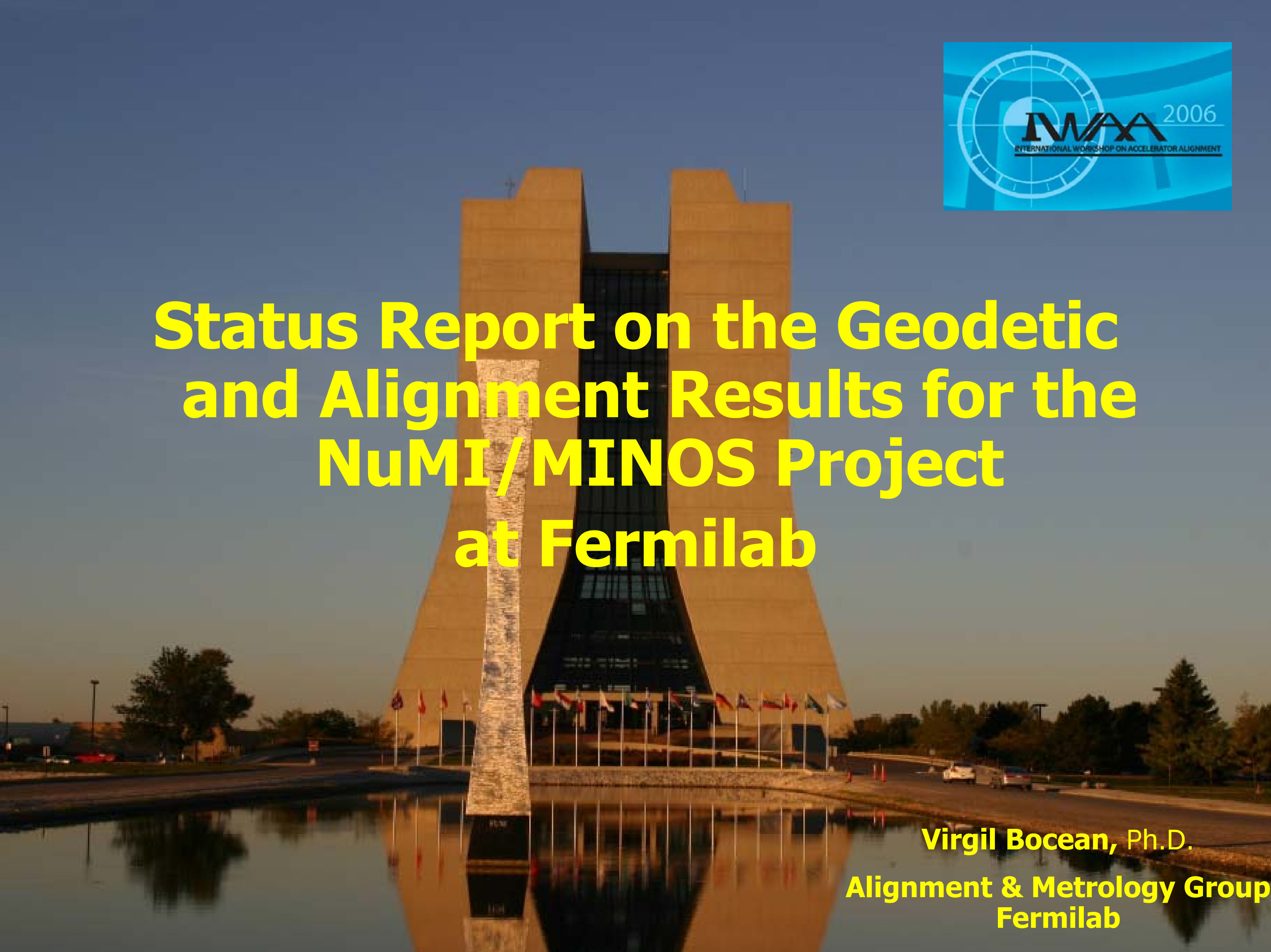

Status Report on the Geodetic and Alignment Results for the NuMI/MINOS Project at Fermilab

Virgil Bocean, Ph.D.

Alignment & Metrology Group
Fermilab

INTRODUCTION

- **Part of the neutrino research program at Fermilab is the search for non-zero neutrino mass**
- **Looks for neutrino oscillations ($\nu_\mu \rightarrow \nu_\tau$) or ($\nu_\mu \rightarrow \nu_e$)**
- **NuMI (Neutrinos at the Main Injector) has built a new particle beamline capable of directing a pure beam of muon neutrinos**
- **MINOS (Main Injector Neutrino Oscillation Search) experiment uses NuMI beam to search with significantly greater sensitivity for neutrino oscillations utilizing two detectors:**
  - **"near" detector - located close to the neutrino source (1 km away from the target)**
  - **"far" detector - 735 km away, in a deep underground mine in northern Minnesota, 710 m below the surface**

NuMI Tunnels and Halls

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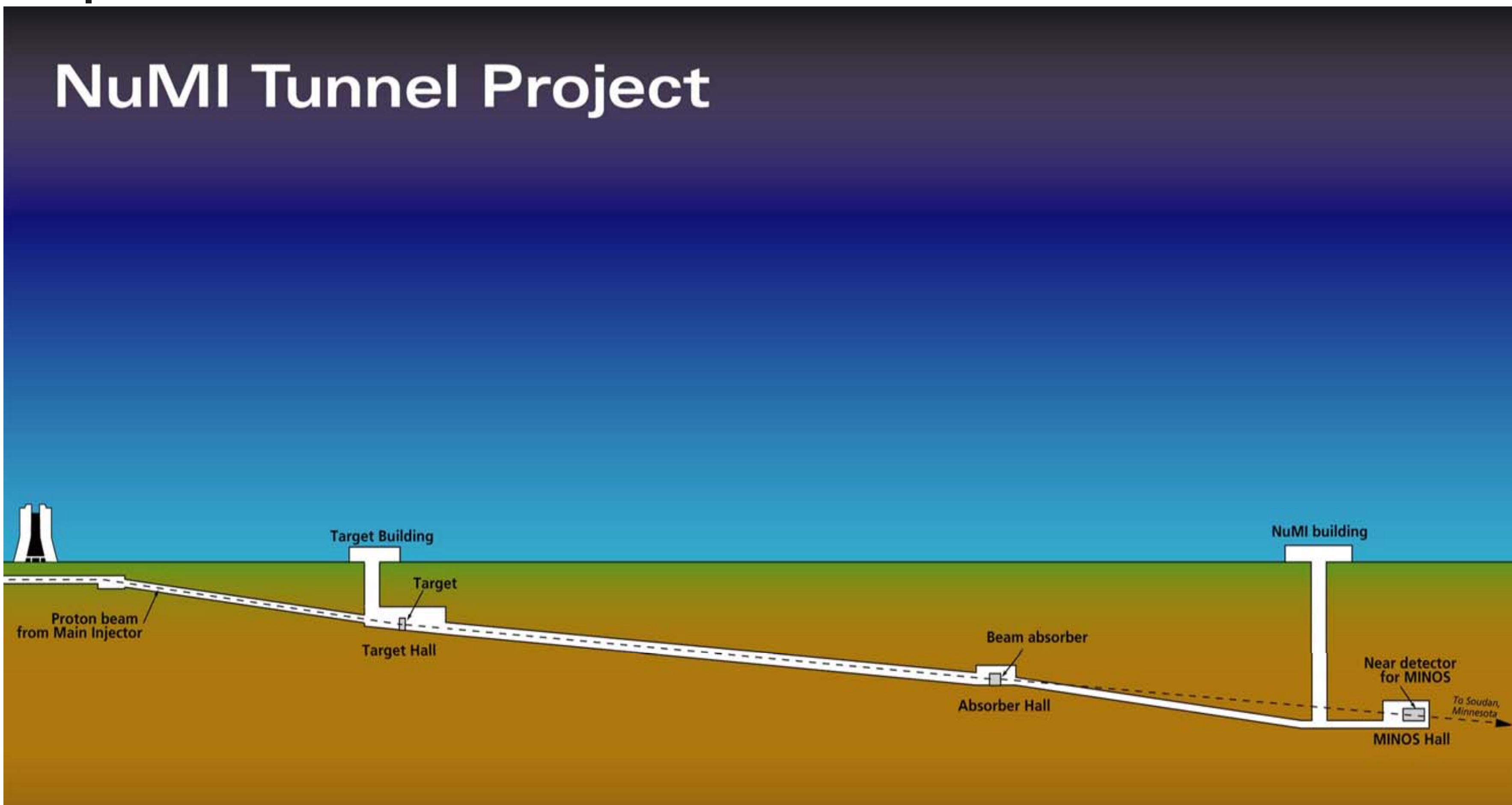
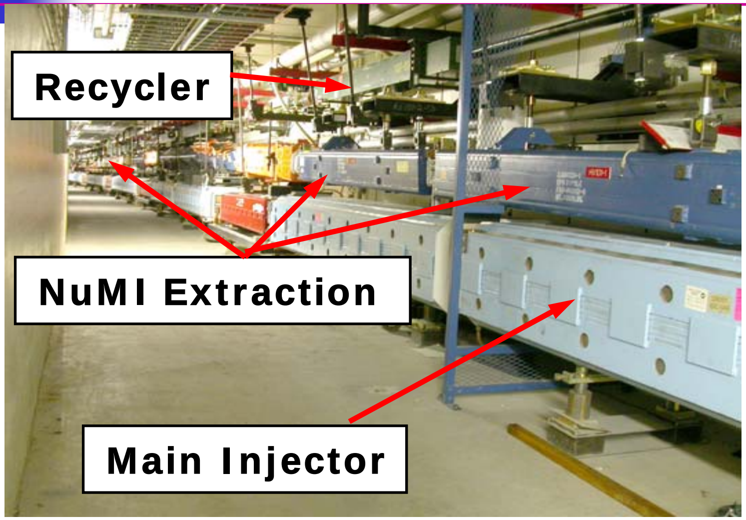
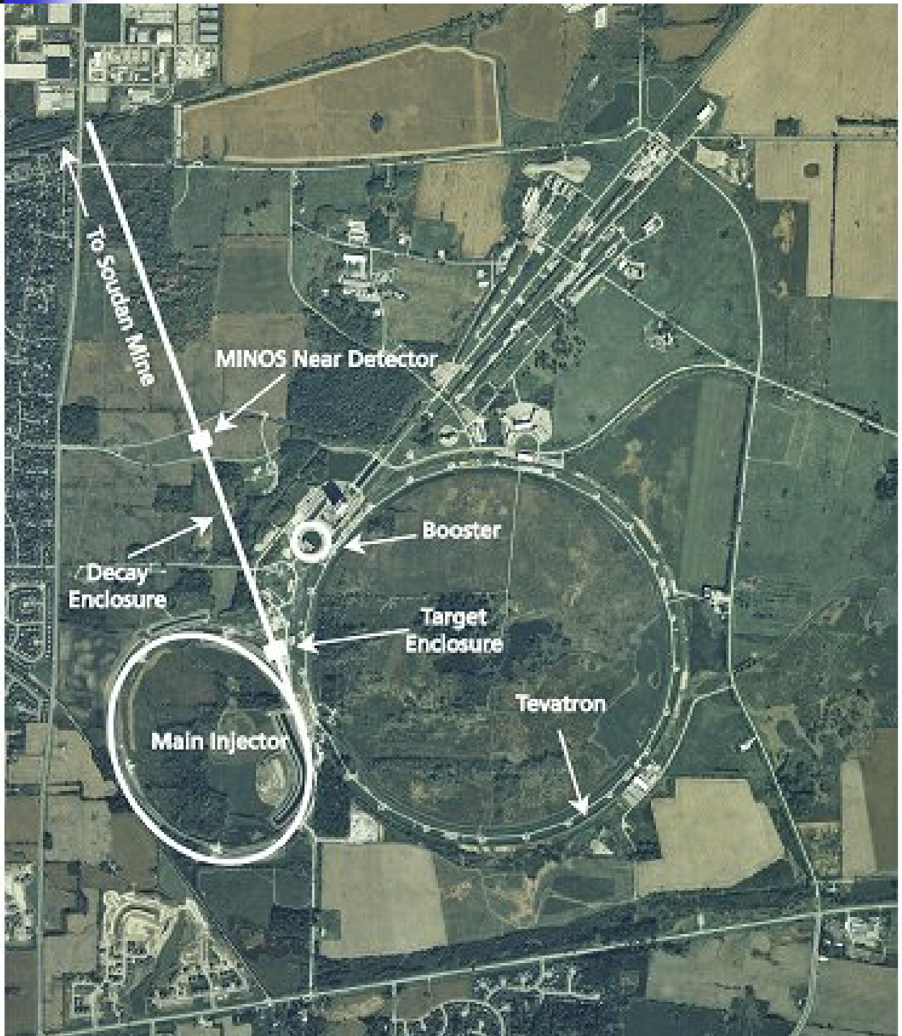
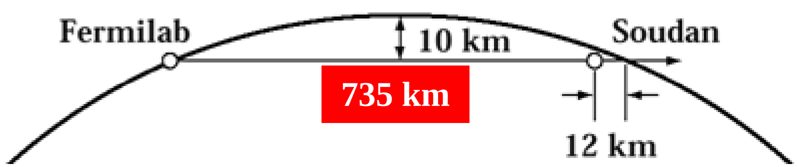


NuMI beamline



NuMI Beamline
From Fermilab to Soudan, MN





Alignment Tolerances

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- primary proton pointed ± 12 m at the far detector (±3.4 arc second)
- neutrino beam centered ± 75 m at the far detector (±21 arc second)

Beam position at target	± 0.45 mm
Beam angle at target	± 0.7 mrad
Target position - each end	± 0.5 mm
Horn 1 position - each end	± 0.5 mm
Horn 2 position - each end	± 0.5 mm
Decay pipe position	± 20 mm
Downstream Hadron monitor	± 25 mm
Muon Monitors	± 25 mm
Near Detector	± 25 mm
Far Detector	± 12 m

- NuMI is mainly sensitive to final primary beam trajectory
- beamline components, target, and horn alignment => relative positions to ±0.35 mm (1σ)

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NuMI: Neutrino Beam

From Protons to Muon Neutrinos (ν_μ)

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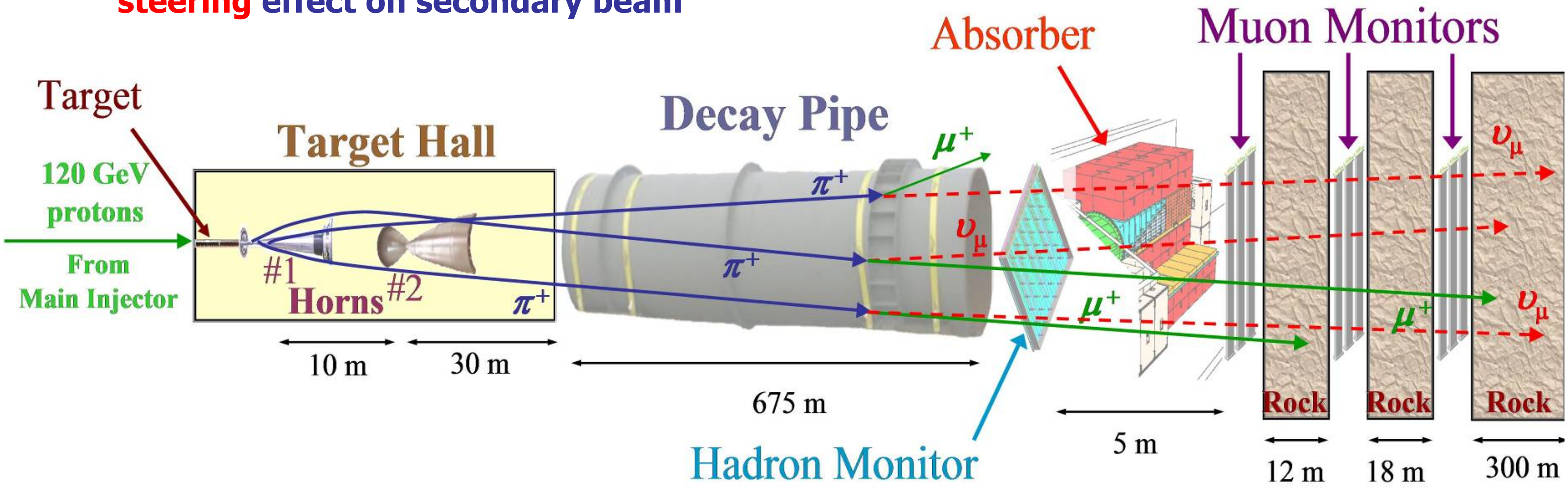
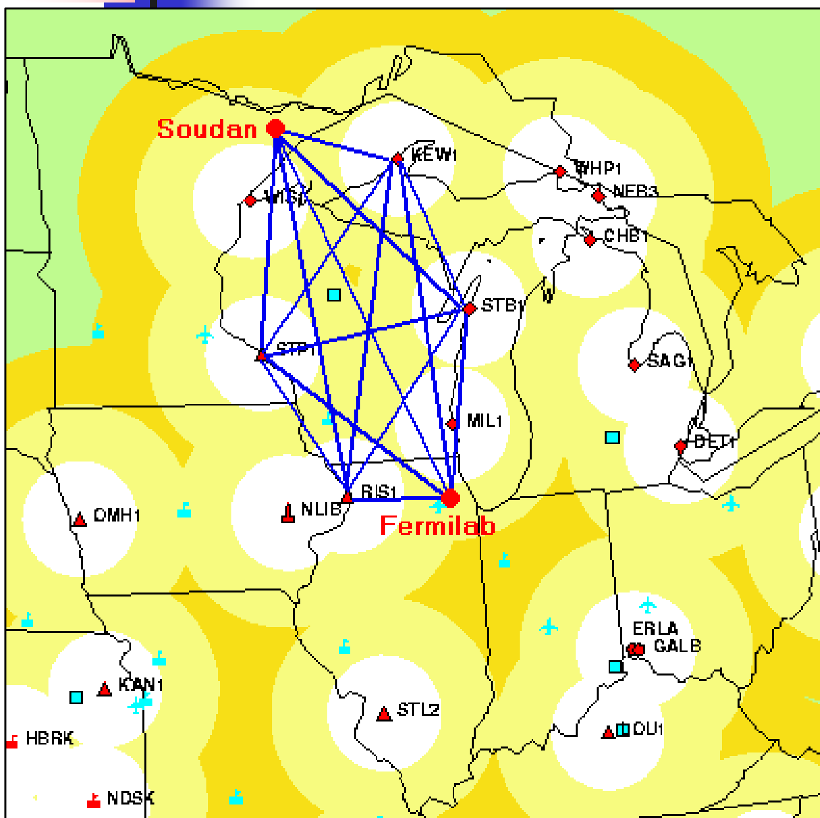
Focusing Horns misalignments have steering effect on secondary beam



Determination of the Global Positions



- <u>geodetic orientation parameters of the beam</u> => absolute & relative positions of target (Fermilab) and far detector (Soudan)
- **GPS tied to national CORS network**
- solution in ITRF96 reference system => transformed in national NAD 83 system
- NGS provided independent solution (excellent agreement)
- **vector known to better than 1 cm horizontally and vertically**
- inertial survey through 713 m shaft tied the the 27th level of the mine to surface geodetic control

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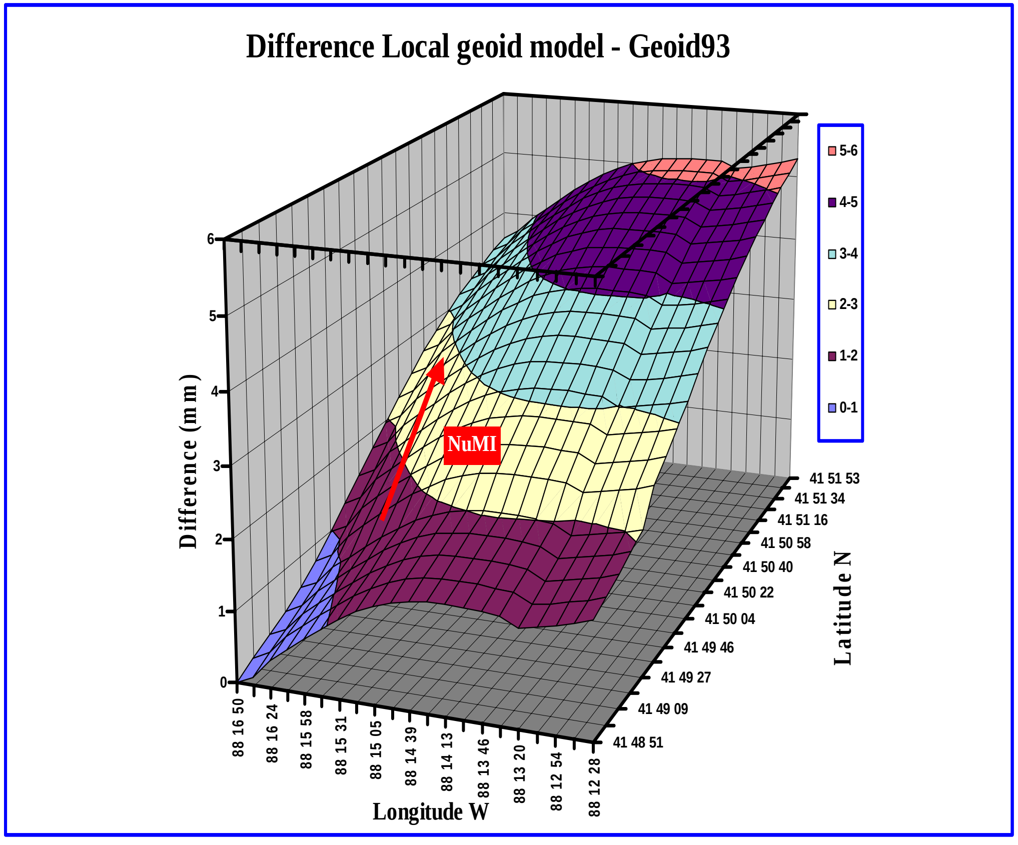
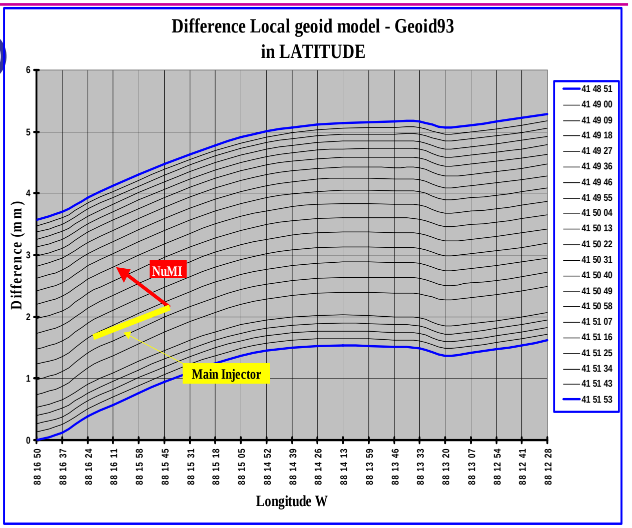
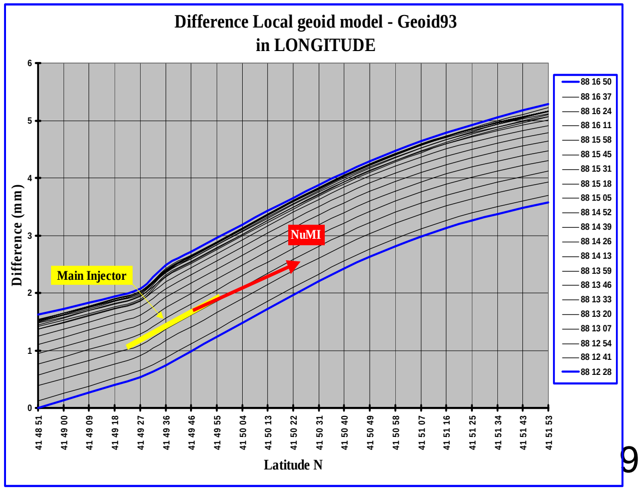
GEOID CONSIDERATION

Models Comparison
(Local Geoid Model and NGS Geoid93)

- **differences up to 5 mm (consistent with expected values)**
- **NuMI beamline in 1.5 mm range of differences**
- **Geoid93 - sufficient to cover tolerance requirements**







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Primary Geodetic Network at Fermilab

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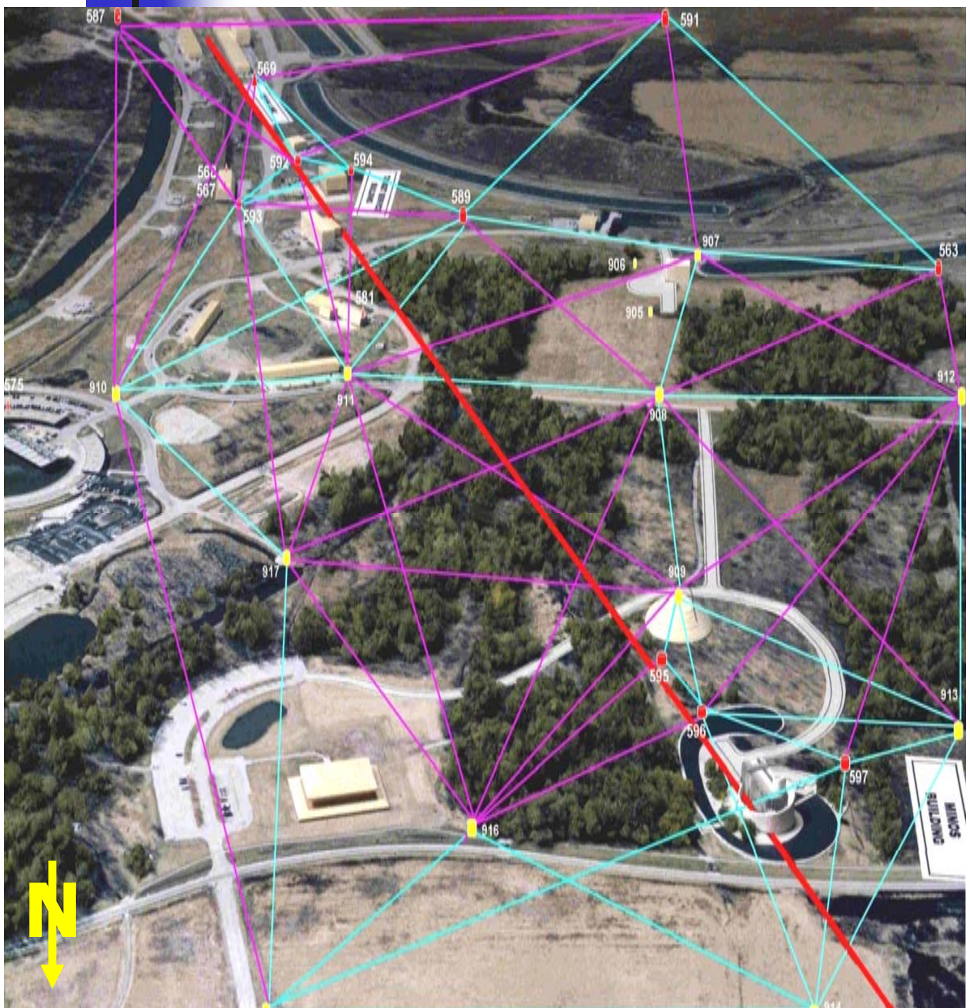

- **existing Fermilab control network**
  (accuracy < 2 mm @ 95% confidence level)
- **NAD 83 horizontal geodetic datum**
  (GRS-80 reference ellipsoid)
- **NAVD 88 vertical datum**
- **Geoid93 NGS model**
- **included 3 monuments tied to CORS**
- **added 6 new geodetic monuments**
  (densification around access shafts)
- **410 GPS, terrestrial, and astronomic observations**
- **error ellipses in millimeter range**
  (@ 95% confidence level)
- **precision levelling: ± 0.58 mm/km double-run**

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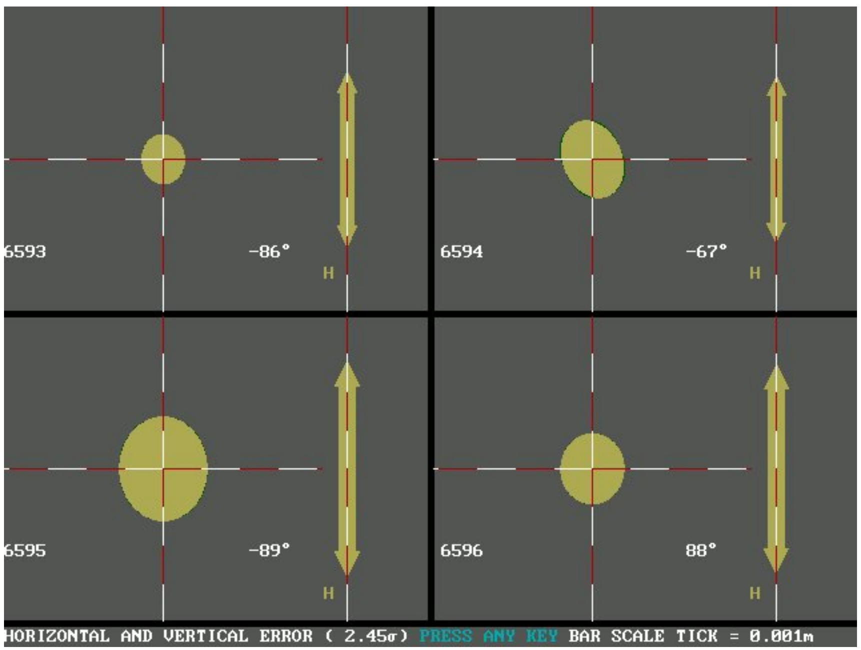
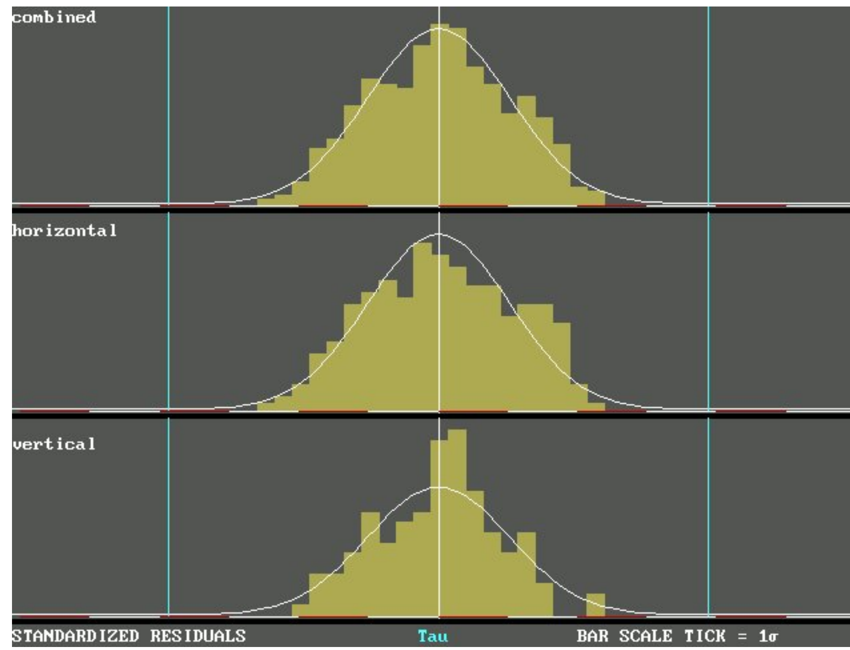
Primary Geodetic Network Results



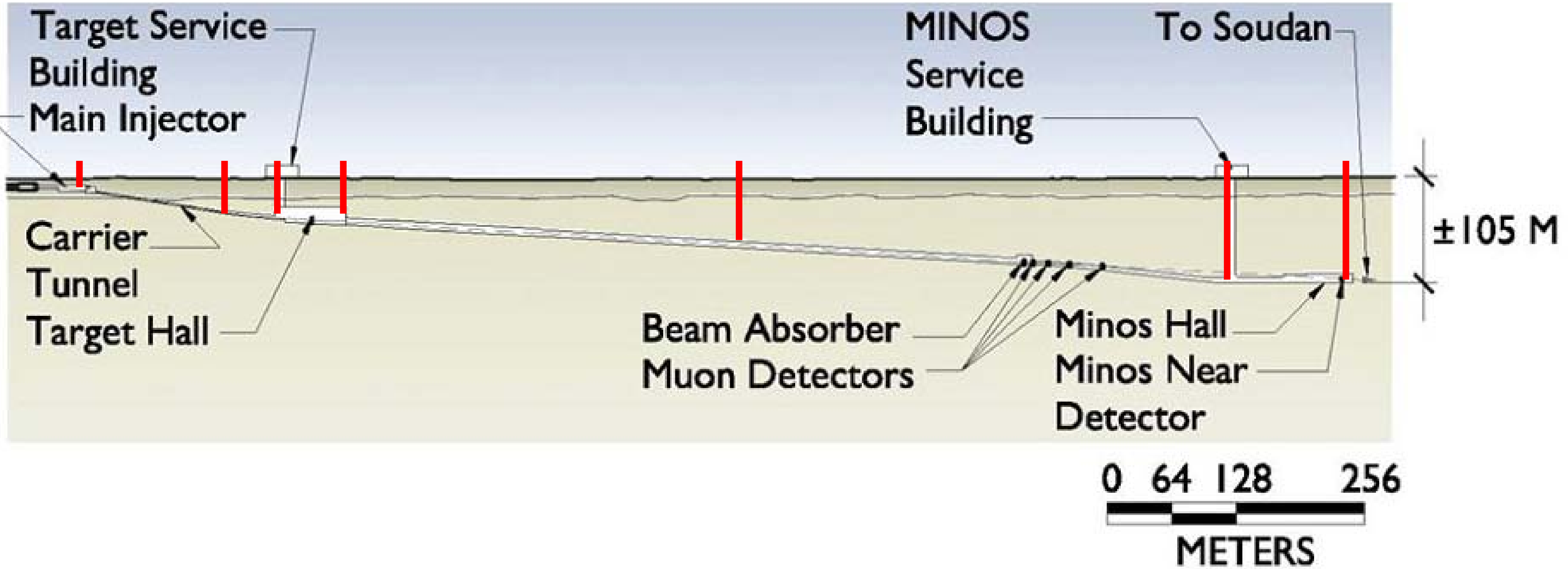
Error ellipses @ 95% confidence level (bar scale tick = 1 mm)



Histogram of standardized residuals (bar scale tick = 1 σ)

Underground Control Networks

- Network simulations => 7 locations for transferring coordinates from the surface (3 vertical sight risers, 2 tunnel Access Shafts, 2 Exhaust Air Vent pipes)



Underground Control Networks
Target Hall and Near Detector Hall

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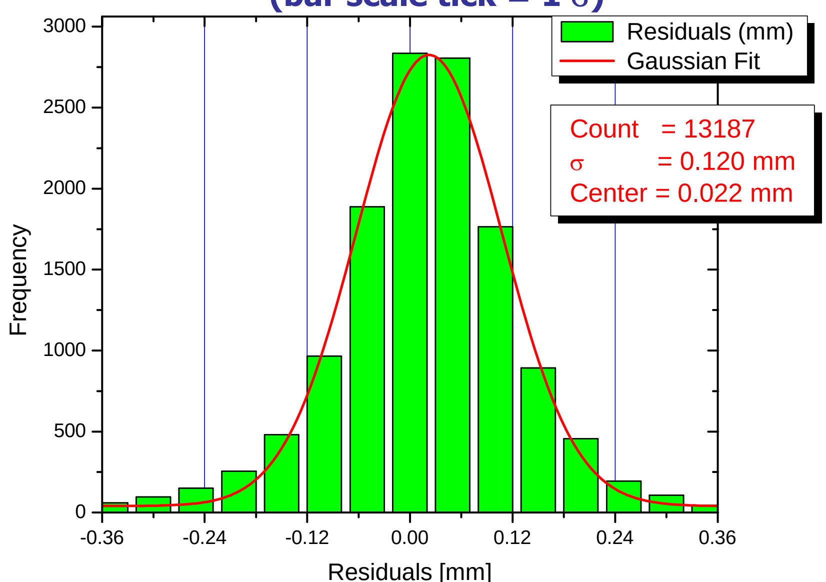
- **First phase: to support components installation in the Target Hall and the construction and alignment of the Near Detector in the MINOS Hall**
- **Measured with the Laser Tracker and processed as trilateration**
- **Additional measurements to study/control network behaviour: Mekometer distances, precision angles, and gyro-azimuths**
- **Network results: errors below ±0.35 mm at 95% confidence level**

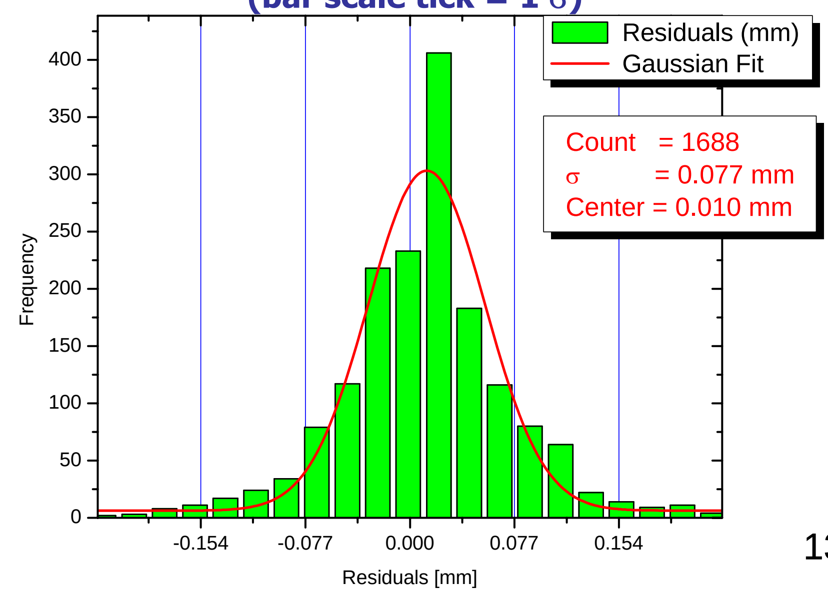
Initial Target Hall Network

Histogram of standardized residuals (bar scale tick = 1 σ)



MINOS detector Hall Network

Histogram of standardized residuals (bar scale tick = 1 σ)



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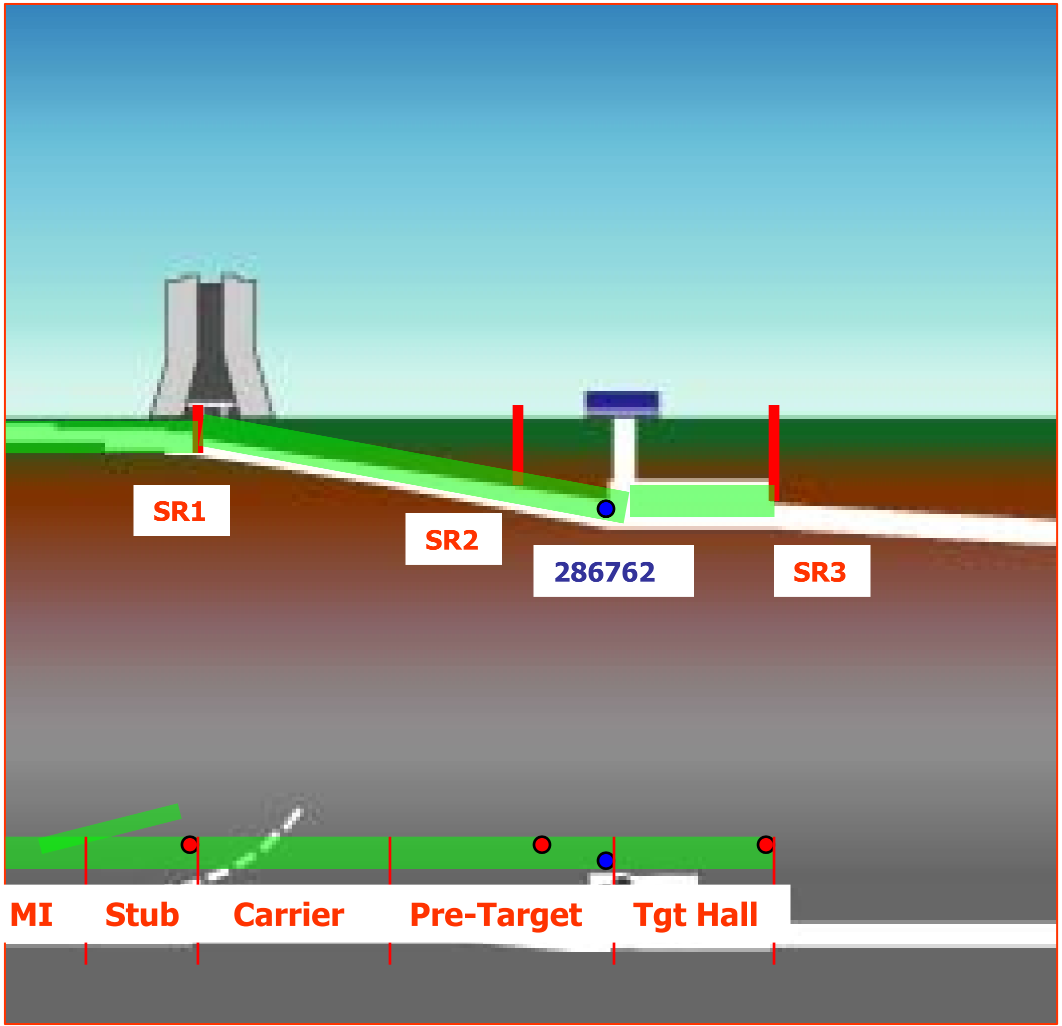
Underground Network for the Primary Beam

- **Second Phase: to support the alignment of Primary Beam components and the Target and focusing Horns**
- **Network: from MI-60 to the downstream end of the Target Hall**
- **Least-Squares Adjustment: constraints at MI-60, SR-1, SR-2, and SR-3**
- **Network type: Laser Tracker processed as trilateration**
- **Additional measurements to study and control network behaviour and for confirmation**
- **23,000 Observations => Laser Tracker (σ=0.050-0.15 mm), Mekometer Distances (σ=0.2 mm+/- 0.2 ppm) , Precision Angles (σ=0.3”), Optical offsets (σ=0.2-0.5 mm), Gyro Azimuths (σ=3”)**
- **Azimuth SR2-SR3 confirmed by first order Astronomical Azimuth: agreement at 0.74 arc second (σ=± 0.21 arc second)**

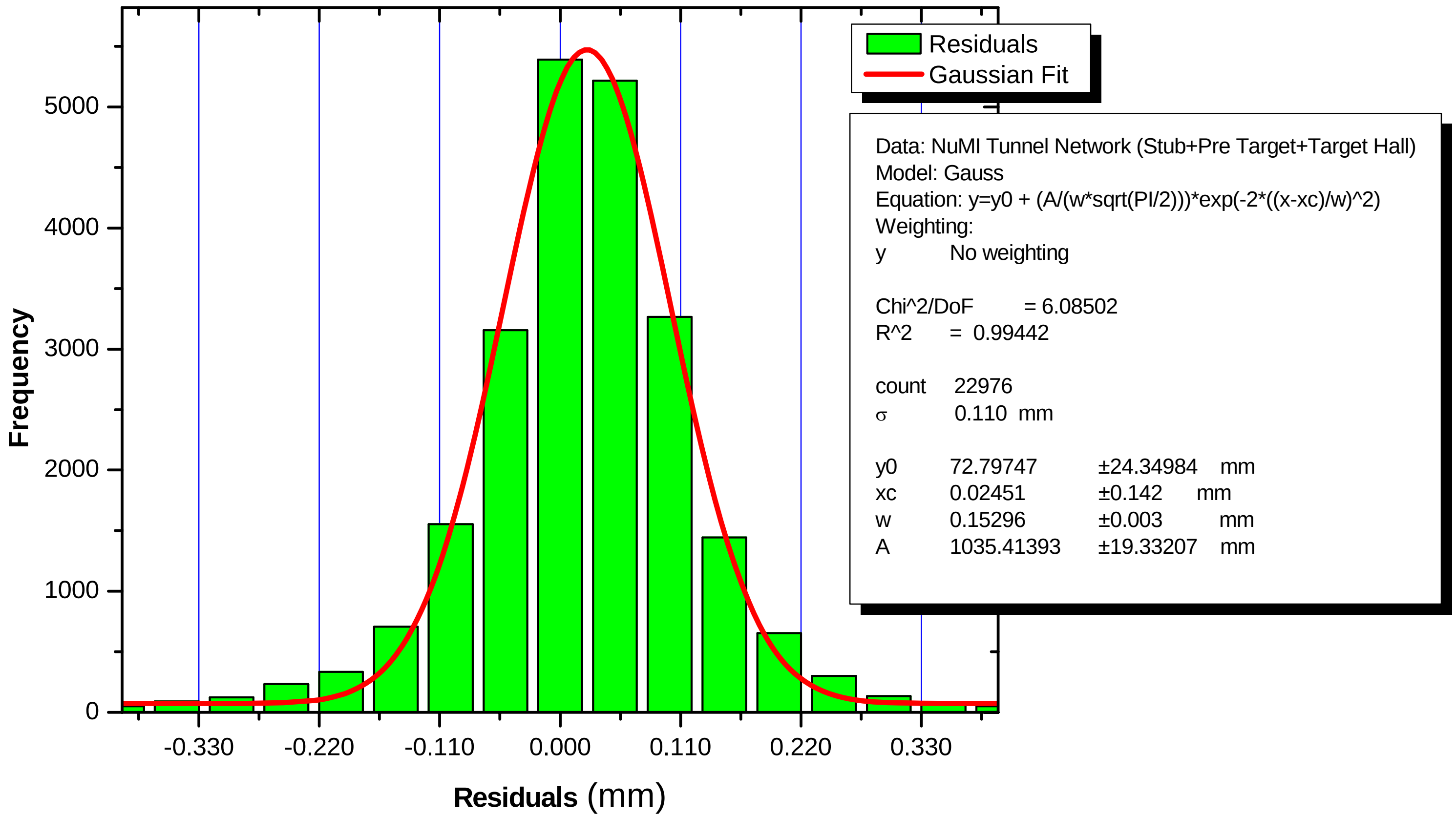
- **Alignment results:**
  - **Primary beam magnets and instrumentation aligned to ±0.25 mm**
  - **Target station components aligned to ±0.5 mm**

Underground Network for the Primary Beam



Underground Network for the Primary Beam

Results: Histogram of Standardized Residuals

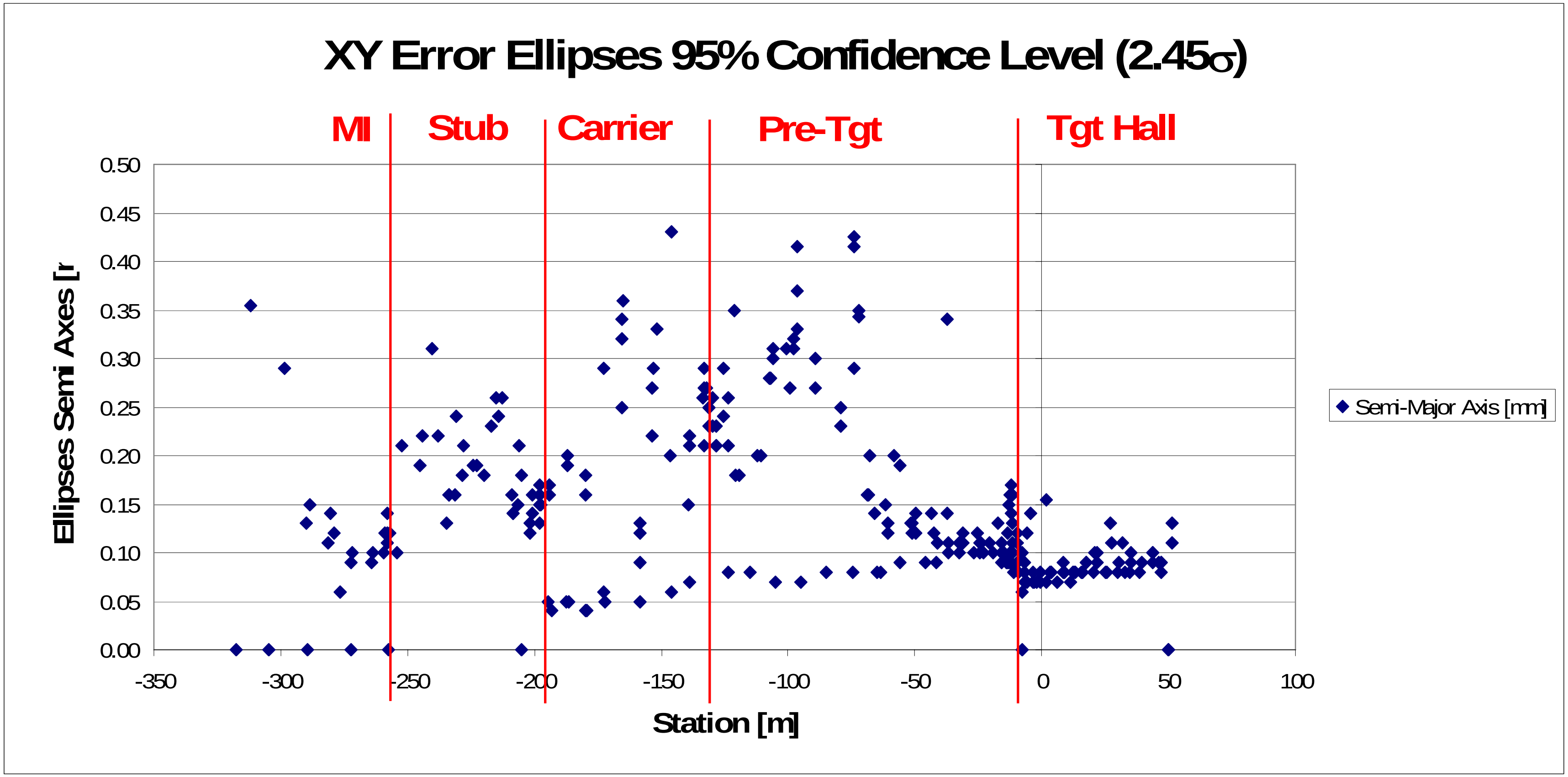


(bar scale tick = 1 σ)

Underground Network for the Primary Beam

Results: Error Ellipses XY Axes

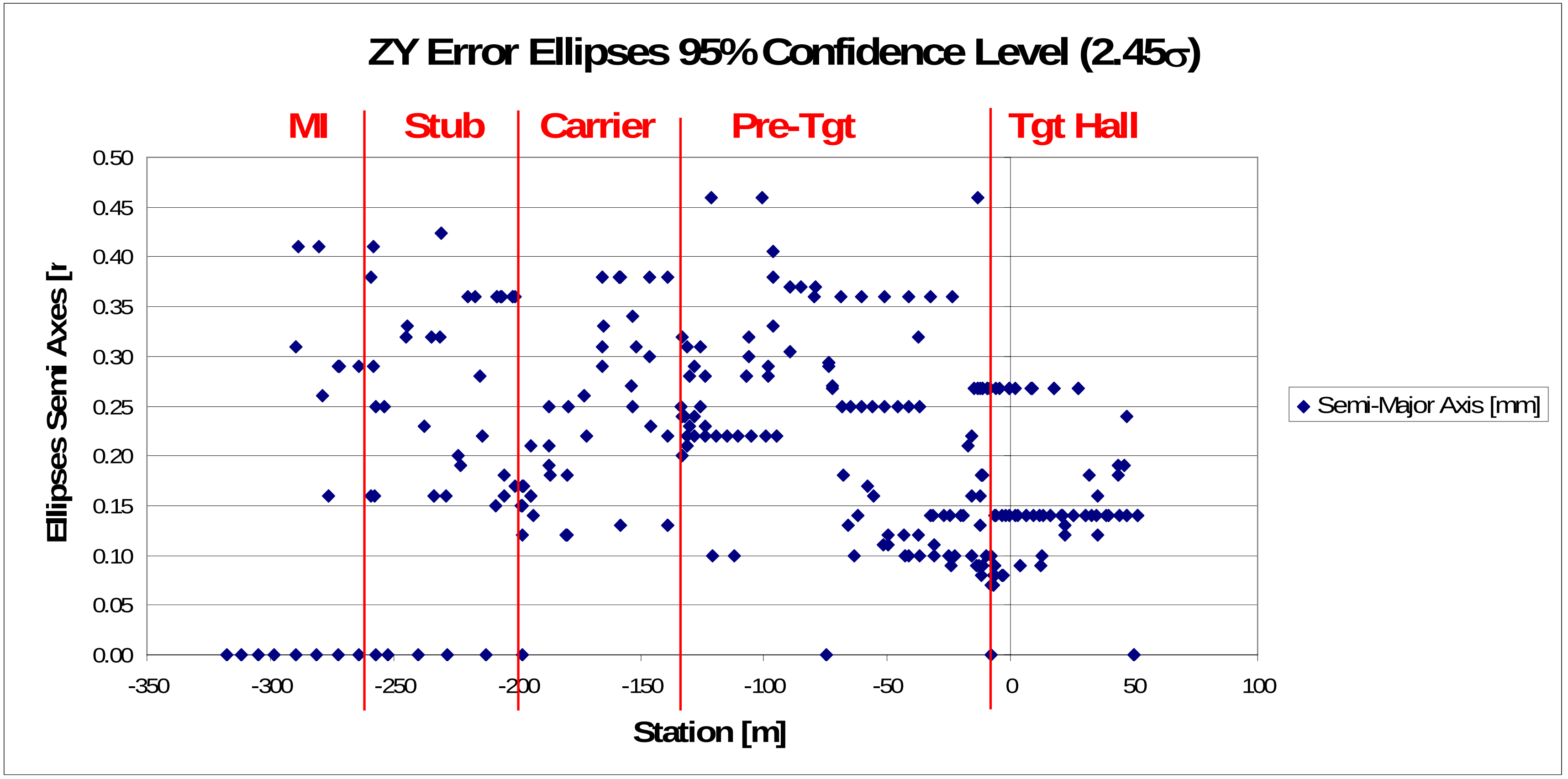
- Errors Ellipses **below ±0.45 mm at 95% confidence level**
- Error budget network requirements **±0.50 mm at 95% confidence level**



Underground Network for the Primary Beam

Results: Error Ellipses ZY Axes

- Errors Ellipses below ±0.46 mm at 95% confidence level
- Error budget network requirements ±0.50 mm at 95% confidence level



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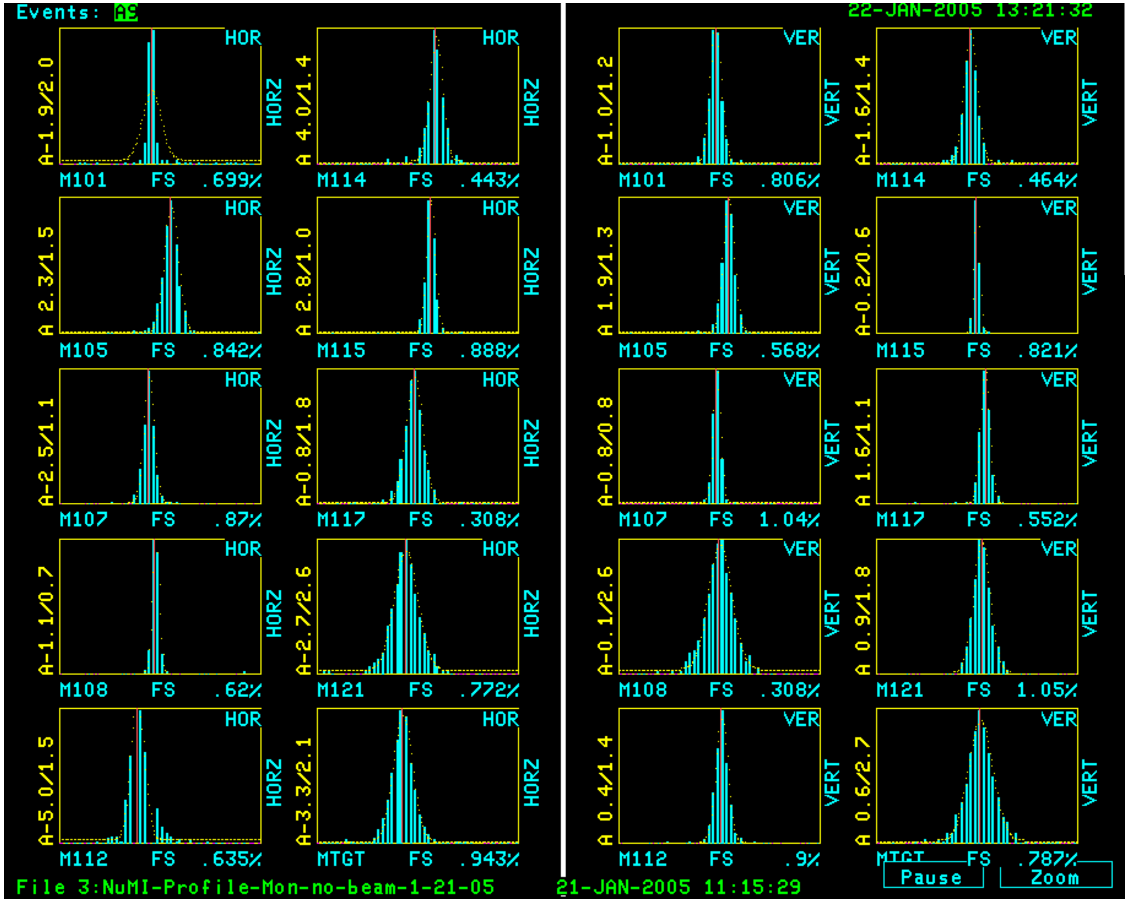
NuMI Beam Commissioning

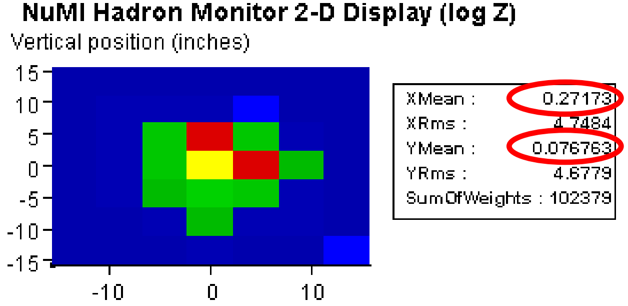
Commissioning the Primary Proton Beam

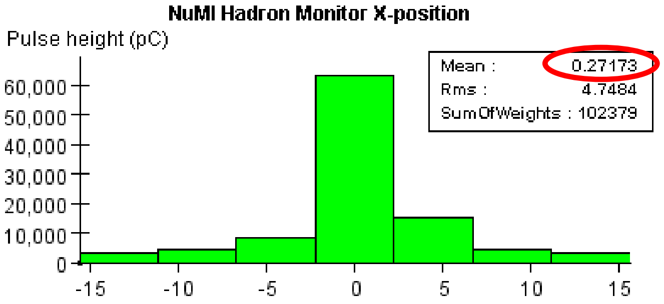
- ***NuMI starts December 3, 2004*** **:**
  - **target OUT of the beam, horns turned OFF**
  - **small number of low intensity pulses carefully planned**
  - **beam extracted out of Main Injector on the 1st pulse, per design parameters – no tuning required**
  - **beam centered on the Hadron Absorber, 725 m away from target, in 10 pulses - very minimal tuning**
  - **beam points in the right direction to < 2 arc second**

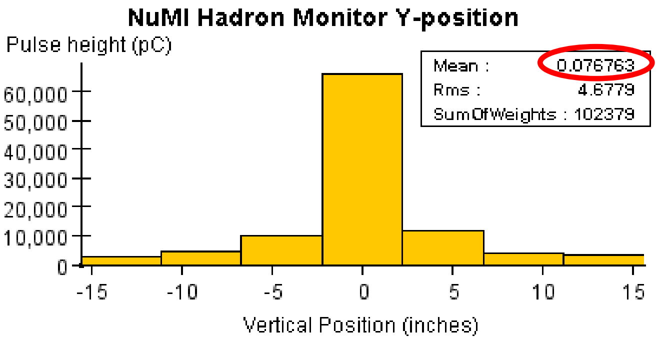
Beam Extraction in 10 Pulses
Centered on Hadron Absorber at 725 m Distance

10th pulse: SEMs and Hadron Monitor readings









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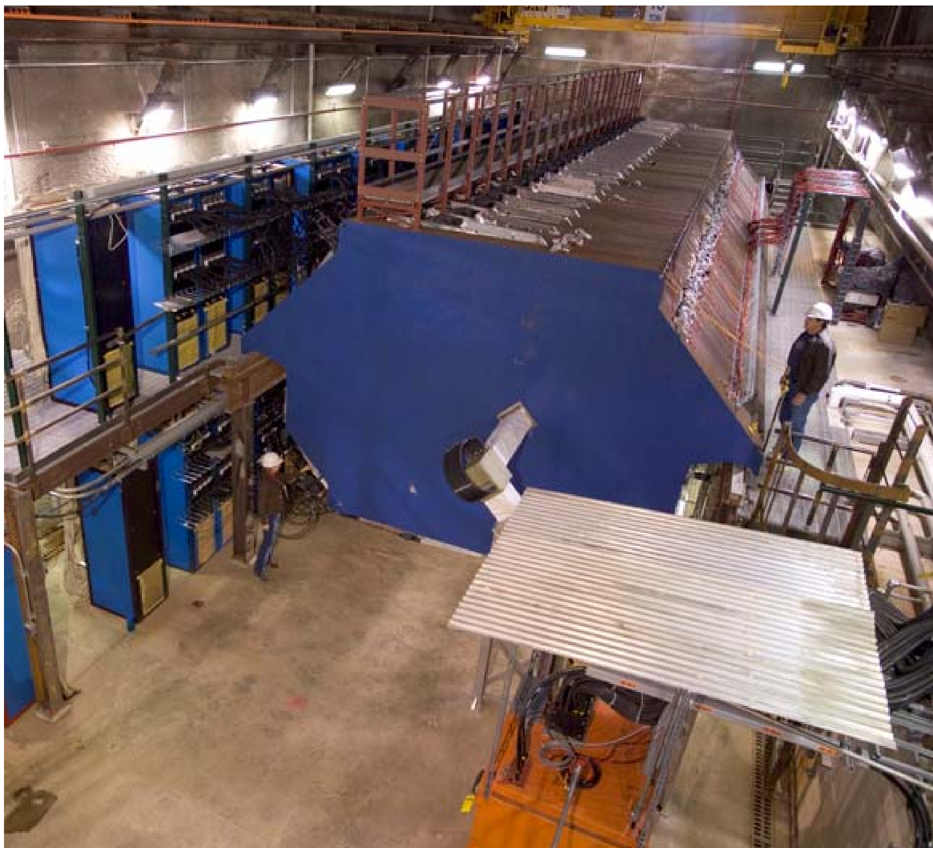
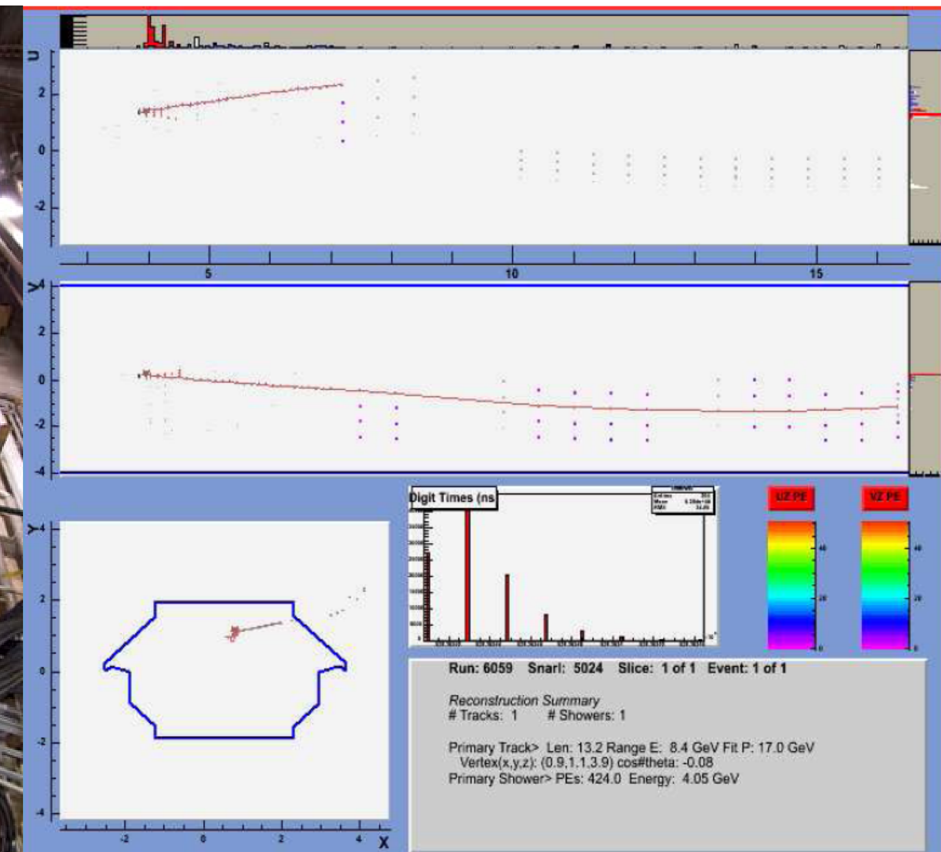
NuMI Beam Commissioning

Commissioning of the Neutrino Beam

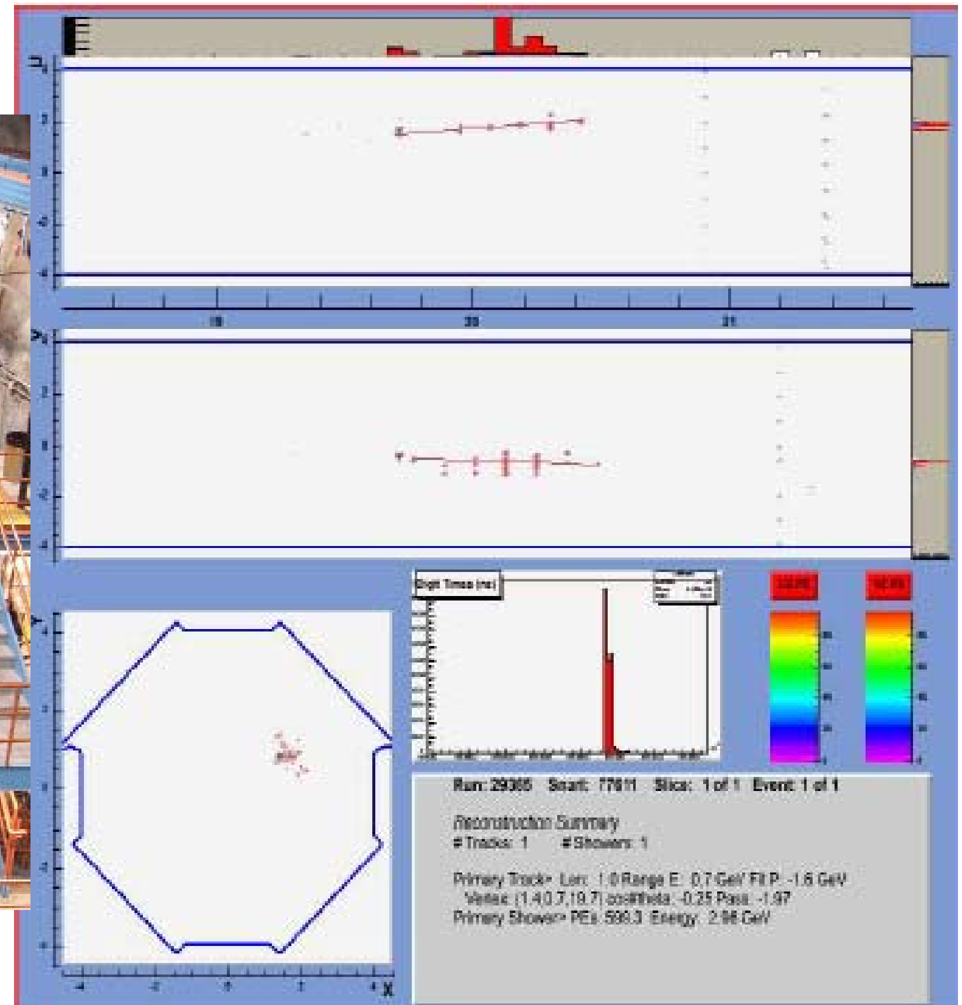
- ***MINOS starts January 21, 2005:***
  - **target at Z=-1m (Medium Energy Beam)**
  - **horns turned ON**
  - **on the 4th horn pulse - first neutrino in the Near Detector**
  - **after fine tuning the proton line, on February 18, 2005, NuMI turn to high intensity beam, operating on 6 multi-batch mode**
  - **March 07, 2005 - first confirmed neutrino in the Far Detector**

First Neutrino in the Near Detector





First Neutrino in the Far Detector



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NuMI Beam Commissioning

Beam-Based Alignment of Target and Horns

- The relative alignment of the primary proton beam, target, and focusing horns affects the neutrino energy spectrum delivered to experiments
- Primary beam magnets and instrumentation aligned to ±0.25 mm
- Target station components aligned to ±0.5 mm.

DEVICE	Horizontal dX (mm)	Vertical dY (mm)
Target	-0.122	-0.151
Horn 1	-0.285	0.303
Horn 2	-0.344	-0.650

- Proton beam used to locate the relative positions and angles of these components
- Procedure:
  - Scan proton beam (σ = 1 mm) across known features of beamline components (Target & Baffle and Horns cross-hairs)
  - Use instrumentation (BPMs and Profile Monitors) to correlate with measured proton beam position

NuMI Beam and Monitoring Instrumentation

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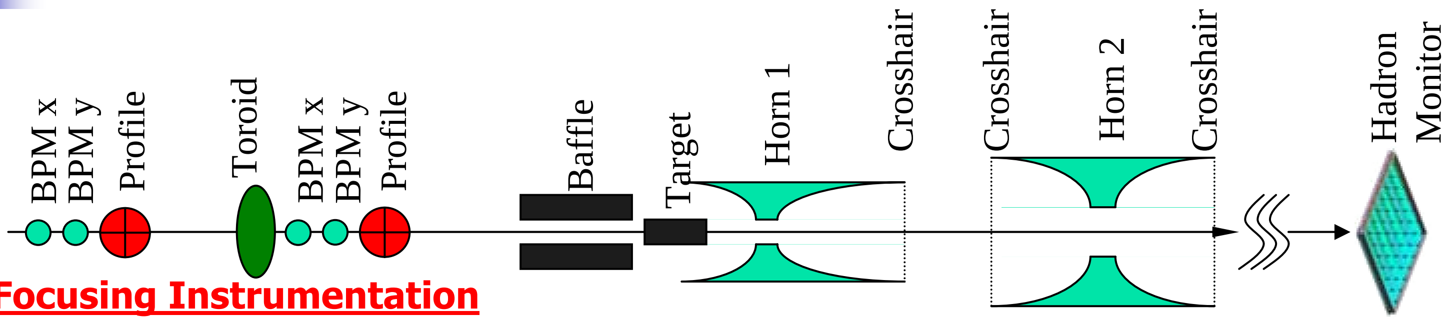
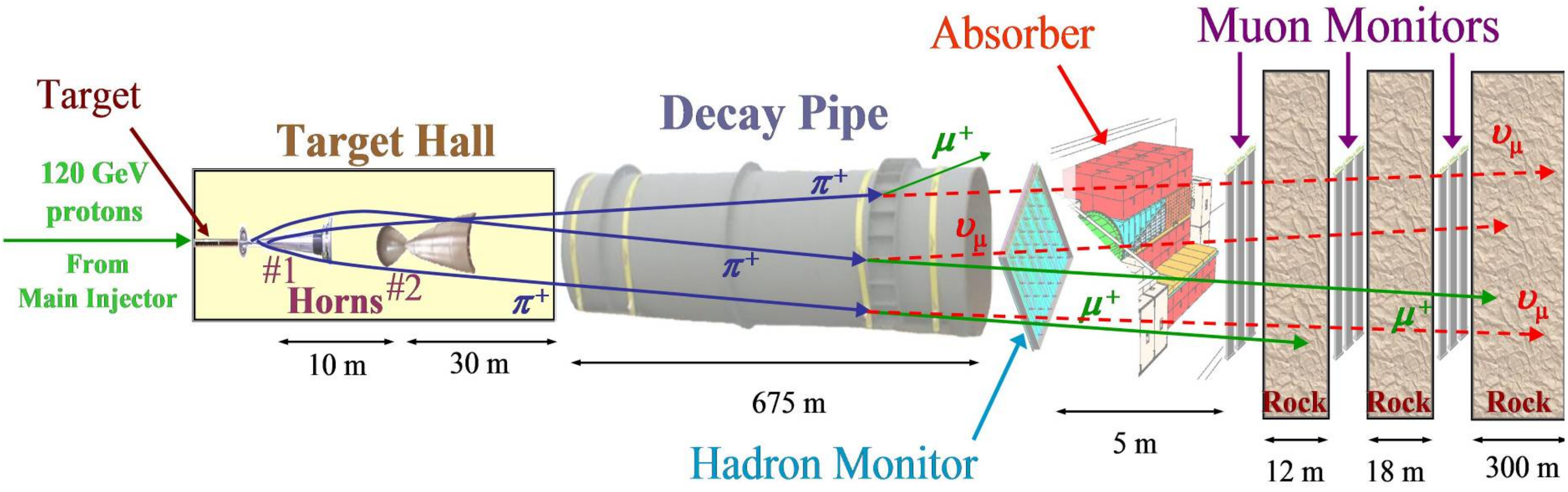


Final Focusing Instrumentation

Downstream Instrumentation



Baffle & Target System

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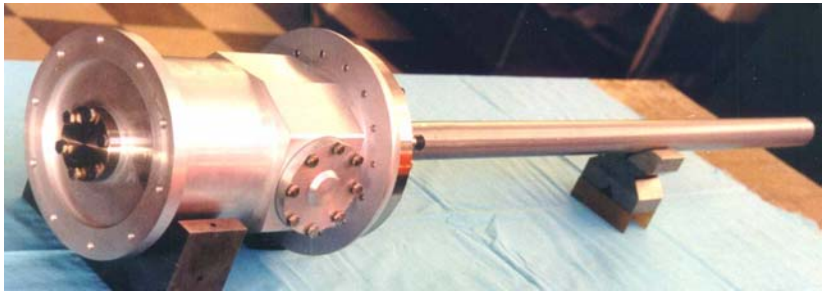
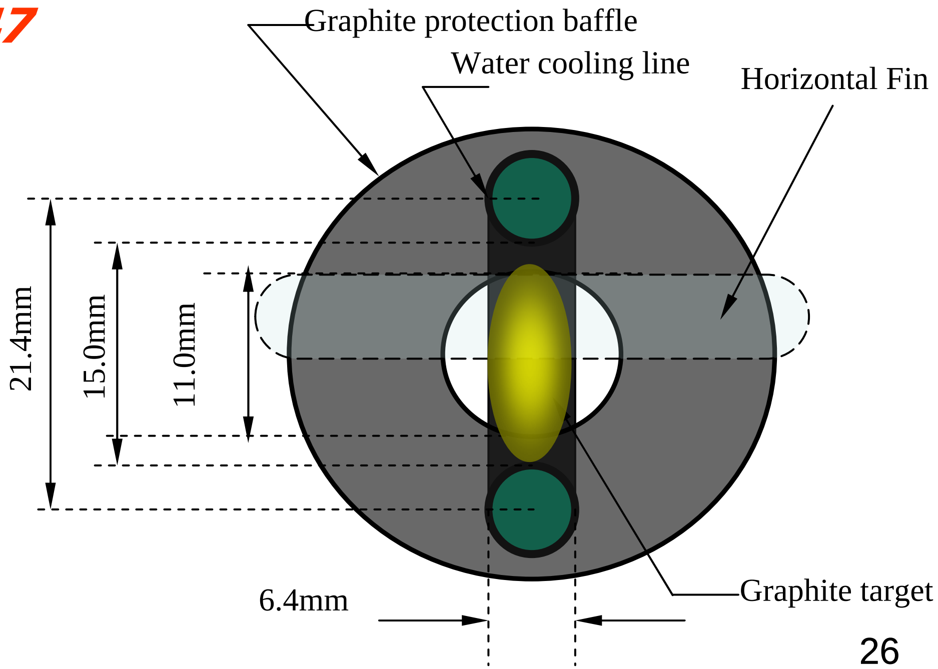
- **Graphite fin core segments:**

(20 mm x 15 mm x 6.4 mm) x 47

- **Target length = 95.4 cm**
- **Baffle length = 150 cm**





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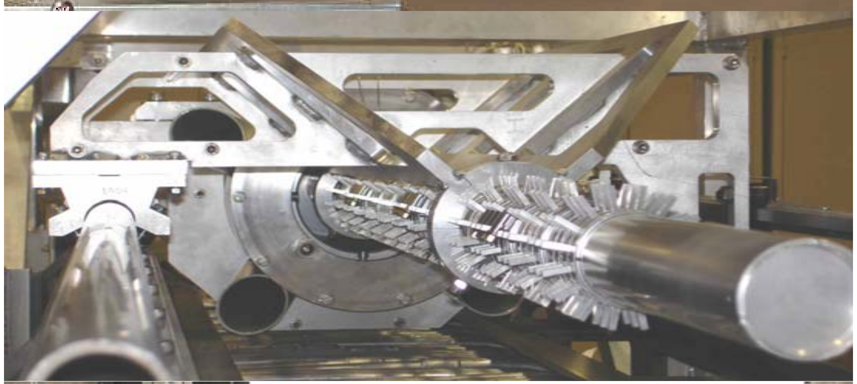
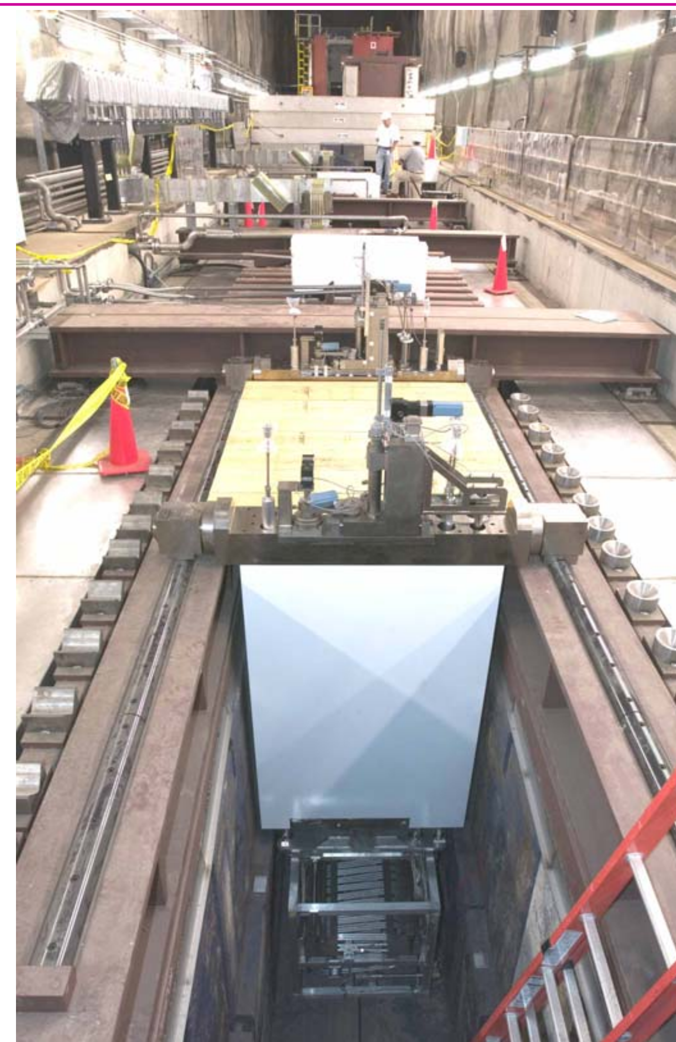
NuMI Target





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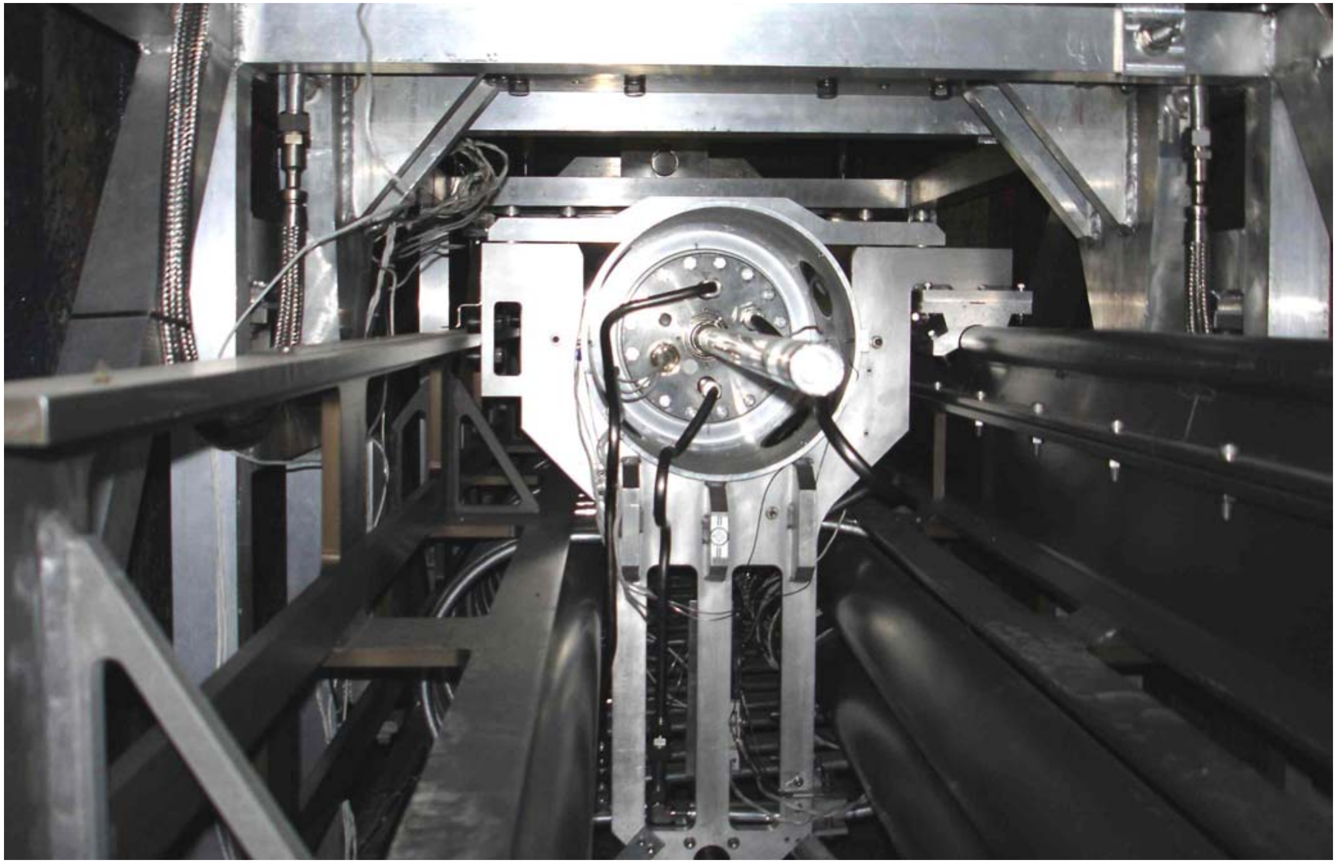
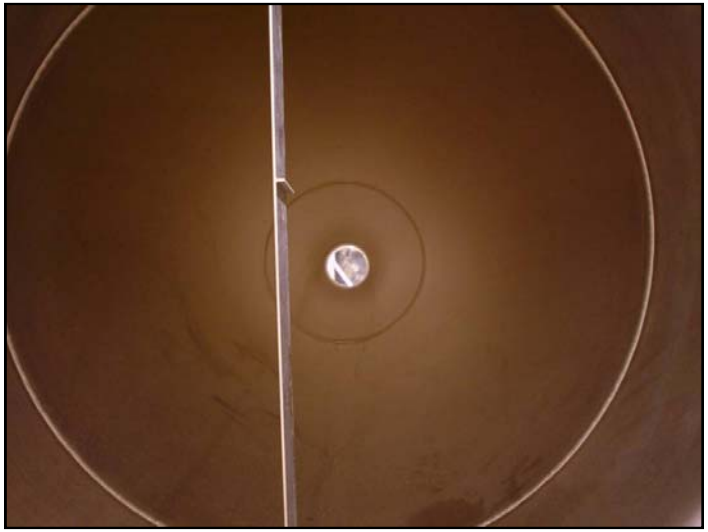
NuMI Target

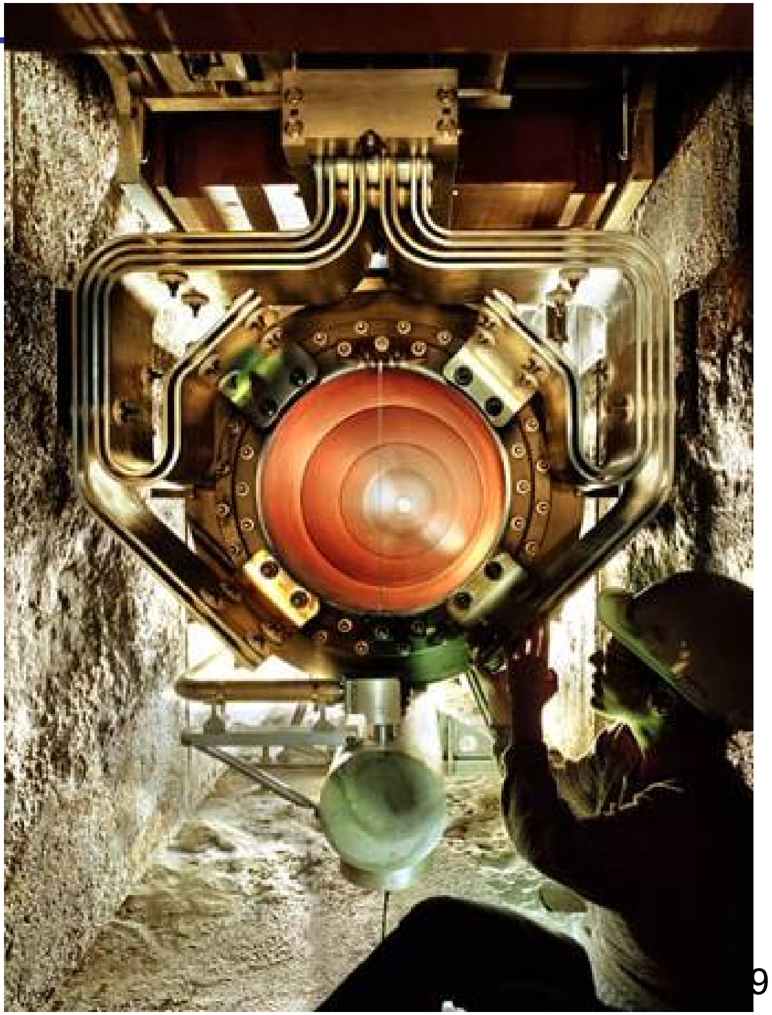
View from inside the chase - for Low Energy (LE) beam configuration Target slides into Horn 1 without touching



NuMI Horns

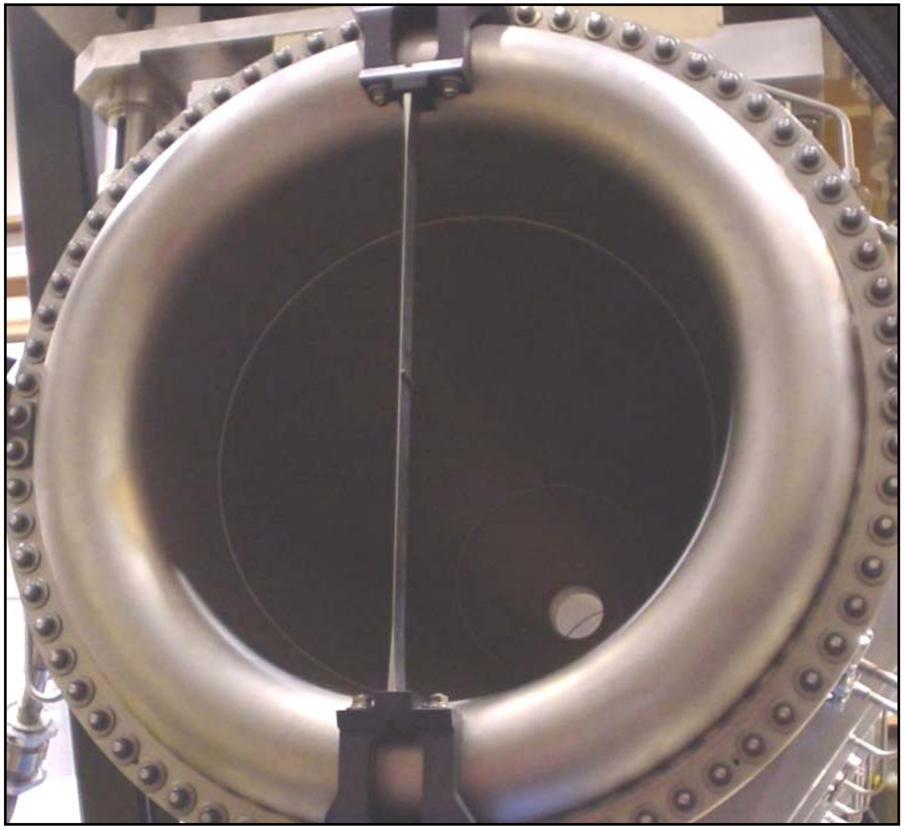
- For scanning Horns, the Target must be OUT
- Cross-hairs intercept primary proton beam:
  - One on the downstream end of Horn 1
  - One on each end of Horn 2

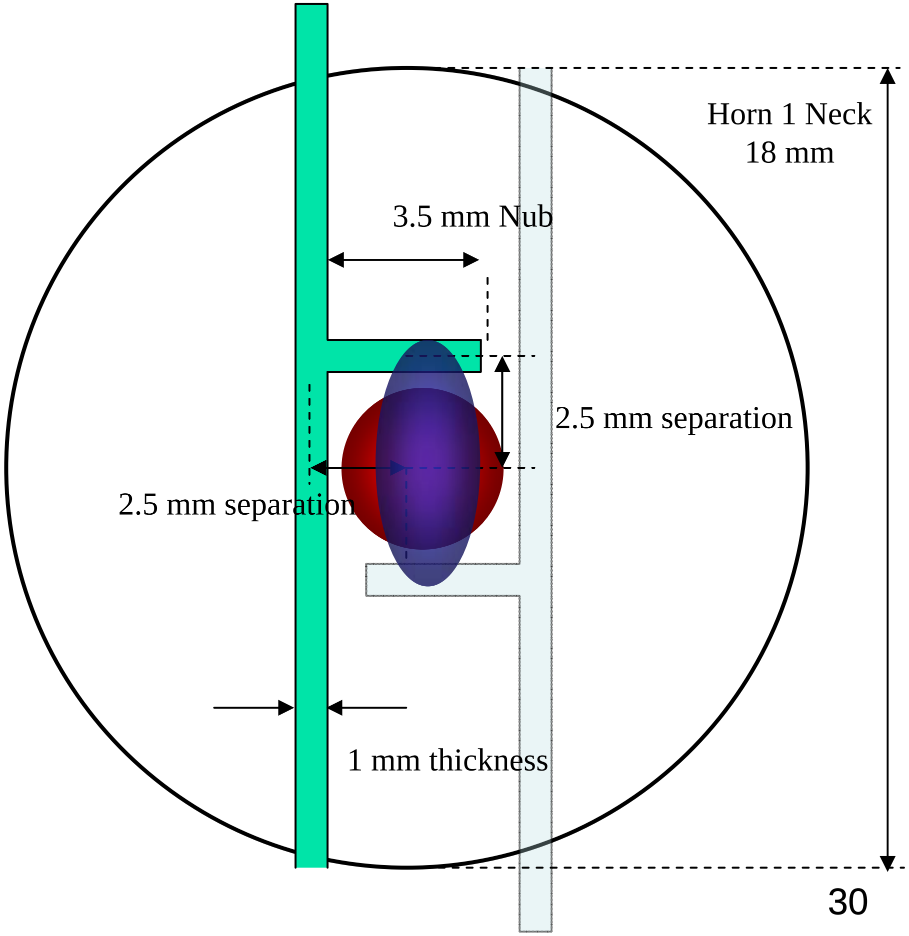




Horns Cross-hairs

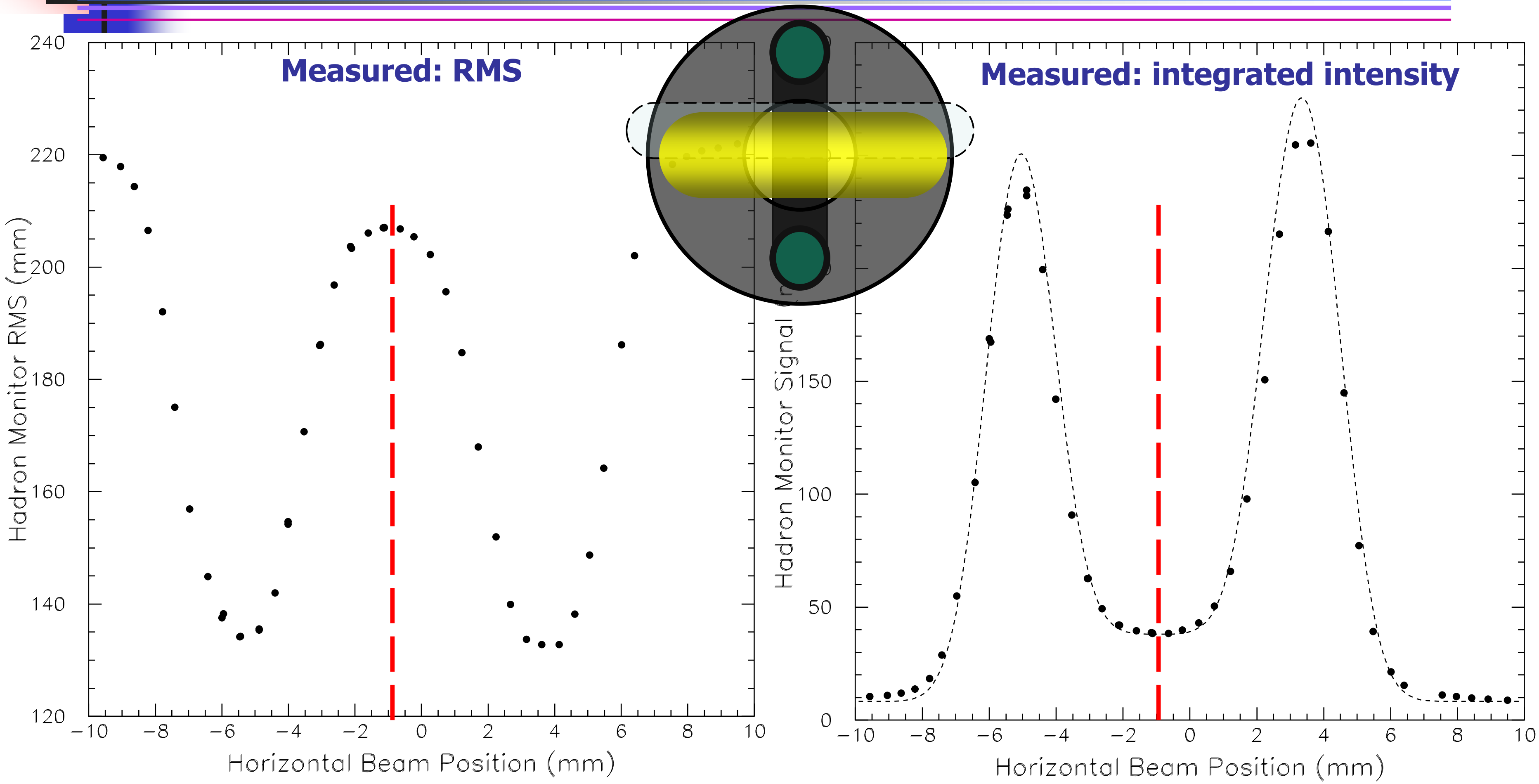
- Beam narrow horizontally, wide vertically





NuMI Horn
Inside the Chase

Target & Baffle Horizontal Positions



- The peaks are the gaps between baffle and target
- Different peak heights => offsets target/baffle or a common angle

Target & Baffle Vertical Positions

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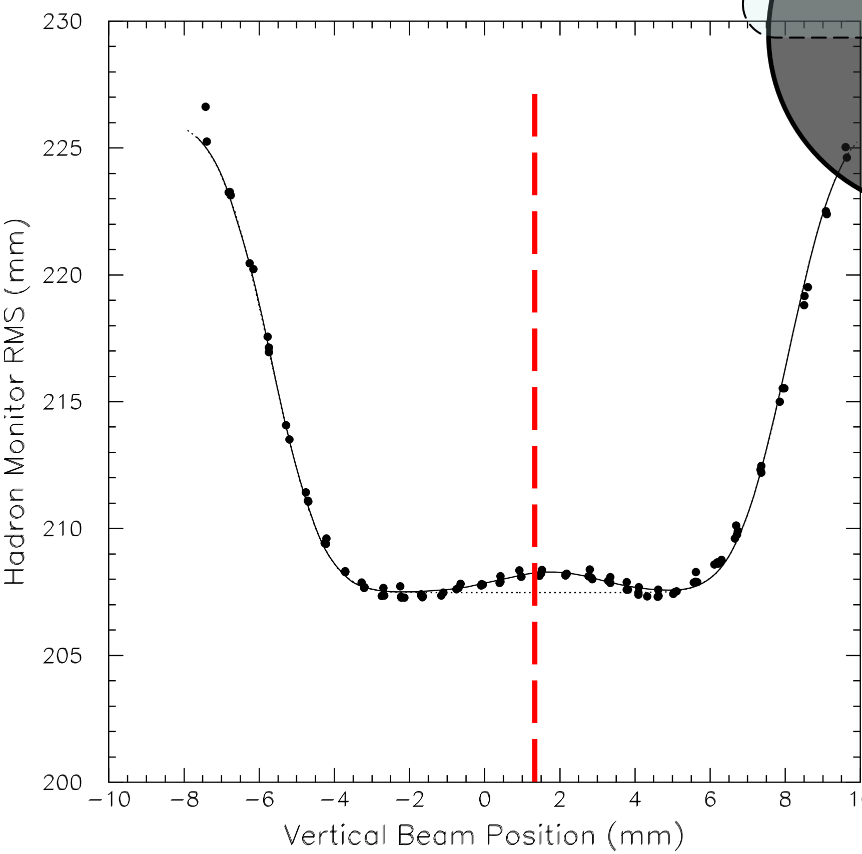
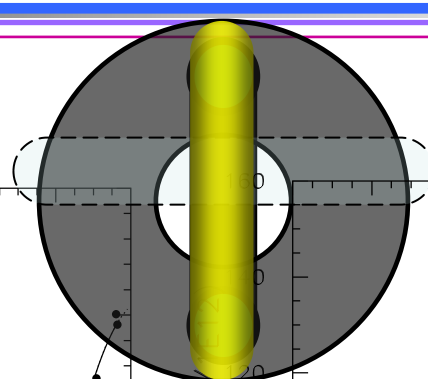
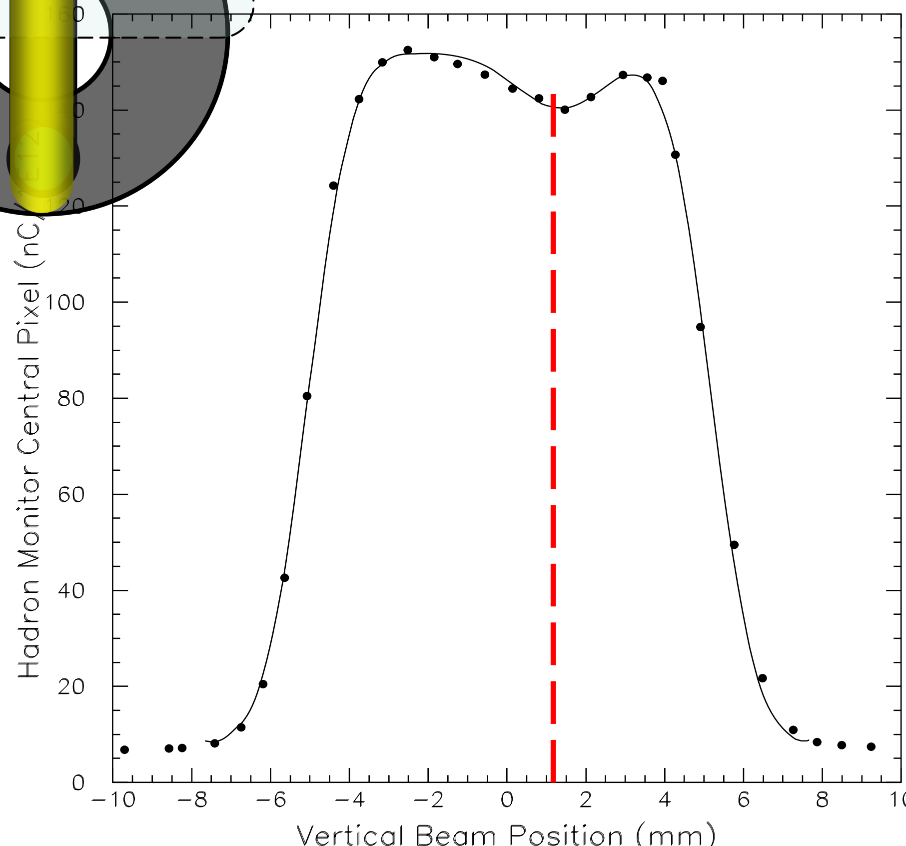
Measured: RMS

Measured: central pixel intensity

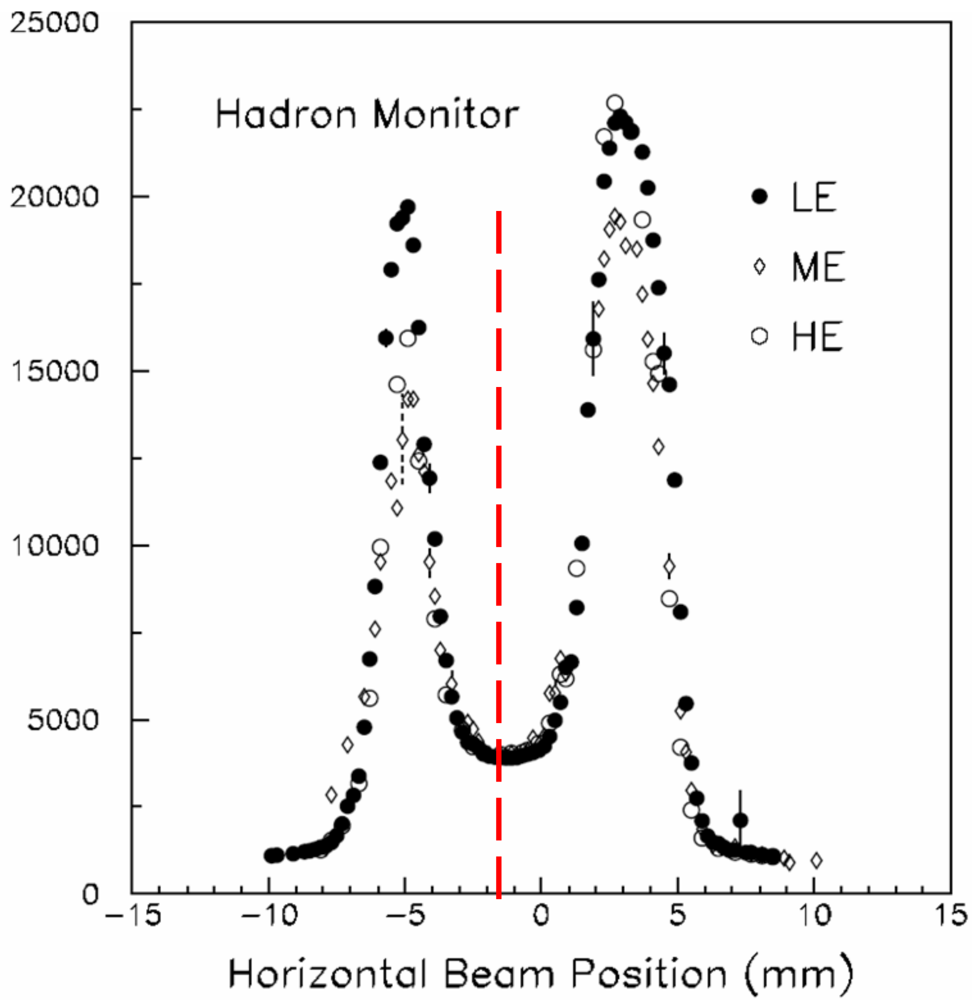




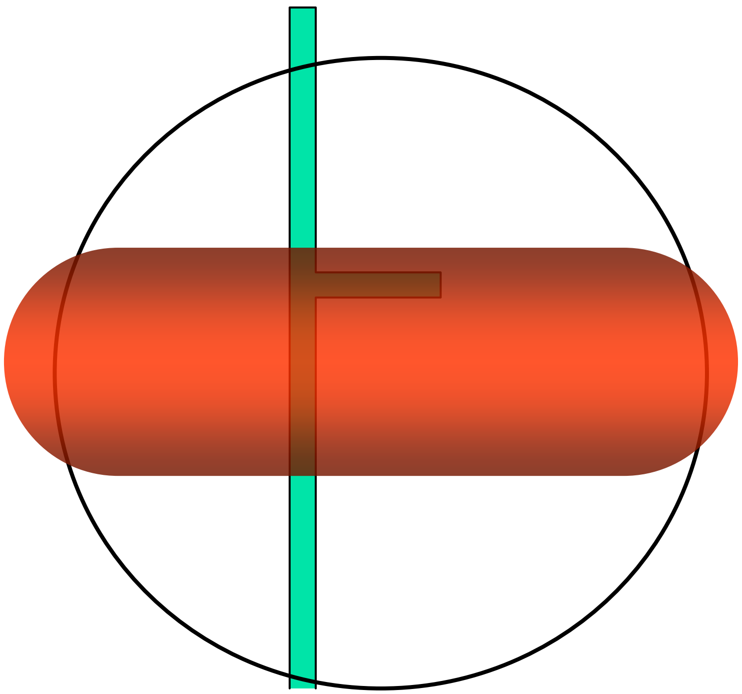


Target Tracks LE → ME →HE

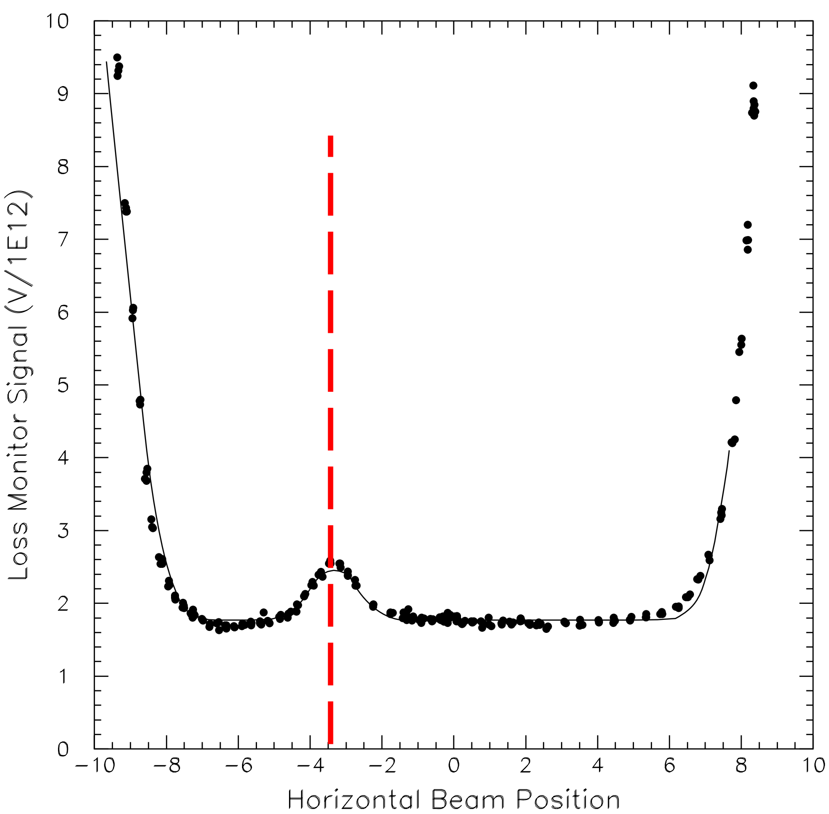
- Scans at **LE** (0 cm), **ME** (100 cm), and **HE** (250 cm)
- Target **parallel** with primary beam better than **0.5mm across 2.5m of travel**



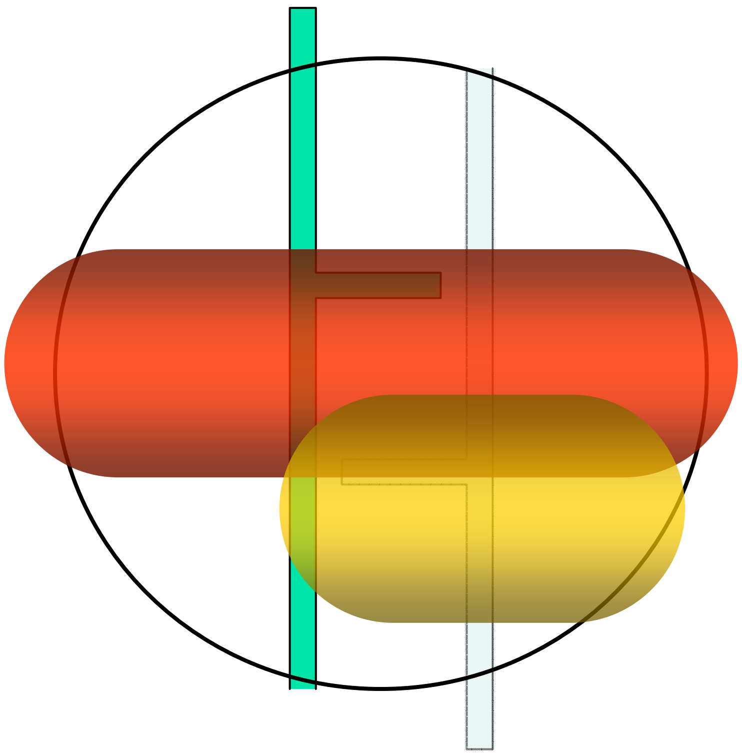
Horn 1 Horizontal Position



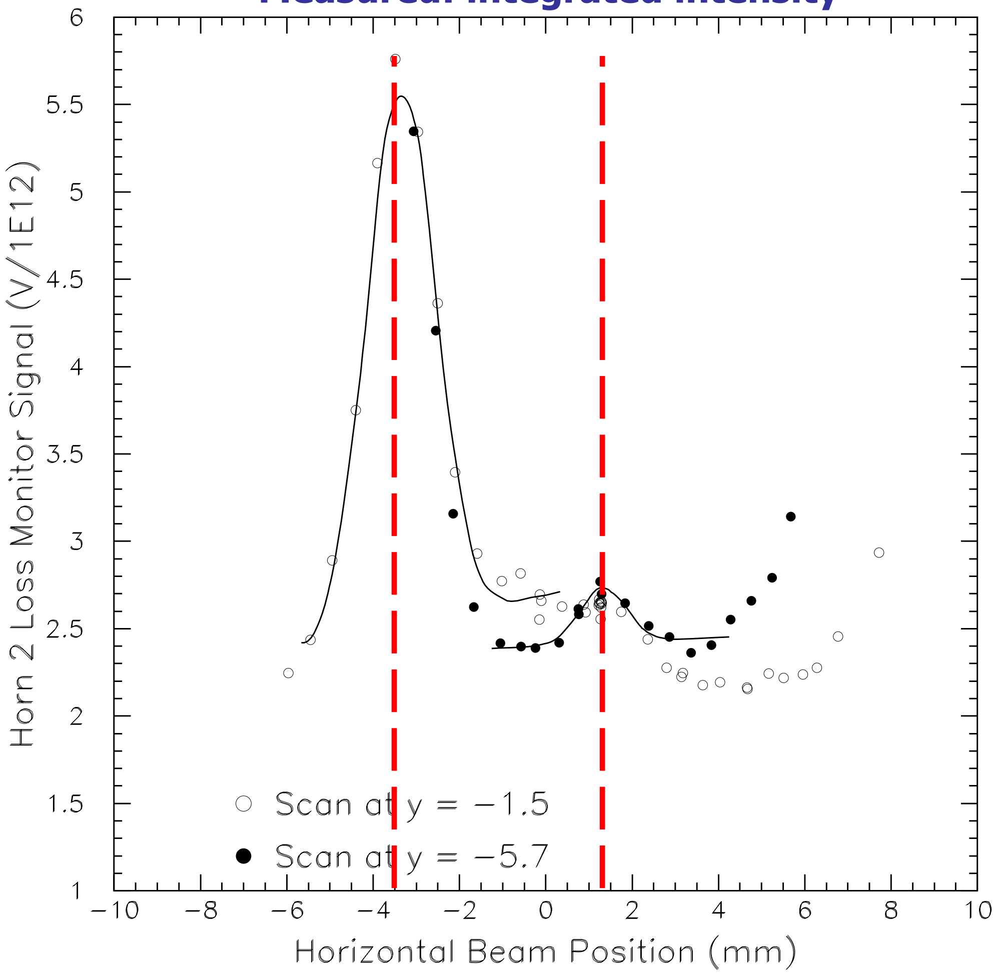
Measured: integrated intensity



Horn 2 Horizontal Positions



Measured: integrated intensity



Summary of Target/Horns Sans on BPM Measurements

Beam Not Steered (x,y) = (0,0) mm

Horizontal

DEVICE	Offset (mm)	Effect %	Angle (mrad)	Effect %
Baffle	-1.21	2.5	-0.14	<0.1
Target	-1.41	2.5	-0.14	<0.1
Horn 1	-1.24	1.1	-0.18	0.3
Horn 2	-1.82	1.2	-0.18	<0.1

Vertical

DEVICE	Offset (mm)	Effect %	Angle (mrad)	Effect %
Baffle	1.12	2.2	-0.7	<0.1
Target	0.13	<0.1	-0.7	0.26
Horn 1	0.81	1.4	0.26	0.43
Horn 2	0.08	<0.1	-0.43	<0.1

- components are consistently to the left , and usually down (exception is that baffle is about 1 mm high w.r.t. target)
- the "effects" represent the Far-to-Near ratio of neutrino fluxes as a result of the measured offsets – <u>tolerance required is < 2 %</u>

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Summary of Target/Horns Scans on BPM Measurements

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Beam Steered at (x,y) = (-1.2,+1.0) mm

Horizontal

DEVICE	Offset (mm)	Effect %	Angle (mrad)	Effect %
Baffle	0.01	<0.1	-0.14	<0.1
Target	-0.21	0.37	-0.14	0.1
Horn 1	0.03	<0.1	-0.18	0.32
Horn 2	-0.62	0.23	-0.18	<0.1

Vertical

DEVICE	Offset (mm)	Effect %	Angle (mrad)	Effect %
Baffle	0.12	<0.1	-0.7	<0.1
Target	-0.87	<0.1	-0.7	0.26
Horn 1	-0.19	<0.1	0.26	0.35
Horn 2	-0.92	0.42	-0.43	<0.1

- **beam is pointed on: Target center horizontally and Baffle center vertically**
  => established as beam RUN PARAMETERS
- **all effects Far-to-Near ratio of neutrino fluxes as a result of measured offsets from beam scans are well below the 2% tolerance required**

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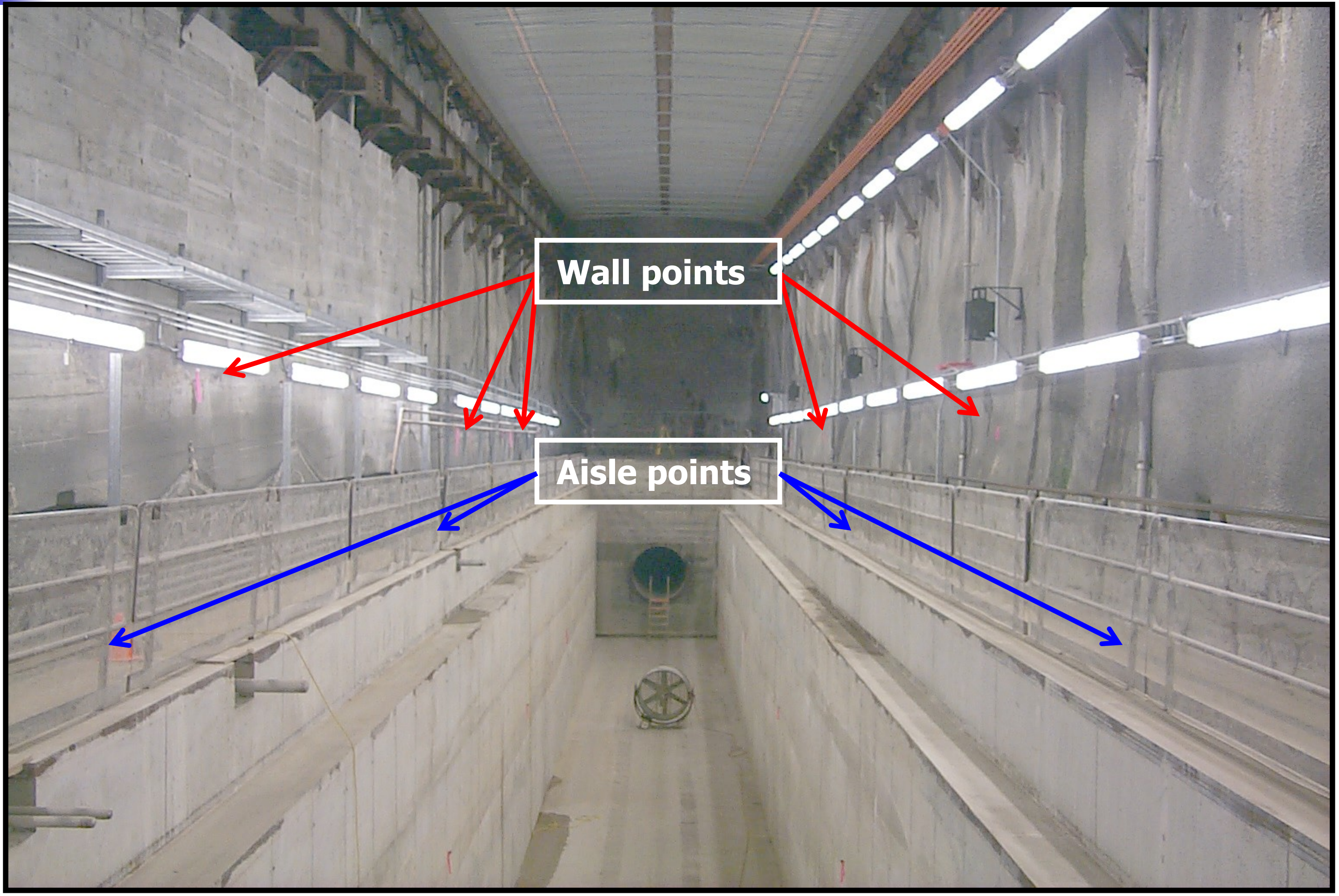
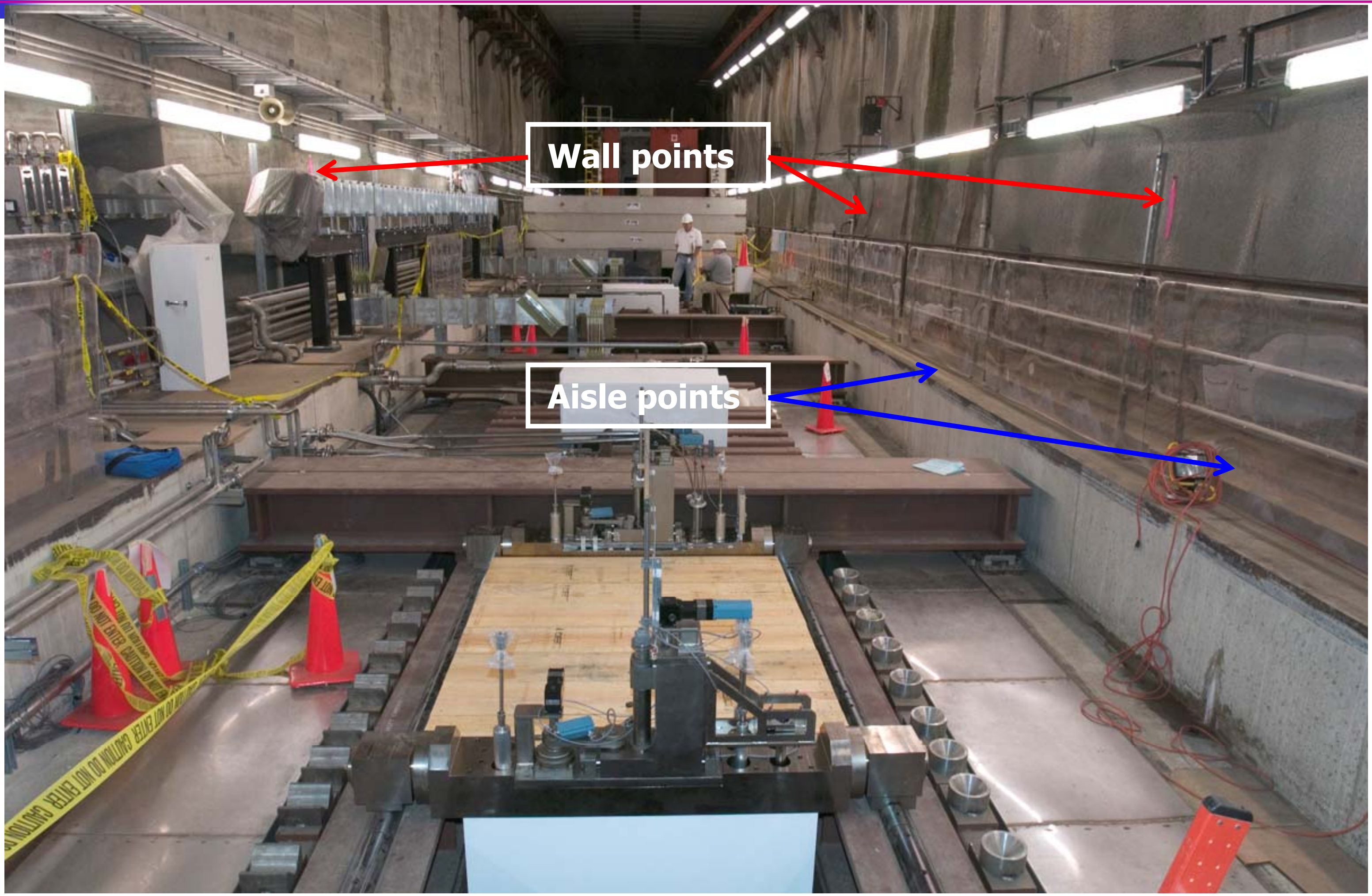
Pre-Target and Target Hall Deformation Analysis

- The beam-based alignment of the Target Hall components indicated that the Target Hall moved with loading of 6400 tons of steel/concrete
- A deformation survey campaign was performed in April 2005 covering the Pre-Target tunnel and Target Hall
- Three scenarios considered and analyzed:
  1. Target Hall empty (un-loaded)
  2. Target and Horns modules loaded into the chase and R-blocks unloaded (partial load)
  3. Target and Horns modules loaded into the chase and R-blocks loaded (full load)
- Methodology used: local Laser Tracker network supplemented by precision leveling

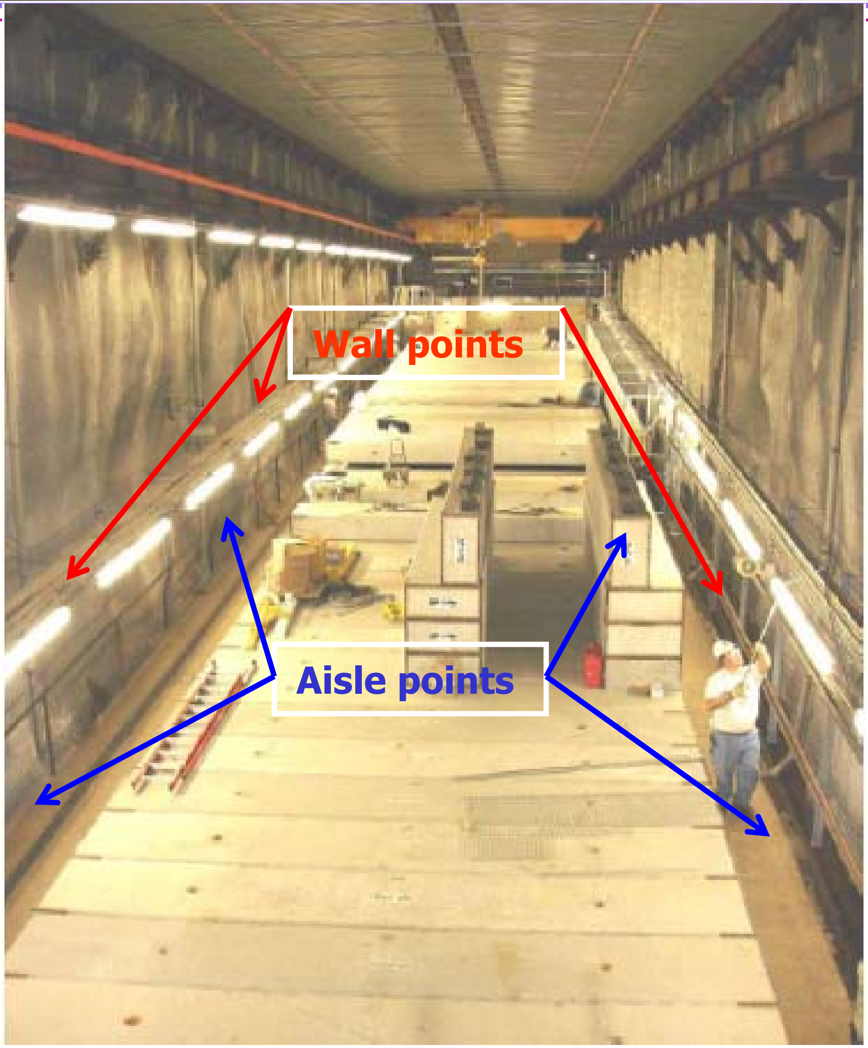
Target Hall During Network Observations



Target Hall During Target and Horns Alignment



Target Hall During Commissioning and Experiment Run

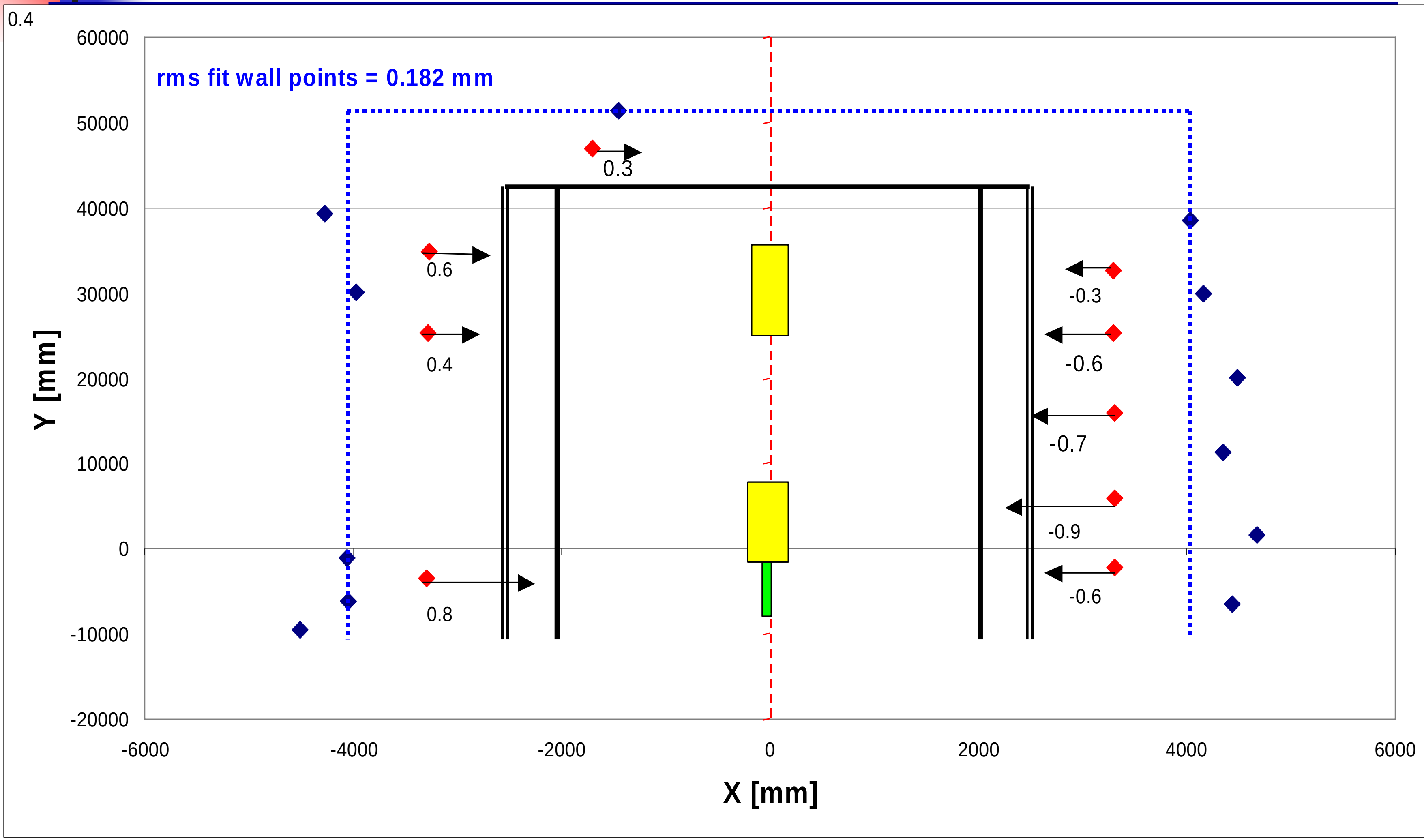


Horizontal Stability Results

- The horizontal stability analysis results showed:
  - **no deformations** in the Target Hall (walls or aisles points) until loading of the R-blocks (February 2005)
  - the trend analysis showed no movement tendency on the Target Hall wall points across all three scenarios
  - **deformations up to 0.9 mm** due to the load on both aisles after the installation of the R-blocks (February 2005) => **both E and W Target chase ledges/aisles moved inwards (towards the beam)**
  - **plastic deformation** => very little (0.2 mm) or no rebound when the R-blocks where removed
- The Pre Target tunnel: no horizontal (or vertical) deformations

Target Hall Horizontal Deformation

R-blocks loaded (as during run)



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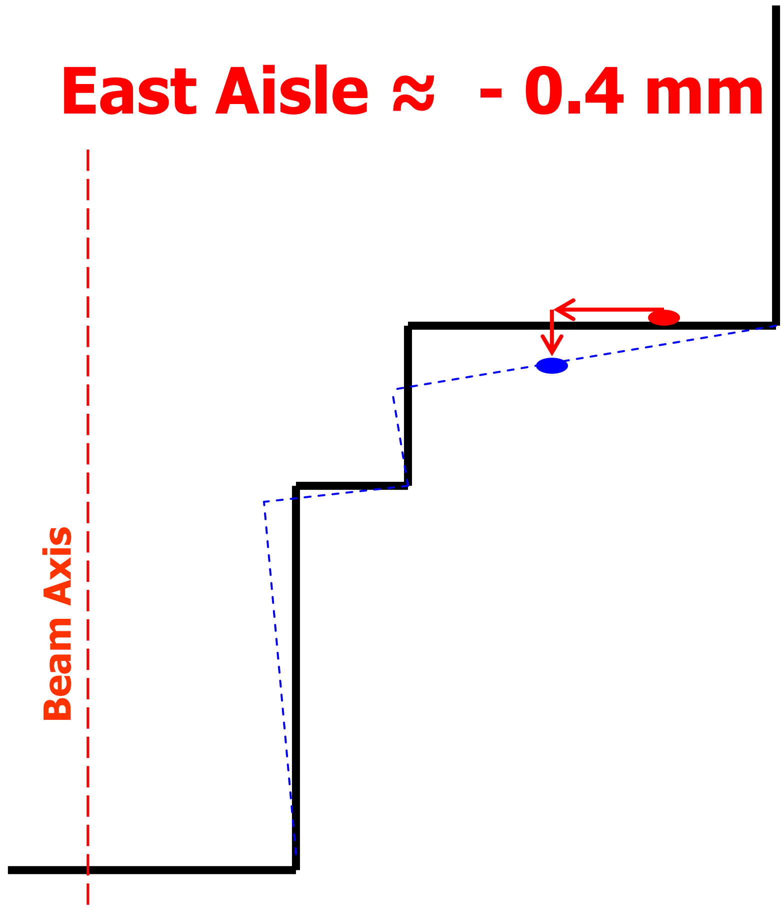
Target Hall Vertical Deformation

R-blocks loaded (as during run)

West Aisle ≈ - 0.7 mm

East Aisle ≈ - 0.4 mm



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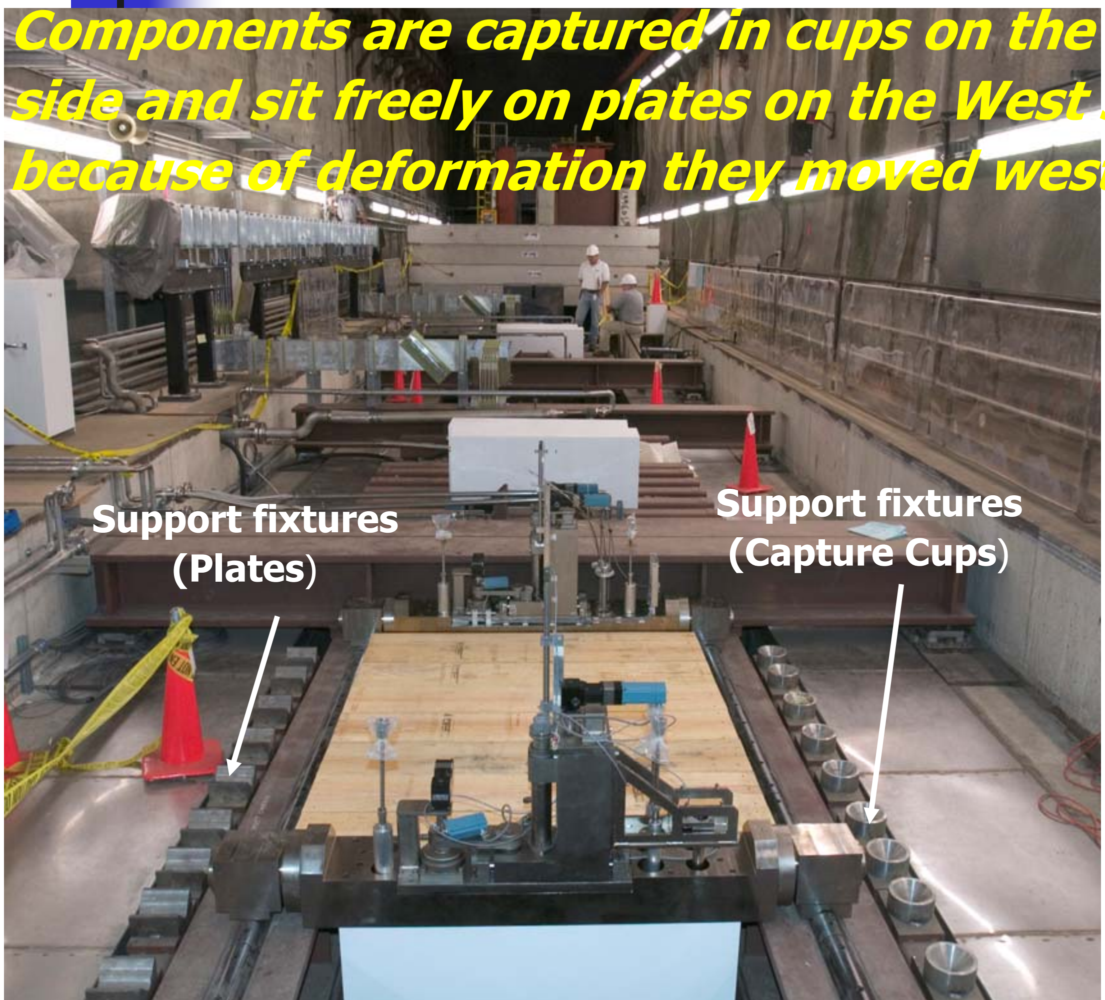
IWAA06
Sep 25-29 2006
SLAC
Virgil Bocean

Support/Capture Fixtures for Target and Horns

Components are captured in cups on the East side and sit freely on plates on the West side; because of deformation they moved westward



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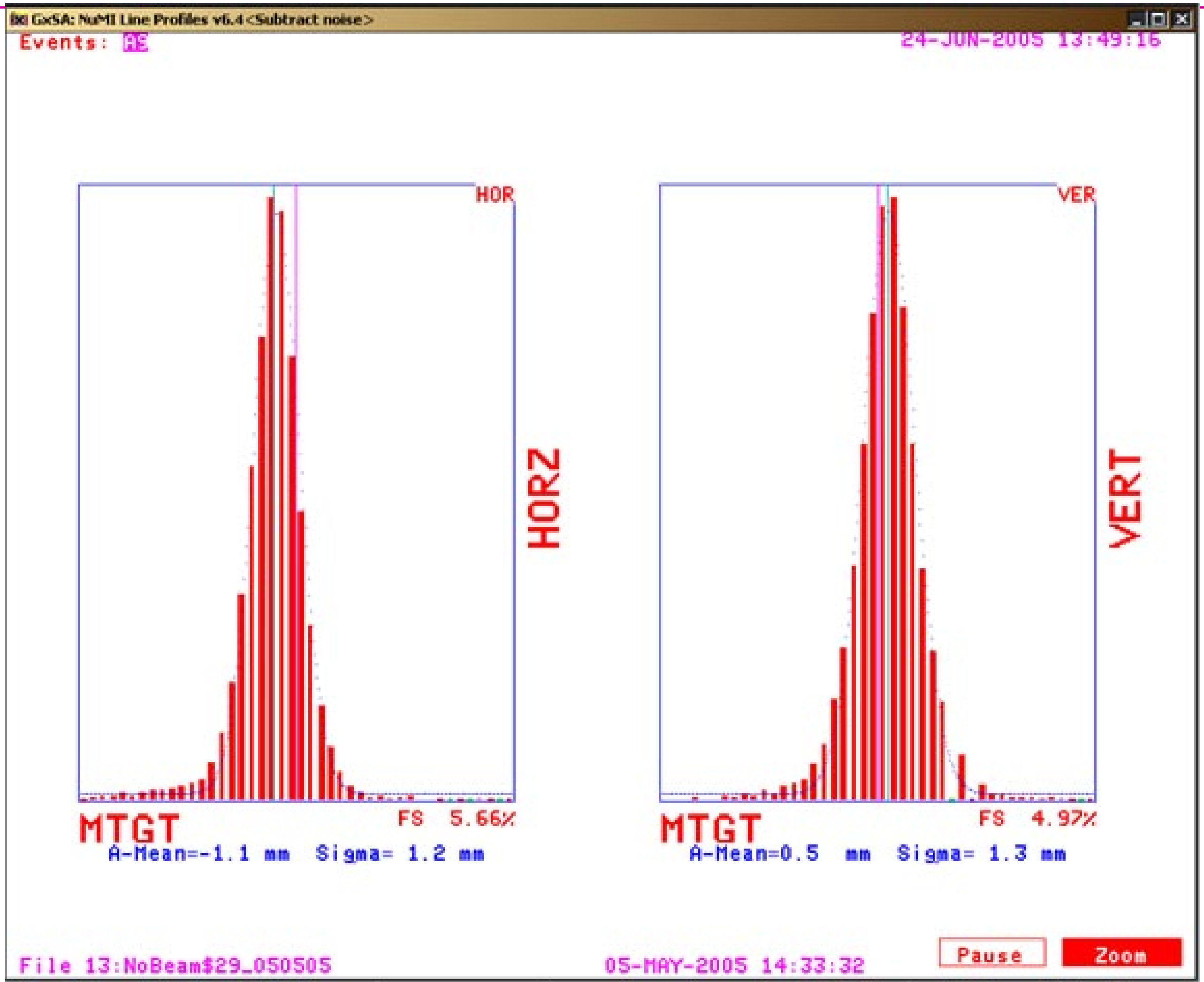
Estimation on Effect of Deformation on Target and Horns

- **Horizontal beam on Target and Horns:**
  - **Aisles (horizontal) deformation due to load = - 0.9 mm**
  - **Displacement due to thermal expansion ($\Delta T = 4^0C$) = -0.1 mm**
  - **Target misalignment =- 0.1 mm**
  - **Total Horizontal estimated displacement = -1.1 mm**
- **Vertical beam on Target and Horns:**
  - **Aisles (vertical) deformation due to load = - 0.5 mm**
  - **Displacement due to thermal expansion (DT = 4^0C) = -0.1 mm**
  - **Target misalignment = -0.1 mm**
  - **Total Vertical estimated displacement = -0.7 mm (the baffle was found 2 mm higher than the target at referencing)**
- **The deformation analysis confirms the beam-based alignment results**

June 24 ,2005 Beam Profile at MTGT



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CONCLUSIONS

- NuMI/MINOS commissioning and transition to Operations (May 12, 2005) successfully concluded, with excellent performance at each step
- NuMI/MINOS delivered to experimenters and running for physics

ACKNOWLEDGEMENTS

- ***I would like to extend our <u>sincere thanks</u> to all the many <u>people and organizations</u> who contributed to the realization and success of the NuMI/MINOS project.***