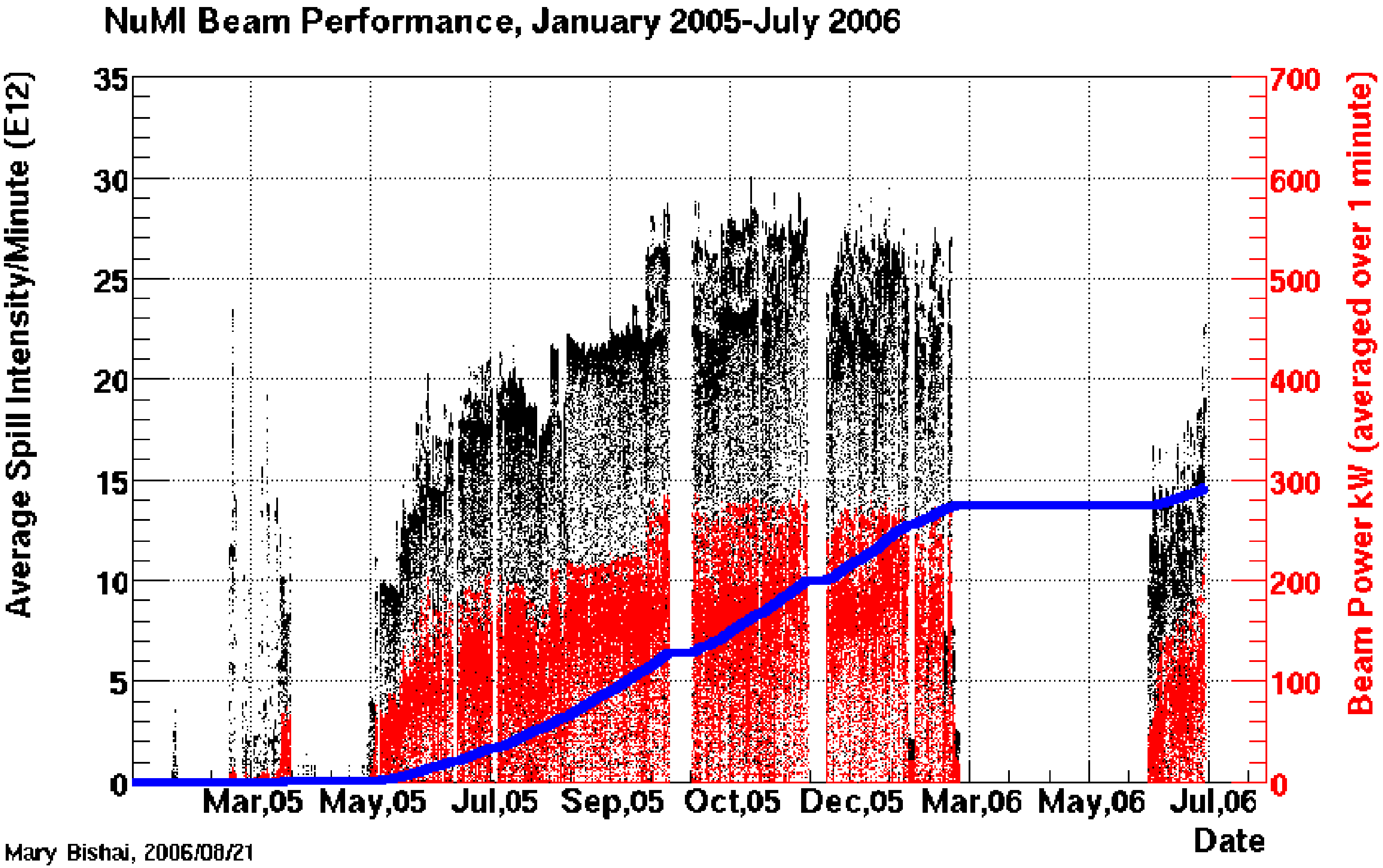
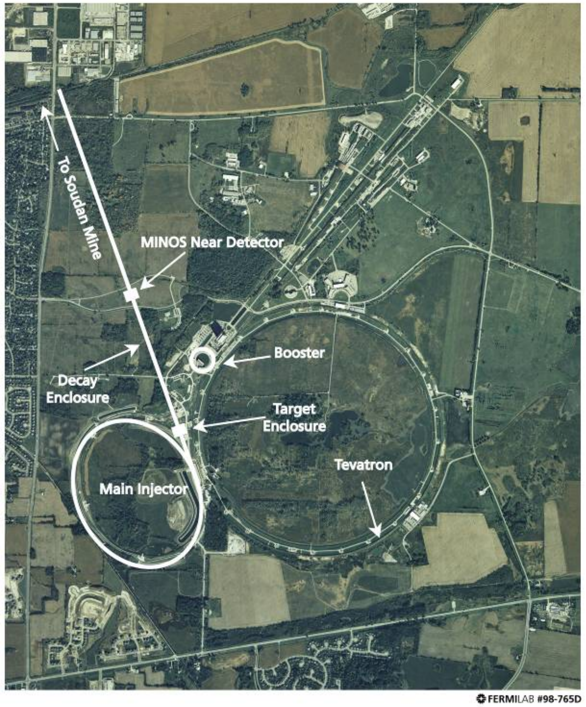
NuMI Primary Proton Beam

Bob Zwaska, Fermilab

for Sam Childress

Focus on Stability





Main Injector & NuMI

Main Injector is a rapid cycling accelerator at 120 GeV

- from 8 to 120 GeV/c in ~ 1.5 s

up to 6 proton batches (~ 5×10^{12} p/batch) are successively injected from Booster into Main Injector

Main Injector in parallel provides protons for the Collider program (anti-proton stacking)and transfers to the Tevatron) and NuMI

total beam intensity ~ 3×10^{13} ppp, cycle length 2 s

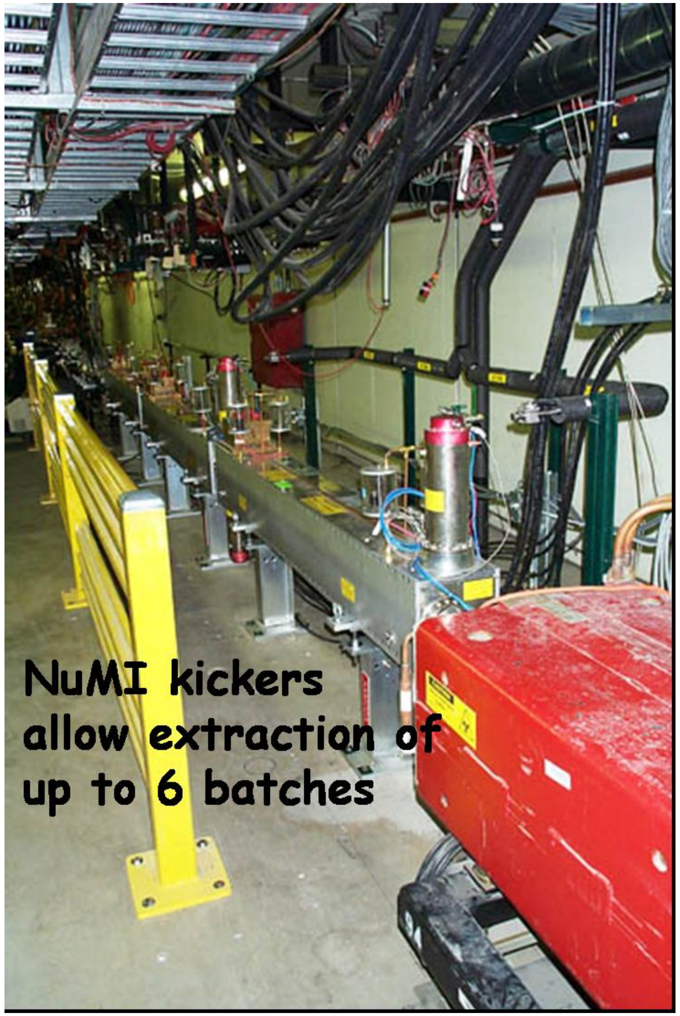
Mixed mode: NuMI & Pbar stacking

- two single turn extractions within ~ 1 ms:
  - 1 batch to the anti-proton target, 5 batches to NuMI
- Normally the batch extracted to the Pbar target comes from **the merging of two Booster batches (“slip-stacking”) (up to 0.8×10^{13} ppp)**
- ***the default mode of operation is mixed-mode with slip-stacking***

NuMI only

- up to 6 Booster batches extracted to NuMI in ~ 10 μs

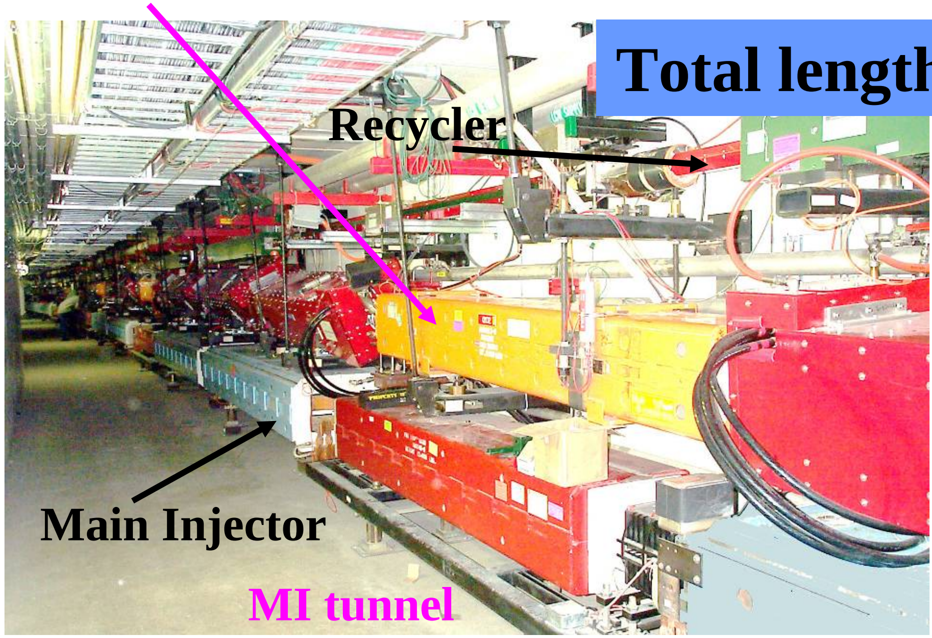
Extraction from Main Injector

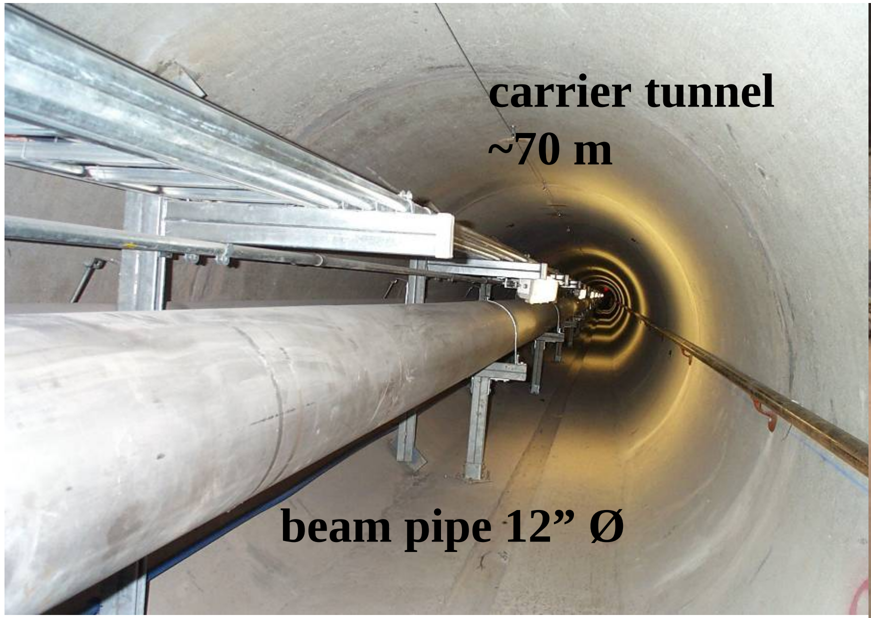


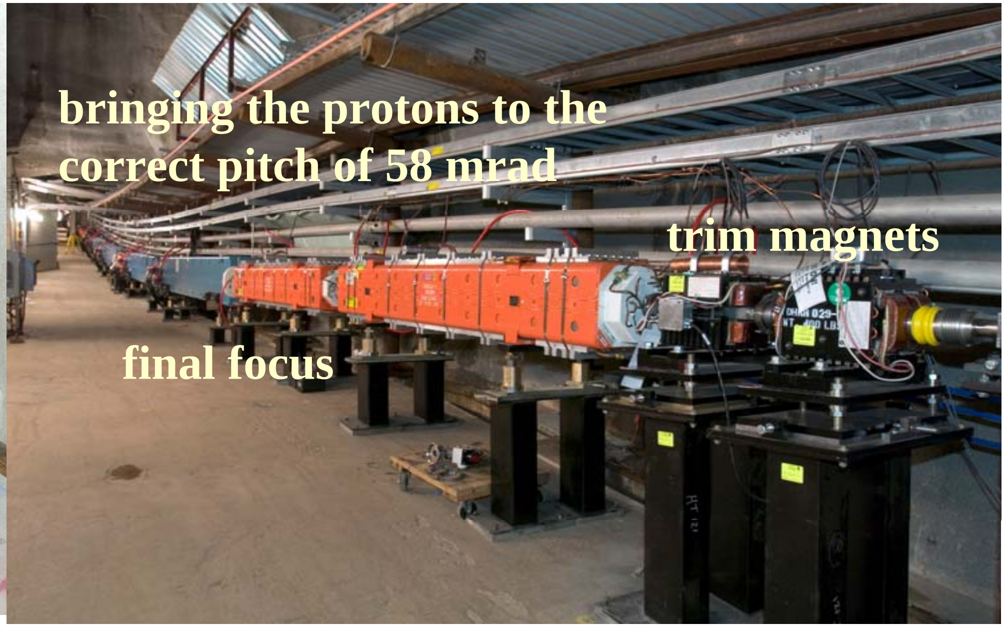
Kickers & Septa

Primary Proton Line

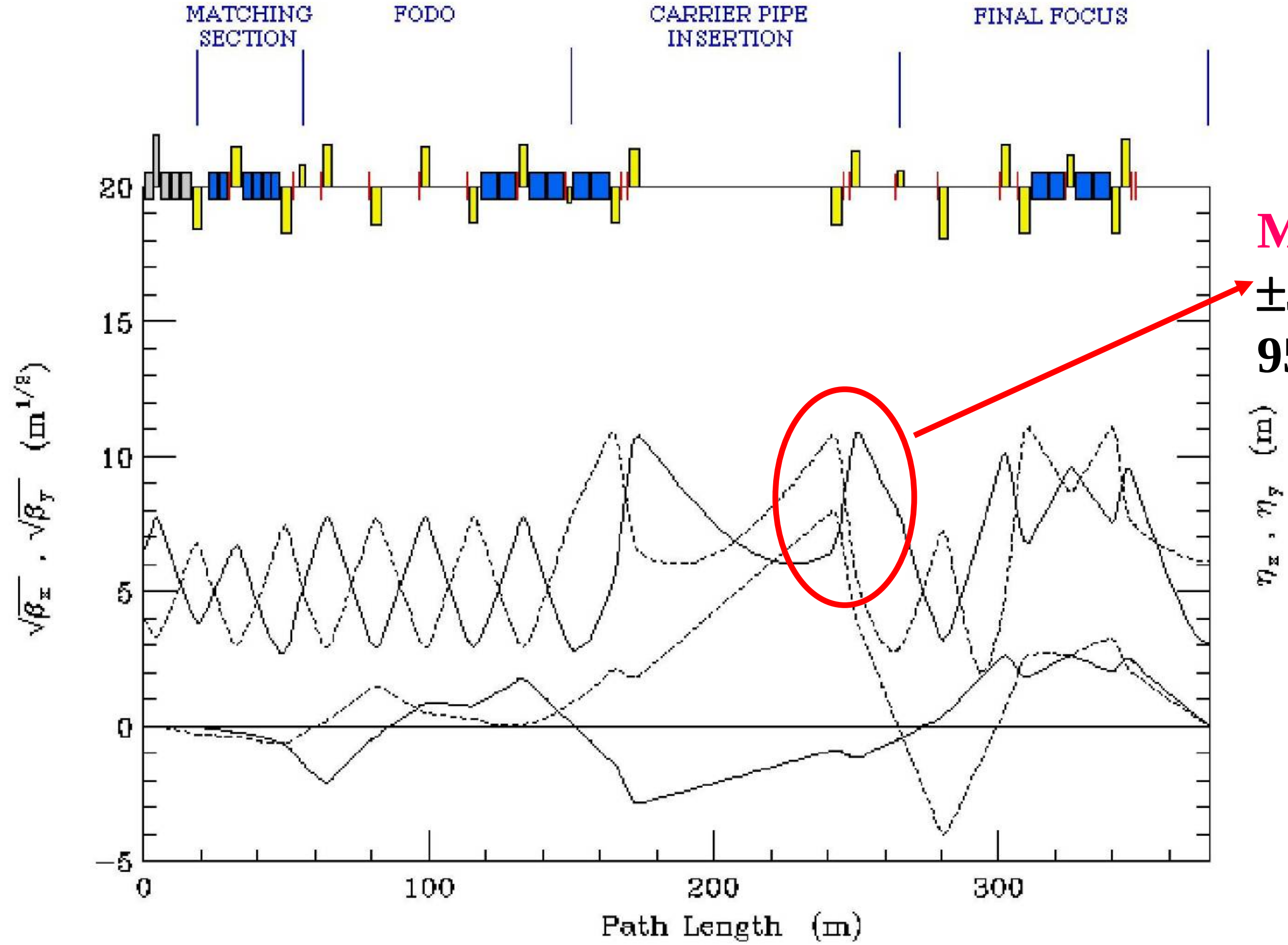
Total length ~ 350 m







Primary Beam Optics



Max. dispersion point
±35 mm aperture
95% beam size ±7 mm

Specifications: fractional beam losses below 10^{-5}

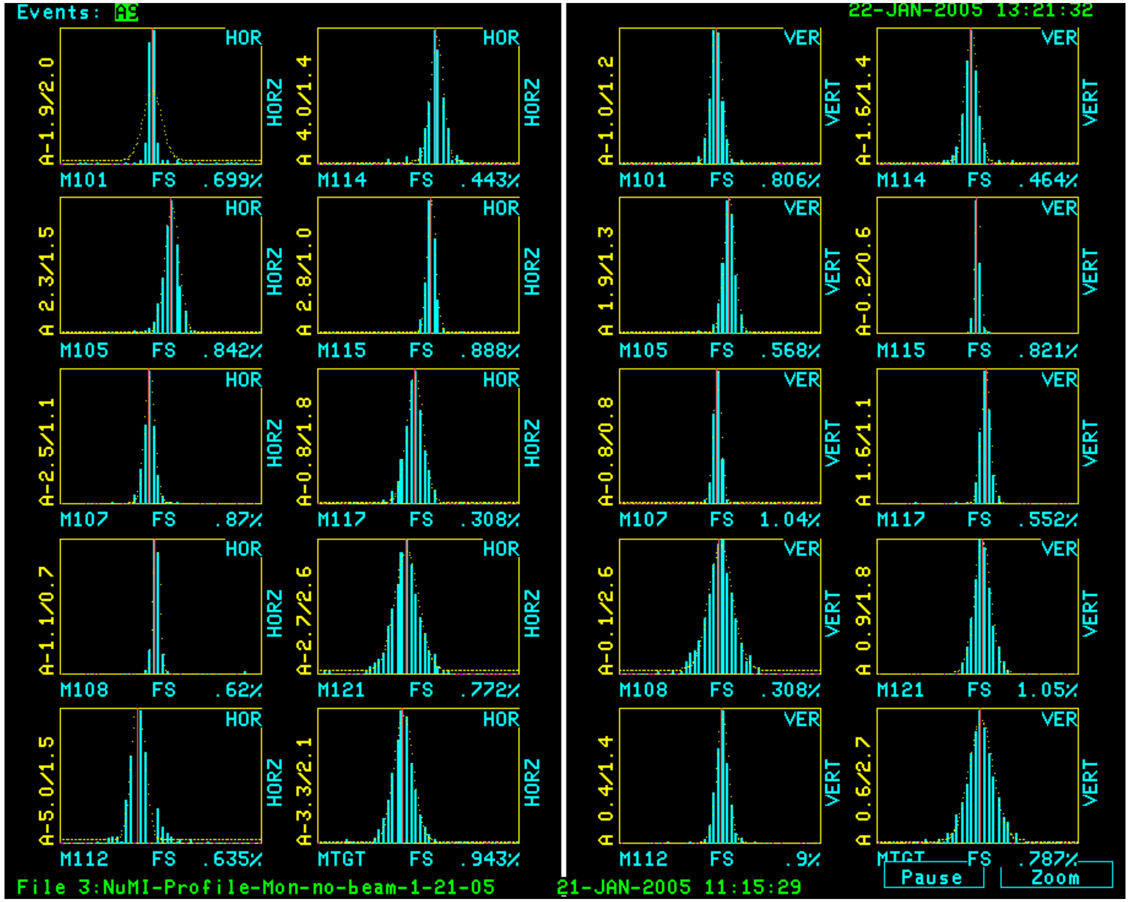
(Groundwater protection, residual activation)

NuMI Initial Beam Commissioning

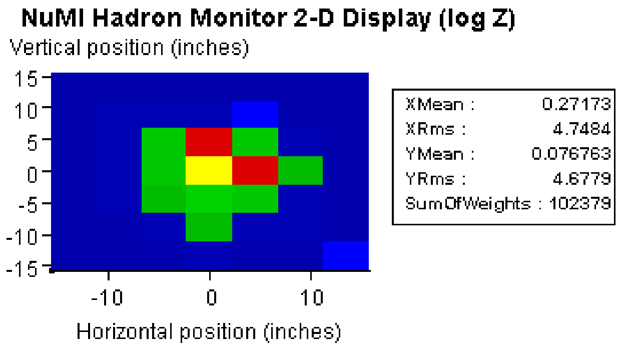
- **December 3-4 2004. Commissioning the primary proton beam**
  - **target out, horns OFF**
  - **small number of low intensity (1 batch with 3×10^{11} protons) pulses carefully planned**
  - **beam extracted out of Main Injector on the 1st pulse**
  - **beam centered on the Hadron Absorber, 725 m away from the target, in 10 pulses**
  - **all instrumentation worked on the first pulse**
- **January 21-23 2005. Commissioning of the neutrino beam**
  - **target at z=-1 m from nominal $\Rightarrow$ pseudo-medium energy beam, horns ON**
  - **MI operating on a dedicated NuMI cycle, at 1 cycle/minute, with a single batch of 2.6×10^{12} protons, few pulses up to 4×10^{12} protons**
  - **final tuning of the proton line**
  - **neutrino interactions observed in Near Detector**
  - **NuMI project met DoE CD4 goal (project completion)**
- **February 18-22 2005. High intensity beam in the NuMI line**
  - **MI operating on a dedicated NuMI cycle in multi-batch mode**
  - **with 6 batches, we achieved a maximum intensity of 2.5×10^{13} p/cycle**

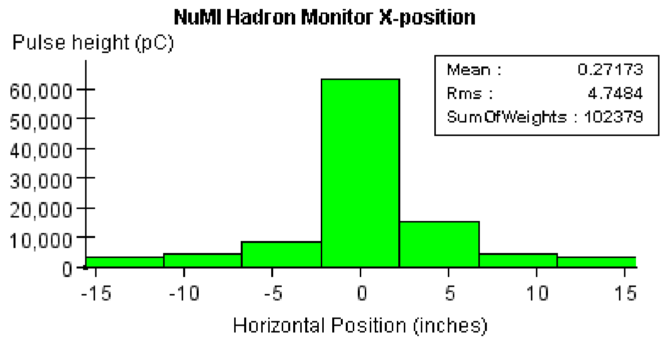
Beam Extraction in 10 Pulses achieved to hadron absorber at 1 km distance

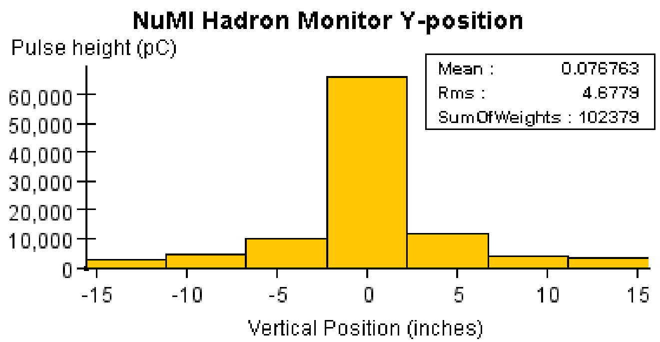
December 3-4, 2004



Profile monitor output along the beamline (few pulses later)
(from the extraction up to the target - ~ 400 m distance)





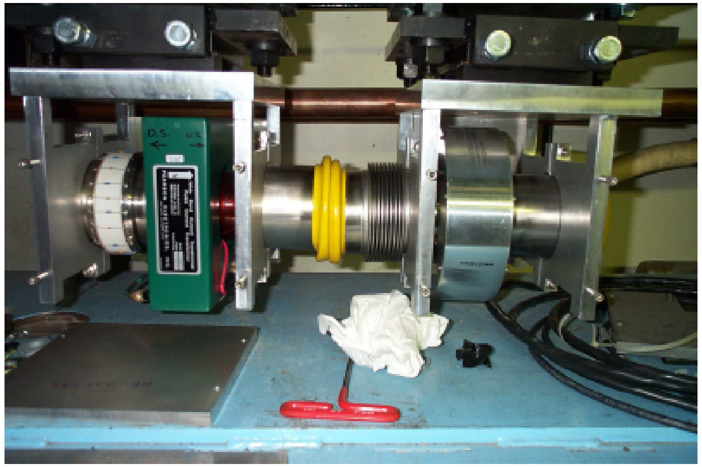


Measuring the Beam Intensity

Three sensors are used to measure the NuMI proton intensity:

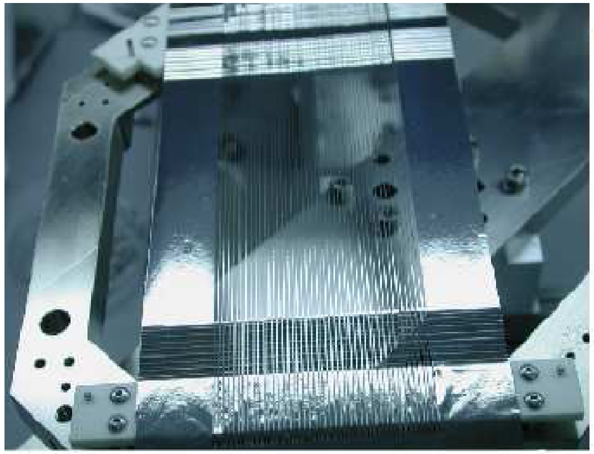
A DC current transformer (DCCT), which measures the intensity in the MI.

2 toroids (Pearson Current Transformers Model 3100) that measure the intensity at the beginning (TOR101) and just before the target (TORTGT)

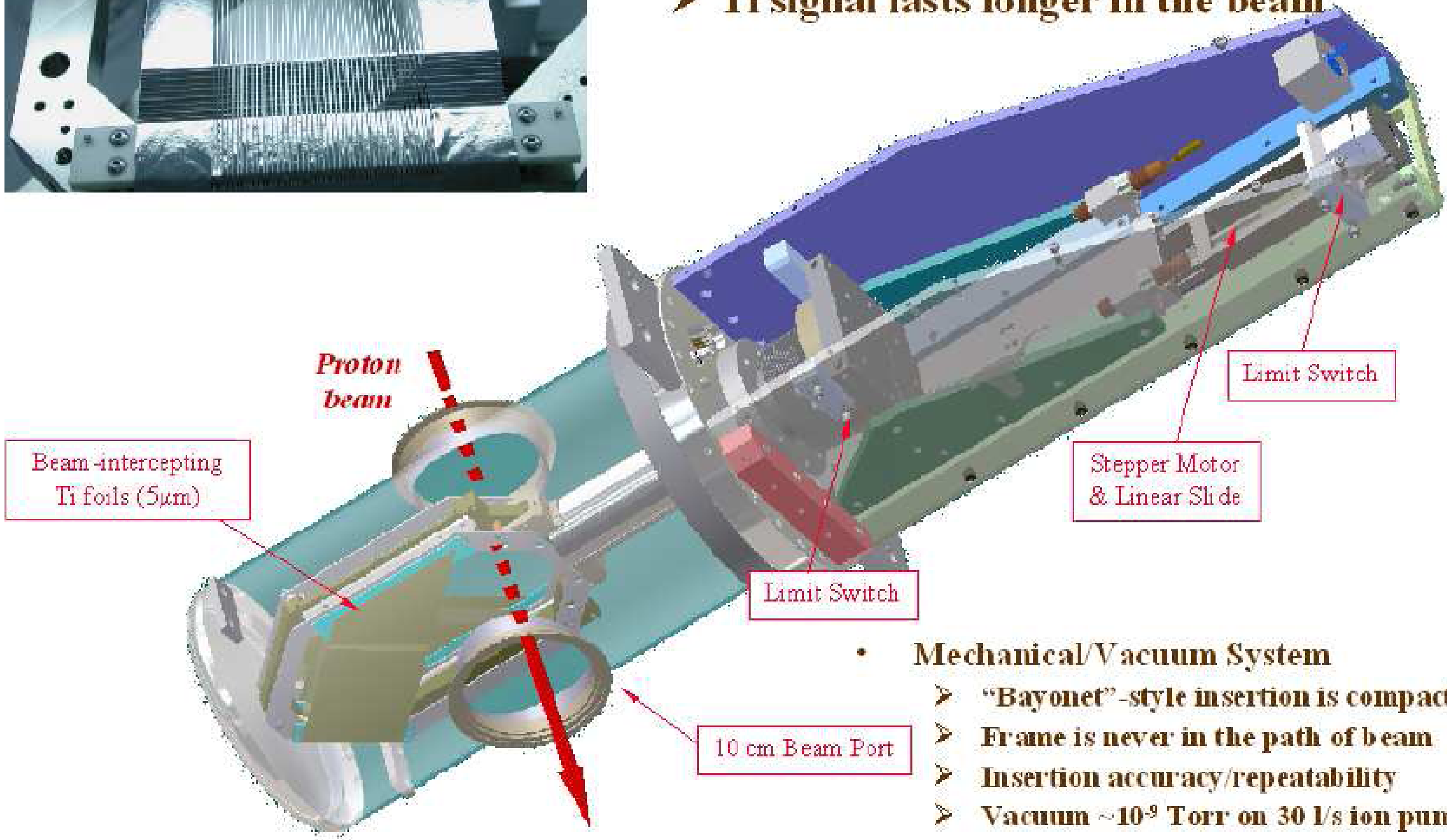


Description	Uncertainty
Absolute calibration with a current source	$< 1.0\%$ for > 1 E12
Calibration with DCCT	-0.6%
TOR101 vs TORTGT difference	0.2%
Stability (compared to DCCT)	0.4%
Sensitivity	0.06 %
Charge leakage	0.5%
Pedestals (TORTGT)	~ -0.0016 E12
Noise (TORGT)	~ 0.008 E12
Total	1.4%

Measuring the Beam Profile



- Foil Secondary Emission Monitors
  - ➢ Beam profile + halo measurement
  - ➢ Very low mass (5 μm Ti)
  - ➢ Reduced Beam Heating problems
  - ➢ Ti signal lasts longer in the beam



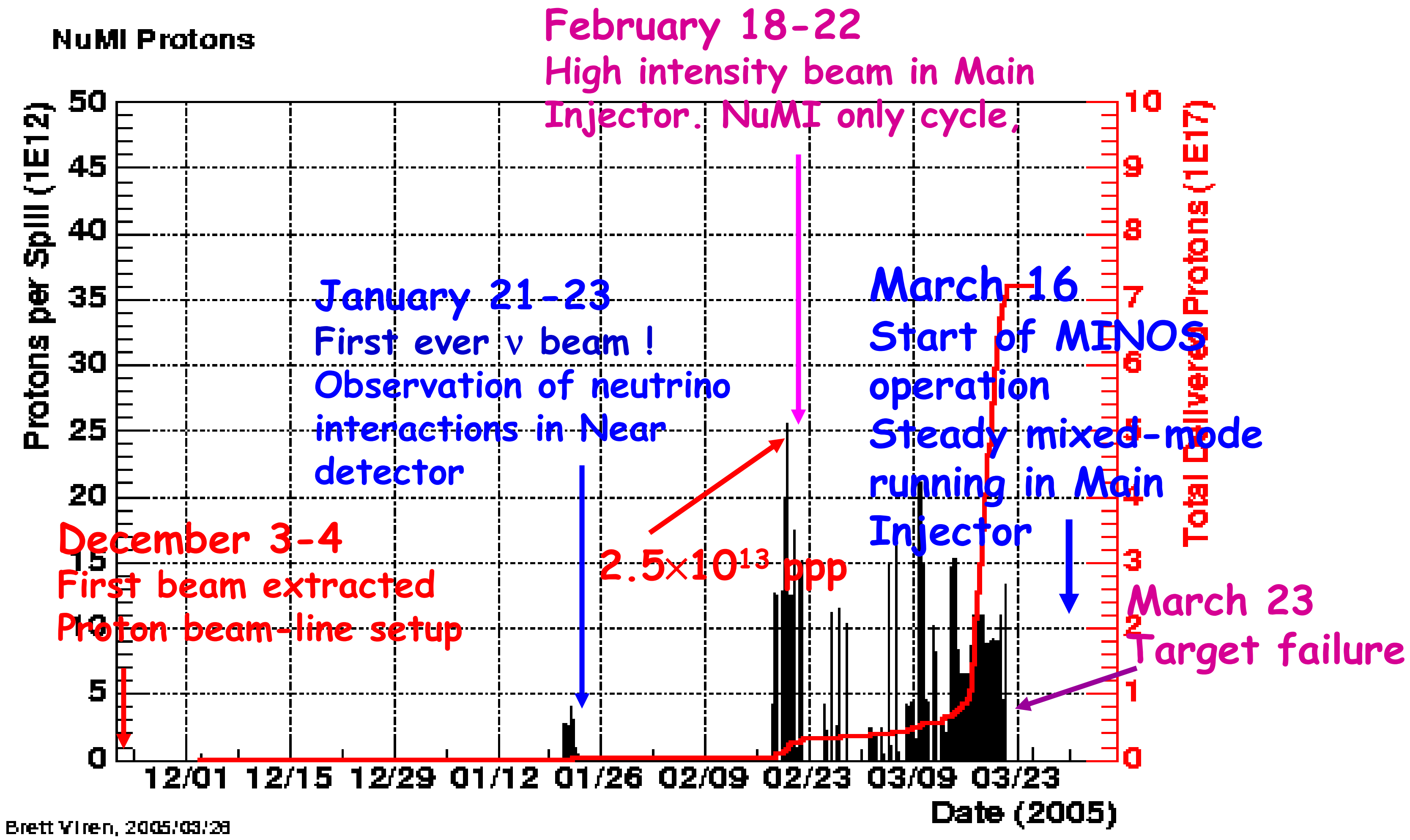
- Mechanical/Vacuum System
  - ➢ "Bayonet"-style insertion is compact
  - ➢ Frame is never in the path of beam
  - ➢ Insertion accuracy/repeatability
  - ➢ Vacuum ~10^{-9} Torr on 30 l/s ion pump

Measuring the Beam Position

Characteristics of NuMI Beam Position Monitors:

- Software algorithm to search 400 μsec to find the beam.
- NuMI bunches come in 6 batches from booster. Position is measured batch by batch.
- Linear over 15-20 mm. 50 μm accuracy in pretarget.
- 11 vertical and 13 horizontal measurements over 360m.

Beam Commissioning & Start up for Data Taking



Transition to Operations

- Restarted after target checkout in late April
- Main Control Room Operators take control of running NuMI beam
  (12 May)
- Initiate NuMI running during Recycler shot setup (18 May)
- Initiate NuMI running during TeV shot setup
  (22 June)
  - We needed to be a “low overhead” beam to Operators to have these running modes

- Keys to NuMI Proton beam operation –
  - Comprehensive beam permit system : ~ 250 parameters monitored
  - Open extraction/primary beam apertures – capability of accepting range of extracted beam conditions
    - **Superb beam loss control**
  - Good beam transport stability
  - Autotune beam position control
    - **No manual control of NuMI beam during operation**

NuMI 120 GeV Primary Beam

- Key specifications are:
  - Very low beam loss <1E-5 fractional loss for large regions of transport. (unshielded intense beam passing thru ground water reservoir)
  - Maintain position on target to 0.25 mm rms & angle to < 60 μrad.
  - Intense 400 kWatt beam (design) => tight control over residual activation

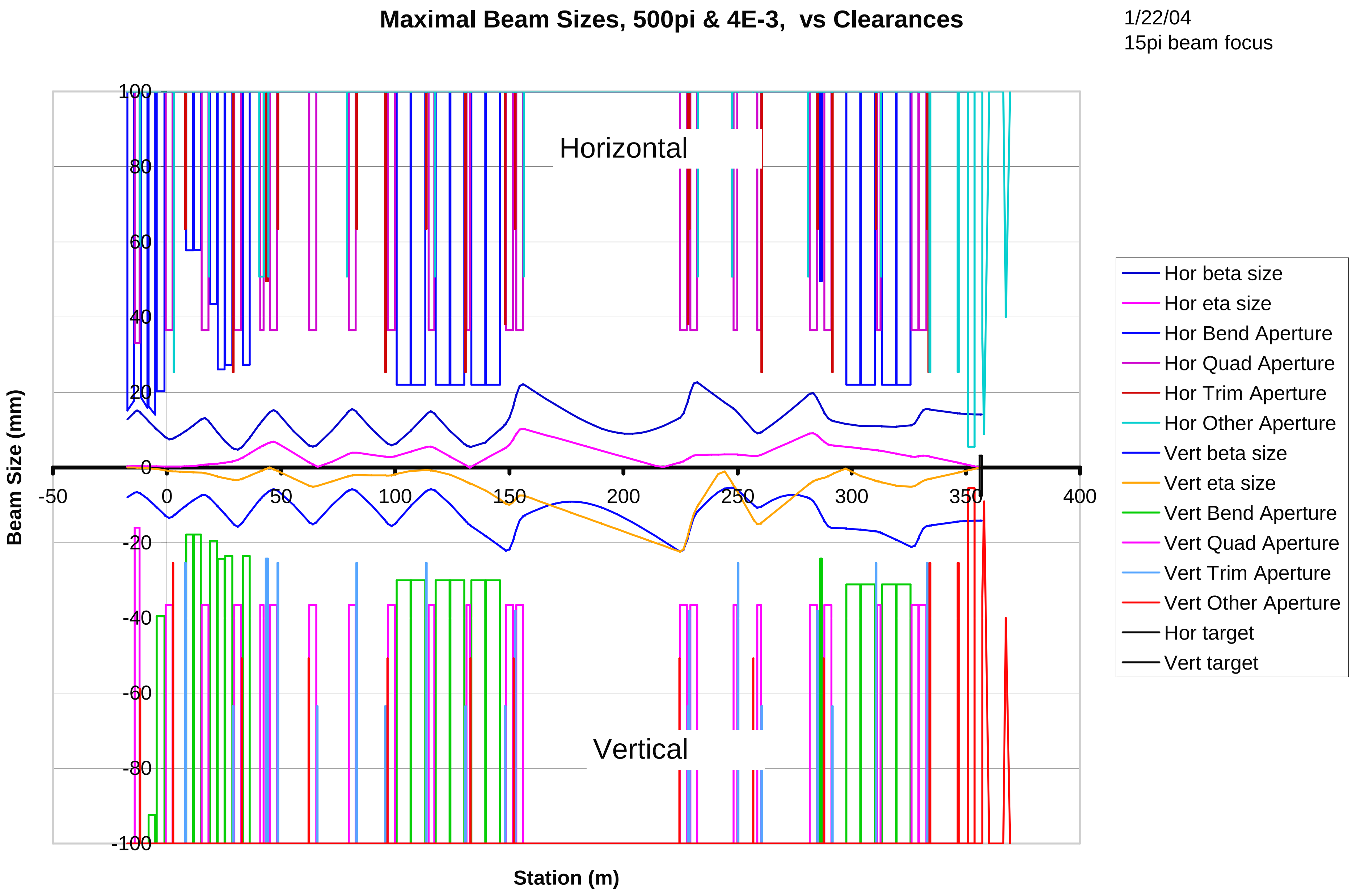
Kicker System Requirements

tightened specs during design process

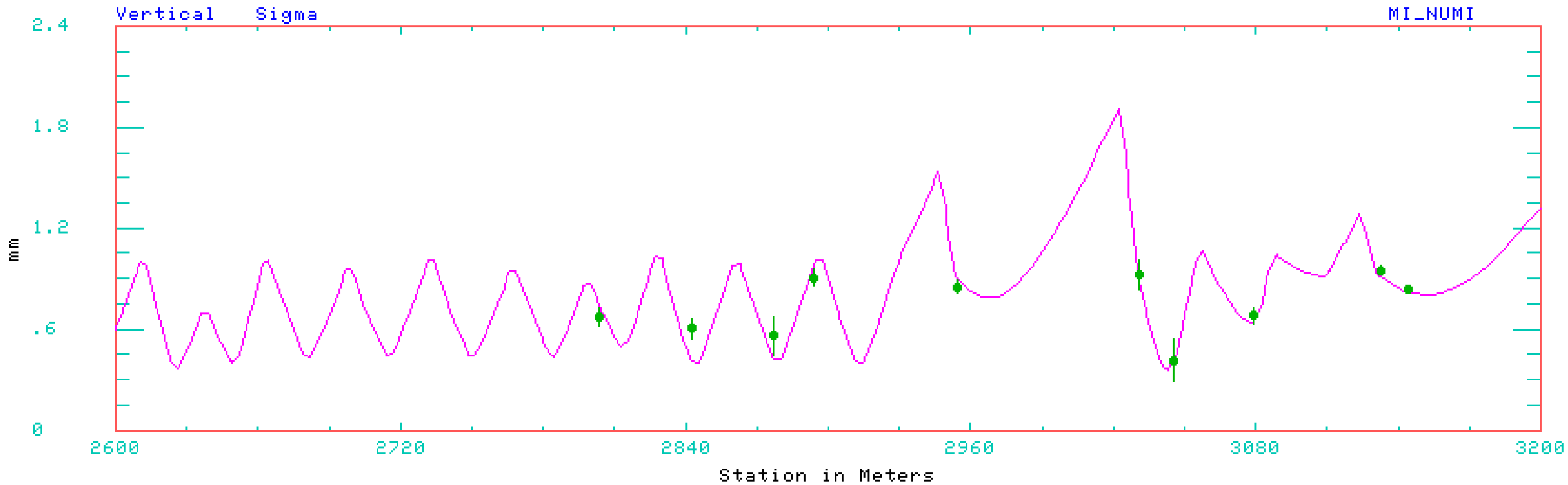
	Early Requirement	Final Requirement
Integrated Field (120 GeV protons)	2.2 kG • m (550 μrad)	3.6 kG • m (900 μrad)
Number of Magnets	2	3
Field Flatness	± 1%	< ± 1 % (Best Effort)
Repeatability (over 8 hours)	± 1%	< ± 1/2% (Best Effort)
Field Rise Time	1.52 μs	
Flat top length	9.68 μs for 6 Batches, 8.08 μs for 5 Batches	
Magnetic Aperture	1.98 m x 10.7 cm x 5.2 cm (each magnet)	

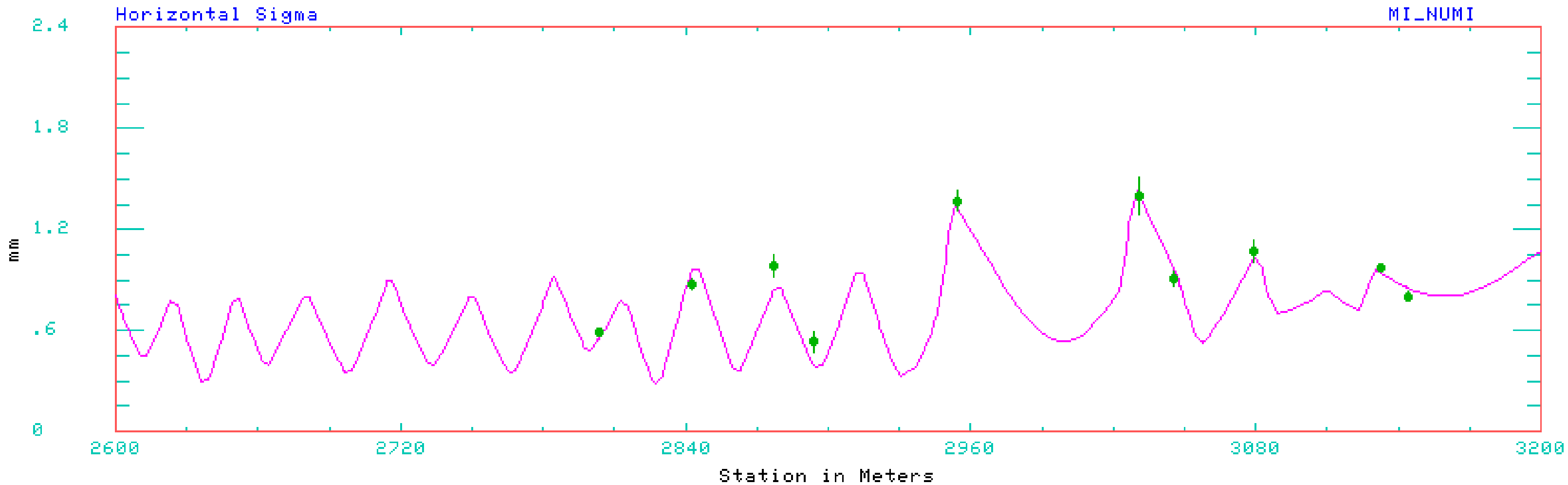
C.Jensen lead enginer

1/22/04
15pi beam focus



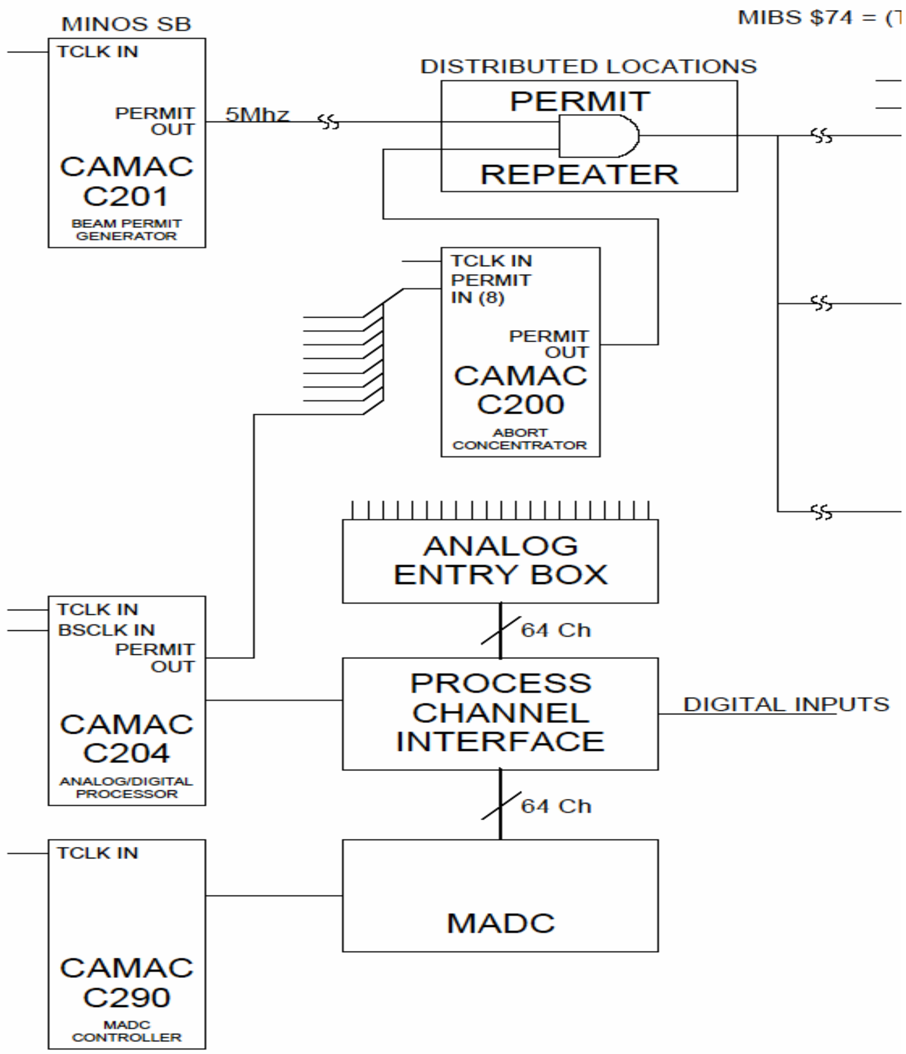
Performance Overview
Optics: Design vs. Measured Beam Sigmas





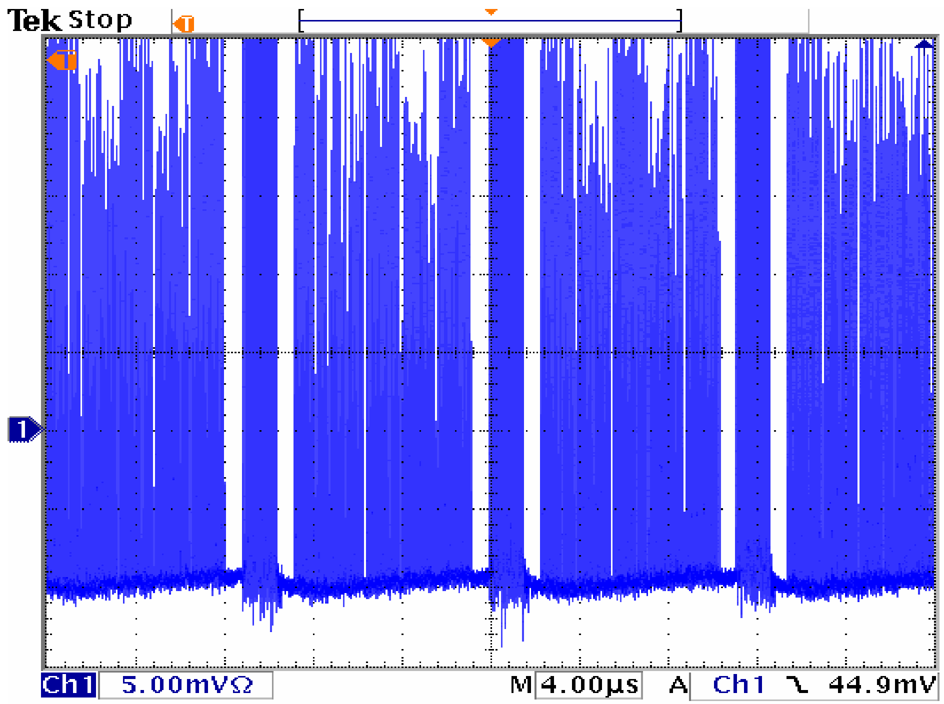
High-Intensity: Beam Permit System

- Inhibits beam on a rapid basis
- > 200 inputs
- Checks that radiation levels have not been exceeded
  - Prevents beam from being accelerated
- Beamline components – e.g. magnet ramps
  - Can prevent acceleration, but also extraction
- Beam quality in Main Injector
  - Position, abort gap



Beam Permit System

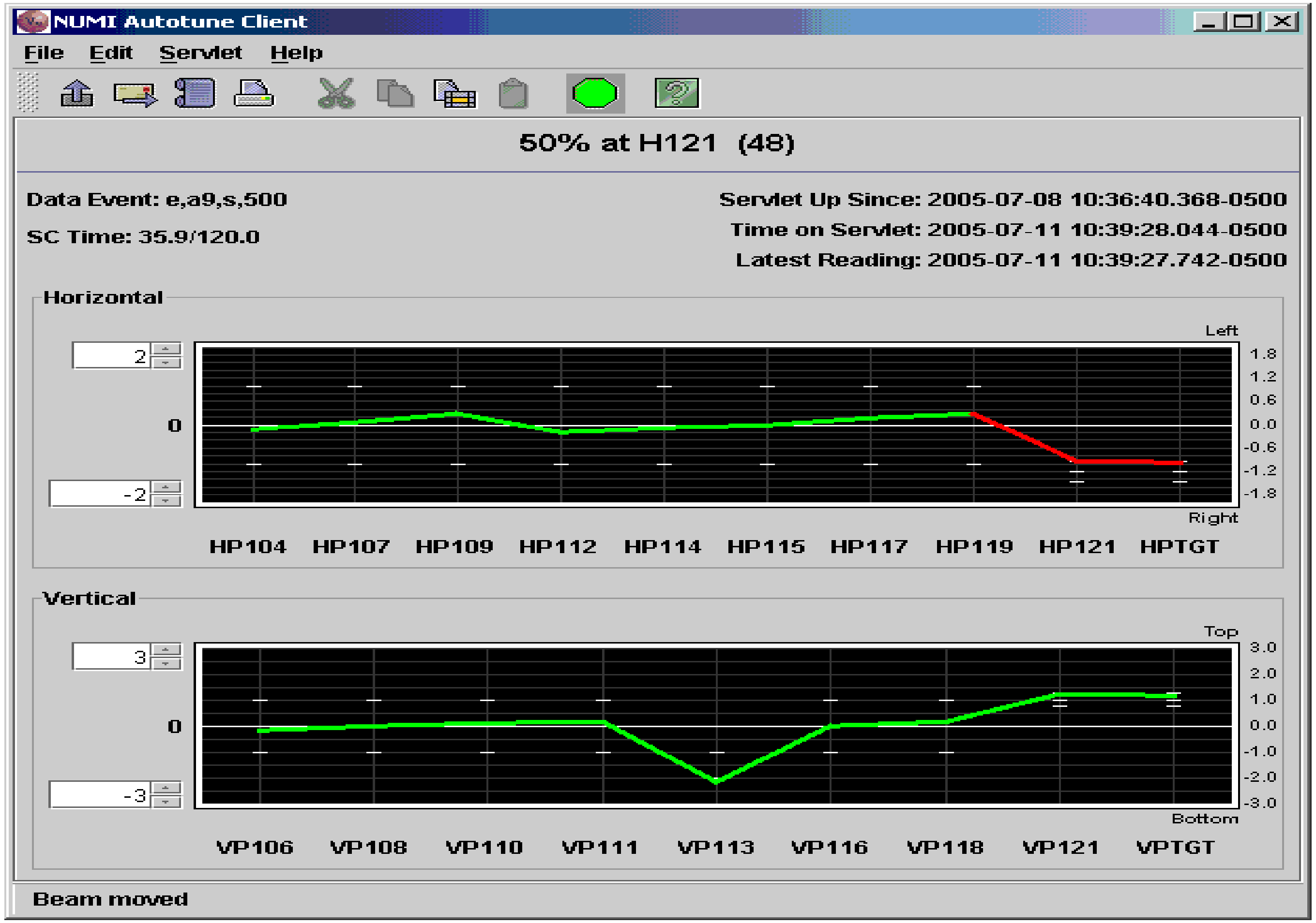
- Routinely inhibits beam when components fall outside tolerancs
- Prevents extraction when magnets are set to correct currents
- Prevents extraction when beam is in the abort gap
- Inhibits beam on unusual behavior
  - E.g. orbit movement
- Can allow one bad pulse because of magnet variation ~ 1%
  - May be upgraded



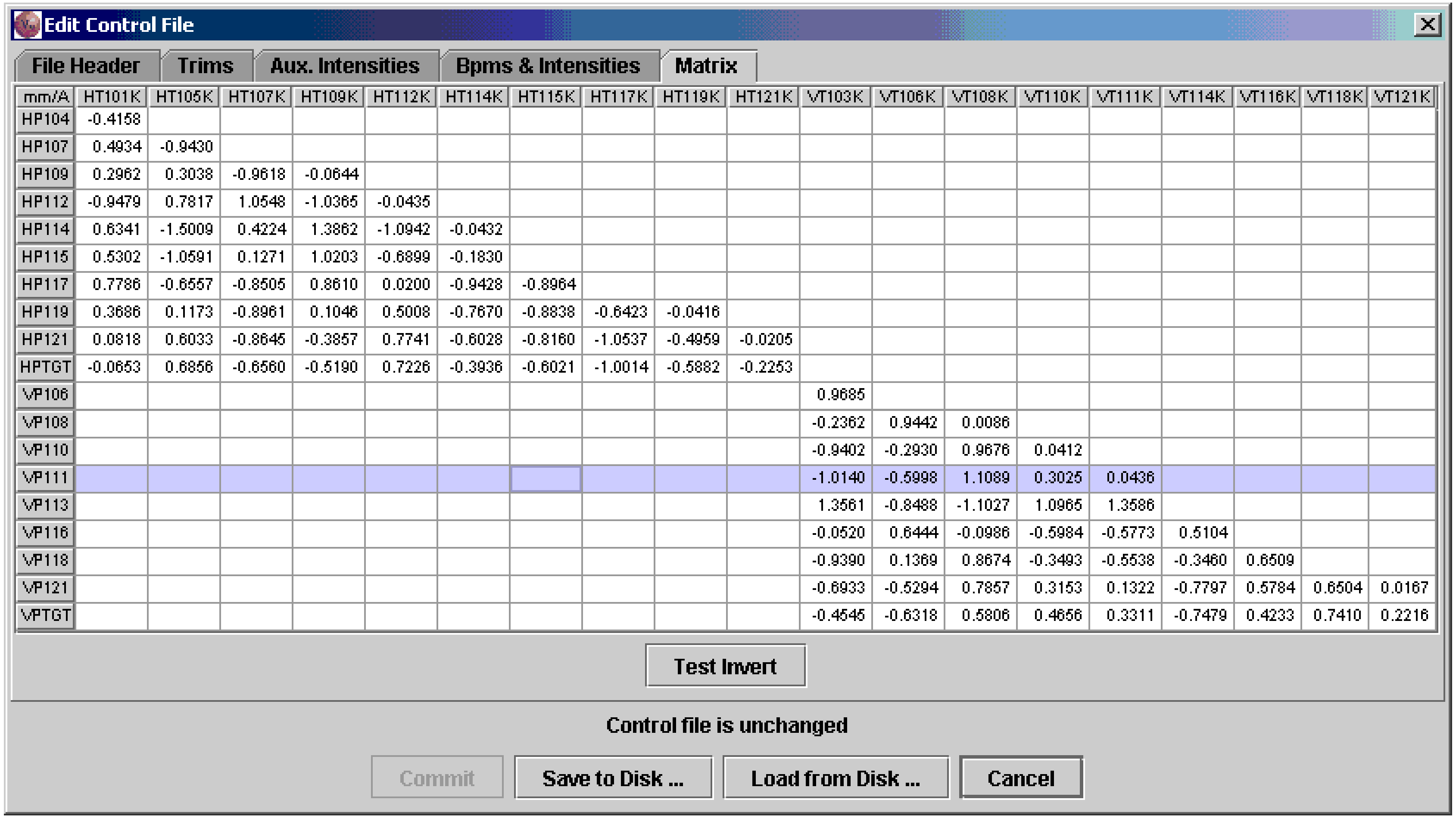
3 turns of RWM output during multi-batch running

Autotune

- Automatic program continuously tunes the beamline
  - Used for commissioning, but numbers were verified and applied by hand
    - Applied to main bends during commissioning, trims during operation



Tuning Matrix (Invertible)



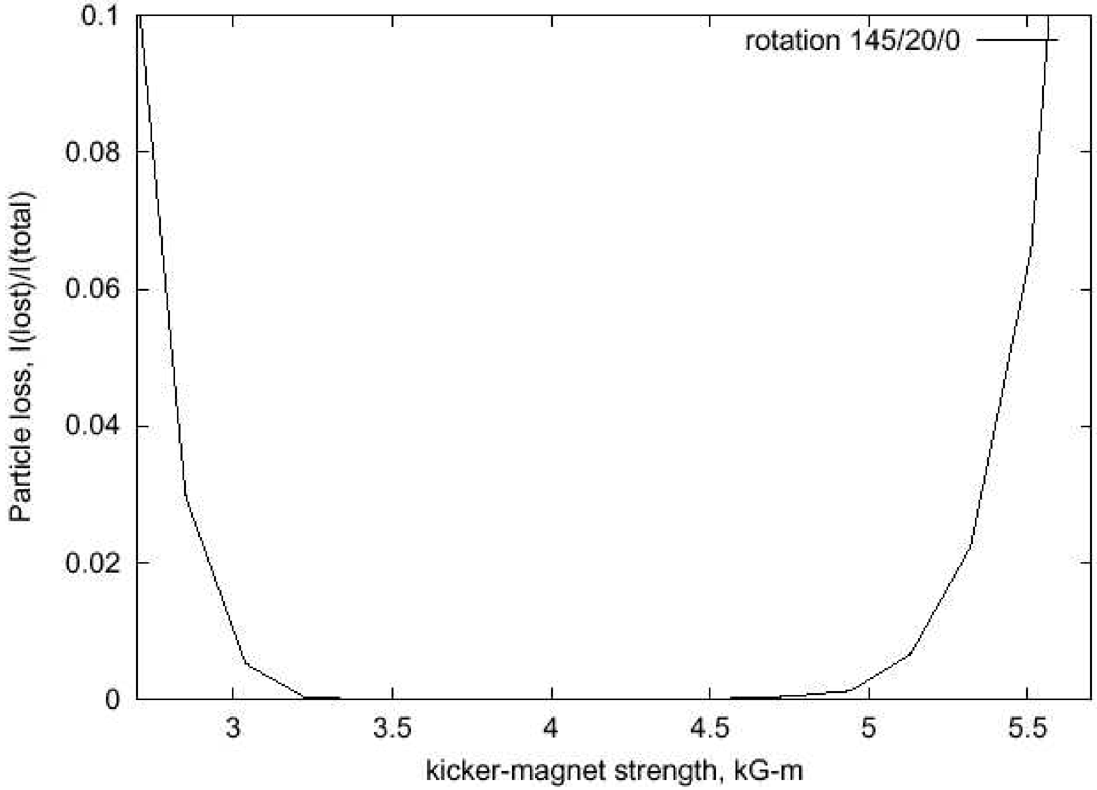
mm/A	HT101K	HT105K	HT107K	HT109K	HT112K	HT114K	HT115K	HT117K	HT119K	HT121K	VT103K	VT106K	VT108K	VT110K	VT111K	VT114K	VT116K	VT118K	VT121K
HP104	-0.4158																		
HP107	0.4934	-0.9430																	
HP109	0.2962	0.3038	-0.9618	-0.0644															
HP112	-0.9479	0.7817	1.0548	-1.0365	-0.0435														
HP114	0.6341	-1.5009	0.4224	1.3862	-1.0942	-0.0432													
HP115	0.5302	-1.0591	0.1271	1.0203	-0.6899	-0.1830													
HP117	0.7786	-0.6557	-0.8505	0.8610	0.0200	-0.9428	-0.8964												
HP119	0.3686	0.1173	-0.8961	0.1046	0.5008	-0.7670	-0.8838	-0.6423	-0.0416										
HP121	0.0818	0.6033	-0.8645	-0.3857	0.7741	-0.6028	-0.8160	-1.0537	-0.4959	-0.0205									
HPTGT	-0.0653	0.6856	-0.6560	-0.5190	0.7226	-0.3936	-0.6021	-1.0014	-0.5882	-0.2253									
VP106											0.9685								
VP108											-0.2362	0.9442	0.0086						
VP110											-0.9402	-0.2930	0.9676	0.0412					
VP111											-1.0140	-0.5998	1.1089	0.3025	0.0436				
VP113											1.3561	-0.8488	-1.1027	1.0965	1.3586				
VP116											-0.0520	0.6444	-0.0986	-0.5984	-0.5773	0.5104			
VP118											-0.9390	0.1369	0.8674	-0.3493	-0.5538	-0.3460	0.6509		
VP121											-0.6933	-0.5294	0.7857	0.3153	0.1322	-0.7797	0.5784	0.6504	0.0167
VPTGT											-0.4545	-0.6318	0.5806	0.4656	0.3311	-0.7479	0.4233	0.7410	0.2216

Test Invert

Control file is unchanged

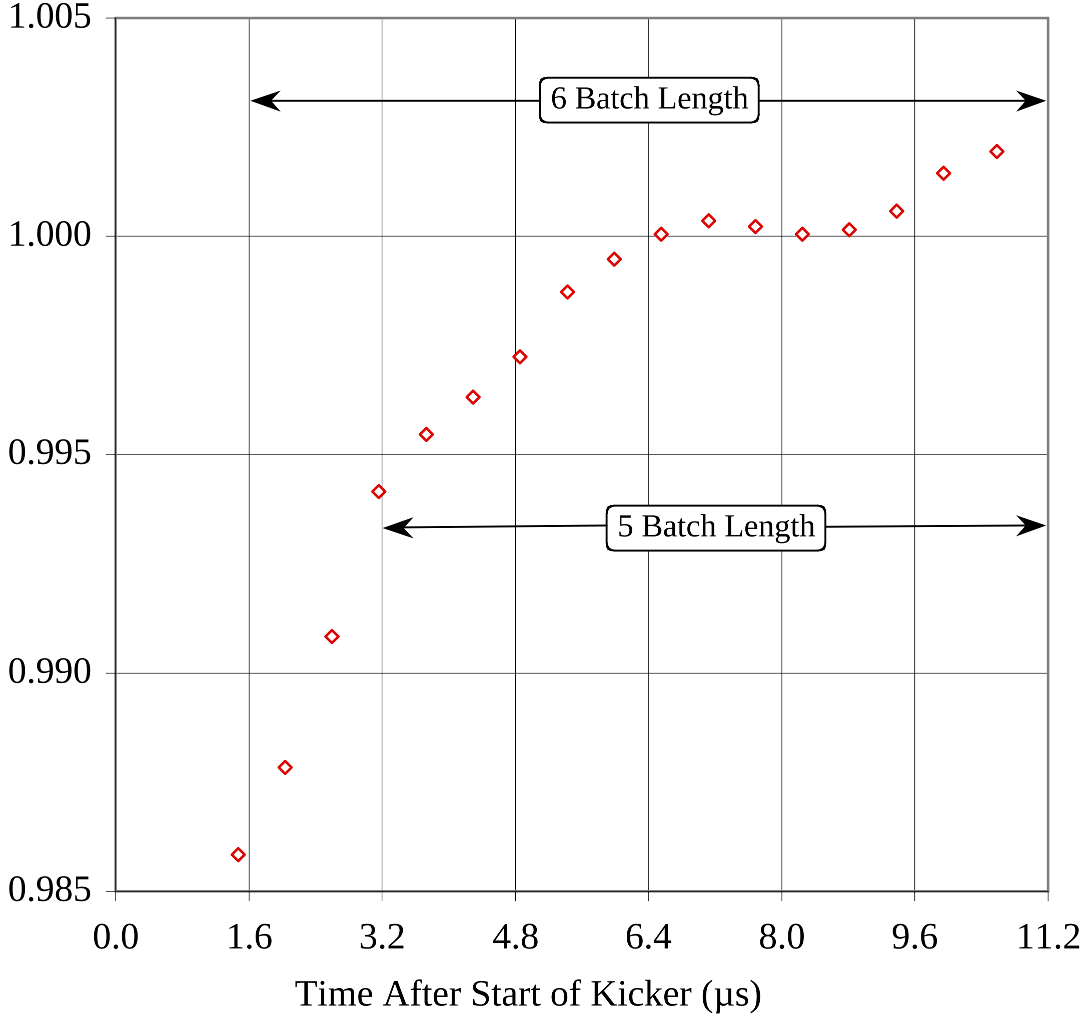
Commit | Save to Disk ... | Load from Disk ... | Cancel

Effects of Kicker Strength



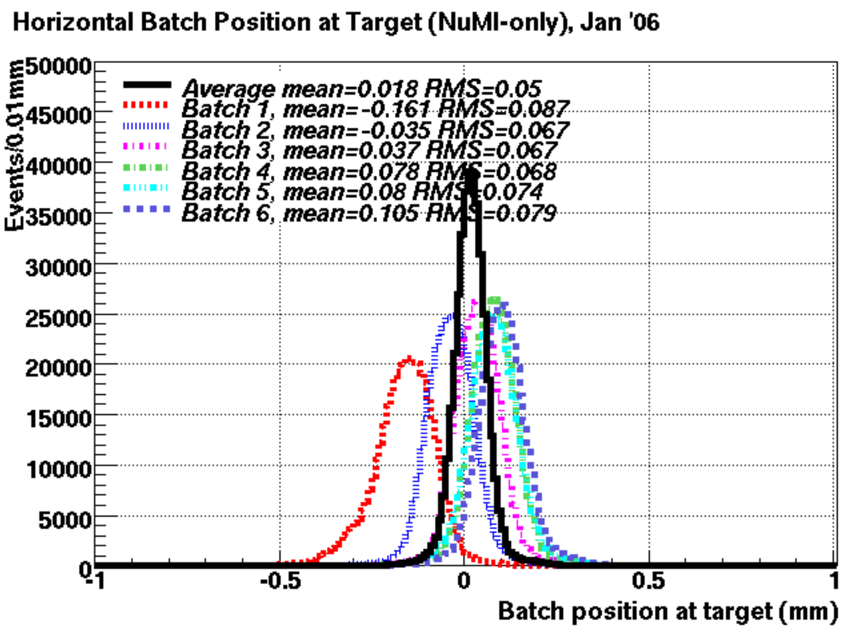
- **Particle loss through line is small for many kicker strengths/displacements**
  - **Position on target varies instead**

Measurement of Kicker Stability with Beam

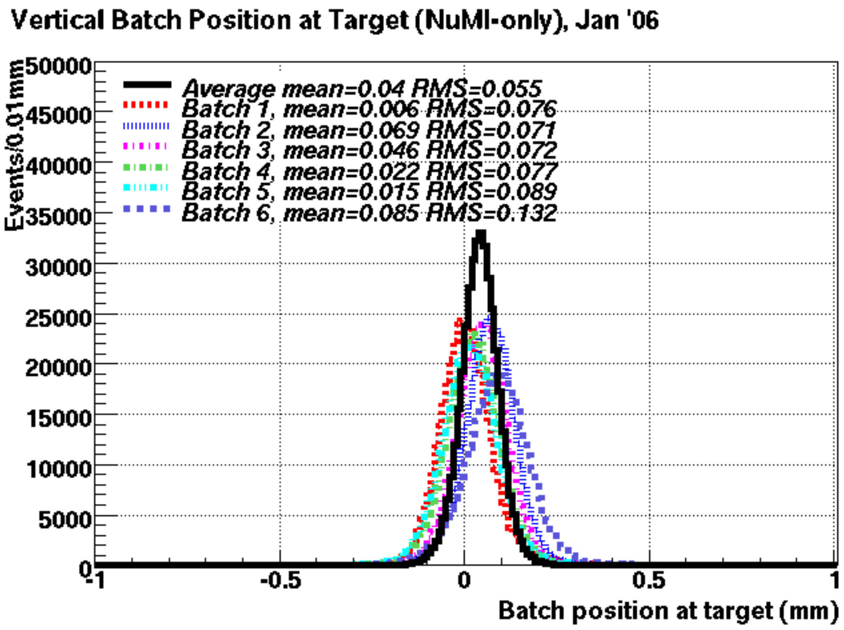


- **Measured Change in Position**
- **BPM Accuracy of ~10 μm**
- **Total Displacement of 43 mm**

Jan. '06 Beam Stability on Target
NuMI Only



Hor

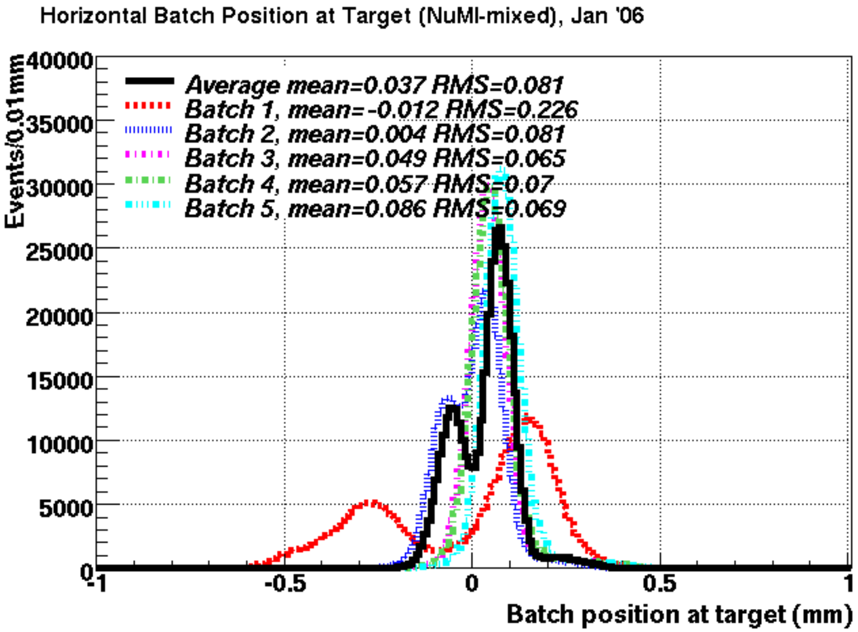


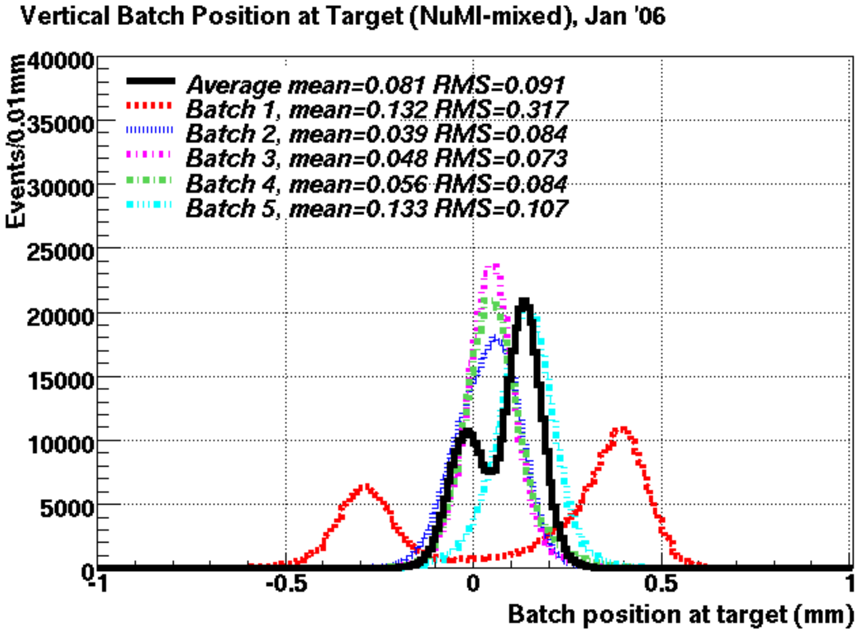
Ver

Note expanded scale. Horizontal sees kicker stability effects.

Error on mean batch position < 60 microns for all batches (160 µ for batch 1)

Jan. '06 Beam Stability on Target
Mixed Mode



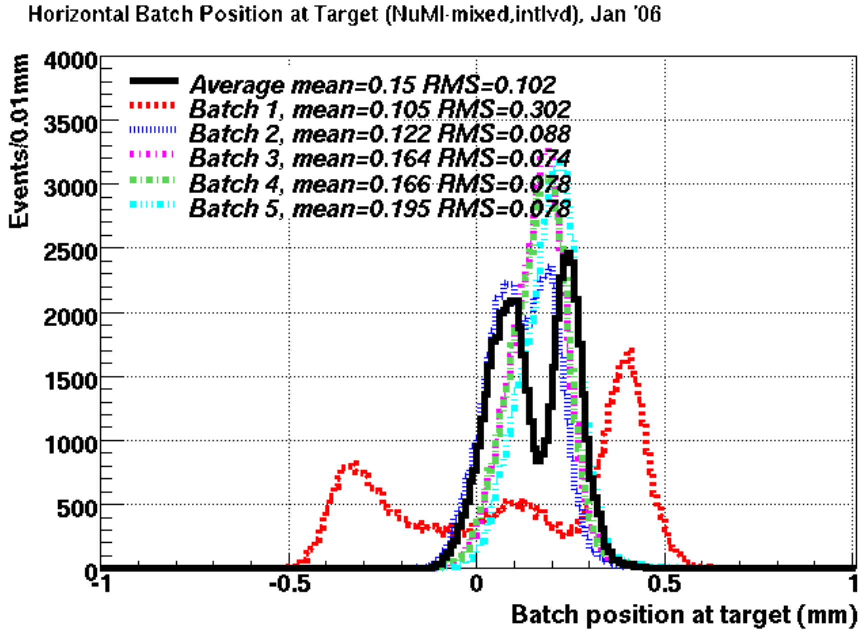


Hor

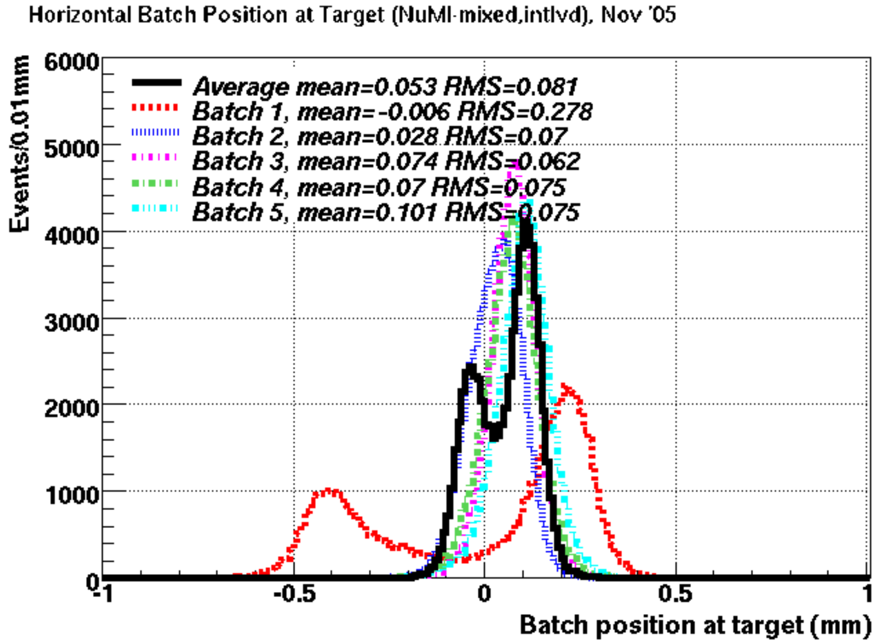
Ver

- Note bimodal effect of Pbar kicker on 1st NuMI batch [Either even or odd # turns between extractions]. Error on mean batch position increased to 90 μ. (Many batch 1 points > 250 μ spec.)

Beam Stability on Target
Interleaved Mode



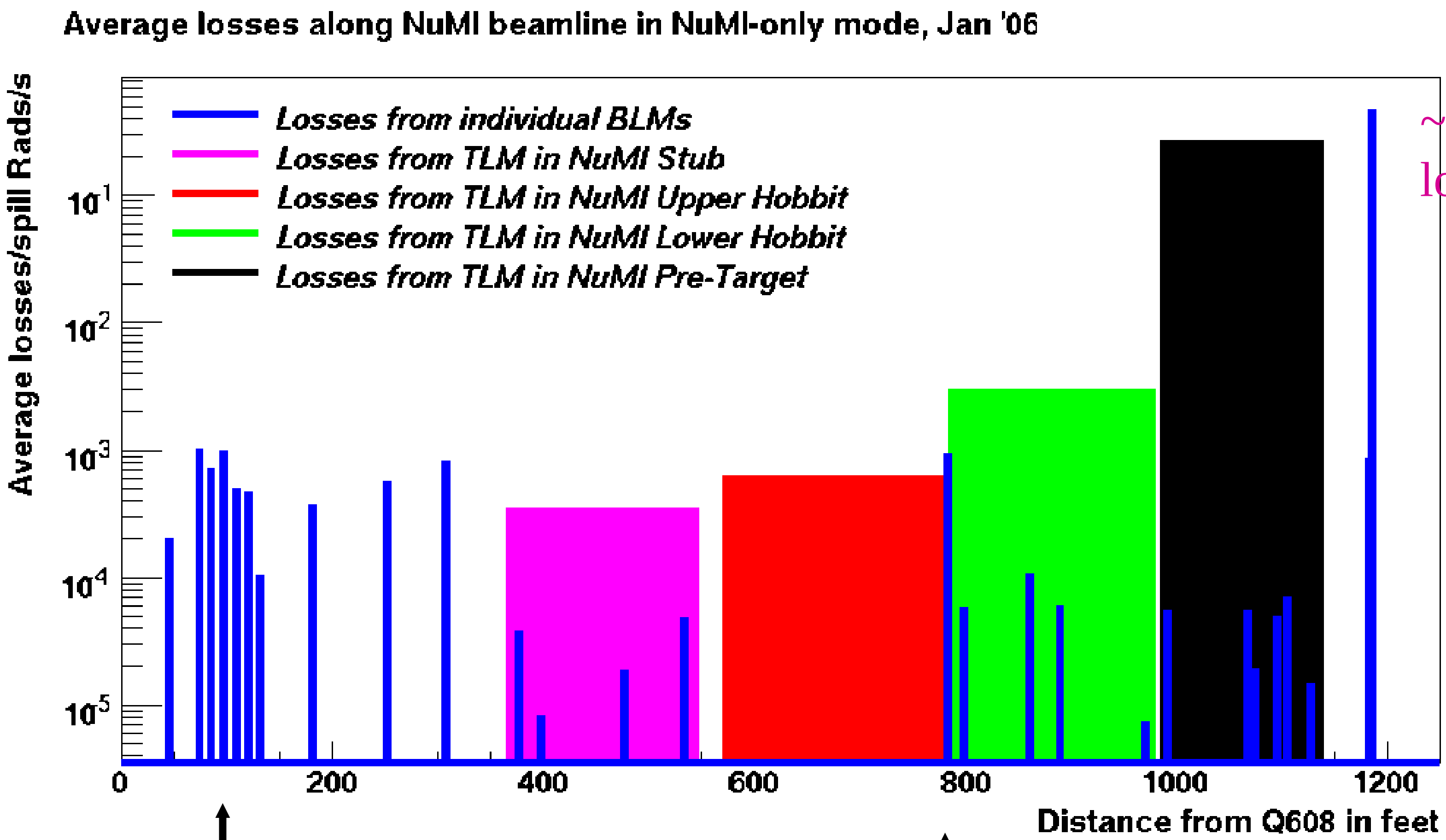
Jan 06



Nov.05

Some worsening of momentum difference between extraction modes.
Are preparing separate Autotune corrector files for each.

Jan ’06 Average per Pulse
Primary Beam Loss – NuMI Only



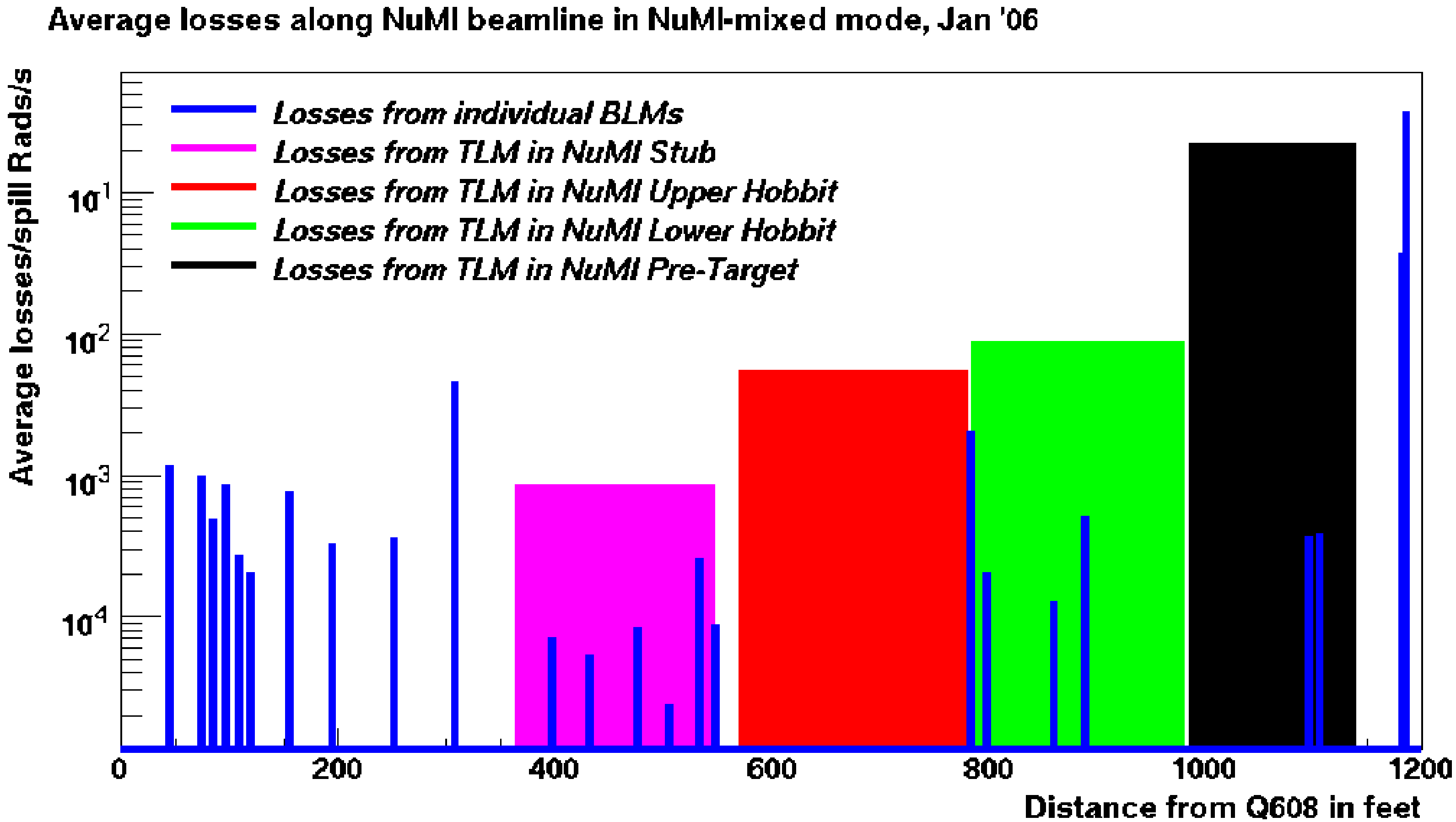
~5E-6
loss

Extraction

Max.Dispersion

Profile
Monitor

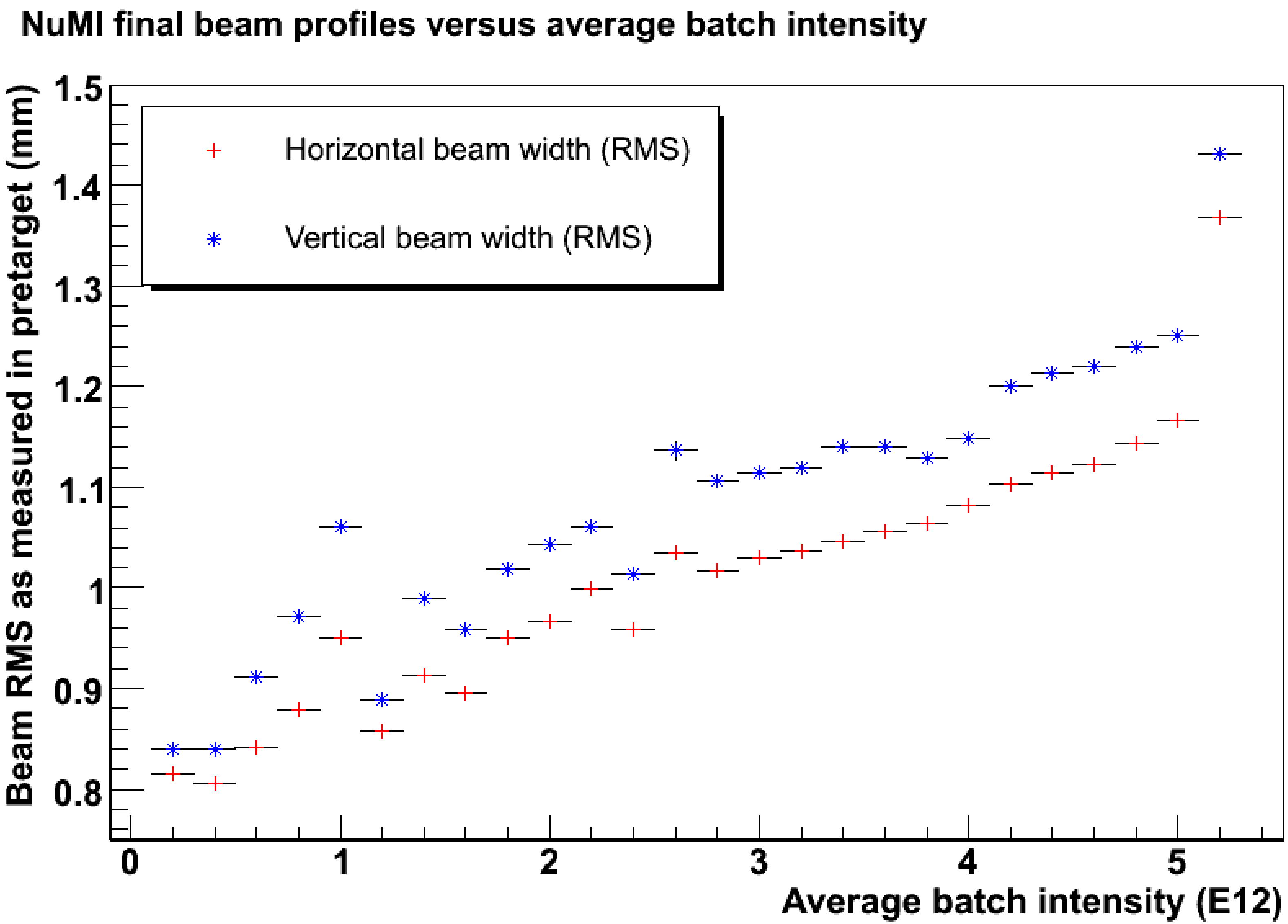
Jan '06 Average per Pulse
Primary Beam Loss – Mixed Mode



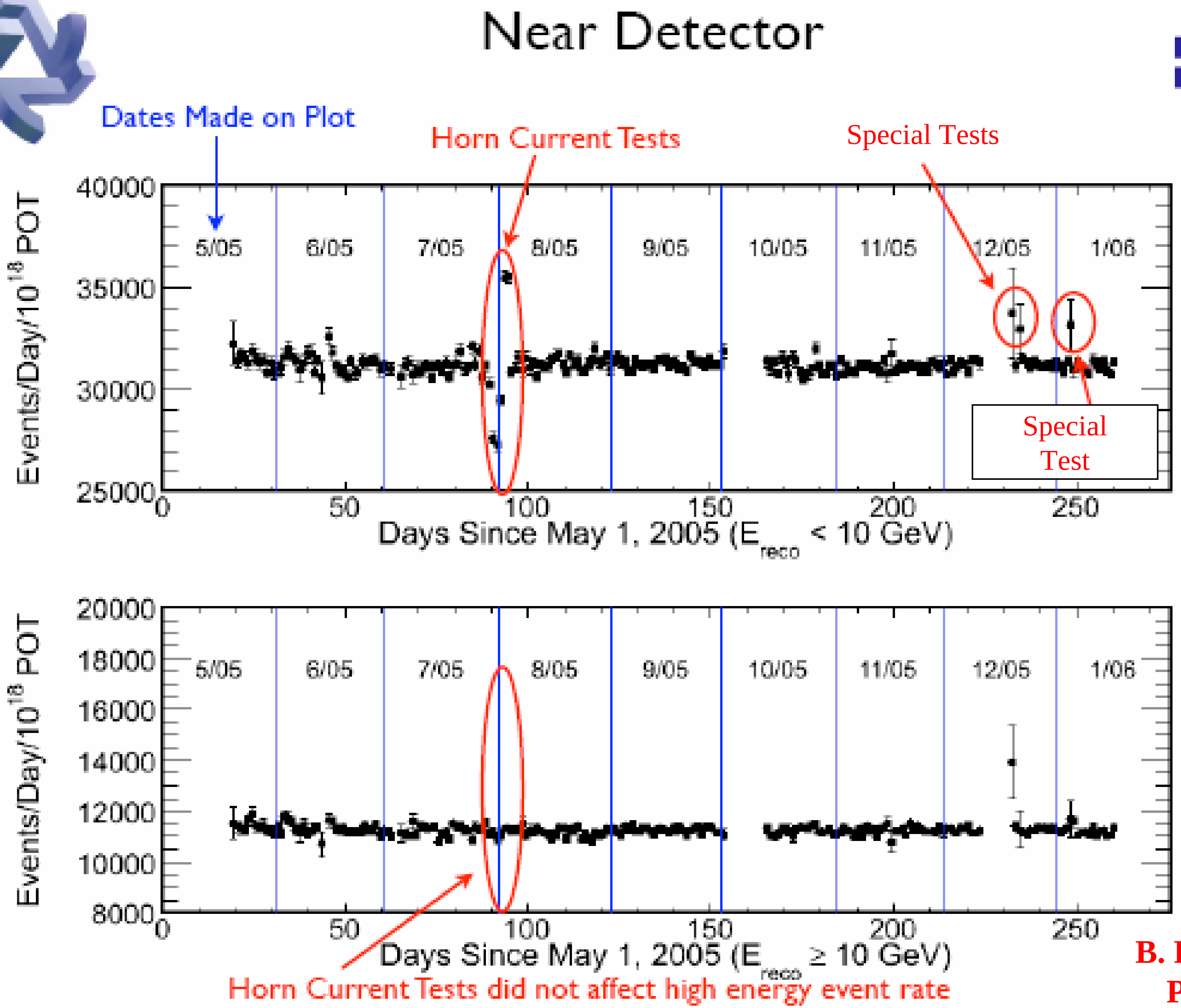
~5E-6 loss

Significant improvements in earlier loss from Pbar slip stacked batch

Beam Widths with Intensity

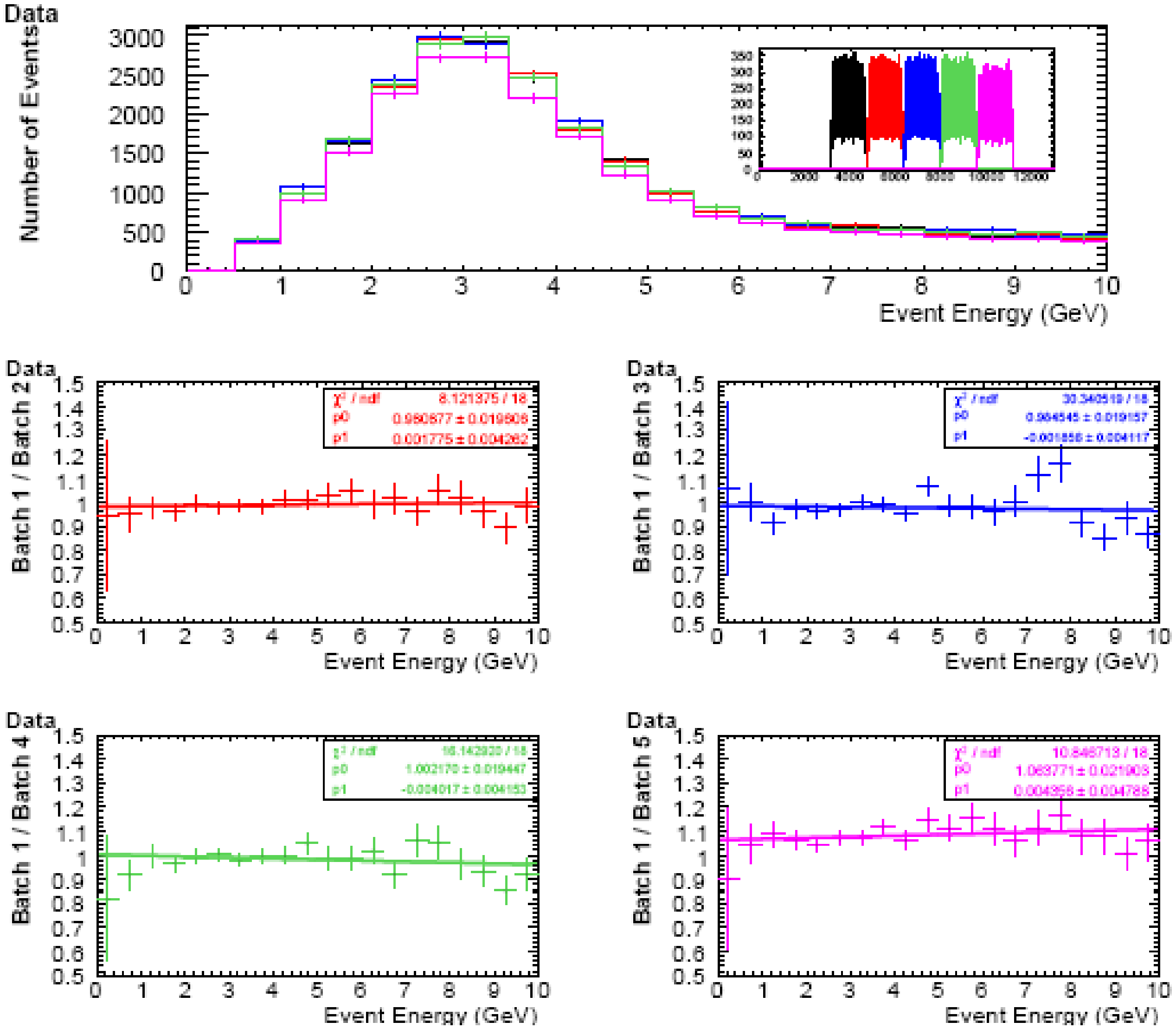


Normalized Neutrino Rates vs Time



B. Rebel Plot

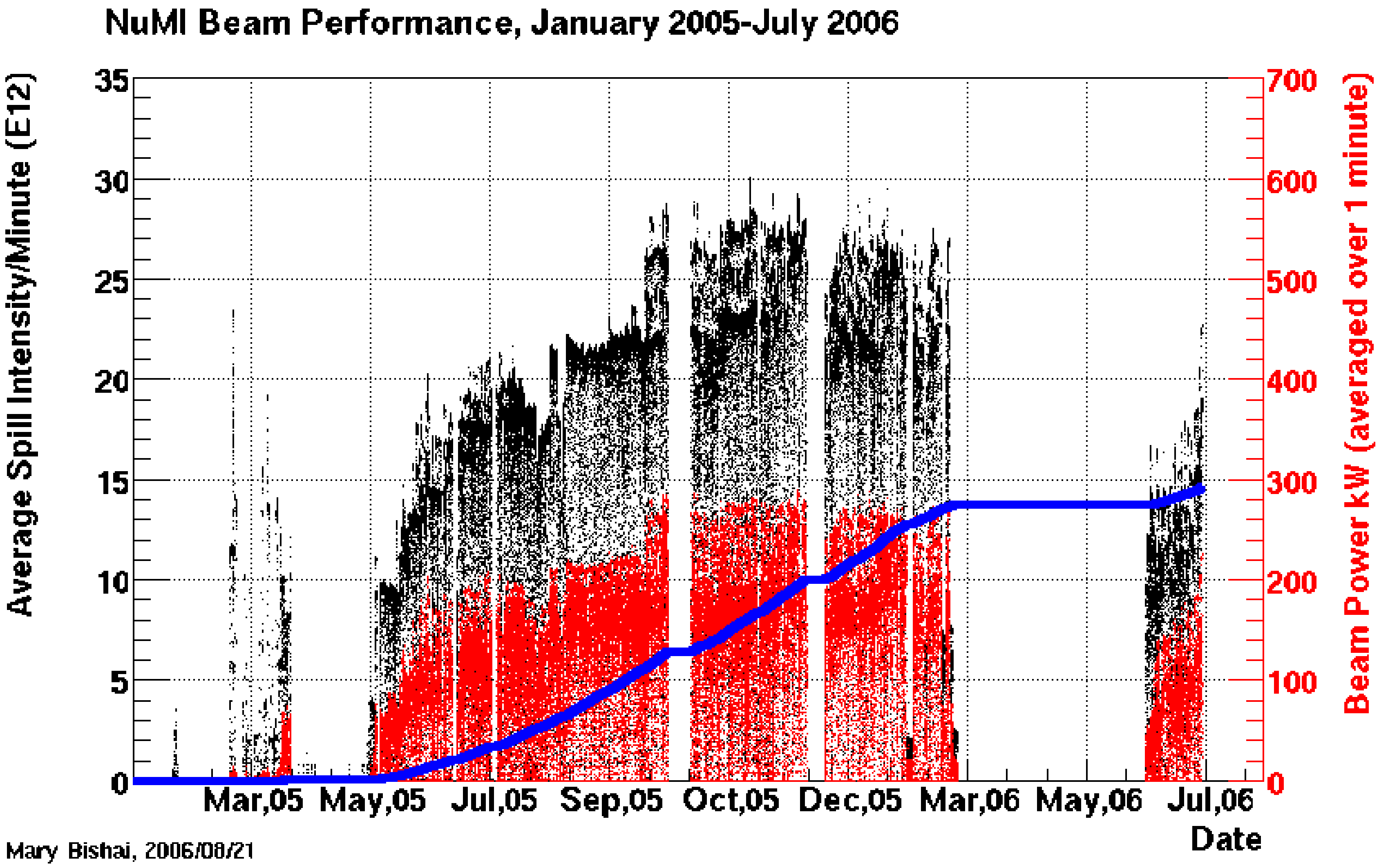
Near Detector
CC Energy Spectra: Batch 1 vs Other Batches



T. Osiecki Plot

NuMI Beam History

Protons, Beam Power, Intensity



Summary

- Primary proton line has been operating reliably since startup
- Well verified optical model
- Autotune keeps beam on target even with perturbations
  – Prerequisites are the optical model and beam permit
- Perturbations come from kicker systems
  – No losses, but beam position at target varies
- Losses come wholly from large amplitude beam generated through slip-stacking