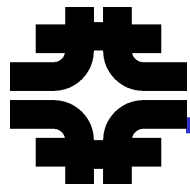


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# NuMI Target Hall Performance/Plans

P. Hurh/J. Hylan  
HPT Workshop 2007  
9/10/07

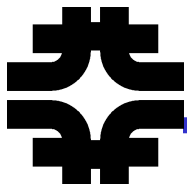
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## Outline

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- Overview of target hall and target/horn experiences.
- Summary of problems causing 1 day or more downtime, and corrective actions underway
- Spares status
- Plans for Target Hall Upgrades for future high power beam.
- Lots of back-up slides, if interest.

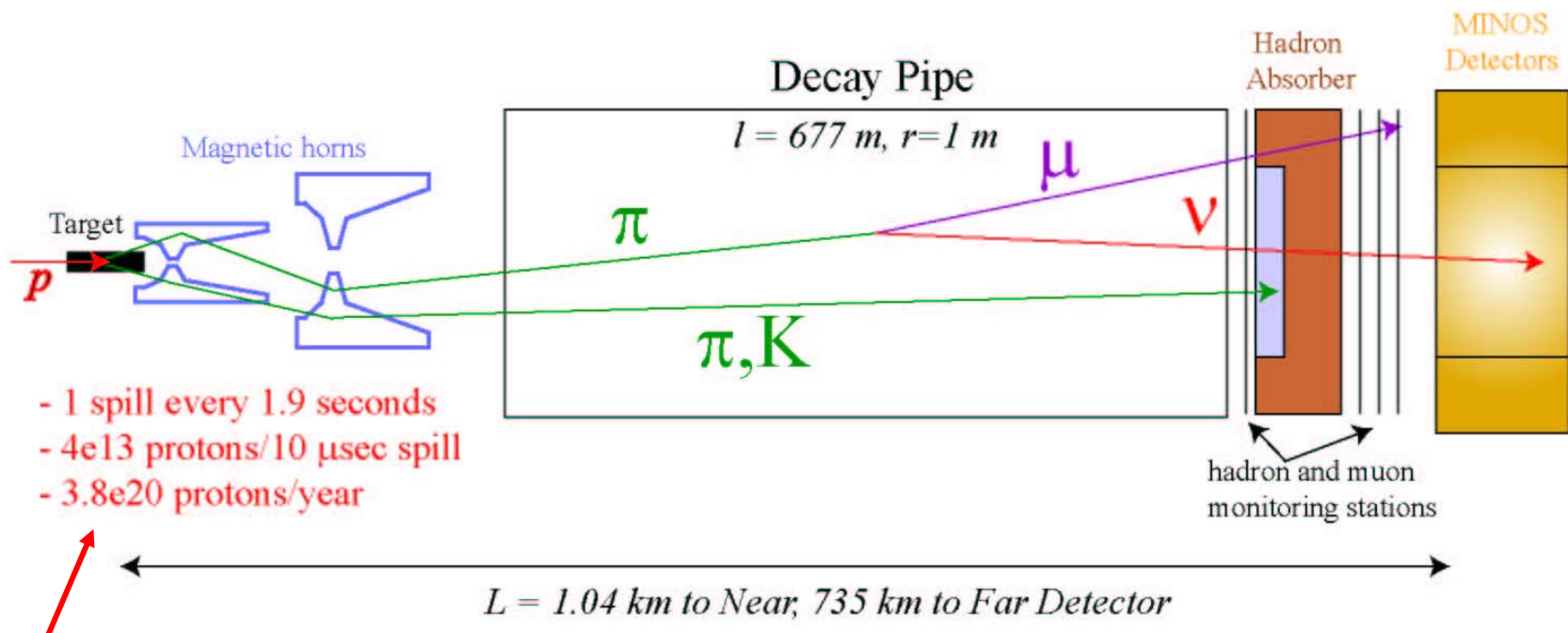


# How NuMI $\nu$ beam is produced

120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos

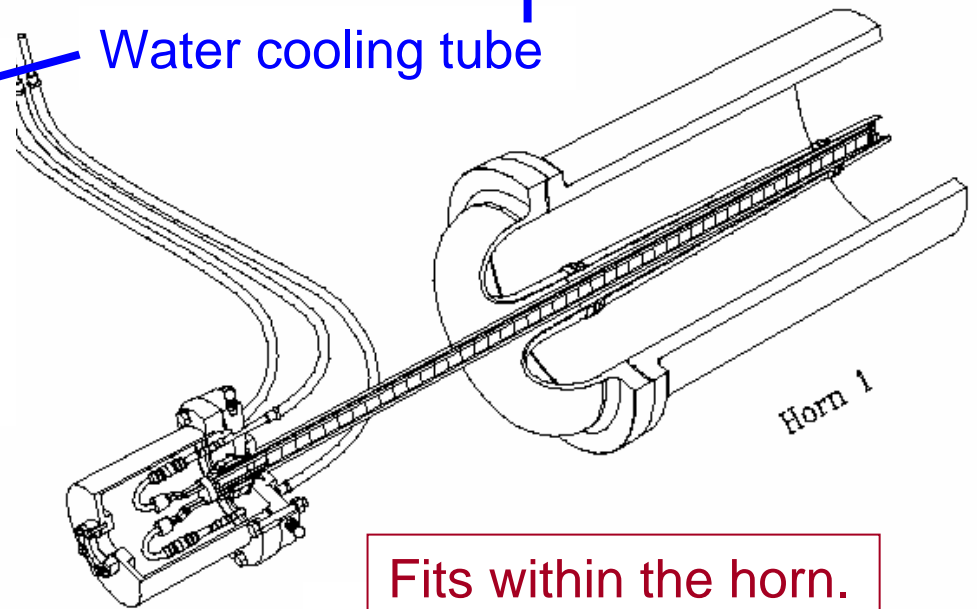
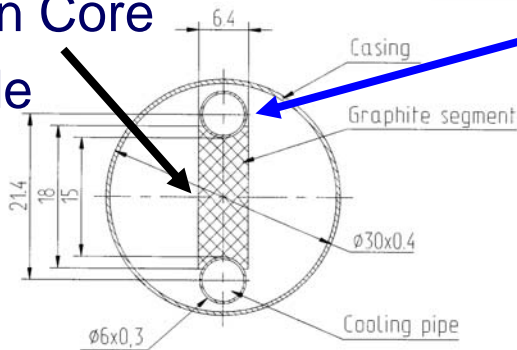


Design for 0.4 MW proton beam

# Target for Low Energy Neutrino Spectrum

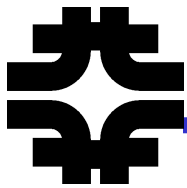


Graphite Fin Core  
6.4 mm wide



Backing target out of horn  
produces neutrinos at  
higher energies

Fits within the horn.



## Experience with the NuMI Target

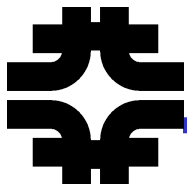
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1<sup>st</sup> Target took beam for over a year, 820 MWhr integrated beam power. Two problems:

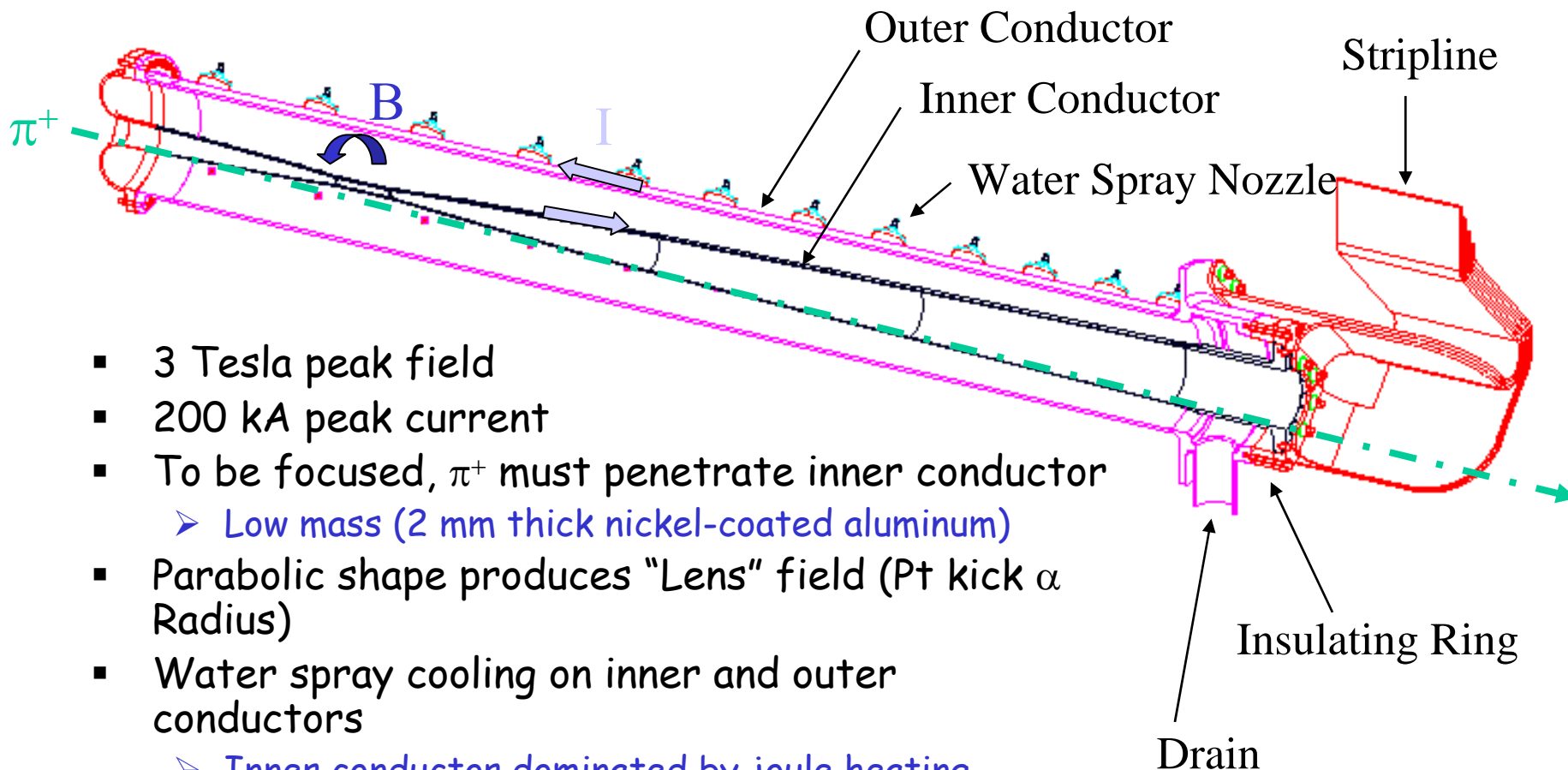
- water leak soon after turn-on; back-pressure with Helium to keep water out
- target motion drive shaft froze up after year of operation – stuck in H.E. focus

2<sup>nd</sup> Target is running (no leak)

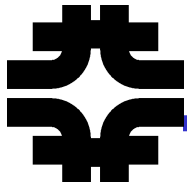
	Max. Proton/spill	Max. Beam Power	Integrated Protons on Target
Target Design specification	40e12 p.p.p.	400 kW	370 e18 p.o.t. lifetime
1 <sup>st</sup> target Before leak	25e12 p.p.p. <i>11-12 day before leak</i>	69 kW	0.7 e18 p.o.t.
1 <sup>st</sup> target After leak	30e12 p.p.p.	270 kW	158 e18 p.o.t.
2nd target	40e12 p.p.p.	320 kW	201 e18 p.o.t.



## Magnetic Horns $\pi$ focused by toroidal field between conductors



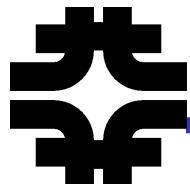
- 3 Tesla peak field
- 200 kA peak current
- To be focused,  $\pi^+$  must penetrate inner conductor
  - Low mass (2 mm thick nickel-coated aluminum)
- Parabolic shape produces "Lens" field (Pt kick  $\propto$  Radius)
- Water spray cooling on inner and outer conductors
  - Inner conductor dominated by joule heating
  - Outer conductor dominated by beam heating
- 3 m long focusing region
  - Achieved  $\sim 0.1$  mm radial tolerance after weld



Parabolic inner conductors:  
3 Tesla max. magnetic field  
3 m active length each horn

Inner conductors welded  
together at FNAL by  
lead engineer Kris Anderson





## NuMI Horns Experience

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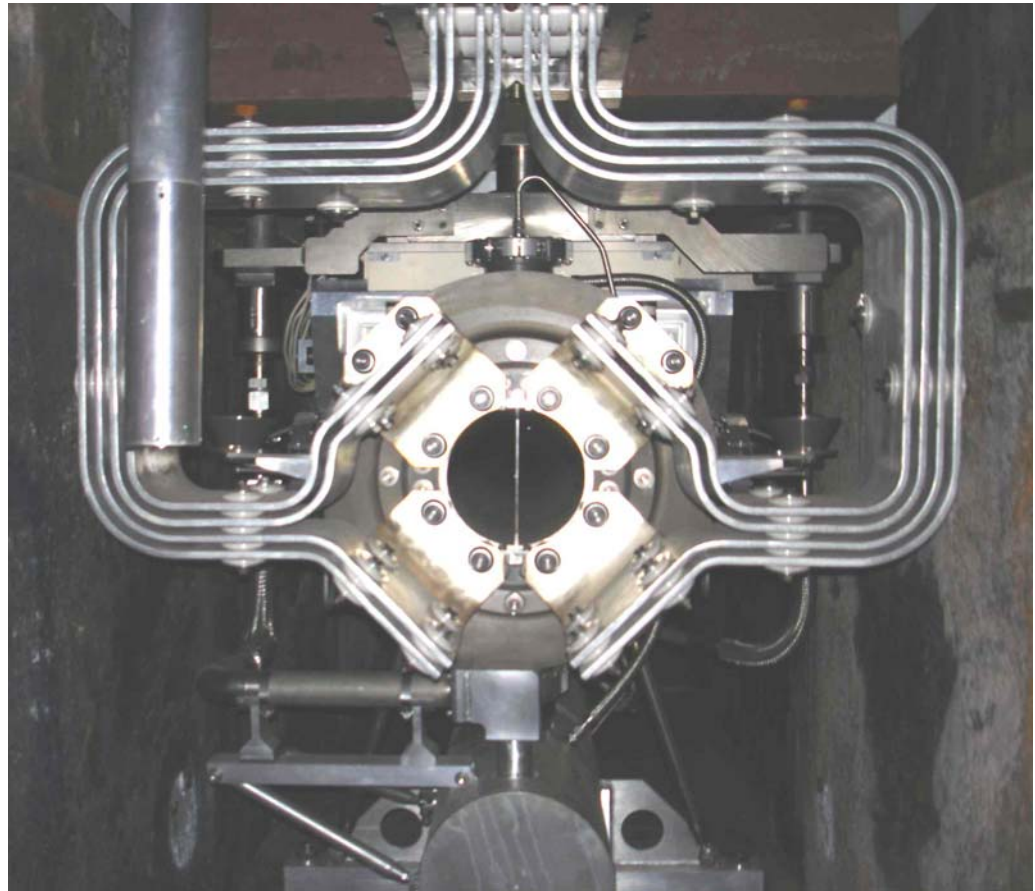
Horns in target hall  
June 2004

1<sup>st</sup> run with beam  
Jan. 2005

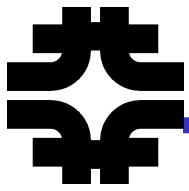
Accumulated:

15 Million pulses

1,350 MWhr  
integrated beam power



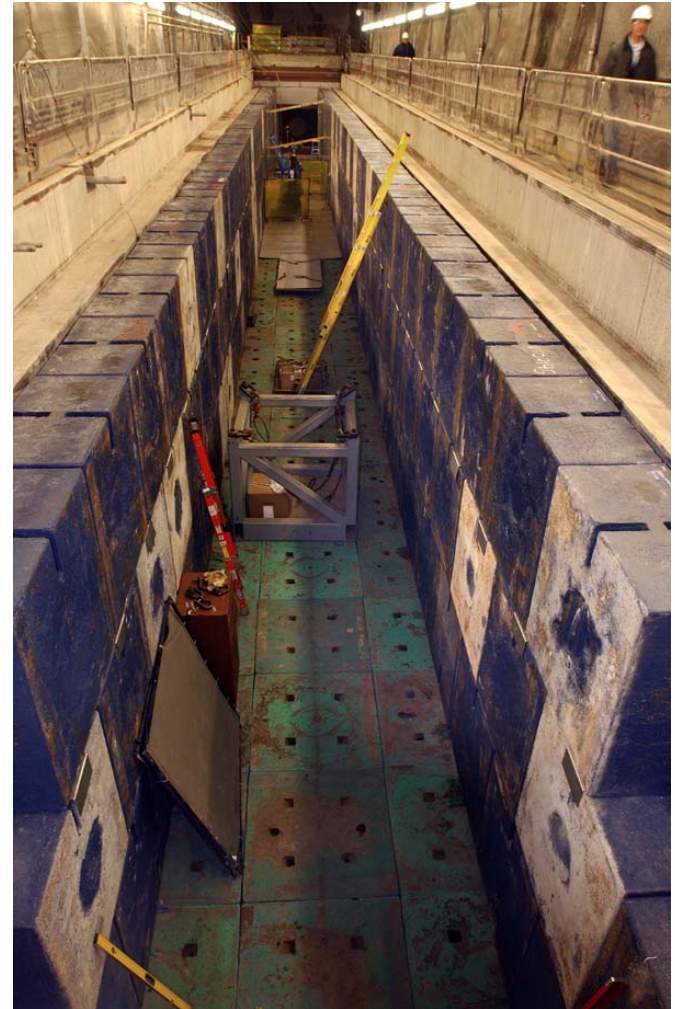
Still running with first set of horns

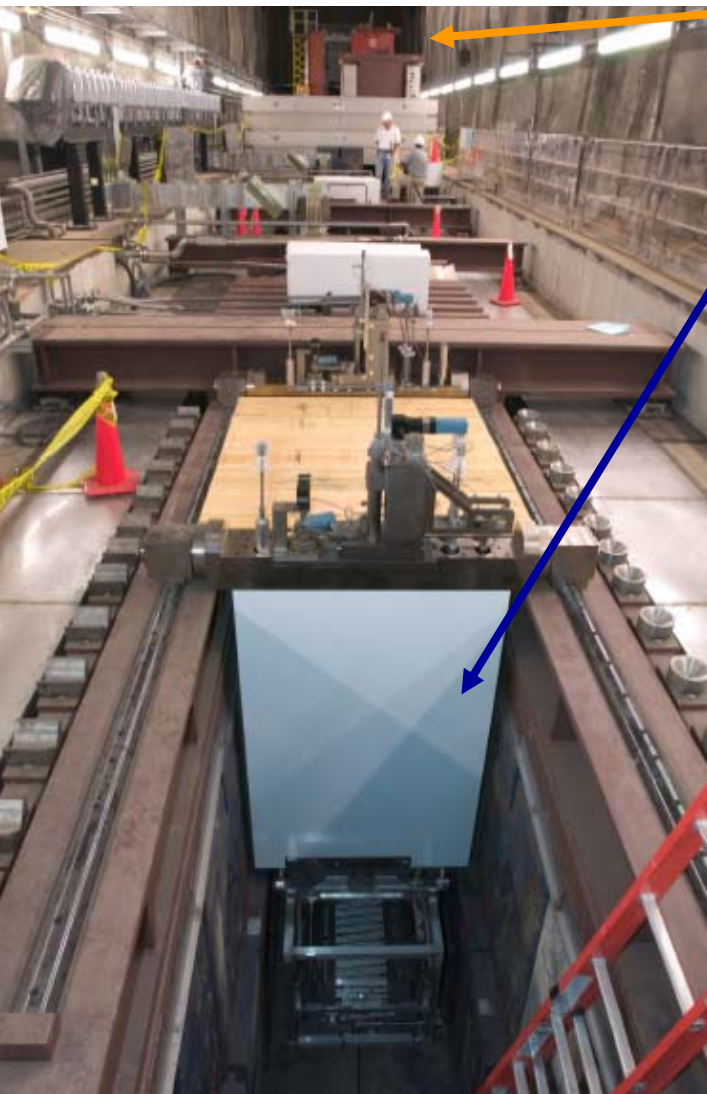
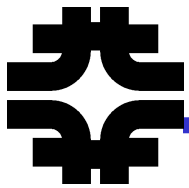


# Target Hall during construction



1/2 of the  
8000 tons  
of shielding  
is installed



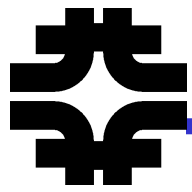


Work cell

Target module in beam-line

1st target being removed





## NuMI work cell for radio-activated components

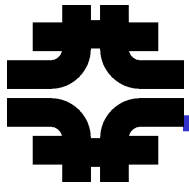


Shown during test-assembly  
above ground

Lead-glass windows (not  
shown)

Remote controlled door

Remotely installable  
top shielding



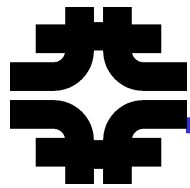
All NuMI target hall beam components and innermost shield layers are installed /removed remotely with crane and cameras



Crane includes remote hook rotation.



Steel shielding block being moved.



# Big Picture of Maintenance

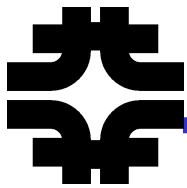
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- NuMI target hall is a difficult system
  - High radiation forces remote handling
    - repairs take a long time
  - Target hall is nasty environment
    - E.g. humidity has PH of 2.6, very corrosive
    - Limited list of materials are rad-hard enough
  - Interventions are time-consuming
    - Access to components requires 1 shift just to put electronics back on target hall crane
    - Must un-stack, then re-seal shielding each access
    - Components are an order of magnitude larger than Pbar's

*Achieving high up-time requires design of robust components*

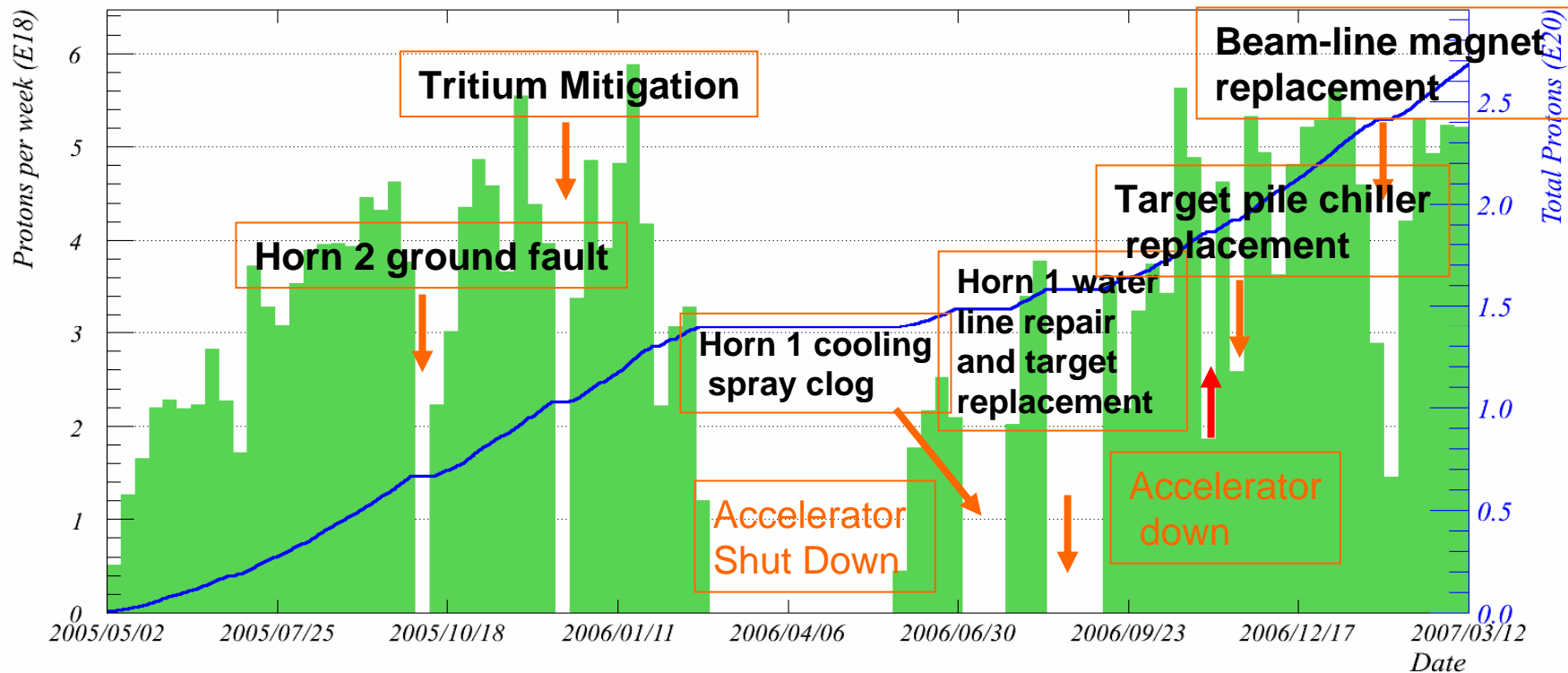
- Biggest current concern:
  - Producing an adequate supply of spare horns
    - Usually replacement takes less time than repair

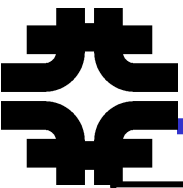
***If you have no spare  
- you must repair !***



# NuMI Performance - POT/week

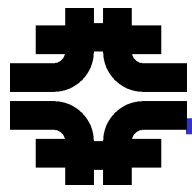
Total NuMI protons to 00:00 Monday 12 March 2007





Up (513) and down (83) days 5/1/05 - 3/22/07  
 86% / 74% efficiency excluding / including sched. shutdown

Days	Description (**non-recurring)	Long term corrective action
513	Up for beam	
95	Accelerator scheduled down	
25	Horn cooling spray clog **	Check valves, filters on skids
14	Horn water line repair	Eliminate braze on spares
14	Target motion frozen	Graphalloy bushing on spare
10	Horn ground fault	Pin feet, float modules
8	Tritium mitigation **	Condensate sys./dehumidifiers
6	Replace NuMI beam-line magnet	
4	Replace accelerator magnet	
2	Replace pile chiller compressor	New hot spare chiller unit



## Two horn water system leaks: Horn 2 in February 2006, Horn 1 in August 2006

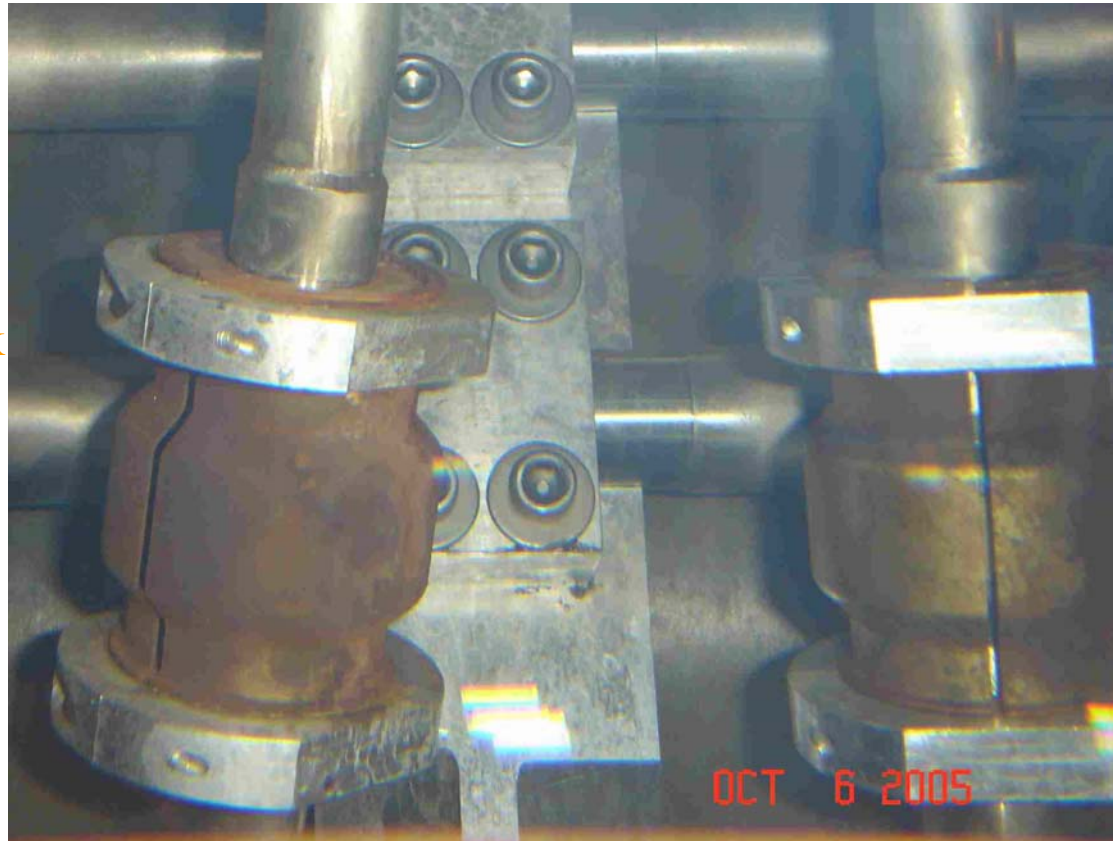
Have brazed ceramic electrical insulators on horn water lines  
They are strain-relieved with invar+ceramic clam-shells

On horn 1, developed a 7gal/day  
water leak on line to spray header

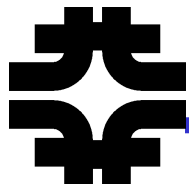
On horn 2, leak on suction line  
drew air in, reducing amount  
of water ejector pump could  
remove from horn collection tank

Both ceramic sections were  
successfully replaced

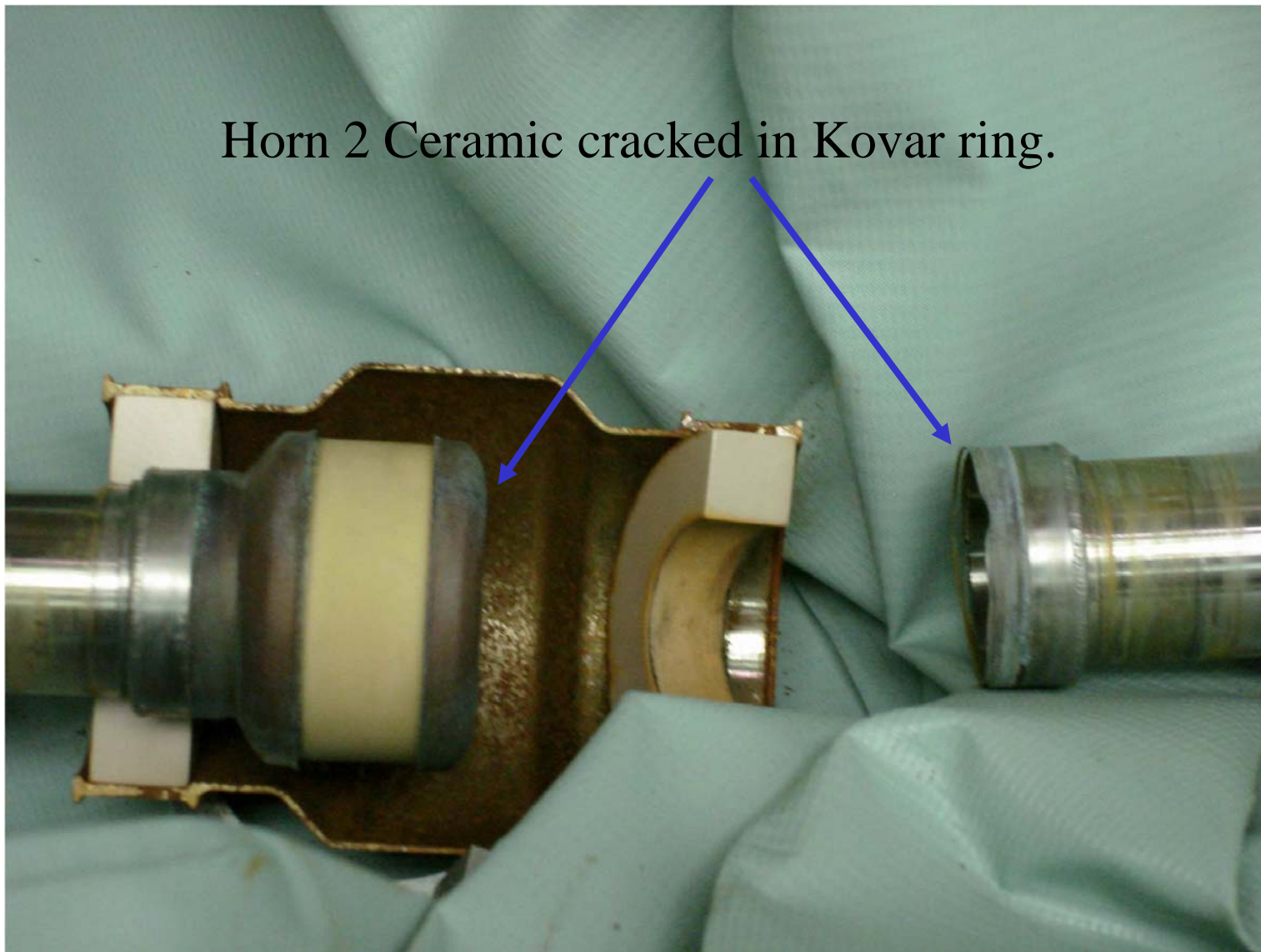
Speculate braze corrodes...  
planning to switch from brazed  
to a shrink-fit ceramic/steel  
connection for spare horns

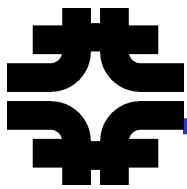


Two horn water system leaks:  
Horn 2 in February 2006, Horn 1 in August 2006



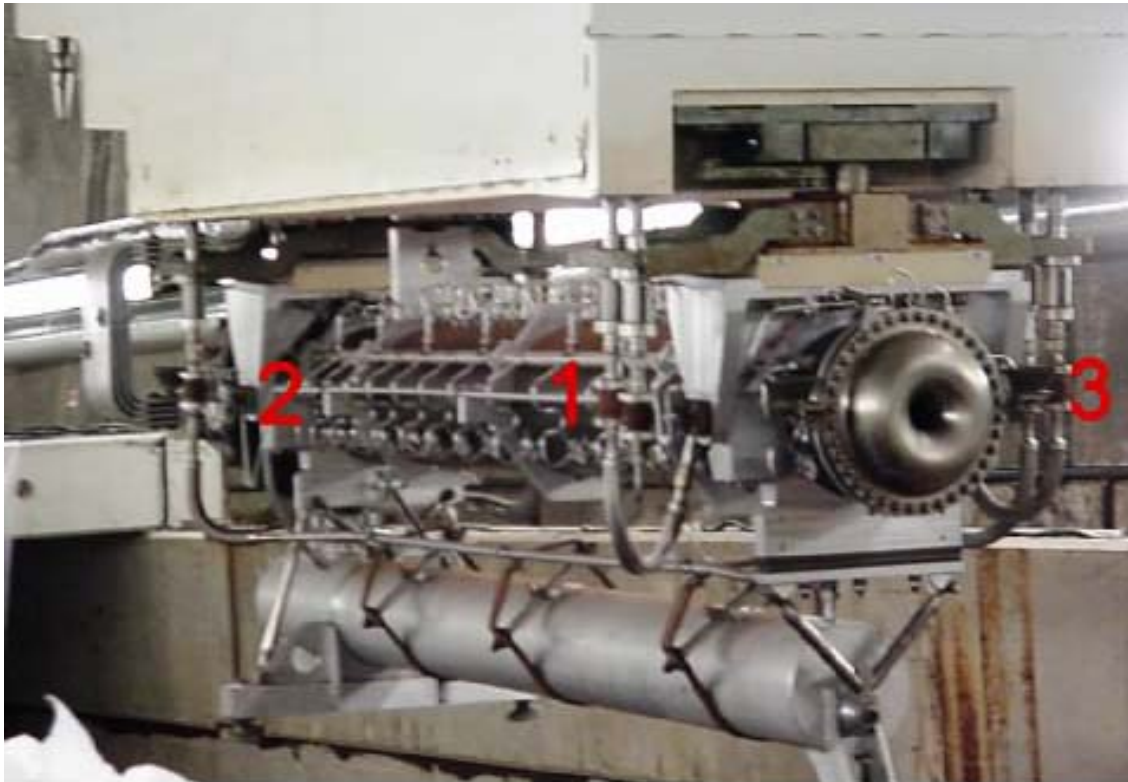
Horn 2 Ceramic cracked in Kovar ring.





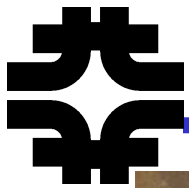
## High dose rates made Horn 1 ceramic replacement challenging

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

Repair people got weekly dose limit in a few seconds

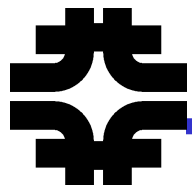


## Shielding for Horn 1 ceramic repair job



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

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



## Mock-up and practice for repair



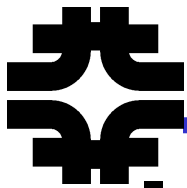
Plan, time, and practice,  
practice, practice repair

Needed to undo two  
Swagelok fittings,  
remove old section,  
insert new section,  
and tighten two fittings.

Time est: 2 min. of  
actual work in slot

Dose for this "2 min." job  
was 371 mr, (3.7 mSv)  
divided over ~10 people.

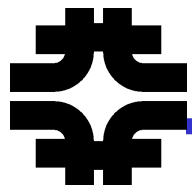
The rest of job is in much  
lower radiation field,  
but dose can be non-negligible  
due to time involved.



## Additional Operational Concerns

---

- Currently investigating 2 more Horn RAW leaks.
- Radiation accelerated corrosion issues.
  - Ionization of air creates nitric acid environment. For Mini-BooNE 25 m absorber this caused 2 failures of HS steel chains under load.
  - Concerns over similar corrosion of NuMI Decay Pipe US window (Al, 1/16" thick) have motivated use of He gas in decay pipe rather than evacuated.
  - Zirconia ceramic discoloration under beam conditions.
  - All HS Steel Belleville spring washers on lower portion of Horn modules cracked and failed (Inconel 718 washers look ok).
  - Anodized Al looks very good. Nickel plating does not (flakes and peels).

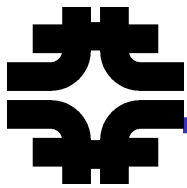


## Additional Operational Concerns

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- HS broken steel chain from hydrogen embrittlement caused by acidic vapors/condensate from air ionization (MiniBooNE 25 m absorber).

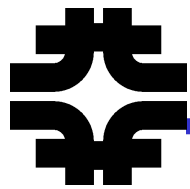


# Spares Status - Horns and target

HORNS	PH1-00	PH1-01	PH1-02	PH1-03	PH1-04	PH1-05	PH2-01	PH2-02	PH2-03	PH2-04
in use	proto	in use					in use			
fiducialize (survey)										
instrumentation										
water tank, hangers										
test pulse			2/3							
stripline								silvered		
water lines etc										
I.C.+O.C assem										
O.C. silvered										
O.C. coated										
O.C. welds										
O.C. machined										
O.C. blanks										
I.C. silvered										
I.C. coated										
I.C. welds			7/7	3/7	3/7	3/7		6/6	5/6	
I.C. machined										5/7
I.C. blanks										
					700kW	700kW				700kW
TARGETS	NT-01	NT-02	NT-03	NT-04						
in use	stuck	in use								
fiducialize (survey)	in									
instrumentation	H.E.									
hangers	posn.									
mount target + baffle										
fab carrier										
fiducialize target										
fab target + baffle				ordered						

Color code

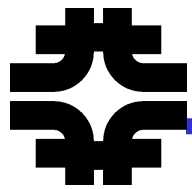
	Used
	Done
	In progress
	to do



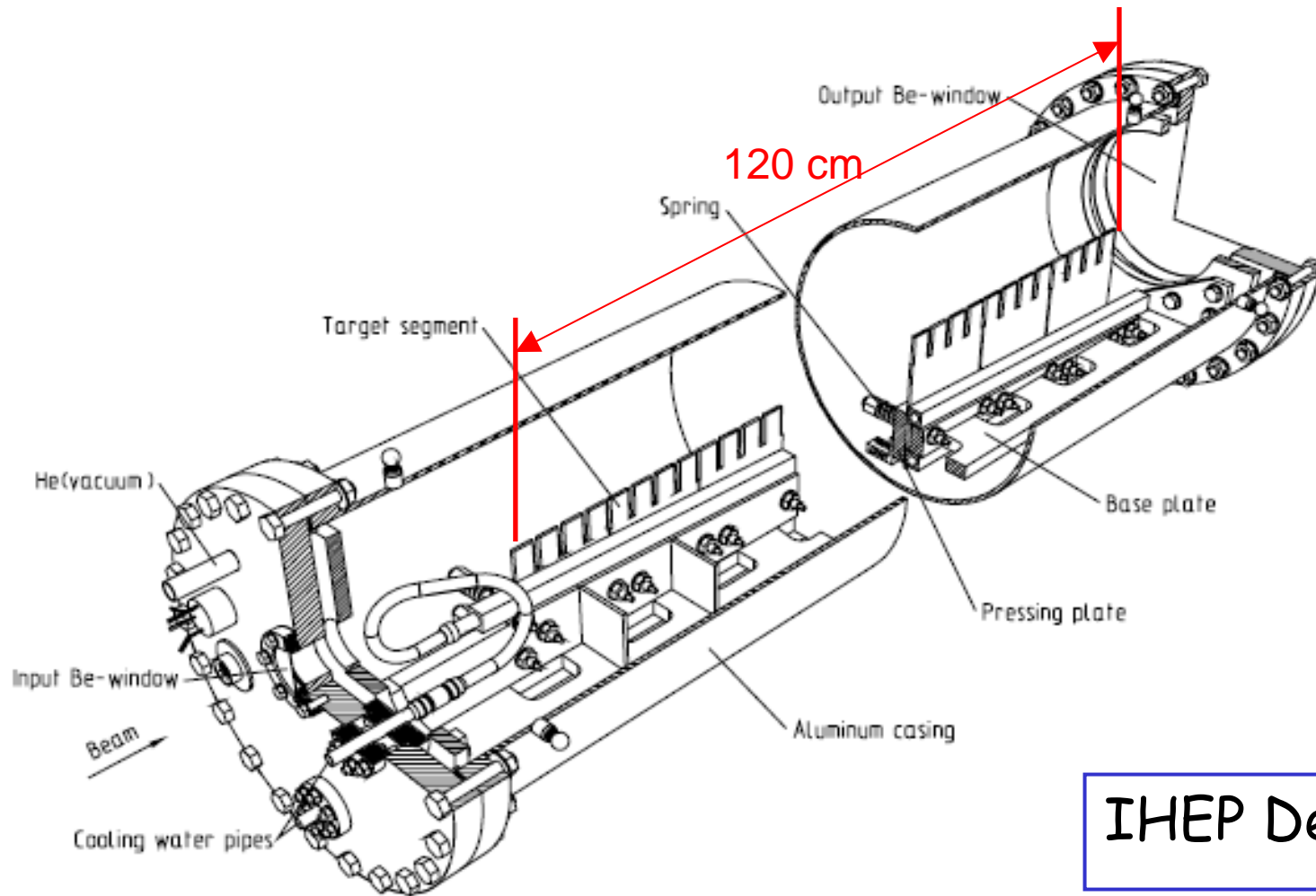
# Plans for future upgrades

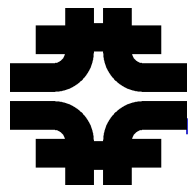
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- 700 kW beam power (NOvA in 2011) -
  - New Medium Energy Target
  - Minor upgrades to Horn/Stripline Cooling
  - Changes in shielding configuration (Horn 2 move)
  - Radioactive Component Removal/Repair Plans
- 1.2 MW beam power (NOvA in 2014?) -
  - Re-design cooling for ME Target
  - Cooling inserts into Target Chase
  - Major upgrades to Horn and Stripling Cooling
  - Radioactive Component Removal/Repair Plans
- 2.3 MW beam power (Project X in ??)



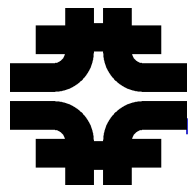
# Medium Energy Target for NOVA running





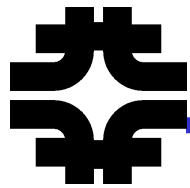
## 2.3 MW limiting issues (Project X Report)

<b>Issue possibly limiting NuMI beam power</b>	<b>Conclusion / Comment</b>
Ground water activation	Calculations indicate groundwater activation limits will not be exceeded by the projected number of protons per year <sup>i</sup>
Radioactive Air Emissions	Calculations indicate that radioactive air emissions would be just below regulatory limits. <sup>i</sup> Alterations such as slowing down the ventilation fans would provide a safety factor.
Decay Pipe Window	(i) Calculations indicate that an accident pulse which missed the target and reached the window would be problematic. This can be mitigated by having the baffle upstream of the target completely occlude the area where beam would miss the target. (ii) Although direct radiation damage to the window is not expected to be problematic, accelerated corrosion due to the high radiation environment is a concern. This concern could be ameliorated by filling the decay pipe with 1 atmosphere of helium, thus reducing the stress on the window.



## 2.3 MW limiting issues (Project X Report)

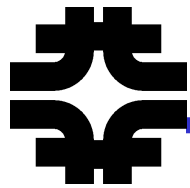
Decay Pipe	Stress due to thermal expansion may limit operation to 2.0 MW beam power.
Hadron Absorber	(i) Calculations indicate the absorber can handle normal operating conditions with 2.3 MW beam. <b>Error! Bookmark not defined.</b> (ii) An accident condition where beam mis-steered off the target would hit the absorber can be prevented by changing the upstream target / baffle geometry. (iii) An accident condition where cooling water flow fails requires further study, and may necessitate mitigation. The pipes carrying water to the aluminum core of the absorber pass through holes in the downstream steel slabs of the absorber. With 2.3 MW beam power, the innermost steel slab will reach 800 C. The concern is that without water flowing, the heat from the steel slab may damage the water pipe.
Residual Dose in work area above chase and in Absorber cave	Dose rate can be mitigated with additional shielding. <b>Error! Bookmark not defined.</b>
General degradation of components and infrastructure (accelerated corrosion and radiation damage).	Direct radiation damage will not be limiting (although extra shielding for electronics in the target hall is needed). Accelerated corrosion is hard to quantify, and further study/experience is needed.



## 2.3 MW Upgrades (Project X Report)

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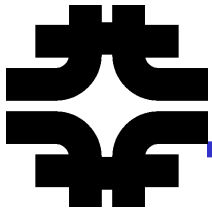
<b>NuMI components to be upgraded</b>	<b>Comment</b>
Target	Preliminary design is described in <i>NuMI Note 1100</i> , IHEP Protvino, July 30, 2005
Horns	The outer conductor of each horn will require increased water cooling.
Hadron Monitor	Existing monitor would saturate; need smaller ionization gap
Beam profile monitor ?	Could certainly use the existing monitors if we drive them out of the beam for high intensity running, so did not examine this issue further
Cooling of beam pipe window	Forced air on face or water at edge
Target pile cooling	Have explored the concept of water-cooled panels lining inner walls of steel shielding
Decay pipe cooling	Increase water flow rate
Absorber cooling	Handle case of water steaming at steel penetrations if pumps fail



## 2.3 MW Upgrades (Project X Report)

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RAW skids	Increase heat exchanger capacities
Cooling pond	May exceed capacity of existing cooling ponds, or want to evaporate tritium for ALARA (further study needed)
Equipment to handle and transport radioactivated horns and target	May want to dig a new side-tunnel for storage of broken horns. Will need increased shielding when working on horns and target.
Refurbishment or replacement of crane rails, target hall drip ceiling, etc.	Depends on corrosion rate and deterioration seen.
Horn and target support modules	Depending on corrosion seen, may build replacement modules.
Equipment for further air containment	Allow more time for decay of short-lived radionuclides in the air
Further shielding for electronics located inside the target hall	Increase thickness of exiting poly shielding

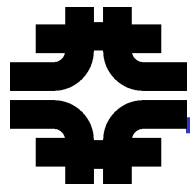


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# Design for a 2 MW graphite target for a neutrino beam

Jim Hylan  
Fermilab AAC meeting  
August 9, 2007

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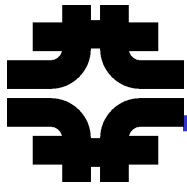
## Introduction

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- Two years ago, a preliminary design study was done for a target for proton driver beam parameters. No further work has been done since then. All numbers, graphs shown are for proton driver parameters, about 10% different.

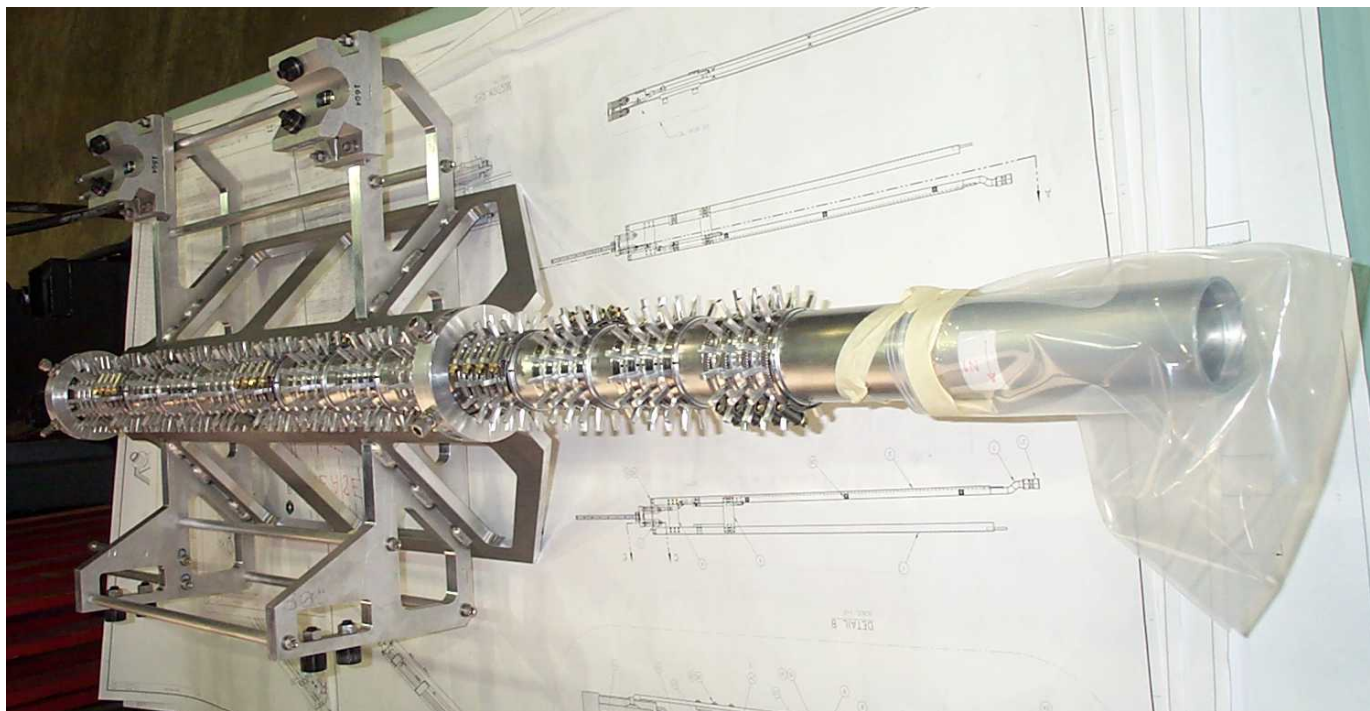
	Proton Driver (this talk)	Project X
Protons / spill	1.5e14	1.7e14
Repetition rate	1.33 seconds	1.40 seconds

- This design is by Valeri Garkusha et. al, IHEP Protvino (NuMI note 1100)



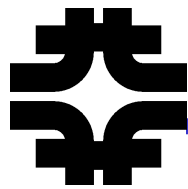
## NuMI baffle as prototype of target

Graphite is good in compression, poor in tension,  
so put pre-stress at outer radius by encapsulating in aluminum or steel



Existing NuMI baffle is 1.5 m long, 6 cm diameter graphite encapsulated in aluminum

Target would be 1 m long, 1.5 cm diameter – very similar,  
get rid of air cooling fins, add water cooling tubes



## Other target details

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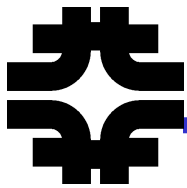
- Graphite in 3 cm long segments with 0.2mm gaps for thermal expansion
- Helium atmosphere in target to prevent possibility of oxidation
- Encapsulation also maintains integrity of the target core in case of thermo-mechanical or radiation damage of some segments
- Encapsulation also prevents direct contact of the cooling water with the heated surface of graphite while providing a good thermal contact
- Study was done with Poco ZXF-5Q graphite (what we have in the NuMI target), although other graphites have up to 30% better Yield/Youngs-Modulus

Pre-stress: ~ 10 MPa if 0.2 mm steel casing, ~13 MPa if 1mm aluminum casing

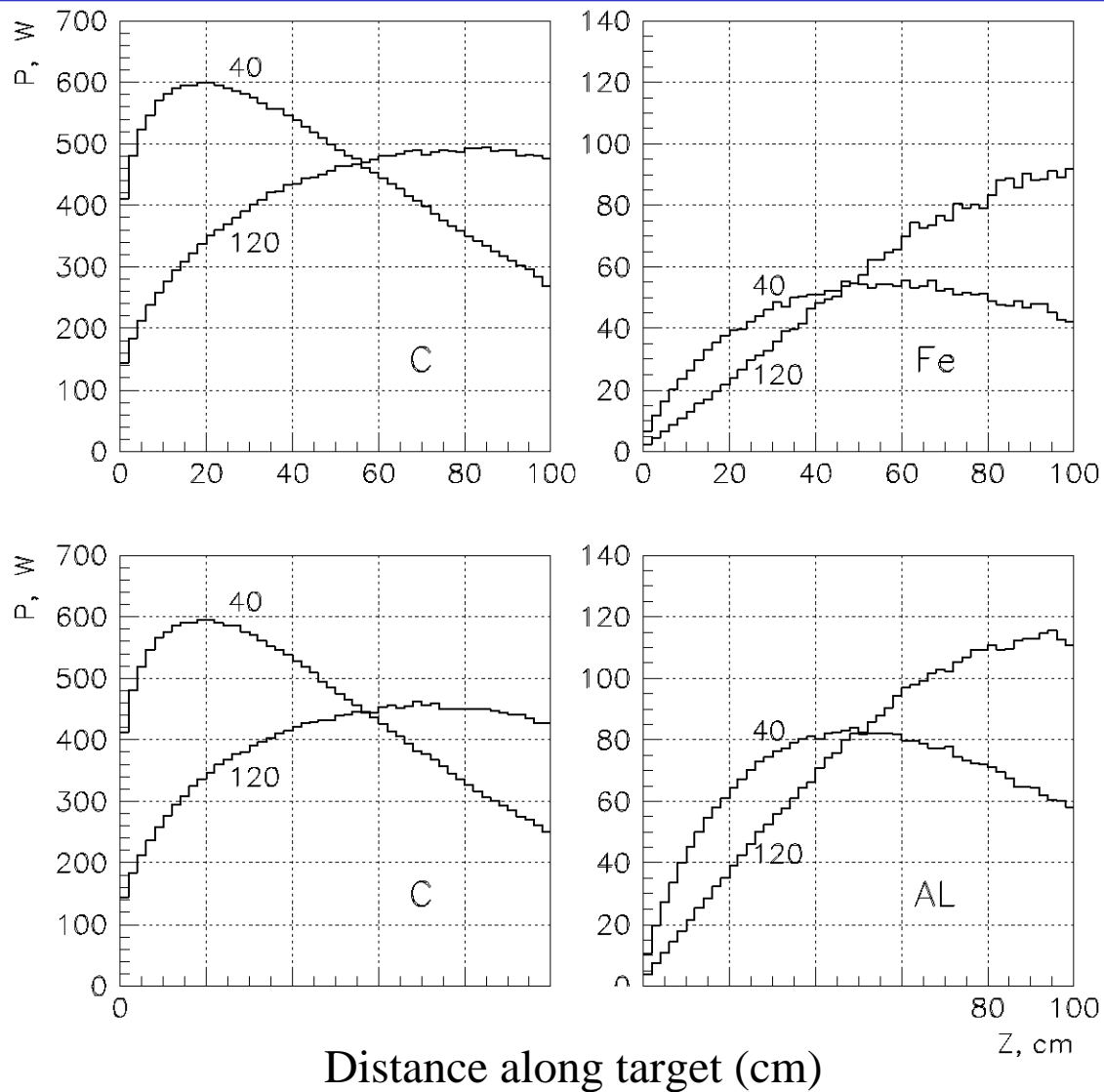
Beam spot size: 1.5 mm RMS

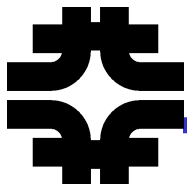
Energy deposition (kW):

Proton beam energy	40 GeV		120 GeV	
Graphite core	23.3	22.7	20.8	19.7
Steel pipe	2.2	—	2.7	—
Aluminum pipe	—	3.4	—	3.7
The whole target	25.5	26.1	23.5	23.4



# Energy deposition (MARS Monte Carlo)

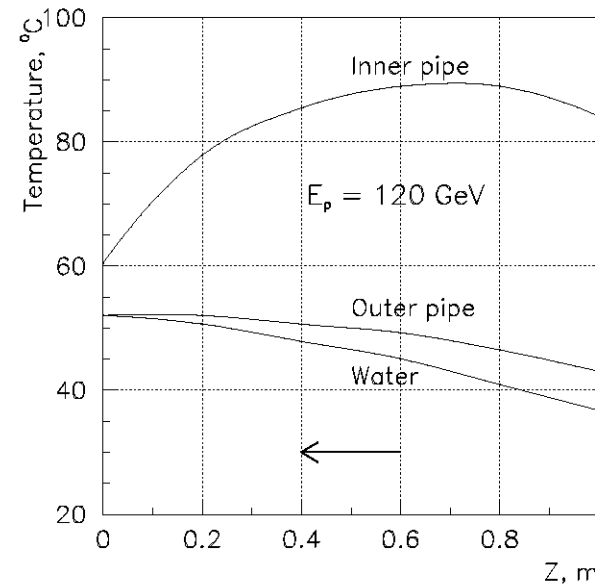
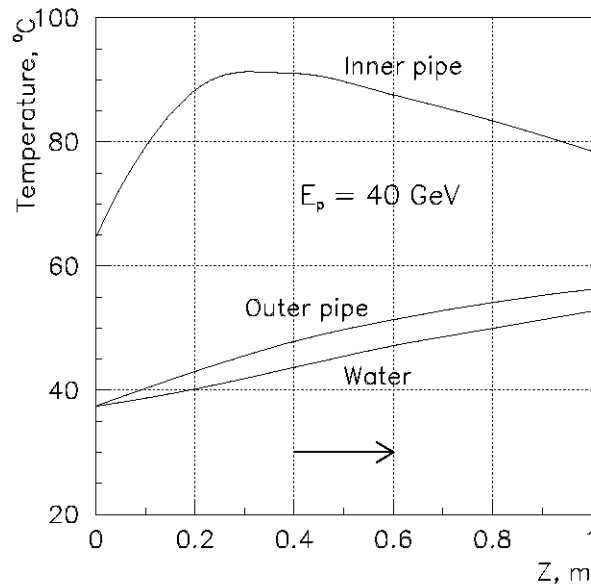


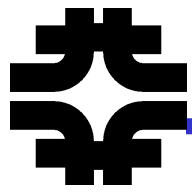


# Target temperature and cooling water

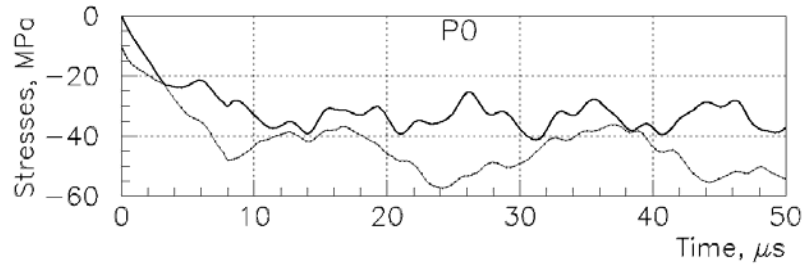
Table 3: Temperatures in target segments with the highest EDD.

Primary proton beam energy, GeV	40	120
Segment number	2	6
EDD at the beam axis, GeV/cm <sup>3</sup> /proton	0.025	0.033
Temperature of a water (see Figure 2), °C	37	50
Temperature at the beam axis, °C		
before the beam spill	120	80
after the beam spill	380	430
Temperature rise at the beam axis, °C	260	350

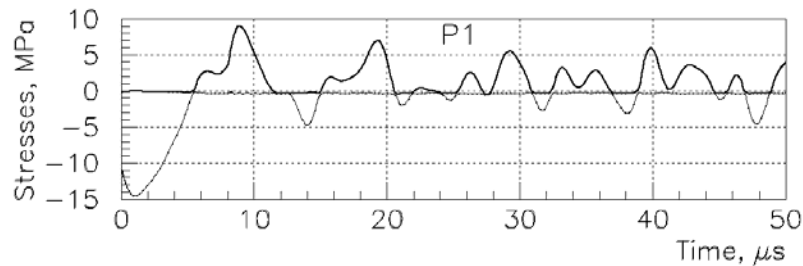




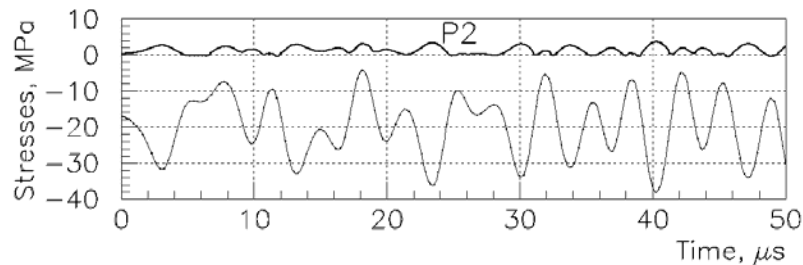
## Time evolution of stresses (sigma1 and sigma3 shown)



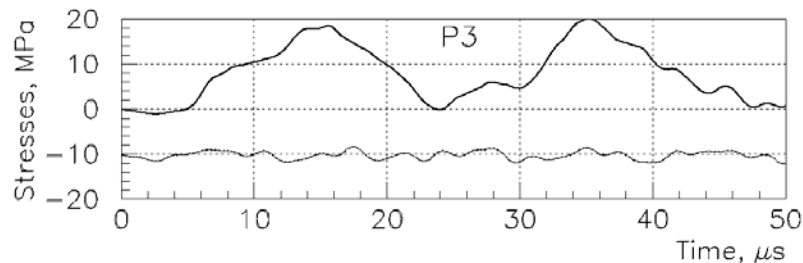
Midpoint of segment



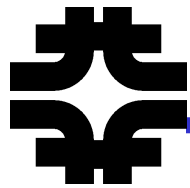
Center of end of segment



Outer radius end of segment



Outer radius center of segment



## Compare stress to failure

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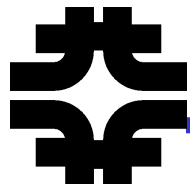
Taking into account decrease of yield strength of 0.5 due to fatigue and applying Mohr-Coulomb criteria, the safety factors (failure stress divided by calculated stress) are:

Table 4: Safety factors for different points of target segments with the highest EDD.

Beam energy, GeV	40	120
$P0(0, 0)$	2.3	1.9
$P1(0, l/2)$	7.5	5.5
$P2(r_0, l/2)$	2.7	2.3
$P3(r_0, 0)$	2.8	2.0

Hence calculation says graphite should not fail.

However, even if a segment fails, there is really no place for it to fall apart into?



# Target cooling design

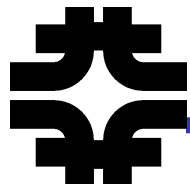
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Water in the cooling tube would experience 2ksi hydraulic shock from heating by the beam spill. Two ways have been suggested to reduce this:

- Two phase flow – e.g. bubble helium through the water similar to what we did when the 1<sup>st</sup> NuMI target developed a leak
- Use “heat pipe” evaporative cooling

Work is needed to prototype and evaluate these and possibly other schemes

Further work is also needed on window design, although calculations for use of graphite windows is encouraging.



# Radiation damage

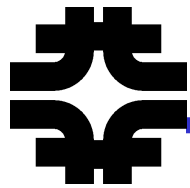
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Although radiation damage data is not available for ZXFF-5Q, neutron damage data for AXFQ and AXZQ indicate that for one year operation

- dimensional changes are not very large
- two times decrease of the thermal expansion coefficient will compensate approximately the same increase of the modulus of elasticity keeping by this means stresses constant
- the strength of graphite increases with irradiation over this period

(for a 40 GeV proton beam, radiation damage is about 3 times as fast)

So currently estimate radiation damage lifetime as 1 year.



# Efficiency of neutrino generation

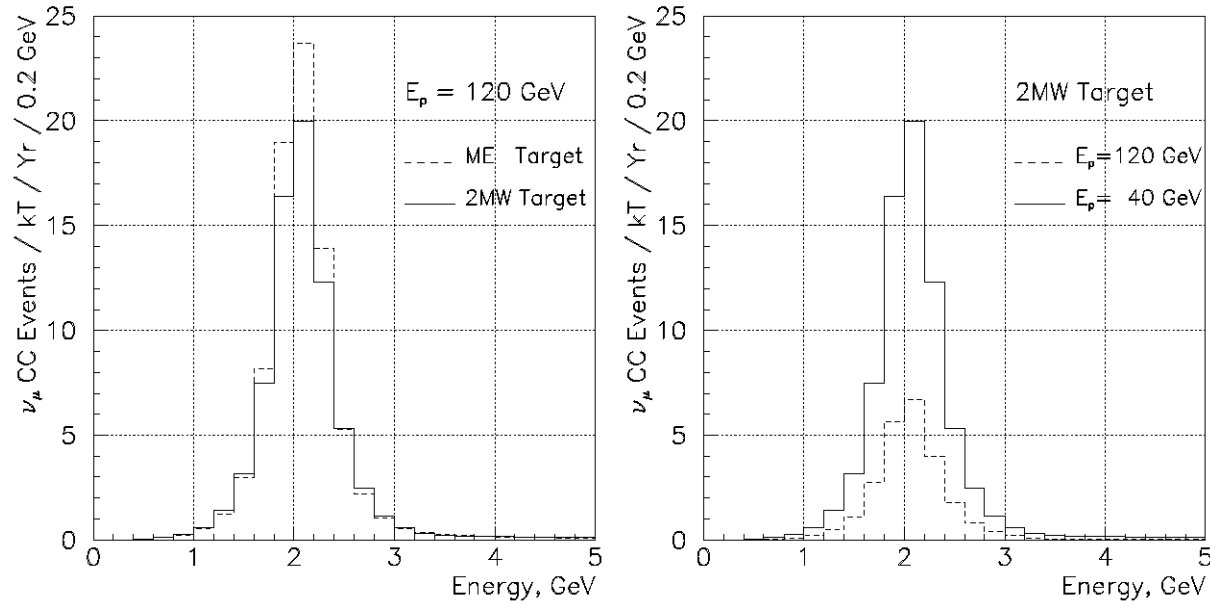
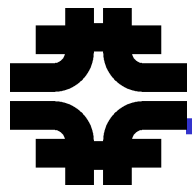
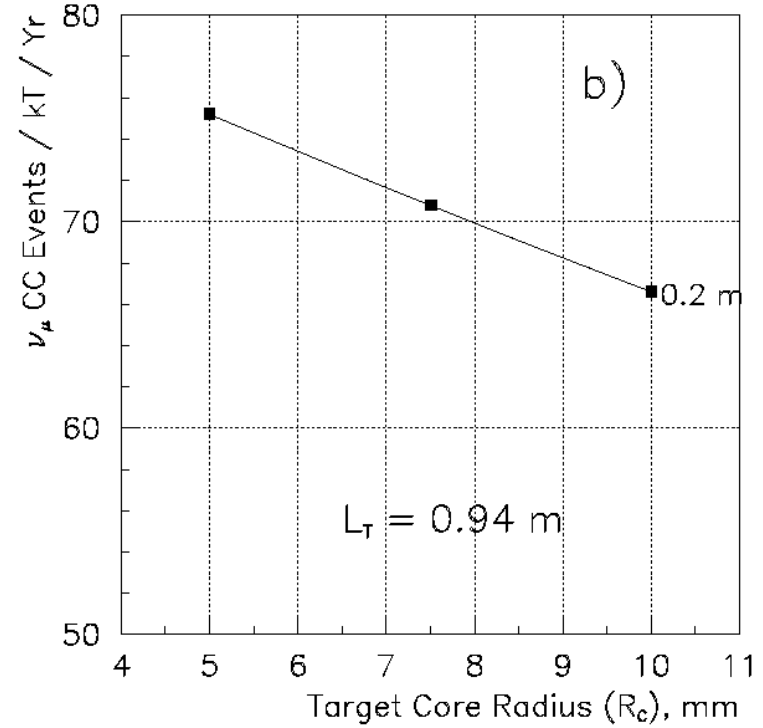
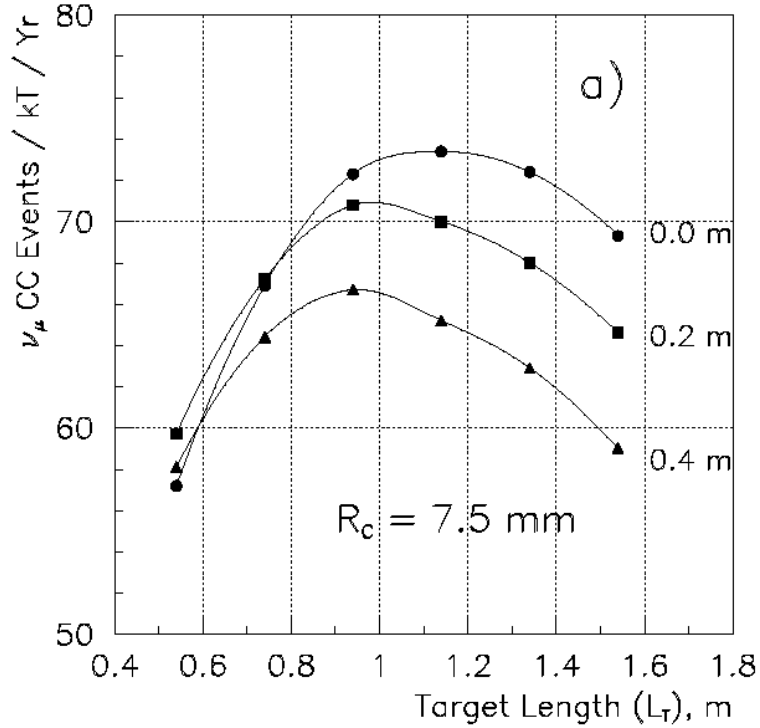


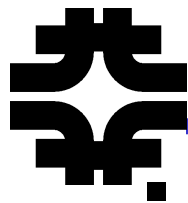
Figure 9: Neutrino event rates at the far detector for the 14 mrad off-axis NuMI beam (1 year =  $3.8 \times 10^{20}$  protons on the target).

The “2MW” target is about 10% less efficient at neutrino generation than a 0.4 MW “Medium Energy” target (ME target is more optimized to NoVA than the existing LE target)



# Neutrinos vs. length and radius of target





## Future AP-0 Target Test Facility

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- A future, limited, Target Test Facility is still possible at FNAL using the AP-0 (p-bar source) Target Hall after Collider Run II (2010).
- Possible beam parameter ranges: 8-120 GeV, 0-4e13 ppp (1.7e14, Project X), up to 700 kW (ANU) or 2.3 MW (Project X), sigma down to 0.12 mm.
- Parasitic running with Minerva, Minos, & NOvA required. This may practically limit testing to pulse testing rather than irradiation studies.
- Need proposals for specific experiments (talk to P. Hurh or A. Leveling).
- Act soon; Current plan is to De-commission!