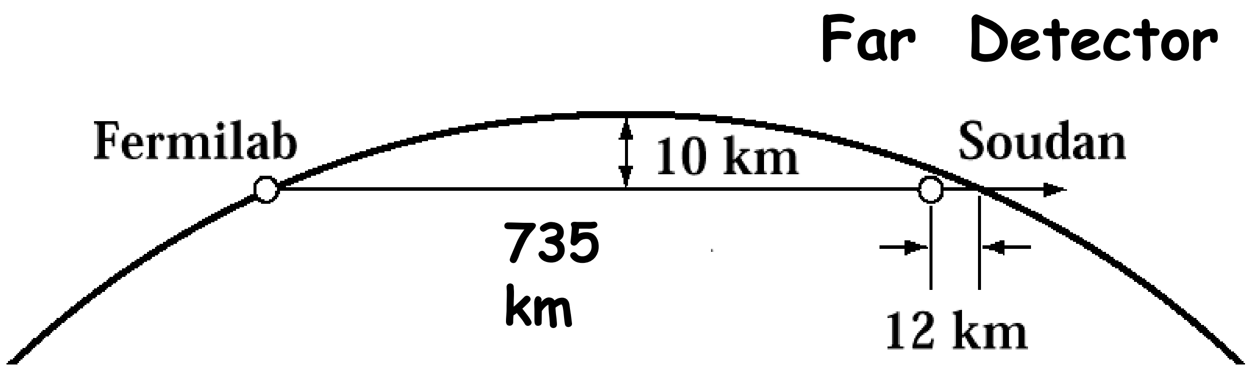
Target Station Infrastructure: The NuMI Experience

Focus of this talk:

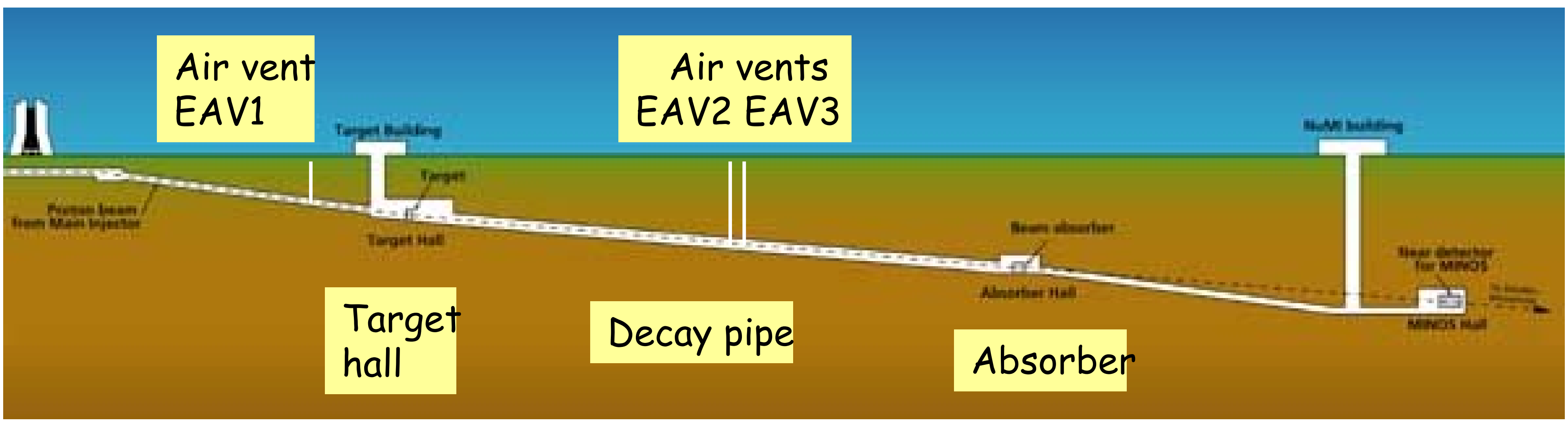
- Hot handling
- Target pile design:
  thick shielding, maintaining alignment, remote connections
- Materials survival experience, including target
- Radiation safety surprise:
  tritium evaporates from the shielding steel
  - motivated upgrade to infrastructure, intercepting tritium

First, a few slide overview of NuMI

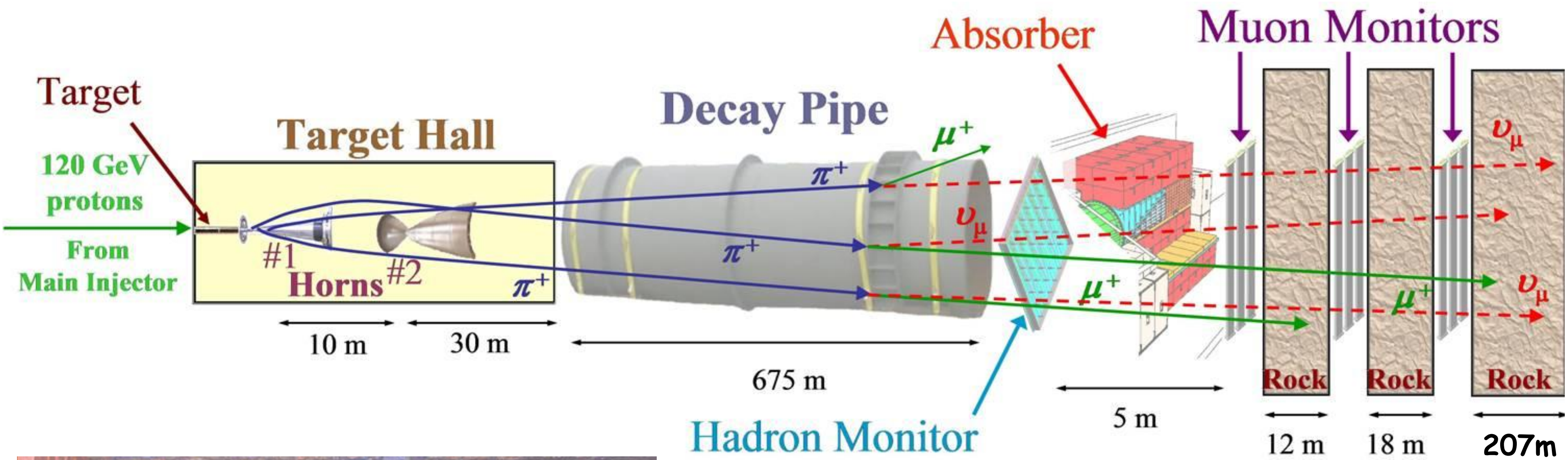
NuMI produces a neutrino beam sent to detector in Minnesota

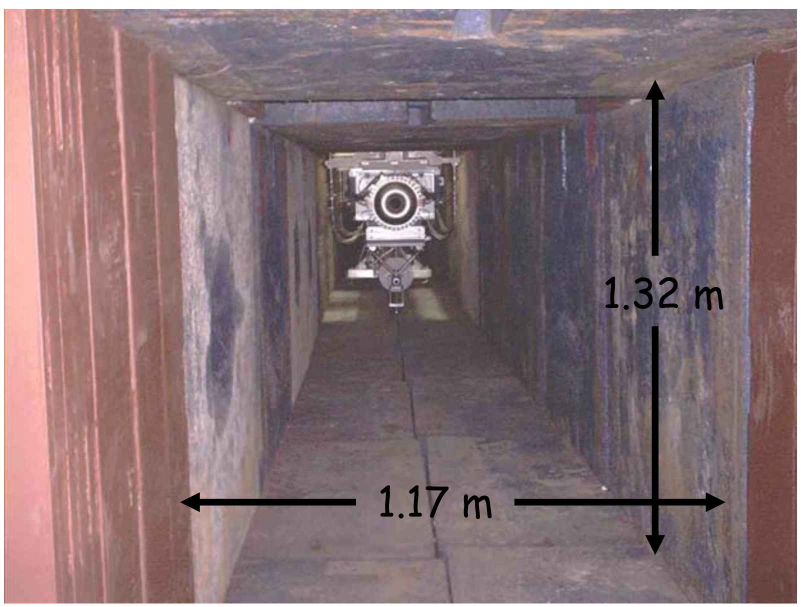


Neutrino beam-line at Fermilab is 30 to 100 m underground

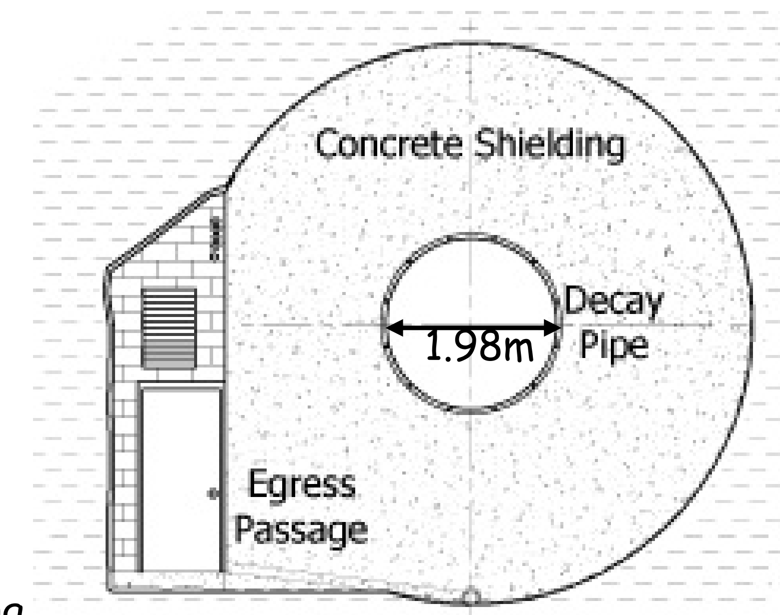


NuMI Neutrino Beam

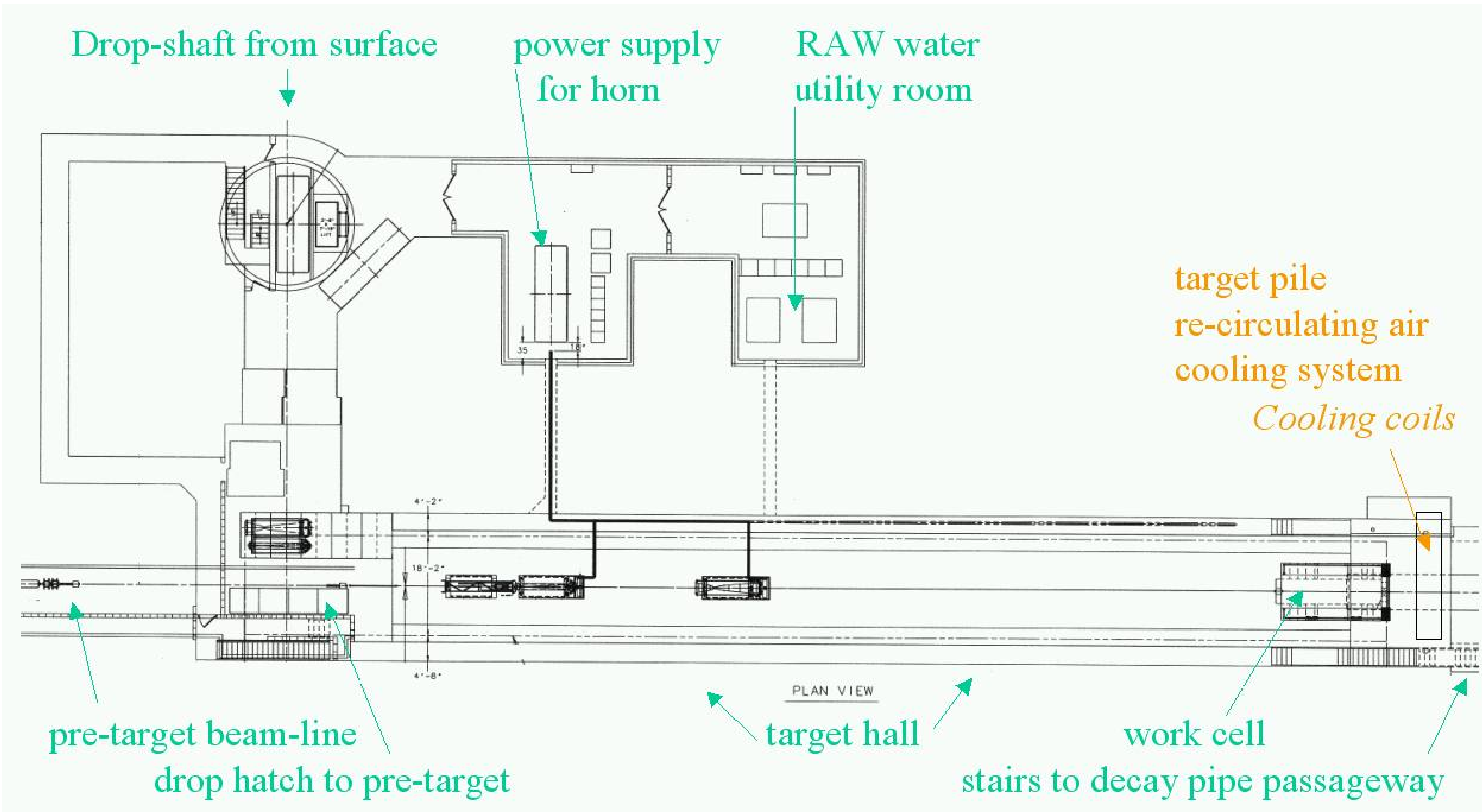




Target pile shield for components is 47 m long

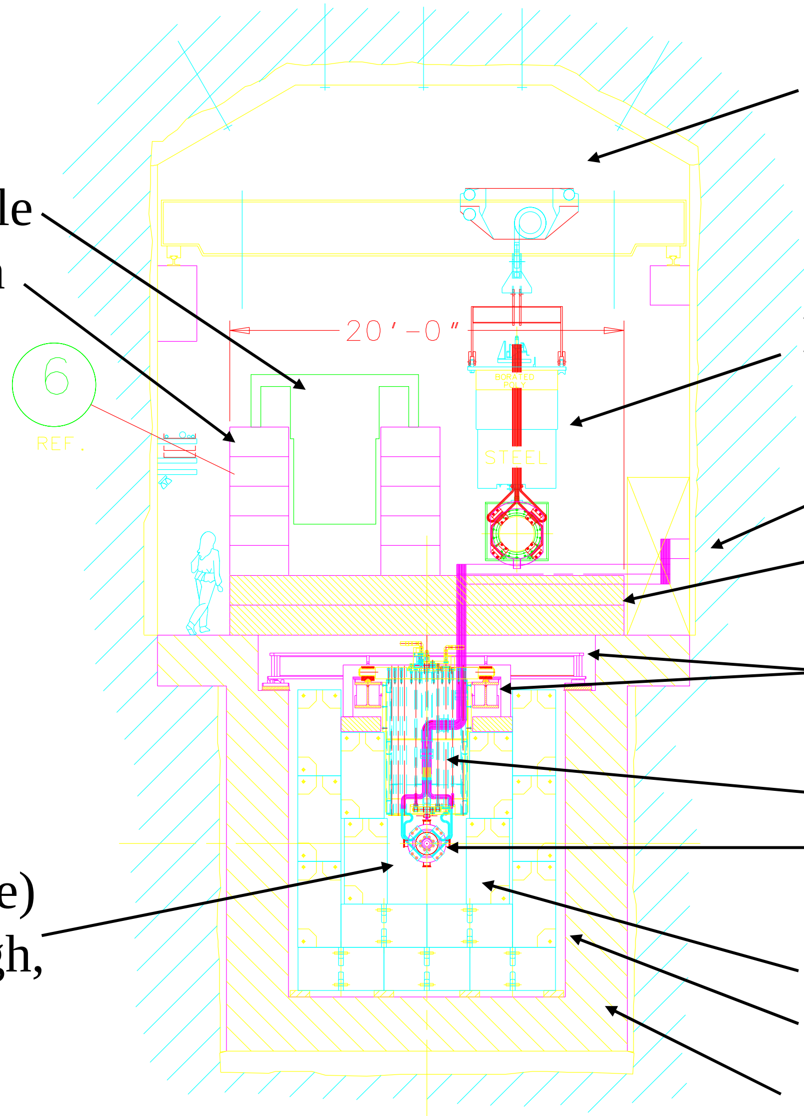


Target hall and support rooms



NuMI Target Hall *general layout*

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



30 ton crane

Horn+Module in transit

Stripline

Concrete Cover

"Carriage" - Module Support Beams

Horn Shielding Module

Horn

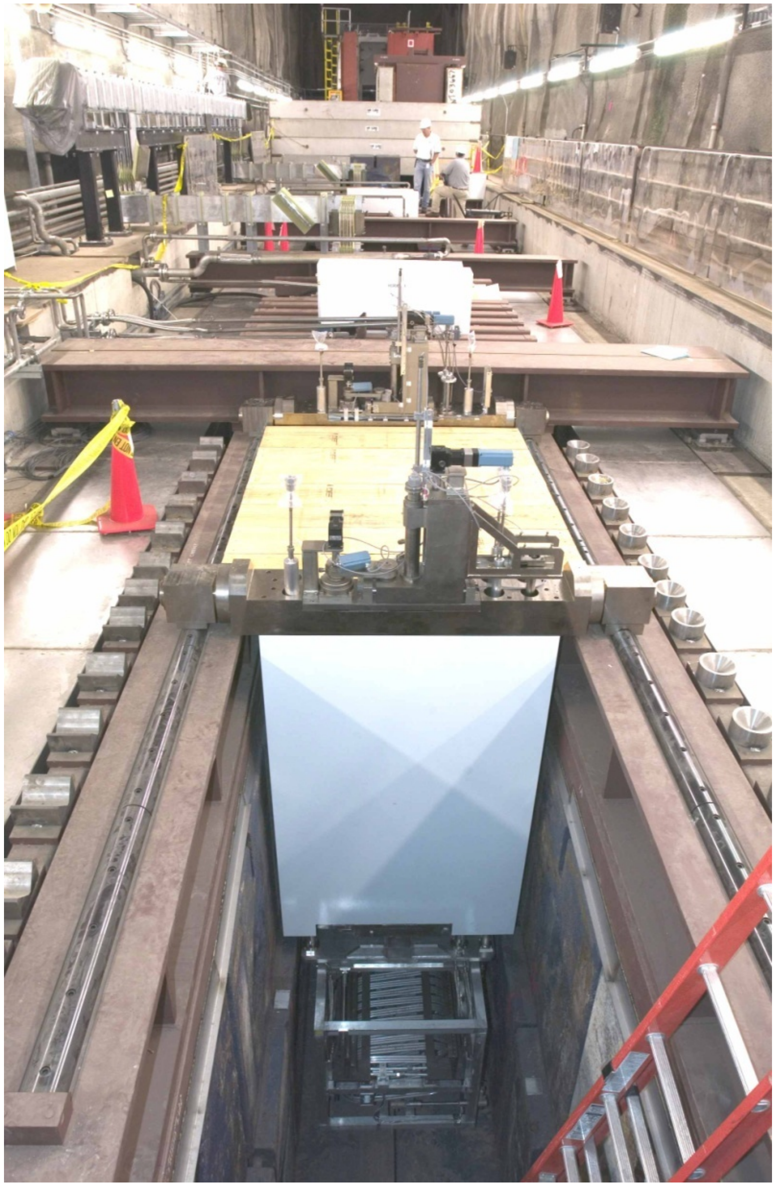
Beam passageway (chase) is 1.2 m wide x 1.3 high, forced-air-cooled

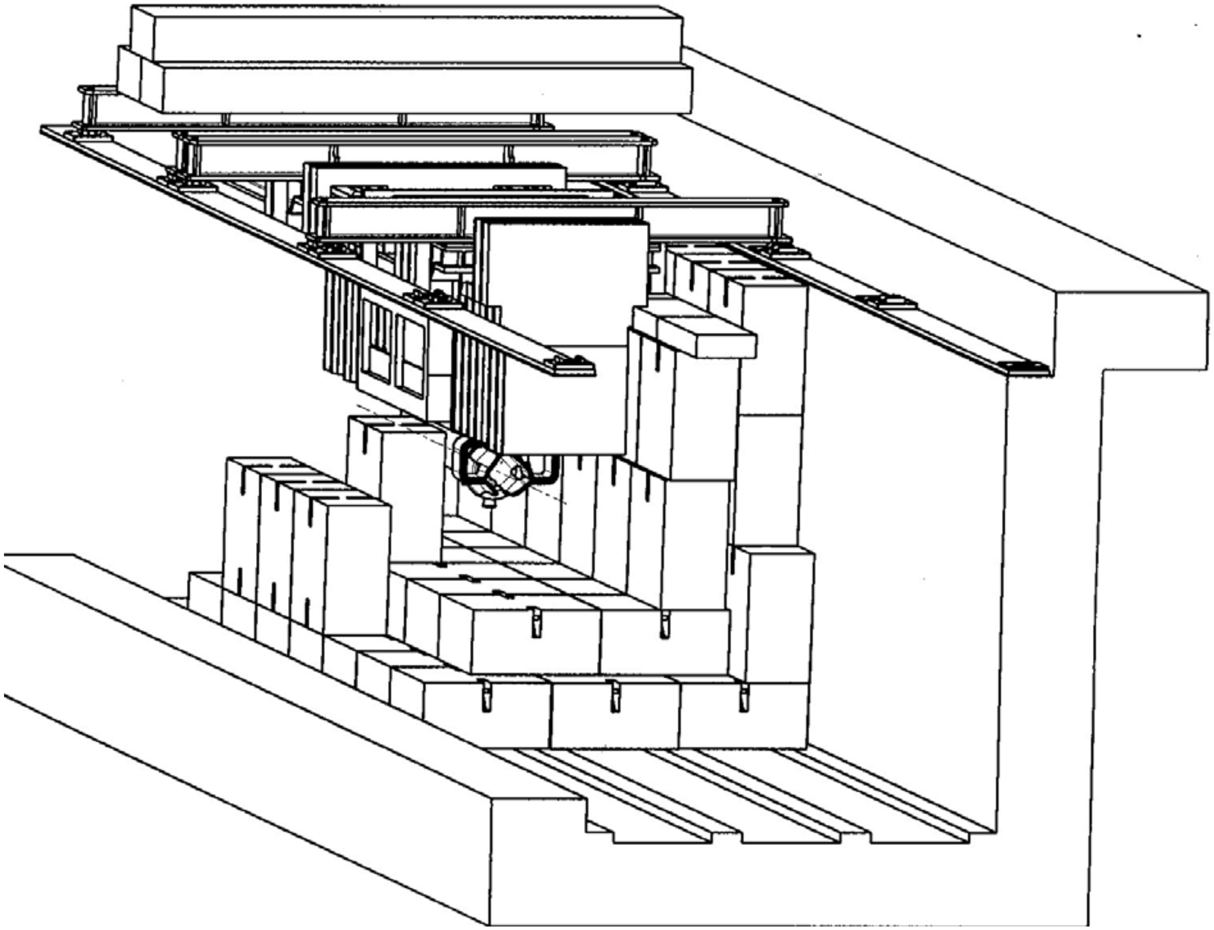
Steel Shielding

Air Cooling Passage

Concrete Shielding

Target hall





Target Station Infrastructure: The NuMI Experience

Setting the scale:

NuMI designed for 400 kW of 120 GeV proton beam power;
currently upgrading to 700 kW

~ 40% of energy ends up in target pile,
~ 1% stays in target as heat

Components inside shielding receive ~ 10 to 100 Giga-Rad/year

Only radiation-hard materials can be used.

Residual rates of components and inner shielding 10 to 100 rem/hr

Putting this in operational terms, during a week a worker could spend between 2 to 20 seconds working directly on a component

Target Station Infrastructure: The NuMI Experience

NuMI design strategy:
Cost containment, minimal hot handling equipment
Enough for target/horn replacement, but very limited repair capability

NuMI experience:
Cost of spares also removed from construction project – no early spares
If you have no spare, you must repair !

Thus far (4 ½ years), NuMI has operated in a cost-effective manner, with modest (~13%) downtime for target hall repairs.
4 component replacements, 7 hot repairs

Looking forward to higher power facilities, as allowable exposure time per person gets below a few seconds, must change tactics. Pick:
- increase spares so don't have to repair
- invest in remote repair facilities
- build components that never break or wear out (*note this is a joke*)
- or risk substantial downtime

NuMI Upgrade: installing work cell with remote manipulator arms in C0 building.

All NuMI target hall beam components and innermost shield layers are installed / removed remotely with crane and cameras

Crane includes remote hook rotation.

Steel shielding block being moved.

NuMI work cell for radio-activated components

Shown during test-assembly above ground

Lead-glass windows (not shown)

Remote controlled door

Remotely installable top shielding

Designed for swapping components on modules, NOT REPAIRS.

Remote 5-axis lift table

puts components on bottom of alignment modules in work cell

Numi target+baffle on lift table

Target on module, ready to crane into beam

Target Alignment Survey

Survey of target tip relative to target tooling balls

After mount of target carrier to module

Done through holes in work-cell lead-glass windows

Component replacement steps in target pile

Install components in pile
– via crane and cameras

Survey component locations
– optical survey through holes in shielding
– final alignment done with low intensity beam scans

Fine alignment of component
- motors drive shafts through holes in shielding

Connection of water and gas and instrumentation lines
- long pipes through holes in shielding

Connection of horn power (carries 200,000 Amps pulsed)
- remote clamp

All are low-dose because people are far away / behind shielding
for component swap activities

Horn 2

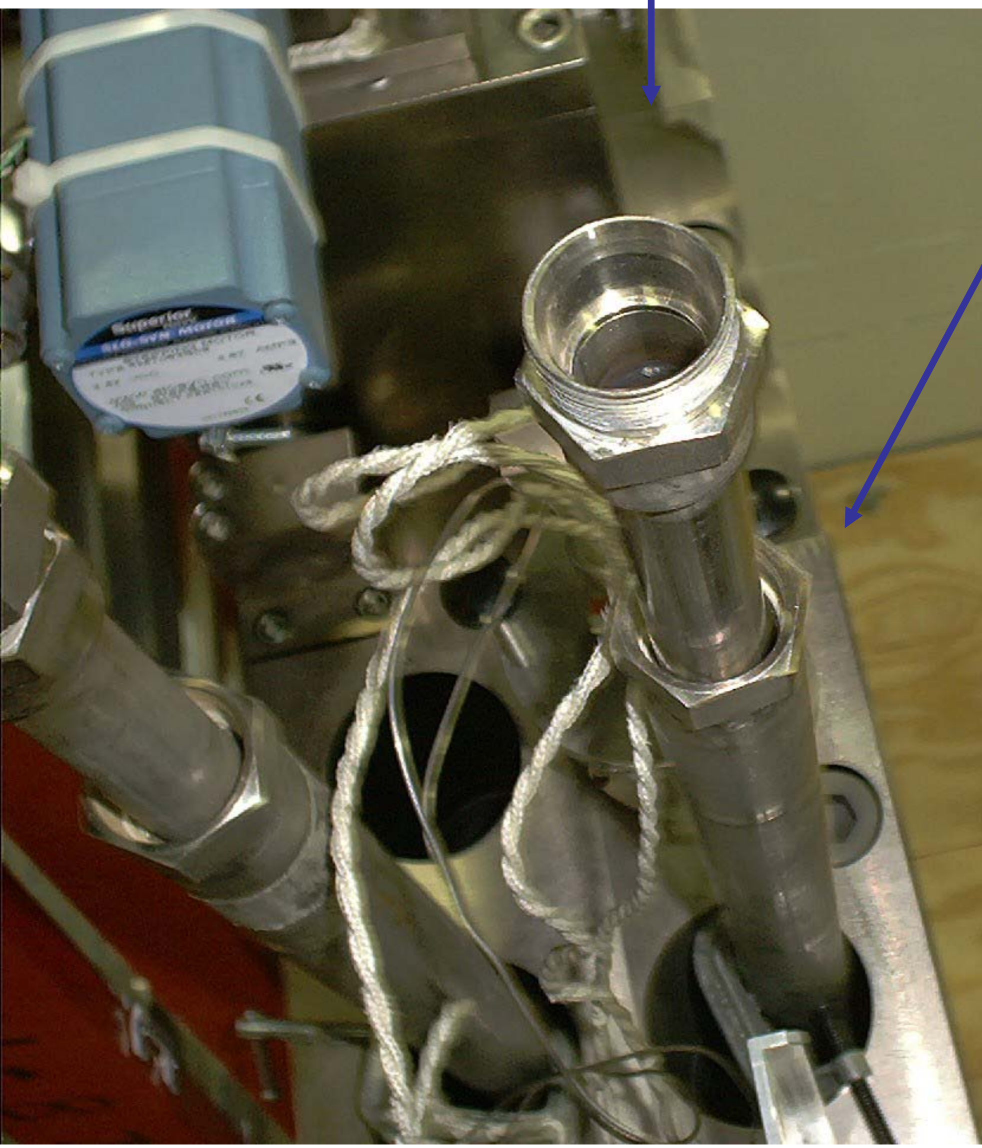
Peak current: 205 kA maximum
Pulse width: 2.3 m-sec half-sine wave
Repetition rate: 1.87 sec

Installation before running,
people no longer get close like this

Water line connections made up from behind shielding

Inner water tube

outer tube to turn swage lock nut
at other end of tube



shielding stepped to reduce
direct line-of-sight cracks

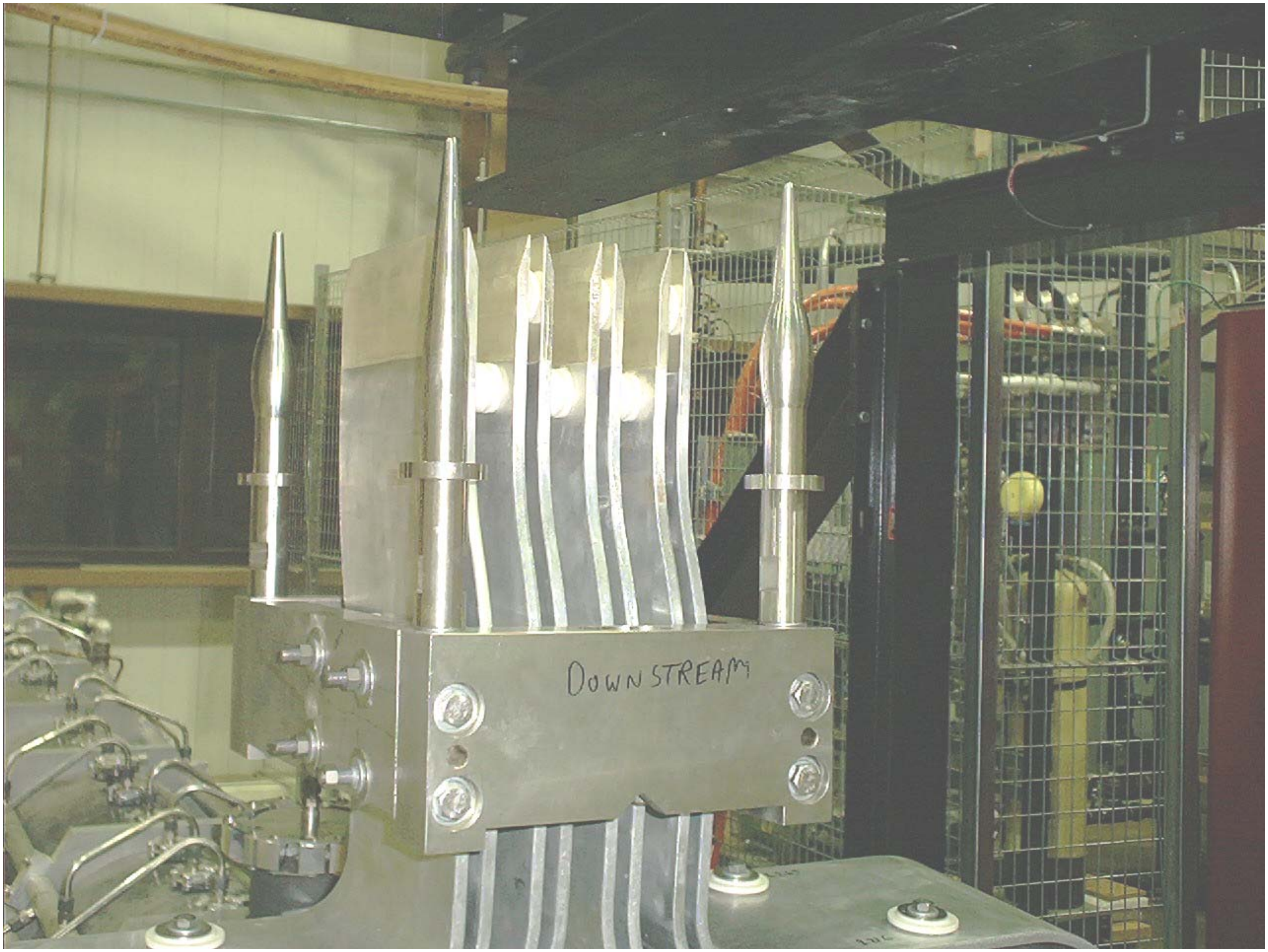
Signal connections

“thermocouple” type ceramic electrical connectors

Other plug on end of 3 meter pole

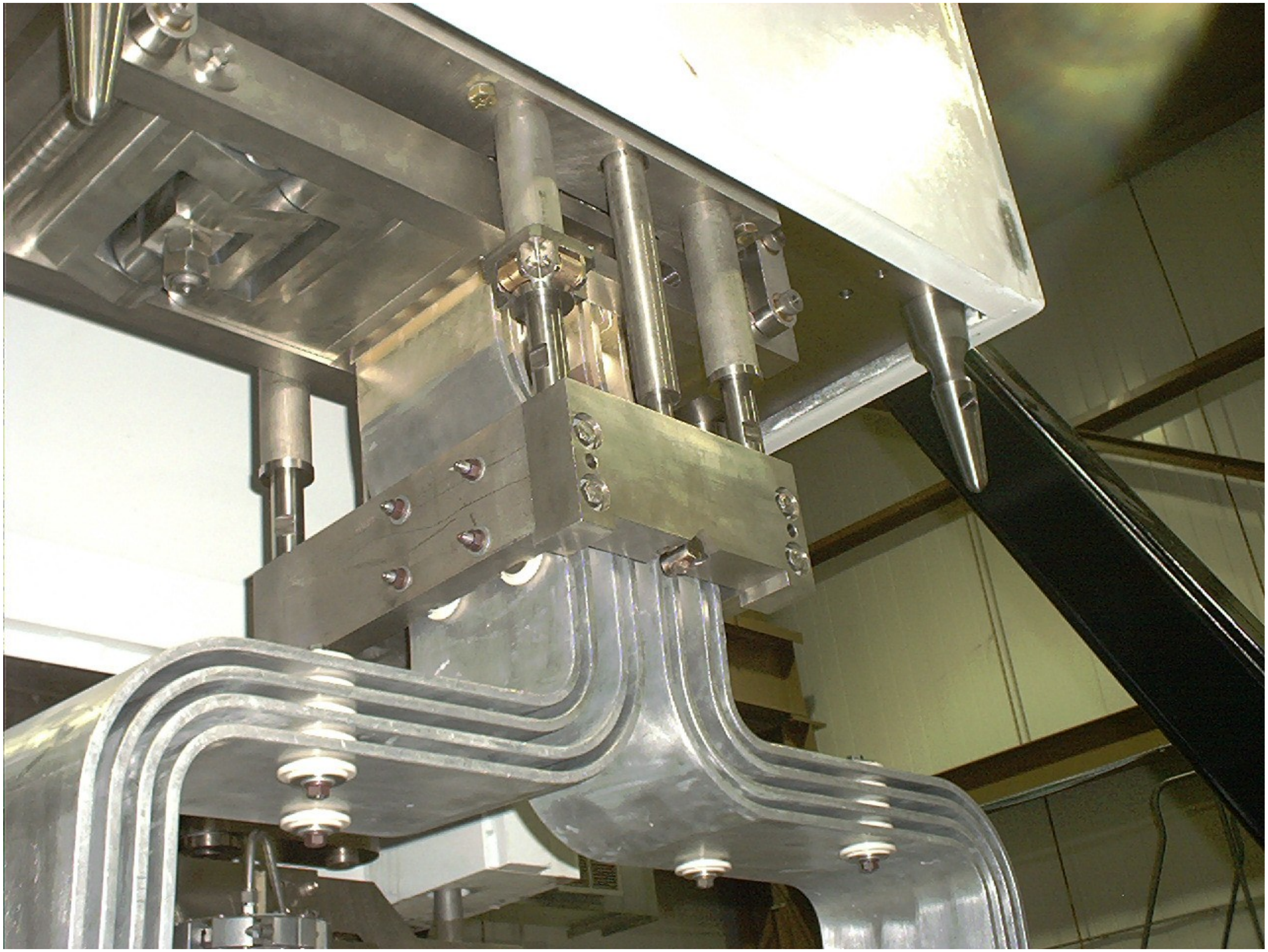
Have somewhat delicate small wire inside connector

Horn strip-line remote connection lead-in



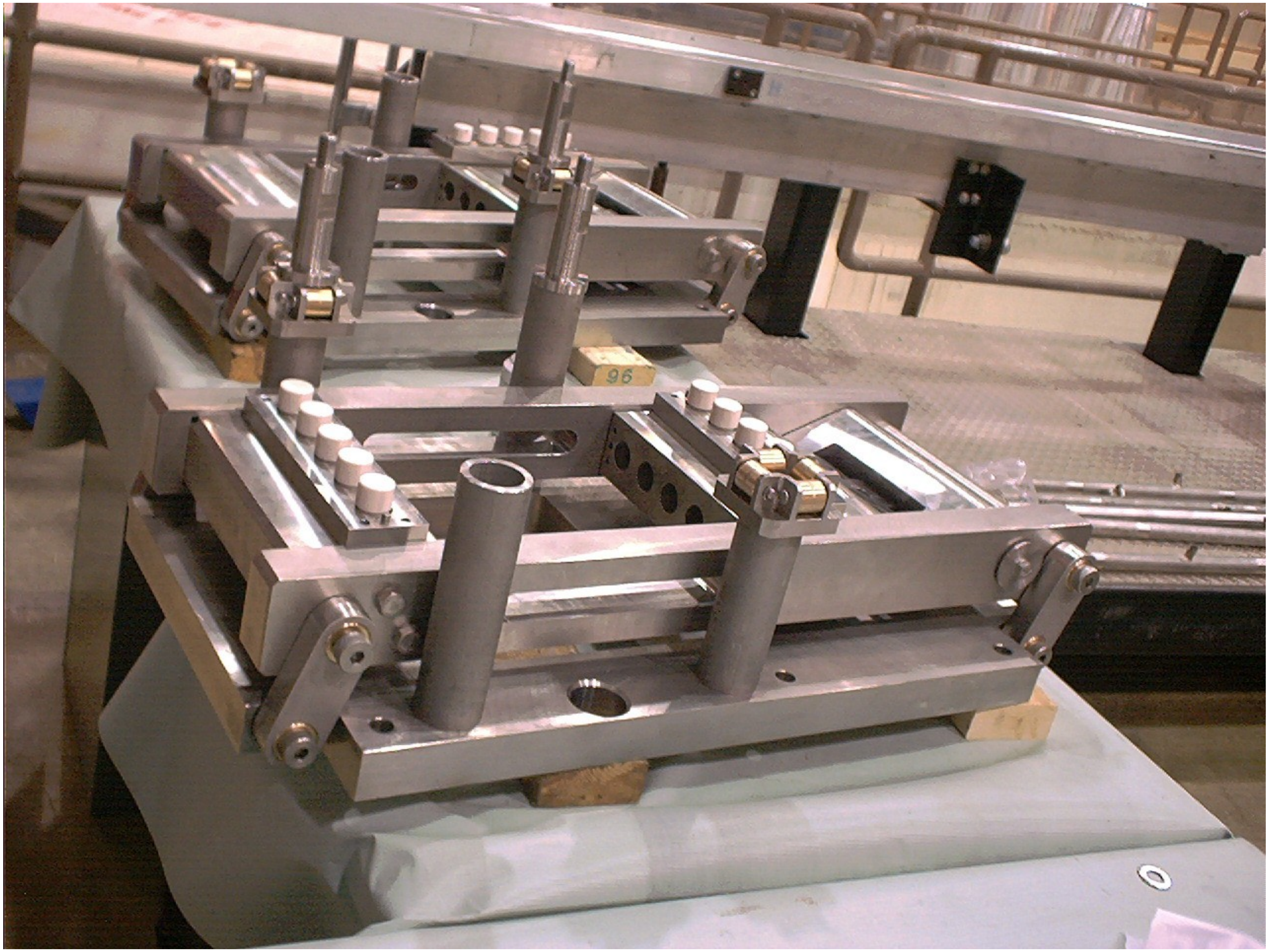
Horn strip-line remote clamp

Pressure applied by screw thread on toggle
System also contains features for prying apart
strip-line connection if they stick



Remote clamp

showing zirconia ceramic insulating pads
which are backed by Belleville washers
that act as springs

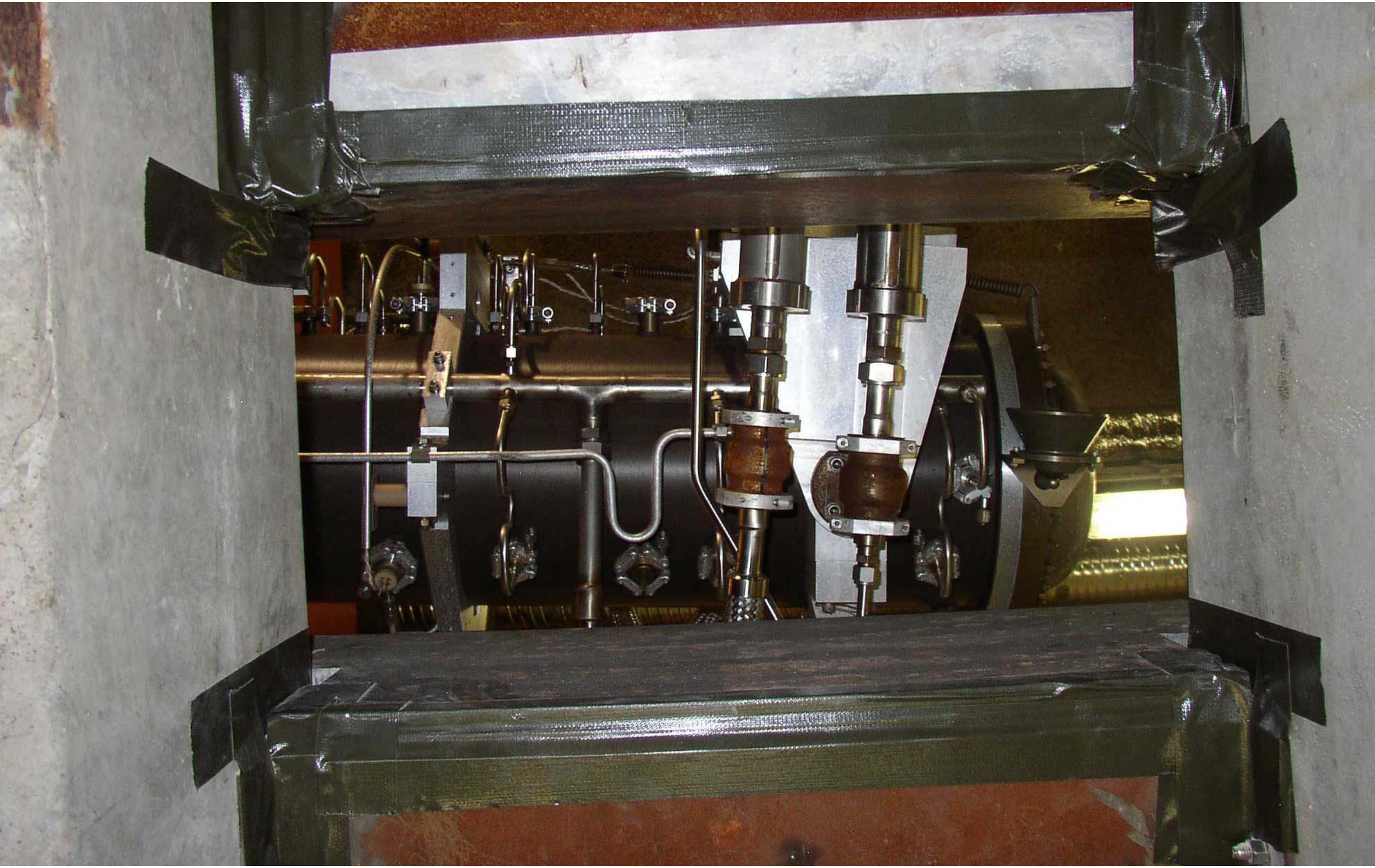


Shielding for Horn water line
HOT REPAIR

Built an extension of the work-cell with window for work

(Horn is in work-cell, behind the door)

View of horn 1 through shielding slot



Practice for horn repair, mock-up

Step 1: Insert new water line

Practice for horn repair

Step 2: Spin up nut -- semi-remotely

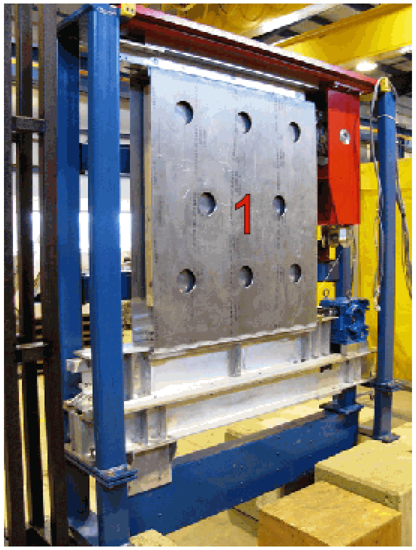
Practice for horn repair

Step 3: Tighten nut -- long handled wrench

Hadron monitor replaced using 7-motor remote fixture

FERMILAB ACCELERATOR DIVISION

DATE:8/4/09	TIME: 1400	PURPOSE: removal survey	RWP #



Hadron Monitor

Point	Doserate @ 1 foot (mr/hour)	Doserate On Contact (mr/hour)
1	400	1000

All Dose Rates Below N/A mR/hr Unless Noted.
Inst Type: teletector
Inst No: 6
Batt/Source Chk: sat
Cal. Due Date: 6/2010

LEGEND
Numbers appearing on map are mR/hr @ 1 ft readings unless denoted with symbols below
* = mR/hr @ contact
A = Air Sample ◯ = Wipe Ⓕ = Floor wipe

Bkgd cpm
Wipe # Reading Wipe # Reading
N/A

Highest Dose Rate Found 400
Note: RSO approval required to work in ar >100 mR/hr @ 1 foot OR >100 CCPM on a
Comments:
Surveyed By: Busch
Reviewed By:

REVISED 8/6/09

1 R/hr residual radiation

Hot job done with pretty sophisticated remote fixturing with essentially no dose to people

More than a year in planning, testing, practicing

Hadron monitor is critical for alignment of target

Spare produced and wired up by Univ. Texas

Coffin for strip-line block

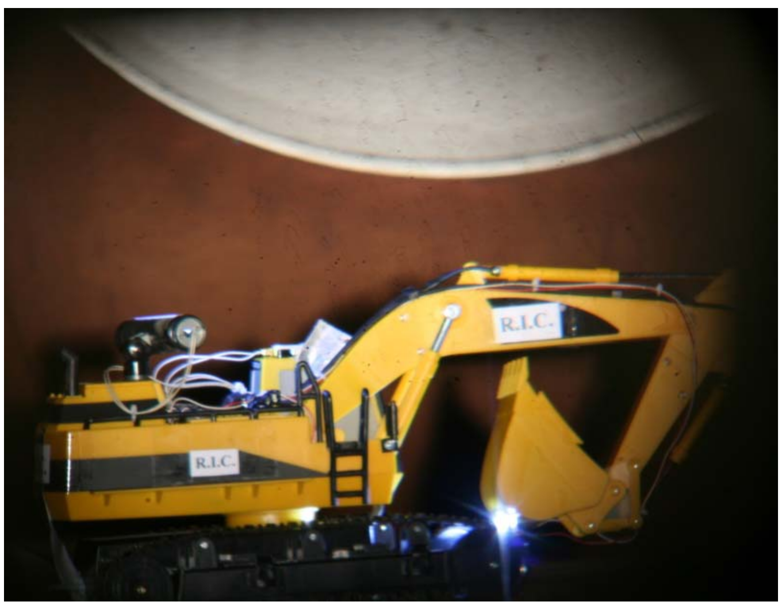
Strip-line block provides remote connection of 200 kA to horn
Have used one per horn replacement
Removed two used blocks from Thall this shutdown

Strip-line block is vertical in target hall, but needs to be horizontal for transport/storage

1 5 R/hr
2 4 R/hr

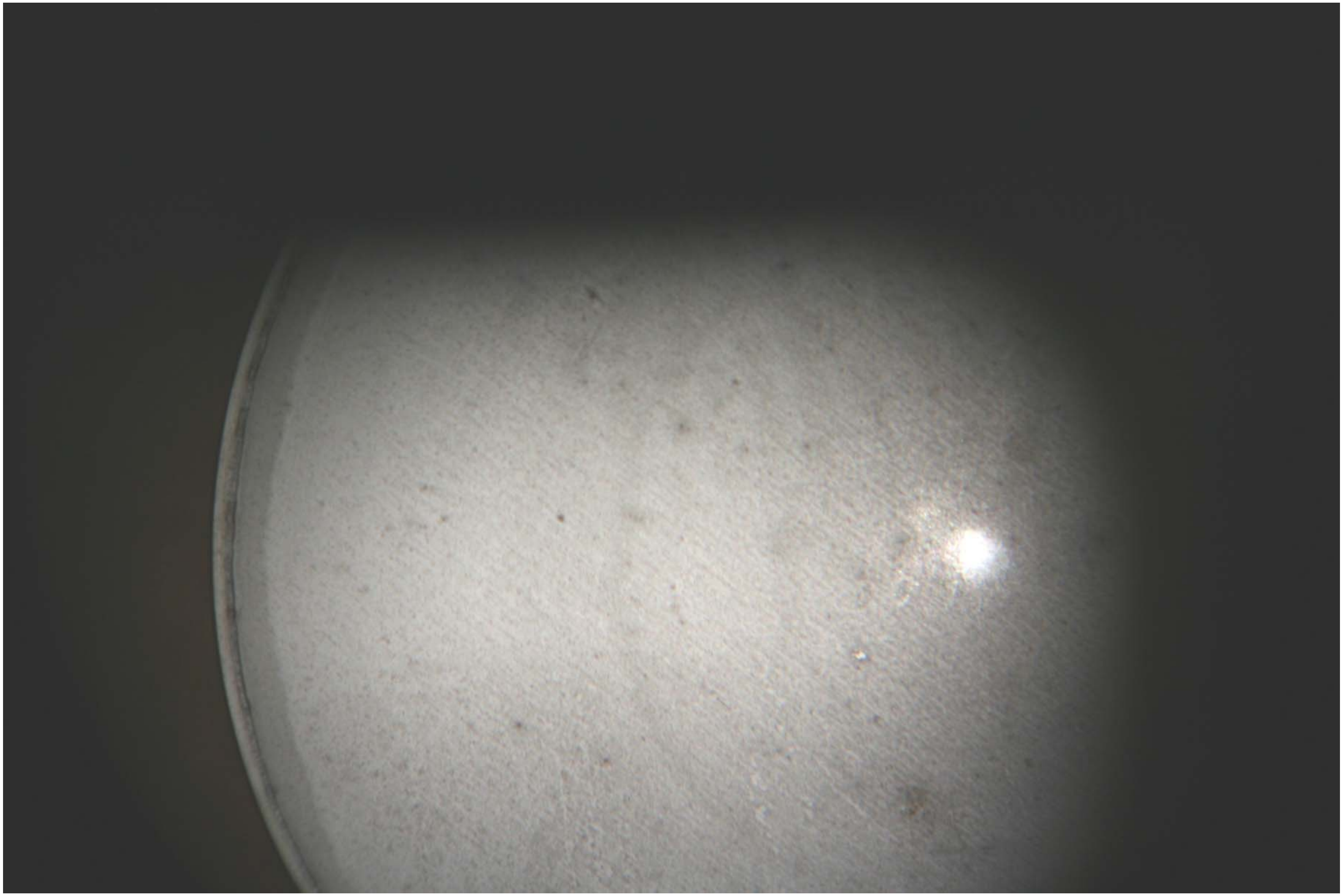
Decay pipe window visual inspection –

115 ft away through periscope
with *Remote Illumination Caterpillar*



Decay pipe window

(1 m diameter, 1/16” thick, Aluminum)
Main new feature – spot at beam center

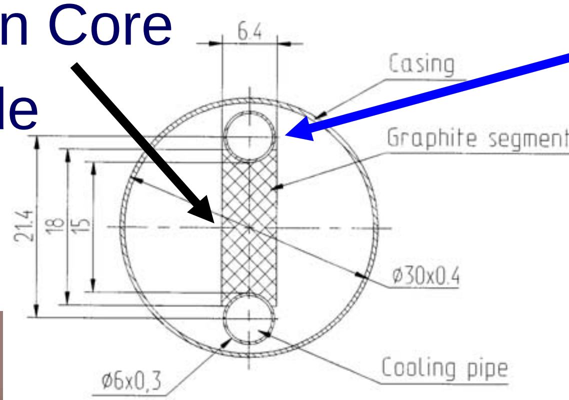


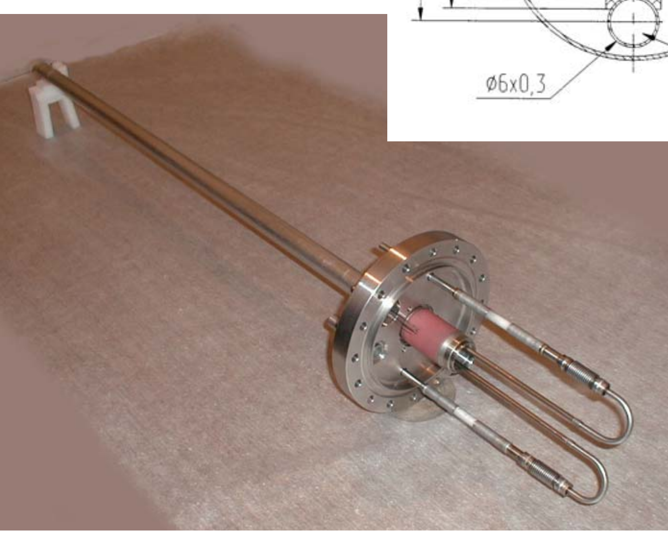
NuMI L.E. Target

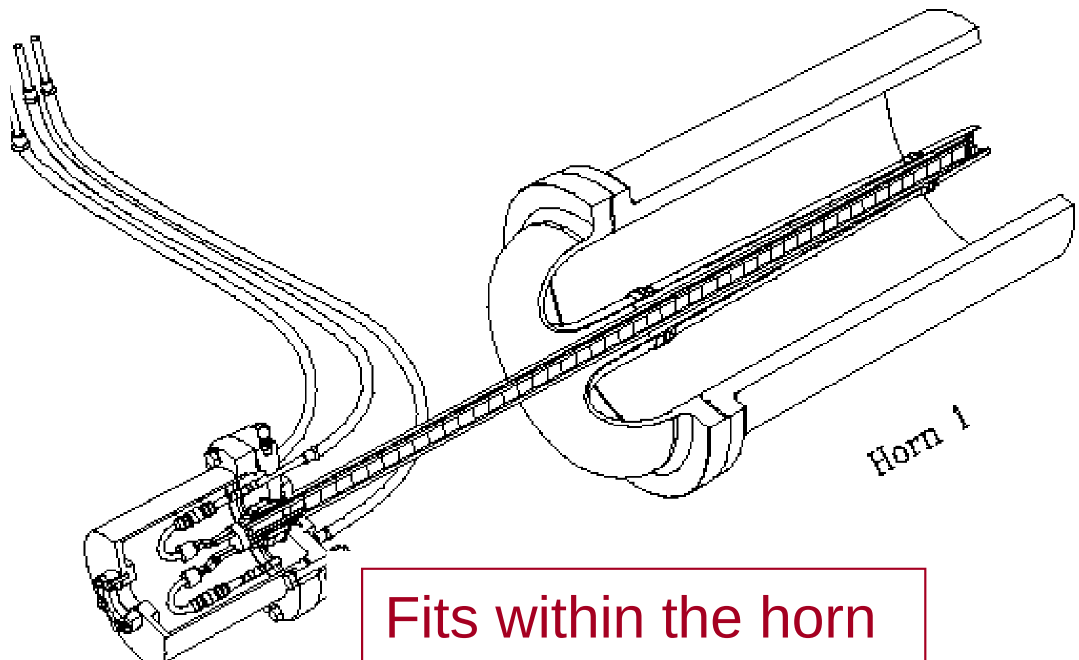
2 int. length long; narrow so pions get out sides without re-interacting

Graphite Fin Core
6.4 mm wide

Water cooling tube







Fits within the horn without touching.

NuMI target experience

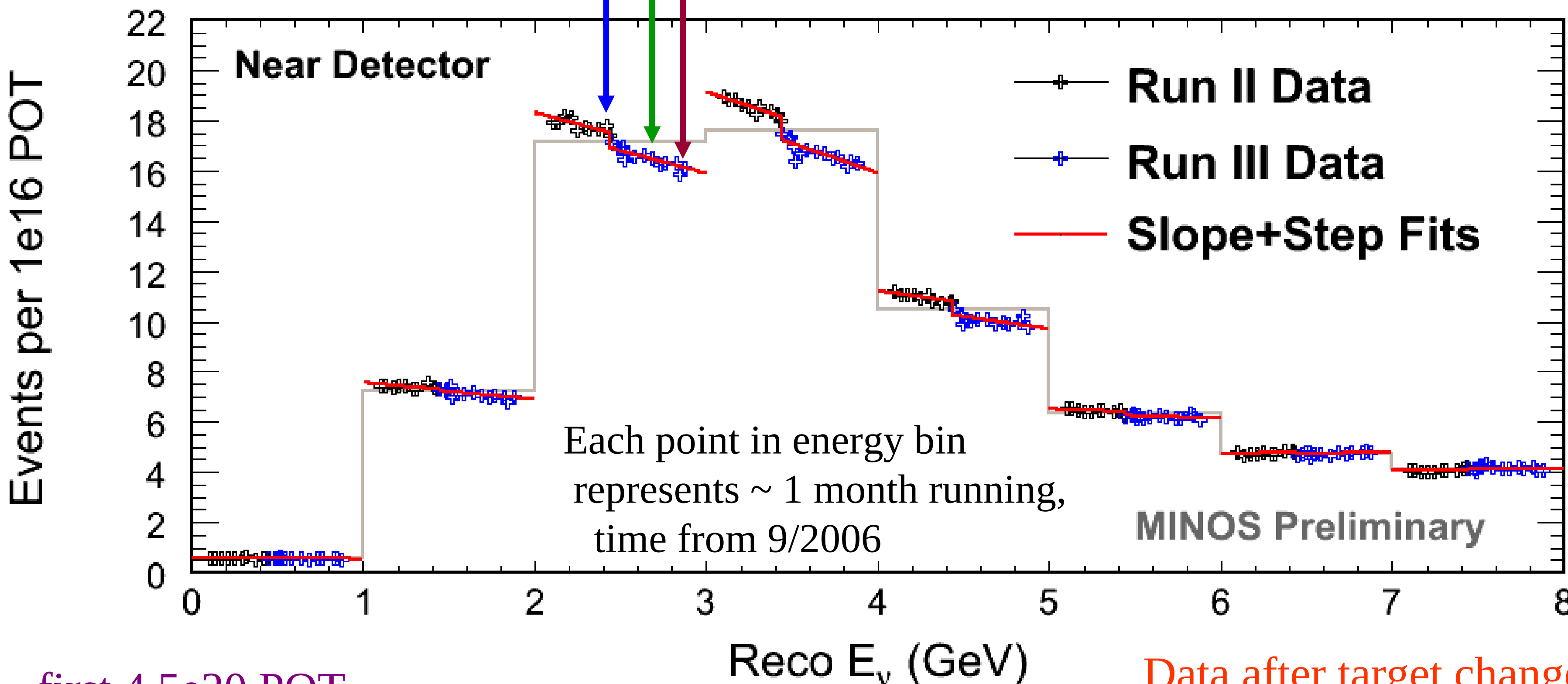
(ZXF-5Q amorphous graphite)

Gradual decrease in neutrino rate attributed to target radiation damage

Decrease as expected when decay pipe changed from vacuum to helium fill

No change when horn 1 was replaced

No change when horn 2 was replaced



first 4.5e20 POT
of total 6.1e20 POT on NT-02 shown on this plot
= *0.7 DPA (MARS M.C.)*

Data after target change-out
not fully processed yet,
but indicates flux regained

Extrapolate NuMI target lifetime to Project X intensities ?

3 years running on this target, beam power 0.1 to 0.3 MW
NuMI accumulated 6 10^{20} POT @ 120 GeV → 4.44 MW-month

Assume Project X 2.3 MW @ 70% uptime → 4.4 targets / year

Similar to anti-proton production target,
but couple shifts/change compared to NuMI couple weeks/change

NuMI used 1.1 mm RMS beam spot
so integrated flux at center is 8 10^{21} POT / cm^2

If Project X target uses 3 mm spot size (9 mm radius target)
and radiation damage scales by (beam-radius)$^{-2}$ → 0.6 targets / year

Save many $M on rapid change-out capability ???

Caveats:
- Is 10% neutrino rate degradation considered acceptable?
- Will encapsulation of the graphite reduce the density decrease?
- Will higher temperature reduce the radiation damage?
- Would another grade of graphite do better?
- Will radiation damage really scale by (beam-radius)$^{-2}$?
- Radiation damage probably twice as fast for 60 GeV protons at same power

Corrosive air

The Mini-Boone intermediate absorber came crashing down, even though there was a design strength safety factor of four on the chain and the chain was not in the beam.

Radiation in humid air creates nitric acid (and Ozone …)

High strength steel does not like hydrogen (embrittlement)

NuMI has also had problems with radiation induced accelerated corrosion (stripline clamp failure, target positioning drive, decay pipe window corrosion)

More resources should be applied to general studies of air + radiation, etc -- we are in rather unusual environmental conditions !

Strip-line block flake problem

To use low-cost steel instead of stainless for shielding, coated it

Some steel epoxy painted – amazingly, this has done pretty well

Some steel nickel coated – BAD !

Only place nickel coating has worked well is horn aluminum inner conductor, in Argon atmosphere !

Tritium 101

Tritium is produced in hadronic showers, proportional to beam power, not hugely sensitive to material choice, hence mostly embedded in the radiation shielding.

NuMI produces few hundred Ci/yr.
- Project X target hall will produce few thousand Ci/yr.

Tritium is super-mobile, penetrates concrete, even solid steel

NuMI has found about 10% of the tritium produced in the shielding ending up in the dehumidification condensate each year.

And it is the gift that keeps on giving, long after the beam turns off.

Drinking water limit (U.S.) is 20 micro-Ci of HTO per liter of H2O.

There are a lot of micro-Ci in a Ci. (Exercise for the reader)

Putting tritium in the water is not good public relations, even if below drinking water standards. Also, standards for tritium may change.

Tritium 102

Half-life of Tritium is 12.3 years, so eventually it takes care of itself.

Beta emission from tritium will not penetrate skin.
Do absorb some HTO from breathing vapor; excreted from body in about 10 days. But drinking HTO is the main hazard.

When elevated Tritium levels were discovered in NuMI sump water, we installed air dehumidification equipment.

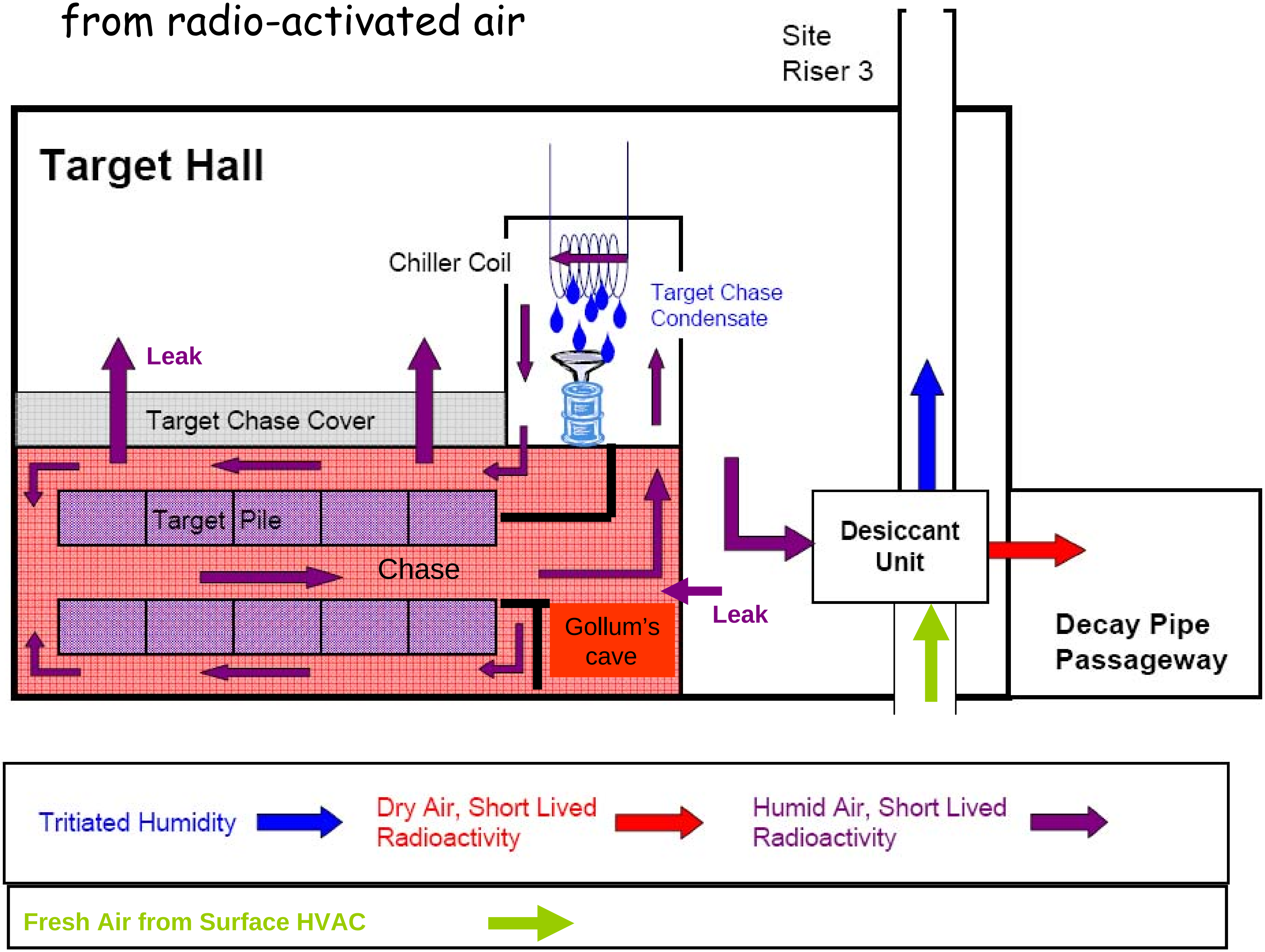
This reduced tritium in ~1000 liter/minute sump water stream by an order of magnitude, and put the tritium in ~ 0.2 liter/minute waste stream.

Originally, waste stream was barreled, solidified and sent to waste facility.

Now condensate is evaporated, and is small component of FNAL overall air emissions.

Lowering humidity in target pile 50%->20% RH also reduces corrosion.

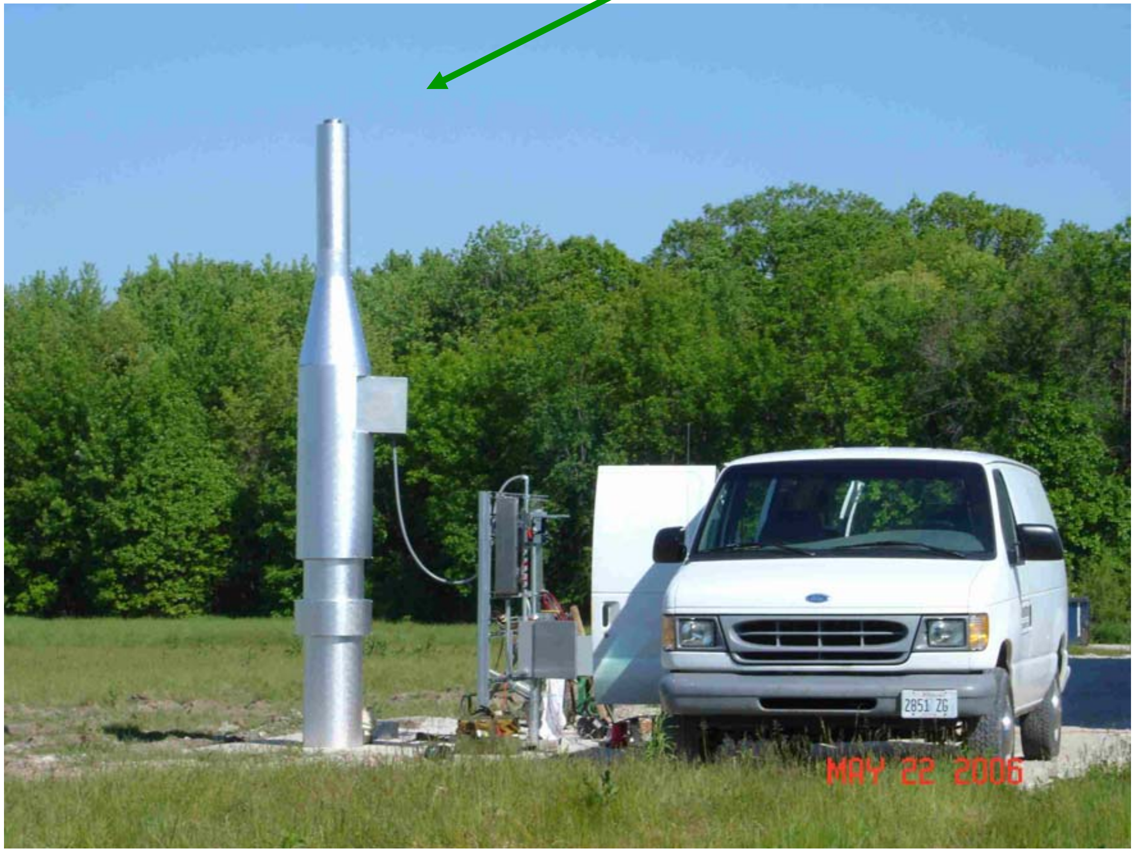
1st tritium upgrade
- separate tritium water vapor from radio-activated air



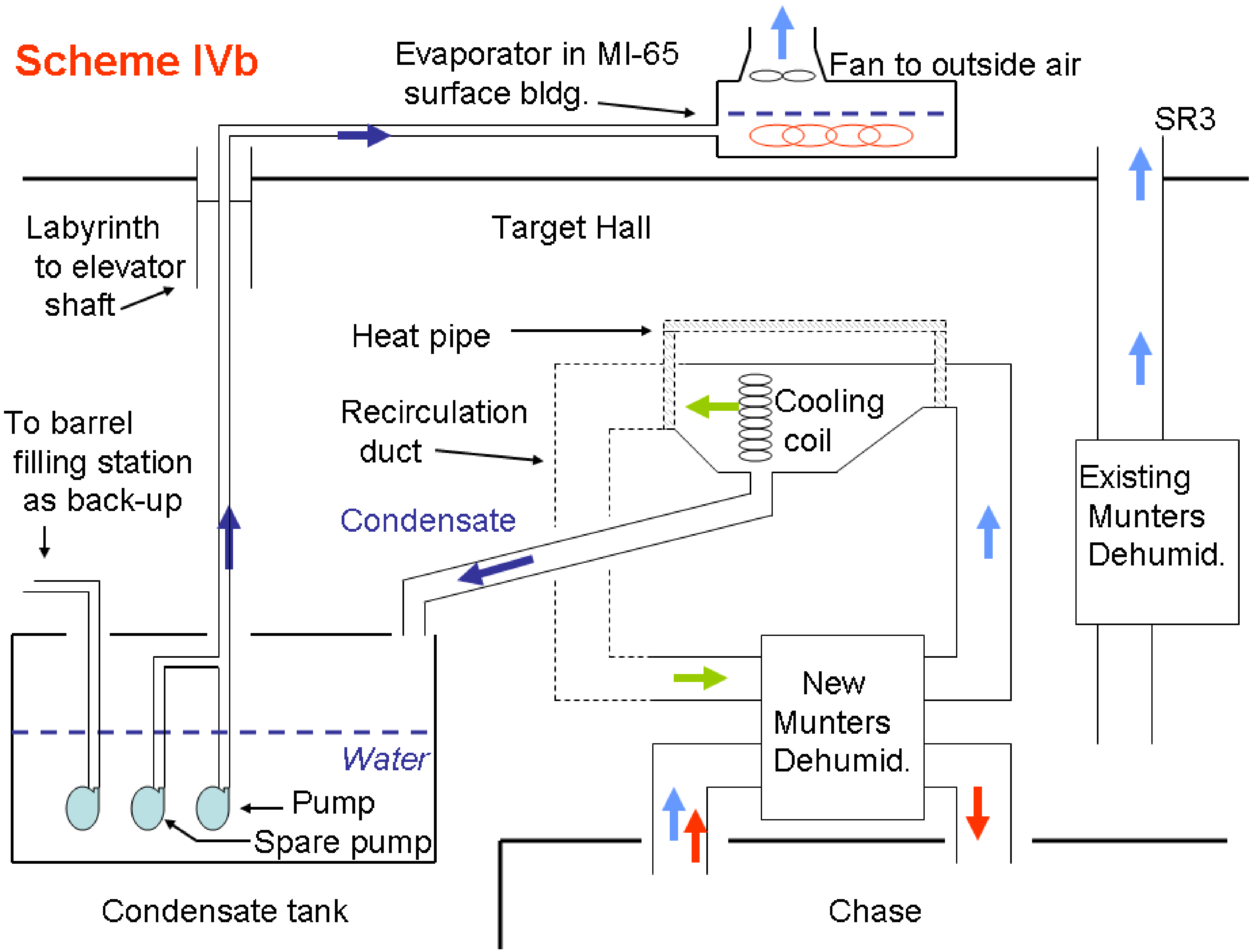
Dehumidifiers for tritium interception

Intercept humidity here,

and send it up new stack at SR3



2^{nd} tritium upgrade – dehumidify inside target pile, evaporate the condensate

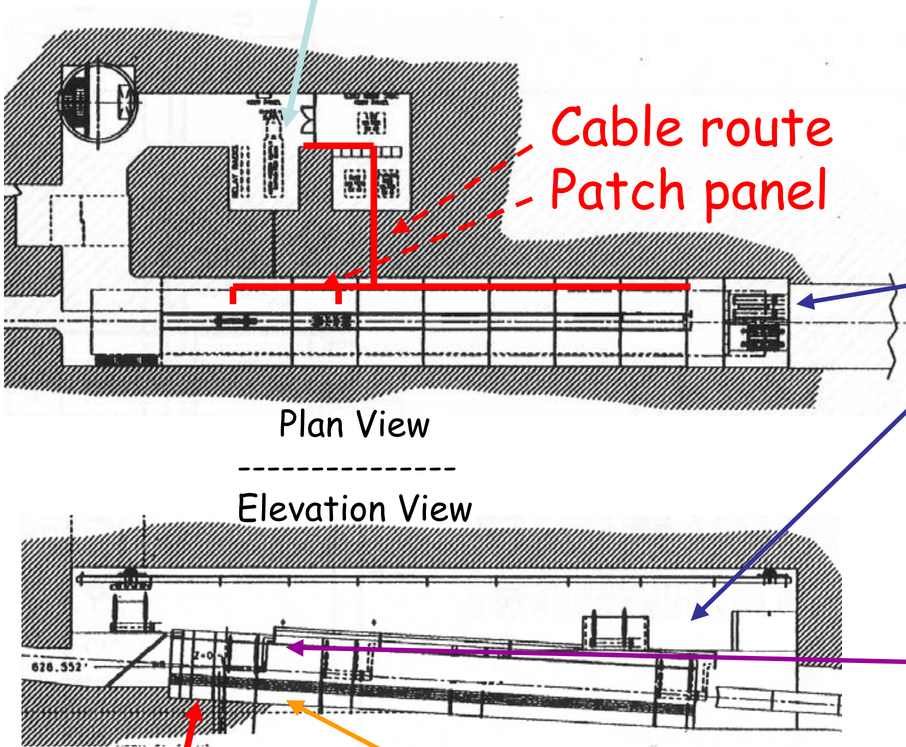


Back-up

Dimple matting around decay pipe – *directs water way flow around decay pipe to get to drain*

Target Hall
Radiation Dose Map

Power Supply Room: ~ 1 - 10 Rad/yr (MADC, differential pressure sensor, …)



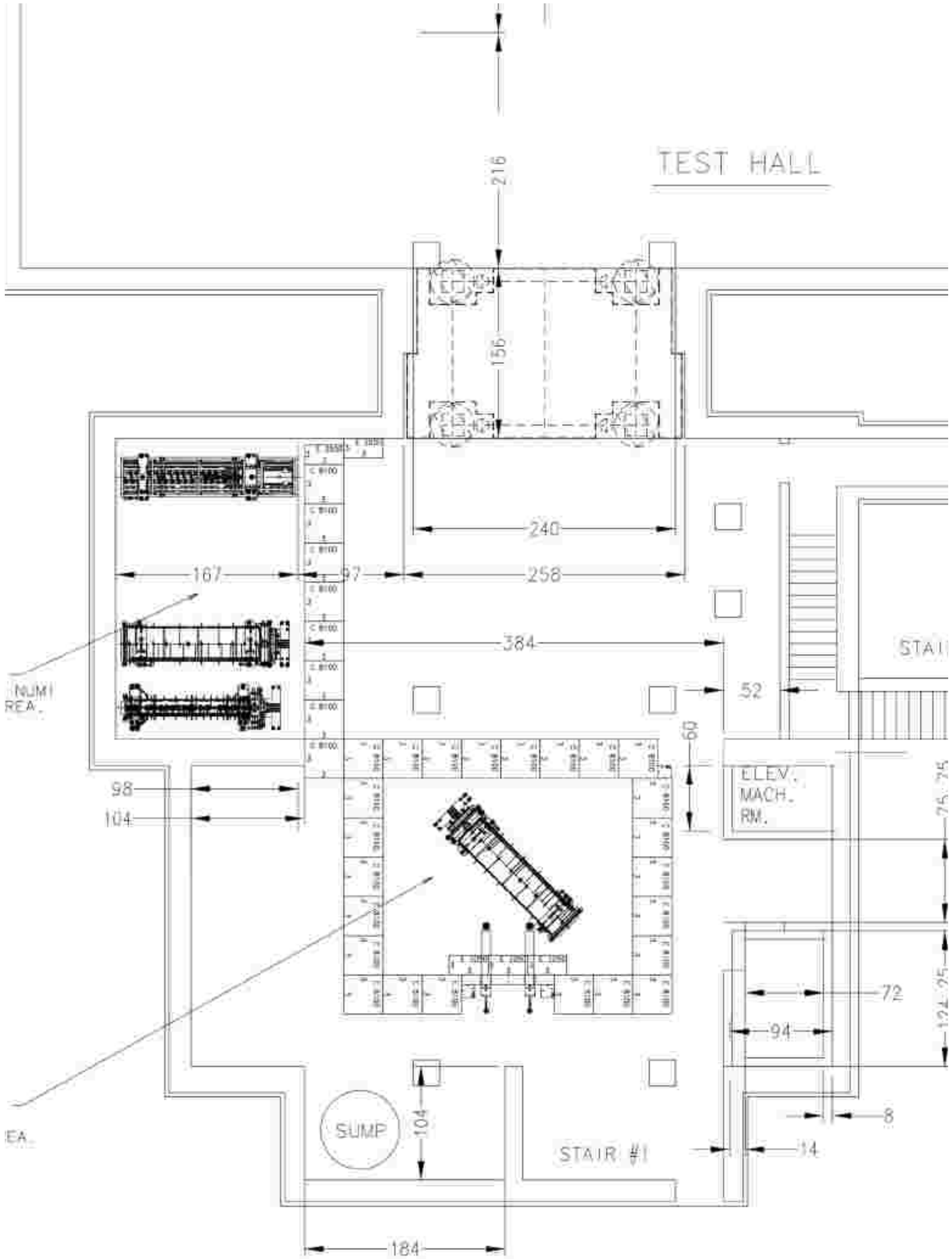
Target Hall above concrete covers:
~ 10^2 – 10^4 Rad/yr
(hot cell system, air recirculation system, humidity sensors)

Top of module, under concrete cover:
~ 10^4 – 10^5 Rad/yr
(motors, LVDTs, limit switches)

Center of target:
3×10^{14} Rad/yr

Chase, around horns: ~ 10^{10} - 10^{11} Rad/yr
(thermocouples, bdot coils, BLM ionization chamber)

C-Zero Horn repair/storage



The C-Zero building (constructed for BTeV) is now being converted to a facility for horn/target repair and long-term horn storage.

Will have radiation window, remote arm manipulators.

Could possibly use this for NT-01 autopsy next summer ?

Switch from vacuum to helium in NuMI decay pipe

Motivation for filling NuMI decay pipe with helium is driven by worry that thin window may be weakened by the nitric acid, ozone, etc in target hall air

Window is welded, is in high residual radiation area, very difficult to reach, very difficult to repair

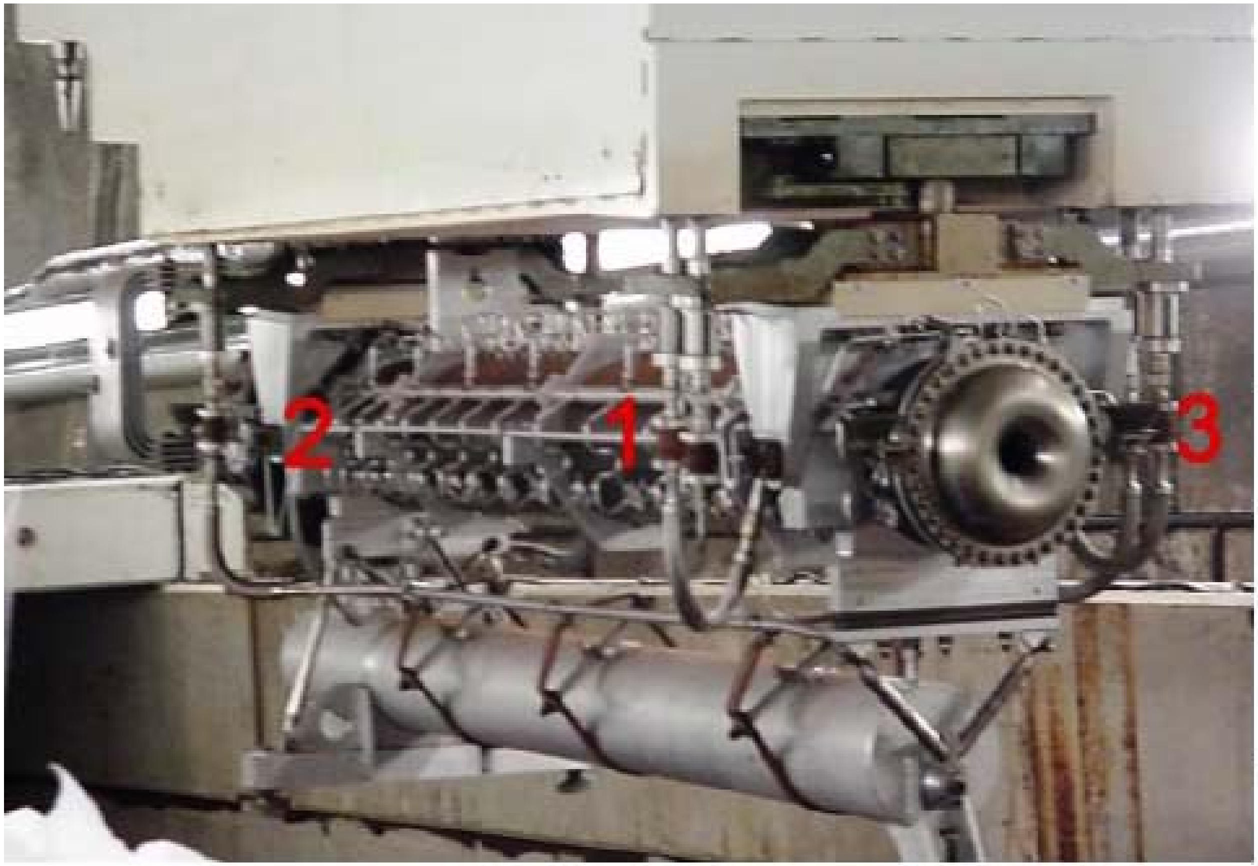
- Prevent single point failure for long term running
  > more likely to get "pinhole" leaks that we can live with rather than rips

- Save several extra days for each access underground
  > catastrophic window failure under vacuum is personnel hazard

Torben Gumstrup calculated wind velocities, up to 170 mph at labyrinth door.
Initial conservative guidance – decay pipe pressure should be within 6% of atm. press. during access

Horn 1 ceramic replacement was not as complicated, but rates were much higher

75 r/hr (0.75 Sv/hr) on contact
35 r/hr (0.35 Sv/hr) at 1 foot



Point	Doserate @ 1 foot (mr/hour)	Doserate On Contact (mr/hour)
1	35000	75000
2	40000	75000
3	35000	80000

This was 10x as much as we had for the Horn 2 repair !

Repair person would get weekly dose limit in a few seconds

Target NT-02 replaced with NT-03

FERMILAB
ACCELERATOR
DIVISION

DATE: 8/5/09 | TIME: 1800 | PURPOSE: movement survey | RWP #

NUMI Target
Beam Right

Point	Doserate @ 1 foot (mr/hour)	Doserate On Contact (mr/hour)
1	200	300
2	600	700
3	3000	3500
4	11300	45000

All Dose Rates Below N/A mR/hr Unless Noted.

Inst Type: teletector
Inst No: 6
Batt/Source Chk: sat
Cal. Due Date: 6/2010

LEGEND
Numbers appearing on map are mR/hr @ 1 ft readings unless denoted with symbols below
* = mR/hr @ contact
A = Air Sample ◯ = Wipe Ⓕ = Floor wipe

Bkgd ________ cpm

Wipe # Reading ccpm Wipe # Reading ccpm

N/A

Highest Dose Rate Found 11300 mR/hr at 1 ft.

Note: RSO approval required to work in areas where it is: >100 mR/hr @ 1 foot OR >100 CCPM on a wipe.

Comments:

Surveyed By: Busch
Reviewed By:

REVISED 8/6/09

Once again, NT-02 target Z-drive did not work

had to remove target from horn by by pulling with crane,

then in work cell hand-crank target back to center for storage

Another failed high-strength bolt

NT-03 has no high strength bolts

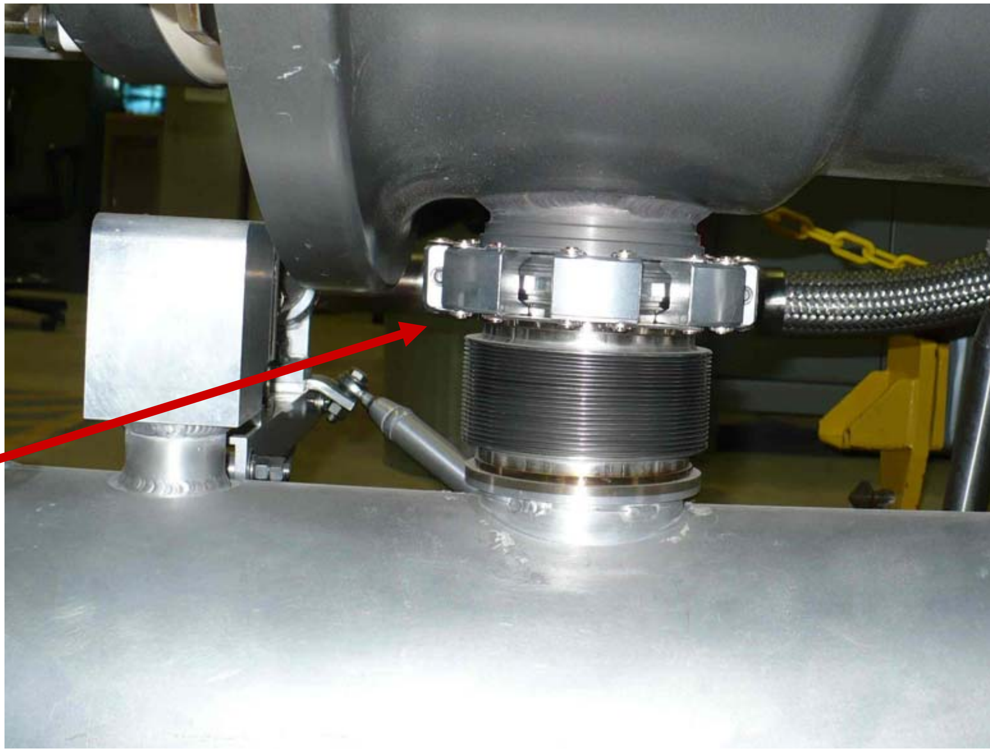
Target was 45 r/hr,
hope to do autopsy 1 to 2 years from now

Horn 2 water leak repair

H2 had a slow water leak since installation Dec 2008.

During shutdown, replaced seal on drain to water tank (Hot job in work cell)

No leak so far since then



Drain seal, with clamp

Work cell

Target module in beam-line

1st target being removed