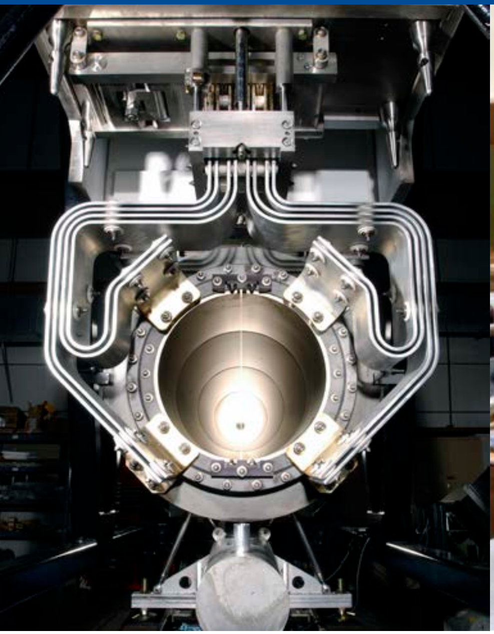


Future Conventional Neutrino Beams

Robert Zwaska,

First 2018 Neutrino Working Group Meeting

5 April 2018

LBNF, The Last Neutrino Beam?

- LBNF may well be the last conventional long-baseline neutrino beam built
  - Must be built so as to explore necessary physics
  - Will have some measure of flexibility
- If there are to be future beams, it depends on what we learn

- Plan for this talk:
  - Neutrino Beam Features
  - Neutrino Beam Challenges
  - Neutrino Beams in Action
  - Future Possibilities

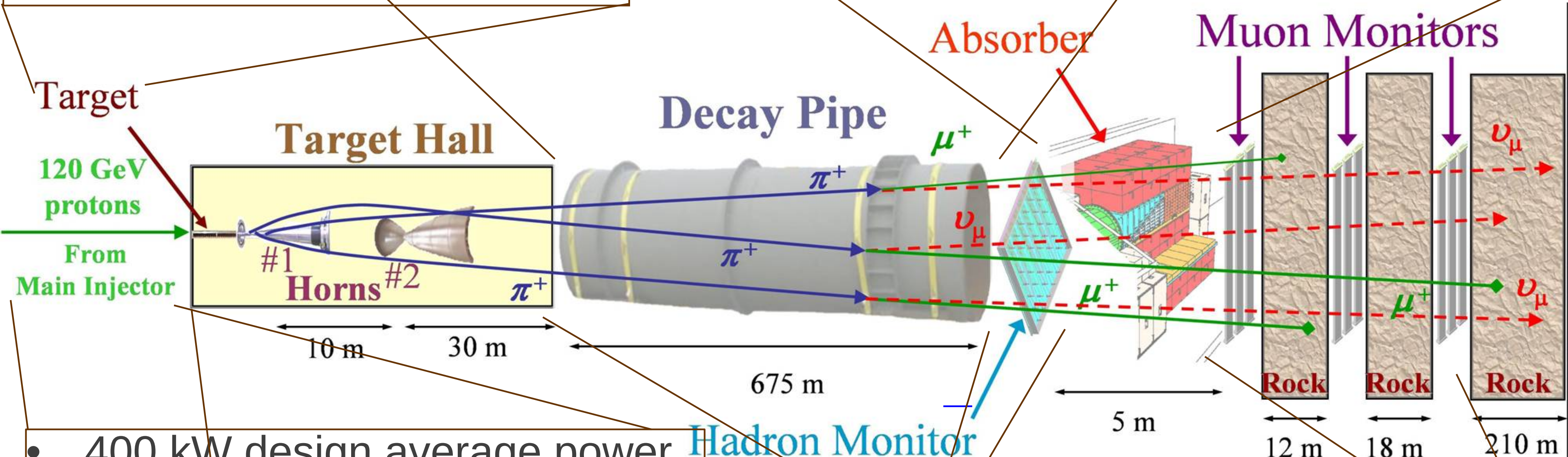
- Our knowledge and ability of neutrino beams will improve over the next decade, for existing and future neutrino beams

Neutrino Beam in a Nutshell (NuMI)

- Absorbs ~ 40 % of beam power
- Allows high-energy muons to penetrate

- 2 m diameter
- Roughly decay length for 10 GeV π^+
- He-filled

- 2 interaction length, C target
- Produces π^+, K^+ mesons



- 400 kW design average power
- 700 kW upgrade for NOvA
- 1MW future
- σ ~ 1-2 mm

- Pulsed focusing horns @ 200 kA
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focuses meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

Fermilab

Pion Decay

- Neutrinos produced at random direction in pion rest frame
  - Boosted in the direction of the beam
  - Ultimate energy determined by the decay angle with respect to the boost, in the lab:

$$E_\nu \approx E_\pi \frac{1-m_\mu^2/m_\pi^2}{1+\gamma^2\theta^2} \approx \frac{0.43E_\pi}{1+\gamma^2\theta^2}$$

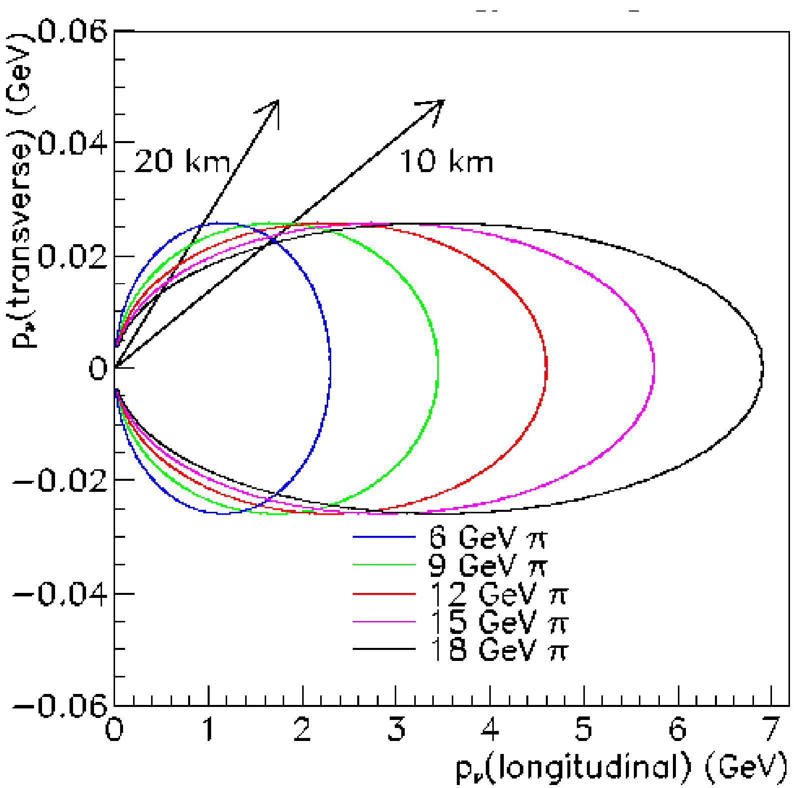
  - Muon carries the balance of the energy
- Flux is also affected such that the beam is strongly directed in the direction of the pion velocity:

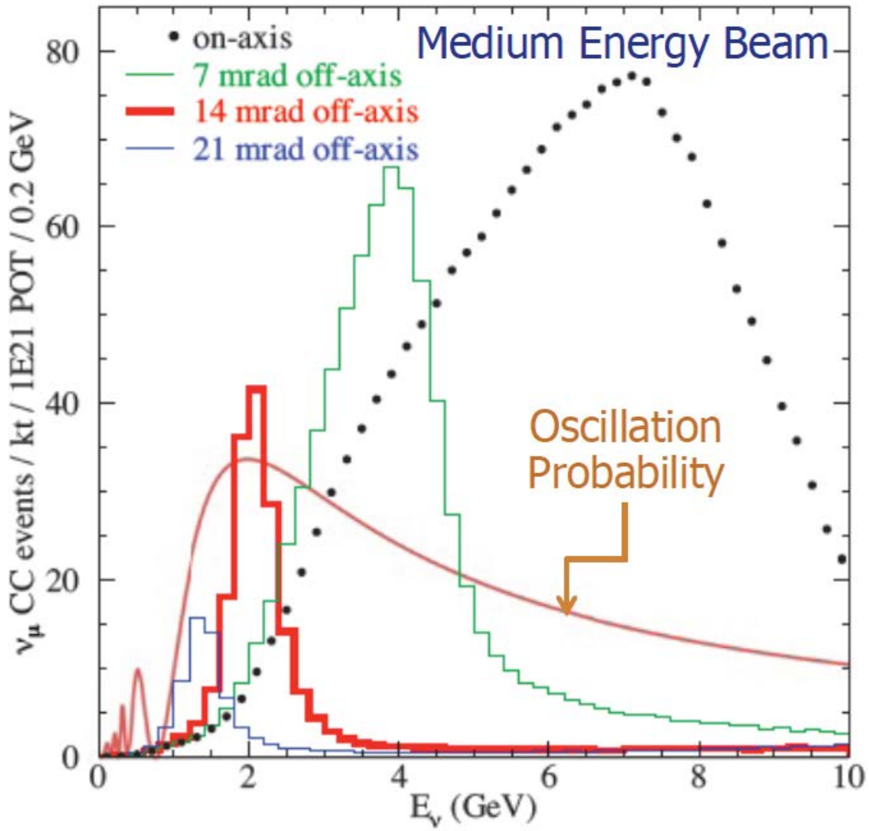
$$\frac{dN}{d\Omega} \approx \frac{1}{4\pi}\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2$$

- All two-body decays have this functional form. Three body-decays are boosted in the same way, but are complicated by the decay kinematics

Off-Axis Beam

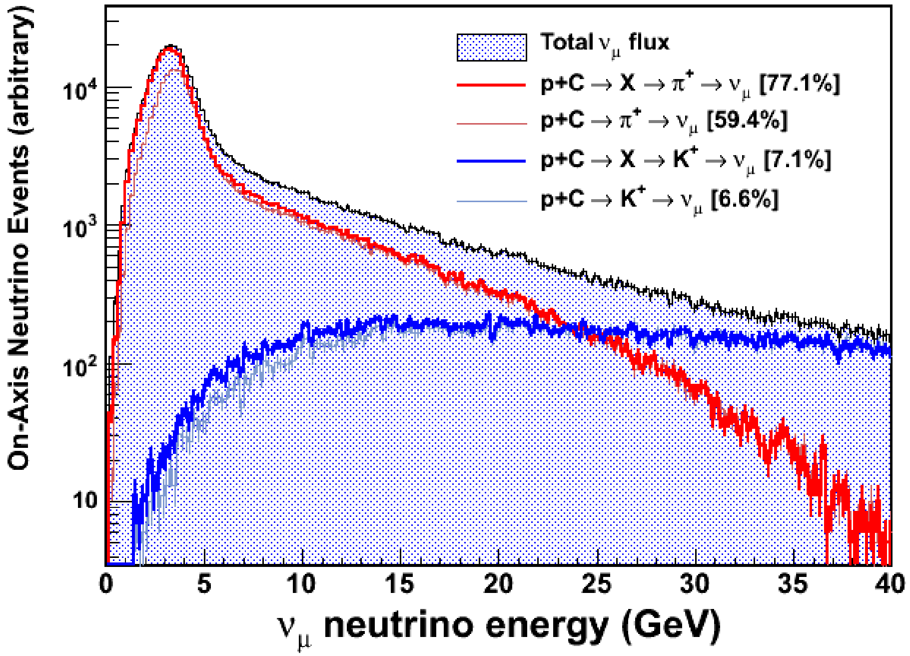
- Technique used by T2K, NOvA (first proposed by BNL)
  - Fewer total number of neutrino events
  - More at one narrow region of energy, tuned to oscillation probability
  - For ν_μ to ν_e oscillation searches, backgrounds spread over broad energies

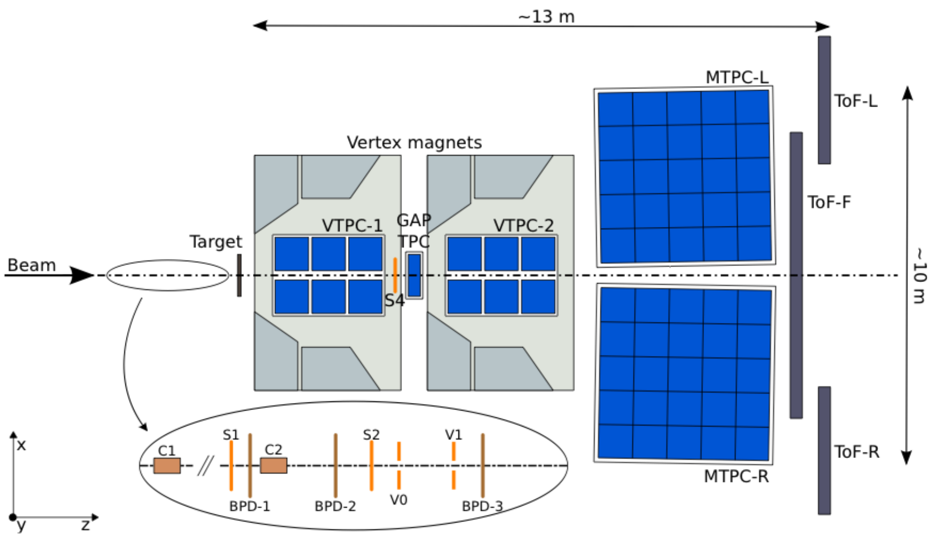




Challenge: Hadroproduction

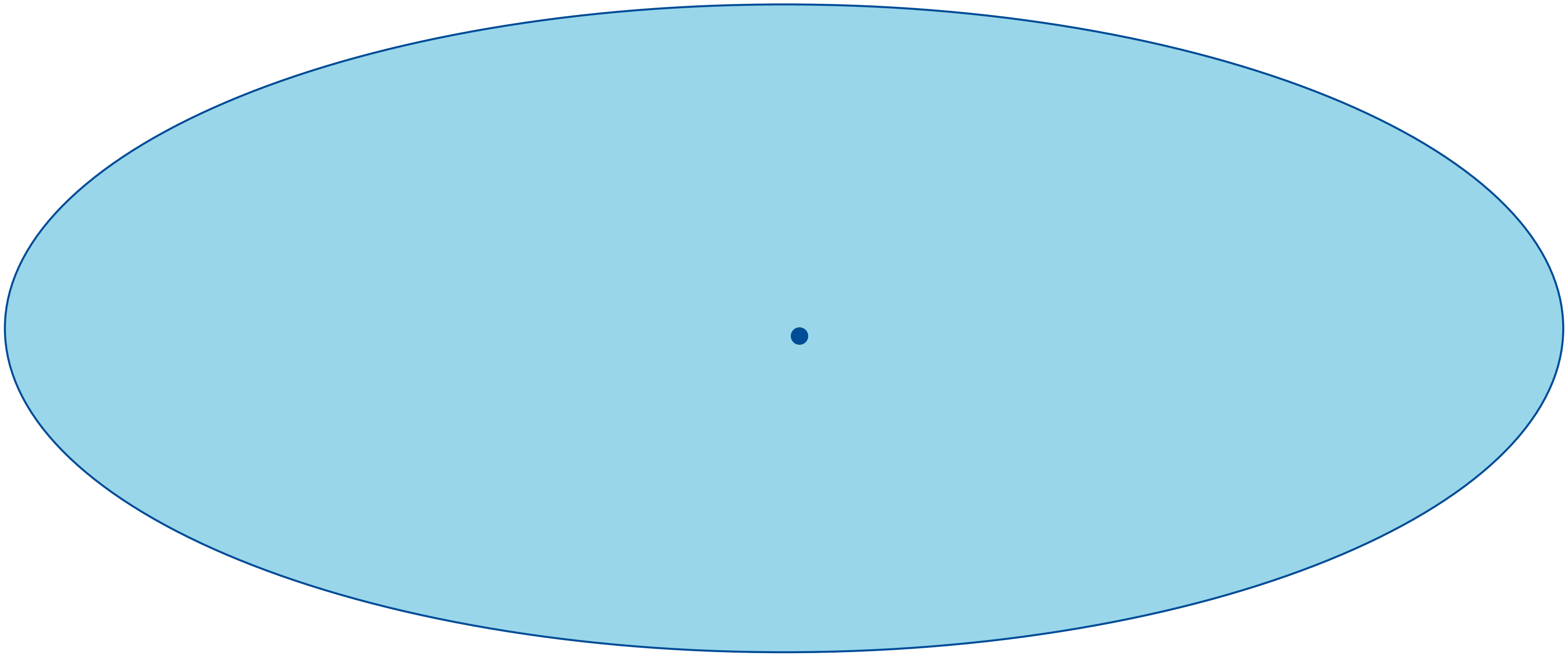
- Simulations give a spectrum
  - But, what is the uncertainty?
- Hadroproduction experiments can constrain simulations, or directly give input to experiments' flux estimation
- Presently, NA-61 at CERN is exploring hadroproduction
  - Gradual series of measurements – not an exhaustive program
  - Some detector limitations mean that some important distinctions in parameter space can't be made
- **Solution:** a dedicated, exhaustive program of hadroproduction measurements could dramatically improve neutrino beam simulation
- Modelling codes and expertise require maintenance and evolution





Challenge: Proton Beam

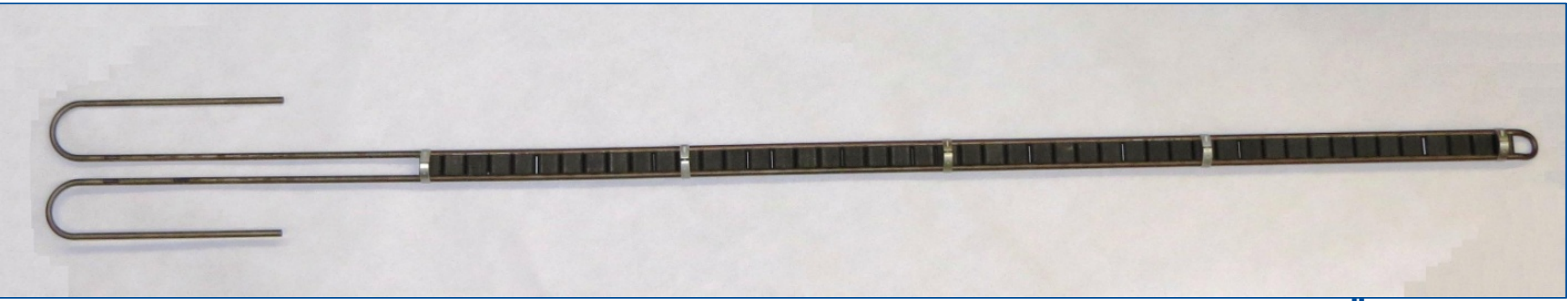
- SNS & NuMI proton beams to scale:



- 200 mm x 70 mm vs. 1.3 mm x 1.3 mm
  - SNS target experience is not directly transferrable
- Greatest challenge for windows and targets
  - Significant challenges for peripheral devices

Challenge: Targets

- Optimal target:
  - Low-Z to optimize pion production (minimize energy deposition in target & horn)
  - High density to stay within the Horns' depth of focus
  - Roughly two nuclear interaction lengths long
  - The optimized width to allow a certain amount of reinteraction, but limit absorption
- But, the target must survive for a non-negligible duration
  - Material must withstand thermomechanical shock
  - Material must withstand radiation damage
  - Heat must be removed
  - Supporting materials (e.g. water & pipes) must be far enough from the beam to avoid boiling
- Above contradictions drive us to graphite & beryllium
  - Water cooling is the baseline, but air is not out of the question
  - **R&D** has a substantial capability to improve the efficiency of neutrino production



RaDIATE Collaboration

Radiation Damage In Accelerator Target Environments

Broad aims are threefold:

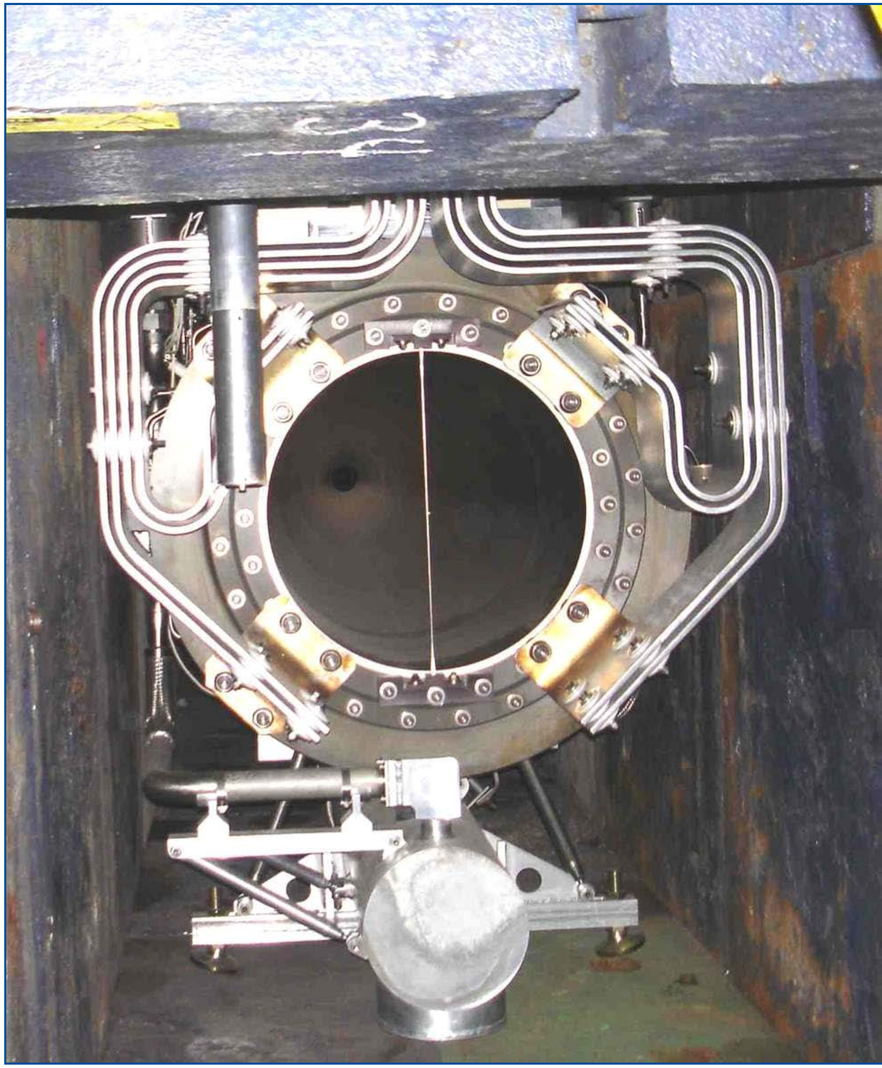
www-radiate.fnal.gov

- to generate new and useful materials data for application within the **accelerator** and **fission/fusion** communities
- to recruit and develop new scientific and engineering experts who can **cross the boundaries** between these communities
- to initiate and coordinate a **continuing synergy** between research in these communities, benefitting both **proton accelerator applications** in science and industry and **carbon-free energy technologies**

Fermilab | University of Oxford | Brookhaven National Laboratory | European Spallation Source | Argonne National Laboratory | Science & Technology Facilities Council | FRIB | Pacific Northwest National Laboratory | Oak Ridge National Laboratory | Los Alamos National Laboratory EST. 1943 | Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

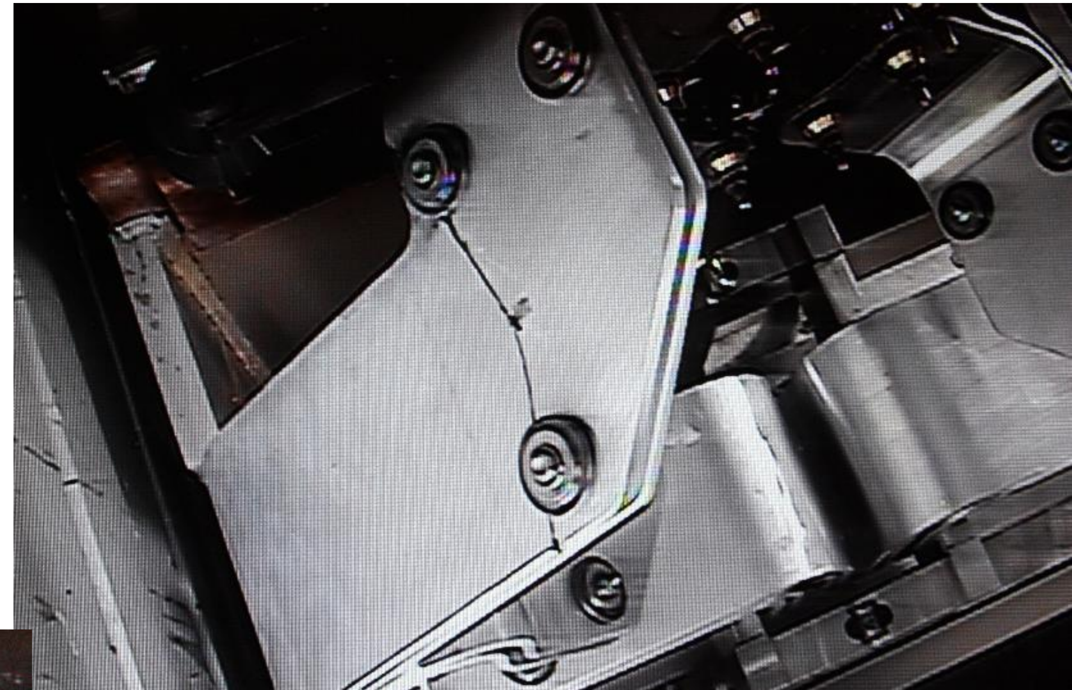
Challenge: Horn Focusing

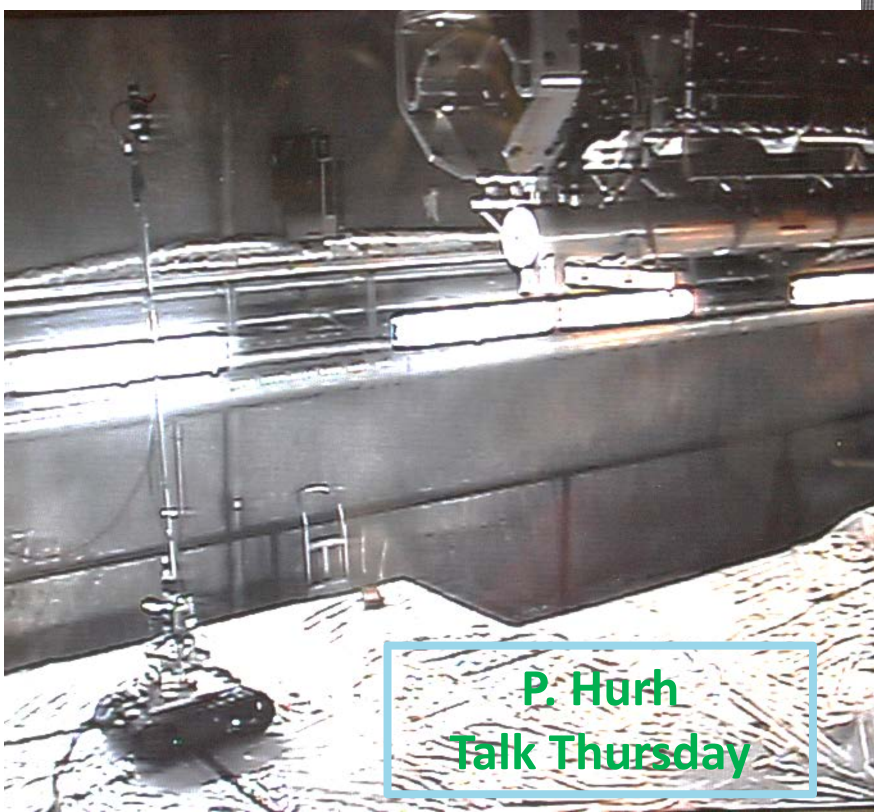
- Horns have a limited depth of focus
  - For a particular momentum in NuMI, roughly:
    - ± 5 mm transversely
    - ± 15 cm longitudinally
  - Target is much longer in *z* !
    - Not so bad: want a broad energy range
  - Overall, horn focusing is very efficient
- Horn currents are limited by ohmic and beam heating (~ 200 kA)
  - Higher currents would allow more efficient focusing
- Corrosion and radiation damage of materials
- Aluminum horn materials cause absorption and heating
  - **Beryllium is an R&D option (exotic)**



NuMI Horn 1 Failure

- Replaced NuMI Horn summer 2016 due to failed stripline
  - First 700 kW capable horn, in service since Sept. 2013, accumulated ~ 27 million pulses
- Failure was due to fatigue, likely enhance by vibrations



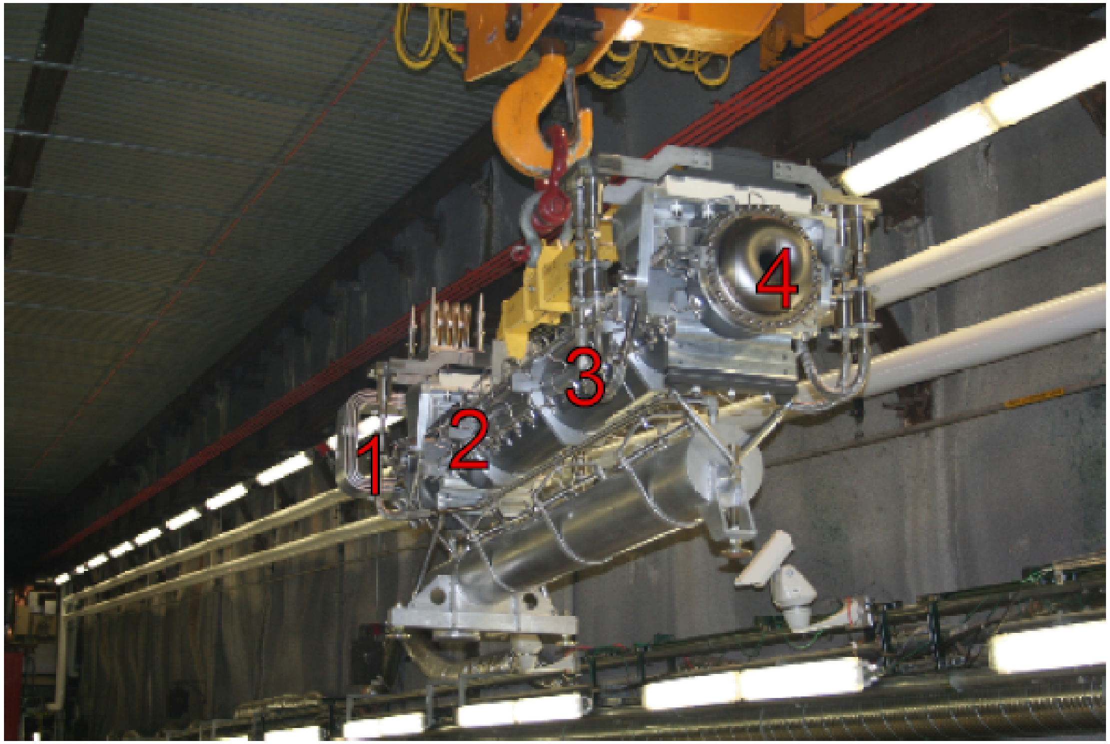


P. Hurh
Talk Thursday

ALARA (As Low As Reasonably Achievable)

FERMILAB
ACCELERATOR
DIVISION

DATE:9/3/15	TIME: 1000	PURPOSE: replacement survey	RWP #



NUMI Horn #1

Point	Doserate @ 1 foot (mr/hour)
1	50000
2	100000
3	110000
4	80000

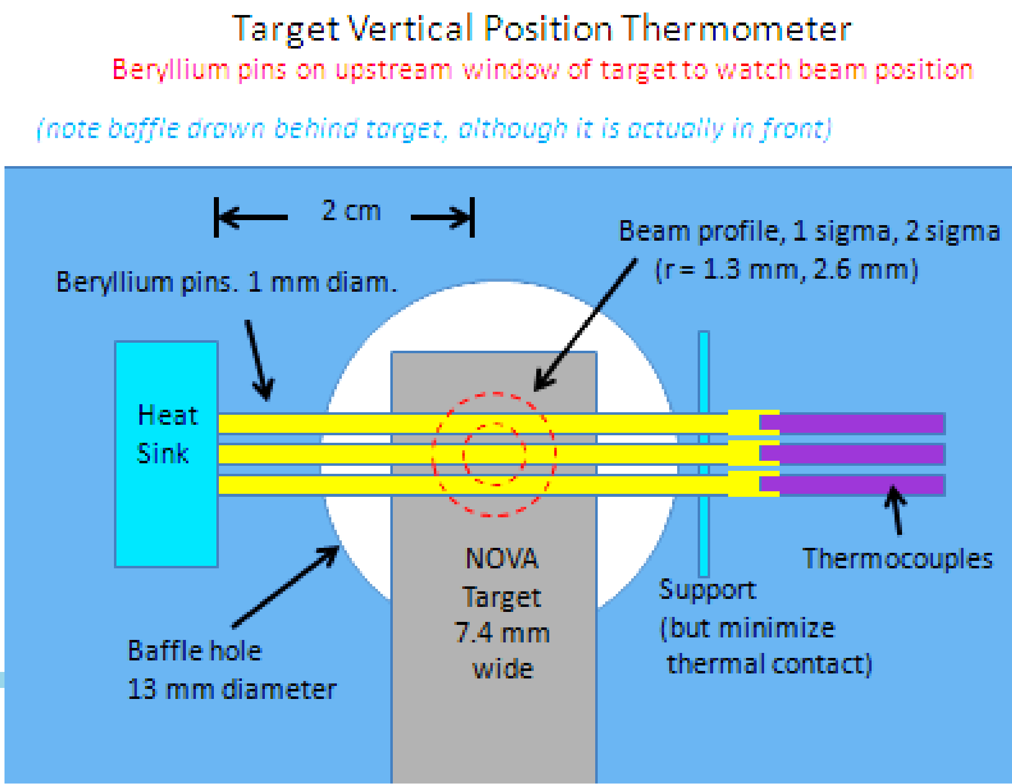
- NuMI Horn exchange was a hot job even after 8 weeks of cool-down
- More power -> hotter jobs -> more changeouts
  - ALARA applied, with some expense of time and effort

Challenge: Radiation/Radionuclide Management

- Extensive shielding to deal with high-energy particles
  - Radioactivation of shielding and components
- Air-borne radiation:
  - Lifetimes of hours, must not be emitted
- Creating of longer-lived mobile isotopes: tritium, Na-22
  - Immediately mobile produced in air, fluid, and some solids
  - Sequestered radisotopes slowly work there way out
  - May become faster with temperature or other factors
- Radiolysis and production of corrosive compounds
  - Many materials degrade with radiation, metals and ceramics more robust
  - Ozone, Nitric acid, and other compounds can be created in gas and fluids

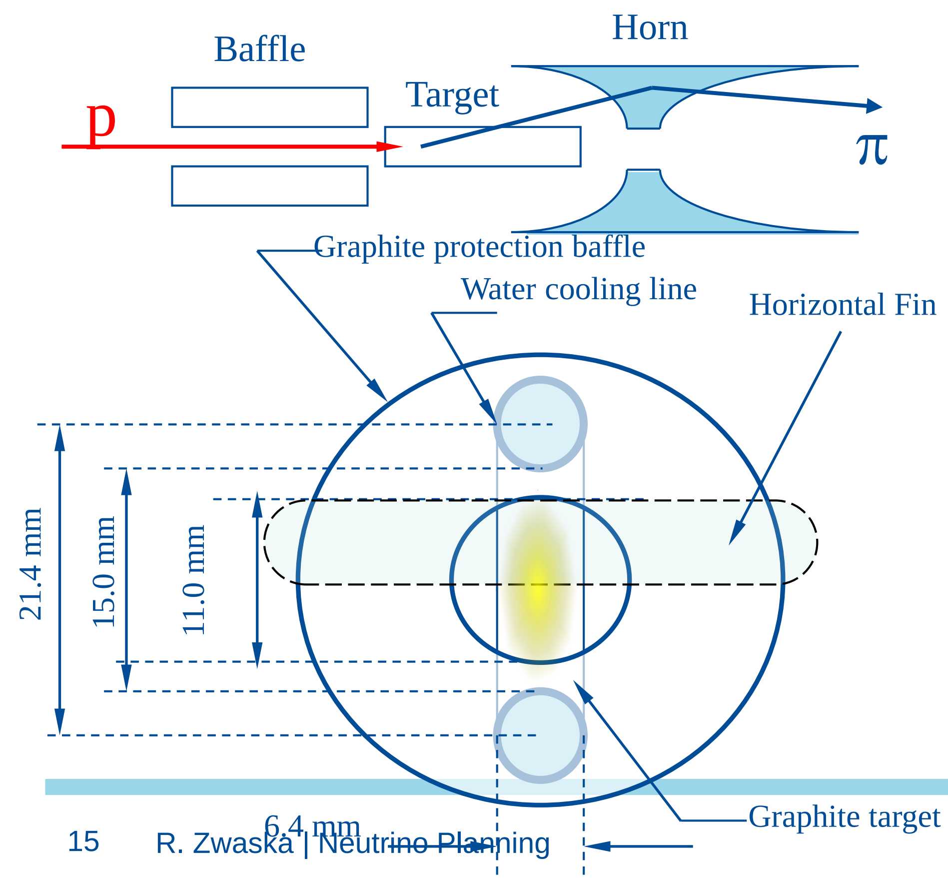
Challenge: Instrumentation

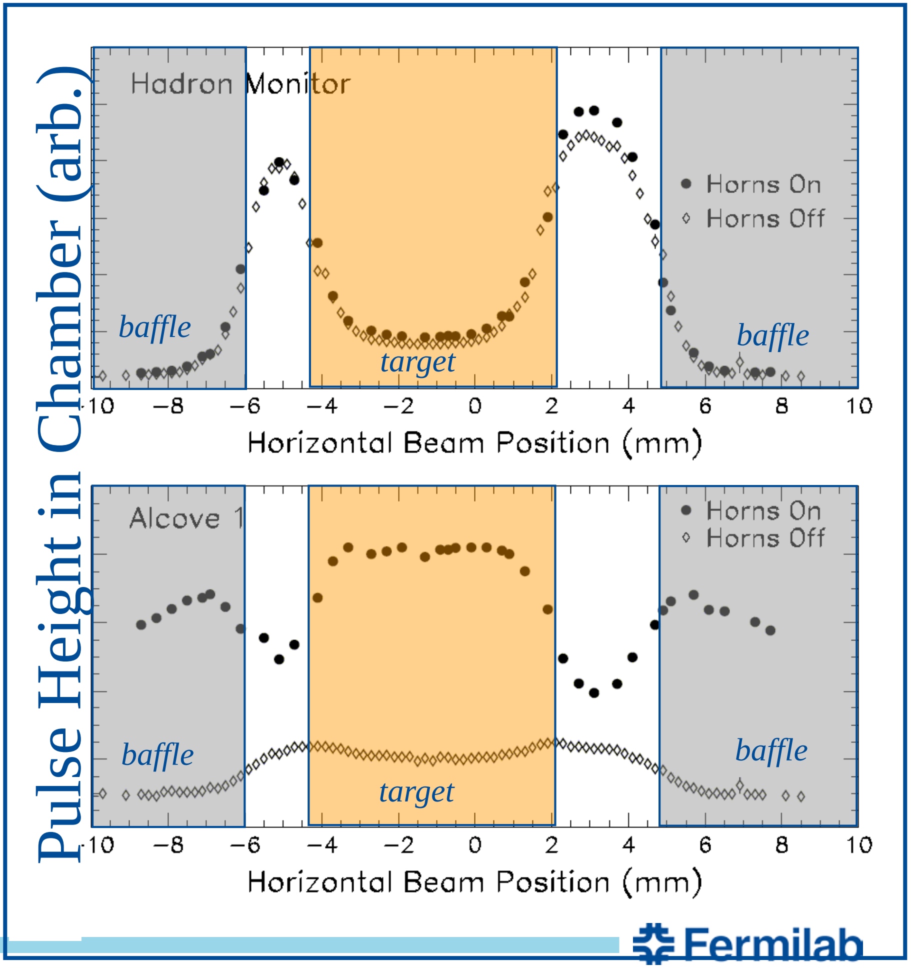
- Instrumentation can be used to measure beamline variations and to reduce the experimental limitations from them
- This instrumentation often needs to live within the secondary beam
  - Radiation-hard
  - Large signals
  - Cooling
- **R&D** on high-radiation instrumentation would improve the precision of neutrino experiments



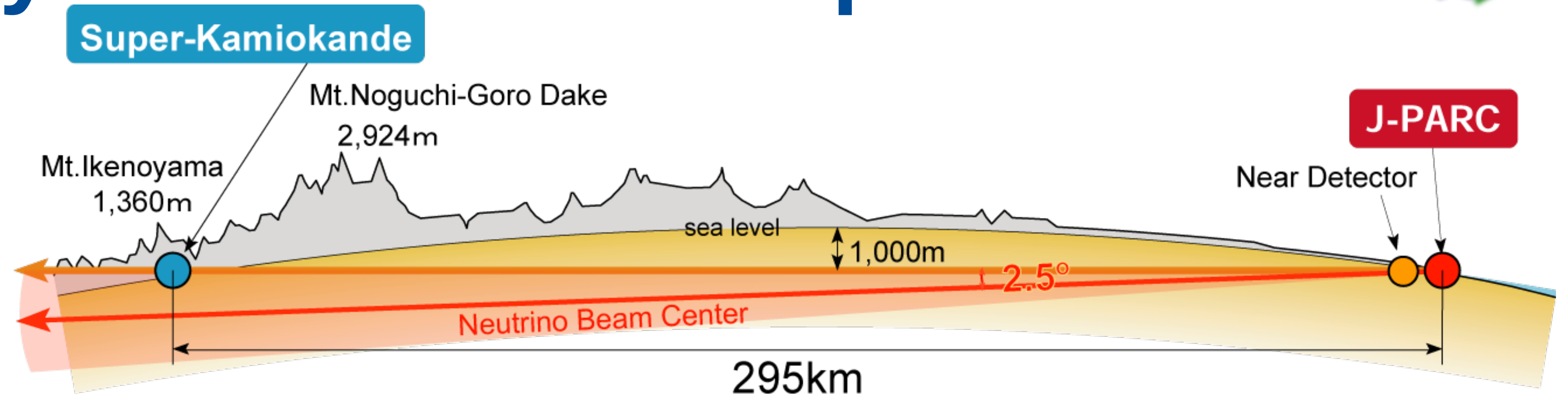
Challenge: Precision Alignment

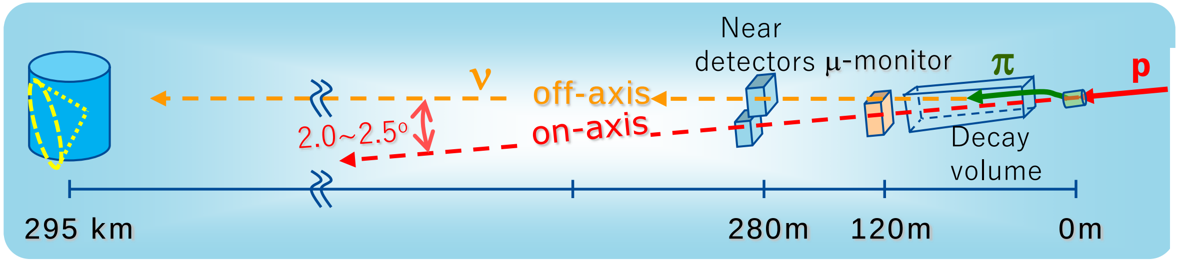
- Proton beam scanned horizontally across target and protection baffle
- Hadron Monitor used to find the edges
  - Measured small (~1.2 mm) offset of target relative to primary beam instrumentation.
  - Systematic effect of this misalignment would exceed statistical uncertainties

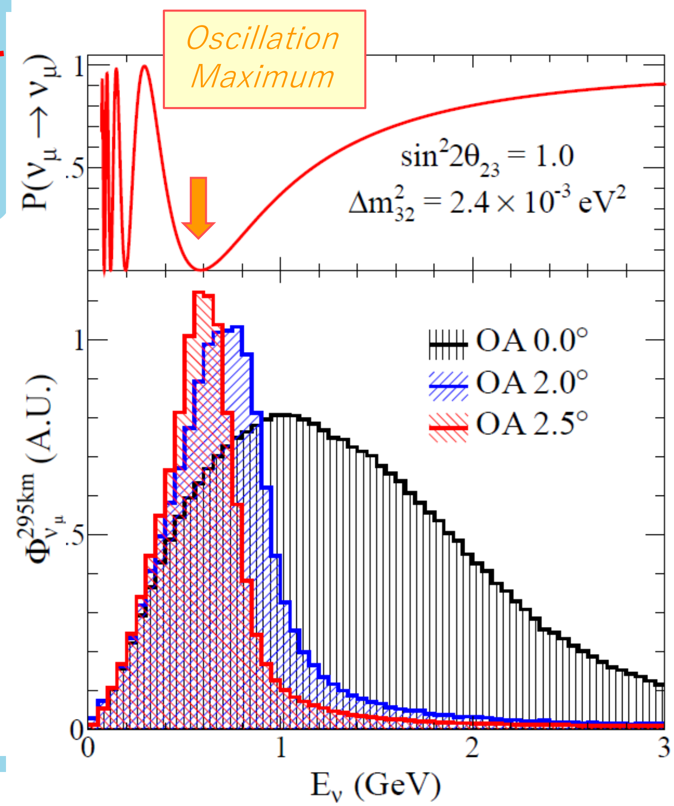




Layout of the T2K experiment





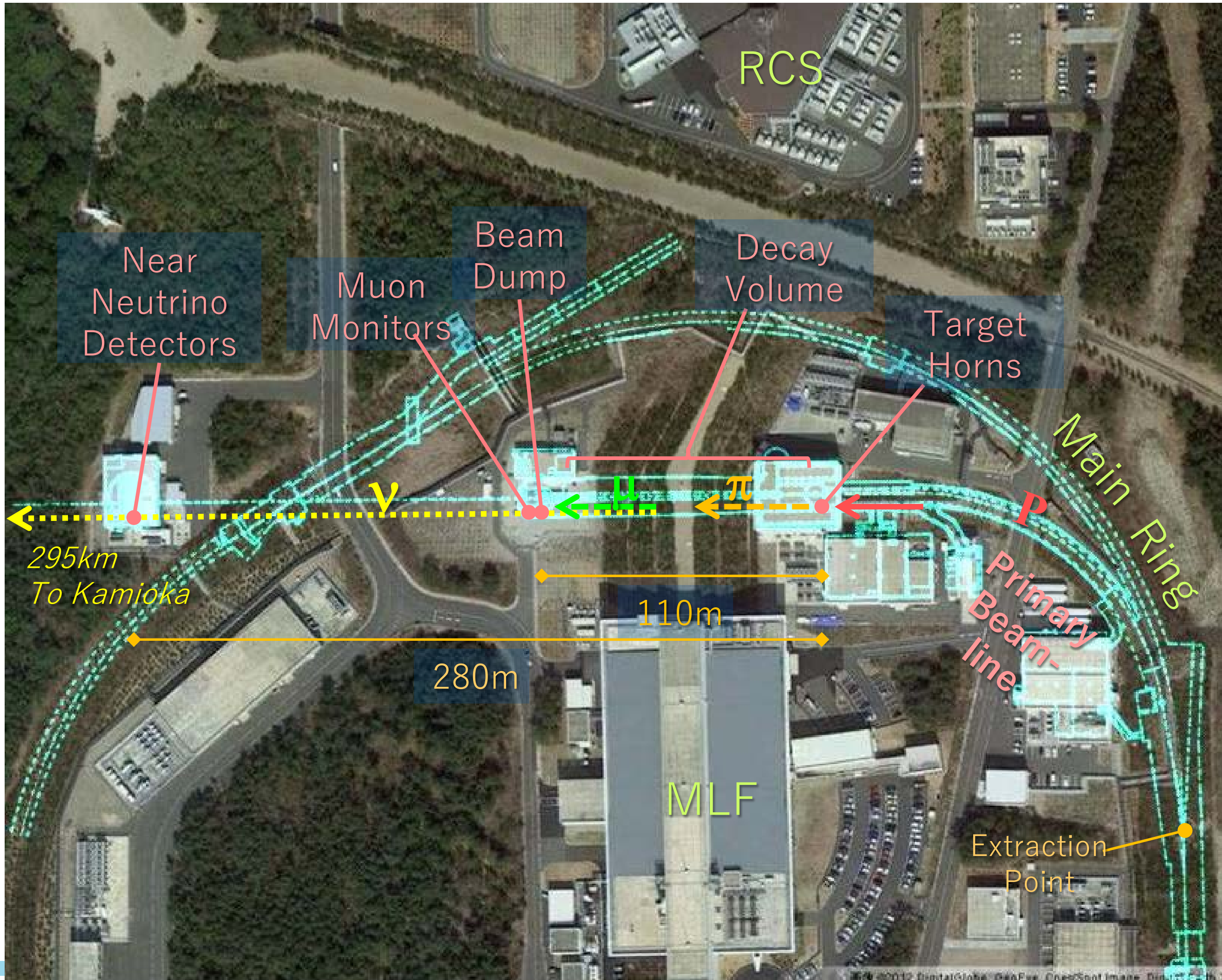


- Conventional "horn-magnet-focused" ν beam
  - 30GeV Protons on a graphite target
  - daughter $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\pi^- \rightarrow \mu^- + \nu_\mu$)
  - Anti-neutrino production by inverse polarity
- First application of Off-Axis(OA) beam: 2.0~2.5° wrt. the far detector direction
  - Low-energy narrow-band beam
  - peak tuned to oscillation maximum
  - Small high-energy tail: reduce inelastic bkgs


Japan Proton
Accelerator
Research
Complex
J-PARC
400 MeV H- Linac
3 GeV Rapid Cycling
Synchrotron (RCS)
25Hz - 1MW
Neutrino
Experimental
facility (ν)
30 GeV Main Ring
Synchrotron (MR)
A round: 1,568m
Materials & Life
Science Facility
(MLF)
MR First Extraction to NU
Design beam power : 750kW
30 GeV beam kinetic energy
2.0 × 10^14 protons per pulse
[8 b x 2.5 x 10^13 ppb in 4.2 us] Repetition Cycle 1.28sec
Hadron
Experimental
Hall (HD)

Neutrino experimental facility at J-PARC

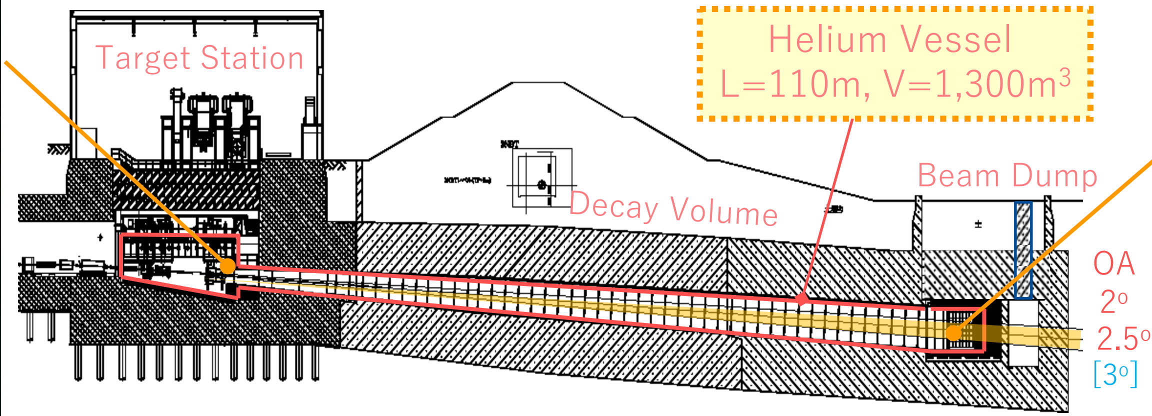
- Conventional horn-focused neutrino beam-line, designed/constructed for T2K long base-line neutrino oscillation experiment and future Hyper-Kamiokande project

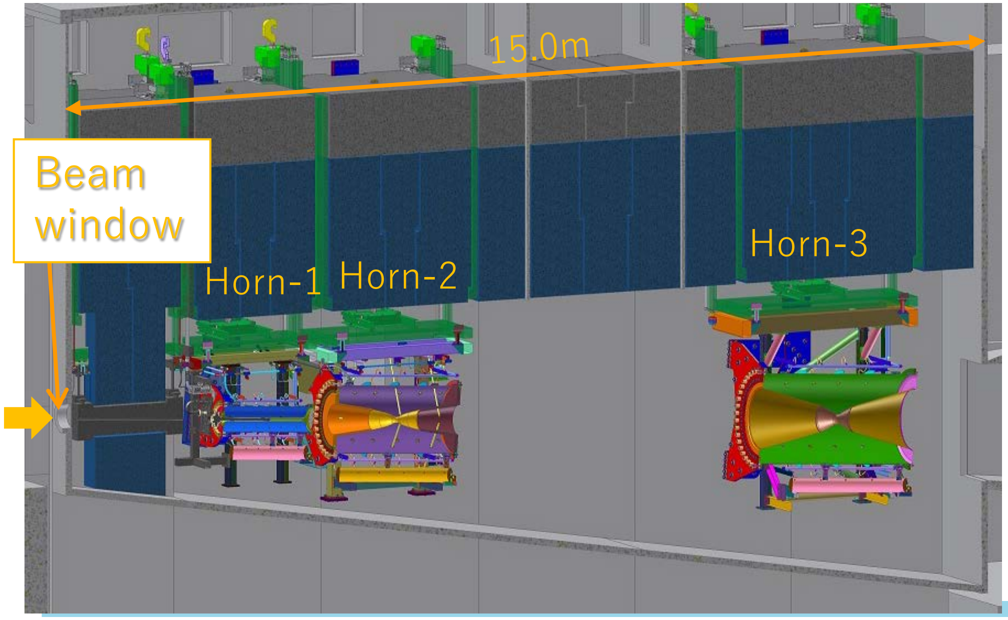


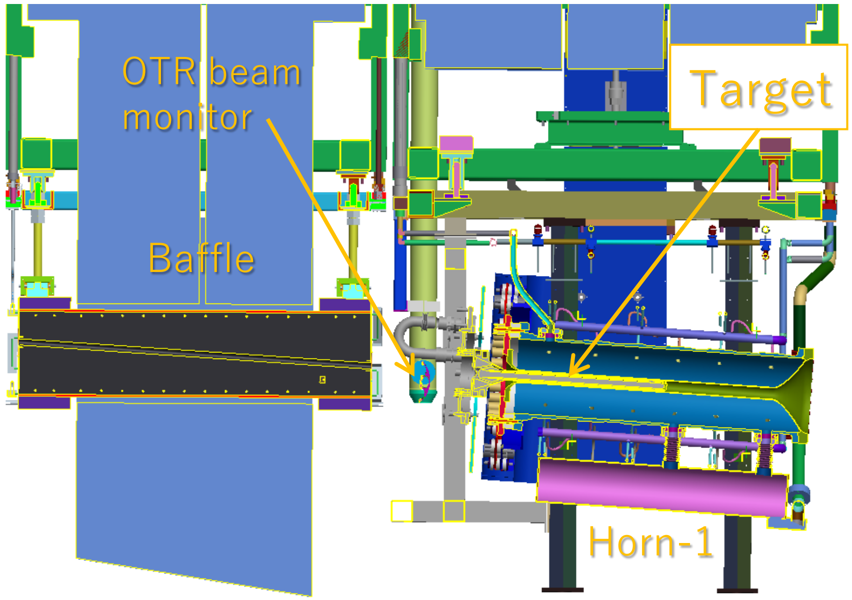
J-PARC, Tokai

Design beam power **750kW**
Future upgrade aiming to **1.3MW**

Target Facility (Secondary Beam-line)







Power upgrade scenario / T2K-2 and Hyper-K

- MR power upgrade : Higher repetition rate scheme is adopted to achieve the design beam intensity (750kW) as mid-term upgrade plan
  - Rep. rate will be increased from 0.4Hz to 1Hz by replacing magnet PS's and RF cavities.
  - Budget for Magnet power supply upgrade has been secured in JFY2016, and new PS's to be operational from JFY2018
  - Recent accelerator improvements / intensive studies : > 1MW is well within the scope, to be realized in 2020-25.
  - Goal of the mid-term plan is to realize 1.3MW operation, corresponding to full RCS 1MW-equivalent beam, injected/extracted with 1.16 sec cycle.
- **T2K-2** : EoI submitted to J-PARC PAC (Feb.2016)
  - Interconnect "desert" between T2K/NOVA and DUNE/Hyper-K era
  - Accumulate 2 x 10^{22} POT by around 2026
  - Another 50% increase of statistics by increasing horn/current, analysis upgrades
  - > 3 sigma CPV sensitivity

target / window is designed

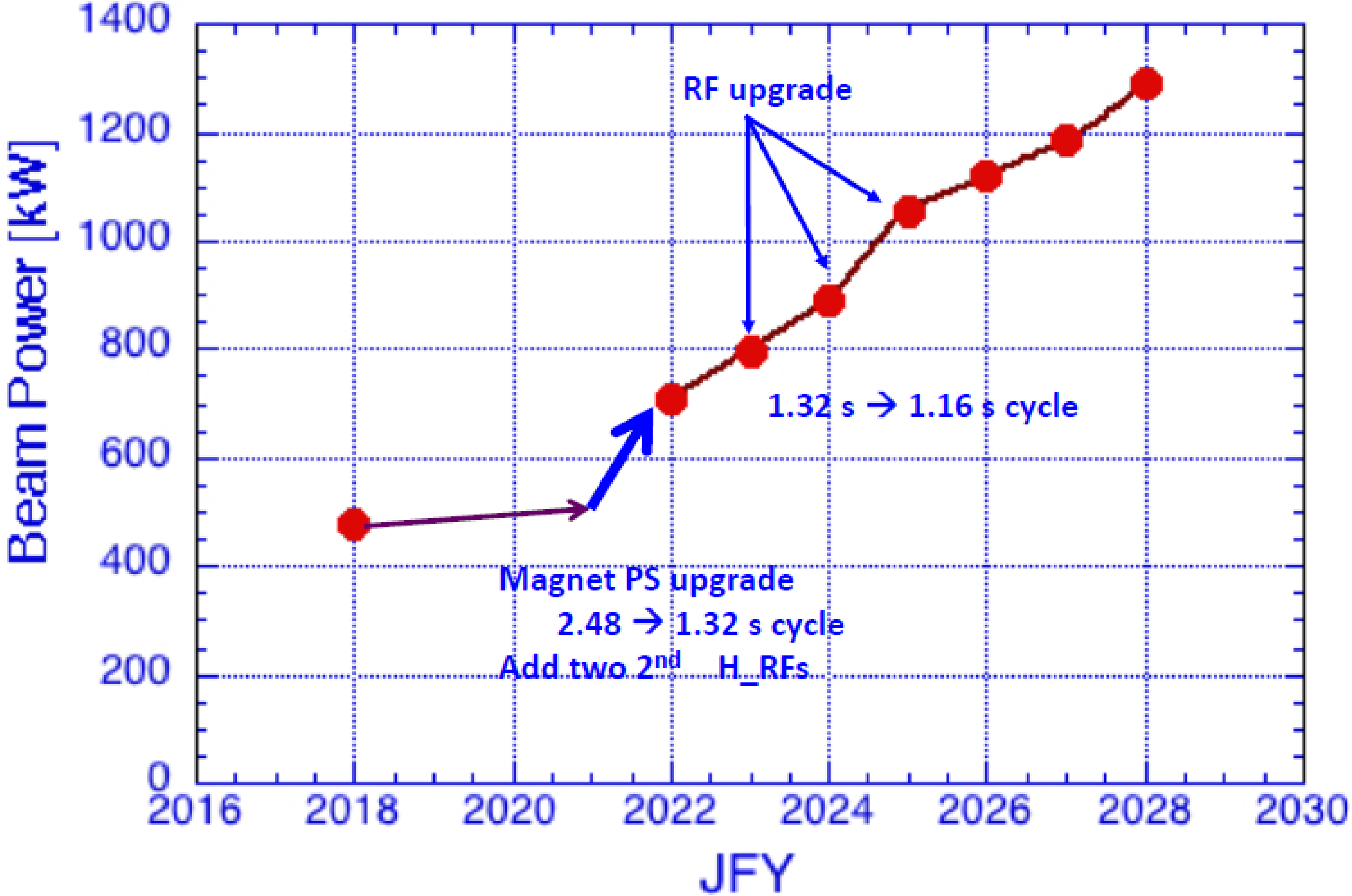
- Hyper-Kamiokande project
  - X ~20 fiducial volume
  - 1.3MW beam power
  - 10 sigma (7 sigma) sensitivities for δ_{CP} = ±90 (45) degrees
  - Hopefully to be started from JFY 2026, assuming budget approval in JFY2018

Beam Powe	ppp	Rep. cycle
390kW (achieved)	2.0 x 10^{14}	2.48 sec
750kW (proposed)	2.0 x 10^{14}	1.3 sec
750kW [original plan]	3.3 x 10^{14}	2.1 sec
1.3 MW (proposed)	3.2 x 10^{14}	1.16 sec

[J-PARC / T2K]

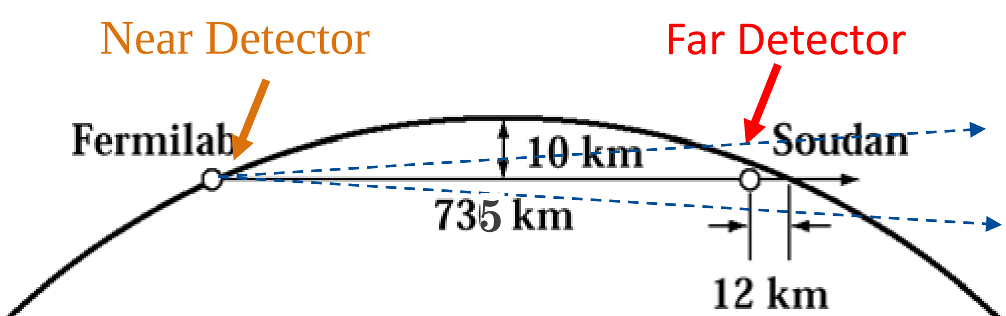
Projection for the Beam Power of 1.3 MW

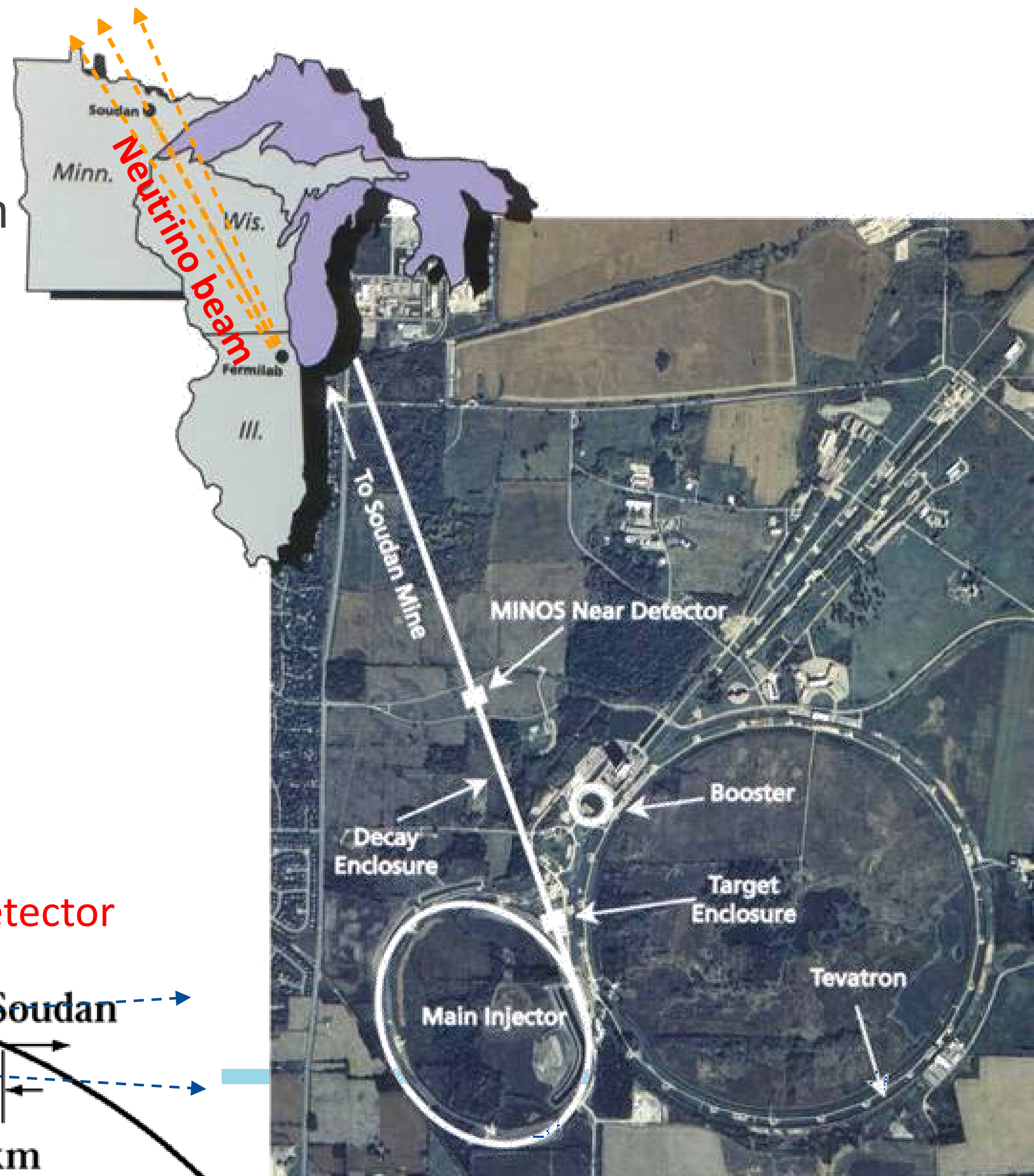
- Major hardware upgrade is necessary for the new target of 1.3 MW.
- Hardware upgrade will be presented by Yoshii san.



The NuMI Facility

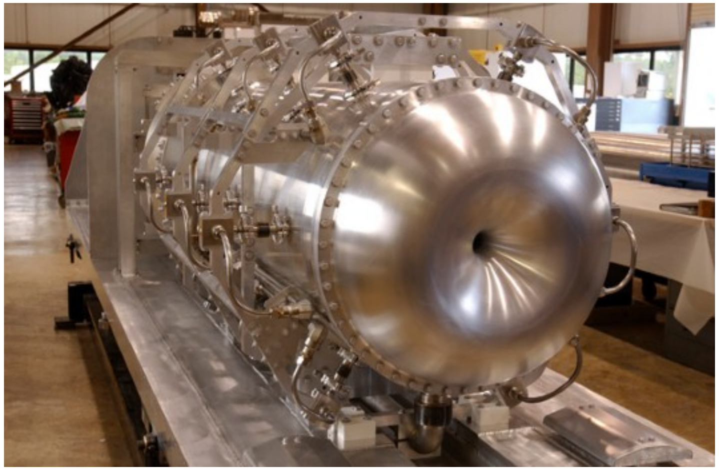
- High-power neutrino beam for oscillation experiments
  - Beam tilted 3.3° down into the earth
- Neutrino beam travels to northern Minnesota
  - 735/810 km baseline
  - Intense source at Fermilab
  - Oscillated source in Minnesota
- Commissioned in 2004
- Operating since 2005
- Designed for 400 kW
  - Upgraded to 700 kW in 2012 for NOvA
  - Upgrading to 1 MW-capable by ~ 2021
- >35e20 POT delivered to date



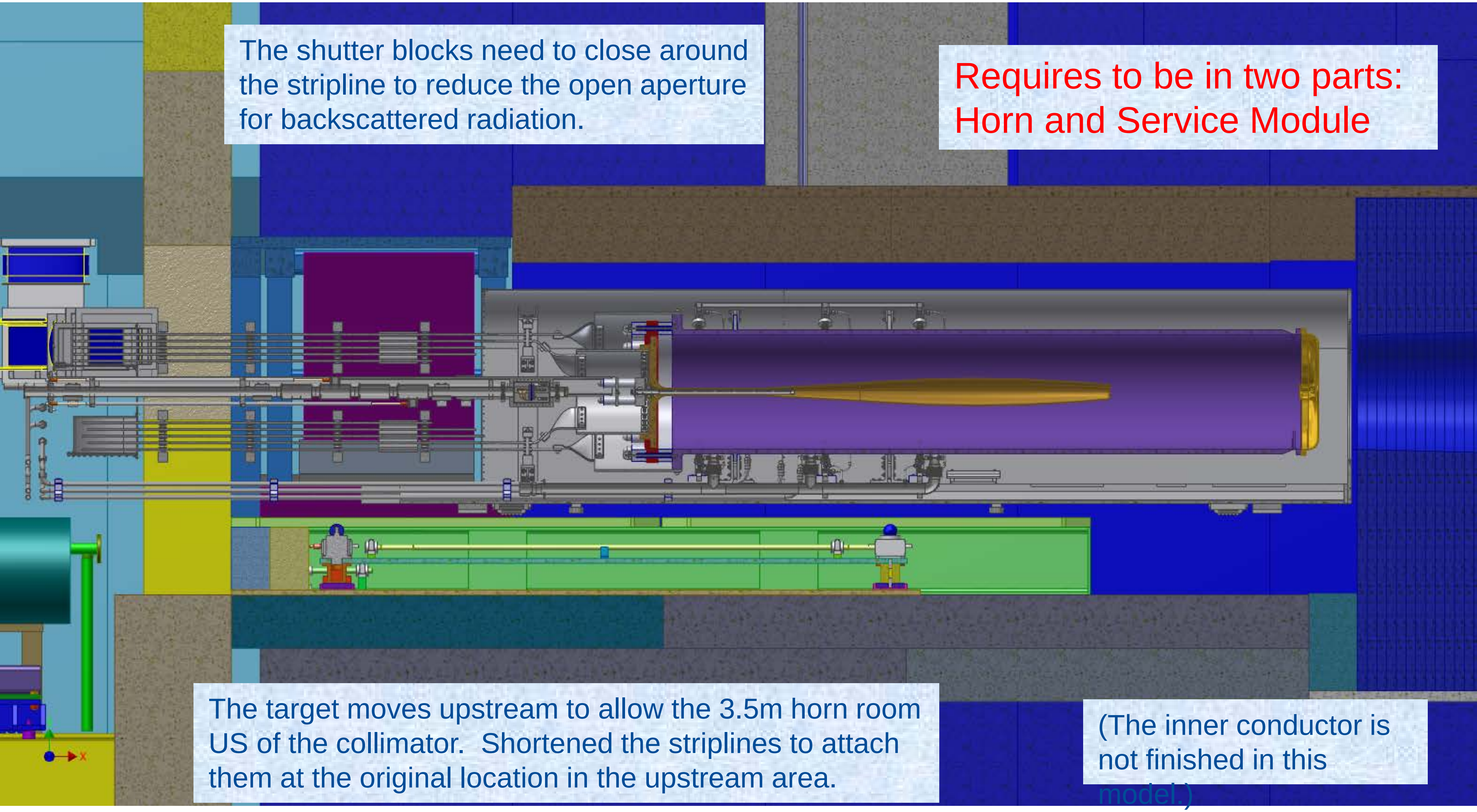


Booster Neutrino Beam (BNB)

- Uses 8 GeV beam from the Booster, operating since 2002
  - Up to ~ 30 kW of beam (5e12 ppp)
  - 27e20 protons deliver to target – to date
- Two target/horn assemblies have been replaced (water, uncoated aluminum corrosion)
  - 2nd horn which lasted ten years and >400M pulses
    - Design lifetime was about one year and 100M pulses
  - Had to also redesign and replace adjustor platform and horn extraction mechanism (corrosion)
  - 5^{th} horn under starting construction



Up to 3.5m Horn to fill in the available space, improve focusing – not presently pursued



The shutter blocks need to close around the stripline to reduce the open aperture for backscattered radiation.

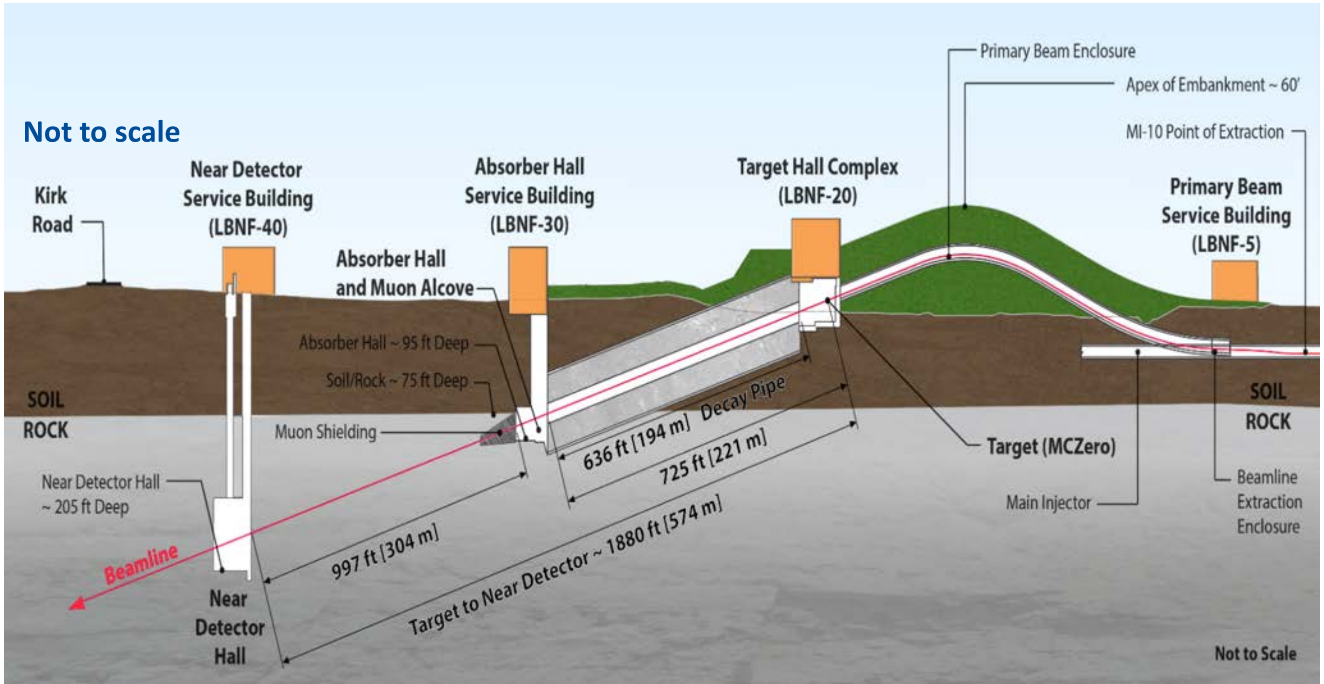
Requires to be in two parts: Horn and Service Module

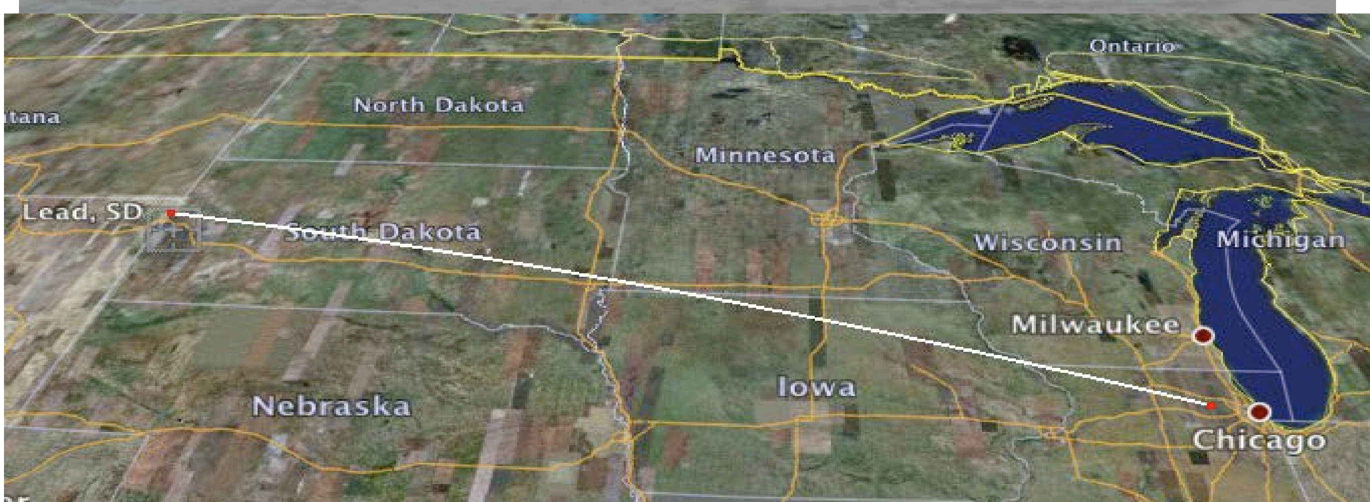
The target moves upstream to allow the 3.5m horn room US of the collimator. Shortened the striplines to attach them at the original location in the upstream area.

(The inner conductor is not finished in this model.)

The LBNF Beamline

Facility designed for initial beam power of 1.2 MW, upgradeable to 2+ MW





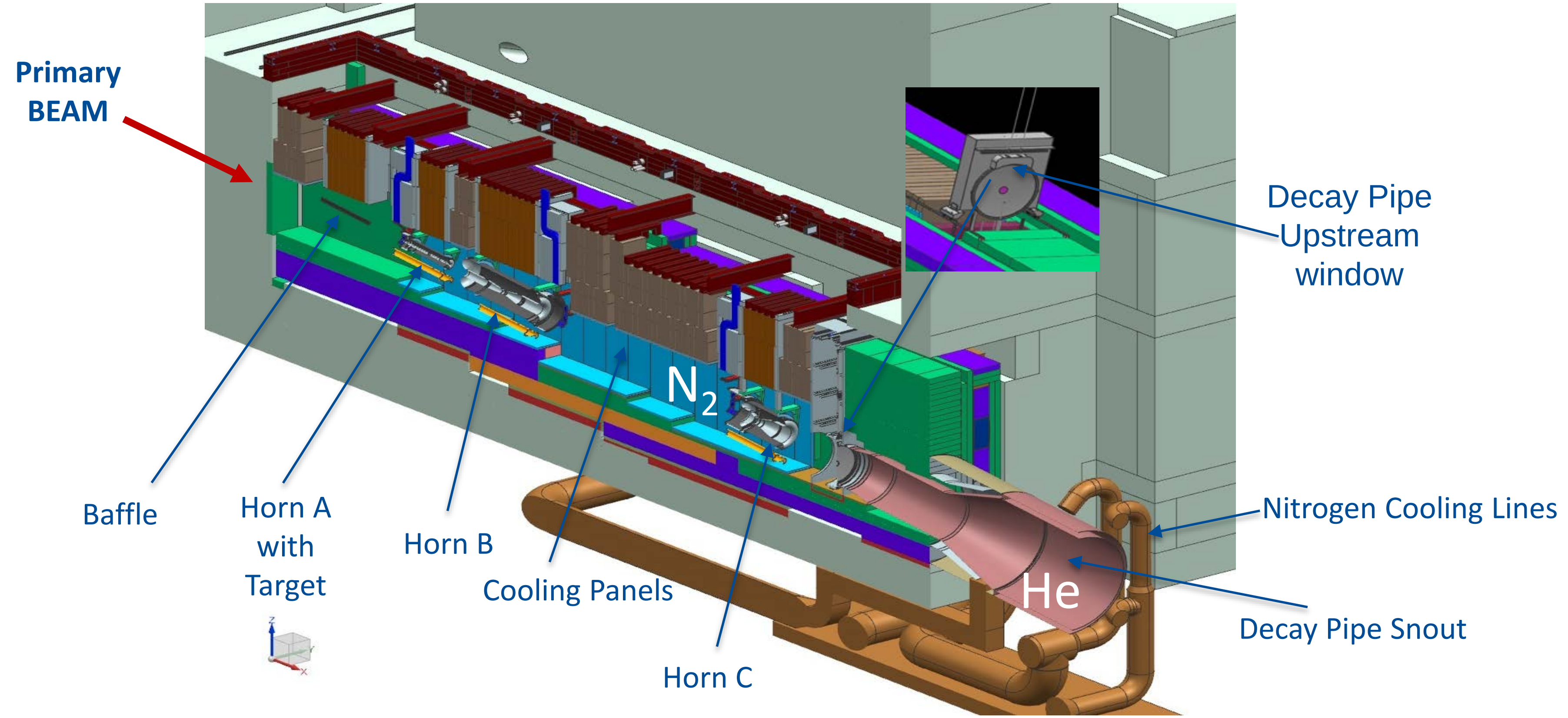
Proton beam extracted from Fermilab's Main Injector in the range of 60 – 120 GeV every 0.7 – 1.2 sec with pulse duration of 10 μs

Protons per cycle:
1.2 MW era: 7.5×10^{13}
2.4 MW era: $(1.5 - 2.0) \times 10^{14}$

Beam size at target tunable between 1.0-4.0 mm sigma

Target Hall Shield Pile Layout – Optimized Design

~ 52% of beam power in target shield pile



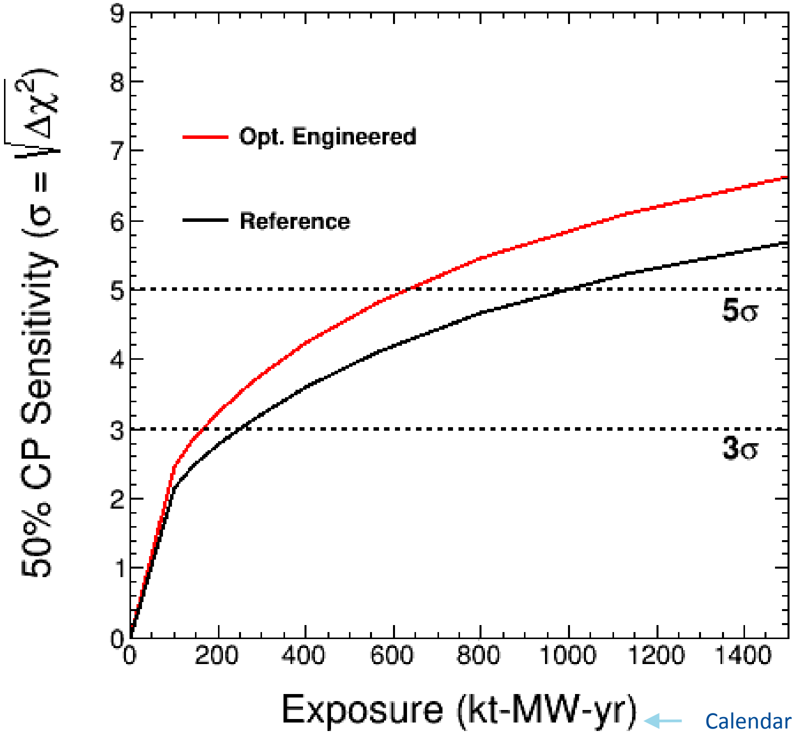
Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (cooling panels). (It used to be air at CD-1R and 2017 IPR).

Preliminary design work started for the Target Shield Pile in FY18.

Optimized LBNF design improves beam effectiveness ~ 50%

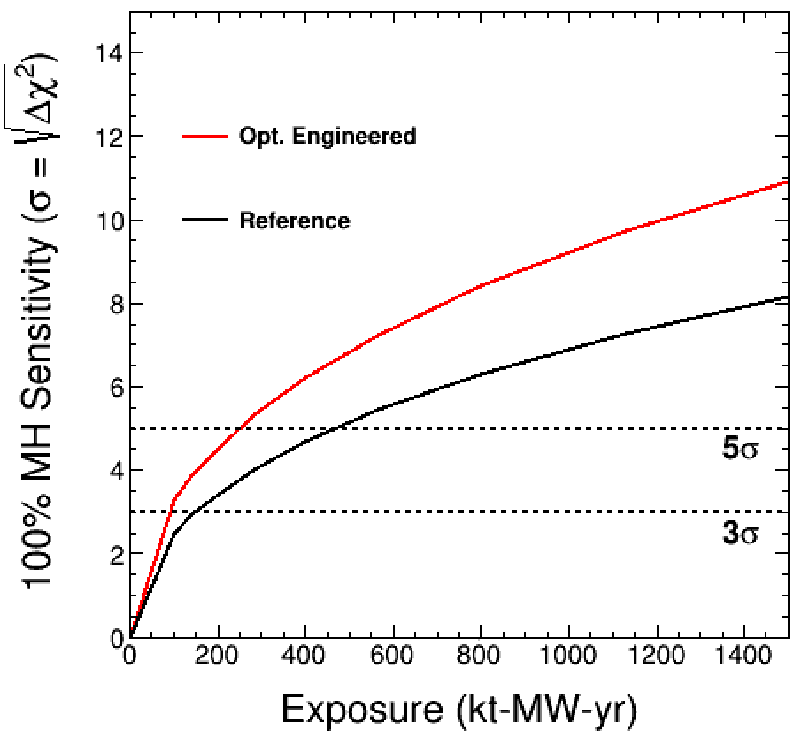
- Improvements are present for all exposures:

CP Sensitivity vs Exposure



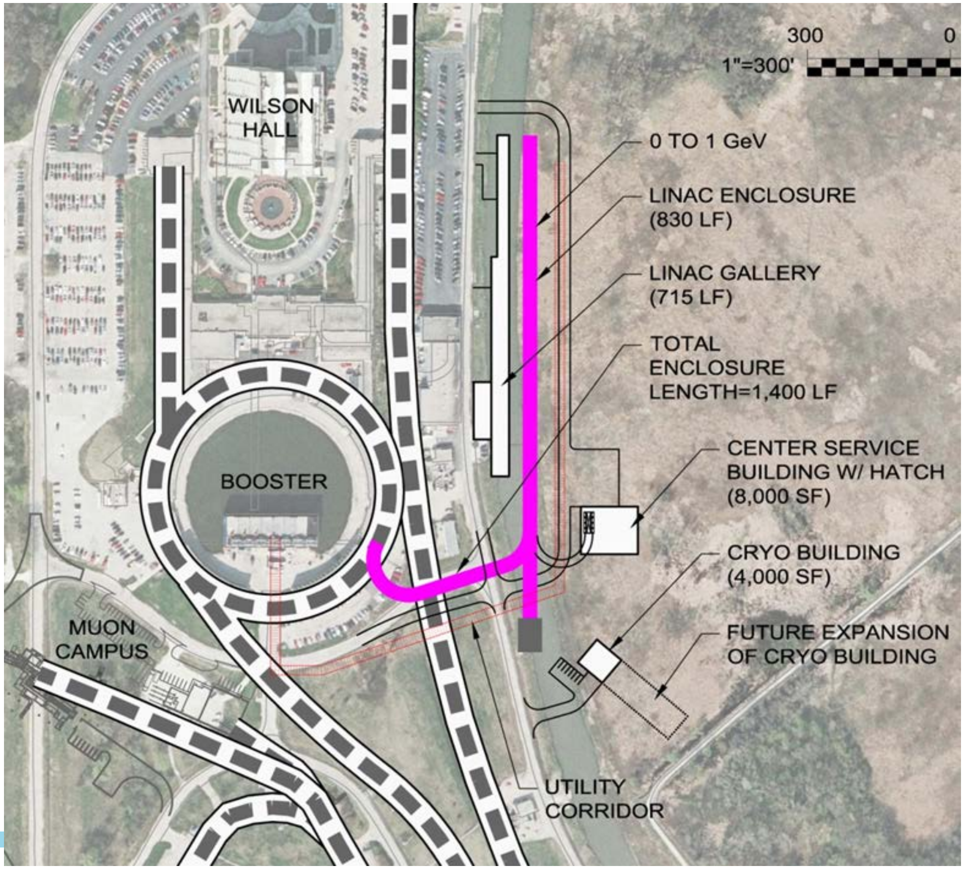
Calendar Years

MH Sensitivity vs Exposure



Proton Improvement Plan II (PIP-II)

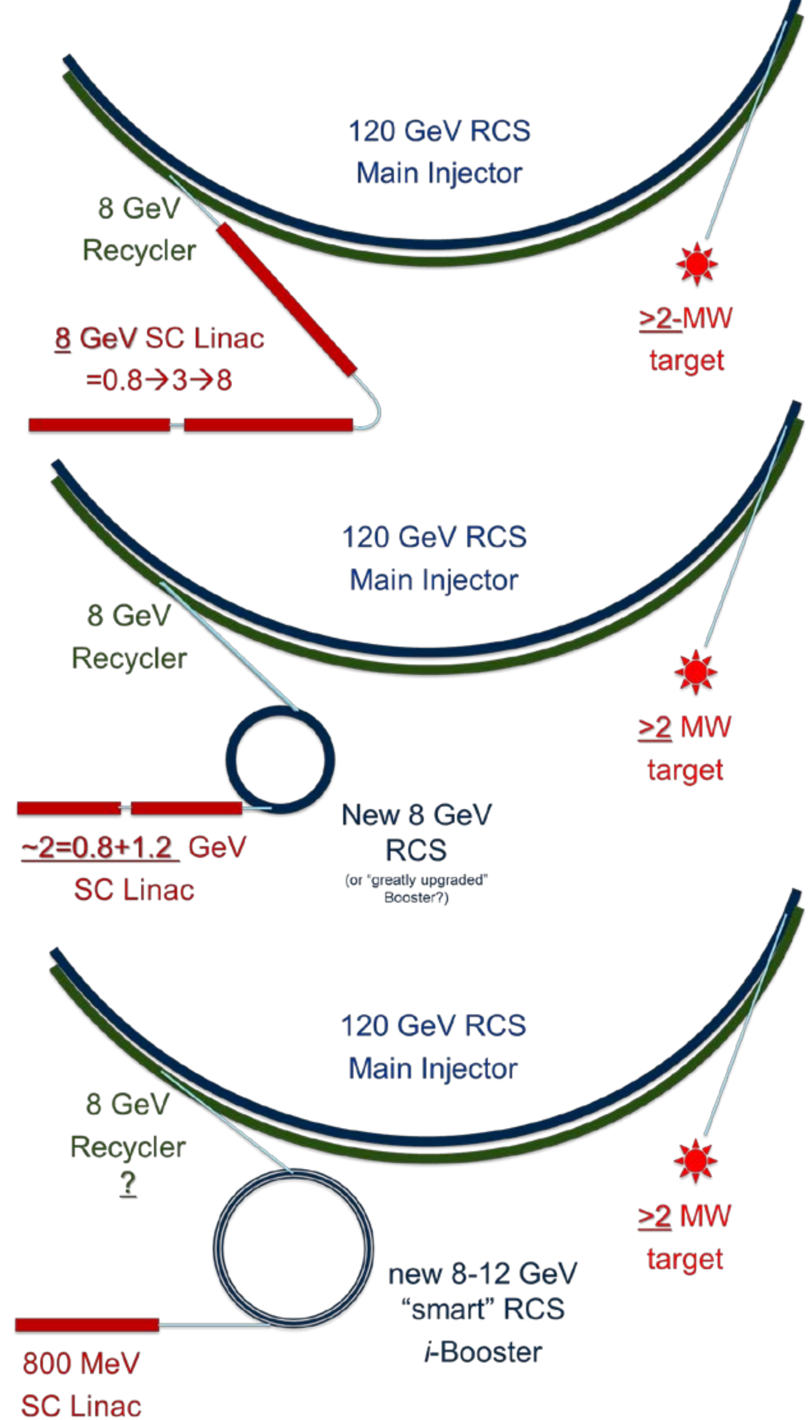
- Increase Main Injector beam power to 1.2 MW.
  - Replace the existing 400 MeV linac with a new 800 MeV superconducting linac => 50% increase in Booster intensity.
  - Shorten Main Injector cycle time 1.33 → 1.2 sec.
- Build this concurrently with LBNF => 1.2 MW to LBNF from t = 0.
- This plan is based on well-developed SRF technology.
- Developing an international partnership for its construction
- Strong support from DOE and P5



http://pip2.fnal.gov/

Future Directions – PIP-III

- PIP-III is a set of concepts to provide 2-5 MW of beam power for future experiments
- Three generalized options:
  1. Extend Linac to 8 GeV, inject directly to MI/RR
  2. Extend Linac to ~ 2 GeV, inject into new RCS (or upgraded Booster)
  3. Develop novel technologies to beat the space charge limit
- The approach will be determined by technical and financial factors once PIP-II construction is underway
- R&D to inform decision
  - Lower the cost of SRF
  - FAST/IOTA program



Balancing Conventional Options and Limits

Options

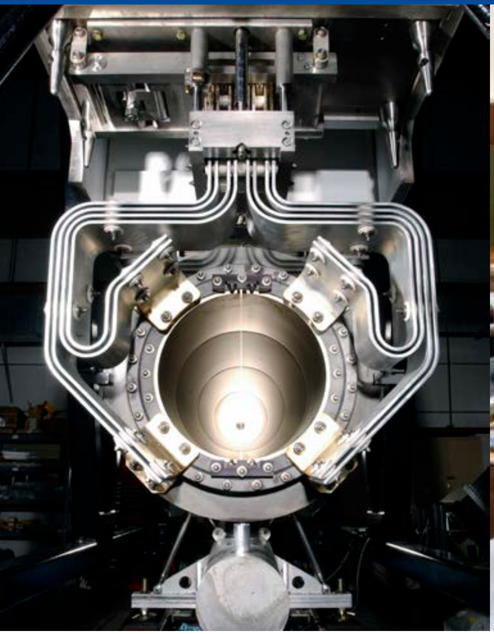
- Higher Power
- Greater Focusing
  - Perfect Focusing
  - Tailored Focusing
- Off-Axis
  - Other narrow band options
- Longer-Baseline
- Flavor-enhanced
  - Suppress Muon decays to suppress electron neutrinos
  - Suppress tertiary interactions to suppress wrong-sign neutrinos
  - Tau neutrinos from higher energy or oscillations
- Short Baseline
- Alternate Focusing

Limits

- Pion Decay Angle
- Hadroproduction
  - Also, angle from production
- Beam devices (Targets, Windows, & Horns)
  - Radiation Damage
  - Internal Stresses
- Heat Rejection
- Radioprotection
- Precision
- Instrumentation
- Reliability

Neutrino Beams beyond LBNF

- Conventional beams are approaching their limits, barring new measurement needs or applications
- Obvious improvements
  - Higher Power (< 10x improvement)
  - Focusing (< 2x improvement)
- Customization
  - Baseline
  - Flavor composition
  - Energy spectrum
- Challenges (numerous)



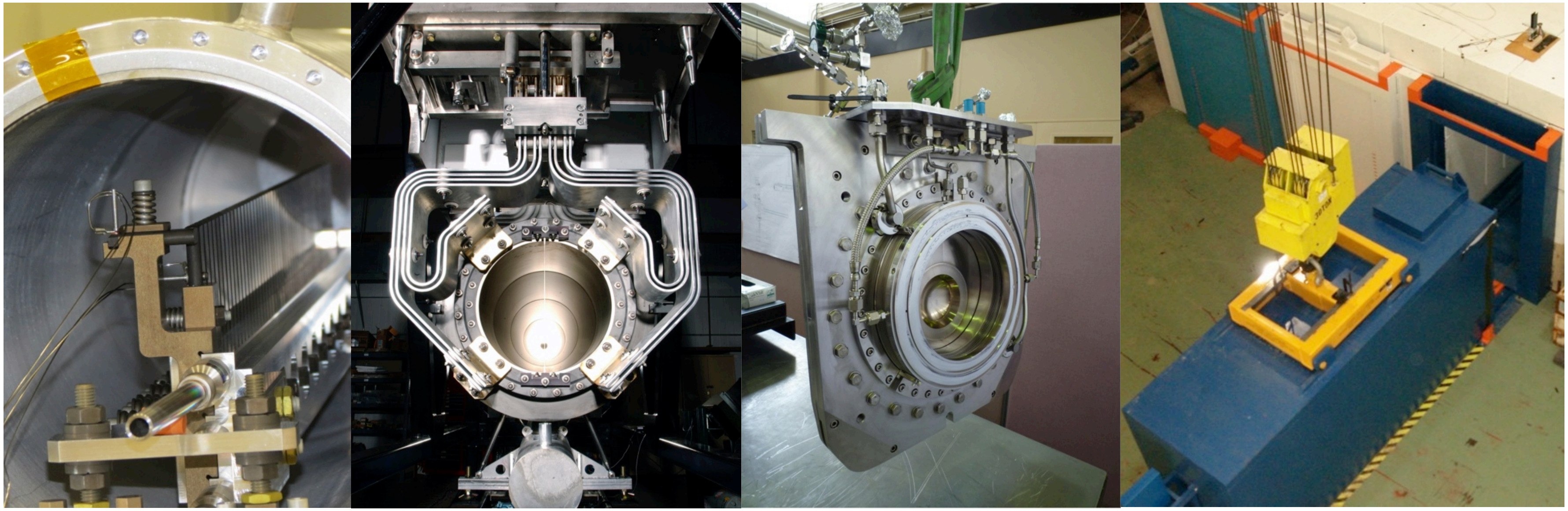
Future Conventional Neutrino Beams

Robert Zwaska,

First 2018 Neutrino Working Group Meeting

5 April 2018

High Power Targetry Scope



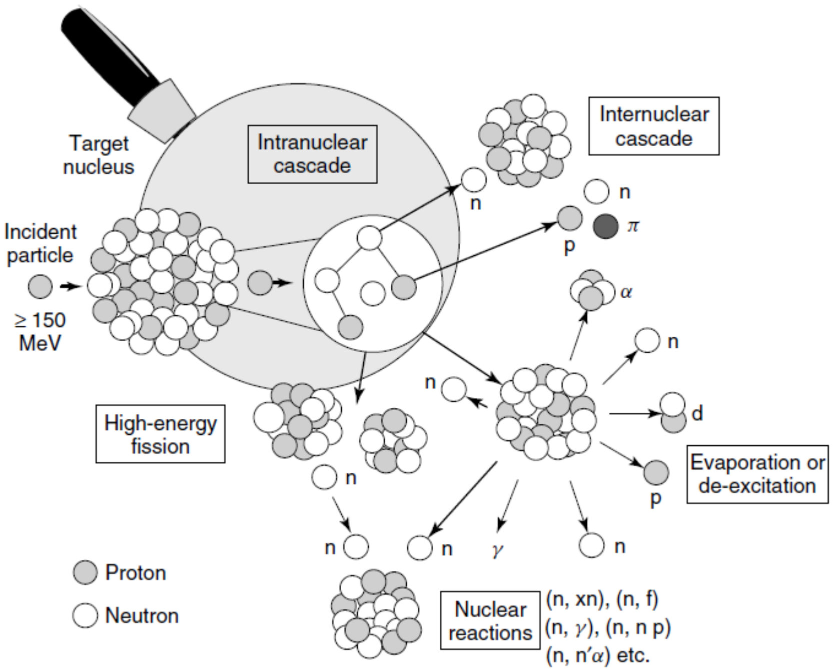
R&D Needed to Support:

- Target
  - Solid, Liquid, Rotating, Rastered
- Other production devices:
  - Collection optics (horns, solenoids)
  - Monitors & Instrumentation
  - Beam windows
  - Absorbers
- Collimators (e.g. 100 TeV pp collimators)
- Facility Requirements:
  - Remote Handling
  - Shielding & Radiation Transport
  - Air Handling
  - Cooling System

High Power/Intensity Targetry Challenges

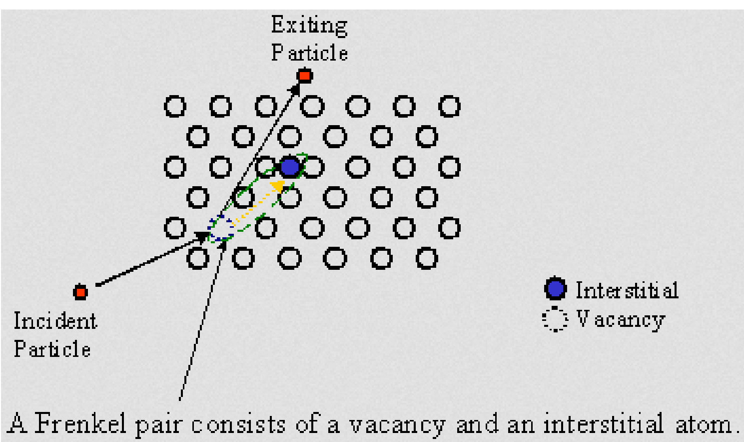
- Material Behavior
  - **Thermal "shock" response**
  - **Radiation damage**
  - Highly non-linear thermo-mechanical simulation
- Targetry Technologies (System Behavior)
  - Target system simulation (optimize for physics & longevity)
  - Rapid heat removal
  - Radiation protection
  - Remote handling
  - Radiation accelerated corrosion
  - Manufacturing technologies

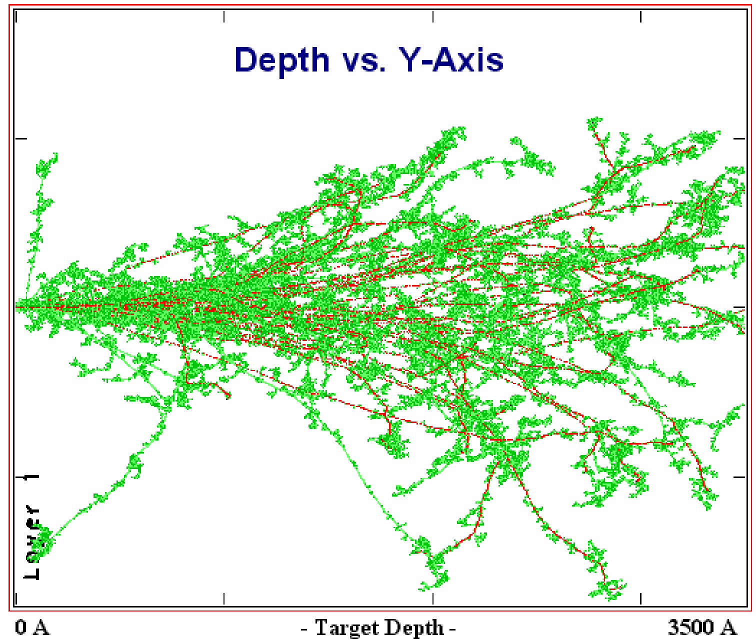
Radiation Damage Disorders Microstructure



Microstructural response:

- *creation of transmutation products;*
- *atomic displacements (cascades)*
  - *average number of stable interstitial/vacancy pairs created = DPA (Displacements Per Atom)*





Slide prepared by V. Kuksenko (Oxford)

HEP HPT Future Needs

Exp/Facility	Laboratory	Time frame (yrs)	"On the books"?	Beam Power (kW)	Comments
ANU/NOvA	FNAL	0.5	Y	700	Ramping Up!
T2K	J-PARC	3	Y	750	Ramping Up!
CENF (SBL)	CERN	5?	?	300	Short baseline nu
LBNF-1.2 MW	FNAL	10	Y	1,200	PIP-II enabled
HyperK	J-PARC	10?	?	1,660+	2+ MW upgrade??
ILC	Japan?	15?	N	220	photons on Ti
Next-Gen Nu Facility –2.5 MW	FNAL	20?	N	2,500?	Mid-Term
Next-Gen Nu Facility - 5 MW	FNAL	30?	N	5,000?	Longer-term

Other low power (but high intensity) target facilities will also be needed. Notably follow-on experiments to Mu2e/COMET, g-2, etc… These are still challenging targets due to high-Z targets and small beam spots, but are not listed here.

Mid-term Plan of MR

FX: The higher repetition rate scheme : Period 2.48 s —> 1.32 s for 750 kW
(= shorter repetition period) —> 1.16 s for 1.3 MW
SX: Mitigation of the residual activity for 100kW

JFY	2017	2018	2019	2020	2021	2022	2023	2024
Event	New buildings →		HD target		Long shutdown			
FX power [kW]	475	>480	>480	>480		>700	800	900
SX power [kW]	50	50	50	70		> 80	> 80	> 80
Cycle time of main magnet PS	2.48 s	2.48 s	2.48s	2.48s		1.32 s	<1.32s	<1.32s
New magnet PS	Mass production installation/test →							
High gradient rf system						- - - →		
2nd harmonic rf system	Manufacture, installation/test →					- - - →		
Ring collimators	Add.collimators (2 kW)				Add.colli. (3.5kW)			
Injection system	Kicker PS improvement, Septa manufacture /test →							
FX system	Kicker PS improvement, FX septa manufacture /test →							
SX collimator / Local shields						Local shields - - →		
Ti ducts and SX devices with Ti chamber	Ti-ESS-1	(Ti-ESS-2)						