Extrapolating NuMI 0.3 MW targeting experience to 2 MW beam

NuMI / MINOS 0.3 MW target survival

- interesting for radiation damage lifetime
- but also checks fatigue cycles, stress limits, corrosion

Side-light: near-term target plans

- A (small) step to 0.7 Mw target for NUM I / NOVA
- A design for 2 Mw target (for NuMI / NOVA / Project X)

Starting to think about 2 MW target for FNAL / DUSEL

- A cartoon design for graphite 2 MW target for FNAL / DUSEL
- Very interested in alternate possibilities
- May want something that can just be demonstrated to work in the near term, and a different more elegant eventual solution.

NuMI Target

long, thin, slides into horn without touching

Graphite Fin Core, 2 int. len.

(6.4 mm x 15 mm x 20 mm) x 47 segments

Water cooling tube also provides mech. support

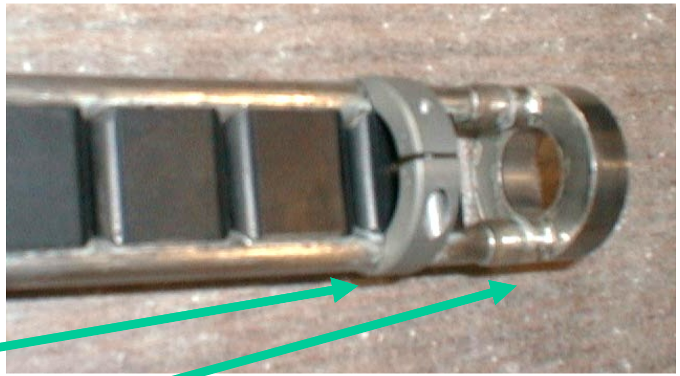
(steel soldered to graphite)

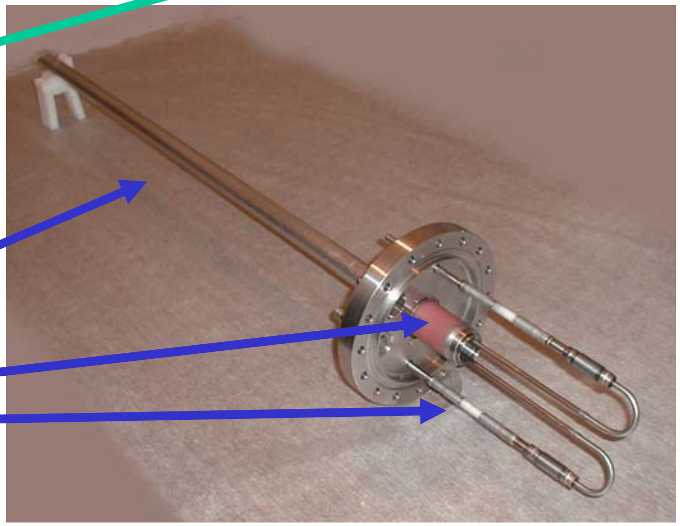
Anodized Al spacer (electrical insulation)

Water turn-around at end of target

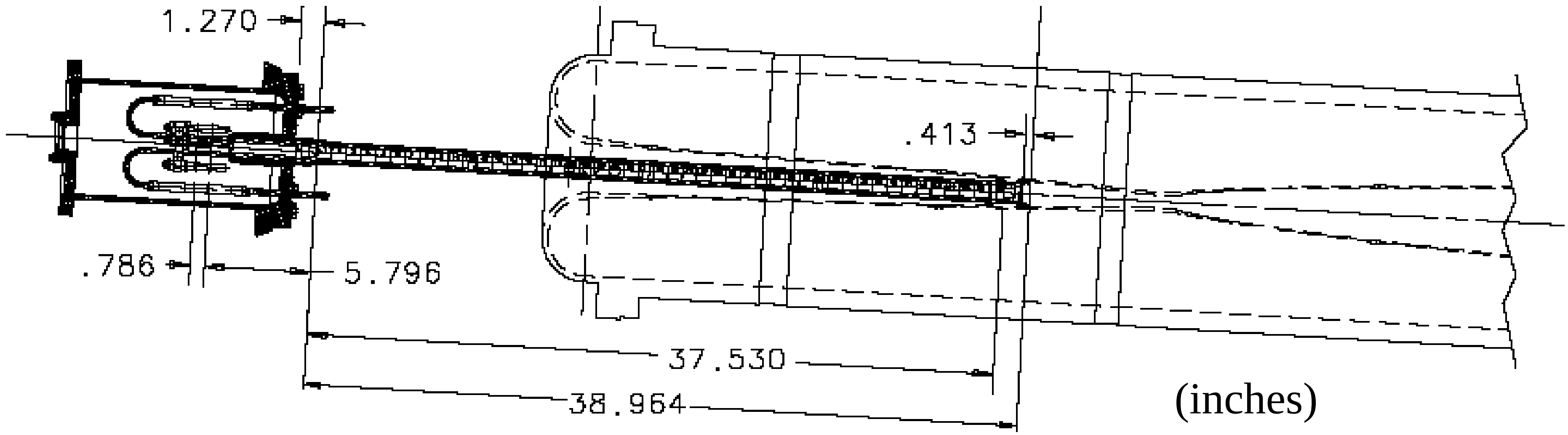
0.4 mm thick Aluminum tube *(He atmosphere, Be windows at U.S. and D.S. ends)*

Ceramic electrical isolation





NuMI target/horn layout for low energy neutrino spectrum



(inches)

NuMI Target Run History

1st target removed after 1 ½ years 1.7e20 POT because motion bearing corroded on support/utility module, could not re-insert target in horn. 2nd target still working.

2nd target	Design	Running
Energy per proton	120 GeV	120 GeV
Beam power	400 kw	260 – 320 kw
Protons per pulse	4.0e13 PPP	3.0 – 3.6 e13 PPP
Repetition rate	1.86 sec	2.2 sec
Spot size	1.0 mm RMS	1.1 mm RMS
Lifetime - time	> 1 year	> 2 years
Lifetime – POT	> 3.7e20	> 4.2e20
Integral flux at beam center	$1 / (2\pi \sigma_X \sigma_Y)$	5.5e19 POT/mm^2 so far

No visible corrosion on target outer Aluminum tube or downstream Beryllium window.

Current condition of target

Some change in neutrino spectrum has been seen in Near Detector (MINOS has not approved a spectrum versus time for public display, so am not showing a plot)

Other changes during the run time (the switch from vacuum to helium in the decay pipe, deterioration of the hadron monitor, repositioning of target, etc.) mean disentangling the effect of target is not straight forward. Also have not completely ruled out other effects like possible baffle failure.

Change corresponds to 0% to 10% reduction of target mass in center of beam spot.

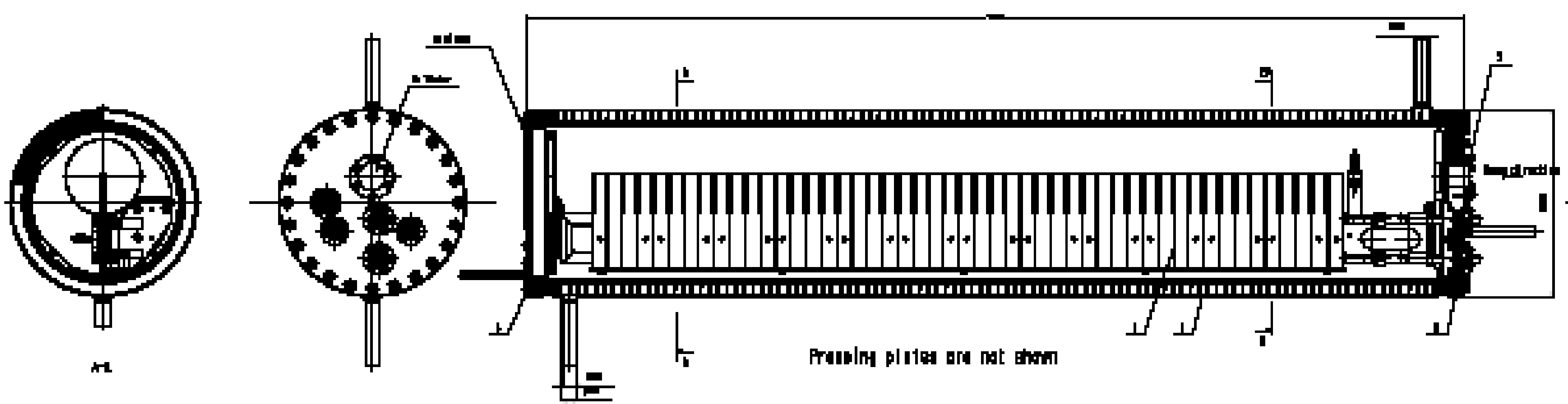
Don't know if this is gradual change in graphite density or catastrophic failure of one or more target segments. When will we know more? Perhaps change out target June 2009, autopsy in 2010 after some radiation cool-down. Month-to-month recently the spectrum looks stable, so no sign of accelerated damage.

Interesting question: how damaged can a target be before one is motivated to replace it?

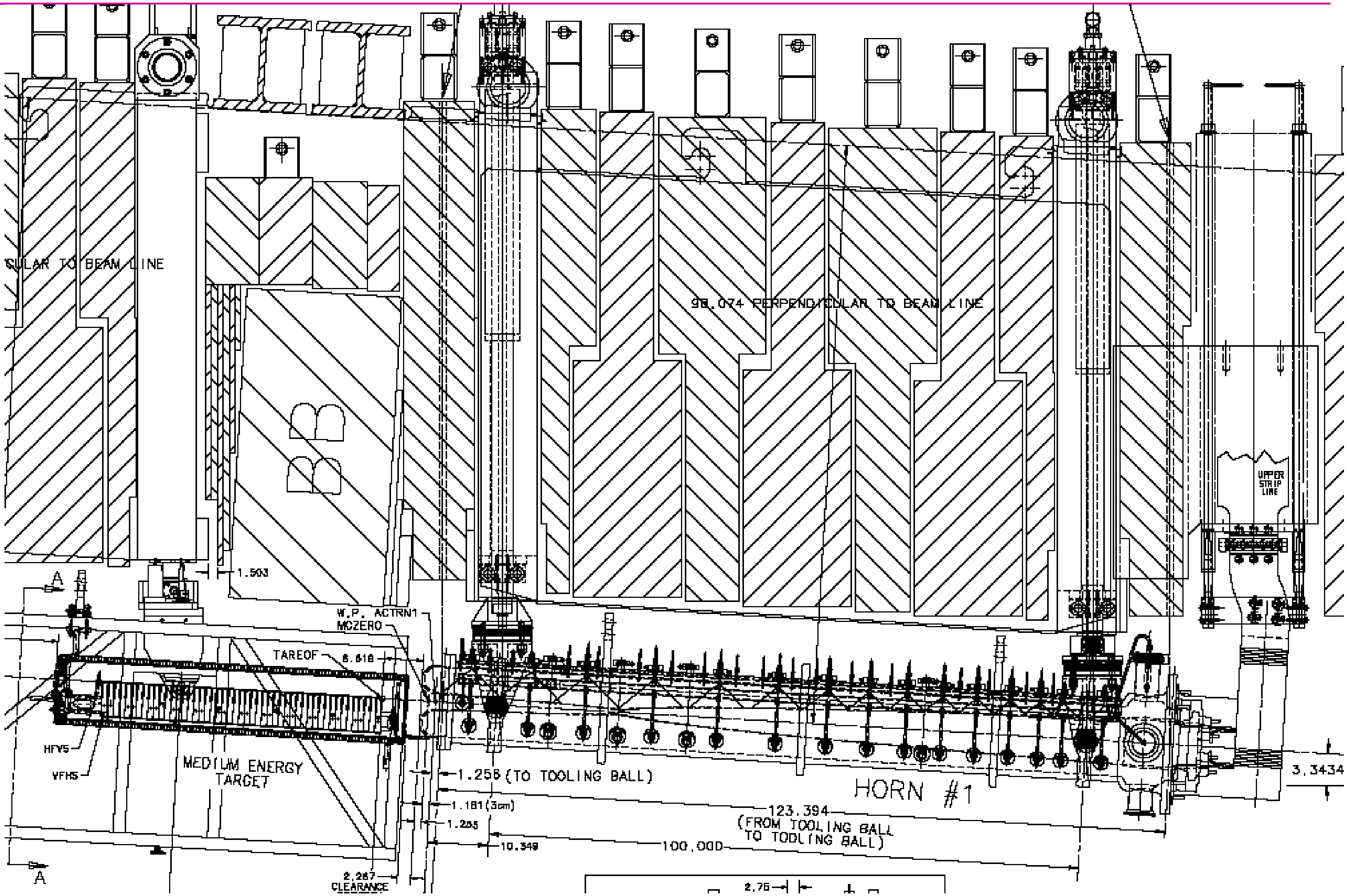
(For MINOS and NOVA, appears to be negligible systematic effect, just statistics)

0.7 MW NOVA-ANU target (NuMI Upgrade)

6.4 mm wide graphite fins, total length 120 cm
Cooled from one end of each fin by water-cooled pressing plate
He atmosphere, contained with Be windows
Water-cooled aluminum outer can
Cross-fin at upstream end for alignment check with beam
Increase spot size from 1.1 mm RMS to 1.3mm RMS to compensate stress for increase in POT/spill (4e13 PPP NuMI → 4.9e13 PPP ANU)
Based on NuMI target survival, expect ~ 1 year lifetime, accept loss of 10% of target.
Design is easier than NuMI or DUSEL because target does not have to fit in horn



NuMI NOVA-ANU target/horn layout

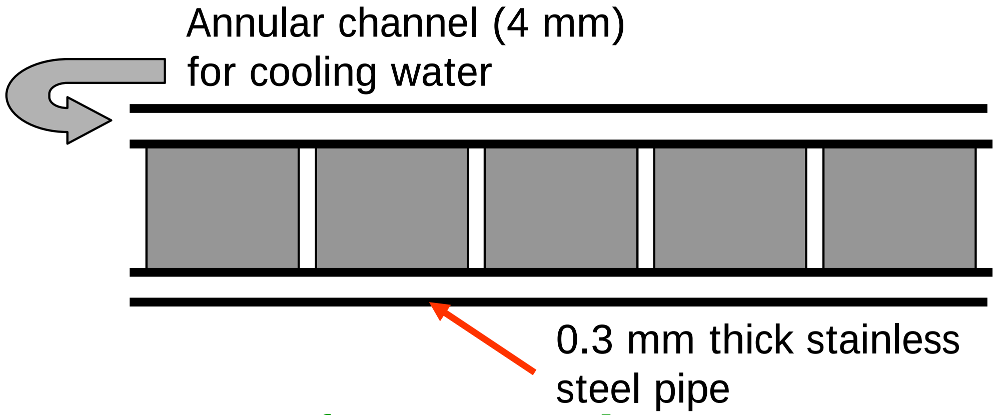


IHEP NOVA-Project X 2MW target

From 2005 study of graphite encapsulated in Al or steel sheath, with water cooling, graphite target stress and temperature were OK for 1.5e14 PPP 2 MW beam.

Remaining issues were:

- Hydraulic shock in cooling water (150 atm.) *(suggested using heat pipe to solve)*
- Radiation damage lifetime *(est. at 1 year but not well known)*
- Windows



NUMI Target for 2 MW upgrades

V.Garkusha, A.Ryabov, T.Ryabova,

F.Novoskoltsev, V.Zarucheisky........(IHEP, Protvino)

A.Mikheyev, I.Ponimash..................(IPPE, Obninsk)

J.Hylen..(FNAL)

IHEP NOVA-Project X 2MW target (2)

For NOVA beam, target is upstream of horn,
lots of extra radial space can help with two of these issues.

- Hydraulic shock in cooling water
  >> use water spray from jets at large radius instead of water cooling channel
- Radiation damage lifetime
  >> from NuMI, graphite lifetime at least a couple months,
  so a wheel of 6 targets like CNGS would last at least a year.
  (Might last longer, since encapsulation may prevent loss of graphite
  compared to open design in existing NUMI target)
- Windows
  >> Beryllium window looks plausible if increase beam RMS to 3 mm

Should work for NOVA,

BUT NOT FOR DUSEL
– DUSEL neutrino spectrum requires target inside horn

2 MW combo horn/target concept

Neither the NuMI horn nor target replacement were due to failure of the components themselves, but failure of components on the utility support module.
Lesson learned – keep supporting equipment at the component as simple as possible.

FNAL Project-X would provide 21 to 25 e20 POT/yr --> 5 to 6 times integral on NT02 so far, so based on NuMI a graphite target should last at least a couple months. However, Project-X beam spot will be larger (perhaps 3 mm RMS compared to NuMI 1 mm RMS), so radiation density / POT will be less, and target lifetime should be longer. But conservatively need to plan frequent replacement.

Motivates the following concept – an integrated target/horn that is one short unit, with a single cooling system. Simple enough that it can be replaced quickly and often.

Can such a concept work? Have others studied this to see if it has a fatal flaw?

Have had no resources to do engineering, so do a back-of-envelop extrapolation, combining the NuMI horn neck and the IHEP graphite target study.

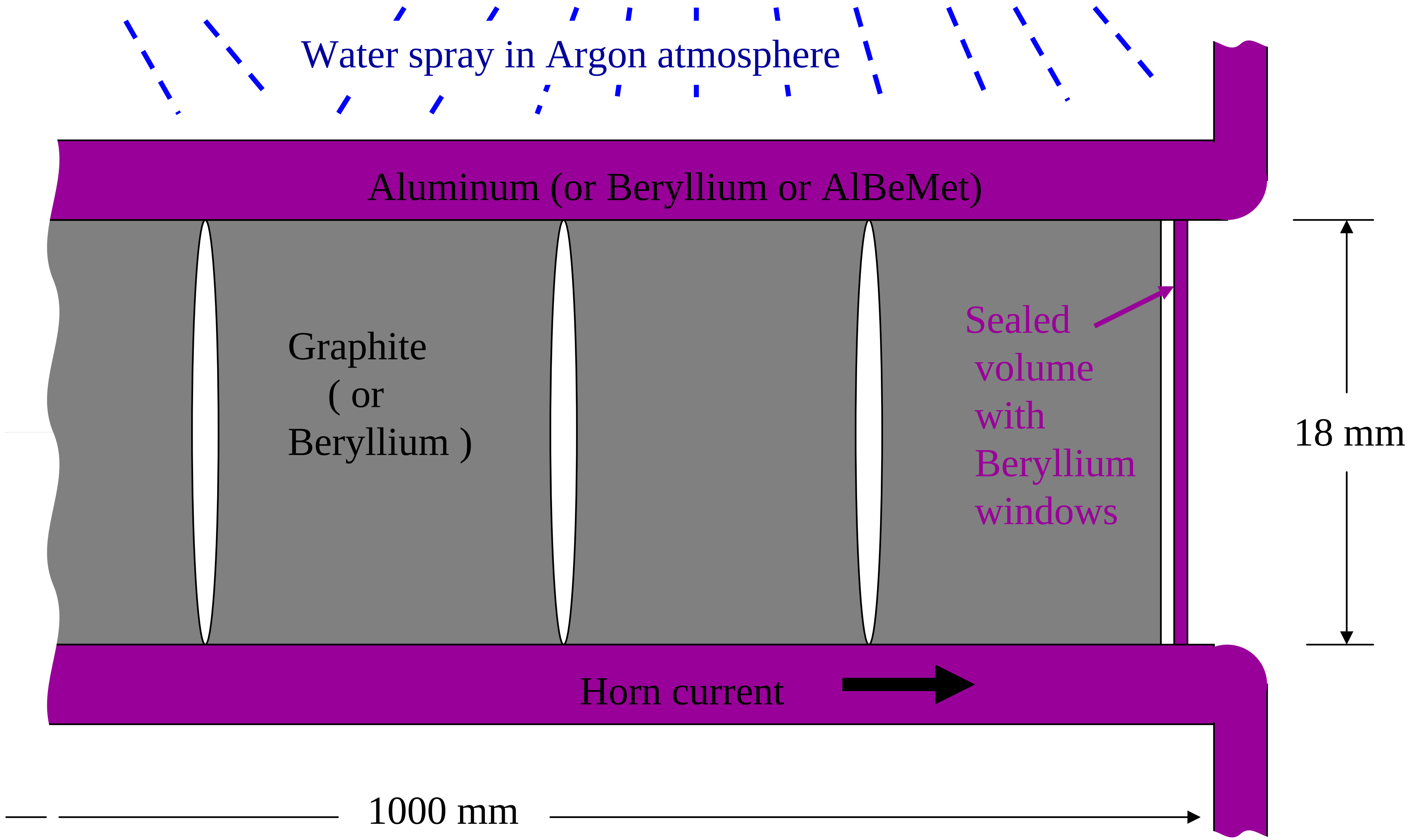
NuMI Horn Run History

1st horn 1 removed June 2008 after 4.9e20 POT because water suction line failed at electrical isolator on support module – probably due to water erosion

High radiation makes repair very difficult

1st horn 1	Design	Running
Horn current	200 kA	185 – 200 kA
half-sine pulse length of current	5 ms	2.3 ms
Repetition rate	1.86 sec	2.2 sec
Radius (OD,ID) of Al. neck	(13.5 mm, 9 mm)	
Lifetime - time	> 1 year	3 years
Lifetime - pulses	> 1e7	2.4e7

Proposed target encapsulated by horn inner conductor



Draft parameter list based on some linear extrapolation

(Need Monte Carlo and real engineering study to optimize)

Horn I.C. O.D. (same as NuMI horn neck)	27 mm	(note K2K horn target region was 30 mm diam.)
Horn conductor thickness (same as NuMI horn neck)	4.5 mm	(may be too conservative)
Horn current Horn pulse length	200 kA 0.6 ms	Same as NuMI (geo-mean NuMI & M.B.)
Graphite diameter (fill in to horn I.D.)	18 mm	(was 15 mm in IHEP 2MW target study)
Target and horn Length (graphite in 2 cm segments)	1 m	(match IHEP study)
Beam spot RMS	3 mm	(Min. from IHEP study for Be upstream window)

Estimates for 2 MW at 120 GeV 1.5e14 PPP

Beam power deposition graphite Beam power deposition Aluminum Joule heating Aluminum	24 kw 17 kw 1 kw	1st order extrapolation away from IHEP report numbers
Water spray heat transfer coef. Average dT for heat transfer	15 kw / m^2 K 33 K	From literature. (x 2 at D.S. end? --> 76 C ?)
Per pulse temperature jump in Aluminum D.S. end	70 K	(Intermittently boiling water?)
Stress Safety Factor in Graphite *(need calc. for Aluminum)*	1.9	IHEP report, Mohr-Coulomb Stress Criterion
Max. Edep/spill Graphite Max. Edep/spill Aluminum	800 J/cm^3 200 J/cm^3	(based on relative CTE, SHC, etc, Al. stress may be OK)

Conclusions / Comments on DUSEL target

Based on back-of-envelop heating extrapolations, and experience of the survival of the NuMI target to 5e19 POT/mm^2, the parameters for an embedded graphite target in aluminum horn inner conductor may work for 2 MW beam; need real engineering analysis to go further. (Dynamic stress in aluminum is worry).

The system gets rid of the hydraulic shock problem in cooling water that a NuMI-like target would have.

Keep horn short for ease of construction, and waste disposal. (Then need 3rd horn like T2K to make up magnetic field length).

Based on NuMI target running, conservatively plan for several target/horn swaps per year, similar to FNAL pbar target/lens operations. (More NuMI running will help clarify lifetime. Larger spot size for DUSEL should probably extend radiation damage lifetime further).

Conclusions / Comments (2)

Beryllium should be somewhat better than Aluminum for horn inner conductor because

- lower density (so less energy deposit)
- coefficient of thermal expansion (11 ppm/K) better matches POCO ZXF-5Q graphite (8 ppm/K) than Aluminum does (23 ppm/K)

Beryllium electrical conductivity is good enough, since joule heating is small.

Beryllium as target slug material should also be explored – advantage: no window needed, and CTE exactly matched between slugs and tube.

Probably requires larger beam spot size than for graphite.

Note NuMI target upstream window has also survived 5.5e19 POT/mm^2 so far, so radiation damage lifetime is tested to that extent.

From Luca Bruno
(NBI workshop)

Material Properties

Graphites and hBN - Material Properties at 20 °C

Property	Unit	Carbone-Lorraine			SGL				POCO	h-BN
		1940	2020	2333	R7500	CZ3	CZ5	CZ7	ZXF-5Q	AX05
Apparent Density	g cm^{-3}	1.76	1.77	1.86	1.77	1.73	1.84	1.88	1.78	1.91
Open Porosity	%	16	9	10	13	14	10	10	16	
Avg. Grain size	µm	12	16	5	10	20	10	3	1	
Young Modulus	Gpa	10	9.2	10	10.5	10	11.5	14	14.5	30
Thermal exp. Coeff.	µm/m °C	4.7	3.5	6	3.9	3.8	5.1	5.8	8.1	0.5
Thermal Conductivity	W/m°C	81	75	90	80	65	100	100		71/121
Electrical resistivity	µΩ m		16.5		14	18	13	13	19.5	$> 10^{14}$
Specific heat	J/kg °C	710	710	710	710	710	710	710	710	800
Flexural strength	MPa	45	41	76	50	40	60	85	115	22
Compressive Strength	MPa	91	100	167	120	90	125	240	195	23
Tensile strength	MPa	30	27	50	33	26	40	56	76	15
Ratio σ_c/σ_t	-	3.1	3.7	3.3	3.6	3.4	3.2	4.3	2.6	1.5
$K \sim (\sigma_t C_p)/(E\ \alpha)$	-	0.45	0.60	0.59	0.57	0.49	0.48	0.49	0.46	0.80

A wide range of graphites was investigated. Based on material data available in literature, the best candidates have been identified. The table shows a selection of grades considered.

Material properties

	Aluminum 6061-T6	AlBeMet	Beryllium I-220H
Density (g/cm3)	2.7	2.1	1.85
Young Modulus (GPa)	69	196	303
Thermal exp. Coeff. (ppm/C)	23.4	13.9	11.4
Thermal conductivity (W/mC)	180	212	216
Electrical resistivity (micro-ohm m)	0.038	0.033	0.043
Specific heat (J/kgC)	963	1506	1925
Tensile strength (MPa)	310	305	448
K (but also need to scale by density and dE/dx, so Al another *x* 1.5 worse)	0.185	0.17	0.25