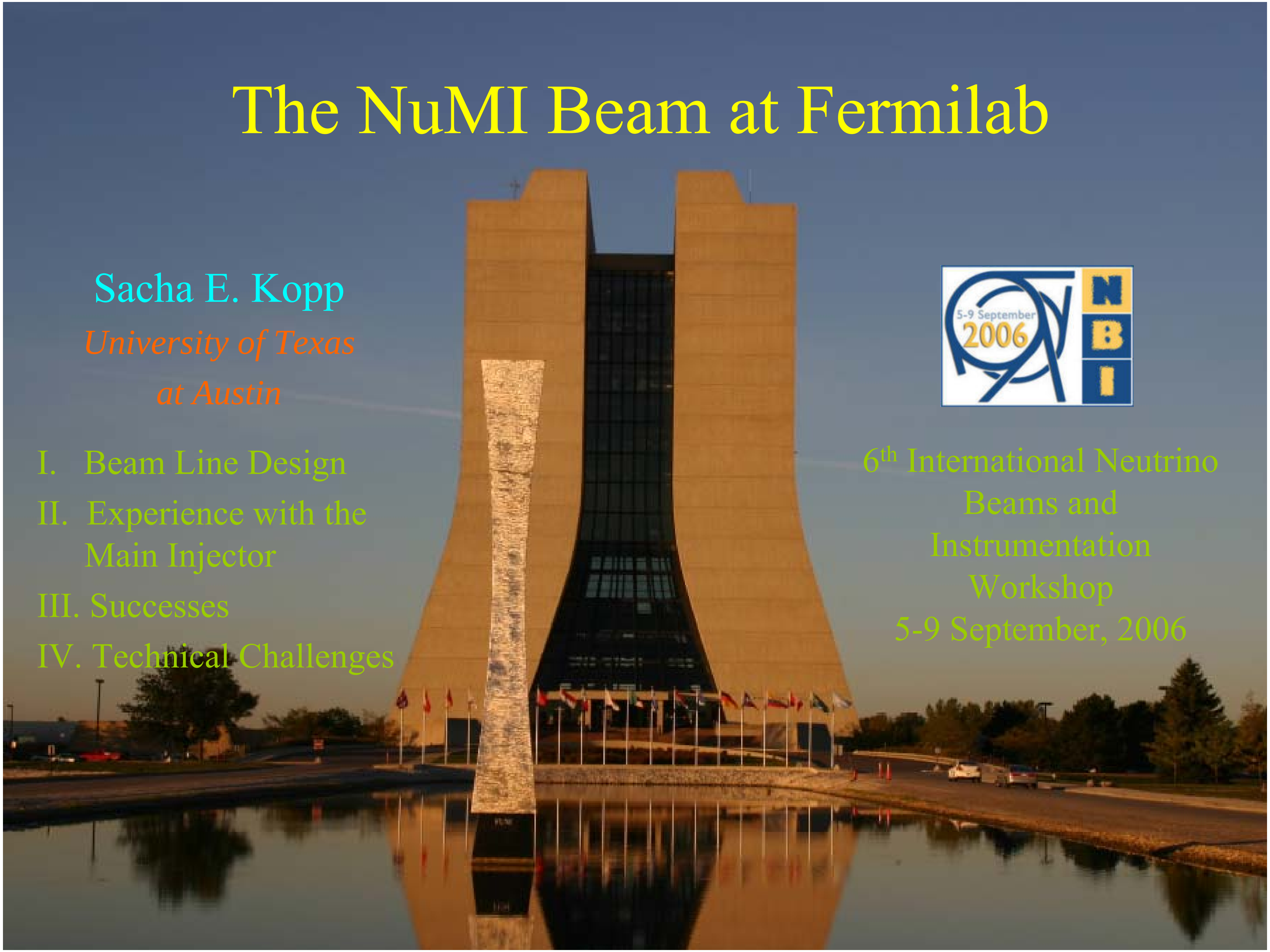
The NuMI Beam at Fermilab

Sacha E. Kopp

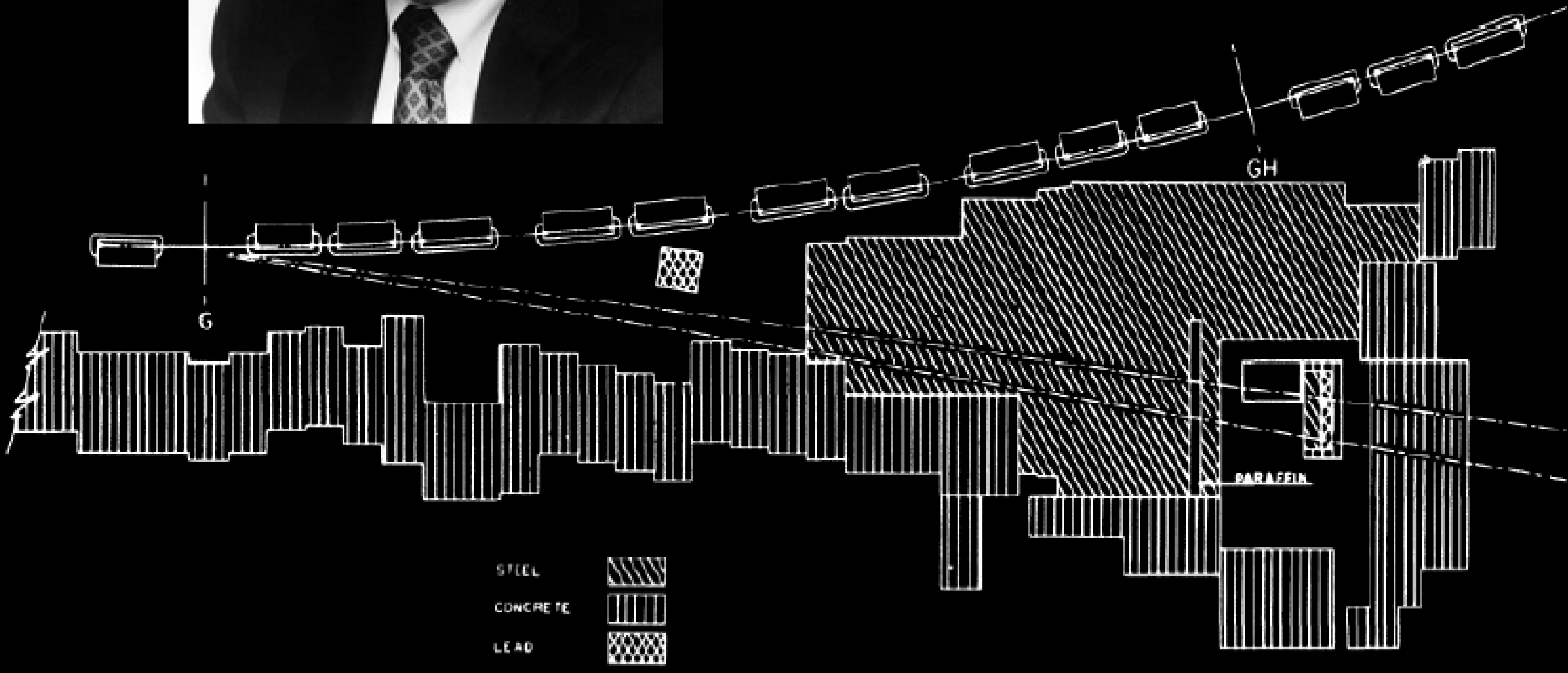
University of Texas at Austin

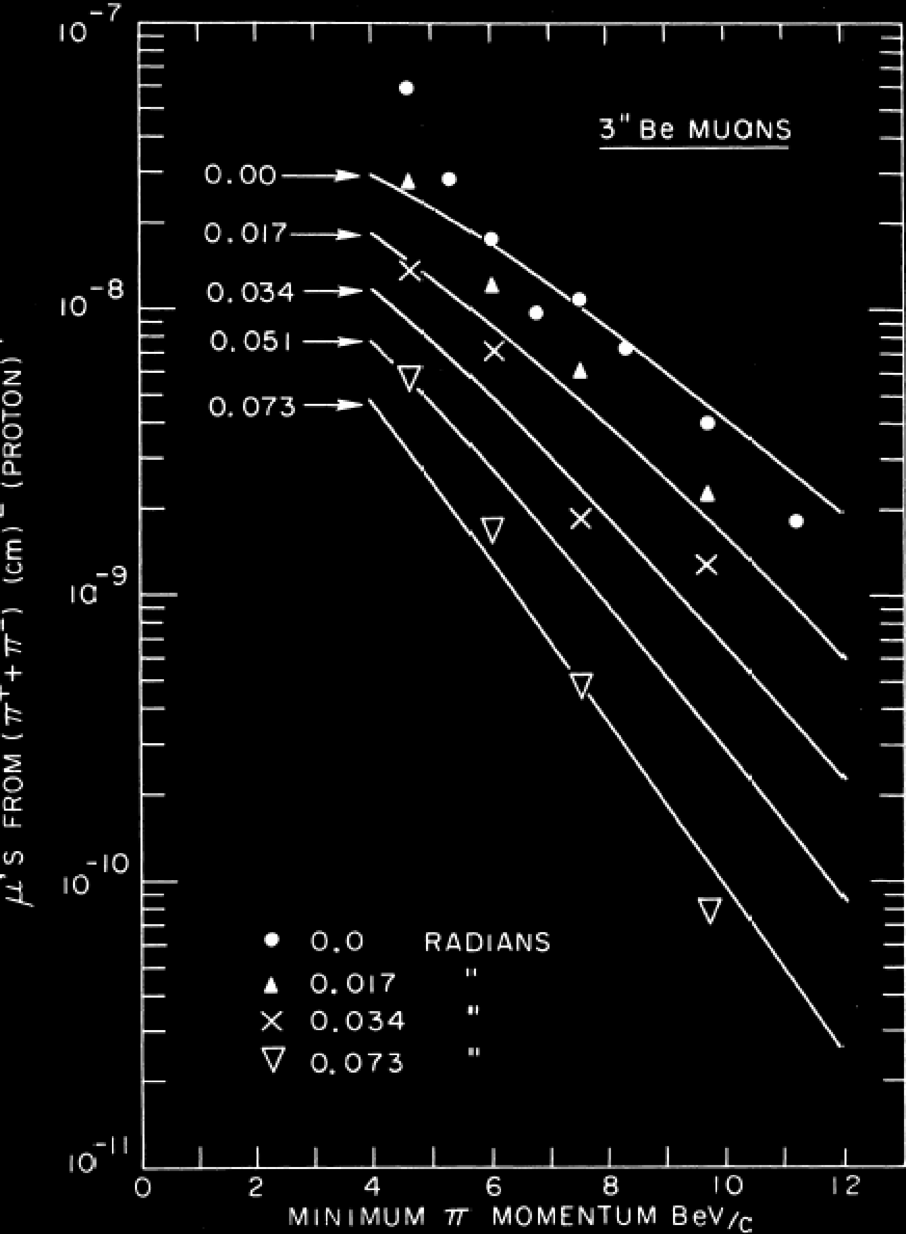
I. Beam Line Design
II. Experience with the Main Injector
III. Successes
IV. Technical Challenges

6th International Neutrino Beams and Instrumentation Workshop
5-9 September, 2006



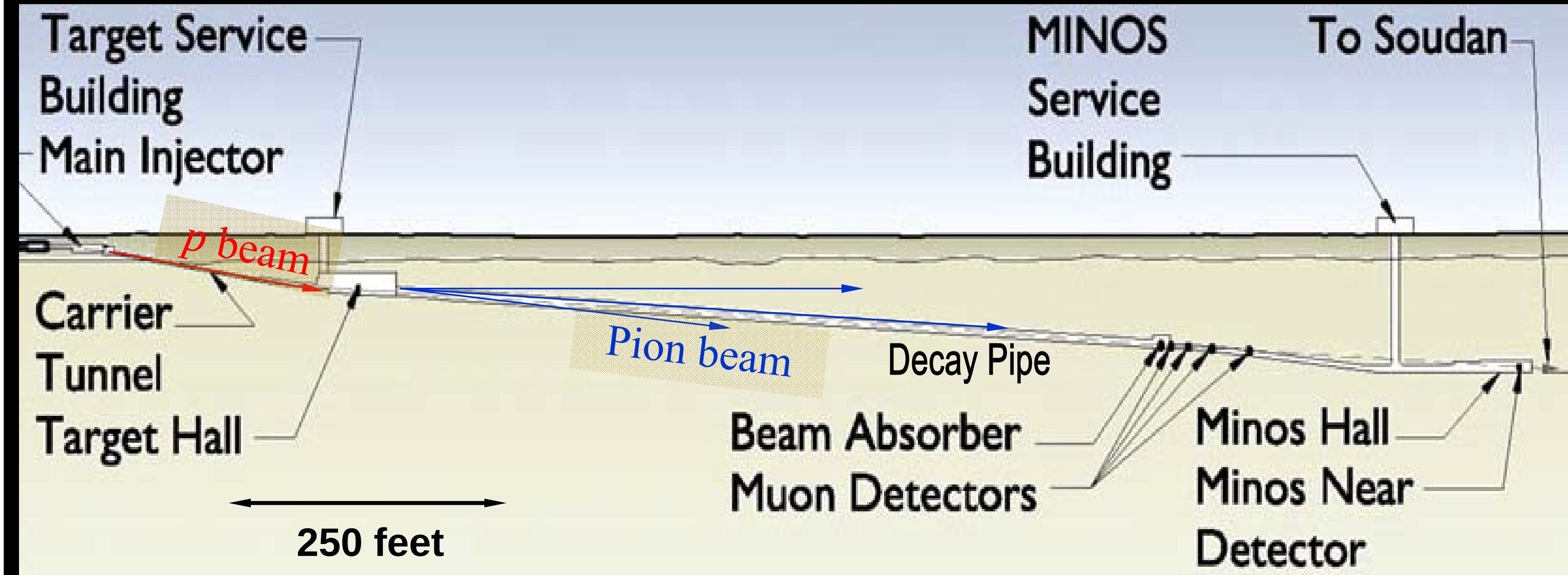
Mel Schwartz
1932-2006





3" Be MUONS
0.00
0.017
0.034
0.051
0.073
μ'S FROM (π+ + π−) (cm)−2 (PROTON)−1
10−7
10−8
10−9
10−10
10−11
0 2 4 6 8 10 12
MINIMUM π MOMENTUM BeV/c
● 0.0 RADIANS
▲ 0.017 "
× 0.034 "
▽ 0.073 "

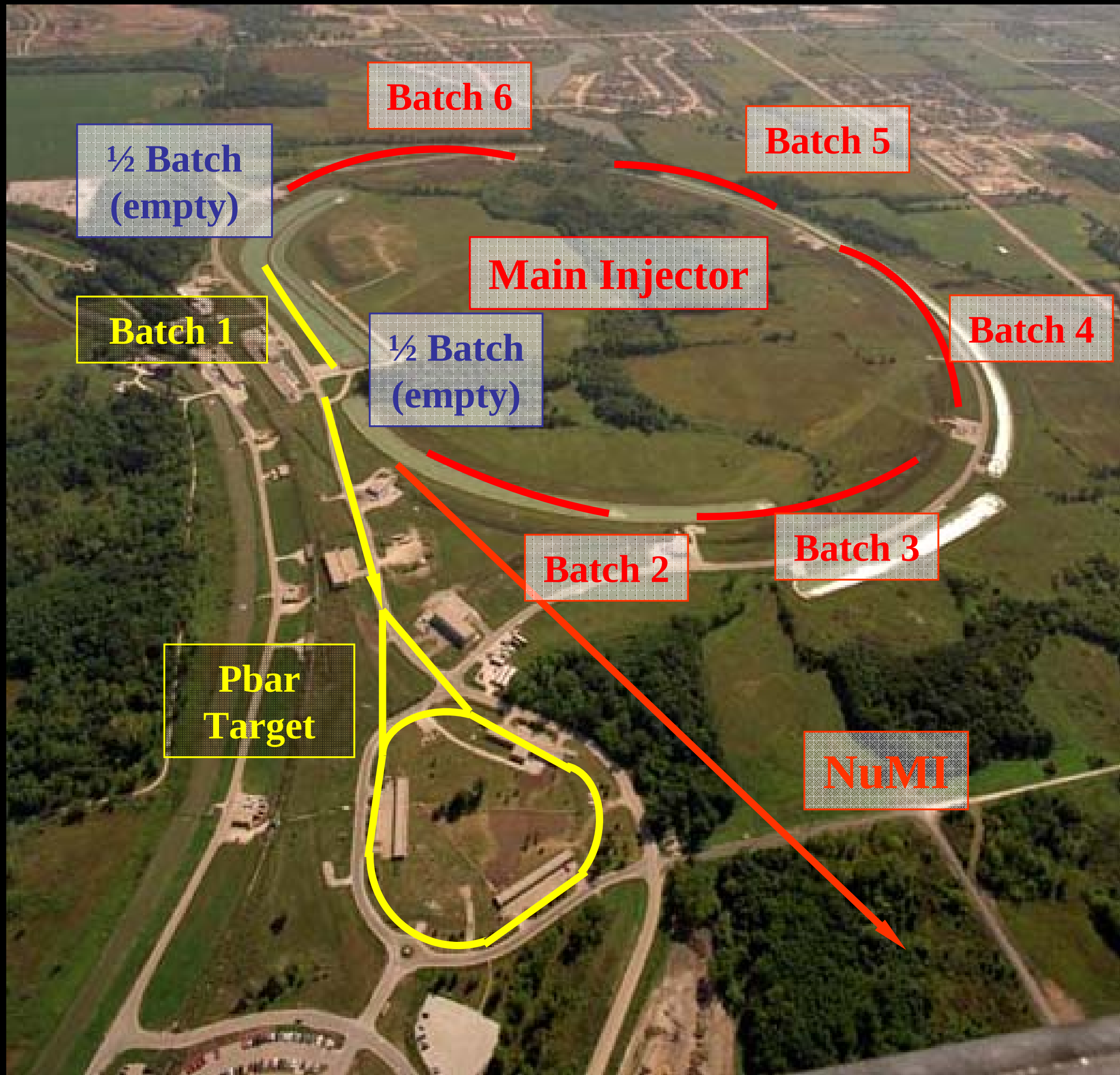
The NuMI Beam



- 120 GeV/*c* protons from Main Injector
- Two hard bends to achieve final 58 mrad inclination
- Large, flexible target station
- Extra long decay volume, μ monitors
- Detector hall at 1040 m

Main Injector is a Shared Resource

- MI ramp time ~1.5sec
- MI is fed 1.56μs batches from 8 GeV Booster
- Simultaneous acceleration & dual extraction of protons for
  - Production of $\overline{p}$ (Tevatron collider)
  - Production of neutrinos (NuMI)
- NuMI designed for
  - 8.67 μs single turn extraction
  - 4×10^{13}ppp @ 120 GeV
- Antiproton Production:
  - Requires bunch rotation (Δt~1.5nsec)
  - Merges two Booster batches into one batch ("slip-stacking")

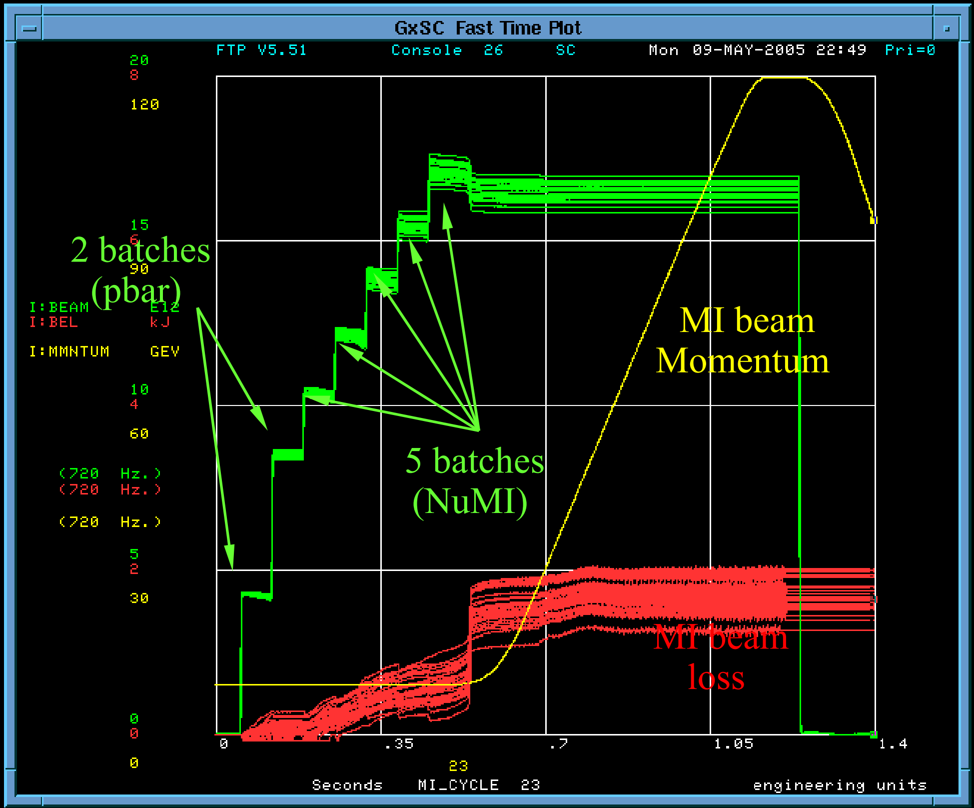


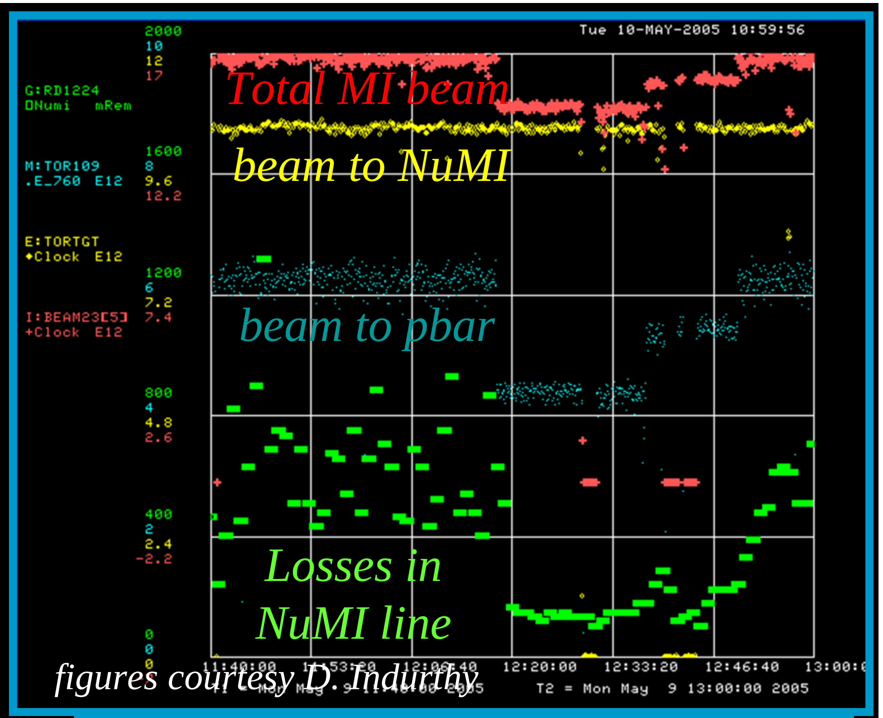
Multi-batch delivery to NuMI

- Plot is from first test in Feb '05, all batches sent to NuMI.
- Typical stored beam in MI today: $(3.0\text{-}3.3)\times10^{13}$
- Progress to improve MI performance (*eg* Mode 1 dampers

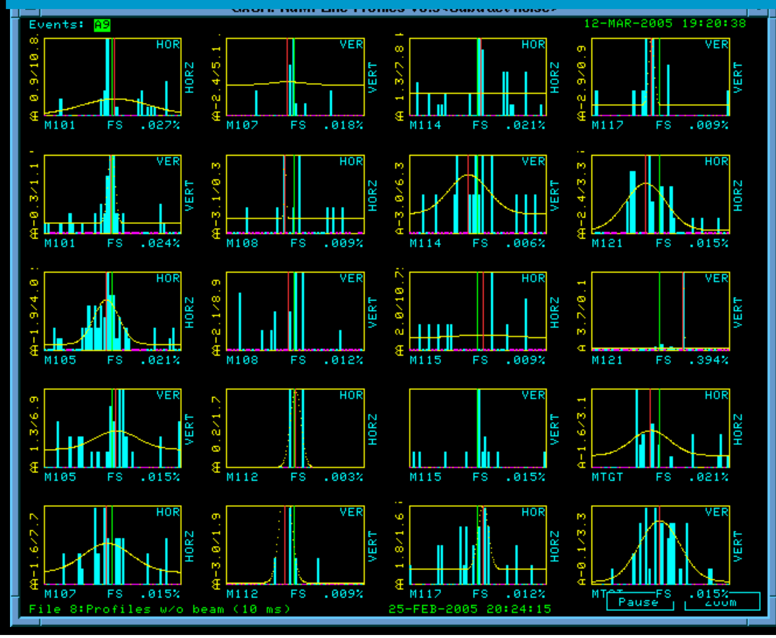
- Slip-stacking for NuMI still in development (see talk by Zwaska)

Mixed-mode cycle



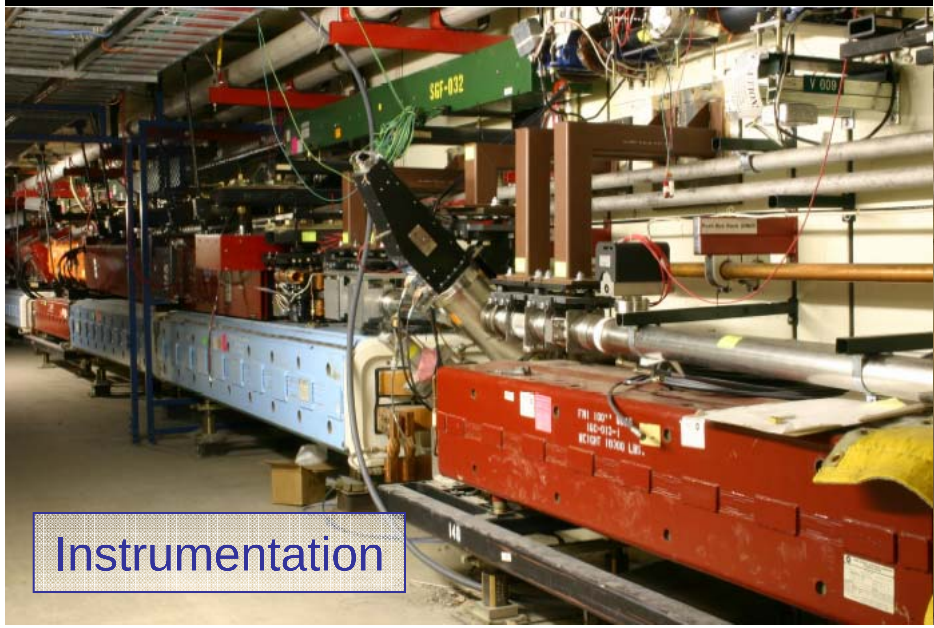


Observe off-momentum beam down NuMI line even when no NuMI batches injected into MI (only the 2 pbar batches)

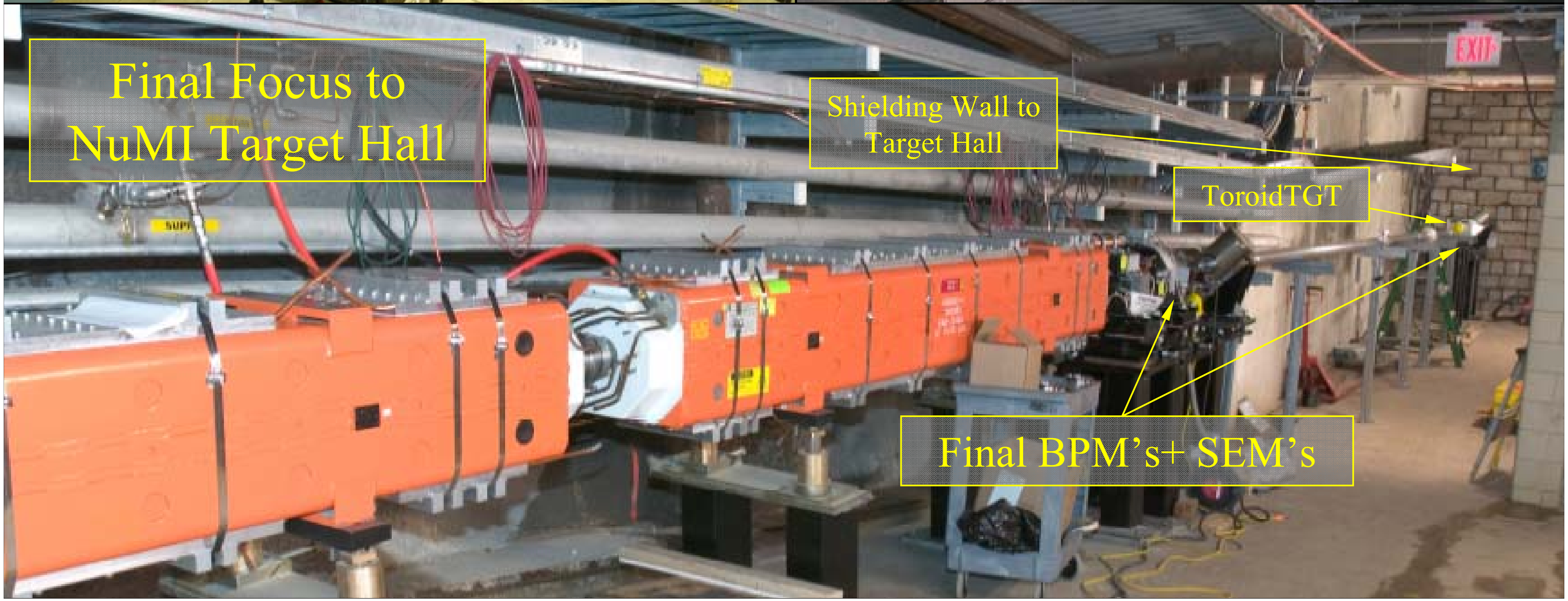


- Simultaneous acceleration of 2 slip-stacked batches (antiproton production) and 5 batches for NuMI.
- Off-momentum, 'uncaptured' beam from slip-stacked batches circulates in MI outside of desired batch location, NuMI batches injected on top of this.
- These plots from May '05. Many stacking improvements reduced these losses for subsequent operations.

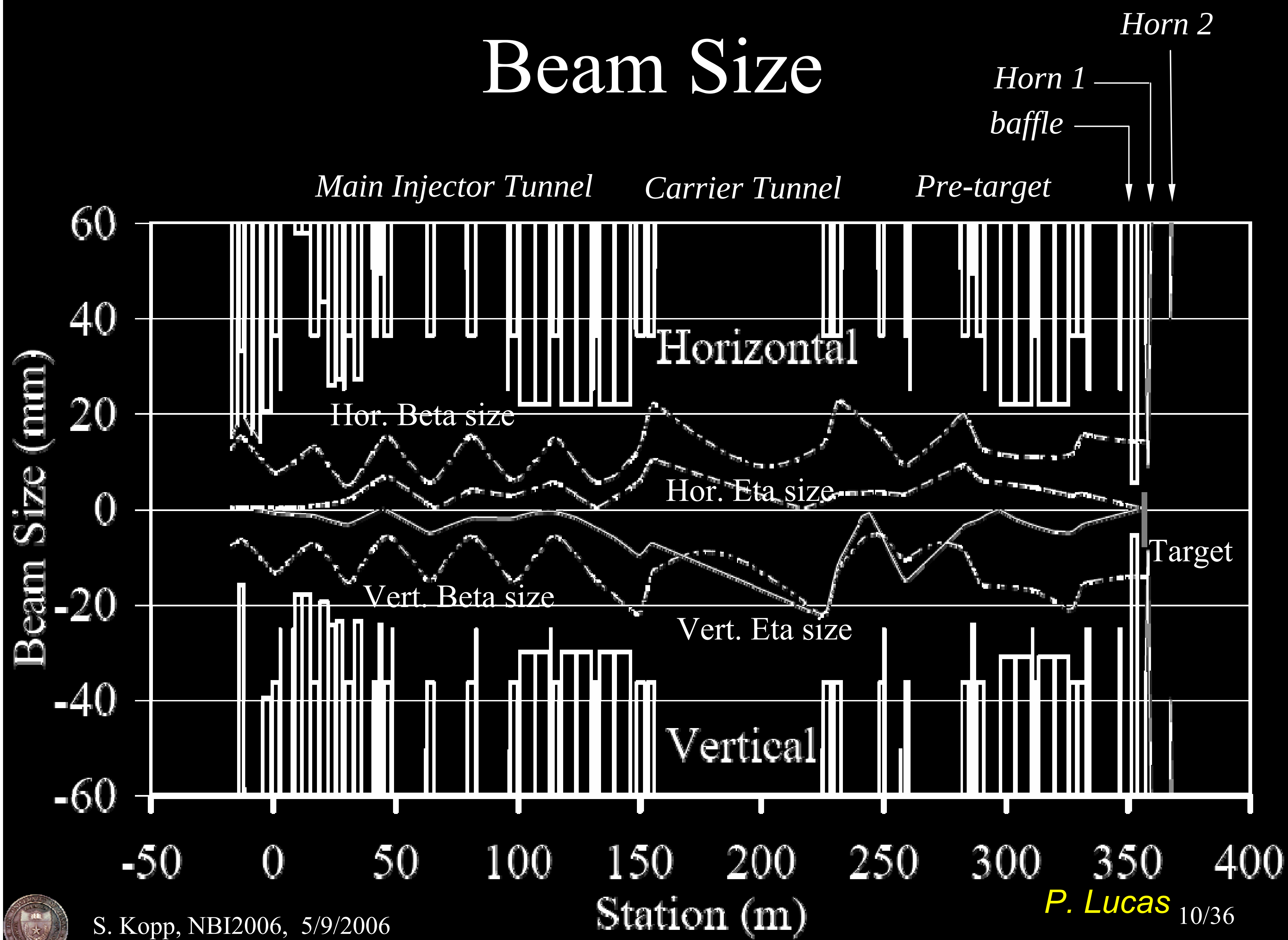
NuMI in Main Injector Tunnel



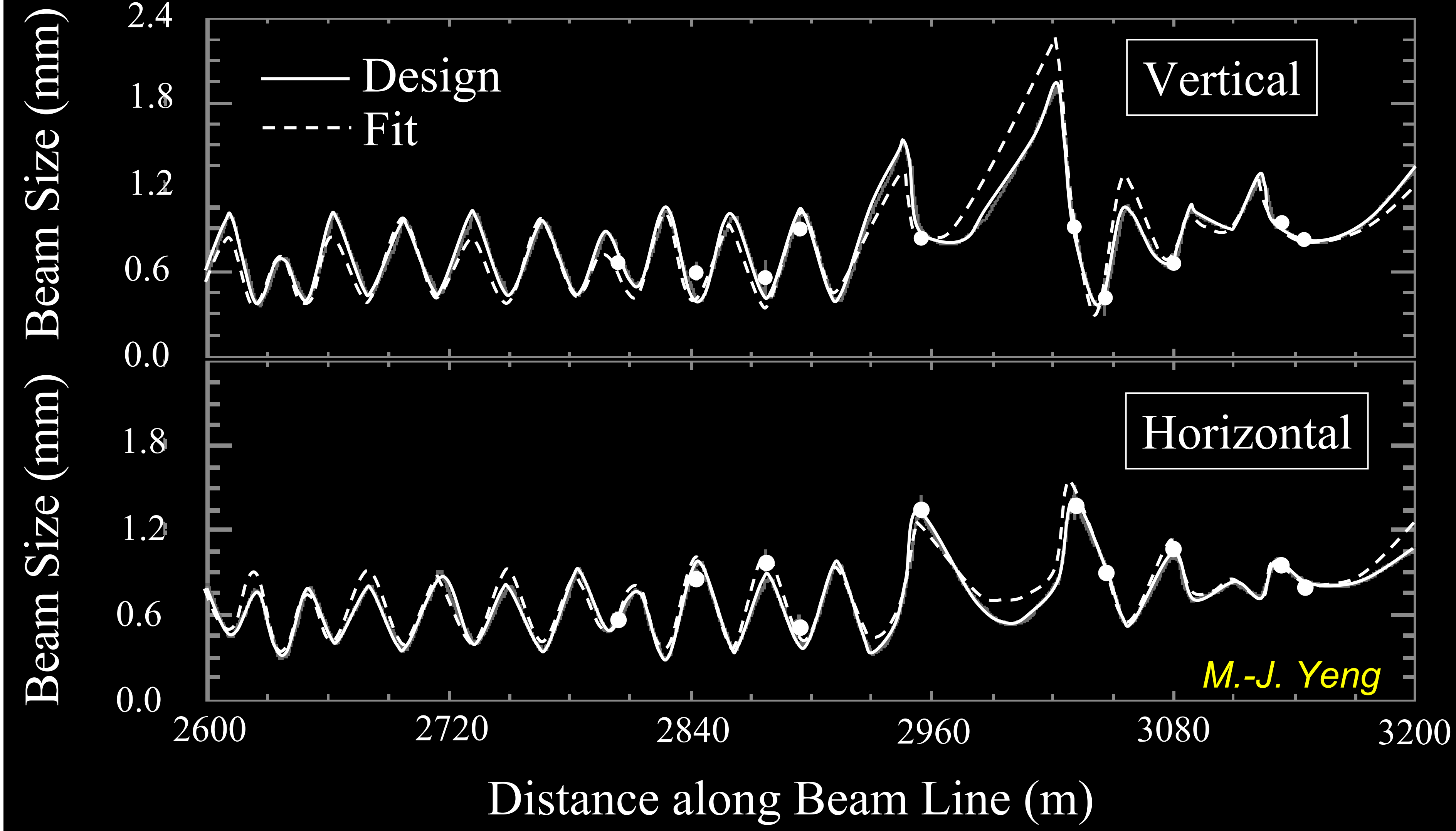
Extracted Proton Beam Line



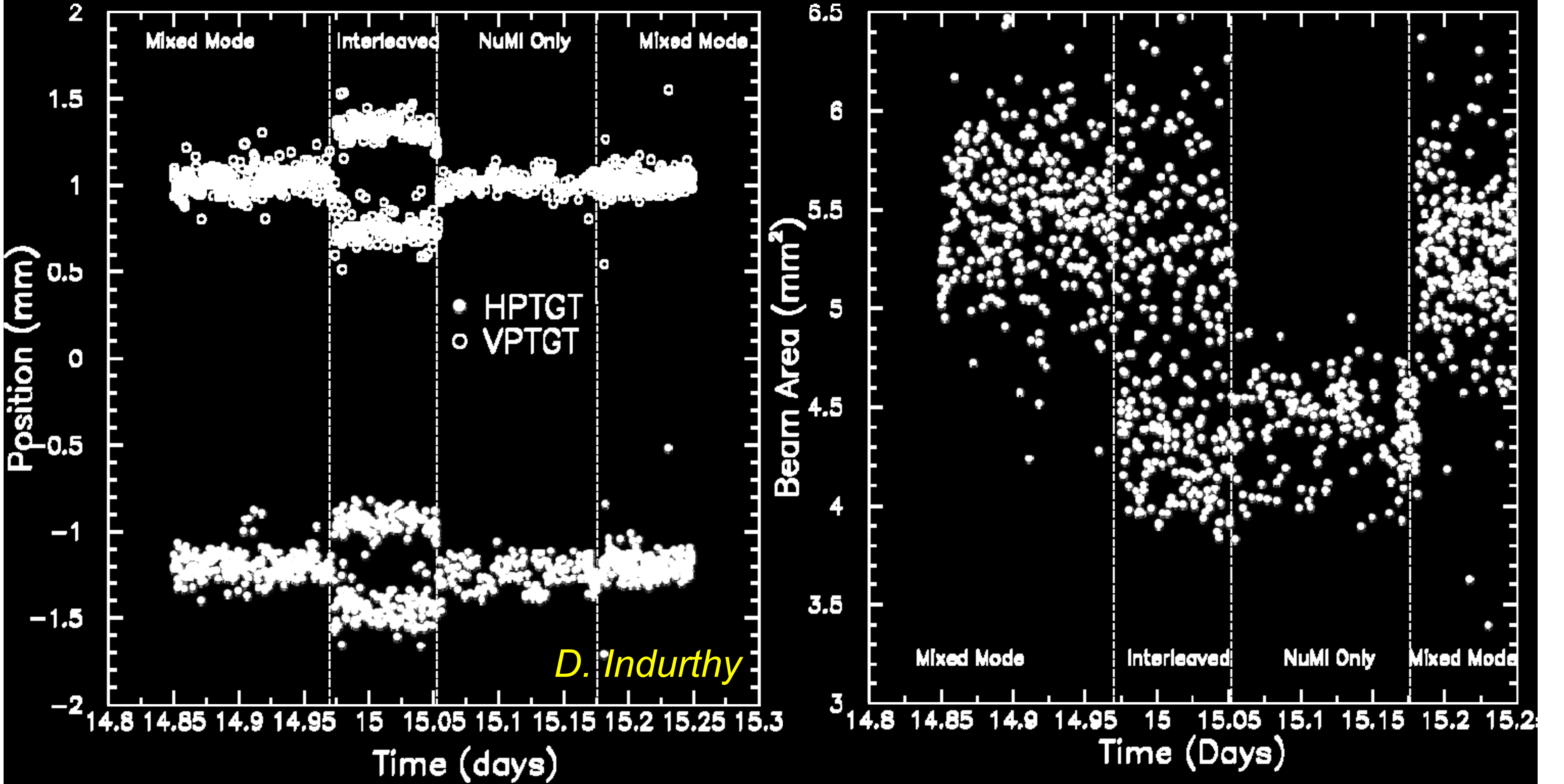
Beam Size


Horn 2
Horn 1
baffle
Main Injector Tunnel
Carrier Tunnel
Pre-target
Horizontal
Hor. Beta size
Hor. Eta size
Target
Vert. Beta size
Vert. Eta size
Vertical
Beam Size (mm)
60
40
20
0
-20
-40
-60
-50
0
50
100
150
200
250
300
350
400
Station (m)
P. Lucas

Observed Beam Sizes

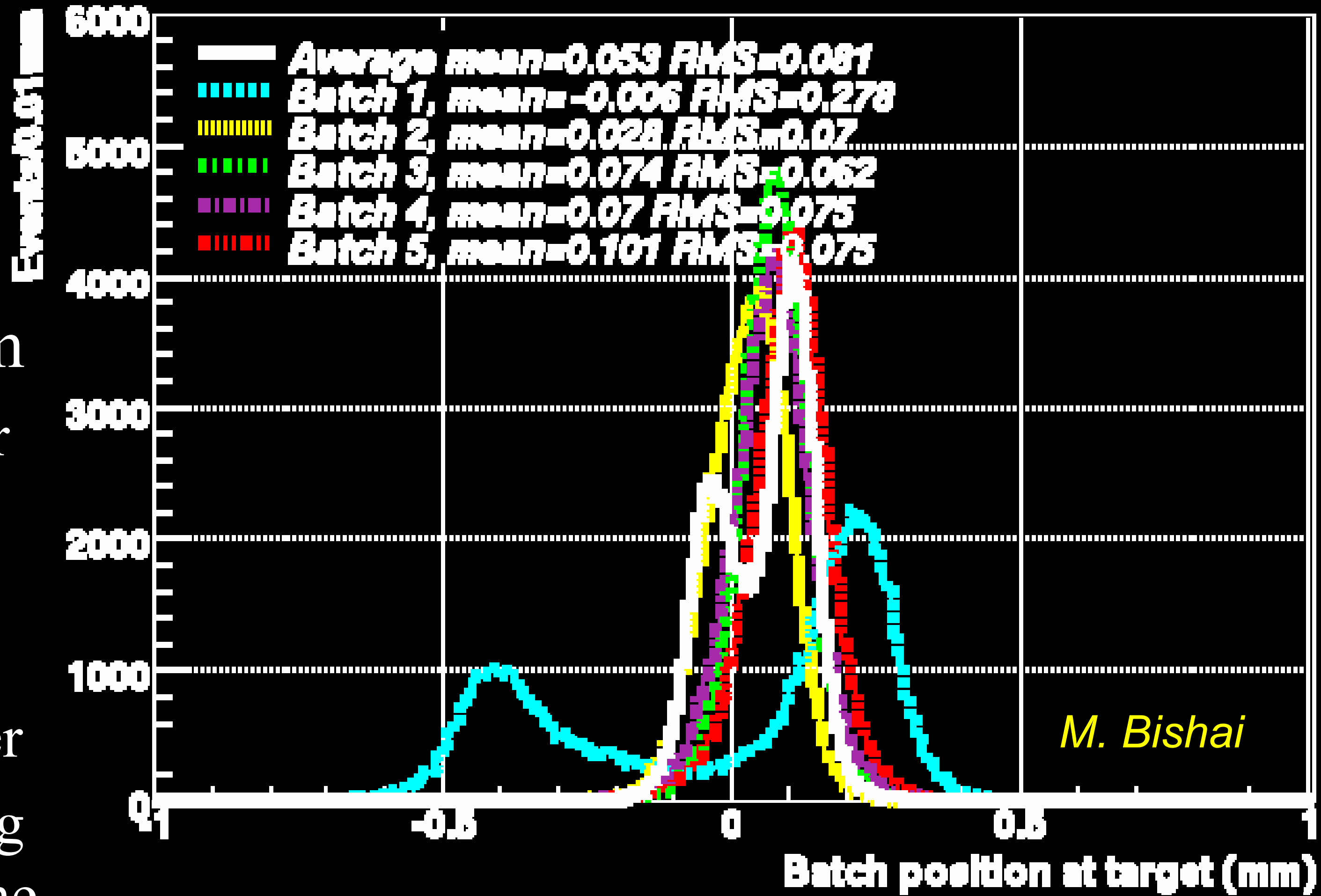


Different NuMI Running Conditions

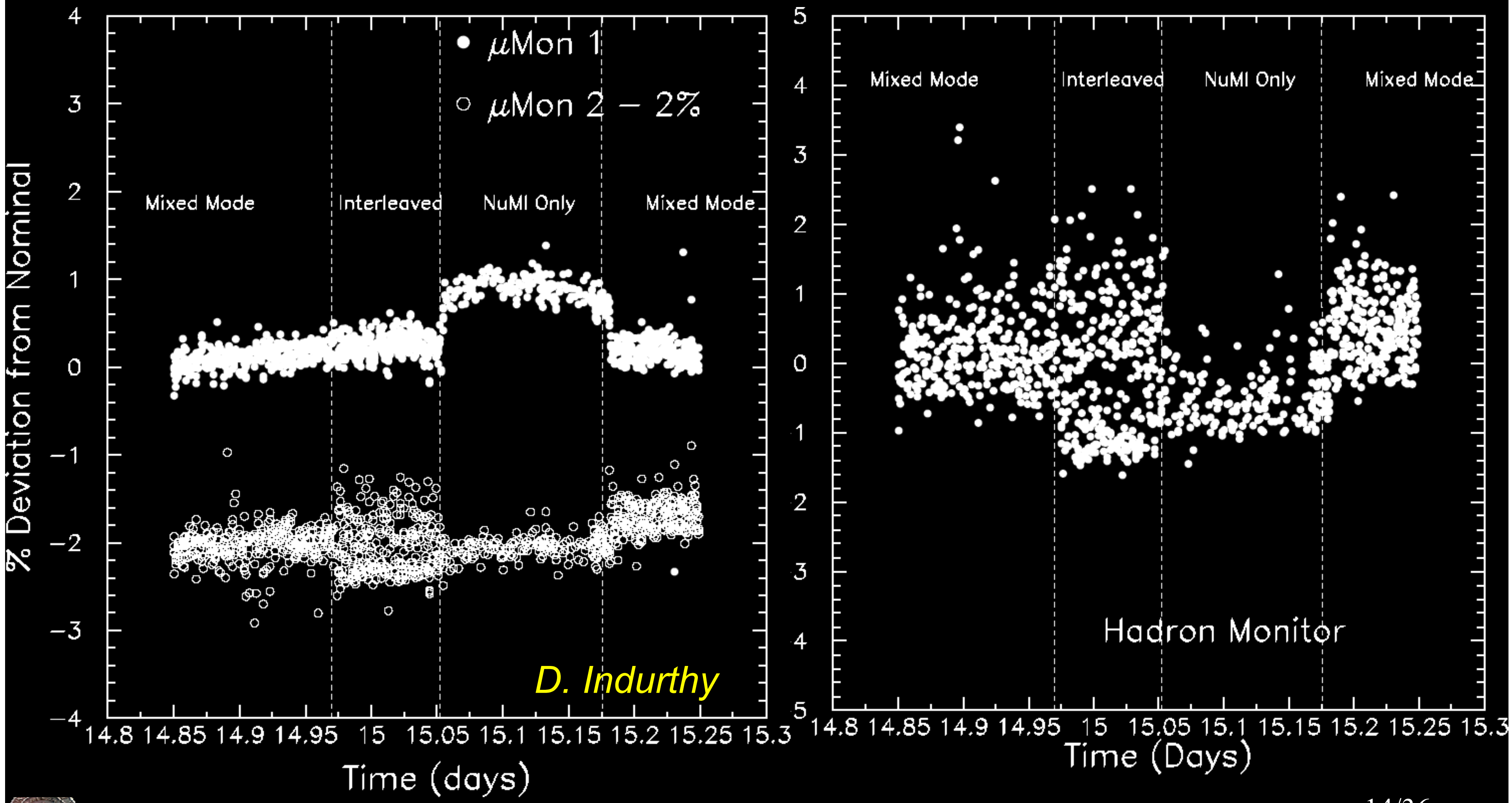


Beam During Interleaved Running

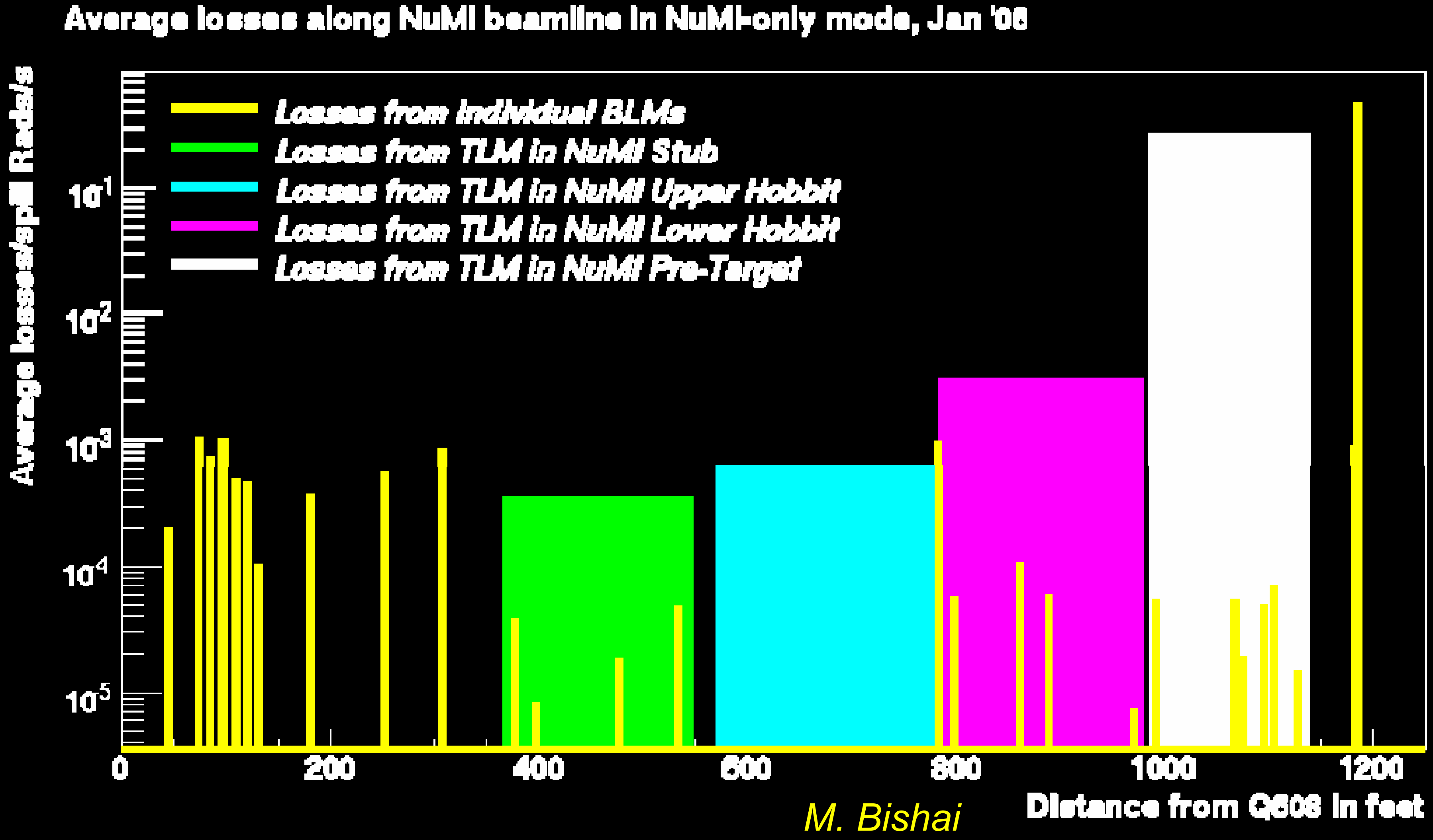
- Effects from
  - Our kicker flat-top
  - Falling edge of pbar kicker
  - Alternating orbits in the MI



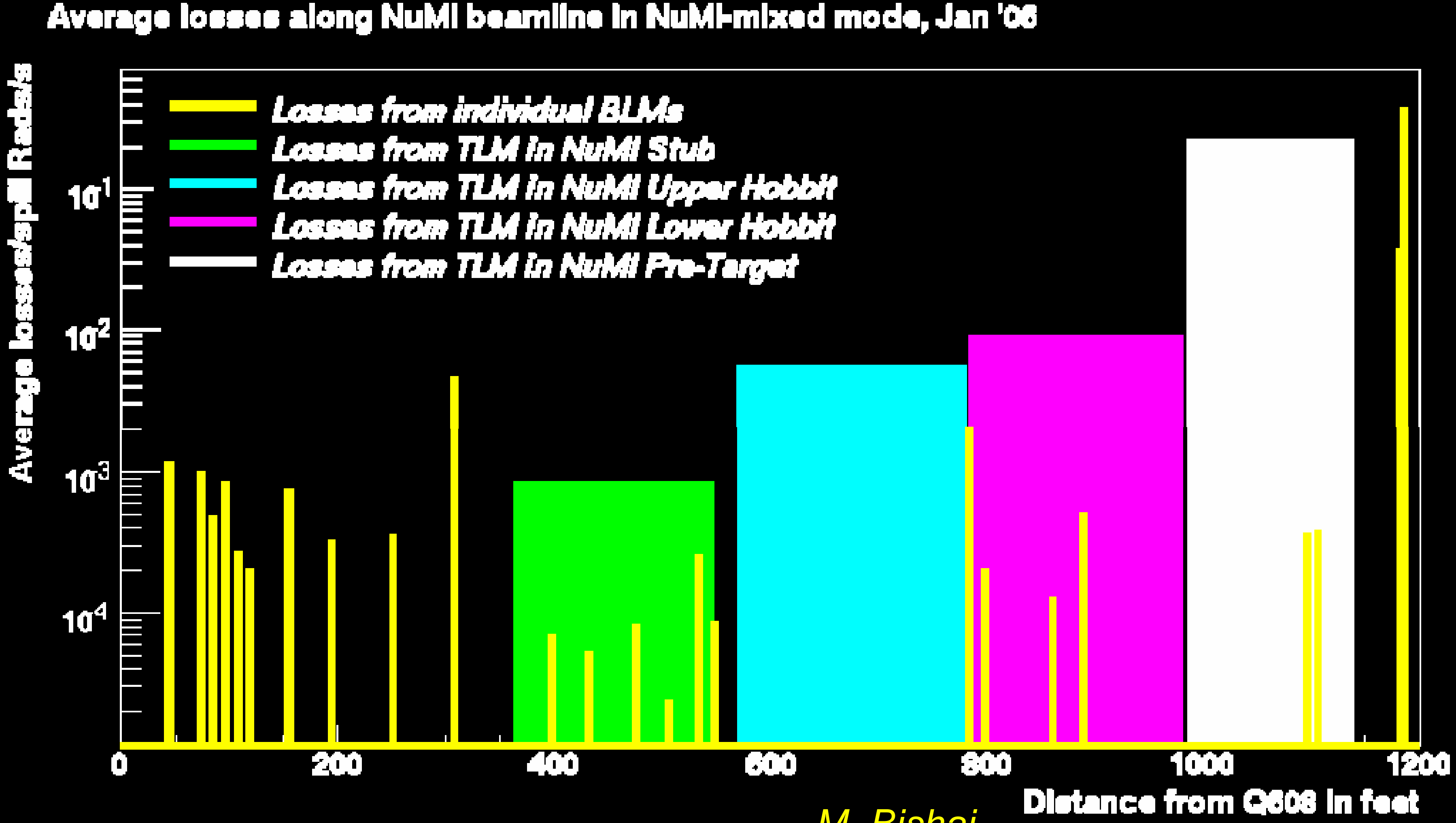
Same Observed in Muon Rates



Losses – NuMI only



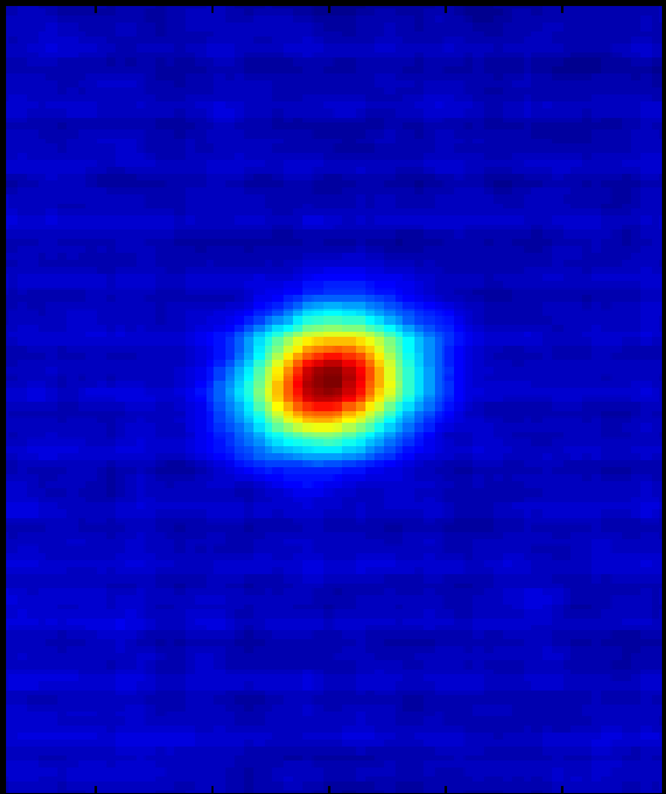
Losses – Mixed Mode

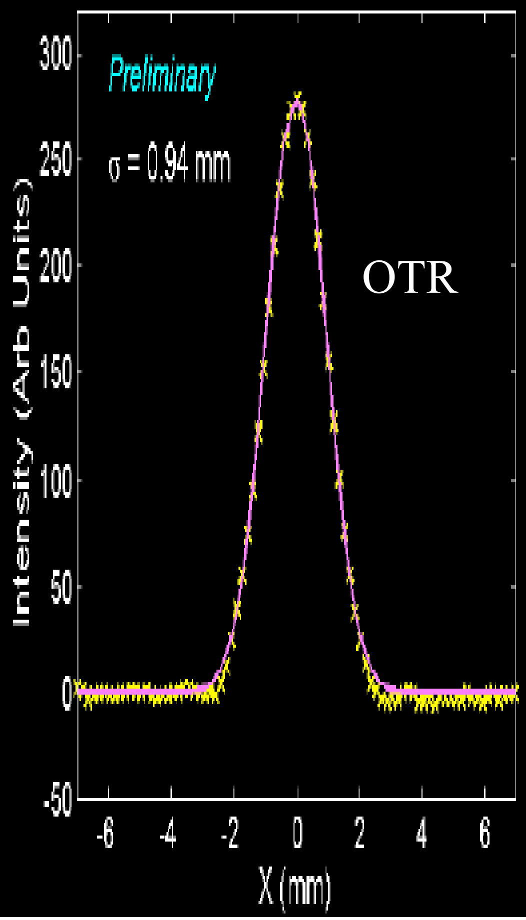


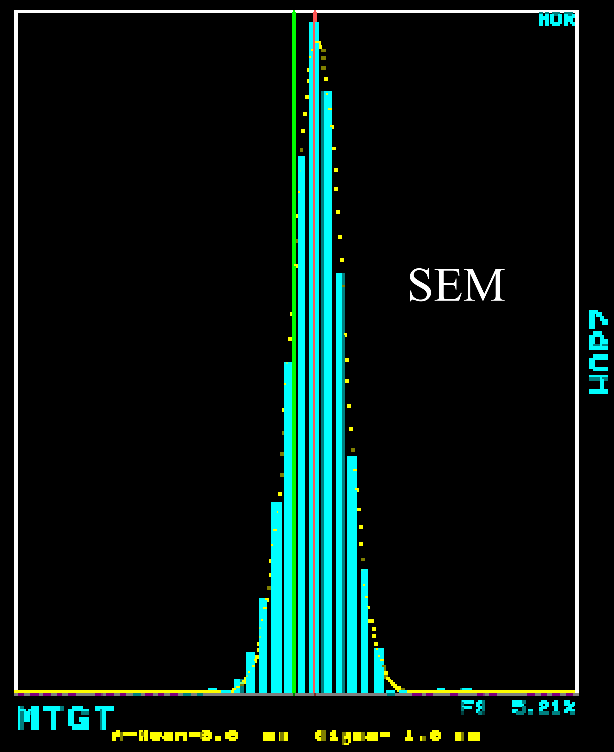
M. Bishai

Beam Spot Measurements

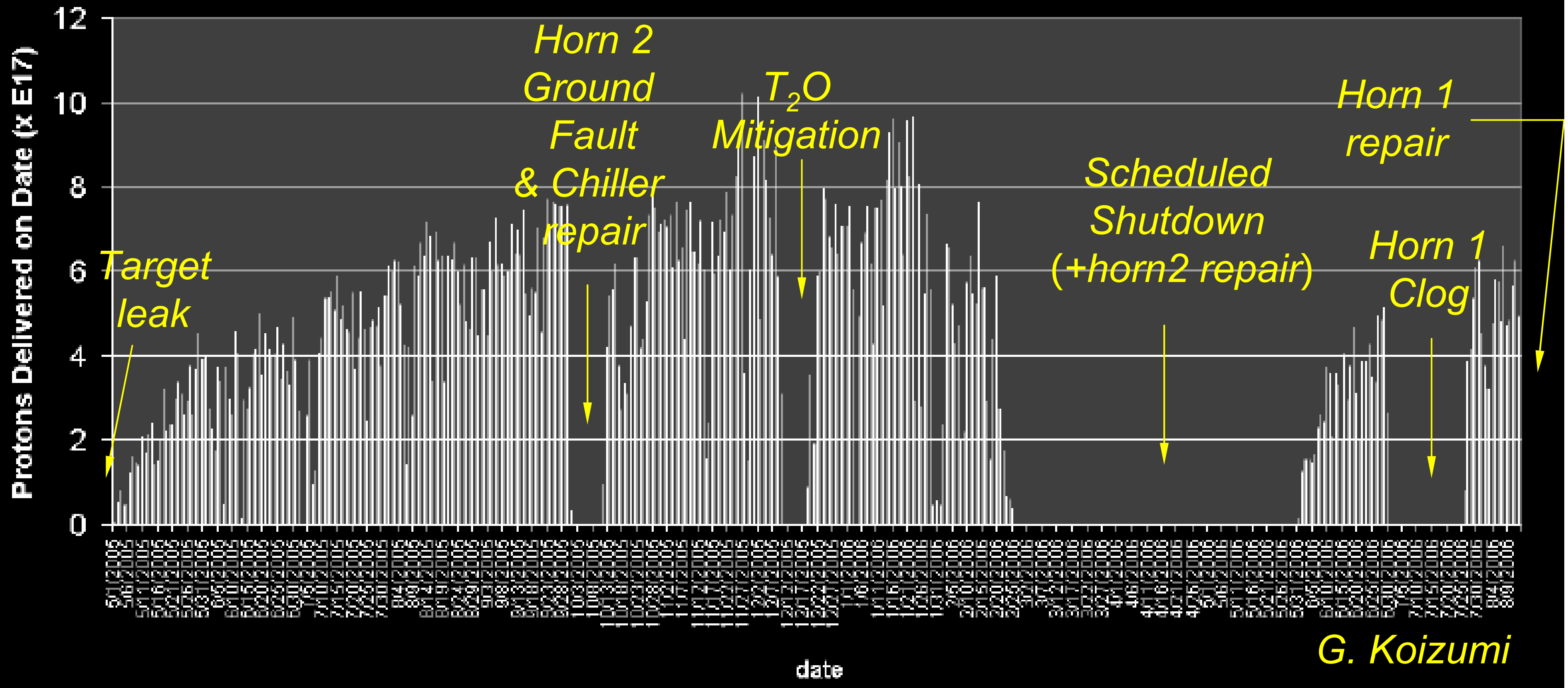
- Foil SEM: record beam dose – (*used every pulse*)
- Recently – added OTR (*not regularly in beam*)







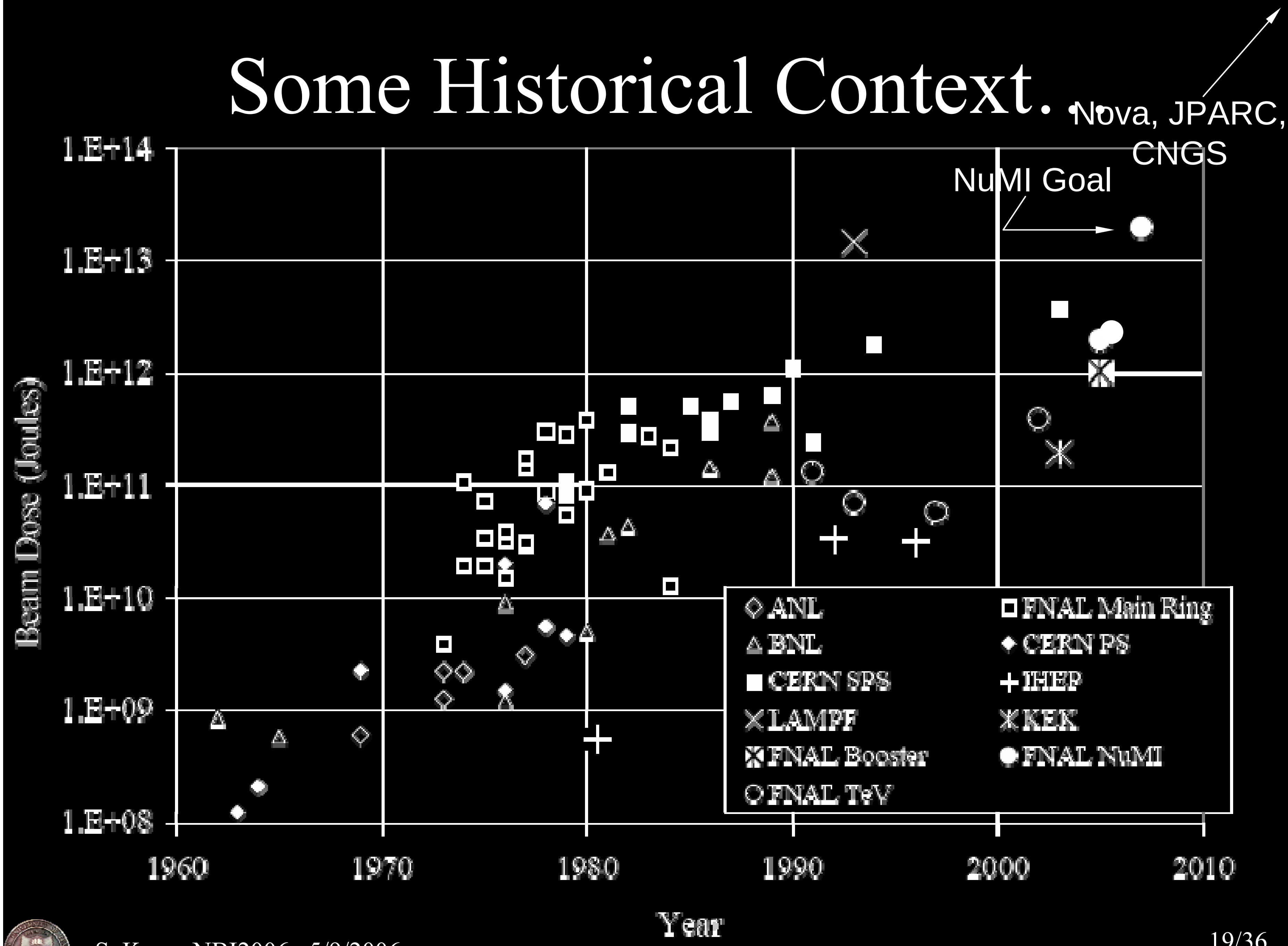
It's All About *Power*



- Achieved max ~290 kW
- Typical 200-230 kW
- Significant downtimes are a major concern

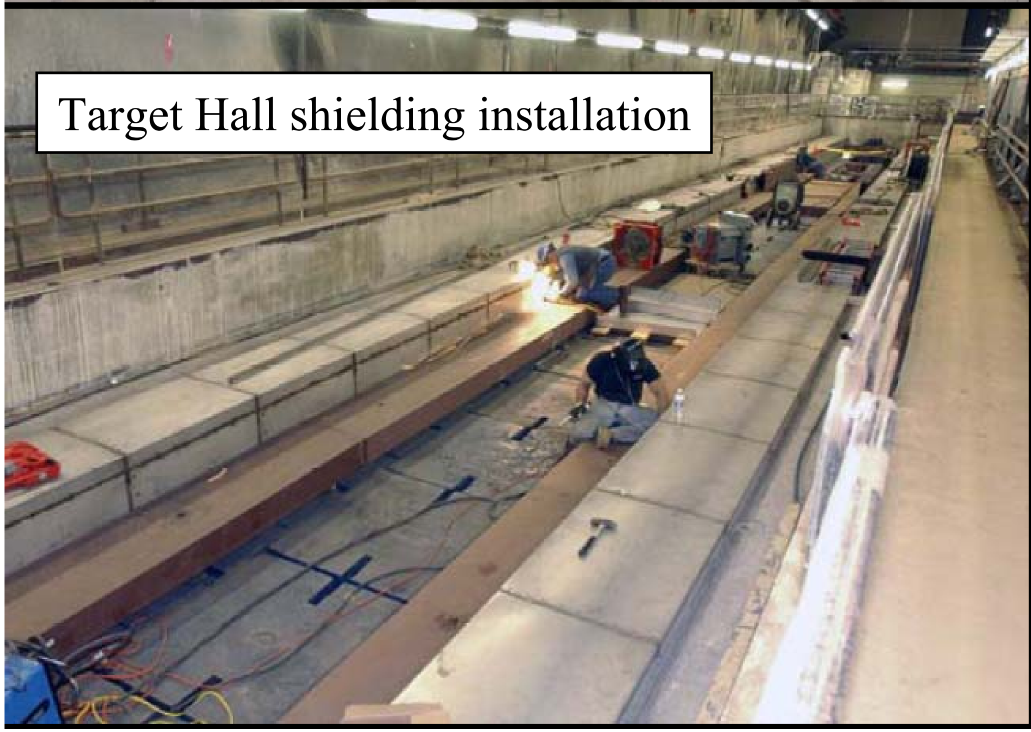
Total since May/05 1.57 E20 pot
(1.39 E20 delivered before June 2006)

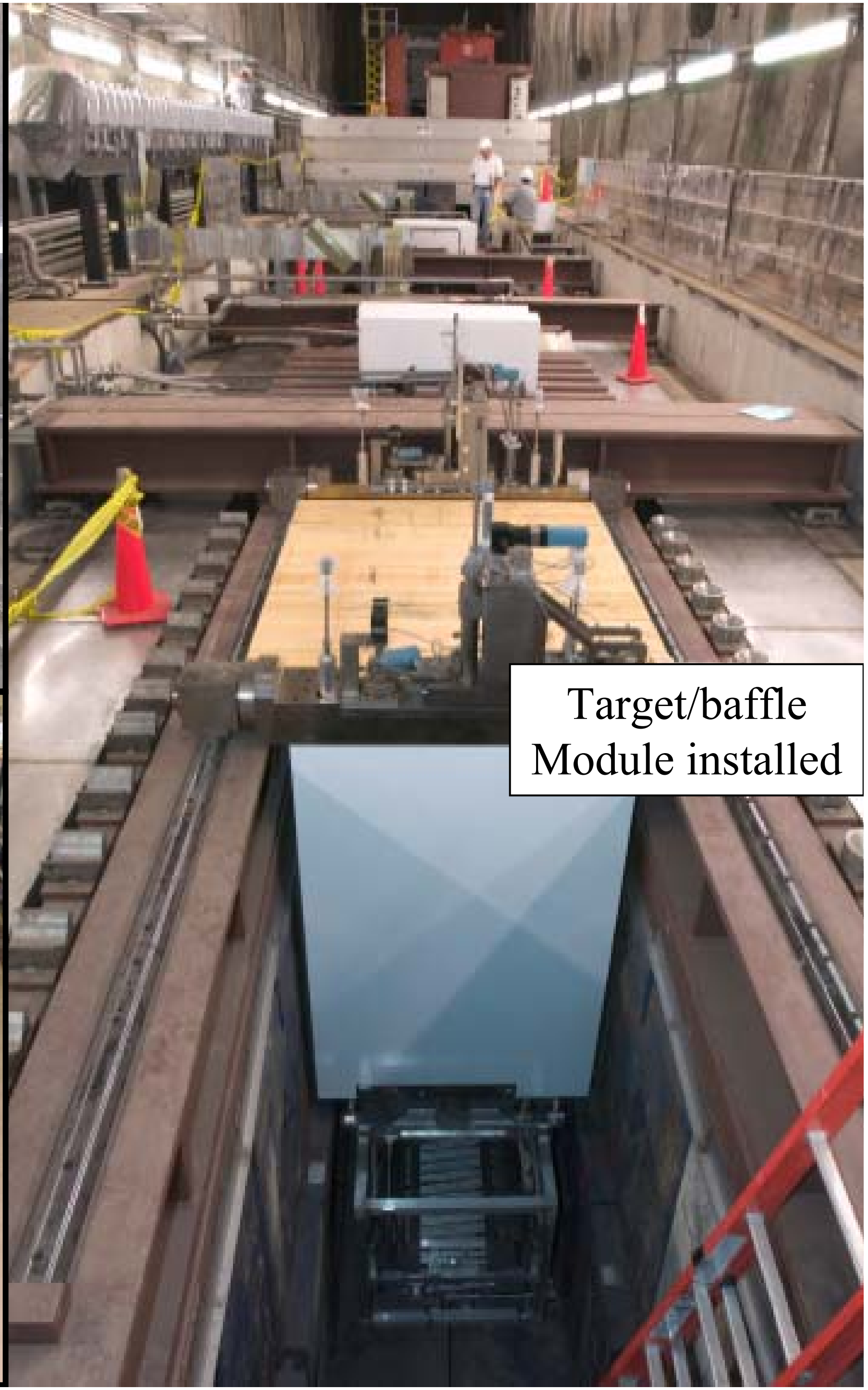
Some Historical Context.



Target Hall

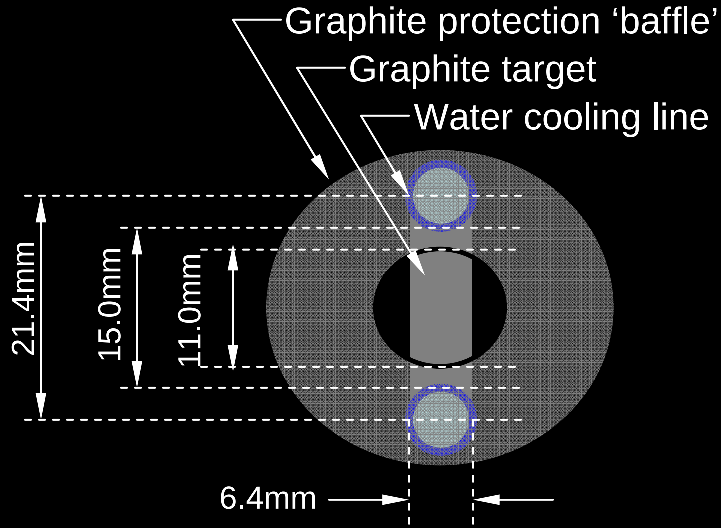

Target Hall
after
Contractor
completion
Decay pipe

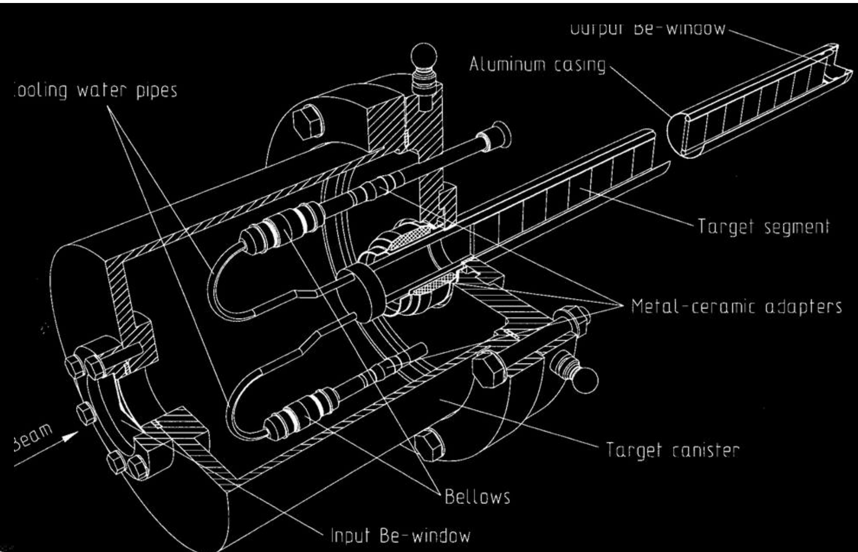

Target Hall shielding installation

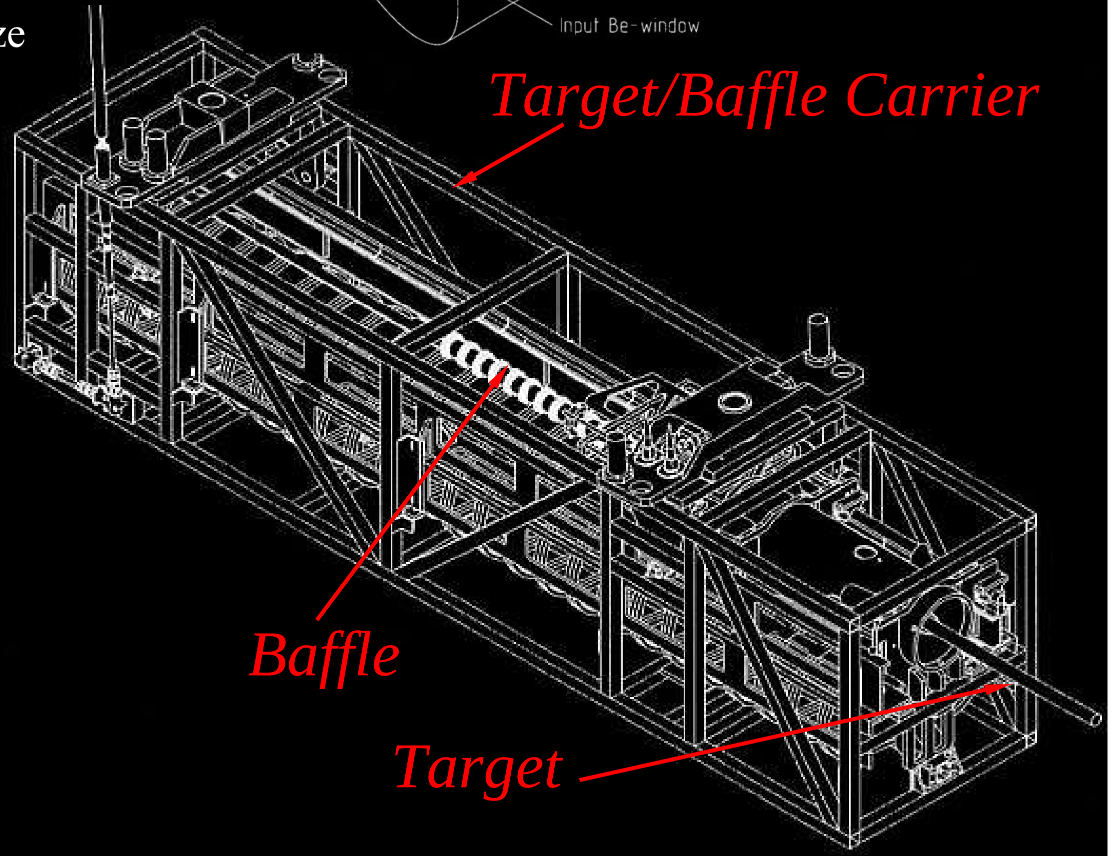

Target/baffle
Module installed

NuMI Target

- 47 × 2 cm graphite segments
  - 6.4 × 15 mm^2 profile (σ_{beam} ~ 1 mm)
  - 1.9 interaction lengths
- Water cooled
  - 4 kW deposited beam power
  - Could survive 1MW if 2mm spot size







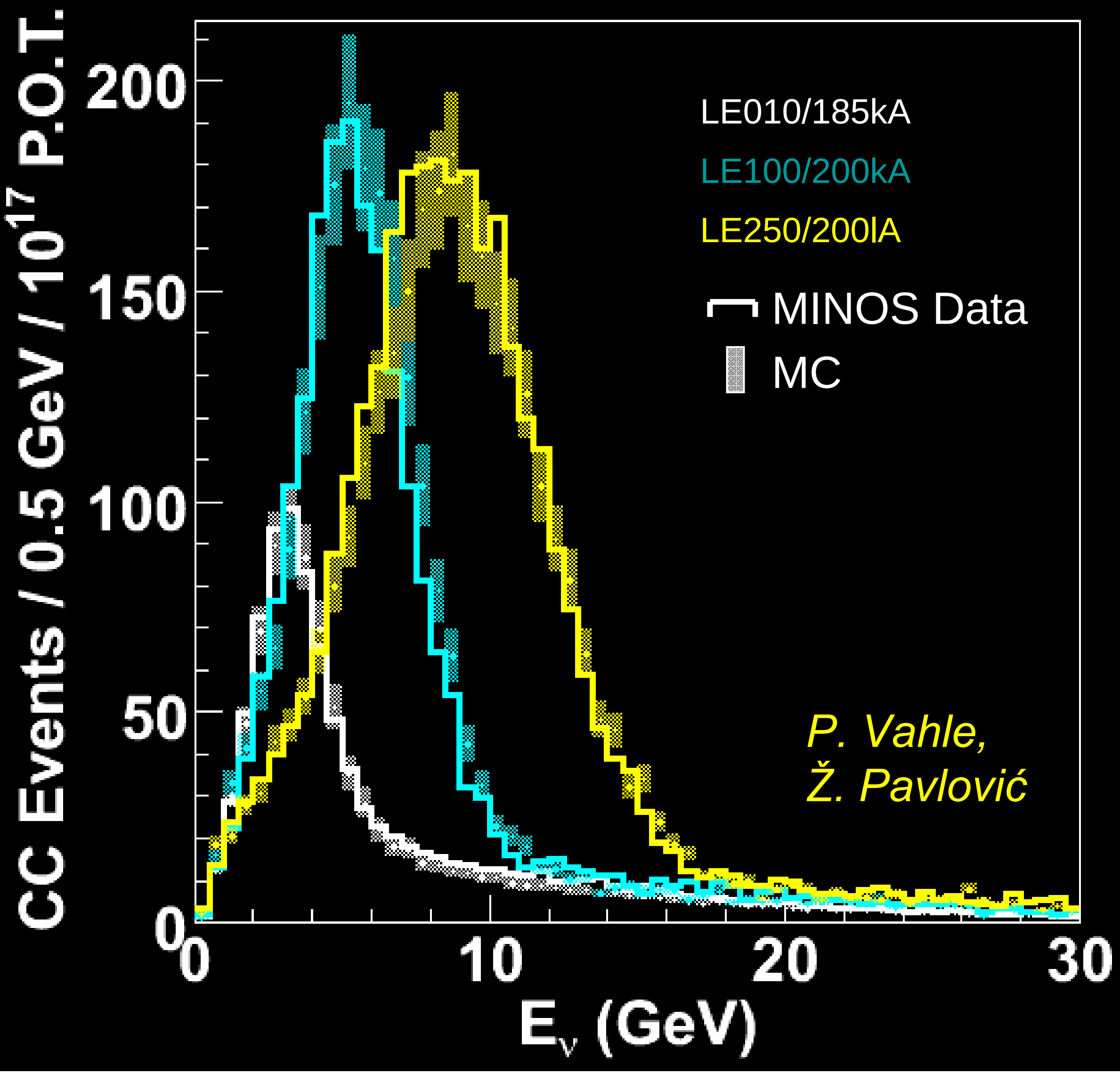

Horn 2 suspended from shielding module being lowered into shielding pit

Focusing Horns

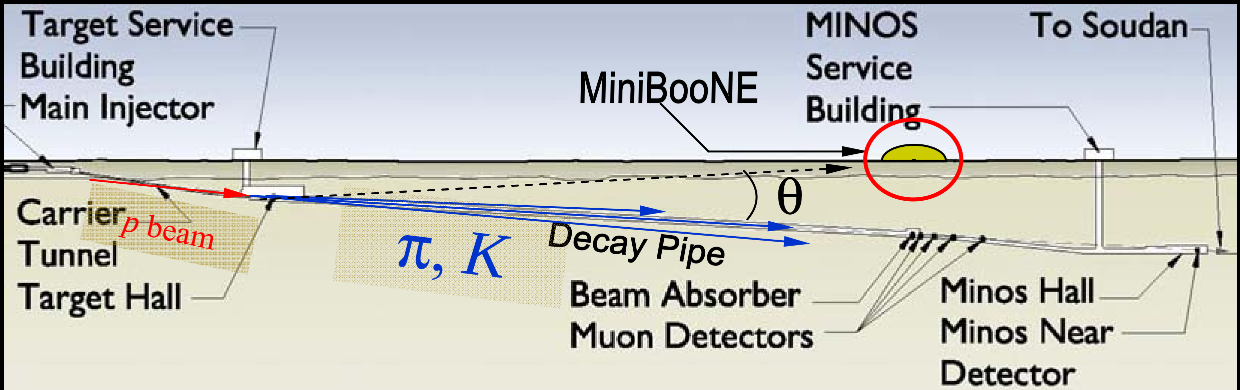
- Parabolic horn $f \propto p$
- 185-200 kA @ 2sec.
- Horn is suspended from shielding module.
- Services connected at top of shielding.
- Remote disconnect underneath shielding.
- Current calibration 0.5%
- Over 8 million pulses.

Variable Energy Beam

- Valuable for rapid publication of results
- Enabled diagnostics of beam + detectors
- Tuning of hadron production models and focusing parameters.
- Best used early in the run (target motion seized!)



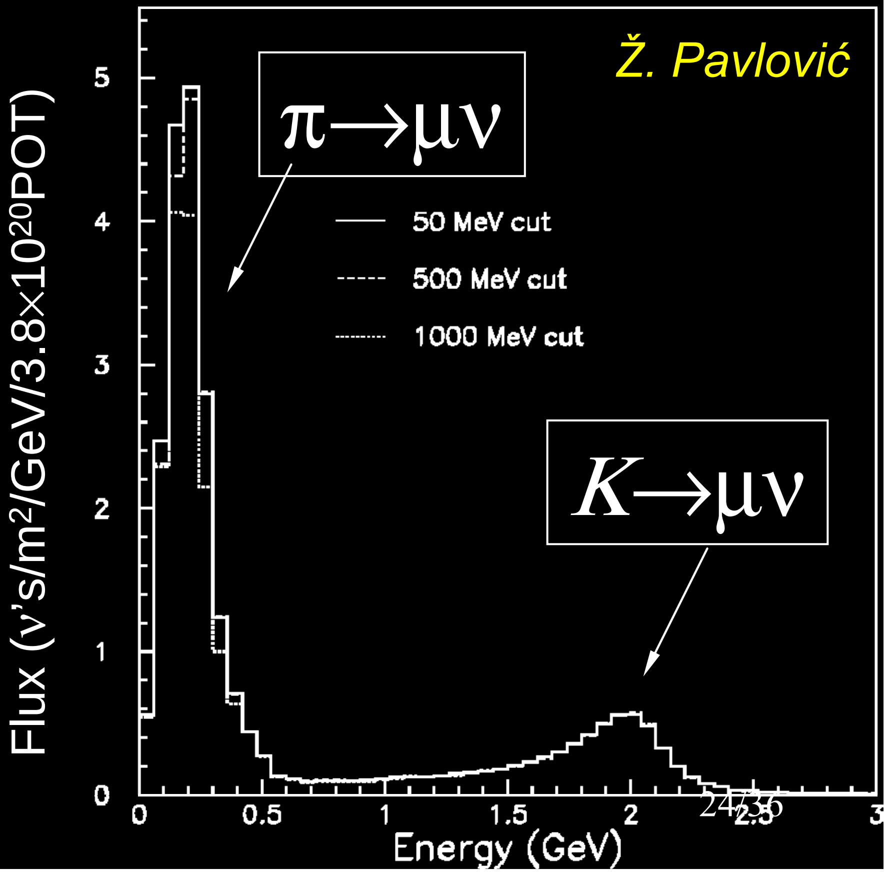
NuMI Flux to MiniBooNE



- MiniBooNE is ~110mrad from NuMI target
- Off-axis flux from π's, *K*'s clearly resolvable.

$$E_\nu \approx \frac{(1-\frac{m_\mu^2}{m_{\pi,K}^2})E_{\pi,K}}{1+\gamma^2\theta^2}$$

- Neutrinos from hadron decay-in-flight and decay-at-rest in dump



Horn/Target Work Cell

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

Railing

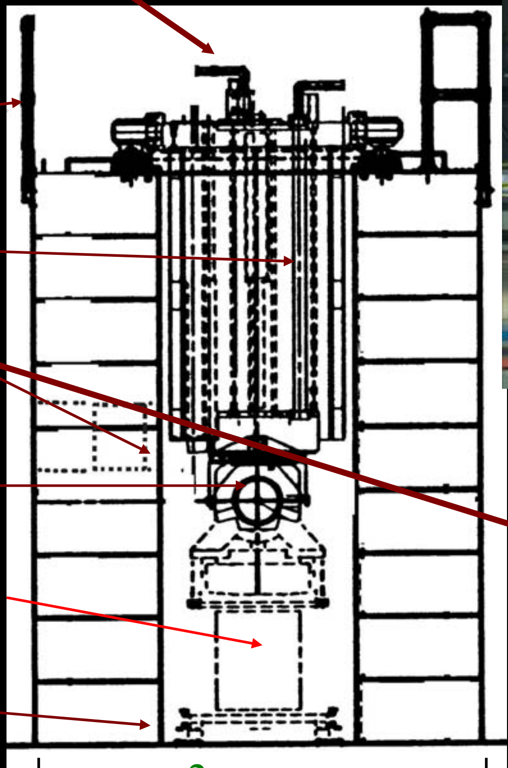
Module

Lead-glass window

Horn

Remote lifting table

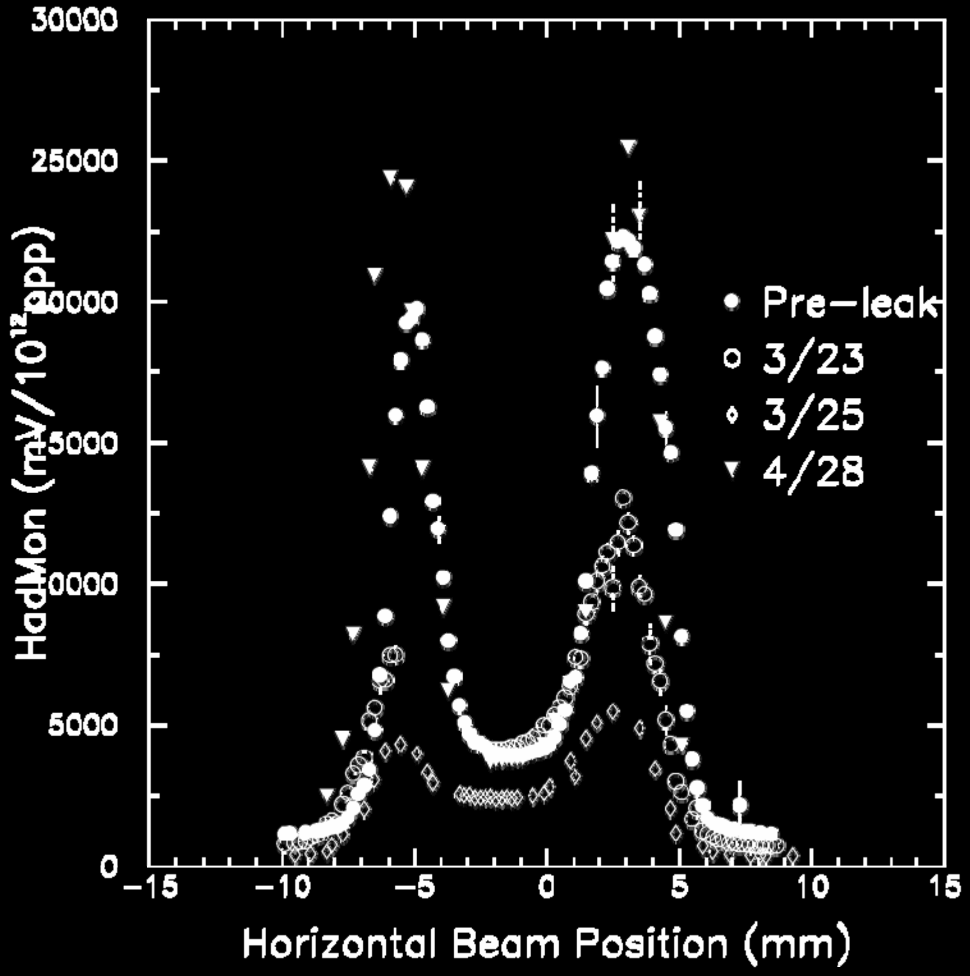
Concrete walls

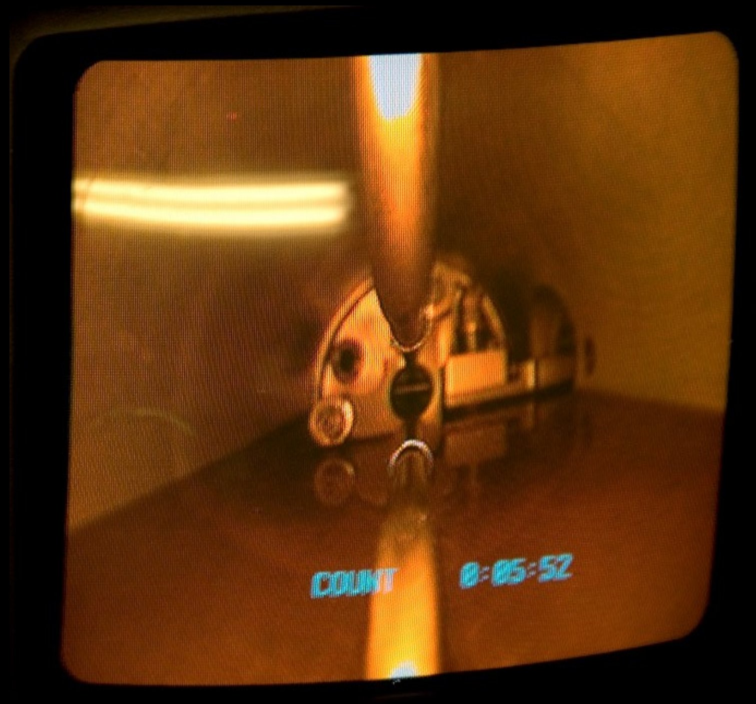


3 m

Some Operational Challenges and Solutions

Beam-Induced H_2O Leak (March '05)





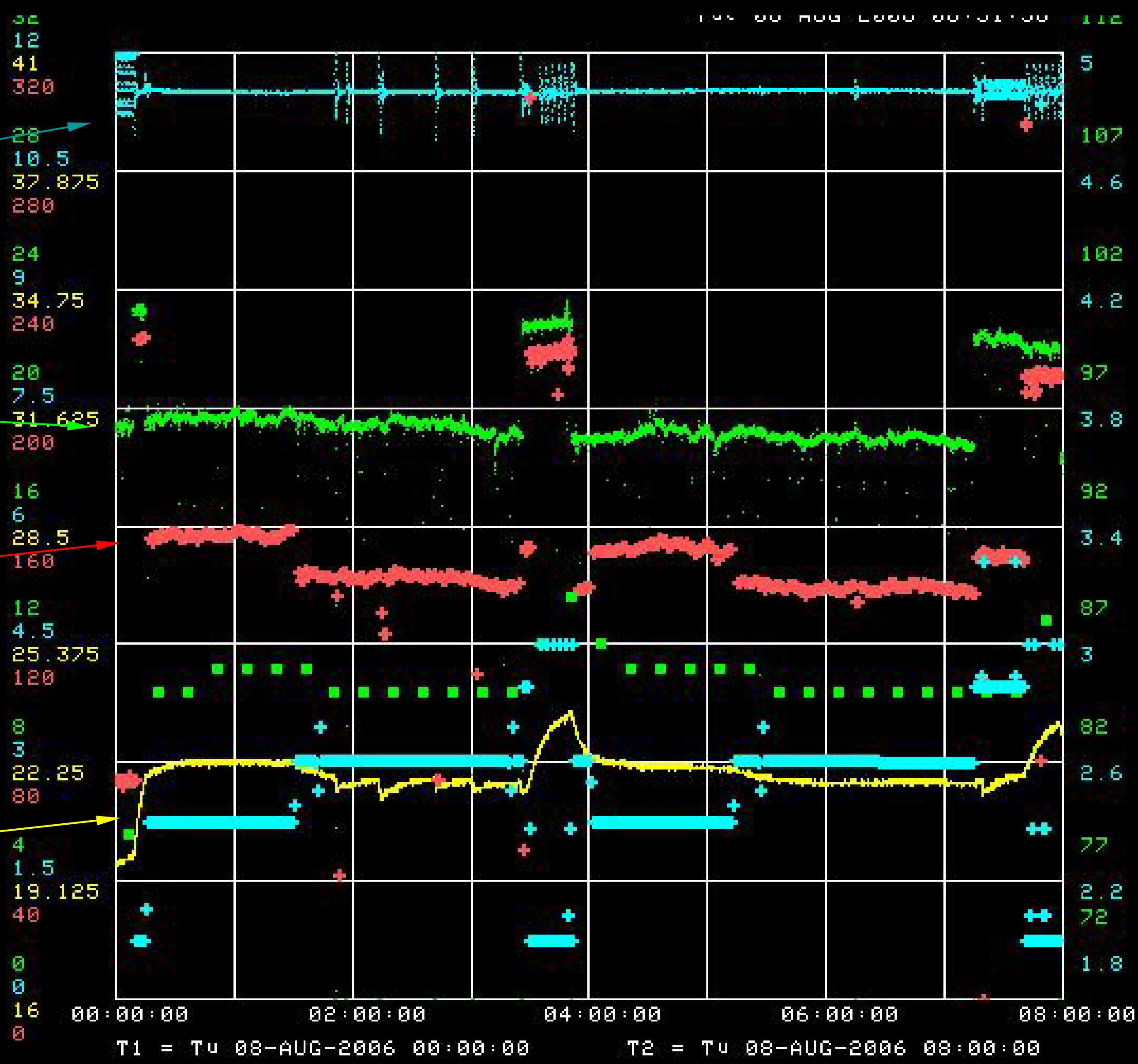
Helium Overpressure of Target

Helium flow to target canister (liter/hr)

Beam Intensity (10^{12}ppp)

Beam power (kW)

Baffle Temp. (°C)



Horn 2 Ground Fault (Oct. ’05)

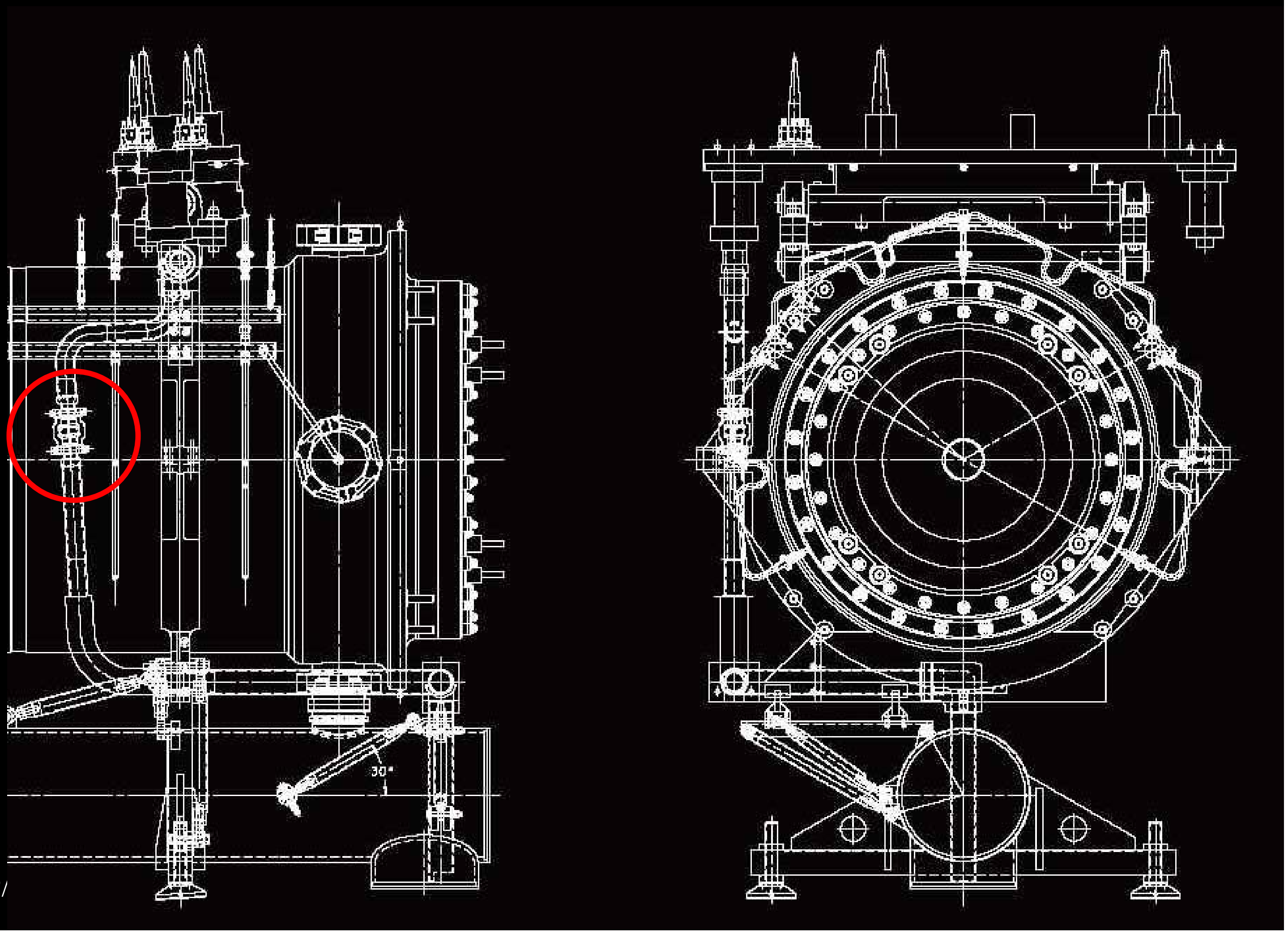
- Moving horn into work cell caused ground fault to disappear
- Mounting foot shook loose.
- Found foot down in beam line
- Replaced foot in work cell.
- False alarm from Ni plating on stripline

Horn 2 Repair (April '06)

- Symptom: Suction of water back from Horn 2 could not keep up with water spray rate to the horn – water built up in the horn

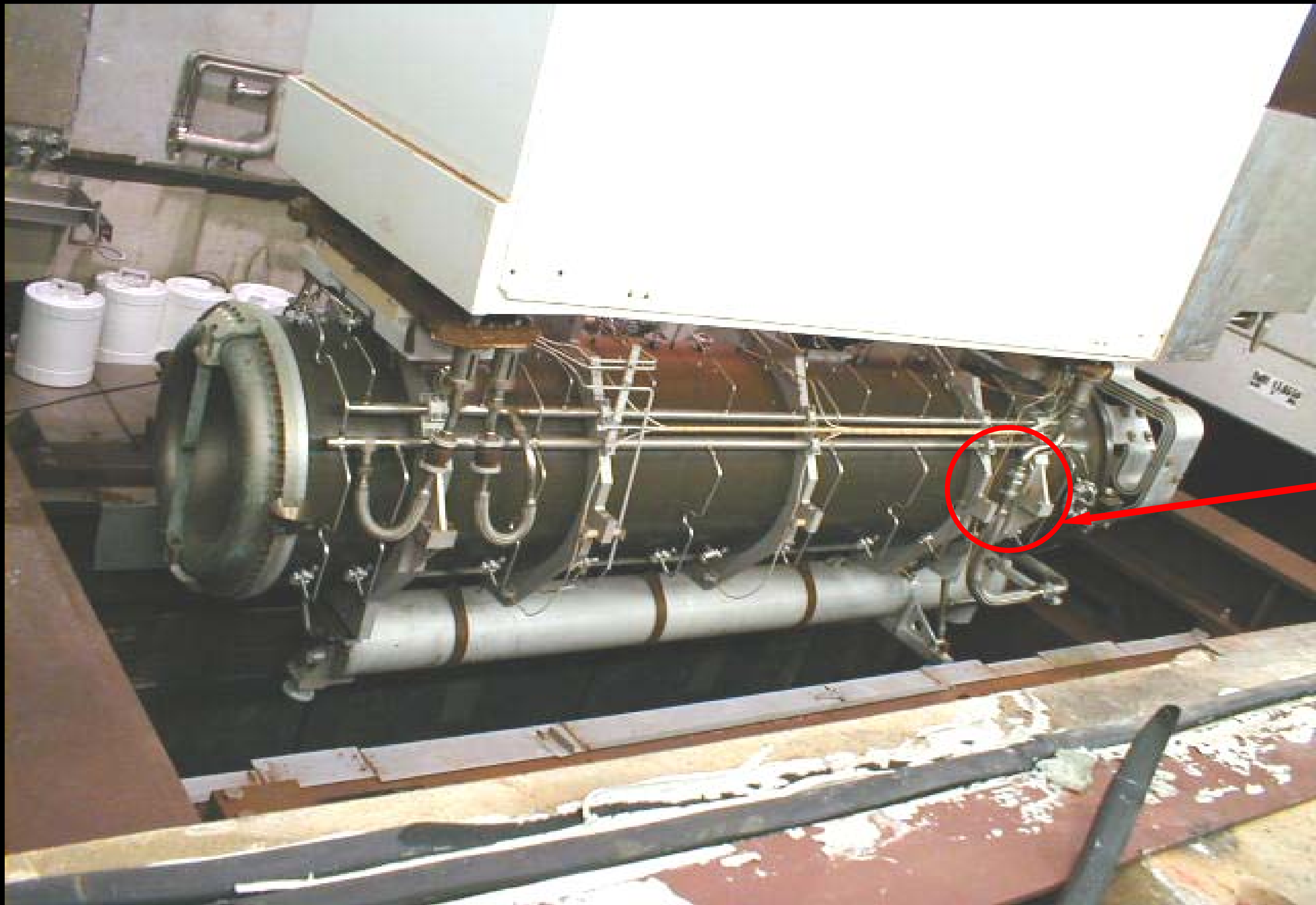
- Impressive effort to replace this cooling line in the work cell

Leaking Ceramic Break in Cooling Line



- Just 280 mrem dose spread over several technicians (*see talk by J. Hylen*)

Returning Horn 2 in Beamline



Repaired line

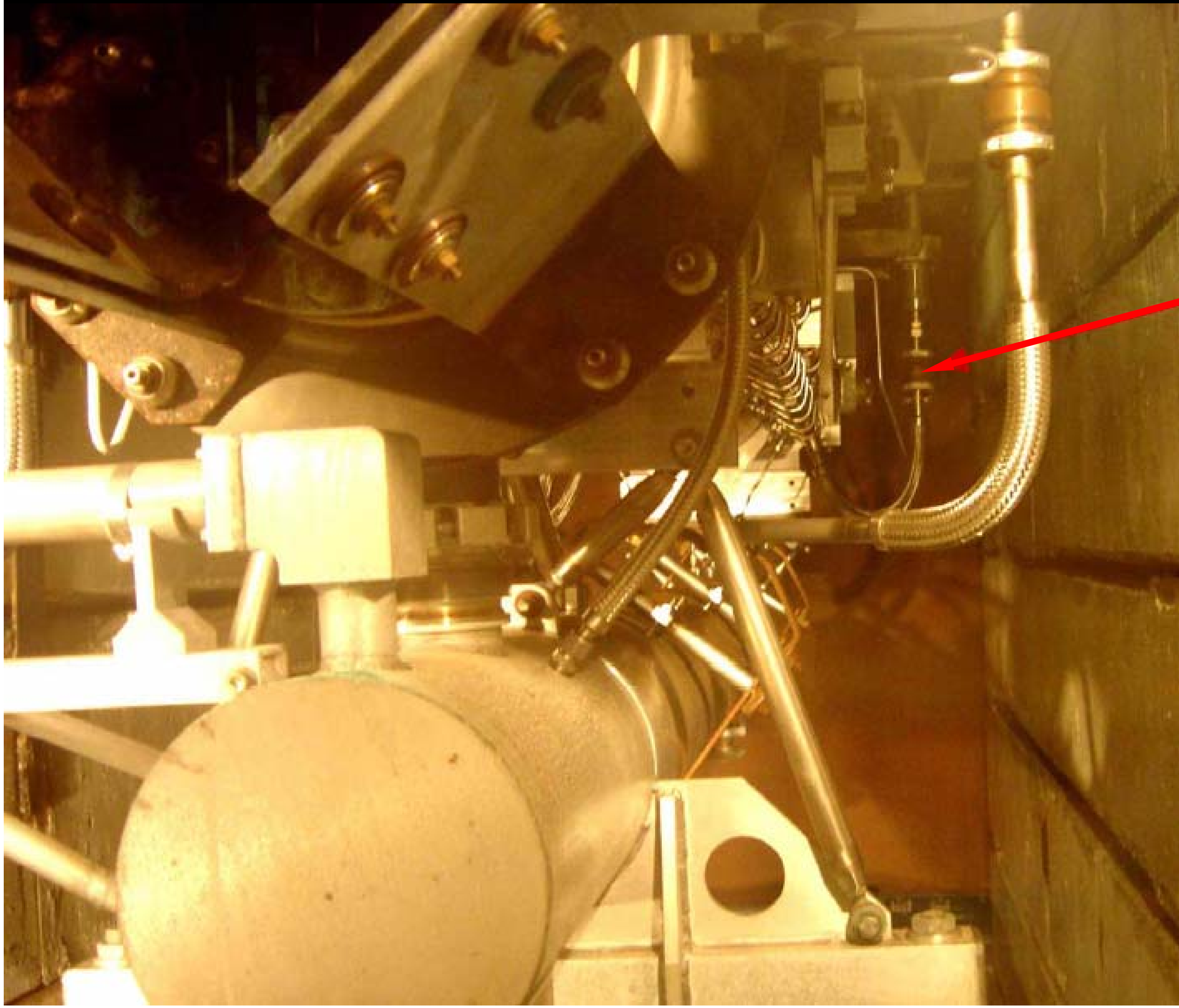
Horn 1 Clog (July 2006)

- In attempting to drain H_2O out of horn 1 surge tank, shut off input line
- Over-pressure caused back-flow through deionized H_2O loop
- Resin beads (0.5mm∅) pushed down into horn, clogging cooling spray nozzles.

- Heroic efforts to suction beads *in situ* out of horn 1 by reverse pressure.

Horn 1 is below the Shielding module

Repair of Horn 1 Cooling Line



Similar ceramic insulator

- Same leak in ceramic
- 15-20 mrem/sec. activation made repair challenging
- Extensive practice, careful planning

Question:
What is the Single Most Important Material in Neutrino Beam Lines?

- Graphite? (*target, beam dump*)
- Aluminum? (*horns, beam dump*)
- Steel? (*shielding*)
- Concrete? (*shielding*)
- TRITIUM

Tritium Discovery

- US surface water standard
  = 2000 pCi/ml
- US drinking water standard
  = 20 pCi/ml
- Typical concentration in FNAL ponds 3 pCi/ml
- Detected outflow in Indian Creek 3 pCi/ml
- Detection limit 1 pCi/ml
- Current level <1 pCi/ml (extensive mitigation!)

- Tritiated water level suprisingly high given NuMI beam power to date
- Water shouldn't have left site

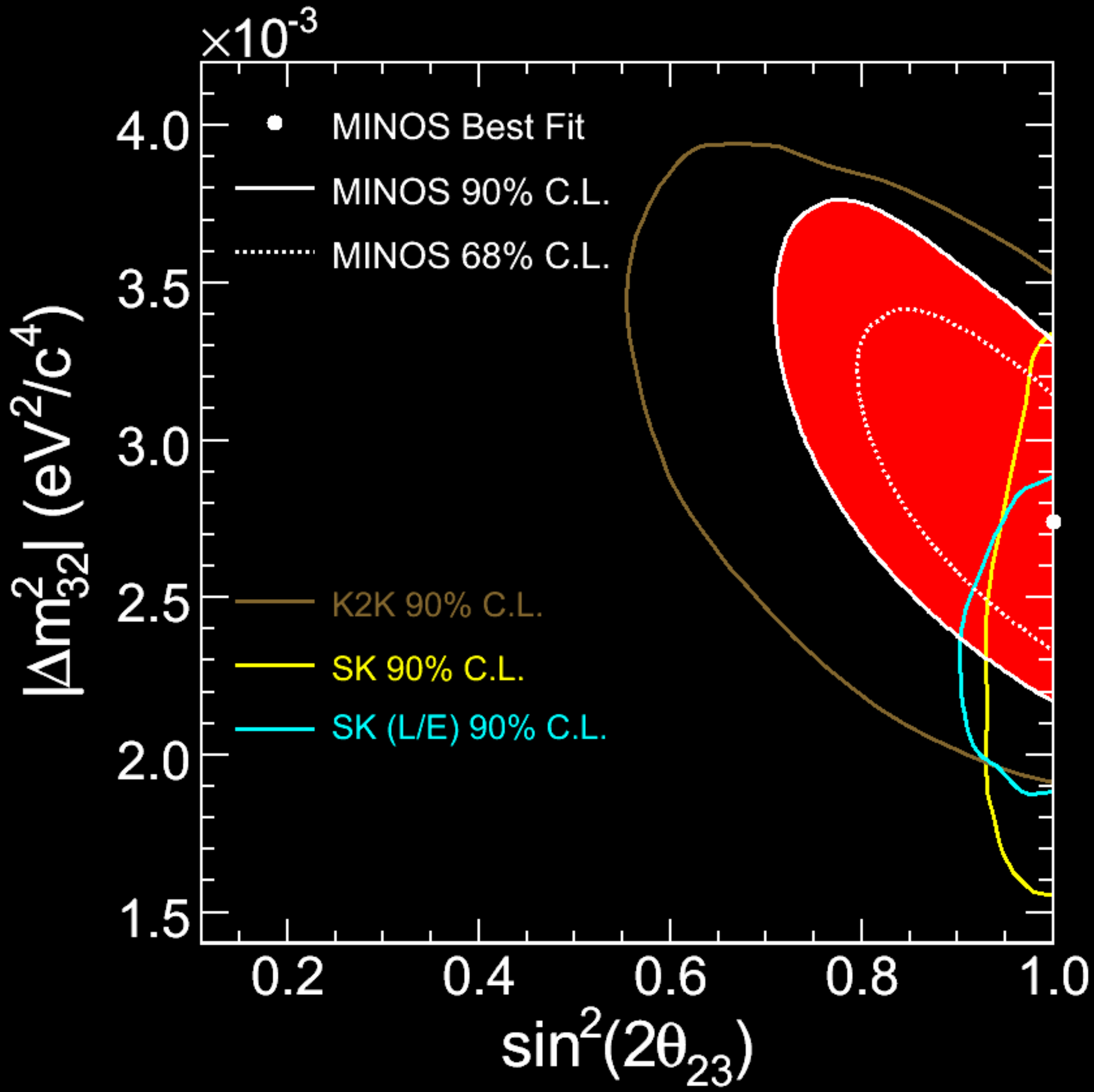
The New Tools of Nu Beams

Collect moisture here

Collection Tank

M. Kordosky – Seminar 4:30pm Today

- Results submitted to Phys. Rev. Lett.
- Based on 1.4×10^{20} POT
- We anticipate much more data to come.



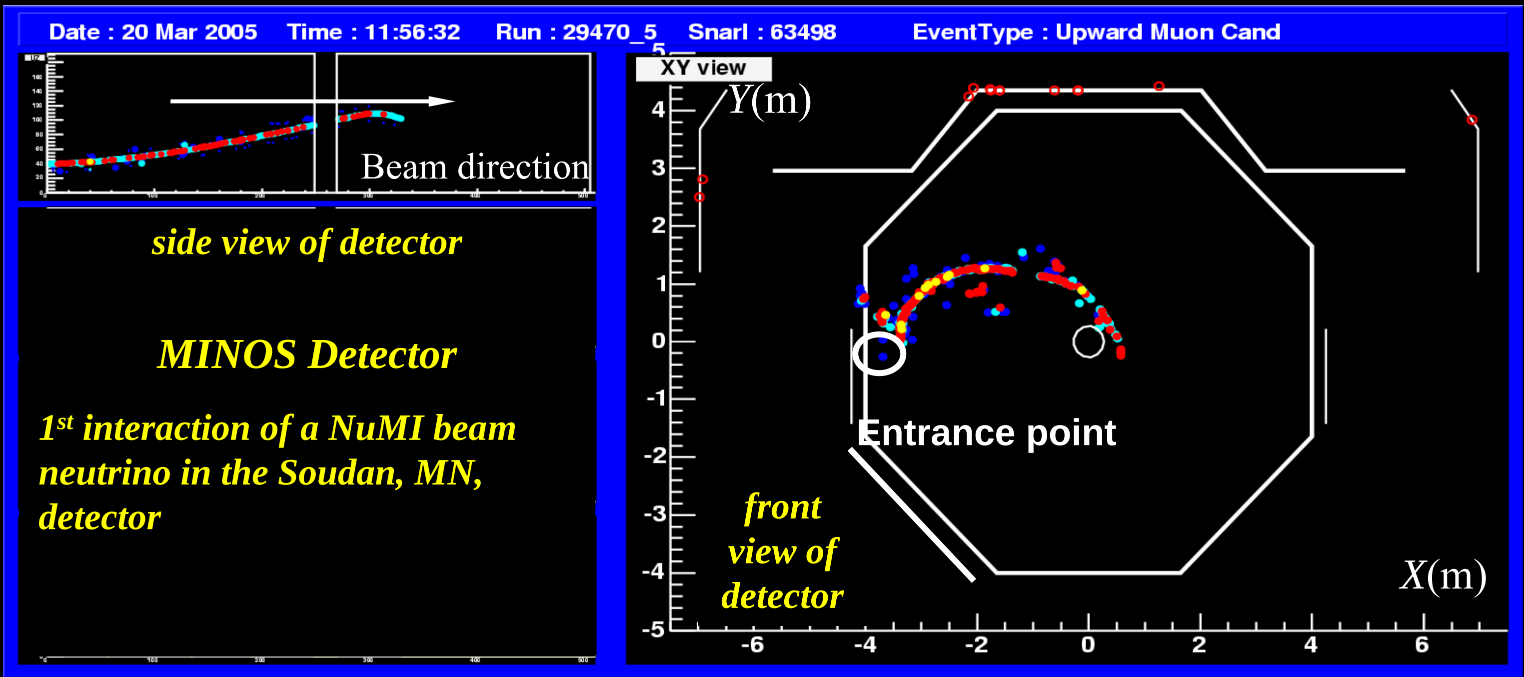
Talks at This Workshop

- Bob Zwaska – Primary Beam Performance
- Bob Zwaska – Main Injector Upgrades for 1 MW
- Mike Martens – NuMI Upgrades for 1 MW
- Jim Hylen – Target/Horn Experience
- Mike Martens – Radiological/Tritium Issues
- Jim Hylen – Hot horn repairs
- Sacha Kopp –*Rant* about Secondary Beam Monitors
- Žarko Pavlović – Beam Simulations
- Jon Paley – FNAL/E907 (particle production)

Summary

- 1st test NuMI primary line 12/3/04 – 12/4/04
- 1st test NuMI target/horns 1/19/05-1/21/05

- 1st test combined MI operation for NuMI and $\overline{p}$ production 3/8/05-3/23/05.
- Thus far ~ 1.6×10^{20} protons on target, superb Main Injector performance.
- Many operational challenges *overcome*, detailed talks in this workshop
- Much planning underway for scaling NuMI to 700 kW and beyond



Thanks for Bringing the Neutrino Conference back to CERN!

ORGANISATION EUROPÉENNE POUR LA RECHERCHE N

CERN EUROPEAN ORGANIZATION FOR NUCLEAR

THE 1963 NPA SEMINARS

THE NEUTRINO EXPERIMENT

GENEVA

CERN 65-32
December 1965

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

INFORMAL CONFERENCE ON EXPERIMENTAL NEUTRINO PHYSICS

held at CERN
20-22 January, 1965

PROCEEDINGS
edited by
C. Franzinetti

GENEVA
1965

CERN 69-28
10 November 1969

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

NEUTRINO MEETING

CERN, Geneva, 13-14 January, 1969

PROCEEDINGS

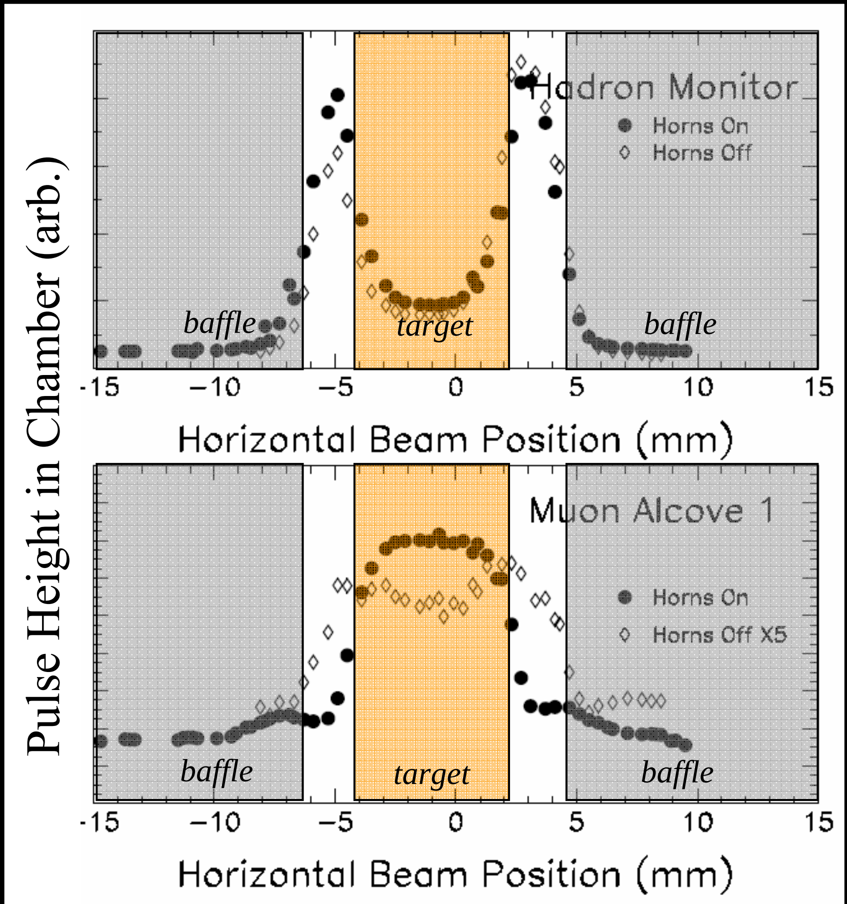
Editors: J.B.M. Pattison
C.A. Ramm
W.A. Venus

GENEVA
1969

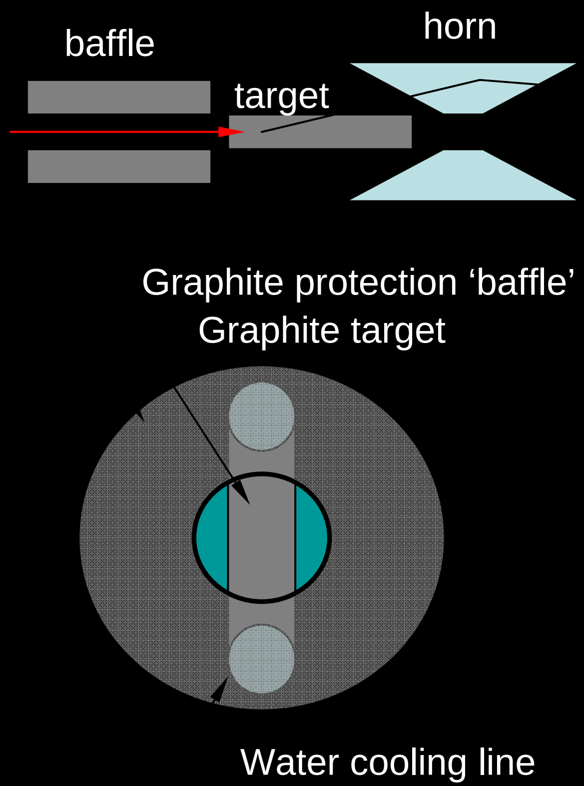
Backup Slides

Beam-Based Alignment of Target Hall Components

- Primary beam scanned horizontally across target and protection baffle
- Small gap between target and baffle allows us to find edges using the Hadron Monitor and the 3 Muon Monitors.



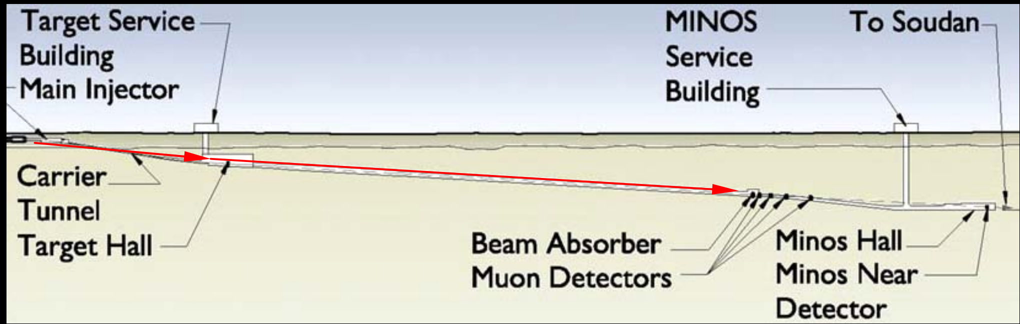
- Discovered small (~1.2 mm) offset of target relative to primary beam instrumentation.

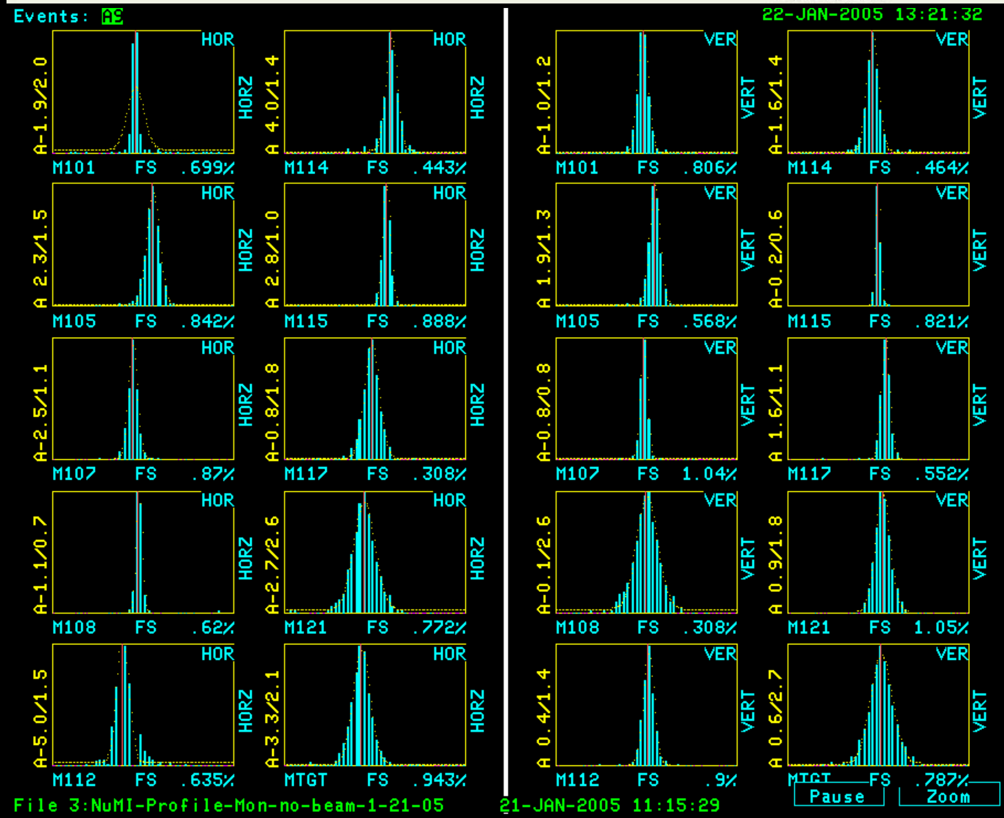


1st Commissioning Run

Dec. 3-4 2004

- Clean delivery of beam through transport line, target hall, and all the way to beam absorber (~700m free drift).





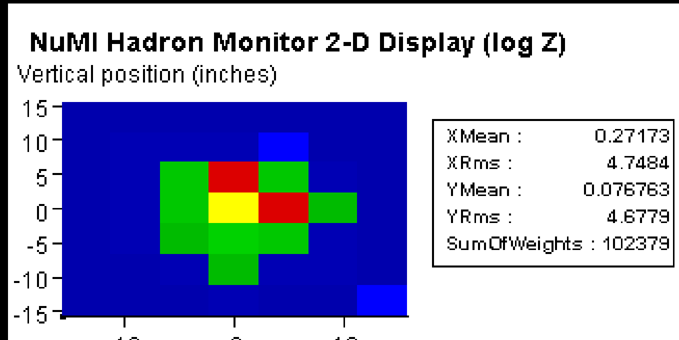
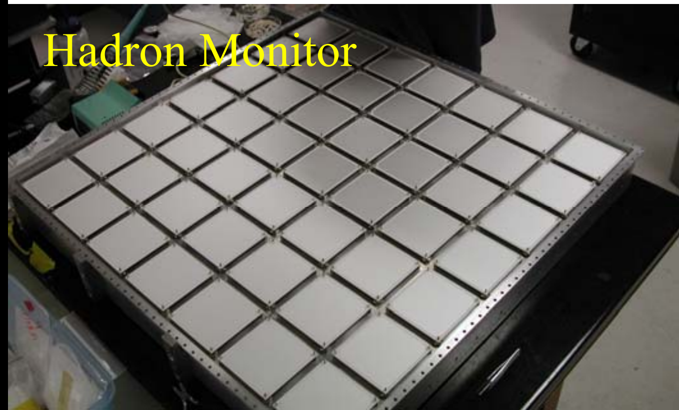
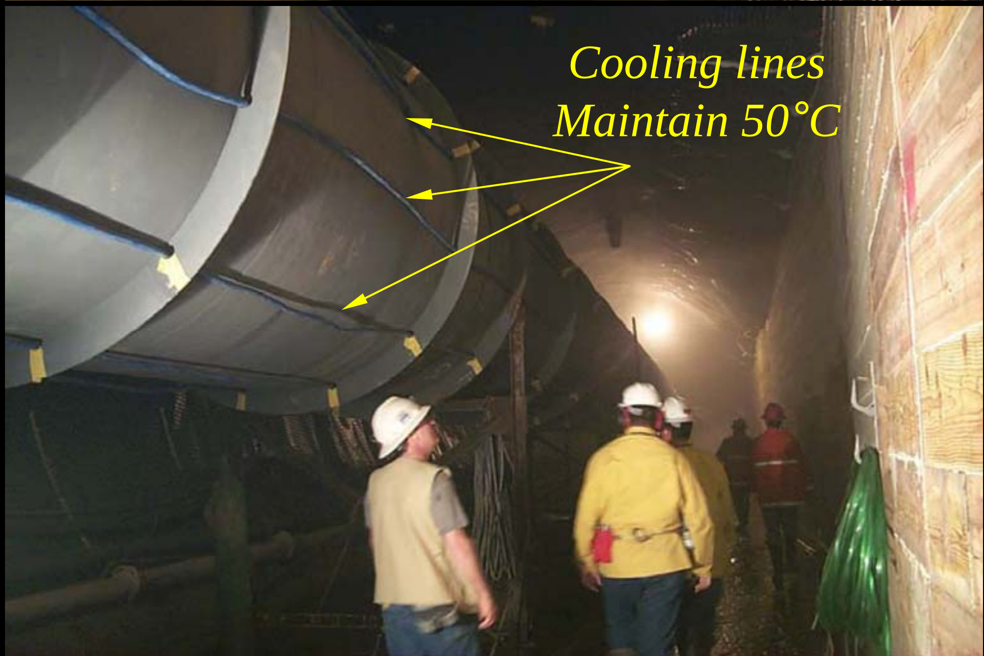


figure courtesy M.Bishai, B.Viren



Decay Volume



- Bored tunnel back-filled with concrete
- Decay region power deposition
  - 63 kW in steel decay pipe
  - 52 kW in shielding concrete
  - Peak power in the steel ~360 W/m
- May be expensive to upgrade for >1 MW beam intensity.

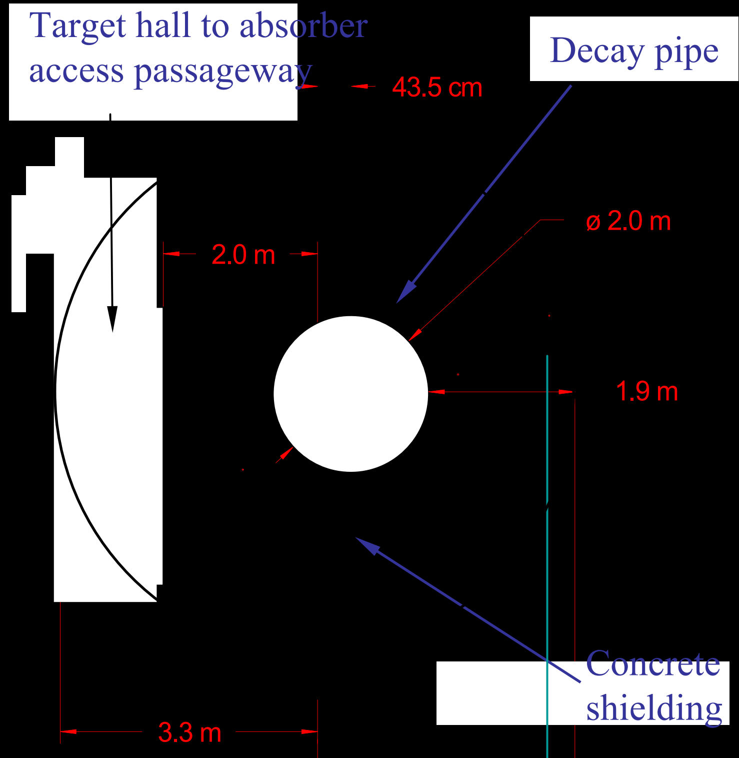


figure courtesy D. Bogert

Beam Absorber

- Absorber core
  - 8 aluminum plates
    30.5 x 129.5 x 129.5 cm^3
  - dual water-cooling paths
    8 kW peak power in one module
    (normal beam conditions)
  - followed by 10 plates of steel,
    each 23.2 cm thick.
- Total power into Absorber: 60 kW

  (400 kW beam power if accident)
- Water-cooled Aluminum easily can accommodate increased beam power from proton upgrade
- Steel is more problematic – require adding water cooling?

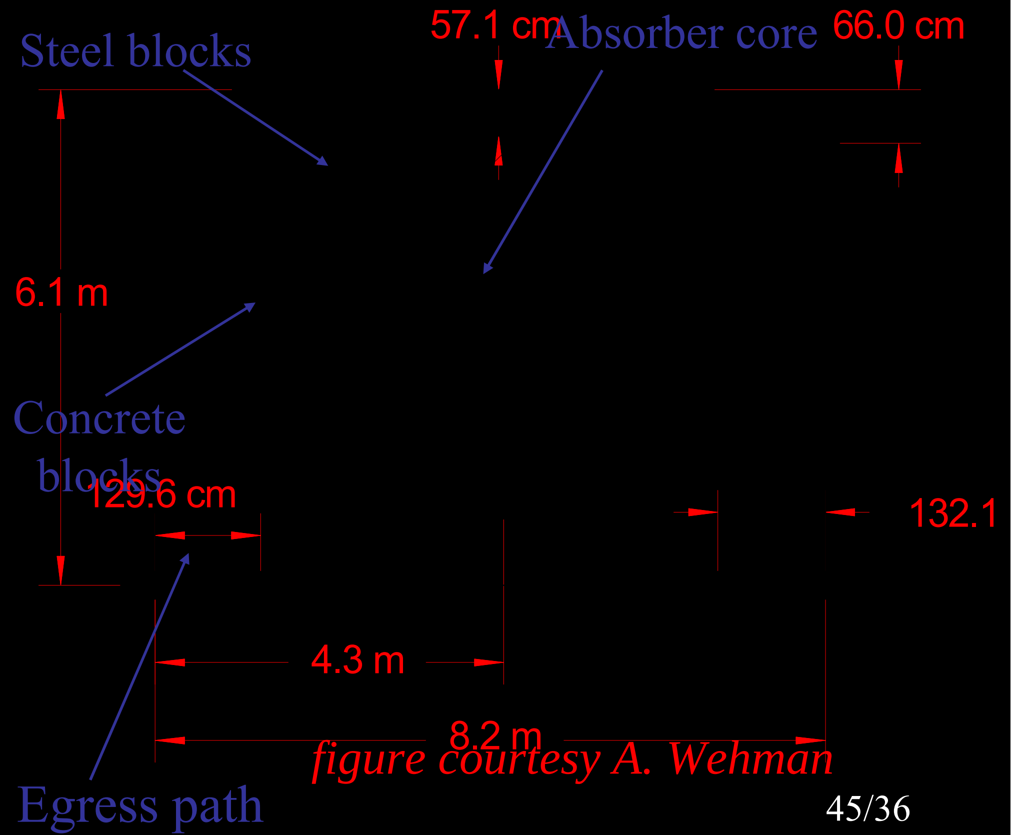


figure courtesy A. Wehman

Measuring Primary Beam on Target

- Primary beam measured by
  - •Beam Position Monitors (BPM’s)
  - •Segmented foil Secondary Emission Monitor (SEM)
  - •Beam Current Toroid