Proton Intensity Improvements for MINOS

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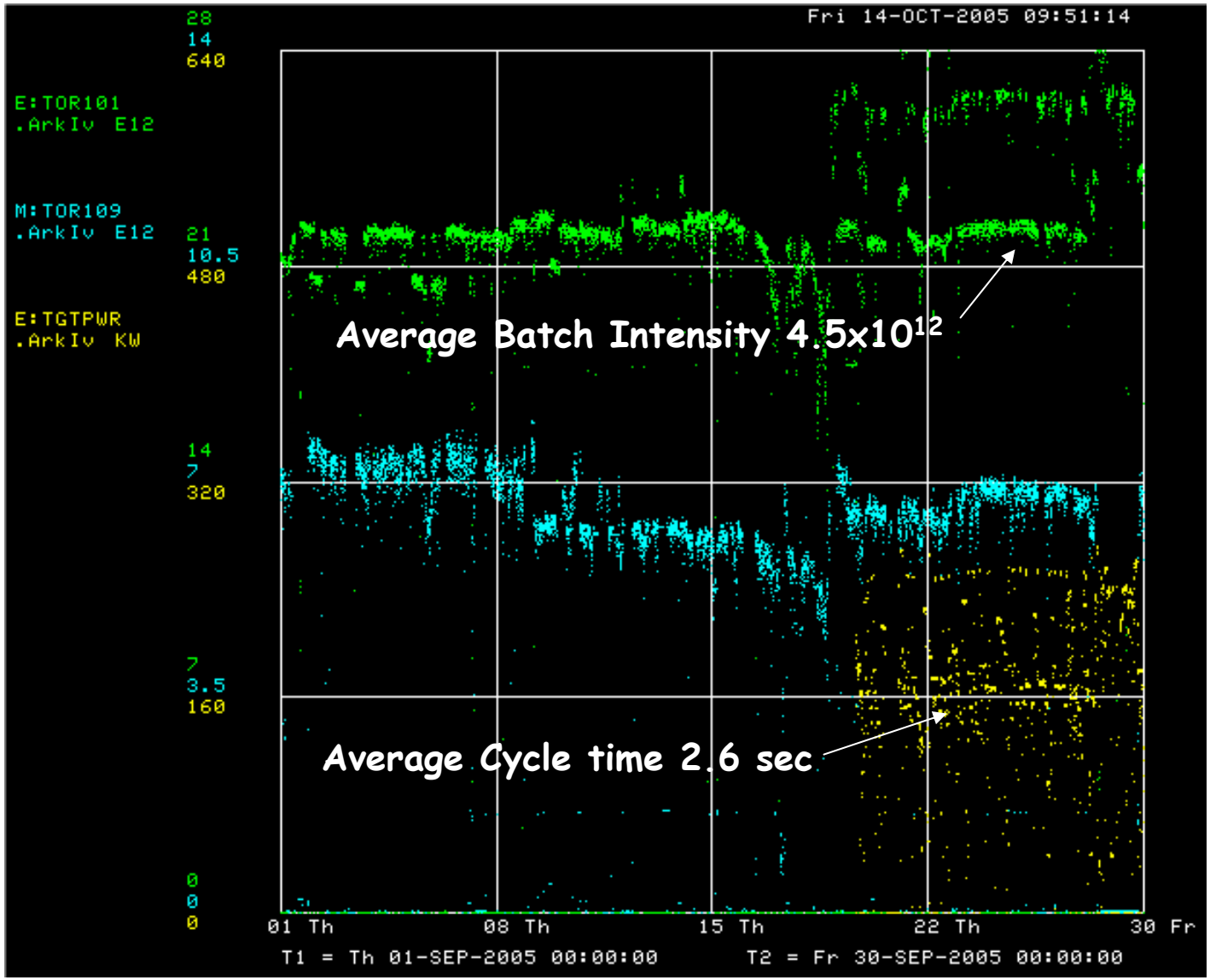
NUMI Performance Sept. 2005



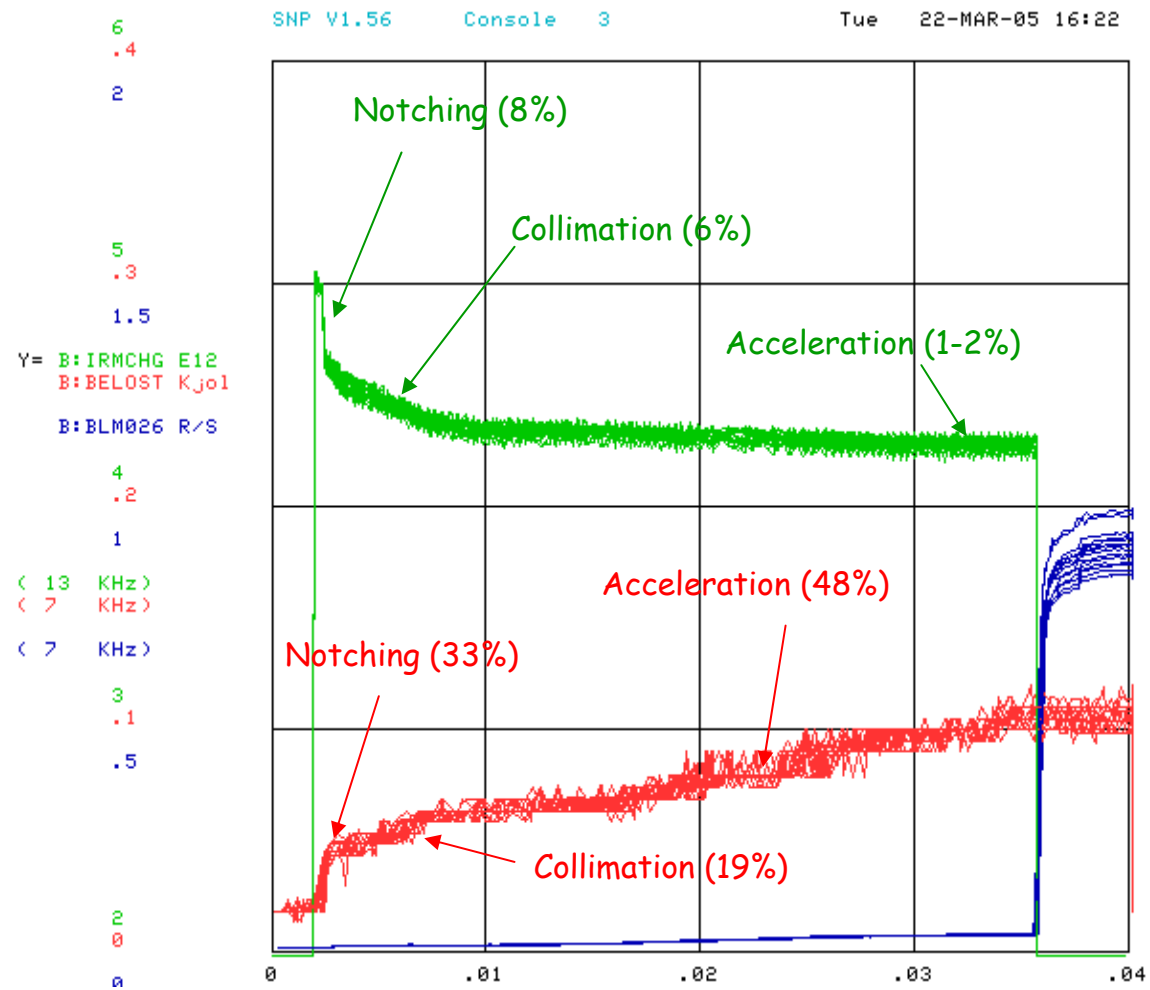
Booster Performance

- Amount of beam power lost per pulse is inversely proportional to the repetition rate

$$P_L = J_L R$$

- For simplicity the beam loss can be divided into two categories,
  - beam loss due to creating the beam gap (notch) for extraction
  - beam lost transversely during acceleration

$$J_L = E_n \Delta N_n + E_A \Delta N_A$$



Booster Performance

- The total efficiency of the Booster is:

$$\frac{N_{ext}}{N_{inj}} = \left(1 - f_n - f_A\right)$$

  - f_n is the ratio of the amount of beam loss during notching to the injection intensity
  - f_A is the ratio of the amount of beam loss during acceleration to the injection

- For a given notching fraction, the fraction of beam loss during acceleration that can be tolerated is:

$$f_A = \frac{P_L - \left(N_{ext} E_n R + P_L\right) f_n}{N_{ext} E_A R + P_L}$$

- Assuming a guassian profile as a simple approximation, the amount of beam in the halo that is outside the aperture is:

$$f_h = e^{-3\frac{A}{\varepsilon 95}}$$

Booster Performance

- The amount of beam that is permitted to be in the halo is:

$$f_h = \frac{\Delta N_A}{2(N_{ext} + \Delta N_A)} = \frac{f_A}{2(1 - f_n)}$$

- The aperture required is :

$$A = \frac{S_f \varepsilon_{95}}{3} \ln\left(\frac{2(1 - f_n)}{f_A}\right)$$

- The half-aperture of the magnets is proportional to
  - The transverse acceptance,
  - The momentum acceptance
  - The closed orbit displacement

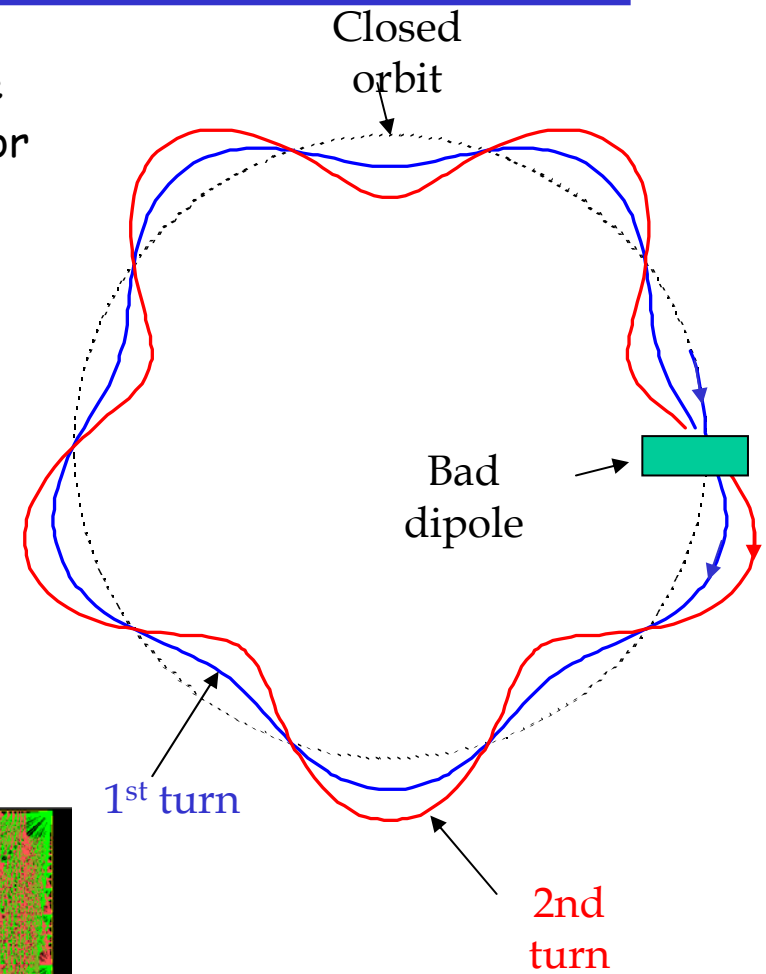
$$\Delta x = \sqrt{\frac{A_n}{\beta\gamma}\beta_{max}} + \frac{\Delta p}{p} D_{max} + \text{c.o.d.}$$

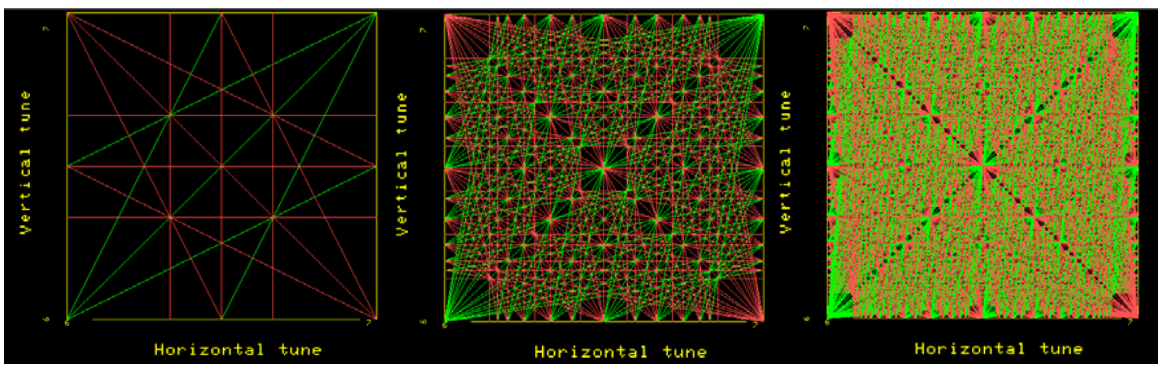
- Compare designs with the same space charge tune shift

$$\varepsilon_n \propto \frac{N_{inj}}{\beta\gamma^2 \Delta\nu}$$

Resonance Lines and Tunes

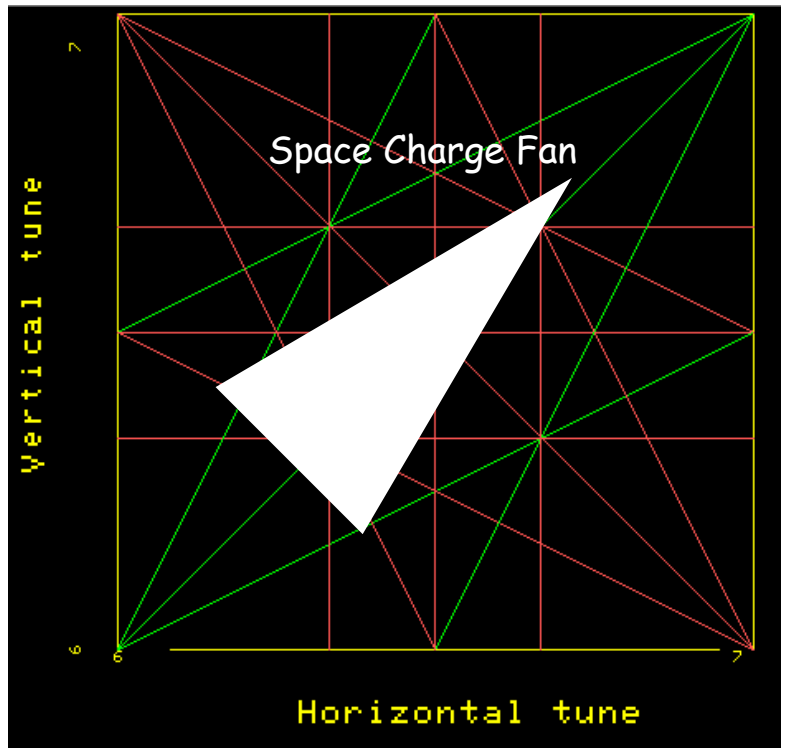
- The betatron tune is the number of "wiggles" a particle makes as it goes around the machine once
- The tune is proportional to the machine focusing or the quadrupole strength (lattice)
- If the tune is an integer:
  - A dipole error would amplify turn after turn
  - The amplification is proportional to the dipole error
- If the tune is an $\frac{1}{2}$ integer a quadrupole error would amplify every other turn, etc…
- For an infinite set of multipoles
  - The tune should **not** be a rational number
  - The growth rate is inversely proportional to the multipole order
  - The growth rate is proportional to the multipole strength



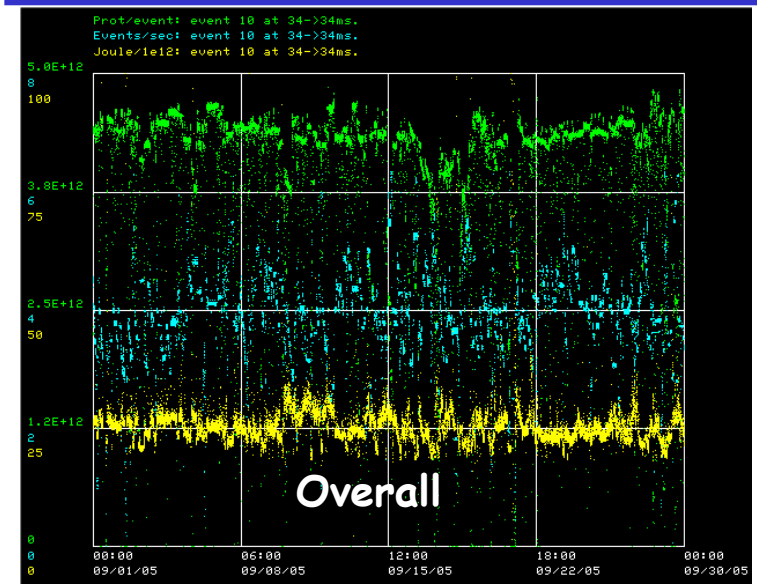


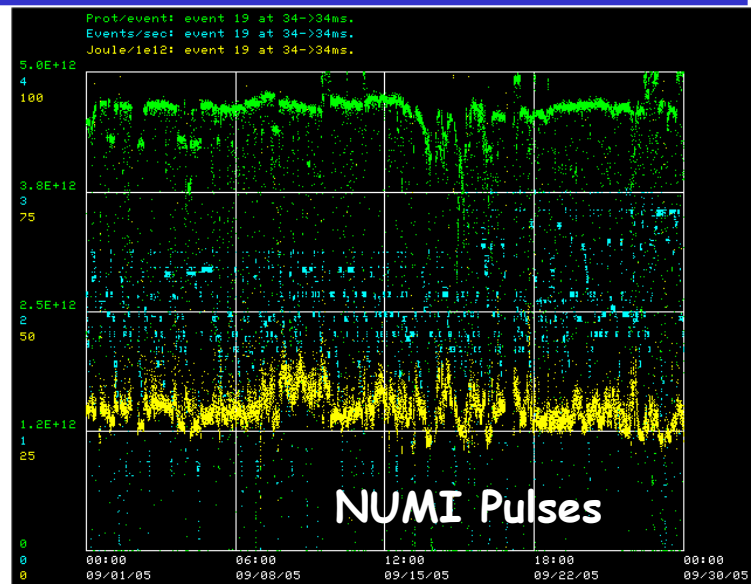
Space Charge Tune Shift

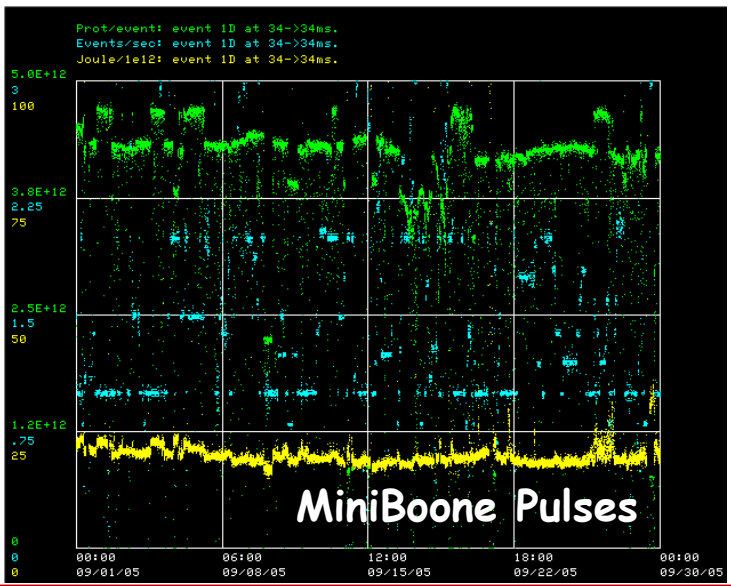
- The beam in the Booster is limited by space charge tune shift
  - Moving particles produce a magnetic field on the other particles which act as a de-focusing lens
  - De-focusing force is
    - proportional to
      - the beam current
      - 1/Energy
    - a function of the phase space amplitude
      - Not all the particles get the same tune shift

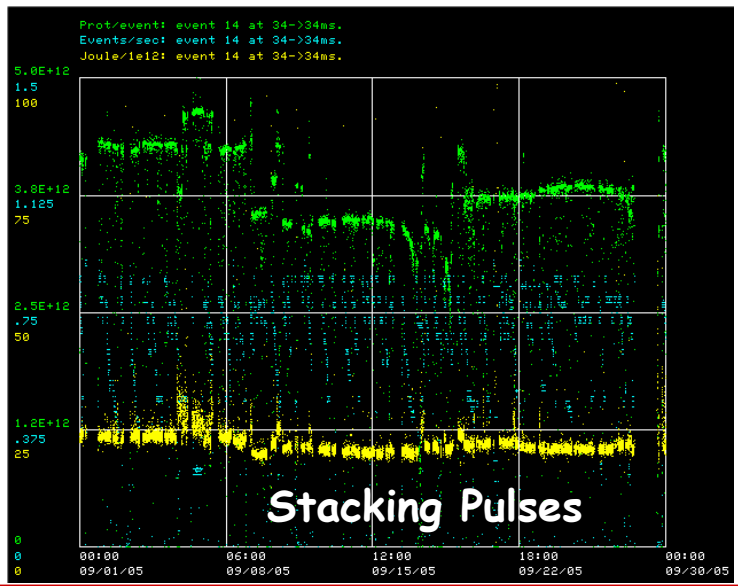


Booster Performance Sept. 2005









Booster Throughput Scenarios

- The vertical aperture in the present Booster is
  - 1.64 inches for the F magnets
  - 2.25 inches for the D magnets
- The horizontal good field aperture is
  - 4.3 inches for the F magnets
  - 3 inches for the D magnets
- The RF cavities in the Booster are located between two D magnets
  - The horizontal beta function is at a minimum
  - The vertical beta function is a maximum.
  - The RF cavity aperture is 2.25 inches.
- To increase Booster throughput for NUMI, we have three knobs available
  - Increase beam power lost in the Booster tunnel
  - Increase the effective Booster aperture (or decrease the closed orbit distortion tolerance)
  - Decrease the amount of beam to other programs
    - MiniBoone (presently ~31% of Booster throughput)
    - Collider (presently ~17% of Booster throughput)

Booster Throughput Scenarios

Parameter	Present	Loss	Aperture	MBoone	Everything	
Slip Stack Final Intensity	6.9	8	8	8	8	$x10^{12}$
NUMI Final Intensity	22	22	22	22	24.5	$x10^{12}$
MI Cycle Time	2.6	2.2	2.2	2.2	2.2	Sec
Slip Stack Batches	2	2	2	2	2	
NUMI Batches	5	5	5	5	5	
Slip Stack Efficiency	88	90	90	90	90	%
NUMI Efficiency	95	95	95	95	95	%

Parameter	Present	Loss	Aperture	MBoone	Everything	
Booster Flux	6.38	7.25	7.25	5.27	7.67	$x10^{16}$/Hr
Collider Flux	1.09	1.45	1.45	1.45	1.45	$x10^{16}$/Hr
NUMI Flux	3.21	3.79	3.79	3.79	4.22	$x10^{16}$/Hr
NUMI Beam Power	162	192	192	192	214	kW
MiniBoone Flux	2.08	2.01	2.01	0.03	1.99	$x10^{16}$/Hr

Booster Intensity Requirements

Parameter	Present	Loss	Aperture	MBoone	Everything	
Extraction Intensity	4.43	4.58	4.58	4.58	4.95	$x10^{12}$
Rep. Rate	4	4.4	4.4	3.2	4.3	Hz
Average Beam Power Lost	440	600	440	440	600	Watts
Notch Bunches	7	7	7	7	7	
Notch Energy	450	450	450	450	450	MeV
Acceleration Loss Energy	1050	1050	1050	1050	1050	MeV
Injection Energy	400	400	400	400	400	MeV
Allowed Tune Shift	0.47	0.47	0.47	0.47	0.47	
Bunching Factor	2	2	2	2	2	

Parameter	Present	Loss	Aperture	MBoone	Everything	
Acceleration loss	8.7	10.8	7.4	10.9	10.1	%
Efficiency	83.0	80.9	84.3	80.8	81.6	%
Injection Intensity	5.3	5.7	5.4	5.7	6.1	$x10^{12}$
Norm. Emittance at Inj	11.4	12.1	11.6	12.1	13.0	π-mm-mrad
Norm Acceptance at Inj	18.9	18.6	20.2	18.6	20.4	π-mm-mrad

Booster Aperture Requirements

Parameter	Present	Loss	Aperture	MBoone	Everything	
F magnet β_x	33	33	33	33	33	m
F magnet β_y	14	14	14	14	14	m
F magnet D_x	3	3	3	3	3	m
D magnet β_x	14	14	14	14	14	m
D magnet β_y	22	22	22	22	22	m
D magnet D_x	2.5	2.5	2.5	2.5	2.5	m
Momentum Acceptance	0.4	0.4	0.4	0.4	0.4	%
Misalignment & c.o.d.	10	10	8.5	10	8.5	mm

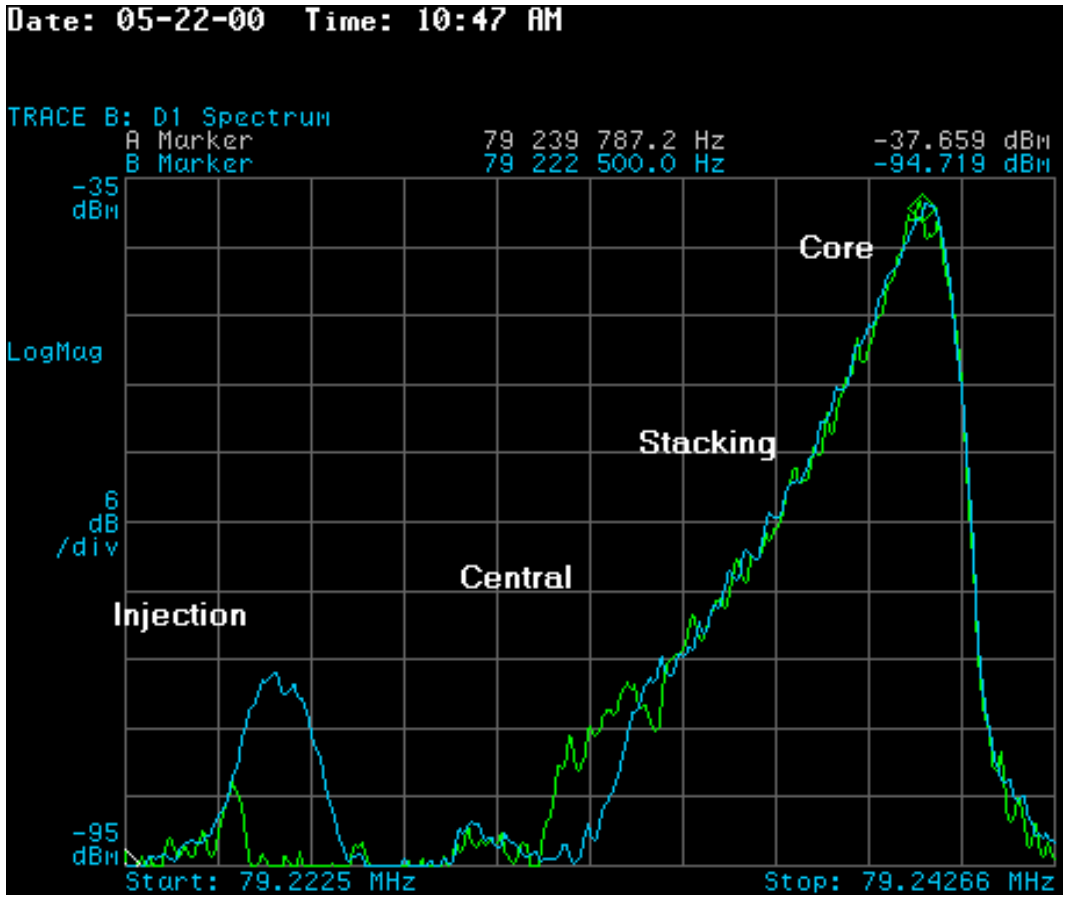
Parameter	Present	Loss	Aperture	MBoone	Everything	
F Aperture Width	2.81	2.80	2.83	2.80	2.83	in
F Aperture Height	1.66	1.65	1.65	1.65	1.65	in
D Aperture Width	2.06	2.05	2.04	2.05	2.05	in
D Aperture Height	1.98	1.97	1.98	1.97	1.99	in

NUMI Cycles and Stacking Rate

- Most of the accelerator operating period is devoted to:
  - making antiprotons for the Collider program:
  - accelerating protons for the NUMI program.
- While stacking antiprotons, the same Main Injector 120 GeV acceleration cycle is used to accelerate :
  - protons bound for the antiproton production target
  - protons bound for the NUMI neutrino production target.
  - This is designated as Mixed-Mode operations.
- The minimum cycle time is limited by the Main Injector ramp rate (~ 1.5 seconds) and the time it takes to fill the Main Injector with:
  - two Booster batches for antiproton production (2 x 0.067 seconds)
  - five Booster batches for neutrino production (5 x 0.067 seconds)
- As the antiproton stack size grows, the Accumulator stochastic cooling systems slow down which requires the cycle time to be lengthened.
- The lengthening of the cycle time unfortunately reduces the NUMI neutrino flux.

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

- The time evolution of the antiproton phase space during cooling is best described by the Fokker-Plank Equation

$$\frac{\partial \psi}{\partial t} = -\frac{\partial \phi}{\partial E}$$

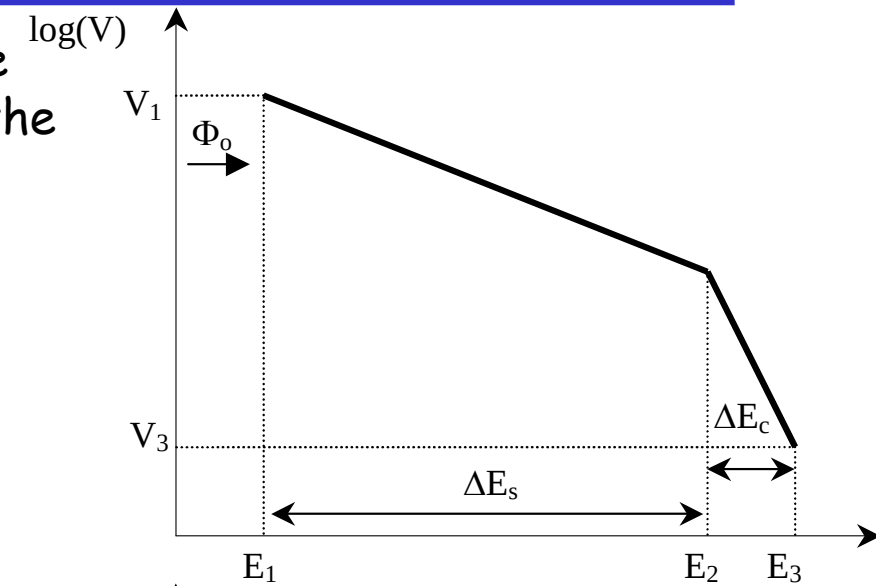
$$\phi_c = \frac{\Delta E_c}{T_o}\psi = eV_o f_o \psi \sum_n \mathrm{Re}\{G_n(E)\}$$

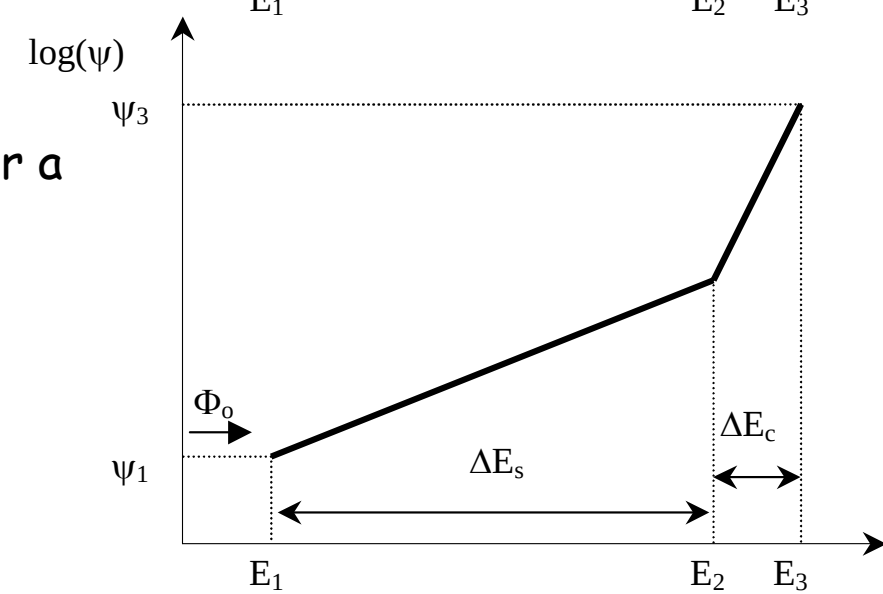
$$\phi_h = \frac{1}{2}\frac{\Delta E_h{}^2}{T_o}\frac{\partial \psi}{\partial E} = \frac{1}{4}(eV_o f_o)^2 \frac{E_o}{\eta f_o}\psi \frac{\partial \psi}{\partial E}\sum_n |G_n(E)|^2$$

- Optimum profile that maximizes dψ/dE for a constant stacking rate is exponential

$$G_n(E) = g_o e^{-E/E_d} \qquad \psi(E) = \psi_o e^{E/E_d}$$

$$\psi_o = \frac{N_T P_D}{\Delta E_{bD}}$$





Antiproton Stacking – Stacktail System

- However, not the entire beam that is injected into the Accumulator from the Debuncher needs to be transported from the injection orbit to the Stacktail deposition orbit.
  - The bucket area of the RF system (ARF1) that decelerates the beam from the injection orbit to the Stacktail deposition orbit can be made smaller than the longitudinal emittance of the extracted Debuncher beam.
  - Beam that is not captured by ARF1 will be left on the injection orbit and be kicked out of the Accumulator when the next Debuncher pulse is injected.

$$\phi = \frac{N_T P_D}{T_{rep}} \frac{\Delta E_c}{\Delta E_{bD}} = \frac{\psi_o \Delta E_c}{T_{rep}}$$

Antiproton Stacking – Stacktail System

- The flux through the Stacktail system is proportional to the gain of the system

$$\phi = \left(2\frac{g_o}{g_{om}} - \left(\frac{g_o}{g_{om}}\right)^2 \right)\phi_m$$

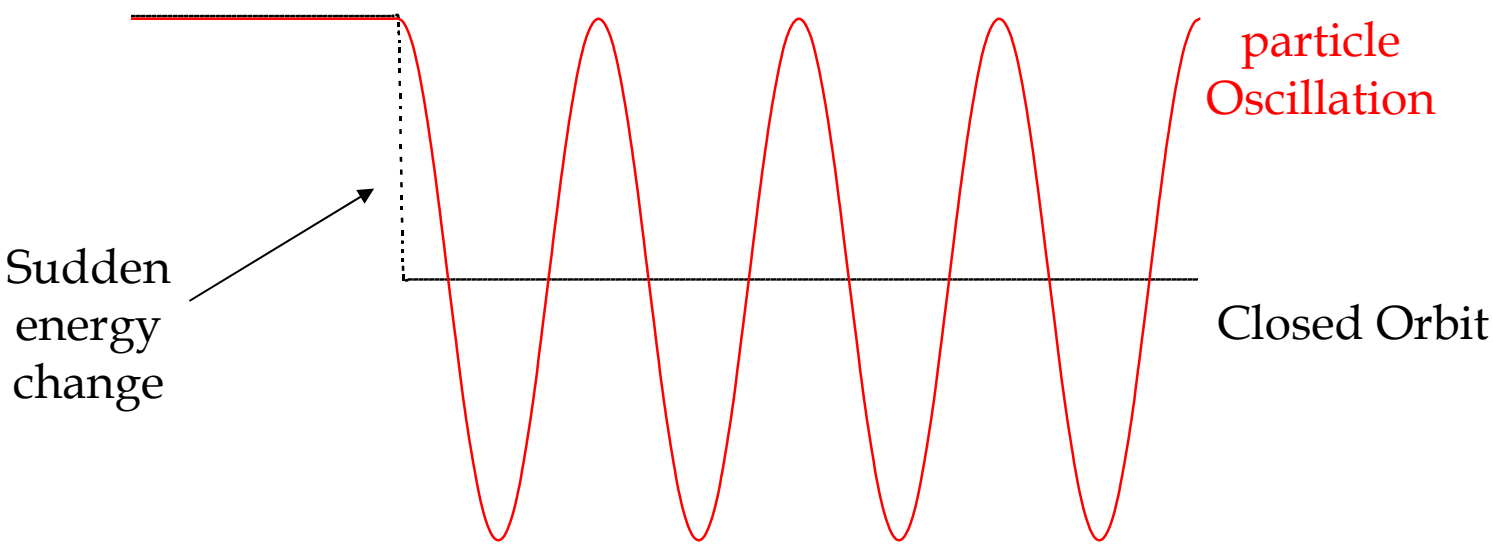
$$\phi_m = \eta f_o \frac{E_d}{E_o} \frac{\left(W/f_o\right)^2}{\ln\left(f_{max}/f_{min}\right)} \qquad g_{om} = \frac{2}{eV_o\psi_o}\frac{\phi_m}{W}$$

- The Stacktail power is proportional to
  - the beam intensity
  - square of the electronic gain

$$P = g_{om}{}^2\left(\frac{g_o}{g_{om}}\right)^2 \frac{V_o{}^2}{2R_k} E_d \psi_o \frac{W}{f_o}$$

Stacktail Heating

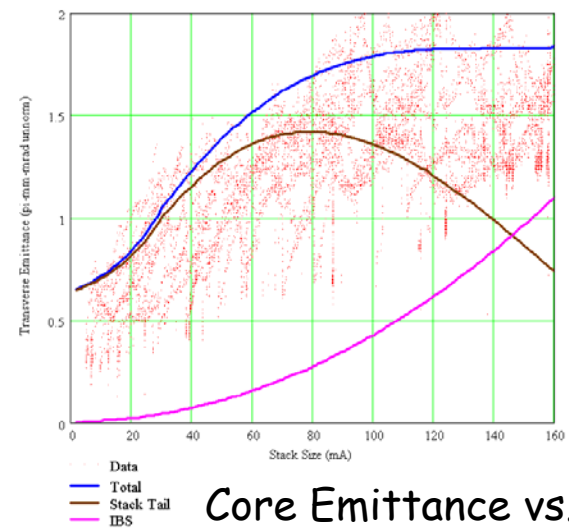
- To push fast cycle times the gain of the Stacktail is increased
- More power in the Stacktail can transversely heat the core beam
  - Longitudinal tanks transversely misaligned give transverse kicks
  - Residual dispersion gives transverse kick
    - Dispersion is defined as the transverse position as a function of energy
    - Longitudinal kick in dispersion changes local reference orbit which results in a betatron oscillation



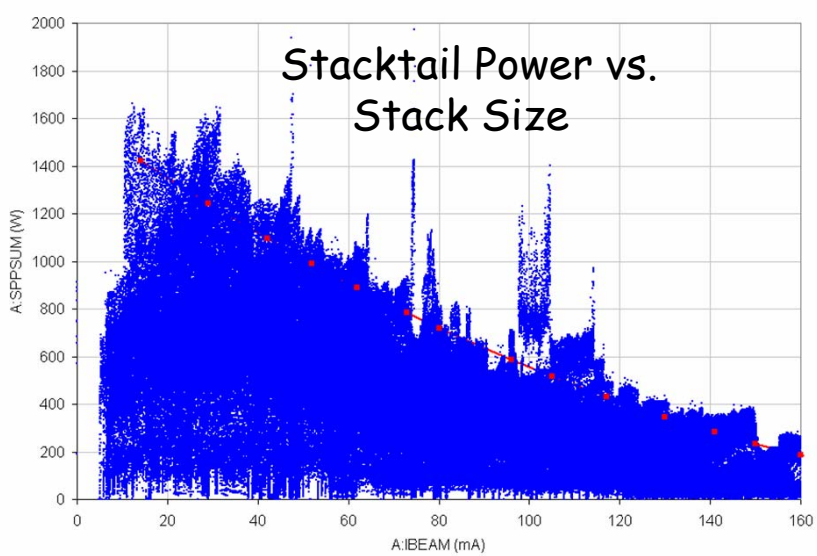
StackTail Heating

- The transverse cooling rate of the core stochastic cooling systems is inversely proportional to the number of particles

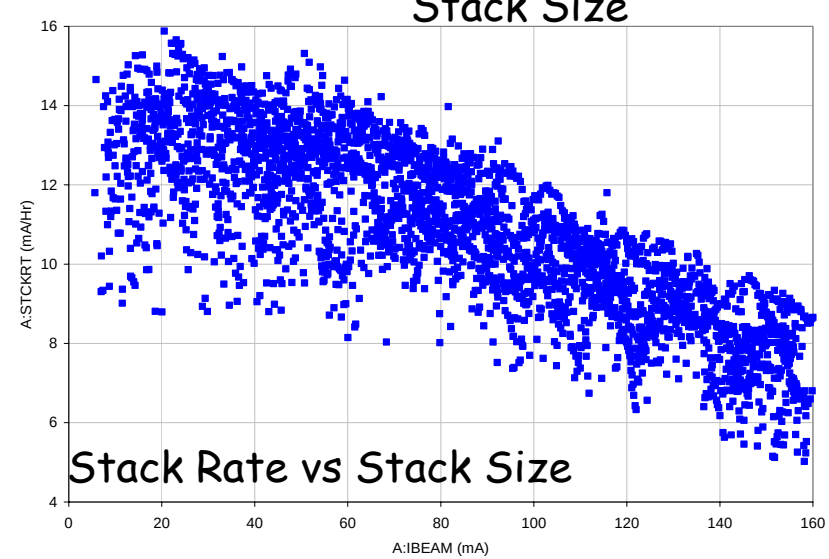
$$\frac{d\varepsilon}{dt} = -\frac{W_c}{NM}\varepsilon + H(N,\varepsilon)$$



Core Emittance vs. Stack Size

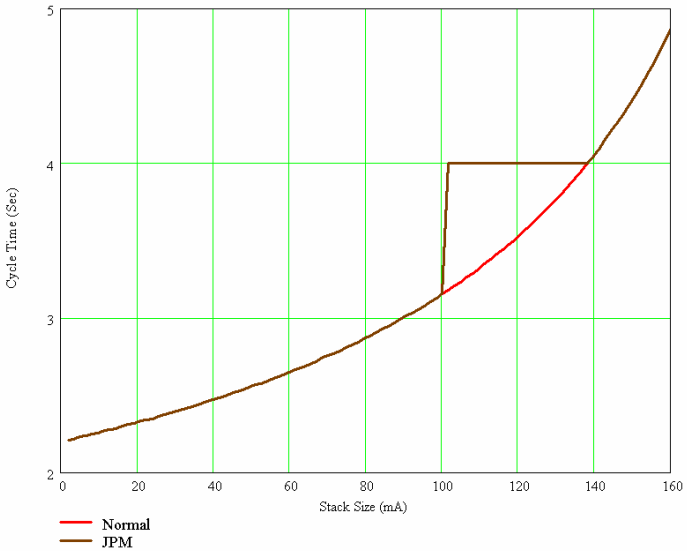


Stacktail Power vs. Stack Size

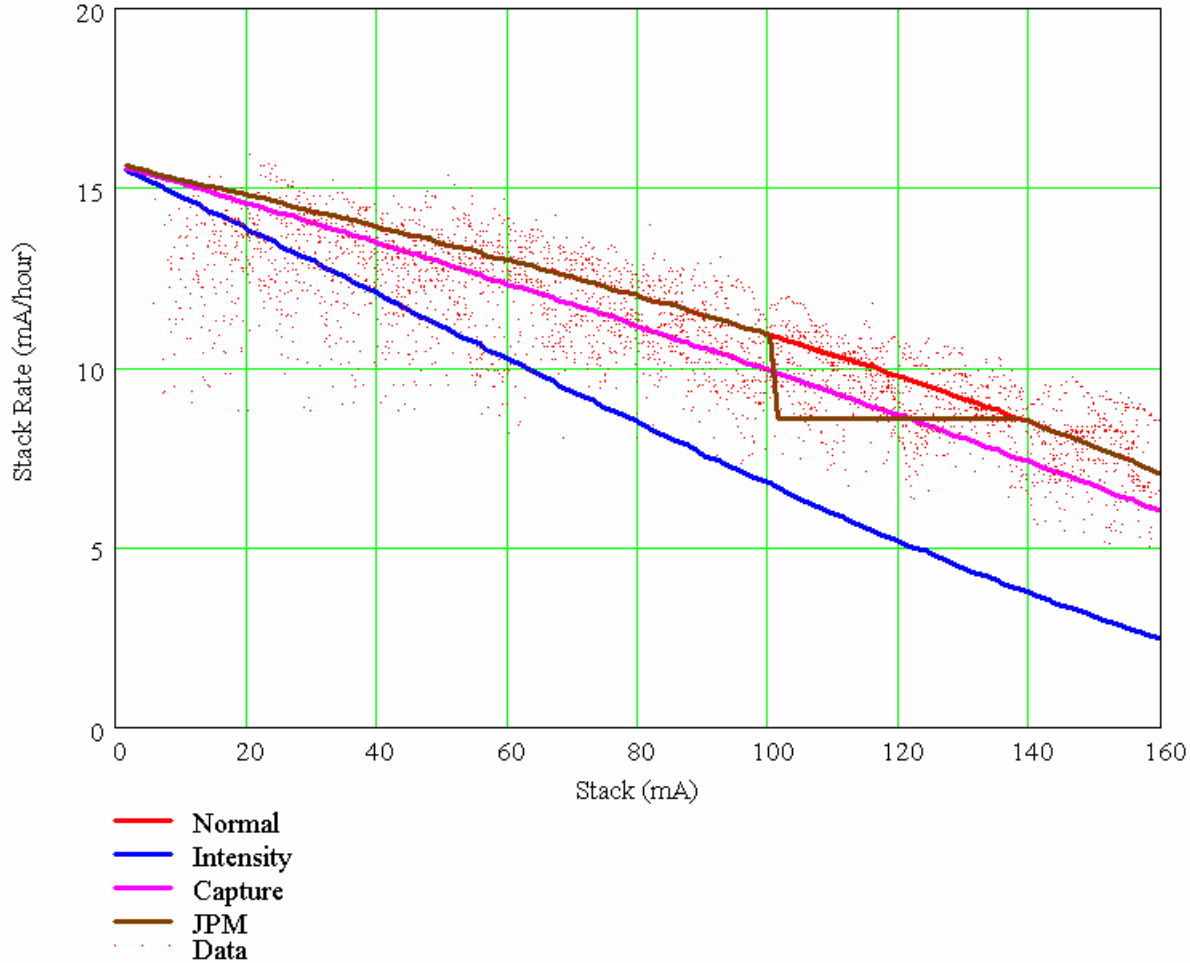


Stack Rate vs Stack Size

Mixed Mode Optimization

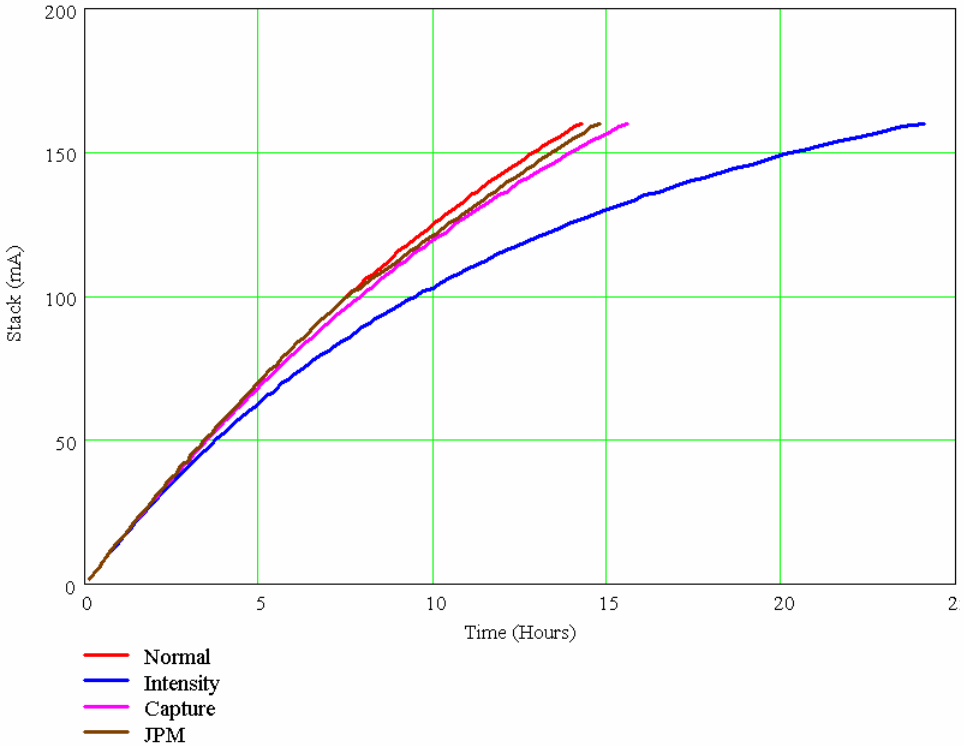


Cycle Time vs. Stack Size

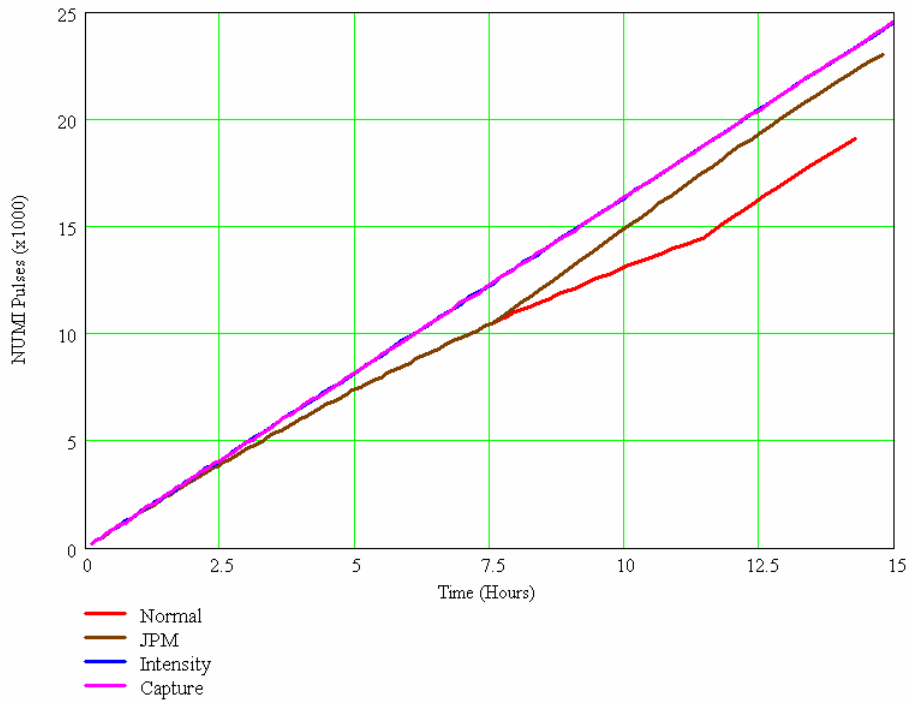


Stacking Rate vs. Stack Size

Mixed Mode Optimization



Stack Size vs. Stacking Time

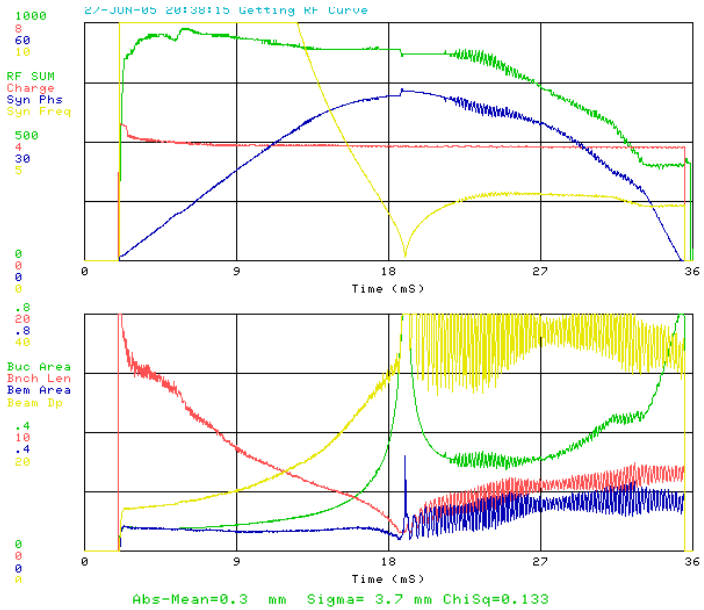


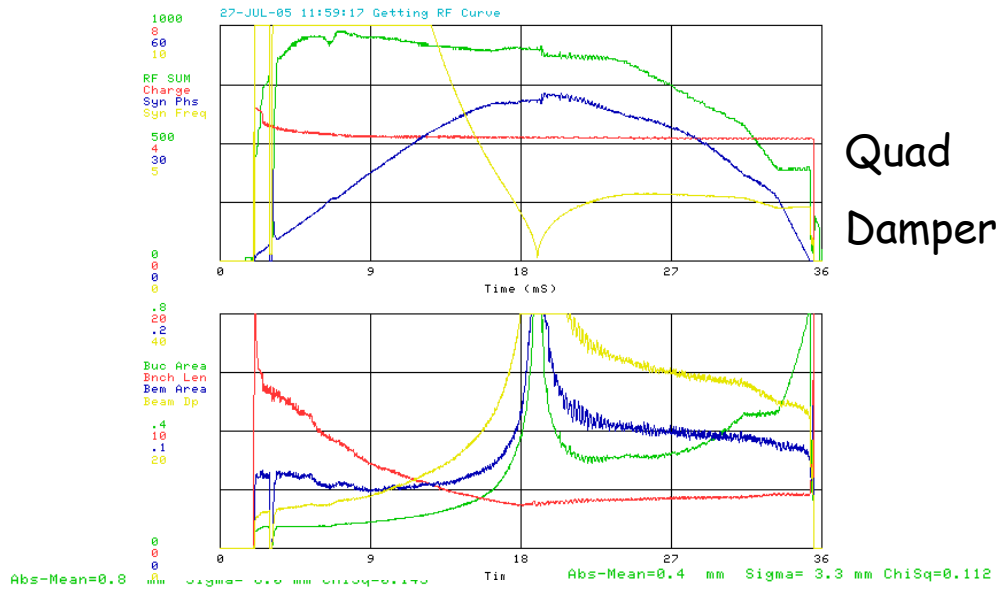
NUMI cycles vs. Stacking Time

Mixed Mode Optimization

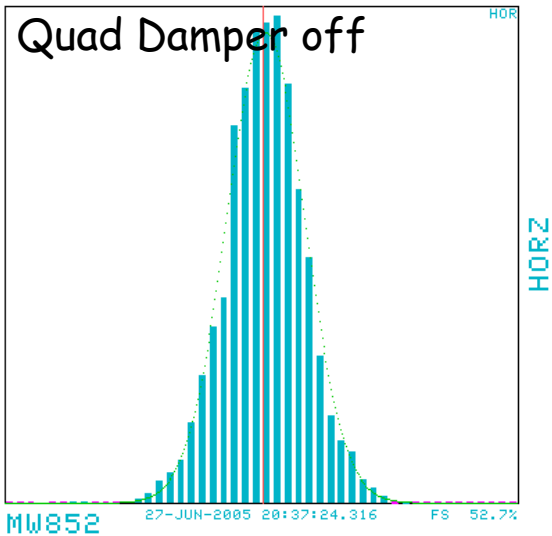
- The transverse emittance of the Accumulator core is dominated by Stacktail heating.
- To keep the emittances of the core under control, the Stacktail power must be decreased as the stack size grows.
- The normal technique has been to reduce the Stacktail power by increasing the antiproton production cycle time.
- Reducing the power by reducing the amount of beam on the antiproton production target is not viable at stacks greater than 50 mA.
- Reducing the ARF1 bucket area as the stack size grows looks promising but suffers from less Debuncher cooling
  - will also result in higher losses in the Main Injector because of the increased number of high intensity slip-stacked pulses.
- The "4 sec. switchover" where the cycle time is lengthened to 4 seconds when the "natural cycle time" reaches 3.2 sec to permit interleaving of NUMI-only cycles in between the Mixed-Mode cycles, increases the number of NUMI cycles significantly
  - Looks to be a reasonable compromise between optimizing the antiproton stack size and increasing the number of neutrino cycles.
- Recycler-Only operations for collider shots will result in faster average cycle times because the Accumulator will spend most of the time with small stacks.
  - Transition should be complete by November 1, 2005

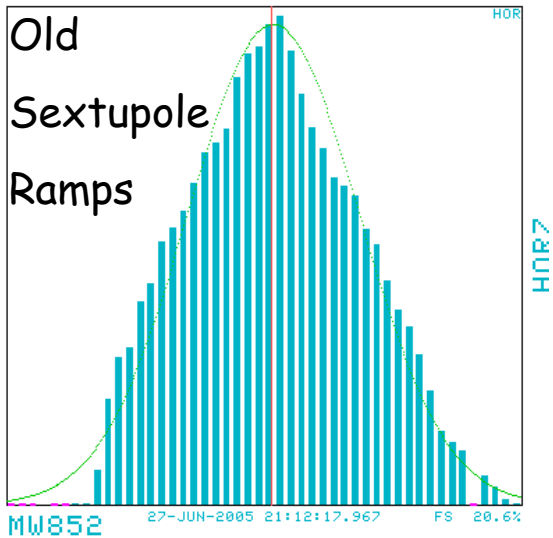
Other Issues: Booster Quadrupole Damper

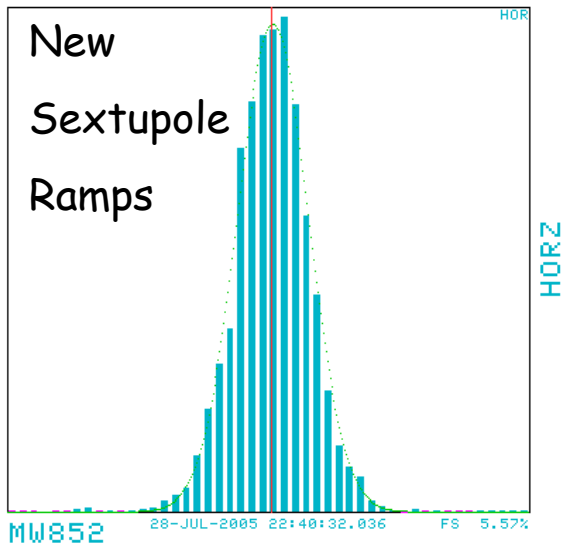




Quad Damper on





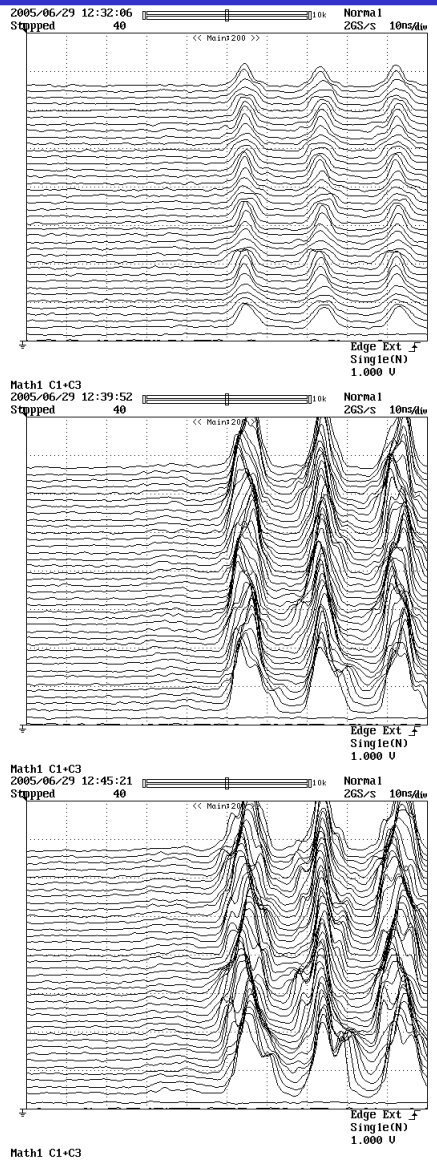


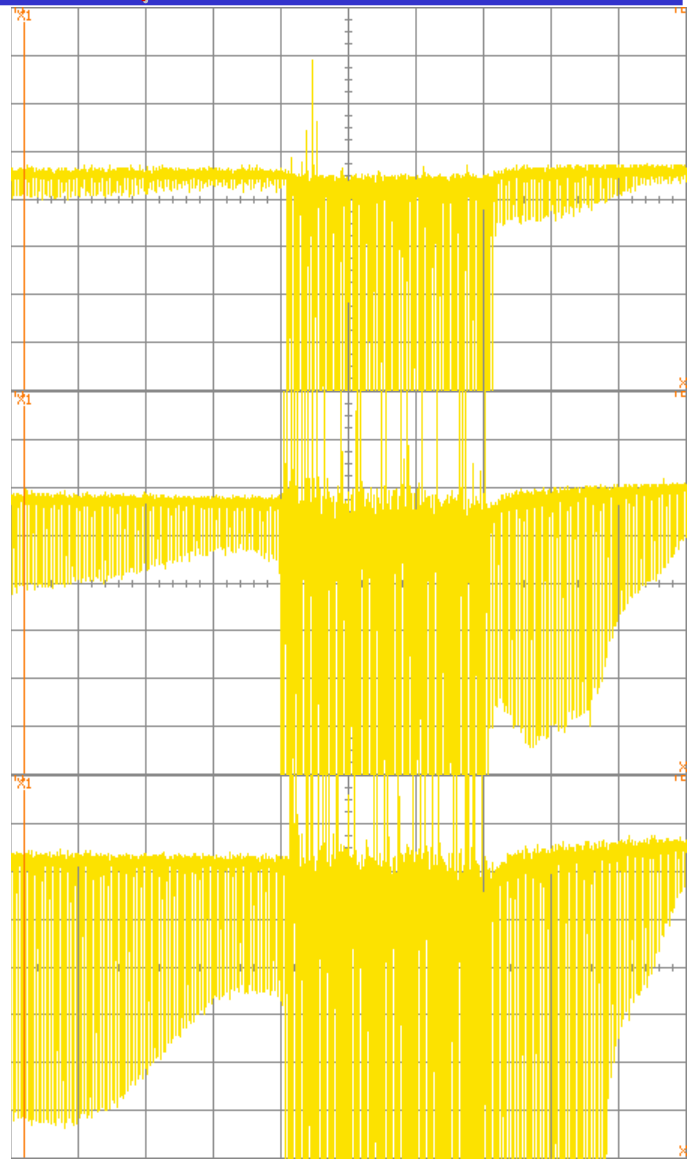
Main Injector Slip Stacking Before Booster Quad Damper

2 turns

8 turns

11 turns



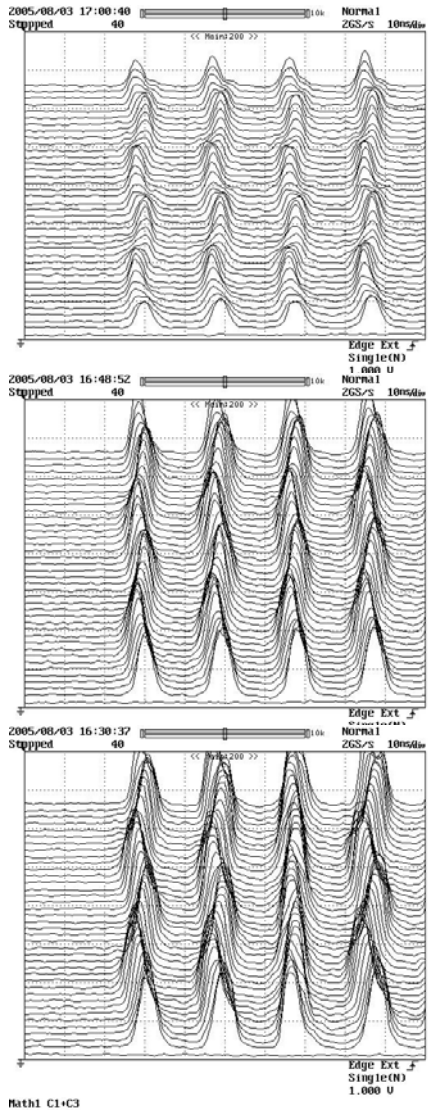


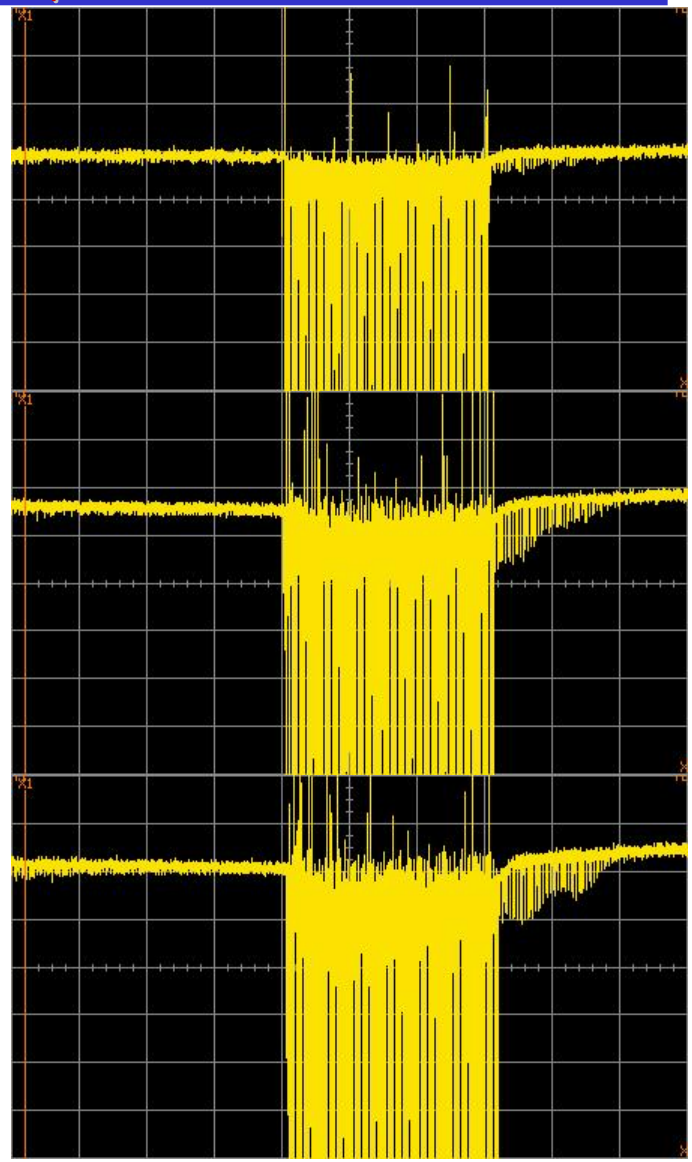
Main Injector Slip Stacking After Booster Quad Damper

4 turns

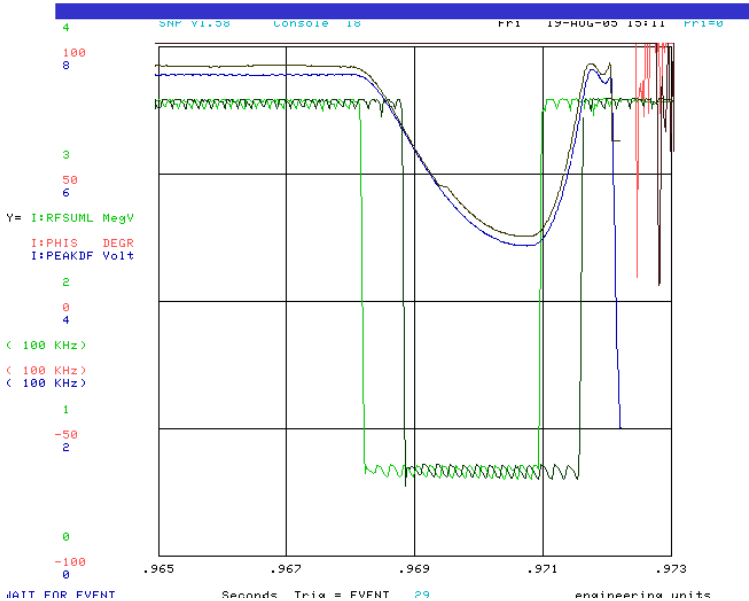
8 turns

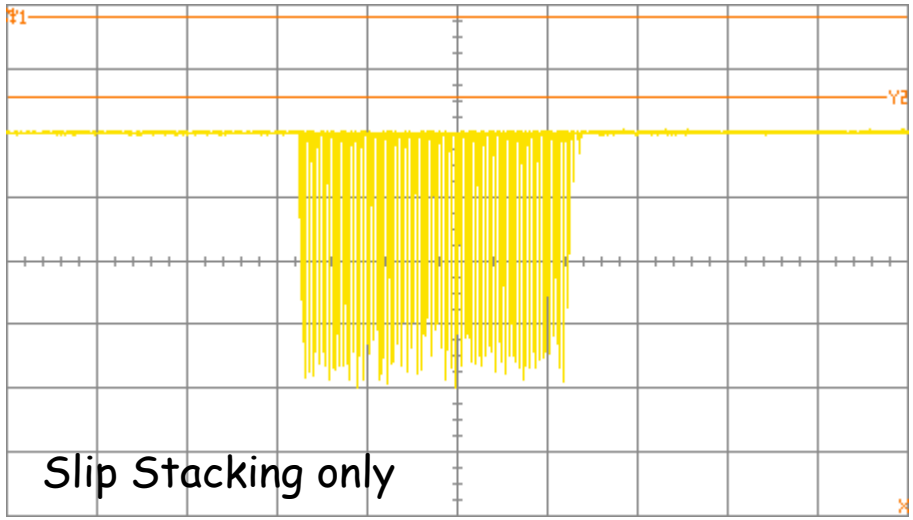
11 turns

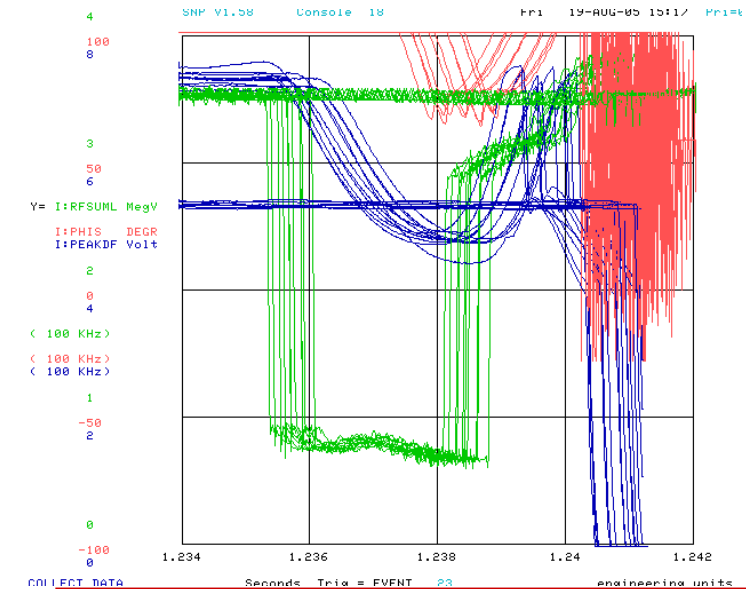


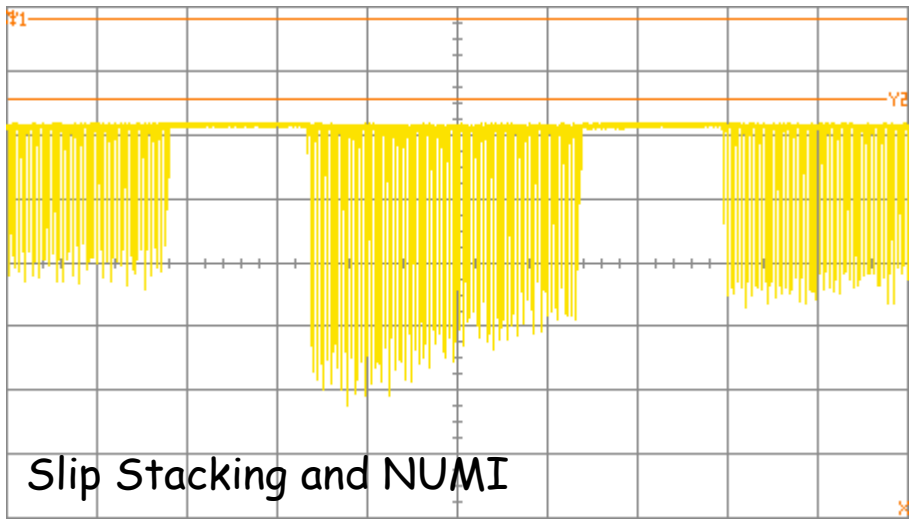


Other Issues: Main Injector 120 GeV Bunch Rotation

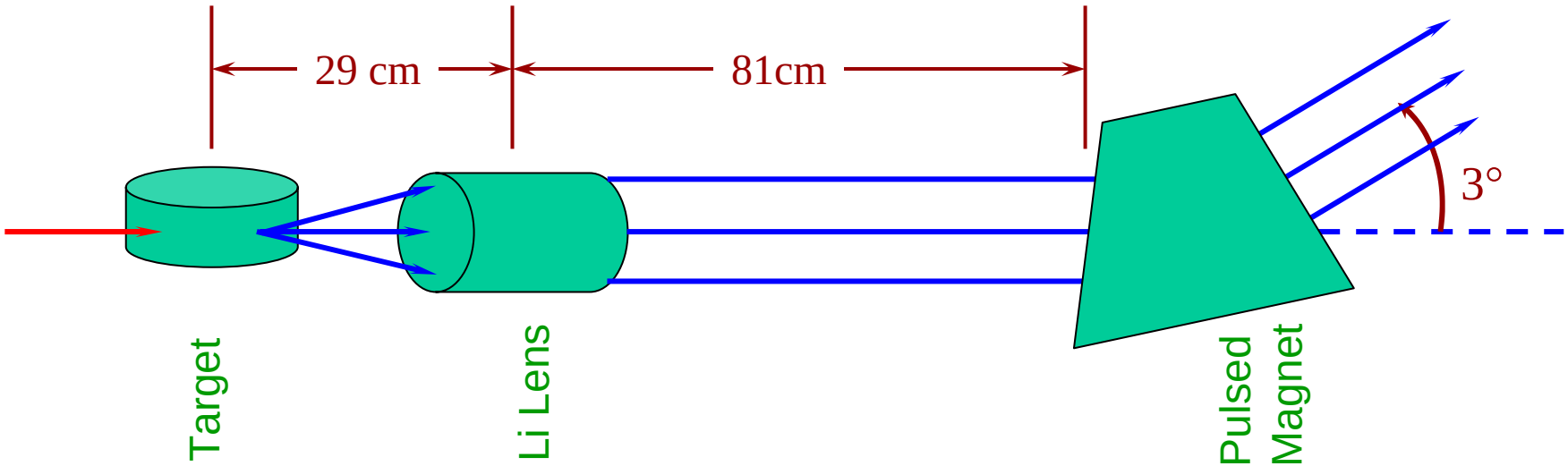


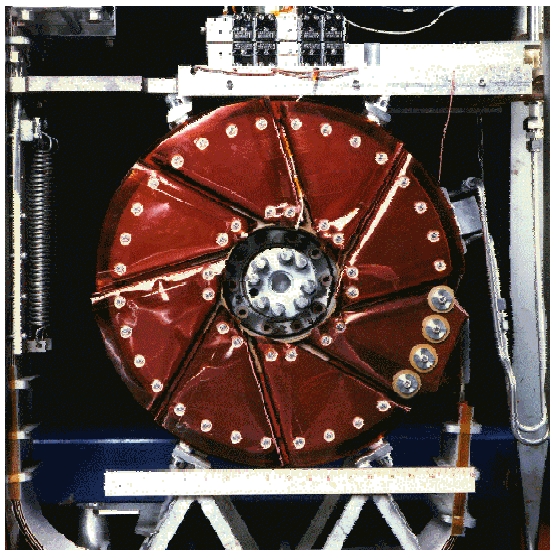


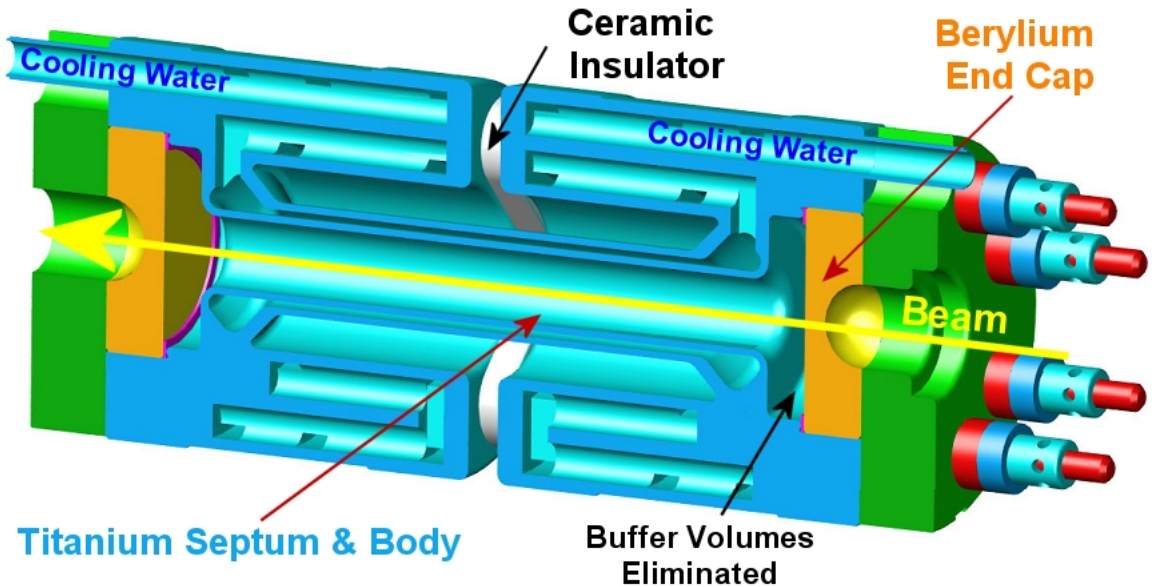




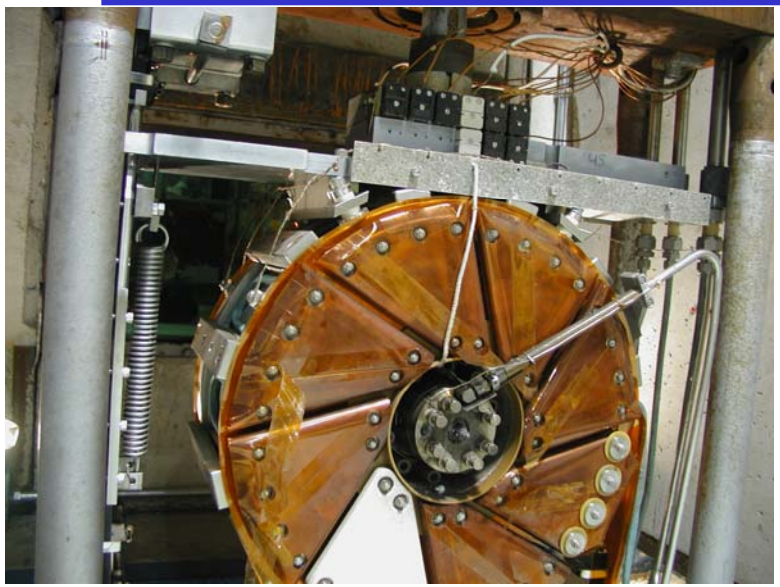
An Example of Beam Power: The Antiproton Target Station

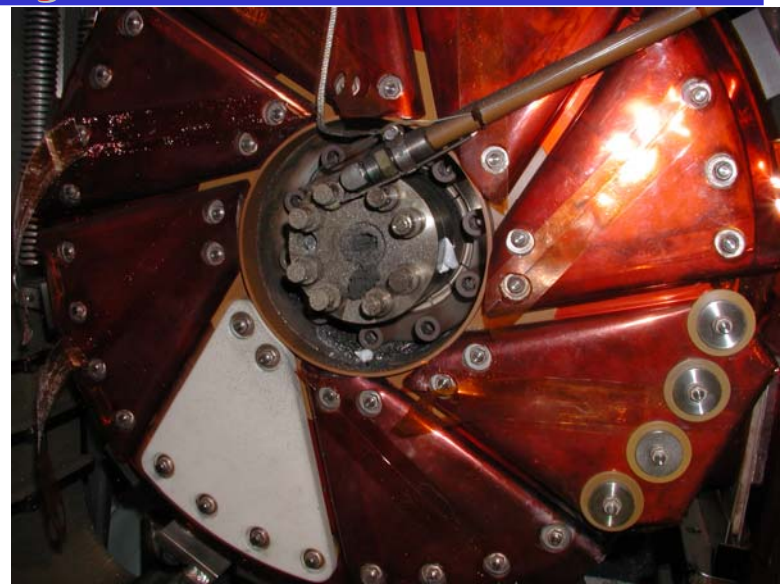


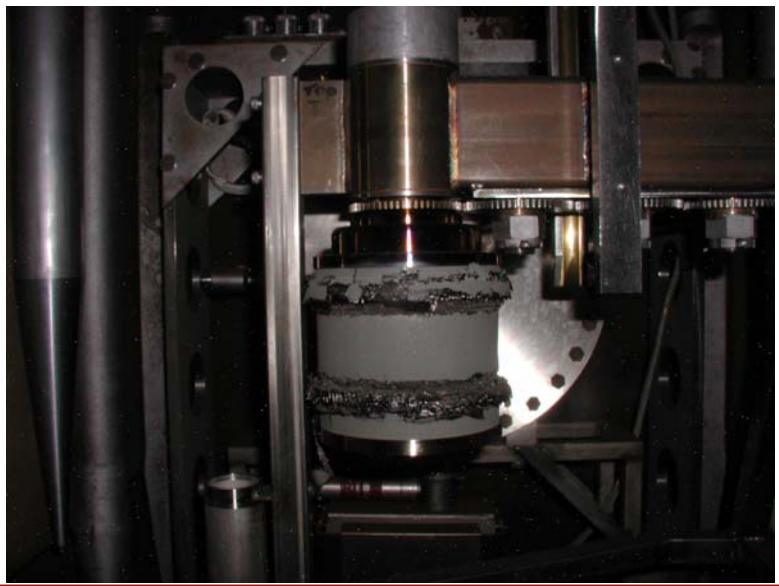




An Example of Beam Power: The Antiproton Target Station







Summary

- The major issue for neutrino flux for NUMI is downtime.
  - Out of ~7months of running, NUMI has been down about 8 weeks (~25%)
  - Lack of spares
  - Lack of experienced manpower
    - Engineers
    - Technicians
- To achieve 190kW <u>on average</u>, will require the Booster to:
  - Run with higher beam power loss (~36%)
  - Bigger effective aperture (or smaller closed orbit distortion tolerance) ~30%
  - Less throughput to other programs
- A cycle time of 2.2 seconds can be achieved by:
  - Interleaving NUMI cycles
  - Reduced stacking bucket area.
  - Recycler only operations