The NuMI Proton Beam at Fermilab:

Successes and Challenges

S. Childress

Fermilab

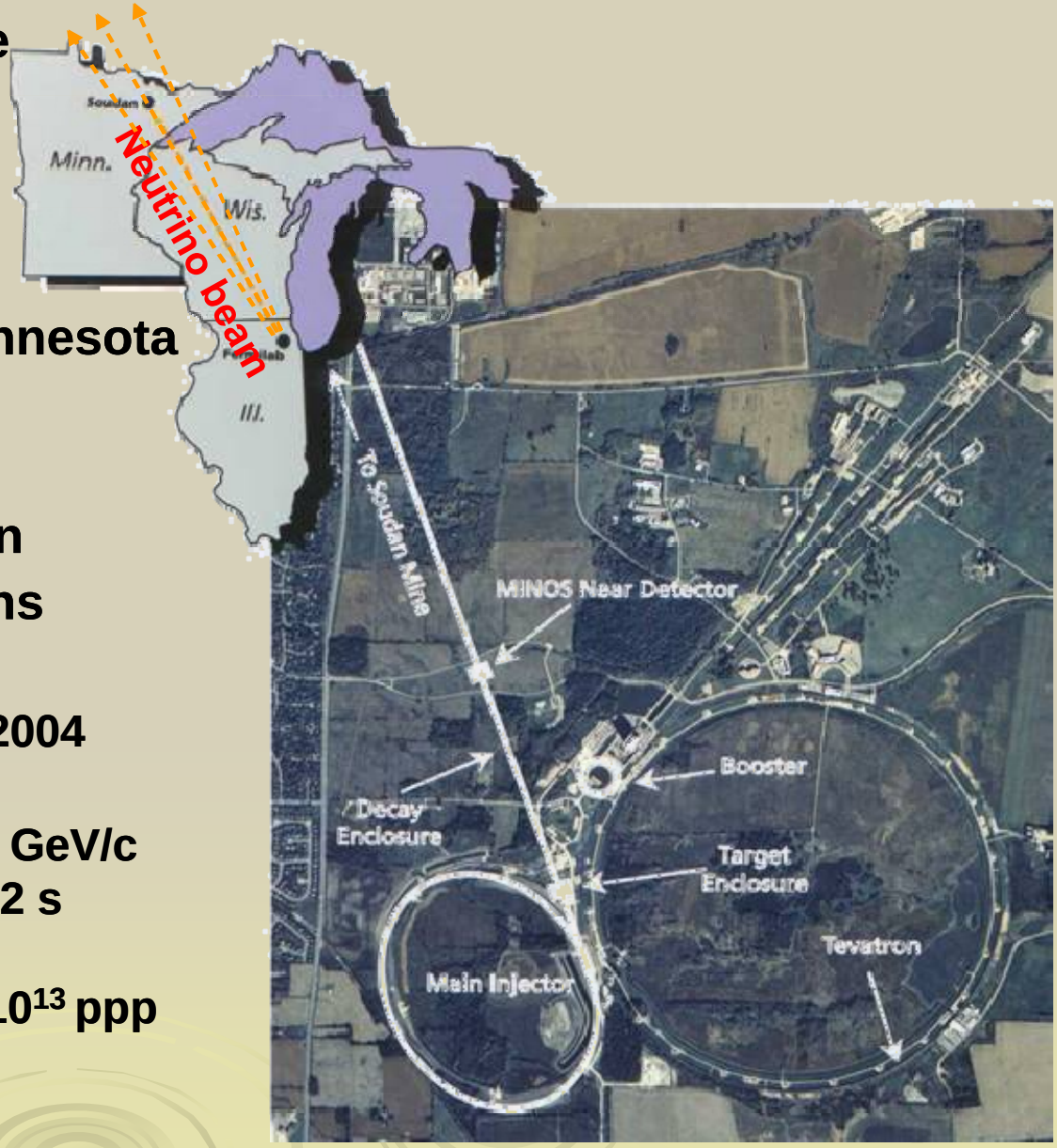
Presentation Outline

- Brief NuMI Overview
- NuMI Proton Beam
- Key Proton Beam Considerations
- Commissioning Plan & Results
- Operations Experience to Date
- Summary

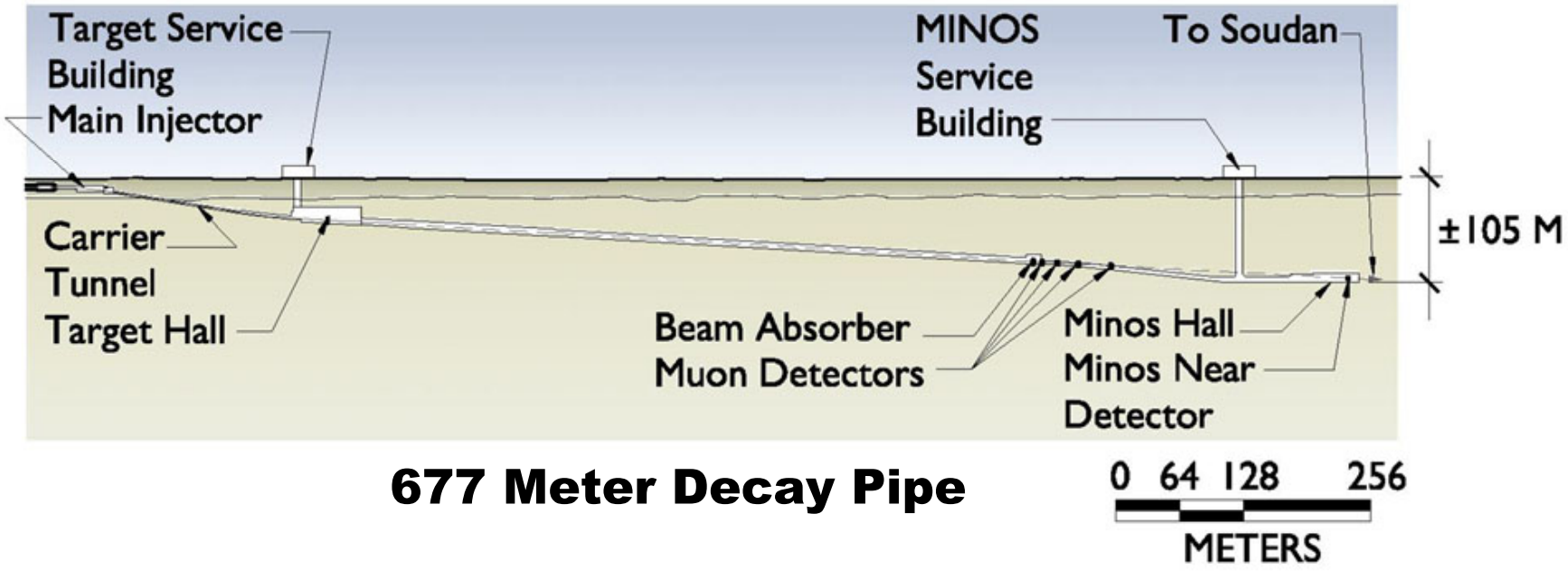
Brief NuMI Overview

NuMI: Neutrinos at the Main Injector

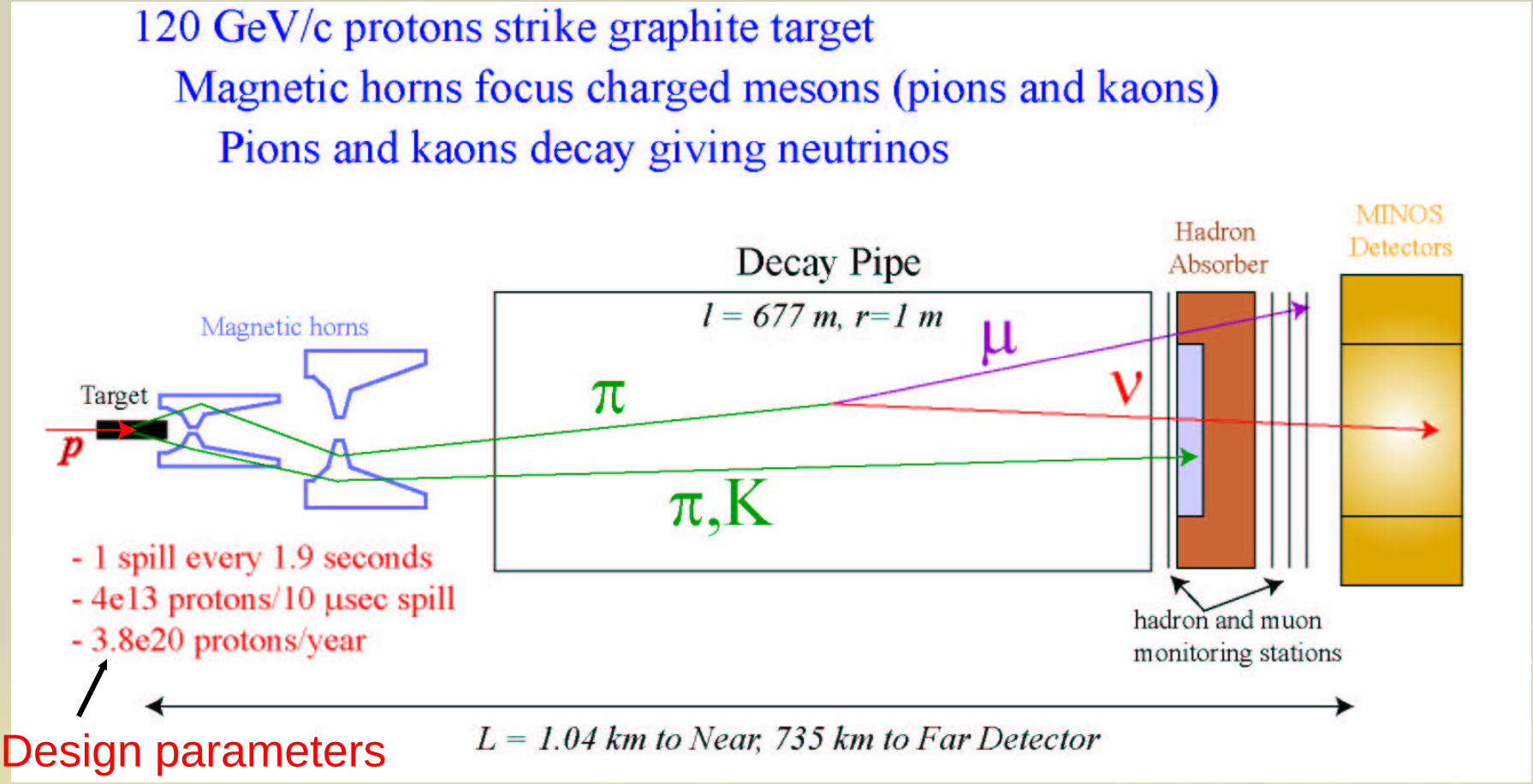
- **Search for long baseline oscillation**
  ν_μ disappearance
- **735 km baseline**
  - **From Fermilab to Minnesota**
  - **Elevation of 3.3°**
- **MINOS experiment**
  - **Near detector: ~1kton**
  - **Far detector: 5.4 ktons**
- **NuMI Proton beam**
  - **Commissioned in late 2004**
  - **Operating since 2005**
  - **From Main Injector: 120 GeV/c**
  - **Current Cycle length: 2.2 s**
  - **Pulse length: 10μs**
  - **Beam intensity: 3-3.7 · 10^{13} ppp**
  - **σ ~1.1 mm H & V**



Elevation View of the NuMI/MINOS Project on Fermilab Site

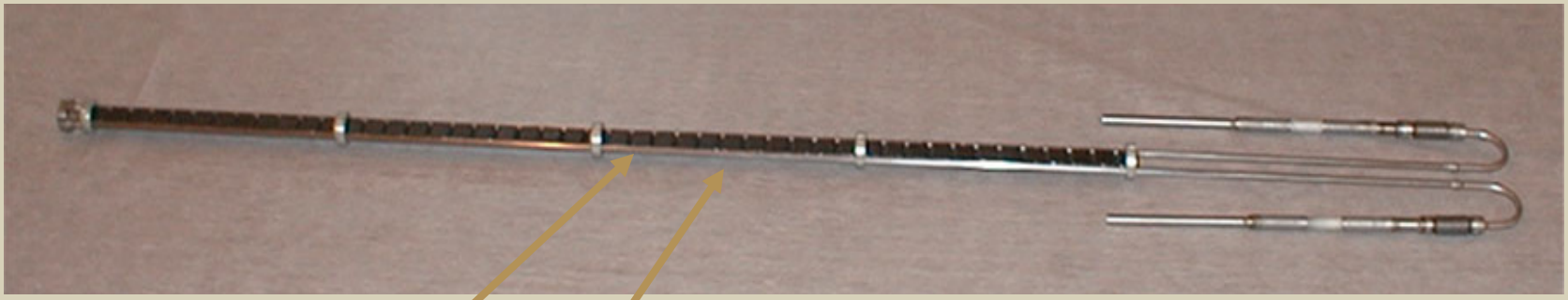


ν Production for NuMI



Design parameters for 0.4 MW beam

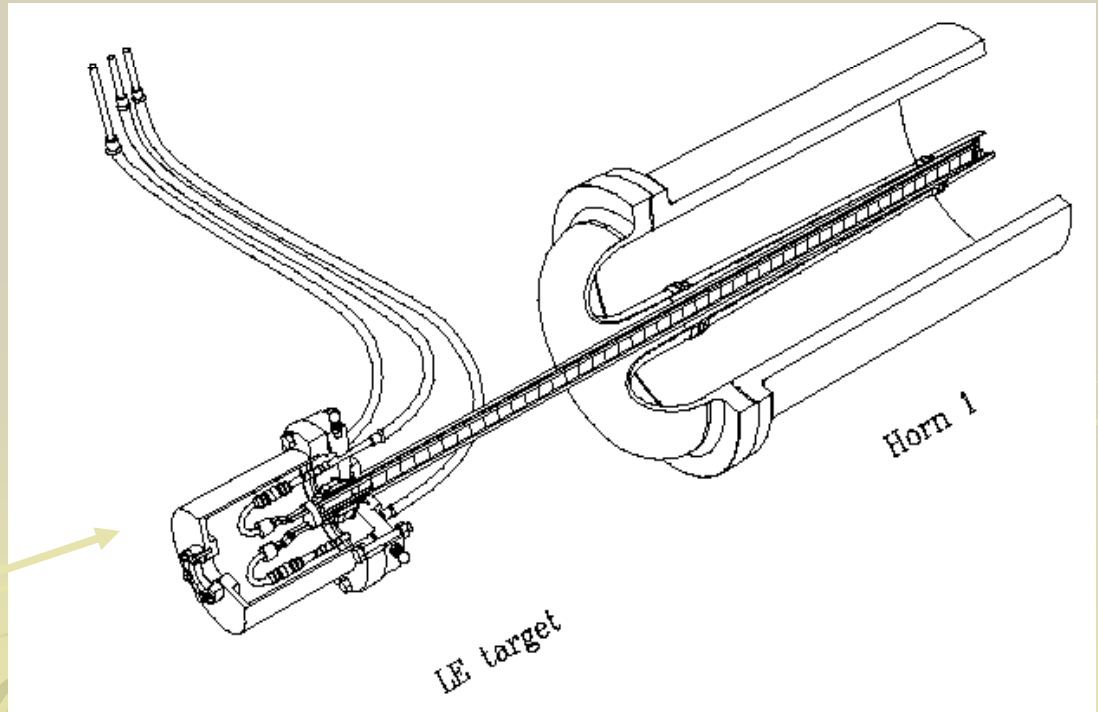
Graphite Target



Graphite Fin Core
2 interaction lengths

Water cooling tube
provides mechanical support

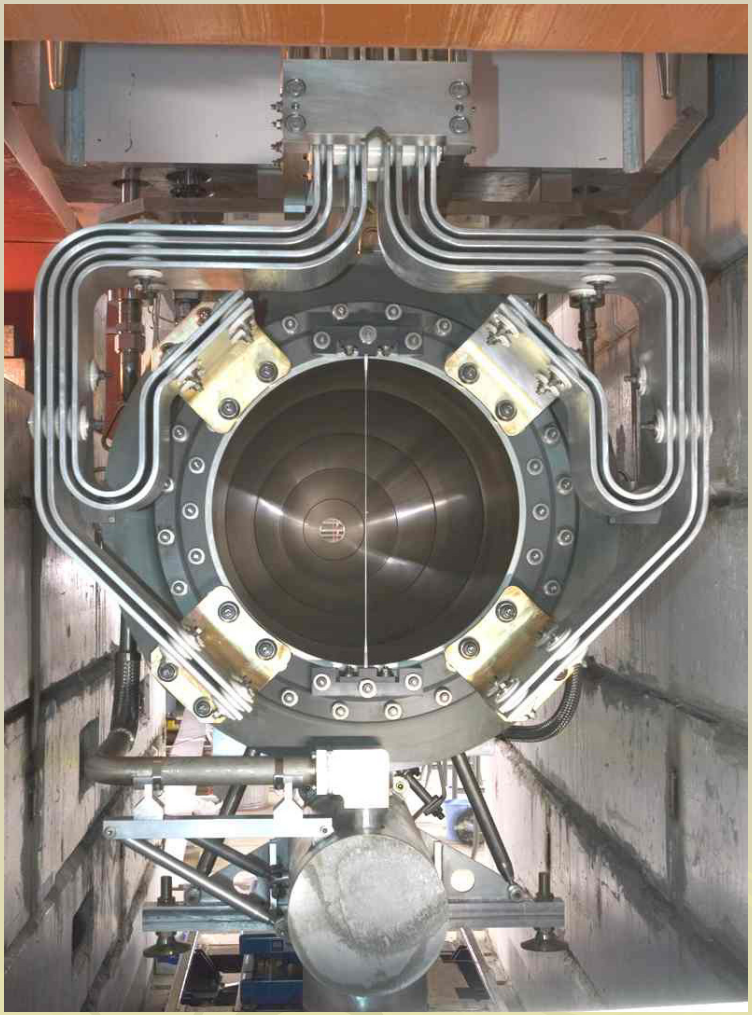
Low Energy Target fits in horn without touching



Horn System – 2 Horns

(Shown in work cell, hanging from support module)





NuMI Target Hall Systems (not the focus of this talk)

- Some VERY challenging one of a kind designs
- Graphite Target
  - Target integrity for intense fast spill beam
  - Low energy beam design precludes rigid support structure – target fits into horn
  - Replaced 1st target after 1 ½ years – mechanical drive failure from corrosion. After a cooling water leak in 1st days of operation ran well with He back pressure controlling water leak until target replacement
- Horn & Reflector
  - Design for > 10 million pulses at 200 kAmps
  - Low mass to minimize secondary beam absorption
  - Intense radiation environment, moisture => corrosive effects
  - Replaced horn 1 after 22 M pulses – ceramic isolator water leak (we have had several of these – now redesigned isolators)
- Essential need for spares, with long lead times
  - Very difficult to repair relatively minor problems due to radiation, but some significant successes – of necessity
- 240 kW forced air target chase cooling system
  - Design constraints not as fundamental, but many challenges

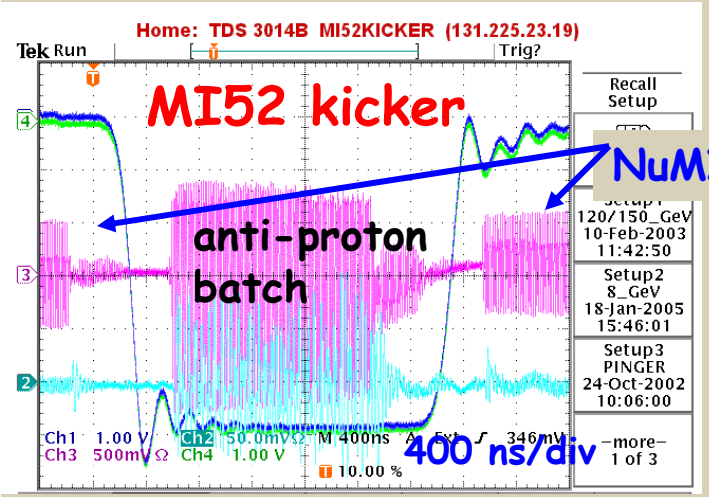
NuMI Proton Beam

8 GeV Booster and 120 GeV Main Injector



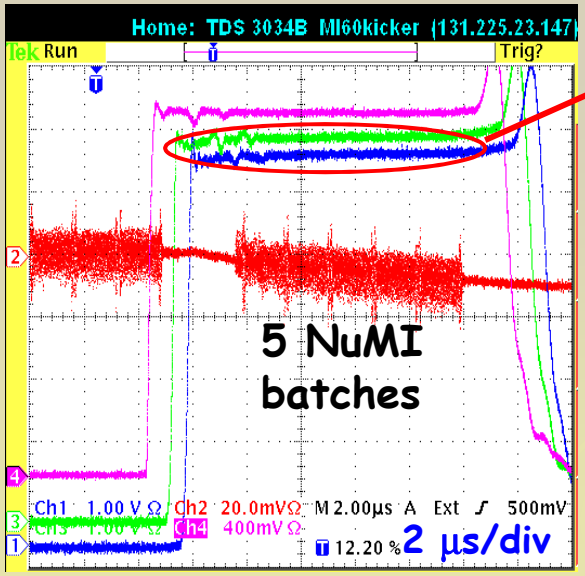
- **Booster provides batches of up to 4.8 e12 protons**
- **Main Injector is a shared resource - to 3.7 e13 protons/cycle.**
  - **Normal is mixed mode operation with multi-batch slip stacking in Main Injector**
    - **2 batches for Pbar production merged into 1**
    - **9 batches for NuMI merged into 5 batches**
    - **NuMI current batch intensity ~ 3.4 e12 protons: limited by slip stacking beam loss in MI. Already a very considerable NuMI intensity increase since multi-batch slip stacking initiated for NuMI in January '08.**
    - **Bruce Brown presentation WG D**
  - **When there is no Pbar targeting, NuMI gets that beam also**
  - **Test beams get ~ 5% of Main Injector beam cycle time**

Extraction from the Main Injector





NuMI kickers



flat within ±0.8 % over 10 µs

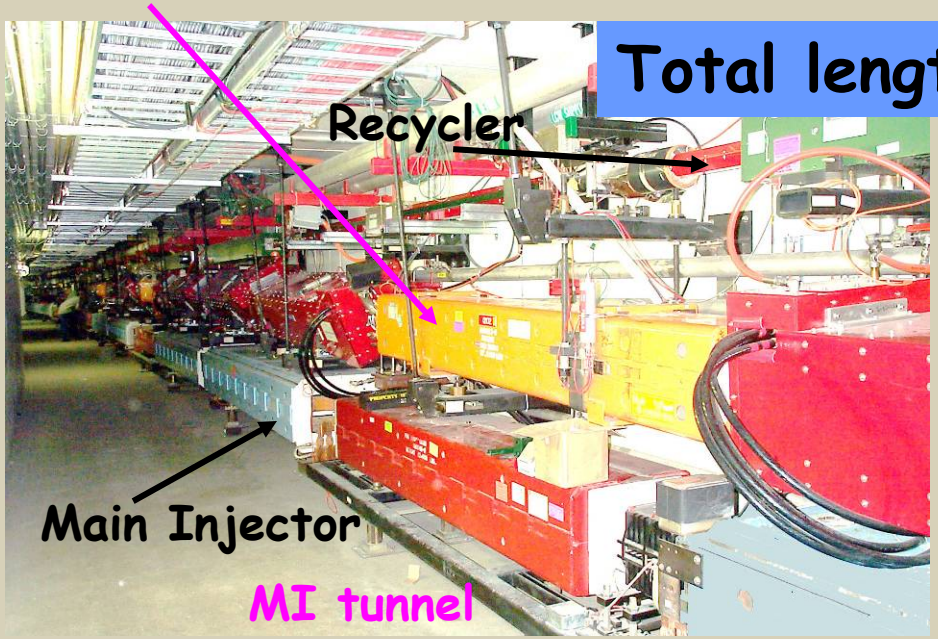


Primary Proton Line

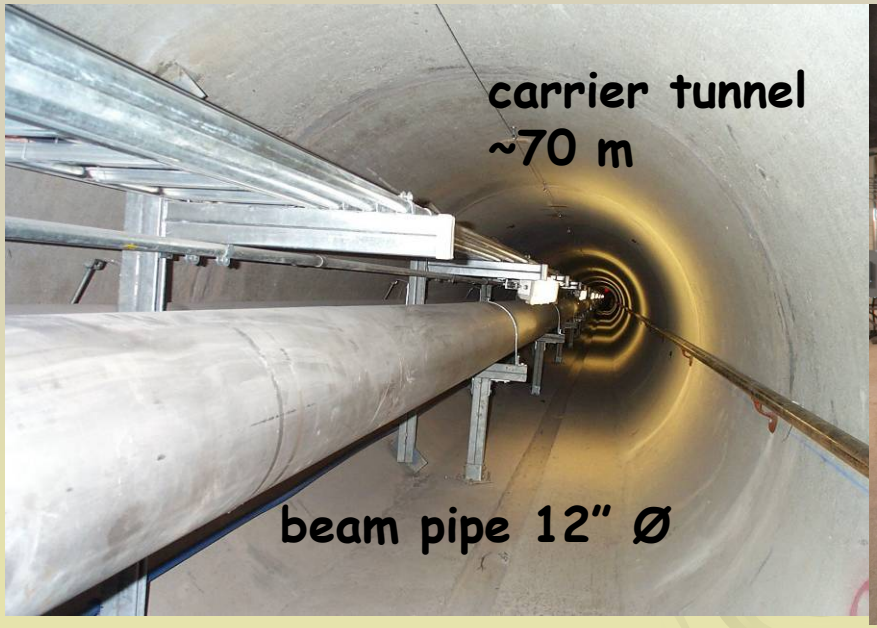
NuMI line

bending down by 156 mrad

Total length ~ 350 m









Key Proton Beam Considerations

A New Regime for Beam Control Requirements

- **The most compelling feature for high energy several hundred kW proton beams is that they can damage most materials very quickly – a few seconds or even one cycle of mis-steered beam**
- **Adjacent photo shows the result of a single wayward 450 GeV SPS beam pulse of 3.4 e13 protons (CERN TT40 line Oct.'04) Magnet vacuum chamber destroyed. Views are from inside beam tube**
- **Now we need millions of pulses!**

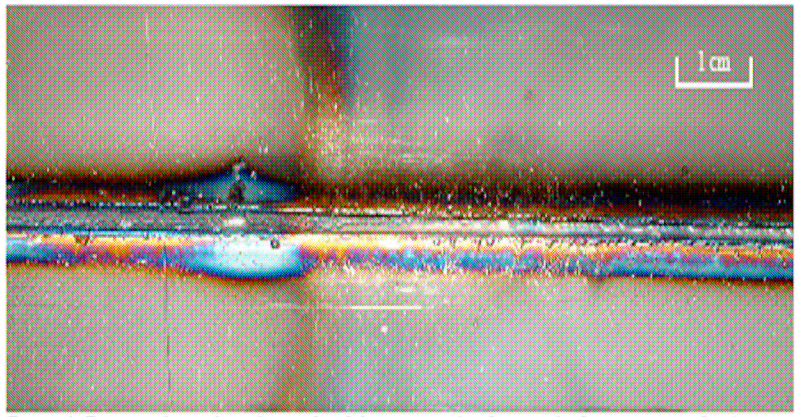


Figure 4. Damage observed on the inside of the vacuum chamber, on the beam impact side. A groove approximately 110 cm long due to removed material was clearly visible, starting at about 30 cm from the entrance.

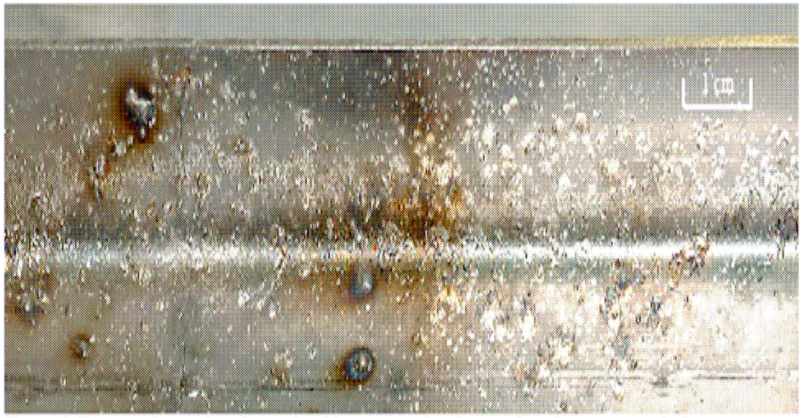


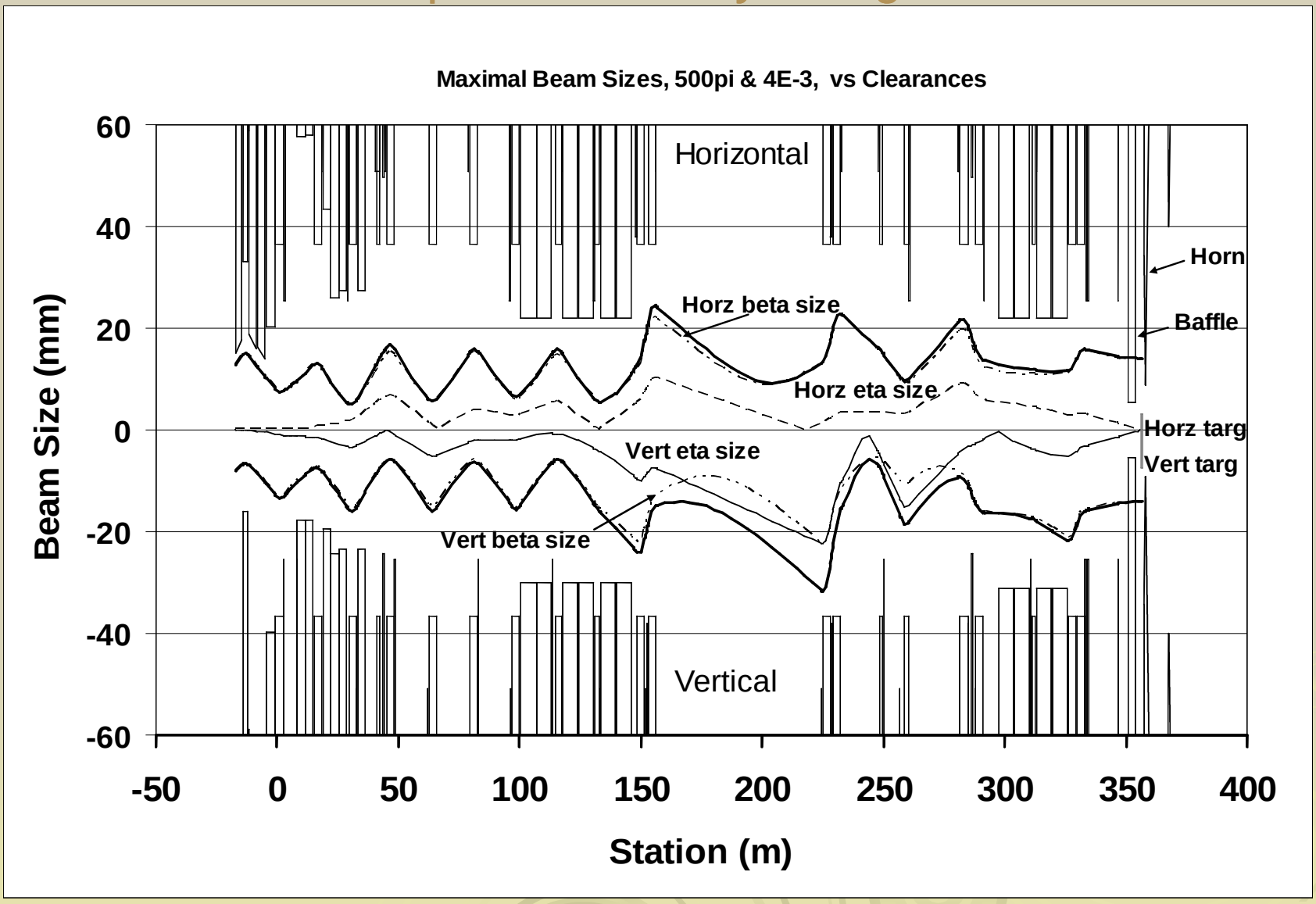
Figure 5. Damage observed on the inside of the vacuum chamber, on the side opposite to the beam impact. Molten material has been projected across the chamber and has condensed in droplets on the other wall.

Other NuMI Beam Constraints

- **Targeting**
  - **Maintain beam centered on target to < 0.25 mm (Physics background constraint)**
  - **Preclude 2nd beam pulse at 1.5 mm off center (6.4 mm target width; 11mm baffle ID). Wayward beam at significant angle could hit target cooling or horns**
- **Severe Limits on Allowable Primary Beam Loss**
  - **For 400 kW beam maximum fractional point beam loss allowed is ~ 10-5 for environmental (ground water) protection.**
- **Also**
  - **Maintain machine quality vacuum to eliminate interface vacuum window. Also prevents gas ionization bkgds for BPMs**
  - **"No mass" BPM's for position measurement; low mass profile monitors for beam transport**
  - **Beam loss control to < 10-4 of beam to minimize residual activation**

500 Pi Beam Envelope vs. Apertures

Open Geometrry Design



Commissioning Plan & Results

Pre-Beam Commissioning

- **We planned to – and did – establish readiness of systems for primary beam prior to first extracted beam pulses.**
- These include:
  - Magnet function & connection polarities
  - Power supply function / ramp parameters
  - Kicker & power supply function
  - Recycler permanent magnet shielding from NuMI EPB dipole fringe fields
  - Instrumentation function and readout polarities
  - Beam Permit System [establish & test 1st limits for all devices]
  - Control timing
  - Verify documentation capability – Beam profiles, positions, intensity, beam loss,etc.
  - Main Injector beam suitable for extraction

NuMI Beam Commissioning Schedule

- Project plan was for beam commissioning during accelerator startup (late Nov.) from Fall '04 shutdown period .
  - **Understand at early stage any fundamental issues with extraction and primary transport requiring Main Injector / Recycler Ring tunnel access to address.**
  - **More than half of NuMI primary transport is in MI/RR interlock region**
- Schedule delays with forced air cooling system for Target Hall precluded option for high power NuMI beam prior to late Feb. '05.
- Decision to proceed with beam commissioning on schedule, with severe constraints for number and intensity of beam pulses to preclude radiating target hall.
- Held three carefully controlled beam commissioning periods during Dec.'04 – Feb.'05. **Met / exceeded goals each time!**

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 ⇒ 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**

Established for Commissioning: 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**

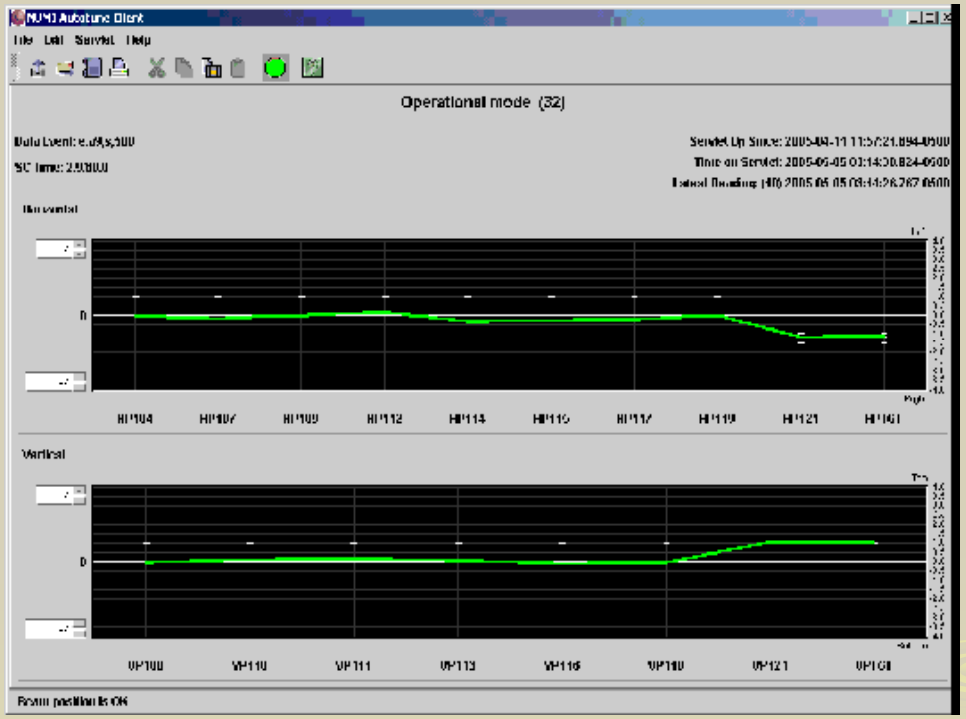
NuMI Beam Permit System

- **Dedicated hardware based on Tevatron fast abort system. Used from 1st beam**
- **Permit to fire NuMI extraction kicker is given prior to each beam pulse, based on good status from a comprehensive set of monitoring inputs**
- **Inputs include Main Injector beam quality prior to extraction, NuMI power supply status, target station and absorber status, beam loss and position for previous pulse**
- NuMI BPS was prototyped initially with MiniBooNE, with excellent results prior to NuMI operation

With the very intense NuMI beam and severe beam loss constraints, perhaps our most important operational tool.

Autotune Primary Beam Position Control

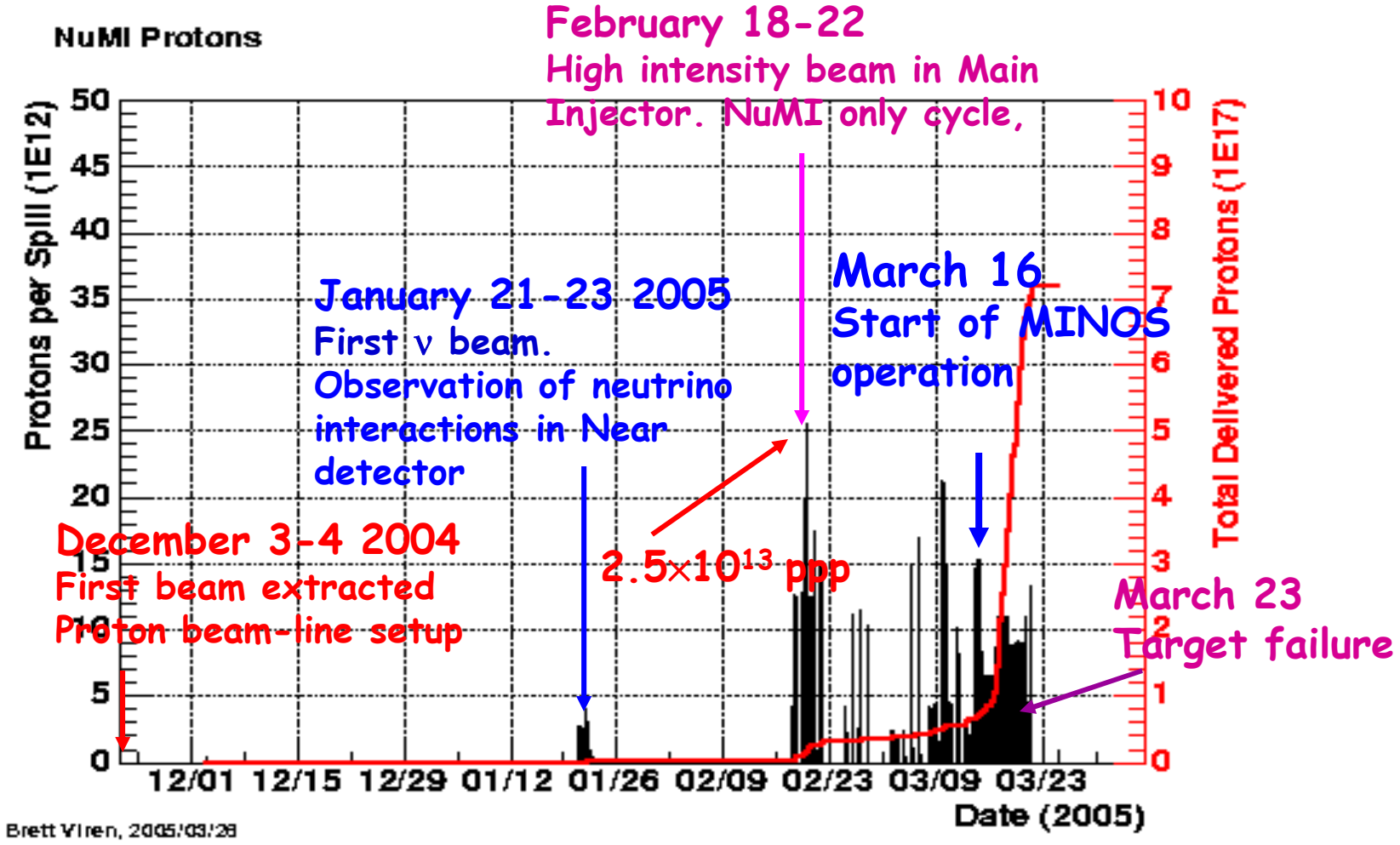
- **Automatic adjustment of correctors using BPM positions to maintain primary transport & targeting positions**
- **Commissioned at initial turn on for correctors**
- **Vernier control for targeting. Initiate tuning when positions 0.125 mm from nominal at target**
- **Very robust. Separate corrector files for mixed mode and NuMI only with automatic file selection**



Autotune Beam Control Monitor

Operations Experience to Date

Beam Commissioning to Start up for Data Taking

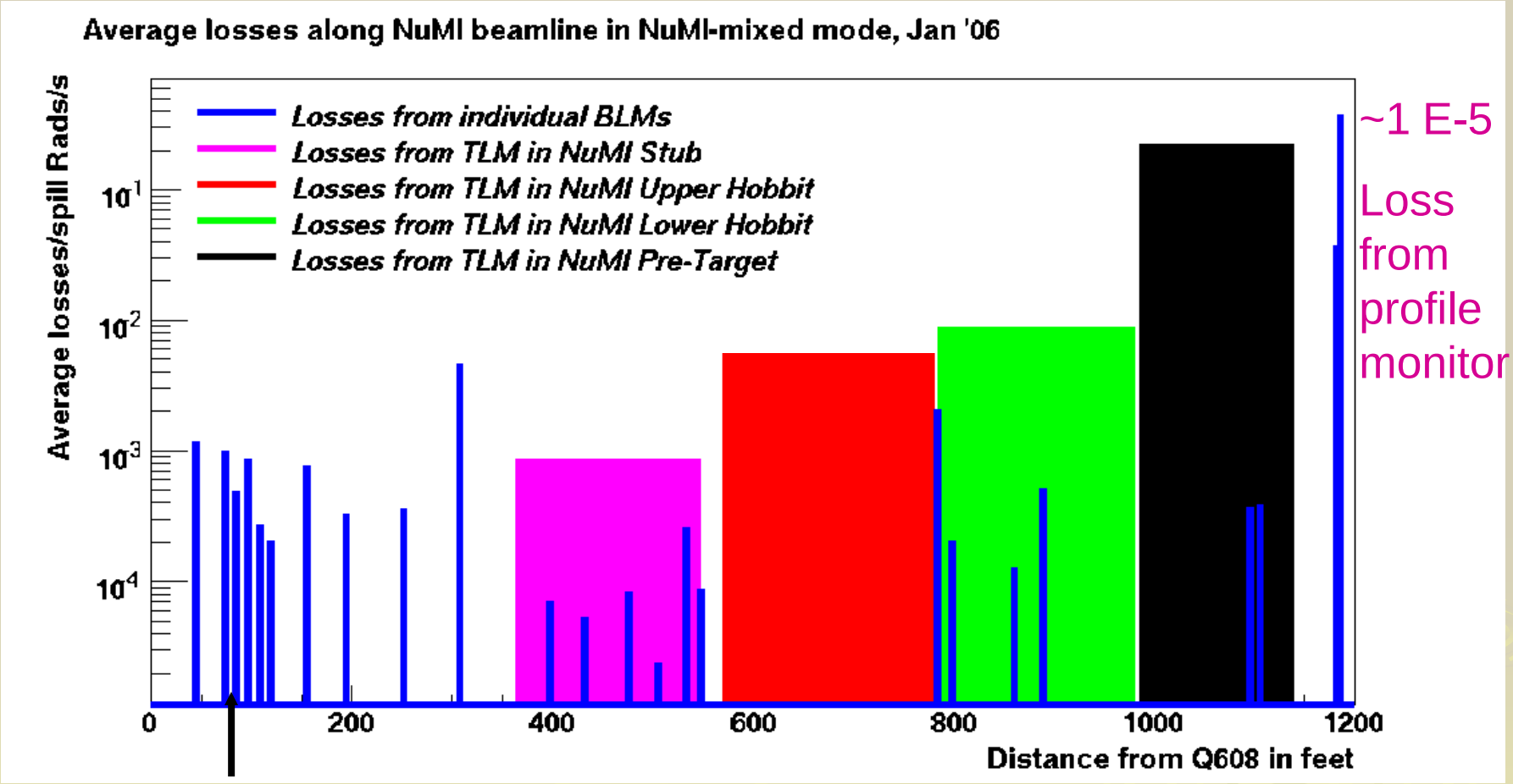


Subsequent Transition to Operations

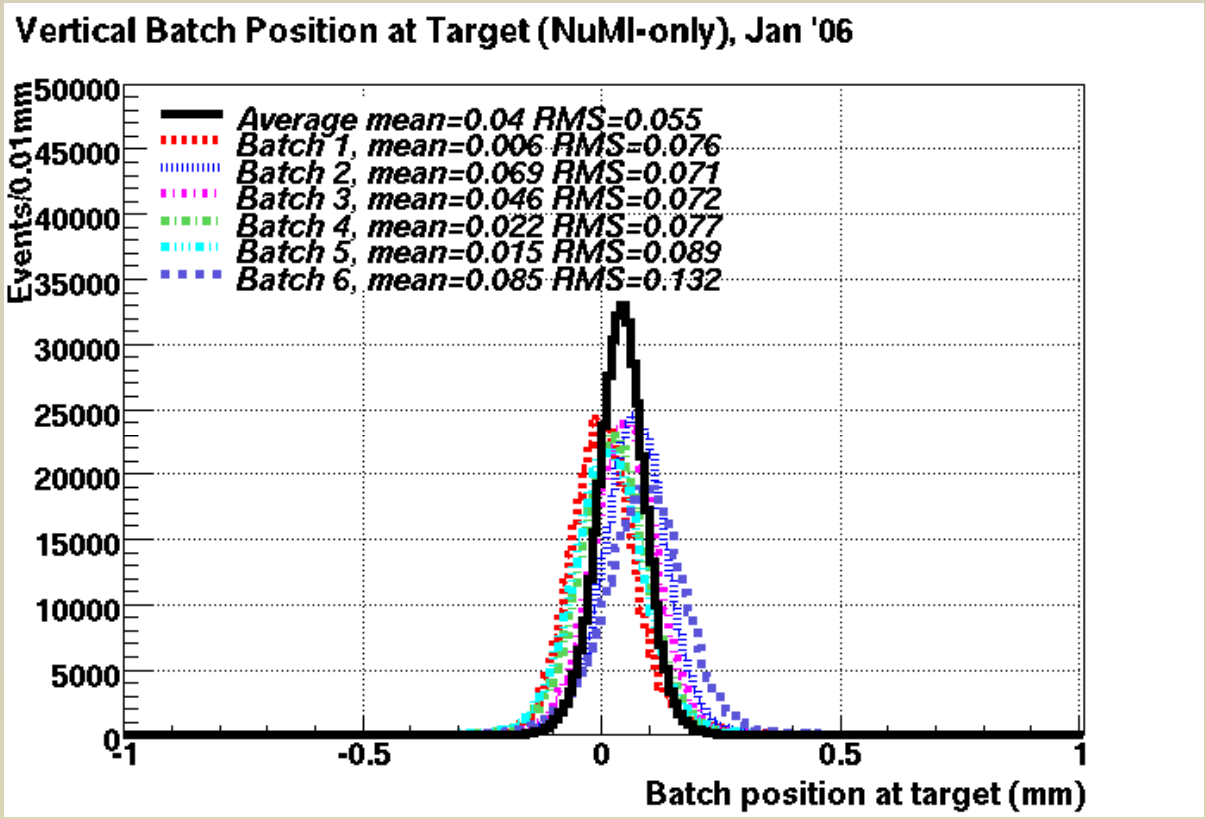
- **VERY** smooth. Restarted after target checkout in late April ’05
  - **Main Control Room Operators take control of running NuMI beam** (12 May ‘05)
  - NuMI operation is “hands free”. No manual beam tuning

Primary Beam Loss – Mixed Mode

Average per Pulse for One Month

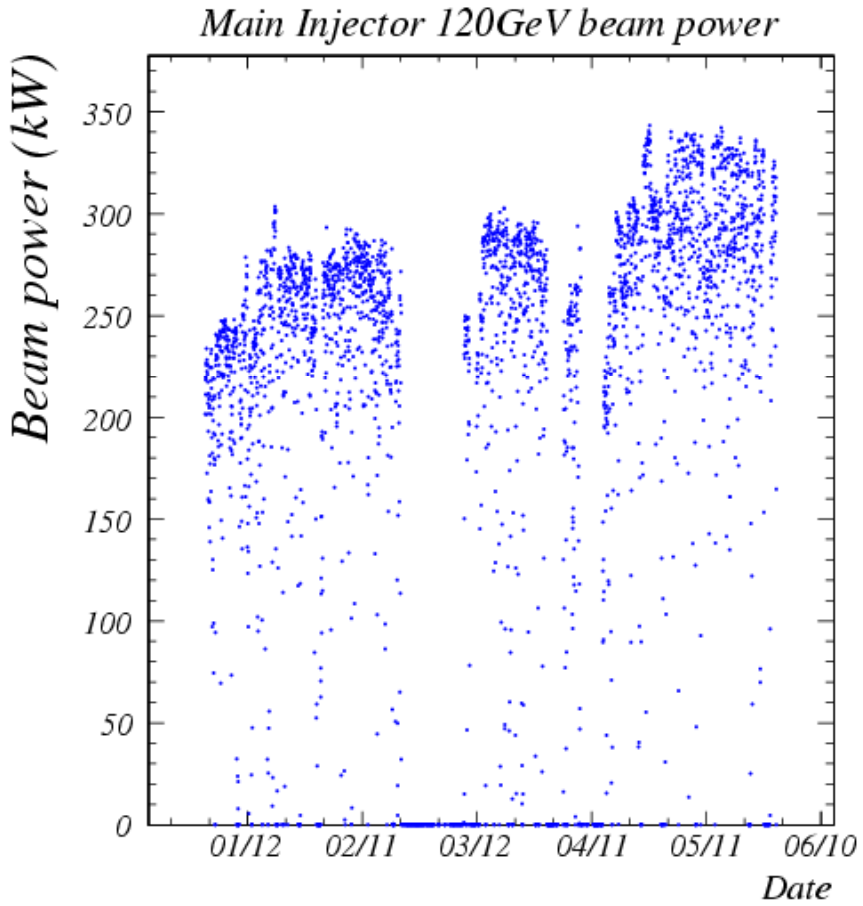


Vertical Beam Stability on Target - NuMI Only Mode 1 Month Data



Note greatly expanded scale (+/- 1mm). RMS variation < 60 μ m for the mean of all batches. Autotune uses batches # 2-4.

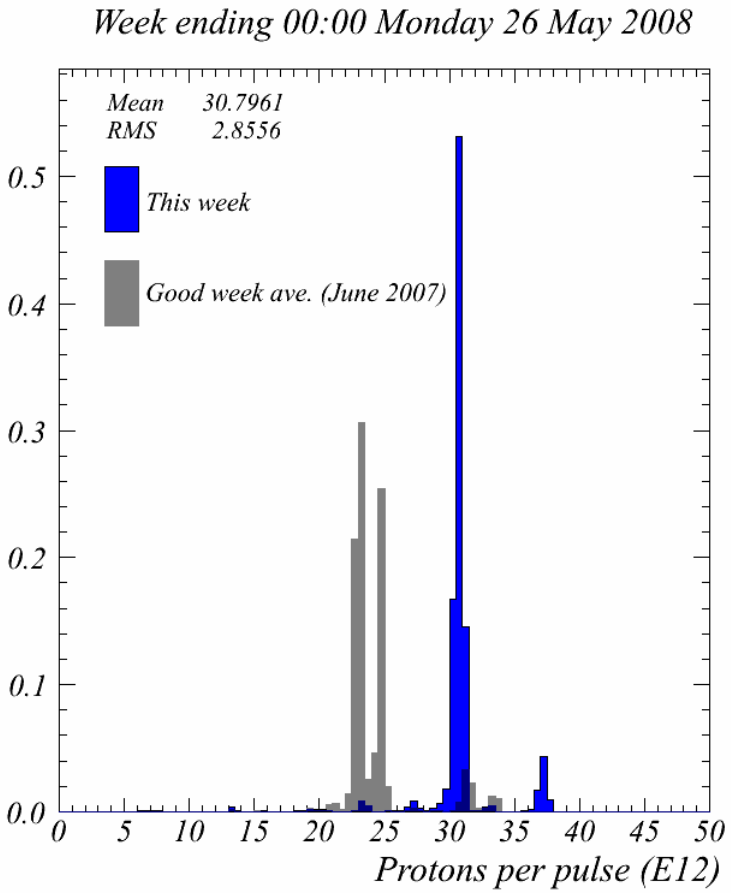
Main Injector Beam Power 2008

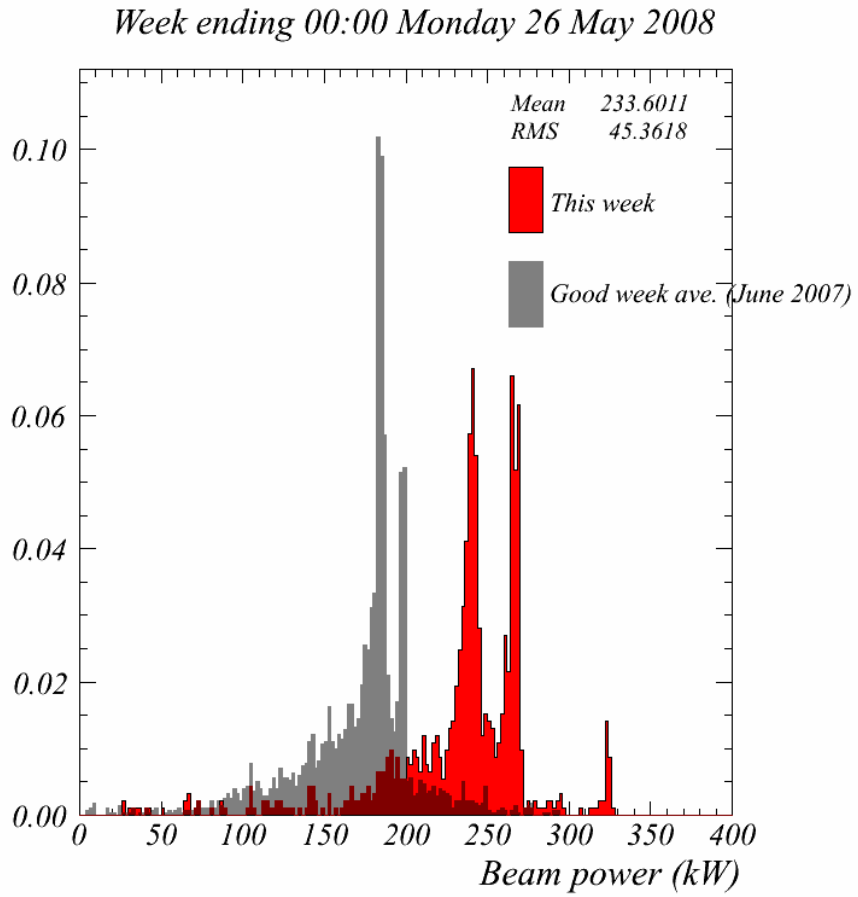


- **Main Injector beam power at 120 GeV since multi-batch slip stacking was implemented in January.**
- **At the end of April all the multi-batch slip stacking optimization and the MI collimation system were commissioned allowing increasing the MI beam power to 340 KW.**
- **The next goal for the MI beam power at 120 GeV is 400 KW.**

Ave. Intensity/Pulse & Beam Power

Compared to 2007 Operation

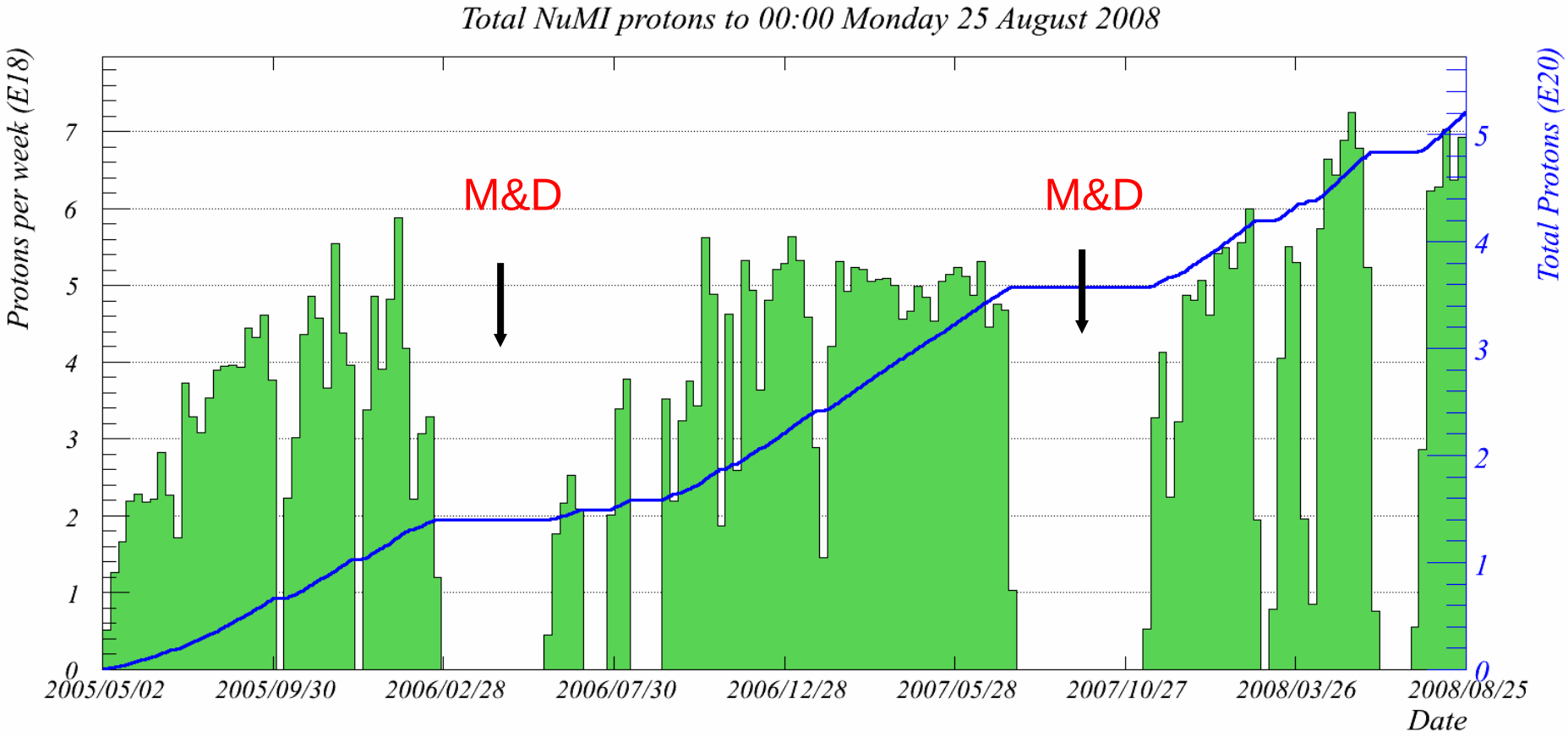




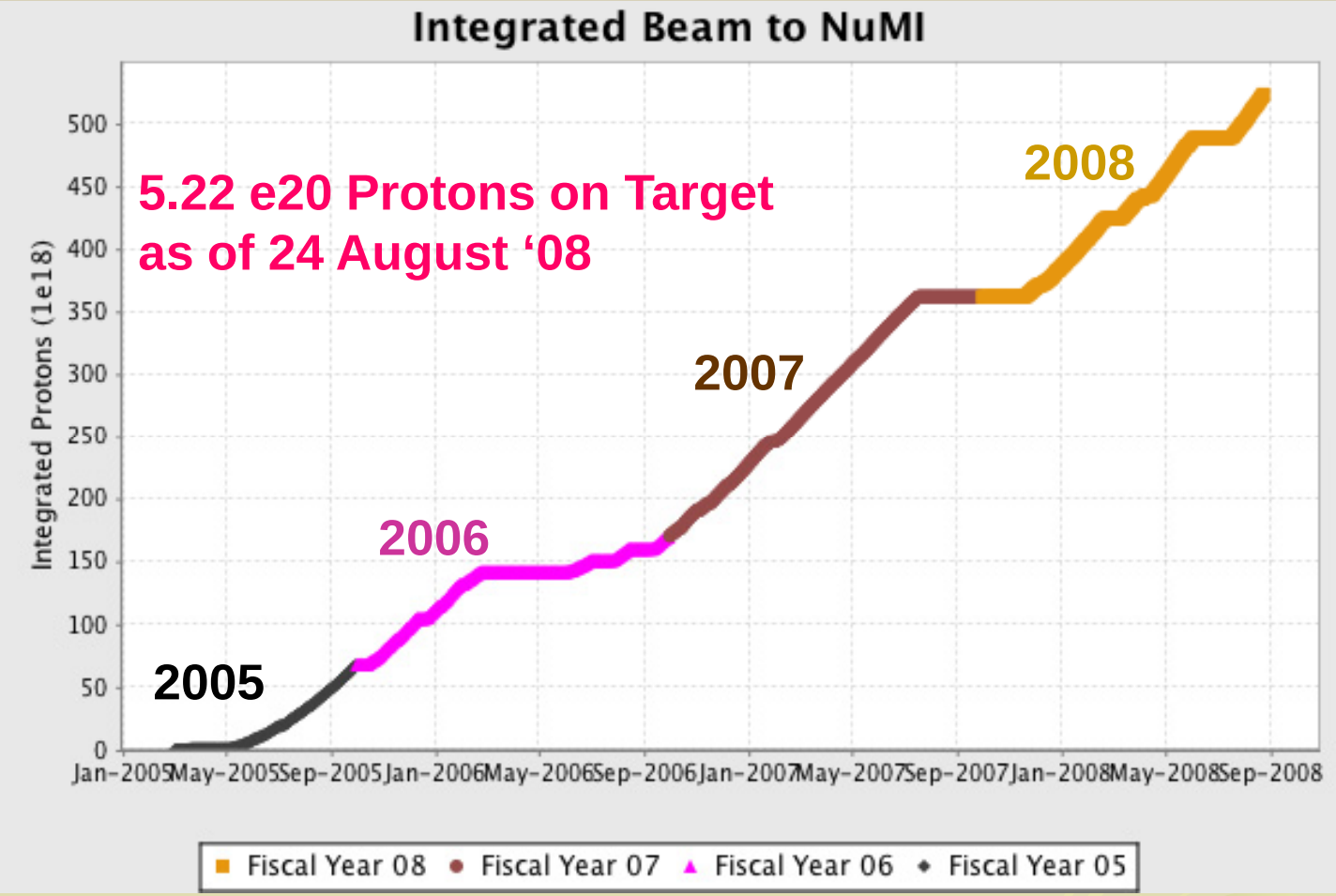
< 3.08 e13 ppp>

< 233.6 kW >

NuMI Protons per Week



NuMI Integrated Protons to Date



Summary

What software / tools / beam instrumentation are the most useful ?

- *The comprehensive beam permit system confirming NuMI readiness for each beam pulse prior to extraction. Commissioning included some tuning of acceptable limits, but our best prior estimates were ready at the beginning.*
- *Real time participation of all system experts in the beam commissioning. We scheduled 12 hour shifts on successive days (if needed) instead of 24 hour around the clock efforts. Invariably, this leads to much more efficient beam commissioning.*
- *Robust beam instrumentation performance from the beginning, especially with beam loss monitors (easy) and beam position monitors (more challenging).*
- *Autotune beam control system, ready at 1st efforts with corrector turn on.*

Another Key for Very Efficient & Successful Commissioning

- Comprehensive pre-beam commissioning. We then expected things to work and almost everything did from the start

Beam Operations Challenges

- A significant number of target hall interventions required. Challenging target and focusing horn systems due to high beam power, activation & corrosion effects
- Getting more (and more) beam power
  - Essential for neutrino oscillation experiments
- Overall performance for primary beam to date has been excellent! Primary beam availability ~ 98-99 %
  - Two magnet change-outs required in 1st three years