	21.6	21.0	23.0	π-mm-mrad

Within 10% of year-end goal

Within 6% of year-end goal

TEV Parameters

17% better than year-end goal

		TEVATRON Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Protons per bunch	248	247	241	237	260	260	$\times 10^9$
Antiprotons per bunch	33	27	33	22	31	25	$\times 10^9$
Proton Efficiency to Low Beta	83	79	79	58	-	-	%
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HourGlass Factor	0.72	0.73	0.71	0.70	0.65	0.65	
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Asymptotic Luminosity Lifetime	23.9	24.6	24.2	25.1	25.0	25.0	hours
Effective Emittance	17.4	18.2	18.8	21.6	21.0	23.0	π-mm-mrad

13% better than year-end goal

10% better than year-end goal

Antiproton Parameters

21% below year-end goal

		Antiproton Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Zero Stack Stack Rate	14.2	12.9	12.4	11.5	18.0	13.7	$x10^{10}$/hour
Normalized Zero Stack Stack Rate	2.7	2.4	2.4	2.3	3.6	2.7	$x10^{-2}$/hour
Average Stacking Rate	7.5	7.1	6.2	7.1	9.3	7.6	$x10^{10}$/hour
Stacking Time Line Factor	92	85	80	88	75	75	%
Stack Size at Zero Stack Rate	270	318	297	300	300	300	$x10^{10}$
Protons on Target	5.2	5.3	5.2	5.0	5.0	5.0	$x10^{12}$
Start Stack	189	150	180	144	155	130	$x10^{10}$
End Stack	19	17	20	16	15	15	$x10^{10}$
Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

28% below year-end goal

31% below year-end goal

Antiproton Parameters

25% below year-end goal

		Antiproton Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
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End Stack	19	17	20	16	15	15	$x10^{10}$
Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

33% below year-end goal

33% below year-end goal

Antiproton Parameters

19% below year-end goal

		Antiproton Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Zero Stack Stack Rate	14.2	12.9	12.4	11.5	18.0	13.7	$x10^{10}$/hour
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End Stack	19	17	20	16	15	15	$x10^{10}$
Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

24% below year-end goal

33% below year-end goal

Antiproton Parameters

23% above year-end goal

		Antiproton Parameters					
Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
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End Stack	19	17	20	16	15	15	$x10^{10}$
Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

13% above year-end goal

6% above year-end goal

Antiproton Parameters

10% below year-end goal

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Zero Stack Stack Rate	14.2	12.9	12.4	11.5	18.0	13.7	$x10^{10}$/hour
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End Stack	19	17	20	16	15	15	$x10^{10}$
Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

6% above year-end goal

1% below year-end goal

Antiproton Parameters

4% above year-end goal

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Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

6% above year-end goal

4% above year-end goal

Antiproton Parameters

22% above year-end goal

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Parameter	Best Store	Last 10 stores Average	Best 10 stores Average	End of FY03	FY04 (End) Design	FY04 (End) Base	
Zero Stack Stack Rate	14.2	12.9	12.4	11.5	18.0	13.7	$x10^{10}$/hour
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End Stack	19	17	20	16	15	15	$x10^{10}$
Unstacked Pbars	169	133	159	128	140	115	$x10^{10}$

3% below year-end goal

16% above year-end goal

Antiproton Parameters

21% above year-end goal

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5% below year-end goal

14% above year-end goal

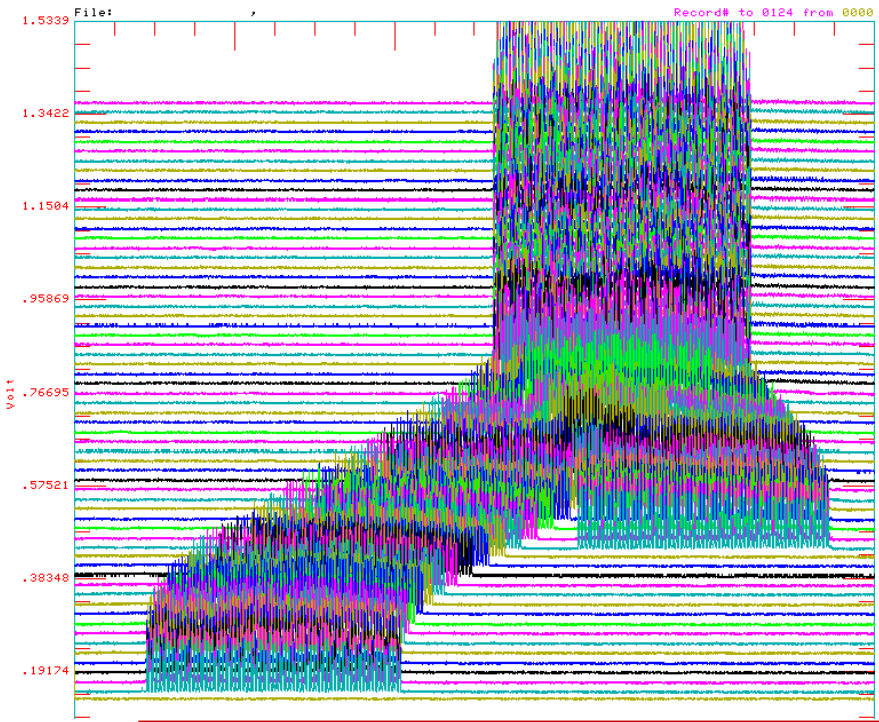
Major Accomplishments

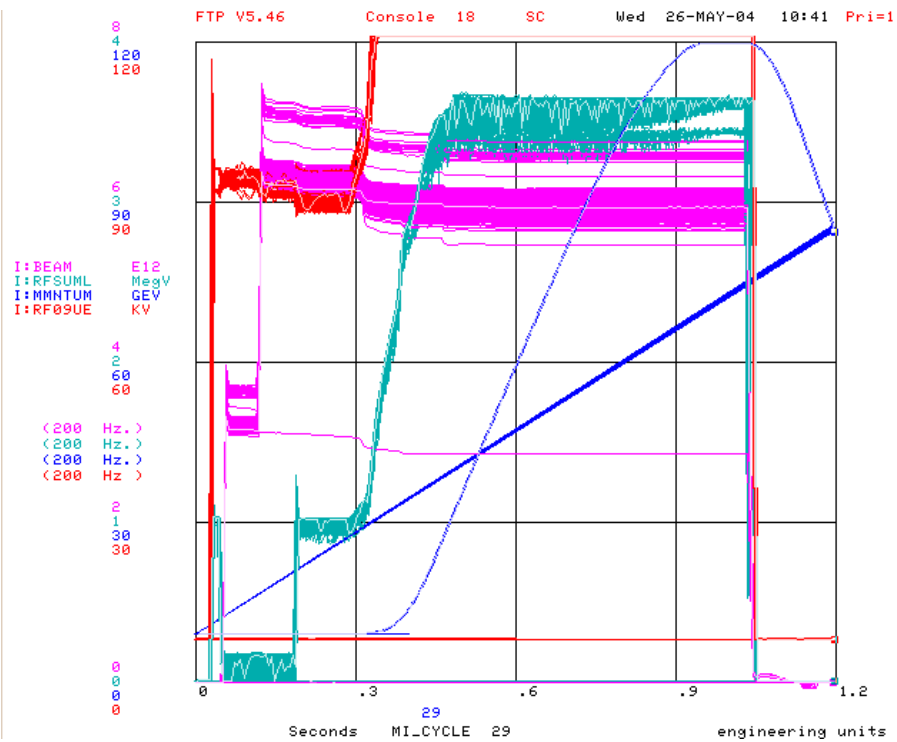
Major Accomplishments

- Proton Source
  - Operational Improvements
    - Booster Aperture
      - Alignment of Booster cavities and Magnets
      - Long 3 septum
    - New dogleg magnets at Long 3
      - Removal of beta wave
      - Less tune shift
    - Damper mode number and Power increase
    - Matching of the 400 MeV Line
    - Harmonic Correction
    - Two stage collimation system
  - Records
    - Record intensities- 6.0×10^{12} protons/pulse
    - Record Efficiencies > 85%
    - Record Throughput
      - > 6.8×10^{18} protons/week
      - > 6.0×10^{16} protons/hour
      - > 4.5×10^{17} protons/shift

Major Accomplishments

- Main Injector
  - Bunch Length reduction from dampers and beam loading compensation
    - 20% for coalescing
    - 50% for stacking
  - 2.5 MHz transfers – 95% pbar coalescing efficiency
  - Slow Spill to SY120
  - Slip Stacking for Pbar Stacking





Major Accomplishments

- Antiproton Source
  - Stacking rate 13.65×10^{10} pbars/hour
  - Largest stack 246×10^{10}
  - Longest sustained stack > 2 months
  - Debuncher Aperture Increase
  - Main Injector – Debuncher Phase alignment system
    - Aperture Increase
    - 8 GeV alignment across the injector complex now possible
- Recycler
  - Recycler bake-out was extremely successful
    - Transverse emittance growth reduced by a factor of 4-5
  - Recycler shots to the Tevatron
    - Initial Luminosity > $17 \times 10^{30} cm^{-2} sec^{-1}$
    - Integrated useable luminosity
  - Stack of $>150 \times 10^{10}$ pbars in the Recycler
  - Recycler is ready to be put into Mixed Source operations
  - Recycler is ready for Electron Cooling

Major Accomplishments

- TEVATRON
  - Lifetime at 150 GeV
    - Larger Aperture
    - Alignment and dipole un-rolls
  - Emittance dilution reduced
    - Smart bolt retrofit -> de-coupling at TEV injection
    - Roll of P1 line
    - Optimization of injection optics
  - High Energy Helix (pre-Fall 2003 shutdown)
  - CDF IP
    - Location of IP was 4-5 mm too high vertically
    - Significant impact on CDF's
      - Silicon tracking efficiency
      - SVX longevity due to radiation damage
    - Rapid response team was organized during the 1 week shutdown in early December (due to the 16 house quench) to find a solution to move the CDF IP down by 4 mm
      - Within 1 week: designed, installed, and commissioned a series of low beta quad moves that
        - » Moved the IP down by 4mm
        - » Put the beam through the center of the low beta quads
        - » Better aligned the quadrupoles
  - New Low Beta Optics
    - 20% increase in luminosity

Machine Issues

Machine Issues

- Linac
  - Availability of low energy Linac RF Power tubes
  - Klystron spare viability
    - Linac Klystron task force led by R. Pasquinelli
- Booster
  - Radiation damage due to the proton demands of the neutrino program.
    - Running at:
      - Record intensities- 5.7×10^{12} protons/pulse on the pbar target
      - Record Efficiencies > 85%
      - Record Throughput > 7×10^{18} protons/week
    - Booster Collimators installed
      - Rapid Response Team has been assigned to commission the collimators
    - Commissioning cogging (needed for slip-stacking and NUMI)
    - Injection matching of the 400 MeV line
    - Preliminary stages of developing a proton plan
      - Pulse component upgrade
      - Aperture upgrade (RF stations and kickers)
      - Alignment upgrade (TEV style alignment network)
      - Closed orbit control (ramped magnets and power supplies)
      - Tune control

Machine Issues

- Pbar Production
  - Minimized the Momentum Spread in the Debuncher
    - Increase the bandwidth of the Debuncher Momentum cooling system (~20%) with equalizers
      - ~3 months - underway
    - Optimize gain and gain ramping in the Debuncher momentum cooling
      - gain ramping finished
      - awaiting parasitic study time for gain optimization – followed by 4 hours of tunnel time
    - Investigate a static change in gamma-t in the Debuncher
      - Trade-off of bunch rotation bucket are vs good mixing for the accumulator
      - ~1 month – studies start this week
    - Investigate the feasibility of ramping gamma-t in the Debuncher
      - ~6 months

Machine Issues

- Pbar Production
  - Optimize the flux through the Stacktail
    - Implement momentum selective ARF1 curves
      - Software and curves done
      - awaiting parasitic study time
    - Increase bandwidth of the Stacktail system by about 10-20% by extending bandwidth of the Stacktail notch filters
      - DONE
    - Install controllable phase shifters in both legs of the Accumulator Stacktail
      - DONE
    - Implement a phase crossover in the Stacktail system using phase shifters
      - design done
      - awaiting dedicated ZERO stack study time
        - » Characterize known configuration of stacktail
        - » Stack in various configurations
  - Increase the flux handling capability from the StackTail into the core
    - Implement 4-8 GHz momentum core cooling during stacking
      - System in place
      - Operational configuration design not started

Machine Issues

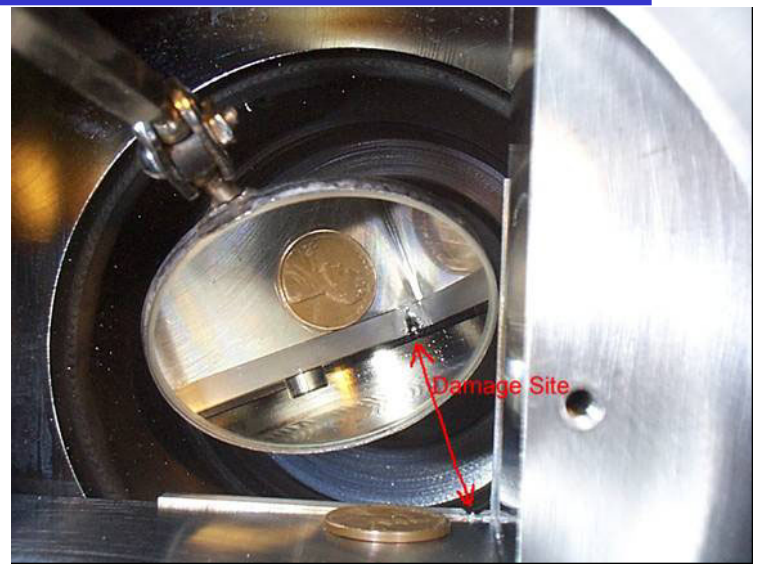
- Recycler
  - Transverse emittance growth is NO LONGER an issue
    - Recycler bake-out was extremely successful
      - Transverse emittance growth reduced by a factor of 4-5
  - Mixed Source Mode Operations
    - Injection and Extraction Transfer mechanics
    - Transverse stochastic cooling cooling rate
    - Longitudinal emittance dilution
      - During injection and extraction
      - During storing
    - Beam stability

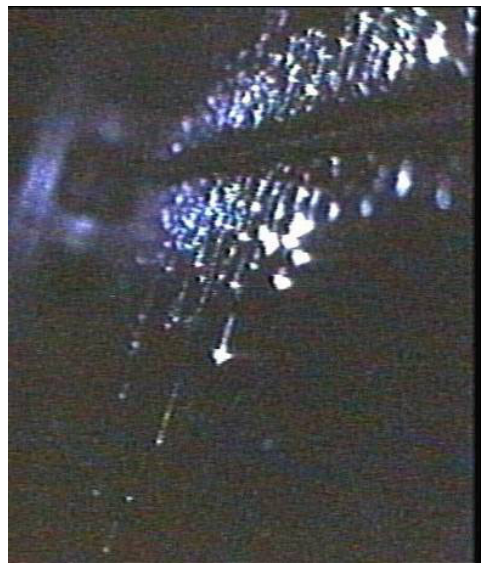
Machine Issues

- Main Injector
  - Bunch length on the Pbar target – No Longer an Issue!
    - Beam loading compensation
    - Longitudinal dampers
  - Antiproton coalescing efficiency
    - Accumulator transfers - Commissioning of 2.5 MHz transfers – **Finished!**
    - Recycler transfers – Commissioning of 2.5 MHz acceleration
  - Slip Stacking
    - Demonstrated 6×10^{12} protons on target
    - Bunch length on target within spec.
      - Beam loading compensation
      - Longitudinal dampers
  - Running the Fixed target program
    - Commissioning of high intensity NUMI multi-batch cycles
      - Transverse and longitudinal dampers
    - Switchyard 120
  - Mixed Pbar Source Operation
    - Multi-level 8 GeV energy ramp ready to go.

Machine Issues

- TEVATRON
  - Cleanup of Low Beta optics change
    - Large differential tune
      - Losses
      - Emittance blowup
  - B2 Snapback Improvements
  - Octupoles
    - Beam Stabilization
    - Differential Chromaticity
  - Orbit Smoothing
    - Automated Orbit smoothing
    - New BPM system
  - TEV Abort
    - Unmasking of inputs for protection
    - New BLM system as abort input
    - Kicker Pre-fires
      - Collimator design
      - Abort block reconfiguration



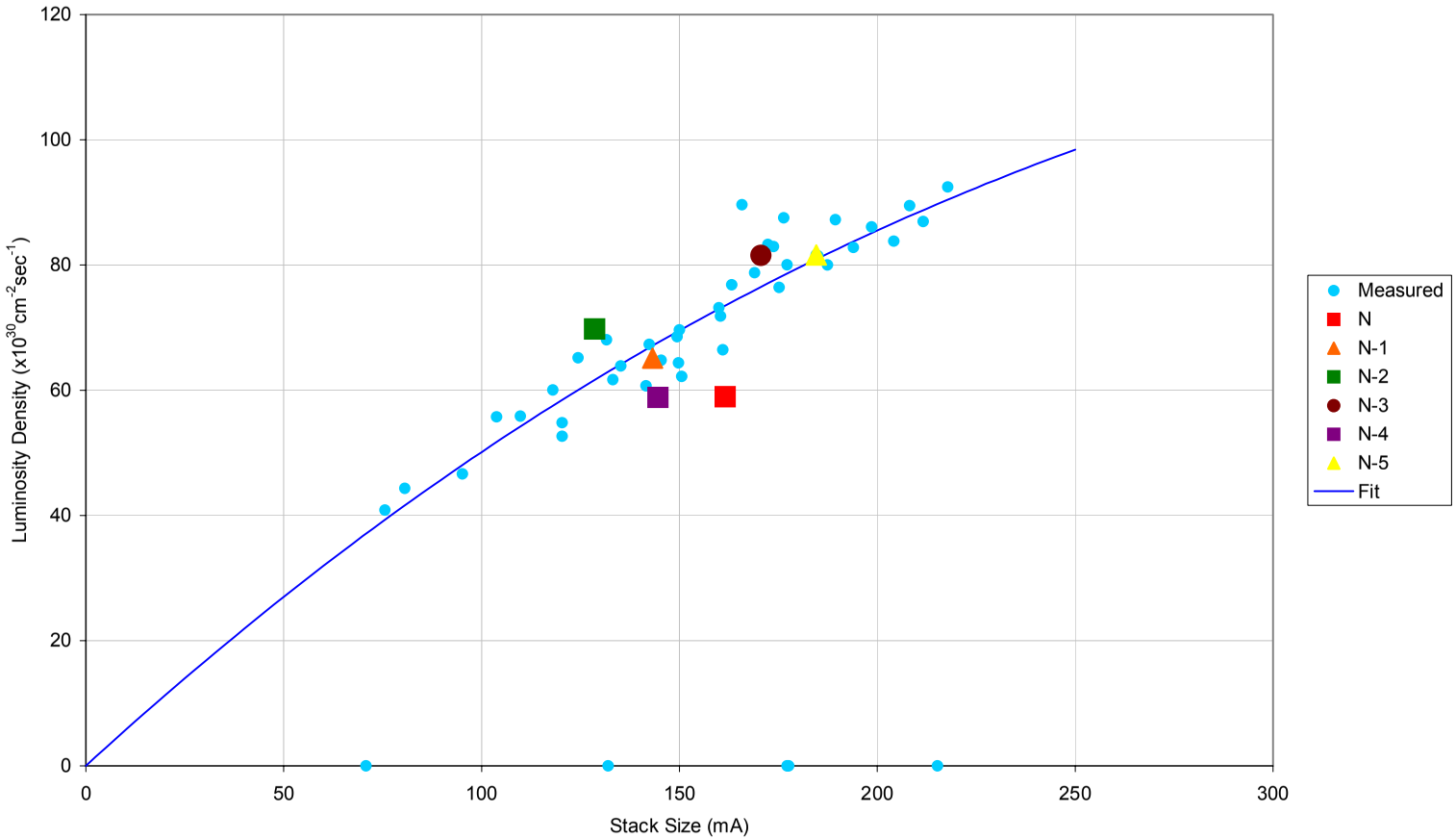


Near Term Future

Mixed-Mode Pbar Extraction

- Extracting pbars from both the Accumulator and the Recycler for the same store i.e.
  - Twenty four bunches from the Accumulator
  - Twelve bunches from the Recycler
- Ratio $I_{Recycler}/I_{Accumulator}$ is governed by:
  - Recycler phase space density (cooling)
  - Recycler transfer time (Rapid transfers)
- Reasons
  - Push Recycler commissioning progress by plunging it into operations
  - Luminosity enhancement – larger amount of pbars for smaller emittances
    - Accumulator stack size limited to <200 mA
      - Stacking Rate
      - Transverse emittance vs Stack Size
  - Flexibility in the Run II Upgrade schedule
    - Natural merging of commissioning of electron cooling
- Obstacles
  - Injector Complex 8 GeV energy alignment
  - Accumulator non-zero intercept of longitudinal emmittance vs stack size
  - Recycler longitudinal emmitance vs stack size with stochastic cooling

Luminosity Potential



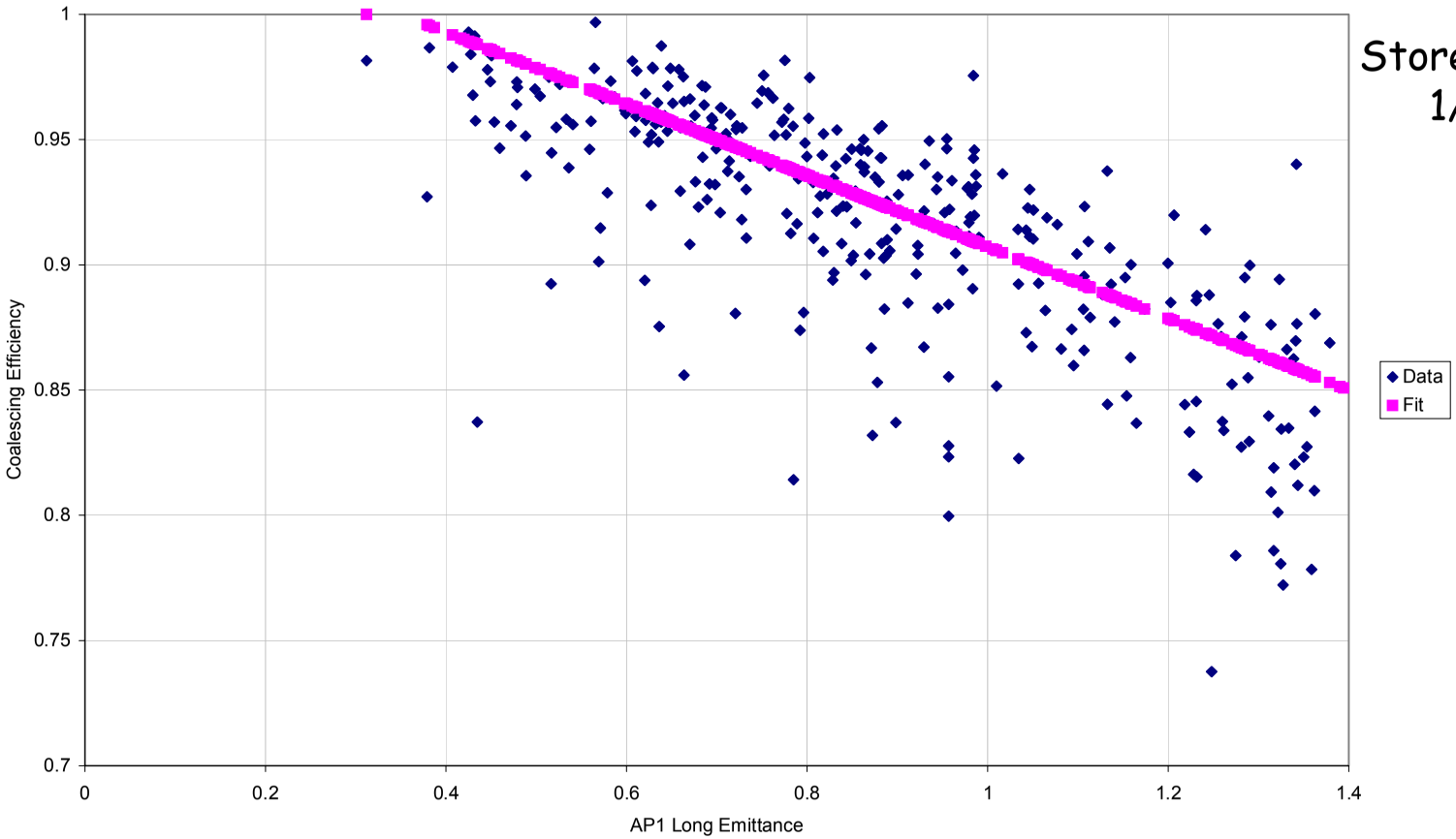
$$L := Lum_{scale} \cdot \frac{\frac{N_{proton}}{250} \cdot S \cdot Extract_{frac} \cdot eff_{coal}}{\left(PbarTranEmit + Emit_{offset}\right)}$$

$$L_{pot} := Lum_{scale} \cdot \frac{S}{\left(PbarTranEmit + Emit_{offset}\right)}$$

$$AccEmit_{offset} := 21.781$$

$$AccLum_{scale} := 12.672$$

Main Injector Antiproton Coalescing Efficiency

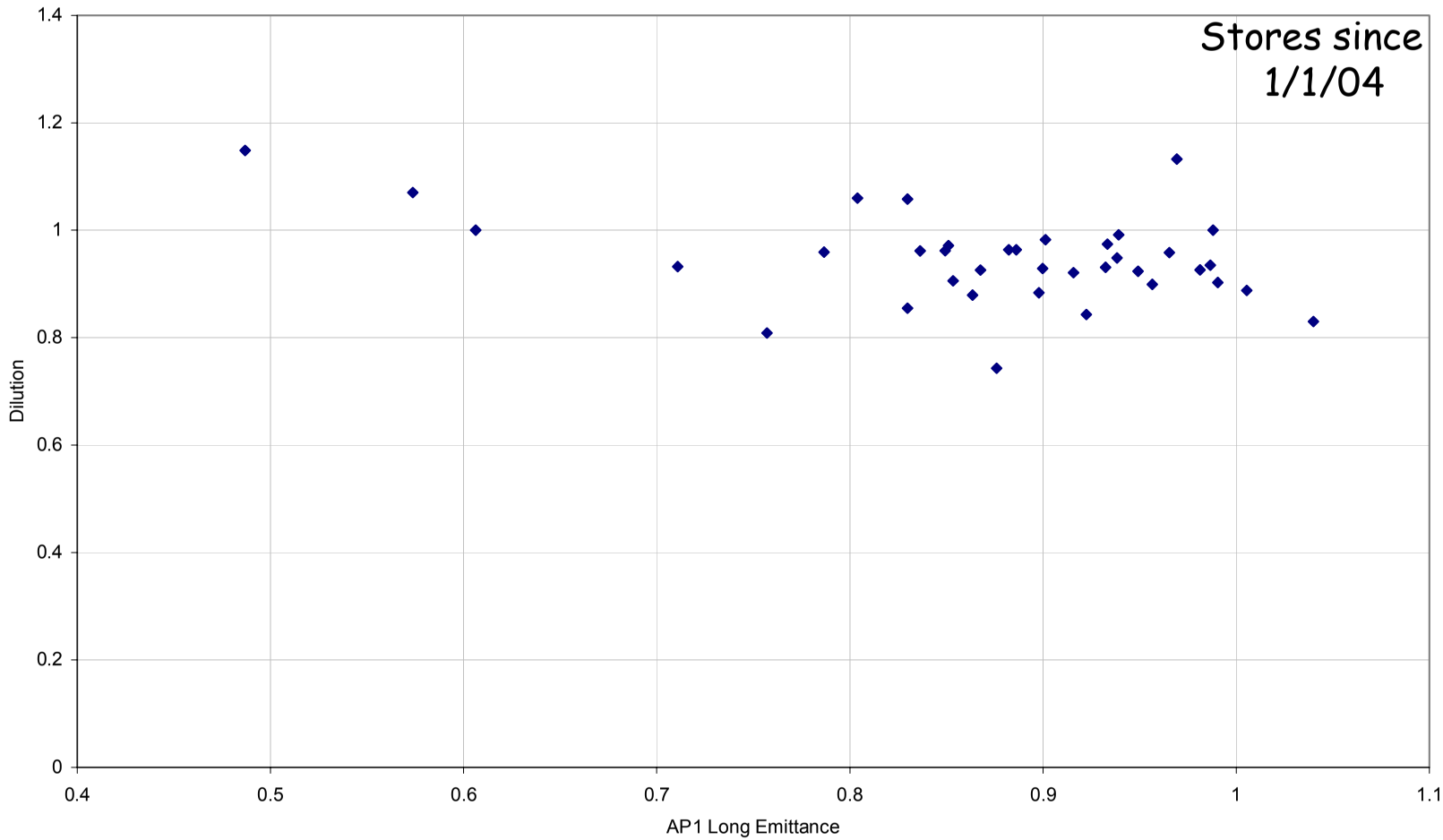


Stores since 1/1/04

$$\text{bucket_eff}_{coal}(A, A_{max}, \text{Eff_Intercept}) := \text{if}\left[A < A_{max}, 1, \text{Eff_Intercept} - A \cdot \frac{(\text{Eff_Intercept} - 1)}{A_{max}}\right]$$

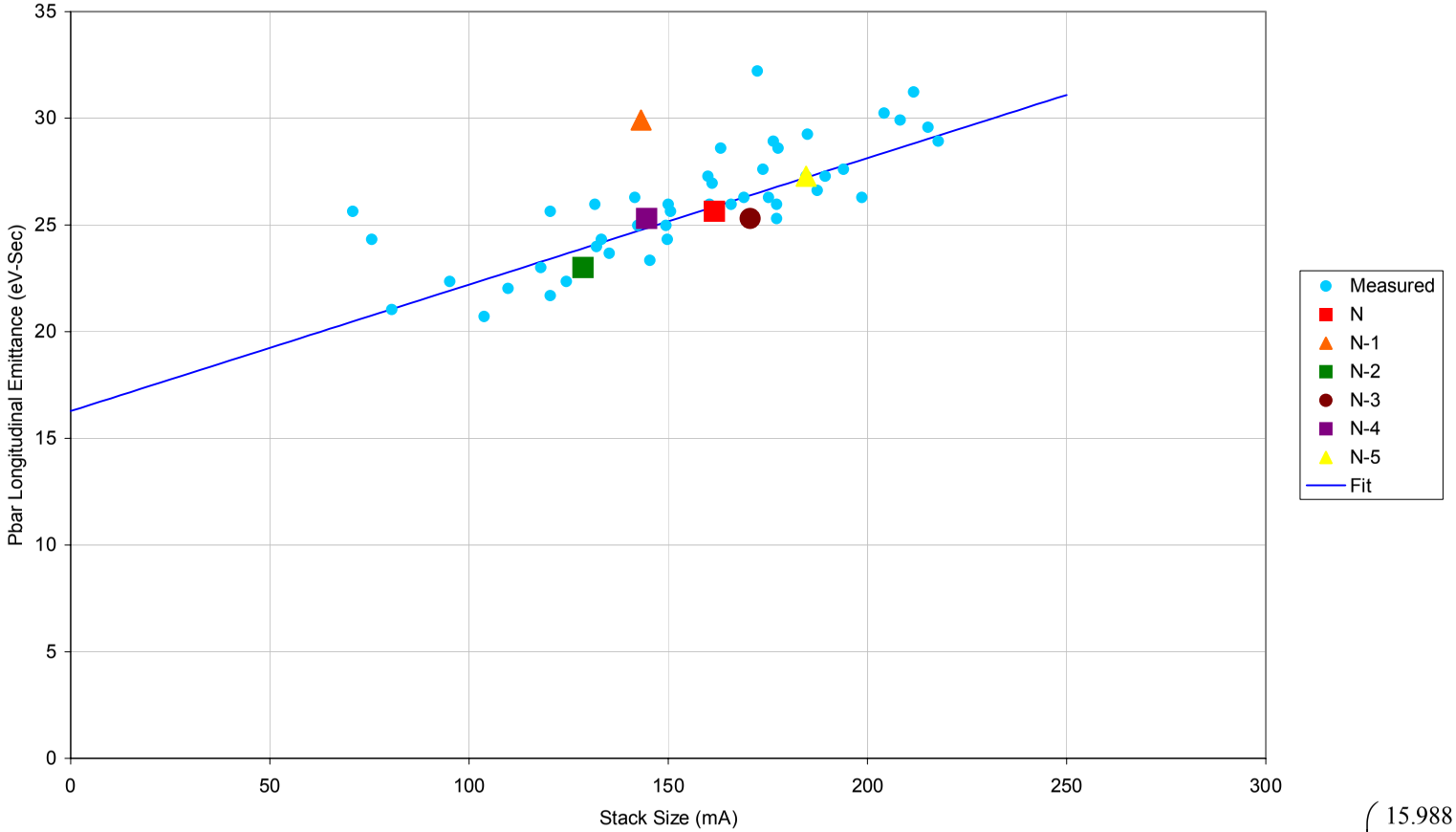
$A_{max} := 0.35$ $\quad$ $\text{Eff_Intercept} := 1.05$

Accumulator Extraction Longitudinal Emittance Dilution



$$a_{i+1} \leftarrow a_i - \Delta a_i + D \cdot \Delta a_i$$

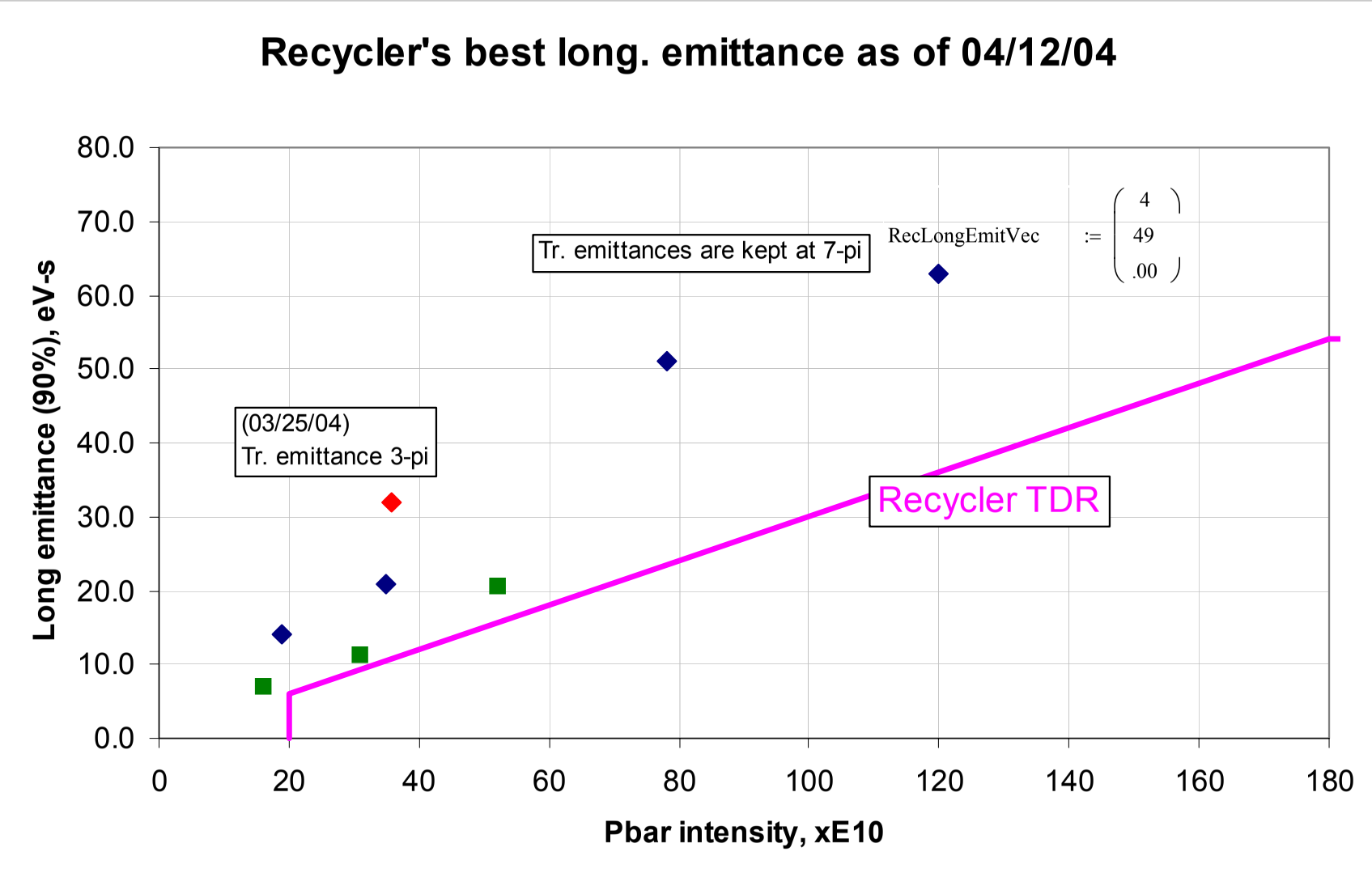
Accumulator Antiproton Longitudinal Emittance vs Stack Size



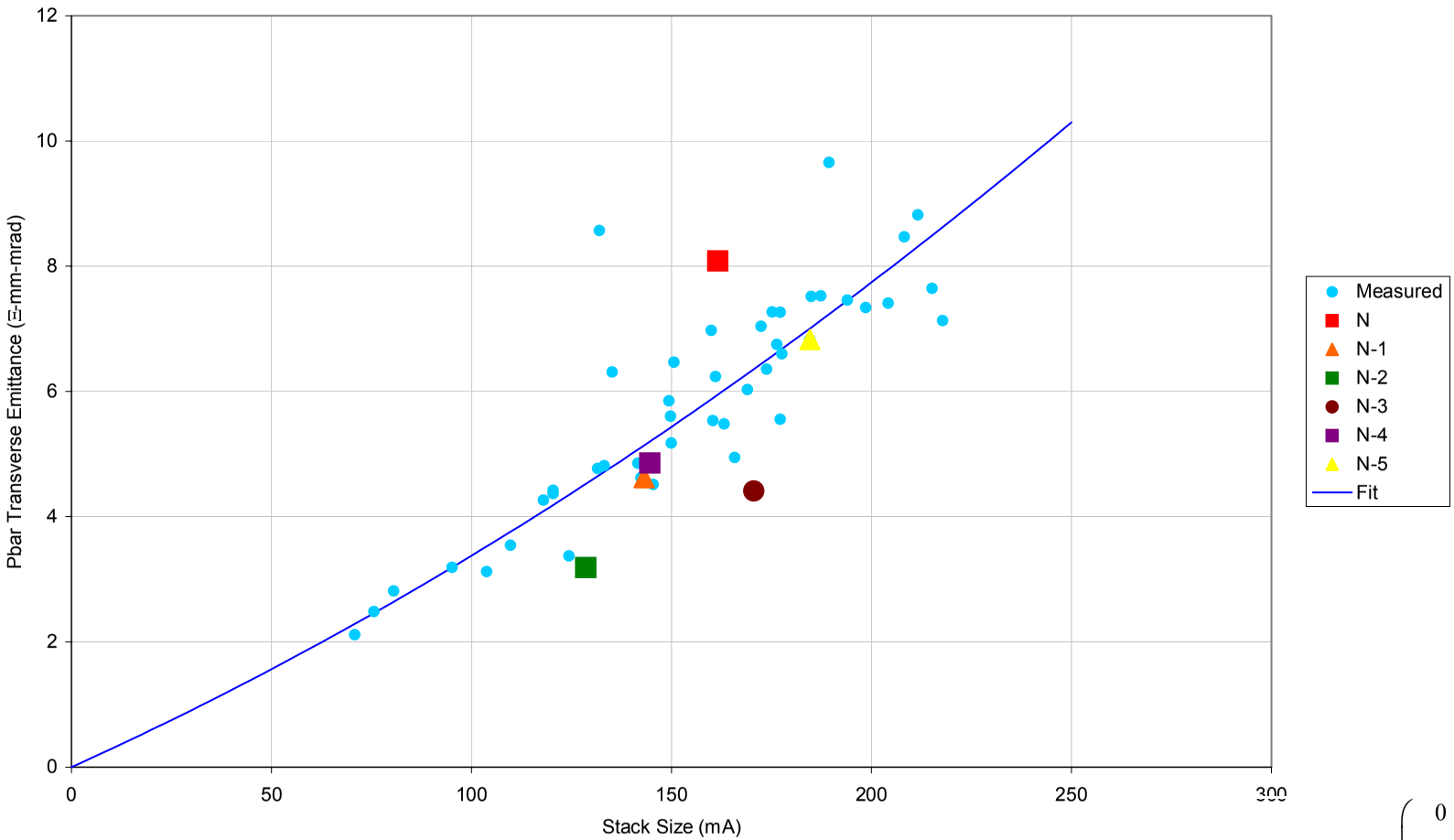
$$\text{PbarLongEmitFit}(\text{coefVec}, S) := \text{coefVec}_0 + \text{coefVec}_1 \cdot \frac{S}{100} + \text{coefVec}_2 \cdot \left(\frac{S}{100}\right)^2$$

$$\text{AccLongEmitVec} := \begin{pmatrix} 15.988 \\ 6.119 \\ .00 \end{pmatrix}$$

Recycler Longitudinal Emittance



Accumulator Antiproton Transverse Emittance vs Stack Size

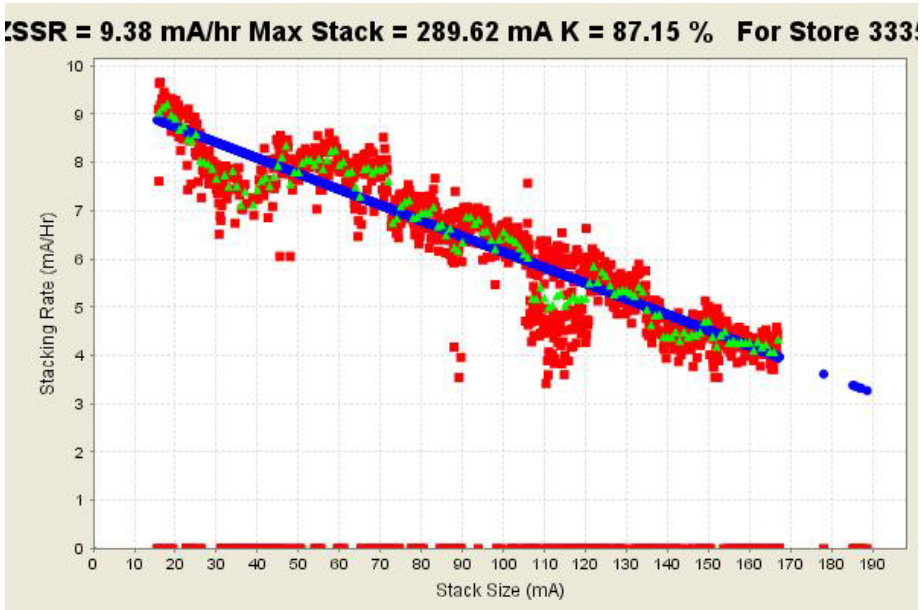


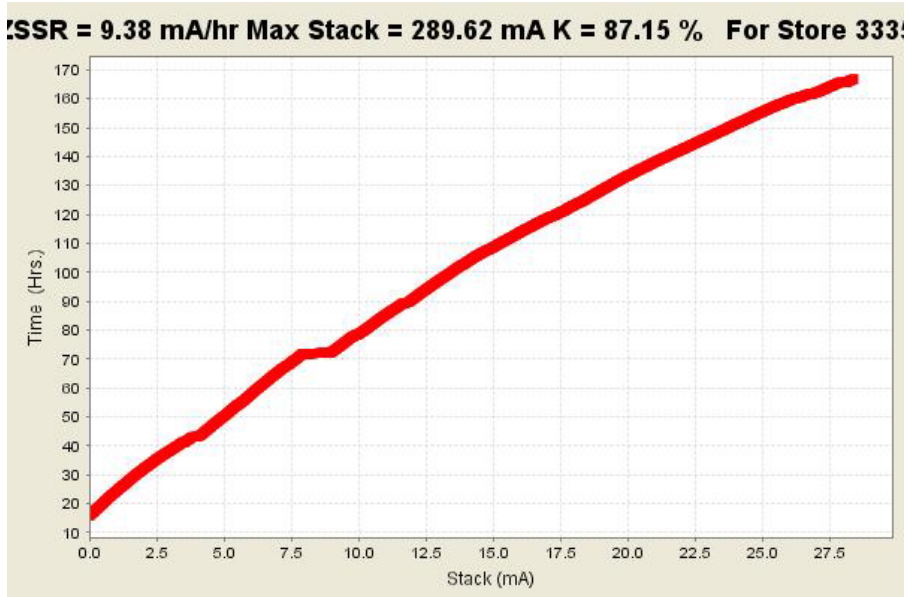
$$\text{AccTransEmitVec} := \begin{pmatrix} 0 \\ 2.919 \\ .424 \end{pmatrix}$$

$$\text{PbarTransEmitFit}(\text{coefVec}, S) := \text{coefVec}_0 + \text{coefVec}_1 \cdot \frac{S}{100} + \text{coefVec}_2 \cdot \left(\frac{S}{100}\right)^2$$

$$\text{RecTransEmitVec} := \begin{pmatrix} 7 \\ 0 \\ 0 \end{pmatrix}$$

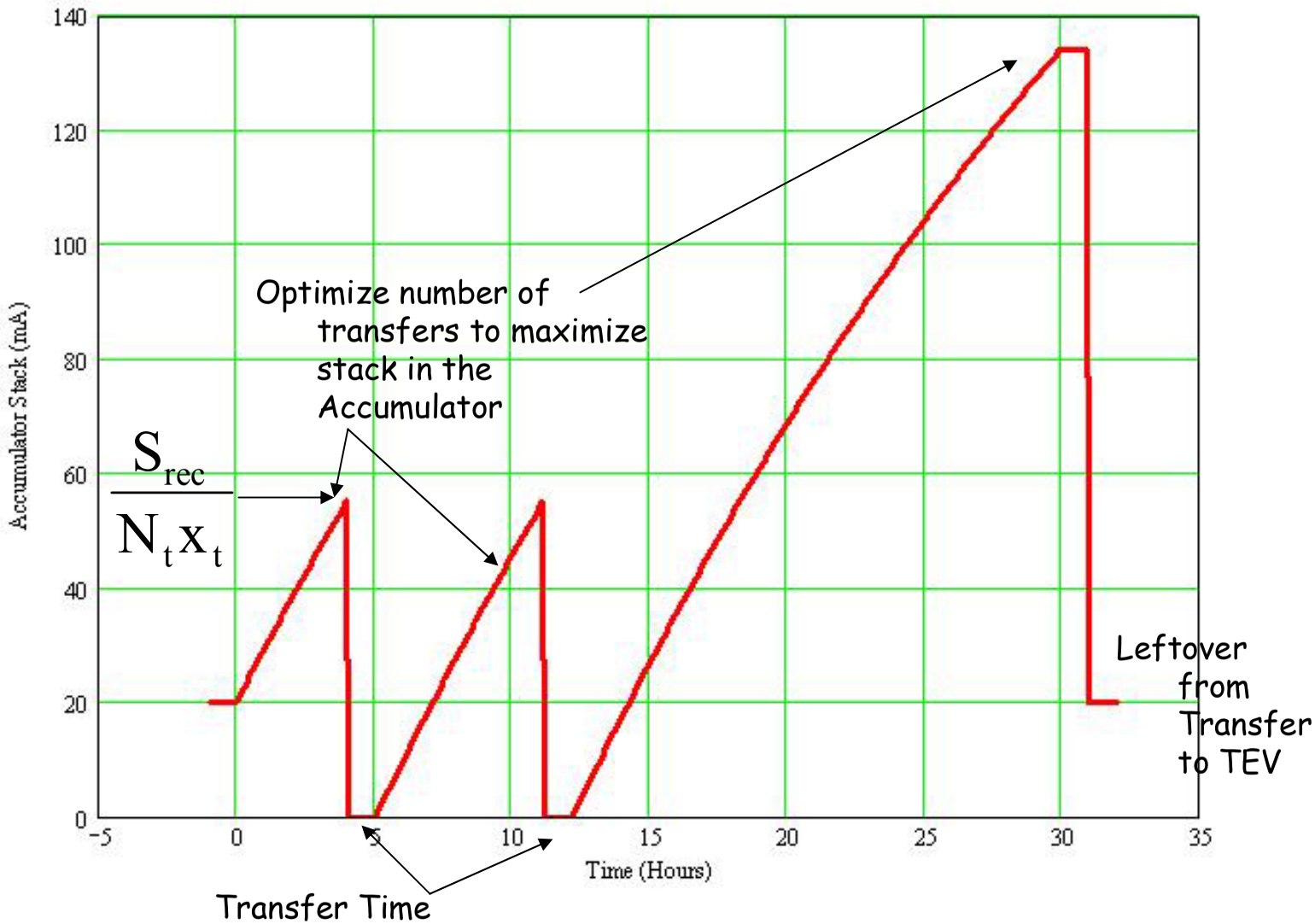
Stack Rate vs Time





$$S(t) = S_{\max} - \left(S_{\max} - S_o\right) e^{-\frac{R_o \kappa_e t}{S_{\max}}}$$

Stacking For the Recycler



Break Even Scenario

$AccLongEmitDilution := .9$ $AccLongEmitCutoff := 0.35$ $AccEffIntercept := 1.05$ $AccEmit_{offset} := 21.781$ $AccLum_{scale} := 12.672$

$$AccTransEmitVec := \begin{pmatrix} 0 \\ 2.919 \\ .424 \end{pmatrix} \qquad AccLongEmitVec := \begin{pmatrix} 15.988 \\ 6.119 \\ .00 \end{pmatrix}$$

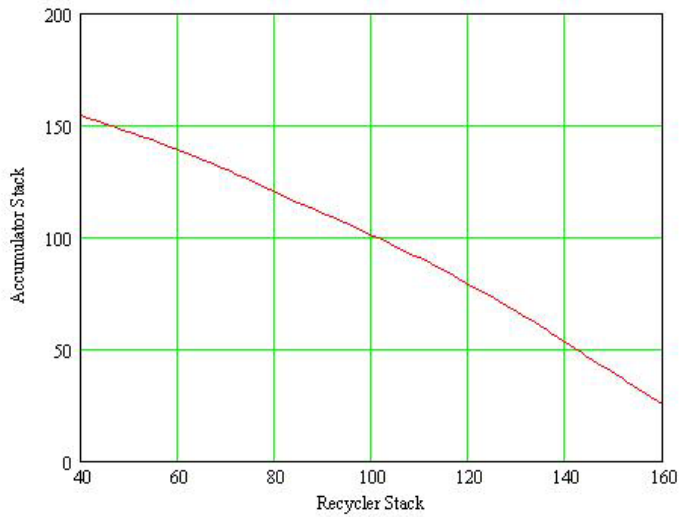
$RecLongEmitDilution := .9$ $RecLongEmitCutoff := 0.35$ $RecEffIntercept := 1.05$ $RecEmit_{offset} := 21.781$ $RecLum_{scale} := 12.672$

$$RecTransEmitVec := \begin{pmatrix} 7 \\ 0 \\ 0 \end{pmatrix} \qquad RecLongEmitVec := \begin{pmatrix} 4 \\ 49 \\ .00 \end{pmatrix} \qquad RecLongEmitVecMeas := \begin{pmatrix} 4 \\ 49 \\ .00 \end{pmatrix}$$

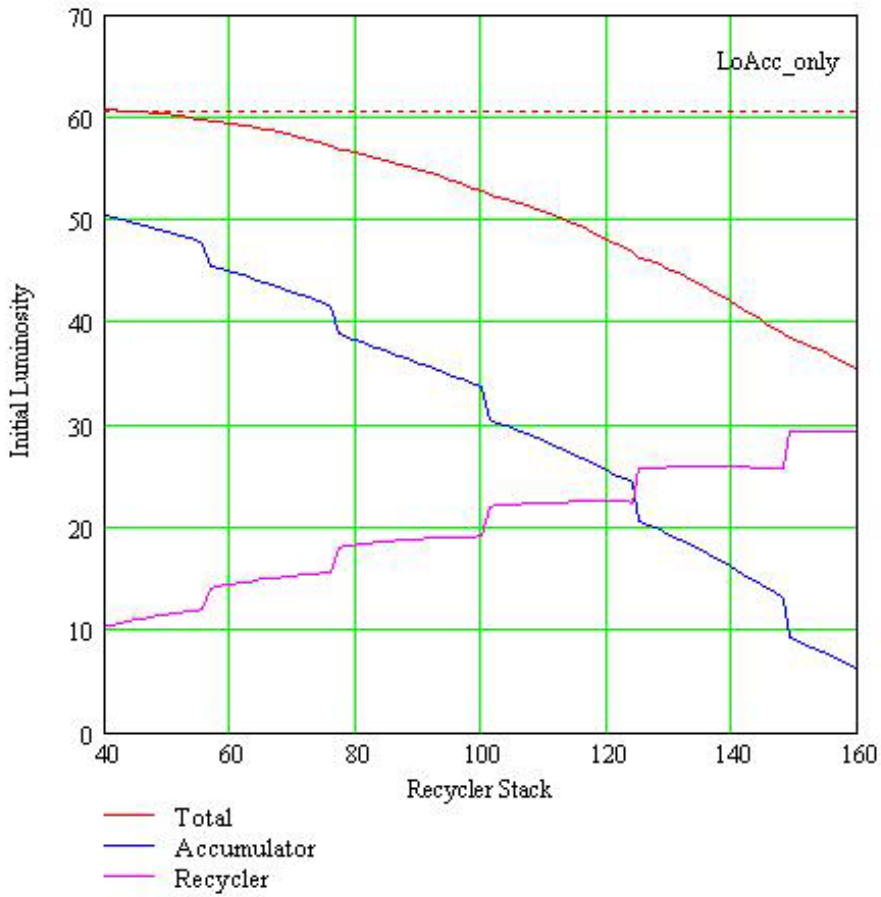
$Rate_o := 10$ $S_{max} := 300$ $AccRecTransEff := 0.90$ $AccRecTransTime := 1.0$ $StoreLength := 25$

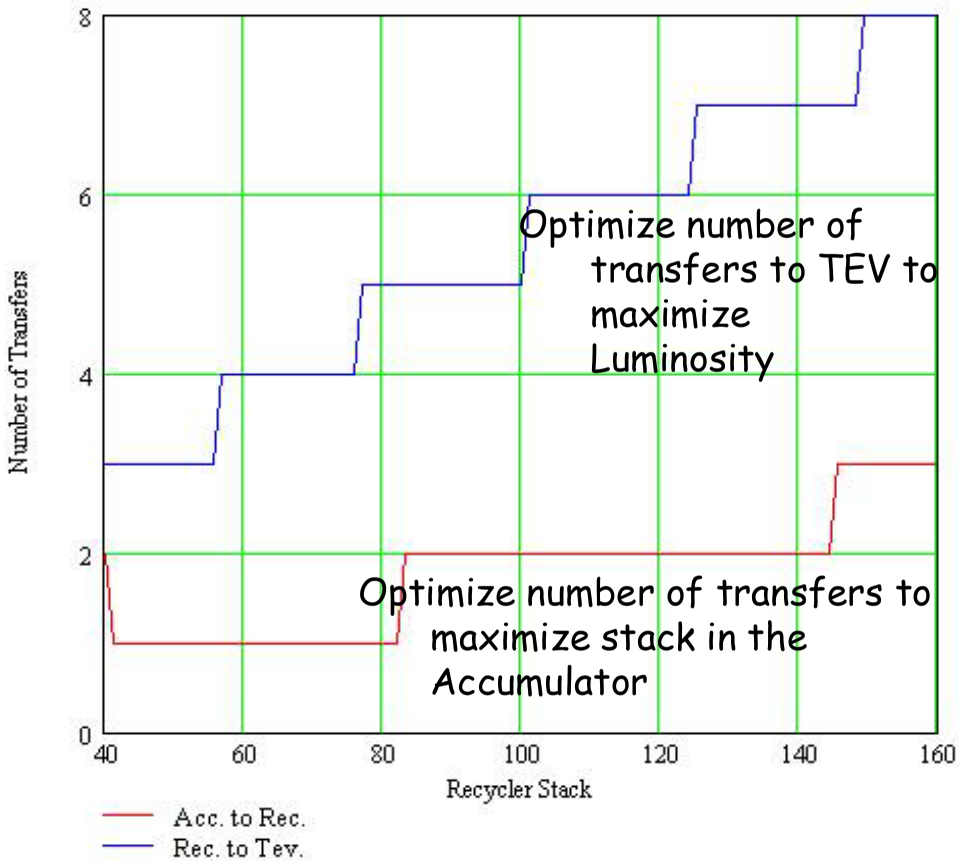
$X_{e_acc} := 0.85$ $X_{e_rec} := 0.85$ $N_{Proton} := 250$

$Rstack_{min} := 40$ $Rstack_{max} := 160$



Break Even Scenario





Optimistic Scenario

$AccLongEmitDilution := .9$ $AccLongEmitCutoff := 0.35$ $AccEffIntercept := 1.05$ $AccEmit_{offset} := 21.781$ $AccLum_{scale} := 12.672$

$$AccTransEmitVec := \begin{pmatrix} 0 \\ 2.919 \\ .424 \end{pmatrix} \qquad AccLongEmitVec := \begin{pmatrix} 15.988 \\ 6.119 \\ .00 \end{pmatrix}$$

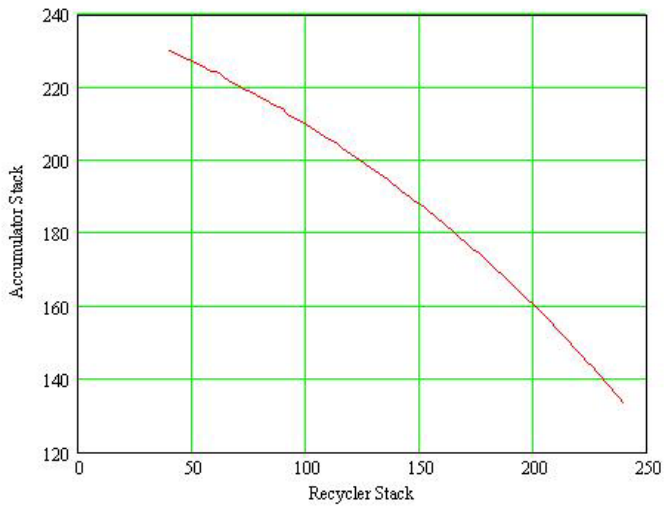
$RecLongEmitDilution := .1$ $RecLongEmitCutoff := 0.35$ $RecEffIntercept := 1.05$ $RecEmit_{offset} := 21.781$ $RecLum_{scale} := 12.672$

$$RecTransEmitVec := \begin{pmatrix} 7 \\ 0 \\ 0 \end{pmatrix} \qquad RecLongEmitVec := \begin{pmatrix} 4 \\ 25 \\ .00 \end{pmatrix} \qquad RecLongEmitVecMeas := \begin{pmatrix} 4 \\ 49 \\ .00 \end{pmatrix}$$

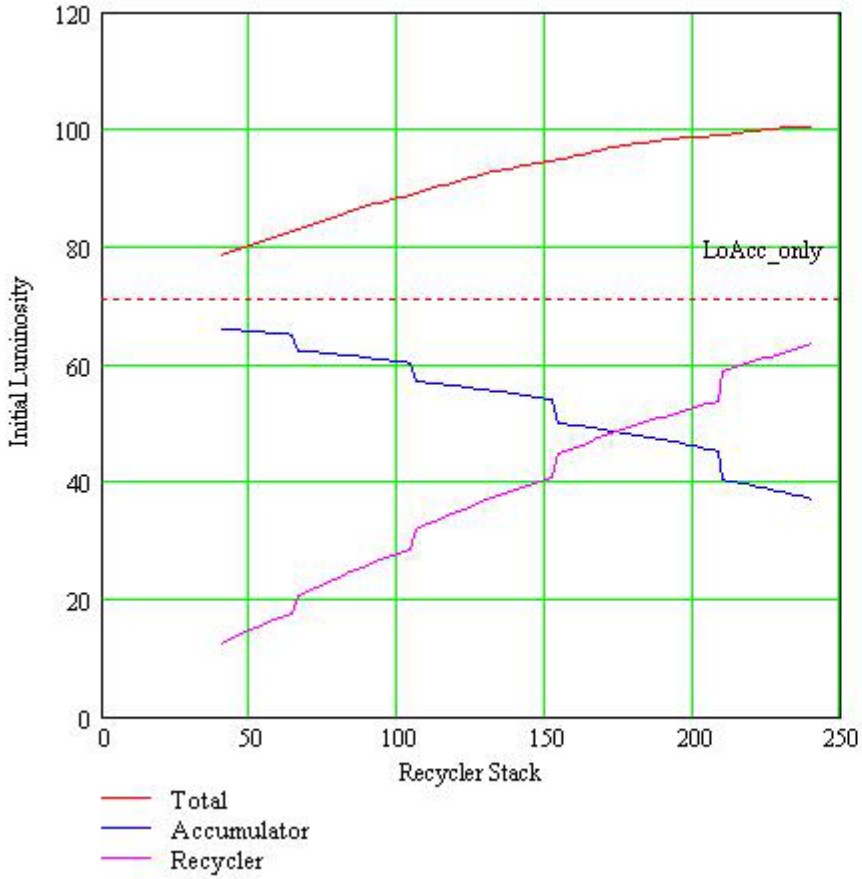
$Rate_o := 15$ $S_{max} := 300$ $AccRecTransEff := 0.95$ $AccRecTransTime := .25$ $StoreLength := 30$

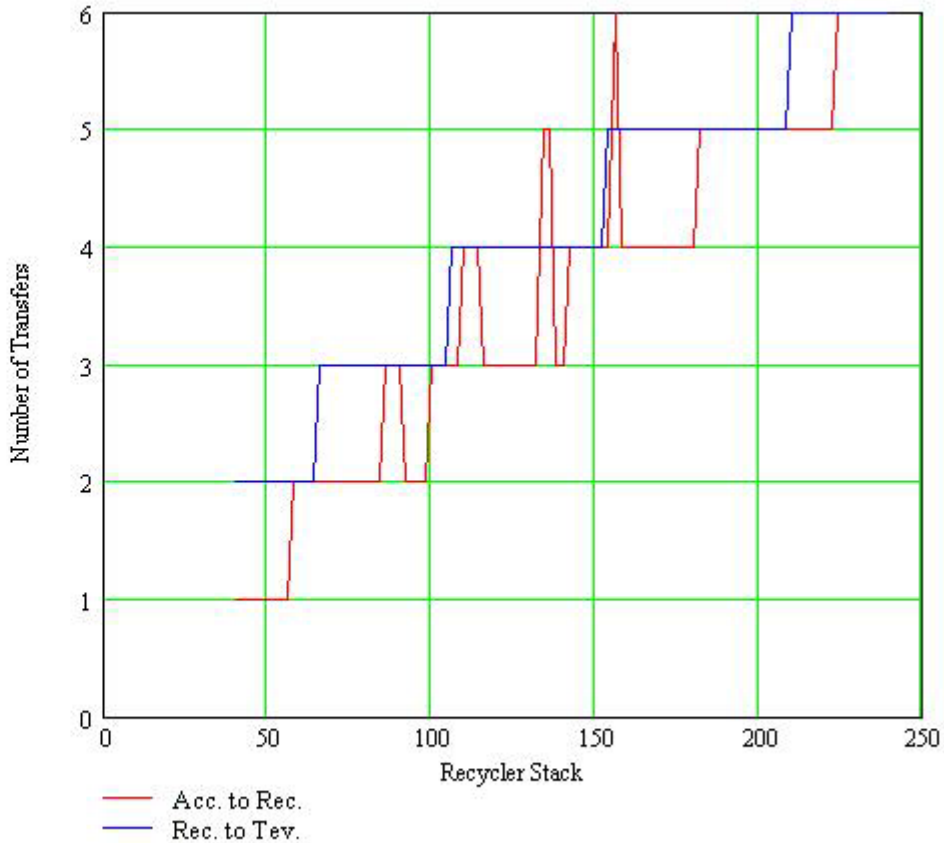
$X_{e_acc} := 0.85$ $X_{e_rec} := 0.85$ $N_{Proton} := 250$

$Rstack_{min} := 40$ $Rstack_{max} := 240$



Optimistic Scenario





Summary

- Our goals in FY04
  - Operate the Collider at the Main Injector project luminosity design goals
  - Integrate over 300pb^{-1} in 39 weeks
  - Prepare the Collider for implementation of the initial stages of the Run II Upgrades
  - Commission the Recycler for electron cooling
  - Protect the TEVATRON and the Detectors
    - Robust Abort system
    - Beam loss monitor system that reliably triggers the abort
- The Fall 2003 shutdown was aimed at
  - Installing equipment needed to attain the FY04 luminosity goals
  - Baking the Recycler
- The current FY04 performance
  - Is above the FY04 design curve
  - The Luminosity per week is up 80% from the previous year
  - Most of the Tevatron parameters are close to the design values
  - Pbar production is well below the design parameters but there is an aggressive cooling plan underway.
  - The Proton Source is operating at record intensities, efficiencies, and throughput
  - We will spend this summer placing the Recycler into mixed-source operations