Neutrino Production with Proton Drivers

Proton Driver Efficiency Workshop, Feb 29-Mar 2, 2016, PSI

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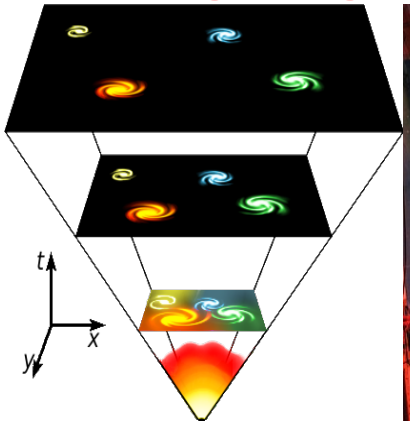
Outline

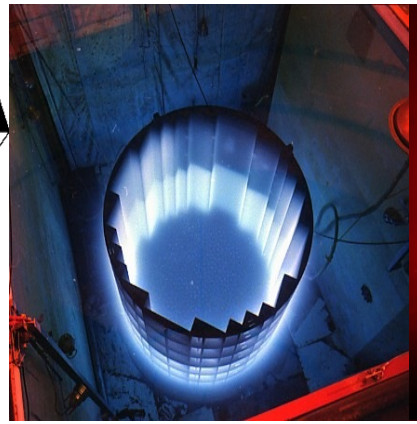
Sources of Neutrinos

Big Bang



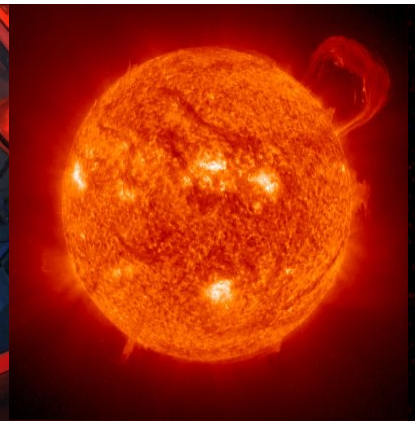
10^{-4} eV
$56/\mathrm{cm}^3$

Reactors



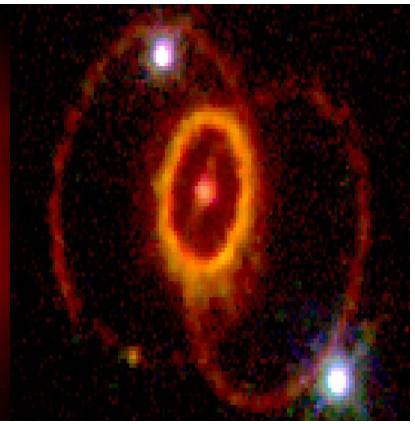
few MeV
$10^{21}/\mathrm{GW}_{th}/\mathrm{s}$

Sun



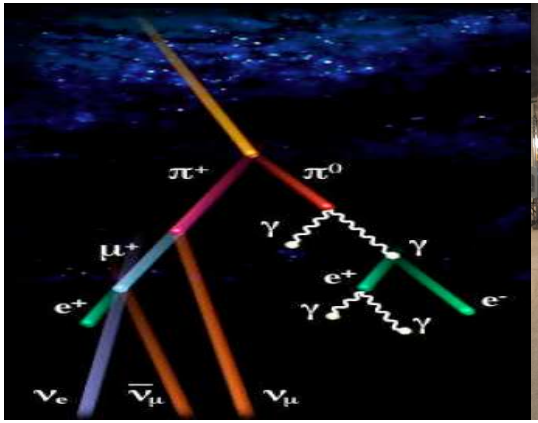
0.1-14 MeV
$10^{10}/\mathrm{cm}^2/\mathrm{s}$

SuperNova



$\sim$ 10 MeV
$10^9/\mathrm{cm}^2/\mathrm{s}$

Atmosphere

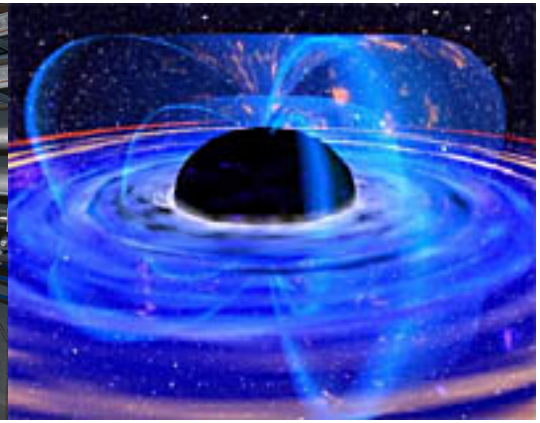


$\sim$ 1 GeV
few/cm^2/s

Accelerators

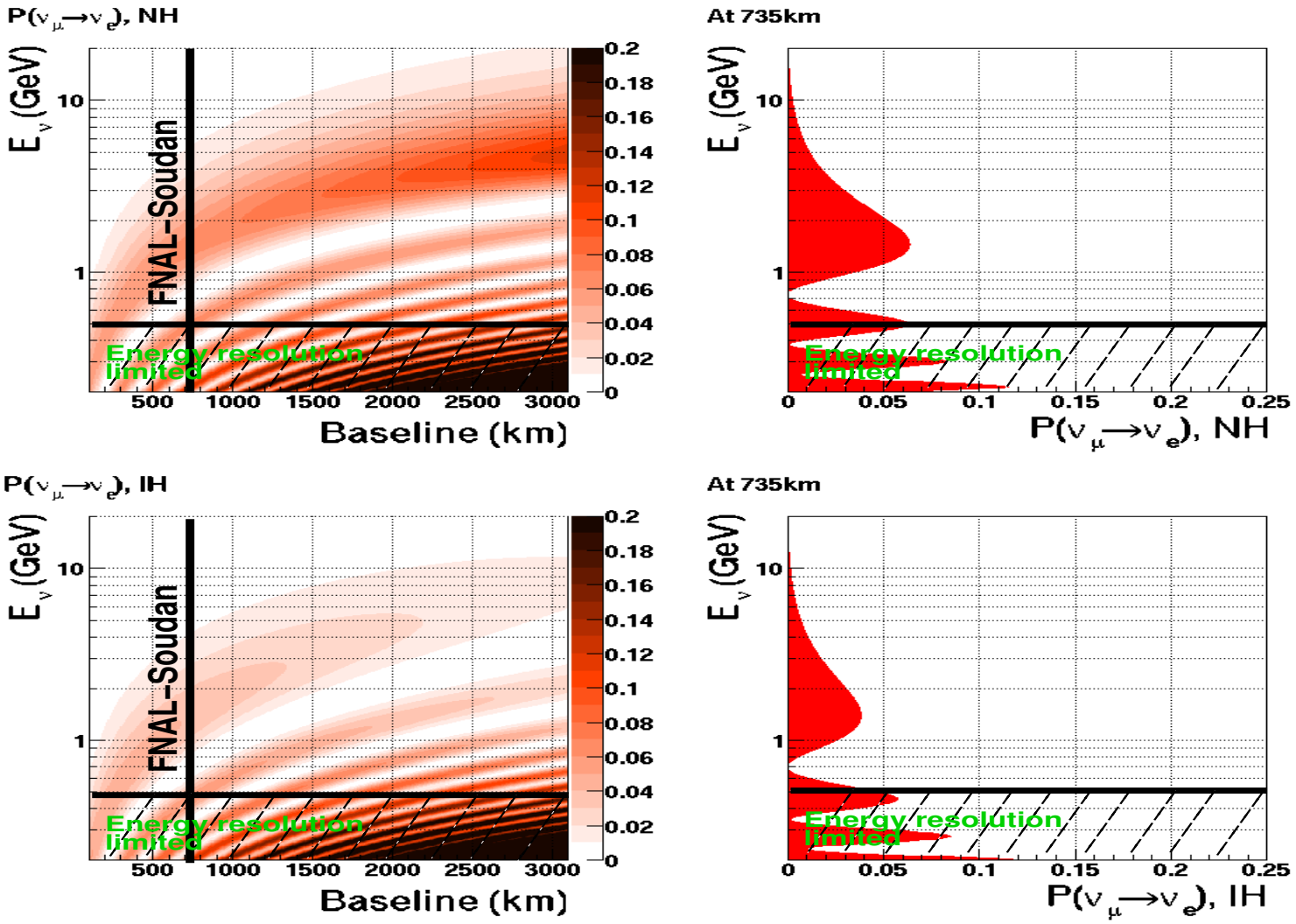
1-20 GeV
$10^5/\mathrm{cm}^2/\mathrm{s}/\mathrm{MW}$ (at 1km)

Extragalactic



TeV-PeV
varies

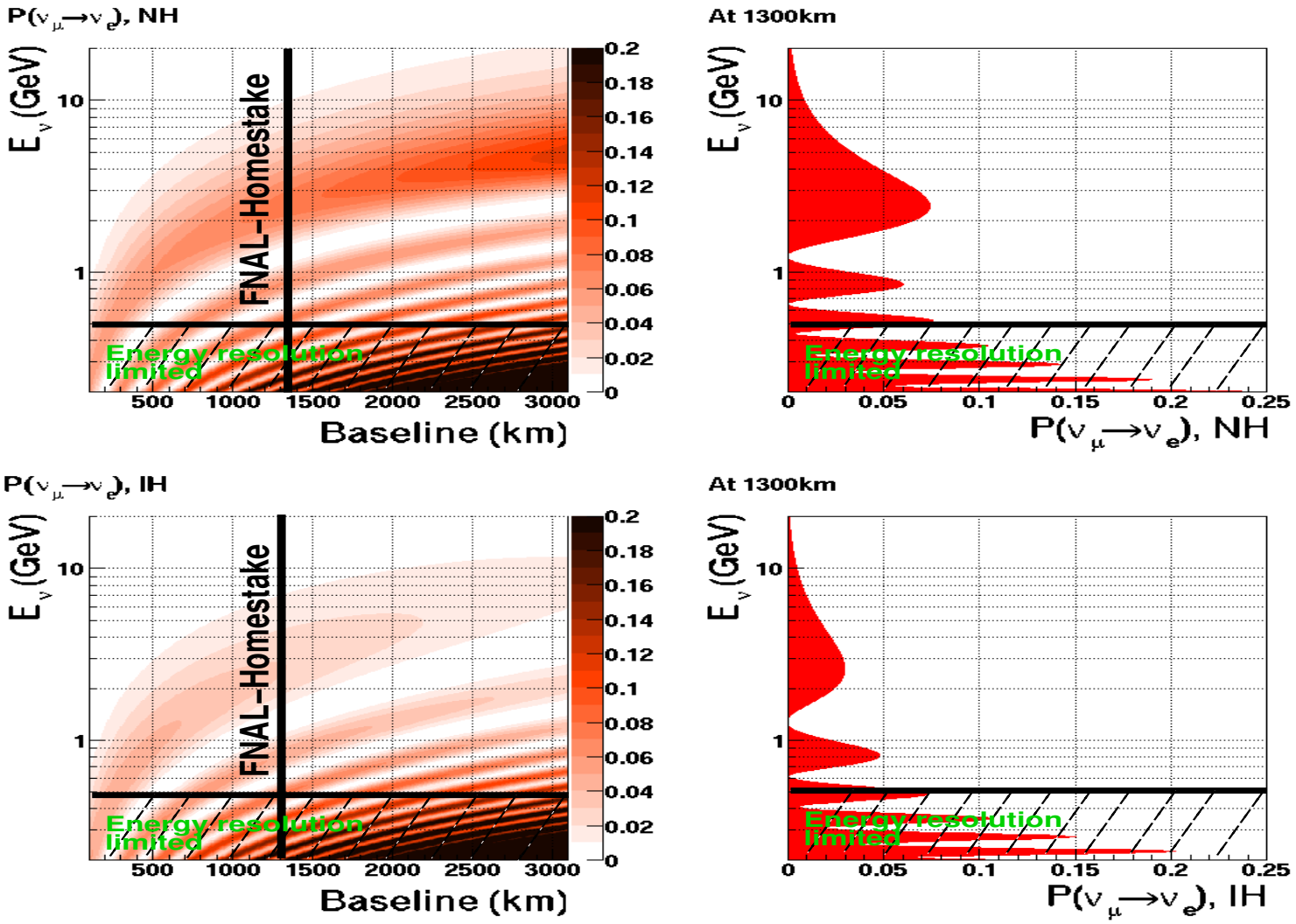
Oscillations of $\nu_\mu \rightarrow \nu_e$ at different baselines



$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E_\nu^n(\mathrm{GeV}) \sim \mathrm{Baseline(km)}/(515 \times (2n-1))$

for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV^2

Oscillations of $\nu_\mu \rightarrow \nu_e$ at different baselines



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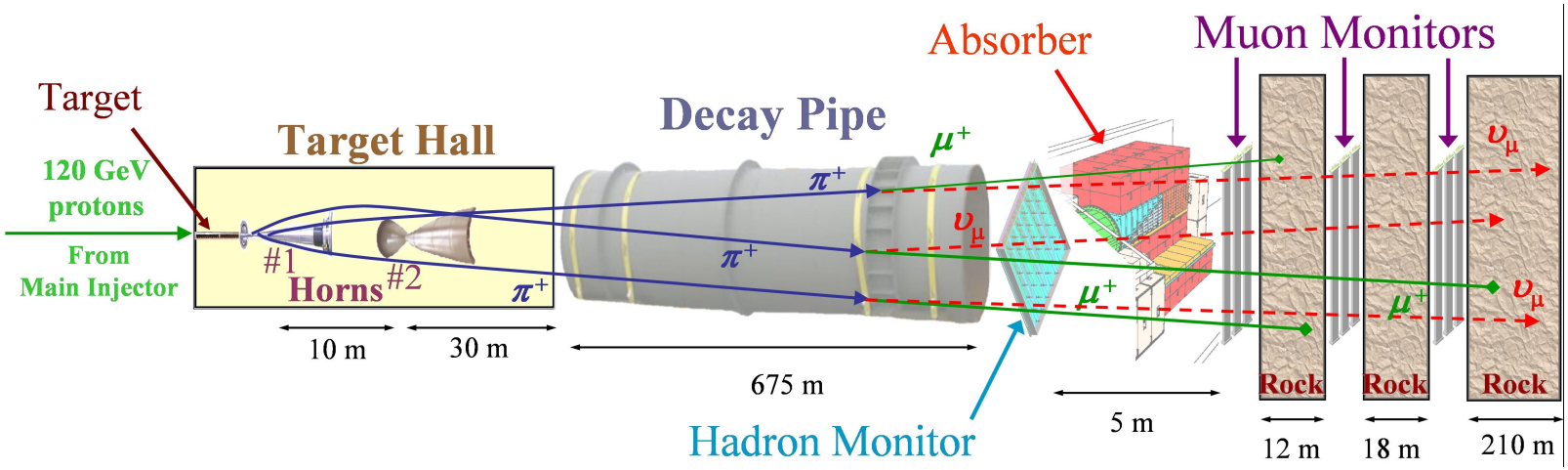
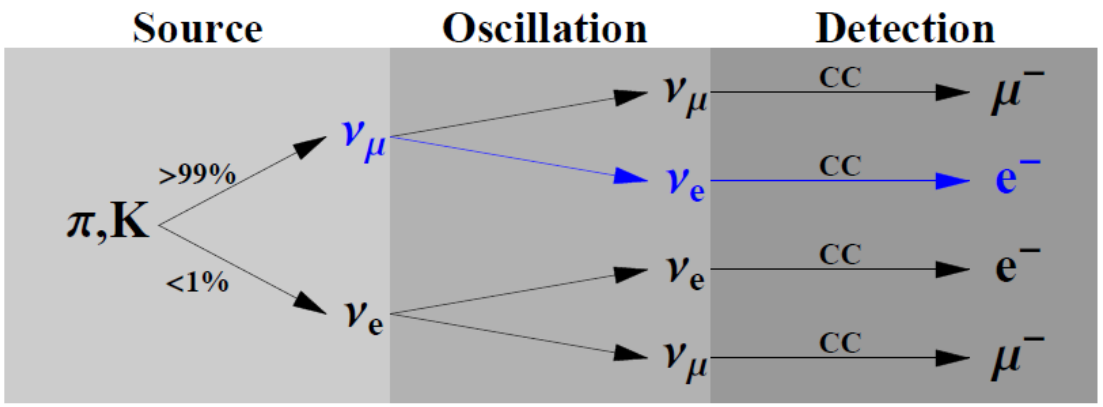
Superbeams

Conventional horn-focused neutrino beams:

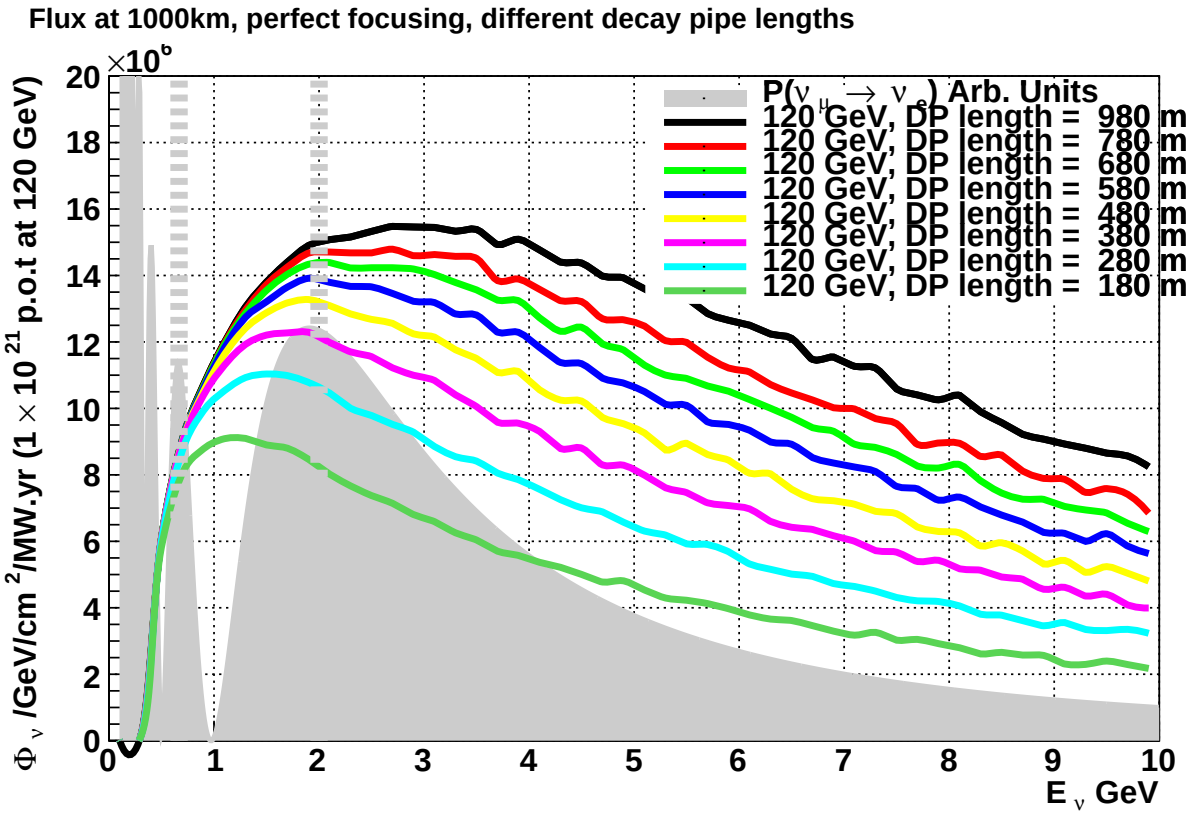




Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

120 GeV, decay channel lengths from 200m to 1km

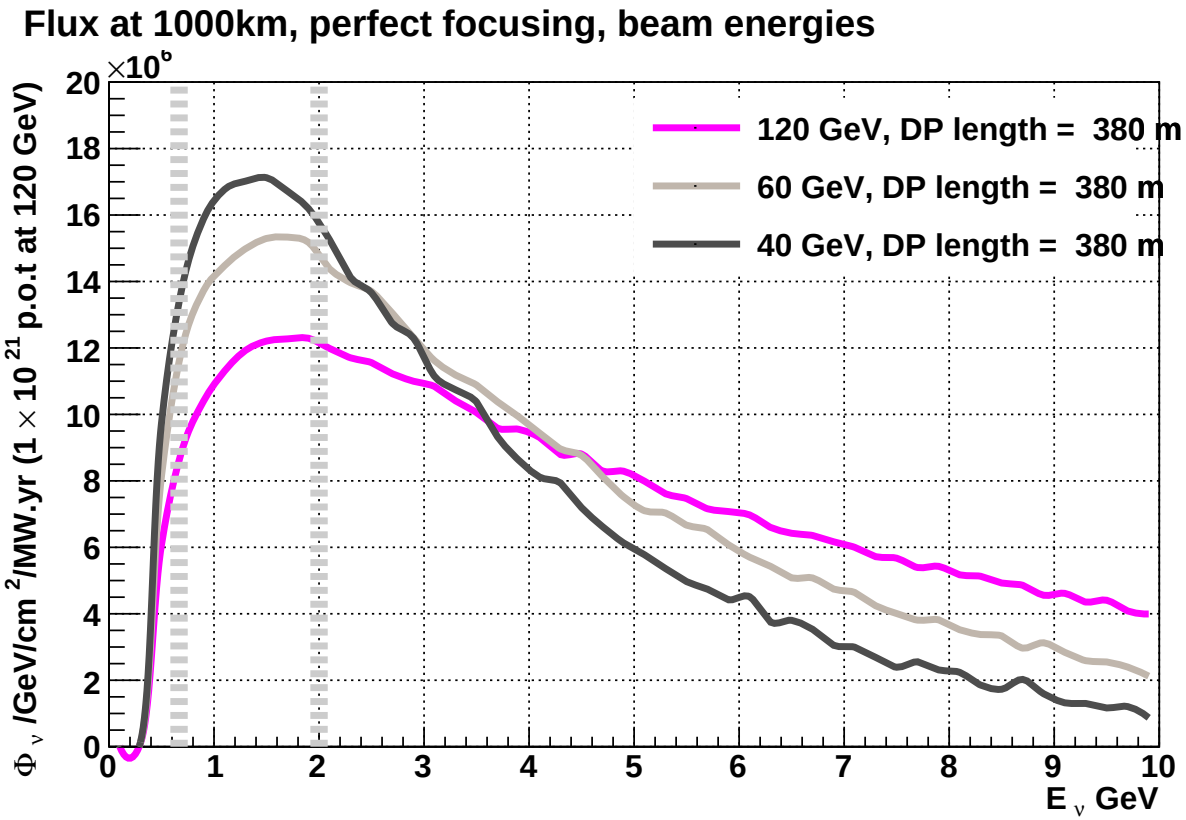


Gain with longer decay channels, BUT excavation is challenging/expensive

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

40 to 120 GeV, decay channel length = 400m

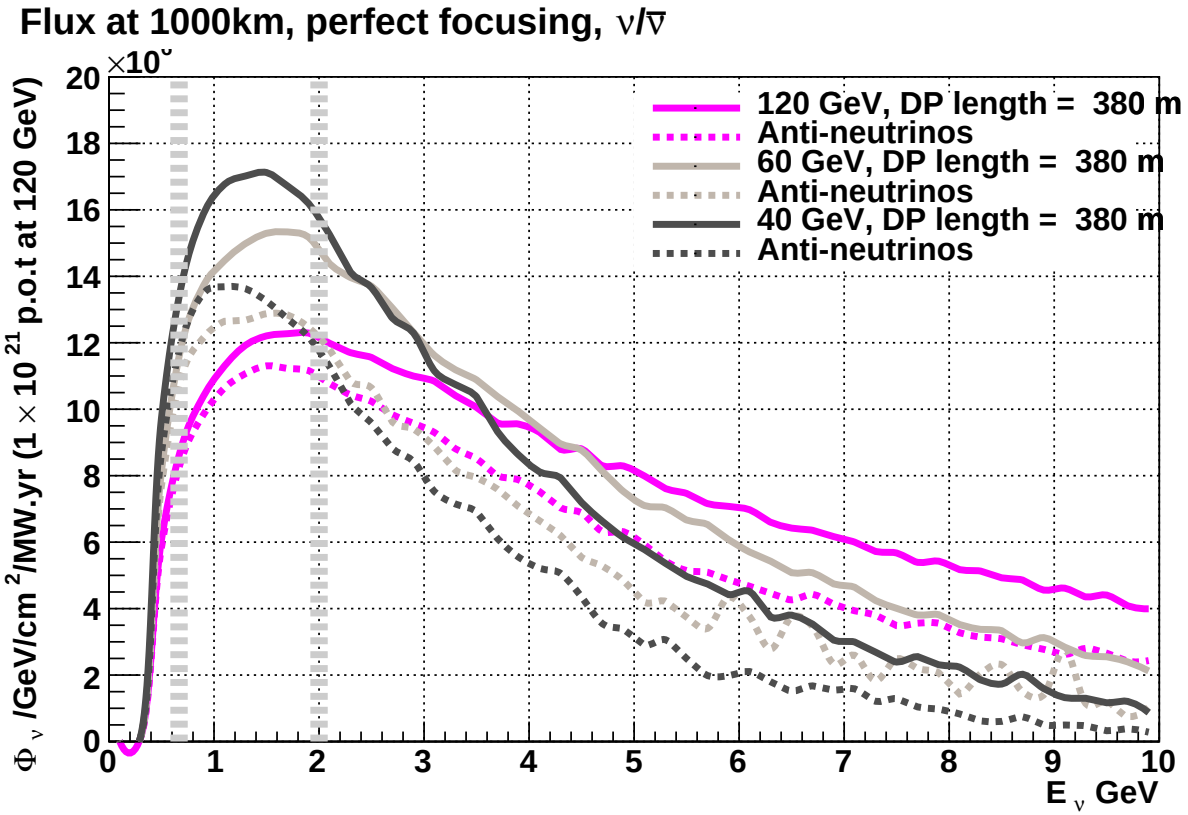


Lower energy flux for benefits at lower P beam energy BUT only at constant power = more protons.

Neutrino fluxes with perfect focusing

ν_μ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

Neutrino vs anti-neutrino fluxes



$\bar{\nu}/\nu$ fluxes are more favorable at higher proton beam energies.

Expected Appearance Signal Event Rates

The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N_{\nu_e}^{\rm appear}(L) = N_{\rm target} \int \Phi^{\nu_\mu}(E_\nu, L) \times P^{\nu_\mu \to \nu_e}(E_\nu, L) \times \sigma^{\nu_e}(E_\nu) dE_\nu$$

Assume the neutrino beam source produces a wide coverage that is flat in energy in the oscillation region and approximate the probability with the dominant term for $P(\nu_\mu \to \nu_e)$

$$\begin{aligned}
\Phi^{\nu_\mu}(E_\nu, L) &\approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/\text{m}^2/\text{GeV}//\text{MW/yr at 1 km} \\
P^{\nu_\mu \to \nu_e}(E_\nu, L) &\approx \underbrace{\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 L/E_\nu)}_{P_0} \\
\sigma^{\nu_e}(E_\nu) &= 0.7 \times 10^{-42} (\text{m}^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 1 \text{ GeV} \\
N_{\rm target} &= 6.022 \times 10^{32} N/\text{kt}
\end{aligned}$$

Assuming constant flux: $C \approx 1.2 \times 10^{17}\ \nu_\mu/\text{m}^2/\text{GeV}/(\text{MW/yr})$ at 1 km:

$$N_{\nu_e}^{\rm appear}(L) \approx (2 \times 10^6 \text{events}/(\text{kt/MW/yr}))(\text{km/GeV})^2 \times \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \ a \equiv 1.27\Delta m_{31}^2.$$

For $x_0 = 100$ km/GeV and $x_1 = 2000$ km/GeV (1st and 2nd oscillation maxima)

$N_{\nu_e}^{\rm appear}(L) \sim \mathcal{O}(20)$ events/(kt/MW/yr)
constant for $L \geq 300$ km in vacuum!

Event Rates vs. Baseline Perfect Focusing

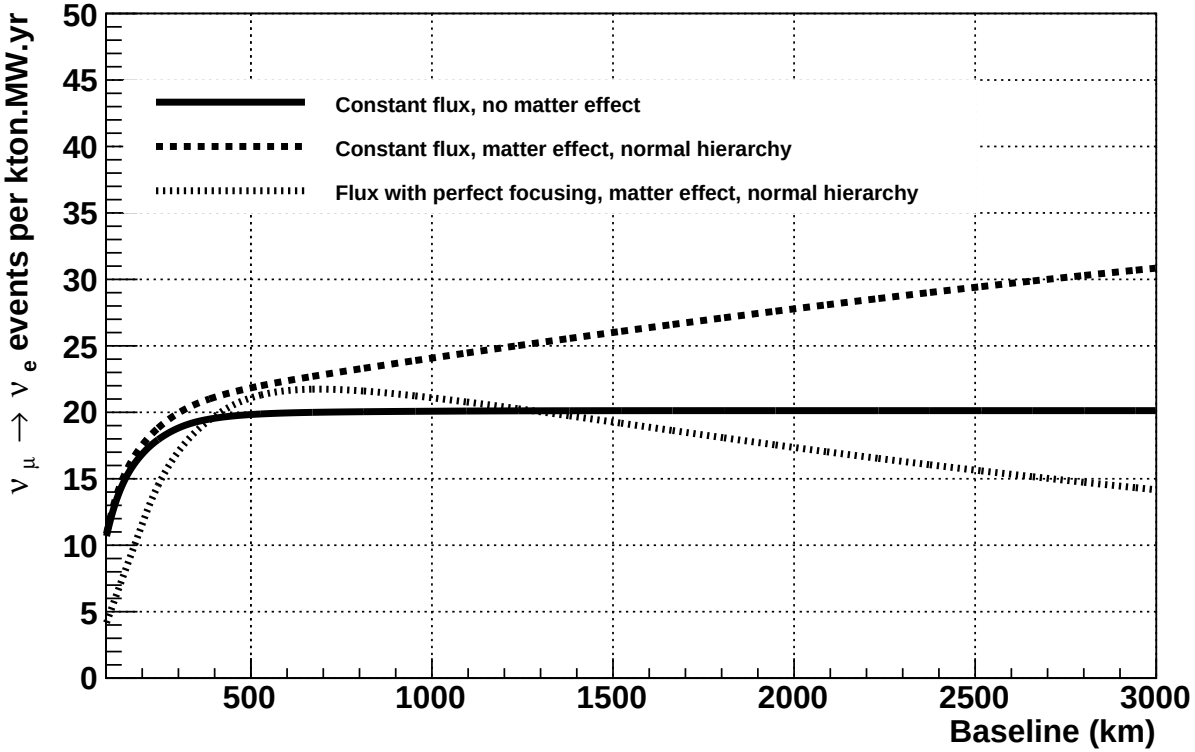
$$\mathcal{R} = \int \Phi^{\nu_\mu}_{\text{perfect}}(E_\nu) \times \sigma(E_\nu) \times P(\nu_\mu \to \nu_e)\, dE_\nu$$

$(\sin^2 2\theta_{13} = 0.09, \sin^2 \theta_{23} = 0.5, \delta_{cp} = 0, |\Delta m^2_{31}| = 2.4 \times 10^{-3})$

Flux: 120 GeV, perfect focusing, $\sim$ 400m decay channel, on-axis

Normal Hierarchy

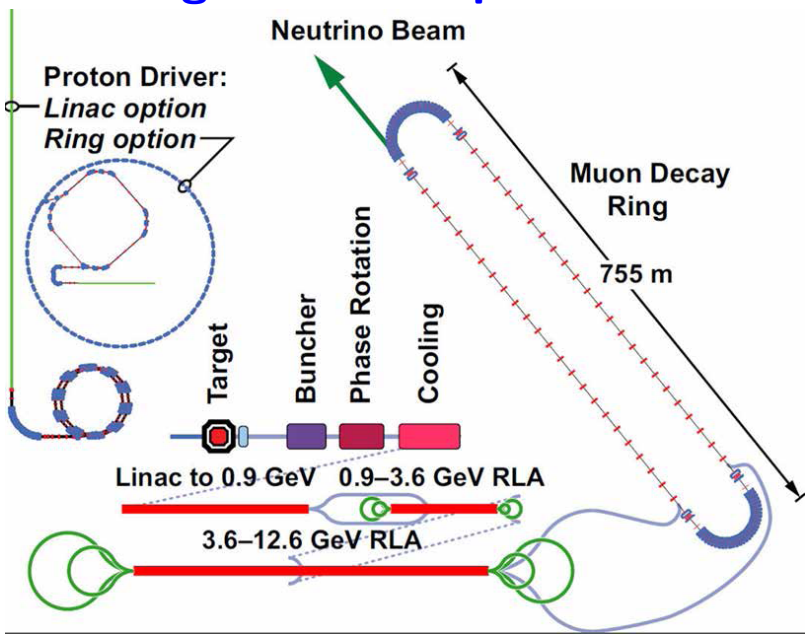
Appearance rates versus baseline

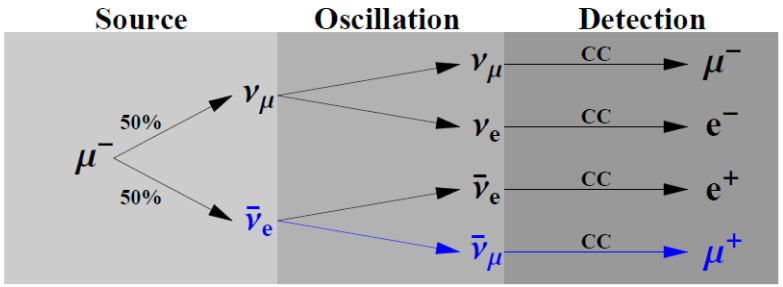


How well can we focus/collect the pions?

Neutrino Factories/Muon Storage Rings

Long baseline experiments



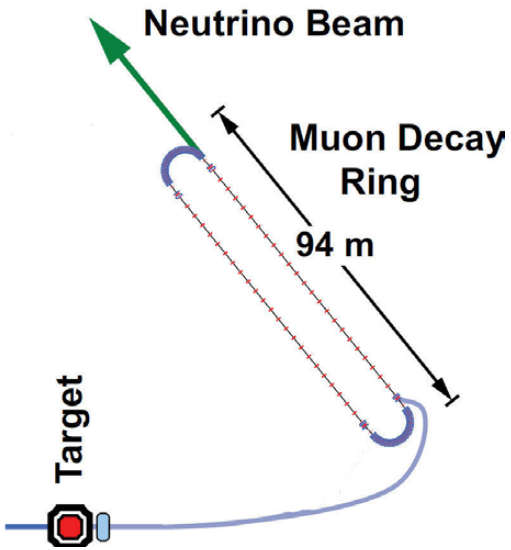


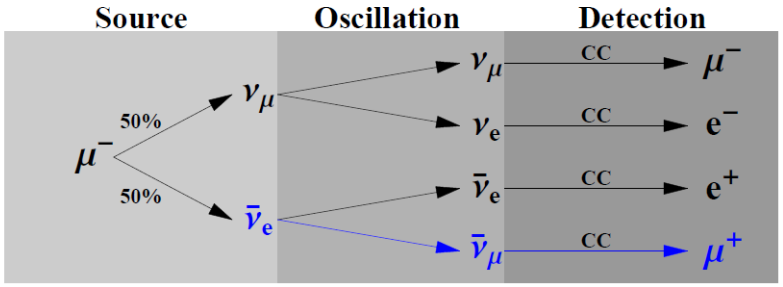
How many μ/p^+ can be collected?

State-of-the-art from mu2e is $\mathcal{O}(10^{-3})$ at 8 GeV

Neutrino Factories/Muon Storage Rings

Short baseline experiments





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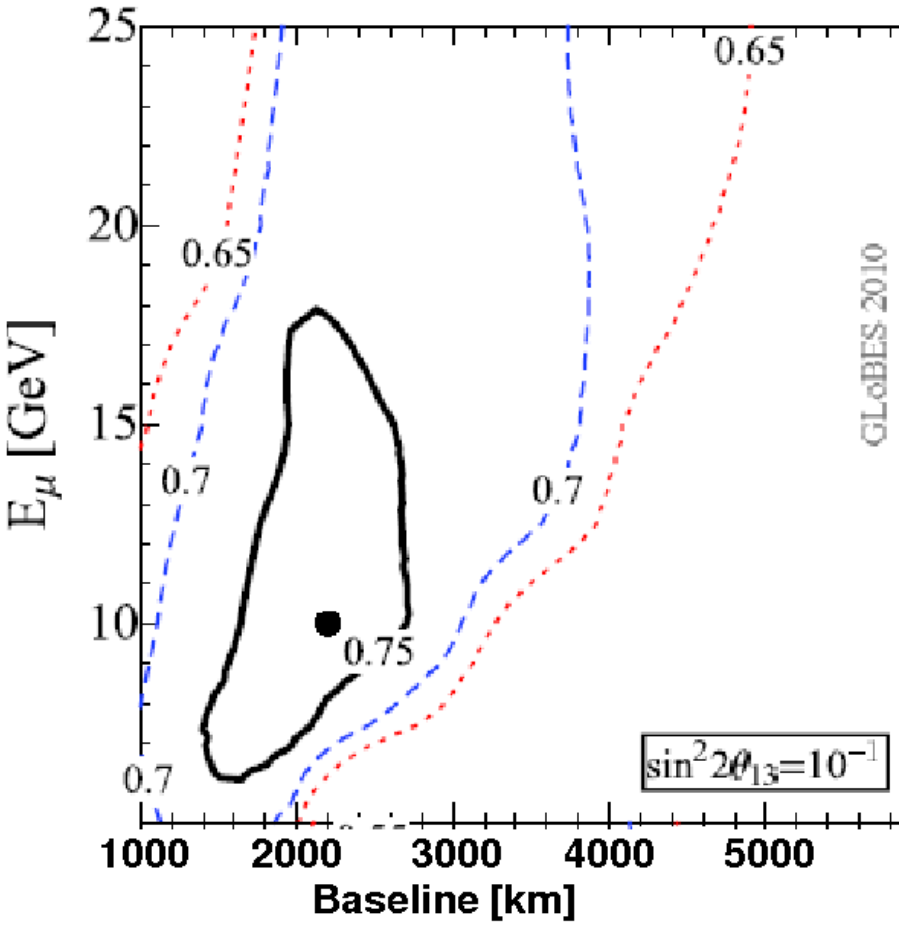
Optimization of NF Baseline and μ Energy (P.A. Huber)



Using MIND (Magnetized Iron Neutrino Detector) and a single baseline:

The optimal range is 1400-2600km for E_μ from 7 - 15 GeV.

Superbeams vs Neutrino Factories

From A. Blondel et. al. NIM A 451 (2000) 102-122

	Conventional	Neutrino factory
Parents	π^+, K^+ or π^-, K^-	μ^- or μ^+
ν_μ beam	ν_μ	$\nu_\mu : \bar{\nu}_e = 1{:}1$
Background	$\sim 2\%$ of $\bar{\nu}_\mu$, $\sim 1\%$ of ν_e	none
$\bar{\nu}_\mu$ beam	$\bar{\nu}_\mu$	$\bar{\nu}_\mu : \nu_e = 1{:}1$
Background	$\sim 6\%$ of ν_μ, $\sim 0.5\%$ of $\bar{\nu}_e$	none
$\Delta E/E$ of neutrino energy	$\pm 10\%$	$< 1\%$
$\Delta R/R$ of neutrino radius	$\pm 10\%$	$< 1\%$
Neutrino flux uncertainty	$\pm 10\%$	$< 1\%$
ν_μ/cm^2 per year at 732 km	3×10^7 for 4.5×10^{19} 400 GeV/c p.o.t.	3×10^9 for 10^{21} injected 50 GeV/c μ

Neutrino factories technologically challenging.

Muon storage rings only viable for short baseline.

Neutrino Event Rates - Various Experiments

From arXiv:1307.7335, for 50 kton.years* of exposure:

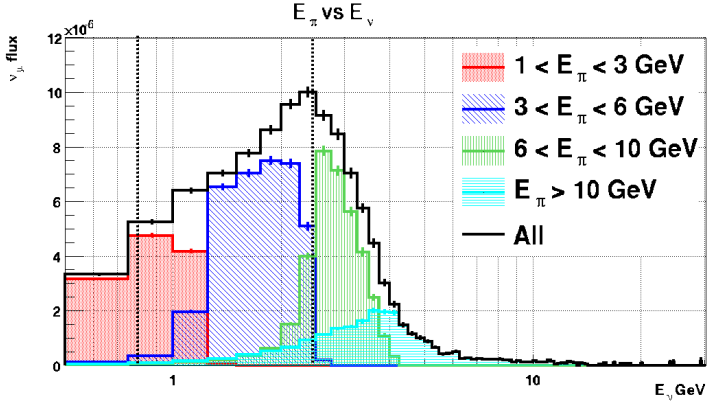
Experiment	Baseline	Super Beams $\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_\mu \to \nu_e$
T2K 30 GeV, 750 kW 9×10^{20} POT/year	295km (off-axis)	900	< 1	40 - 70
MINOS LE 120 GeV, 700 kW 6×10^{20} POT/year	735km	11,000	115	230-340
NOνA 120 GeV, 700 kW 6×10^{20} POT/year	810km (off-axis)	1500	10	120 - 200
LBNE (LBNF) LE 80 GeV, 1.2MW 1.5×10^{21} POT/year	1,300km	4300	160	350 - 600
LBNE (LBNF) ME 80 GeV, 1.2MW 1.5×10^{21} POT/year	1,300km	12,000	690	290 - 430

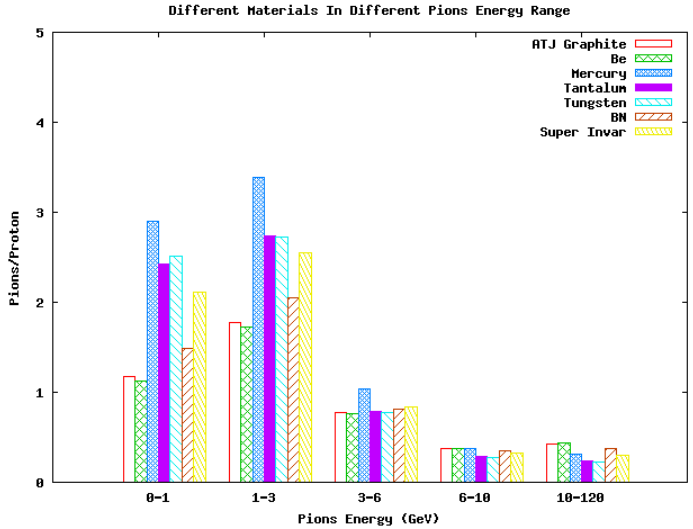
Experiment	Baseline	ν Factory at Fermilab $\nu_\mu \to \nu_\mu$	$\nu_\mu \to \nu_\tau$	$\nu_e \to \nu_\mu$
NuMAX I 3 GeV, 1MW 0.94×10^{20} μ/year (no μ cooling)	1,300km	340	30	70 - 120
NuMAX II 3 GeV, 3MW 5.6×10^{20} μ/year	1,300km	2000	300	420 - 700

* Facility duty factor taken into consideration

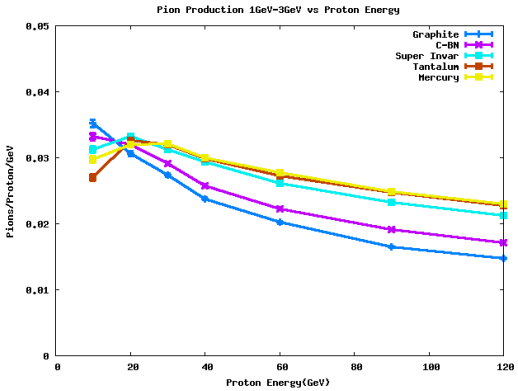
Optimization of Pion Production from the Target (FLUKA05)

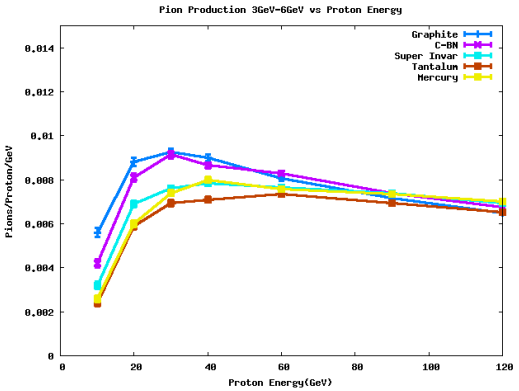
Sample ν beam with 120 GeV - horn focused:

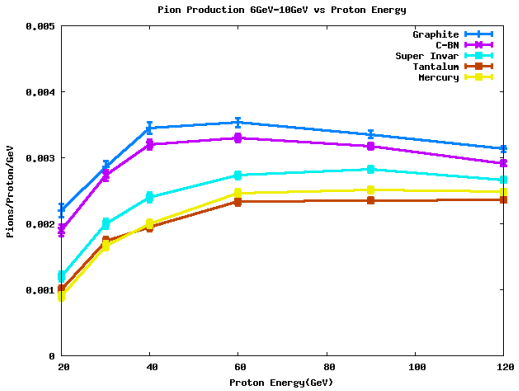




π^+ production vs proton beam energy, different materials.





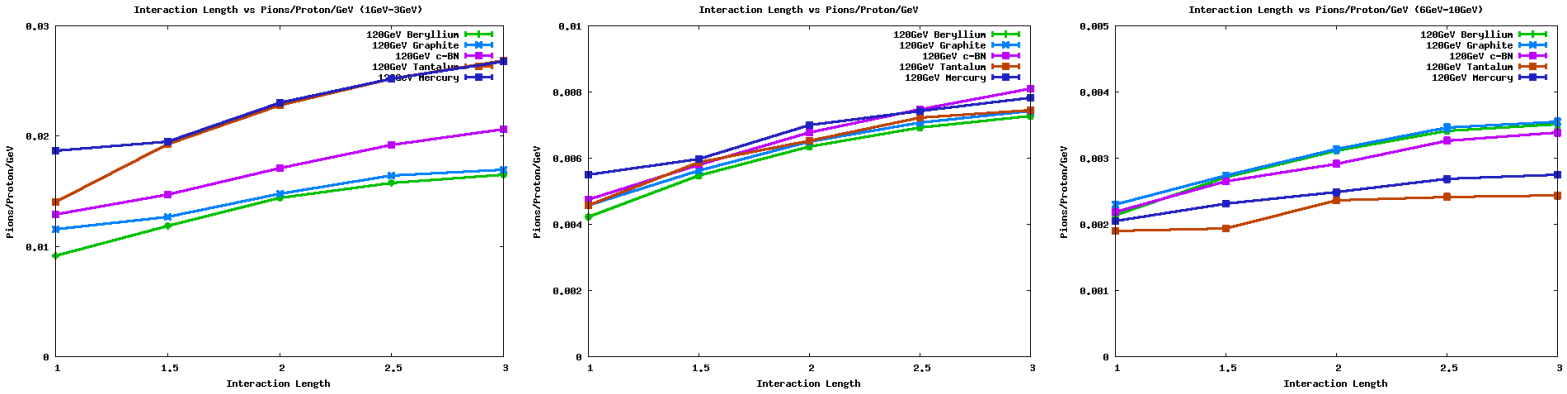


For pions 3-10 GeV, low-Z materials, beam energies of $\sim$ 40 GeV

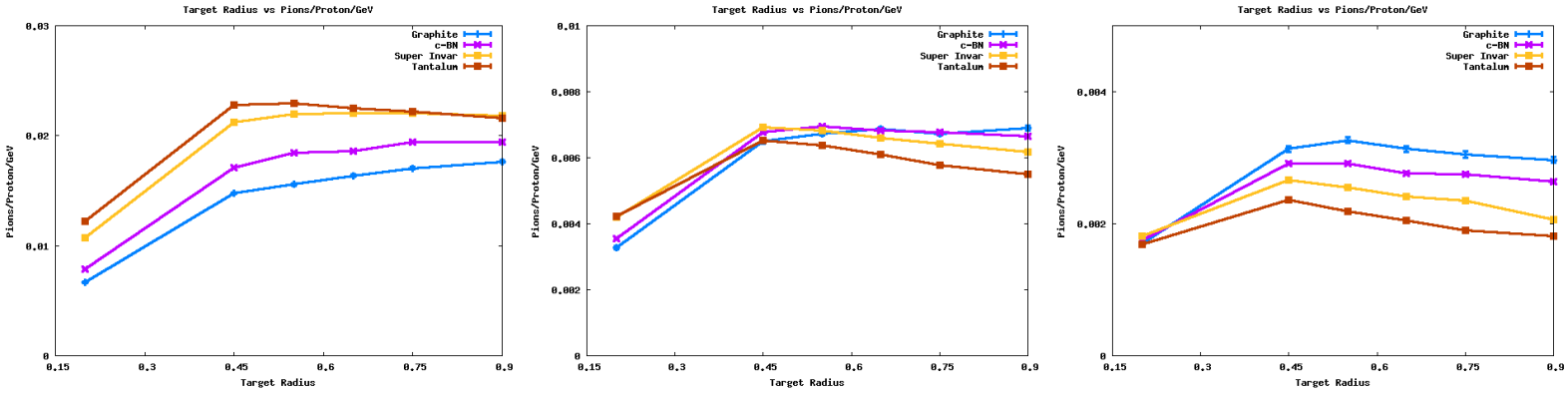
Optimization of Pion Production from the Target (FLUKA05)

Target size optimization for cylindrical geometry, $\sigma_{\mathrm{beam}} = 1.5$mm.

Target length in interaction lengths



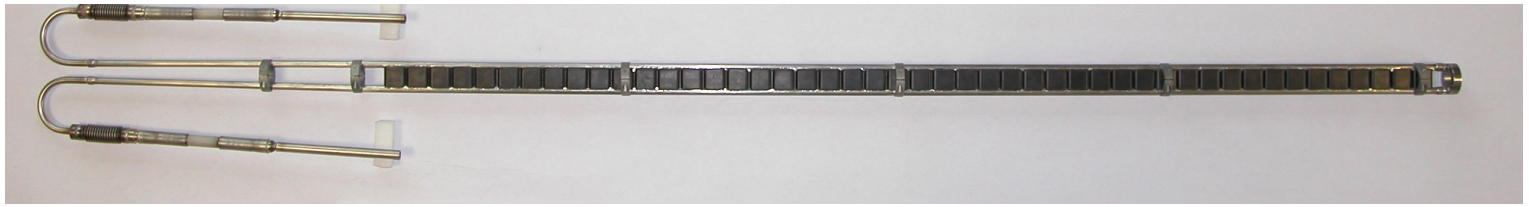
Target radius - fixed beam width



$1 < E_\pi < 3$ GeV $\quad$ $3 < E_\pi < 6$ GeV $\quad$ $6 < E_\pi < 10$ GeV

Longer target lengths preferred, width = 3x beam width

Example targets: NuMI/MINOS



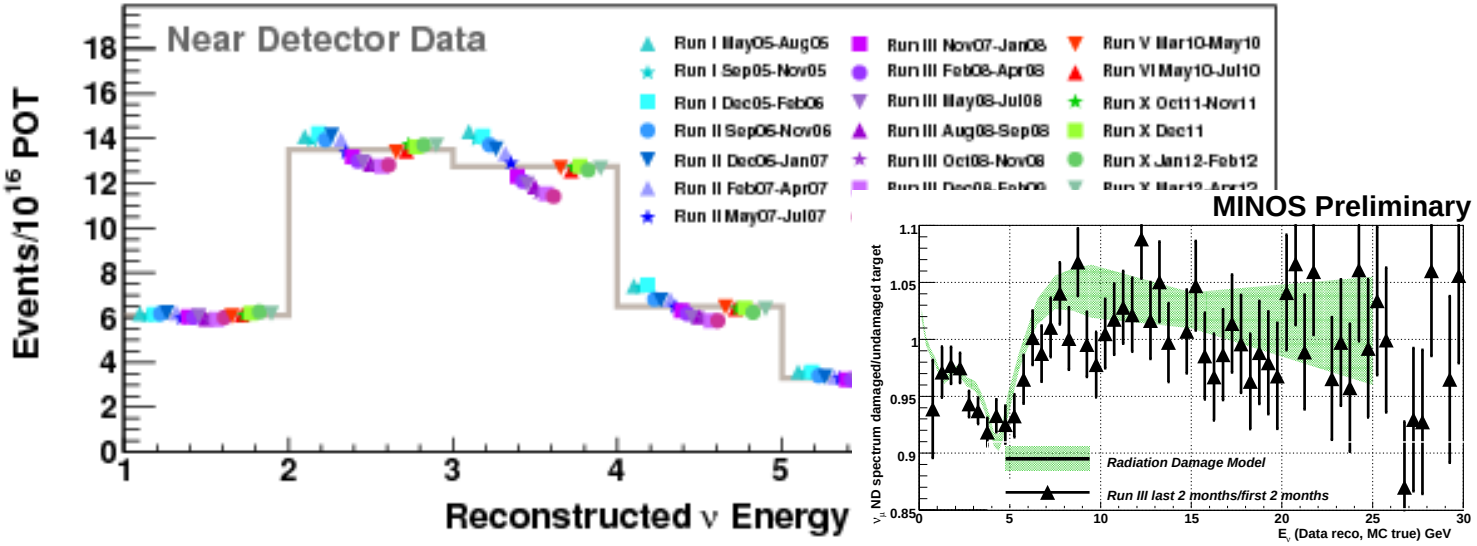
6.4 x 15 mm^2 graphite segments.

1m long = 1.9 interaction lengths.

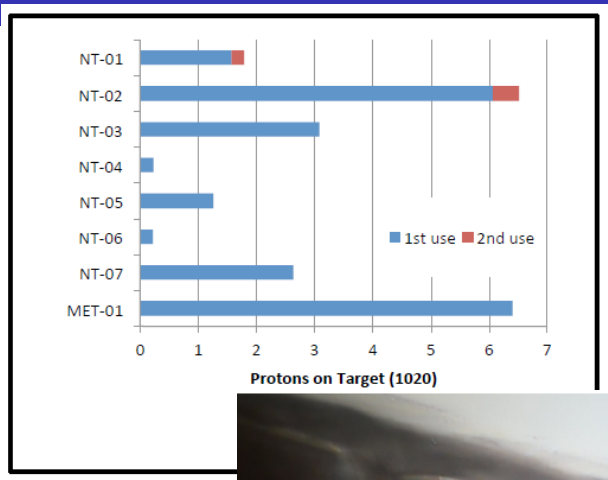
$\mathcal{O}$(10) KW beam power at 1 mm beam width.

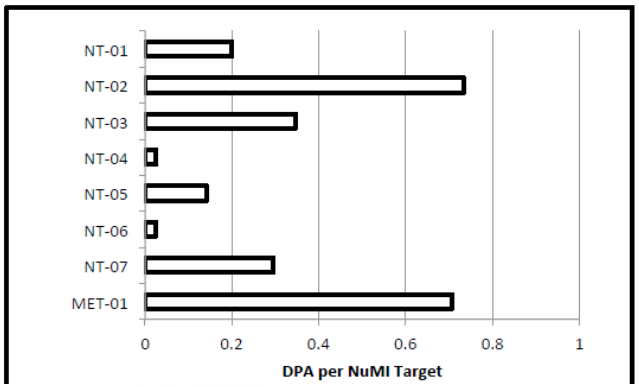
Water cooled.

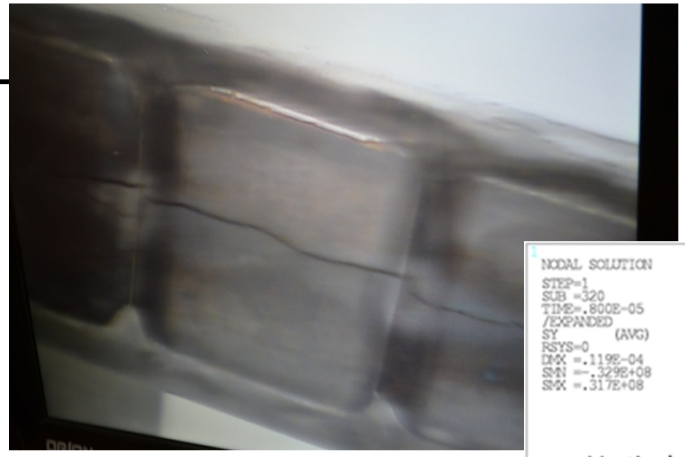
Evidence of NT02 damage after integrating 6×10^{20} POT:



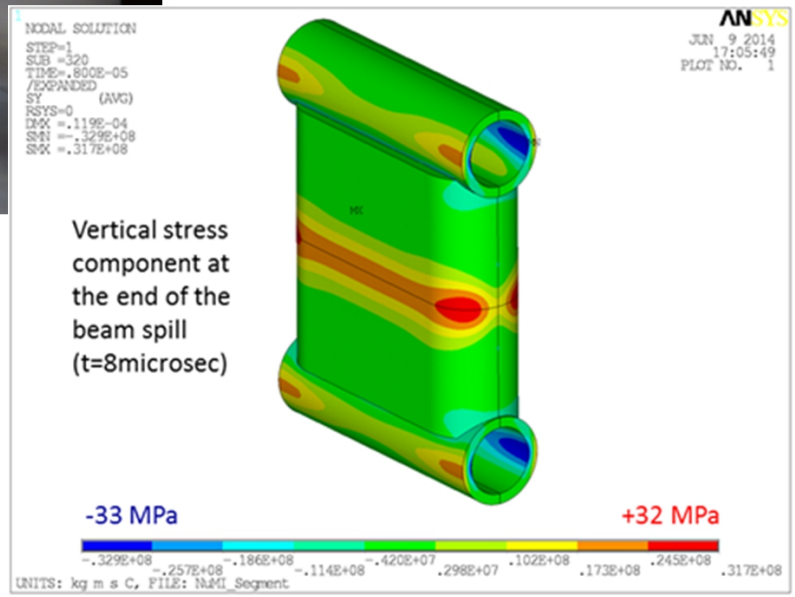
NuMI target operational experience







Autopsy of NT-02 (photo courtesy of V. Sidarov)

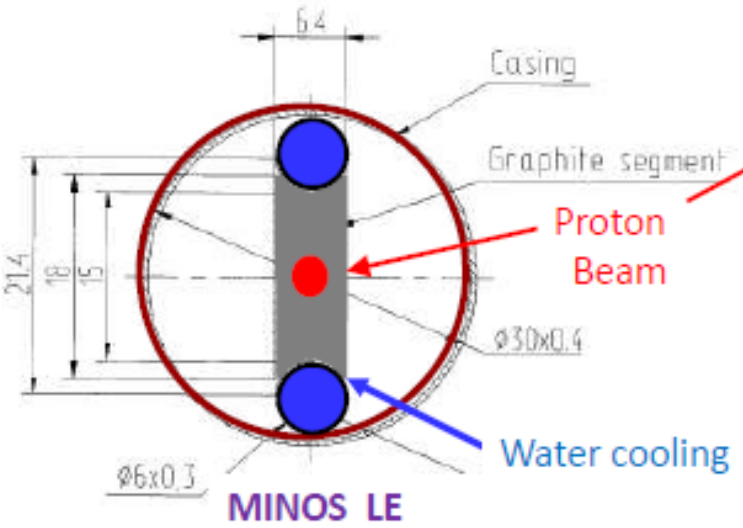


Possible explanation: high tensile stress after beam pulse 400 kW beam (T. Davenne/P. Loveridge)

NuMI/NOνA Modifications

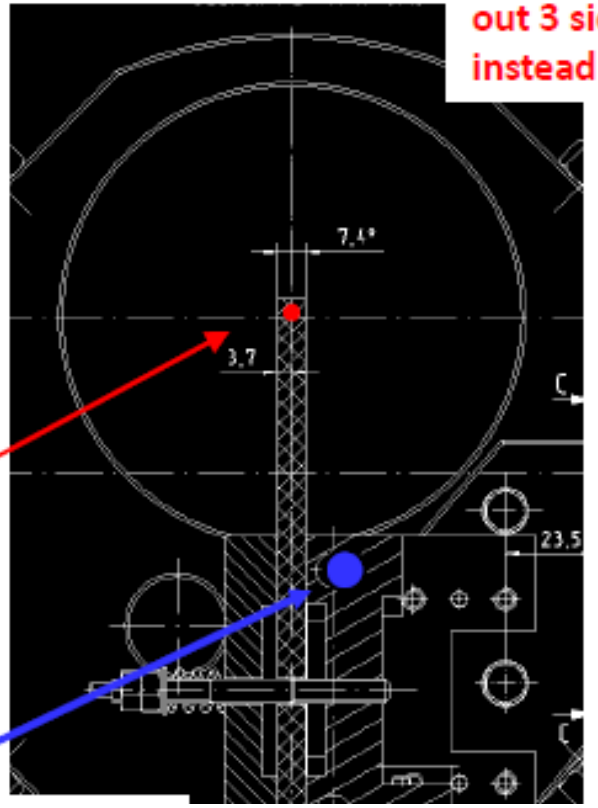
MINOS beam spot size of 1.1 mm RMS is increasing to 1.3 mm for NOVA, increasing 6.4 mm target width to ~ 7.4 mm
- reduces the neutrino flux ~ 1%, but eases alignment tolerance.

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

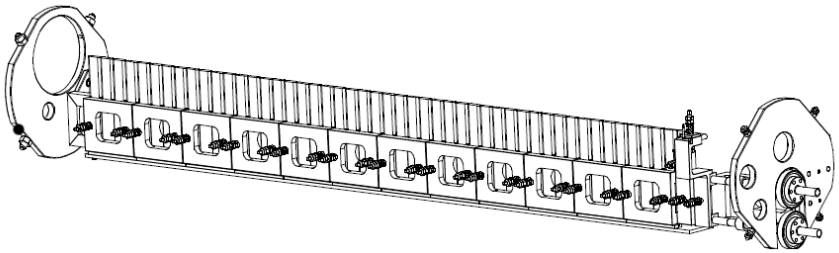


4/15/2011

Pions come out 3 sides instead of 2



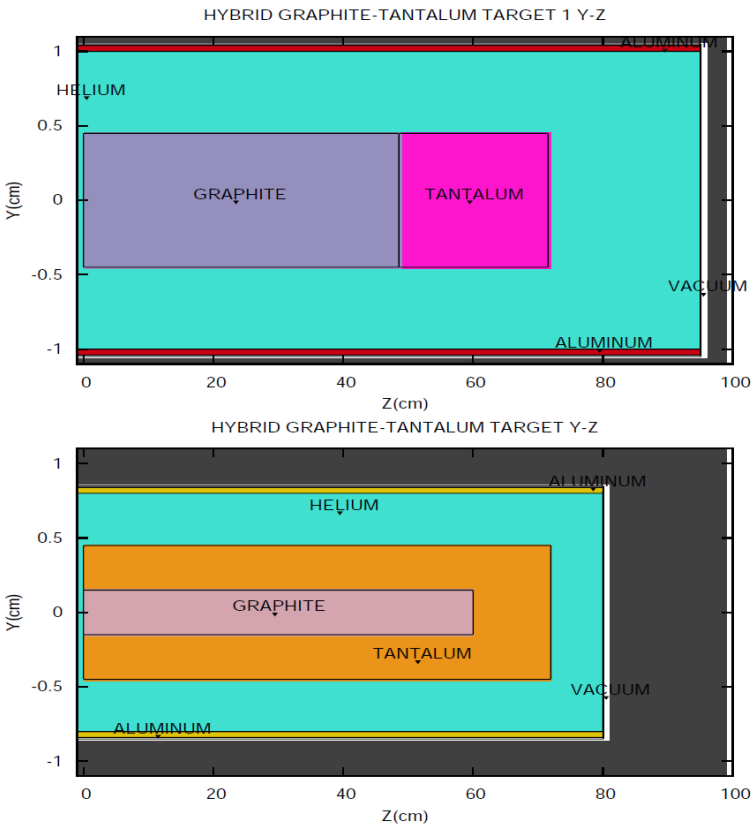
All units

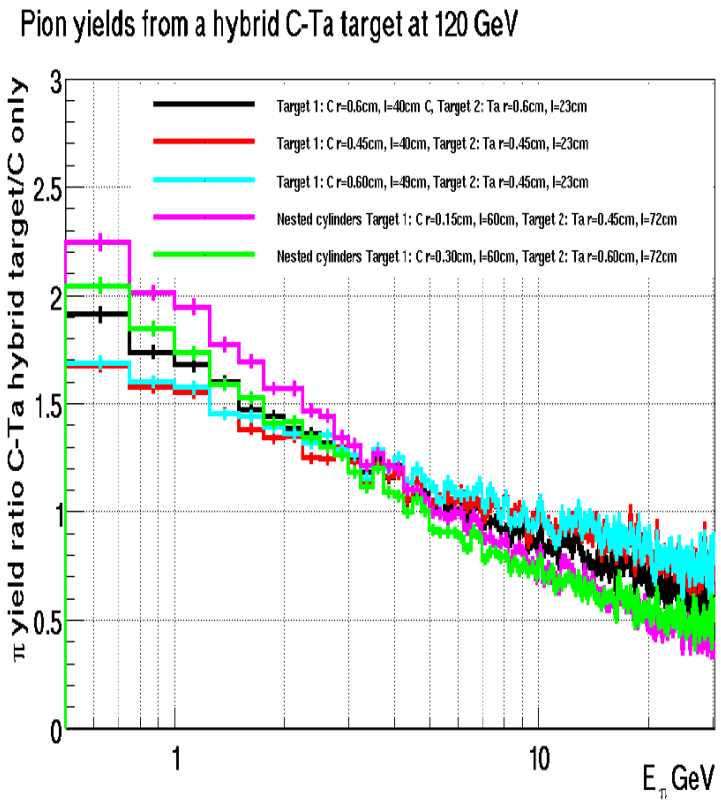


For 700kW NOνA beam, 9.9kW in target core, 4.7kW in target casing

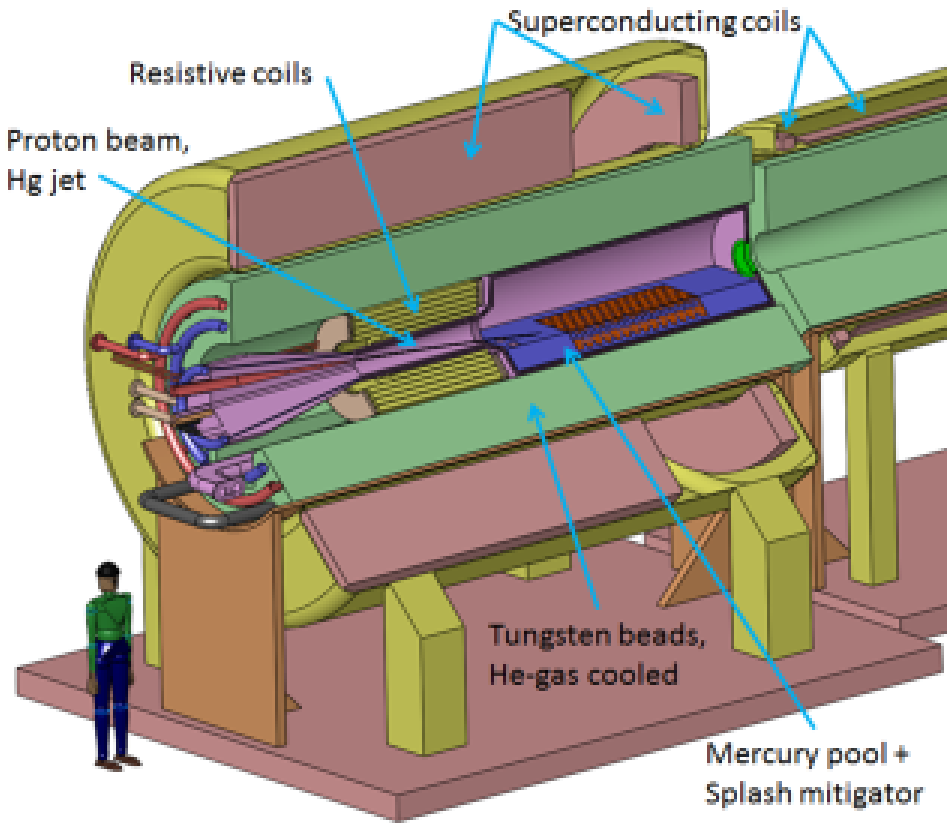
Example targets: Hybrid Target

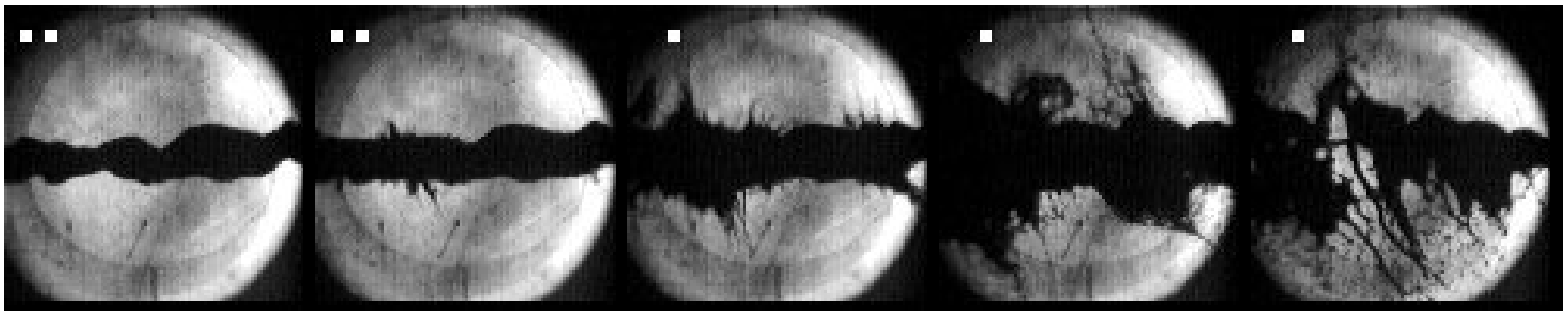
Use combination Low-Z/High-Z to increase π production



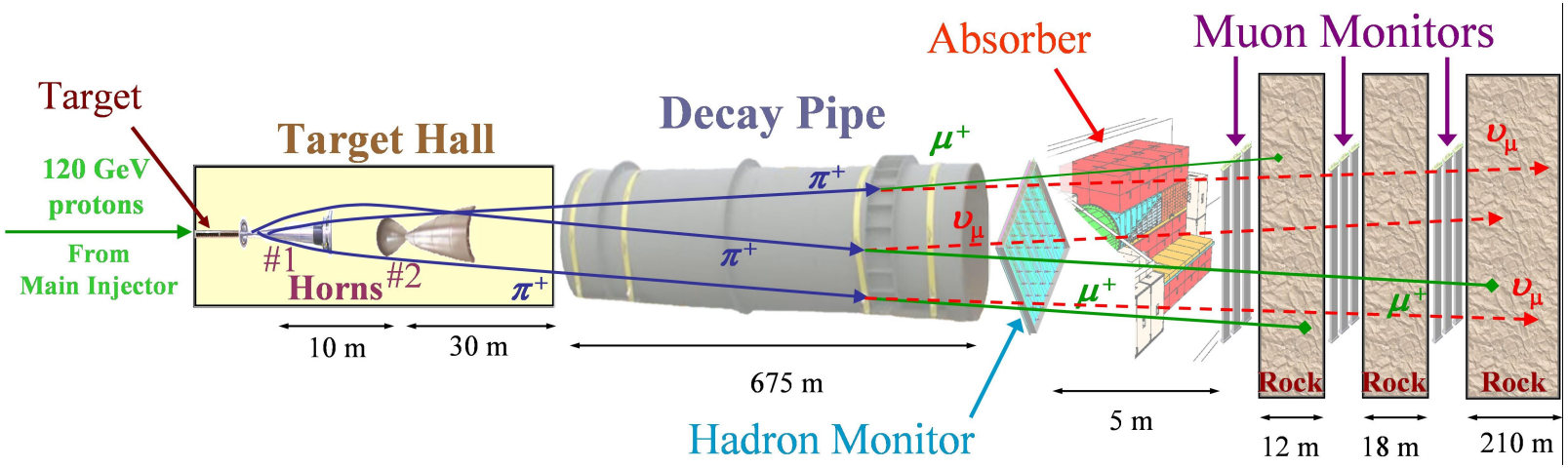


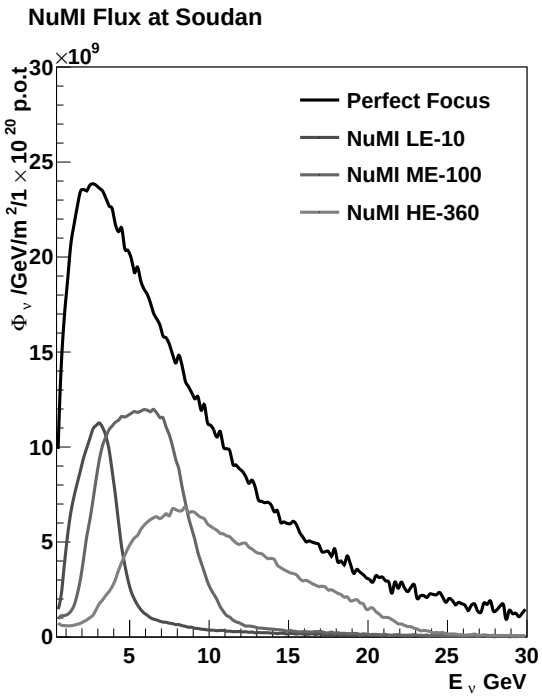
Example targets: Mercury jet

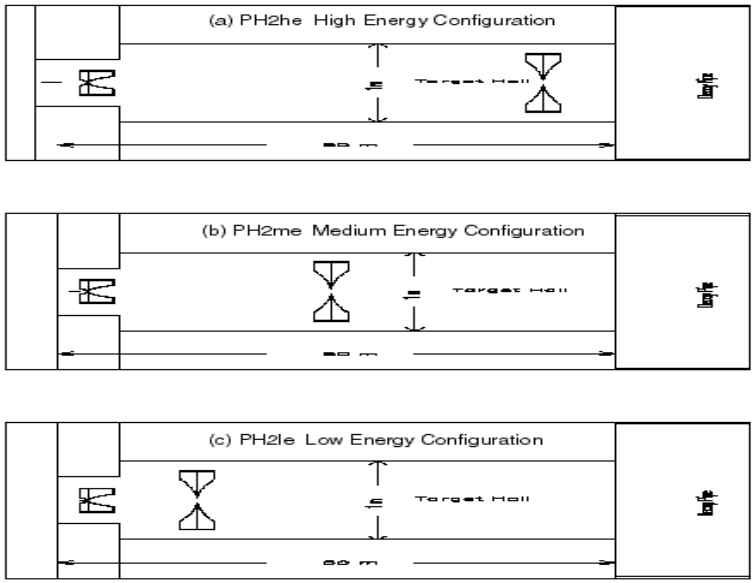




Tunable Focusing with Double Parabolic Horns (NuMI)







H1-H2: LE=10m, ME=23m, HE=40m

Target z_0 = -35cm from H1

NuMI Horn Performance

FNAL MI ν beams operational parameters at 120 GeV:

Beam Parameter	NuMI LE	NOνA	PIP II
Beam power to target (kW)	400	700	1200
MI Intensity (PPP)	4.0×10^{13}	4.9×10^{13}	7.6×10^{13}
MI Cycle Time	2.1s	1.33s	1.2s
Target Upstream End(Z,cm)	-35	-140	TBD
Horn 2 location	10m	19m	TBD
Annual uptime	1.6×10^{7} s	1.7×10^{7} s	1.8×10^{7}

Horns and striplines are made of Al. Inner conducter is water cooled. The horn heating loads are:

Heating Loads (kW)		NuMI 400 kW				NOvA 700 kW				
		Inner Conductor	Outer Conductor	Ceramic Ring	Clamps	Inner Conductor	Outer Conductor	Ceramic Ring	Clamps	Stripline
Horn1	Joule heating	5.8				8.5				1.2
	Beam heating	5.6	13.8	0.5	2.3	6.7	15	0.9	4.52	2.1
	Thermal Radiation		1.5				2.57			
	Total	29.5				38.2				3.3
Horn2	Joule heating	1.1				1.5				1.2
	Beam heating	0.4	4			1.5	7.2			0.17
	Total	5.5				10.2				1.4

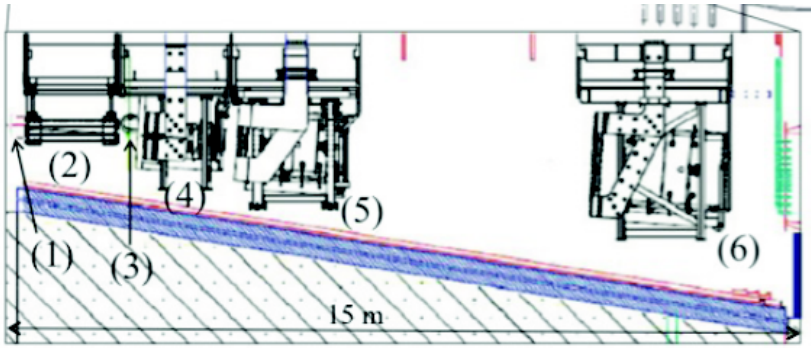
NuMI/NOνA at 700 kW, 48.4 kW heating load in Horns

NuMI Horn Performance

Horns	Status	# Pulses	Location	Comments
PH1-01	Very Used, Water Leak	24.2M	C0 Bay	9 R/hr @ 1 ft. on 5/12/14
PH1-02	Used, Still Operational 400kW "Spare"	45.9M	C0 Bay	35 R/hr @ 1 ft. on 9/10/14
PH1-03	400kW Spare, Upgraded Cooling for higher beam power	0	MI-8	
PH1-04	700 kW Horn Stripline Fracture	27M	NuMI Target Pile	Must be replaced Very Radioactive
PH2-01	Used, Stripline Fracture	28.1M	C0 Bay	Intend to ship off-site FY16
PH2-02	In operation	65.1M Pulses 4/13/2015	NuMI TH Beamline	

Robust design allows for improved facility uptime

T2K 3 Horn Design



(1) Beam window
(2) Baffle
(3) OTR
(4) Target and horn-1
(1) Horn-2
(2) Horn-3

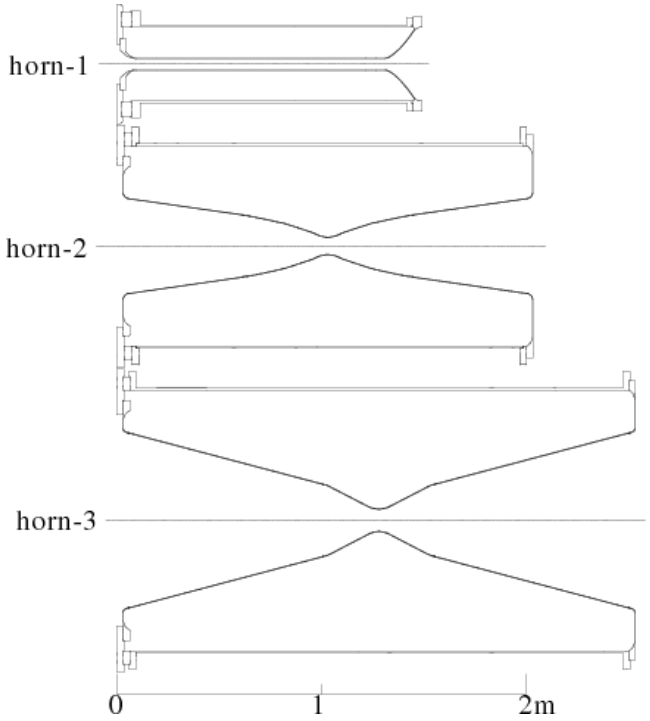


Table 1: Typical dimensions of T2K magnetic horns.

Parameters	horn-1	horn-2	horn-3
Inner diameter	54 mm	80 mm	140 mm
Outer diameter	400 mm	1,000 mm	1,400 mm
Length	1.5 m	2.0 m	2.5 m

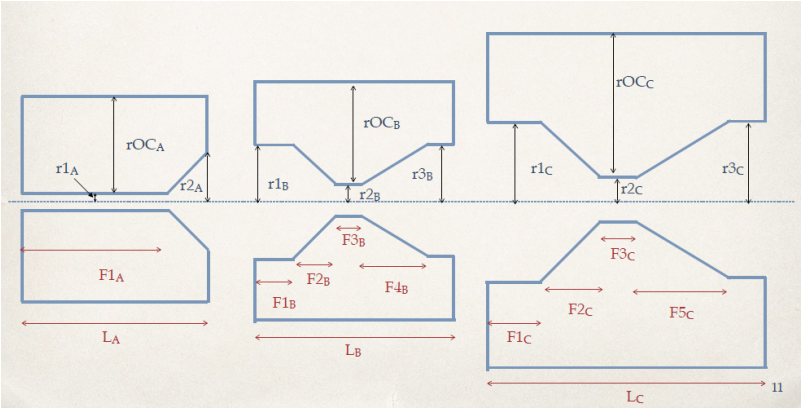
Table 2: Summary of heat deposit in each horn. Heat deposit from beam exposure is based on the design intensity of 3.3×10^{14} protons/pulse. Joule heating for each horn is estimated for pulse widths of 2.4 (horn-1) and 3.6 ms (horn-2 and horn-3). The calculation of the total heat deposit in units of kW is based on a 2.1-s cycle.

	horn-1		horn-2		horn-3	
	inner	outer	inner	outer	inner	outer
Beam (kJ)	14.7	9.7	4.1	7.6	1.1	2.4
Joule (kJ)	11.7	0.6	6.1	0.4	4.1	0.2
Total (kJ)	36.7		18.2		7.8	
Total (kW)	17.5		8.7		3.7	

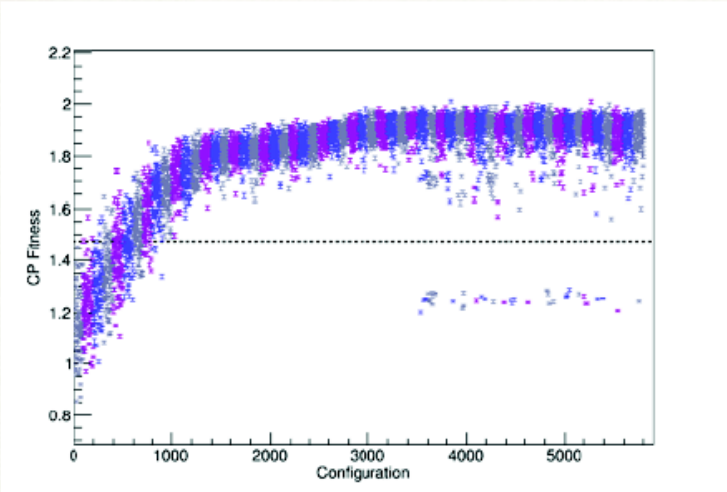
For 750kW beam, 30kW deposited in horns

Optimization of focusing for LBNF/DUNE (PRELIMINARY)

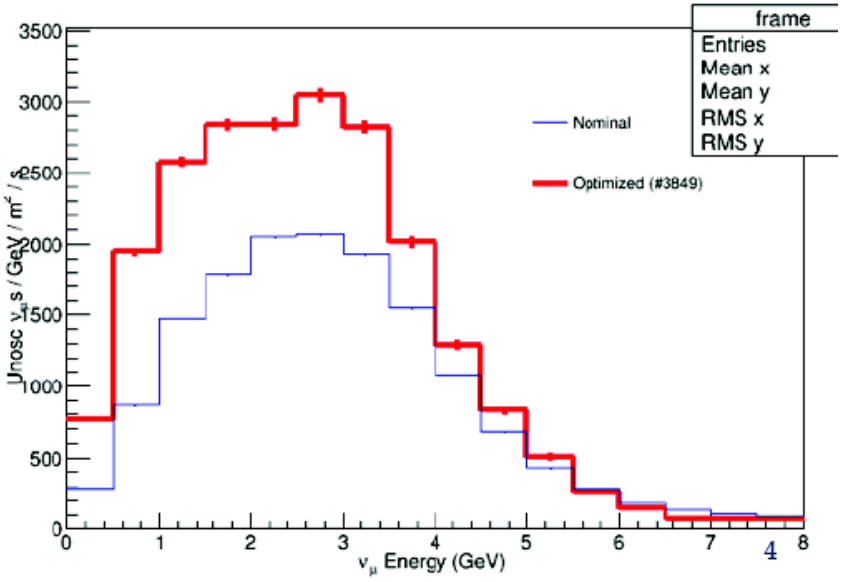
- **Reference design for LBNF/DUNE is NuMI-like target and 2 NuMI horns 6.6m apart**
- **Optimized focusing design with 3 horns obtained from a genetic algorithim with the physics parameter to be measured (CP) used to gauge fitness.**
- **Target geometry is optimized at the same time, as well as proton beam energy with realistic Main Injector power profile (1.07 MW at 60 GeV to 1.2 MW at 120 GeV).**
- **Limits on horn diameter and length are imposed based on experience with T2K and NuMI horn manufacturing**
- **Limits on horn separation imposed based on size of target chase.**



Optimization of focusing for LBNF/DUNE (PRELIMINARY)



Best fitness: 2.01
Compared to 1.47 reference and
1.97 (NuMI-style target, optimized)

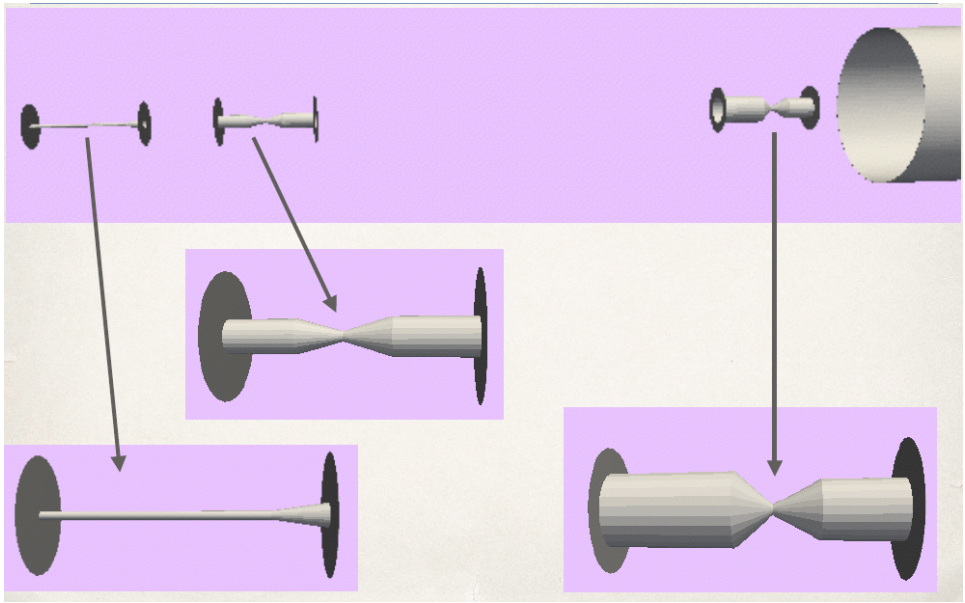


Computationally advanced optimization techniques

= significant gain in flux

Optimization of focusing for LBNF/DUNE (PRELIMINARY)

Parameter	Lower Limit	Upper Limit	Unit	
Horn A: L_A	1000	4500	mm	3717
Horn A: $F1_A$	1	99	%	51
Horn A: $r1_A$	20	50	mm	33
Horn A: $r2_A$	20	200	mm	147
Horn A rOC_A	200	650	mm	630
Horn B: L_B	2000	4500	mm	2551
Horn B: $F1_B$	0	100	%	37
Horn B: $F2_B$	0	100	%	12
Horn B: $F3_B$	0	100	%	2
Horn B: $F4_B$	0	100	%	16
Horn B: $R1_B$	50	200	mm	186
Horn B: $R2_B$	20	50	mm	47
Horn B: $R3_B$	50	200	mm	179
Horn B: ROC_B	200	650	mm	633
HornB: Z position	2000	17000	mm	5453
Horn C: L_C	2000	4500	mm	2694
Horn C: $F1_C$	0	100	%	30
Horn C: $F2_C$	0	100	%	21
Horn C: $F3_C$	0	100	%	2
Horn C: $F4_C$	0	100	%	9
Horn C: $R1_C$	50	550	mm	388
Horn C: $R2_C$	20	50	mm	26
Horn C: $R3_C$	50	550	mm	306
Horn C: ROC_C	550	650	mm	620
Horn C: Z Position	4000	19000	mm	17836
Target Length	0.5	2.0	m	1.98
Beam spot size	1.6	2.5	mm	2.1
Target Radius	9	15	mm	7.8
Proton Energy	60	120	GeV	108
Horn Current	150	300	kA	270

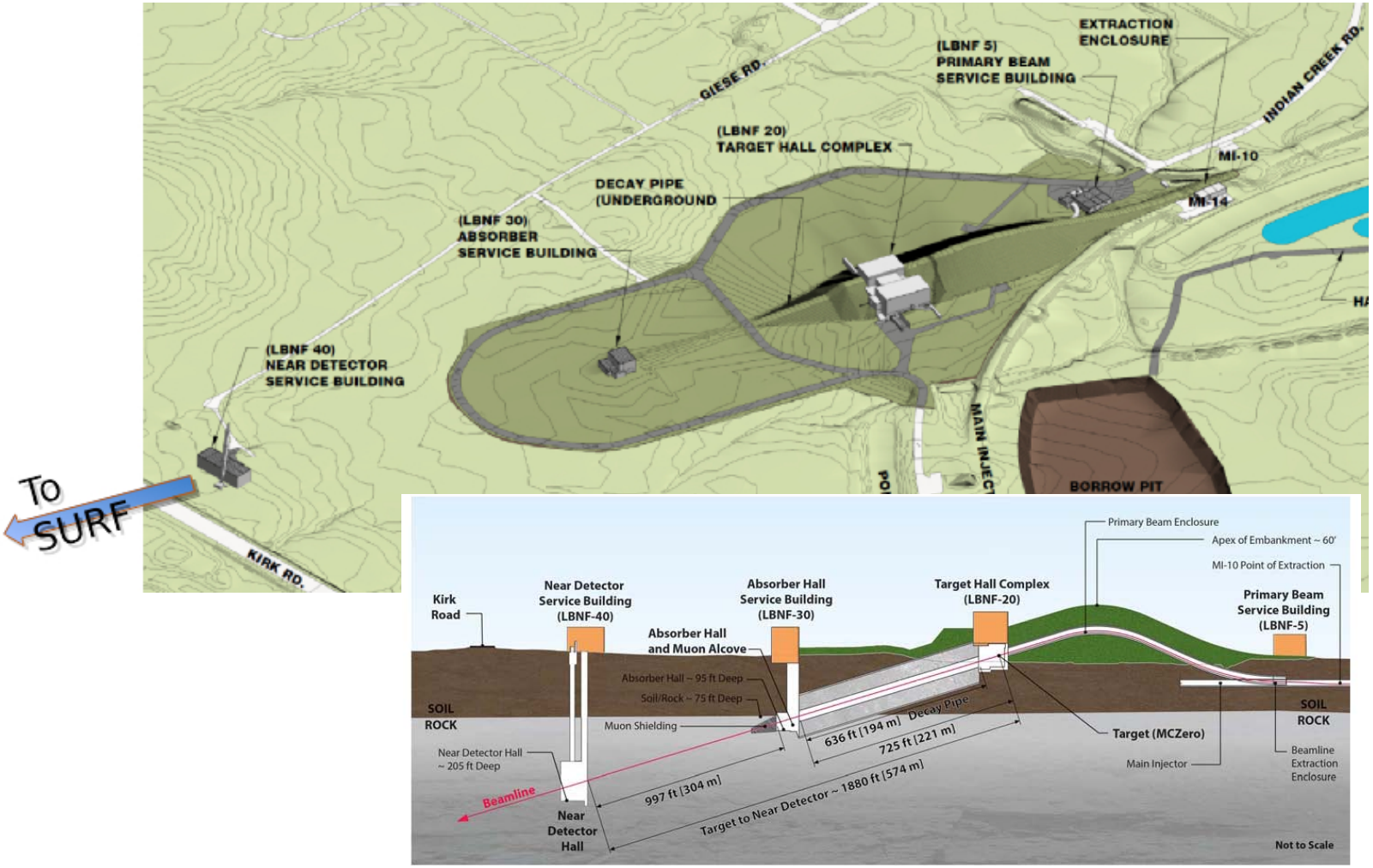


Horn	Location (m)	Length (m)	ID (mm)	OD (mm)	Current (kA)
Horn A	0	3.7	66	1260	270
Horn B	5.4	2.6	94	1266	270
Horn C	17.8	2.7	52	1240	270

Target (graphite) L=2m, R=7.8mm, $E_p = 108$ GeV, $\sigma_{\rm beam} = 2.1$ mm

The LBNF Beamline

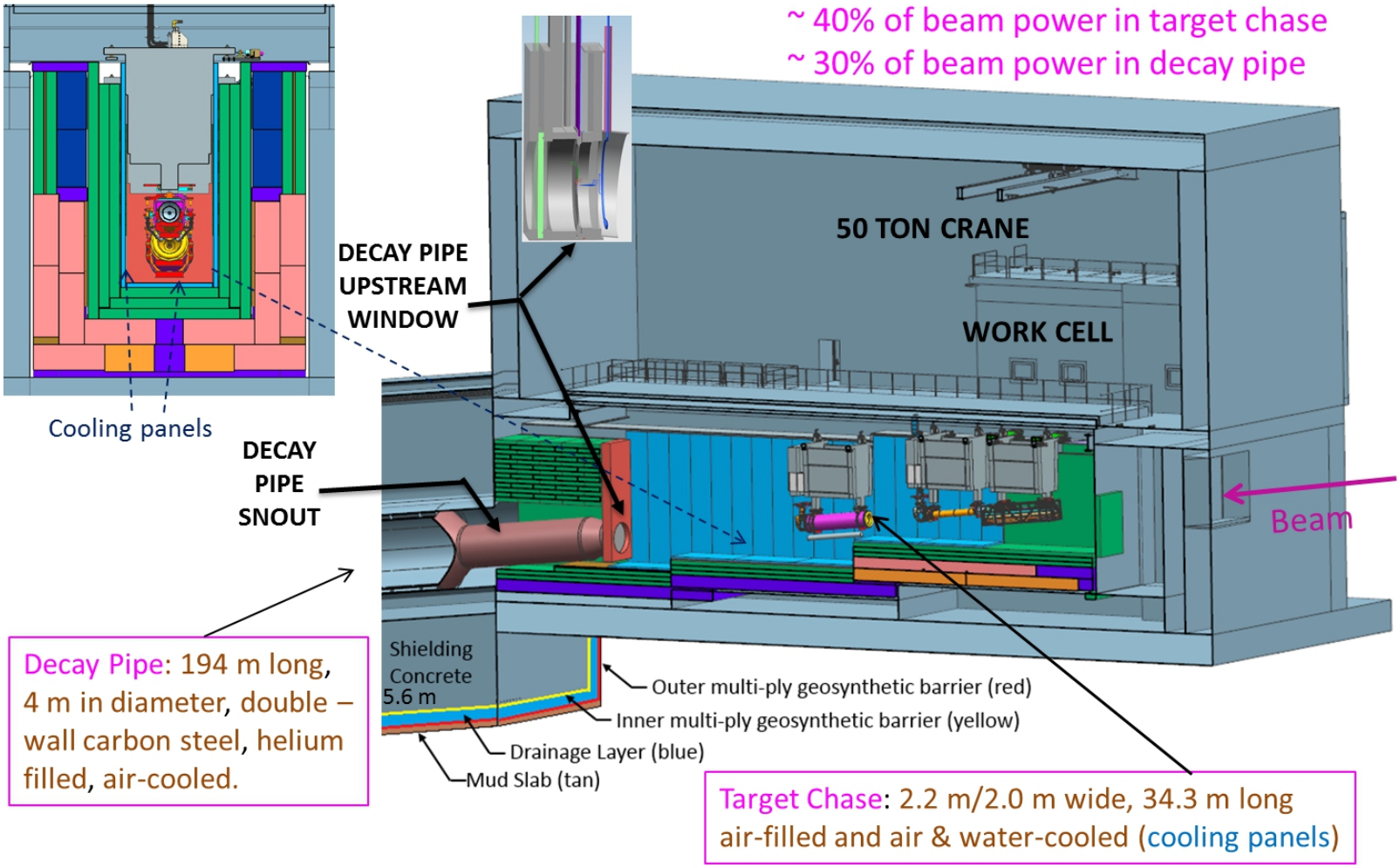
Novel concept beam-on-a-hill reduces cost.



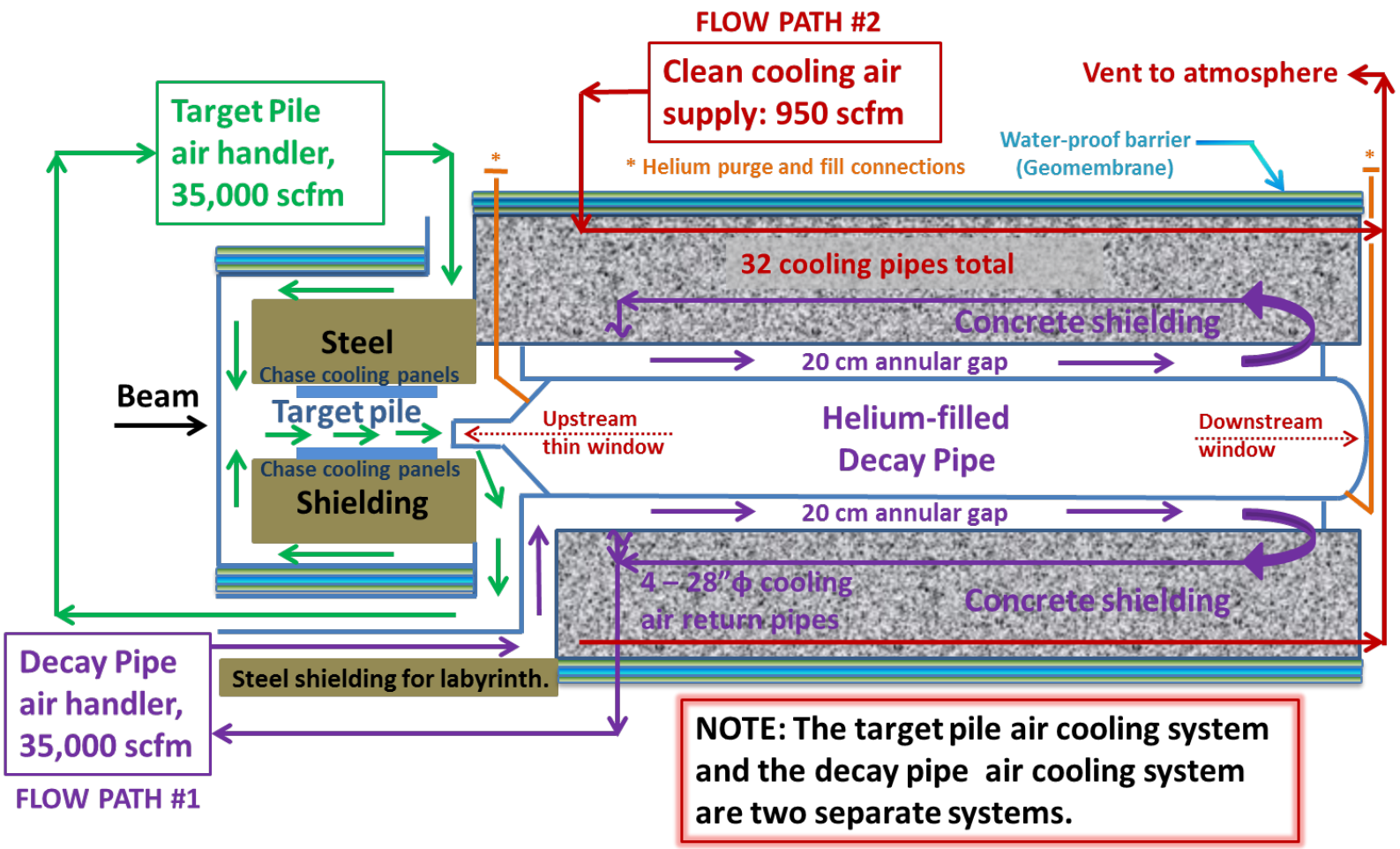
Primary proton beamline: extracts 60-120 GeV designed for 1.2MW upgradable to 2.3MW

The LBNF Beamline

Advanced conceptual design with upgraded tunable NuMI focusing:



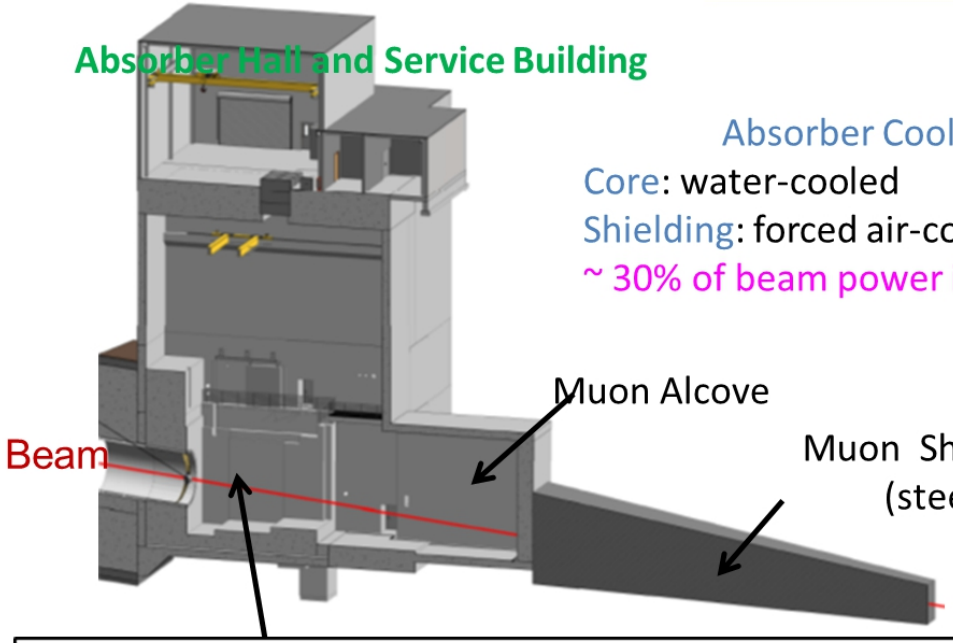
LBNF Decay Pipe



LBNF Absorber

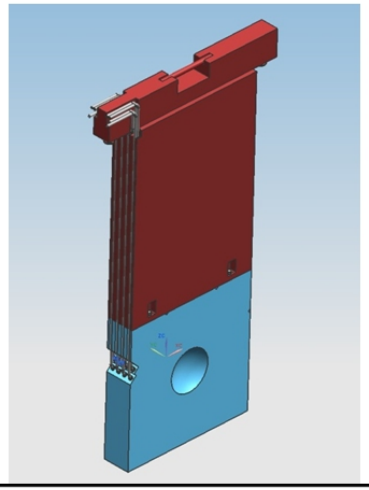
Hadron Absorber

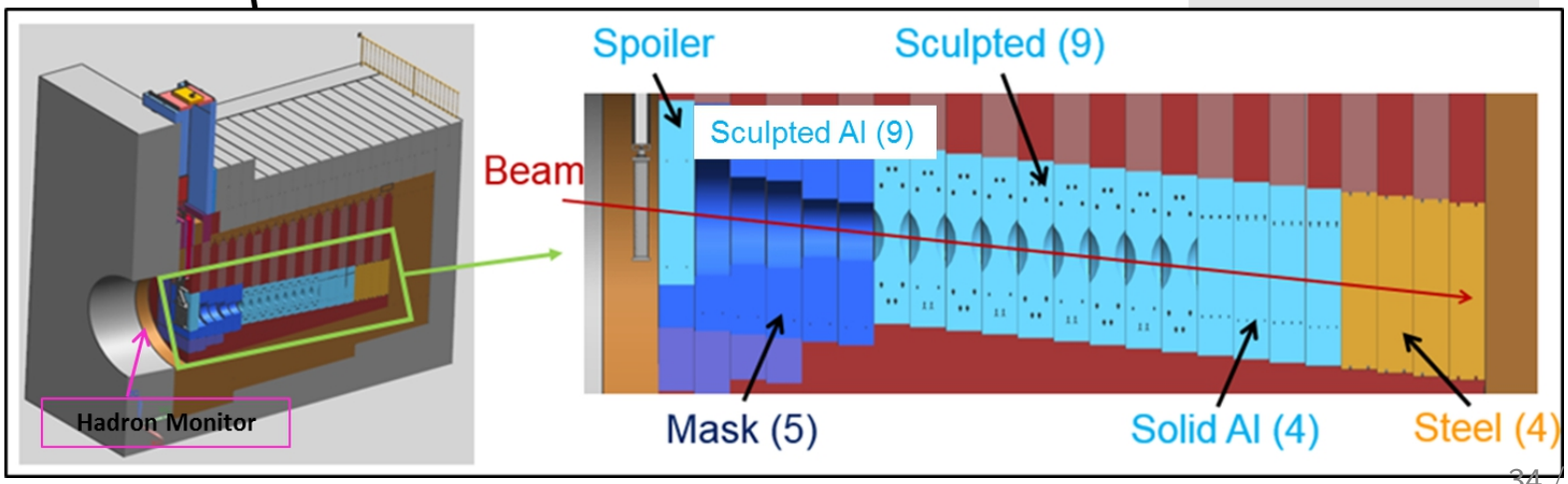
The Absorber is designed for 2.4 MW



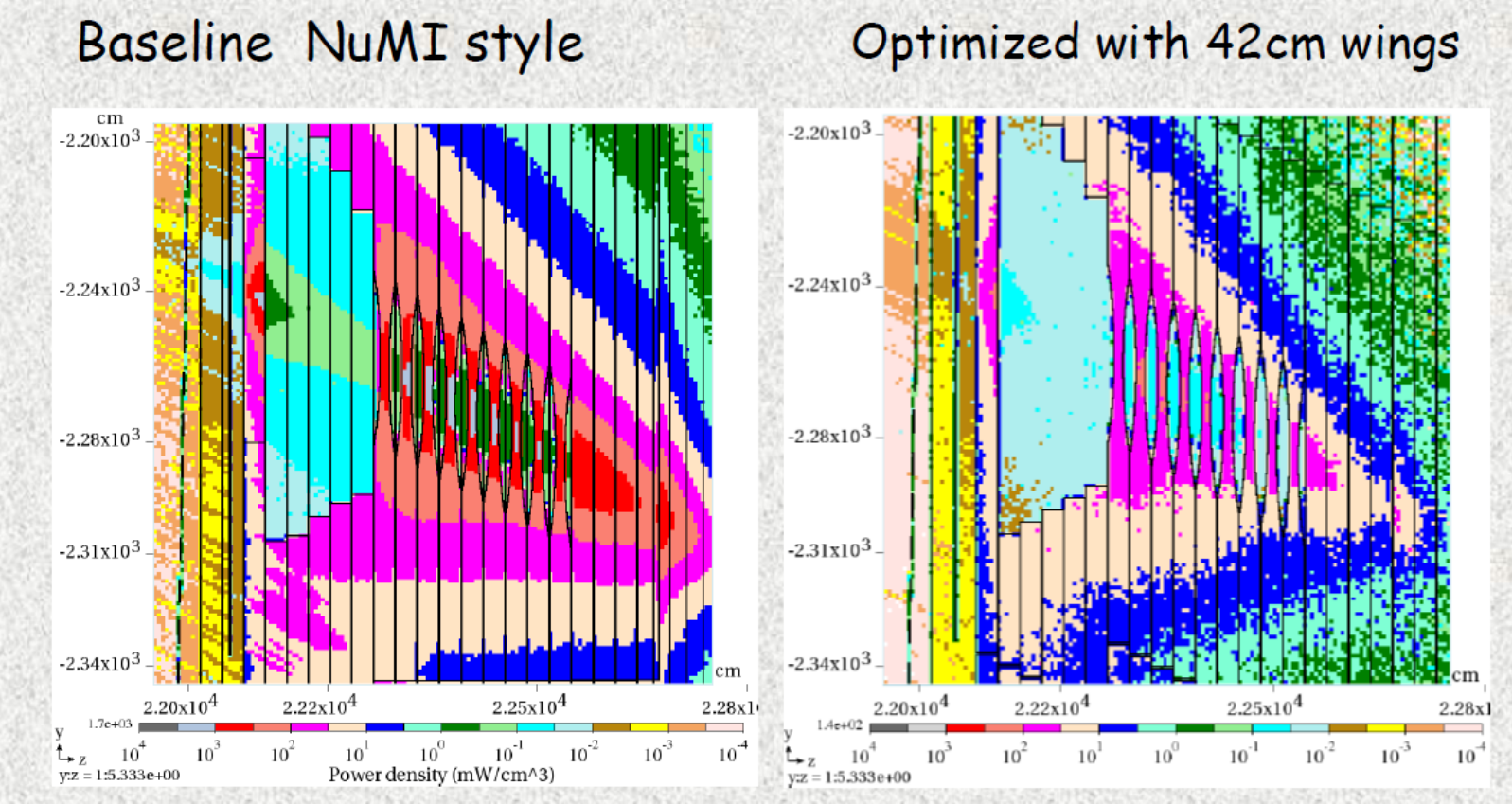
Absorber Cooling
Core: water-cooled
Shielding: forced air-cooled
~ 30% of beam power in Absorber

Core blocks replaceable (each 1 ft thick)





LBNF Absorber Energy Deposition



PRELIMINARY: Optimized focusing design and possible wings added to target could reduce peak energy deposition in absorber 8-12 $\times$.

Summary

In most long-baseline ν expts, 50 kton.MW.yr of running produces only $\mathcal{O}(100)$s of $\nu_\mu \rightarrow \nu_e$ CC events in the FD

- **Longer decay channels, smarter focusing designs, novel target and focusing materials could potentially increase ν/p x2 for equal power on target.**
- **Facility uptime and efficiency requires robust focusing/targeting designs - lessons learnt from current beamlines.**
- **Neutrino factories require more beam power on target than conventional beams to produce equal statistics of $\nu_e \rightarrow \nu_\mu$ events. But only an NF produces high intensity ν_e beams.**
- **The vast majority of the beam power $>$ 70% is deposited in the target chase and absorber = challenging design.**

THANK YOU

LBNF Near Site Schedule