Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

NuMI 700 kW Operation

Jim Hylen

NBI 2017

19 September 2017

Outline

(Note to organizers: thanks for delaying this NBI until NuMI actually reached 700 kW - it took a while)

- Accelerator upgrades to achieve 700 kW proton beam
- Some observations starting when I joined NuMI
- NuMI from 400 kW to 700 kW
- The big surprise: jump in tritium release
- *Best part of NBI* – **what went wrong since last NBI**
  - Target window failure & target replacement
  - Horn PH1-04 stripline failure
  - Target pile air cooling heat exchanger leak
  - Horn module bushing failure, horn PH1-03 sags
  - Decay pipe cooling pump seals being chewed up
  - Decay pipe water cooling leak
  - Drainage blocked by calcification, MINOS muck
  - Air injection into drains (for Tritium)

Very little down-time from these !

(Almost all repairs done during scheduled shutdowns)

Disclaimer: The views and opinions expressed are those of Jim Hylen, and do not necessarily reflect those of ... anyone else.

Fermilab accelerator complex

Linac overlays ~ dozen turns of beam into Booster

Booster accelerates a “batch”

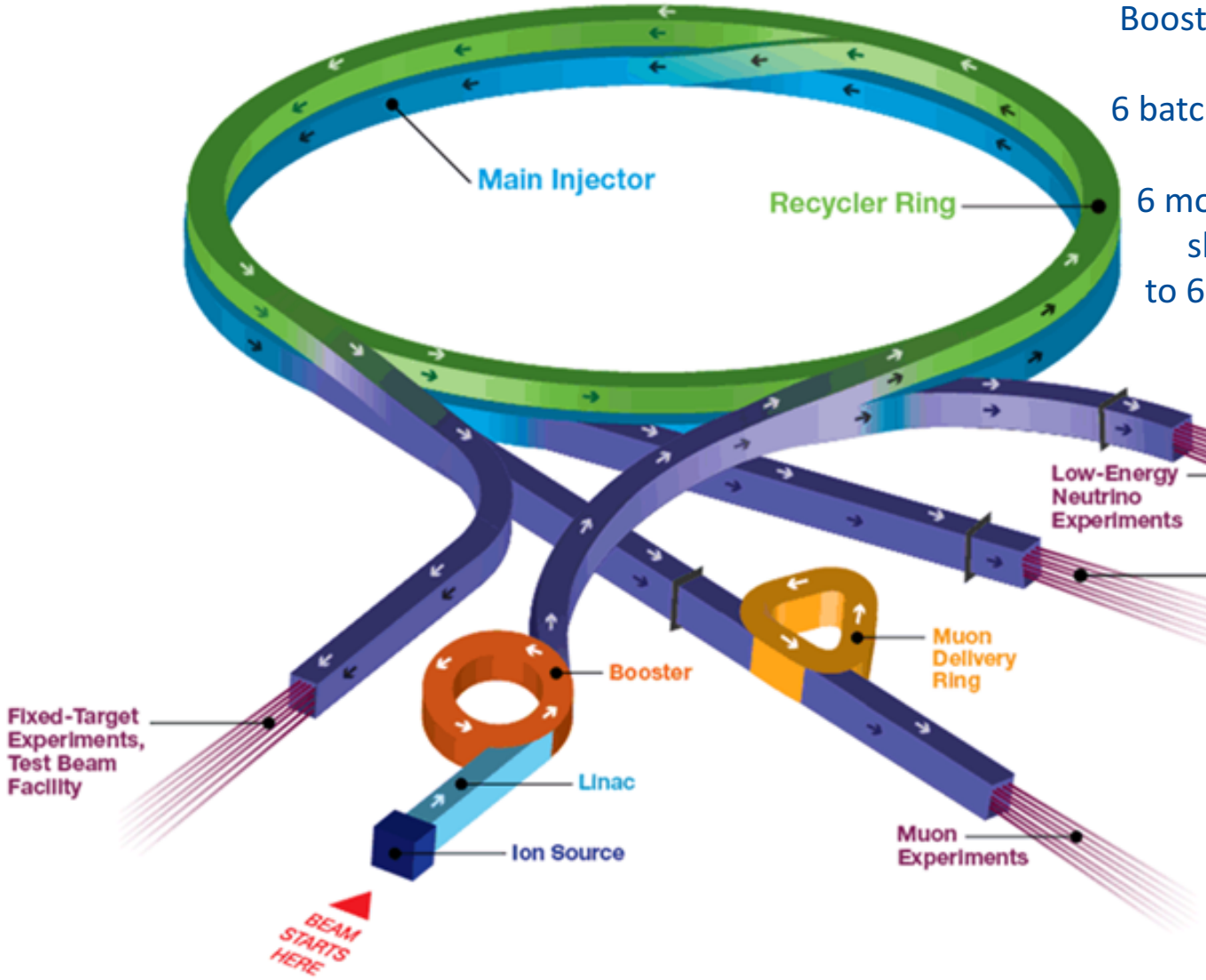
6 batches fill Recycler circumference

6 more batches to Recycler slipped and recaptured to 6 double-intensity batches

Transferred to M.I. Accelerated

Single turn extraction to NuMI

NuMI



Fermilab

400 kW to 700 kW 120 GeV proton beam

Key: Slip stacking in Recycler rather than M.I.

Main Injector can be ramping previous stacked batches
while Recycler accumulates 12 batches from Booster for next M.I. ramp

- Turn Recycler from pbar to proton ring
  - New Injection and extraction lines
  - Associated kickers and instrumentation
  - New 53 MHz RF

Ramp M.I. faster: 1.33 second M.I. cycle

- RF upgrades
- Power Supply upgrades

Collimators installed to collect losses in Booster, 8 GeV line, Recycler, M.I.

New dampers to lower chromaticity in recycler during slipping

Booster upgrade so can fill all 15 cycles per second; NuMI needs 9 batches / sec

In process: Laser notching of bunch edges (notching at Linac rather than Booster)

The year I joined NuMI design team

THE NEW YORK TIMES **SCIENCE** TUESDAY, JANUARY 23, 1996

'Neutrino Bombs' Idea Expands Debate on Human Extinction

"Neutrinos killed the dinosaurs" theory was publicized
while NuMI/MINOS was seeking approval and funding
to send neutrinos through Wisconsin and Minnesota

Gina walks into my office and says "we're dead"

First year of NuMI beam

State No. 1 in tritium spills

Illinois leads nation in leaks over decade

have been reported.

Tritium leaked in at least 10 sites across the country in the last 10 years, according to watchdog lists. Four, includ-

mined none of the leaks pose a threat to human health, but the NRC nonetheless set up a task force last month to probe the issue.

"We need to conduct an in-

year of the first Braidwood leak, until now.

By Aug. 31, it will consider potential public health effects, how the NRC responded and how the leaks were publicly

Illinois power plant tritium leaks caused public uproar

just when NuMI discovered greater-than-expected tritium levels

NOVA approval

(The world is upside down)

NOVA proposal March 21, 2005

Combined NOVA + ANU (*Accelerator & NuMI Upgrades*) CD1 approval April 2007

December 2007: project shut down and zeroed by Congress

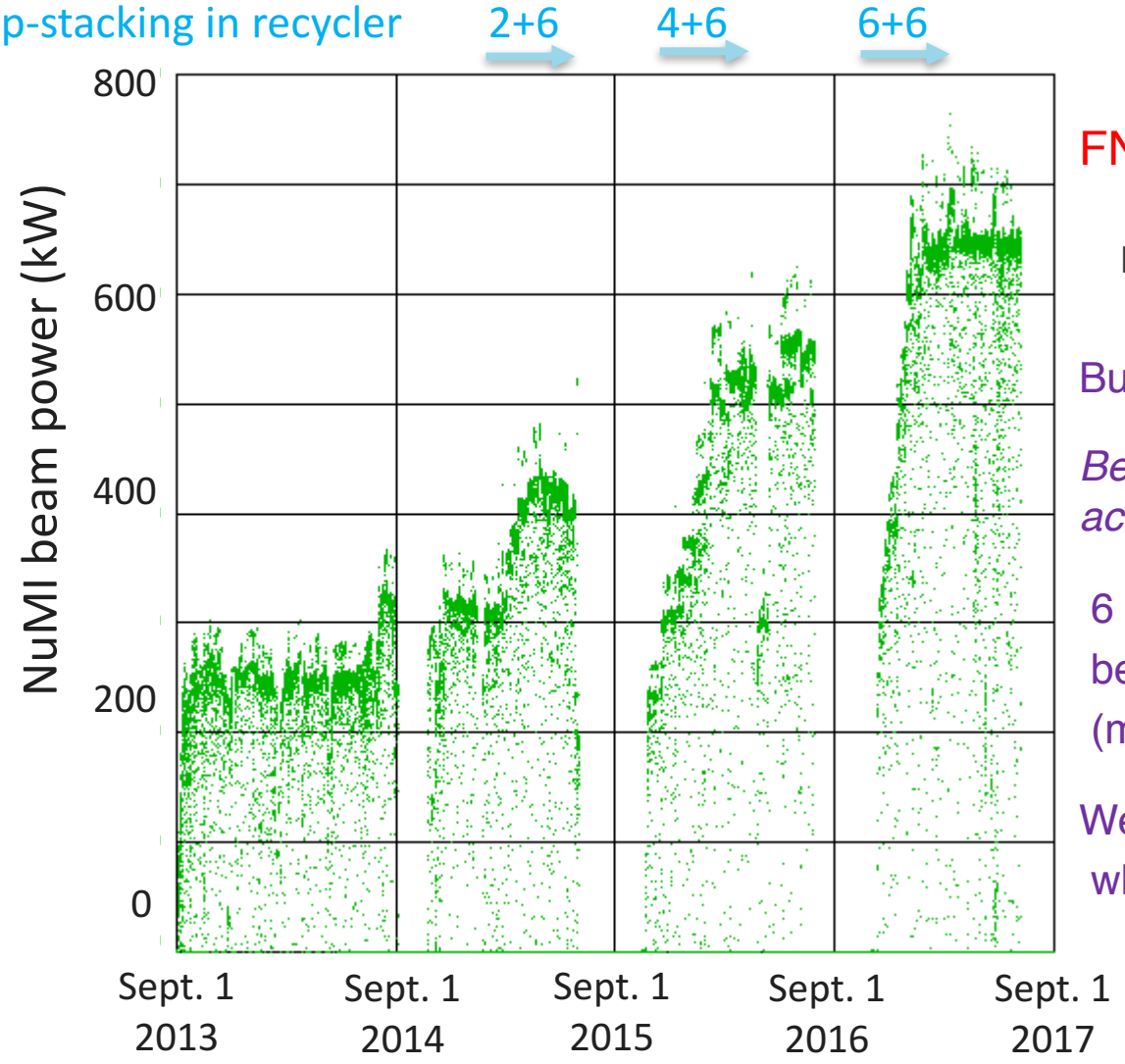
Summer 2008 reborn saved by economic crash

A “shovel-ready” project ?

Shutdown for ANU upgrade May 2012 – August 2013 NuMI ready!

Then couple years for Accelerator incremental upgrades and beam tuning

YES, we are finally enjoying design beam power



700 kW !!

FNAL PARTY to CELEBRATE!

(apparently I drank so much I forgot to note the exact date)

But…

Be nice, and share your accelerator with others…

6 seconds of every minute, beam sent to switchyard, (mainly SeaQuest experiment)

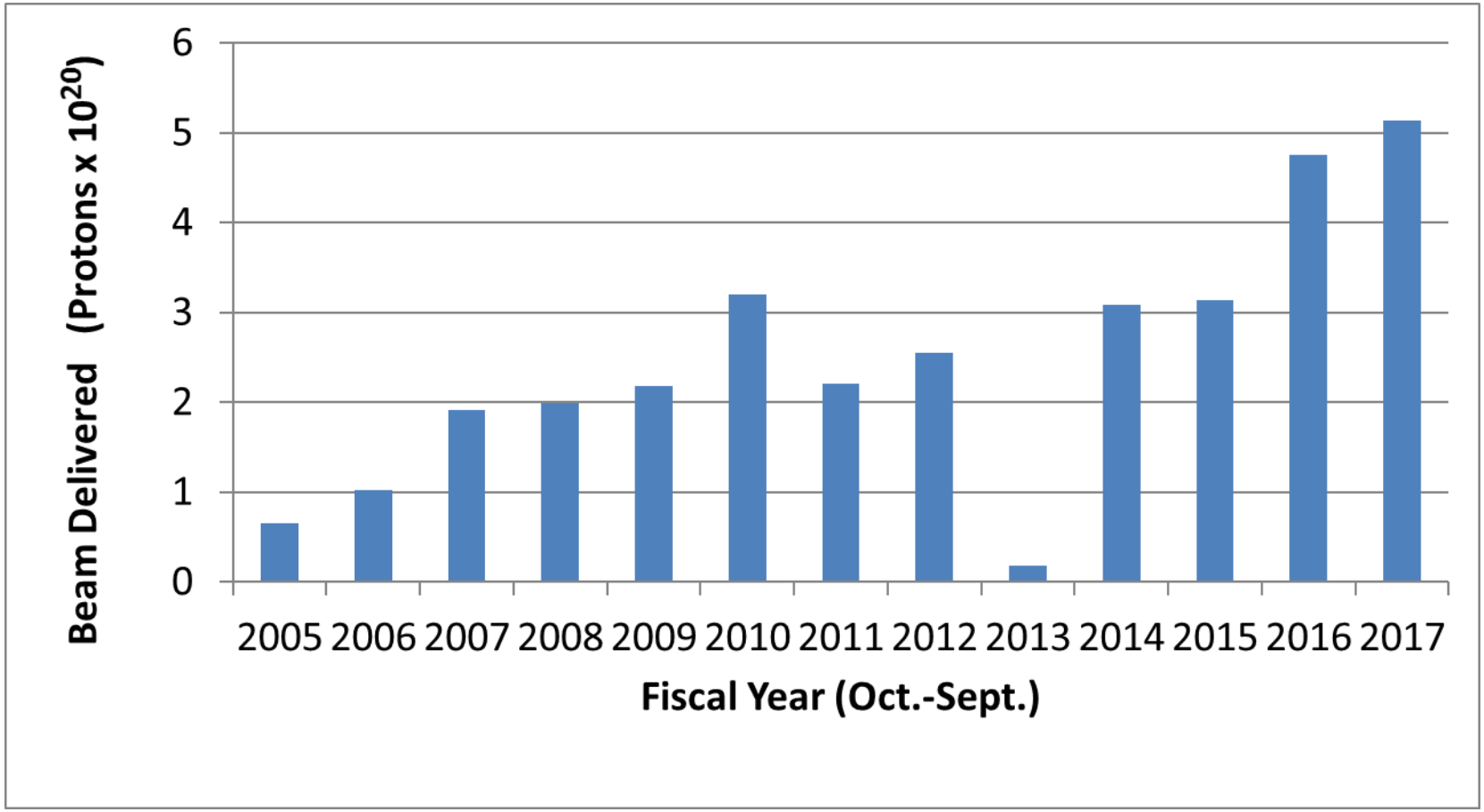
We get 640 kW except when they are down.

Beam Parameters

Beam parameters	NuMI design	NuMI pre-ANU	ANU design	ANU achieved
Protons/spill (max.)	4.0×10^{13}	4.4×10^{13}	4.9×10^{13}	5.4×10^{13}
Spill cycle	1.87 sec	2.2 sec	1.33 sec	1.33 sec
Beam power (max.)	400 kW	375 kW	700 kW	740 kW

NuMI POTs

- NuMI has now taken **3.2 x10^{21}** POT at 120 GeV
- Integrated beam power is **1.95 MW-year**

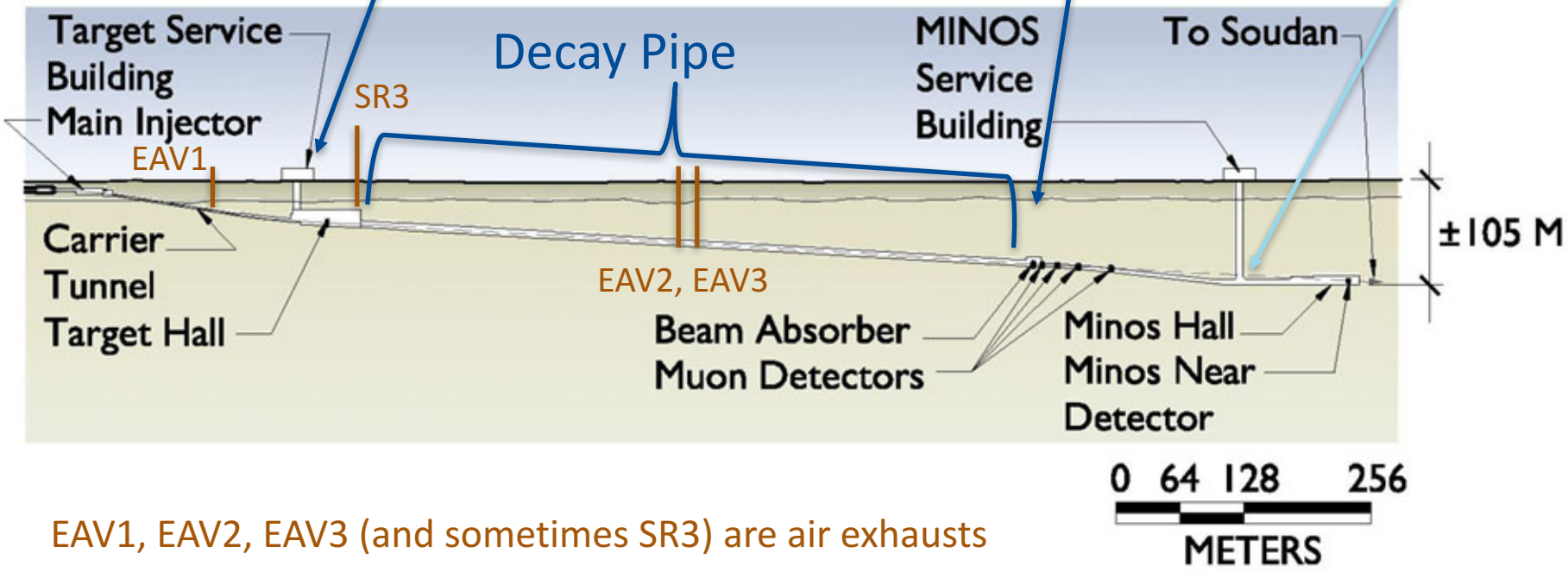


NuMI background for tritium discussion

Evaporator
of condensate
~ 250 gallon/day

Absorber dehumidifier condensate
is pumped to target hall, mixed
with target pile condensate

Underdrain water all
flows to MINOS sump,
then pumped to CUB
cooling towers and ICW
~ 100 gallon/minute



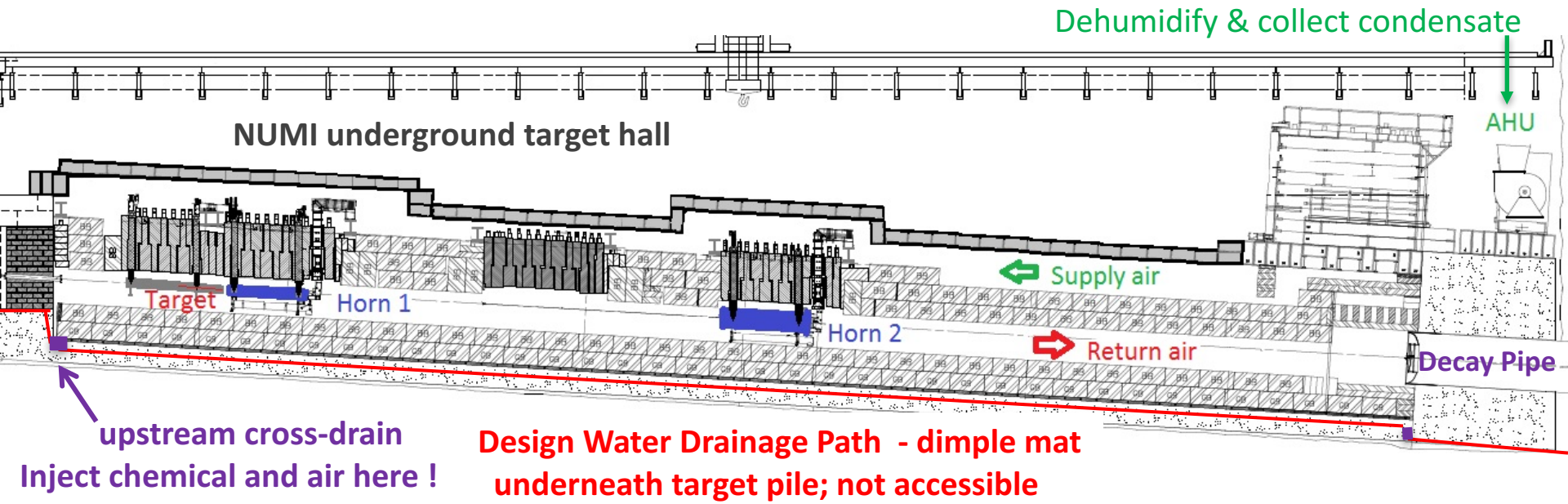
EAV1, EAV2, EAV3 (and sometimes SR3) are air exhausts

Tritium producing particle shower power is deposited ~ 1/3 in each of
(i) target hall, (ii) decay pipe, and (iii) absorber at end of decay pipe

NuMI tritium

Groundwater protection strategy is thick shielding + maintain inward water gradient

- Primary issue: keep drains open, which had been filling with calcification. Drains not directly accessible, so do chemical de-scaling.
- Secondary issue: Use dehumidifiers to intercept & evaporate majority of tritium rather than have it go to MINOS sump & build up in the lab water+pond system.



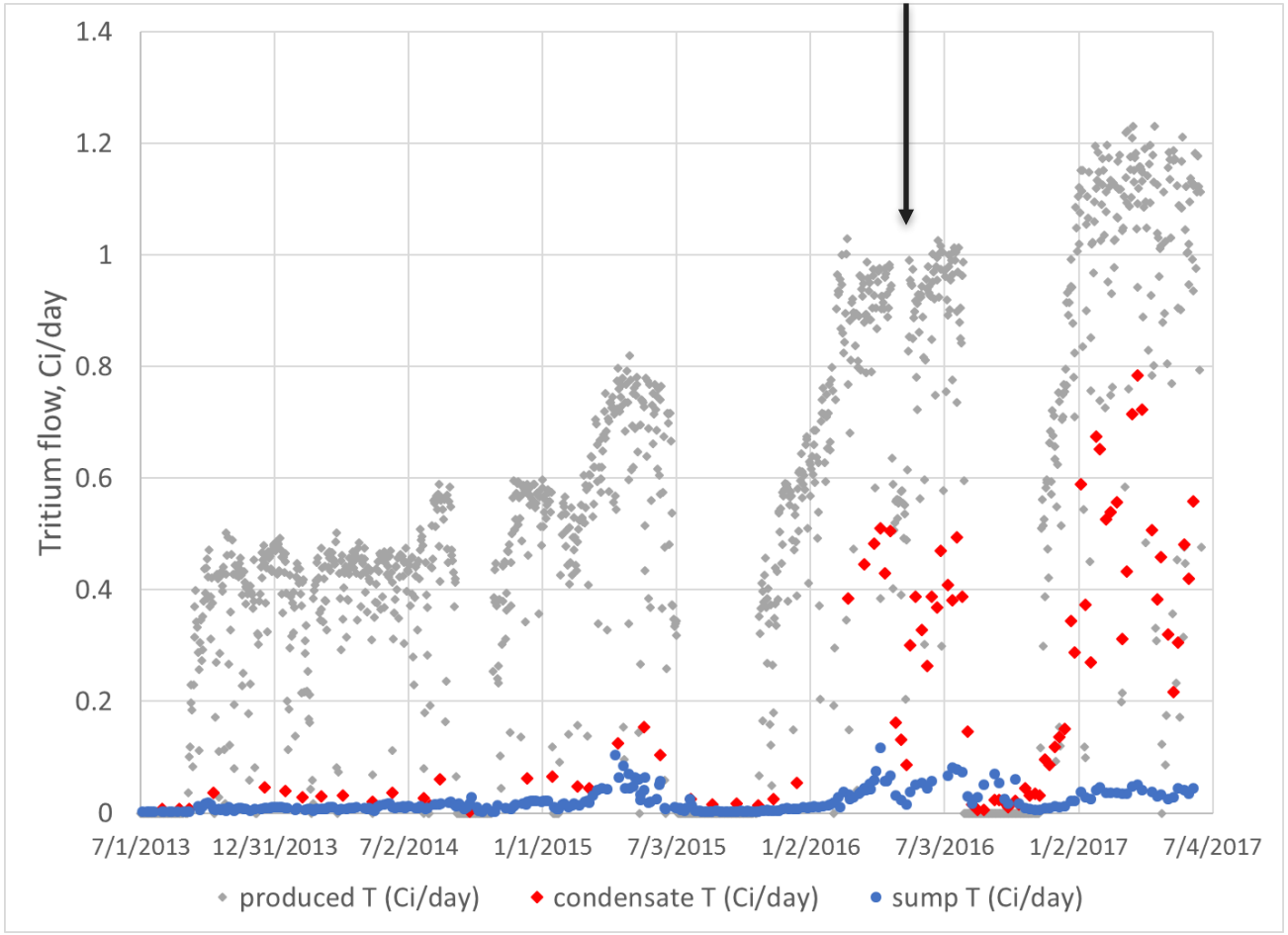
Surprise! At higher beam power, fraction of produced tritium released increased rapidly

Comparison of

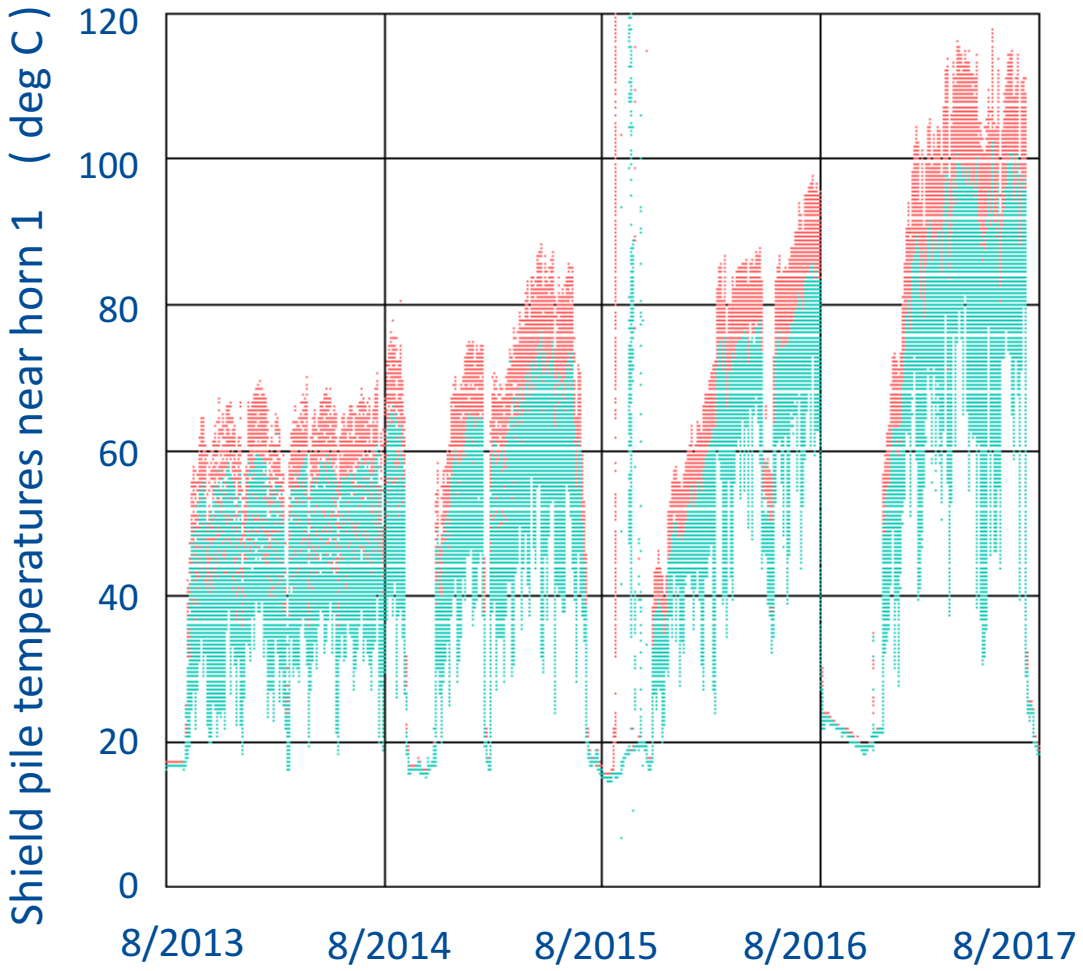
Tritium produced, based on Monte Carlo times protons delivered (not including absorber)

Tritium collected in condensate and evaporated

Tritium to MINOS sump (to lab water + ponds)



Our best explanation: steel shielding temperature



And diffusion & evaporation from surface is non-linear

New MARS Ci/10^{20} POT	Produced in
24	target pile steel
11	decay pipe concrete
2.5	decay pipe steel
0.22	chase air
0.03	decay pipe helium
??	absorber
1.3	horns
1.7 - 4.2	Target
41 - 44	**TOTAL**

Tentative conclusions

Given the published ranges of diffusivity of tritium in steel which vary widely, and our use of recycled non-standard steel shielding, attempts to model releases have not yielded at all precise predictions to compare to the observed releases.

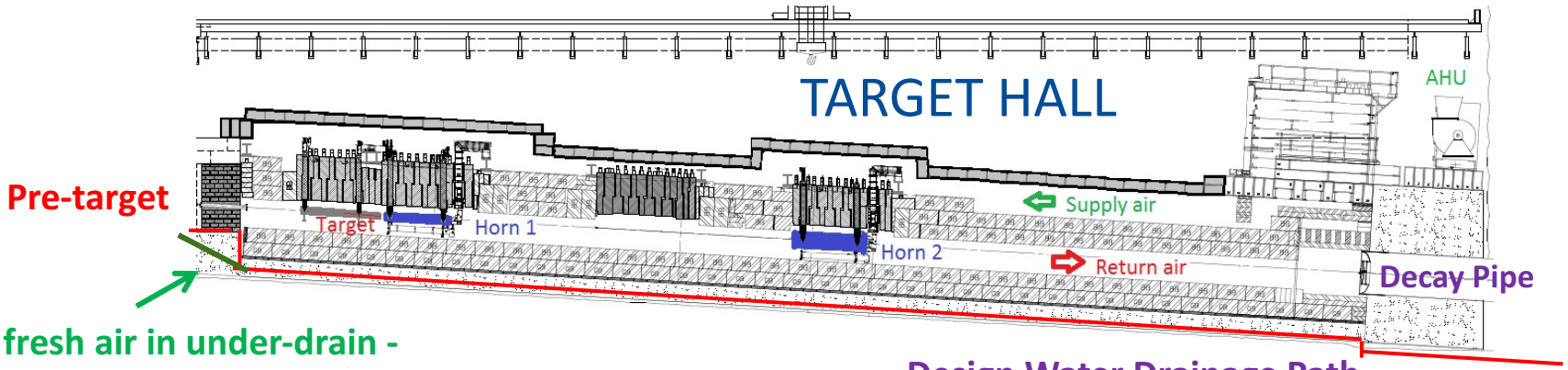
Beam power to NUMI reached full design in 2017. The air release of tritium is modestly higher than 2016; may be saturating fraction that can come out.

Also, comparing to MARS production model, can't get much (x2 ?) worse.

The NuMI release is currently only a few percent of Fermilab allowed overall radioactive air release budget, so this is not a near term problem.

Given what we see in NuMI, the conservative assumption for future facilities would be that the majority of tritium produced in the steel shielding can migrate to the air. **This is being folded into plans for LBNF.**

While on tritium - - - new air injection to drain ran during FY17



Inject fresh air in under-drain -
back-pressure prevents tritium-contaminated air getting to sump water; sends bigger fraction to evaporator

Design Water Drainage Path
- dimple mat underneath target pile

Cored through 11 ft of concrete to drain, and added air duct and fan

Air injection to underdrain

Operating since November 2016

from	to	Protons/day	Beampower (kW ave.)	sump Tritium (Ci/day)	fraction to sump	condensate Tritium (Ci/day)	fraction to condensate
2/8/16	7/28/16	1.98E+18	441	0.049	12%	0.348	88%
1/2/17	6/17/17	2.30E+18	512	0.037	7%	0.490	93%

Tritium to the MINOS sump relative to evaporator down by almost a factor of two this year, so this system appears to be successful.

NuMI part of ANU

What neutrino beam stuff was upgraded for 700 kW?

- Target (actually easier because does not have to fit in horn)
- Added TVPT position monitor (because target no longer symmetric)
- Horn 1, more water cooling
- Horn 1 stripline (oops)
- Horn 2, moved to new location (NOVA request, not 700 kW)
- Extra heat exchanger for target pile air cooling
- Extra portable shielding for working on top of modules

LE target for MINOS experiment NT series used 2005-2012

Special challenge: target must fit in narrow neck of focusing horn

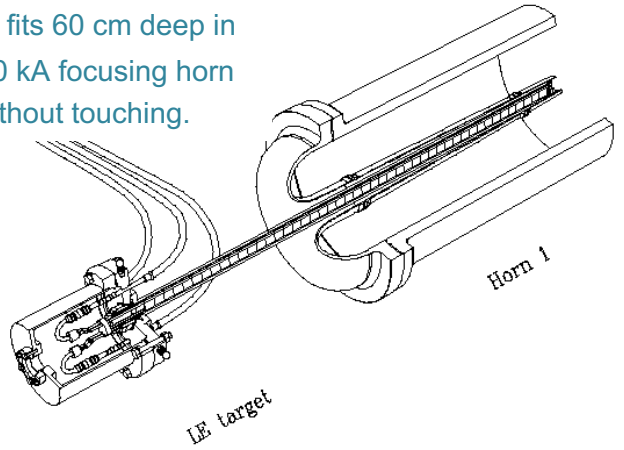
Helium atmosphere
Beryllium windows
Cooling: water in steel tube brazed to graphite

47 graphite fins: Each fin 20 mm long & 6.4mm wide
Proton beam spot sigma = 1.1 mm

Operation: 7 targets in 7 years;
ran at reduced intensity for significant time,
limping target that had water cooling leak,
while completing spare target

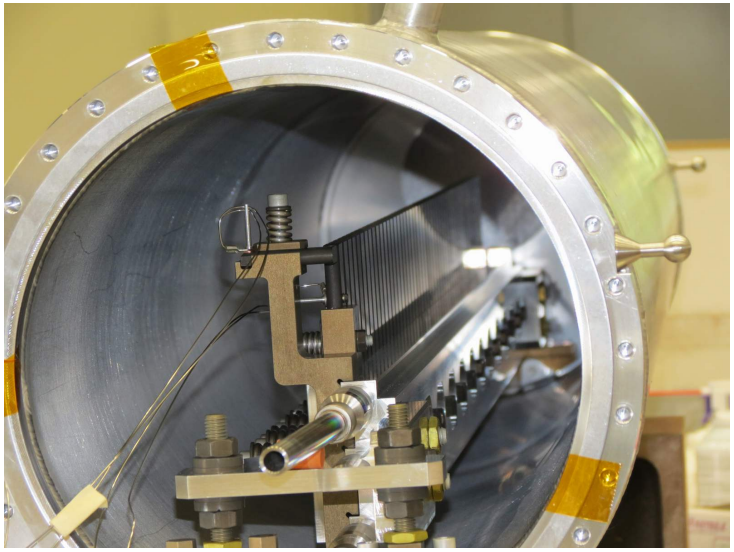
* * Center of peak fin	Design	achieved
Proton beam (per proton)	120 GeV	120 GeV
POT / 10 micro-second spill	4.0e13	4.4e13
Repetition time	1.87 sec	2.1 sec
Proton beam power	400 kW	375 kW
Peak max. Edep. per spill * *	355 J/g	390 J/g
Peak max. power deposition * *	190 W/g	178 W/g
Instantaneous power during spill * *	35 MW/g	39 MW/g

Target fits 60 cm deep in the 200 kA focusing horn without touching.



NuMI NOVA-era targets

MET-01 target for NOVA experiment
Used: 2013-2016



Initial design by IHEP-Protvino
Final design RAL/FNAL
Constructed at RAL

50 Graphite fins: each 24 mm long & 7.4mm wide

Design Proton beam spot sigma = 1.3 mm

Helium atmosphere

Beryllium windows

Cooled by aluminum pressing plates,
pressing plates and outer can water cooled

MET-01 target lasted 3 years

MET-01 * * Center of peak fin	Design	seen
Proton beam (per proton)	120 GeV	120 GeV
POT / 10 micro-second spill	4.9e13	4.4e13
Repetition time	1.33 sec	1.33 sec
Proton beam power	700 kW	619 kW
Peak max. Edep. per spill * *	310 J/g	240 J/g
Peak max. power deposition * *	235 W/g	180 W/g
Instantaneous power during spill * *	30 MW/g	24 MW/g

Fermilab

MET-01

Started leaking helium 5/26/2016, leak gradually increasing

Ran fine in beam until summer shutdown, 7/29/2016

At end, leak was 7.5 lpm at 0.7 psig

Used summer shutdown to replace target.

Localized leak (next slide).

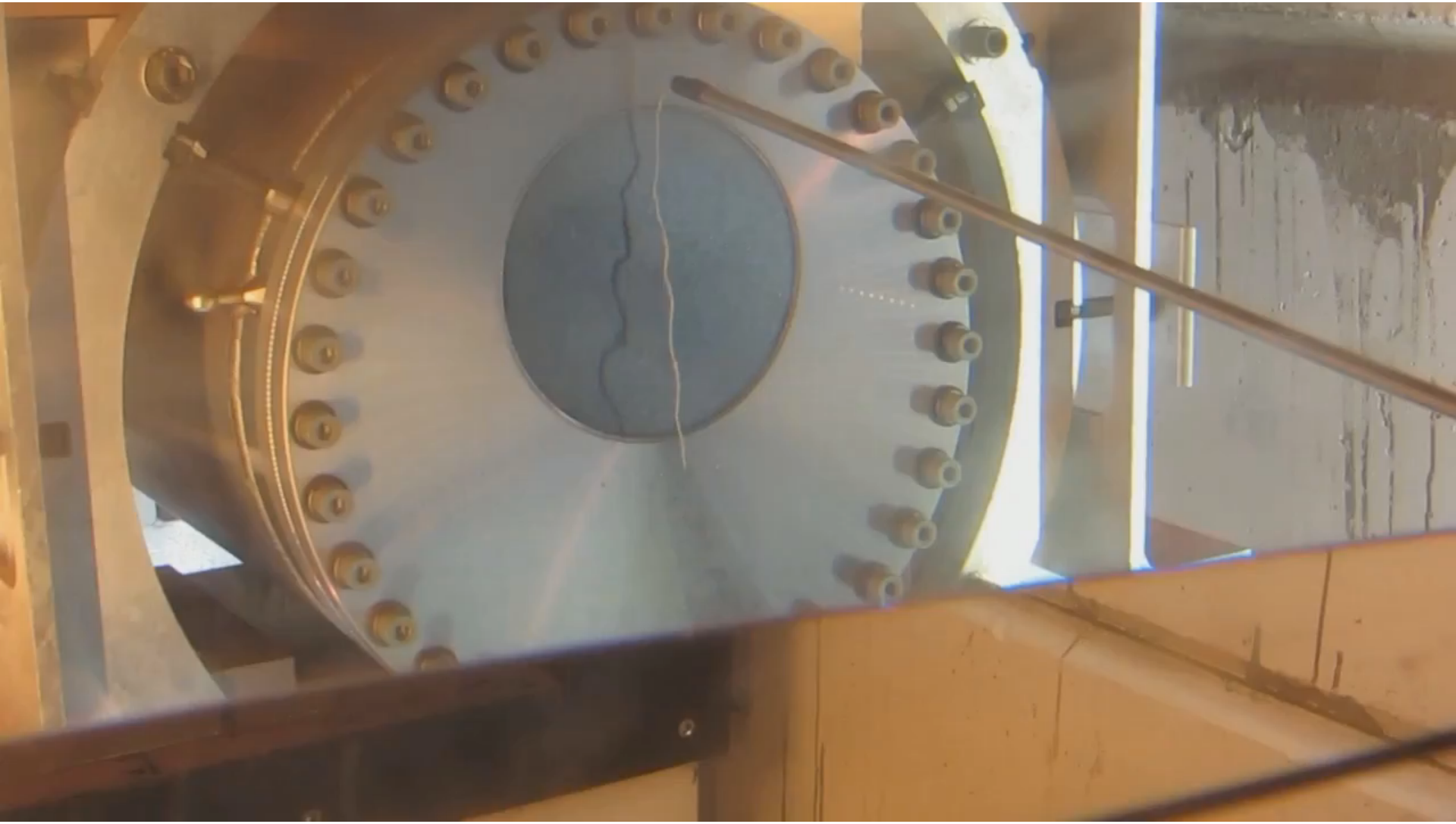
Stuck in Morgue in Target Hall for 1 year to cool down.

Just moved to C0 storage area, where we have work-cell.

Will look inside at fins in coming year.

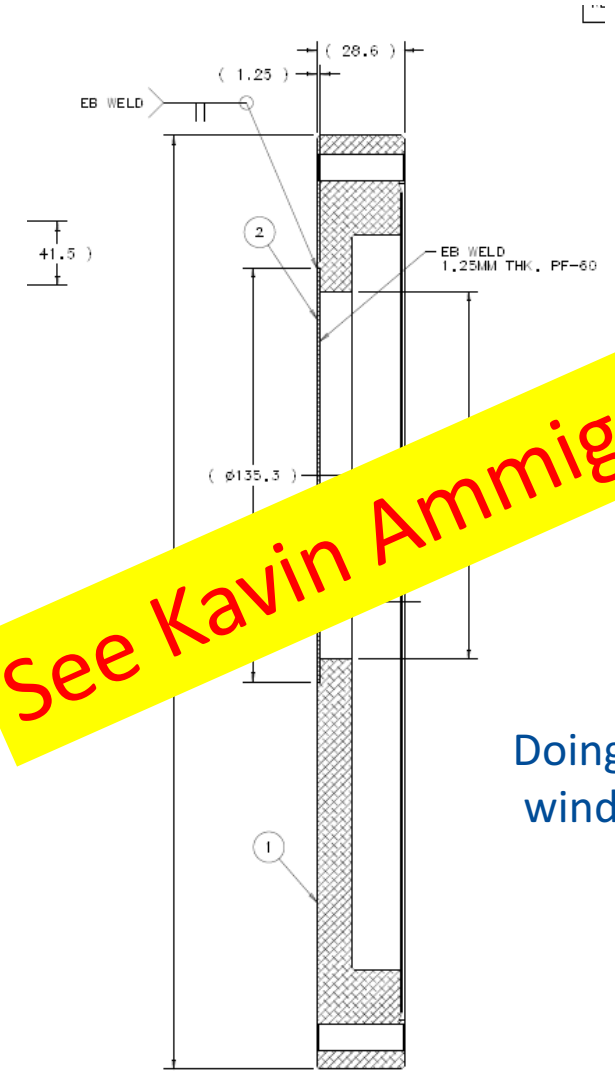
Locating helium leak in workcell

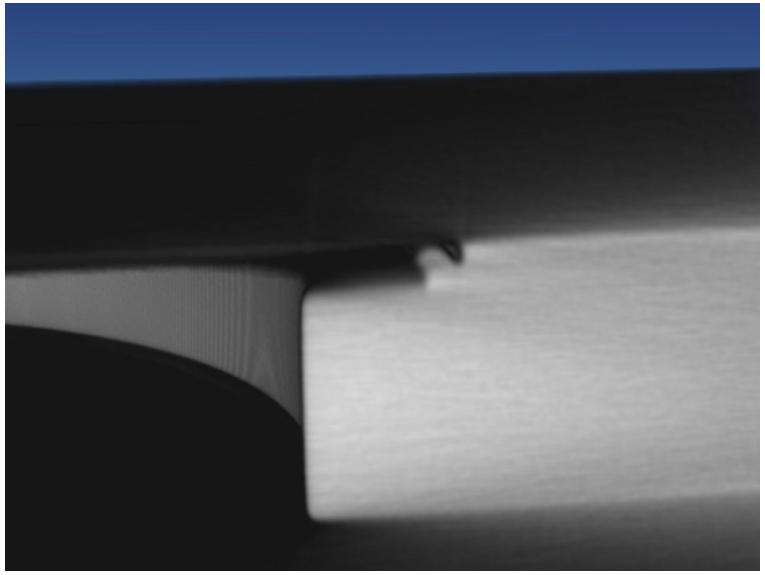
(ultrasonic microphone, smoke, He sniffer, FLIR with CO_2 did not work nearly as well)



CT scan of spare window –

EB weld of 1.25 mm thick Be window to Al flange only ~ 1 mm across





See Kavin Ammigan's talk for discussion

Doing re-design of window attachment

Fermilab

MET-01 on way to morgue to cool off for a year

FERMILAB
ACCELERATOR
DIVISION

Helium leak was at edge of beryllium window

NUMI Target
MET 01 Beam Right

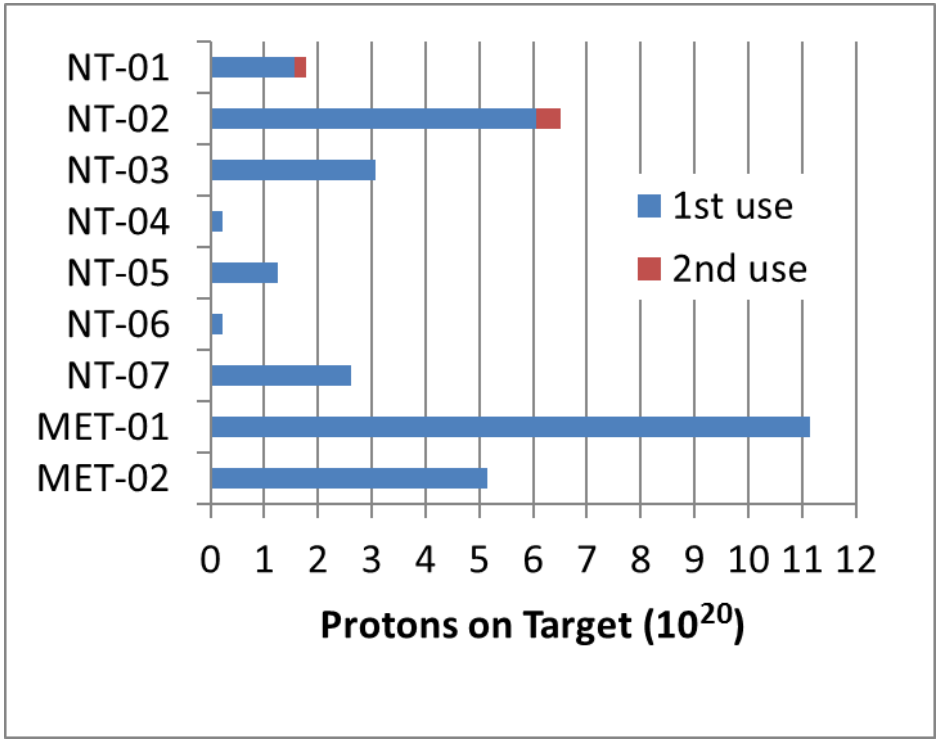
Point	Doserate @ 1 foot (mr/hour)
1	28000
2	15000
3	10000
4	3000

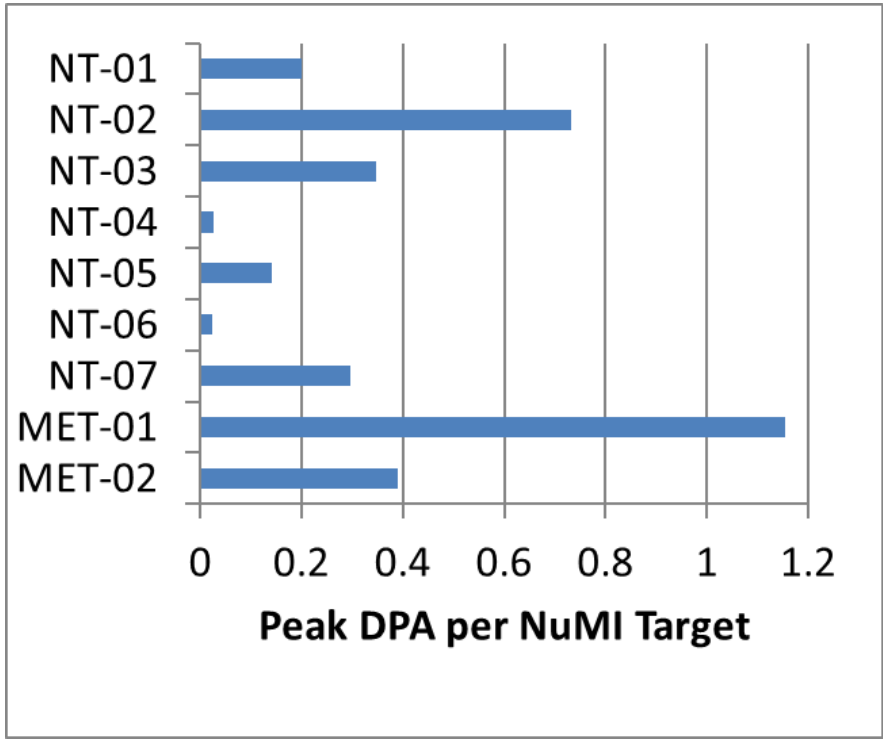
NuMI Medium Energy Target – MET-02 (constructed at FNAL)

- In MET-02, as part of target R&D, 3 of the 50 graphite target segments are replaced by beryllium S-65, to compare their survivability.

Unfortunately, it has the same style window as MET-01; so has risk of helium leak.
It has run one year so far with no problems.

NuMI target history





NT01 – NT06 failed with water leaks. NT-07 was fine at end.

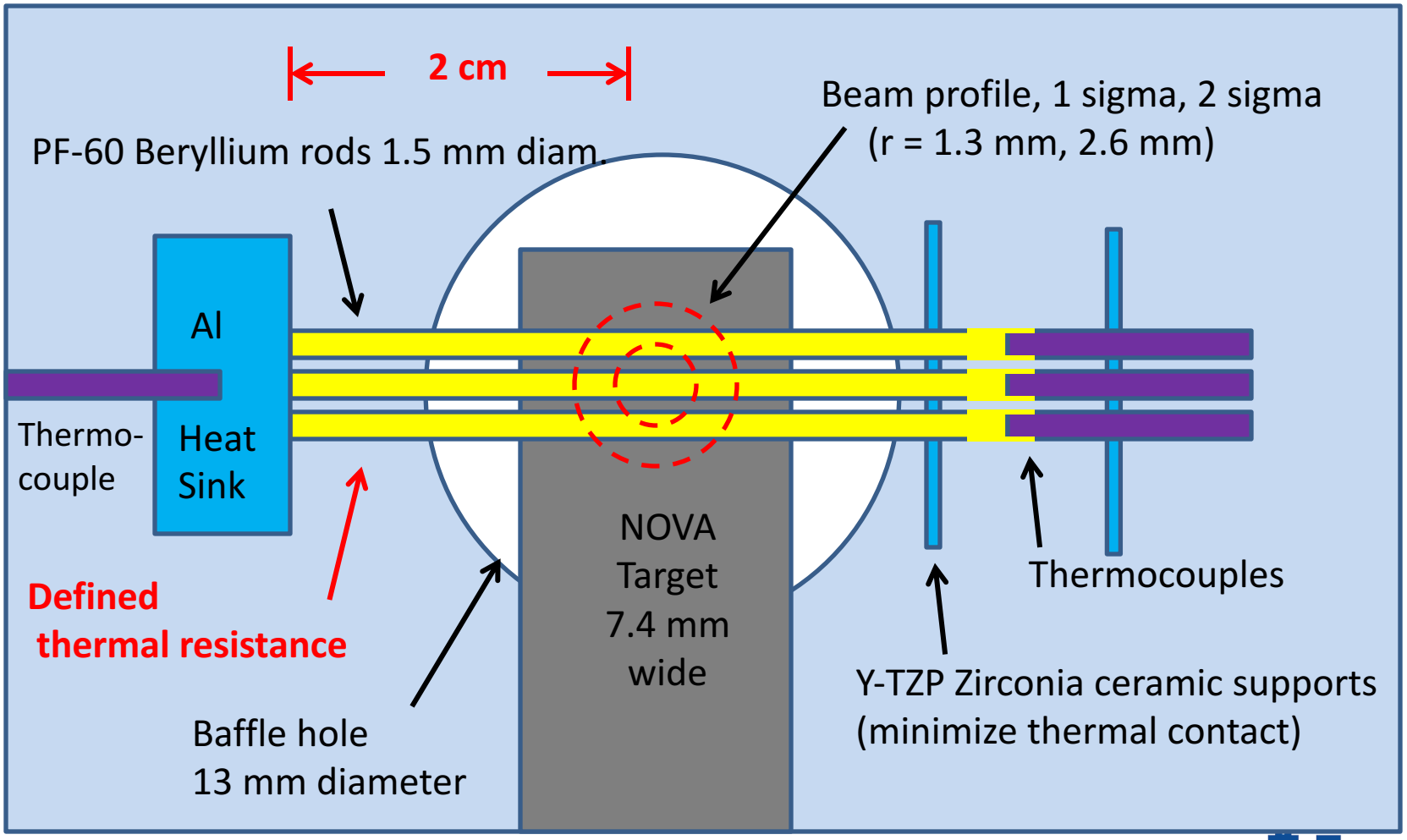
MET-01 failed with helium leak. MET-02 is fine so far.

Only NT-02 showed definitive degradation of neutrino yield.

TVPT is a Thermal Beam Position Monitor

Beryllium rods, near upstream window of target, measure beam position

First presented at NBI 2014

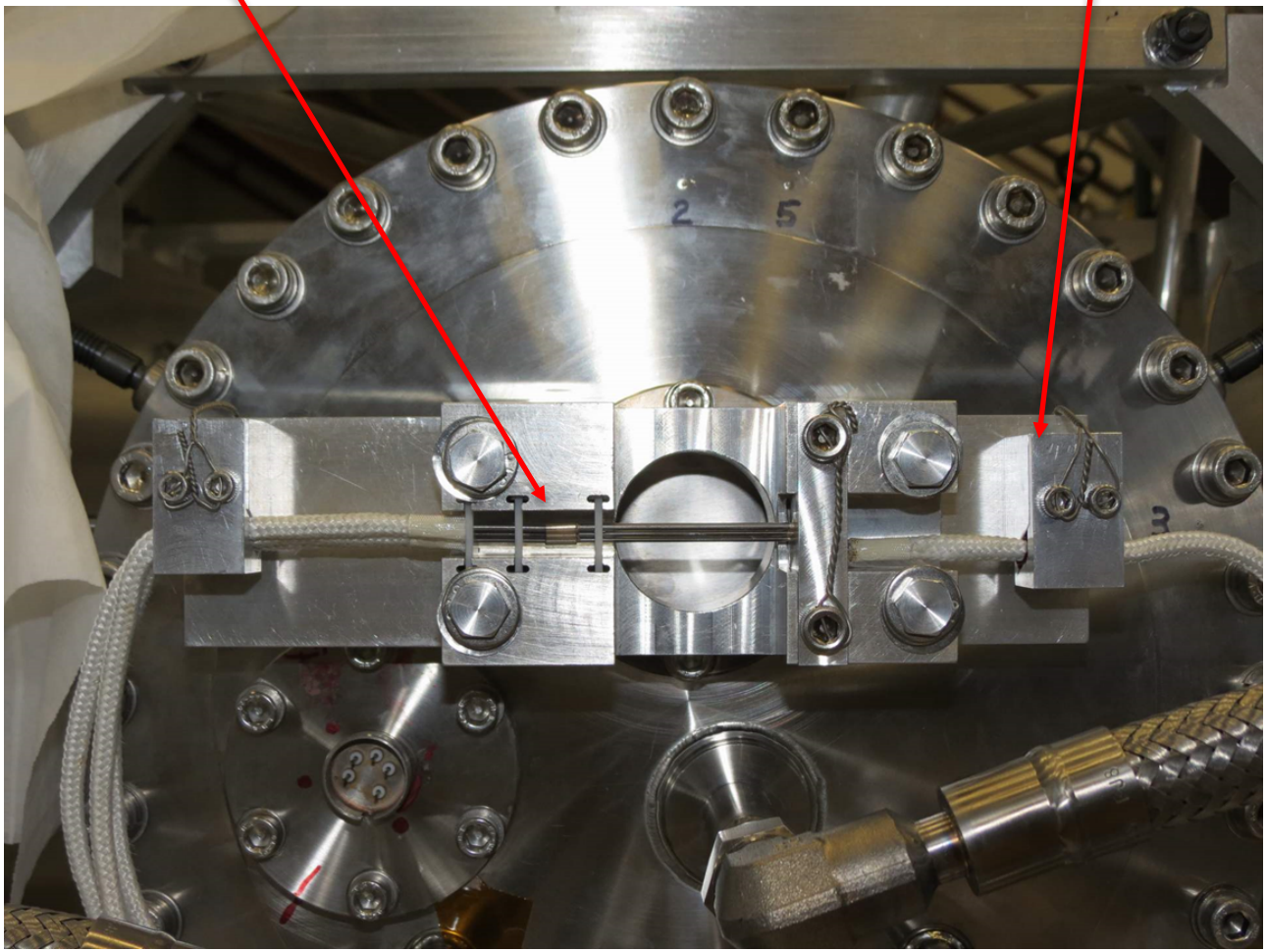


Fermilab

Beams-eye view of TVPT on NuMI target MET-01

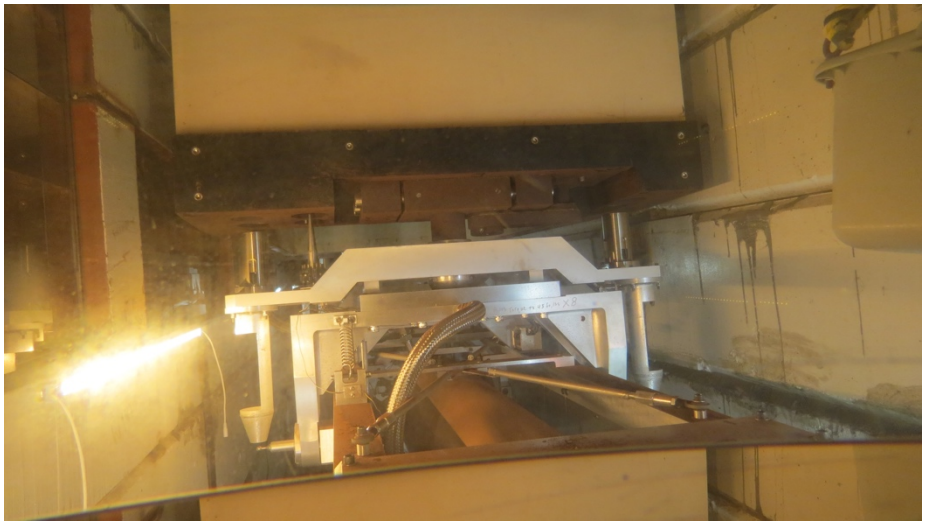
- Thermocouples

Heat sink



Fermilab

Update on operation of TVPT system

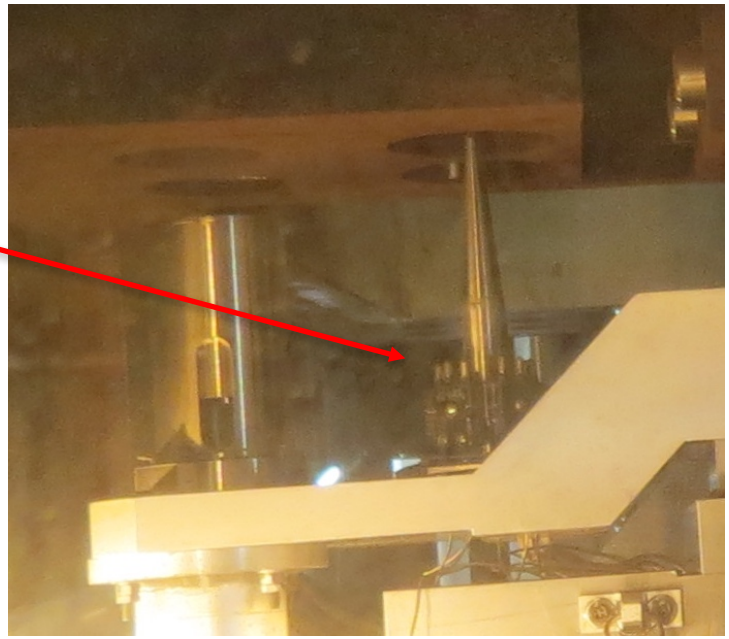


After couple years, had connector problem on TVPT for MET-01, but still got good position data using thermocouples that were left.

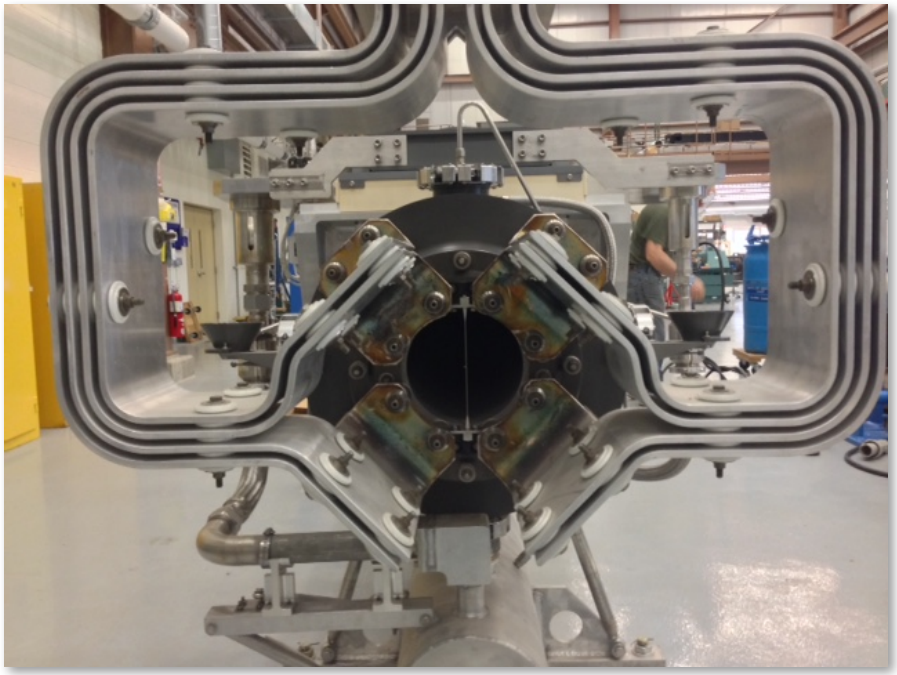
So far, no corrosion problem on MET-02, which has both vert. and horz. systems

Corrosion of pins in remote connection plug for thermocouples is the vulnerability of TVPT

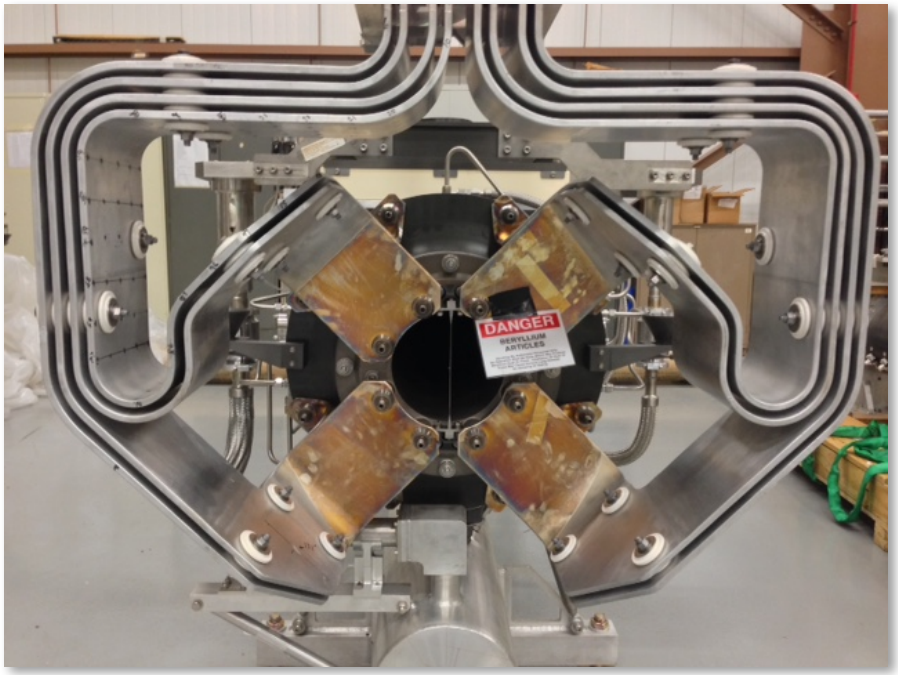
Pack with grease to protect



Horn 1 was a redesign to handle higher 700 kw beam power
13 June 2015, PH1-04 strip-line failed after 2 years, 27 million pulses



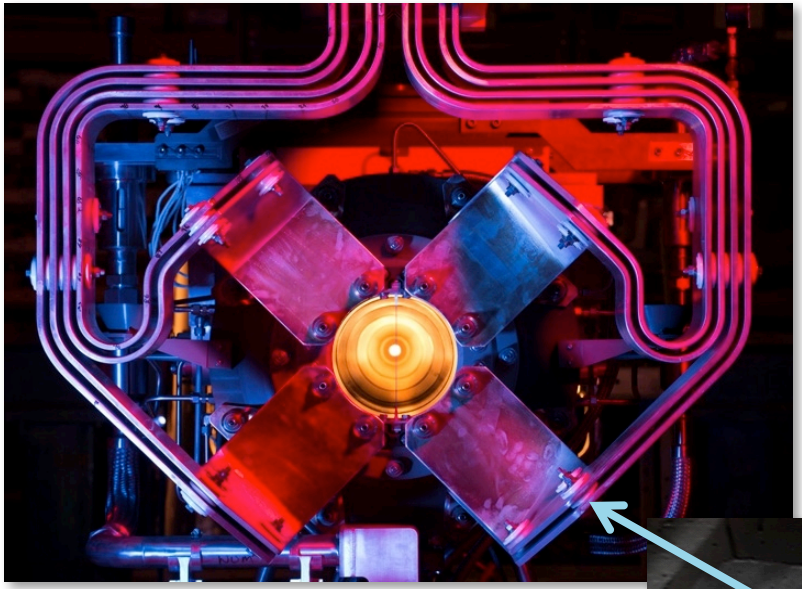
400 kW Design

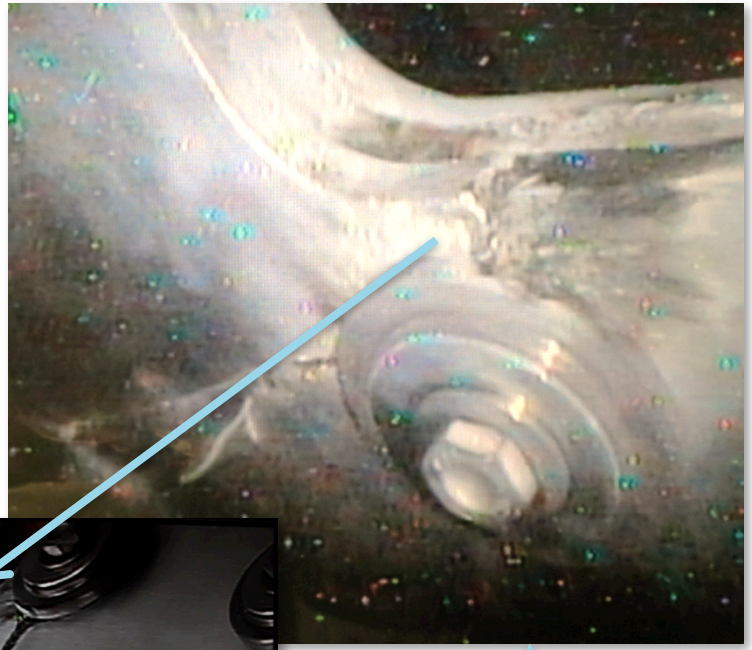


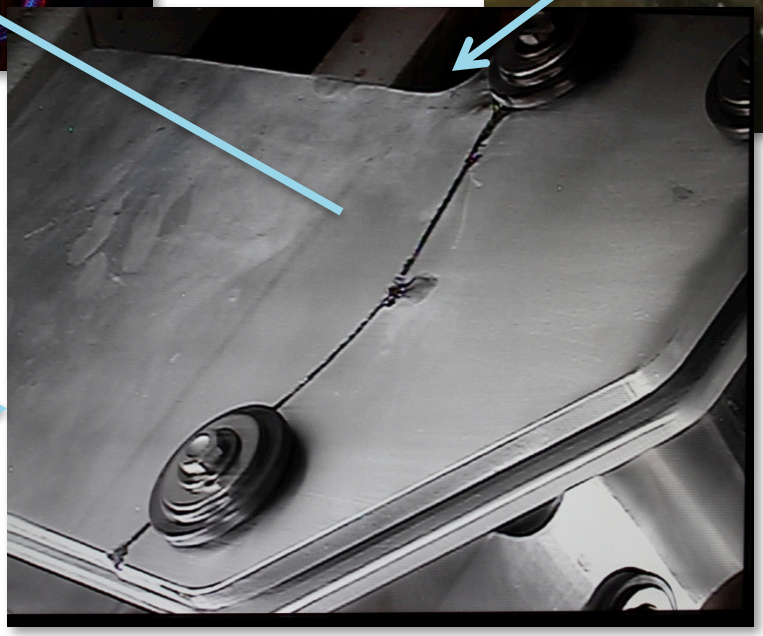
700 kW Design

- Stripline Flags were moved outward to lessen beam heating and enhance convective air cooling by target chase air flow
- Results in longer unclamped distance on lower stripline
- Fatigue failure from magnetic forces? Longer ring-down increases fatigue cycles

The PH1-04 strip-line failure







Crack in outer conductor on the underside (looking from bottom up)

Appears to have been initiated on inside radius or clamp bolt hole

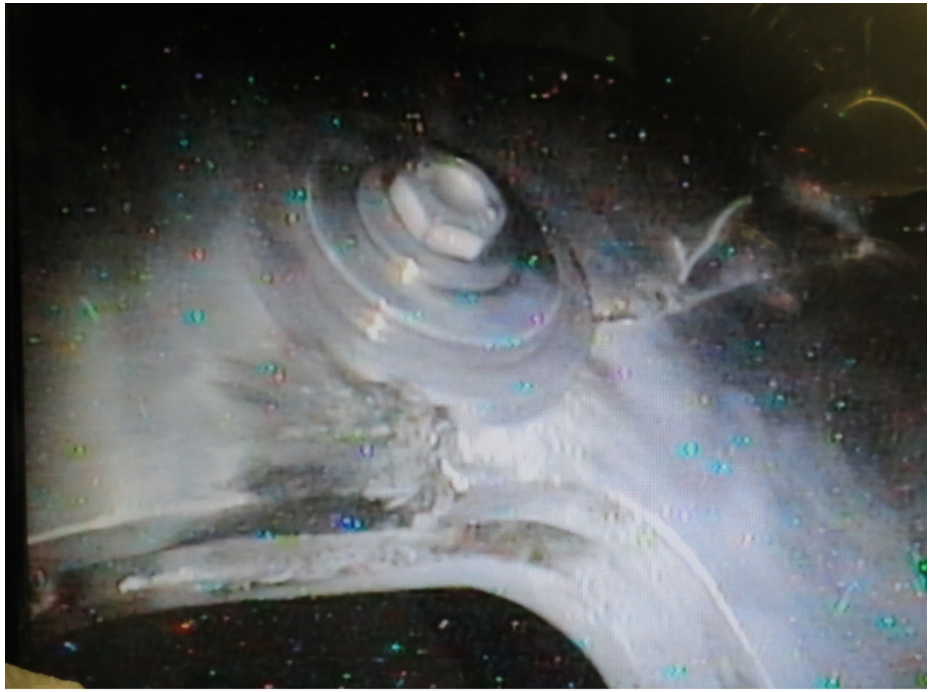
Fermilab

Operational impact

- Lucky it happened near end of run (3 weeks to shutdown)
  - Took 19 days of **horn-off** data to end of scheduled run
  - Useful for experiment systematics

- To get a jump on understanding, accessed to diagnose
  - *Turn beam off*
    2 AM 17 June 2015
  - *Open up target pile*

photograph broken stripline on horn



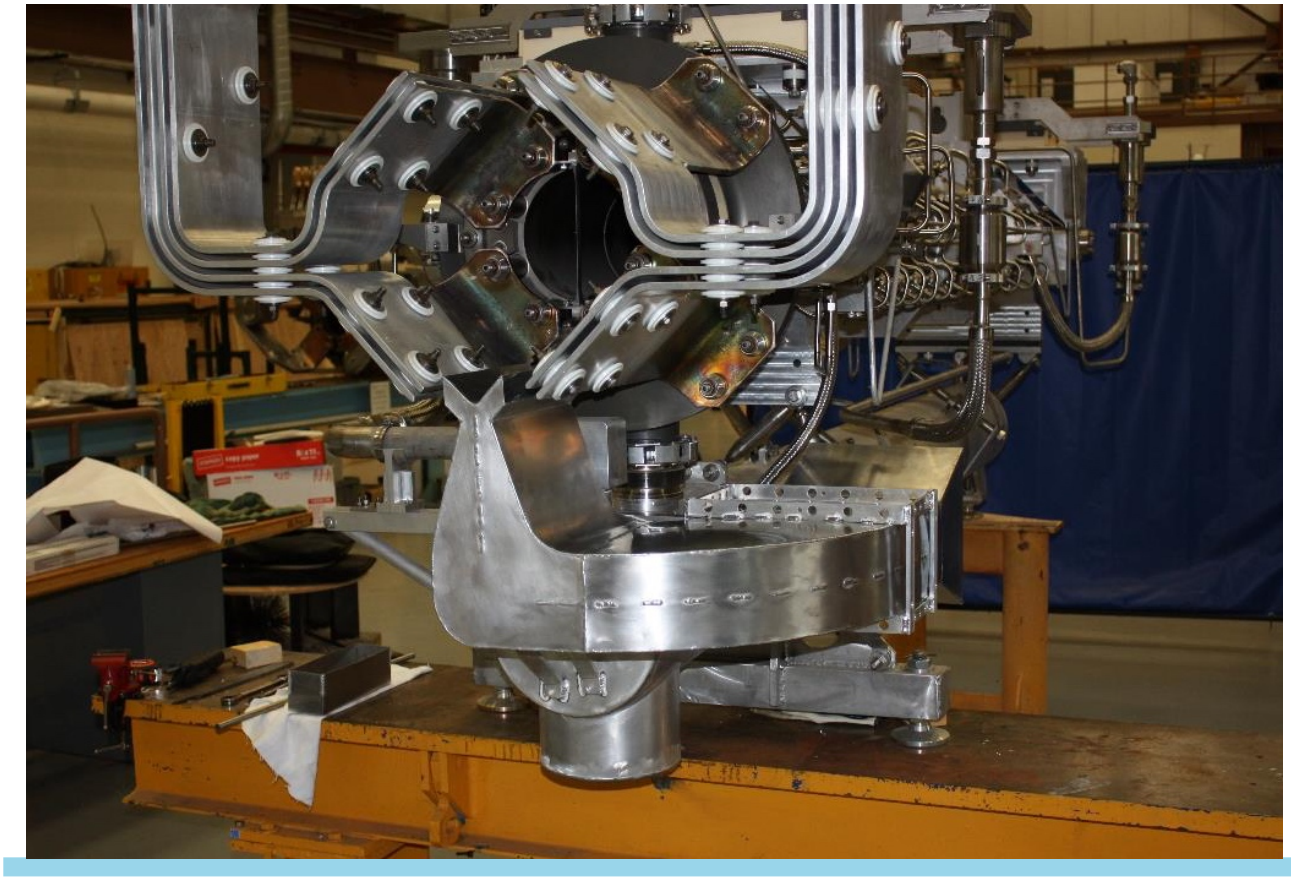
  - *Turn beam back on*
    Noon 19 June 2015

2 1/2 day downtime for diagnosis

Horn replacement 2015 shutdown

PH1-03 Modifications for higher beam power

- Went back to the smaller radius, stiffer 400 kw strip-line design
  Vibration ring-down is much faster
- Air duct added (wind tunnel result)
  cools stripline for higher beam power
- Water cooling of DS flange added
- Al cross-hair replaced with Be



Modifications were based on detailed measurements of vibration and heat transfer done summer 2015

Two years of operation; so far so good

NuMI horn statistics

	NuMI horns since 2005 start	Pulses	Start date	End date
PH1-01	failed water line	24,200,000	2005	Jun-2008
PH1-02	removed for 700 kW upgrade	45,900,000	Jun-2008	Jun-2012
PH1-04	Stripline fatigue on 700 kW modification	26,960,000	Aug-2013	Jun-2015
PH1-03	operating	27,871,104	Oct-2015	running
PH2-01	H.S. steel washer caused stripline failure	28,100,000	2005	Dec-2008
PH2-02	operating	96,831,104	Dec-2008	running

Shortest
2 years

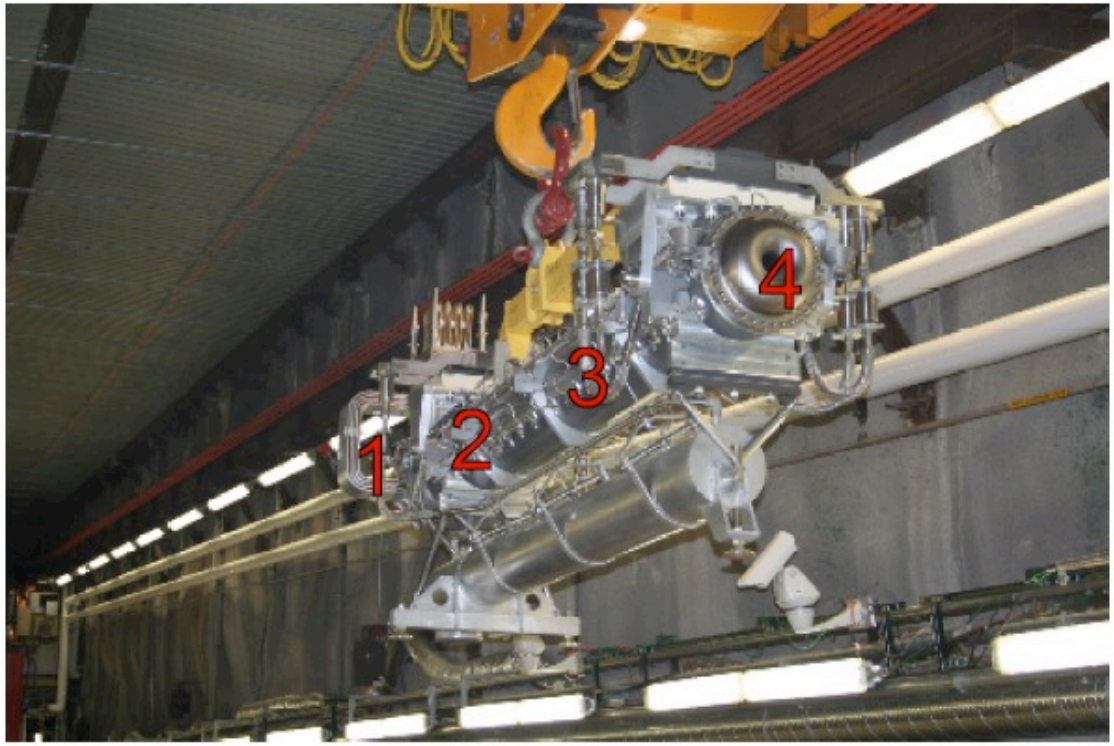
Longest
9 years

Fermilab

Components are getting pretty hot

FERMILAB
ACCELERATOR
DIVISION

DATE: 9/3/15	TIME: 1000	PURPOSE: replacement survey	RWP #



NuMI Horn PH1-04

After 2 month cool-down

Point	Doserate @ 1 foot (mr/hour)
1	50000
2	100000
3	110000
4	80000

- Worker would accumulate weekly dose limit in 2 seconds

Breaking news – horn PH1-03 hanger water leak

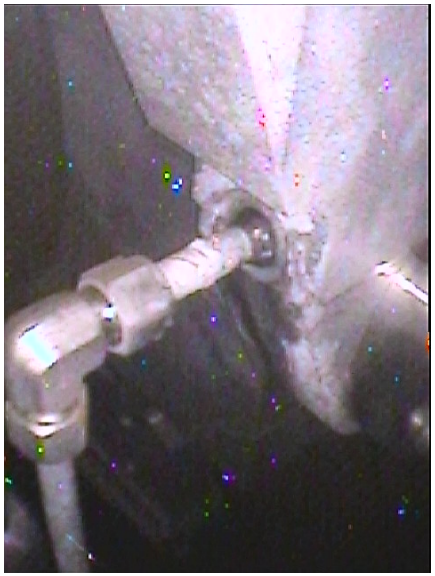
after 2 years operation

~ 1 liter / week water leak when beam-off;

maybe a few times that beam-on.

May turn off this cooling circuit
if leak gets > 100 x bigger

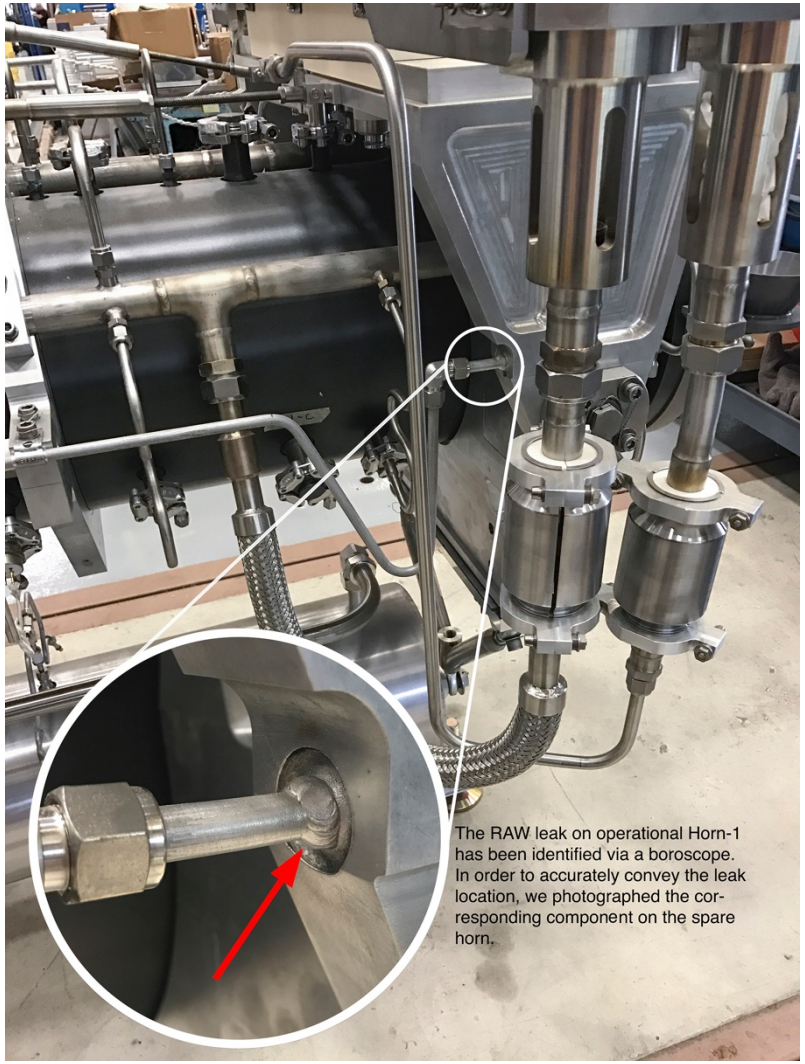
Purpose of this cooling circuit is to maintain good alignment by limiting thermal expansion of hanger



Probably due to porosity in weld

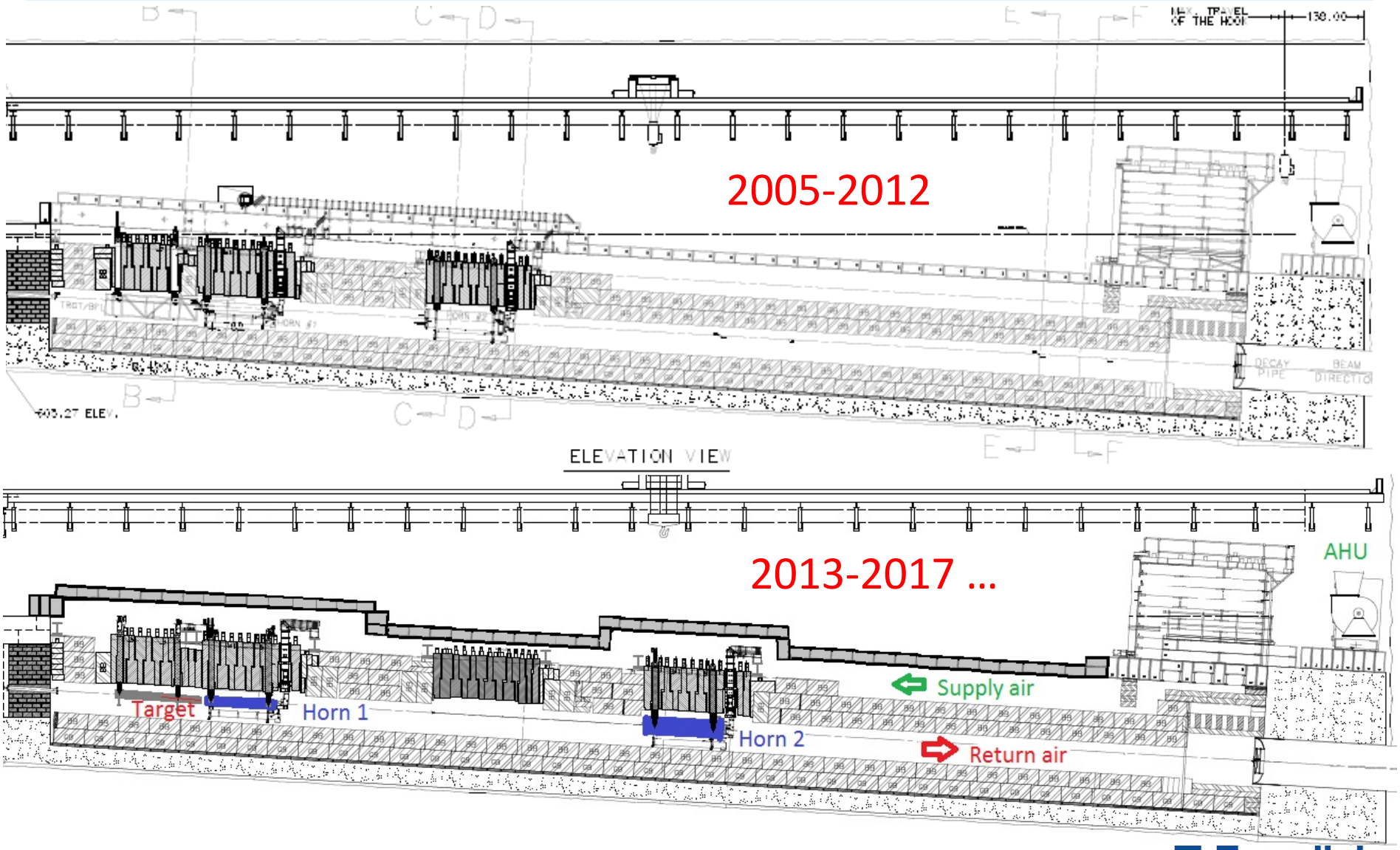
Remote investigation on leaking hanger

Picture of same area on spare horn



Fermilab

For upgrade for NOVA experiment, build new “nest” in the radioactive shield pile, and moved Horn 2



Heat exchanger for target pile recirculating air cooling

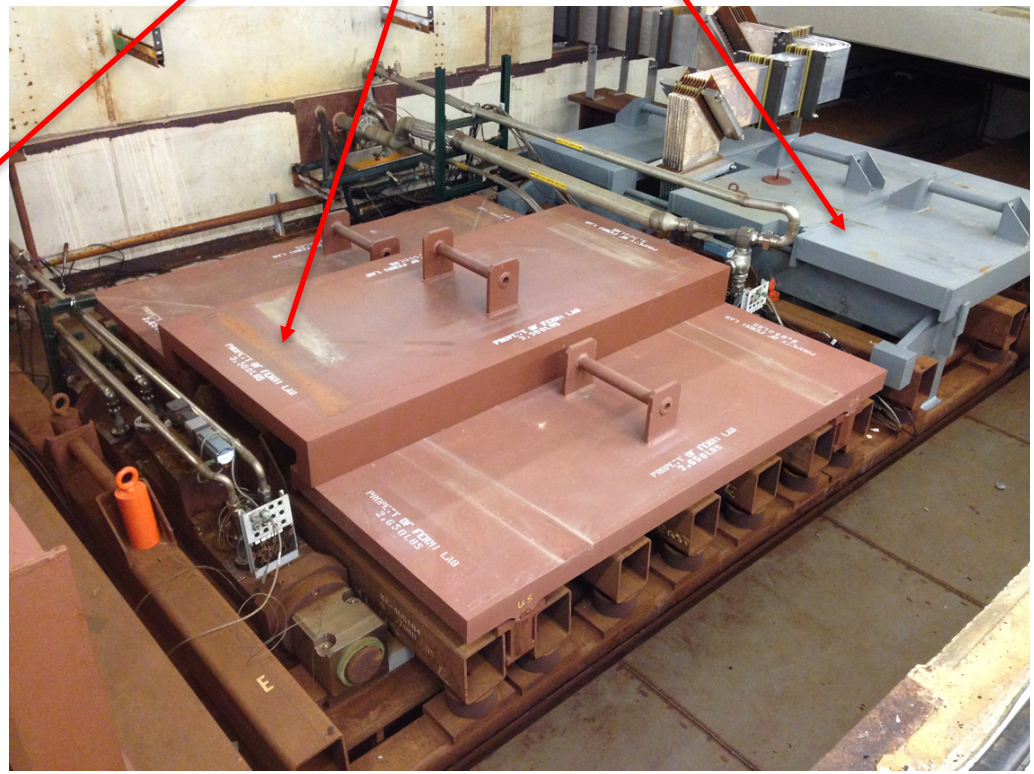
Extra heat exchanger was added for ANU upgrade

Started leaking, finally up to 80 gallon/day. Can run with one coil off.
Valved it out 5/25/2017. Replaced it during summer shutdown.

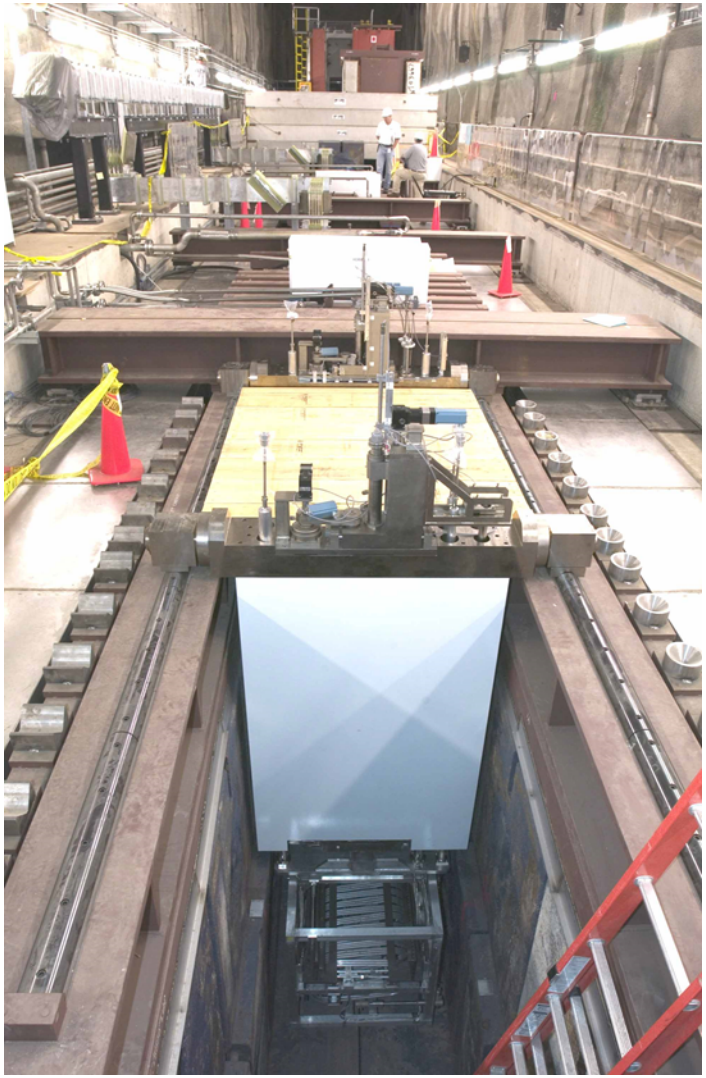
Target pile dehumidification can handle extra ~ 100 gallon/day of water.

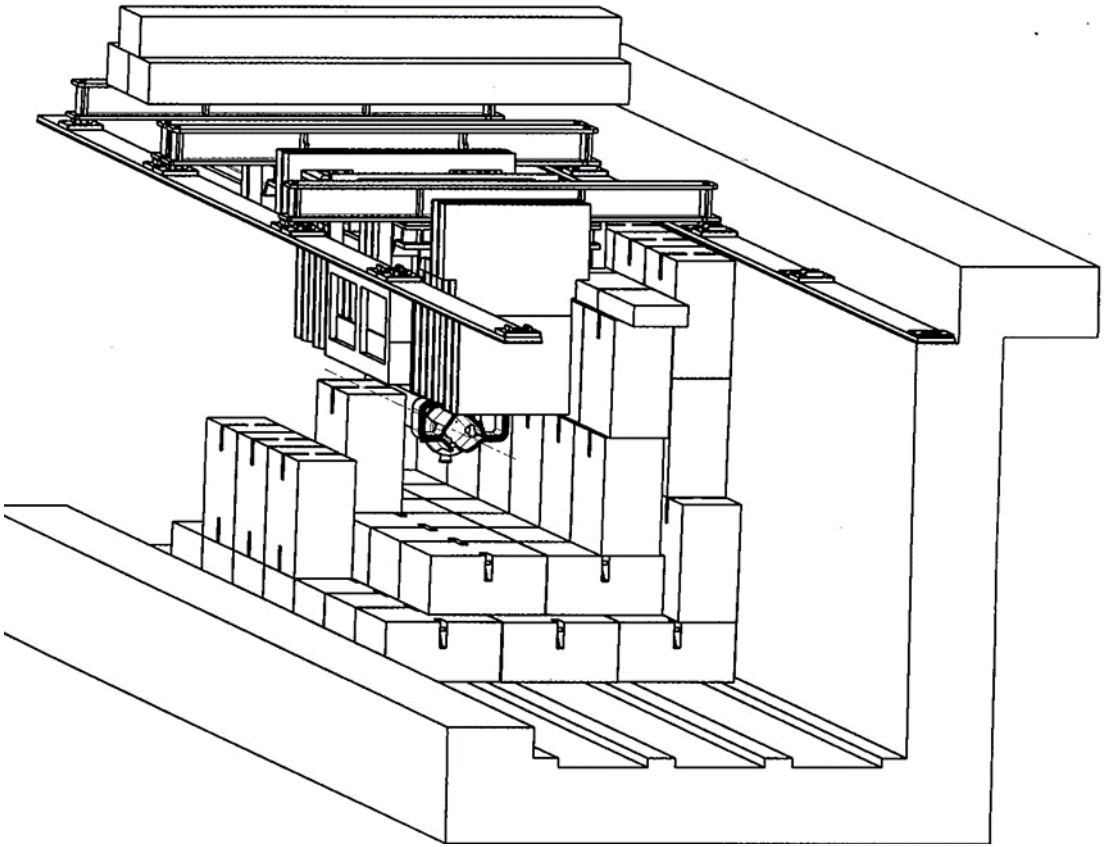
Constructed portable shielding

Lower the dose to workers servicing modules
(higher residual radiation at higher beam power)



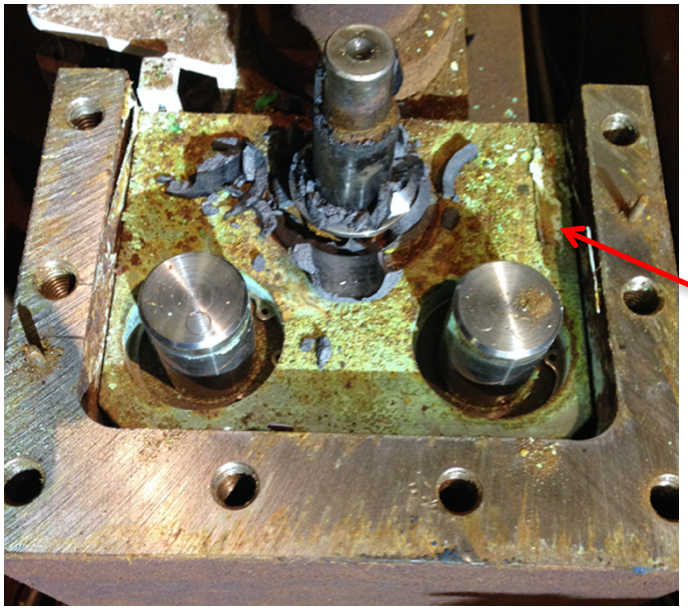
Components hang from Modules
Motors drive shafts through modules to align components



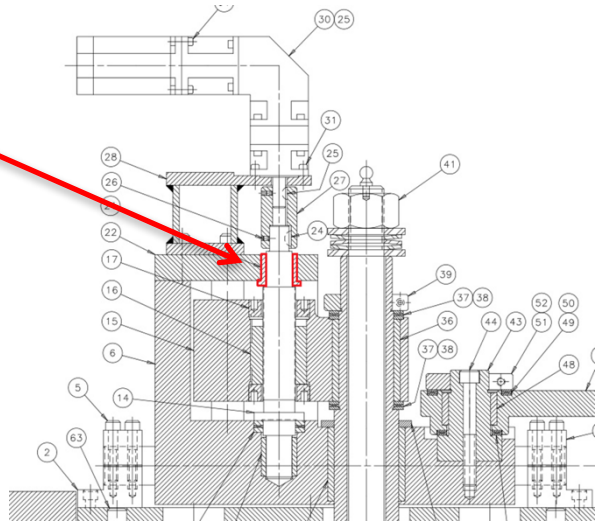


Horn PH1-03 was installed fall 2015

The module allowed US end of horn to sag, neck sank 2.5 mm



Guess Graphalloy was considered OK for this location because weight of horn rests on other end.



Reconstruction of event: Horn alignment/support shaft corroded, stuck.
Drive had to push **DOWN** to move horn to proper location during survey.
This crushed the graphalloy bushing, left horn hanging by friction.
Pulsing the horn vibrated the shaft down until stopped by bushing at other end.

As discussed in monitoring talk, this appears to have taken a few months.
The Graphalloy was replaced with Bronze.

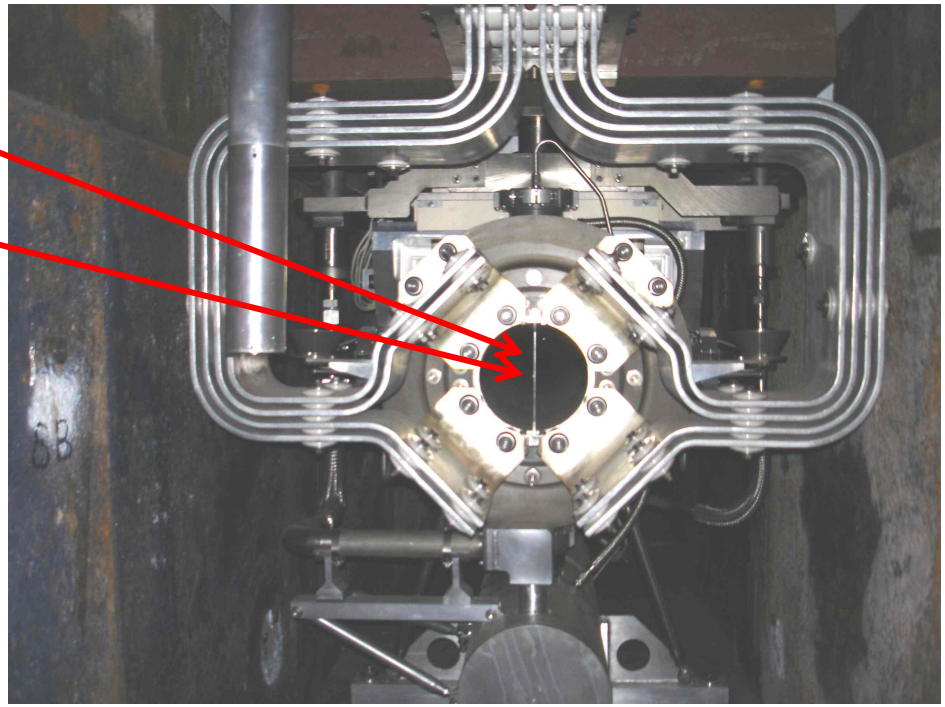
Problem was identified during beam scan of horn cross-hair (with target out of beam) 10/30/2016 … took a week to identify and fix

Fin for beam horz. alignment

Nub for beam vert. align

Beam loss mon. to detect beam scatter from fin (“cross-hair”),

also from beam to horn neck



January 2016

Decay pipe water cooling pump seals start failing quickly

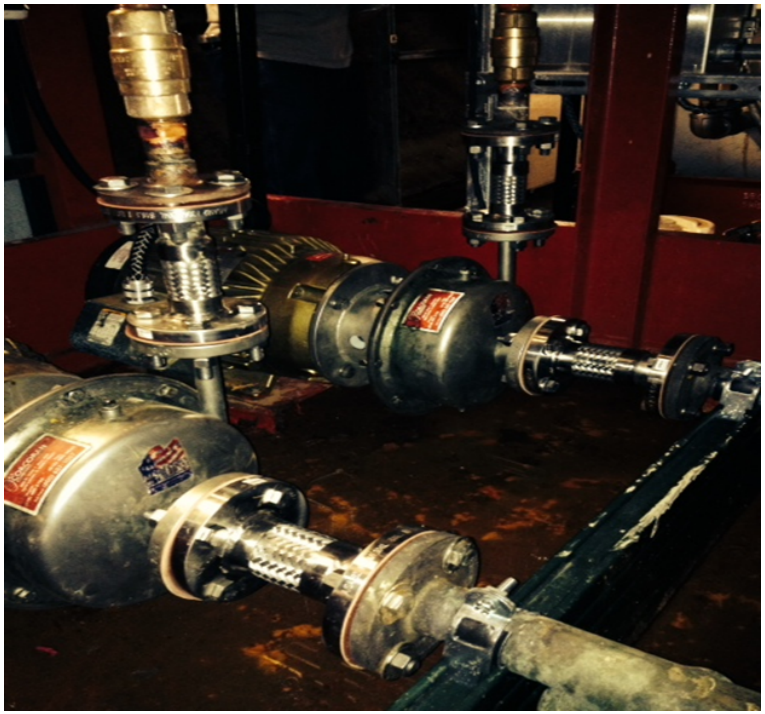
Water turning dark with copper particles.

(Tried different seal types; did not help).

Drained and re-filled 800 gallon system.

Put argon instead of air in the expansion tank head space.

(Complicated history with using and not using D.I. on the system, and grounding & bonding.)



No problems this year

Decay pipe cooling water leak

5 miles of buried copper pipe (ASTM B88 K-type) cooling the 675 m long NuMI decay pipe

12 lines equally spaced azimuthally

This spring, found one weeping, where lines are exposed on way to skid.

Temporary patch, then permanent repair done during summer shutdown

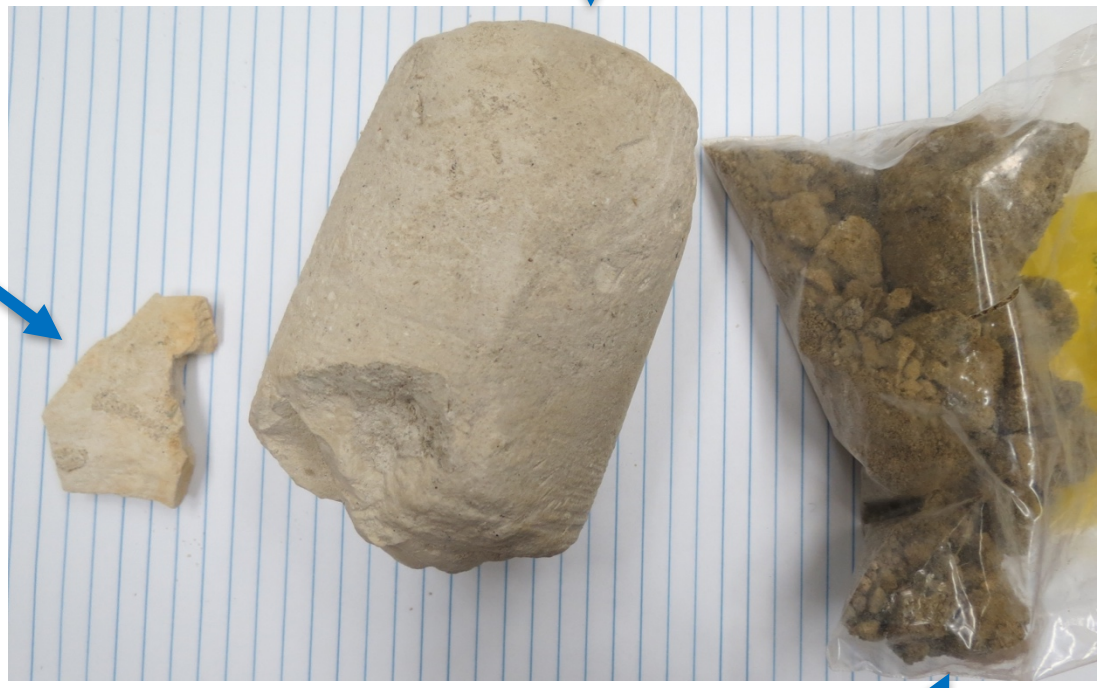
Keeping under-drain open - don't want to flood target pile

Water was backing up;

Cored down to the upstream cross-drain to investigate

Plug of sediment removed from cross-drain by coring machine

Sediment removed from pre-target gutter for comparison



Loose stuff sucked out of cross drain

Pump & Manual injection

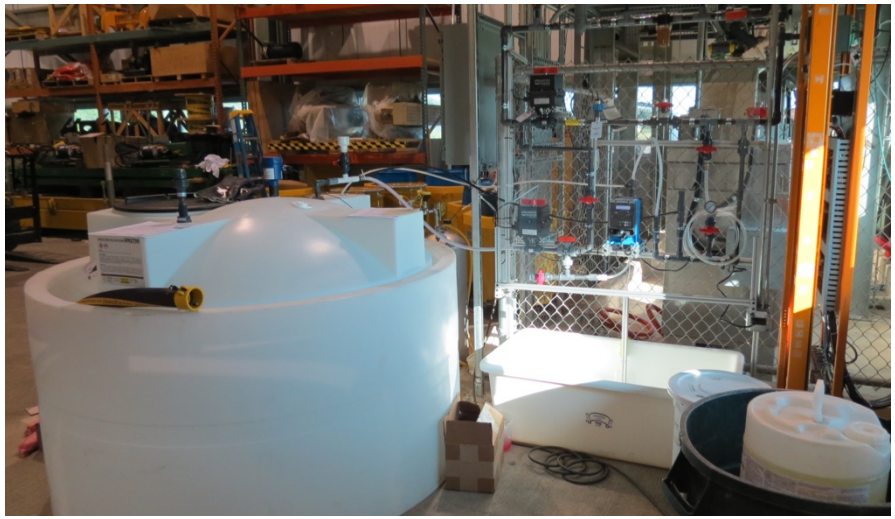
New system to pump out cross-drain

Put 100 gallons of food-grade acetic acid into drain each week

2017 - Automated

Installed acetic acid continuous-injection system to descale NuMI drain under target pile (replacing weekly manual dose)

Operating since mid-January 2017



The use of acid to decalcify the NuMI under-drainage appears to be highly successful, as observed by:

- The cross-drain is no longer backing up, and the local sump pump no longer runs
- Boroscope shows the inches-thick calcification layer in cross-drain is gone
- Boroscope shows that water deliberately injected into cross-drain drains immediately

However - MINOS MUCK

Had been doing occasional injection of chlorine to kill bio-slime
--BUT--- apparently not enough!

Sump Pumps at MINOS N.D. started clogging
- Also FNAL central utility bldg.

The use of acetic acid appears to have encouraged growth of slime bacteria in the MINOS sump. Based on recommendations of consultant, are switching chemicals to

- primarily continuous injection of scale inhibitor (PBTC)
- with occasional injection of de-scaler (Sulfamic acid)
- and occasional injection of biocide (Hydrogen Peroxide)

The future

- NuMI designed for **6 year** run for MINOS experiment at **400 kW** beam power
  - Civil was told to plan for 10 years
- Have now run **13 years**, reaching **700 kW** beam power
  - Warranty has expired
- May have to run **until 2024 (+/-?),** shortly before LBNF turns on
  - Given 10 year design, could well have one major hiccup by then
    Decay pipe water cooling or decay pipe window ? (Fun for next NBI)
- Under discussion: upgrade of NuMI to 1000 kW beam power …

A final conclusion:

NuMI runs well at 700 kW !

PIP-I+

- Proposal: “Campaign” funded via Accelerator Ops (like PIP)
  - Goal: Increase NuMI intensity up to ~1 MW prior to PIP-II
  - Benefit of many improvements will carry over to PIP-II
- Strategy
  - Shorten MI cycle time from 1.333 to 1.2s
    - Cuts rate to Muon Campus ~50% (vs 1.4s cycle), unless increase rep rate to 20 Hz
    - May be able to use this mode between g-2 and Mu2e operation
  - Increase intensity from Proton Source
    - 4.3E12→5.5E12
    - Requires improvements to sustain beam quality while reducing beam loss (%)
  - Increase rep rate from 15 Hz to 20 Hz
    - Requires significant control system changes
    - Requires RF upgrades in Booster and MI/RR
  - All of these require a target station that is robust at 1 MW
- DOE has instructed not invest in existing Linac beyond stocking up on tubes which may become obsolete
  - Limits us to ~900 kW since the Linac can’t run at 20 Hz

Possible PIP-I+ schedule

	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27
MI ps/RF 1.2s cycle										
NuMI target station 1 MW										
Proton Source ppp										
20 Hz										
Infrastructure										
PIP except Booster cavities										
PIP Booster cavities (20 Hz)			Push off this task from current PIP schedule to allow NuMI target work							
Power (kW)	700	700	800	900	900	900	900	PIP-II	PIP-II	PIP-II

1.2s cycle in between g-2 and Mu2e

Gains from ppp

20 Hz capable on timescale of LBNF / PIP-II

Fermilab