NuMI Beamline
Radiation Safety Issues

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NuMI Beamline Radiation Issues

- Overview
- Some Details
  - Air Activation
  - Groundwater Protection
  - RAW Water Calculations, Containment
  - Air and Water Monitoring
  - Residual Dose Rates/Hot Component Handling
- Decontamination & Decommissioning
- Conclusions

Radiological Safety Overview

Regions

- MI/Extraction
- Carrier Tunnel Lined Region
- Carrier Tunnel Drill &Blast Region
- Pre-target Region
- Target Hall
- Decay Tunnel
- Hadron Absorber
- Muon Alcoves

Mitigation

- Passive shielding
- Interlocked Radiation Detectors
- Beam Permit System (BPS)
  - Only extract if beamline ready & "good" beam

Radiological Areas

- Prompt radiation
- Residual activation of enclosures and components
  - Hot component handling
- RadioActive Water (RAW) systems
  - Cooling systems
- Airborne activation
- Groundwater activation/contamination

Designs are reviewed in accordance with Chapter 8 of the *Fermilab Radiological Control Manual* (FRCM).

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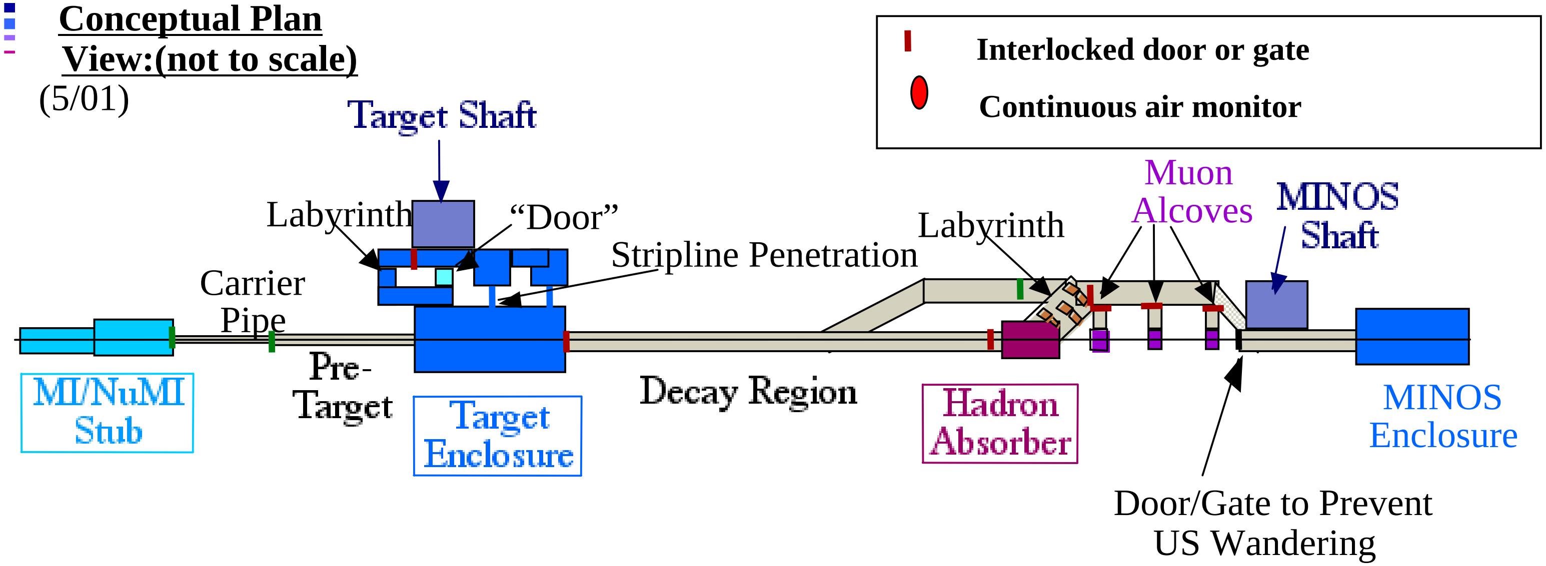
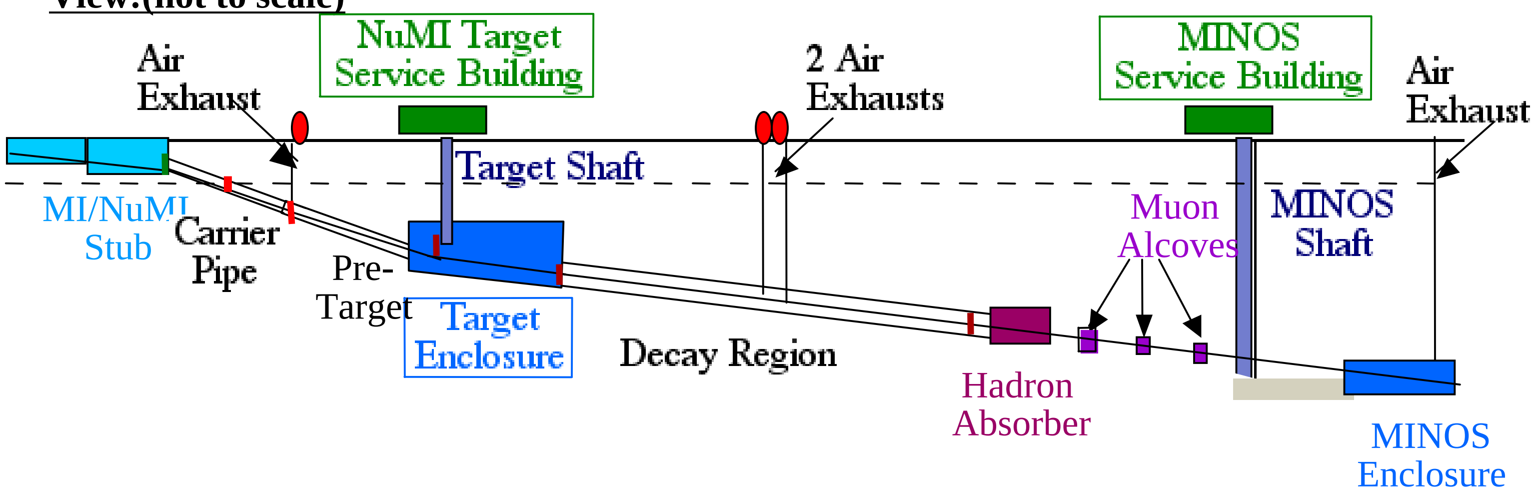
NuMI Radiation Safety Overview

Conceptual Plan View:(not to scale)
(5/01)



Conceptual Elevation View:(not to scale)



Radiological Safety: Assessment Process & Issues

1. Presentations to NuMI Radiation Safety Advisory Committee (NRSAC)
   - Initial validation of calculation methods
2. "Preliminary Radiation Shielding Assessment" to start civil construction in 1/00
3. Final "Radiation Shielding Assessment" approval needed to operate with beam
   - This occurs near the end of the project
   - Need "buy-in" on methodologies and rough results early on in design phase in order to have workable designs & no surprises

Issues

- We almost always underestimated the amount of work needed to determine radiation safety input to designs
- Radiation calculations almost always lagged design effort
  - Not enough manpower, experts
  - Often brought in non- radiation protection physicists to do the work
  - Used overall experience and general expertise of radiological personnel at FNAL until time could be spent to better calculate the effect.
  - At times this required modifications later, none significant fortunately

NuMI Radiation Protection Overview

Prompt Radiation (source term: MARS hadronic flux density):

- FNAL "standard" method/model
  - Based on personnel-sized labyrinths with bends
  - Rough (conservative) correction factor for long and/or small penetrations
- NuMI method/model (brought old model up to date)
  - More accurate for long straight and/or small penetrations
  - Automatically looks at "short circuits" and does curved penetrations
- Once start running, hope to benchmark this methodology

Groundwater (source term: MARS star density in rock):

- FNAL "standard" method/model
  - Beams in glacial till (~clay), thus water assumed static (no flow)
  - Model migrates water to aquifer, few cm's/yr movement, decay in transit
- NuMI method/model (NuMI in aquifer, water flows into tunnel at 350 gpm)
  - Water only activated as long as resident in rock, then pumped to surface
- Activation of water less an issue where water flows than at interface region

NuMI Radiation Protection Overview

Air Activation (source term: MARS hadronic flux density):

- FNAL “standard” method/model
  - Single volume of activated air, leaves activation region, decays in transit
  - CAP 88 program required for use for determining rates at site boundary
- NuMI method/model
  - 2 activated volumes, one highly activated & confined, leaks to outer volume
- Air in Target Pile and Hadron Absorber must be confined as much as possible

Cooling Systems Activation (source term: MARS hadronic flux density):

- No FNAL “standard” method/model, estimates made, measure as run
- NuMI method/model
  - Develop method/spreadsheet for calculation similar to air activation spreadsheet
  - Use flux densities from MARS and cross sections
- Levels get very high for horns, target – determine frequency of changes

NuMI Radiation Protection Overview

Component Activation (source term: MARS residual dose rate):

- FNAL "standard" method/model
  - Previously used CASIM star density with correction factors
  - MARS is now the "shielding code" that must be use & gives residual dose rates
- NuMI method/model
  - Benchmarked MARS residual dose rate values at FNAL AP0
  - Use MARS residual dose rates with uncertainty factors based on the benchmark data
- Cracks between shield blocks are important, but not as big a contributor to residuals as was generally thought
- Material composition can be very important, especially sodium content of concrete

some details to follow…..

Groundwater Protection

- Hired several groundwater consultants to determine water levels and flow rates around the unlined regions of the NuMI tunnel.
  - All water within 10' (3 m) of tunnel flows into the tunnel (within the aquifer region)
  - Most water flows in rapidly through the fractures
  - Determine an average inflow velocity based on groundwater consultant's inflow estimates

- Use the Fermilab Concentration Model, modified to allow for water flow
  - Fermilab Reports TM1851, TM2092, TM2009 (NuMI).
  - Updated to include our latest understanding of groundwater contamination by ^{22}Na and ^{3}H, the only radionuclides of concern (NuMI-B-495)
  - Flow dependent residency time of water in the region of the beamline (inflow or outflow) where applicable.
  - Irradiation time = residency time of the water in the activation region
  - Groundwater Methodology document completed and approved.

Groundwater Protection

Standard Groundwater Model	NuMI	Resulting Model
Static water	Water flows	Inflow (^{22}Na retarded)
Leaching based on glacial till, 90% leaching volume of water	Dolomite with fractures rock with porosity -> water volume	"Leaching" volume of water is the porosity "volume"
Radionuclide production based on Borak et. al	Direct production of tritium in water	^{22}Na: FNAL measurement ^{3}H: based on Borak et.al.

Calculations must be below the regulatory limit including uncertainties (FNAL memo, DOE Environmental Assessment response letter)

- Use uncertainties in <u>all</u> parameters to determine overall uncertainty
  - Determine effect on results and add in quadrature

Calculations are conservative (for inflow regions):

- Comparing concentrations in inflow water, which will be pumped to the surface, to groundwater limits
- Model includes worst case conditions (dry), which we did not encounter
- Does not include decay during migration to a well
  - **Water along the unlined beamline tunnel can not get to any well other than the NuMI beamline "well"**
- Does not include dilution & dispersion in transit to a well

Bottom Line: <u>Ensure compliance with monitoring well(s)</u>

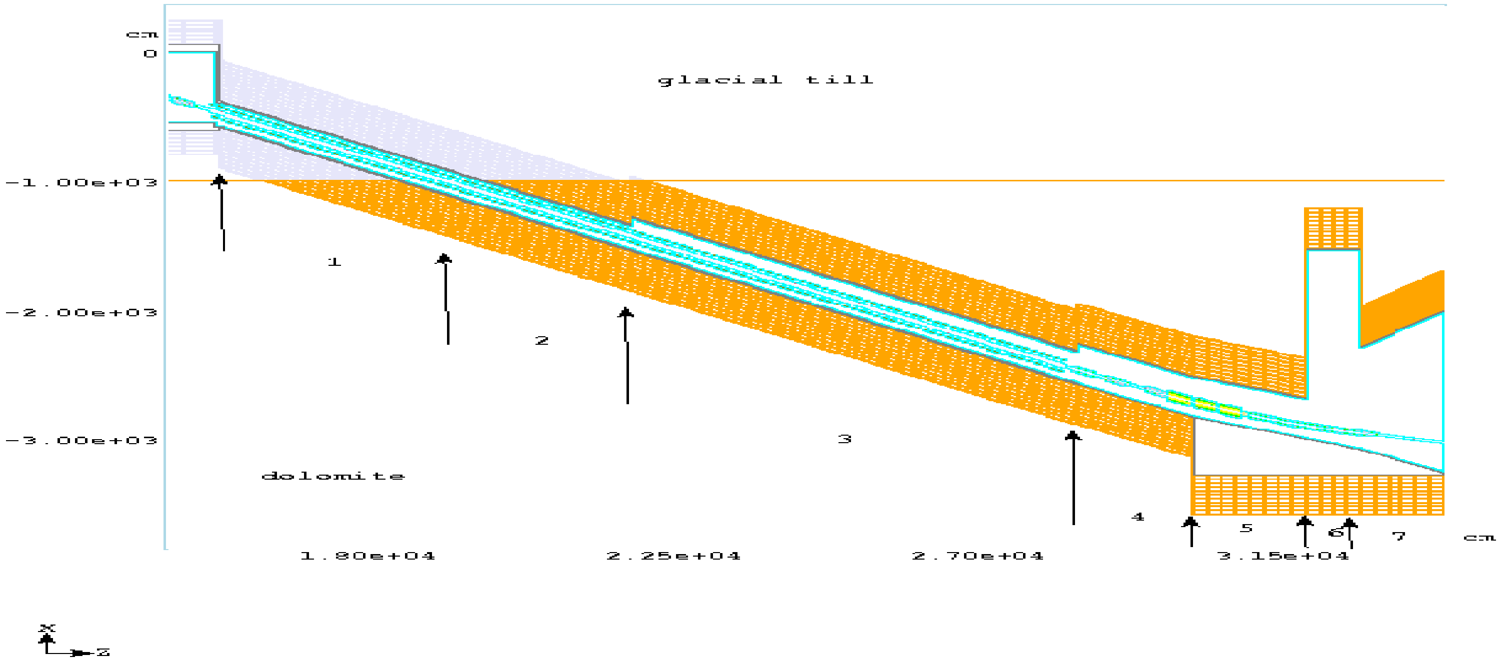
Groundwater Protection: Primary Beam- Clean

- Open apertures and “Autotune” will help keep beam nominal and “clean”
  - Have determined power supply regulation needed for clean beam
  - Beam optics dynamic aperture matches that of the Main Injector
- Beam to NuMI only when conditions are nominal (Beam Permit System, BPS)
  - Magnet currents within nominal limits this pulse
  - Limit on beam loss last pulse and integrated beam loss (beam loss monitors, Beam Loss Budget Monitor, BLBM)
  - Interlocked radiation detectors (detect large loss in carrier tunnel region)
    - Part of Radiation Safety System to prevent multiple accident pulses
  - “Clean” Main Injector beam
- Detailed simulations (MARS14) of the primary beamline and possible accident and DC (continuous) loss conditions have been studied.
  - Strong indication that beam loss monitors (BLM) signals closely track groundwater activation levels.
  - Testing BPS in MiniBooNE

Groundwater Protection: Primary Beam

MARS14 Primary beamline: 7 different regions based on geometry & geology (water flow rates different in each region)

- water velocity varies from a few cm's/year in the upstream glacial till region to
- 50-200 meters/year in the lower rock regions



Groundwater Protection: Primary & Secondary Beam

<u>Primary Beam:</u>

Lined Carrier Tunnel, Interface Region - driving region:

– 125 lost pulses in 1.5 years

Dimensions:

- 6' (1.8 m) diameter tunnel,
- 1' (0.3 m) diameter beam pipe
- ~100' (30 m) long section

<u>Accident Loss:</u>

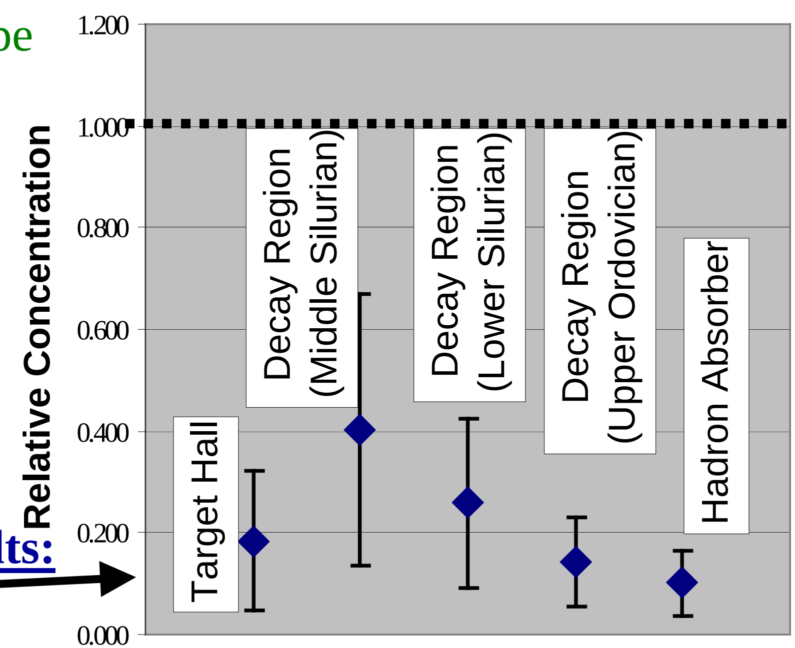
- Unlikely to happen often.
- Loss detected and next pulse not extracted.

<u>Normal Loss: ~10^{-4}/4e13ppp</u>

<u>Secondary Beam (Inflow Region) results:</u>
(no accident condition)

Groundwater limit: ^{3}H: 20 pCi/ml, ^{22}Na: 0.4 pCi/ml
Surface water: ^{3}H: 2000 pCi/ml, ^{22}Na: 10 pCi/ml

Radionuclide Concentrations Relative to the Regulatory Limit

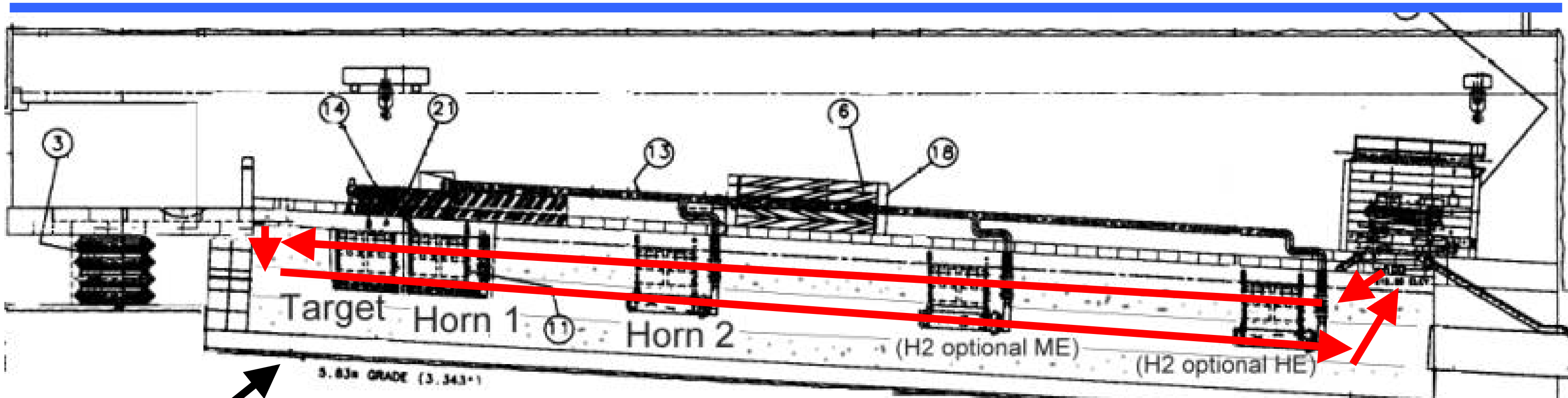


Airborne Activation

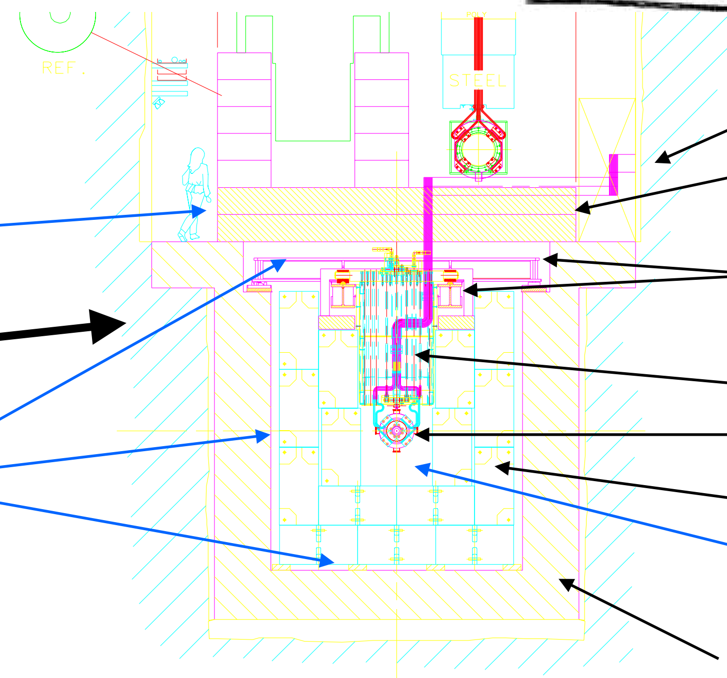
Radioactive Air calculations:

- Goal for NuMI is < 45 Ci/year:
  - ~0.025 mrem/year (1/4 continuous monitoring limit)
- Majority of the air activation occurs inside the Target Pile
  - **Closed system at negative pressure relative to the air outside the shield (recirculated at ~25,000 cfm, 30 km/hr)**
  - **Preliminary calculations based on re-circulation:**
    - **@ 700 cfm (20 m^3/minute) vent rate to stack, leakage @700 cfm-> ~20 Ci/year (4E13 p/pulse)**
- Hadron Absorber contributes a significant amount also
  - **Need to seal the Hadron Absorber.**
  - **Preliminary calculations based on sealing:**
    - **@ 2250 cfm (64 m^3/minute) vent rate to stack, leakage @200 cfm-> ~10 Ci/year (4E13 p/pulse)**
- Have a variable rate ventilation system for both stacks.
- <u>Measurements of air activation</u> will be made early on and the ventilation rates can be adjusted (and both piles can be better sealed if necessary)

Airborne Activation



Elevation



Cross Section

Stripline

Concrete Cover (oops – really only one layer)

Top air seal

"Carriage" - Module Support Beams

Horn Shielding Module

Horn

Steel Shielding

Air from chiller runs down outside of pile

Air returns down center of beam-line

Concrete Shielding

Radioactive Water (RAW)

(^{3}H, ^{7}Be main concerns)

Activity in cooling water, maximum estimates, 1 year of operation, 1 hour cooldown

- Horn 1 RAW water system (horn 2 RAW about a factor of 3 less):
  - Change ~ yearly
  - 7 Ci/yr, ~140 μCi/ml
- Target RAW water system:
  - 1 Ci/yr, very small volume
- Decay Pipe RAW water system:
  - Most likely last lifetime of NuMI
  - 11 mCi/yr, ~700 pCi/ml
- Hadron Absorber RAW water system:
  - Most likely last lifetime of NuMI
  - 40 mCi, ~0.1 μCi/ml

Water will be sampled periodically to check levels, alarm systems for water loss, procedures for access to RAW Room.

(FRCM guidelines recommend not exceeding 0.67 μCi/ml)

Radioactive Water (RAW)

Target Hall RAW Water – Secondary Containment

- Slow Leak Scenario: Surface discharge much less than the limit, so that long term leaks are not a problem.
- Sudden failure (20 Ci in system, 20 out of 100 gallons leaks before shutdown
- Water can not go directly in to the under drain, seepage through the concrete floor is sufficient

	H3	Be7
resulting water radio activation, slow leak	8 piC/ml	47 piC/ml
resulting water radio activity, sudden failure	0.4 Ci	2.1 Ci
Water flow rate	150 gal/min	150 gal/min
Surface Water Limit	2000 piC/ml	1000 piC/ml
sudden failure duration (to not exceed limit)	6 hr	61 hr

Air and Water Monitoring

Operation of the NuMI Facility will be included in the comprehensive laboratory water and air monitoring program

Air:

- Permanent air monitors will be located at both ventilation shafts in the decay region (Hadron Absorber air and Target Hall air release points)
  - Probably 3rd monitor at the release point in the upstream end, good indication of beam loss
- Measurements will be watched closely when NuMI starts up at low intensity (flow rates can be decreased, shielding piles can be better sealed)

Water:

- One monitoring well is located just down gradient of the carrier tunnel interface region.
- Regular sampling of the monitoring wells (monthly initially)
- Regular sampling of the water pumped from NuMI and released to the surface waters.
- Regular sampling of the cooling water systems (RAW and LCW)

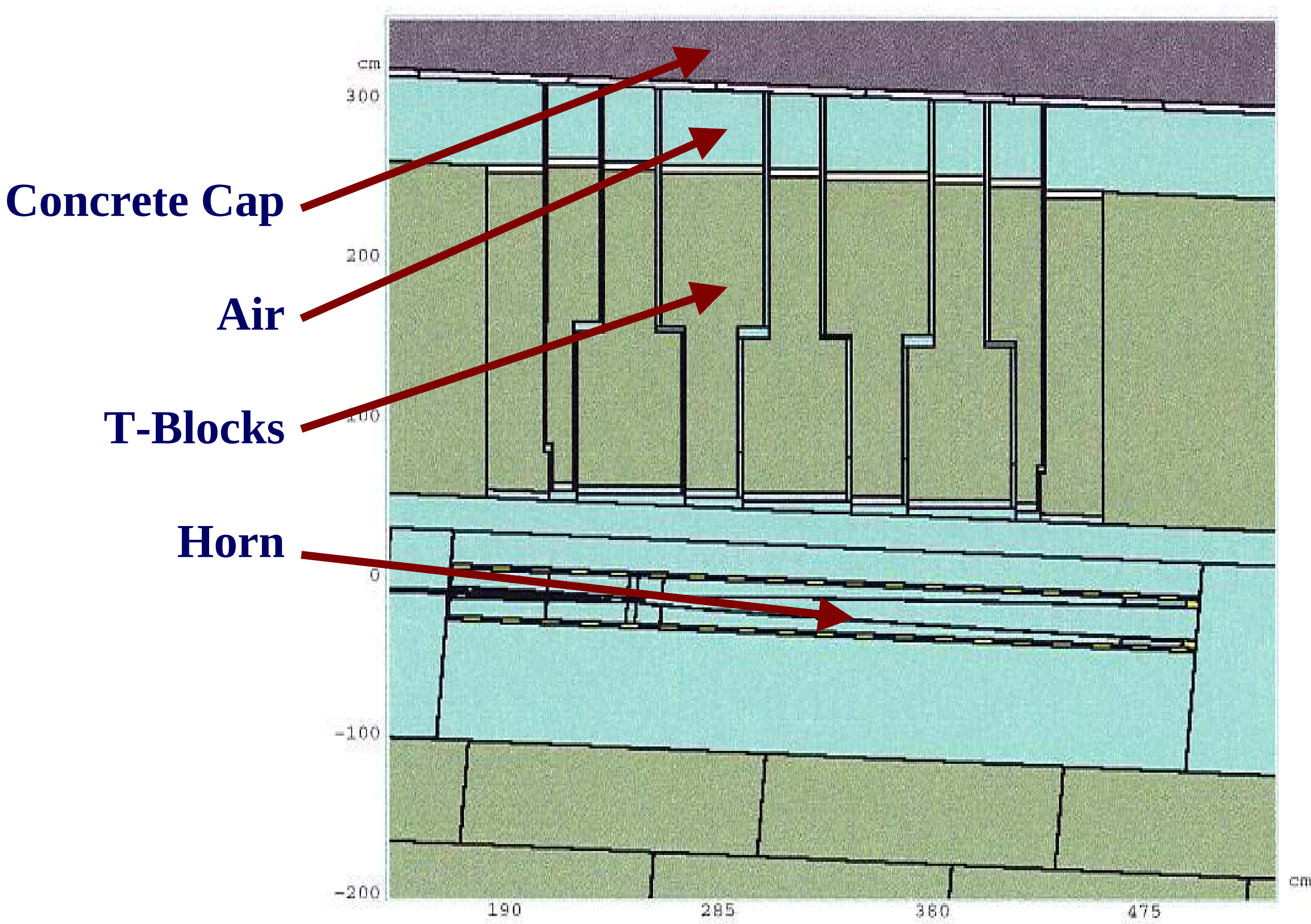
Residual Dose Rate Estimation with MARS

Much Progress has been made in this area:

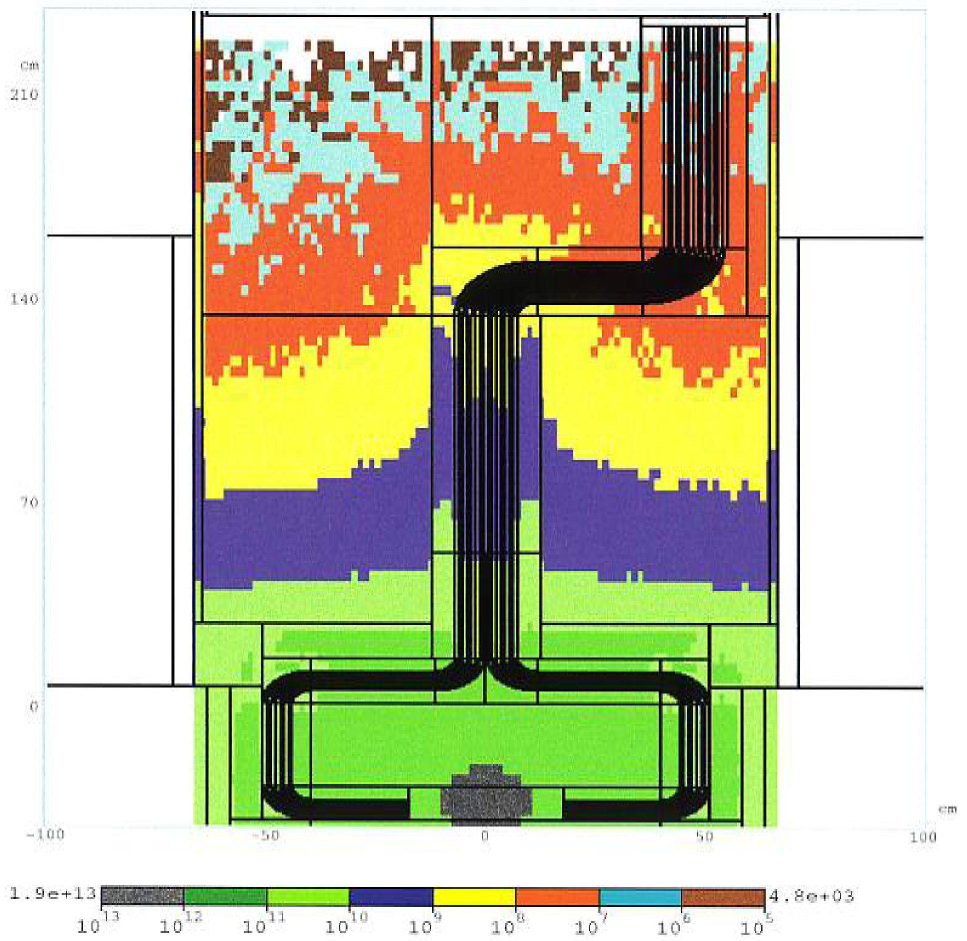
- "Benchmarking Residual Dose Rates in a NuMI-Like Environment", I. Rakhno et. al.
  - Agreement is within a factor of 3
  - Must carefully put in geometry, materials and get sufficient statistics (neutrons dominate as source)
- Detailed Target Hall geometry around horn 1 is complete.
  - Cracks around module and between T-blocks
  - Stripline penetration
- Robust draft Hot Horn Handling procedure, drawings and dose estimates are complete.

details to follow….

Residual Dose Rates with MARS: Horn 1, Module, T-Blocks, Cracks



MARS: Horn 1 Stripline Cross Section Flux



MARS14: Target Chase & Residual Dose Rates

mrem/hr on contact, 30 day irradiation, a day cooldown

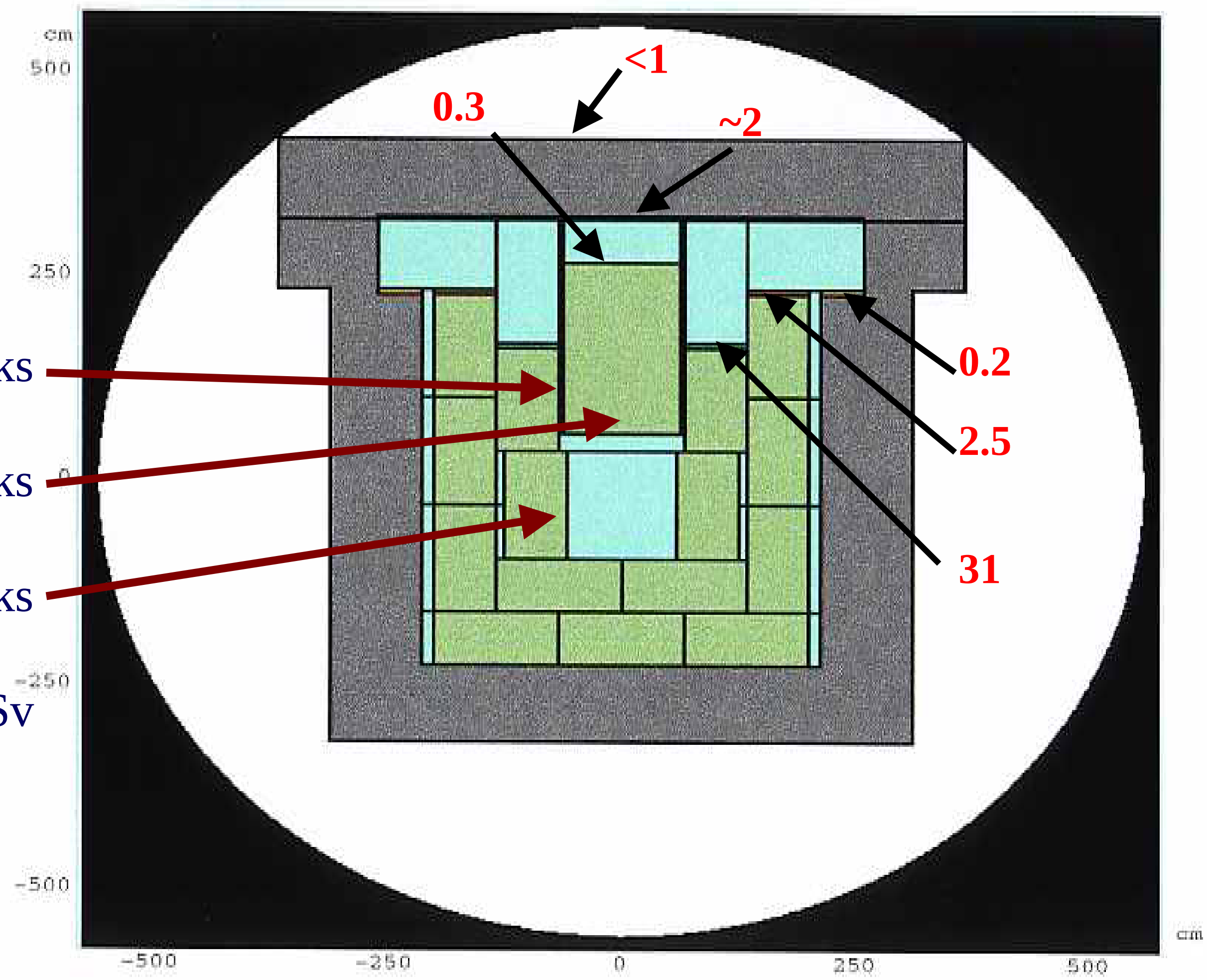
100 mrem = 1 mSv

Inner side of top blocks

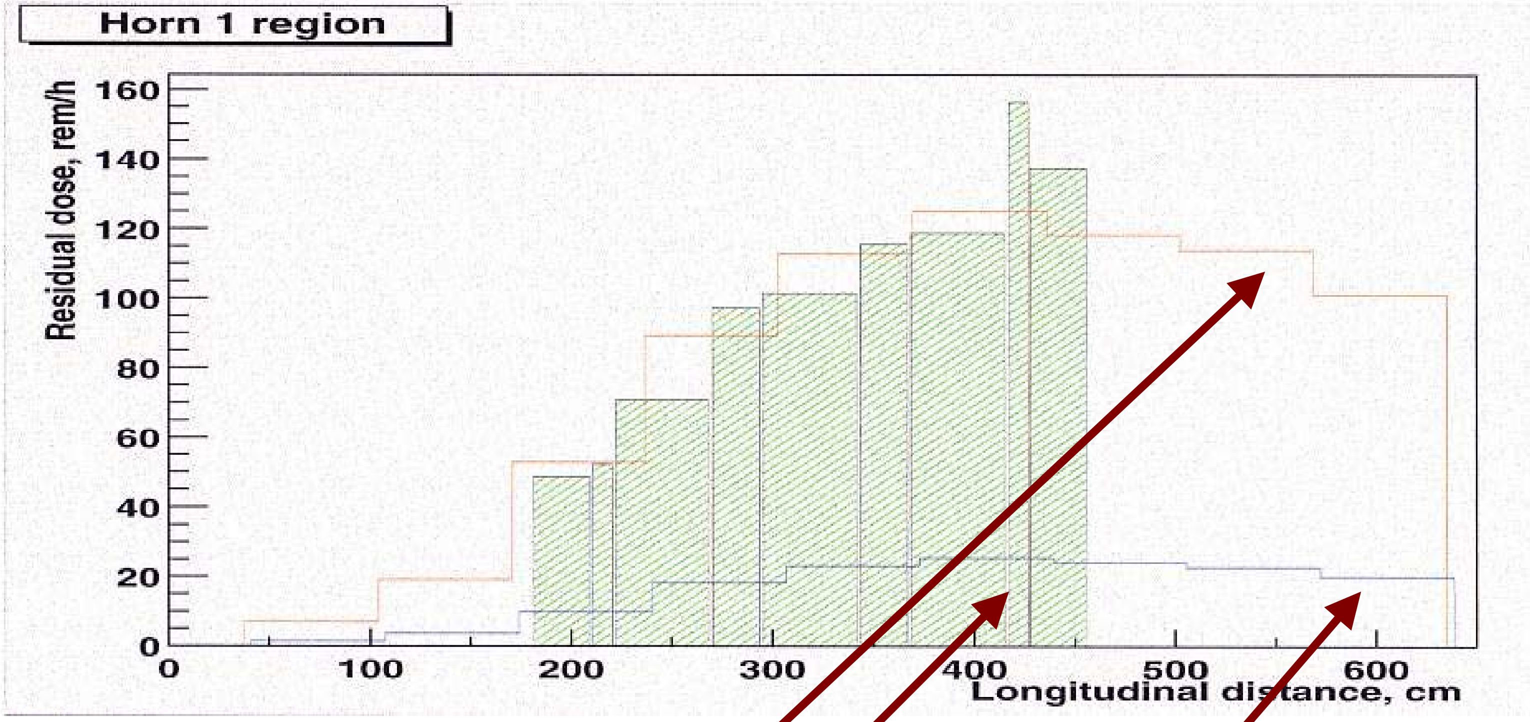
Bottom of T-blocks
98,000

Inner side of bottom blocks

100 mrem= 1 Sv



Residual Rate Distributions



Top Curve: inner side of bottom set of steel blocks in chase

Shaded Curve: bottom of T- Blocks

Bottom Curve: inner side of top steel blocks in chase 100 rem = 1 Sv

Residual Activation

Location	Dose Rate (on contact)
Target Hall: concrete floor of work area	< 1 mrem/hr
Target Hall: Top of T-Block (horn 1)	~ 5 mrem/hr
Target Hall: Bottom of concrete “cap”	~ 2 mrem/hr
Target Hall: near hot cell	
Target Hall: near air handling equipment	
Target Hall: DS horn baffle (old result)	25 rem/hr
Target Hall: bottom of T-Blocks above horn 1 (average)	100 rem/hr
Target Hall: inside cave walls around horn 1	80 rem/hr
Target Hall: horn 1 outer conductor	600 rem/hr
Target Hall: target	6000 rem/hr
Target Hall: upstream wall	
Decay Region: outside edge of concrete	~100 mrem/hr
Decay Region: emergency egress (rock & conc)	~100 mrem/hr
Decay Region: upstream window	5 rem/hr
Decay Region: downstream window	700 mrem/hr
Decay Region: decay pipe	30-200 rem/hr
Hadron Absorber: Core Near Beam	~100’s rem/hr
Hadron Absorber: Core Sides	~ 10’s rem/hr
Hadron Absorber: Steel Blocks	~1’s rem/hr
Hadron Absorber: Front	~ 1’s rem/hr
Hadron Absorber: Labyrinth Side	~100 mrem/hr
Hadron Absorber: Non-Labyrinth Side	
Hadron Absorber: Top	
Hadron Absorber: Back	< 30 mrem/hr

MARS13 Residuals:

30 days irradiation,

1 day cool down

(@2E13protons/sec)

100 mrem = 1 mSv

NuMI Hot Component Handling

NuMI Target Hall Utilizes Three Basic Beamline Elements

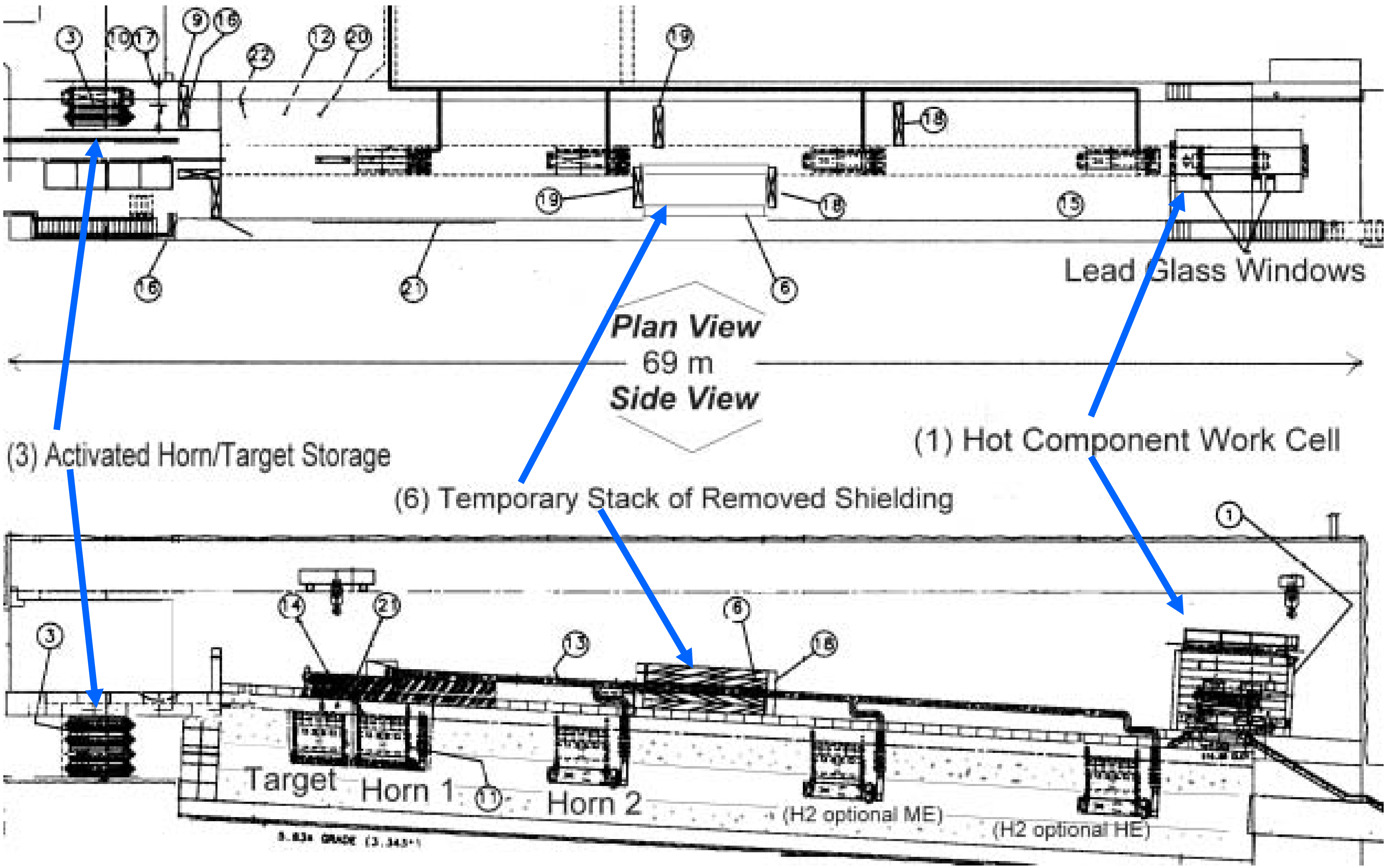
- Horn Protection Baffle & Target Assembly
- Magnetic Focusing Horn 1
- Magnetic Focusing Horn 2

Basic Operational Criteria

- Protection baffle/target assembly and horn 1 require motion capability in beamline chase
- Shielding design should allow the position of horn 2 to be changed along the beamline to accommodate a LE, ME, and HE beamline configuration
- Low energy target is designed for 10^7 pulse, 1 year lifetime
- Focusing horn 1 is designed for 10^7 pulse, 1 year lifetime

We anticipate changing failed horns and targets during the experiment (and allow flexibility for configuration changes)

NuMI Target Hall



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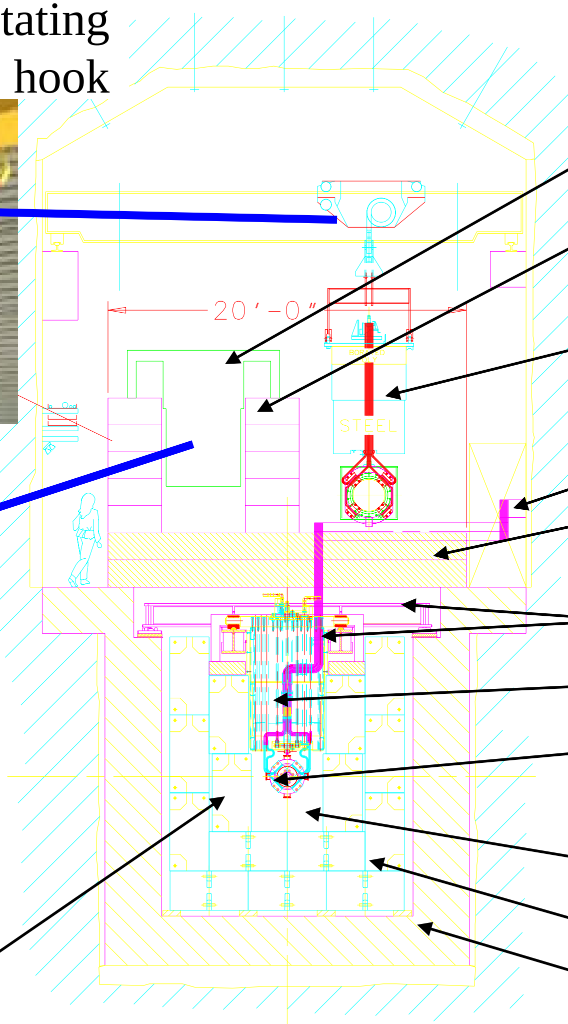
NuMI Target Hall

Beam line is below floor level

Remote rotating crane hook

Beam passageway (chase) is 1.2 m wide x 1.3 high



Temporary Stackup of removed shielding
Steel from module middle
Concrete from over horn

Horn+Module in transit

Stripline

Concrete Cover

Module Support Beams

Horn Shielding Module

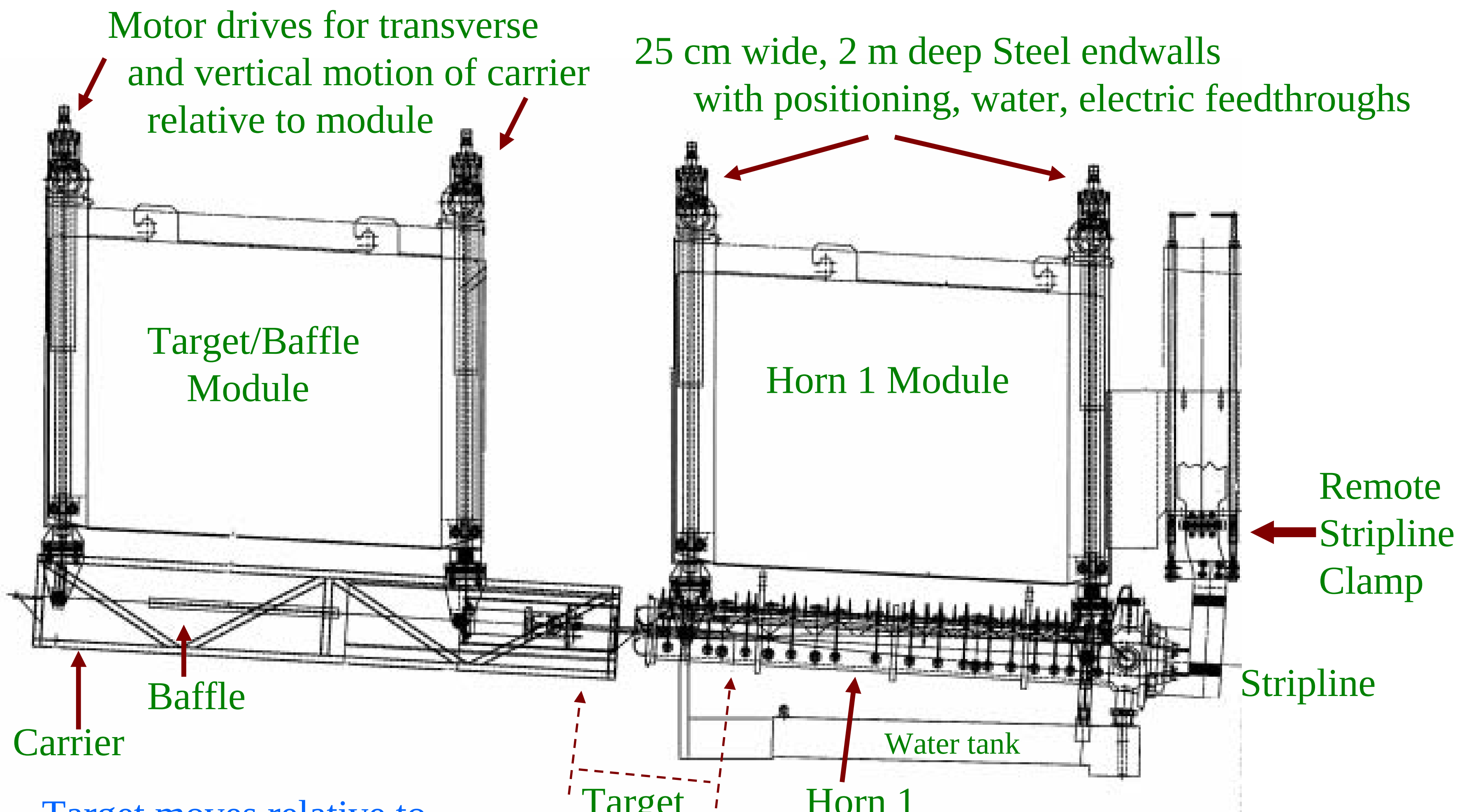
Horn

Steel Shielding

Air Cooling Passage

Concrete Shielding

Target and Horn Modules



Target moves relative to carrier for insertion into horn for L.E. beam

Hot Handling Work Cell

Mount/dismount components on modules

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

Railing

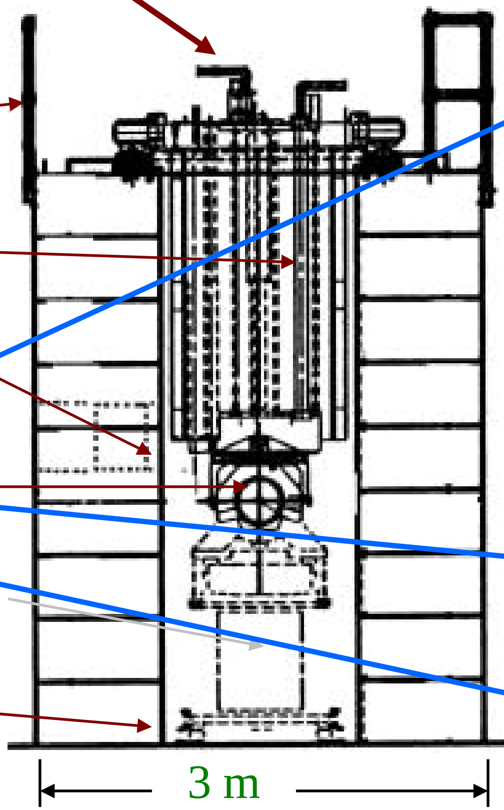
Module

Lead-glass window

Horn

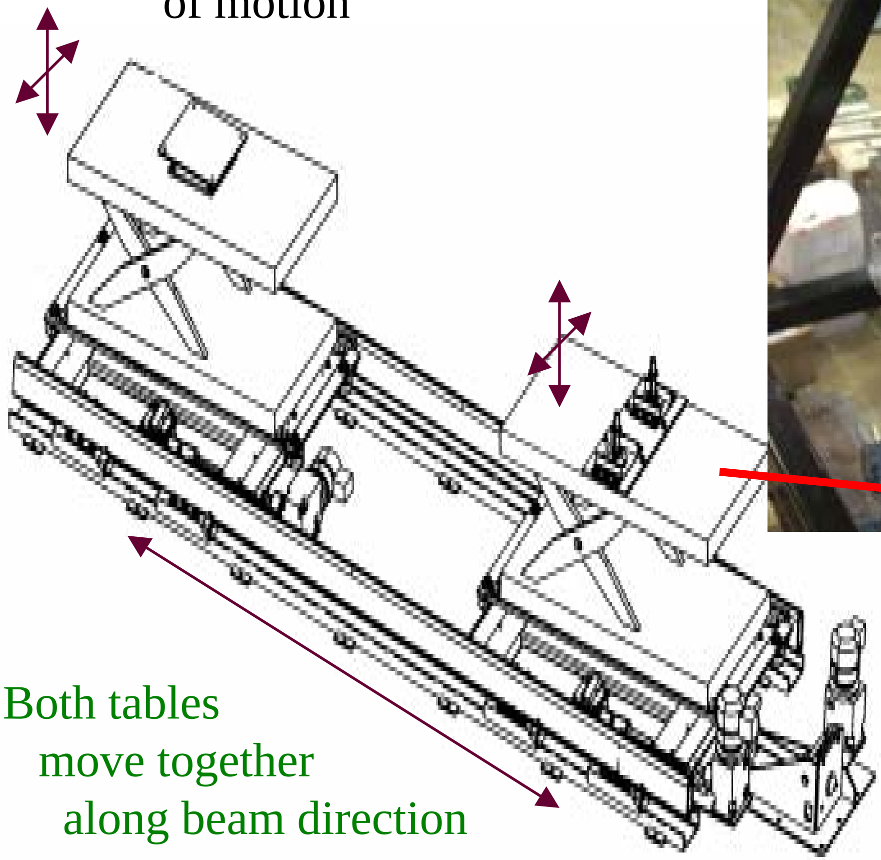
Remote lifting table

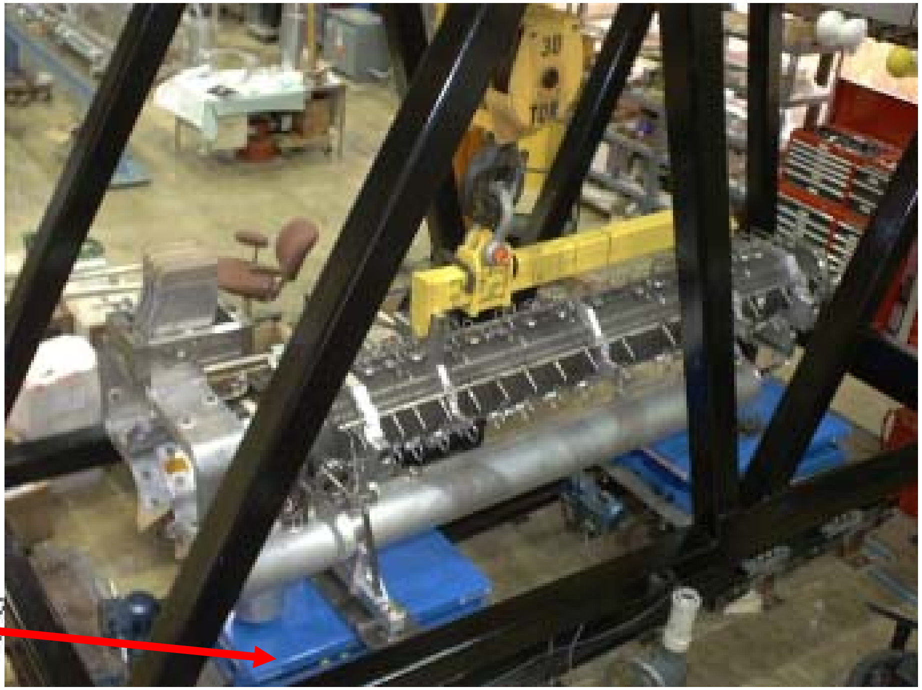
Concrete walls



Lifting Table in Hot Cell

Push horn or target up into module remotely – 5 degrees of motion





Both tables move together along beam direction

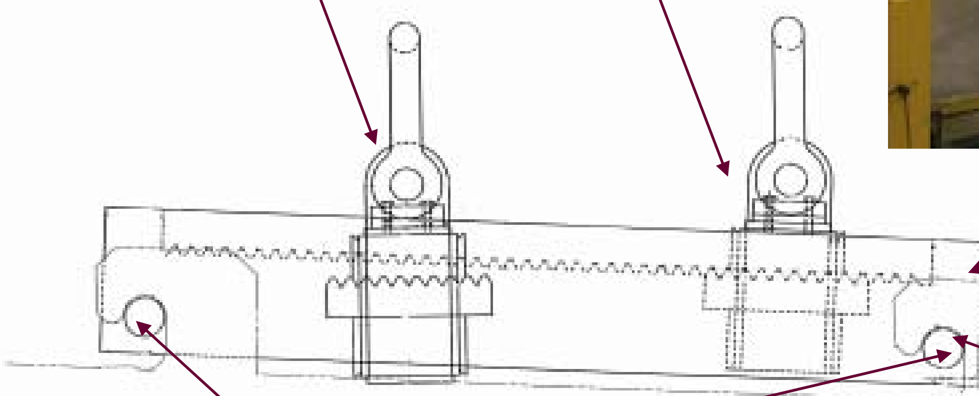
Each table has independent vertical and transverse motion

Lifting Fixture for Module

Remotely change pick point to match center of gravity

Teeth disengaged to enable movement of hook relative to lifting fixture frame

Teeth engaged at center of gravity for horn 1 pick



Lifting fixture box frame

Module hook

Pins to engage module hooks

Hot Horn Replacement Procedure

italics denotes remote operation (camera)

- Remove concrete cover, use to build temporary shield
- Disconnect utilities from top of module
- *Crane the shield T-blocks from module to temporary shield pile*
- *Crane module+horn to hot cell (close cell door, place covers on top)*
- Disconnect utilities through module, loosen horn attachment
- *Lower horn with lifting table*
- *Crane hot module out of way (back in chase)*
- *Crane hot horn to Morgue (hot horn storage area), cover*
- Crane new horn in Hot Cell
- *Crane hot module to hot cell*
- *Insert horn onto module with remote lifting table*
- Connect horn utilities through module
- *Crane module+horn back into beamline*
- *Insert shield T-blocks into module*
- Connect utilities to top of module
- Replace concrete cover

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Hot Handling Dose

for hot horn replacement

Source Description	Dose Rate on Contact (mrem/hr)	RSO Measured	(30 Day, 1 Day)	(30 Day, 7 Day)	(252 Day, 1 Day)	(252 Day, 7 Day)
Walls, Floor, & Ceiling	0	0	0.05	5.50E-03	6.13E-02	1.58E-02
Bottom of Horn Module	213,083	0	100000	6.14E+04	2.55E+05	2.13E+05
Top of Horn Module	2	0	1	6.14E-01	2.55E+00	2.13E+00
Horn Module Connection Region	2	0	1	6.14E-01	2.55E+00	2.13E+00
Inside Horn Chase (Steal)	66	0	31	1.90E+01	7.89E+01	6.61E+01
Face of Unremoved H-Blocks	6	0	20	2.20E+00	2.45E+01	6.34E+00
Horn (Side View)	19,399	0	600000	7.04E+03	6.13E+05	1.94E+04
Horn (Upstream View)	25,865	0	800000	9.38E+03	8.18E+05	2.59E+04
Horn (Downstream View)	38,797	0	1200000	1.41E+04	1.23E+06	3.88E+04
Bottom of T-Blocks From Horn Module	213,083	0	100000	6.14E+04	2.55E+05	2.13E+05
Top of T-Blocks From Horn Module	2	0	1	6.14E-01	2.55E+00	2.13E+00
Concrete H-Block Shield Wall #1	3	0	10	1.10E+00	1.23E+01	3.17E+00
Concrete H-Block Shield Wall #2	3	0	10	1.10E+00	1.23E+01	3.17E+00
Single Wall Reflection From Chase	0	0	0.01	6.14E-03	2.55E-02	2.13E-02
Material In Morgue	0	NA	NA	NA	NA	NA
Top of T-Blocks in Target Module	2	0	1	6.14E-01	2.55E+00	2.13E+00
Top of Target Module	2	0	1	6.14E-01	2.55E+00	2.13E+00

☑ Hide Repair Doses

Dose Per Person (mrem)

	Crane Operator	Technician #1	Technician #2	Radiation Safety Official	Engineer
HORN WILL BE REPAIRED					
HORN WILL BE DISCARDED	4.13E+00	1.41E+00	1.22E+00	6.82E-02	2.47E-02

Total Dose For All Personnel (mrem)

HORN WILL BE REPAIRED	
HORN WILL BE DISCARDED	6.84E+00

Note 1 sievert = 100 rem

Decontamination & Decommissioning

- Guidelines of FESHM 8070 will be used for D&D of the NuMI Beamline.
- No hazardous materials have been used in construction of the beamline
  (except lead bricks for hot cell shielding, ones already activated).
- Major isotopes produced will have 2.6 and 5.3 year half-lives (exception of tritium).
- Sump pumps removing water from the NuMI tunnel will continue operation.
- Items put in the NuMI tunnel during construction are being chemically analyzed.
  - Mostly those items not accessible after tunnel construction
  - Grout, rock bolts, shotcrete, wire mesh

Summary/Conclusions

- We have come a long way:
  - Much progress in developing new methodologies for air, groundwater, residual radioacitvation
  - Building/installing beamline
  - Culture, acceptance of “new” methodologies is occurring
    - Mainly groundwater and beam permit system understanding
    - Need to better communicate outside the project
- Higher Intensity beams, deep underground beams have new issues
  - Groundwater activation was never much of an issue at FNAL
    - NuMI is in a drinking water aquifer
  - Need to minimize beam loss for groundwater & residual rates
    - Need very good beam control
  - Air needs to be contained, recirculated in target pile and beam stop, air levels too high otherwise