NUMI Targets:
MINOS experience and NOVA/LBNE designs

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FNAL

"Past performance is not necessarily indicative of *future* results…"

"Your mileage may vary…"

After 5 years of decent performance with MINOS LE targets,
the last ½ year has been a real headache.

We need to run this style of target for 1 more year.

NUMI MINOS target

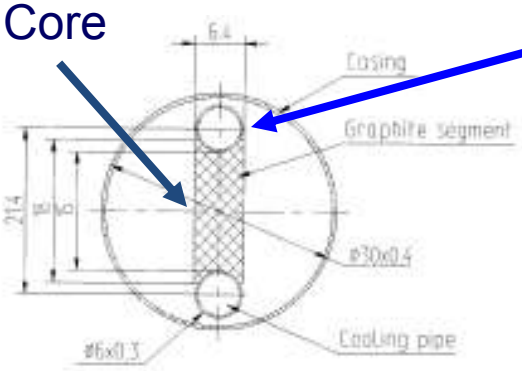
Designed with and constructed by IHEP Protvino Beams Group

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

Graphite Fin Core

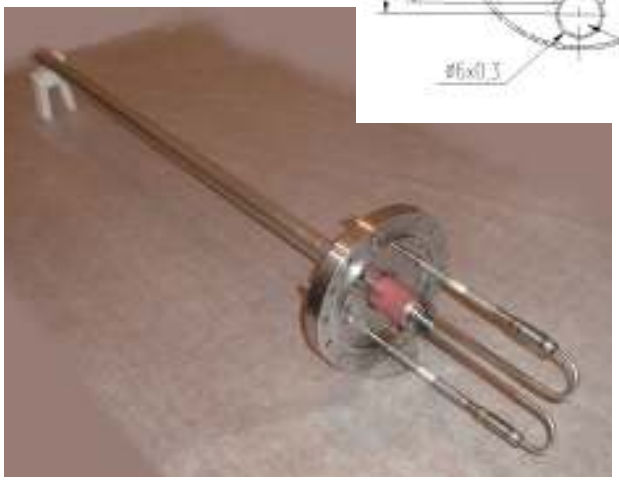
6.4 mm wide

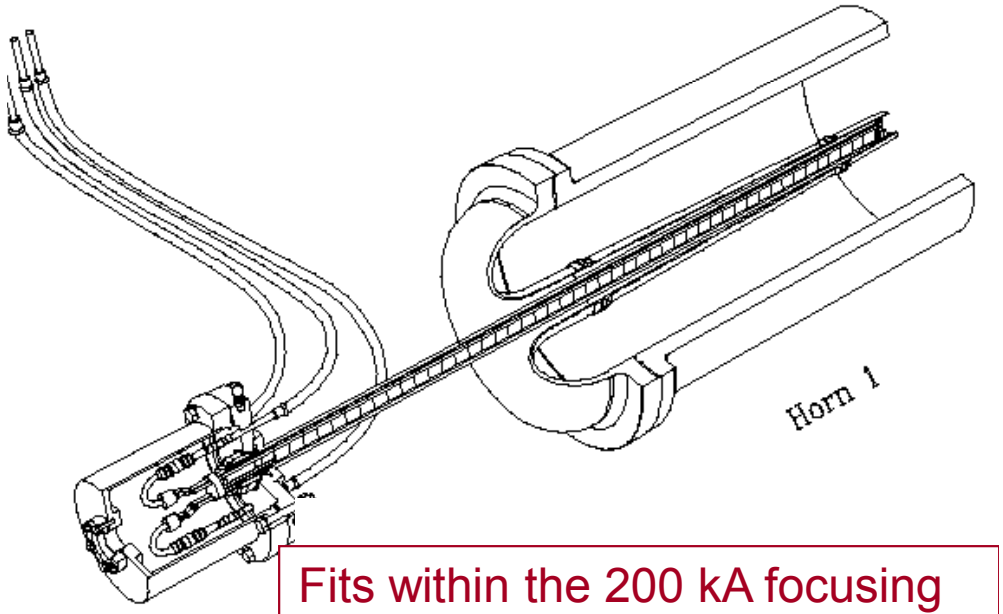
Water cooling tube



1 mm RMS

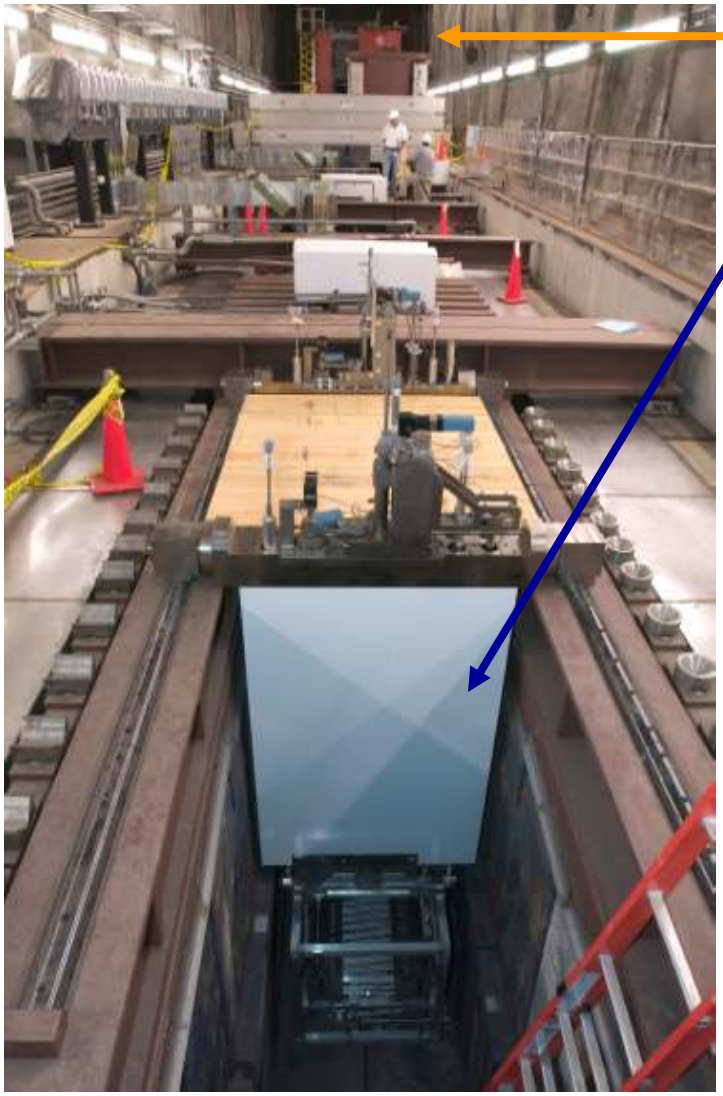
beam spot





Fits within the 200 kA focusing horn without touching.

MINOS Target carrier



1st target being removed

Experience with MINOS targets

during 0.75 MW-yr of integrated beam power in 6 years

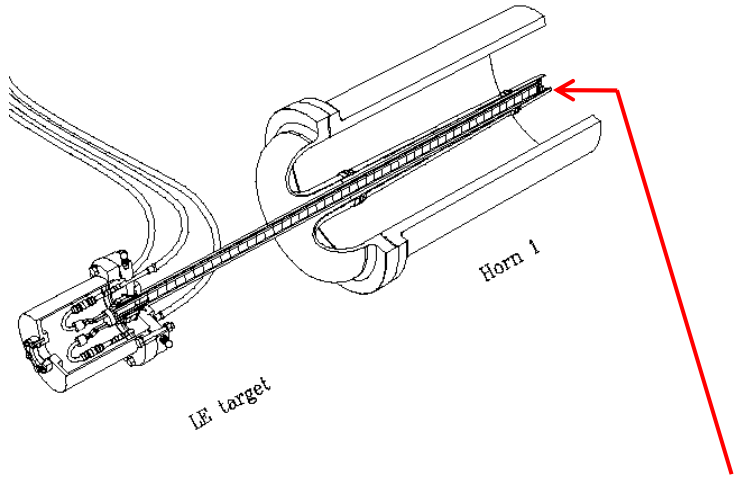
	Max. Proton/pulse	Max. Beam Power	Integrated Protons on Target
Target Design specification	4.0e13 p.p.p. *at 120 GeV*	400 kW	3.7 e20 p.o.t. or 1yr minimum lifetime
1st target	3.0 e13 p.p.p.	270 kW	1.6 e20 p.o.t.
2nd target	4.0 e13 p.p.p.	340 kW	6.1 e20 p.o.t.
3rd target	4.4 e13 p.p.p.	375 kW	3.1 e20 p.o.t.
4th target	4.3 e13 p.p.p.	375 kW	0.2 e20 p.o.t.
5th target	4.0 e13 p.p.p.	337 kW	1.3 e20 p.o.t.
6th target	3.5 e13 p.p.p.	305 kW	0.1 e20 p.o.t. so far

NUMI Target 5 failed 2/24/2011

Target 6 modified, start high intensity beam ~ 4/9/2011

(first low intensity beam target scans 4/7/2011)

- *water-cooled target must fit inside small radius of focusing horn*
- *intense beam; center of graphite $\Delta T = 270\ ^{o}C$ each 9 μs pulse*



Target life-time history

Design goal	*12 months*
1st target	16 months
2nd target	33 months
3rd target	10 months
4th target	< 1 month
5th target	4 months

After two targets quickly failed with water line leaks (downstream water turnaround):

-- Did autopsy on highly radio-activated target 5 to confirm location of leak

-- Then modified target 6 (more robust weld and geometry) before putting it in beam

← Old design

New design →

Problematic laser weld – will TIG weld

NT-05 Autopsy

When aluminum tube was cut off, water turnaround was missing

It was not cut by our tool

Note that the transition tubes are still on the water pipe

came apart at the laser weld transition

NT-05 Autopsy

Water turnaround came off in the cutting tool with the aluminum tube

Do not see cracks or corrosion

Just failure of laser weld

NT-05 Autopsy

Before cutting tip, tried smoke test of outer tube to see if we could spot other leaks in helium containment

- - but smoke test did not work (only set up for low-pressure test)

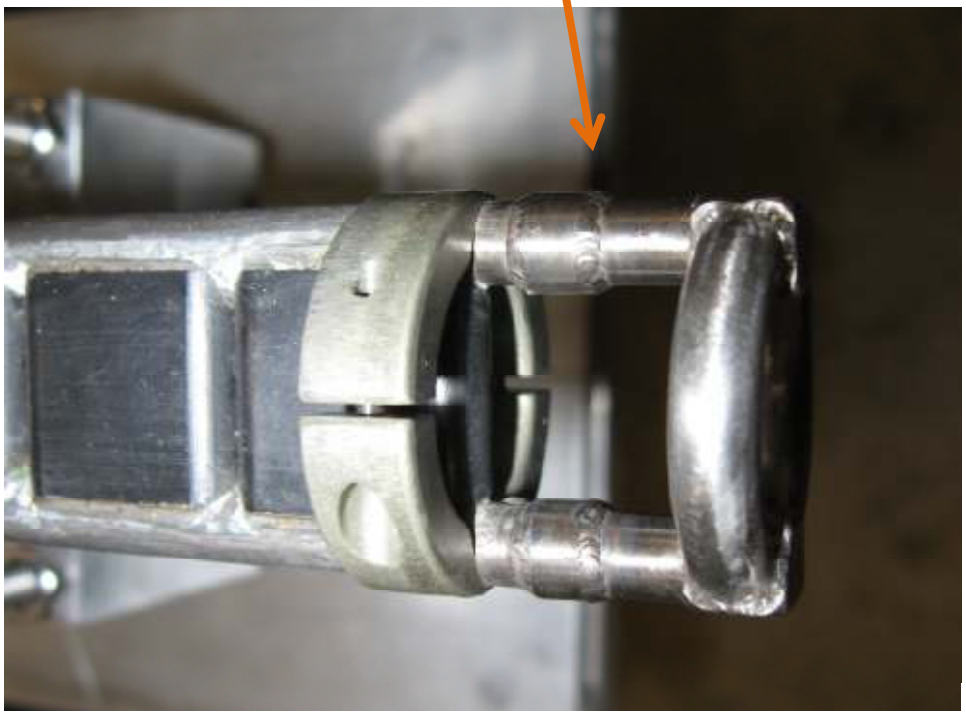
After tip was cut off, plugged the two water-line tubes at the end, then pressure tested target to see if there were any other leaks in water lines

- - no other leaks, so ceramic transitions were fine

NT-06 reworked

Ream old weld of water-feed-through at base (not shown)
Wire EDM off old water-turn around (minimal vibration)
Clean up and make room for new connection tube (made special tool)
Micro-tig-weld new tip on
Re-weld water feed-through
Pressure leak test

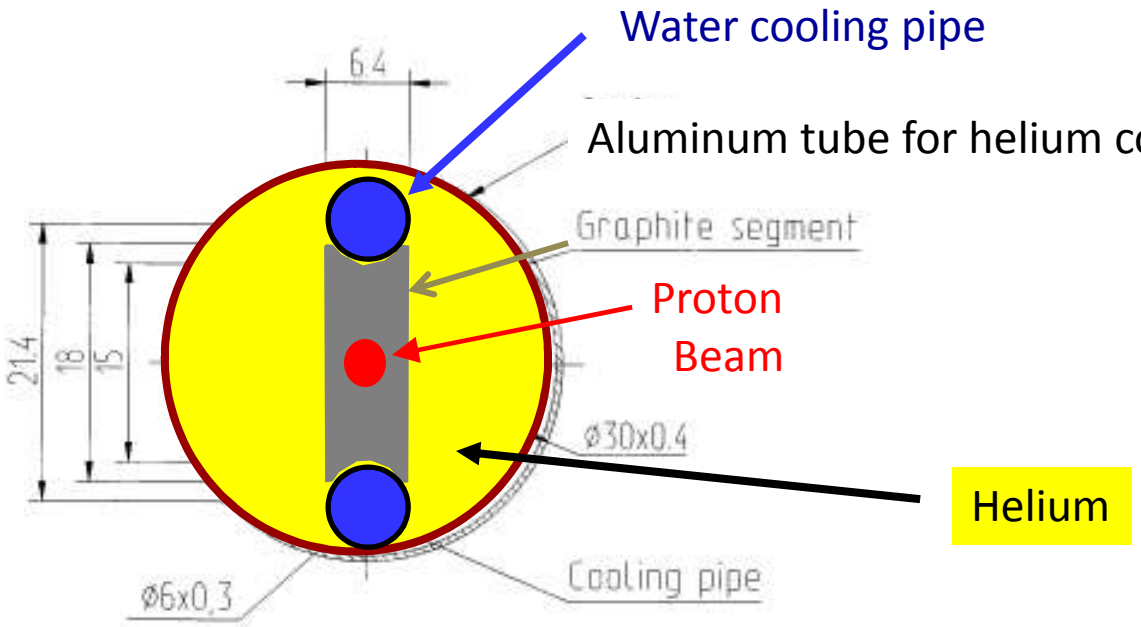
Before (note solder patch?)



After

NUMI LE Target

We had never opened up a target before to see insides after operation.
At least now we have some pretty pictures !



MINOS LE target

All units mm

NT-05 Autopsy March 2011

downstream end

This part of graphite looks perfect after 1.25e20 POT in 1 mm RMS spot

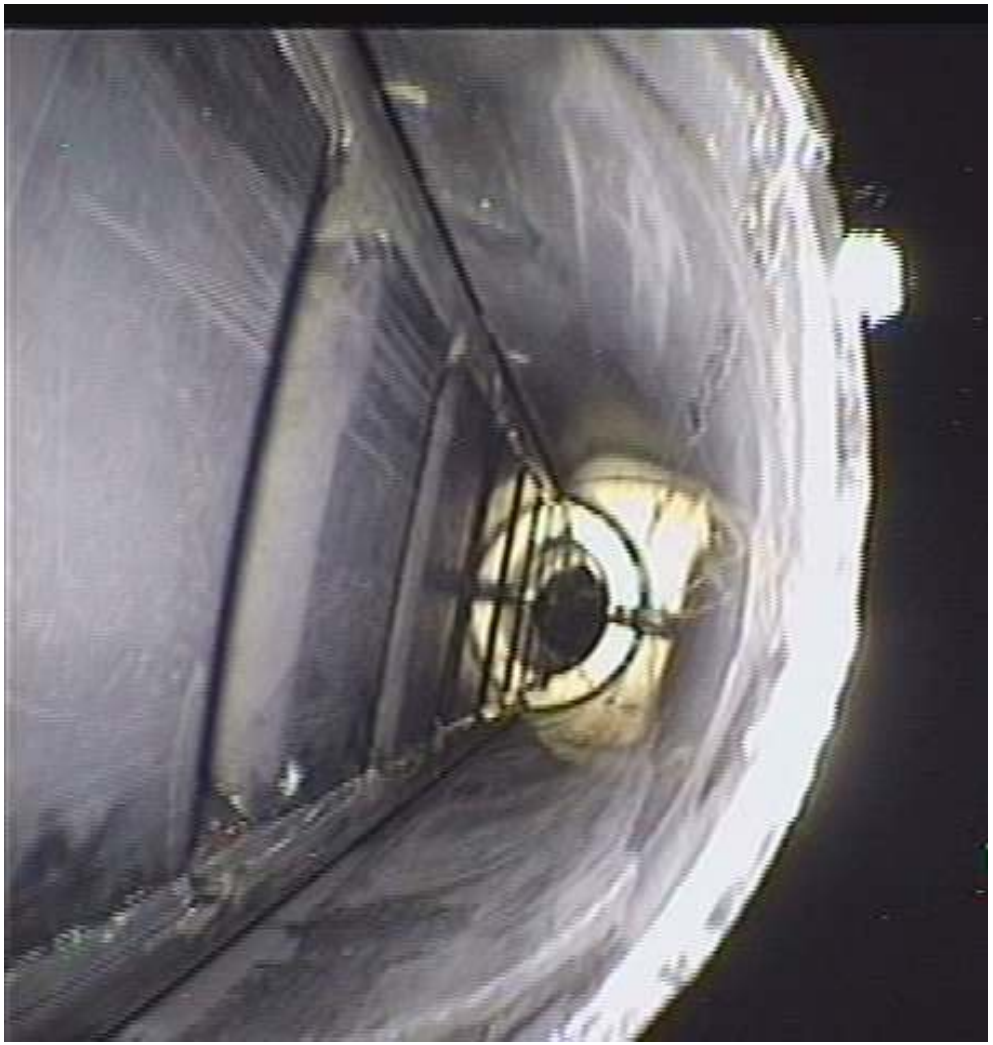
1st time we have ever had direct view of graphite after running !

No corrosion of aluminum

Solder joint to graphite looks fine

Steel cooling pipes look fine

Downstream spacer ring had walked several inches upstream



NT01 inspection April 2011

upstream end

Target interior flooded
early during operations
- leak location unknown

Dried out, then operated for 1 yr
Removed when drive stuck
– then 4 yr on shelf

Accumulated 1.6e20 P.O.T.
120 GeV protons in
1 mm RMS spot on
6.4 mm wide graphite fin
Neutrino spectrum did not visibly change during operation

Cannot see most of fin, but upstream end of graphite looks good.

Drive for insertion into horn has now being repaired, upstream beryllium window replaced, and are re-aligning target for use as spare.

NuMI 2nd target depletion (ZXF-5Q amorphous graphite)

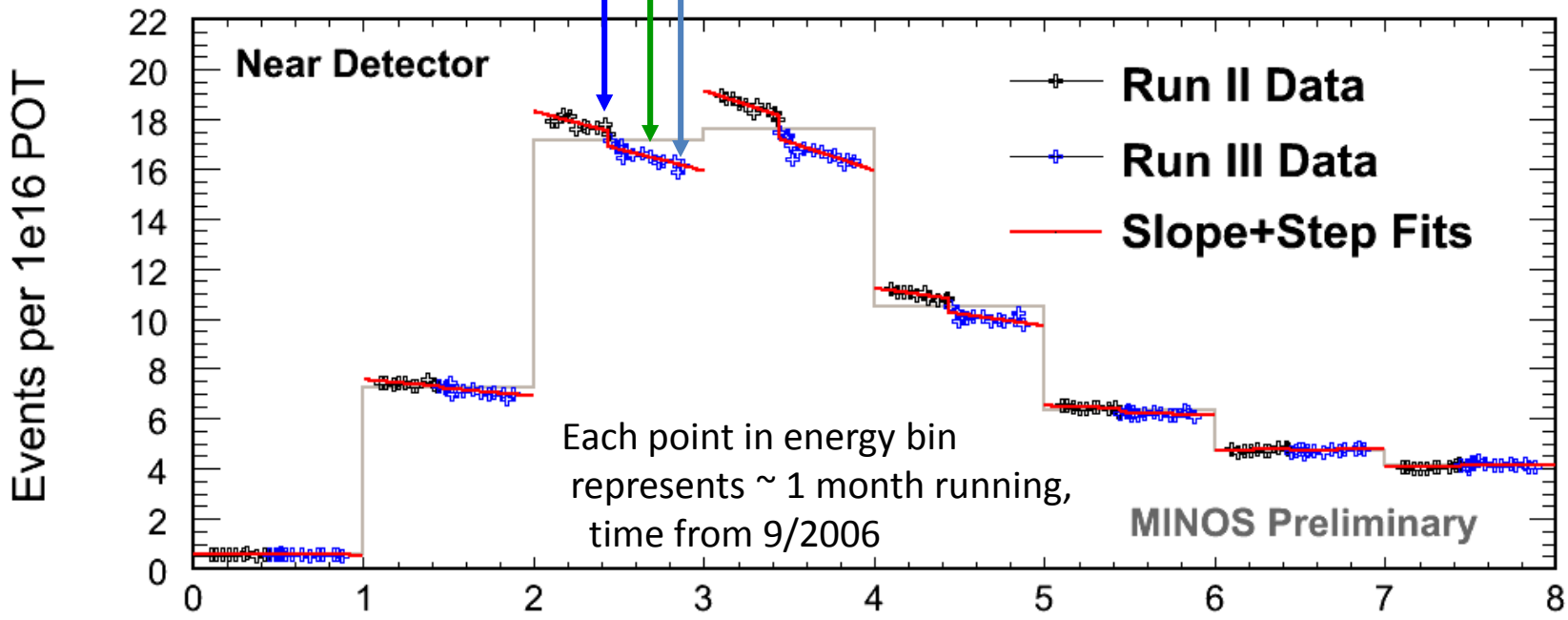
NT-02 replaced when spectrum shift became too large.

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



NT02 took 6e20 POT total
in 1 mm RMS spot size
~ 0.7 DPA

Spectrum recovered when
new target was inserted

? ? ?

- Why decent lifetime with three targets, then 3 quick failures?
  -- We do not know.
  -- Only NT05 was cut open to definitively locate the leak.
  -- On NT06, we changed the joint that failed on NT05, but still had failure.

- Stress calculations in progress by RAL collaborators
  -- preliminary result: not much safety factor in steel cooling line

- Given recent failures, we are prototyping titanium cooling tubes:
  - Less temperature rise, stress buildup than steel
  - good match to graphite CTE
  - Non-magnetic (no interaction with possible horn fringe field;
    the current steel used to match graphite CTE is magnetic)

NT-01 Frozen drive shaft

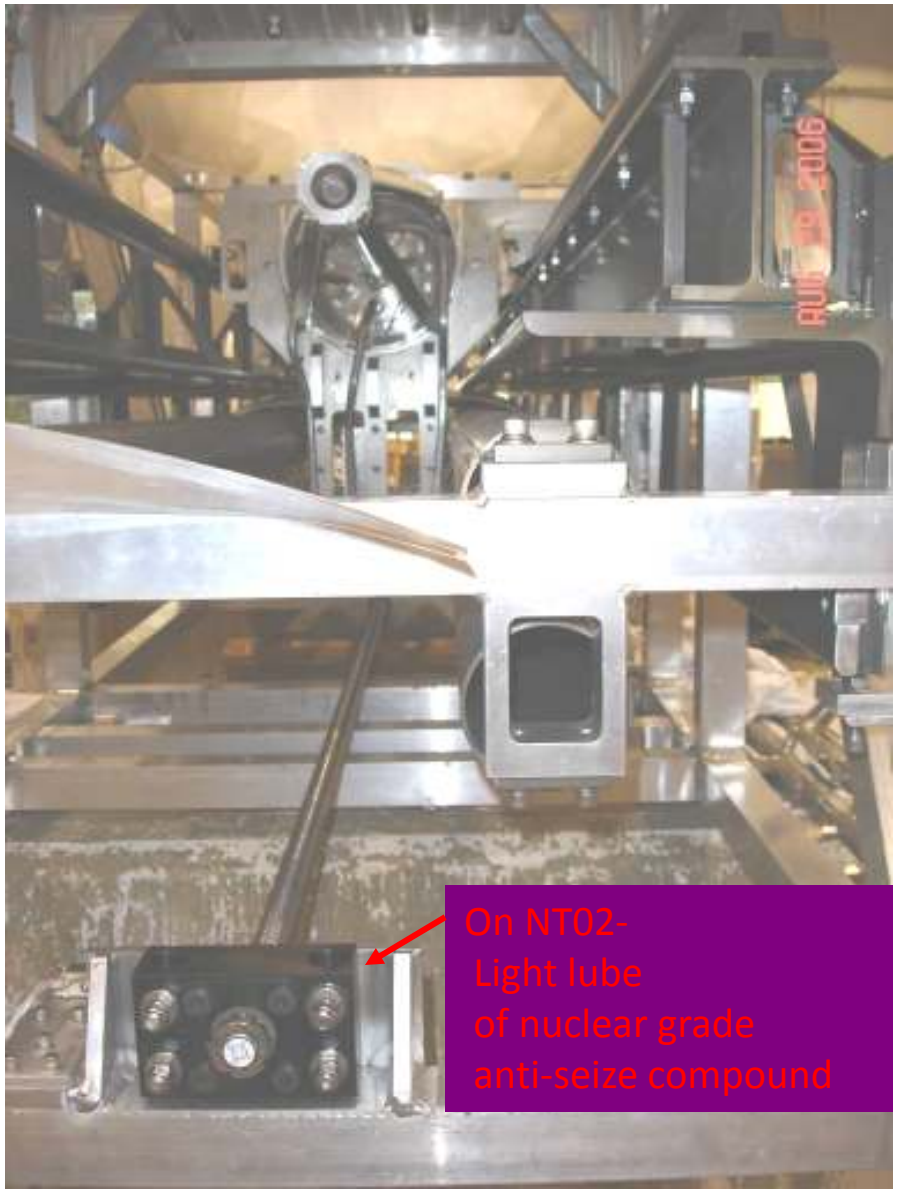
target replaced because could not move it to LE position

After month-long test in High Energy position
drive shaft would not rotate to move target into Low Energy position

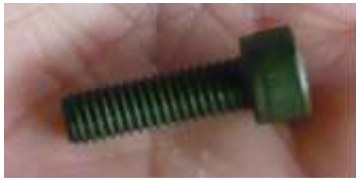
Changed to spare target + carrier (NT02)
(drive also became sticky after beam)

NT03 onward, changed to graphite bushing
NT-03 drive moved smoothly at the end of it's year lifetime.

Old jammed pillow-block



Target remote drive coupler failure (repaired)

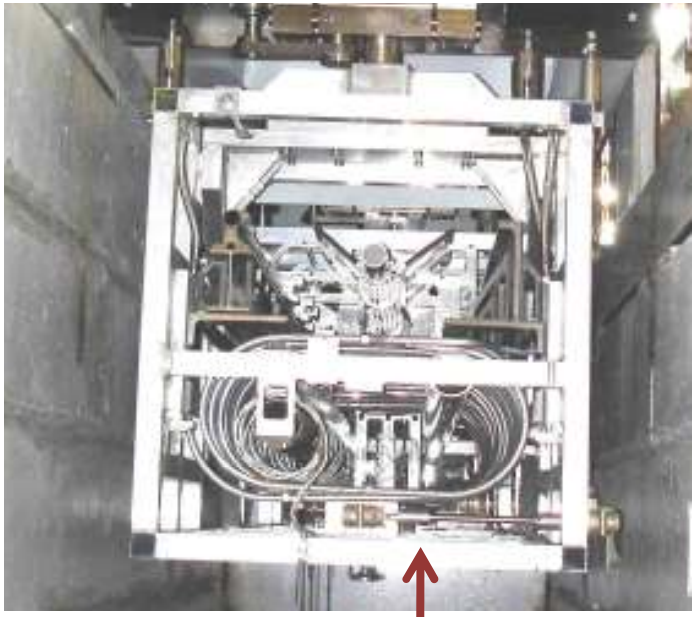


Air + radiation = nitric acid

Nitric acid atmosphere

→ hydrogen enbrittlement of high strength steel

→ steel cracks



High strength steel bolts in couplers on target drive linkage failed, so could not move target to different position.

Have changed to non-high-strength bolts.

No more failures of this type.

NT-03 failure

Helium leak developed, and target fin moved beam-left.

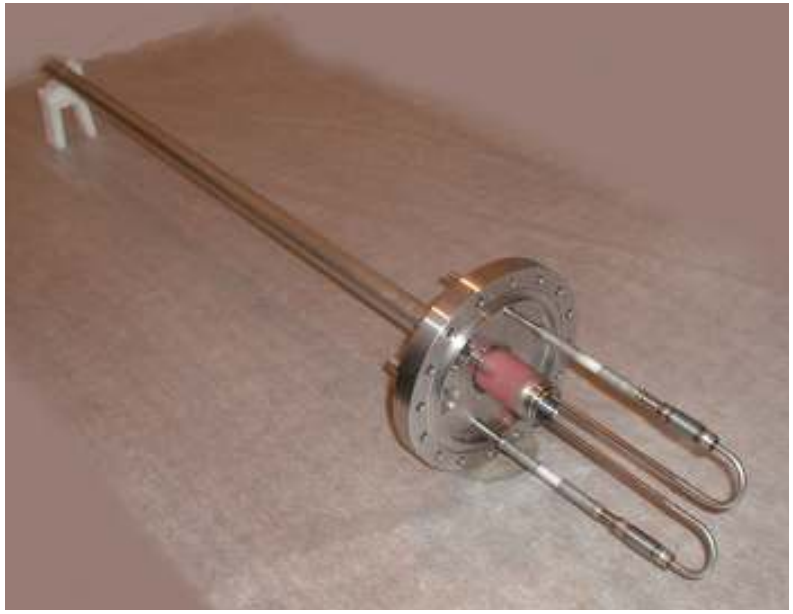
We re-adjusted target so parallel to beam again, and ran another two months.

Exam showed leak at ceramic insulator at base of target – presumed cause is failure of braze joint or ceramic causing (X=4 mm, Y=8 mm) displacement of target tip

Exam also showed helium leak/damage at bottom of target tube

- presumed collateral damage from horn current with target resting on horn conductor (which limited the vertical displacement to 6 mm)

(Since target is fin shaped, vertical mis-alignment is not as important)



NT-04 failure

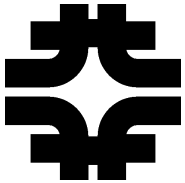
What upstream “window” looks like:

What it should look like

Target tip with drip

Water leaked into helium volume
Beam dissociated H2O into Hydrogen and Oxygen
Small spark ignited Hydrogen
The burn punched out the upstream window
Also damage at downstream tip

NT04 had Helium at lower pressure than water.
Now always run with Helium at higher pressure than water,
so helium goes to water system, not water into target



Summary of experience with MINOS targets

during 0.75 MW-yr of integrated beam power in 6 years

1st Target took beam for over a year. Two problems:

- water leak soon after turn-on;
  back-pressured with Helium to keep water out, continued running
- target motion drive froze up after year of operation – stuck in High Energy focus
- motion drive now repaired; will be emergency spare

2nd Target ran 3 years, replaced when

- neutrino spectrum gradually changed ~ 10% - 15% (graphite radiation damage?)
- available for emergency spare

3rd Target ran 10 months (at lower helium pressure)

- target tube support ceramic broke after 8 months, ran two months after that

4th Target ran 1 month (at lower helium pressure, doesn't keep water out of casing)

- water leak, dissociation of H2O, hydrogen burn punched off upstream window

5th Target ran 4 months

- water leak soon after turn-on;
  back-pressured with Helium to keep water out, continued running
- removed when water leak past helium and through target casing onto horn

6th Target in use

- water leak soon after turn-on;
  back-pressured with Helium to keep water out, continuing running

Target NT-02 residual radiation when removed

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 (F) = Floor wipe

Bkgd _____ cpm

Wipe # | Reading | Wipe # | Reading

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

Target dose rate was
45 R/hr
=
0.45 seivert / hour

(has dropped ~4x after 20 months)

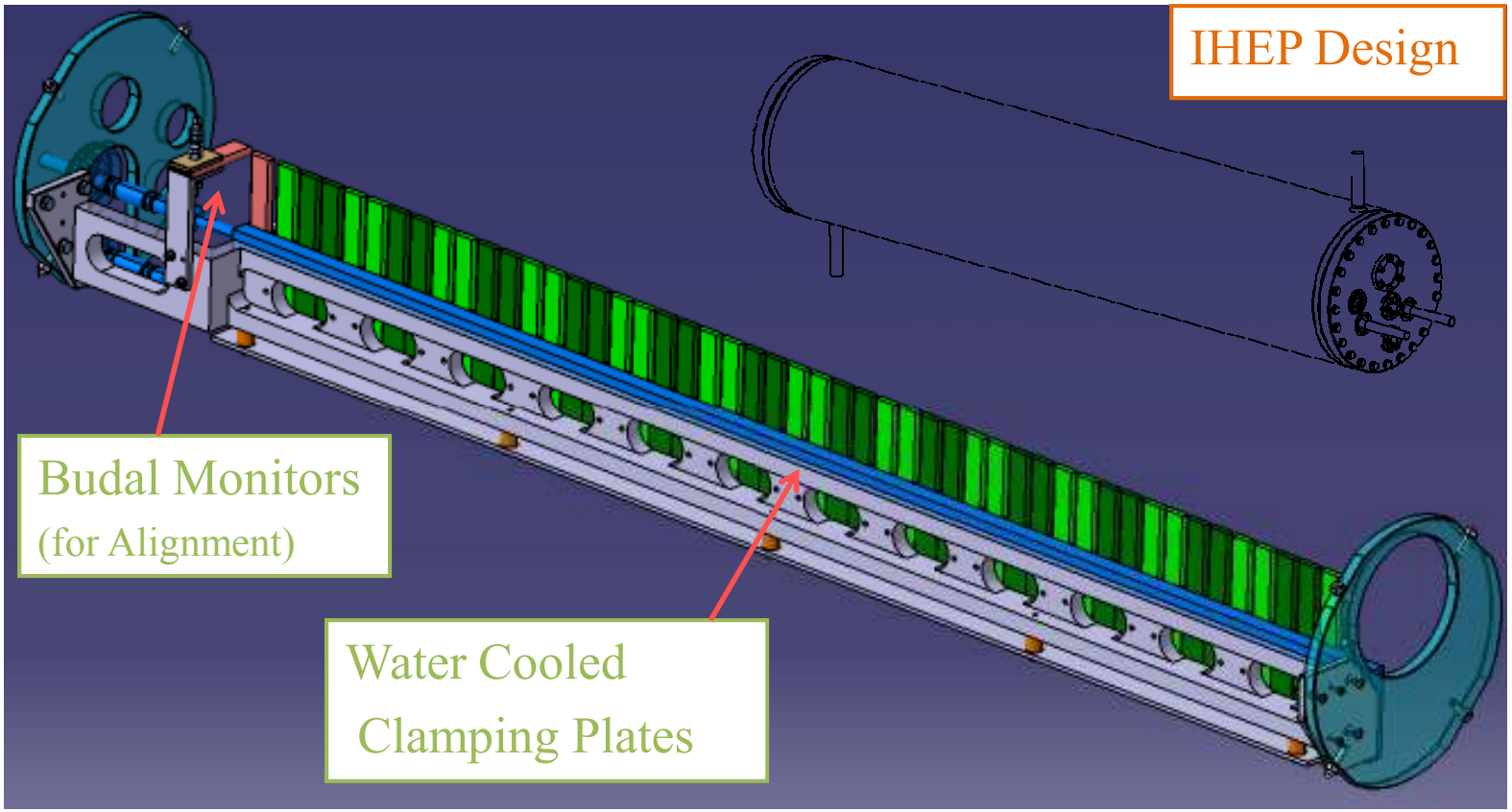
Residual radiation limits the autopsy

FNAL is setting up a cell with remote arms *- capability for much more detailed exam within coming year.*

MINOS / NOVA / LBNE Targets

	NUMI / MINOS	NUMI / NOVA	LBNE / DUSEL
Distance to far detector	735 km	810 km	1300 km
Desired ν energy	1 to 15 GeV	2 GeV	0.8 & 2.7 GeV
Detector Off-beam-axis angle	0	14 milli-radian	0
Design beam power	400 kW	700 kW	700 kW (2.3 MW)
Energy per proton	120 GeV	120 GeV	60 - 120 GeV
Number of horns	2	2	2
Target length	0.95 m	1.2 m	1 m
Distance between target downstream end and horn	1.6 m to -0.6 m (Variable)	0.2 m (Not in horn)	-0.95 m (In horn)
Protons/spill	4.4 E13 max.	4.9 E13	4.9 E13 (1.6E14)
Repetition rate	2.2 sec	1.33 sec	1.33 sec

NOVA ME Target



Nominal max. beam power 700 kW

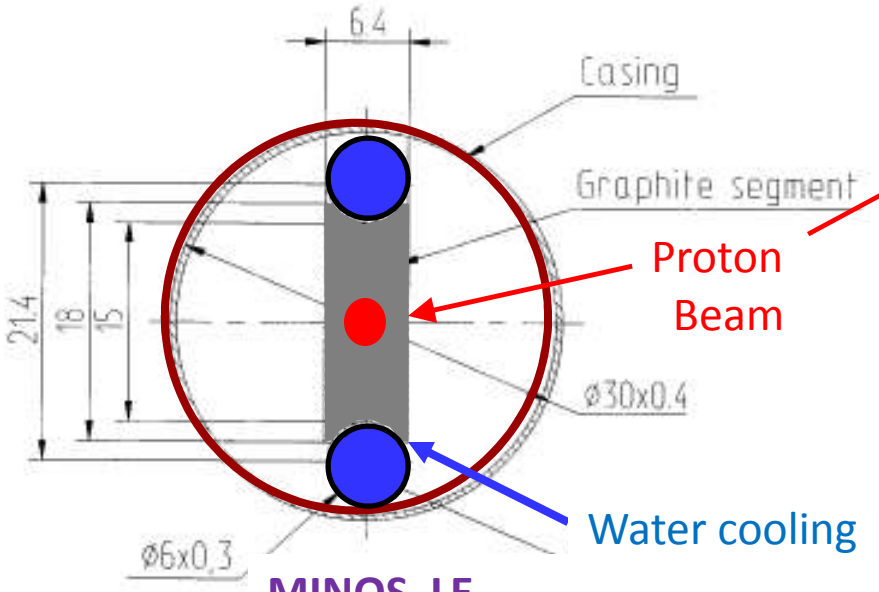
Target cross section comparison

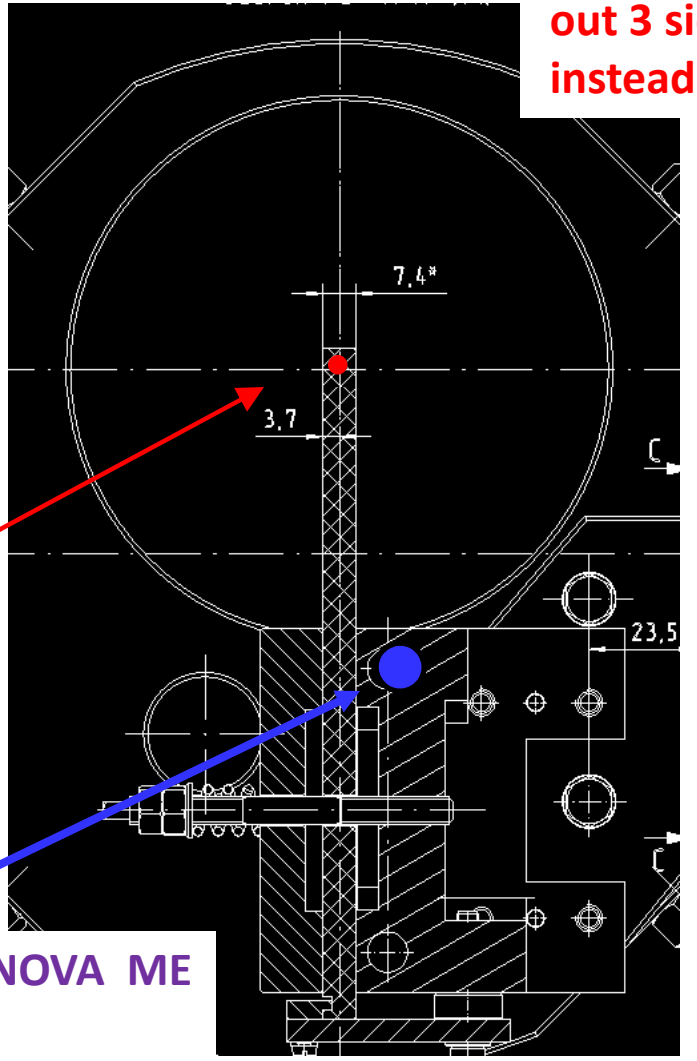
water cooling 8 times as far away, 0.1 x the water hammer

MINOS beam spot size of 1.1 mm RMS is increasing to 1.3 mm for NOVA,
increasing 6.4 mm target width to ~ 7.4 mm
- reduces the neutrino flux ~ 1%, but eases alignment tolerance.

Spacing between fins
0.5 mm / 24 mm versus 0.2 mm / 20 mm

Pions come out 3 sides instead of 2





MINOS LE **NOVA ME**

All units mm

MINOS and NOVA Energy Targets

In both cases:

- Beryllium upstream and downstream windows
- Helium atmosphere – prevent graphite from oxidizing
- Graphite (POCO ZXF-5Q) target
- Water cooling of graphite (but radiative cooling has significant effect in NOVA target)

Difference:

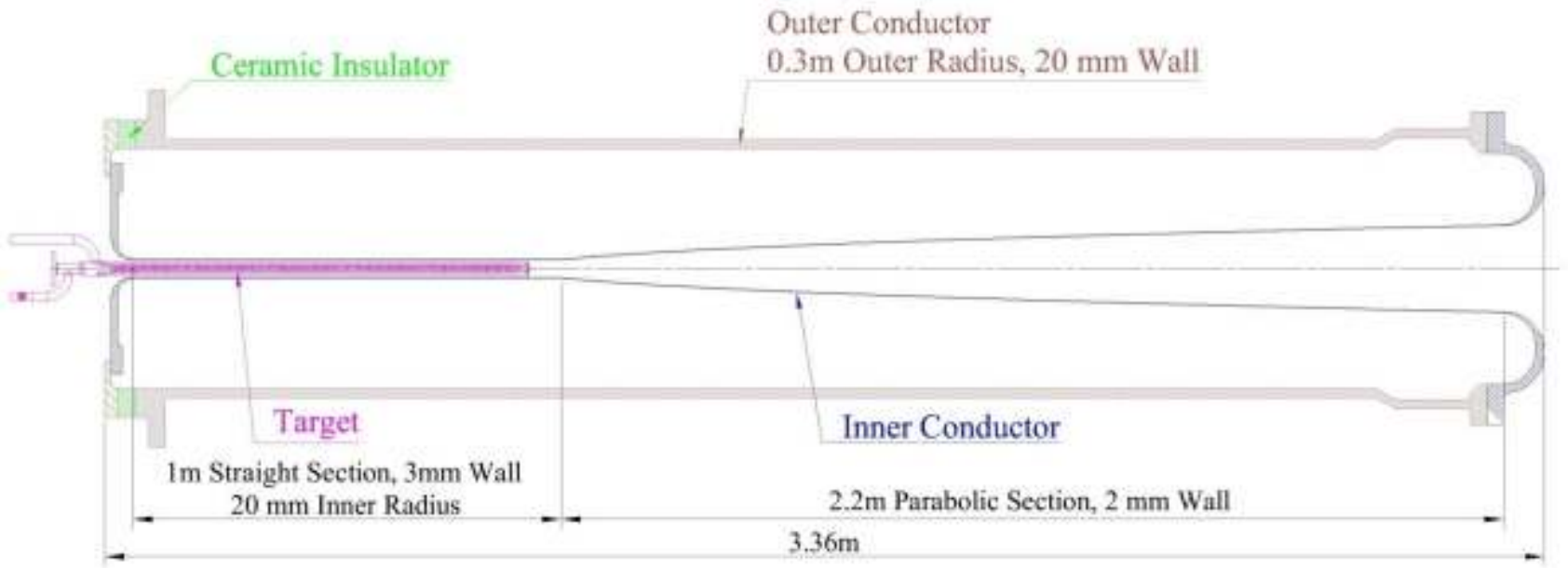
The NuMI LE target aluminum shell and downstream window would get too hot for it to operate in the 700 kW beam.

The larger space for ME target allows moving the aluminum shell to greater radius and water cooling it.

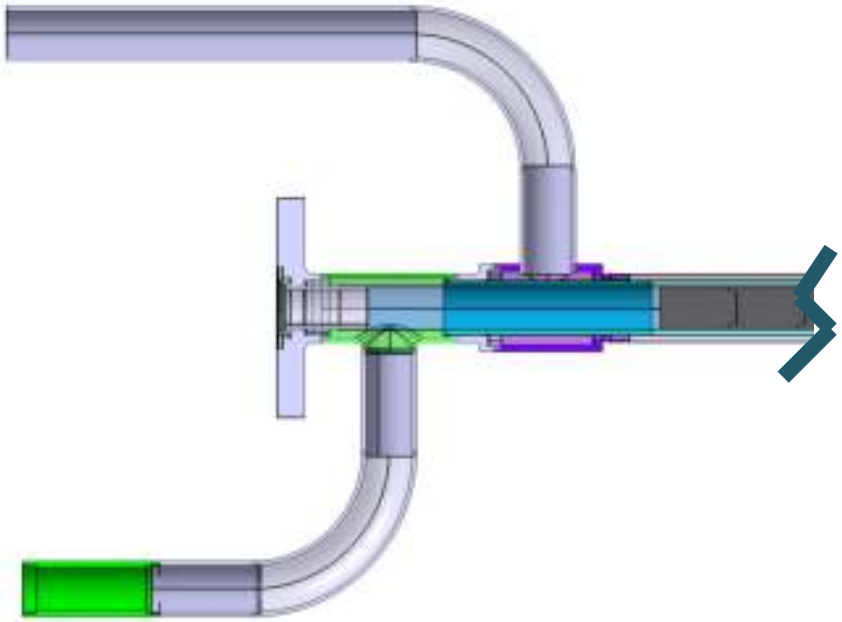
For NOVA, the water cooling is much further from beam center, eliminates the high stress, thus addresses our current water leak headaches.

LBNE target more similar to NUMI LE

In horn neck without touching



IHEP Protvino design of LBNE target



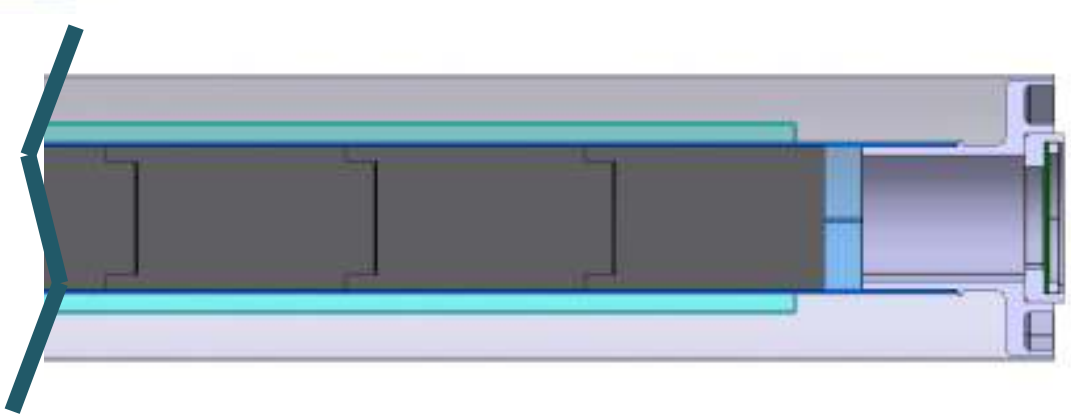
1 m long

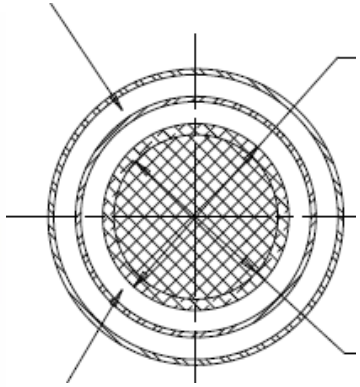
15.3 mm diameter segmented graphite core

0.3 mm thick steel tubes encapsulate graphite and form water channels

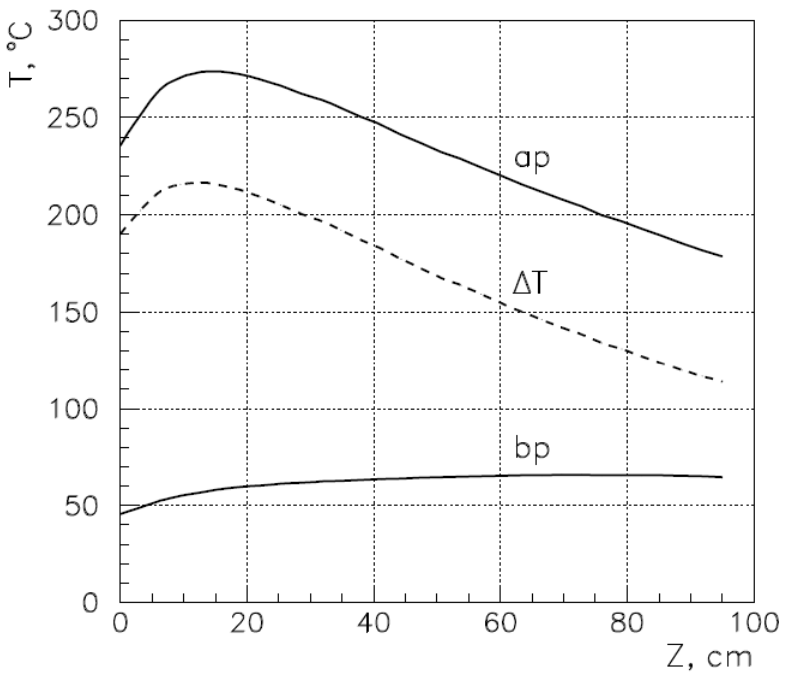
Supply and return water rings

Bubble some gas in water lines to relieve pressure spike due to beam heating

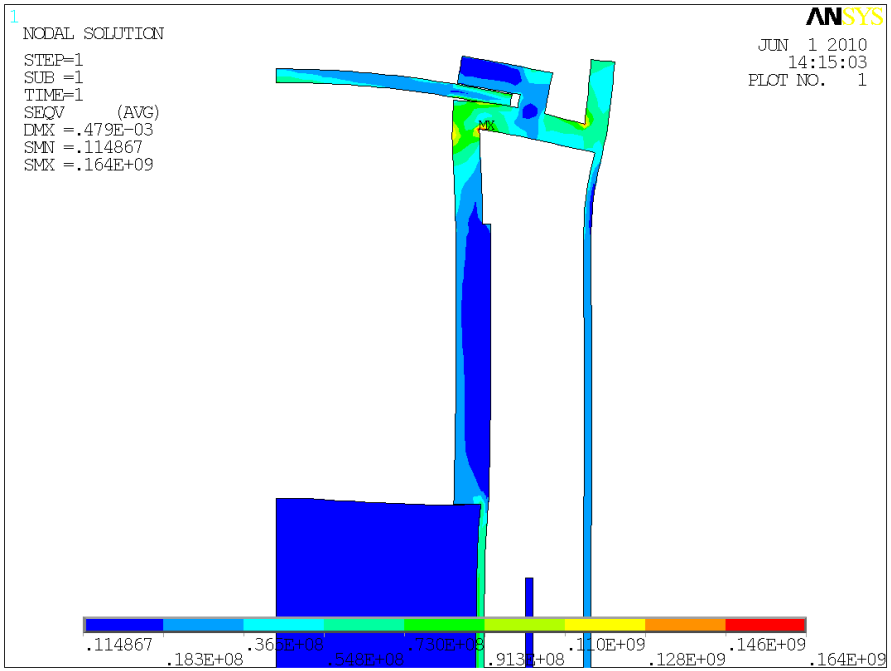




IHEP LBNE target



Temperature along center of target before and after beam pulse



Stress (color) and deformation (x120) of downstream target tip just after beam

IHEP LBNE design is a step towards 2.3 MW target

- As power increases, maximum stress /yield is tensile at outer edge of fin rather than compressive at center
  - Encapsulation with stainless steel pre-loads and counters this stress;
    calculated graphite stress OK at Project X 2.3 MW intensity, 1.6 E14 POT/spill

- The encapsulation may prevent graphite from falling out of beam as radiation damage accumulates
  - Encapsulation may substantially increase target lifetime

Given recent experience with NUMI LE target, would likely switch to another material like titanium for the outer tubing.

We are still examining other target designs for LBNE as well:

It would be so nice to not have to deal with water for cooling !

Believe beryllium may have longer radiation damage lifetime.