Status and Future of high-power Neutrino Target Stations

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Fermilab

Looking at my last talk at NuFACT, 9 years ago, Target Station issues are same:

Target & horn stress and radiation damage

Tritium release

Containment of other radioisotopes

Cooling & maintainability

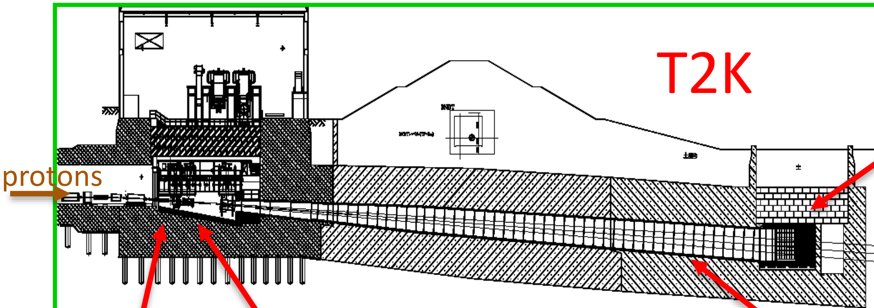
Remote Handling

We now have significant experience from the NuMI and T2K target stations that can help us in planning the next power upgrades

Facilities present and future

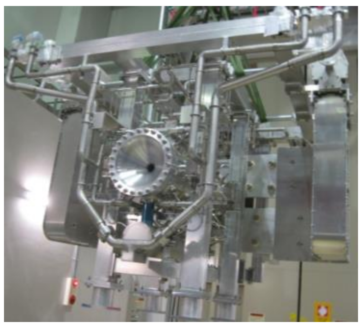
- NuMI (Fermilab)
  - 1^{st} beam ~2005, *designed for **0.4 MW***
  - Upgraded in 2013 for **0.7 MW**; achieved last couple years
  - Planned upgrade over next couple years to **0.9 ~ 1 MW**
- T2K (J-PARC)
  - 1^{st} beam ~2010, *permanent parts designed for **3 ~ 4 MW***
  - Currently **0.5 MW**
  - Planned upgrade over next few years to **0.75 MW**
  - Has longer term detailed plans for **1.3 MW**
- LBNF (Fermilab) <- at stage where significant design decisions being made
  - Has stage 1 approval, scheduled for **1.2 MW** by ~2026
  - *Permanent parts designed for **2.4 MW***
- ESSνSB(European Spallation Source)
  - **5 MW**, proposed to be built after ESS is completed 2023

How neutrino beam is made
& generic Neutrino Target Station components

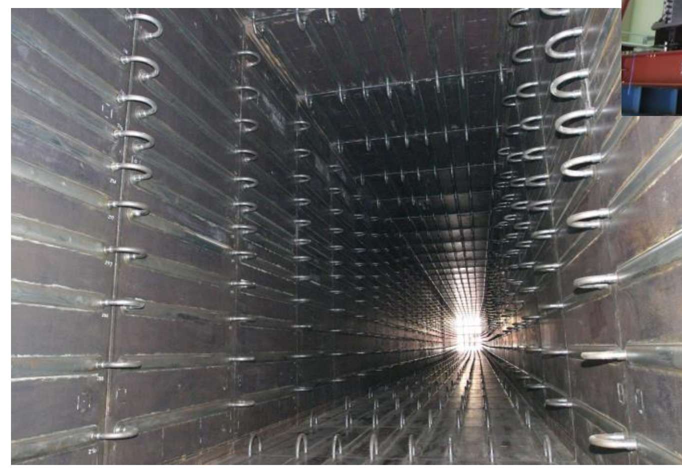


Beam dump / absorber
for leftovers

Target
produces π
from proton

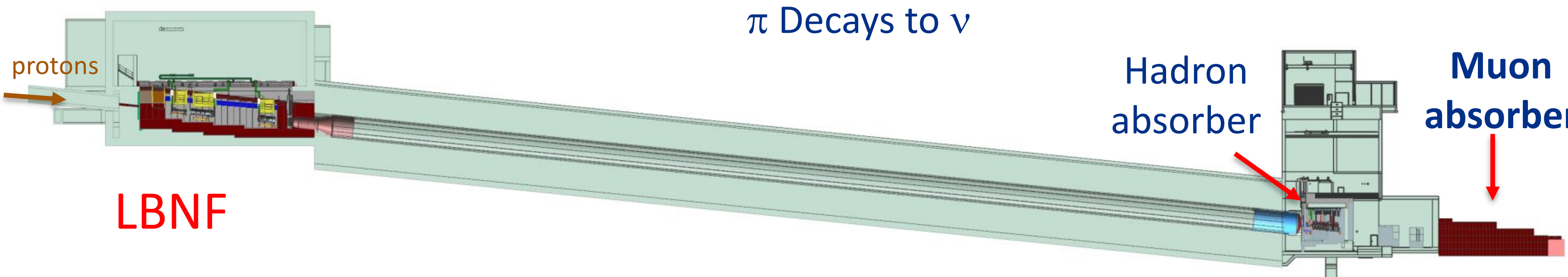


Magnetic horns
focus/defocus $\pi^{+/-}$



Drift space
π Decays to ν

Lots of
radiation
shielding
everywhere



Hadron
absorber

**Muon
absorber**

Recent good operation and uptime, T2K and NuMI

- NUMI has integrated 3.8 x10^{21} POT at 120 GeV

  2.3 MW-years of proton beam power *(real-365 day years of MW)*

  but of course it has taken us over a decade to do that

- T2K has integrated 3.1 x10^{21} POT   at 30 GeV

  0.5 MW-years of proton beam power

NuMI had a string of target water-leaks early on; T2K had an earthquake

but

In recent years both have had targets and horns last several years each

and pretty good uptime in general

We are decently up the learning curve.

NuMI planned upgrade

Proton beam to target station

- Shorten repetition cycle from 1.33 s to 1.20 s; rest from increased POT/spill
- 700 kW -> 900 kW in fall 2020? Dependent on funding.

Target station upgrades needed for 1 MW

- 20% wider target for larger beam spot size
- Upgrade pre-target beam window (this summer)
- Add another water heat-exchange coil to target pile air cooling circuit
- Address horn strip-line heating (different Al grade, better air-flow)
- Increase cooling capacity for horn RAW skids
- Add to RAW room shielding to prevent
  loss of beam-on access to power supply room

Significant design work has been done and continues on all of these items

Target station upgrades to address aging infrastructure

- Design decay pipe window remote repair mechanism
- Replace target & horn module positioning mechanisms

T2K planned upgrade

Proton beam to target station:

- Shorten repetition cycle from 2.48 s to 1.32 s; 750 kW in 2022
- Gradually increase POT/spill, shorten cycle to 1.16 s; reach 1.3 MW in 2028

Target station upgrades needed for 750 kW

- Replace horn power supply for faster repetition rate
- Increase Tritiated water disposal capacity

Significant design work has been done and continues on all of these items

Further target station upgrades for 1.3 MW

- Primary beam window cooling capacity
- Increase cooling of strip-line to horn
- Increase helium cooling flow to target
- Improve hydrogen removal from horn cooling circuit
- Expand capacity of heat exchange systems for horn & helium vessel & beam dump
- Increase shielding above target pile

LBNF design basis outline

Will discuss:

1) Target

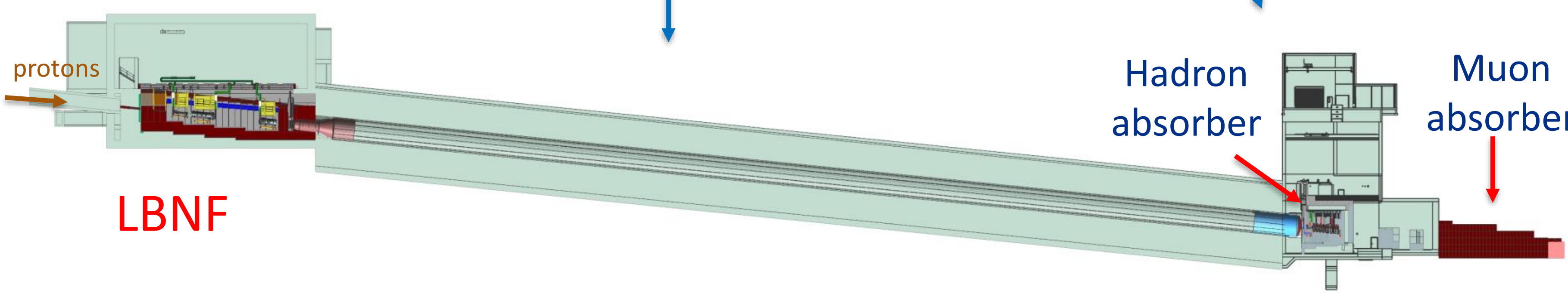
2) Horns

3) Power & Radiation

4) Target Hall

5) Decay Region

6) Absorber region

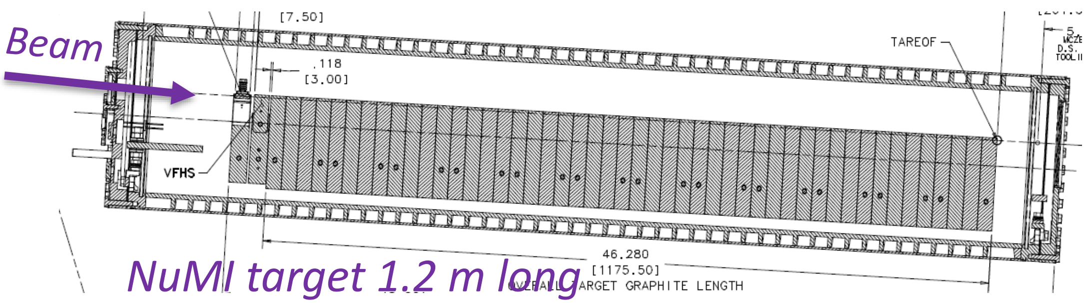


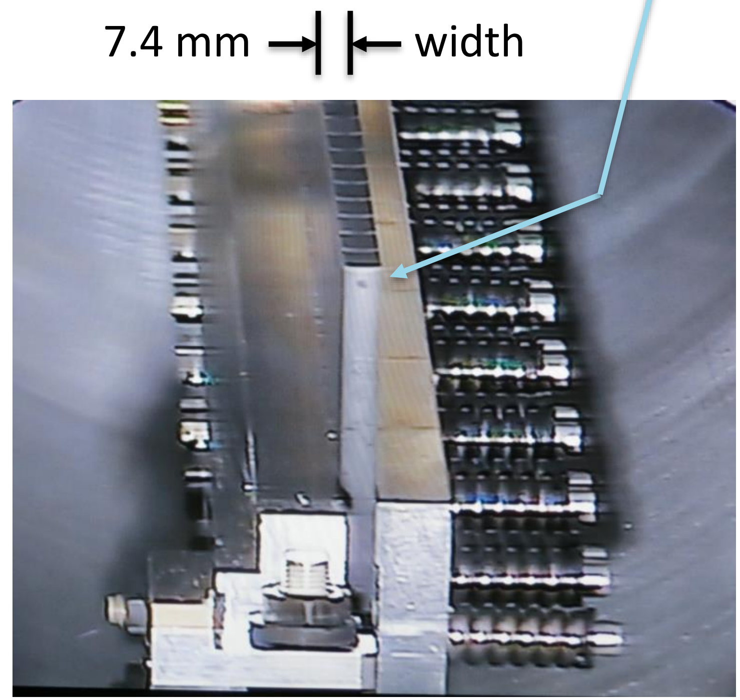
Target Radiation Damage Tested at NuMI actually looks OK

NuMI graphite target MET-01 took 1.1 x10^{21} Protons-On-Target

- As many POT as planned per year for LBNF at 1.2 MW
  in 1.2 mm RMS spot size (smaller than planned for LBNF)
- Autopsy this spring saw no visible graphite deterioration
  (Target was removed due to gas leak at window)

Spot from left-over protons exiting target

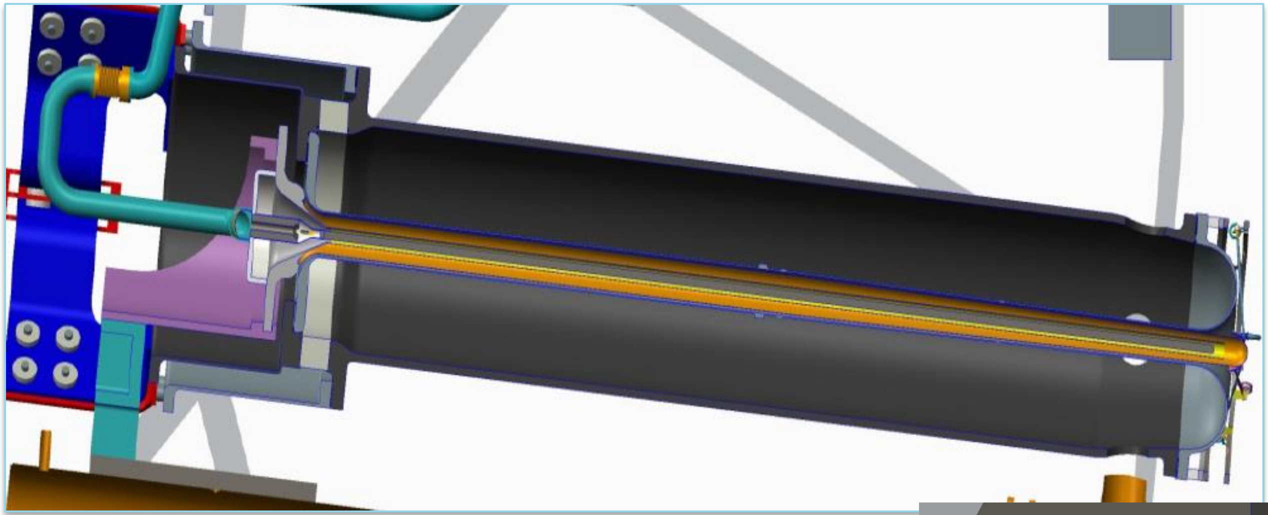




- *Good lifetime may be due to:*
  – Use of small grain isotropic graphite
  – Running at higher temperatures,
    where radiation damage will anneal

LBNF Target – RAL design based on proven T2K target

(MET-01 would not fit in horn)



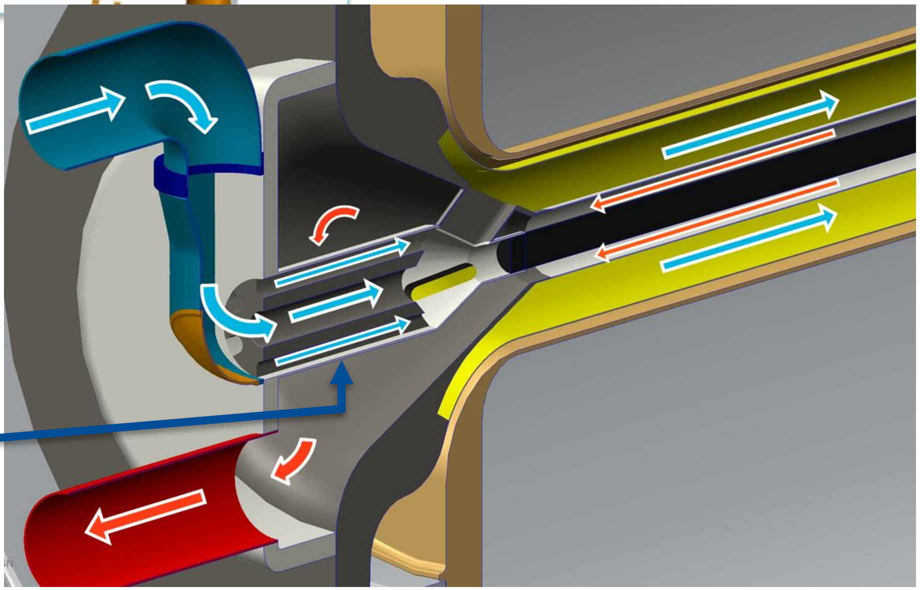
(see Chris Densham talk on JPARC target upgrade)

1.2 MW target

Graphite cylinder, helium cooled
16 mm diam.
~ 2 m long

Fully inserted into horn

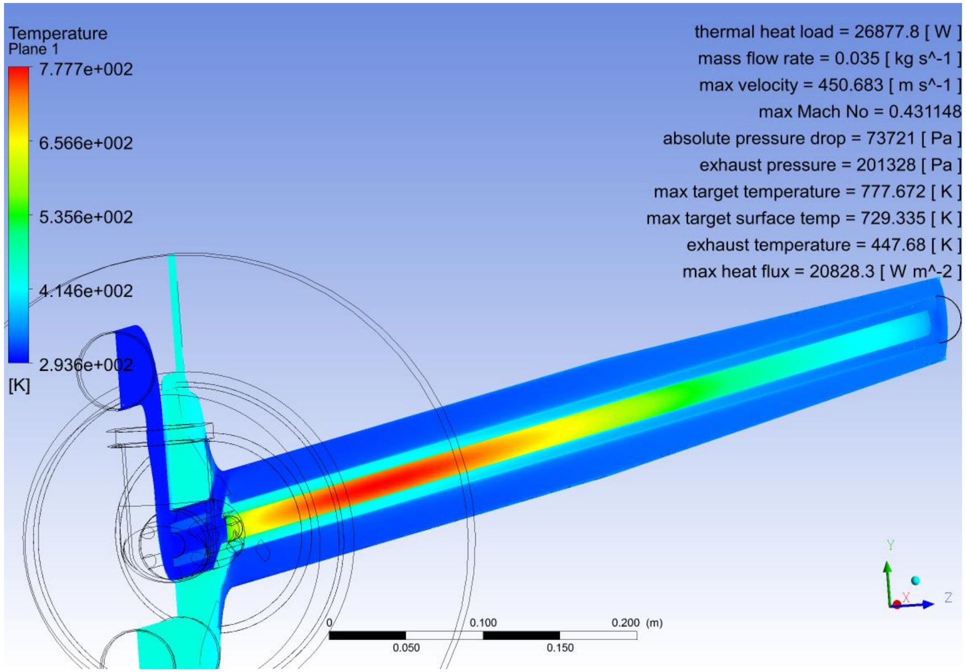
Includes upstream "bafflette" to prevent beam from damaging downstream components

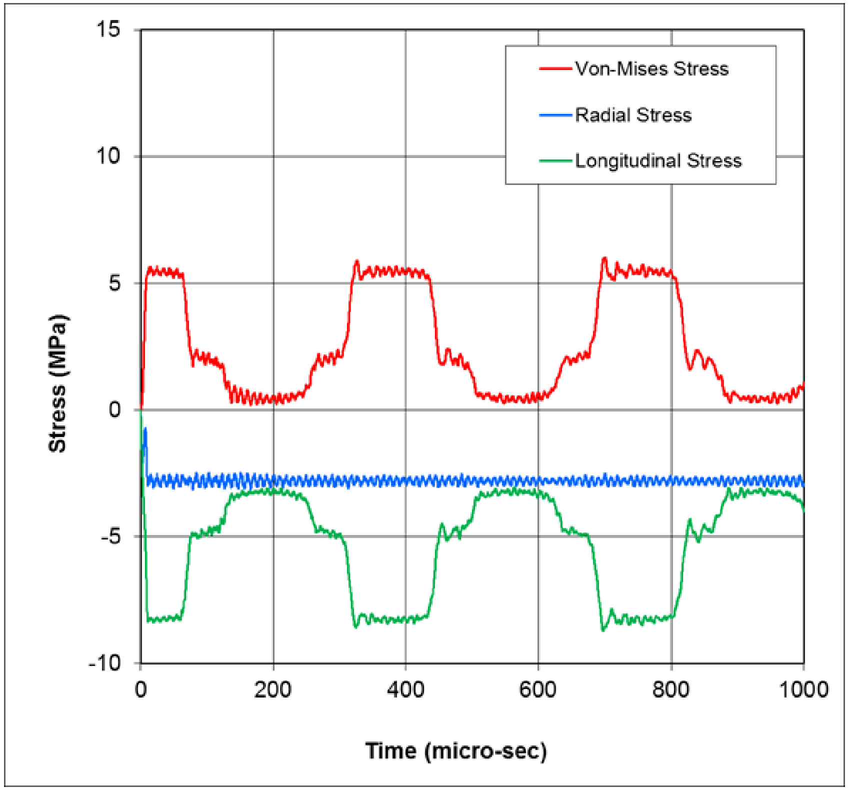


First pass Thermal and Stress analyses look good

LBNF 1.2 MW target

Max. temperature 777.7 K





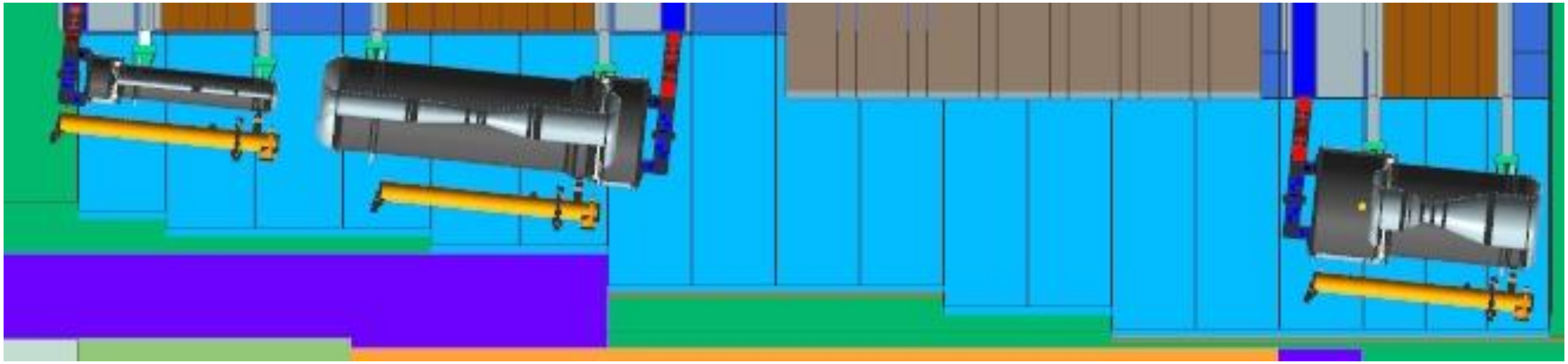
IG43 fatigue endurance limit ~ 18 MPa

Fermilab

LBNF optimized horns

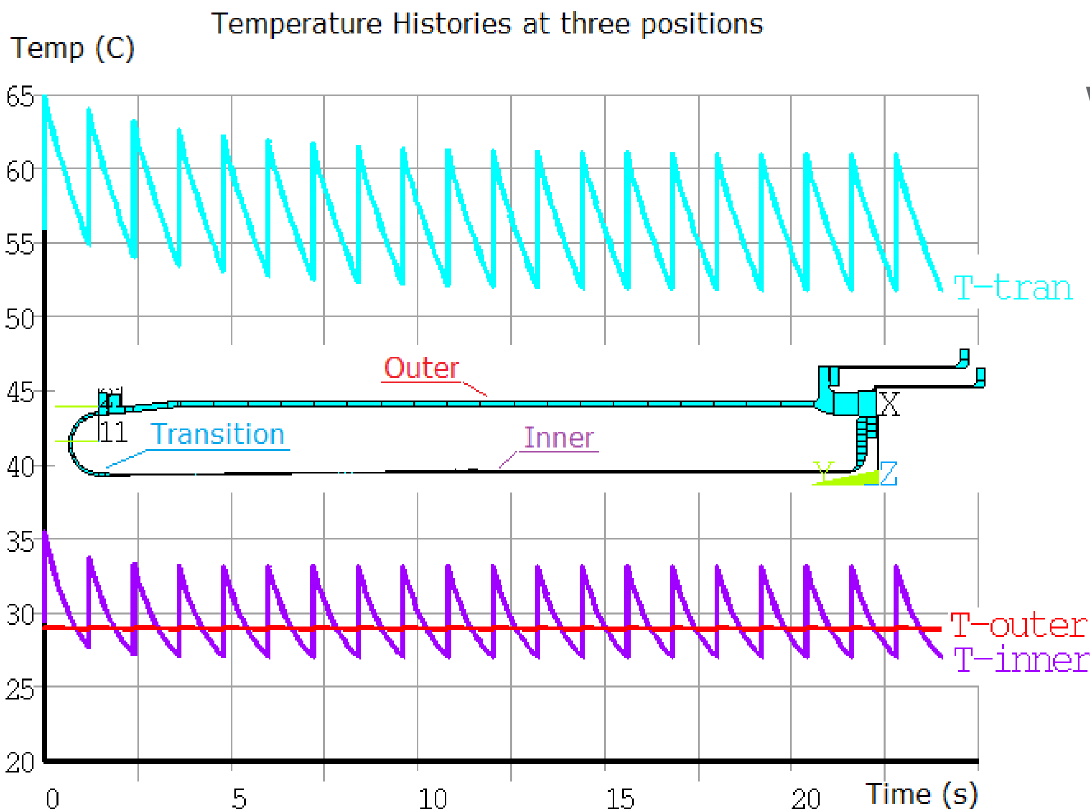
After several years of optimization studies, last fall LBNF adopted what we call the "optimized" configuration of target and horns.

Three horns, with target fully inserted in the first horn.
Rather similar to T2K.



Mary Bishai will discuss optimization and the neutrino spectrum in her talk on LBNF Beamline this afternoon.

Have completed conceptual design of LBNF optimized horns



FEA of Horn A
which has highest current density
and beam heating

Temperature and
Stress looks OK

Lowest fatigue safety factor
at any point is 2.18

Similar to NuMI horn

Maximum equivalent stress (MPa)	Normal operation	Cold start 2nd pulse	Cold start 7th pulse	Stop-n-go	Beam heating only	joule heating only
Before pulse	13.5	5.86	6.71	15.7	13.4	8.72
After pulse	14.6	21.5	22.1	19.0	19.2	5.18
After/mag load	29.7	31.0	34.8	24.9	NA	28.1
Before/mag load	29.1	27.7	26.3	32.9	NA	

Energy & radiation deposition

- Much of work for design of high power neutrino beam is radiation and rad safety
  - Prompt, air-borne, ground-water, residual, remote handling, radiation damage, …

Let's start by looking at where the beam power ends up.

System	Power (kW)
Target Pile	1238
Decay Pipe Region	542
Hadron Absorber	400
Infrastructure, binding energy, sub-threshold	151
Neutrino power	69
Total	**2400**

For 2.4 MW proton beam power

kW deposited in region

~ 10^{-13} watt deposited in far detector !

from MARS Monte Carlo for LBNF

Radiation challenges

(Just a partial list)

- *Destroys almost anything except metals and ceramics*
- *Leaves residual radiation so you can't go in to fix things*

- High energy radiation in target station

+ water	➡	H_2 & O_2	explosive gas
+ water	➡	H_2O_2	(rocket propellant ?)
+ humid air	➡	Nitric Acid	embrittles steel
+ air	➡	Ozone	corrodes
+ air	➡	^{41}Ar	air borne radioisotope
+ air (or N2)	➡	^{11}C	air borne radioisotope
+ anything	➡	Tritium	very mobile radioisotope

Toward more robust target stations

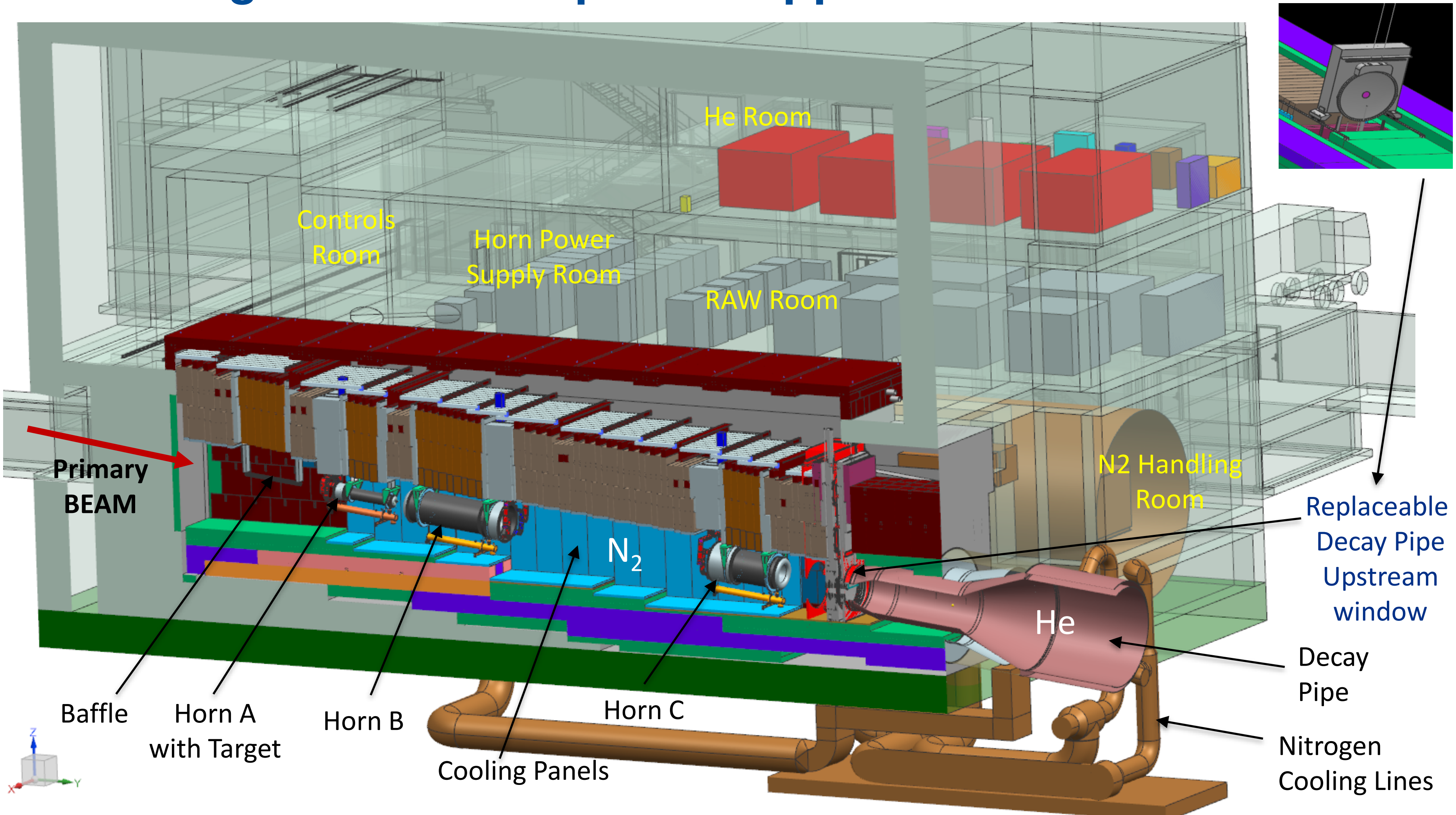
- NuMI was designed for **6 year** experiment; civil was specified for **10 years**.
  (Although it has operated for 13 years, and will probably go half that again)

- Limited budget & expected lifetime, NuMI was built with 3 long term vulnerabilities:
  - Inaccessible Decay Pipe water cooling (5 miles long)
  - Inaccessible water cooled Absorber (with some redundancy)
  - Inaccessible thin Decay Pipe upstream window (1/16” aluminum)

- LBNF is being designed for **20 years** of experiment & **30 years** civil.

- LBNF addresses above vulnerabilities as follows:
  - Decay Pipe cooling uses inert (nitrogen) gas cooling; no water or oxygen
  - Absorber core is repairable/replaceable; no unreachable water lines
  - Thin Decay Pipe upstream window replaceable with remote handling designed

LBNF target hall shield pile & support rooms

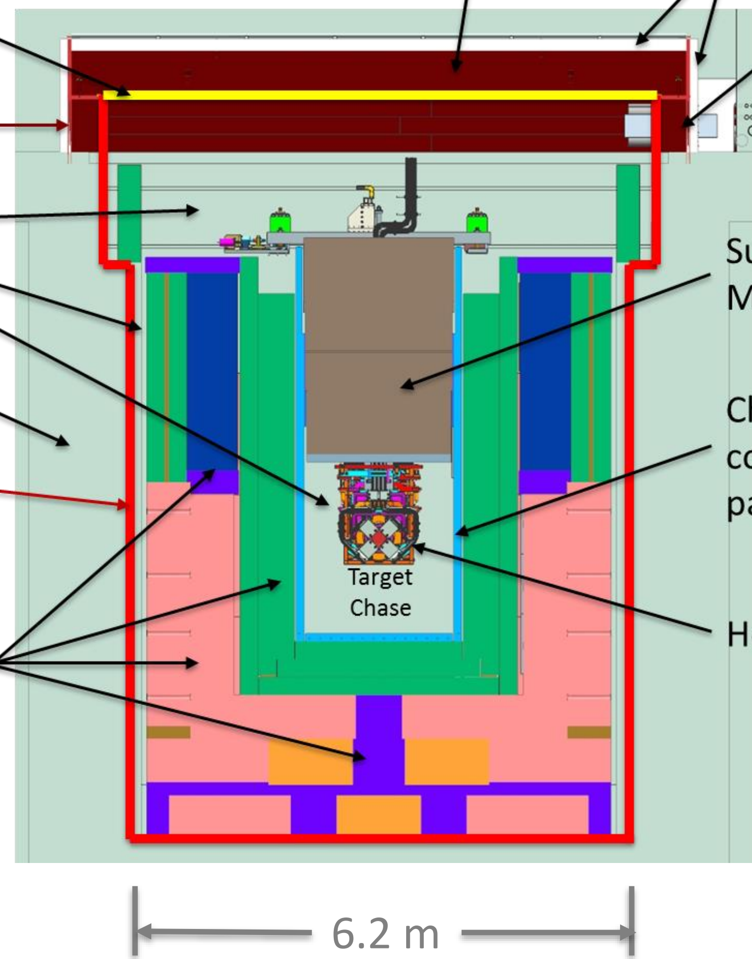


Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (replaceable cooling panels).

Target pile design choices

Replaceable water cooling panels are used for innermost steel layer

Bulk shielding is cooled by 35,000 ft³/minute flow of N_2 gas



<u>Lessons learned being applied:</u>

- Concrete is all outside the N_2 vessel
- Vessel includes all gas in high radiation (containing short-lived air-activation)
- Steel (emitting tritium) is all in vessel
- Continuously purge tritium by slow N_2 release (1 to 7 cfm)

N2 gas in LBNF target/horn vessel

NuMI successfully operates target/horn in air at 700 kW.

109 min. half-life

As power goes up, **the production/release of ^{41}Ar** from 1% Ar in air becomes more problematic, would need more cooldown containment time before release.

- Eliminate Ar from target vessel (N_2 cheapest way to do that)

As power goes up, release of **tritium** from shielding becomes more problematic if you store (seal) it all up during running.

12 yr. half-life

It gets to level where workers cannot access to do repairs.

- Do continuous purge/release of Tritium during running, as NuMI does (N_2 cheap enough to do that)

Although manageable, **corrosion** is better controlled without O_2 and H_2O

- Dry N_2 does that (although, like NuMI & T2K, LBNF should plan to operate for periods with water leaks in vessel, hence significant humidity)

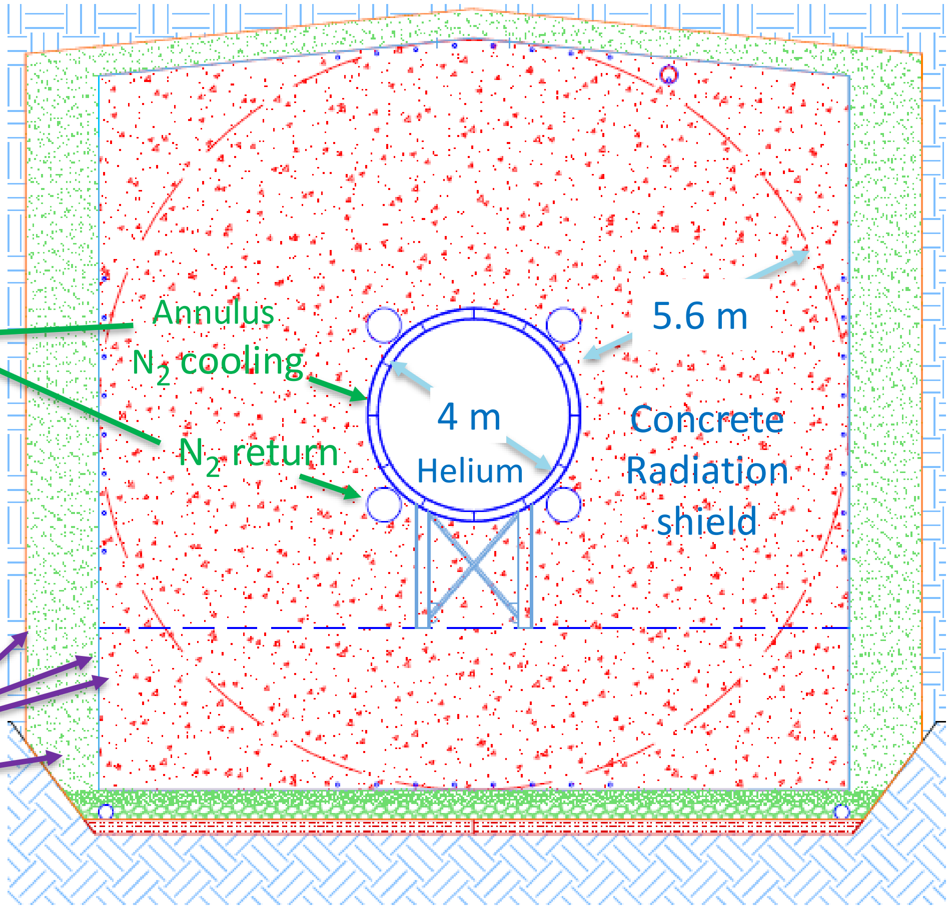
- Significant gas cooling is much cheaper/easier with N_2 than e.g. helium
- Change-over from air (for access) to N_2 (for running) is pretty easy
- Leaky seals not as problematic

20 min. half-life

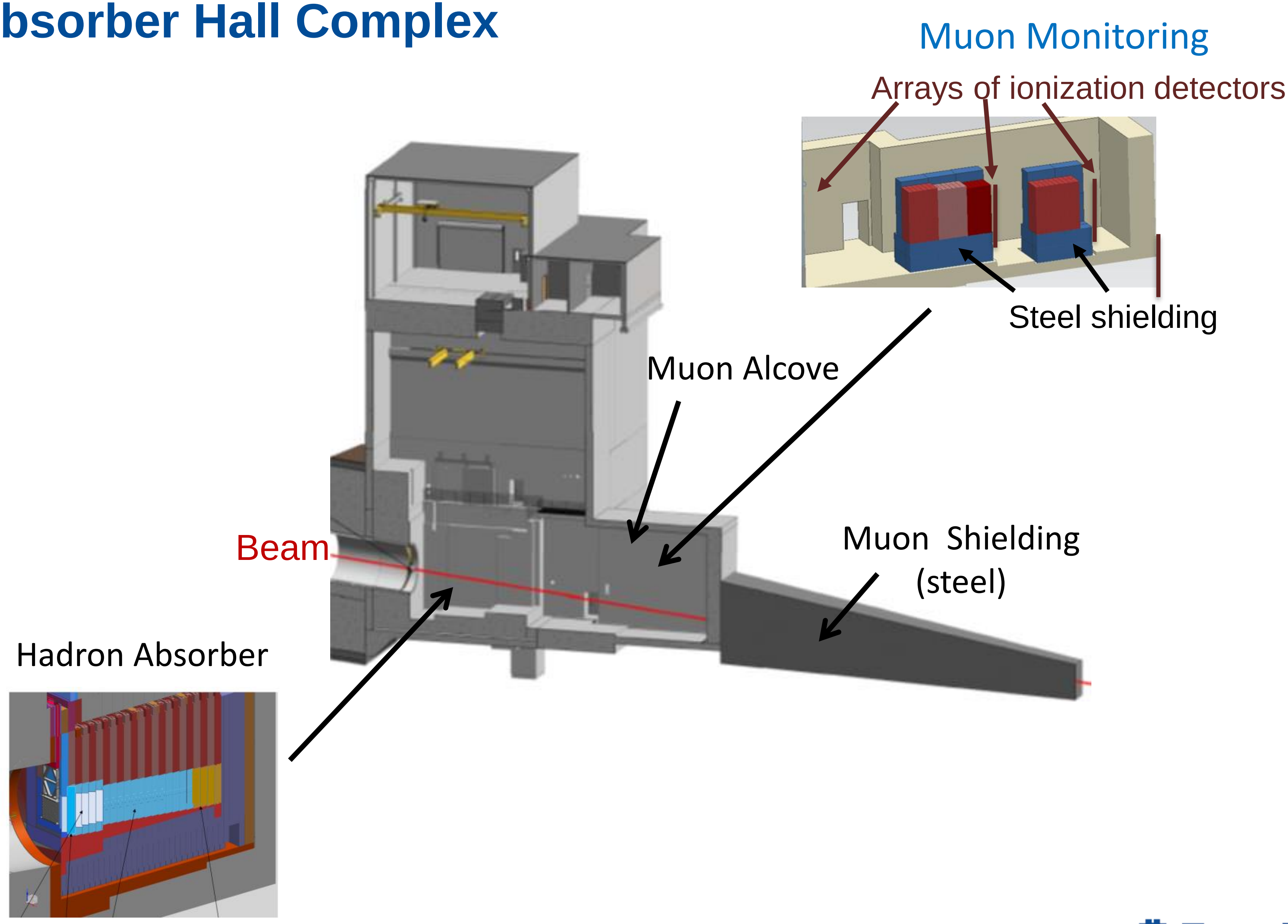
Sill don't want too much gas leakage because still produce ^{11}C from N_2.

Decay pipe region

- Two concentric steel pipes
  4 m diam., 194 m long
- Static helium fill
  10% more ν compared to air fill
- Cooled by flowing 35,000 ft^3/minute of nitrogen gas
- Structure dominated by concrete radiation shield
  5.6 m thick
- Multiple features to keep water out

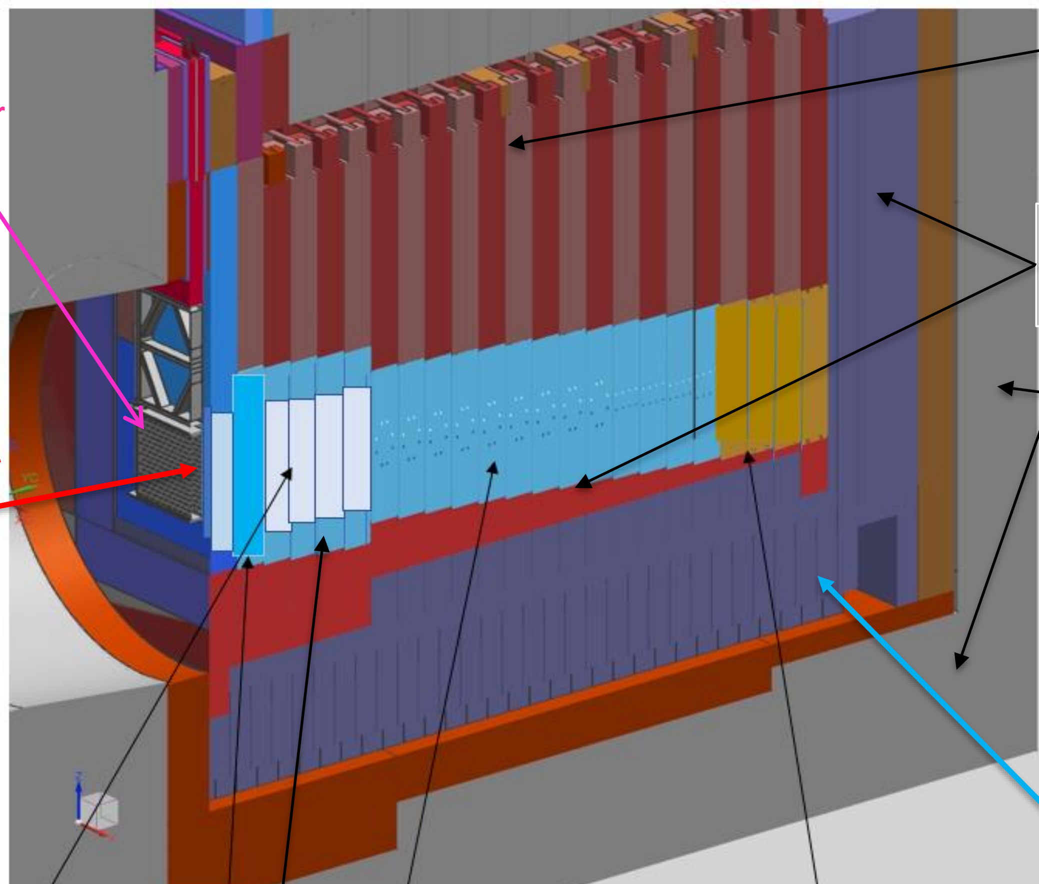


Absorber Hall Complex

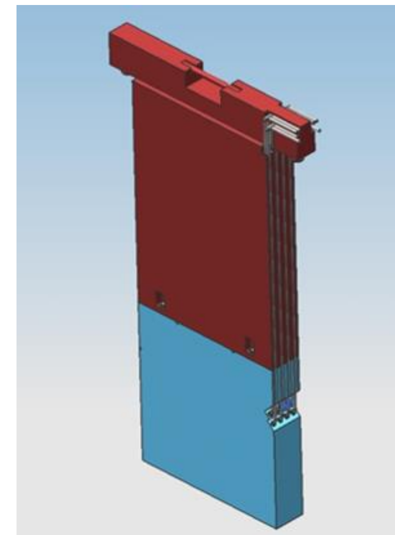


LBNF Hadron Absorber

Large diameter core with uniform density to enable good muon monitoring



Flexible, modular hanger design of water cooled core

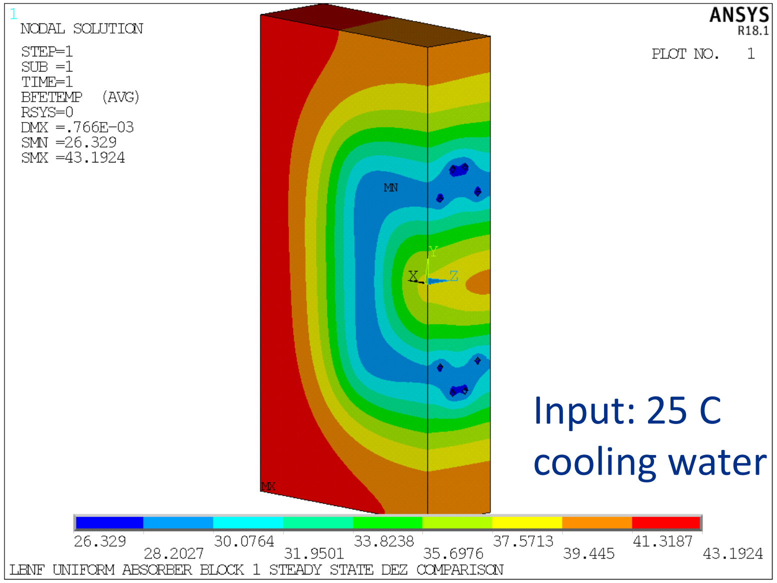


1 ft thick core blocks are easily replaceable via Remote Handling

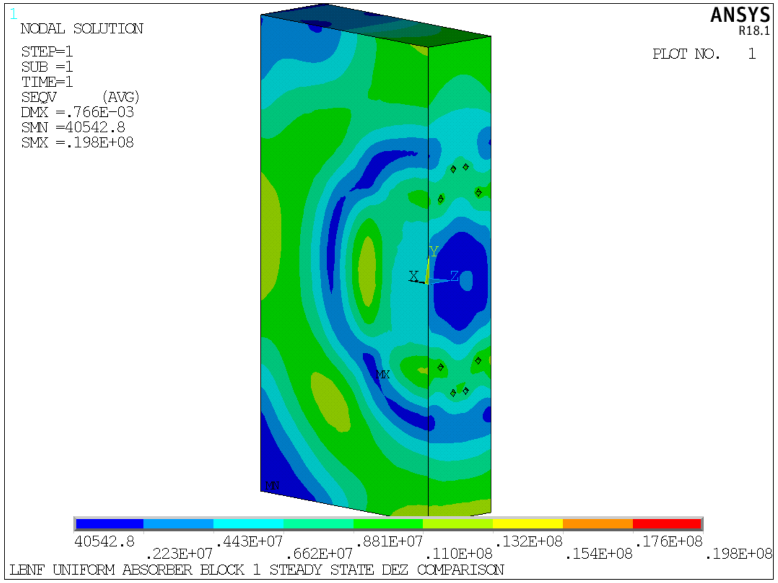
Absorber temperature and stress

Hottest Al **at 2.4 MW**

Temperature – 43 C Max



Stress – 20 MPa Max



1st Al Block after spoiler

Very mild compared to desired criteria of T < 100 C for Al
and stress << than fatigue limit of 165 Mpa

We have also checked that accident scenarios are OK.

NuMI decay pipe upstream aluminum window has already seen as much radiation as the LBNF absorber aluminum will over its 20 year lifetime, and it has not failed.

Thus we have high confidence in this design !

LBNF still has interesting questions to study

- What muon monitoring technology can withstand the radiation environment?
- What hadron monitoring technology can withstand the radiation environment?
- What radio-chemistry and tritium transport do we need to understand to assure Tritium doesn’t trip us up?
- How can we monitor target & horn positions, warping, deterioration during operation?

(you may skip this ad in 15 seconds…)

- LBNF wants and needs international participation

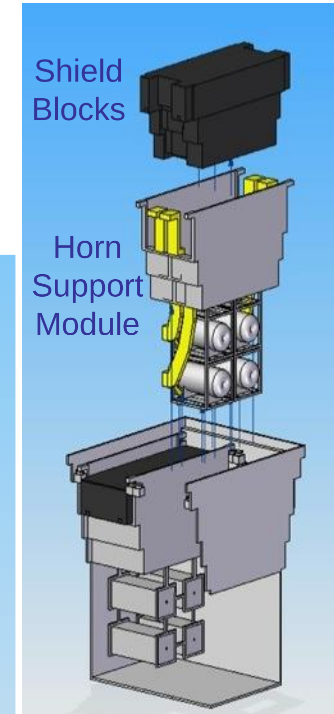
- Designs are solidifying –

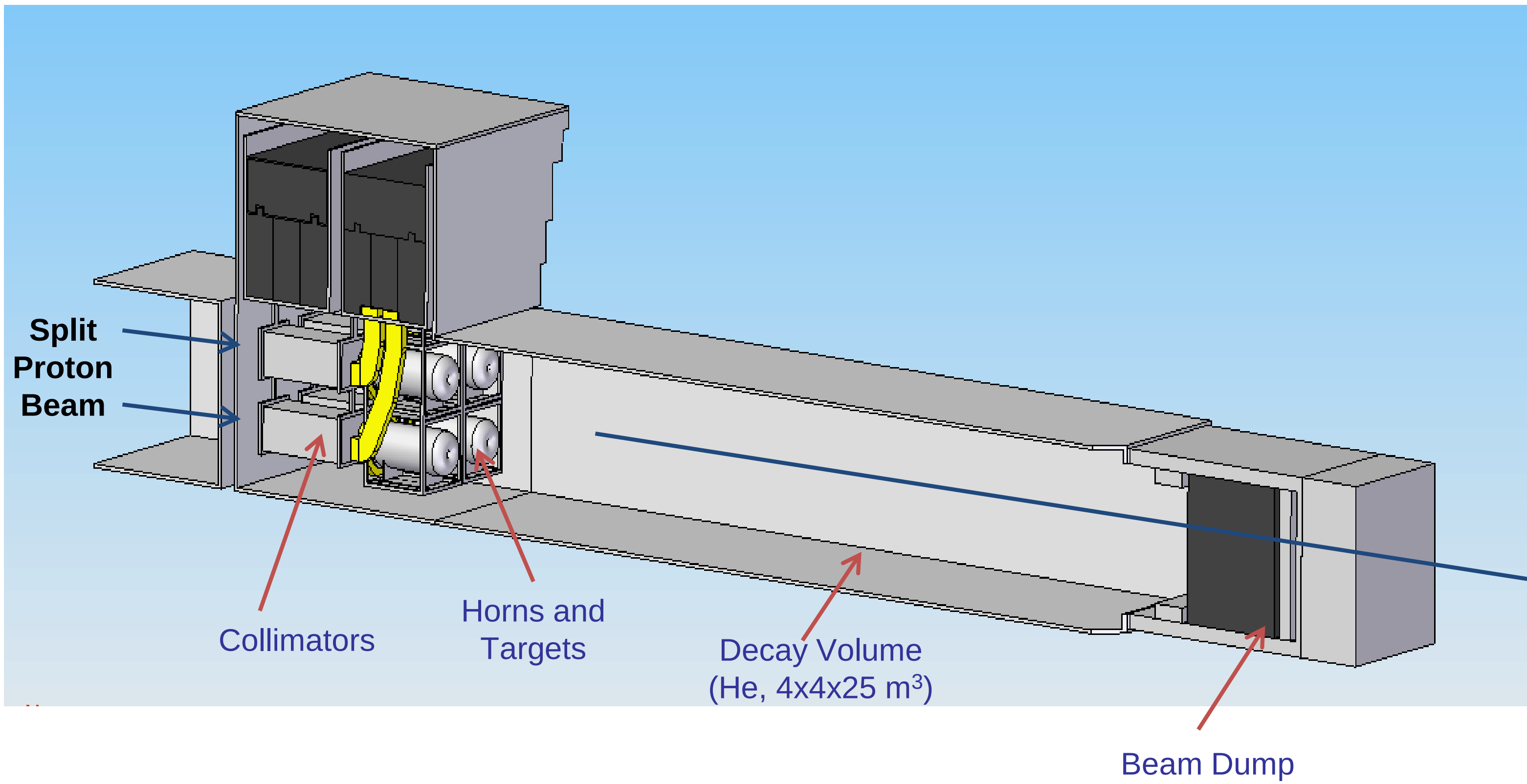
  baseline costs and schedule needed for Fall 2019 D.O.E. CD-2 review

- Now is the time to get involved

- Already for LBNF target station:
  - RAL/UK is taking responsibility for target.
  - KEK/Japan (T2K) people are constructing prototypes of LBNF vessel hatch covers and horn strip-line feed-throughs.

European Spallation Source neutrino Super Beam





European Spallation Source neutrino Super Beam

5 MW 2 GeV proton kinetic energy 2.7e23 POT/year

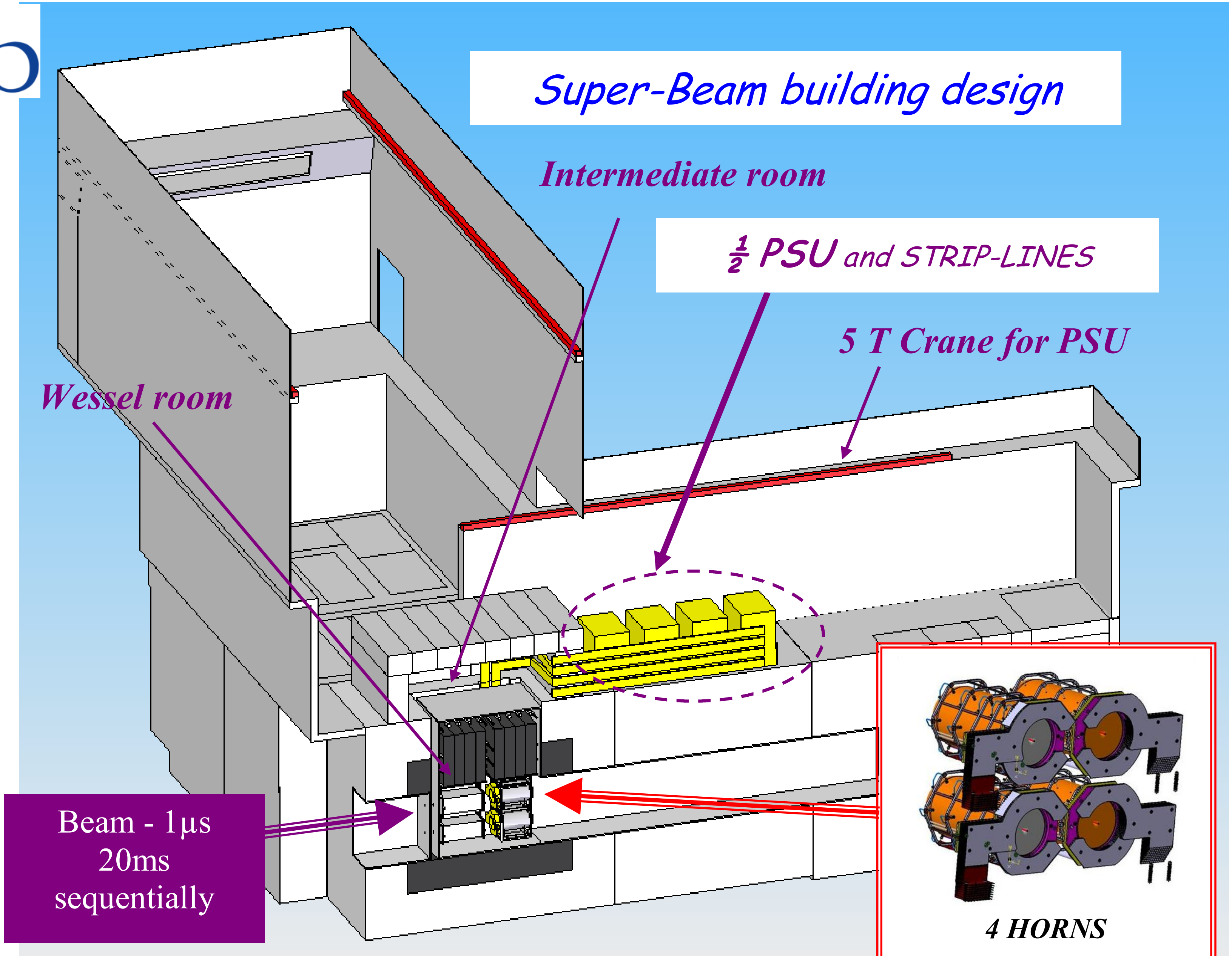
- Target station layout is similar to T2K
  - Horns, decay region, absorber in one sealed helium vessel
  - Steel shielding around target region
  - Thick concrete shielding everywhere
  - Vertical access to hanging horns/target

- Addresses target/horn heating/stress problem by running four beams in parallel
  - Power per target/horn system is thus similar to next generation T2K, LBNF
  - One-horn focusing, similar to Fermilab Booster Neutrino Beam (BNB)

- Low energy neutrinos; decay region much shorter than other target stations

MANY more interesting details in Marcos Dracos ESSνSB talks Mon. & Thur.

Super-Beam building design



Out of time…

There are other lessons learned, like

- Underdrainage systems need to be designed with maintainability in mind
  - Think of this as a technical system rather than just civil ?

Did not even mention

- Setting and maintaining alignment
- Monitoring
- Horn issues like inner conductor erosion, ionization currents
- Remote handling

Conclusion:

Exciting times for target station aficionados !

lots going on…