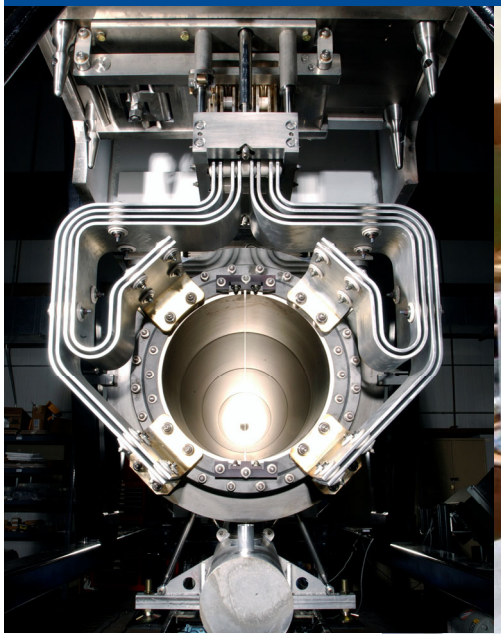
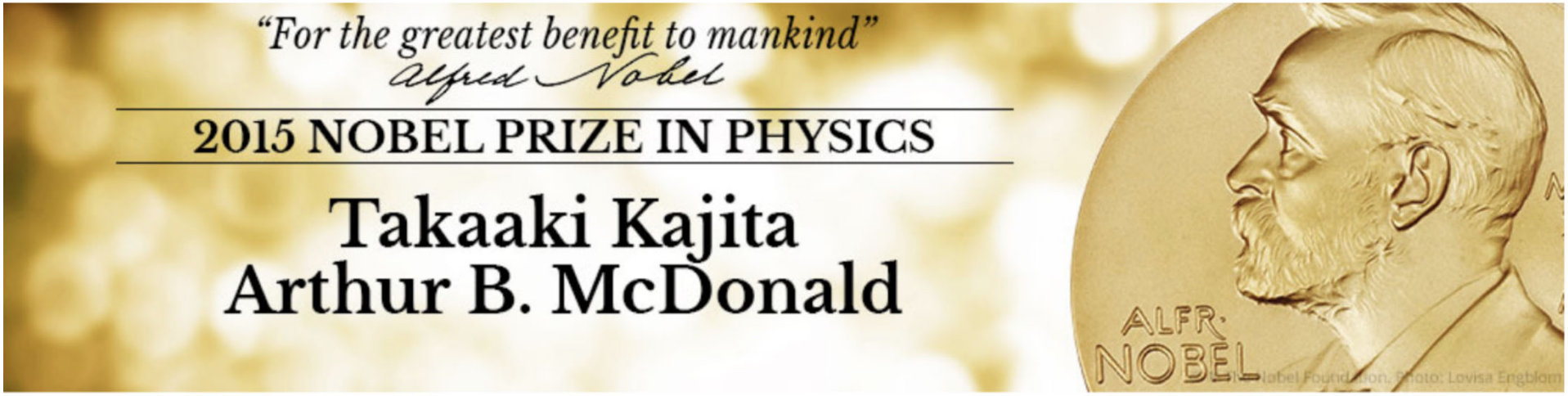


How to Make a Neutrino Beam

Bob Zwaska
Fermilab Ask-a-Scientist
2 June 2019

Outline

- Neutrinos' impact
  - About neutrinos?
- Making a neutrino beam
  - Overview
  - The accelerators provide the raw energy
  - The target converts the energy to new matter
  - The beamline defines the beam towards detectors
  - Neutrinos go forward (inexorably)
- A little of the physics of neutrino beams
- A little of the challenges of neutrino beams
- Neutrino beams around the world
- A little of the practicalities of neutrino beams



The Nobel Prize in Physics

Awarded to 201 Nobel Laureates since 1901

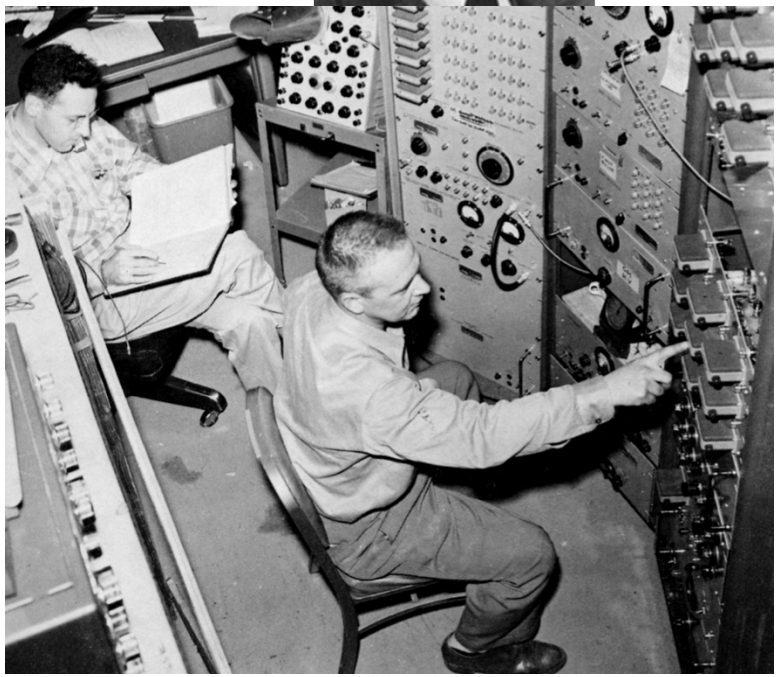
"The said interest shall be divided into five equal parts, which shall be apportioned as follows: /- - -/ one part to the person who shall have

Most Popular Physics Laureates

1. Takaaki Kajita
2. Arthur B. McDonald
3. Albert Einstein
4. Niels Bohr
5. James Chadwick

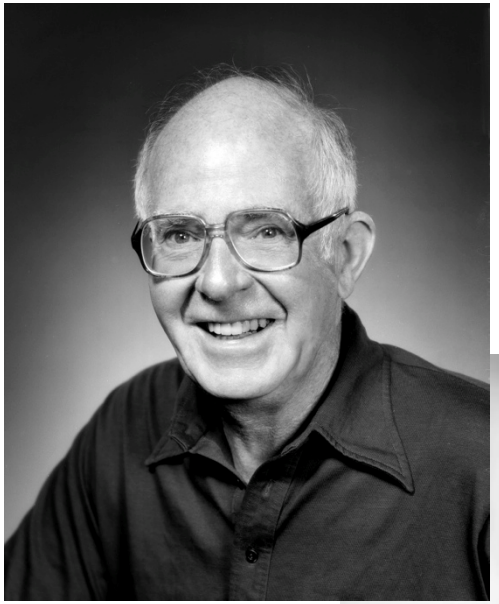
The Nobel of Neutrinos

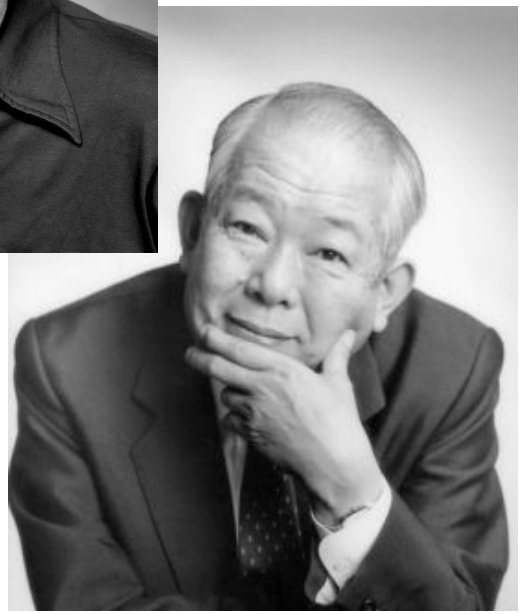
- Invented as a particle “impossible” to detect (Pauli, 1930)
  - Save conservation of energy and angular momentum
- Detected by Cowan & Reines in 1956 (Nobel 1995)
- Lederman, Schwartz, & Steinberger developed the **Neutrino Beam** in 1962 (Nobel 1988)



The Nobel of Neutrinos

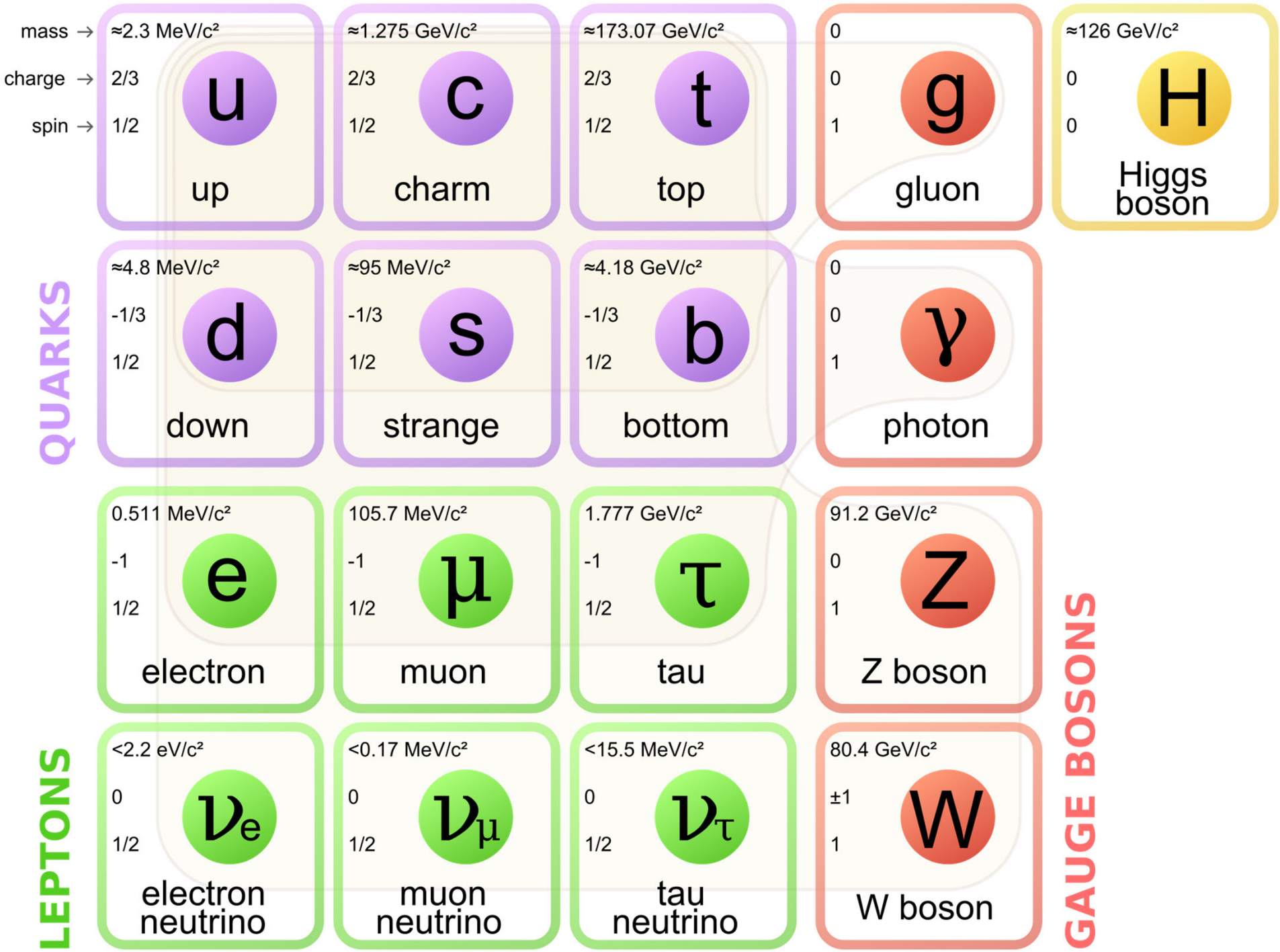
- Cosmic Neutrinos (solar, atmospheric, and supernovae) discovered over several decades, for Koshiba & Davis (Nobel 2002)





- Neutrino Oscillations (solar & in-beam) for Kajita & McDonald (Nobel 2015)

- What is left in store?


mass →
charge →
spin →
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2/3
1/2
u
up
≈1.275 GeV/c²
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1/2
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1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
QUARKS
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
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γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
LEPTONS
<2.2 eV/c²
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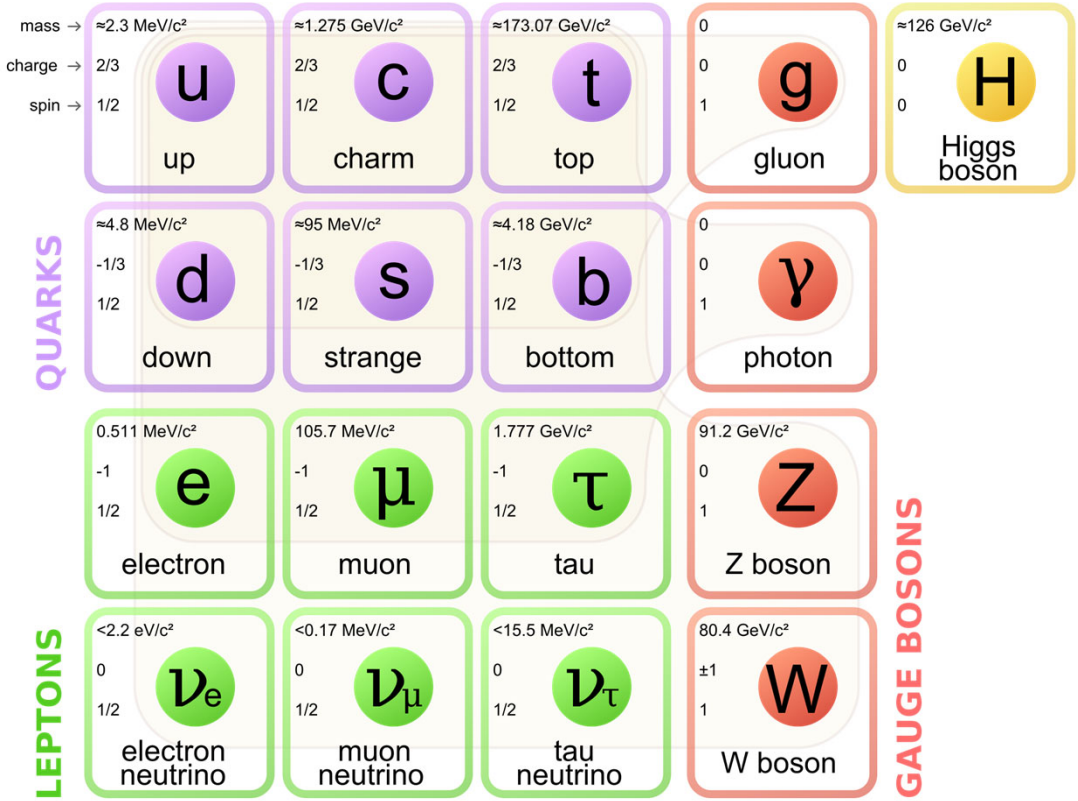
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS

Neutrinos are….

- Fundamental
- Ubiquitous (numerous)
- Massive, but almost massless
- Difficult to detect or stop
- Difficult to make



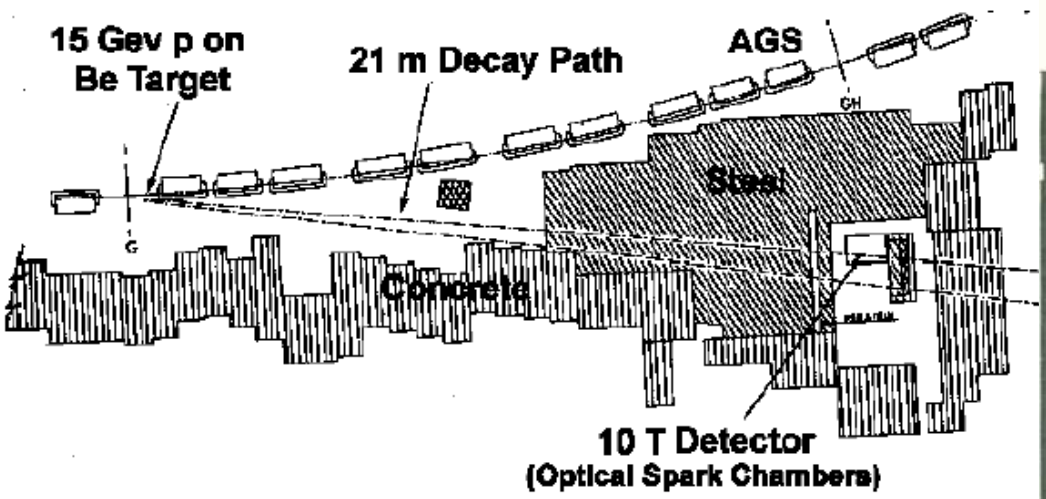
The First Neutrino "Beam"

- In 1957, Brookhaven AGS and CERN PS first accelerators intense enough to make ν beam

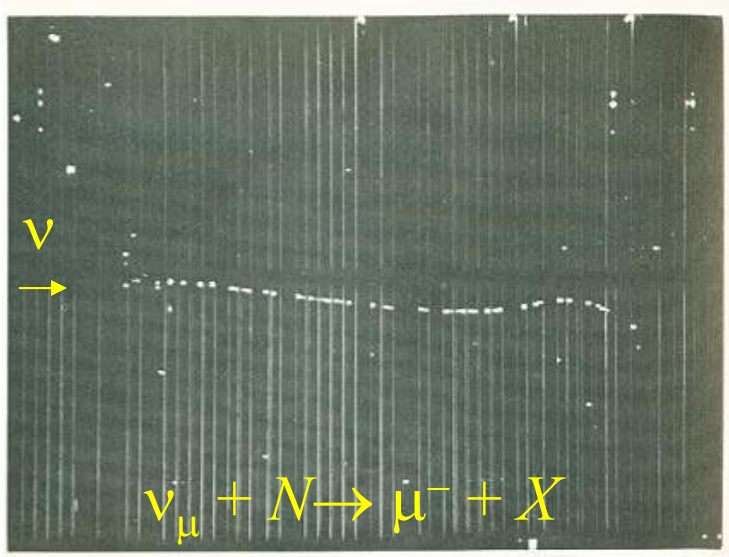
  $p + Be \rightarrow \pi^+ + X, \quad \pi^+ \rightarrow \mu^+ \nu$

- 1962: Lederman, Steinberger, Swartz propose experiment to see

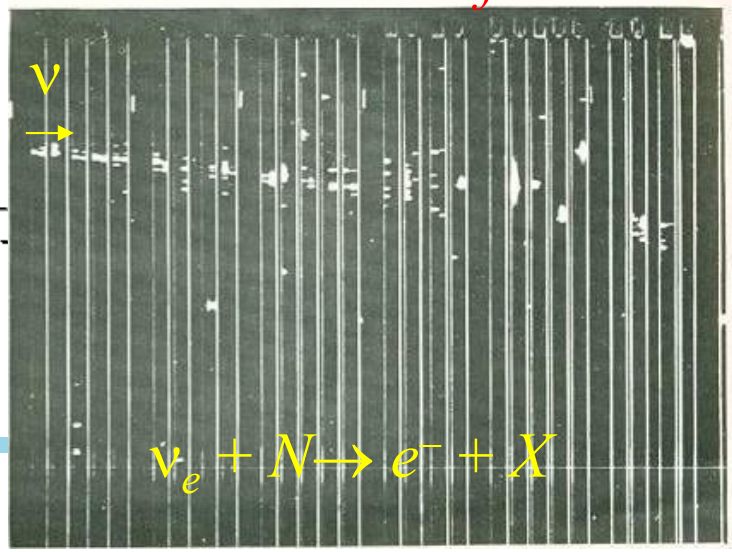
  $\nu_\mu + N \rightarrow \mu^- + X$ (*Phys.Rev.Lett.* ***9***, *36 (1962)*)



Saw lots of…



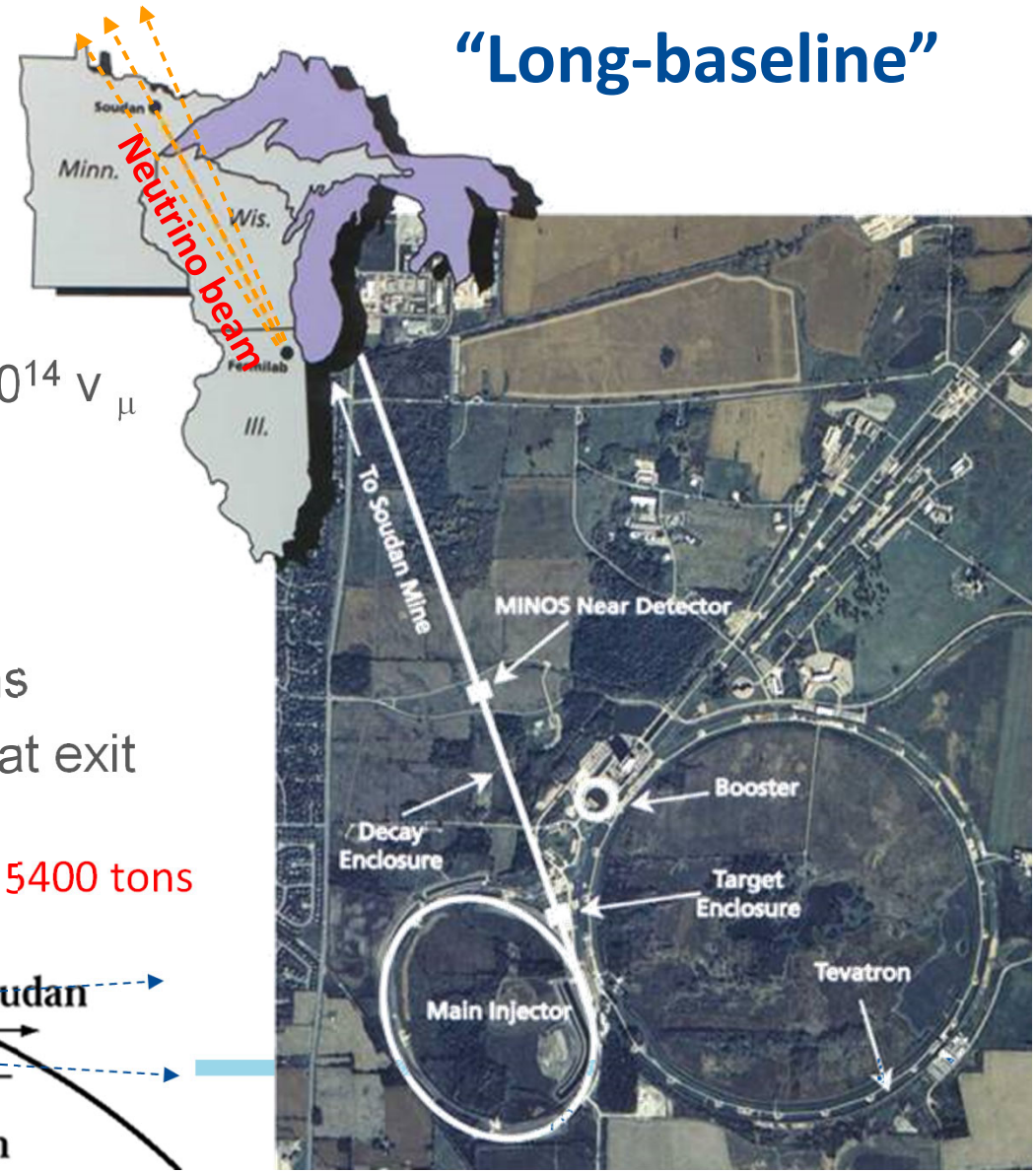
Saw none of…

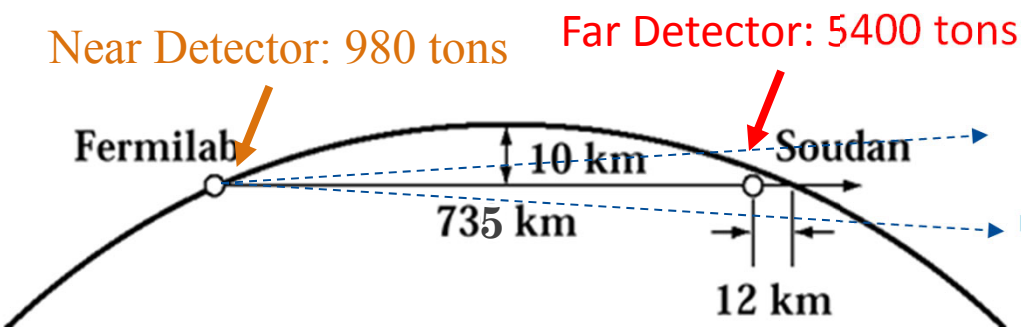


The NuMI Facility

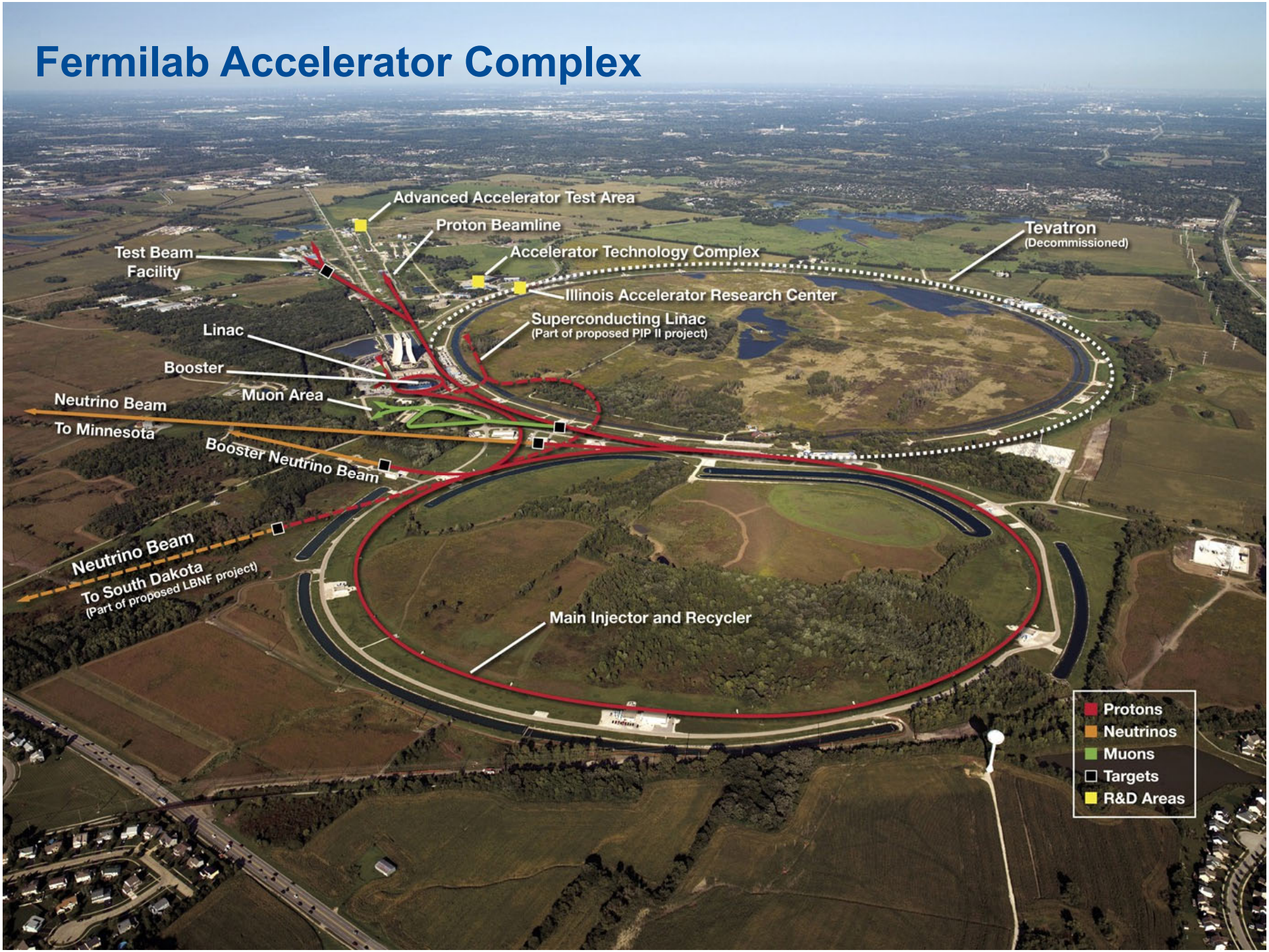
"Neutrinos (ν –> Nu) at the Main Injector"

- Intense muon-neutrino beam directed towards Minnesota
- Main Injector supplies 25 – 50 trillion 120GeV protons every 1.4 seconds
  - Operating regularly at 700 kW
- Each pulse produces about 2×10^{14} ν_{μ}
  - ~ 20,000,000 Pulses per year
- Direct beam 3° down
- On-site and off-site experiments
- Different types of neutrino beams
- Beam is 10s of kilometers wide at exit



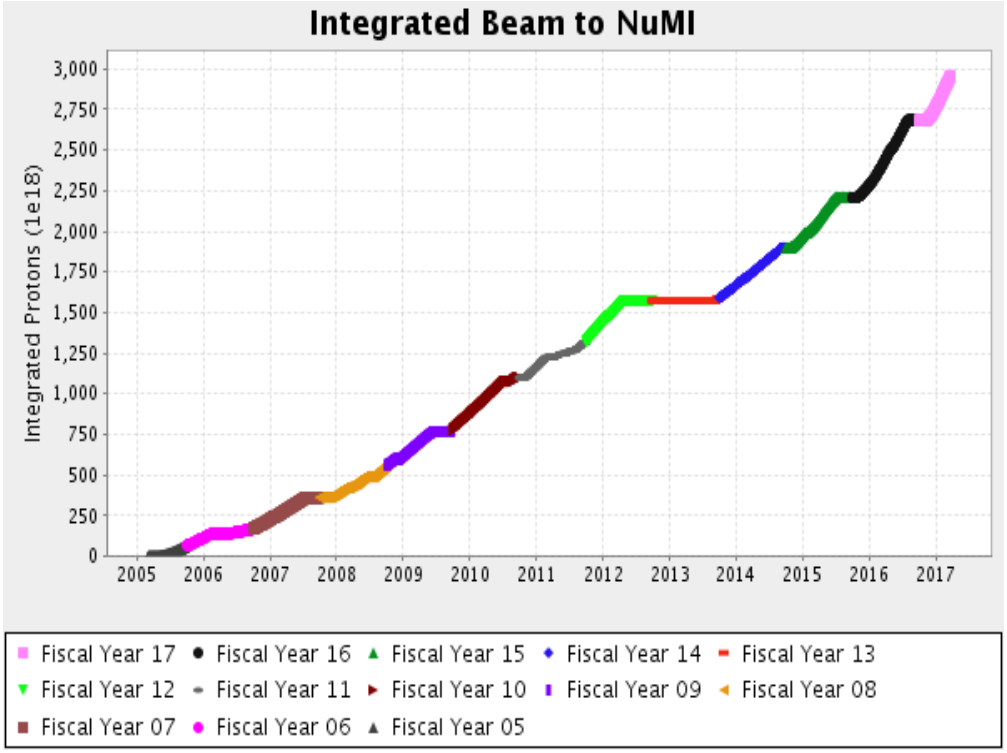


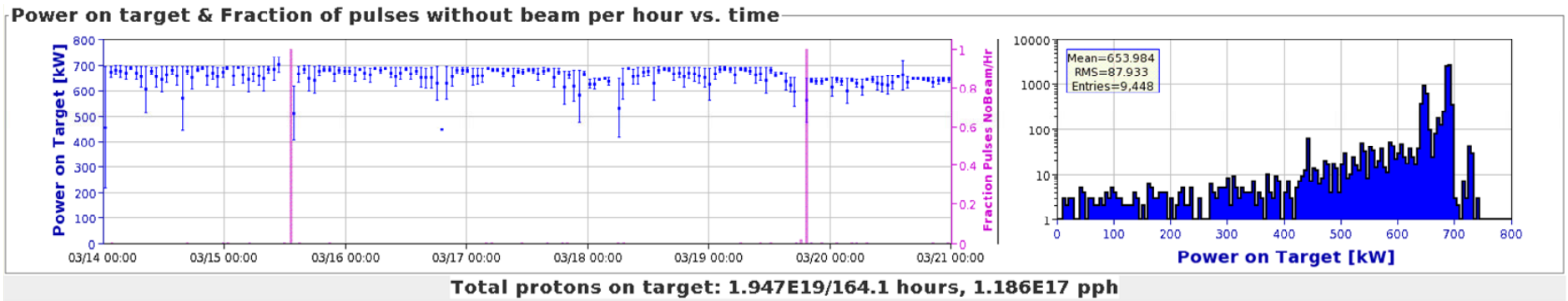
Fermilab Accelerator Complex



700 kW Average Power

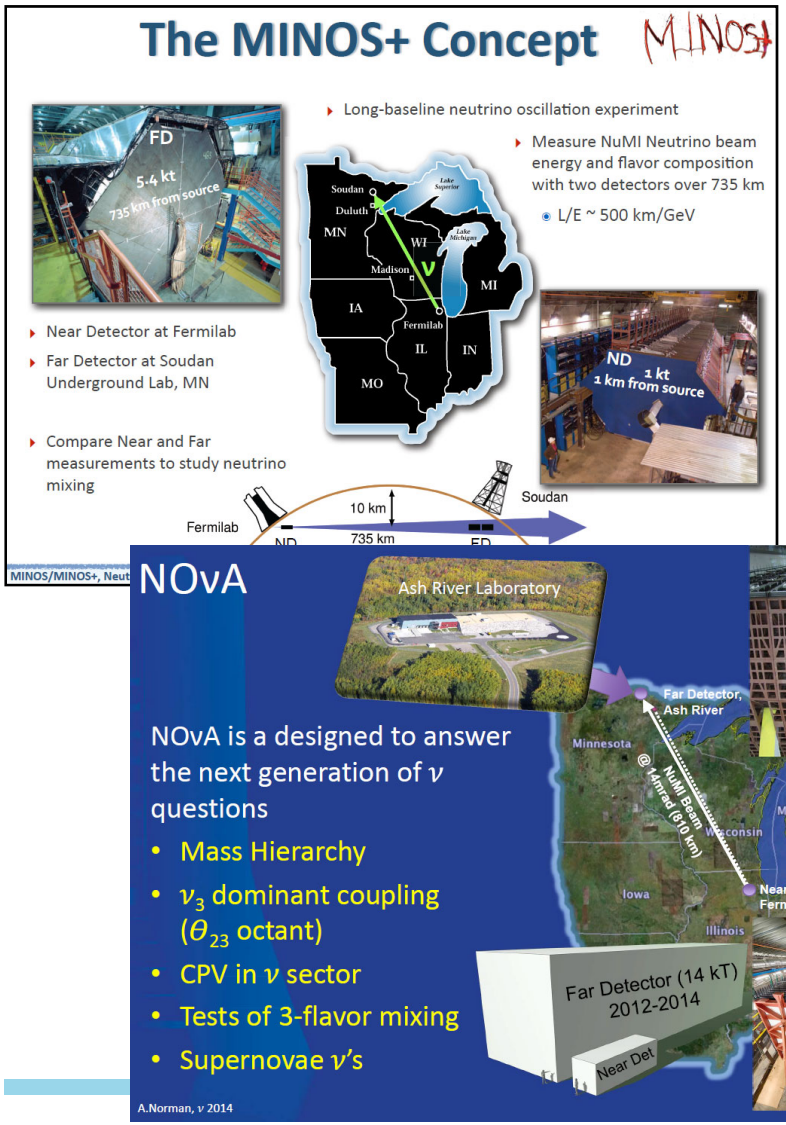
- Have achieved extended running above 700 kW
  - Up to 750 kW for short periods (7% above design)
  - Up to 53.9e12 protons
- Typical running is 650-740 kW
- Will approach a Megawatt in the next few years
  - Future beams will push into the Multi-MW regime



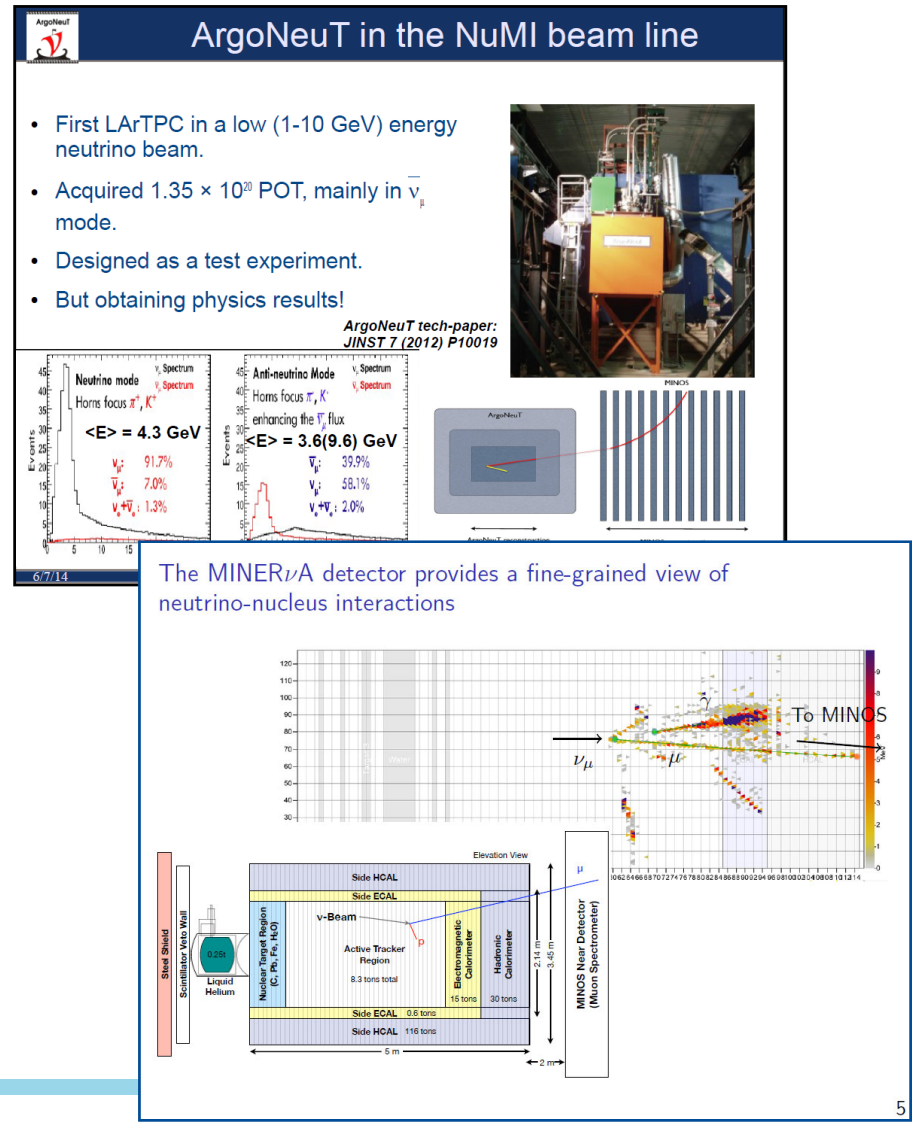


Multiple Experiments in the NuMI Beam

Long-baseline oscillation experiments



Neutrino scattering experiments

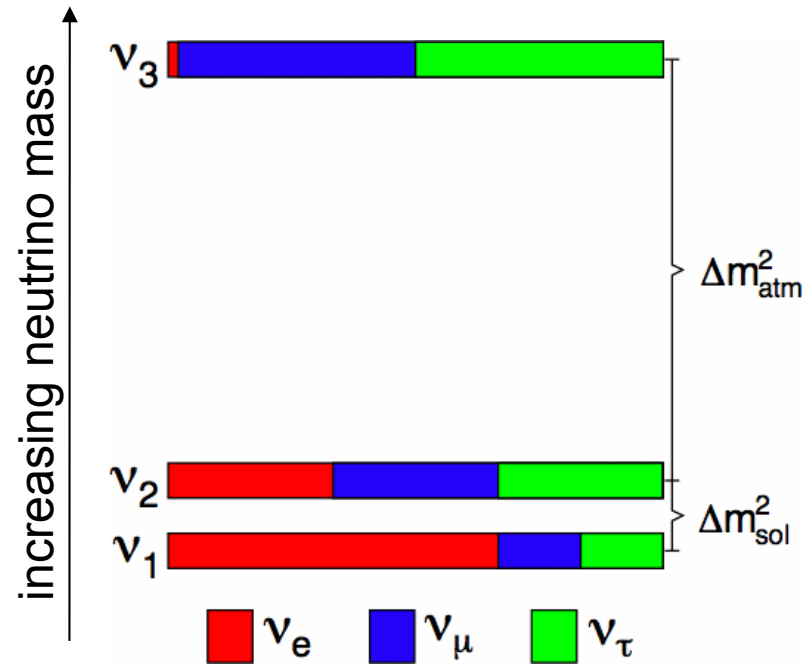


Neutrino physics drives the push to beams

→ Why is θ_{23} near maximal?
→ What is θ_{13} and why is it small?
→ Why so different than quark mixing?

$$U_{\rm CKM} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ 0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$U_{\rm MNS} \sim \begin{pmatrix} 0.8 & 0.6 & 0 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



→ Is CP violation is present?
→ Are neutrinos Majorana?
→ What is the hierarchy of neutrino masses?
→ What is the source of the matter-antimatter asymmetry

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Accelerator/Atmospheric/Reactor}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar sector}} \times \underbrace{\begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana phase}}$$

Why a Beam? – Controlled Laboratory Experiment

- Natural sources exist – but they are very weak and not necessarily well understood
  - Solar and atmospheric neutrinos only understood once oscillations were established and well understood
    - Moving from observation to experiment
  - Supernovae are hard to come by
- Artificial beams are controlled and intense ⇨ Precise!
  - Decide when, where, and how the beam is generated
  - Detectors are placed strategically
  - Beams can be controlled with precision – vital as measurements approach 1%
- Applications:
  - Today neutrino oscillation is the first focus
  - Probe of nuclear structure
  - Observation of the neutral current
  - Demonstration of neutrino flavor (muon, tau)
  - Measurement of weak mixing angle

LBNF / DUNE – The International mega-science project

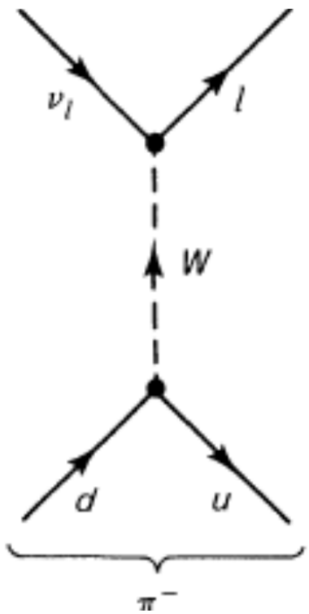
URL to the LBNF/DUNE Video:

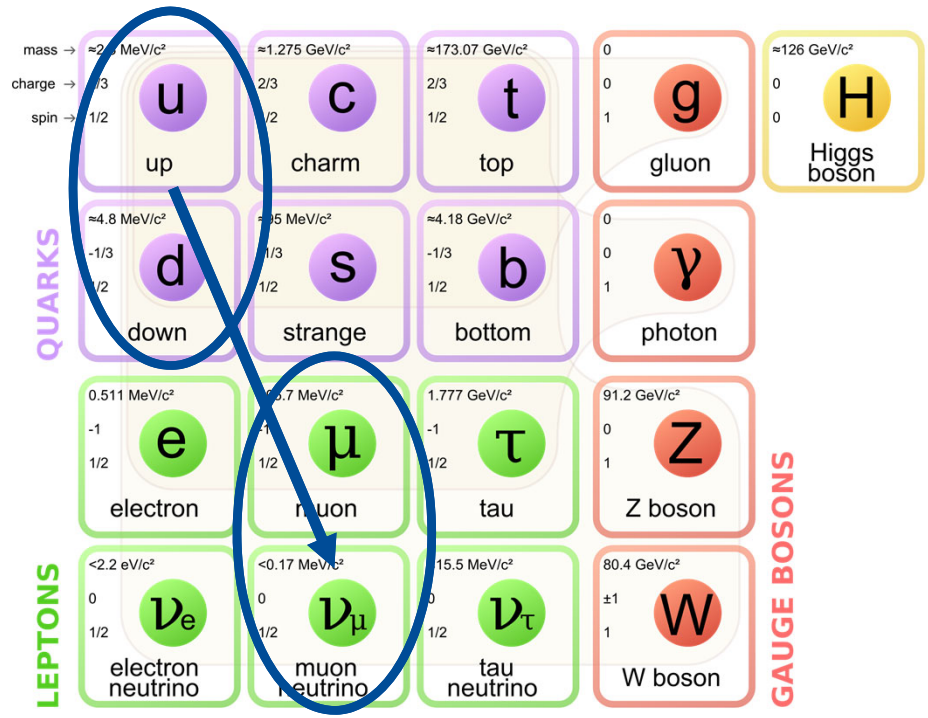
https://www.youtube.com/watch?v=AYtKcZMJ_4c&feature=youtu.be

Pion Decay!

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

- Most all of our neutrinos come from pion decays
- Two quarks, bound together by gluons, convert into a neutrino and muon





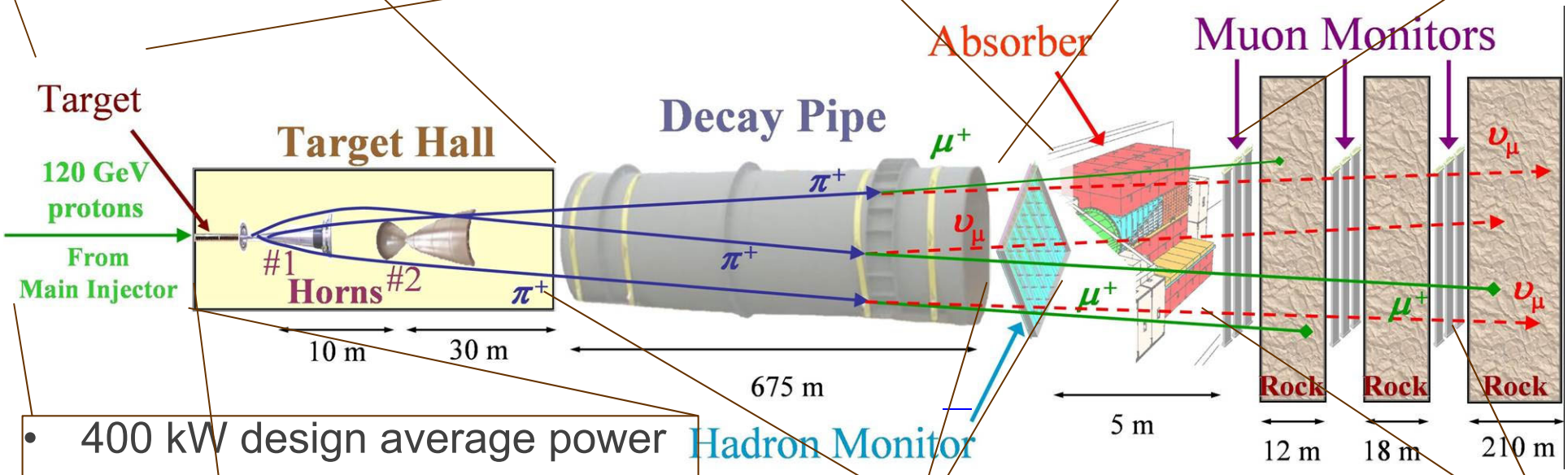
- A "simple" decay (at first)
  - Pion mass ~ 140 MeV/c^2, Muon mass ~ 105 MeV/c^2

The NuMI Beam "Neutrinos at the Main Injector"

- 1 meter long, C target
- Produces π^+, K^+ mesons

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

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



- 400 kW design average power
- 700 kW upgrade for NOvA
- 1 Megawatt Upgrade 2021
- $\sigma \sim 1$ mm

- Pulsed focusing horns
- Toroidal magnetic field
- Parabolic inner conductor profile
- Focus meson momentum band

- Measure hadron & muon fluxes
- Arrays measure distributions

Energy is our raw material

Energy and momentum in accelerators are usually expressed in units of electron Volts:

$1\ eV = 1.602 \times 10^{-19}$ Joules

We use energy units:

eV - Chemical

keV $= 10^3$ eV - xrays

MeV $= 10^6$ eV – nuclear physics

GeV $= 10^9$ eV – particle physics

And finally, for mass, the units are eV/c^2. For instance

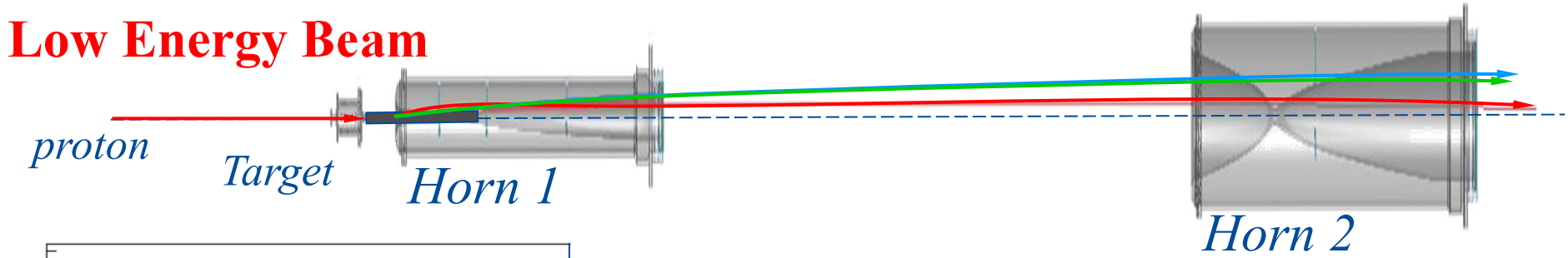
m_p = mass proton = 938 MeV/c^2

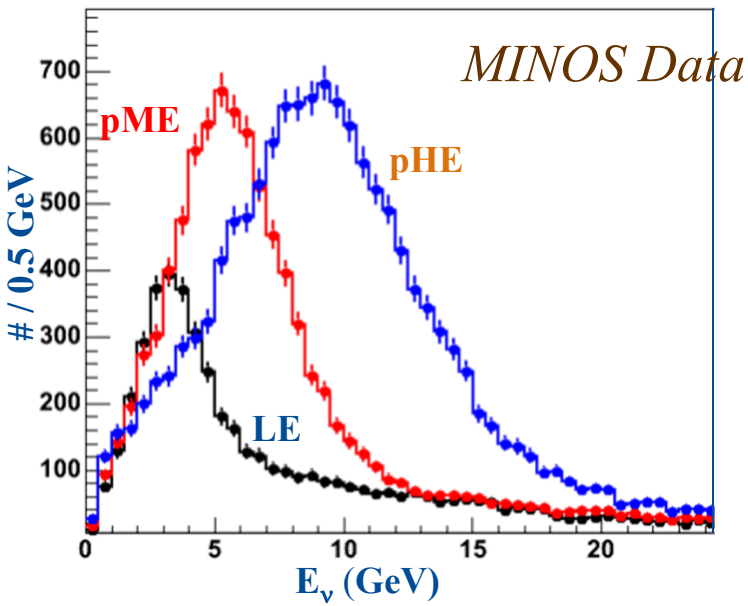
m_e = mass electron = 511 keV/c^2

Fermilab's accelerators give 120 GeV to a proton – that raw energy will be used to make new matter

Variable Energy Neutrino Beam

Low Energy Beam





Pions with

p_T=300 MeV/*c* and

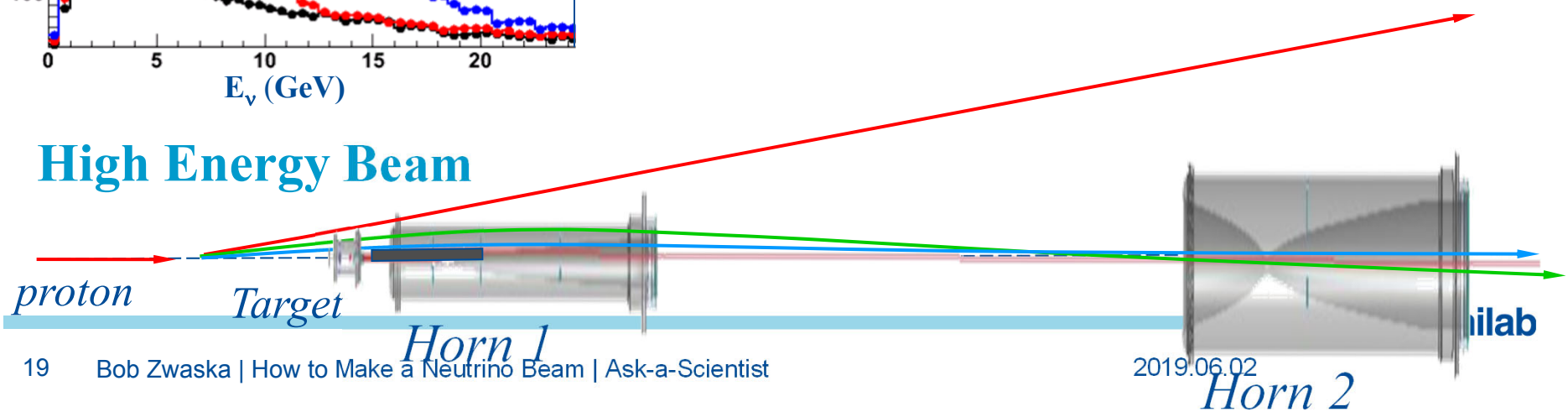
p*=5 GeV/*c

p*=10 GeV/*c

p*=20 GeV/*c

Vary ν beam energy by sliding the target in/out of the 1st horn

High Energy Beam



Defining Characteristics of Long Baseline Beams

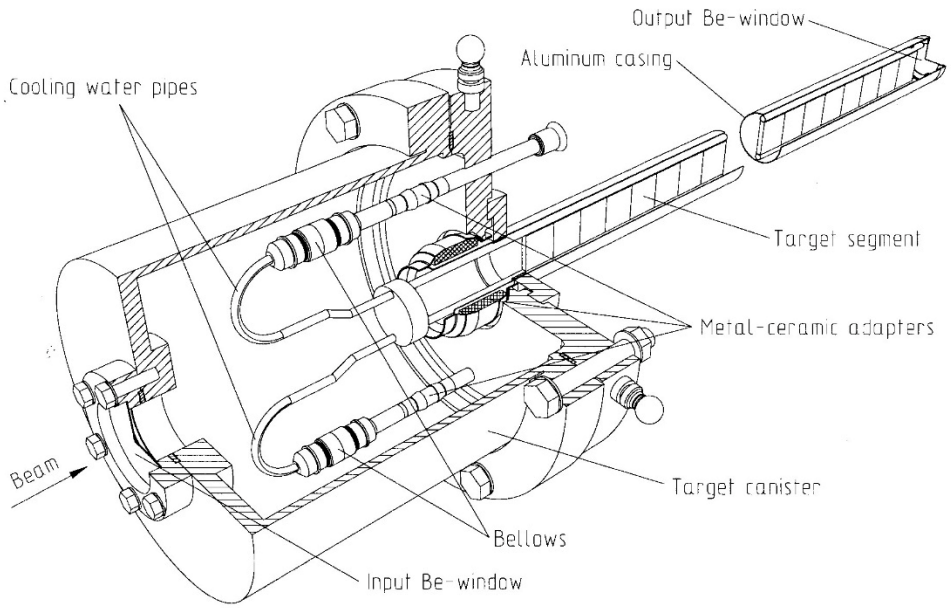
- Proton Beams: synchrotron based, nearing 1 MW
  - High Stored Energy: ~ 1 MJ
  - Small Beam Spot: 1 – few mm
  - High Proton Energy: 30-120 GeV
  - Single-turn extraction, long cycle time: 1 – few seconds
- Pion Focusing: Pulsed horns
  - Horns more efficient than quads
  - High currents: few hundred kA
- Large Decay volume
  - Meters in cross-section
  - 100s of meters in length
- Beam radiation dispersed over extended area

  Tritium, activation, corrosion, cooling

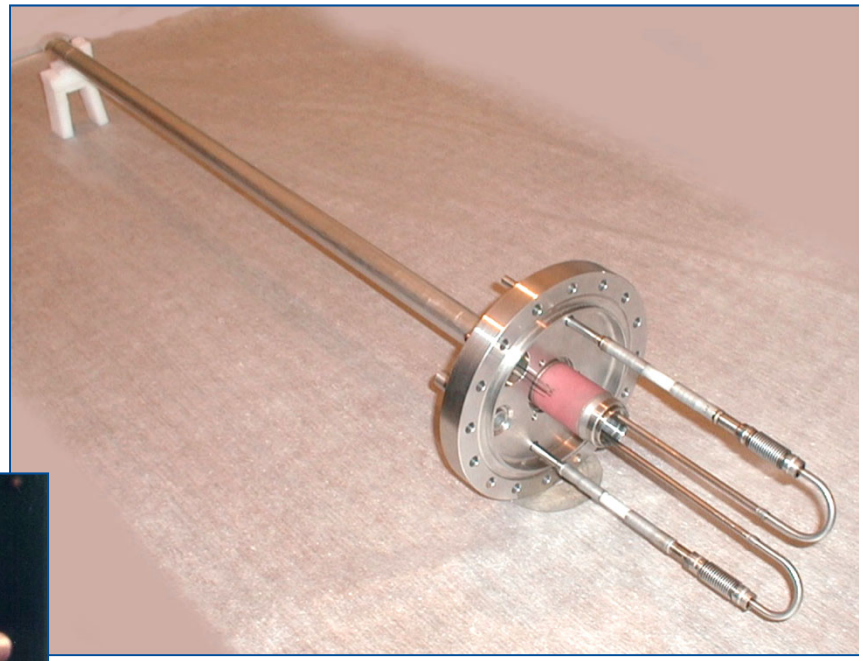
Challenges to Conventional Neutrino Beams

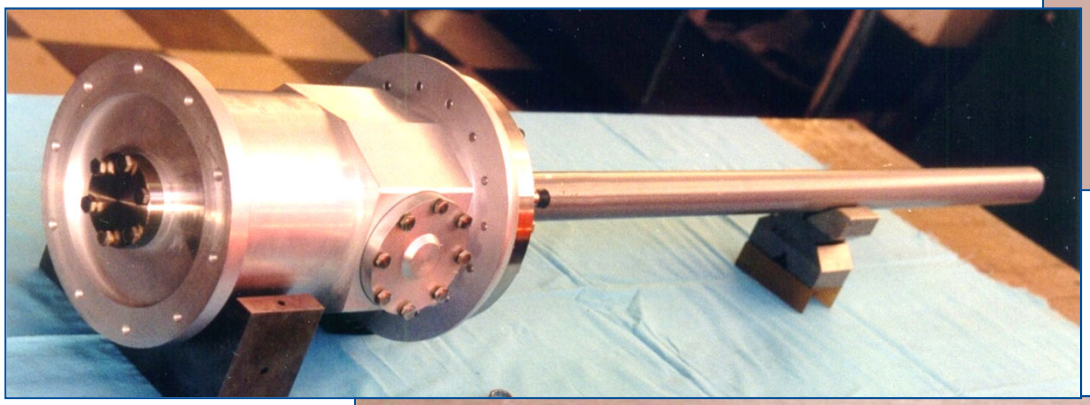
- Proton beams
- Targets
- Horns / focusing
- Precision
- Instrumentation
- Hadroproduction Modeling & Experiments
- Radiation Protection
- Radionuclide handling

The MINOS Target



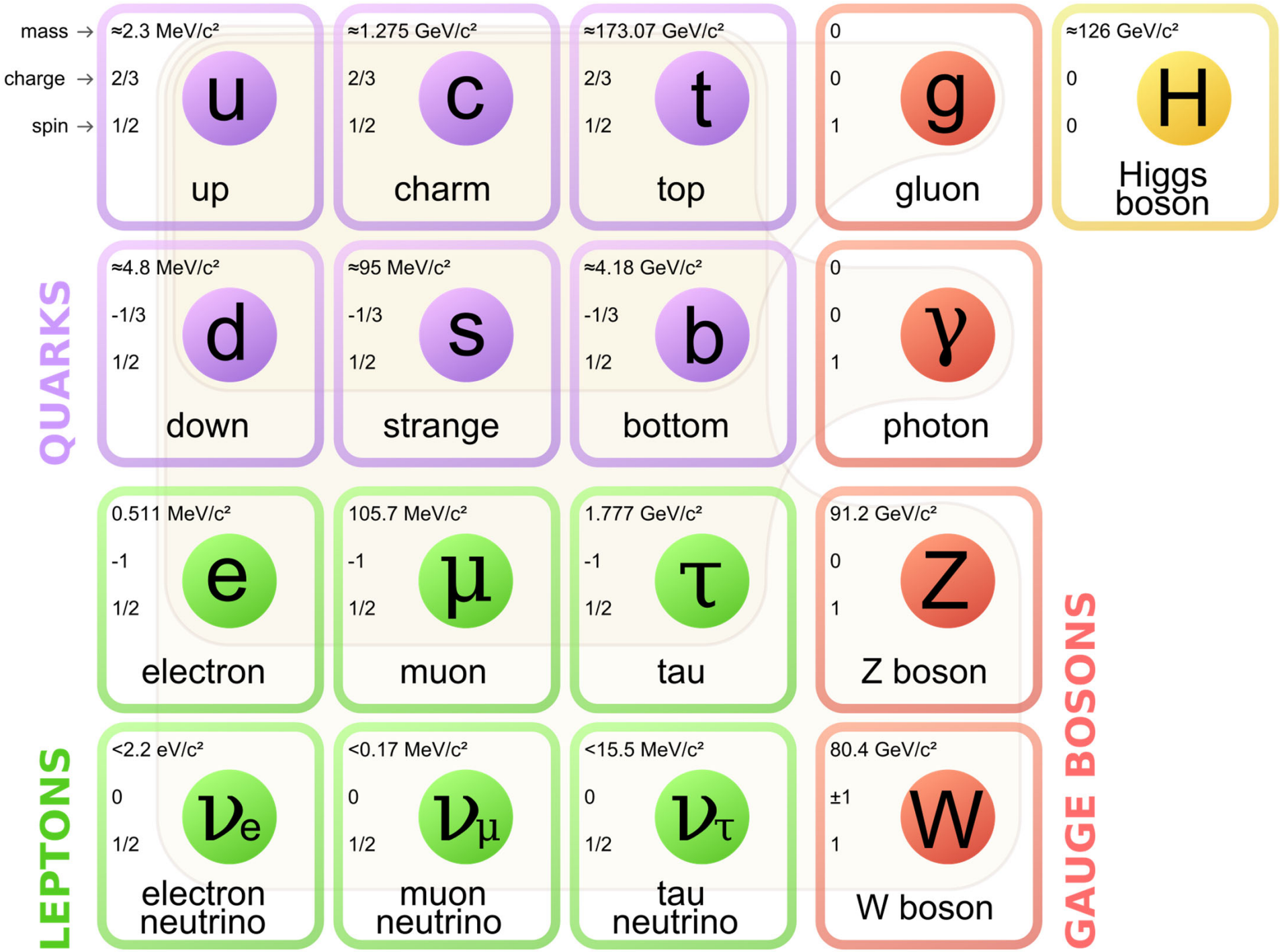
~ 4 kW beam power deposited in target





Encased in vacuum / helium can with beryllium windows

Water cooled graphite core


mass →
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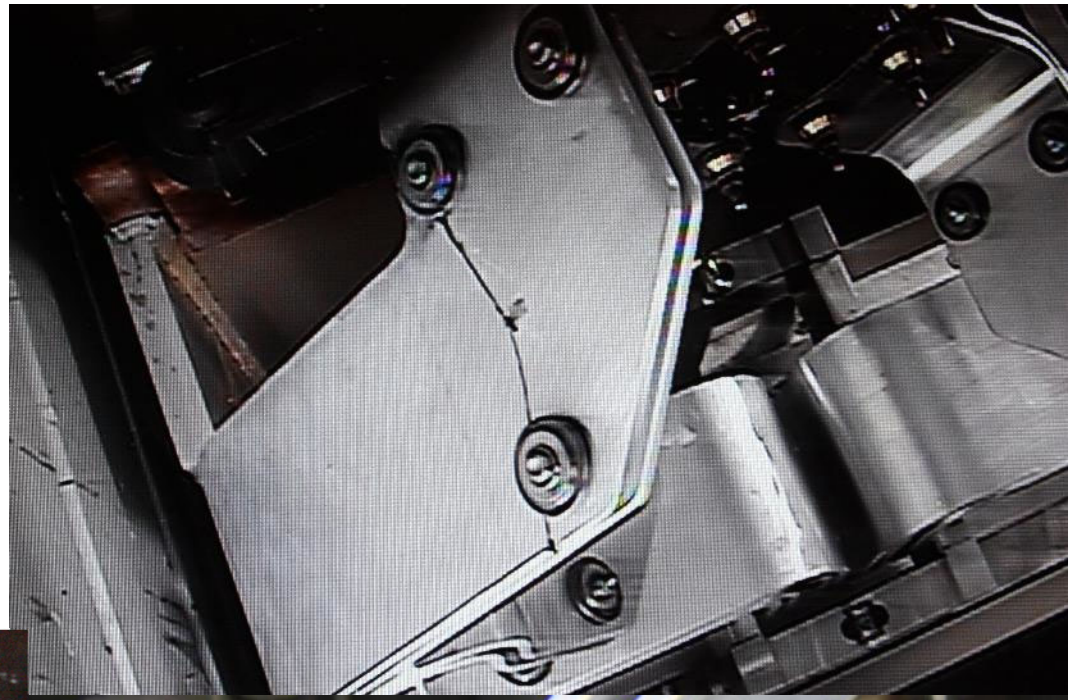
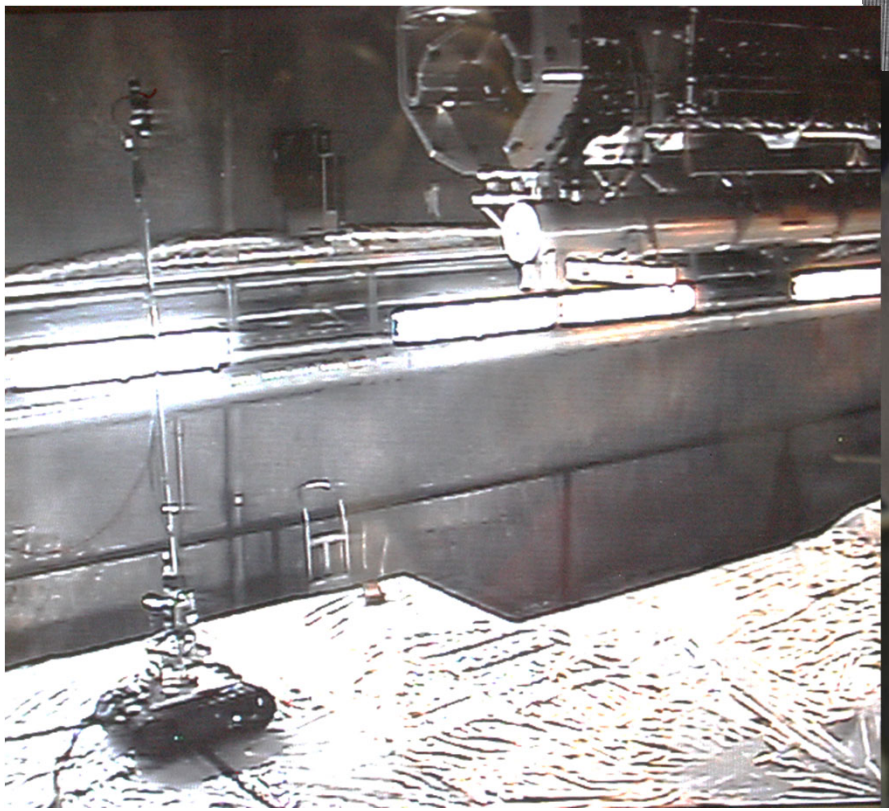
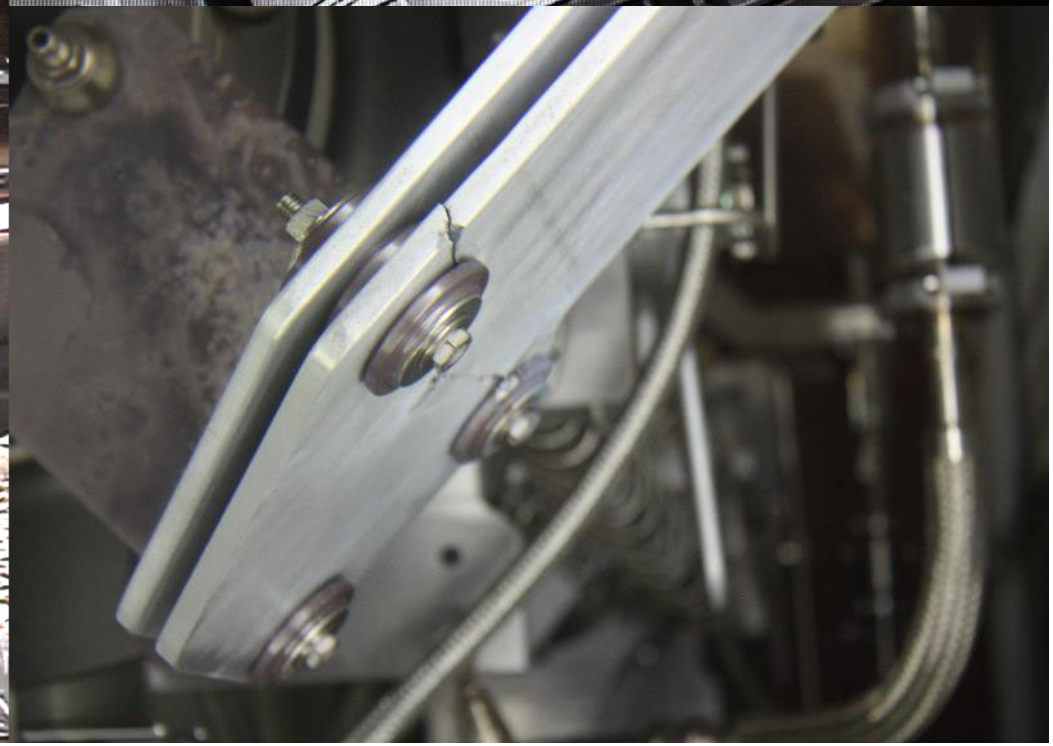
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
GAUGE BOSONS

Challenging Environments

- Replaced NuMI Horn summer 2015 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



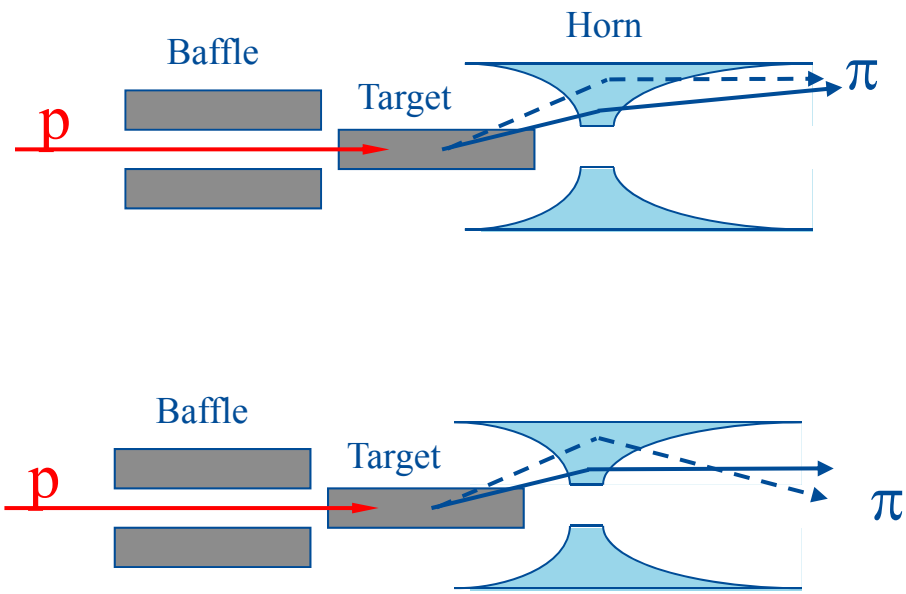


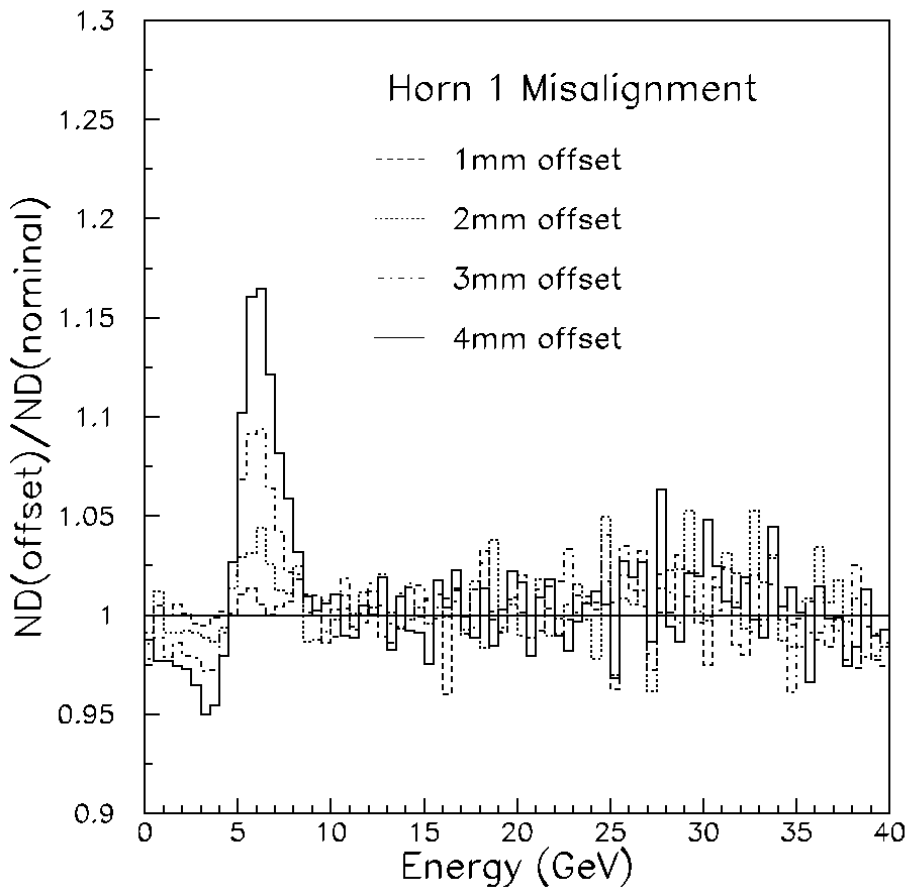


Achieving a Precision ν Spectrum

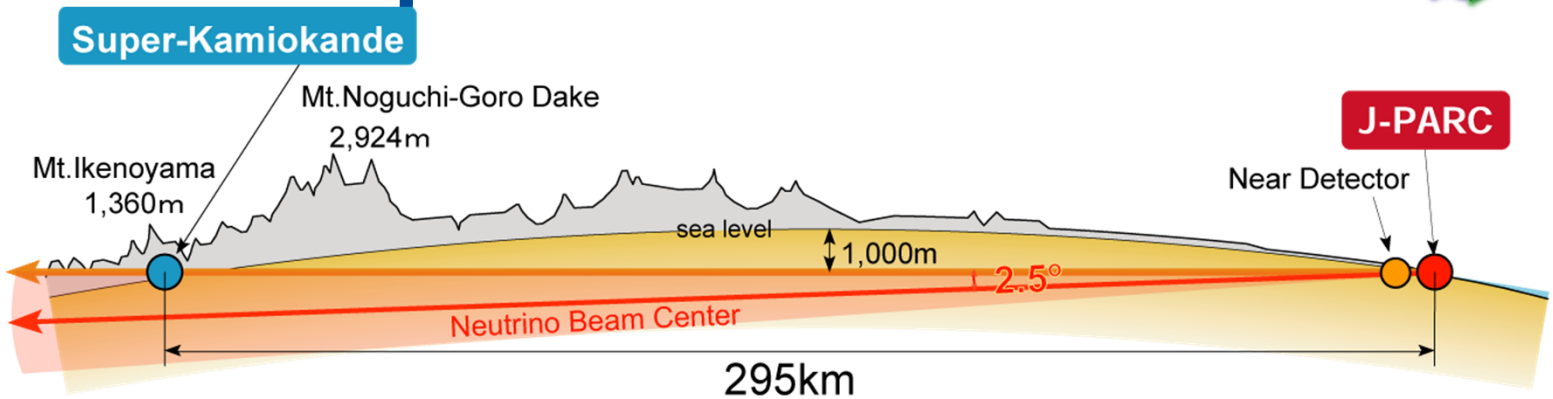
- Component placement affects the ν beam
  - Beam monitors detect changes in muon & hadron beams
  - Variation measured spill-to-spill
- Beam based alignment for all major components

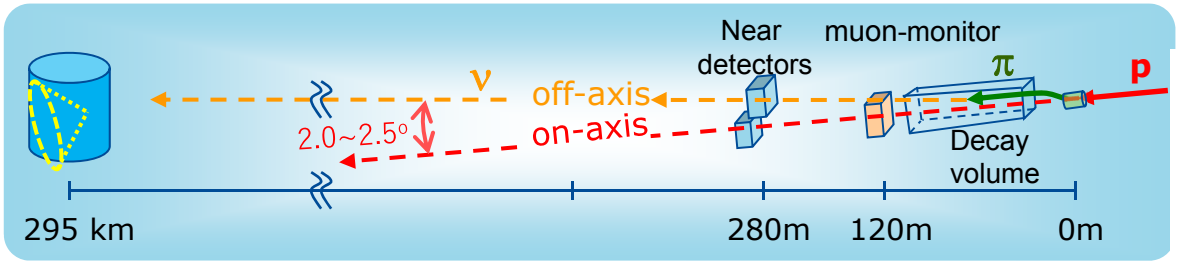
- Horn 1 displacements affect pion focusing



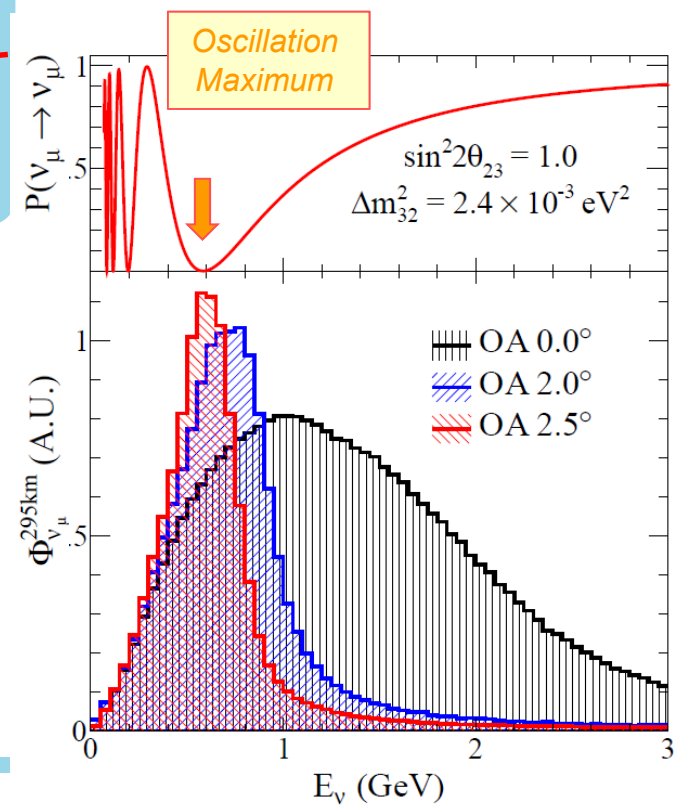


The T2K experiment



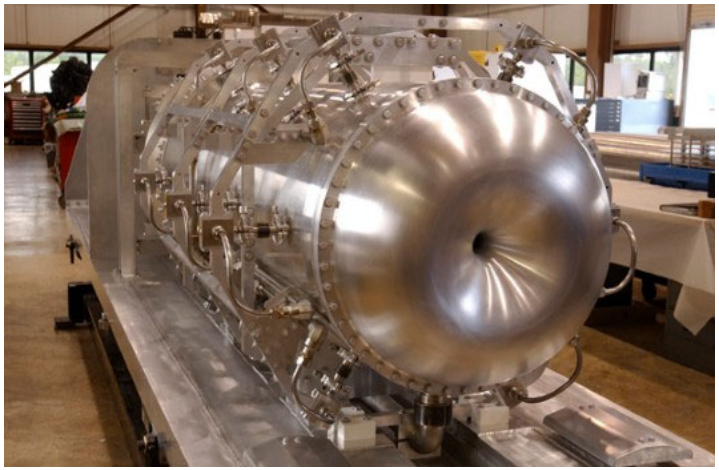


- Conventional "horn-magnet-focused" ν beam
  - 30GeV Protons on a graphite target
  - daughter $\pi^+ \rightarrow \mu^+ + \nu_\mu$ ($\pi^- \rightarrow \mu^- + \nu_\mu$)
  - Anti-neutrino production by inverse polarity
- First application of Off-Axis(OA) beam: 2.0~2.5° wrt. the far detector direction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

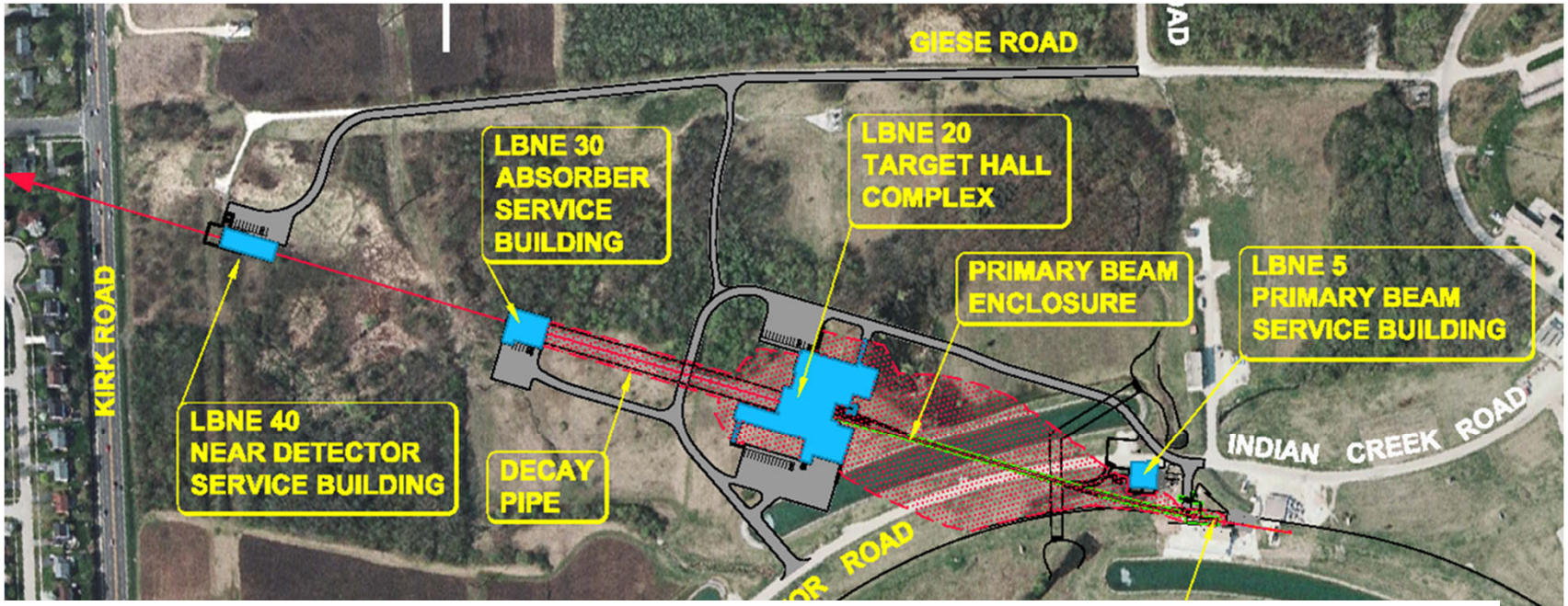


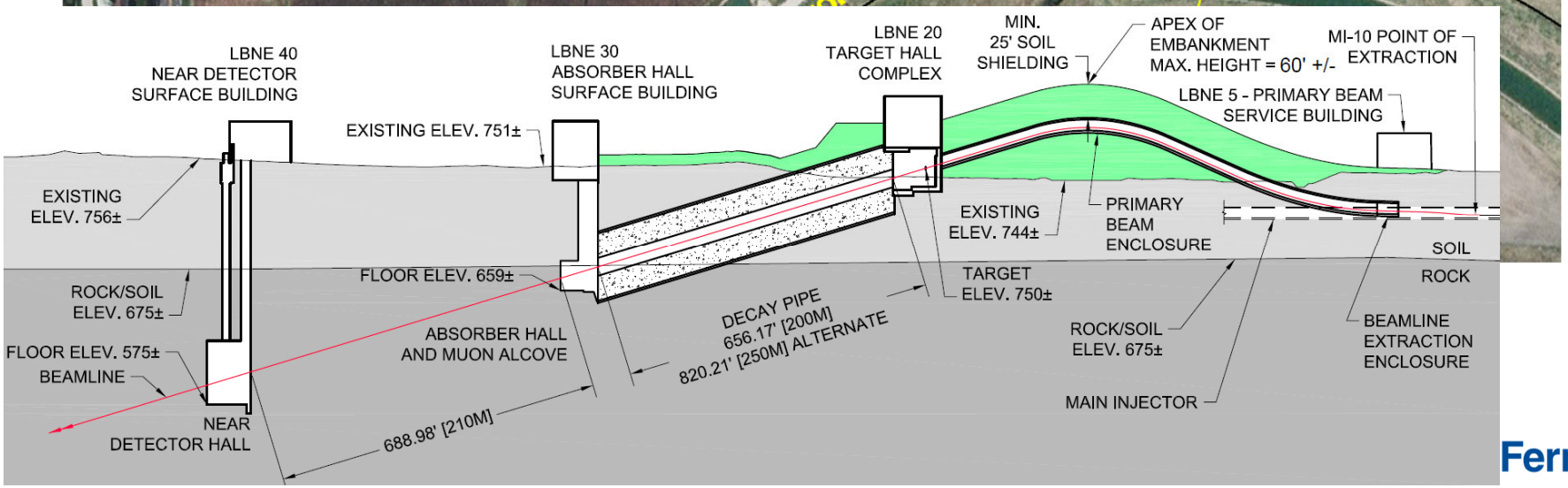
Booster Neutrino Beam (BNB)

- Uses 8 GeV beam from the Fermilab Booster, operating since 2002
  - Up to ~ 30 kW of beam (5e12 ppp)
- Beryllium target integrated with single focusing horn
- Services a suite of experiments at Fermilab: the Short Baseline Neutrino (SBN) program



DUNE: Deep Underground Neutrino Experiment
LBNF: Long-Baseline Neutrino Facility





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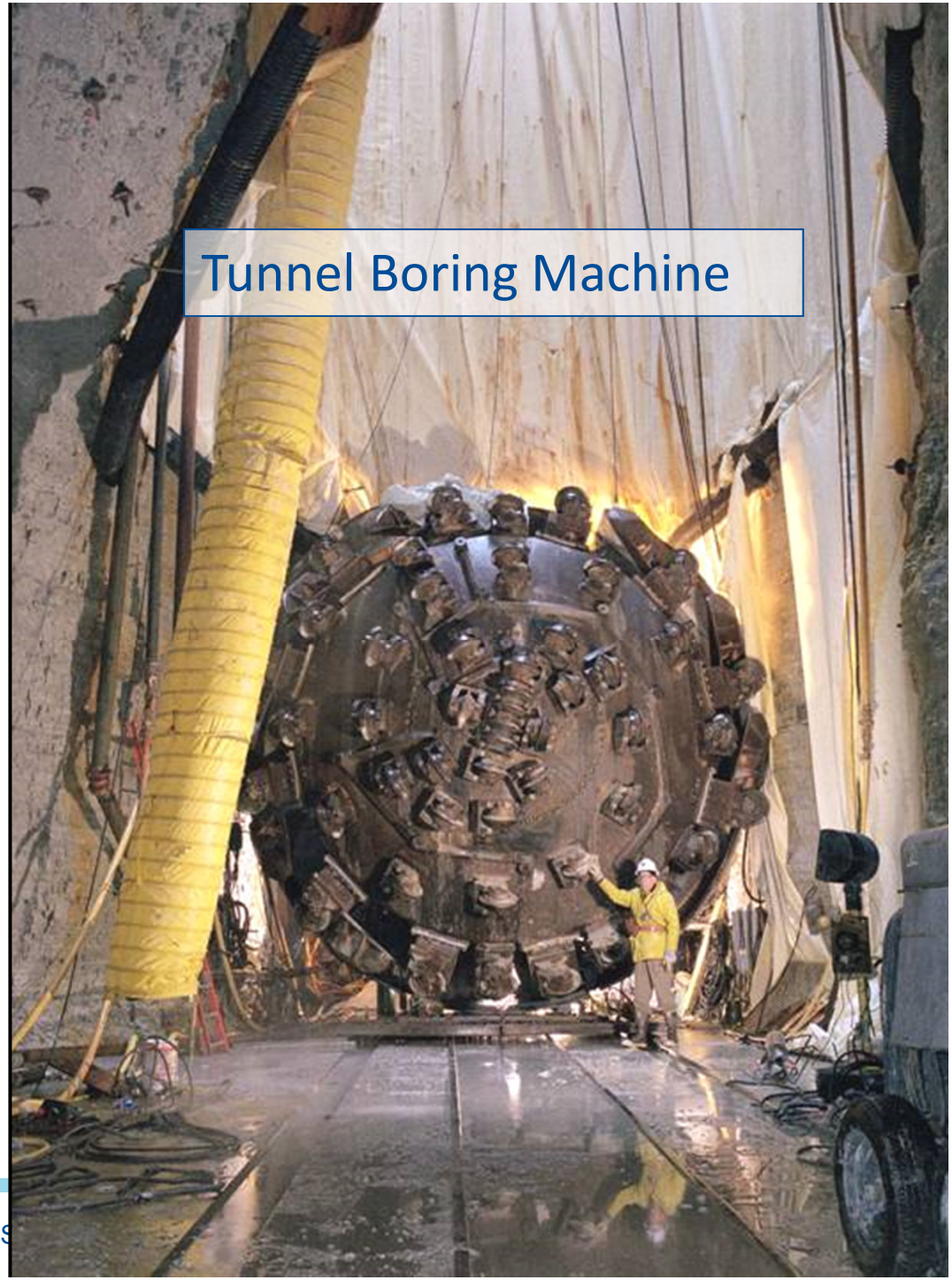
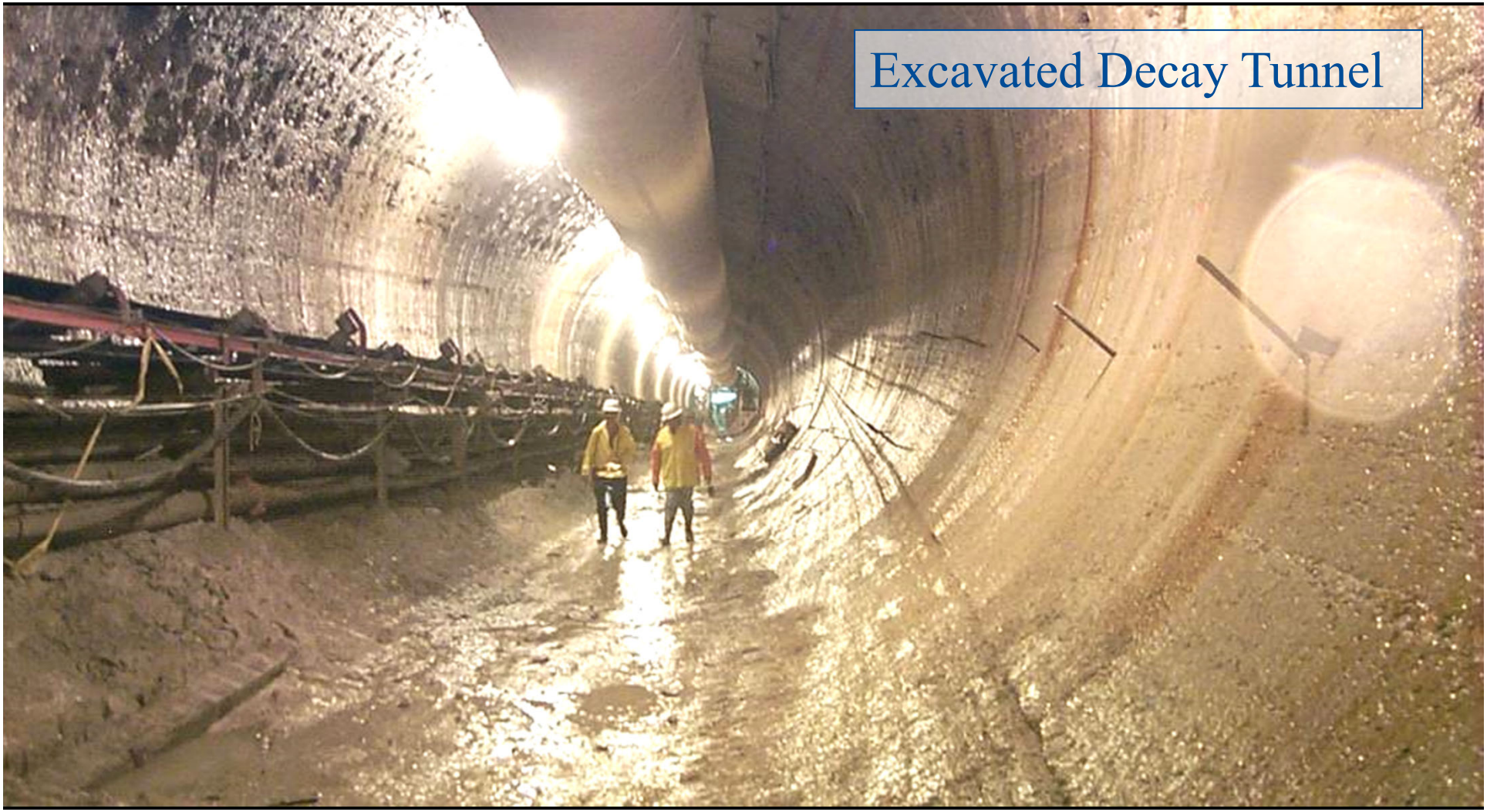
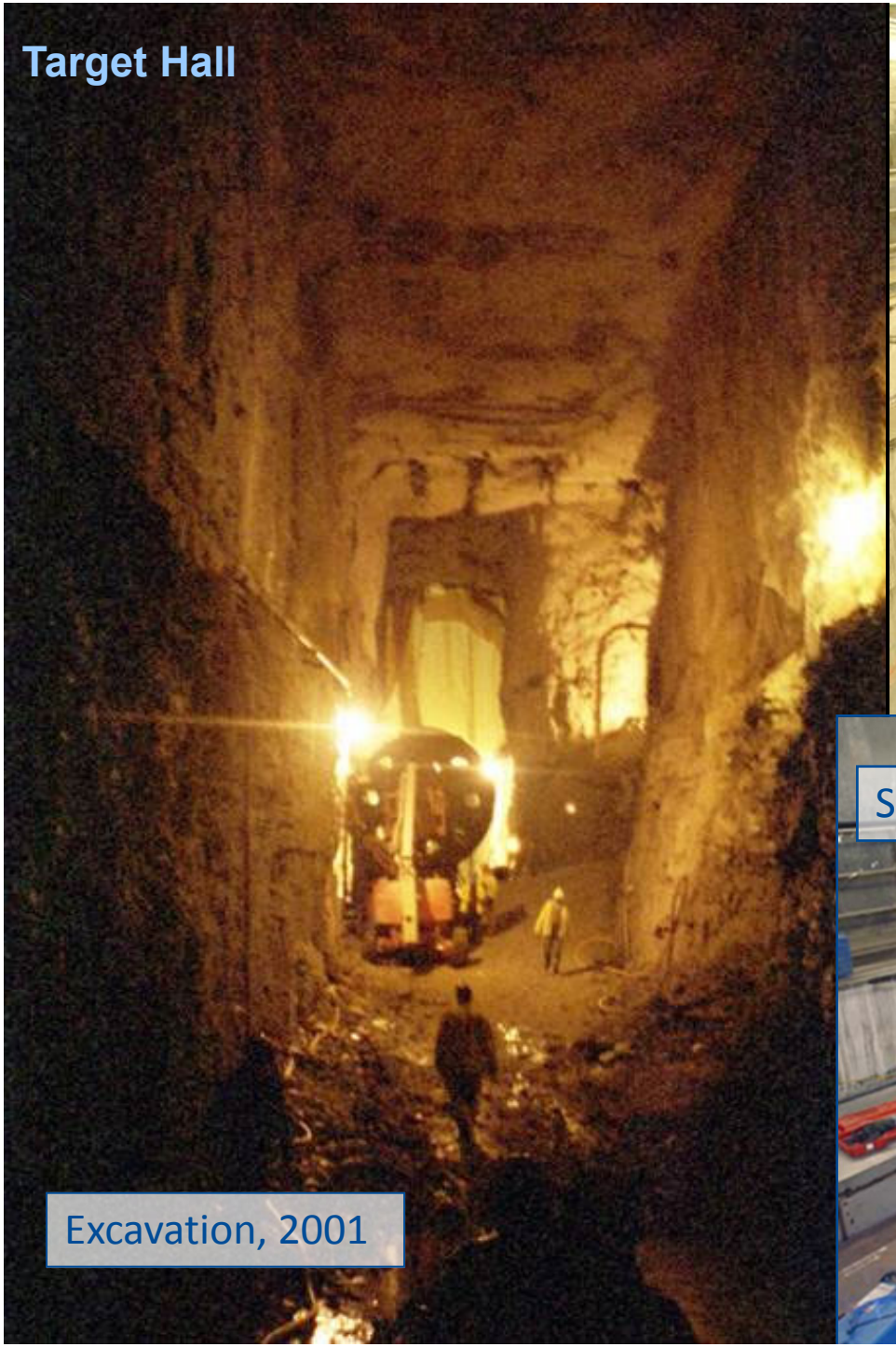
Civil Construction

- Major underground excavation
- Used drilling, blasting, & boring
- Completed 2003



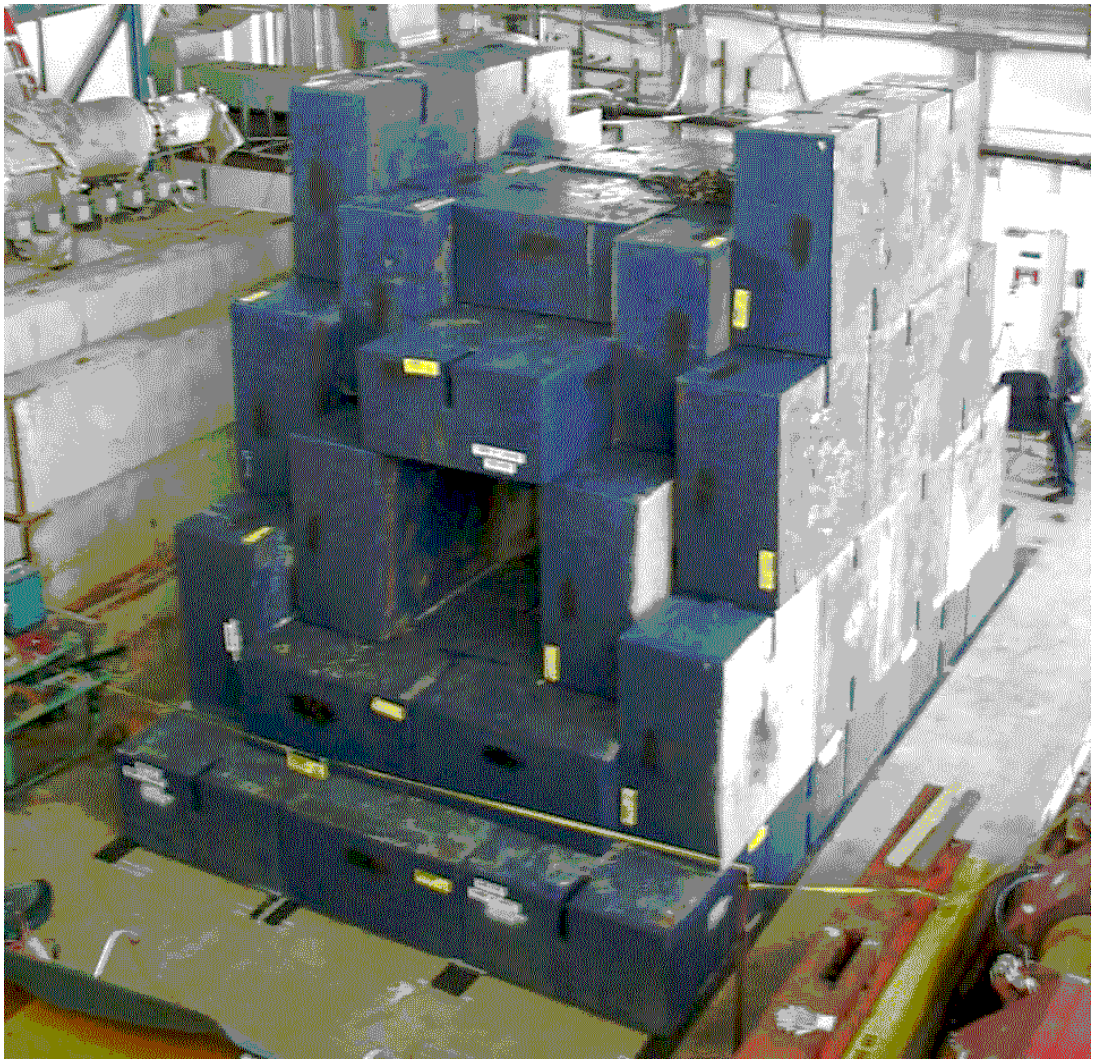

Excavated Decay Tunnel

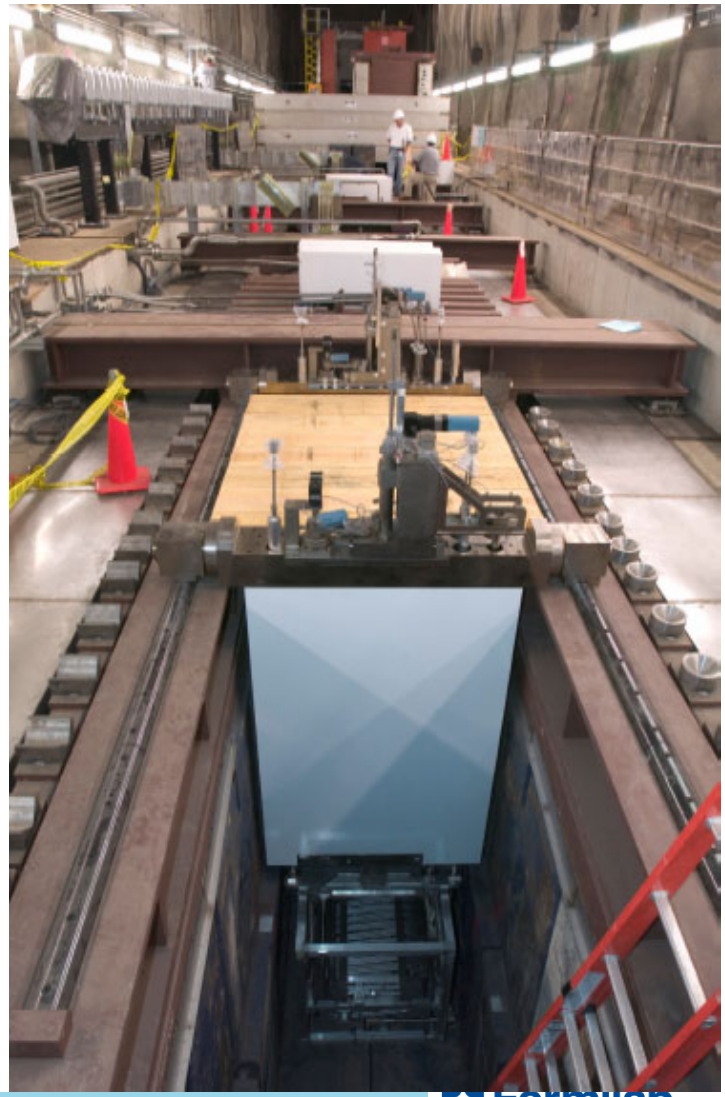

Target Hall
Excavation, 2001

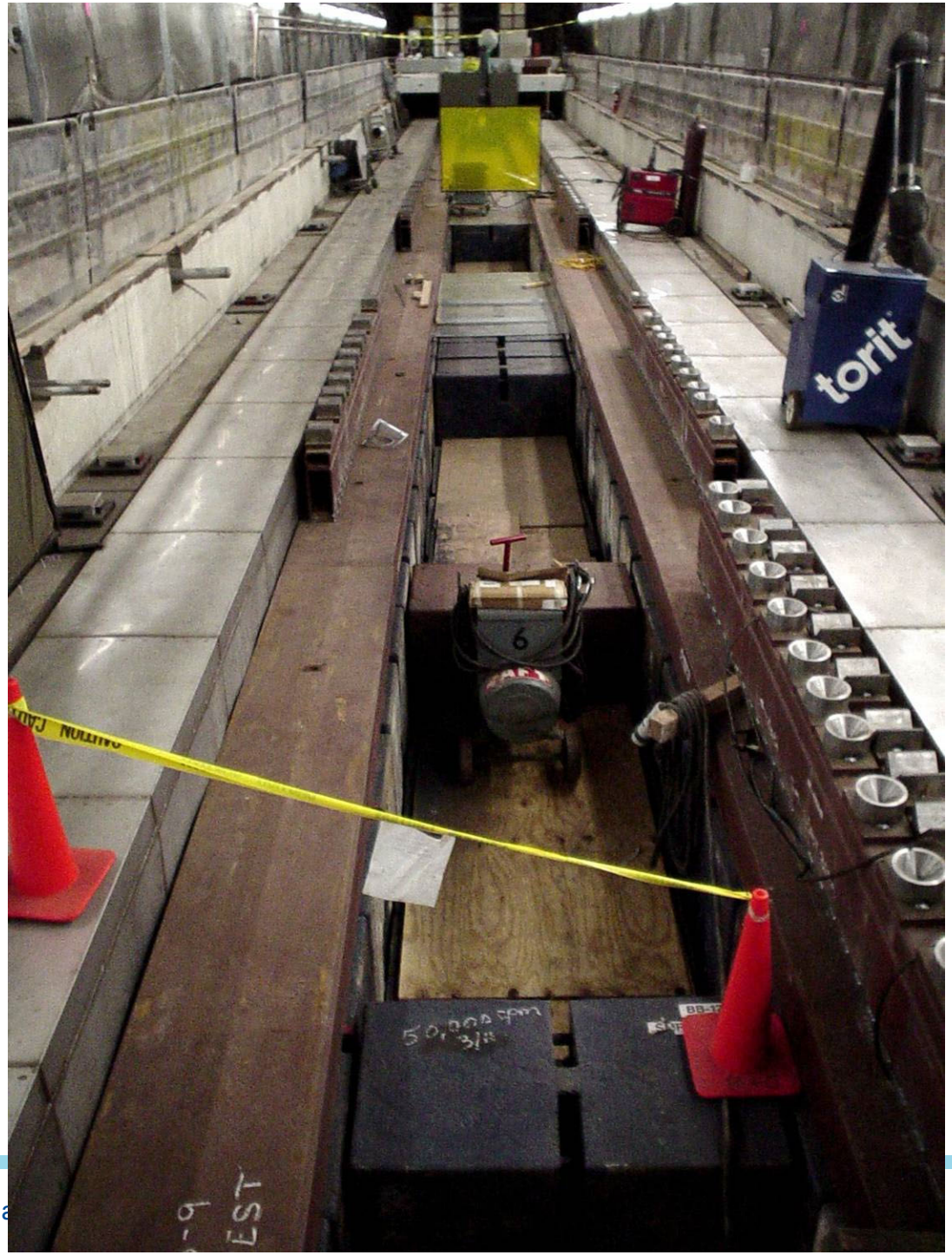
Construction complete

Shielding installation

Installing Components







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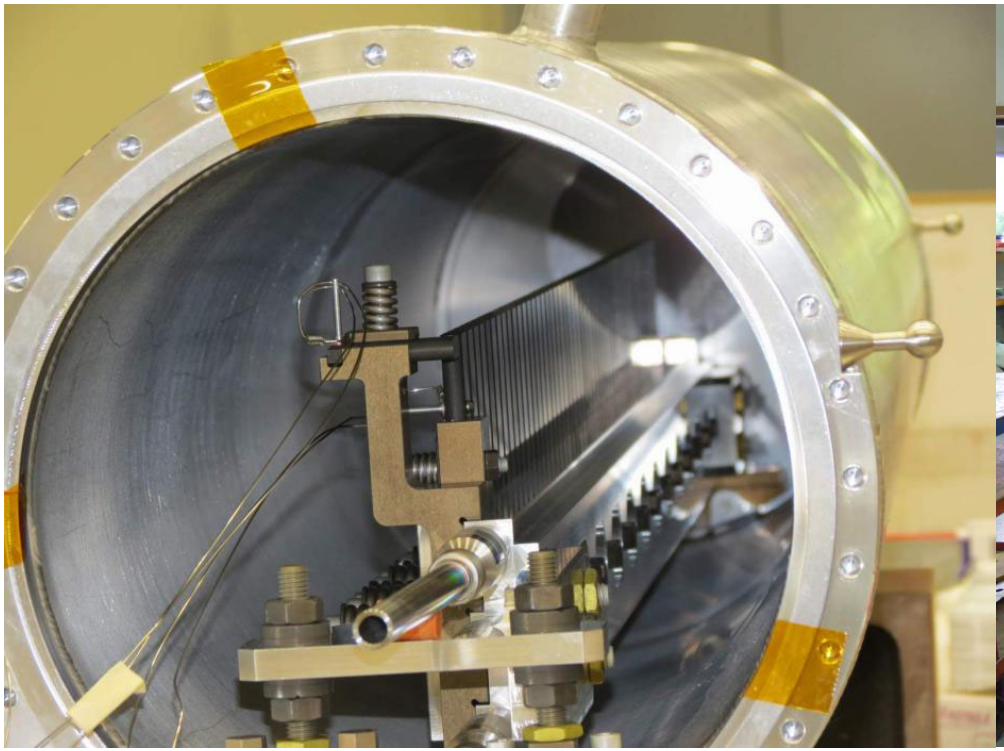
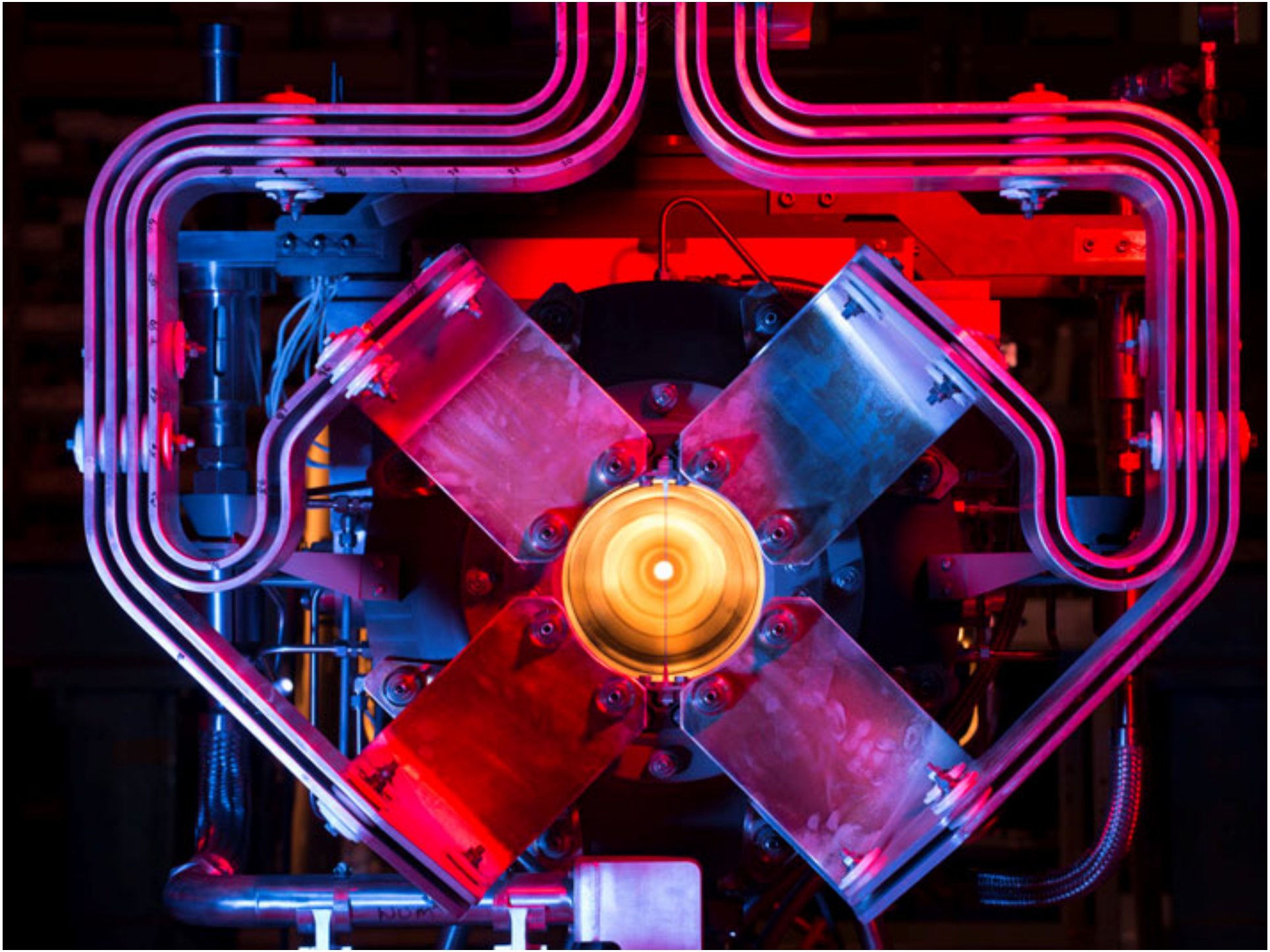
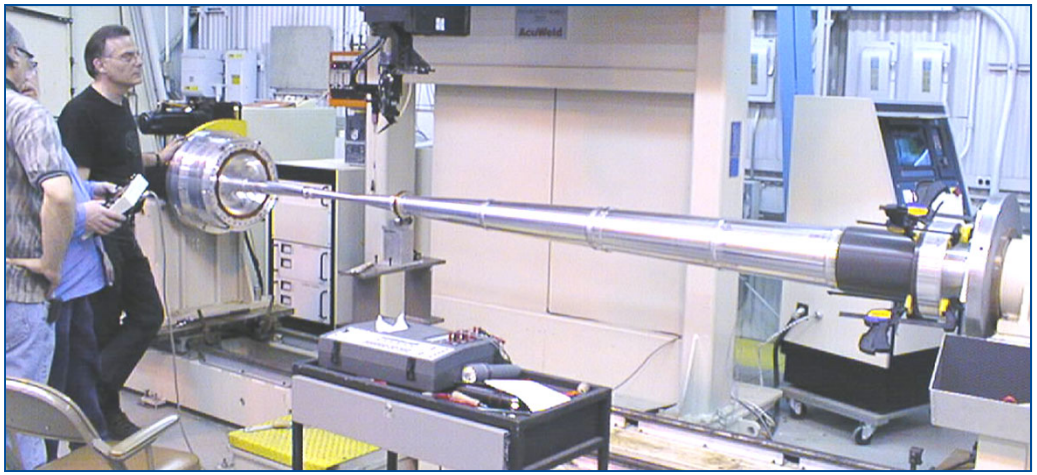
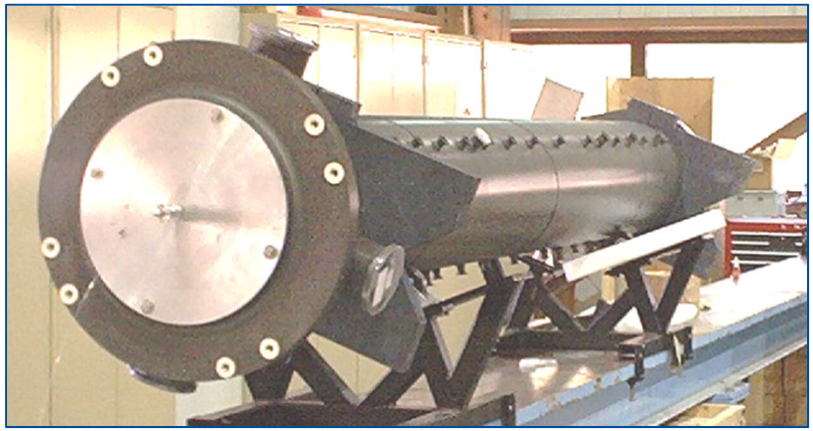
NOvA Target

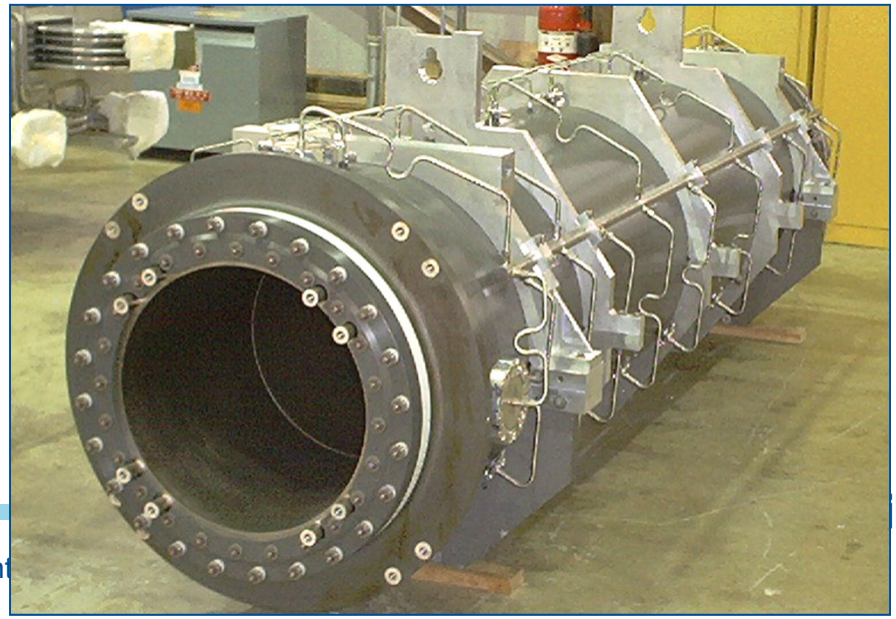




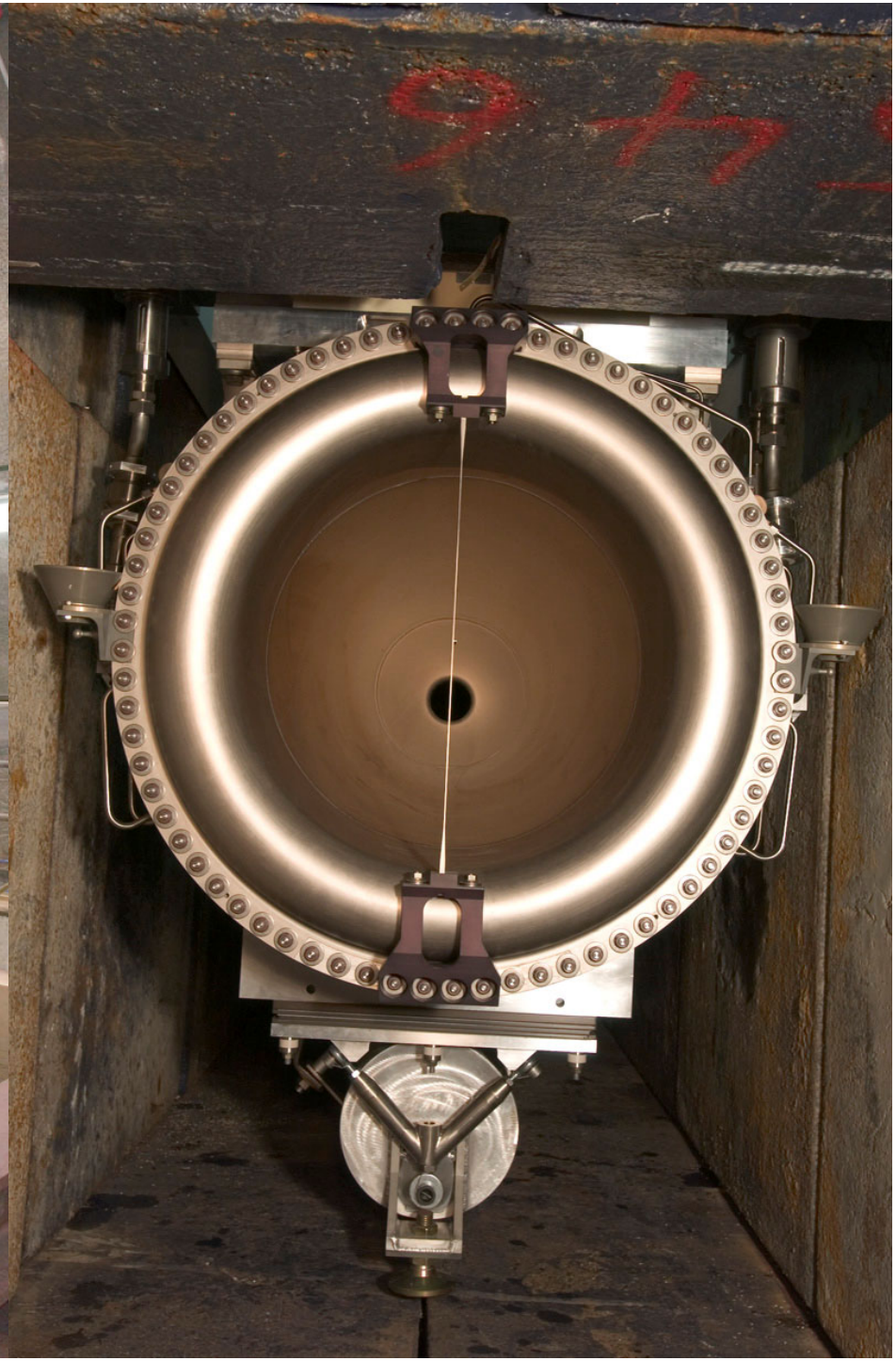
Horn Production

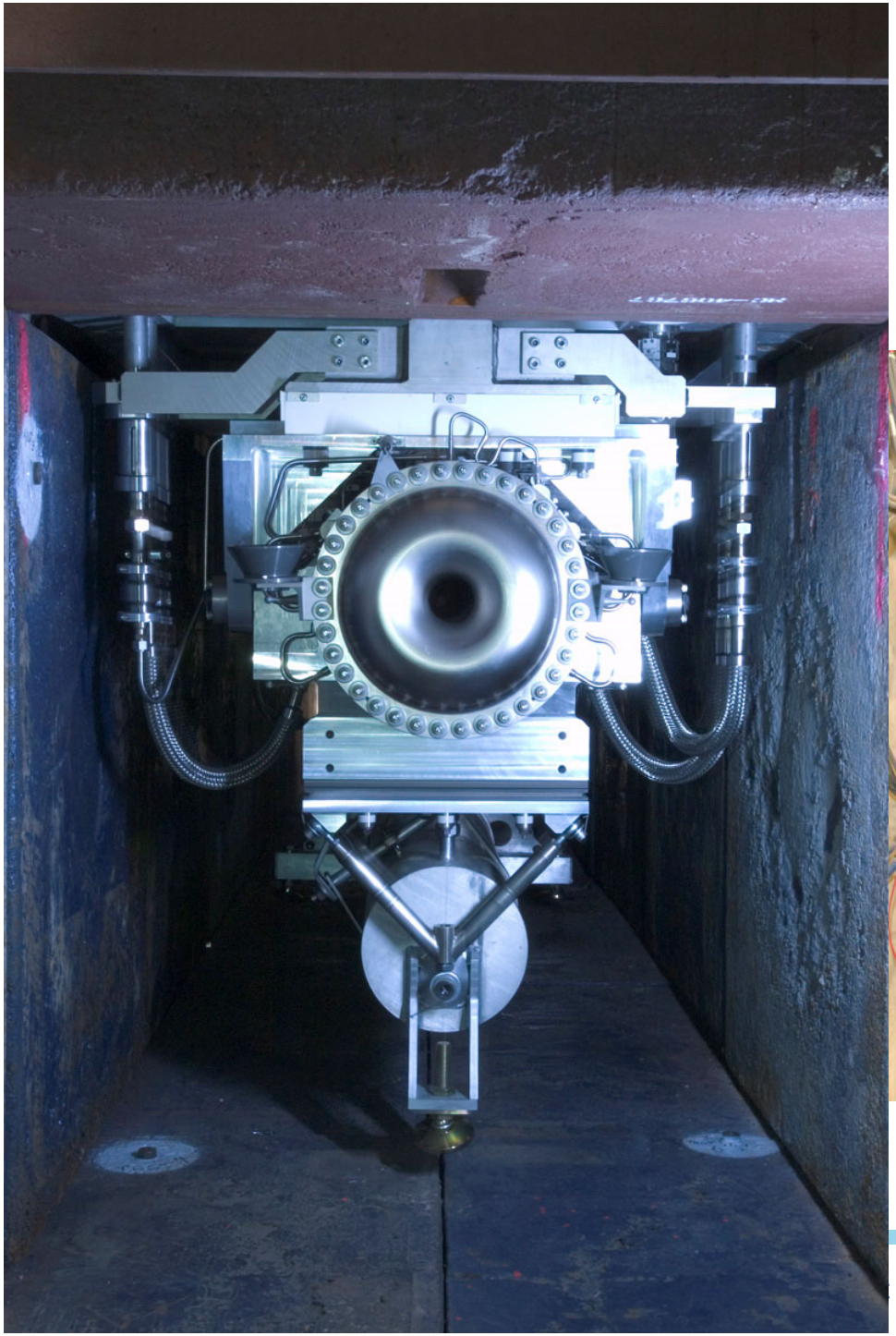




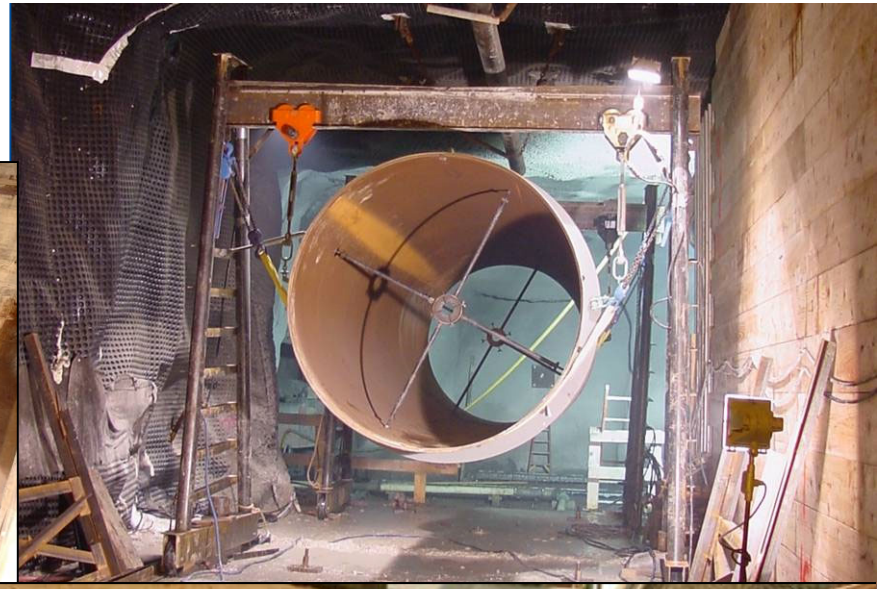


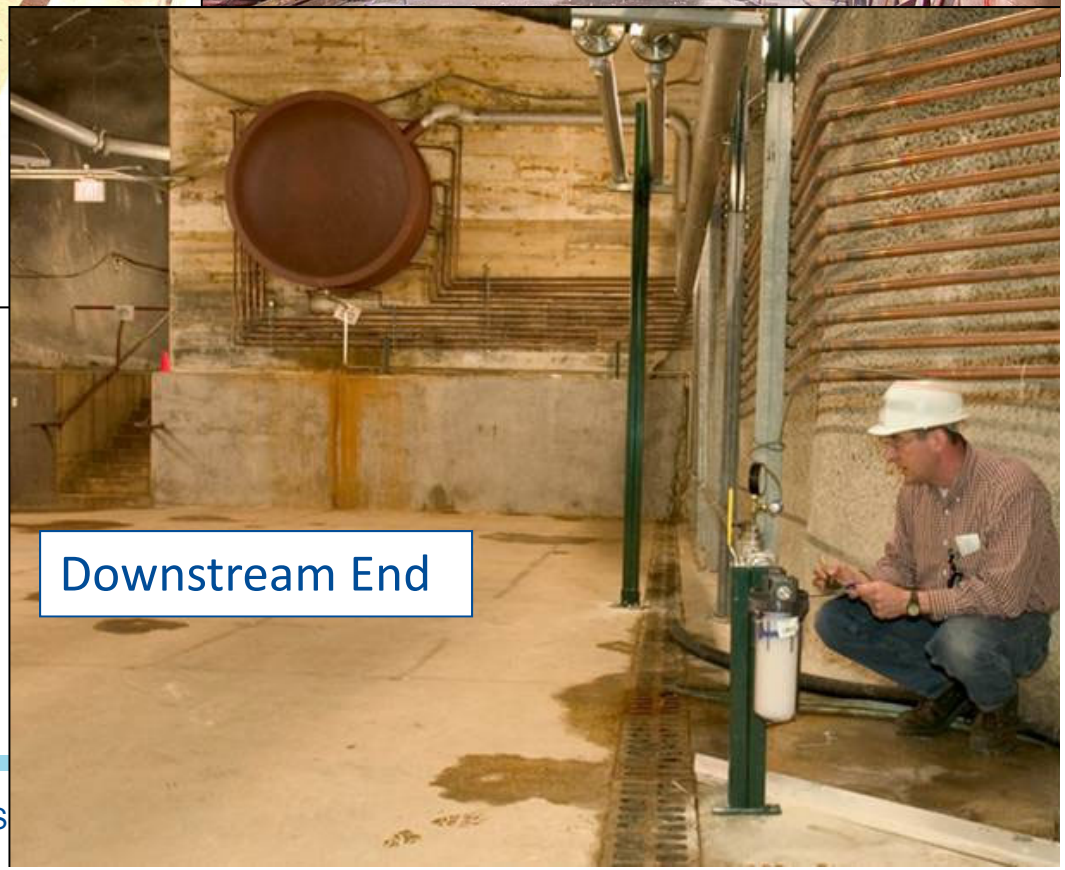
KCI





Meson Decay Tunnel





- Steel decay pipe installed, encased in 6-8 ft. of concrete.
- Decay Pipe evacuated to 1.5Torr (May 2004).
- Filled with helium a few years later
- Water cooling system for decay pipe operational.

10TONMAX

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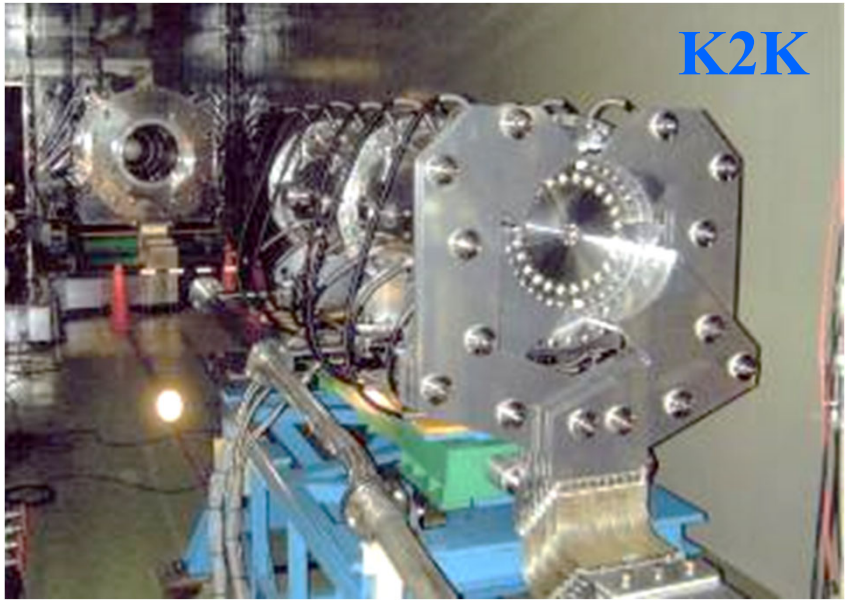
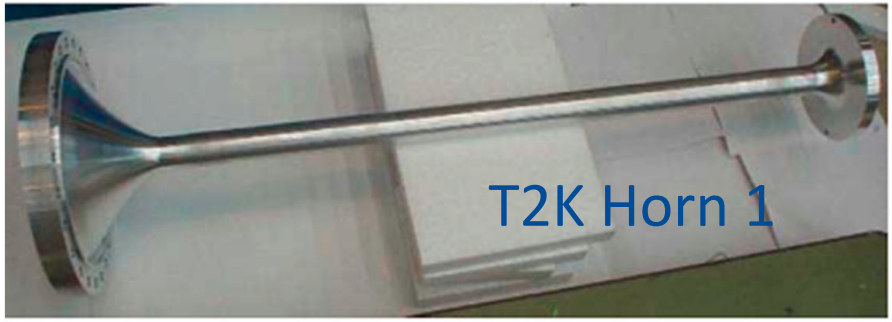
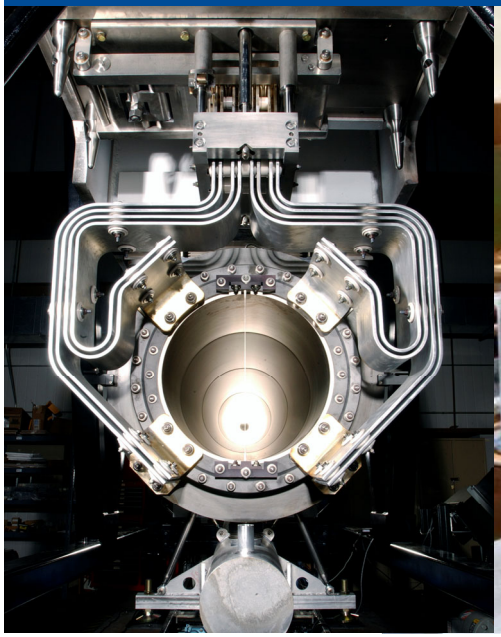
Other Horns







How to Make a Neutrino Beam

Bob Zwaska
Fermilab Ask-a-Scientist
2 June 2019