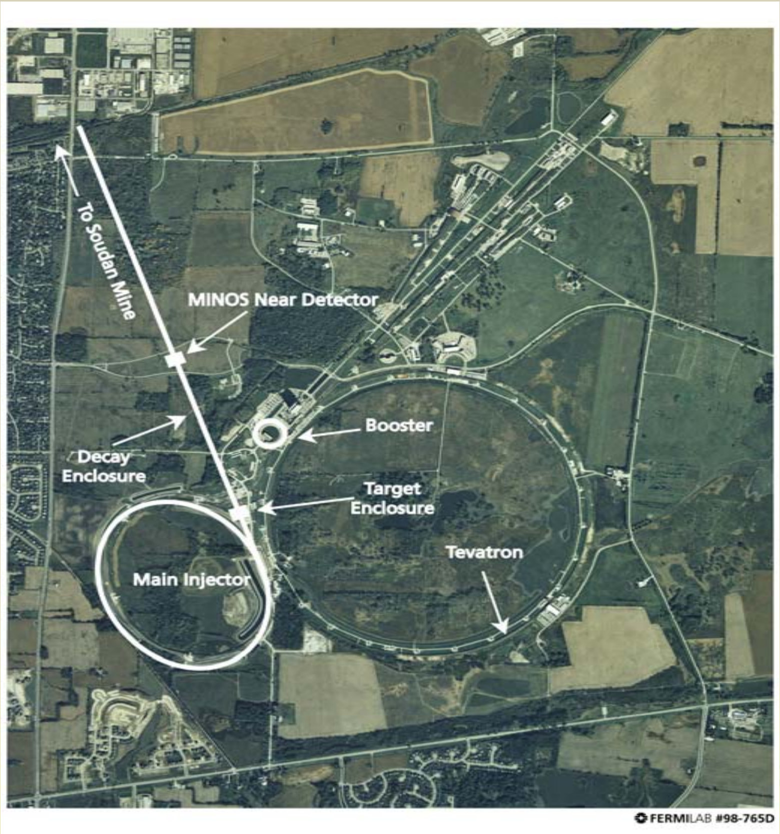
The NuMI Beam System: Commissioning & Initial Operation

Sam Childress, Fermilab



Fermilab to Soudan, Minnesota

Outline of This Talk

- NuMI / MINOS Overview
- Tunnel Construction
- NuMI Beam System Layout & Installation
- Commissioning & Initial Operation
- Problems & Solutions
- Progression to Higher Beam Power
- Near Term Projections

NuMI: ν's at the Main Injector (Focus of this talk)
MINOS: Main Injector Neutrino Oscillation Search

A neutrino beam from Fermilab to northern Minnesota

- 120 GeV protons from the Main Injector (400 kWatts)
- Production of a high power neutrino beam
- On-axis over 735 km to Soudan mine (MINOS experiment)
- 15 mrad off-axis over 810 km (future NOνA experiment)

A large near hall at ~ 1 km from the target

- MINOS near detector (980 Tons)
- MINERνA – future

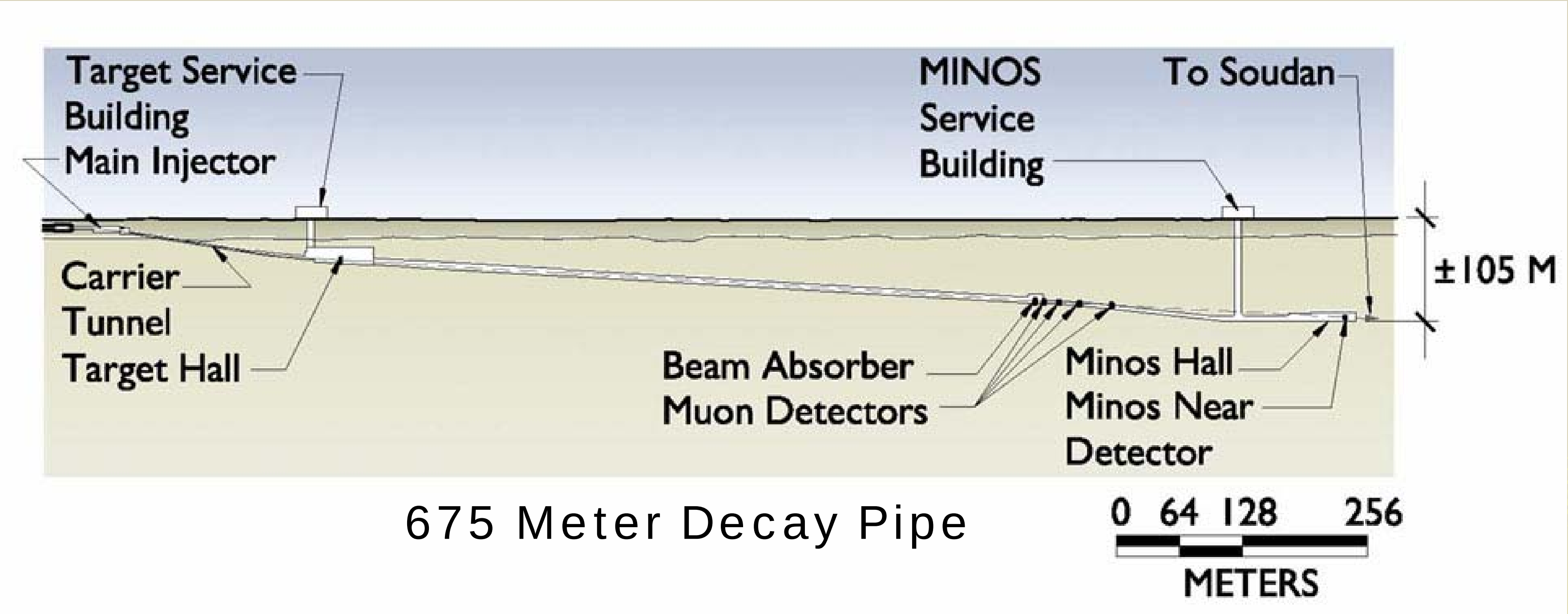
A deep underground hall at Soudan, Minnesota

- MINOS far detector (5400 Tons)

NuMI Construction Project

- Initiated in late 1998
- Main Injector extraction enclosure for NuMI was built earlier as part of Main Injector construction
  - Considerable gain for NuMI construction, as most could then be done during Main Injector Operation
  - A final tie-in during scheduled accelerator shutdown time
- Facility construction completed in Fall 2003
- NuMI technical component installation from 2003 to early 2005
  - Extraction & primary beam components in Main Injector interlock area installed during scheduled machine shutdown times in 2003 & 2004.

Elevation View of the NuMI/MINOS Project



Excavation of NuMI Tunnels by both Drill & Blast and Tunnel Boring

The TBM is assembled in Target Hall

Lowering pieces of Decay Pipe into shaft

Left: First piece of the decay pipe. Anchor section visible on lower end of pipe.

Right: Standard length of decay pipe being lowered.

Decay Pipe Installation

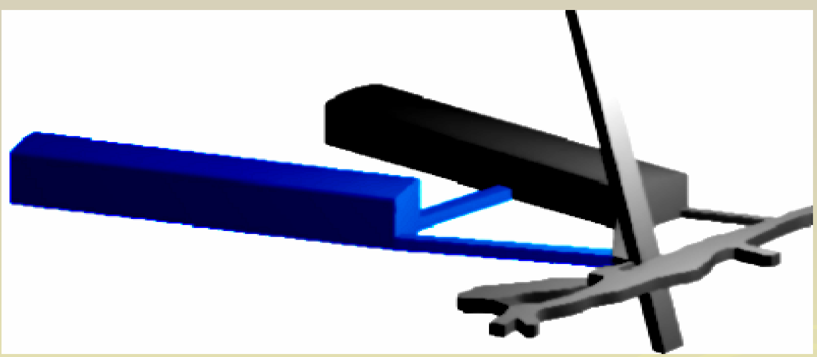
Visual Evidence of a straight Decay Pipe – Light at end of 675 meters of Pipe

Completion of Buildings, Shafts

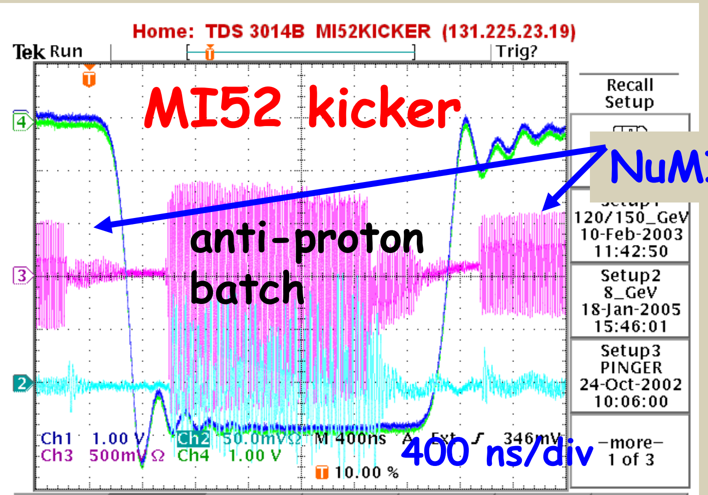
Soudan Underground Laboratory

Hall, Far Detector & Near Detector part of MINOS

- Operated by U. of Minn. and Minnesota Dept. of Natural Resources
- Soudan Mine - tourist attraction during summer months
- 1 elevator shaft limits loads to 1m x 2m x 9m

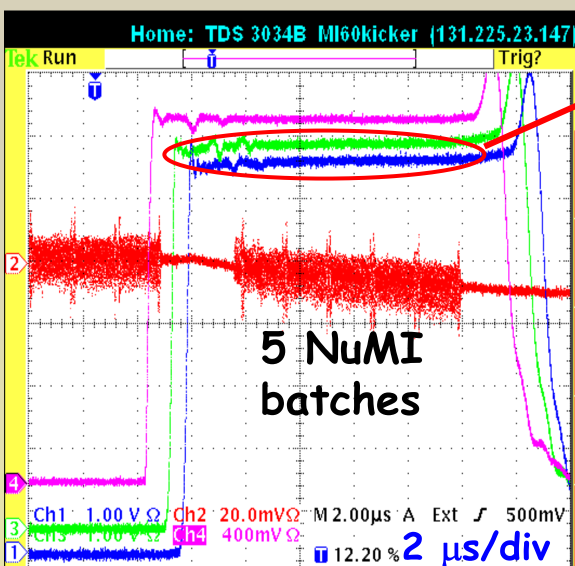


Extraction from the Main Injector



NuMI batches

NuMI kickers

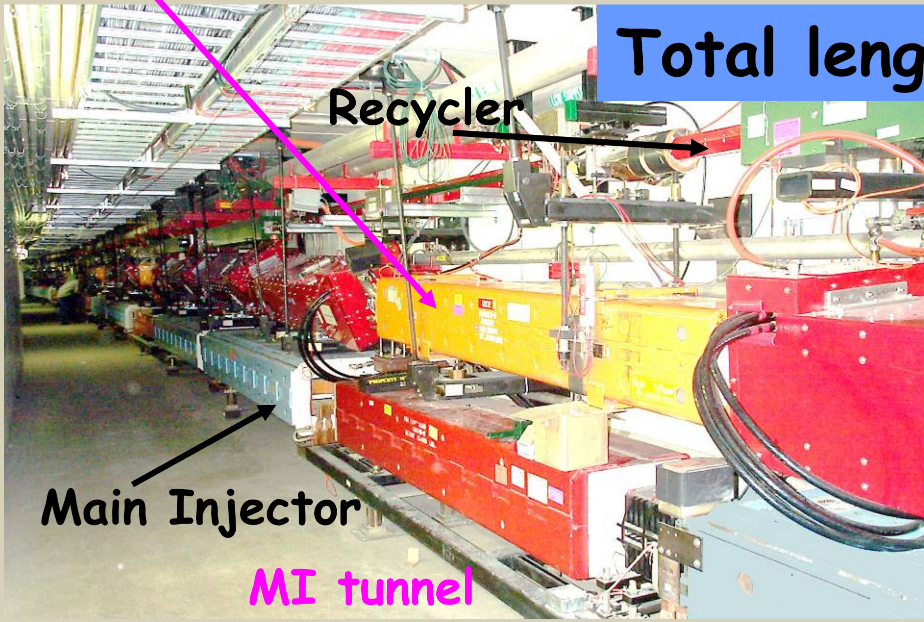


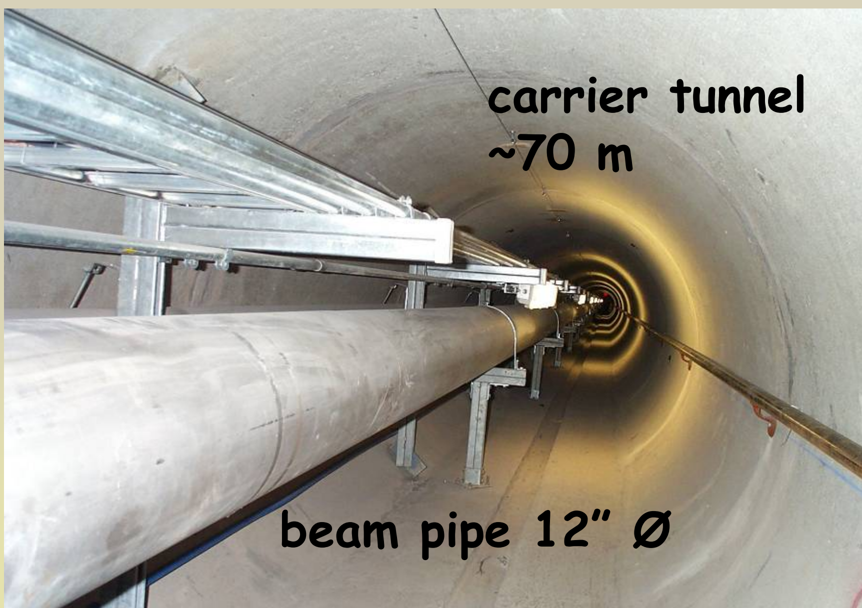
NuMI kickers flat region

flat within ±0.8 % over 10 μs

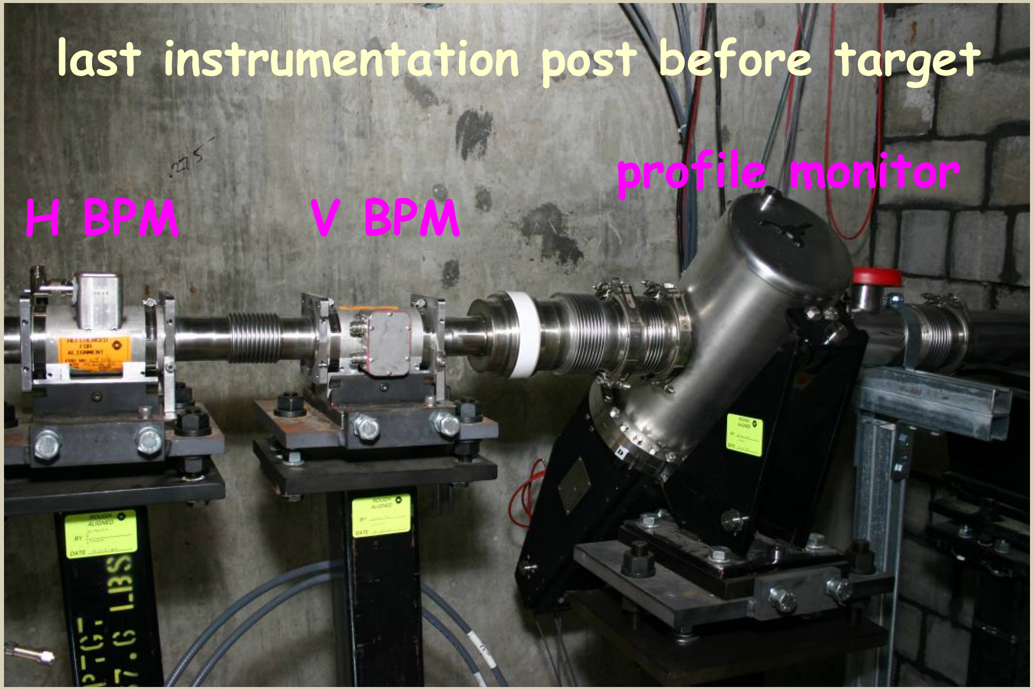
Primary Proton Line

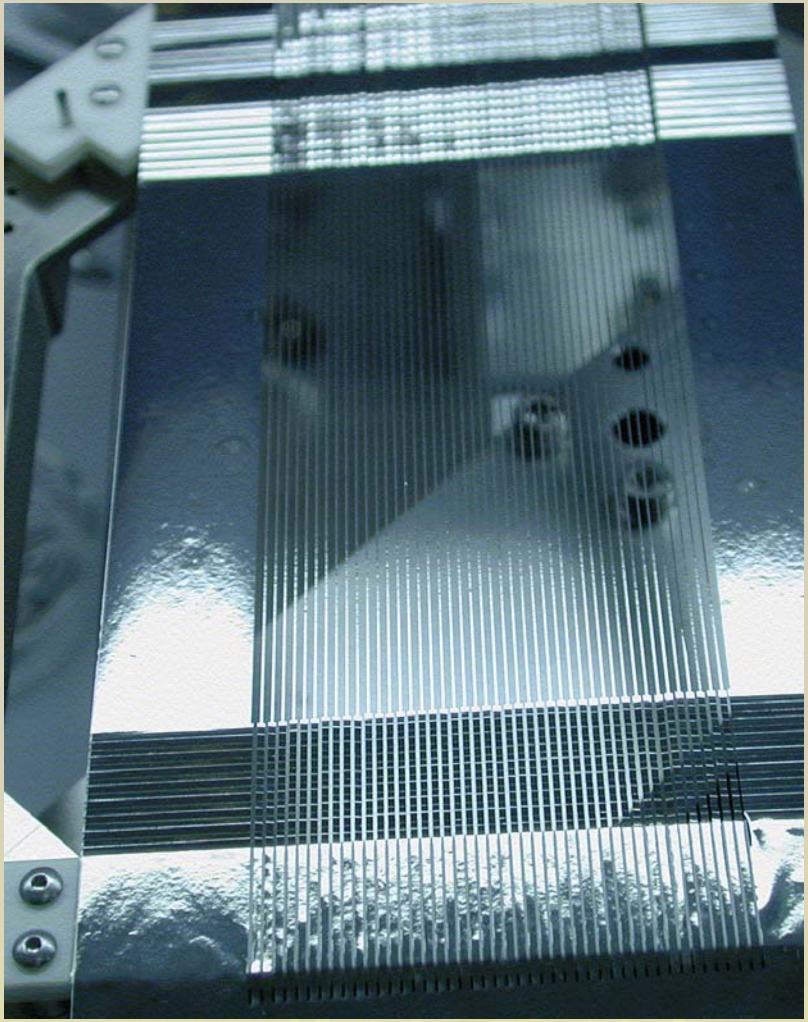
Total length ~ 350 m





Primary Beam-line Instrumentation

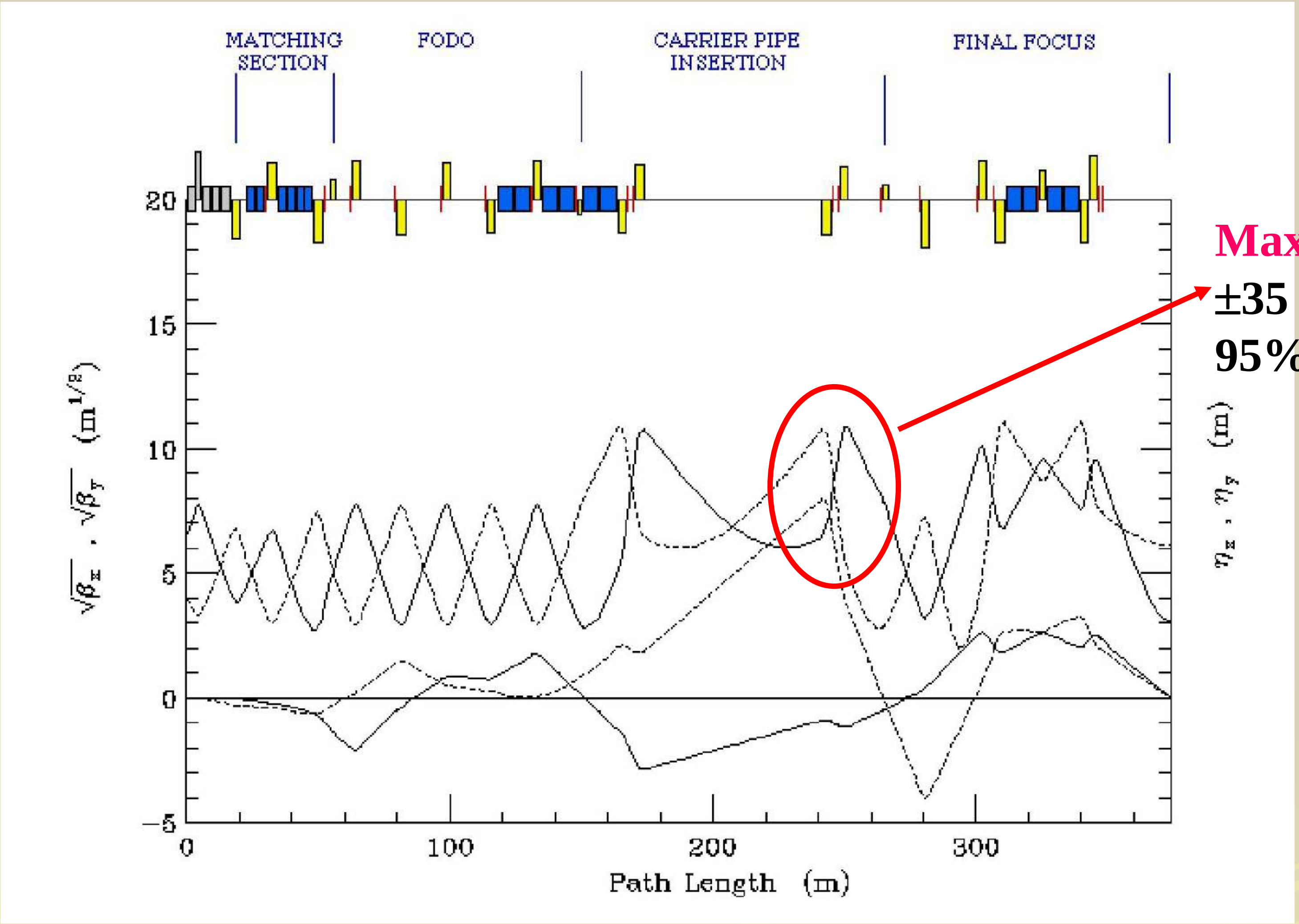




- 2 beam toroids
- 24 beam position monitors
- 54 loss monitors
- 10 thin-foil profile monitors (SEM) developed at U. Texas
    - **5 micron Titanium foils**

Profile monitor
(0.5,1.0 mm pitch)

Primary Beam Optics



Max. dispersion point

±35 mm aperture

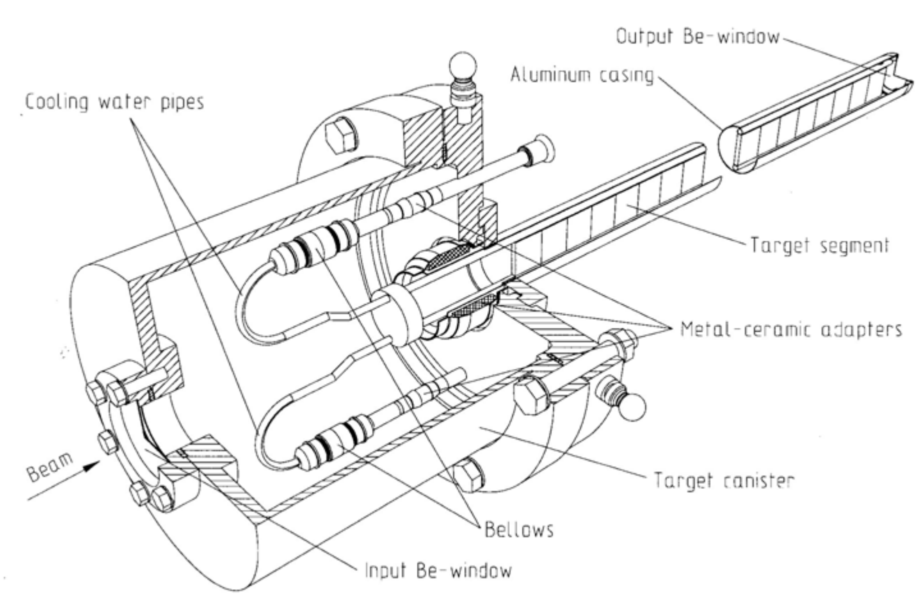
95% beam size ±7 mm

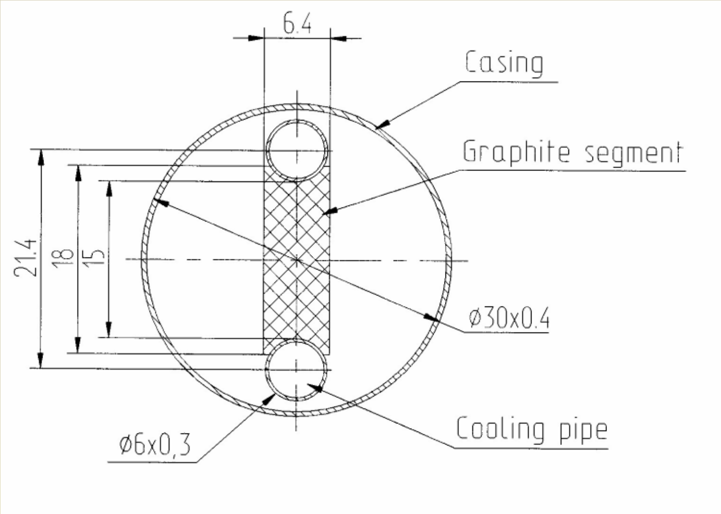
Specifications: fractional beam losses below 10^{-5}

(Groundwater protection, residual activation)

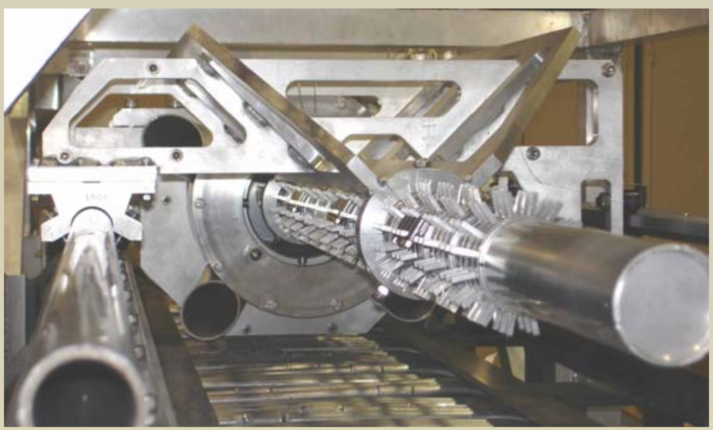
Graphite Target

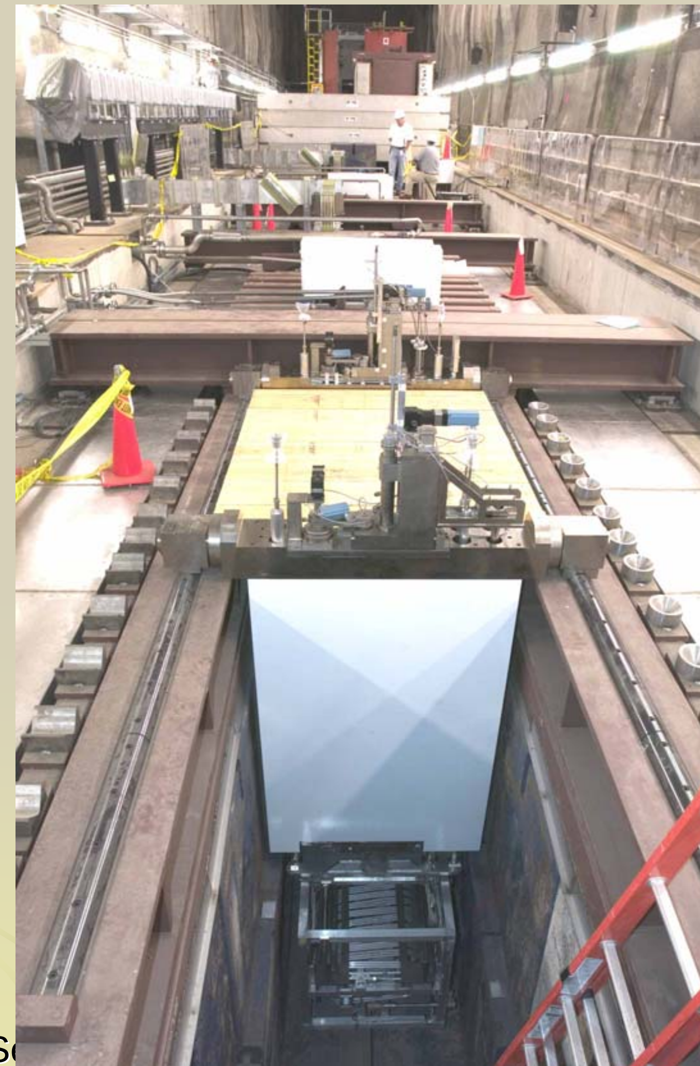
- 47 segments of graphite of 20 mm length and 6.4×15 mm^2 cross section
- 0.3 mm spacing between segments, for a total target length of 95.4 cm





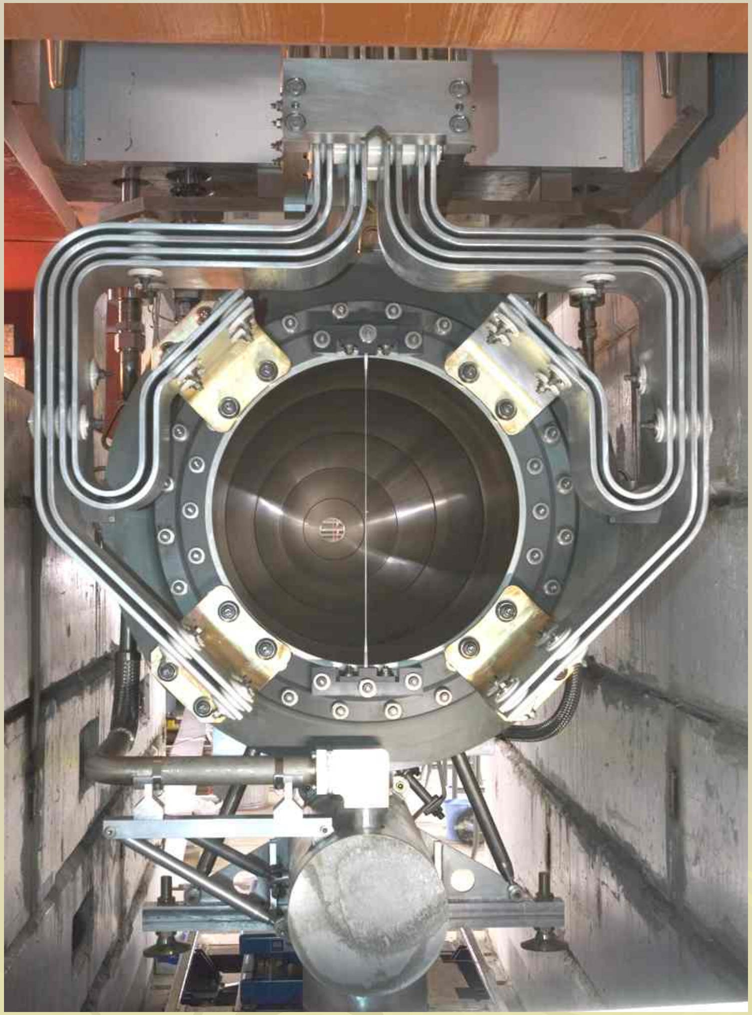
Target, Carrier & Insertion Point in Shield





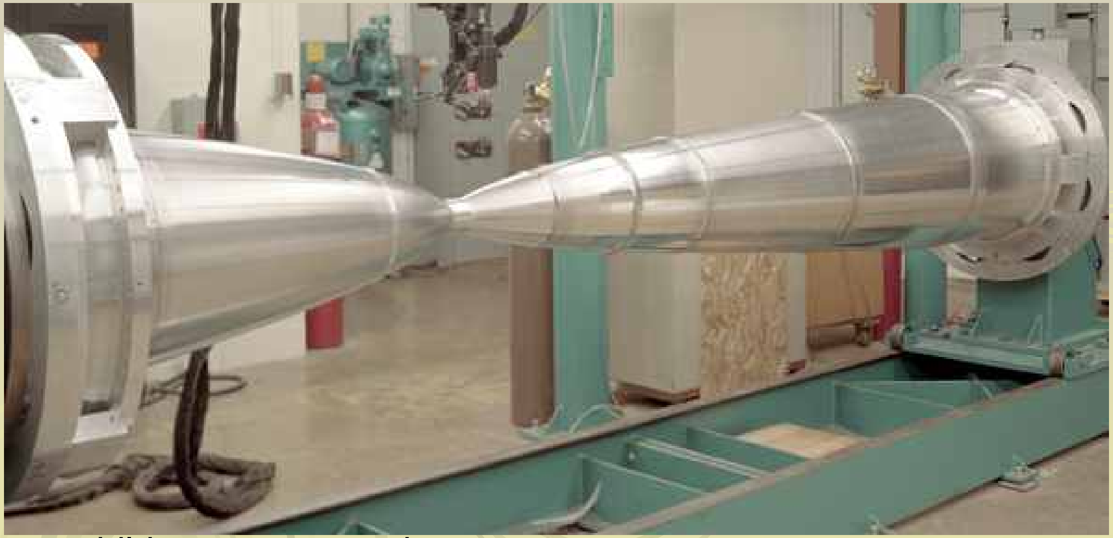
Horn System – 2 horns

(shown in work cell, hanging from support module)

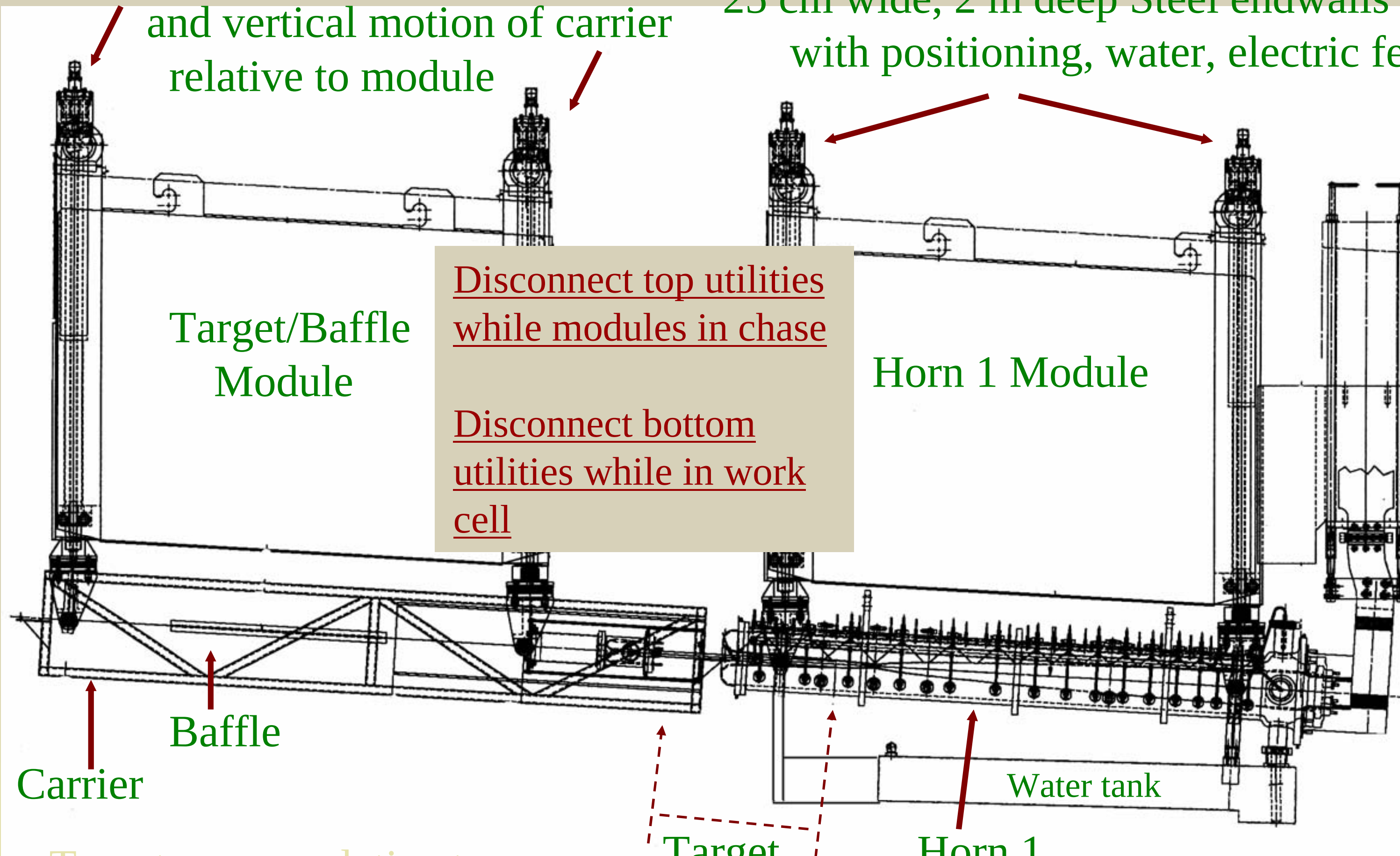


Horn Inner Conductors

Parabolic inner conductors:
3 Tesla max. magnetic field
3 m active length each horn



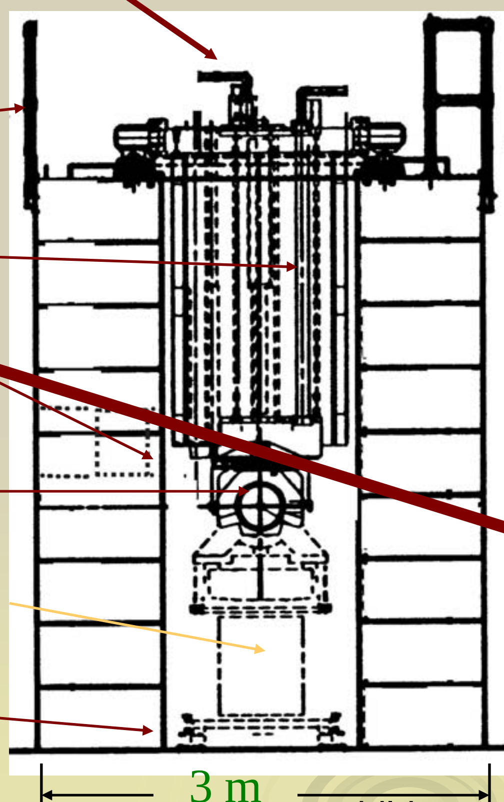
Target and Horn Module Mounting



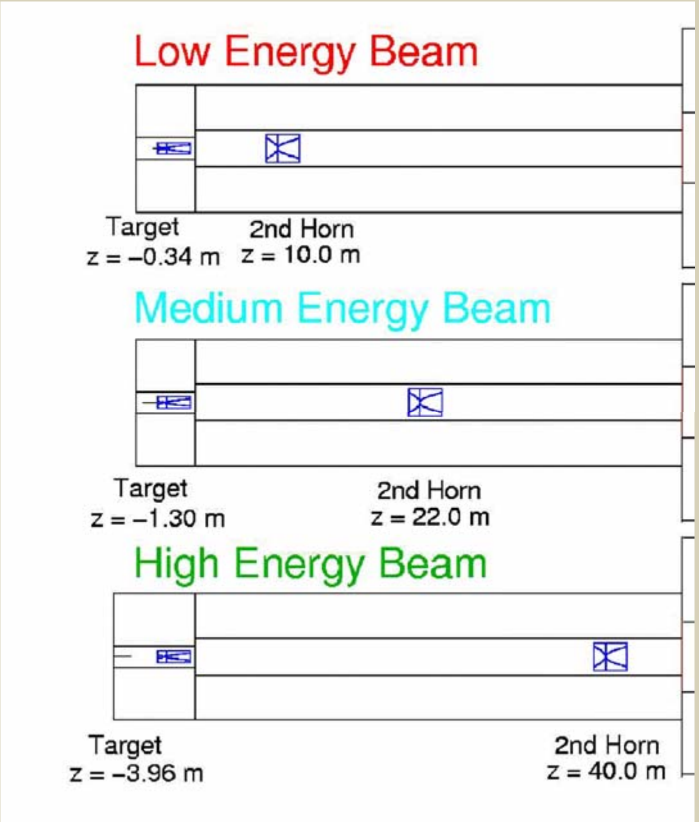
Work Cell

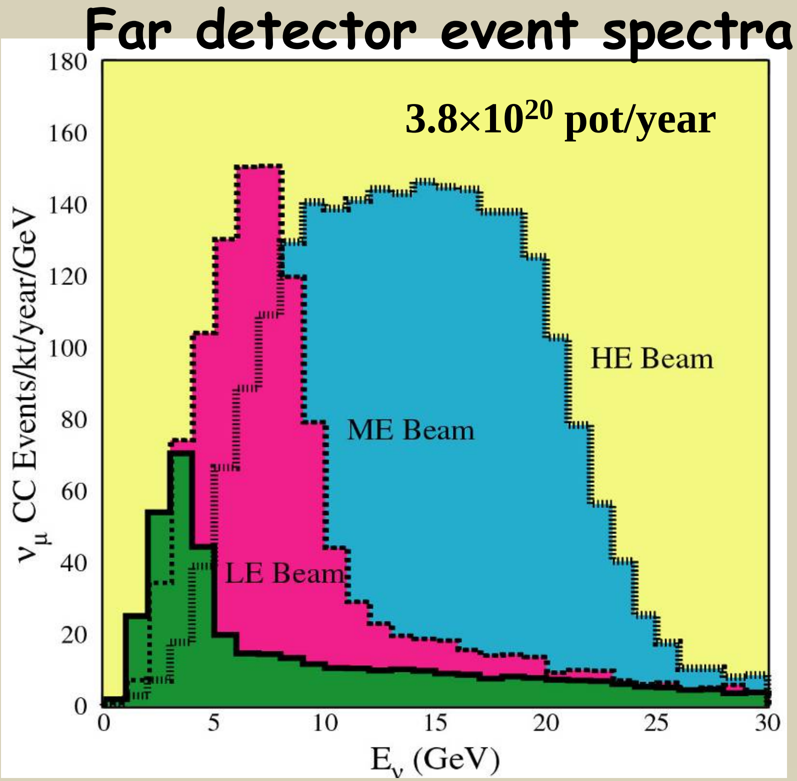
Mount/Dismount Components

Horn connections are all done through the module by person on top of work cell



A Flexible Target and Horn System





- Fully optimized spectra for each energy are obtained by moving the target and the 2nd horn. Target motion is remote – operational method of choice
- in LE configuration, 2/3 of the target length is positioned inside the 1st horn
- With a parabolic shaped horn inner conductor, the horn behaves like a lens (p_t kick proportional to the distance from the axis), with a focal length proportional to the momentum

Hadron Absorber Assembly

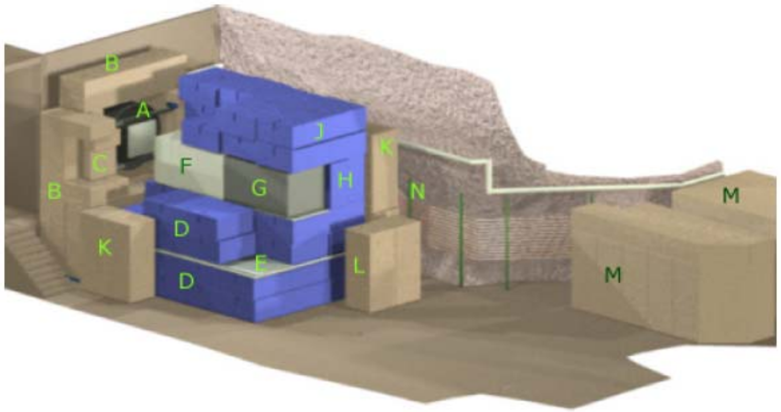


Fig. 4.4-08 : Cutaway isometric diagram of the Hadron Absorber, above, and a plan view, below. The letters label the same items in both diagrams. See text for description.

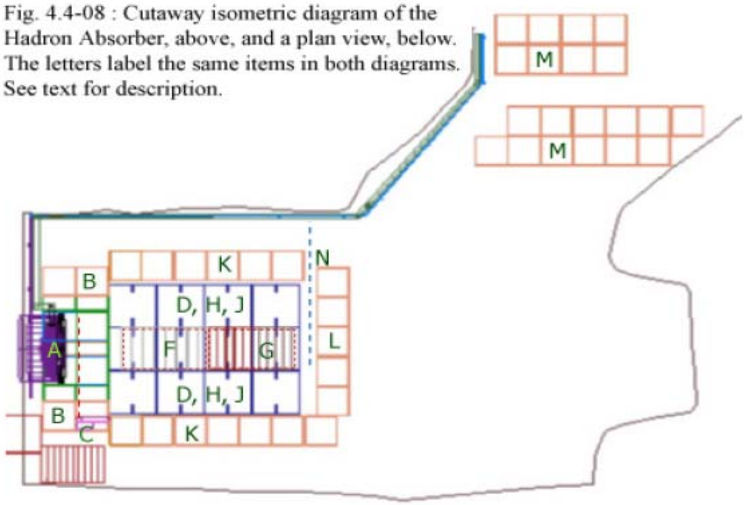
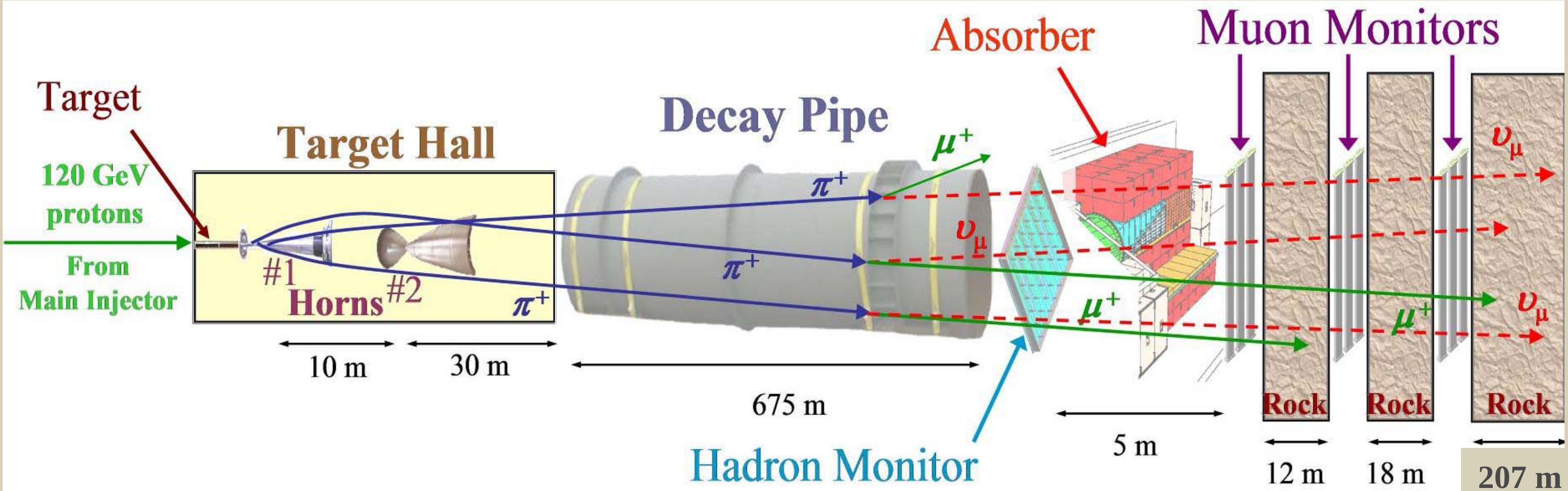


Figure 4.4-10 : Completed concrete block shielding around the downstream end of the Decay Pipe. The yellow beam is the temporary crane used during installation.

NuMI ν Beam and Monitoring Instrumentation



❖ water cooled graphite target, 2 interaction lengths, which provides interaction of ~ 90% of the primary protons

❖ target readily movable in beam direction

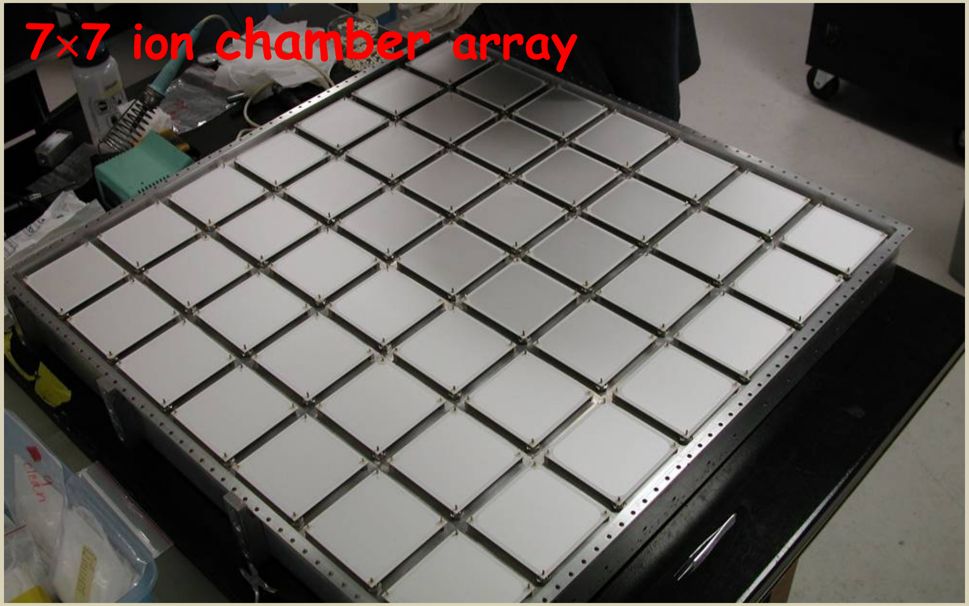
❖ flexible configuration of 2 parabolic horns, water cooled, pulsed with a 2 ms half-sine wave pulse of up to 200 kA

❖ 675 m long decay pipe with a radius of 1 m, evacuated to 1 Torr

❖ 1 hadron monitor and 3 muon monitor stations

Secondary Hadron and Muon Instrumentation

Hadron Monitor
Max flux ~ 10^9 part./cm^2/spill

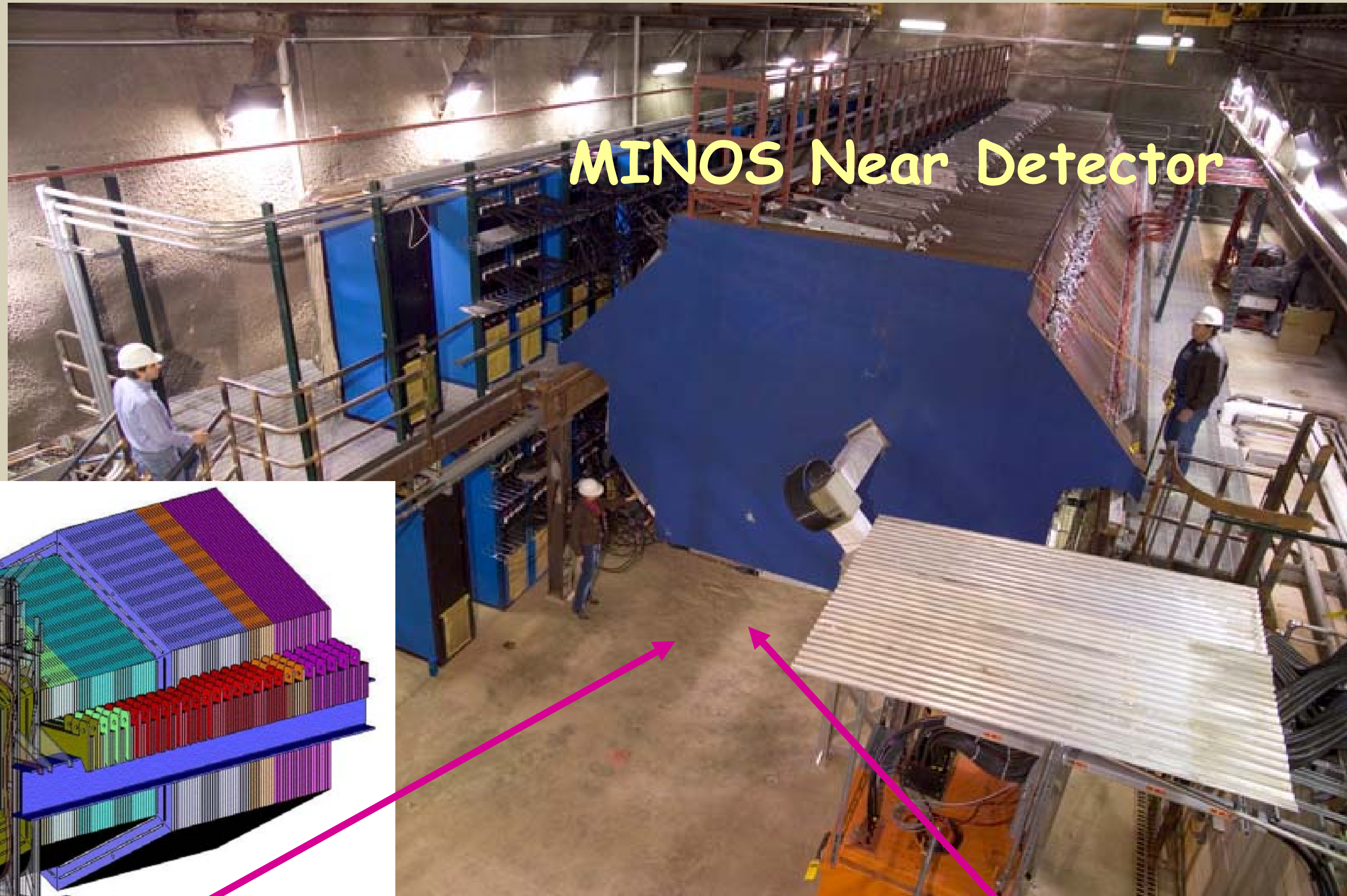


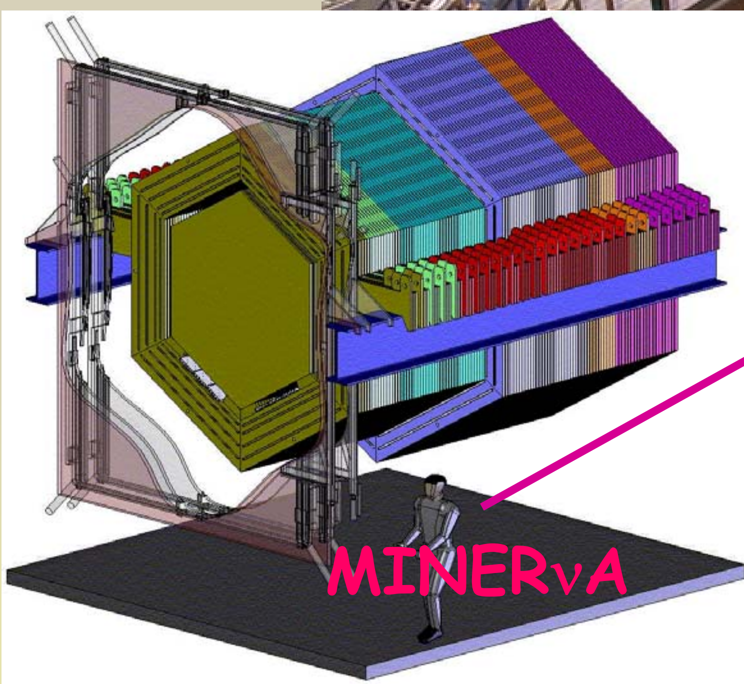
3 Muon Stations in excavated alcoves
Max. flux ~ 3×10^7 part./cm^2/spill

- **4”×4” parallel plate ion chambers made from ceramic wafers with Ag-Pt electrodes**
- **Hadron monitor 1 mm, Muon monitor 3 mm gap**
- **gas: He**

Near Hall and Detectors

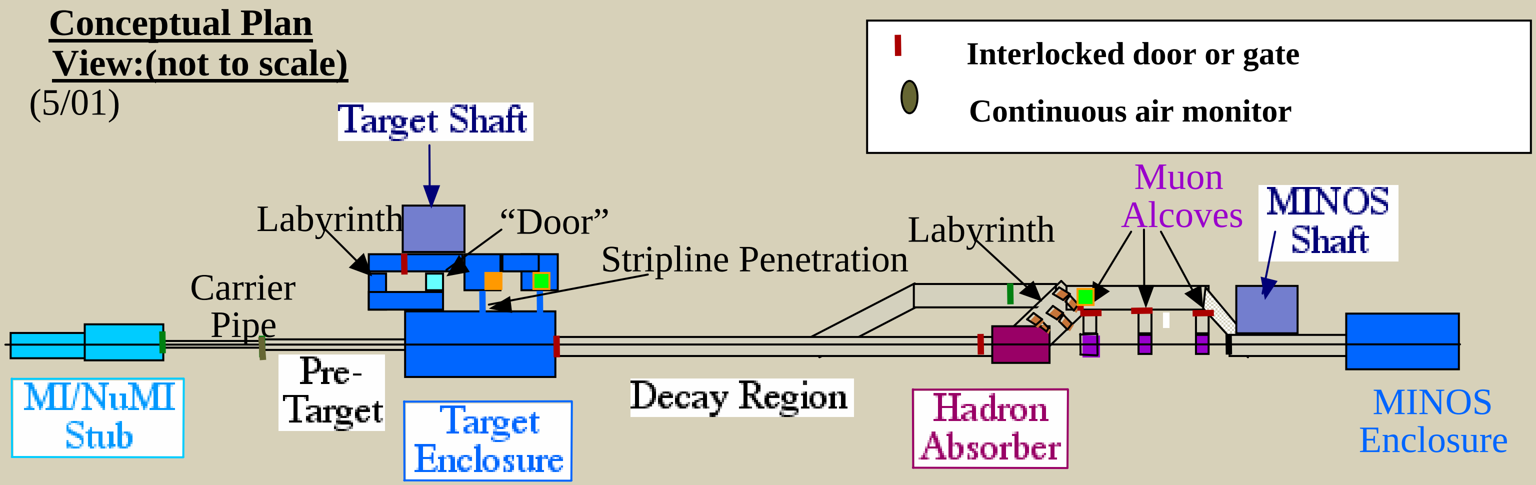
Surface:
46×9 m^2

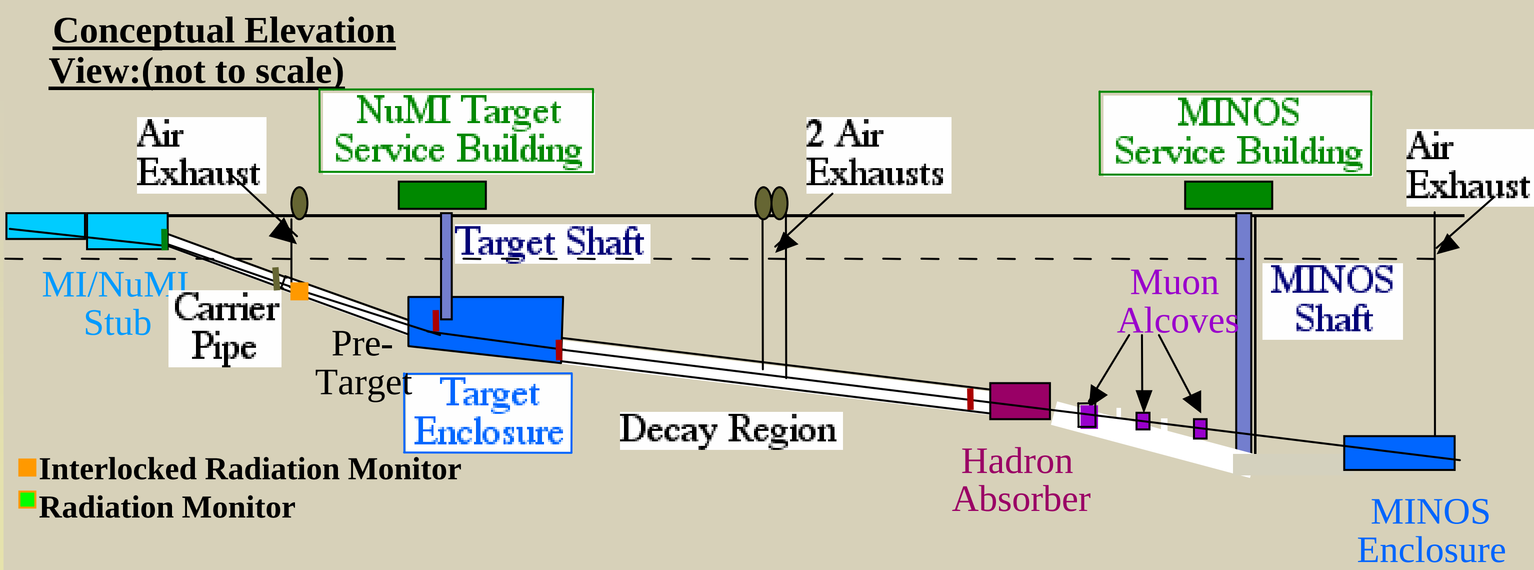




Small scale exposure of OPERA bricks in the MINOS Near Hall (Peanut)

Radiation Safety Overview Schematic





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NuMI Alignment

Align the center of ν beam to the Far Detector in the Soudan mine. Goal is within 12 m.

Fermilab to Soudan surface done using GPS

- determined vector to 1cm horiz., 6 cm vertical

Soudan surface to 27th level

- 0.7 m per coordinate

Fermilab surface to underground

- gyrotheodolite with 0.015 mrad precision

Primary beam component network to 0.25 mm

Transverse alignment of baffle, target and horn at 0.5 mm

NuMI Beam Permit System

coordinated by R. Ducar

- Dedicated hardware based on Tevatron fast abort system
- Permit to fire NuMI extraction kicker is given prior to each beam pulse, based on good status from a comprehensive set of monitoring inputs
    - ~ 250 inputs to NuMI BPS
- 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 with MiniBooNE, with excellent results
- Very similar in function to LHC,CNGS beam interlock system

With the very intense NuMI beam, perhaps our most important operational tool.

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 shielding from EPB 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

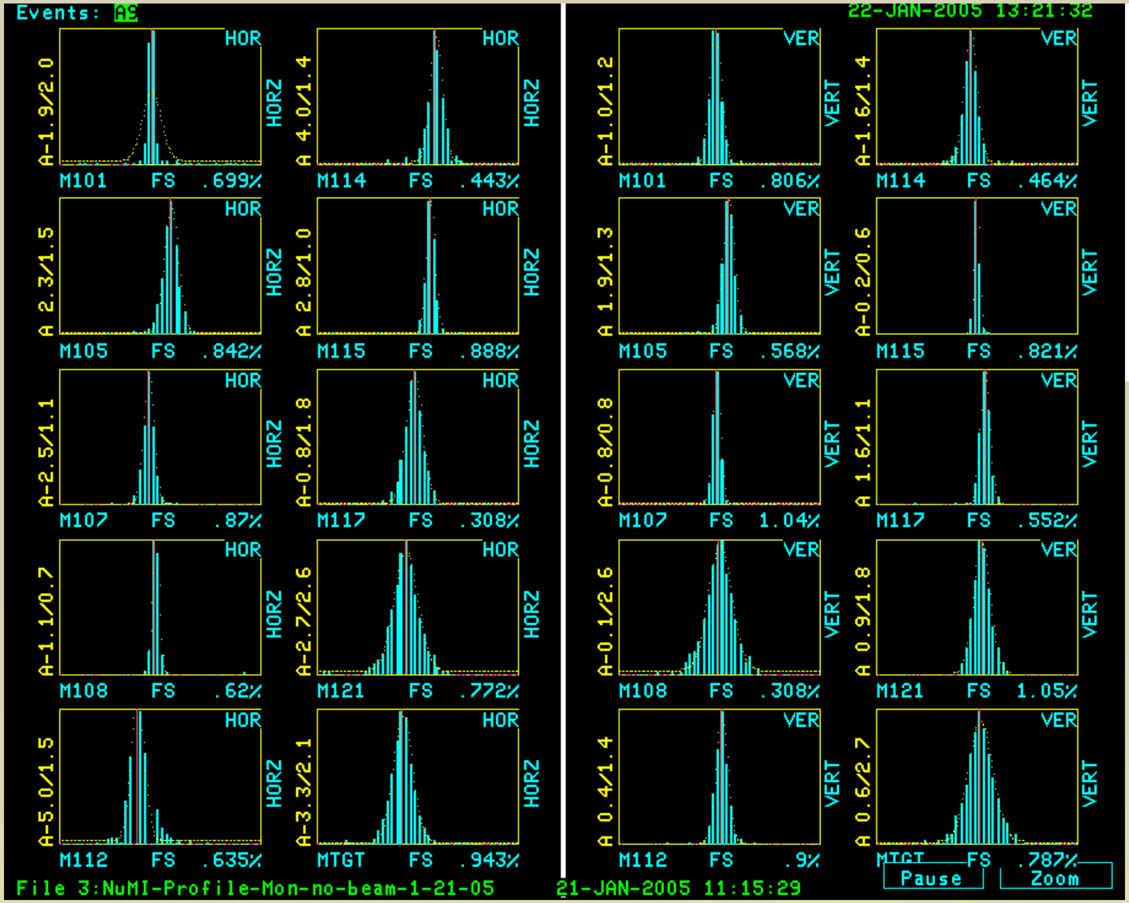
- Project plan was for beam commissioning during accelerator startup (late Nov.) from Fall ’04 shutdown period .
  - Understand at early stage any fundamental issues with extraction and primary transport requiring Main Injector / Recycler tunnel access to address.
  - More than half of NuMI primary transport 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!**
  - **MANY** thanks to Malika Meddahi, CERN - AB/ATB for helping with NuMI commissioning

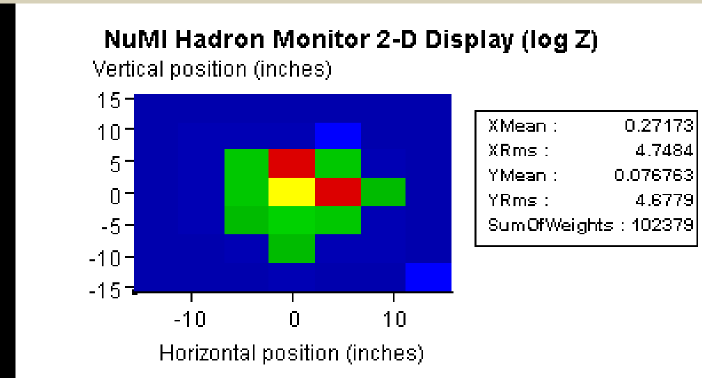
NuMI Initial Beam Commissioning

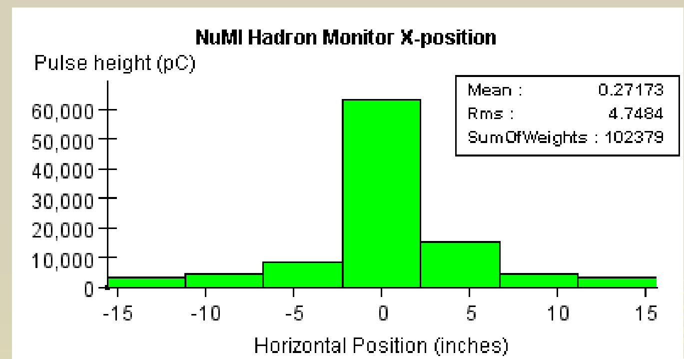
- **December 3-4 2004. Commissioning the primary proton beam**
  - **target out, horns OFF**
  - **small number of low intensity (1 batch with 3×10^{11} protons) pulses carefully planned**
  - **beam extracted out of Main Injector on the 1st pulse**
  - **beam centered on the Hadron Absorber, 725 m away 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**

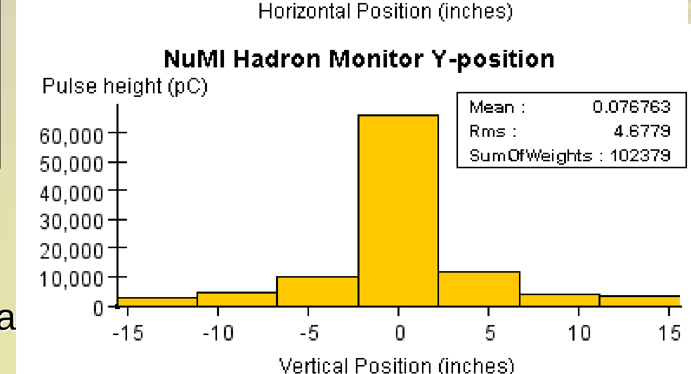
Beam Extraction in 10 Pulses achieved to hadron absorber at 1 km distance

December 3-4, 2004





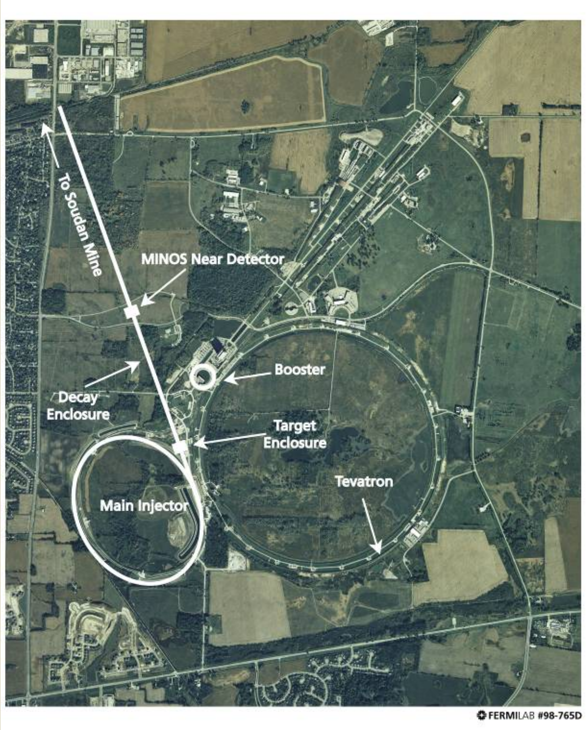




Profile monitor output along the beamline (few pulses later)
(from the extraction up to the target - ~ 400 m distance)

Champagne in Main Control Room is always nice …

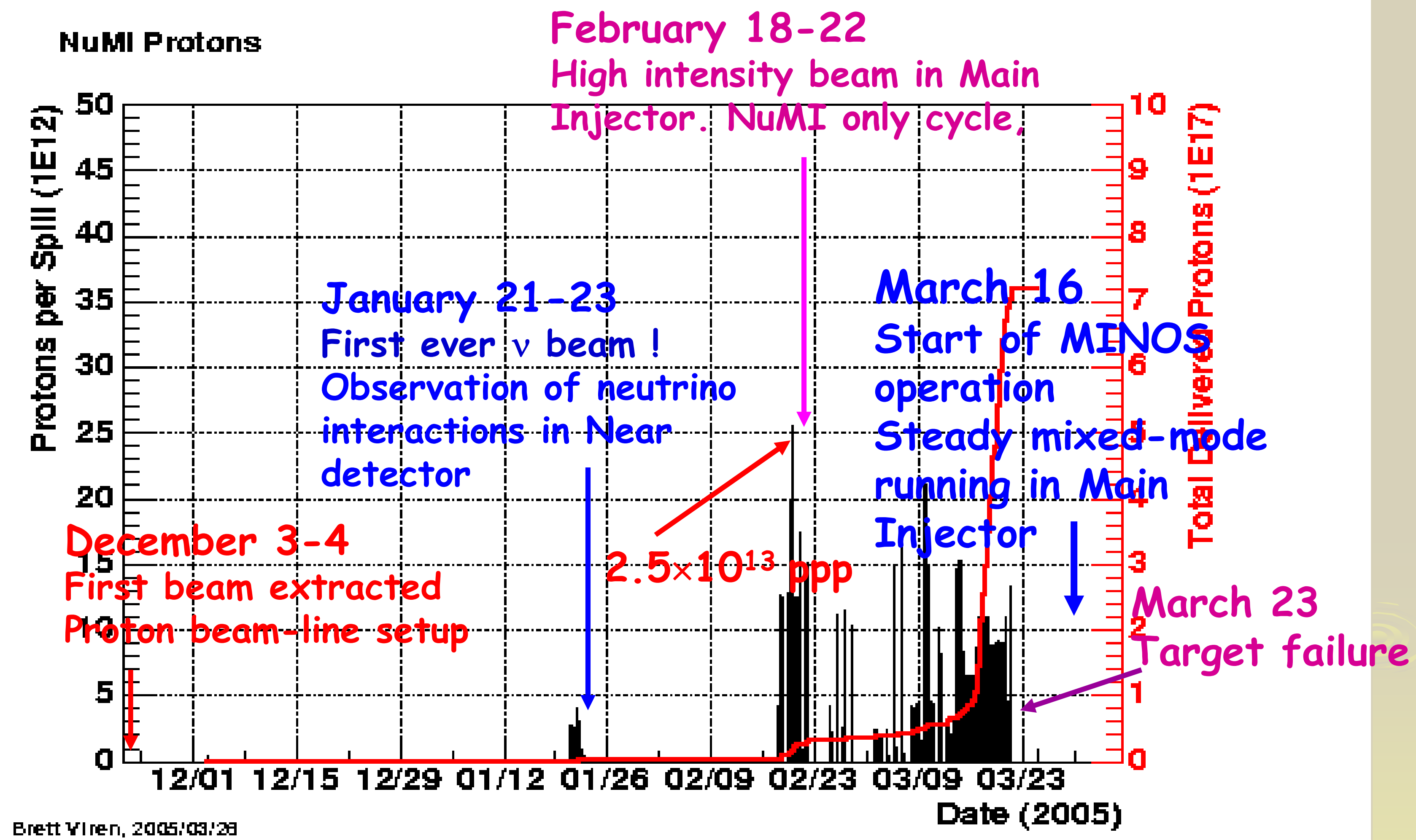
Main Injector & NuMI



- **Main Injector is a rapid cycling (up to 204 GeV/c/s) 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 has to satisfy simultaneously the needs of the Collider program (anti-proton stacking and transfers to the Tevatron) and NuMI**
- **total beam intensity ~ 3×10^{13} ppp, cycle length 2 s**

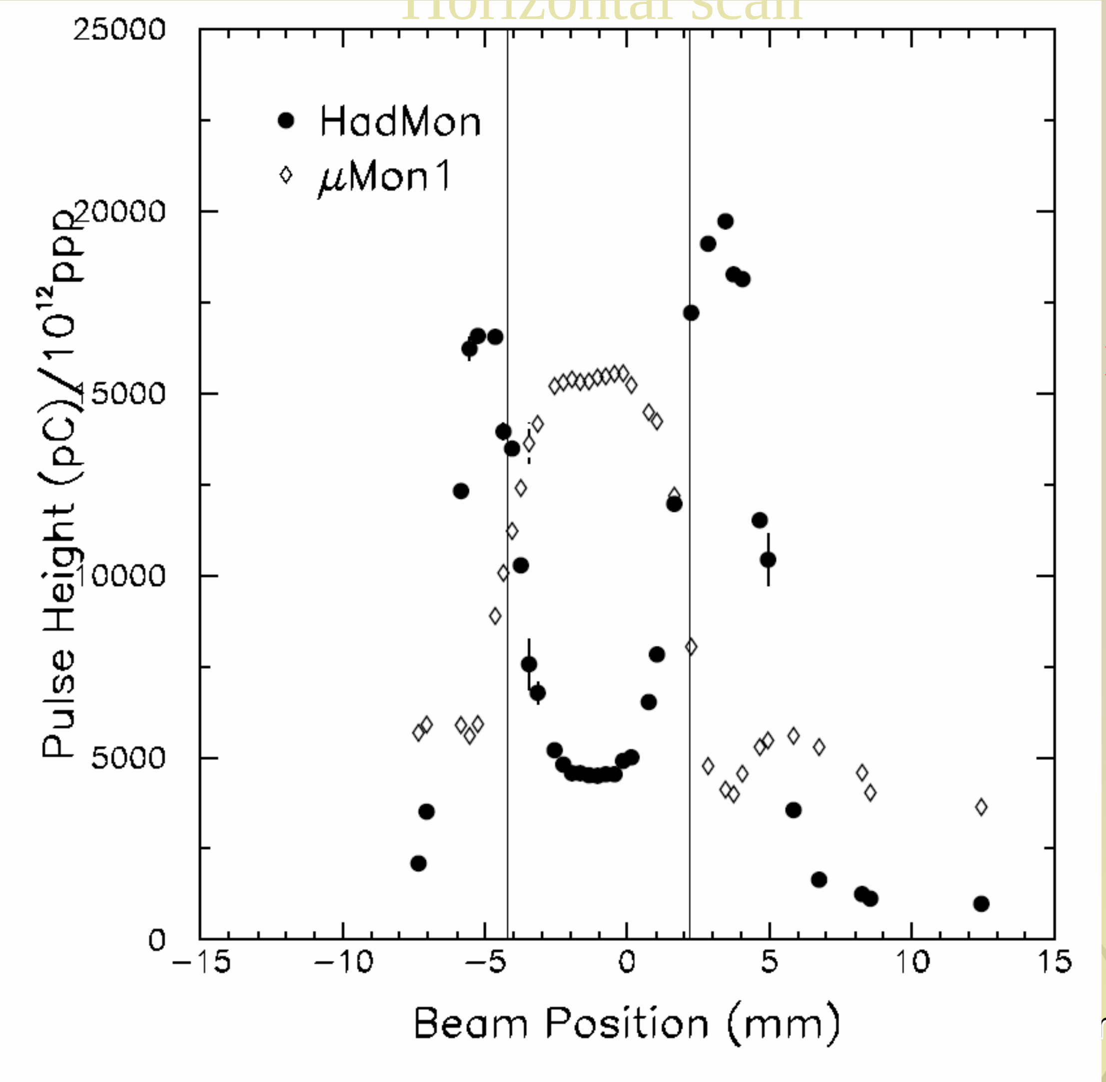
- **Mixed mode: NuMI & anti-proton stacking**
  - two single turn extractions within ~ 1 ms:
    - 1 batch to the anti-proton target, following the firing of the MI52 kicker
    - 5 batches to NuMI, following the firing of the NuMI kickers, in ~ 8 μs
  - the batch extracted to the anti-proton target comes from
    - either a single Booster batch
    - **or 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

Beam Start up for Data Taking

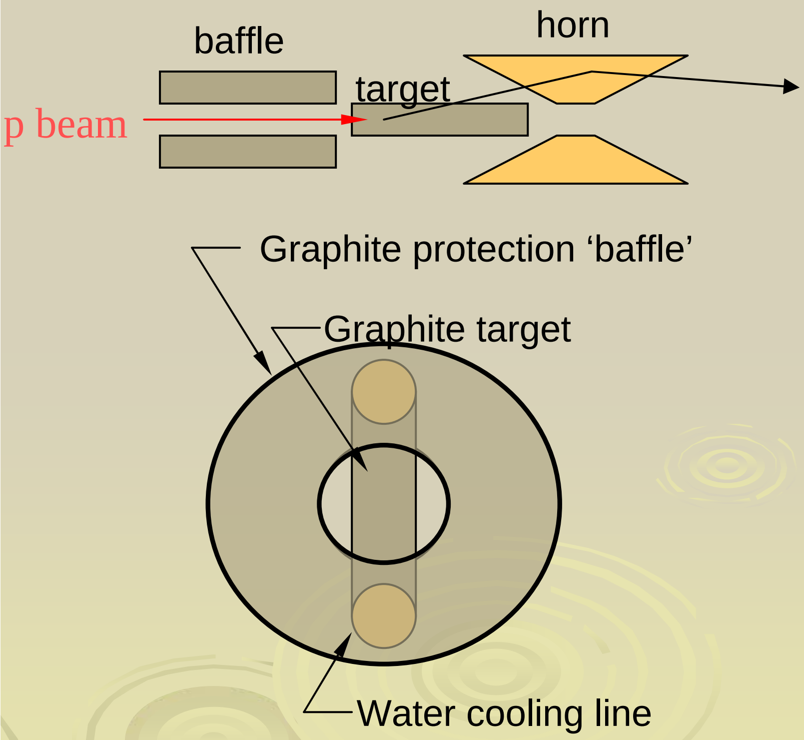


Beam Scans - with Target Hadron and Muon Monitors

Horizontal scan

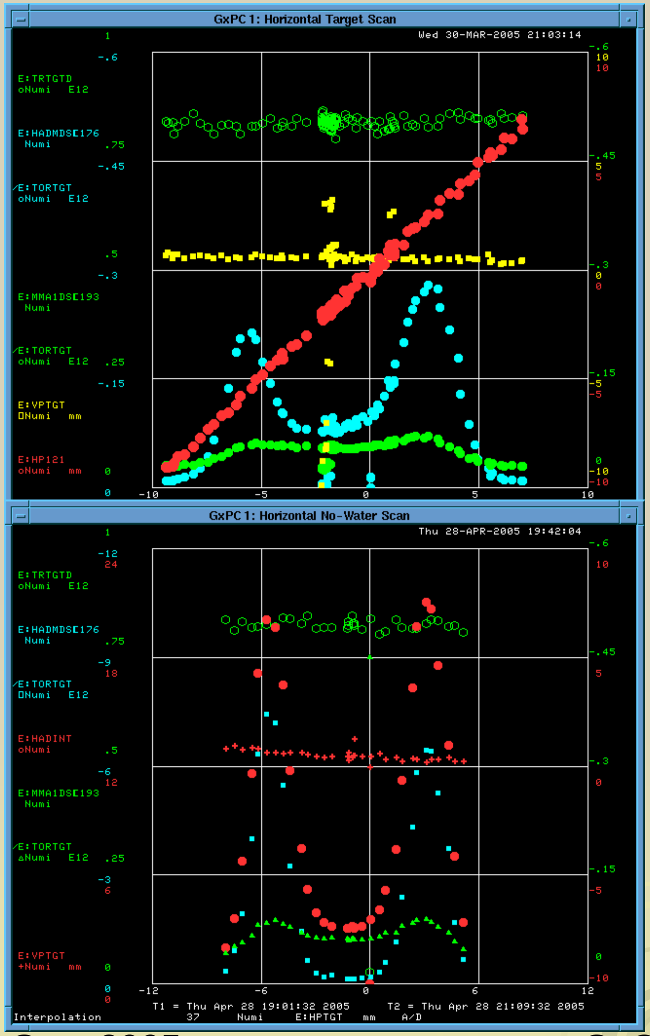


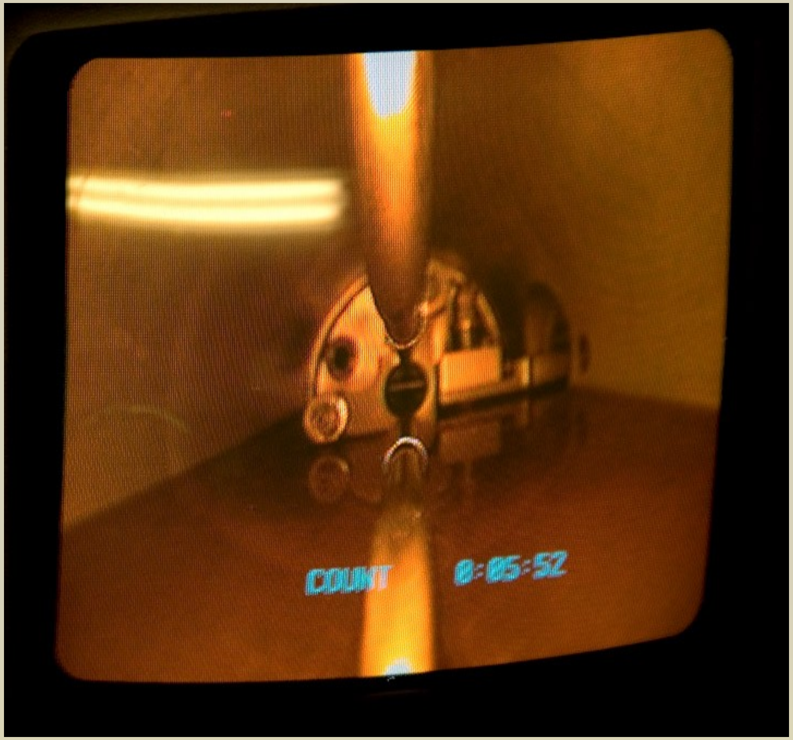
Baffle, target, horn geometry



Target Scan using Hadron Monitor provides verification of major change

Scan after water leak





Normal target scan

Target Diagnosis Period

- No NuMI beam for ~ 1 month while work to diagnose target cooling water leak
- Target removed from beam chase to hot cell
  - Water leak has closed after moving target
  - Many diagnostic steps – no firm answer for cause of water leak
  - Modifications made to fill target vacuum vessel with He gas (small overpressure)
  - Water removed by combination of He pressure and vacuum pumping
- Replace target in beam chase in preparation for operation using He backpressure to hold water out.
- Leak reopens after 1st hours of beam again, but He backpressure technique has worked very well – **so far!**

Transition to Operations

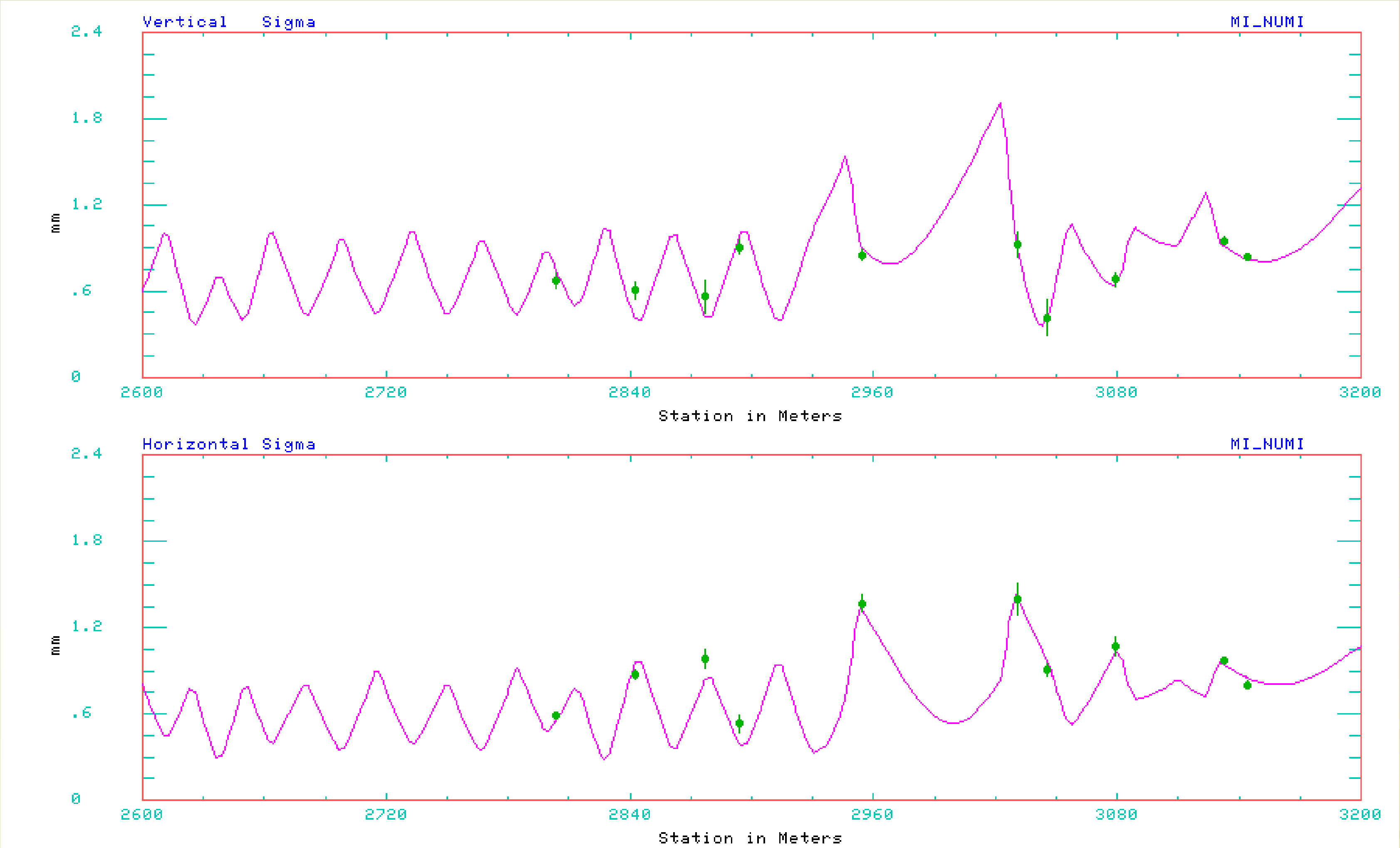
- Transition to Operations –
  - **VERY** smooth
    - Restarted after target checkout in late April
    - Main Control Room Operators take control of running NuMI beam

      (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

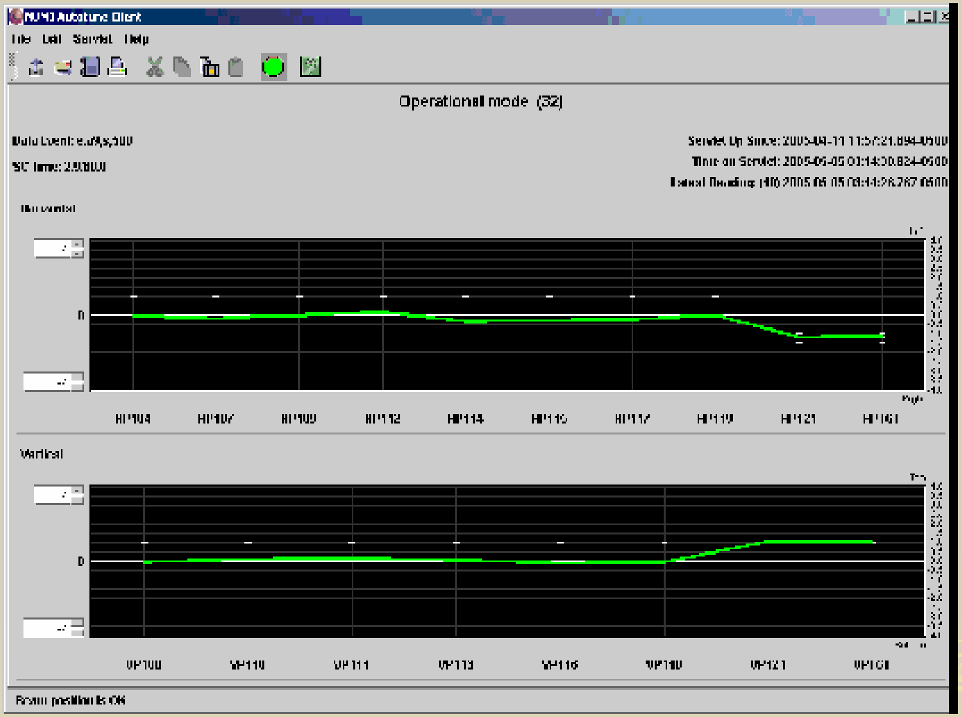
- Keys to NuMI Proton beam operation –
  - Comprehensive beam permit system : ~ 250 parameters monitored
  - Open extraction/primary beam apertures – capability of accepting range of extracted beam conditions
    - Superb beam loss control
  - Good beam transport stability
  - Autotune beam position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

Primary Optics: Design vs. Measured Beam σ



Autotune Primary Beam Control

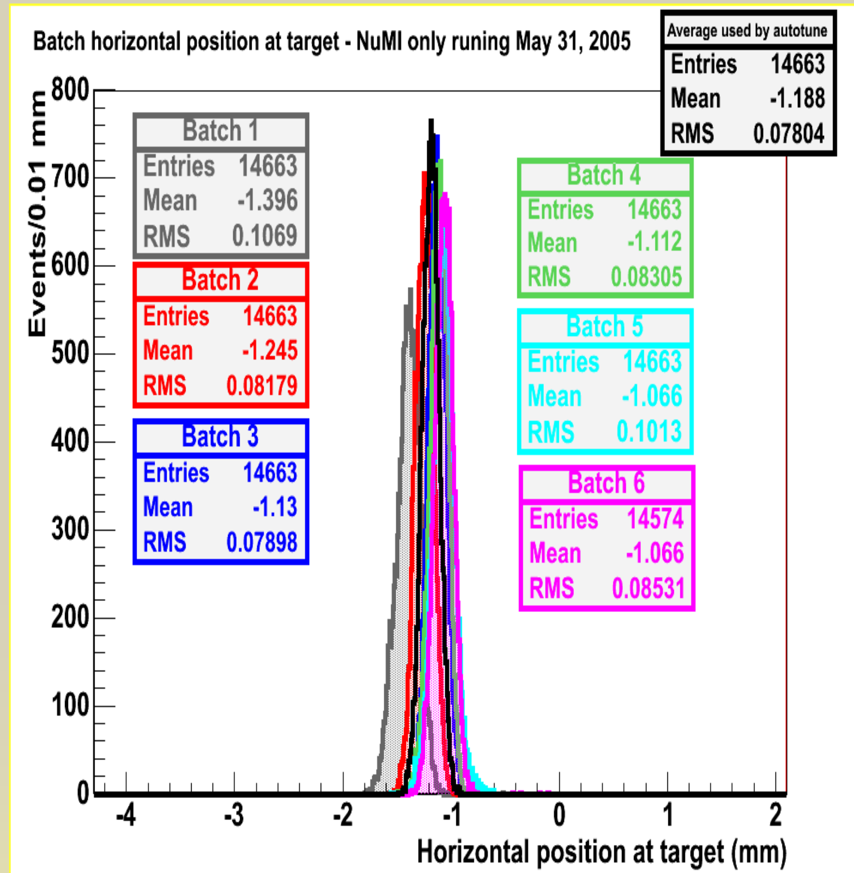
- Automatic adjustment of correctors using BPM positions to maintain primary transport & targeting positions
- Commissioned at 1st turn on for correctors
- Initially controlled targeting for beam centroid to 250 microns
- Recent upgrade to vernier control for targeting. Now control to 125 microns at target



Autotune Beam Control Monitor

Beam Stability on Target
NuMI only mode

- Major bend dipole power supply stability ~ 60 ppm.
  - Good beam position control
- Robust NuMI beam optics
  - Some periods when emittance from Booster varies. Gives larger beam at target, but no beam loss
- Kicker flattop stability ~ 0.8%– best effort toward 0.5% specification.
- Autotune controls beam center distribution
  - Tune on batches 2-4

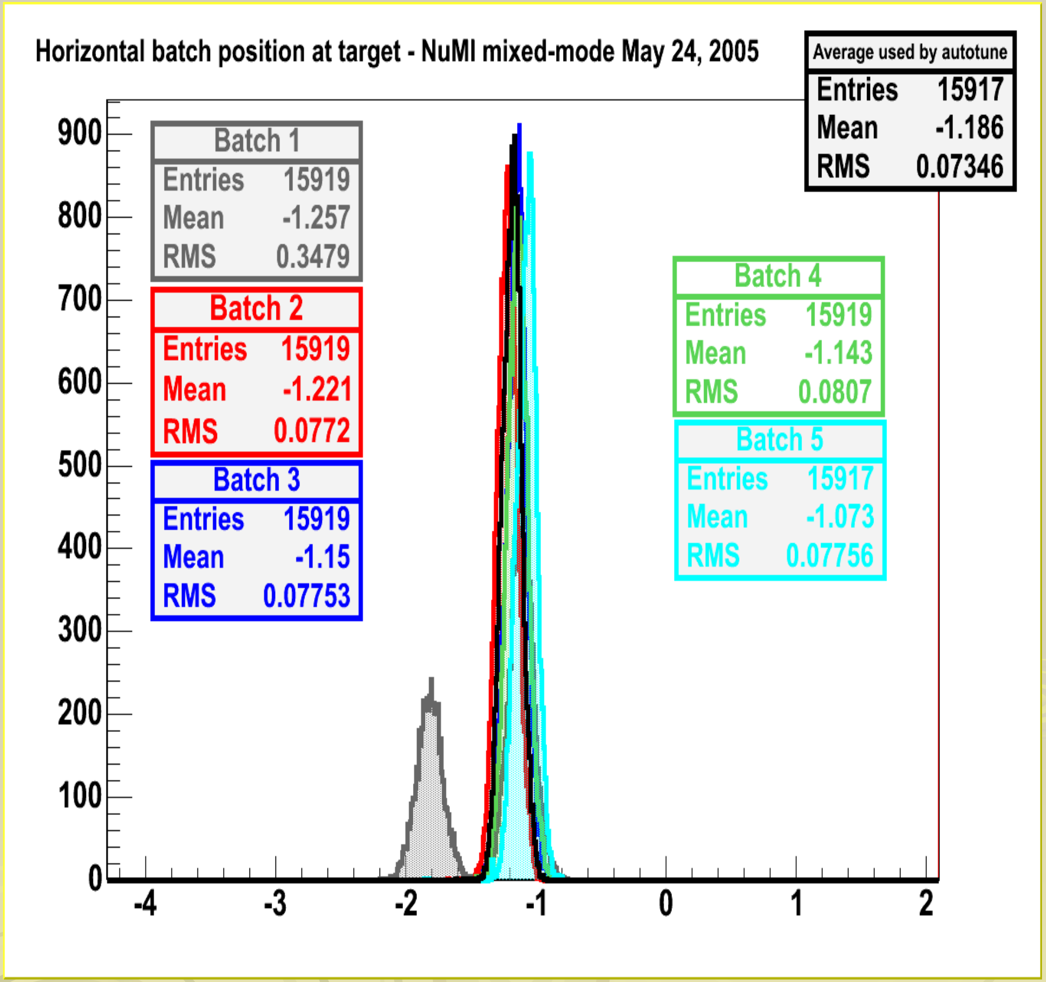


Plot courtesy of M. Bishai, BNL

Mixed Mode Operation

Pbar kicker effect on 1st Batch

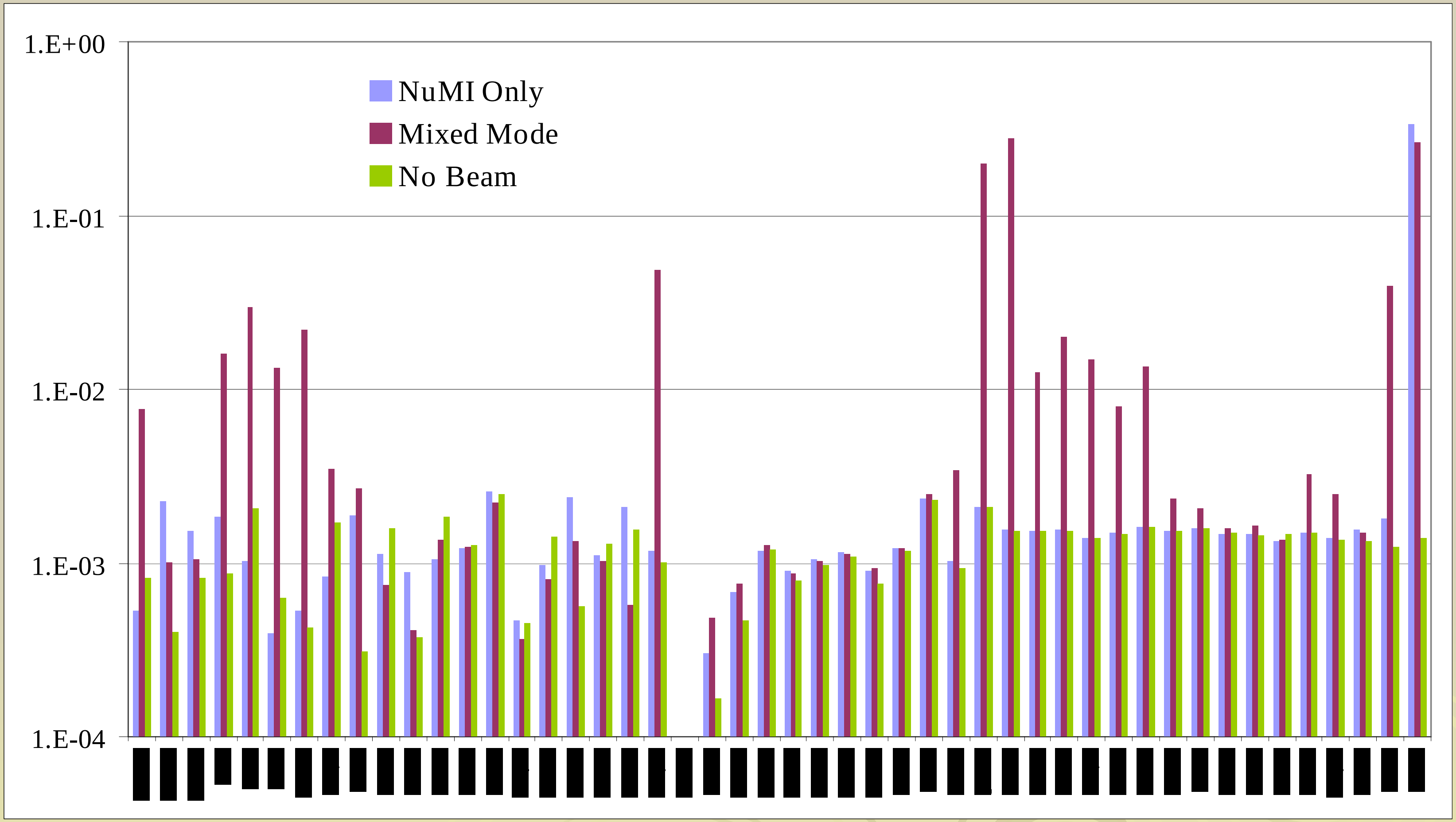
- RMS variation for 1st batch position to 350 mcrons
  - Due to fall-time effects for Pbar kicker
- Until we have shutdown time to fix this (Spring '06) 1st batch is excluded from Autotune

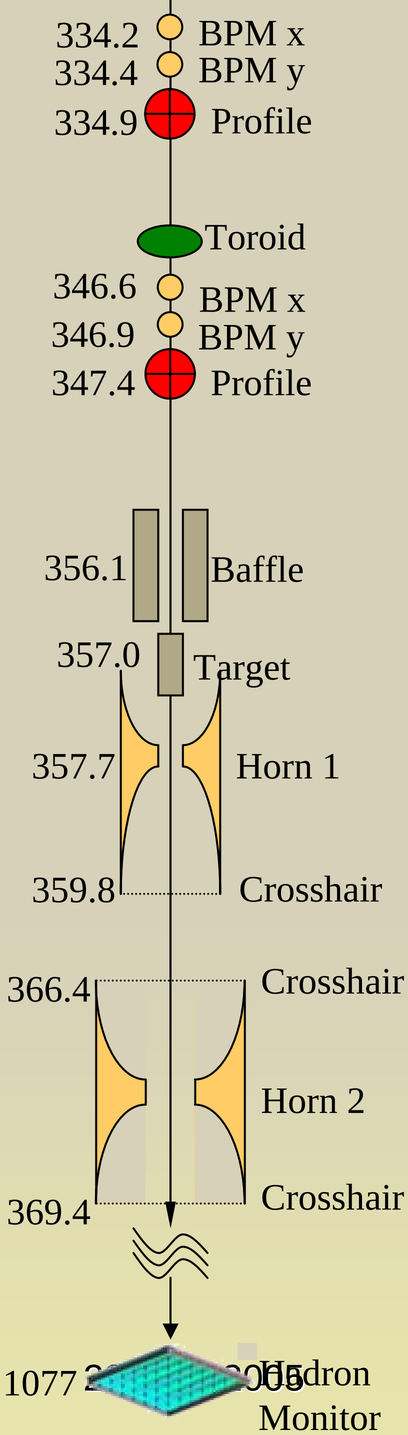


Primary Transport Beam Loss

Rads/sec

Beam permit system inhibits set at 5 Rads/sec ~ few e-5 fractional loss





Beam Alignment Strategy

- Procedure
  - Scan low intensity proton beam across known features of beamline components
    - Target & Baffle material
    - Horn neck and cross-hairs
- Move proton beam with pairs of horizontal & vertical trims
  - Mostly parallel translation
- Use instrumentation to correlate measured proton beam position with component features
    - Loss Monitors
    - Hadron Monitor
    - Muon Monitors

Summary of Measurements w.r.t Beam Coordinate System

- Found Components are consistently to the left , and typically down by ~ 1 mm
  - Exception is that baffle is about 1 mm high w.r.t. target – appears consistent with direct observations in target hall

		Offset (mm)
Horizontal	Baffle	-1.21
	Target	-1.41
	Horn 1	-1.24
	Horn 2	-1.82
Vertical	Baffle	+1.12
	Target	+0.13
	Horn 1	+0.81
	Horn 2	+0.08

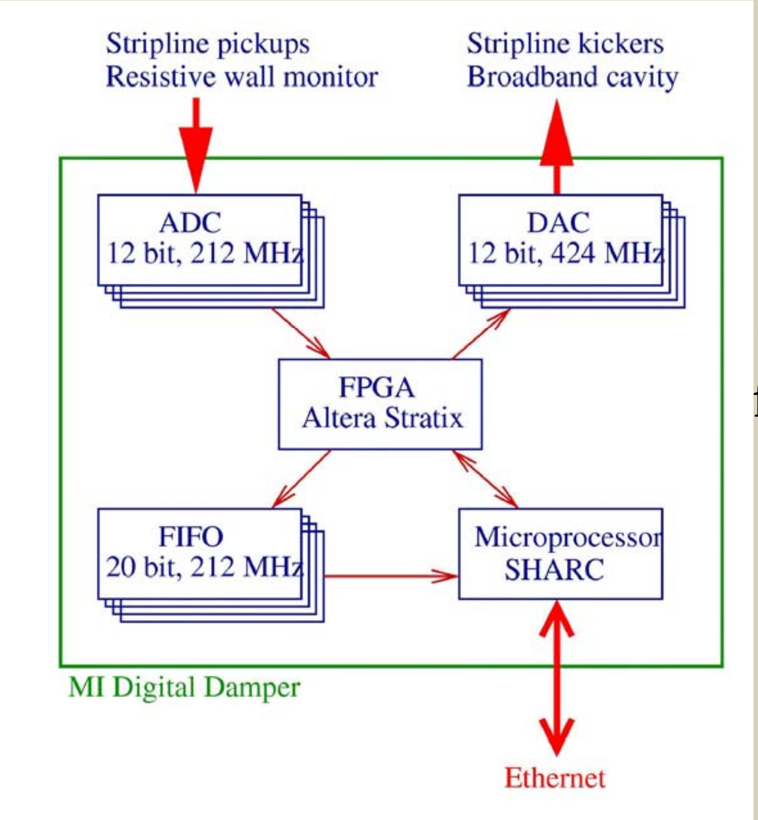
Based on beam-based alignment, shift targeting by -1.2 mm hor. and +1.0 mm ver.

Follow-up Information from Survey

- **Appears that target hall deformed slightly with loading of 6400 tons of steel/concrete**
  - Effects only about 1 mm; now stable

Progression to Increased Beam Power

- Keys to improving beam power for NuMI have included:
  - Continuing enhancement in accelerator intensity capability and control of beam loss – especially for pbar slip stacking process
    - NuMi only operation has been very smooth from the beginning, but this is not the normal operational mode
  - Steady improvement in number of beam cycles available for NuMI
    - Now running during Recycler and Tevatron shot transfers
    - Adapting operational modes to interleave extra NuMI cycles as pbar stacking cycle times increase (due to stacktail core cooling limitations as stack increases)
  - Most recently, targeting highest possible intensity in NuMI only mode
    - Since 20 Sep. when spare NuMI target is ready



A Bunch-by-Bunch Digital Damper System

B. Foster et al.

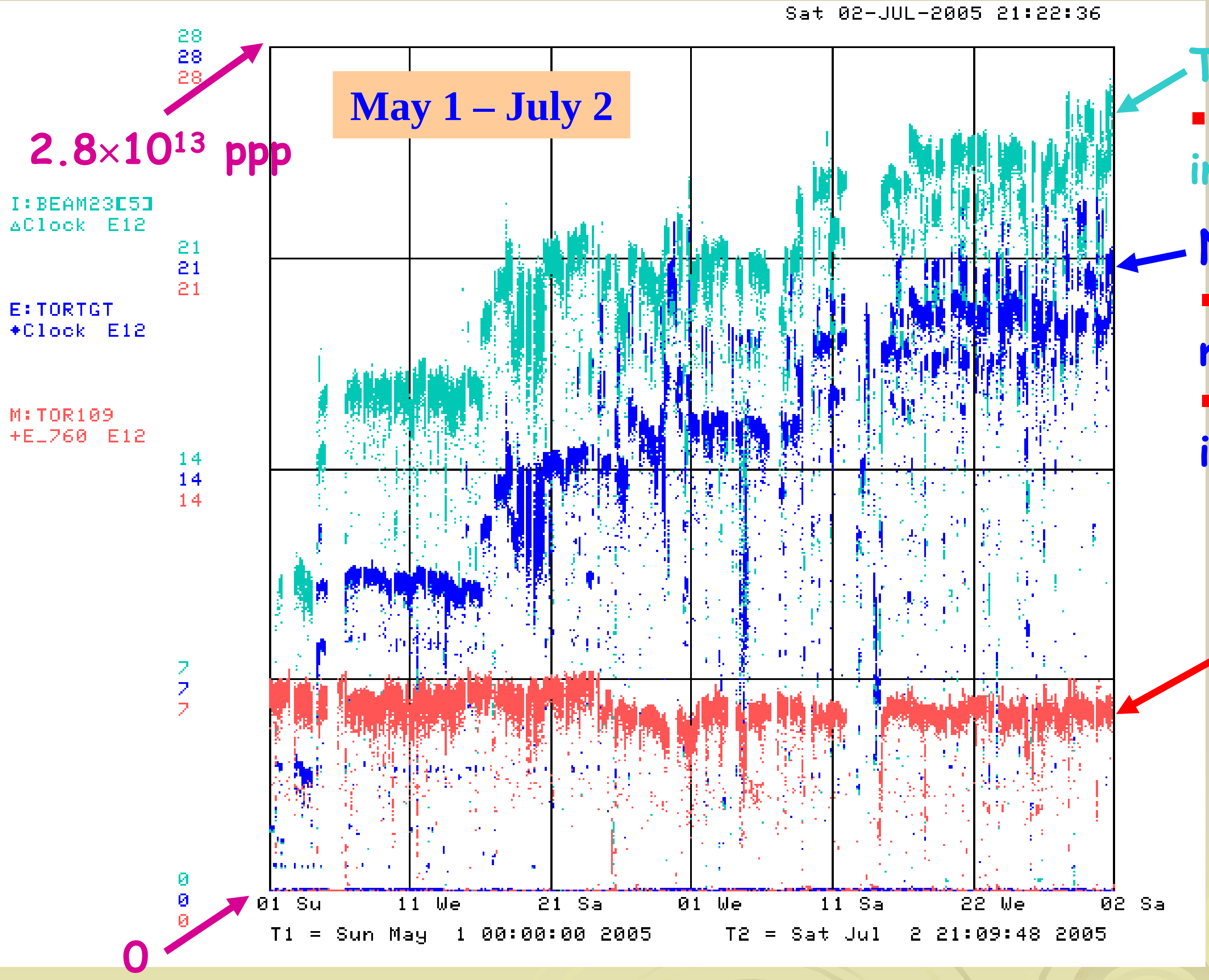
❖ **The digital damper system has been essential for high intensity operation in the Main Injector**

- **Final board installed in summer `04**
- **Achieved a max intensity of 3×10^{13} protons @ 120 GeV in MI**

❖ **The system consists of beam pickup signals (RWM, stripline) with corresponding kickers and a single digital board serving both transverse and longitudinal dampers**

- **pickup signals digitized at 212 MHz, with 12 bit resolution**
- **digital pipelined processing in a large FPGA**
- **damper kicks digitally synthesized by a 424 MHz DAC**

Increasing Beam Intensities in Main Injector

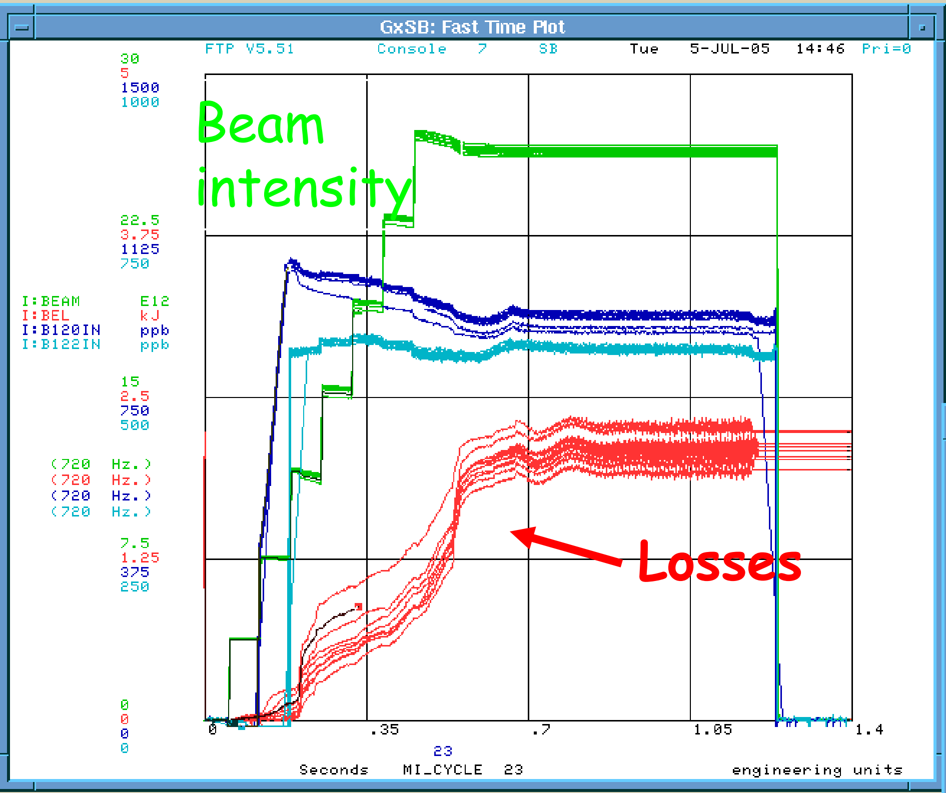


Total MI beam
- up to 2.6×10^{13} ppp in mixed-mode

NuMI beam
- up to 2×10^{13} ppp in mixed-mode
- up to 2.3×10^{13} ppp in NuMI only mode

Beam to anti-proton source

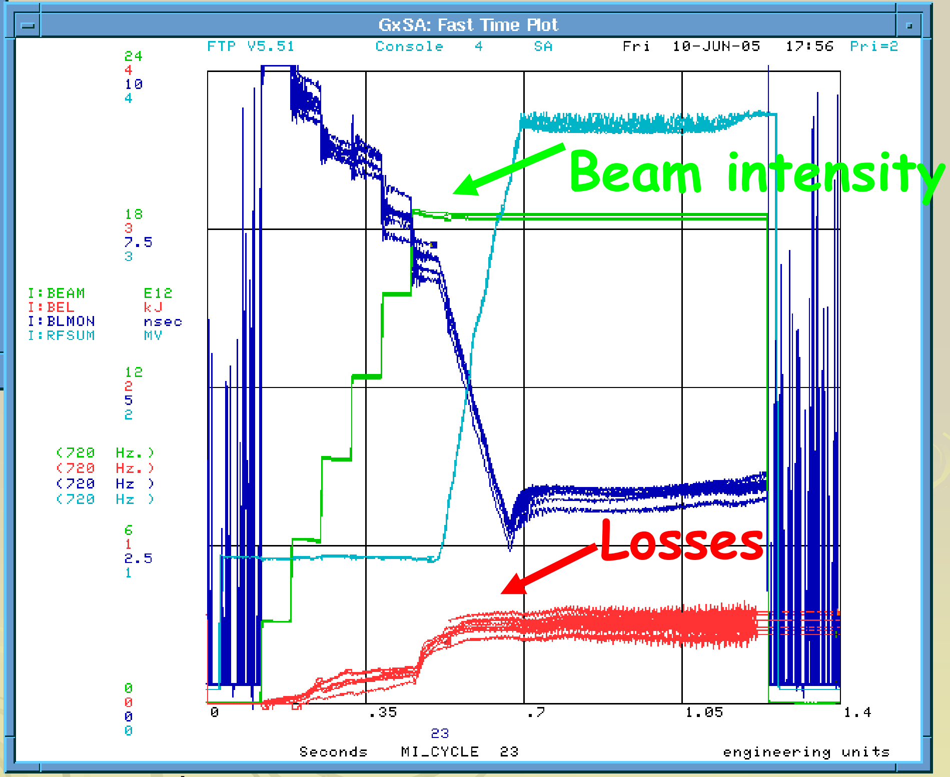
Main Injector Modes of Operation



July 2005

NuMI only

- NuMI beam ~ 1.9×10^{13} ppp

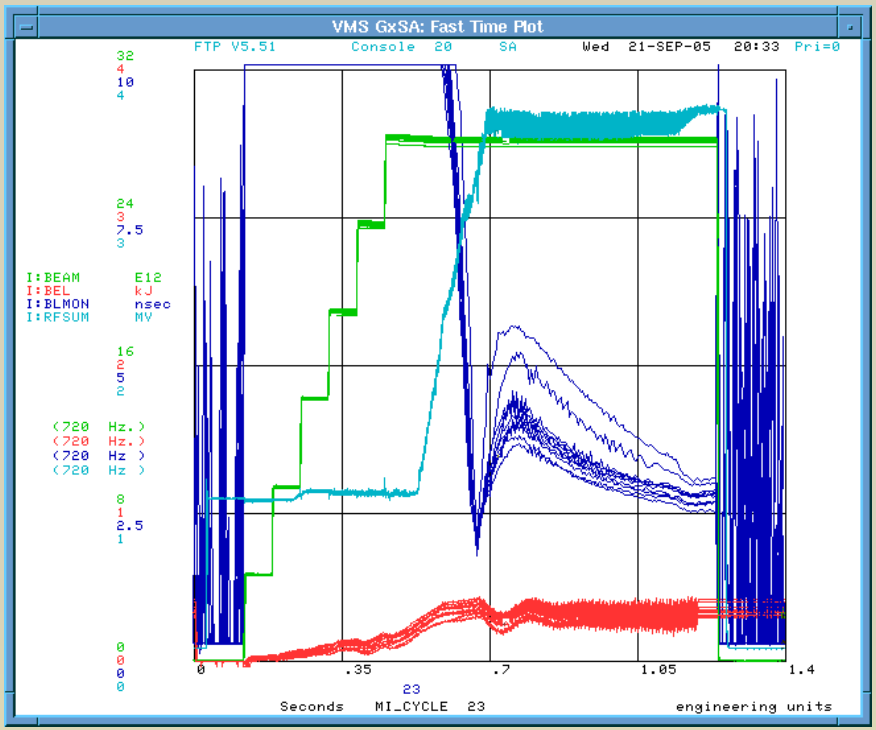


mixed-mode

- NuMI beam ~ 2.0×10^{13} ppp
- beam to anti-proton source ~ 6×10^{12} ppp

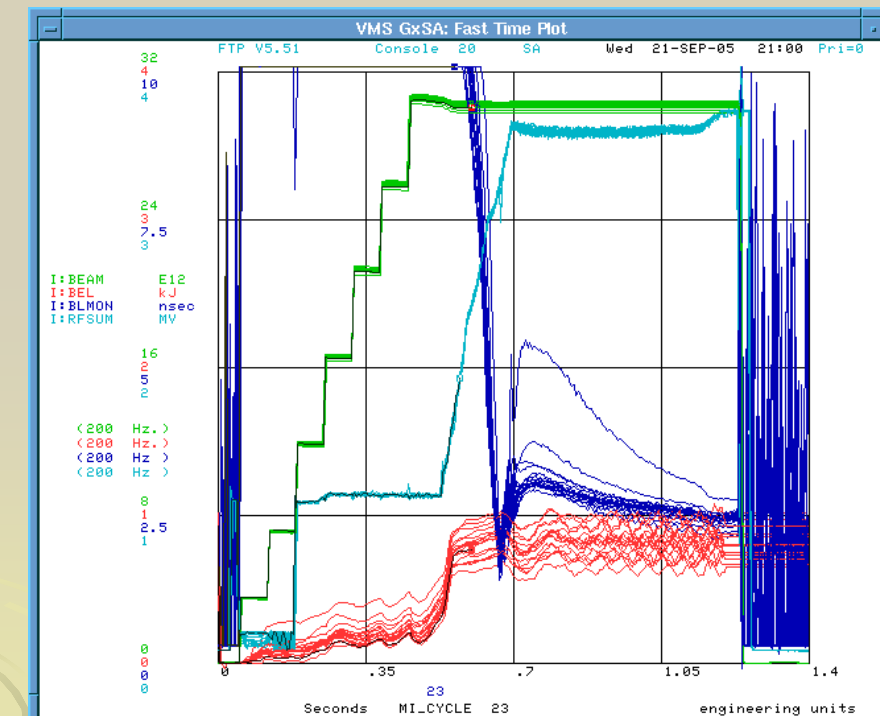
Improving Accelerator Performance

NuMI only mode
total beam in MI 2.8×10^{13} ppp



Running @12
Booster turns

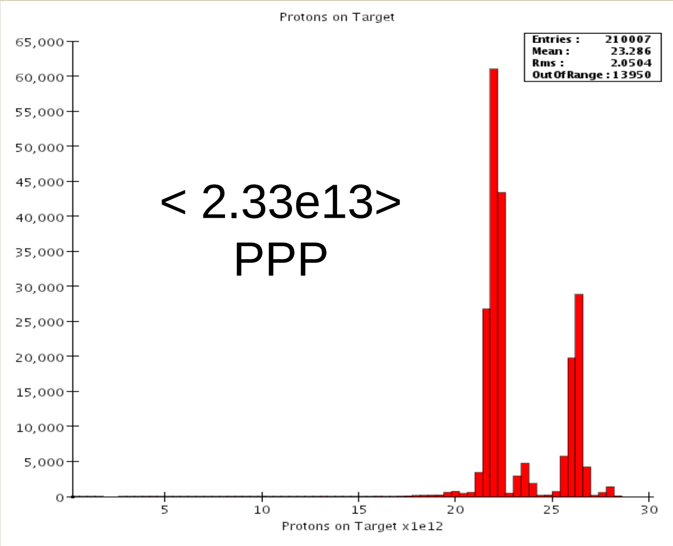
Mixed mode
total beam in MI 3×10^{13} ppp

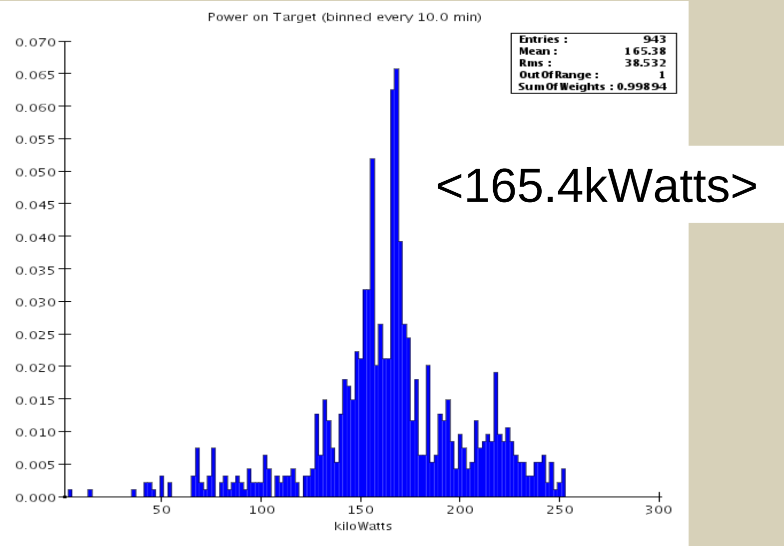


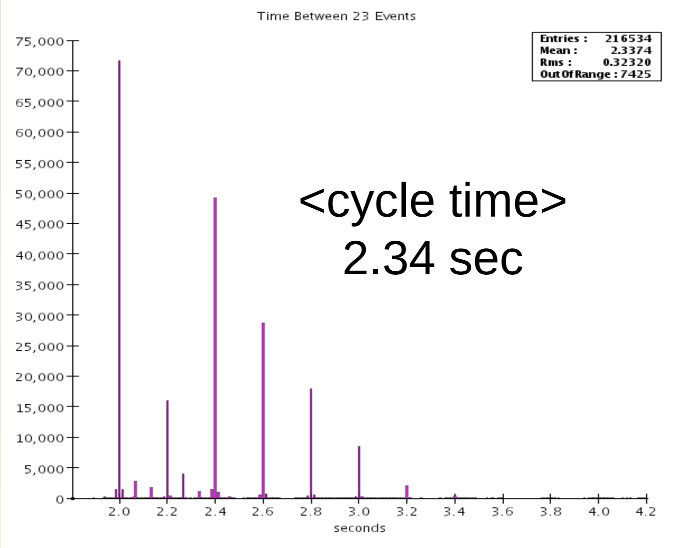
September 2005

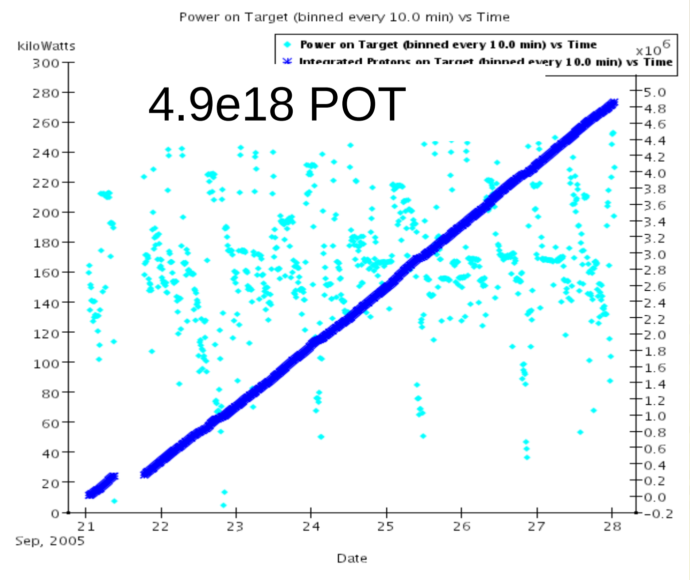
Week of 21-28 September

210,000 pulses

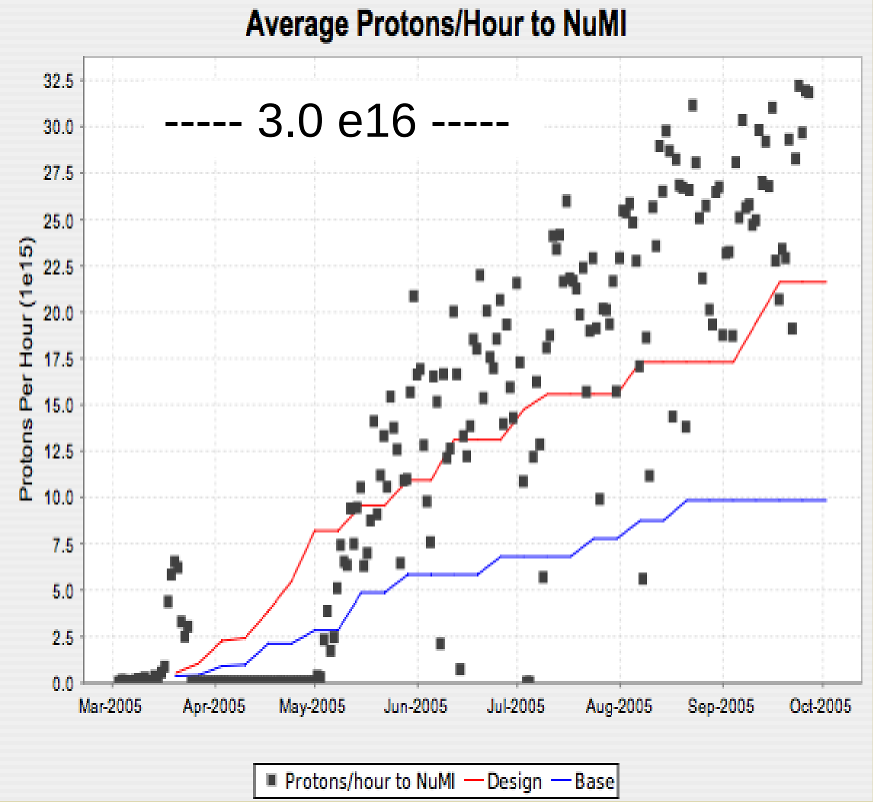


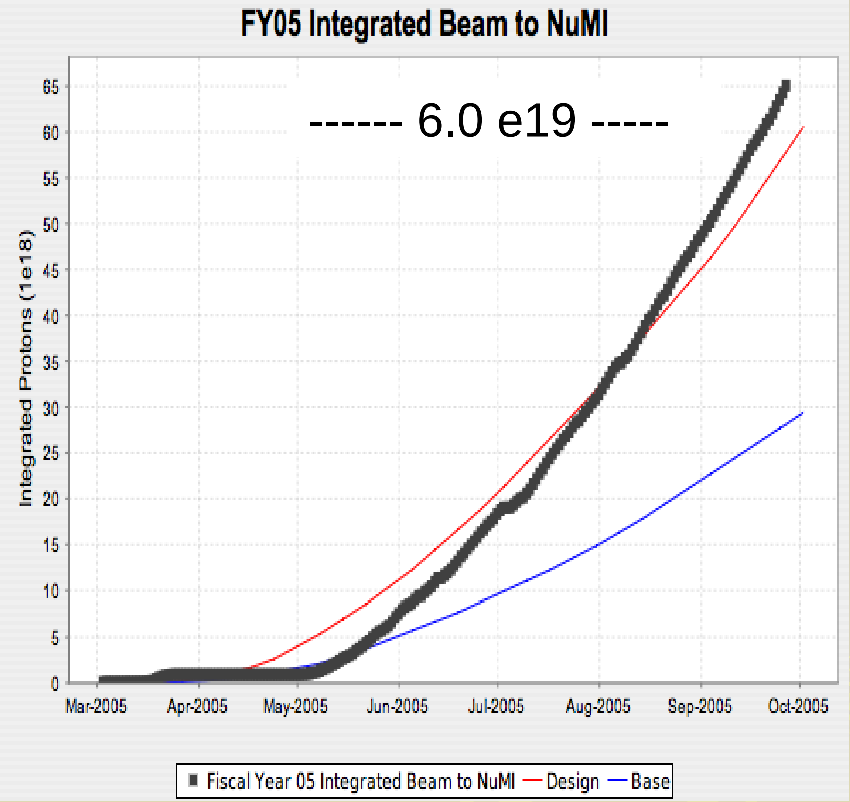






2005 Beam to NuMI





6.6 E19 Protons on Target to Date !!

Projections toward Higher Beam Power

- Are still on a rising curve for NuMI beam power, which has continued since May restart.
- **Goal for 2005 has been to reach ~2.5×1013 ppp every 2 s to NuMI (240 kW)**
  - **We are now approaching this!**
- **Anti-proton cooling improvements required by the Collider program, as are improvements with proton source**
  - **Major efforts are ongoing to accomplish this, and progress continues to be made**
  - **In earlier operation, best NuMI operation was without pbar, and same for the collider efficiency**
  - **This week, both NuMI and collider luminosity records were set together!**
- By 2008-9, we look toward ~3.4 e20 protons/year to NuMI

Summary

- NuMI has had an extremely productive beam commissioning, and first year of operation to date
- We survived a major target problem, and continue to take ever higher beam power on the same target
  - Unfortunately, we do not really KNOW what caused the target water leak
- Prospects are very bright for near term MINOS neutrino oscillation physics at Fermilab

Acknowledgements: Completion, commissioning and operation of the NuMI beam system has been a concerted effort for many years for a very large number of people from Fermilab and our member universities.

We have also benefited greatly by much feedback and assistance from our CERN CNGS colleagues, and colleagues from the Japan neutrino programs.