NuMI Target: Today and Tomorrow

Outline:

- NuMI Beam Parameters
- Design Constraints
- Thermal and Stress Analysis
- Instrumentation
- Radiation Damage
- Target Tests
- Upgrade to 1.6 MW(+)

Beam Parameters and Upgrade Path

NuMI beam design parameters:

- 0.4 MW beam power
- 120 GeV/c proton beam
- 4×10^{13} protons per 8.6 μsec beam spill
- 1.87 sec repetition rate
- 1 mm RMS circular beam spot size

Upgrade path considered to 1.6 MW (+) design:

- 120 GeV/c proton beam
- Double number of protons per spill
- Double repetition rate (higher repetition rate easier to handle than instantaneous)

IHEP Protvino design team

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FNAL design team

J.Hylen, K.Anderson

FNAL beam test

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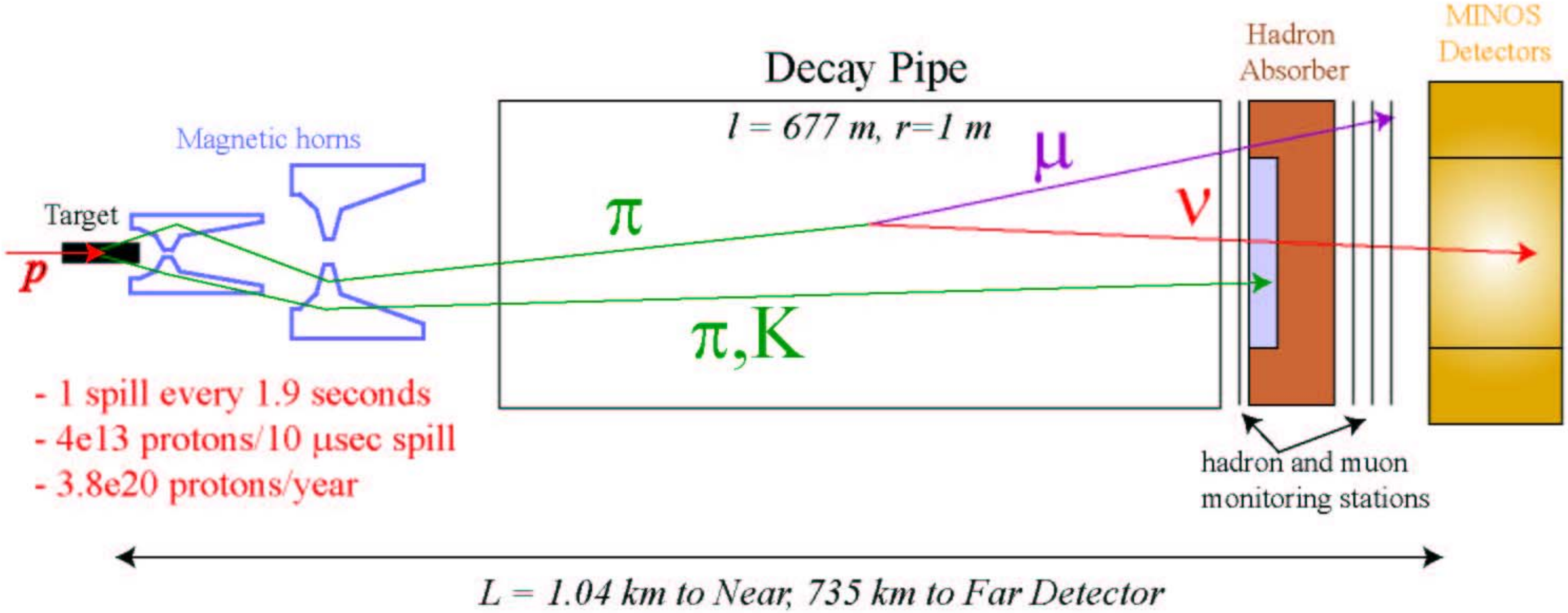
Energy deposition calculations done with MARS
Target construction done at IHEP

How ν beam is produced

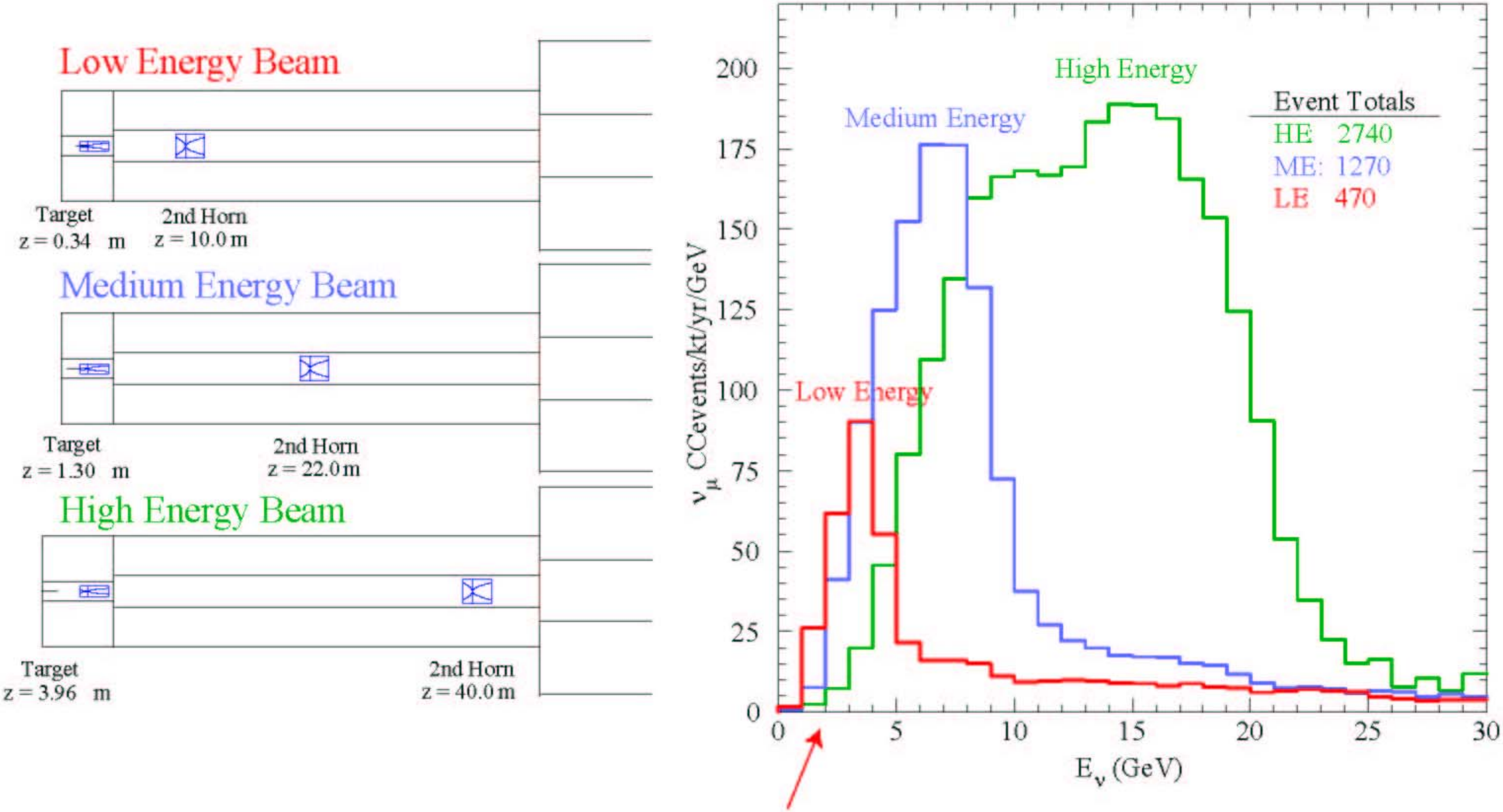
120 GeV/c protons strike graphite target

Magnetic horns focus charged mesons (pions and kaons)

Pions and kaons decay giving neutrinos

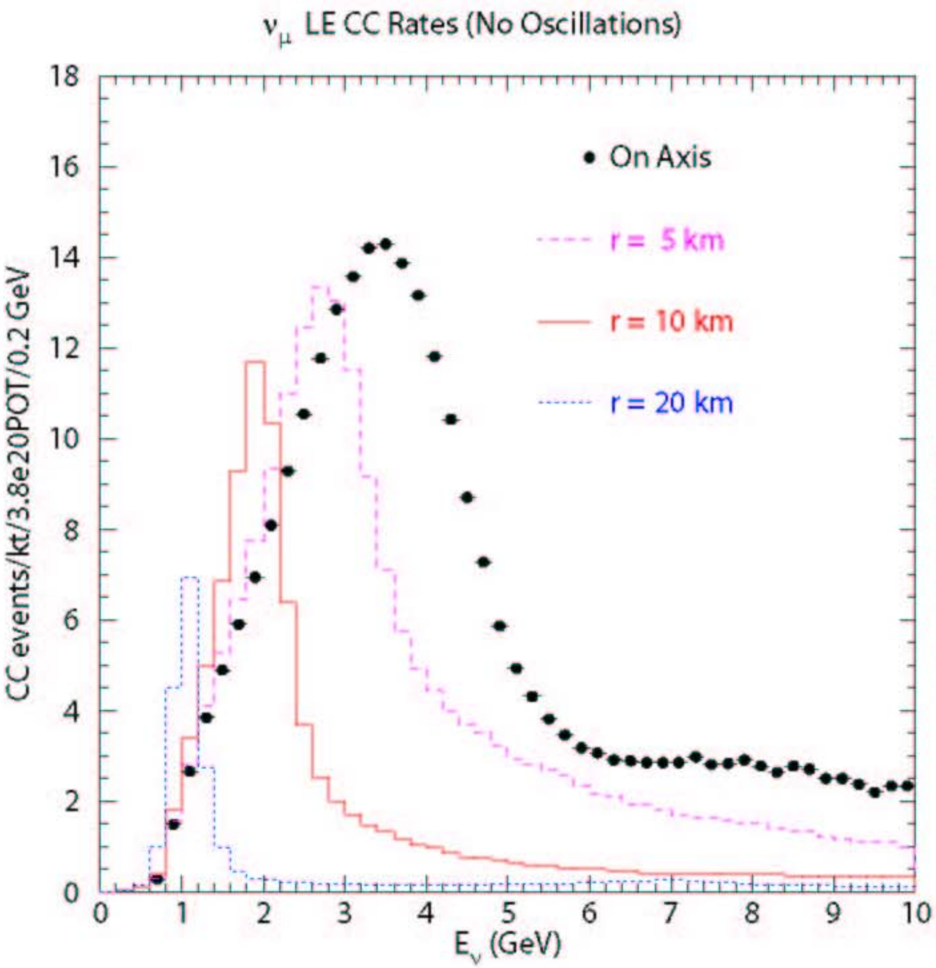


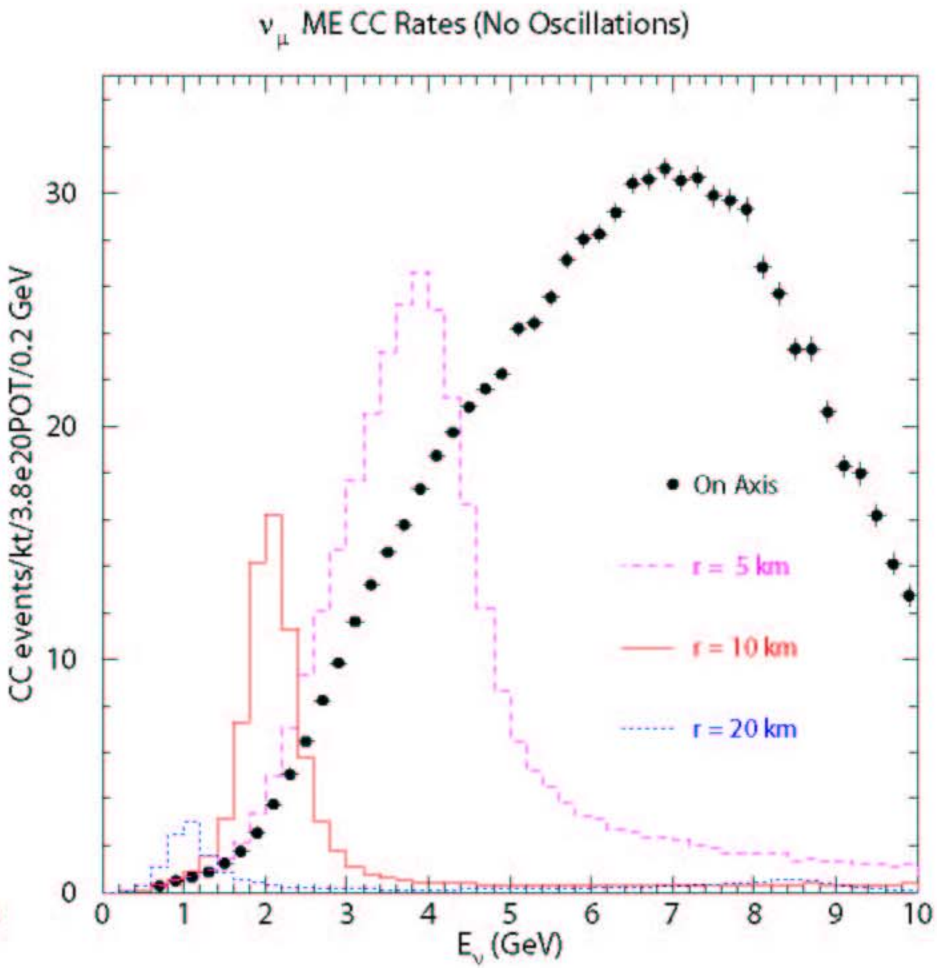
Different ν spectra obtained by moving target and 2nd horn



MINOS on-axis: Low energy beam selected to start -> Target in horn (L.E. configuration)

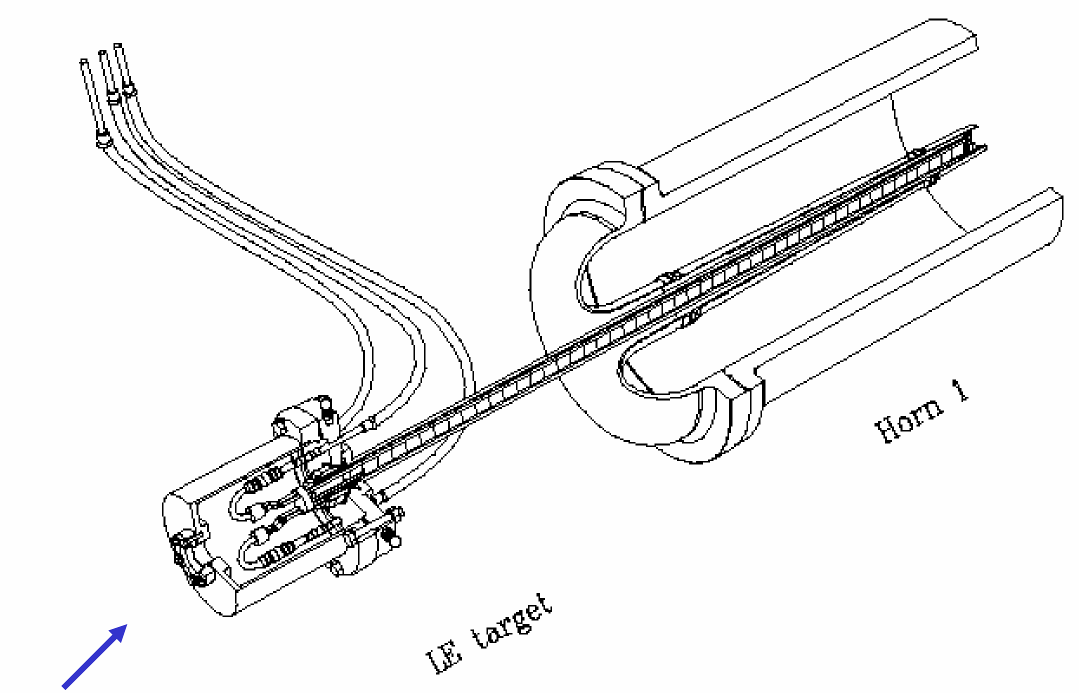
ν_μ spectra moving off-axis
(unoscillated, GEANT M.C.)



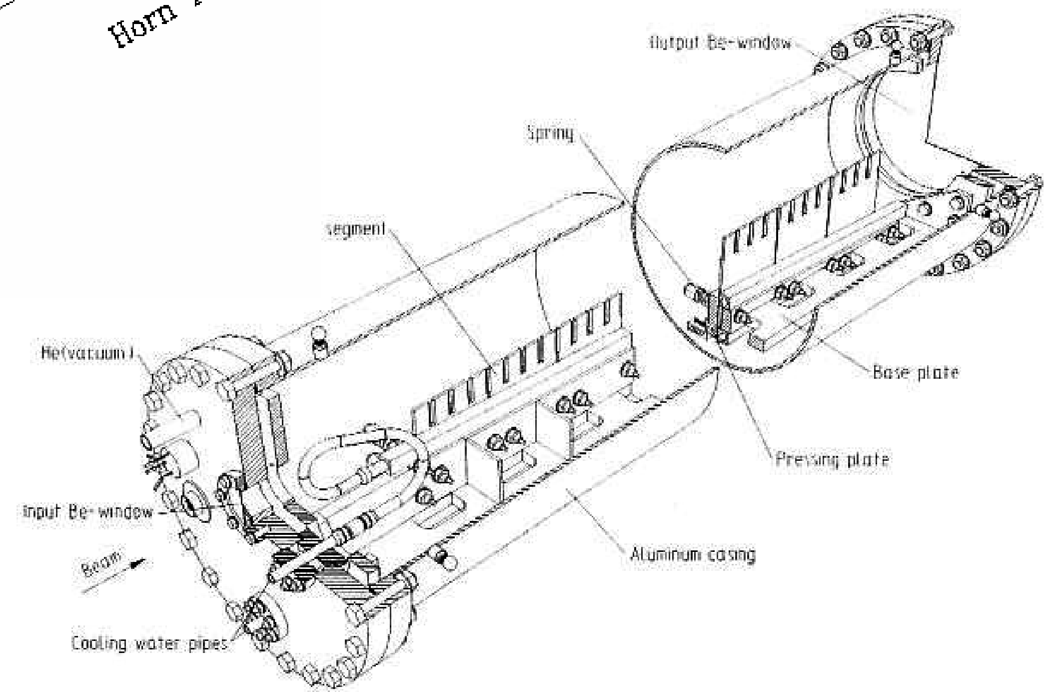


Off-axis detector experiment probably prefers M.E. configuration (target outside horn)

NuMI target types



Low Energy Target must fit in horn



Medium Energy Target

has more space for cooling,

target outer vessel gets less beam

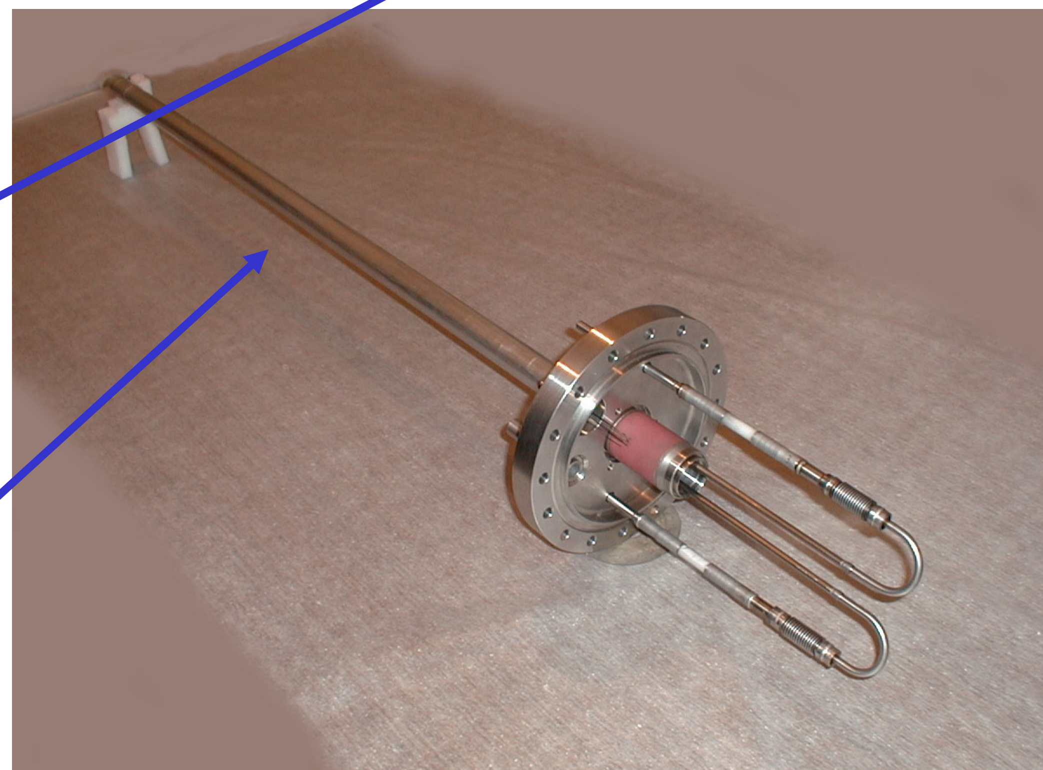
Low Energy Target

will be used for MINOS

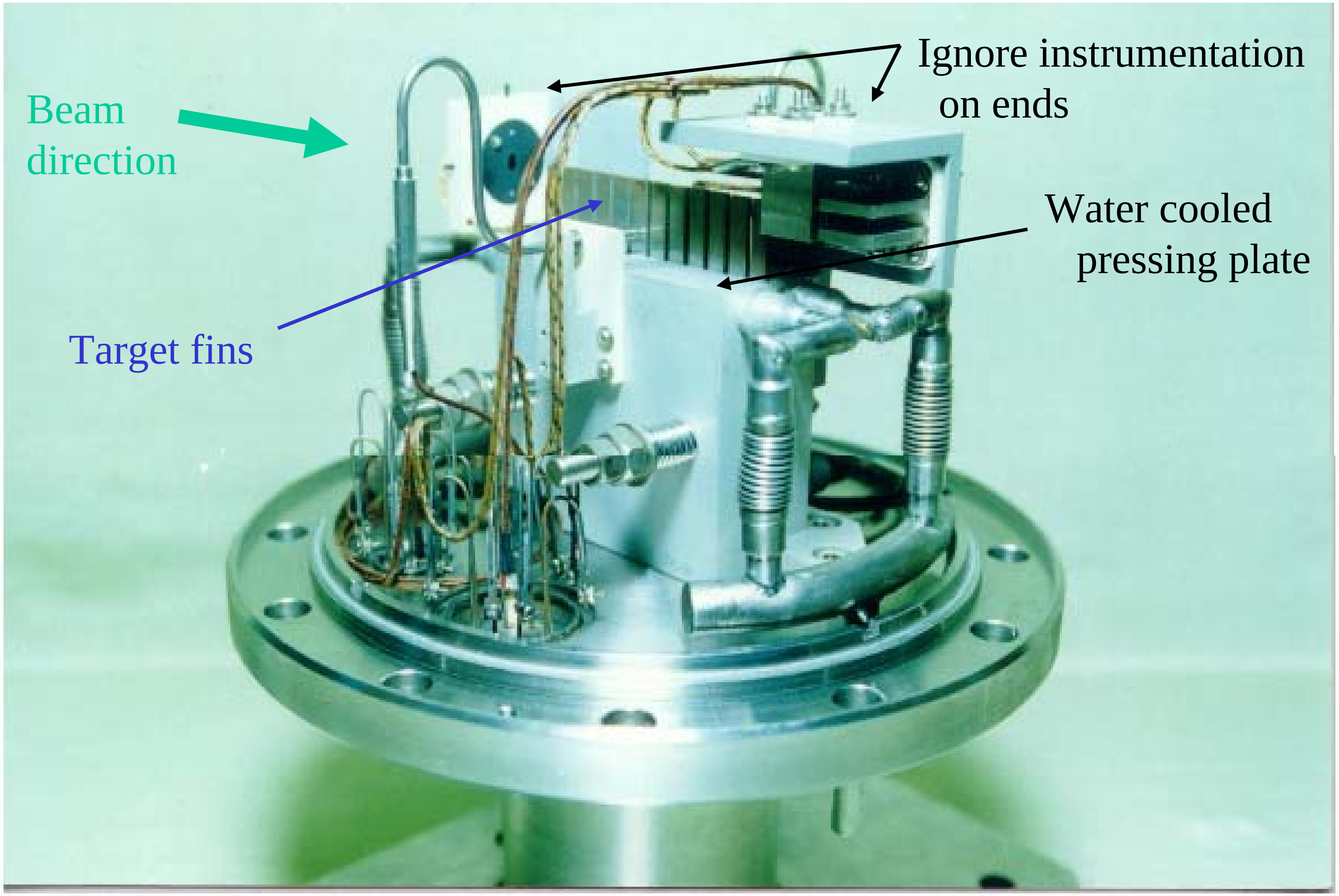
Graphite Fin Core
2 int. len.

Water cooling tube
also provides mechanical
support

Aluminum vacuum tube



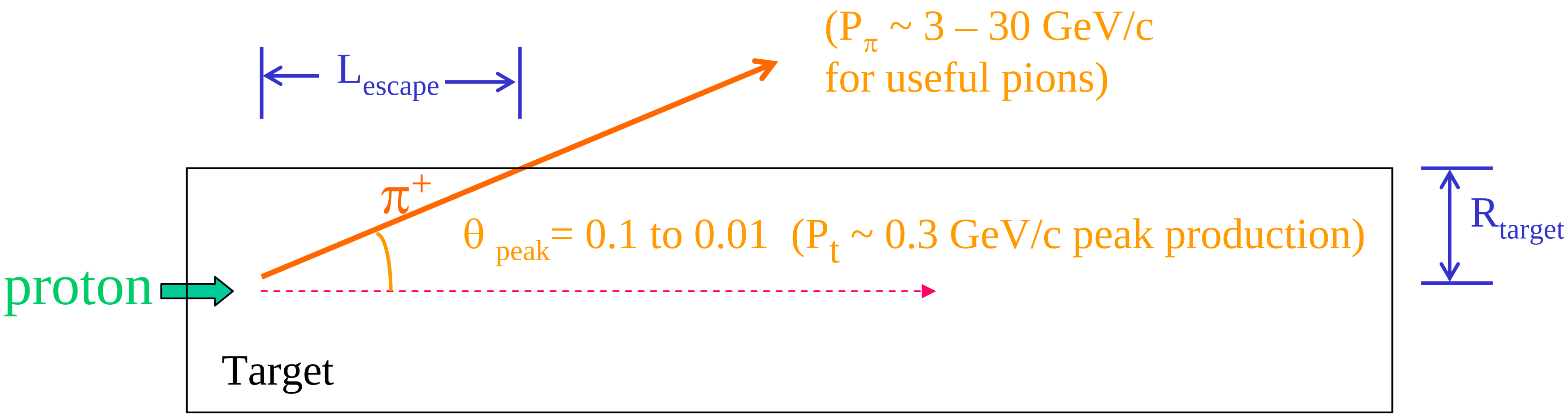
NuMI Prototype Target
M.E. style section used in beam test



Space between fins prevents buildup of dynamic stress along beam direction

Neutrino targets should be long, narrow, low density

(less true for L.E. : larger angle + less horn depth of field)



Example:

For R_{target} = 3 mm => L_{escape} = 3 cm to 30 cm

compared to 48 cm int. len. for graphite

NuMI full width of fin: 6.4 mm (L.E.) / 3.2 mm (M.E.)

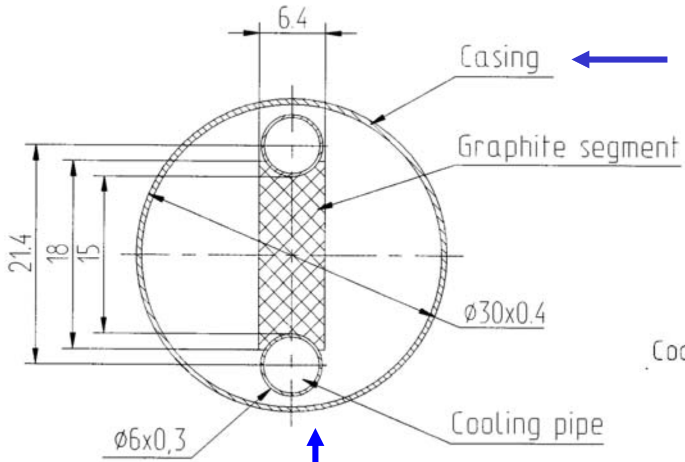
Narrow target lets π escape out sides

but

Small p-beam spot size -> high stress

Target – Low Energy Version

(Low Energy refers to neutrino spectrum, not beam power)



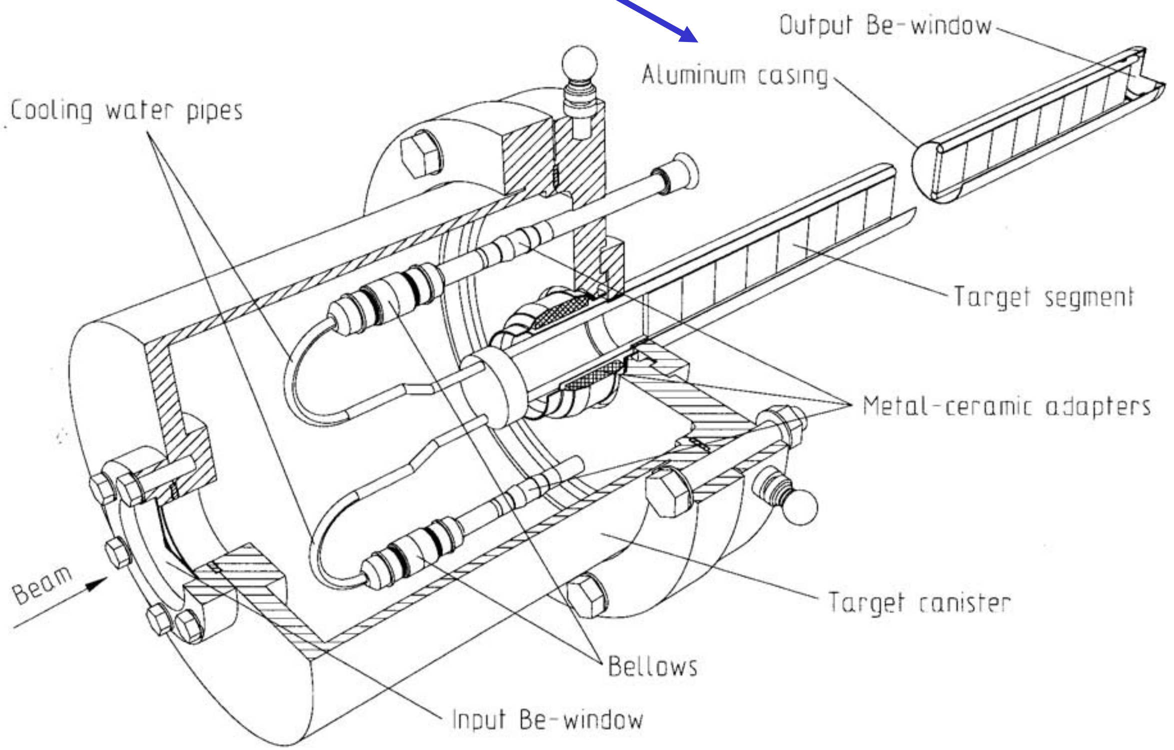
Casing of target fin electrically insulated from base. Wire strung from case to top of module. When moving, can sense if case touches horn by short to "ground".

Narrow – location checked by scanning beam across edge.

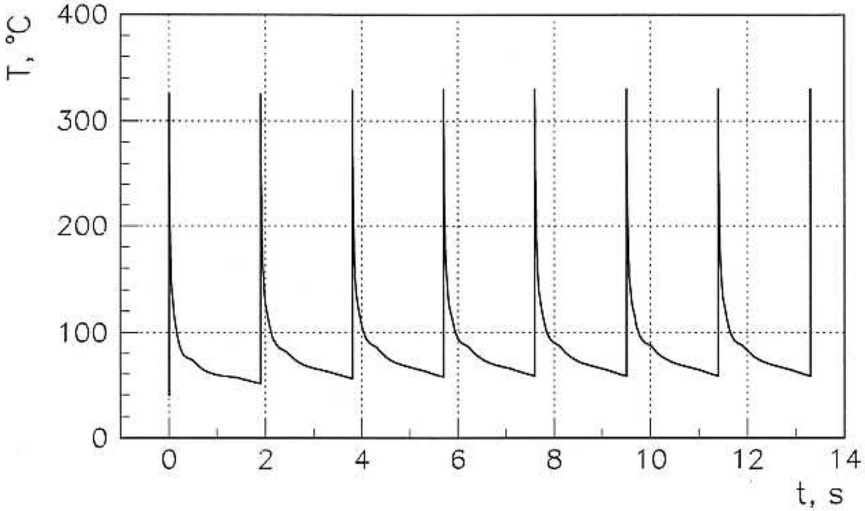
Sense by:

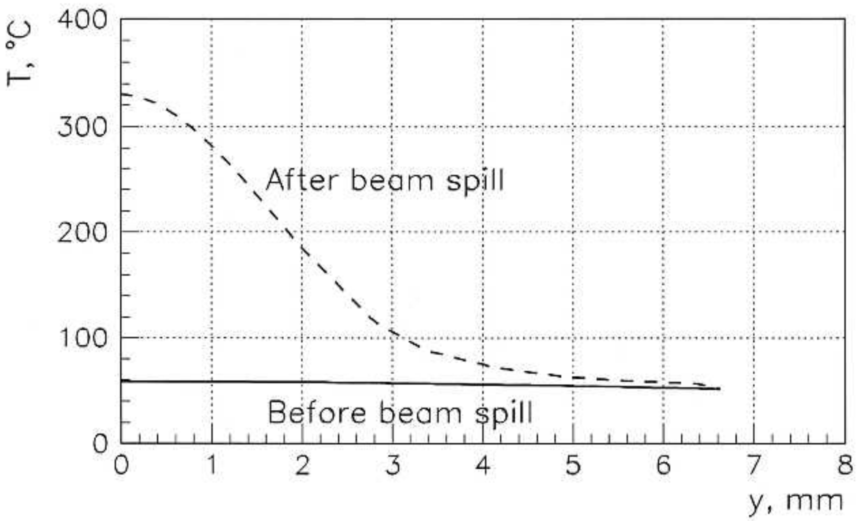
(i) charge (delta-rays) knocked out (wire connected to target) (called Budal)

(ii) scattered beam into cross hairs ionization chamber (BLM)



Target Temperature
- lots of headroom



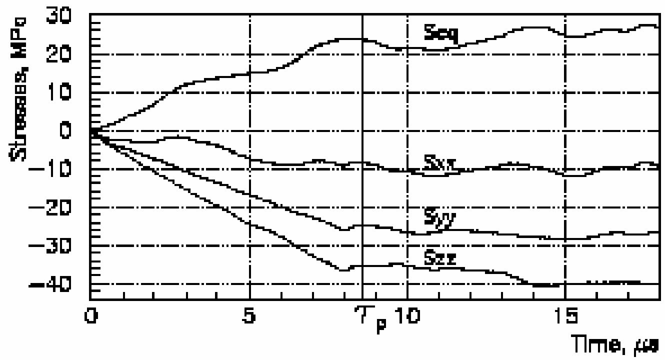


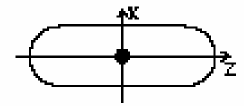
- Instantaneous temperature
  - room for large factor increase, far from even sublimation (~2000 C)
- Heat easily conducts to water line, many times average load no problem
- *Would want to increase diameter of water line to allow for more flow so L.E. target does not warp*

Velocity of a cooling water, m/s	2	3	4
Heat transfer coefficient, $kW/m^2/K$	10	14	18
Pressure drop, atm	0.32	0.68	1.2
Water flow rate, l/min	2.7	4.1	5.5
Water temperature rise, °C	18	12	8.8

Target dynamic stress?

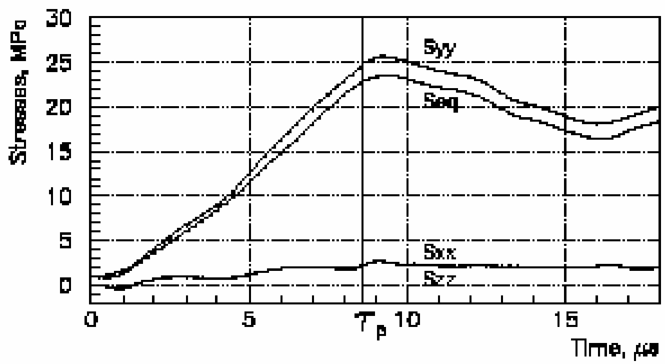
(Approximately linear with instantaneous protons)

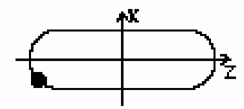




$(S_{eq})_{max} = 27.4$ MPa

Current safety factor of 3.8
at fin center
– can increase with:
larger spot size
different graphite (next slide)





$(S_{eq})_{max} = 23.5$ MPa

Current safety factor of 2.2
at curved edge of fin
– can increase with:
different graphite (next slide)
thicker fin (at some cost in ν)

ZXF-5Q (1.81 g/cm^3): Compressive Strength 210 MPa
Tensile Strength 95 MPa

The high cycle fatigue endurance limit of graphite is 0.5–0.6
The safety factor is $\frac{(0.5-0.6)\times 95}{23.5} \sim 2.2$

Our target concept evolves reasonably well to double the instantaneous proton rate

Target Material - Graphite

(Higher A would give more pi for low energy beam, but energy density becomes problematic)

From L.Bruno, CERN

Graphites and hBN - Material Properties at 20 °C

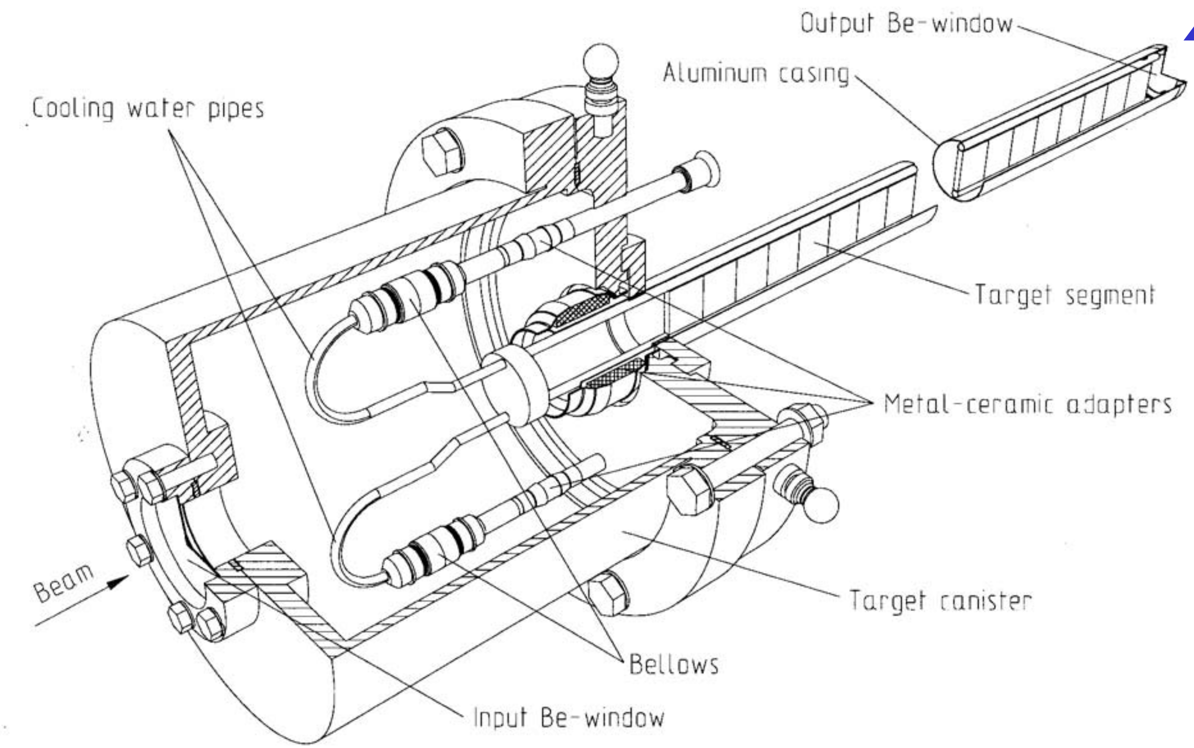
Property	Unit	Carbone-Lorraine			SGL				POCO	h-BN
		1940	2020	2333	R7500	CZ3	CZ5	CZ7	ZXF-5Q	AX05
Apparent Density	$g\ cm^{-3}$	1.76	1.77	1.86	1.77	1.73	1.84	1.88	1.78	1.91
Open Porosity	%	16	9	10	13	14	10	10	16	
Avg. Grain size	µm	12	16	5	10	20	10	3	1	
Young Modulus	Gpa	10	9.2	10	10.5	10	11.5	14	14.5	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

Graphite R7650 has figure-of-merit K = 0.66,
presumably improves safety factor by x 1.4 over NuMI ZXF-5Q

Carbon-fiber/carbon-matrix composite materials may be even better

Budal for L.E. target

In current design, downstream end of aluminum vacuum tube reaches 190 deg C
- it is insulated from water cooling to allow Budal monitor to work.



For higher beam power, must connect this tube to water cooling – probably giving up Budal *(alternative – make casing from Be?)*

Budal could be retained in M.E. target

Radiation Damage

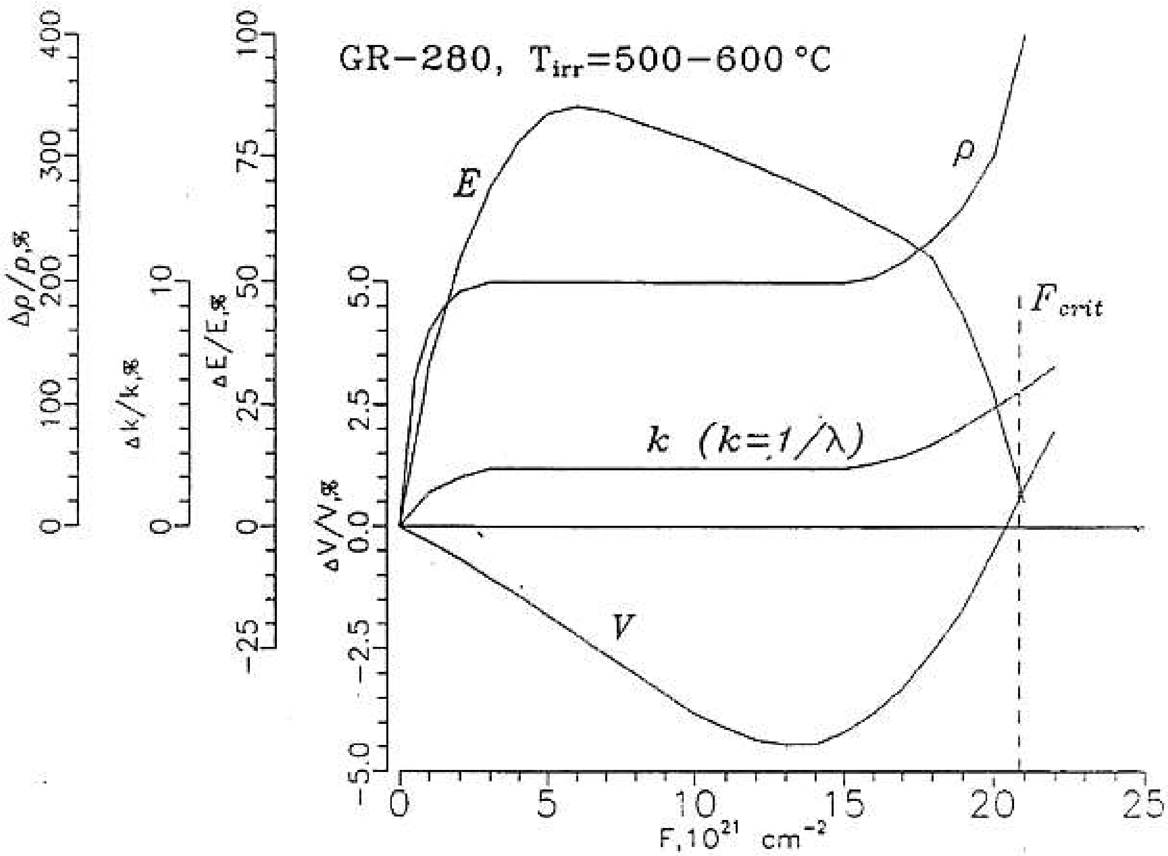


Fig.1. Determination of critical value of neutron fluence for graphite and changing of its physical properties under irradiation. V – volume changing; E – elastic modulus; k – thermal resistance; ρ – electrical resistance.

Radiation Damage and Life-time Evaluation of RBMK Graphite Stack, *XA9642904*, P.A.Platonov, O.K.Chugunov, V.N.Manevsky, V.I.Karpukhin, Russian Research Center Kurchatov Institute

Most radiation damage info is from reactor neutrons

In this example, graphite self-destructs at ~ $2x10^{20}$ n/mm^2

Highest radiation density in NuMI target is proton spot near entrance ~ $0.5x10^{20}$ p/mm^2 / year

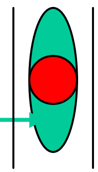
NuMI target test accumulated $0.023x10^{20}$ p/mm^2 with no visible damage

Target longevity uncertain – will gain experience in 2005

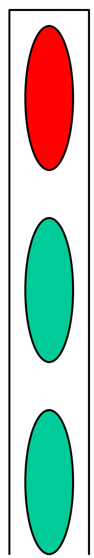
Any fall-backs in case of rapid radiation damage ?

Factor of a few:

1) Increase spot size along fin (current L.E. could increase both directions)

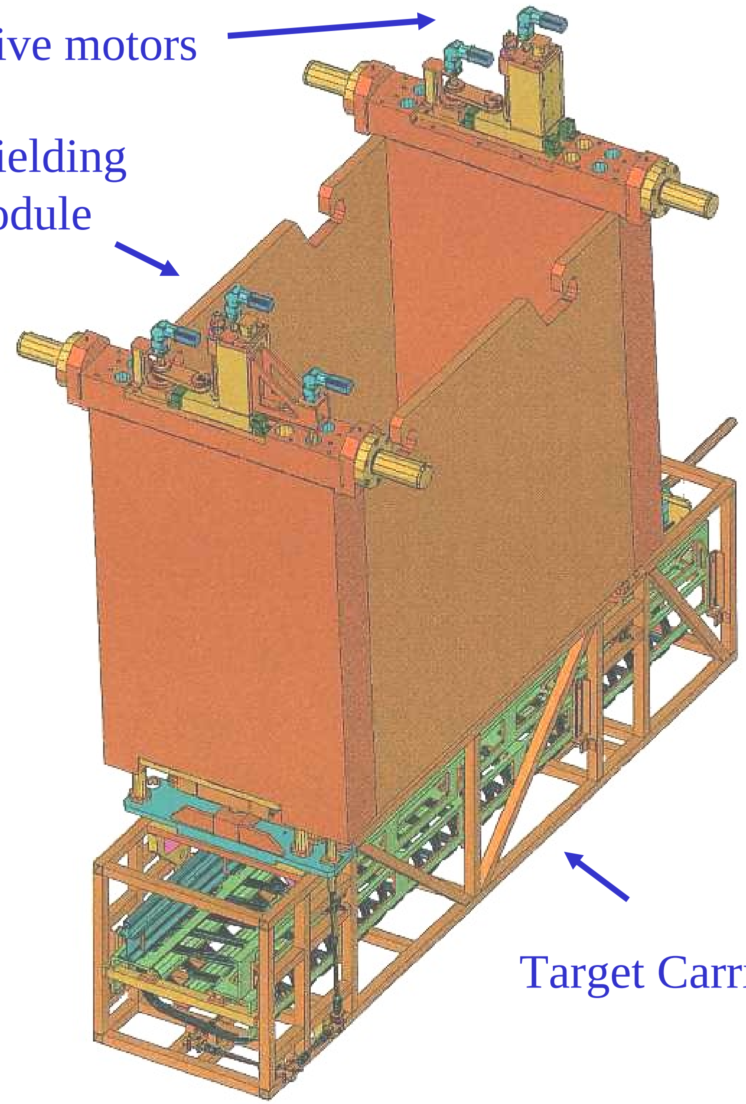


2) In case of M.E. style, periodically move fin to get fresh material



Modest loss in efficiency further from top of fin

Target module already has capability to do this



Target Test Conditions

Goals:

- High stress pulses cause visible damage?
- Radiation cause visible damage?
- Budal monitor work for beam alignment?
- Graphite vs Beryllium

Prototype thinner fin, smaller spot to obtain similar stress, temperature

Highest stress pulses in test 10^{13} protons 0.21 mm x 0.16 mm calculated to be at non-fatigue stress limit
-- no visible damage under microscope !

PROPOSAL	Graphite			Beryllium	
	Baseline	Prototype		Baseline	Prototype
Subsegment length (mm)	18.4	8.0		12.6	6.0
Thickness (mm)	3.2	1.78		4.1	2.29
Beam Intensity (protons per pulse)	4×10^{13}	0.5×10^{13}	1×10^{13}	4×10^{13}	1×10^{13}
Beam size $\sigma_x \times \sigma_y$ (mm $\times$ mm)	0.67×1.28	0.30×0.30	0.40×0.40	0.88×2.00	0.49×0.98
T_{max} at steady state (^oC)	508	467	557	220	173
ΔT (^oC)	280	394	425	82	90
Maximum equivalent stress (MPa)	25	27	30	152	150

target test used:
7×10^{17} protons
3×10^{5} pulses
mostly 0.2×10^{13}ppp
0.2 to 0.3 mm RMS

Target Budal Monitor
in test beam

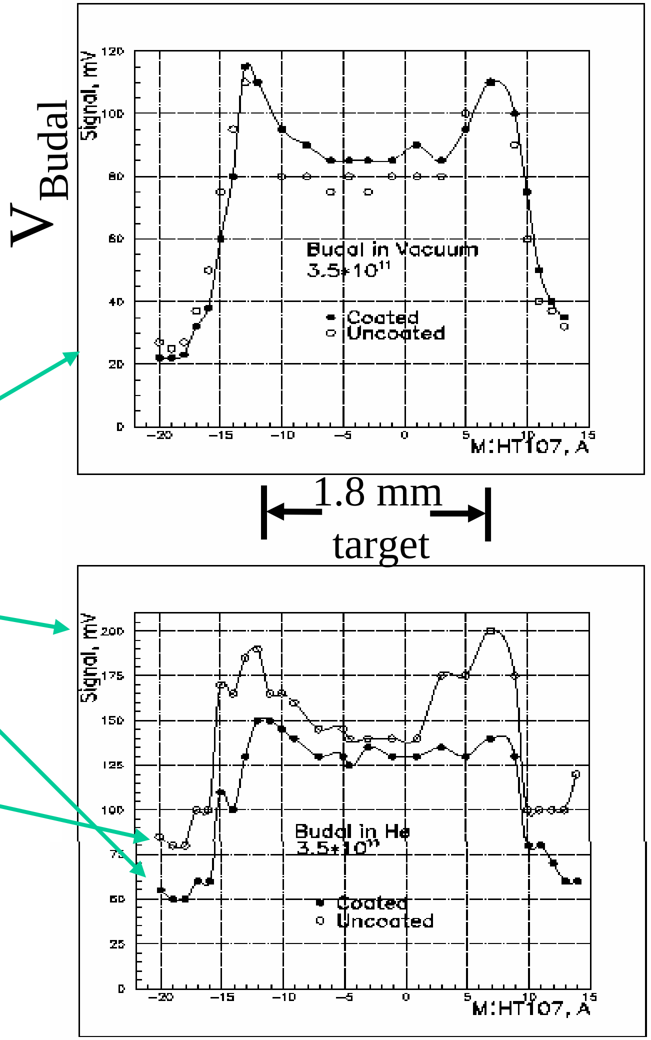
1) Electrically insulate target
2) Scan beam across target
3) Delta rays knocked out induce target voltage
4) Electronic readout of target = Budal Monitor

Highest signal is at edges of target

Better signal-to-noise for target-in-vacuum than target-in-He

In Helium, insulator coated (silicon nitride) graphite gets less background than bare graphite

Can locate target to ~ 0.1 mm



Target Upgrade summary

System	Issue	2 x 0.4 MW = 0.8 MW	2 x 0.4 MW = 0.8 MW	4 x 0.4 MW = 1.6 MW
(structure of delivered proton rate increase)	**preliminary**	Double protons per pulse: 8e13 at 0.5 Hz	Double repetition Rate: 4e13 at 1 Hz	Double both: 8e13 at 1 Hz
Target - assume switch to NuMI ME type target for off-axis (prefered)	cooling	increase water line diameter and water flow rate; check if need to water cool outer can	increase water line diameter and water flow rate; check if need to water cool outer can	increase water line diameter and water flow rate; check if need to water cool outer can
Target - if still want LE type target	cooling	larger water line, connect cooling to outer can giving up on Budal monitor	larger water line, connect cooling to outer can giving up on Budal monitor	pull back few cm, allowing larger target can for larger water lines, no Budal
(generic to both targets)	radiation damage	target lifetime not well known; will gain experience with MINOS	target lifetime not well known; will gain experience with MINOS	target lifetime not well known; will gain experience with MINOS
	dynamic stress	change target material, increase fin thickness (?)	OK	change target material, increase fin thickness (?)
	sublimation	OK	OK	OK

New target, but water-cooled graphite probably OK
if
radiation damage lifetime OK

Conclusion

NuMI–style target with modifications look good for 1.6 MW (or even higher) beam
with caveat that radiation damage lifetime not known

Modifications:

- Probably choose different grade of graphite
- Increase water cooling tube diameter
- M.E. style target is more robust – good for off-axis
- Cool (or change material) of outer can for L.E. style target