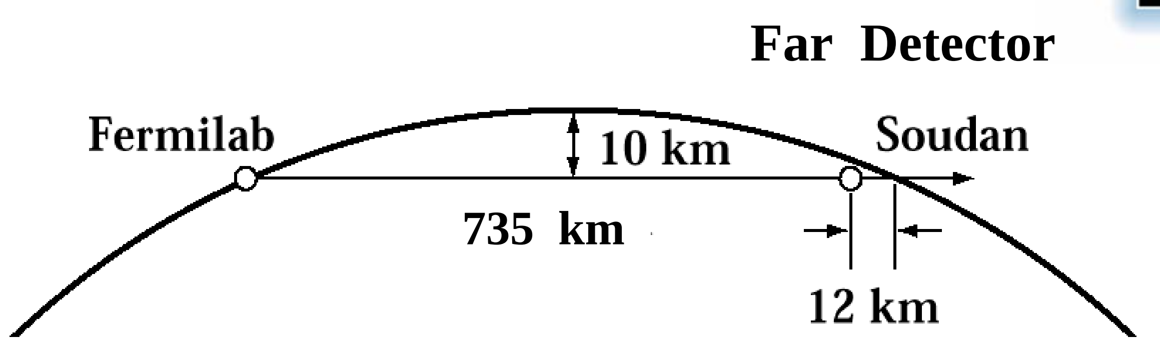
NuMI

NuMI Beam Characteristics

In this talk:

- Component layout and flexibility
- Neutrino flux for MINOS
- Report on first year of operation
- Off-axis neutrino flux for NOνA
- Target for higher power



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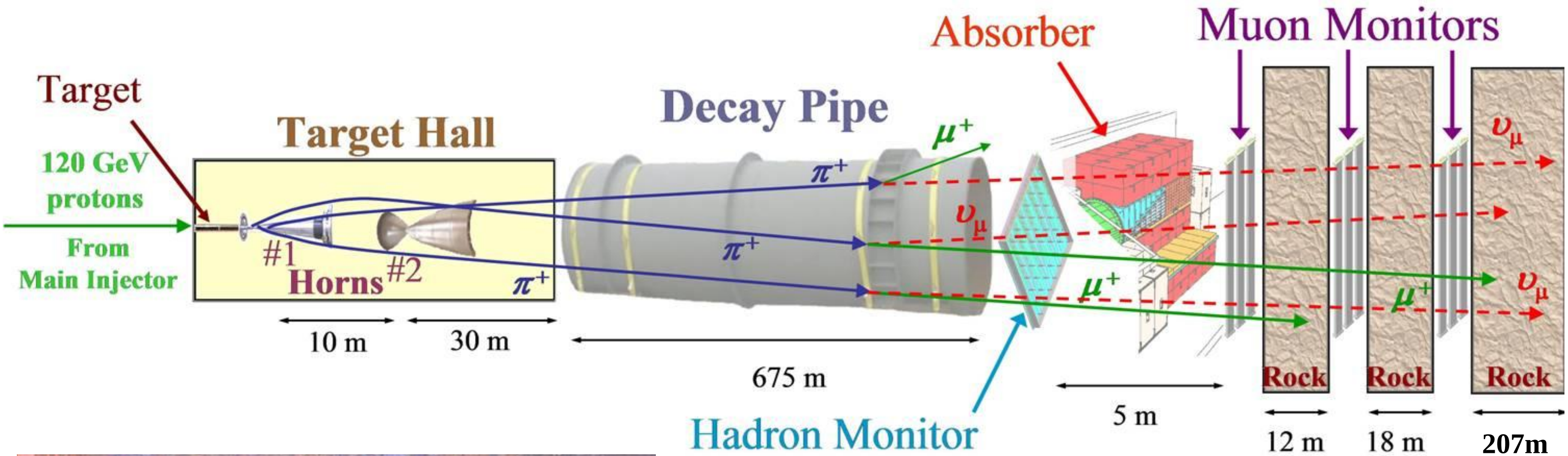
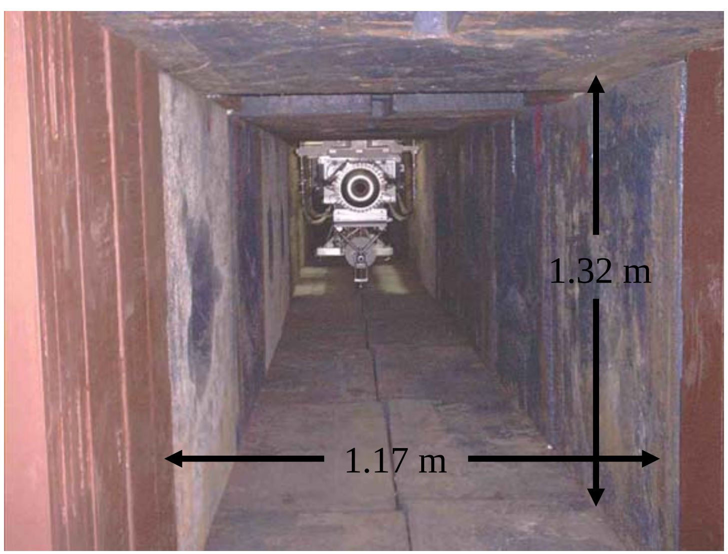
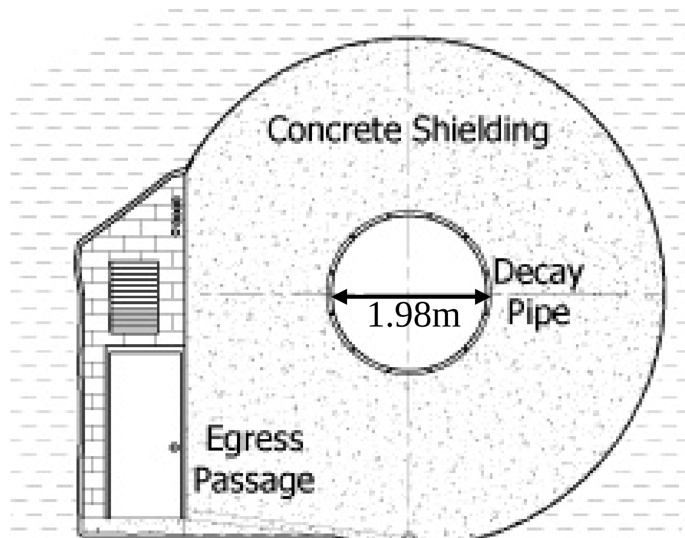
NuMI Neutrino Beam





Target pile shield for components is 47 m long



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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*

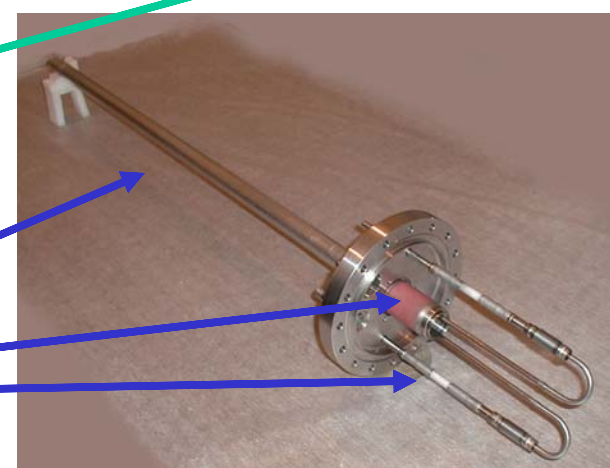
Water cooling tube also provides mech. support

Anodized Al spacer (electrical insulation)

Water turn-around at end of target

0.4 mm thick Aluminum vacuum/Helium tube

Ceramic electrical isolation



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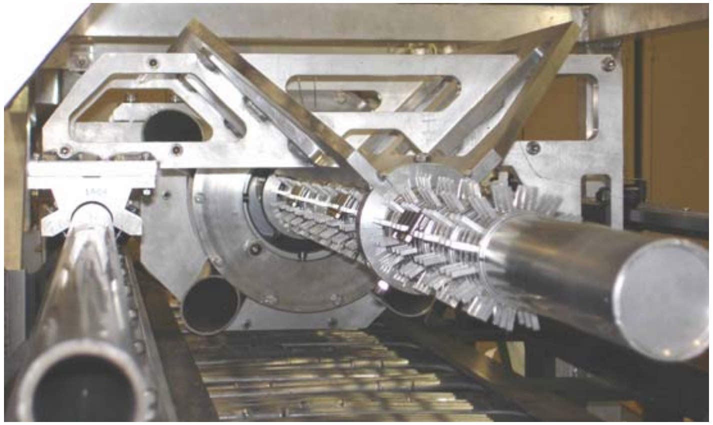
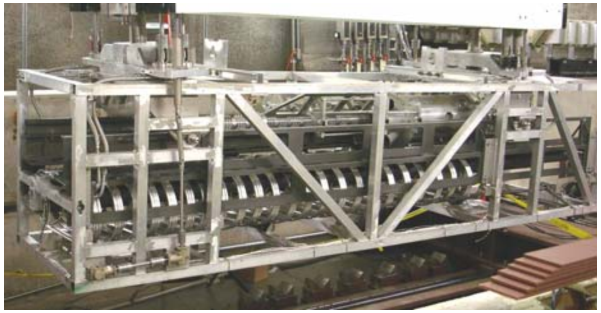
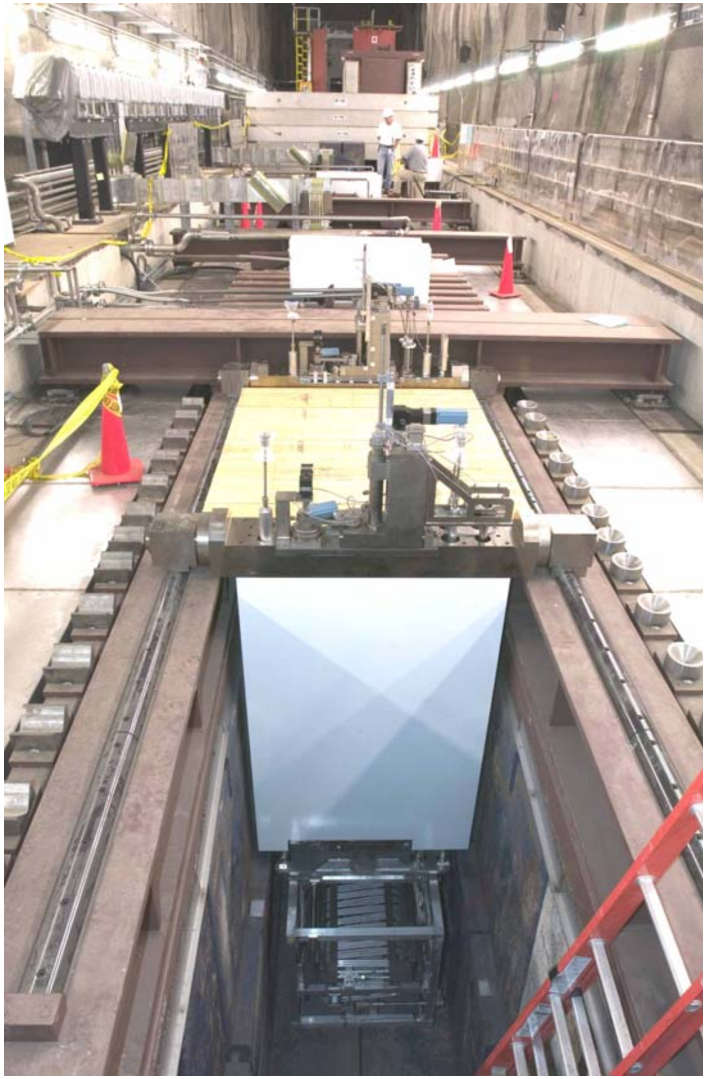
Target Carrier

Remote controlled movement 2.5 m along beamline

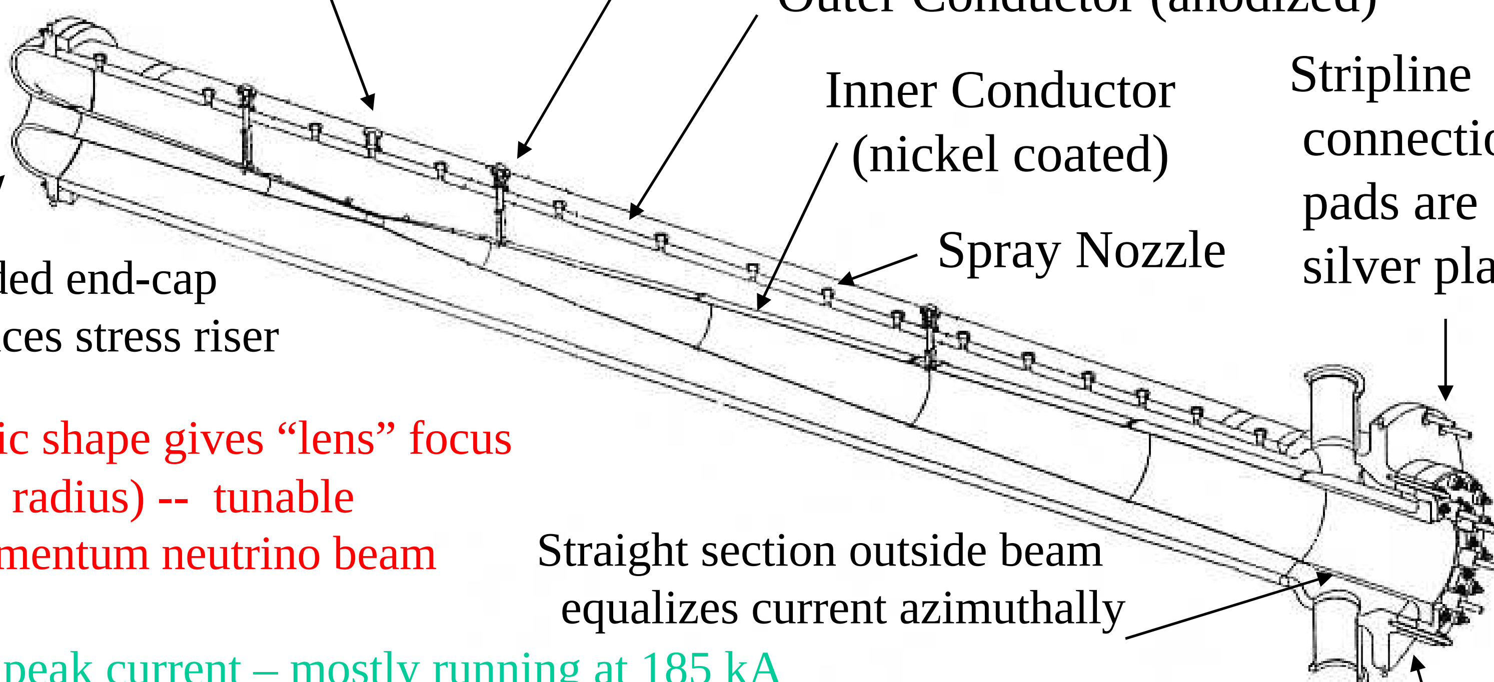
Upstream baffle to protect water pipe from beam;







NuMI Horn
General Design Features



Parabolic shape gives "lens" focus
(Bdl α radius) -- tunable
momentum neutrino beam

205 kA peak current – mostly running at 185 kA
3.0 Tesla peak field
2.3 milli-sec half-sine wave pulse
1.87 sec repetition rate

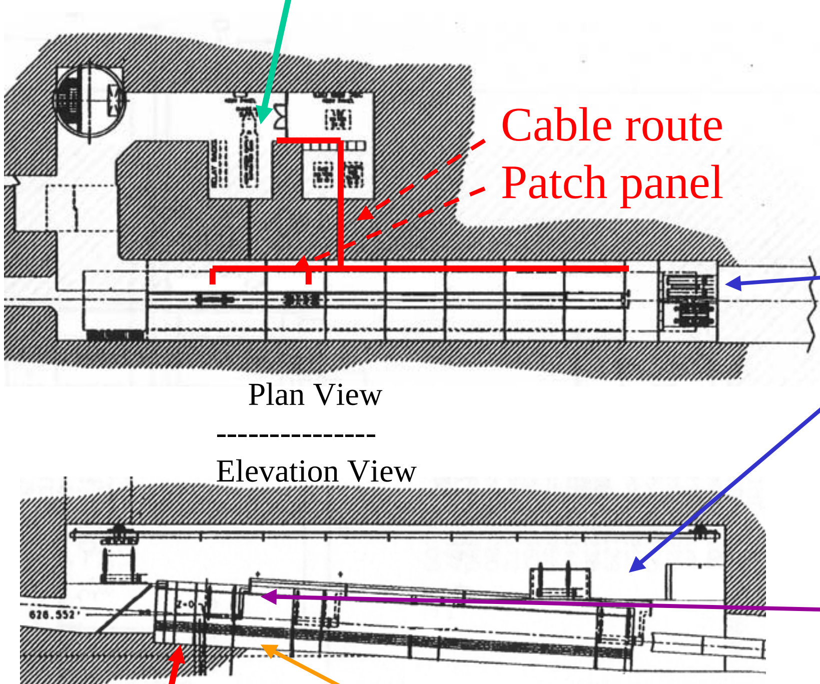
NuMI

Horns connected in series with power supply by strip-line

Have also done this installation remotely (via cameras) on radio-activated horn to replace horn foot

Radiation Dose Map

Power Supply Room: ~ 1 - 10 Rad/yr (MADC, differential pressure sensor, …)



Cable route

Patch panel

Target Hall above concrete covers:
~ 10^2 – 10^4 Rad/yr
(hot cell system, air recirculation system, humidity sensors)

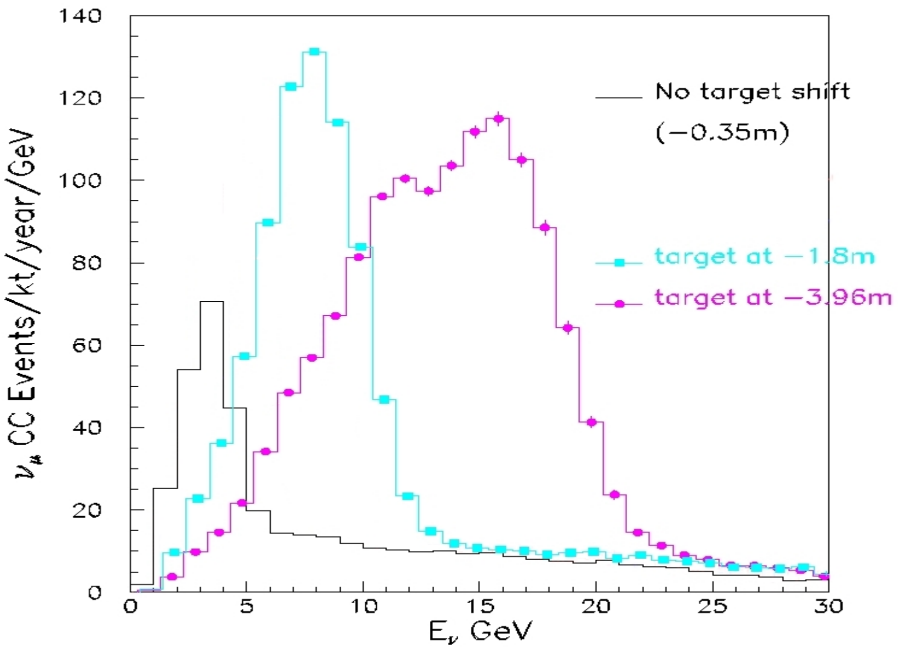
Top of module, under concrete cover:
~ 10^4 – 10^5 Rad/yr
(motors, LVDTs, limit switches)

Center of target:
3×10^{14} Rad/yr

Chase, around horns: ~ 10^{10} - 10^{11} Rad/yr
(thermocouples, bdot coils, BLM ionization chamber)

Reasonable High Energy beam can be produced by just moving LE target; get more efficient beam by also moving horn 2

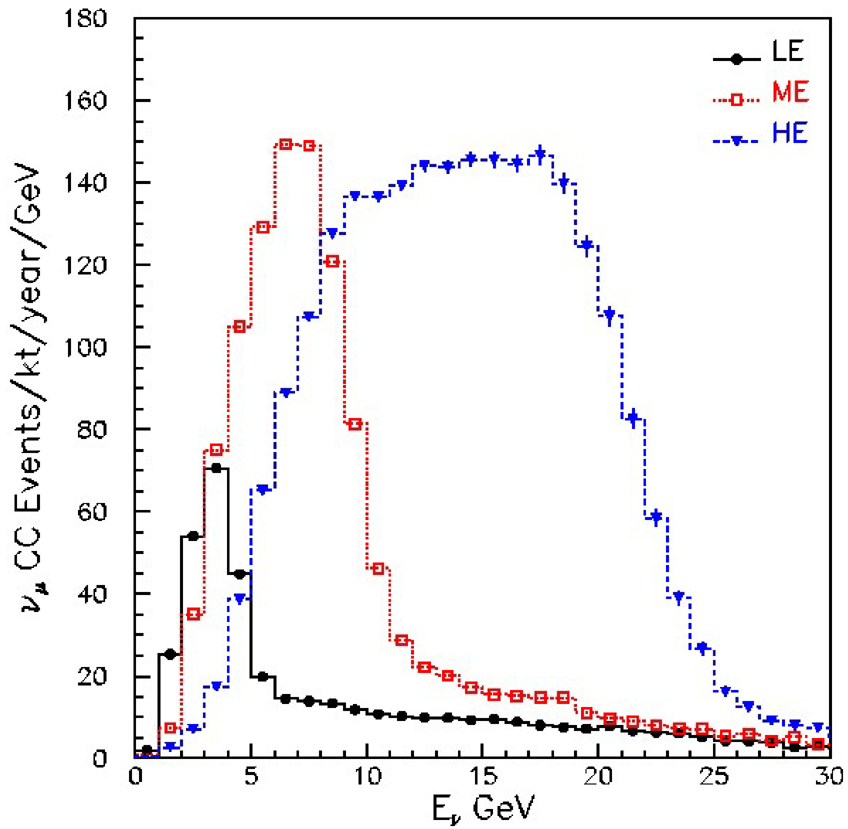
(Old M.C.s – just to show effect of moving horn)



“Semi-beams”

Just moving LE target

-can do at touch of button !



Full Beams

New target, move horn 2

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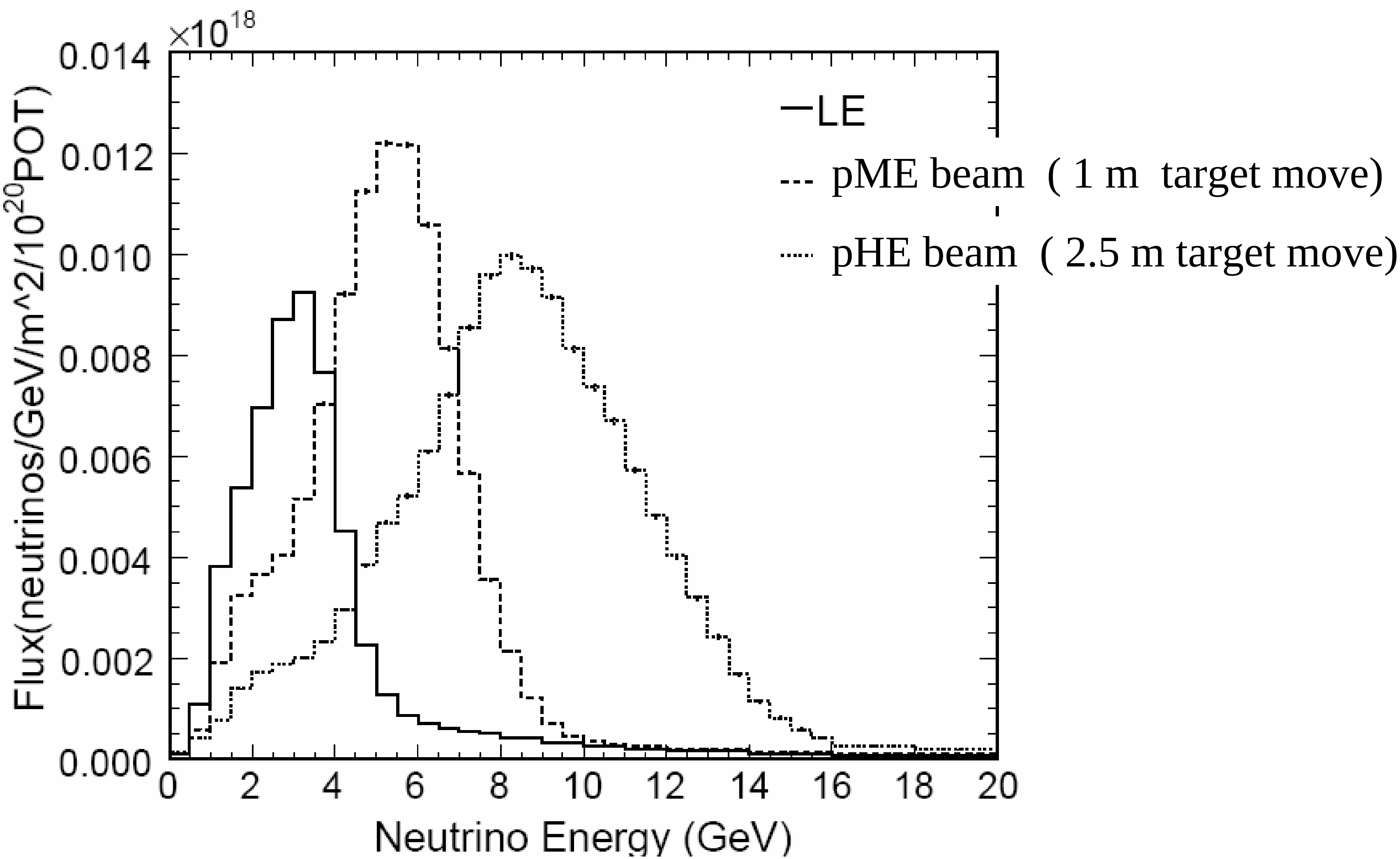
NuMI Neutrino Flux (M.C.) at MINOS far detector (735 km)



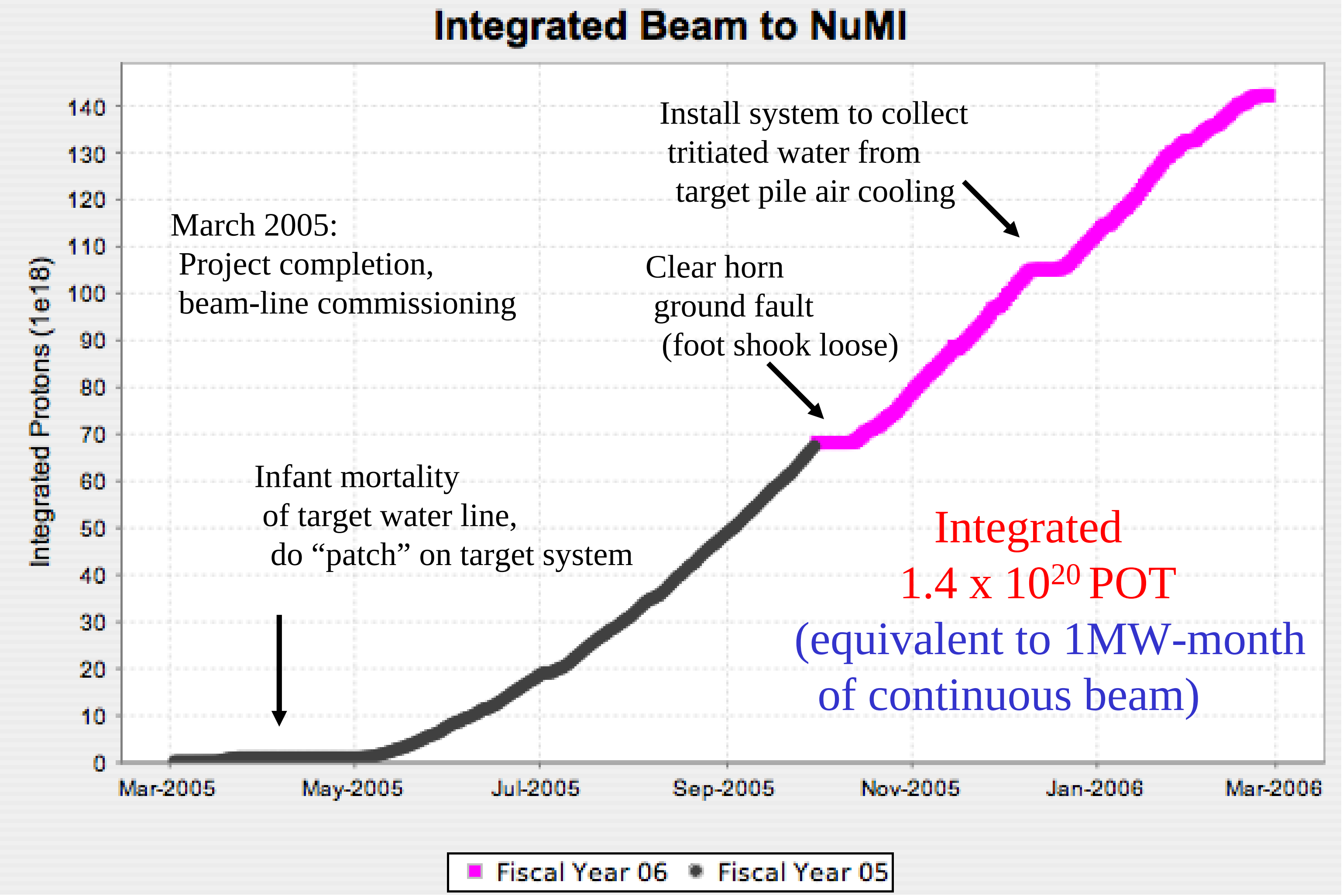
Operational Experience

Had one big bump in the road – a target water leak early in commissioning –

but now operating well !

	Max. Proton/spill	Max. Beam Power	Integrated Protons on Target
Designed to handle	40e12 protons / pulse	400 kW	370 e18 p.o.t. per year
Goal for 2005	25e12 p.p.p.	240 kW	75 to 100 e18 p.o.t.
Before target leak	25e12 p.p.p. *11e12 day before leak*	69 kW	0.7 e18 p.o.t.
After leak	30e12 p.p.p. *typically 22e12*	270 kW *typically 200 kW*	140 e18 p.o.t.

1^{st} year of beam operation



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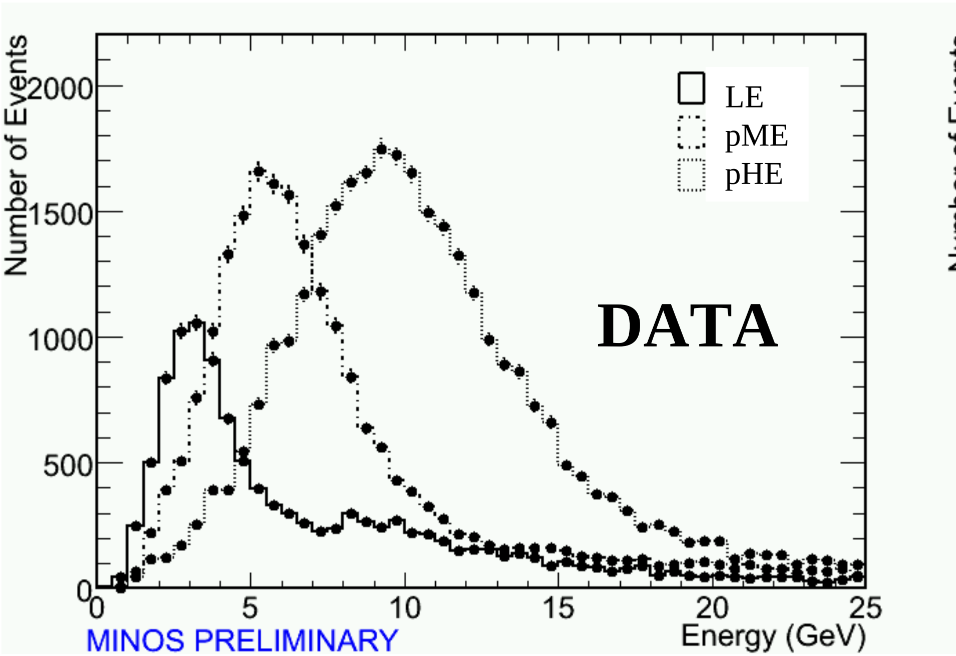
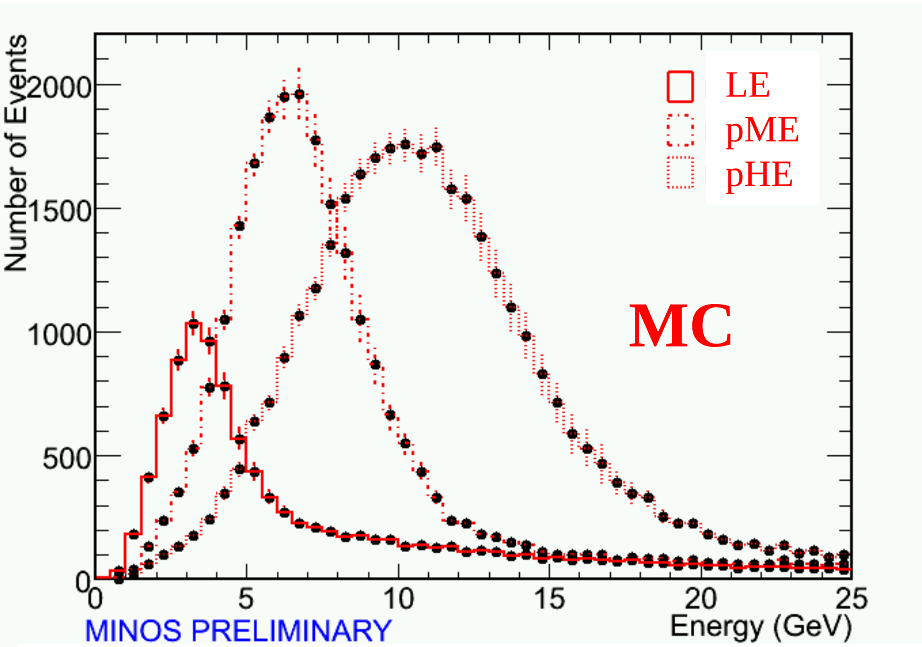
Neutrino data demonstrating variable focusing (*preliminary*)

MINOS Near Detector, normalized to Protons-on-Target





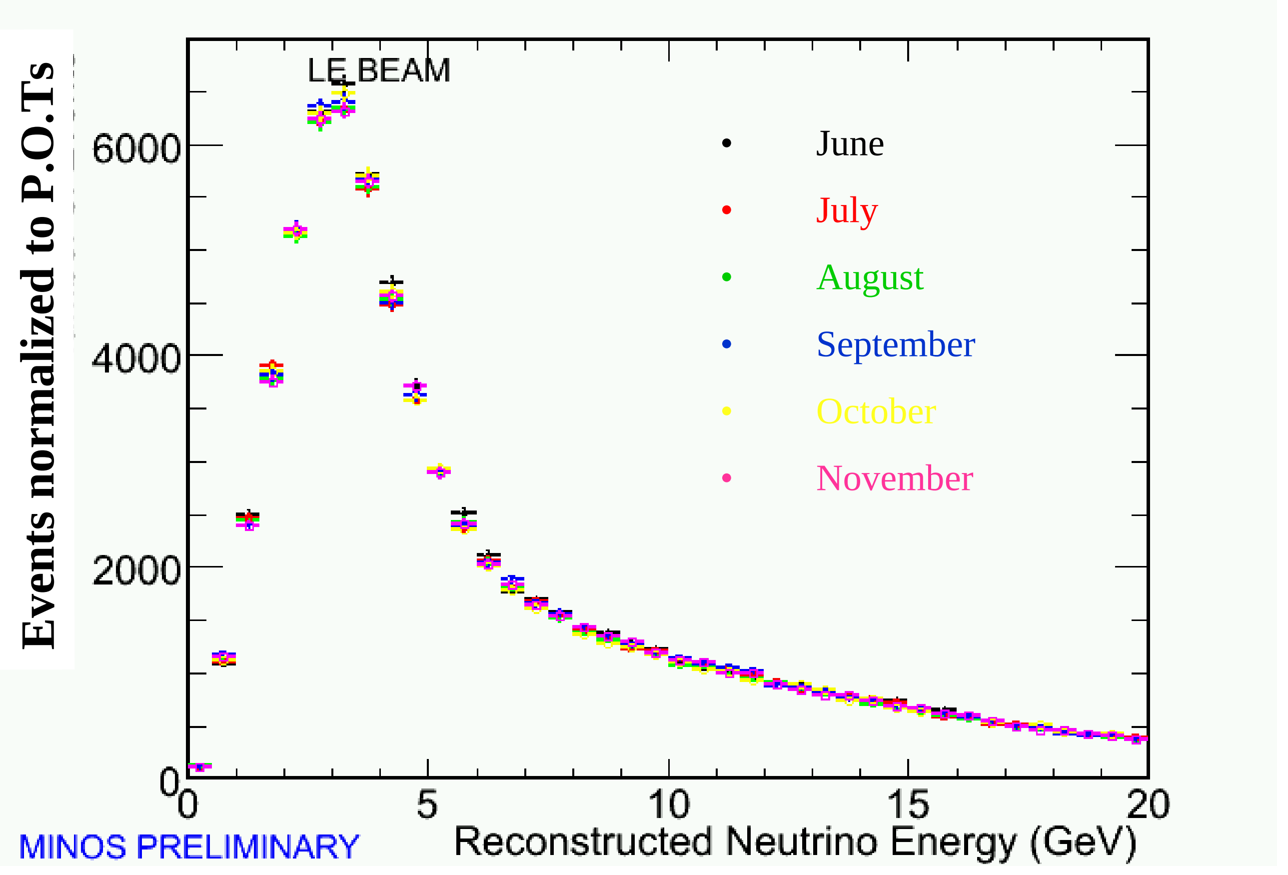
NO BIG SURPRISES

Working on systematics for detailed comparison:

- **Hadron production in target - (being measured in E907 / MIPP Experiment)**
- **Neutrino cross sections**
- **Event reconstruction**

Beam &Near Detector Stability - Data

Beam, Detector Performance and Event Reconstruction very stable.



(Not yet corrected for beam spot size on target, etc.)

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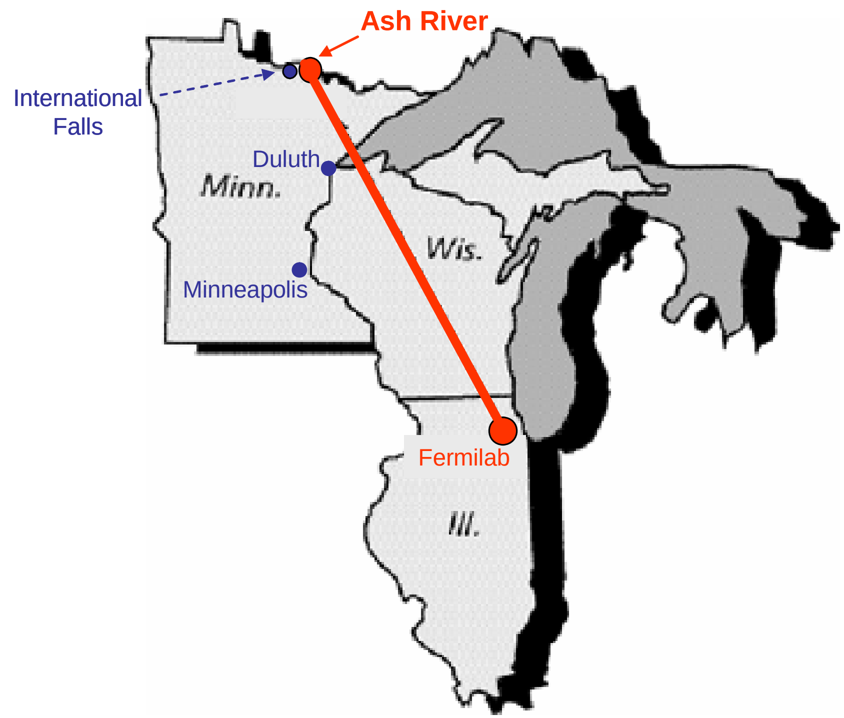
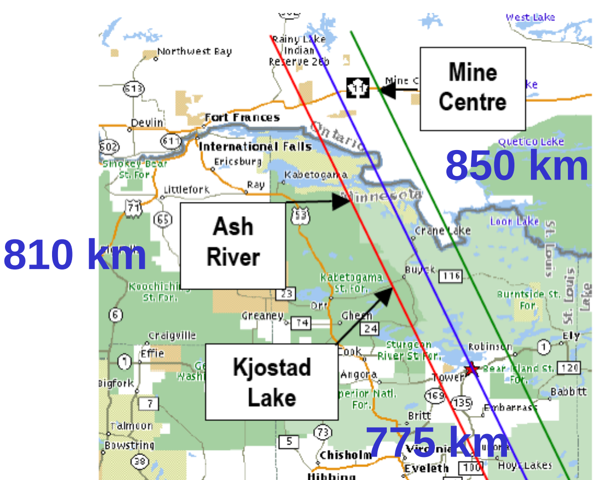
NOvA Detector off central axis of NuMI beam





NuMI

Can tune target-horn spacing for off-axis spectra

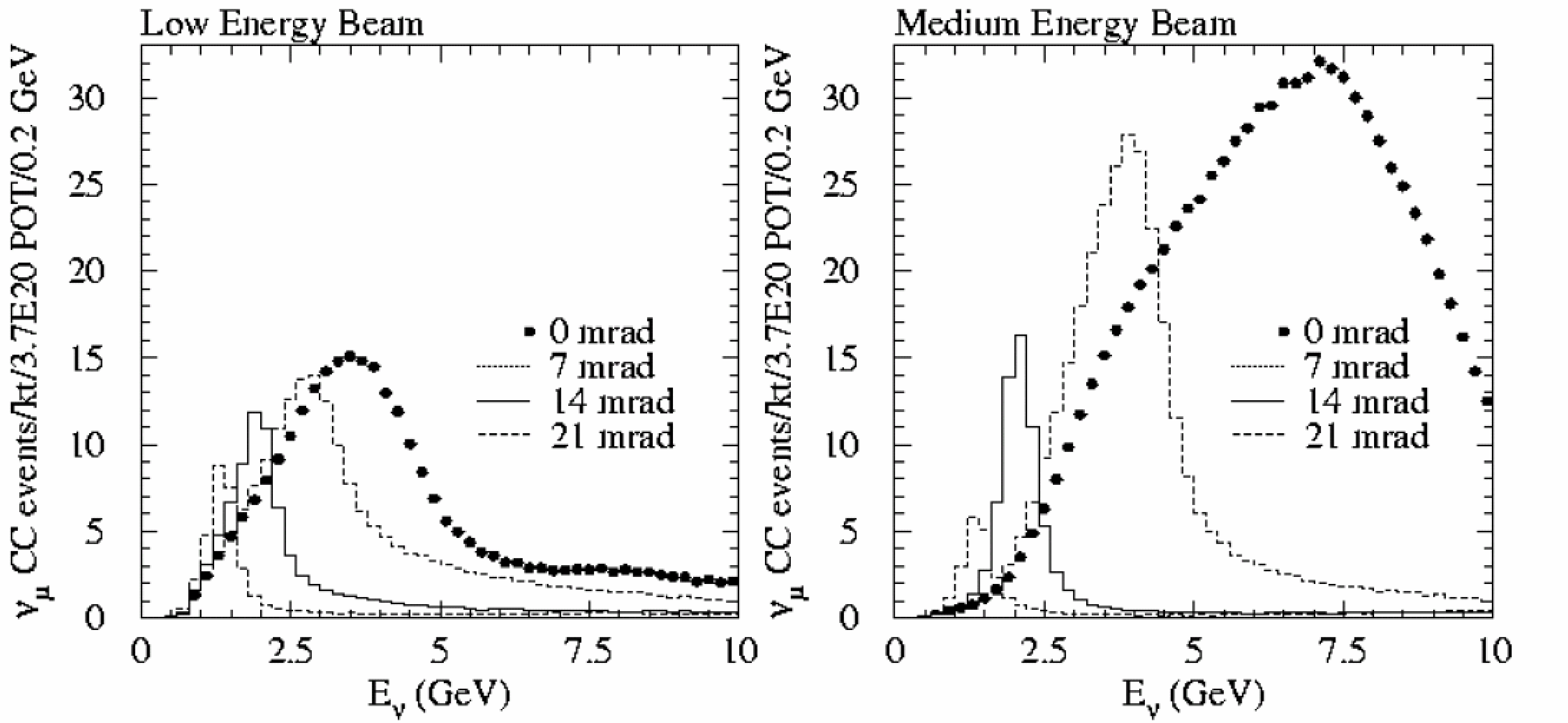


Fig. 2.7: CC ν_μ event rates expected under a no-oscillation hypothesis at a distance of 800 km from Fermilab and at various transverse locations for the NuMI low-energy beam configuration (left) and medium-energy beam configuration (right).

LE better for 21 mrad, ME better for 14 mrad

Rates and Spectra

Source of π^o's to be cut

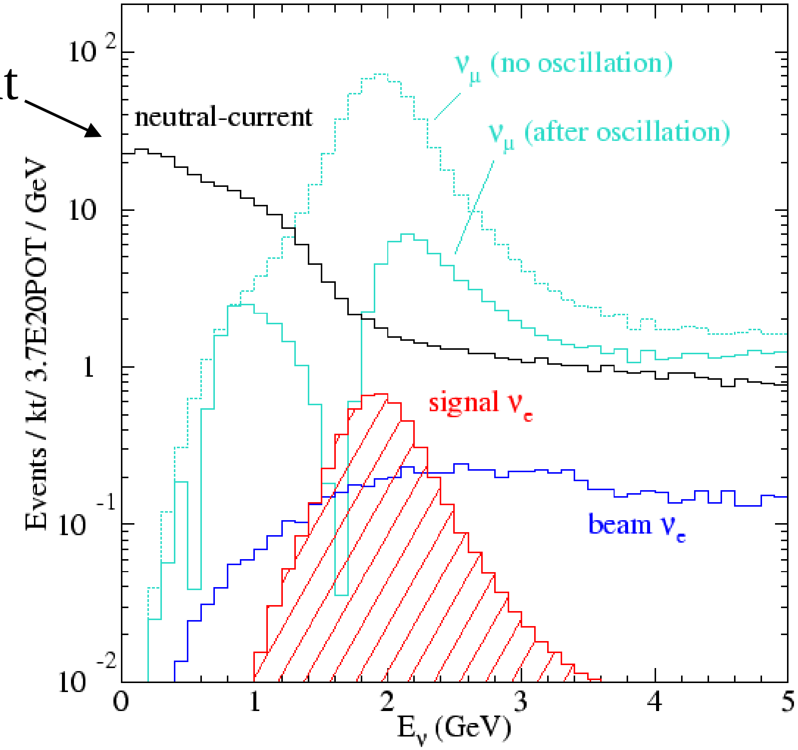


Fig. 2.8: Simulated energy distributions for the ν_e oscillation signal, intrinsic beam ν_e events, neutral-current events and ν_μ charged-current events with and without oscillations. The simulation used $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0.04$. An off-axis distance of 12 km at 810 km was assumed.

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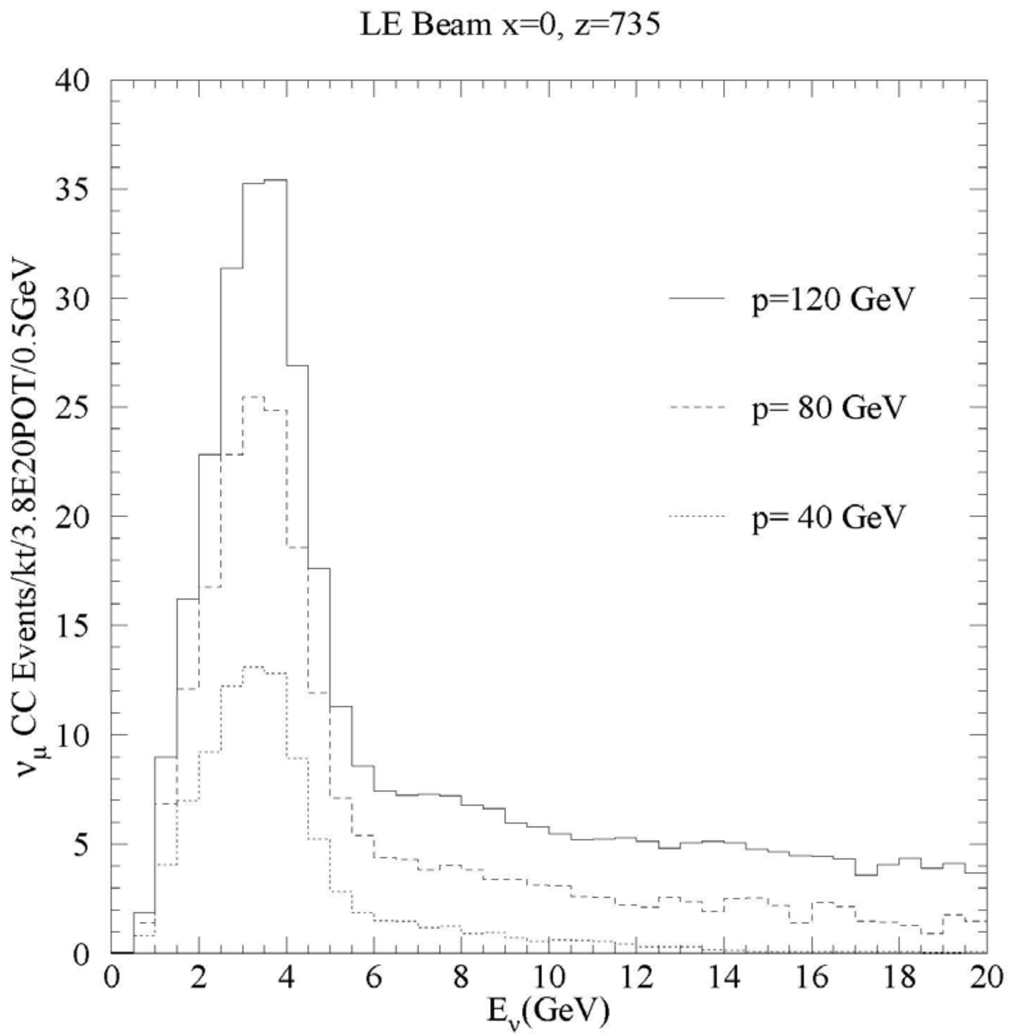
Vary Primary Proton Energy
LE beam on axis

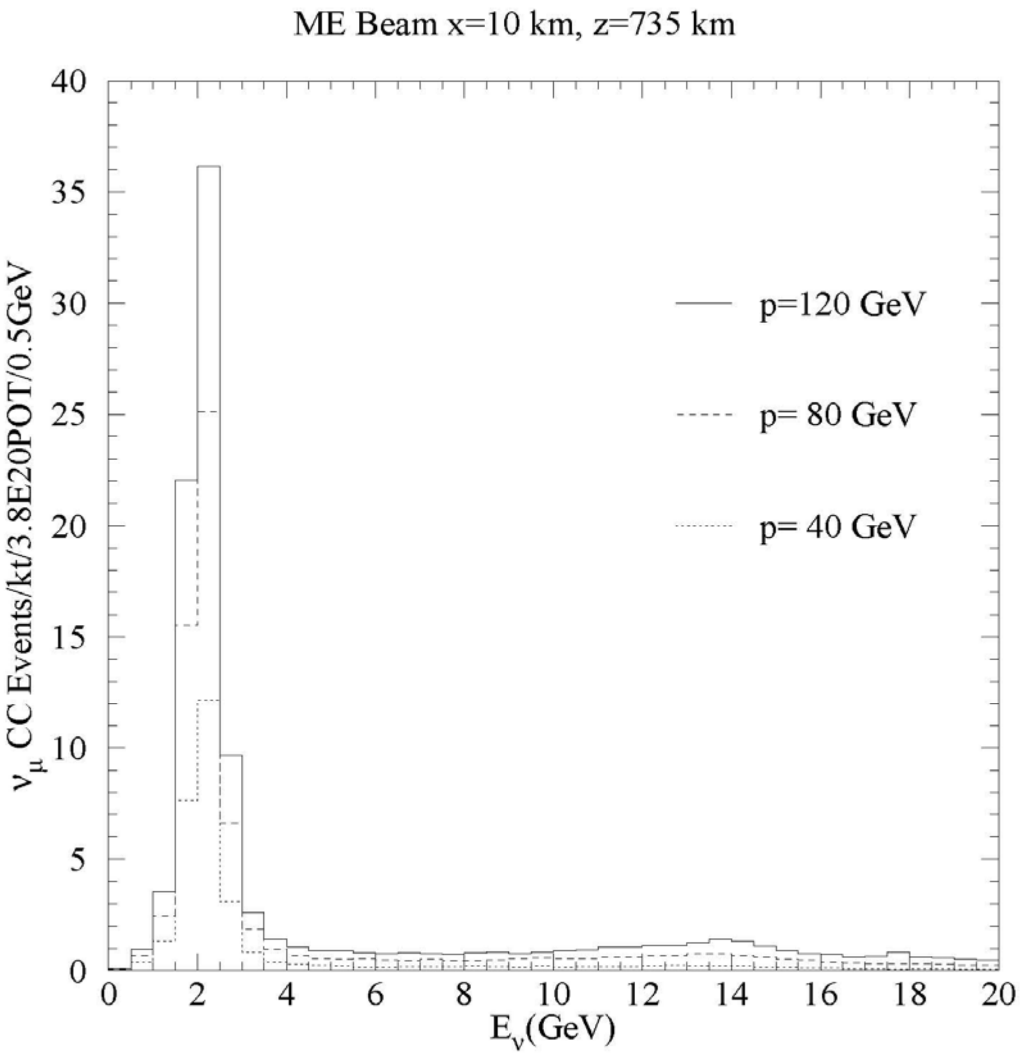


Number of neutrinos in few GeV region proportional to beam power, *insensitive to proton energy*

High energy tail less for lower energy protons

NuMI

Vary Primary Proton Energy
ME beam off axis



Number of neutrinos in few GeV region proportional to beam power, *insensitive to proton energy*

High energy tail less for lower energy protons

Target study for 2 MW beam

Target Working Group:

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

V.Zarucheisky……..(IHEP, Protvino)

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

J.Hylen………………………………………(FNAL)

- Target Design
- Energy Deposition
- Temperature and Stresses
- Cooling of Target
- Radiation Damage Estimate
- CC ν_μ Event Rates

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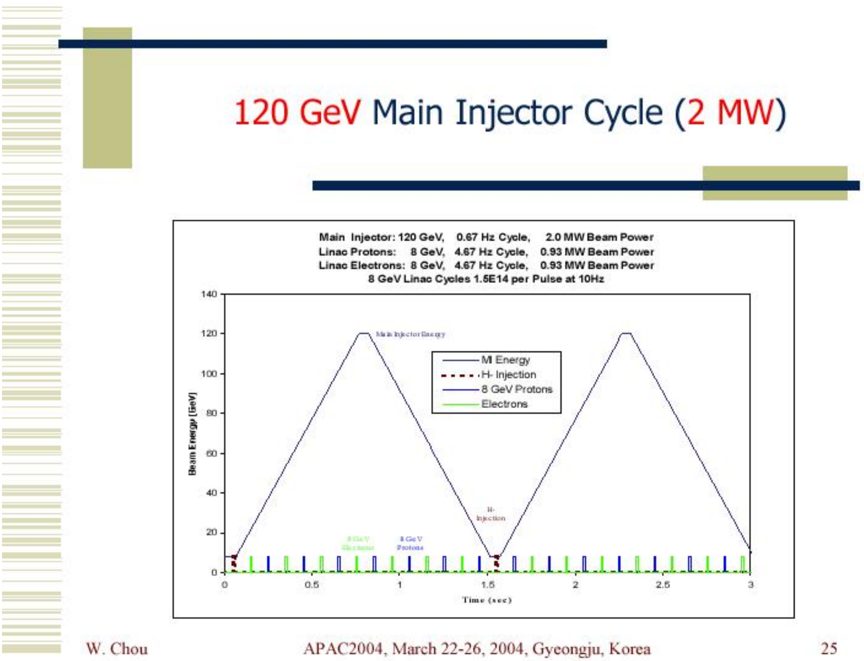
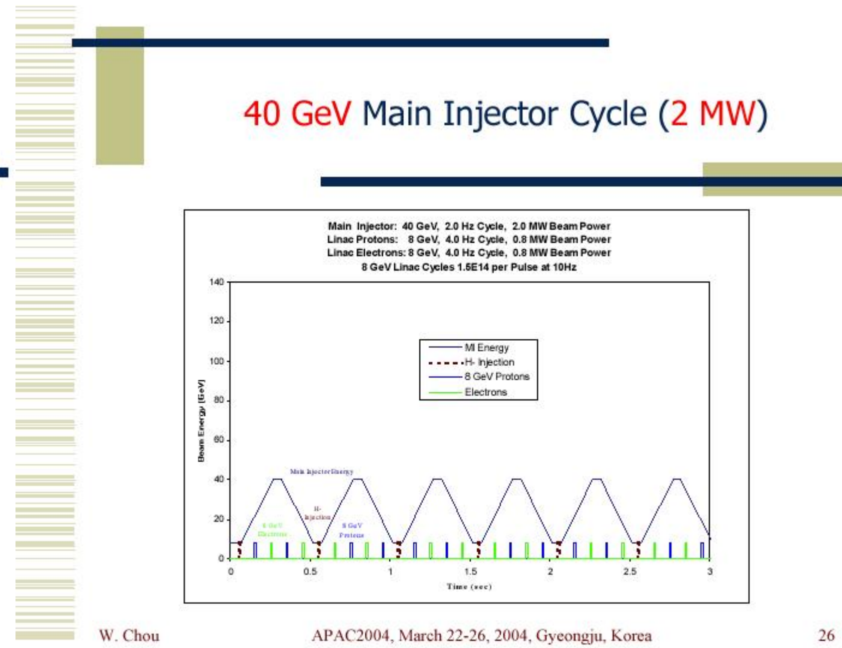
Proton Driver Parameters used for this study





0.67 Hz cycle

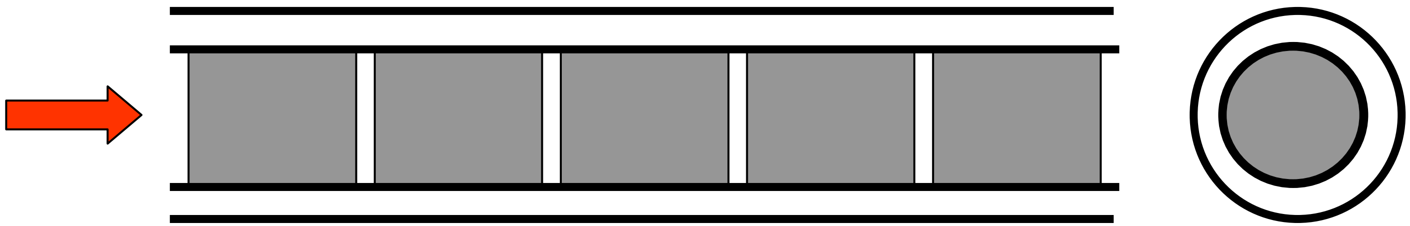
2.0 Hz cycle

1.5×10^{14} protons per pulse !

vs. 4 $\times10^{13}$ ppp at 0.53 Hz cycle for the current NuMI target design

Target Design

Encapsulation of graphite cylinders (segments) with a prestress of about 10 MPa into stainless steel or aluminum thin-walled pipe:



- Provides an integrity of the target core and keeps it even in the case of thermo-mechanical or radiation damages of some segments
- Prevents a direct contact of the cooling water with the heated surface of graphite
- Provides a good thermal contact between graphite and metal pipe

Prototype of the baffle collimator (2002):

∅58 mm graphite cylinders are encapsulated into 1.5 mm thick *aluminum pipe*

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Target Material

Target core: ~32 graphite cylinders, each ∅15 mm and 30 mm length, with 0.2 mm gaps (~1 m length)

Metal pipe: 0.2÷0.3 mm thick stainless steel pipe or ~1 mm thick aluminum pipe

Apparent density	1.8 g/cm^3
Particle size	1 micron
Modulus of elasticity	14.5 GPa
Compressive strength	195 MPa
Tensile strength	90 MPa
Thermal conductivity	70 W/m K
Coefficient of thermal expansion	8.1×10^{-6} 1/K
Specific heat	710 J/kg K
Oxcidation threshold	450 ^{0}C

ZXF-5Q graphite grade of Poco Inc.

Properties at 20 ^{0}C

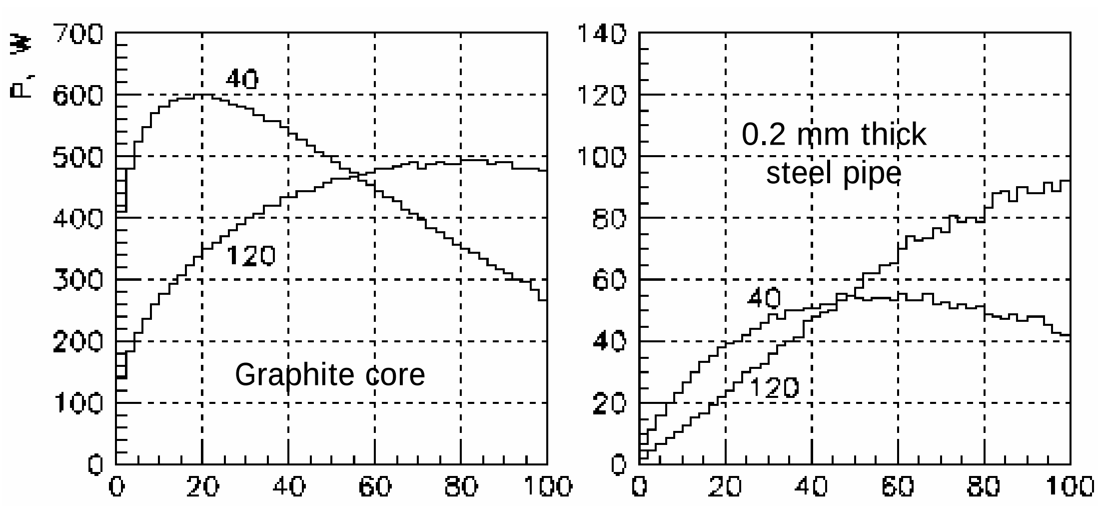
This is the graphite used

in the current NuMI target

Other materials ?

NuMI

Energy Deposition



$$\sigma_{BEAM} = \frac{1}{5} R_{TARGET}$$

Approx. the same distributions take place in case of graphite, encapsulated in the 1mm aluminum pipe

Energy deposition (kW) in different parts of the 1 m length target

Proton beam energy	40 GeV		120 GeV	
Graphite core	23.3	22.7	20.8	19.7
Steel pipe (0.2 mm)	2.2		2.7	
Aluminum pipe (1 mm)		3.4		3.7
The whole target	25.5	26.1	23.5	23.4

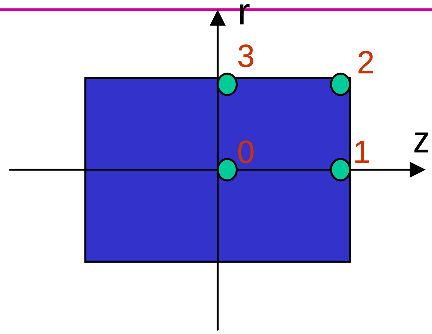
Temperatures

Were calculated by ANSYS for target segments with highest energy deposition density (EDD) under following conditions:

- prestress to graphite segments is equal to 10 MPa
- zero thermal resistance between target segments and steel pipe
- heat transfer coefficient to a cooling water is equal to 15 $kW/m^2/K$

Beam energy	40 GeV	120 GeV
Segment number	2	6
EDD, $GeV/cm^3/proton$	0.025	0.033
Temperature of water, ^0C	37	50
Temperature at beam axis, ^0C		
before beam spill	120	80
after beam spill	380	430
Temperature rise at beam axis, ^0C	260	350

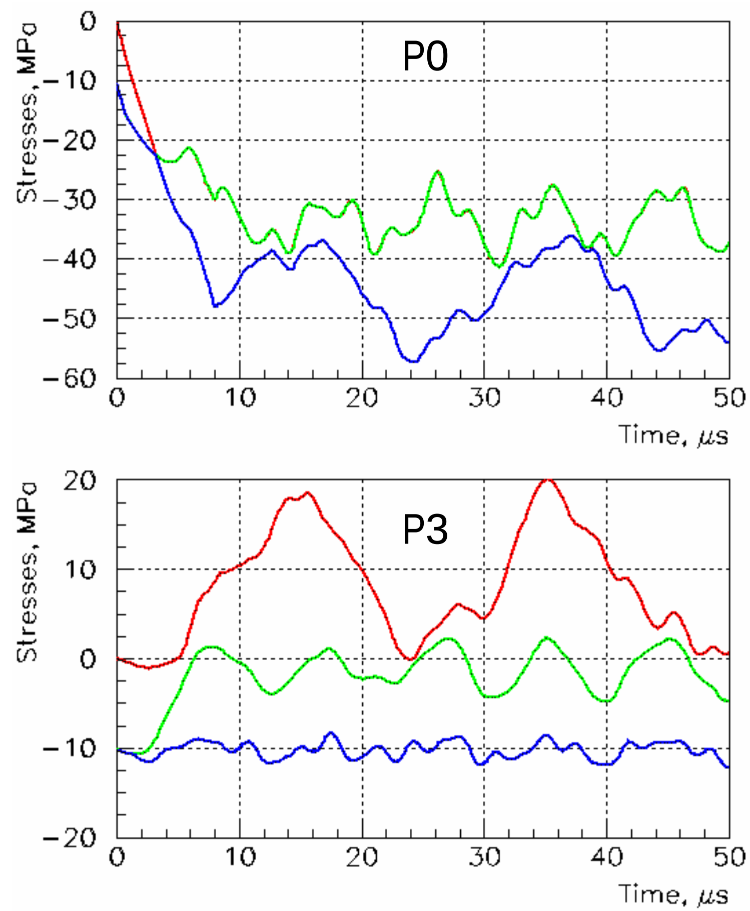
Stresses on graphite are OK



Safety factors for different point of segments with the highest EDD

Beam energy	40 GeV	120 GeV
P0	2.3	1.9
P1	7.5	5.5
P2	2.7	2.3
P3	2.8	2.0

E = 120 GeV



- Mohr-Coulomb Stress Criterion (used for brittle materials with different tensile and compressive properties)
- 10^7 cycle fatigue endurance limit of graphite ~0.5÷0.6

The remaining problem is cooling of target

$$\Delta P = \frac{\beta \Delta T_{water}}{\kappa}$$

Instantaneous pressure rise in a cooling water:

$\beta\left(T = 20^0 C\right) = 0.2 \times 10^{-3}$ - coeff. of volume change

$\kappa = 0.46 \times 10^{-9}$ - volume compressibility

$\downarrow T_{water} \rightarrow \downarrow \beta \rightarrow \downarrow \Delta P$

For 120 GeV proton beam ΔT_{water} reaches 20 ^{0}C → $\Delta P \sim 90$ atm !

(hydraulic shock)

Next steps of a cooling system study:

1. Estimation of the hydraulic shock impact on the cooling system
2. Use of the two-phase flow for shock absorption:

   Loading of a cooling water with He or Ar bubbles (10-15%)

   Phase transfer (boiling of water)
3. Use of the heat pipe technology (evaporating cooling) for target cooling

Radiation Damage

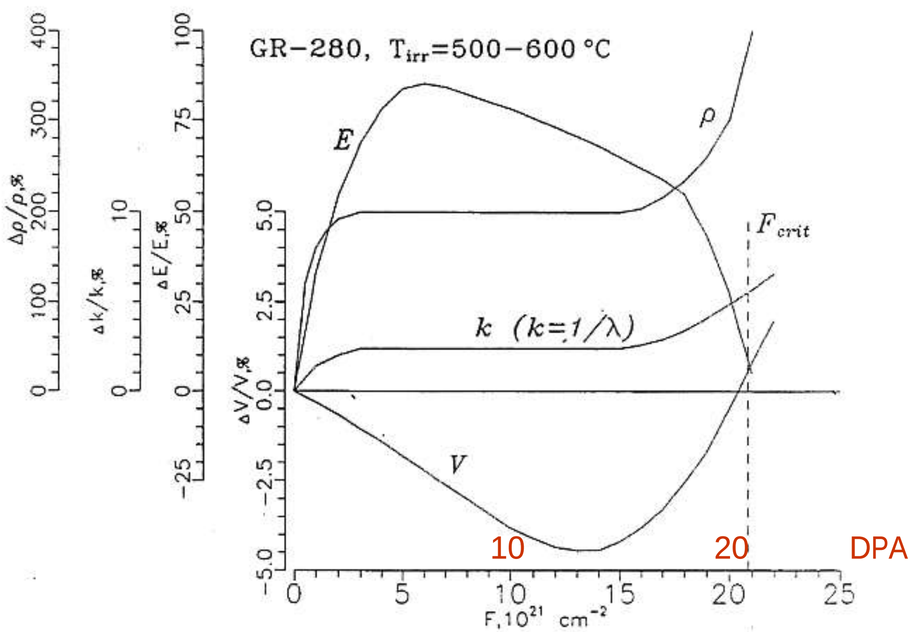


Fig.1. Determination of critical value of neutron fluence for graphite and changing of its physical properties under irradiation. V – volume changing; E – elastic modulus; k – thermal resistance; ρ – electrical resistance.

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

<u>2 MW NuMI Target (upper estimate)</u>

120 GeV beam → 5 DPA per year

40 GeV beam → 15 DPA per year

Have radiation damage data for some other types of graphite but not Poco ZXF-5Q !

Note some preference for 120 GeV beam because target should last longer and also horn heating is less (fewer horn pulses)

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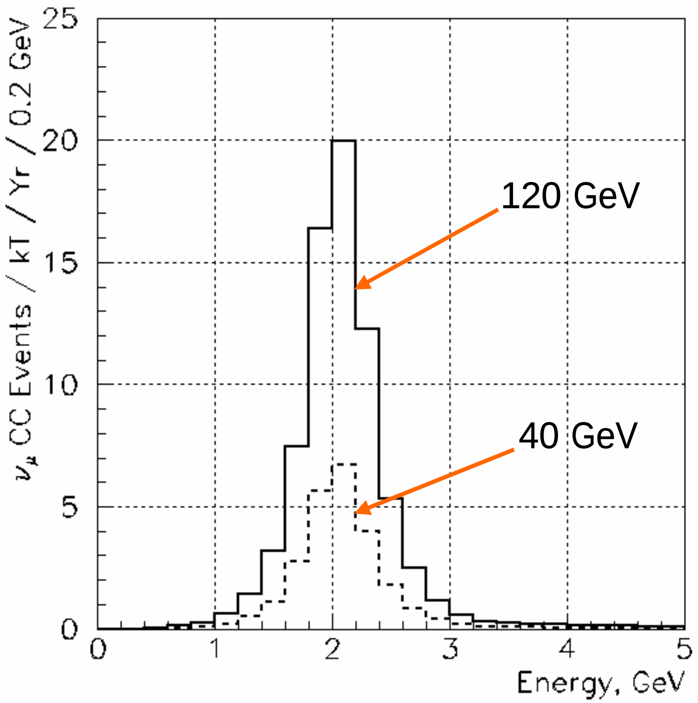
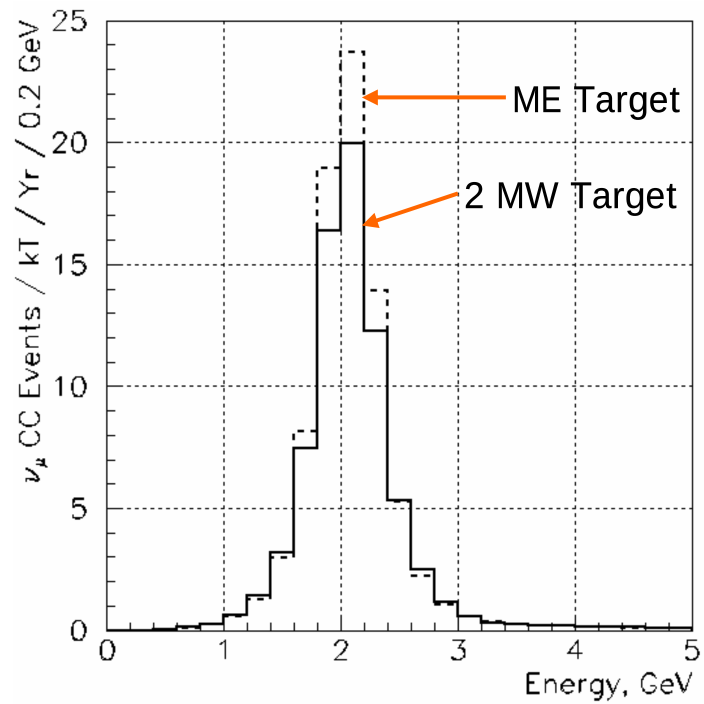
Target for 2 MW intensity is ~ 90% as efficient for NOvA M.E. off-axis

2 MW Target



1 year = 3.8×10^{20} pot

E = 120 GeV



- There is no difference in the event rate between 40 GeV and 120 GeV beam options
- New target, irradiated by the 2 MW proton beam gives 4.5 times increase of the total neutrino event rate, as compared with the ME target, irradiated by the 0.4 MW beam