Survey of Target Facility Landscape: Neutrino Beam Facilities

5th High Power Targetry Workshop
Jim Hylen / Fermilab
May 20, 2014

Operating Conventional Neutrino Beams
- BNB (FNAL)
- T2K (JPARC) – beam power being upgraded 750 kW ~2017
- NUMI (FNAL) – beam power being upgraded 700 kW end of 2015

Proposed Conventional Neutrino Beams
- LBNE (FNAL) – 2023/2024 - has DOE CD-1 approval
- CENF
- LBNO LAGUNA CN2PY
- ESSnuSB

Proposed not-so-conventional Neutrino Beams
- IsoDAR & DAEδALUS – cyclotron, decay at rest
- NUSTORM – neutrions from muon decay rather than pion decay
- Beta beams (neutrinos from decay of accelerated isotopes)

- What beam parameters are neutrino targets facing ?
- What is current experience ?
- What is unique about each of the neutrino facilities ?

Conventional Neutrino Beam Basics

Neutrino beam targets

- Proton interactions produce pions, which decay to produce neutrinos
- Targets are narrow, lower density to let pions get out the sides; not rotating
- Hence small beam spot size
- Targets are long to make up for low density
- Accelerators typically extract a short spill in long cycle, stress waves during pulse
- Typically ~ 1% to 3% of beam power deposited in target core

Beam focusing

- Pion focusing is done with 1, 2 or 3 magnetic horns just downstream of the target
- Sets neutrino beam energy: Increases ν in a certain energy by ~ 5 – 10 x
- Selects either neutrinos or anti-neutrinos

Neutrino beam facilities

- Long open space downstream of target (50 – 1000 m) to allow space/time for pions to decay to neutrinos
- May use helium or vacuum to reduce loss of pions from interactions and to reduce air activation and corrosive gas

Compare proton beam parameters

	turn-on	E proton beam (GeV)	Beam power (kw)	proton RMS spot size (mm)	Target diameter or width (mm)	Target material	max. POT/spill	cycle time (sec.)	Baseline (km)	slope
Operating			**So far**				**So far**			
BNB	2003	8	*26*	1.5	9.5	Beryllium	5.E+12	0.07	0.5	
NuMI	2005	120	375	1.1	6.4	Graphite	4.30E+13	1.33	735, 810	-5.8%
T2K	2009	30	235	4.2	26.0	Graphite	1.20E+14	2.48	295	
CNGS	*2006*	*400*	*480*	*0.5*	*5.0, 4.0*	Graphite			730	-5.6%
Upgrades			***Design***				***Design***			
NuMI	*2015*	120	700	1.3	7.4	Graphite	4.90E+13	1.33	735, 810	-5.8%
T2K	*2017*	30	750	4.2	26.0	Graphite	2.00E+14	2.48	295	
Proposals										
LBNE	*2024*	80 - 120	1200	1.7	10.0	Graphite	7.50E+13	0.8 - 1.2	1300	-10%
LBNE II		60 - 120	2400	1.5 to 3.0	?	?	1.50E+14	0.6 - 1.2	1300	
CENF		100	200		12	Graphite		6	0.5, 1.6	1.6%
CN2PY		400	750				7.00E+13	6	2300	-18%
CN2PY II (HP-PS)		~ 50	2000				1.90E+14	0.75	2300	-18%
ESSnuSB		2	5000				1.14E+15	0.071	360, 540	

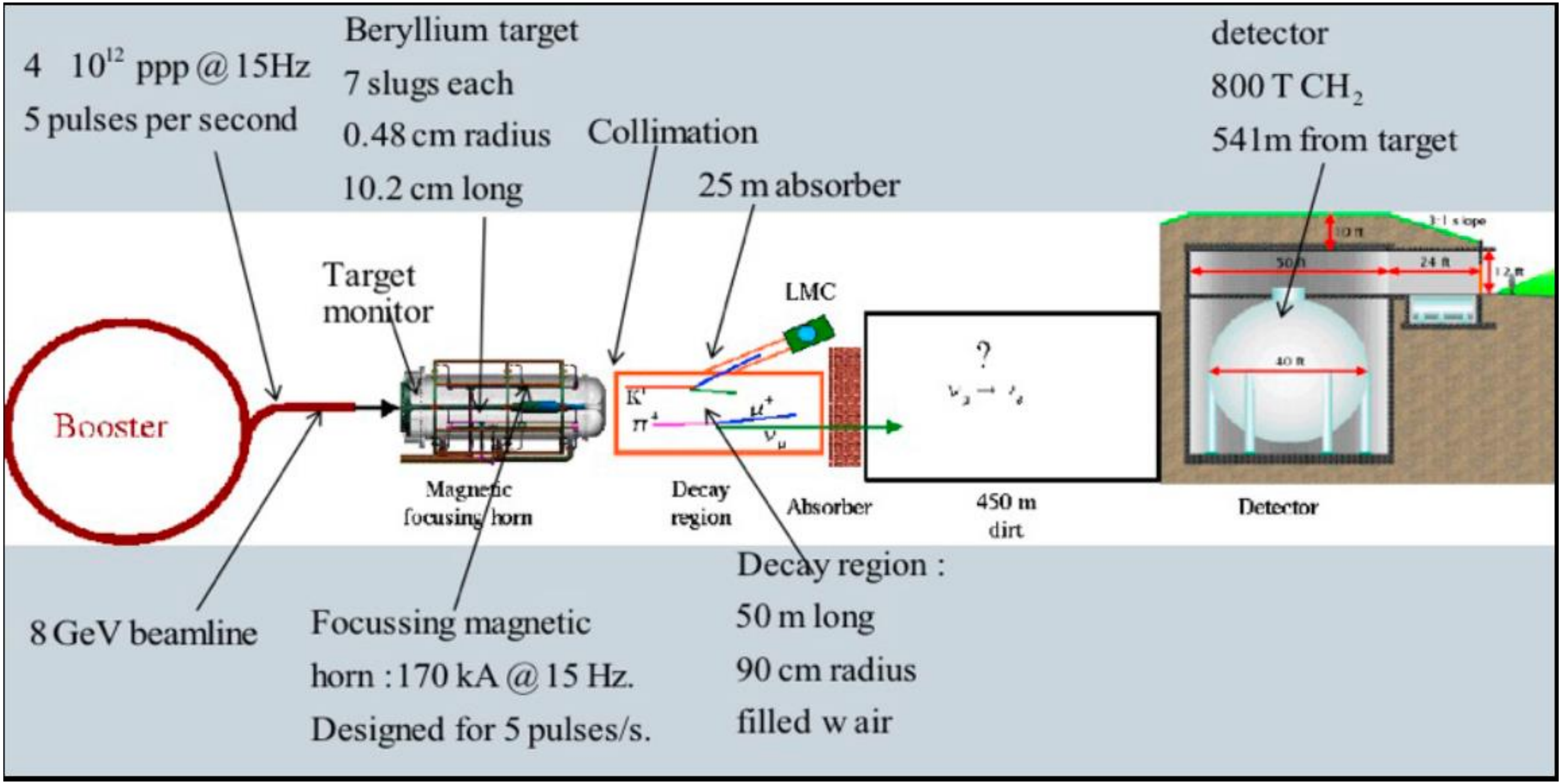
Some history

	turn-on	integrated POT	E proton beam (GeV)	max. power so far (kw)	integrated beam power (MW-yr)	proton RMS beam spot size (mm)	max. POT/spill so far	pulses	Peak integrated POT/mm2 on 1 target
Operating									
BNB	2003	**2.10E+21**	8	*26*	0.09	1.5	5E+12	**4.82E+08**	1E+20
NuMI	2005	1.78E+21	120	375	**1.09**	1.1	4.30E+13	7.01E+07	7.9E+19
T2K	2009	6.63E+20	30	235	0.10	4.2	**1.20E+14**	1.20E+07	6.0E+18
CNGS	*2006*	*1.82E+20*	*400*	***480***	*0.37*	***0.5***			**1.2E+20**

Present FNAL accelerator complex and Neutrino Beam-lines

BNB

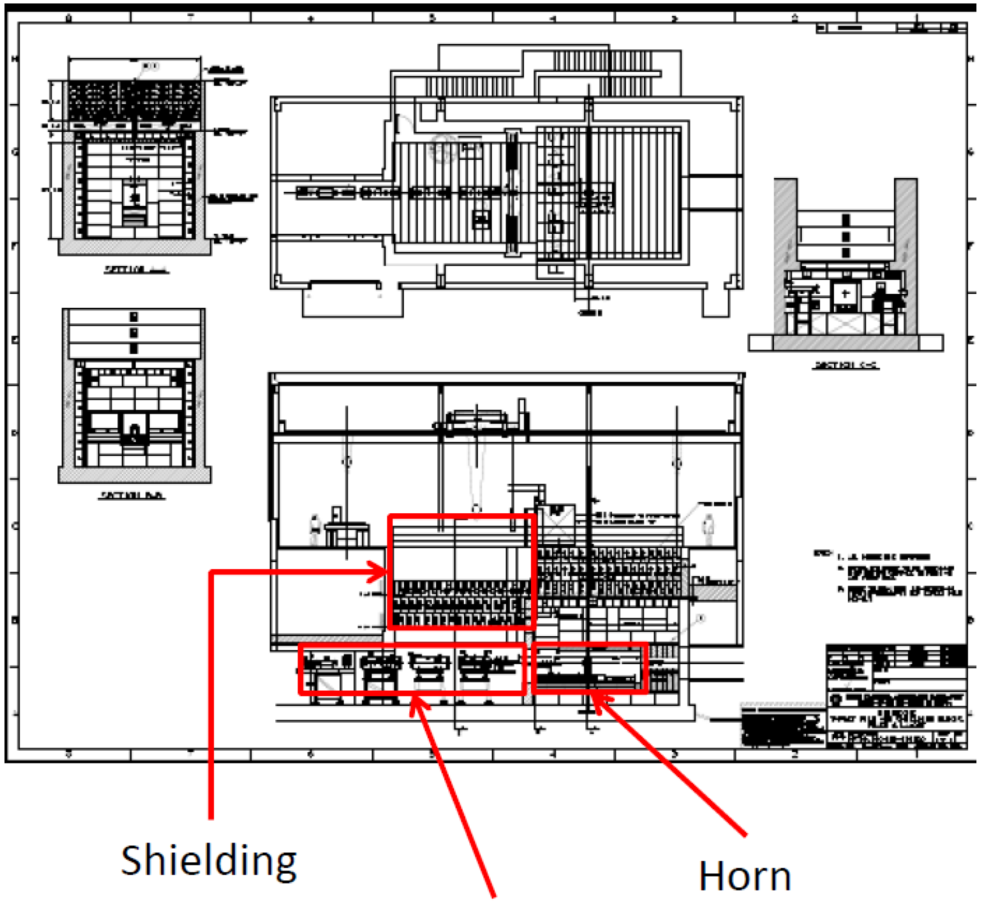
BNB (Booster Neutrino Beam)



BNB – what is unique

- Replacement of Horn/Target is done by pulling old device upstream out of the shielding into a storage cask. **FRONT-LOAD instead of TOP-LOAD**
- Target is beryllium, forced air cooled
- Has ability to cut decay path in half (intermediate movable absorber)
- Currently running a special mode where beam deliberately bypasses target/horn so Interactions are on absorber; looking for low mass weakly interacting particles such as **dark matter, axions, paraphotons**
- Will switch back to neutrino mode when MICROBOONE is ready
- Has been very reliable – nearly half a billion horn pulses (world record)
- but discovered High Strength Steel is bad in radiation area

BNB horn/target change-out (done once)

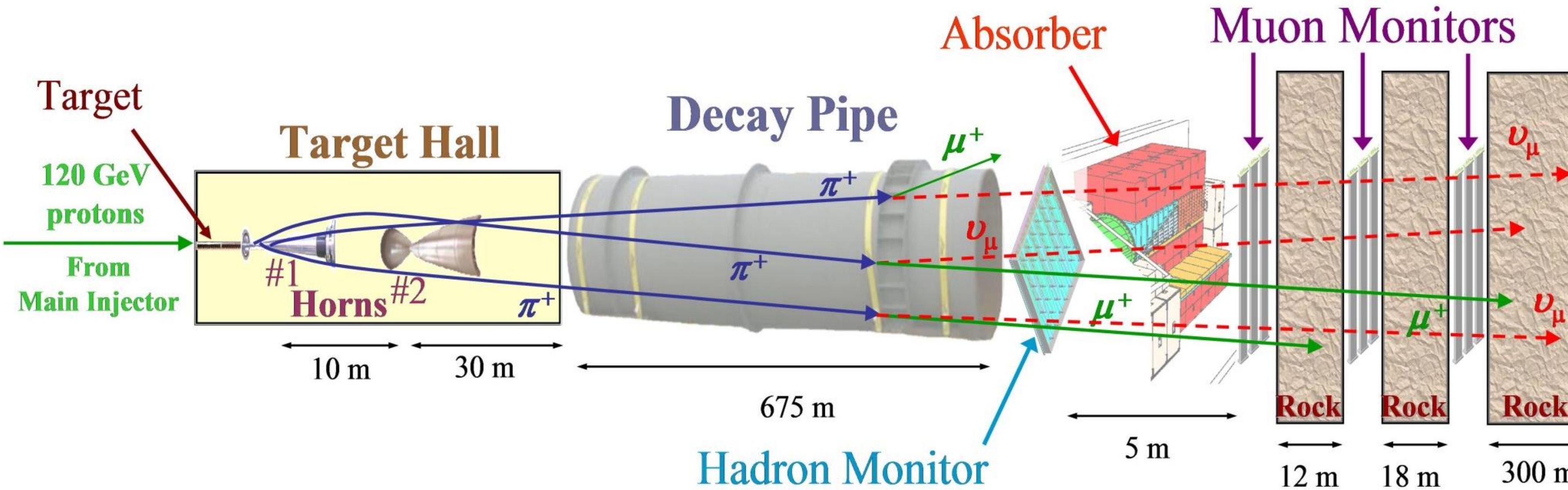


- Target/Horn is buried in a shielding.
- Unstack 6x15 shielding blocks. Blocks needed to be wrapped
- Remove final focus triplet.
- Lower coffin.
- Remove horn.
- Reverse procedure.

Total time: 12 weeks.

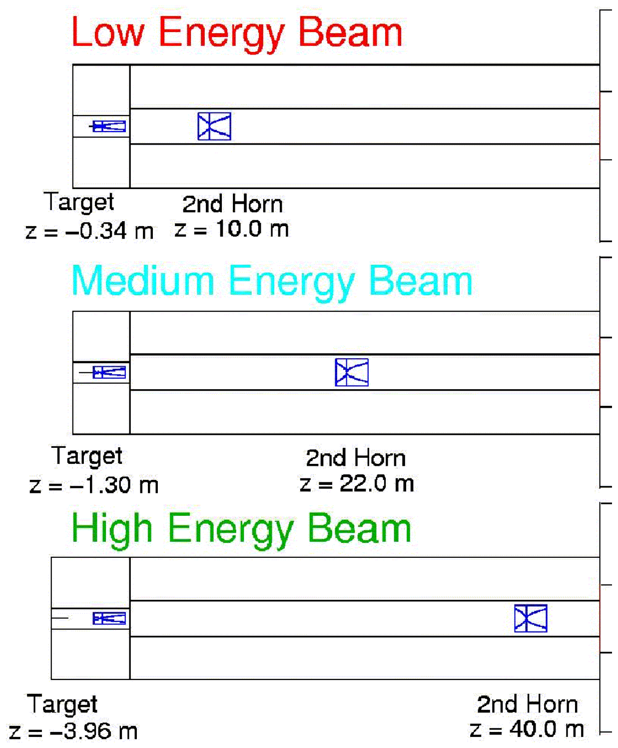
NUMI

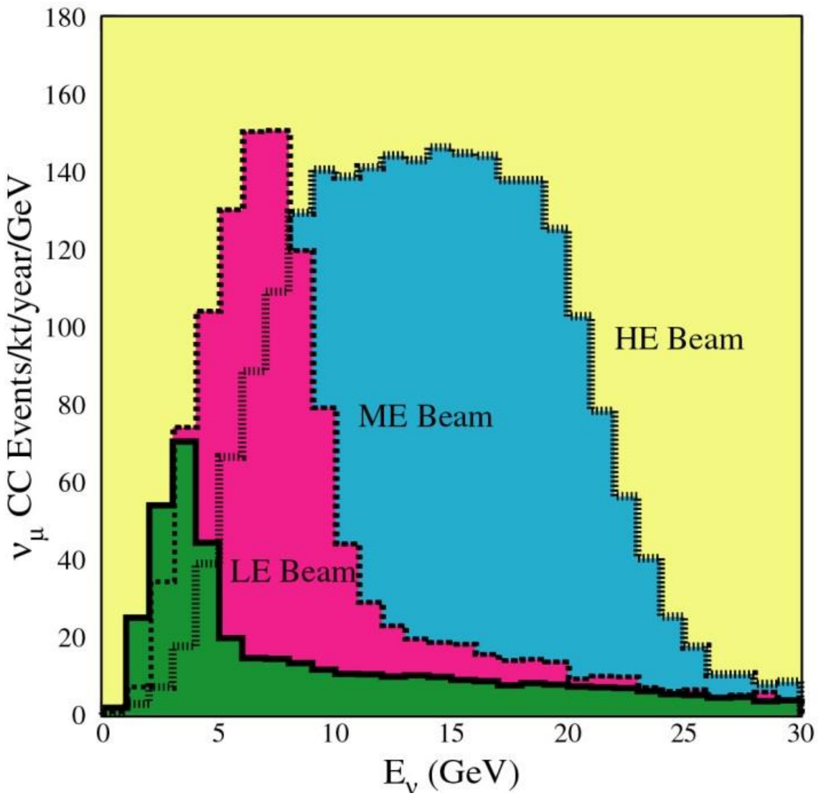
NuMI beamline



NUMI – what is unique

- By moving target and horns longitudinally along beam line
  - Able to change energy spectrum, from peak at 3 GeV to peak at 15 GeV
- Has accumulated more beam power than any other conventional neutrino beam





NUMI experience

NuMI Experience: (continuous air ventilation, local morgue, crane coverage)

- Takes ~ 1 ½ weeks to change out a target
- Took 3 ½ weeks to change out horn PH2-01 *(included ~1 week diagnostics of old horn)*

Biggest NuMI surprise:

- Although NuMI target chase is in air,
  biggest Tritium release is from evaporation from steel shielding
  (CNGS saw similar effect)

Other lesson learned:

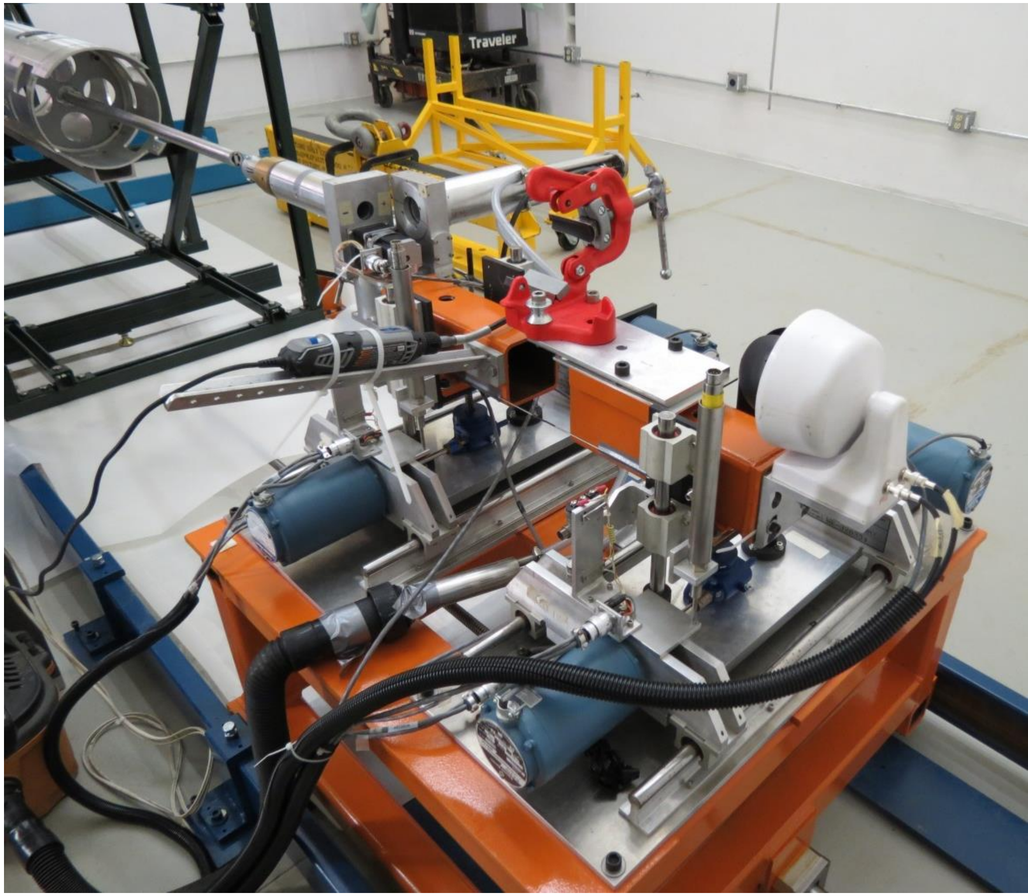
- High strength steel fails in radiation+air -> NOx environment
  (stripline washer on horn PH2-01, had to replace whole horn)

NuMI graphite target experience & upcoming autopsy

- NuMI has run 8 targets.
- 5 died of water line failures (QA problem; no degradation of spectrum 0–3e20 POT)
- 2 show no degradation after 2 – 3 e20 POT, still usable
- 1 slowly degraded over 6 e20 POT
  - Was this radiation damage?
  - Was this bad gas?
  - Will open up this target in a few months for examination

Target mock-up

Machine to remotely remove graphite core in FNAL C0 work cell

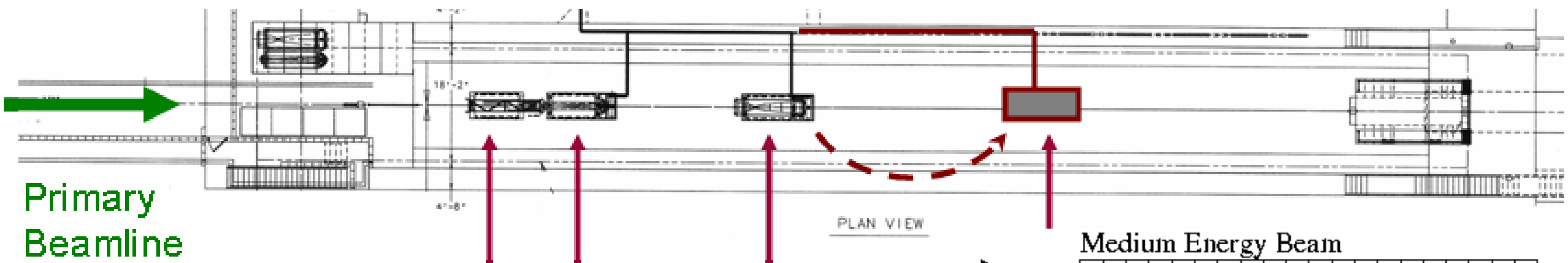


NUMI UPGRADE

NuMI neutrino line upgrades

- **NuMI** was designed for 4E13 ppp every 1.87 s (400 kW beam power)
  - **Cycle rate from 0.5 to 0.75 Hz X1.5**
  - **Per pulse intensity from 4.0E13 to 4.9E13 X1.2**
  - **Beam power from 400 to 700 kW x1.75**
- **NOvA** required Medium Energy Neutrino Configuration:

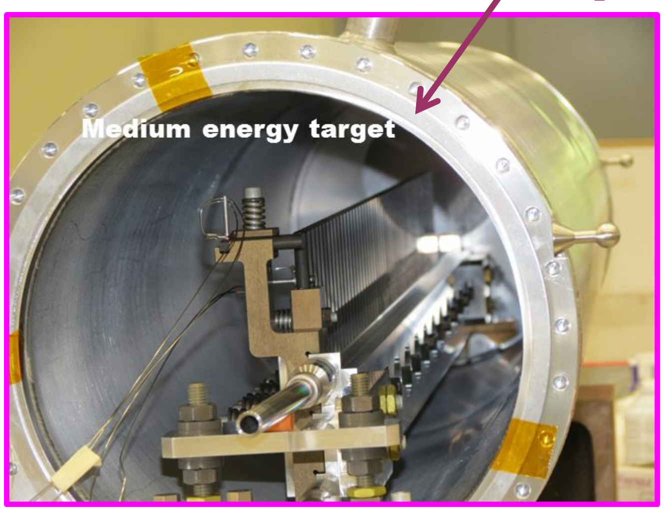
  Built new horn nest in high radiation area, moved horn (see poster session)



Target

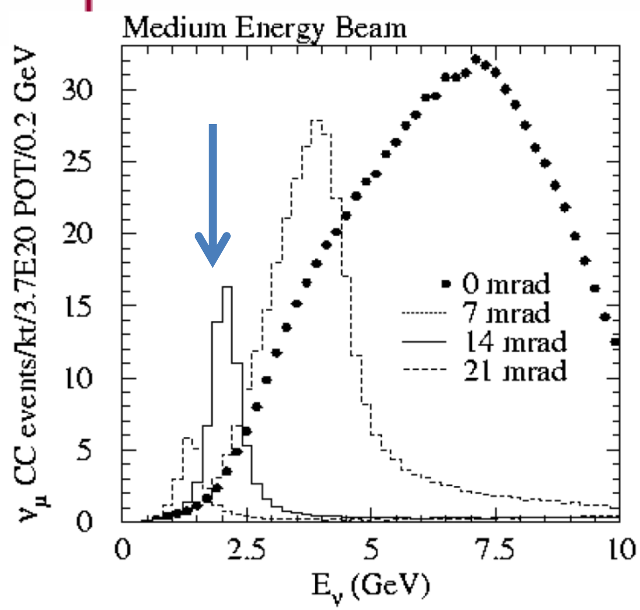
Horn 1

Horn 2
Low Energy
Configuration



Target no longer has to fit in horn!

Revised design IHEP, RAL, FNAL



NuMI beam-line ready for 700 kW

Other changes (finished):

- Improved cooling on Horn 1
- Baffle modification – 20% larger hole for 20% larger beam spot
- Improved target/horn water systems, exchange radioactivated water remotely
- Increase air cooling capacity

Accelerator complex status and plans

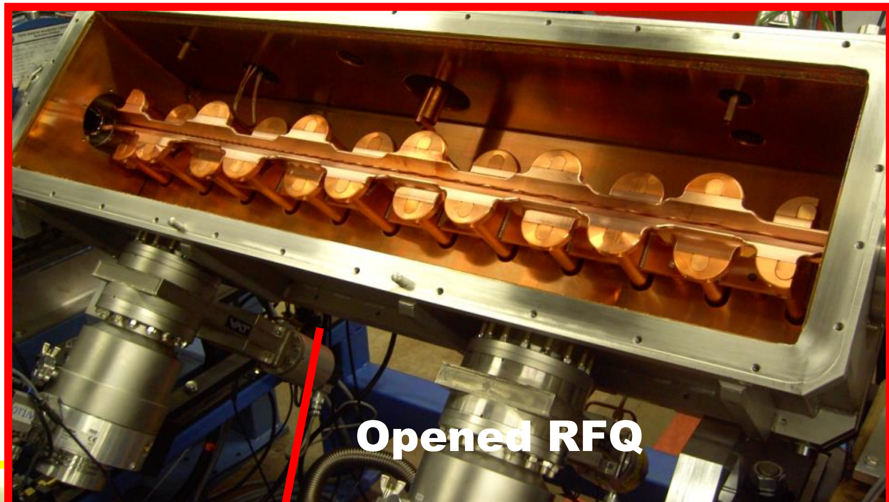
- **Presently running mostly with Main Injector only, 6 Booster batches**
  - 2.5E13, 1.67 s cycle time, 280 kW peak power

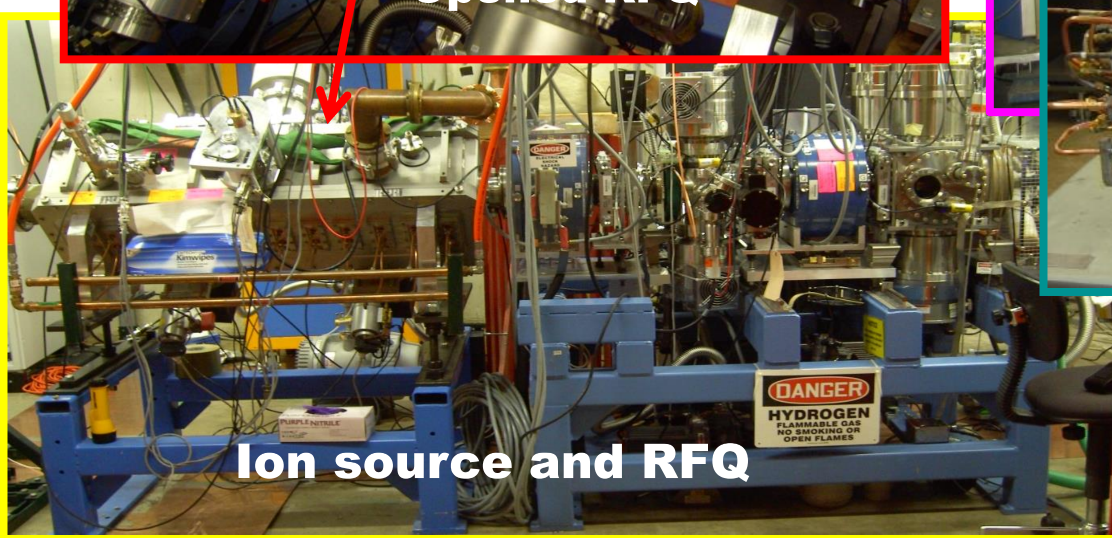
- **Commissioning of Recycler ring proceeding**
  - Currently, a few hours/day run accumulating 6 booster batches in recycler then transferring to Main Injector in 1.33 s cycle time
  - Will start slip-stacking beam in recycler next fall, 12 booster batches can give 400 to 500 kW

- Booster cavities done end of 2015, be able to accelerate on more booster cycles; NuMI ~ 700 kW

Proton Improvement Plan (PIP)

- Replace obsolete components and improve reliability
  - **40 year old Proton Source**
- Refurbish Booster RF cavities to run at 15 Hz





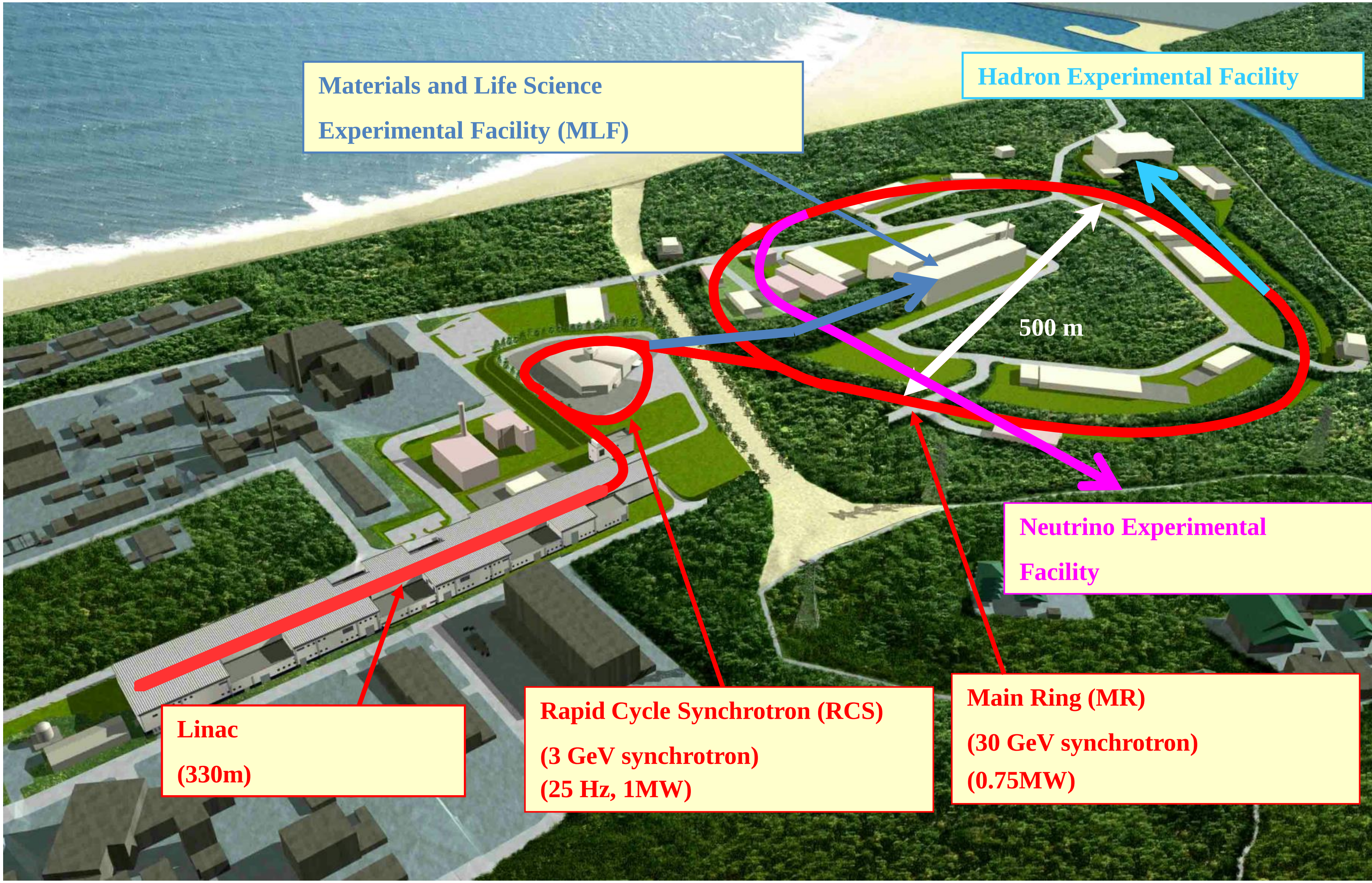
- **10 of 19 cavities have been refurbished to run at 15 Hz**

Will be some Beryllium test fins in next NuMI graphite target

- In poster session see: Beryllium materials test

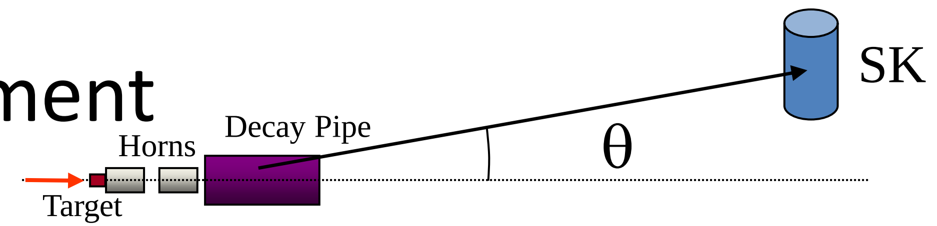
T2K

J-PARC

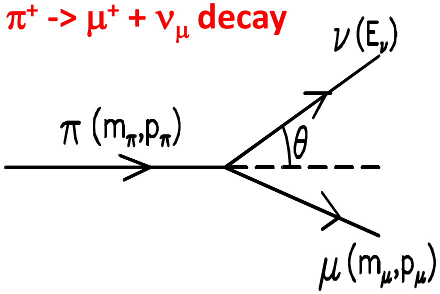

Materials and Life Science
Experimental Facility (MLF)
Hadron Experimental Facility
500 m
Neutrino Experimental
Facility
Linac
(330m)
Rapid Cycle Synchrotron (RCS)
(3 GeV synchrotron)
(25 Hz, 1MW)
Main Ring (MR)
(30 GeV synchrotron)
(0.75MW)

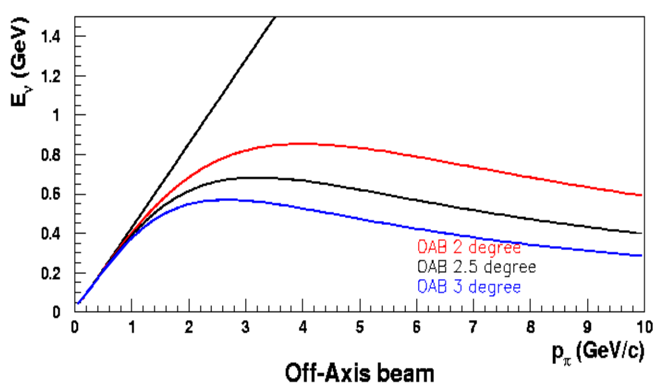
T2K

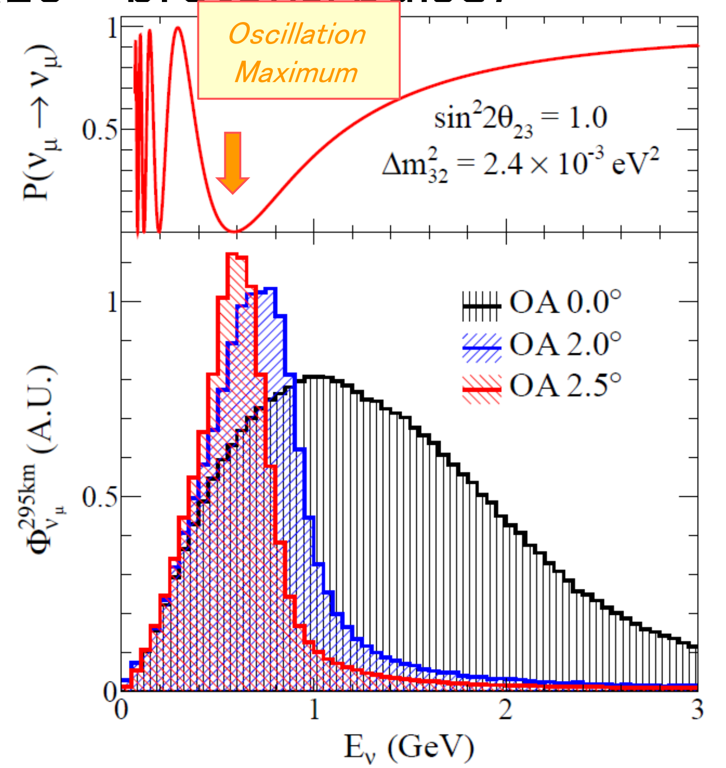
- Conventional neutrino beam
  - $p + C \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$
- Designed for T2K experiment
  - High intensity beam
    - **750kW** proton beam (30 GeV, 3.3×10^{14} protons/pulse)
  - **Off-axis** beam (2~2.5°)
    - Narrow band beam ~ 0.6 GeV
      - 1st oscillation maximum



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



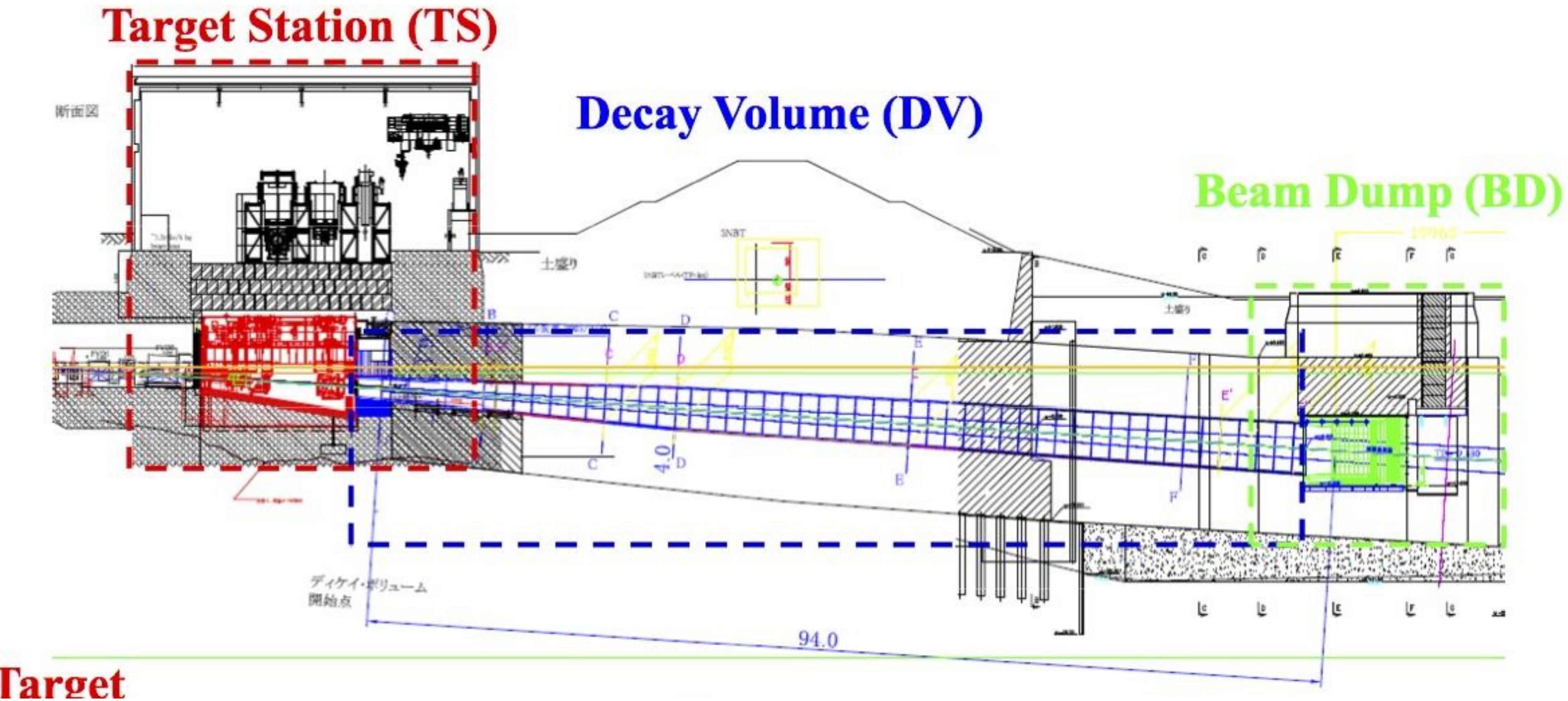




T2K – what is unique

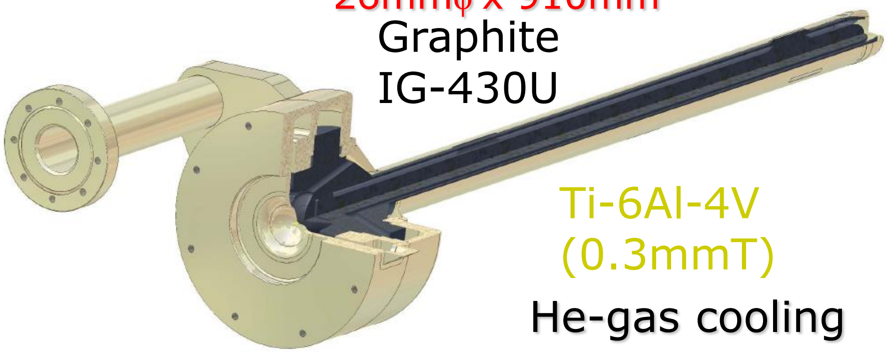
- First to do a detector-off-axis neutrino beam
- Target/Horn chase is in Helium instead of air
  - Decay region and absorber are in same helium volume as chase
- By replacing components, has ability to change beam direction by 1 degree
- Some parts (absorber, decay pipe cooling, and shielding thickness) designed for 4MW (highest power design so far)

Secondary Beamline



Target

26mmϕ x 910mm
Graphite
IG-430U

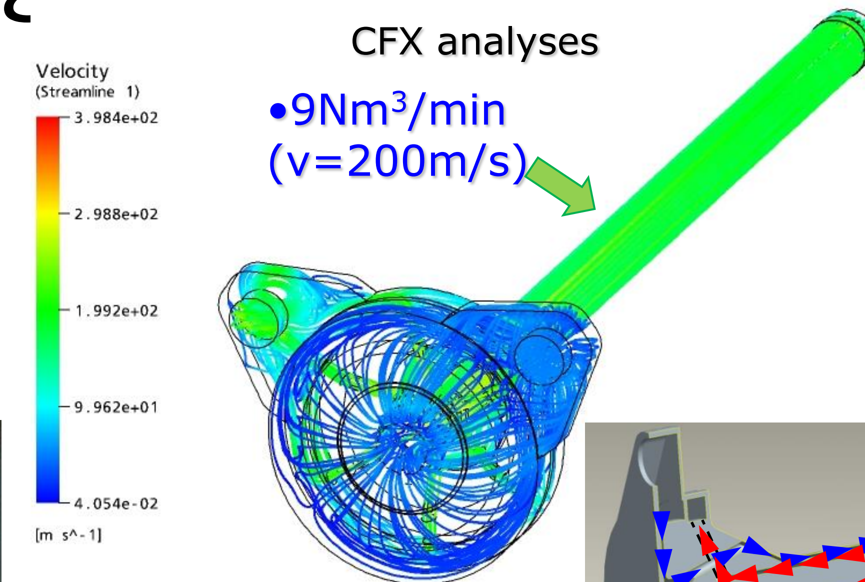


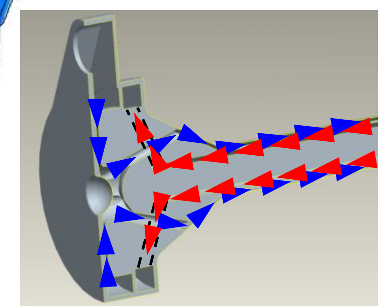
Ti-6Al-4V
(0.3mmT)

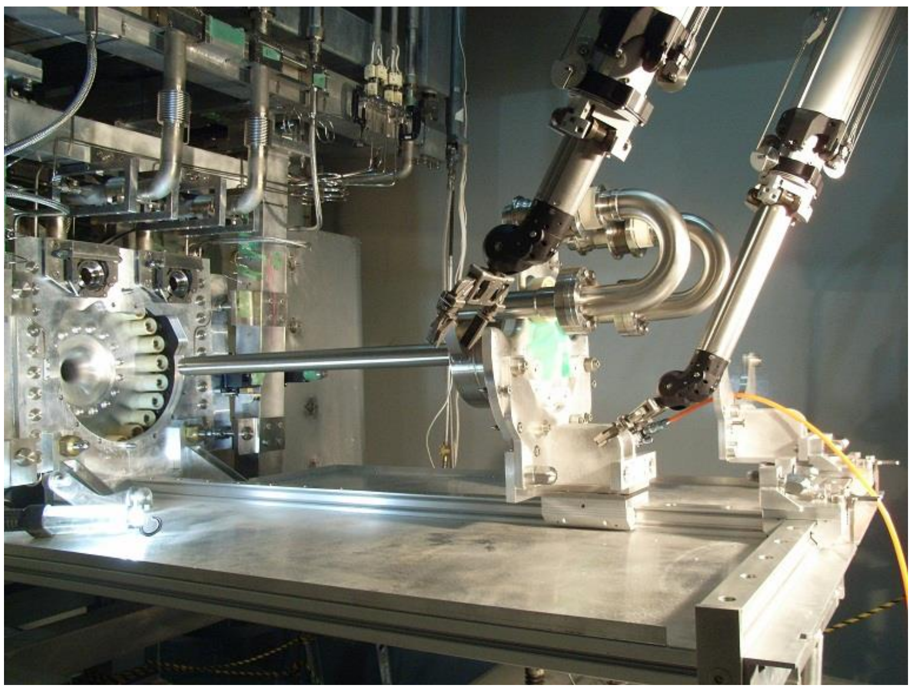
He-gas cooling

CFX analyses

•9Nm^3/min
(v=200m/s)



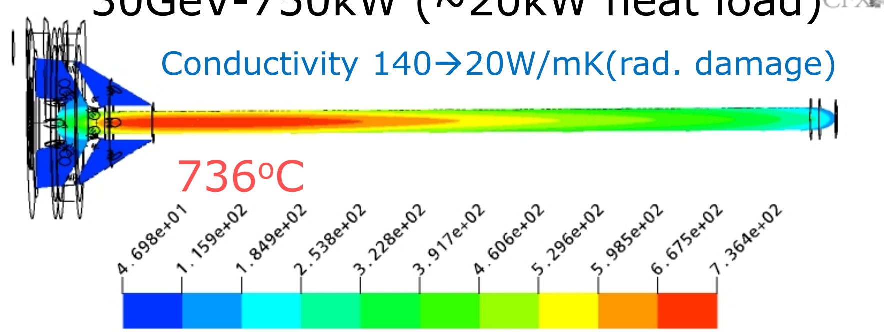




• **Remote maintenance**

30GeV-750kW (~20kW heat load)

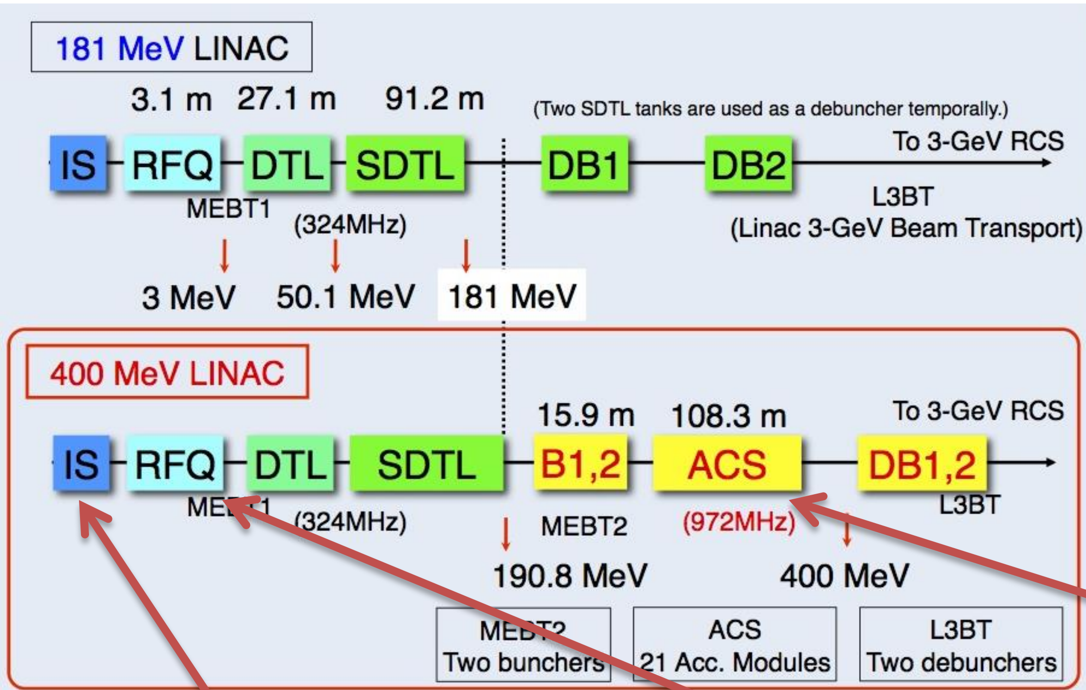
Conductivity 140→20W/mK(rad. damage)

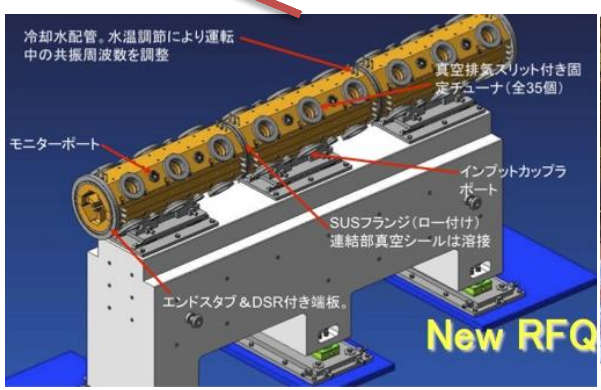


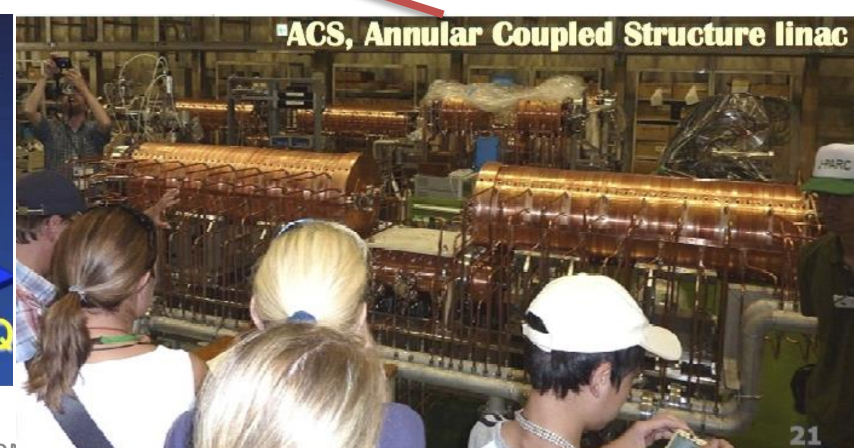
ΔT~200K ~7MPa (Tensile strength 37MPa)

T2K upgrade

Linac Upgrade

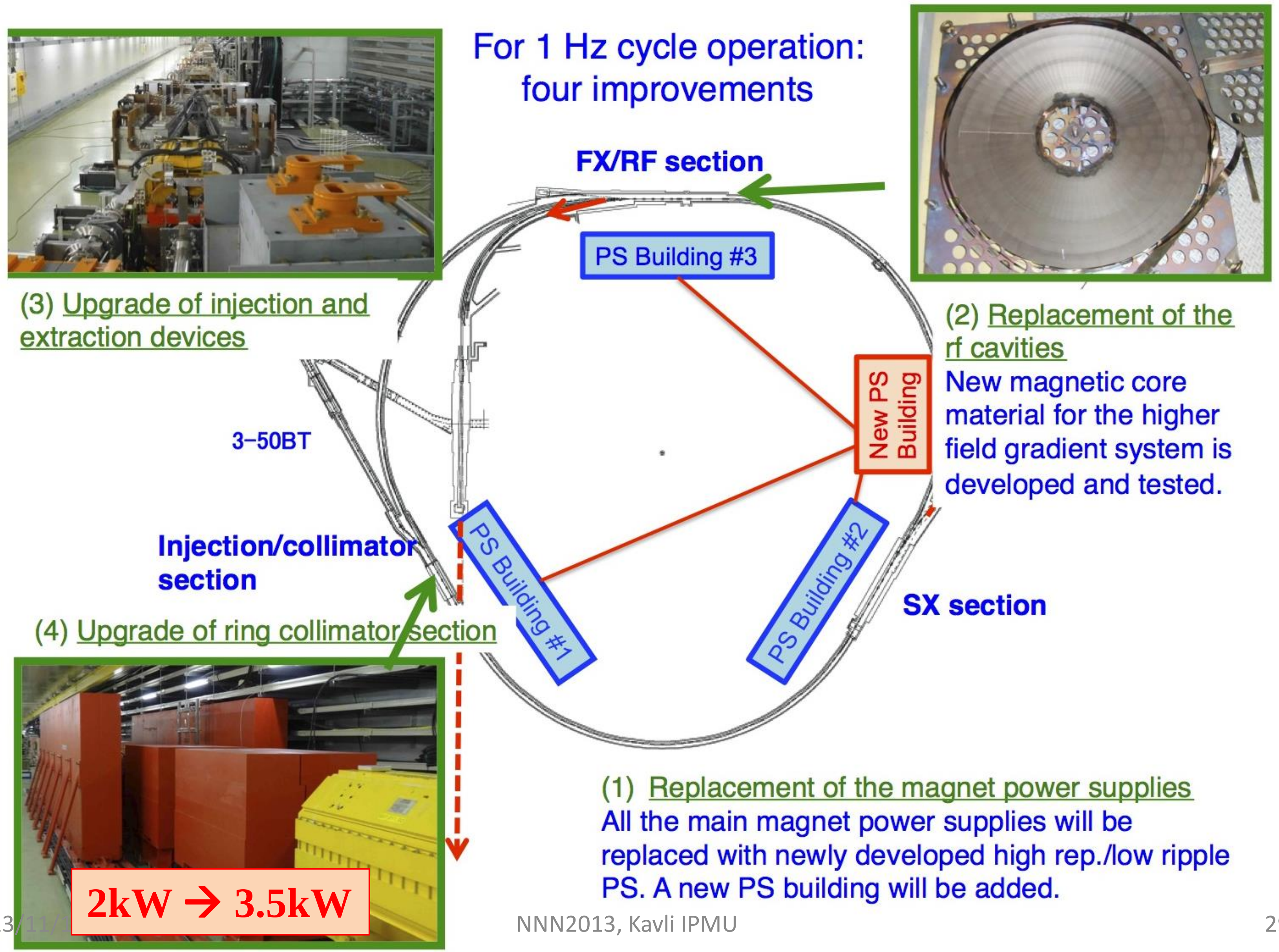






- New accelerating structure, ACS, will be installed to increase the extracted beam energy from 181MeV to 400MeV (JFY2013)
- Front-end part (IS+RFQ) will be replaced to increase peak current from 30mA to 50mA (JFY2014)

MR Upgrade


For 1 Hz cycle operation:
four improvements
FX/RF section
PS Building #3
New PS Building
PS Building #1
PS Building #2
3-50BT
Injection/collimator section
SX section
(3) Upgrade of injection and extraction devices
(2) Replacement of the rf cavities
New magnetic core material for the higher field gradient system is developed and tested.
(4) Upgrade of ring collimator section
2kW → 3.5kW
(1) Replacement of the magnet power supplies
All the main magnet power supplies will be replaced with newly developed high rep./low ripple PS. A new PS building will be added.

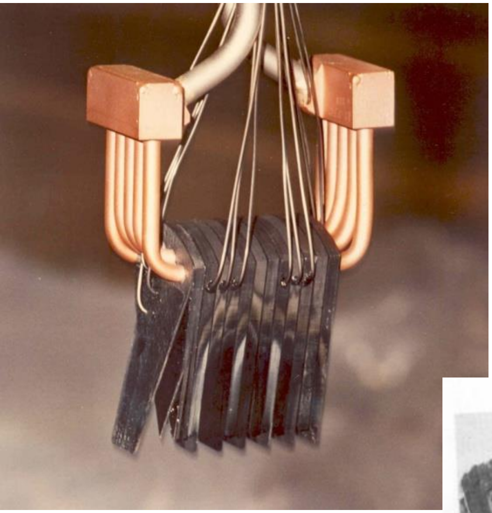
T2K Beam Line changes for upgrade beam power

- Acceptance of each component for high power beam
  - **Target**
    - Mechanical: **0.75MW**
    - Cooling: **0.75MW**
  - **Horn**
    - Cooling for conductors: **1.85MW**
    - Cooling for striplines: **0.4MW** → **0.75MW** (2014~)
    - Hydrogen production: **0.3MW** → **> 1MW** (2014~)
    - Power supply: **0.4Hz, 250kA** → **1Hz, 320kA** (2014~)
  - **He vessel, Decay Volume & Beam Dump**
    - Cooling: **4MW**(HV&DV), **3MW**(BD)
  - **Facility**
    - Water disposal: **0.5MW** → **2MW** (2016 or 2017~)
    - Radio-active air: **0.5MW** → **> 1MW** (2014~)

Neutrino Target experience

Ashes to ashes, dust to dust...

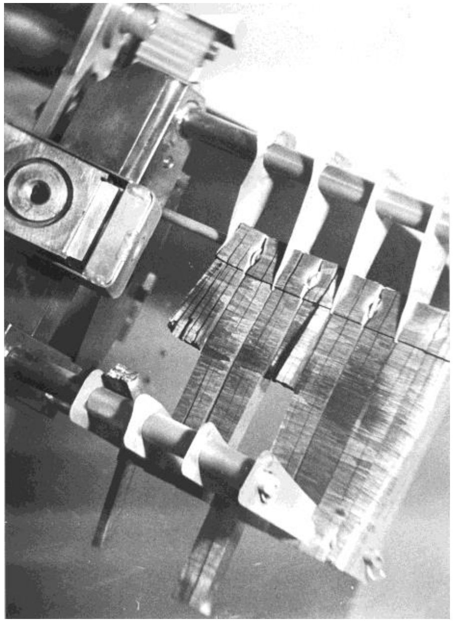
The ultimate destiny for all graphite targets
(T2K c.10^{21} p/cm^2 so far)



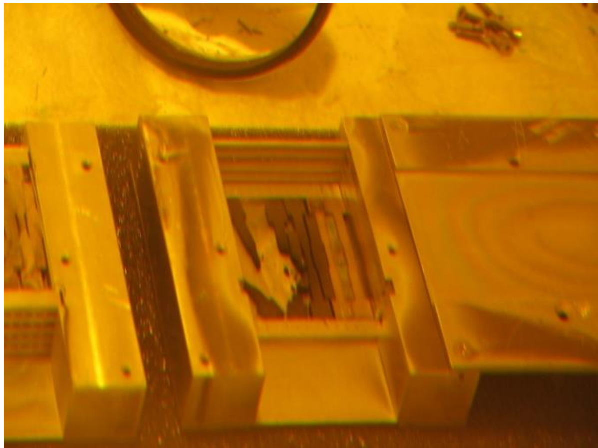
LAMPF
fluence
10^22
p/cm2

(from Chris Densham,
ICFA meeting)

PSI fluence
10^22 p/cm2



BNL tests (in water):
fluence ~10^21 p/cm2



But experience with graphite neutrino targets is not quite as bleak

Fluence at center of beam spot, (with **no degradation of neutrino yield** seen):

(BNB 1e22 POT/cm2 with Be target)

T2K 6e20 POT/cm2

NUMI 4e21 POT/cm2

CNGS 1e22 POT/cm2

Why did CNGS target survive so well?

Type of graphite?

High temperature?

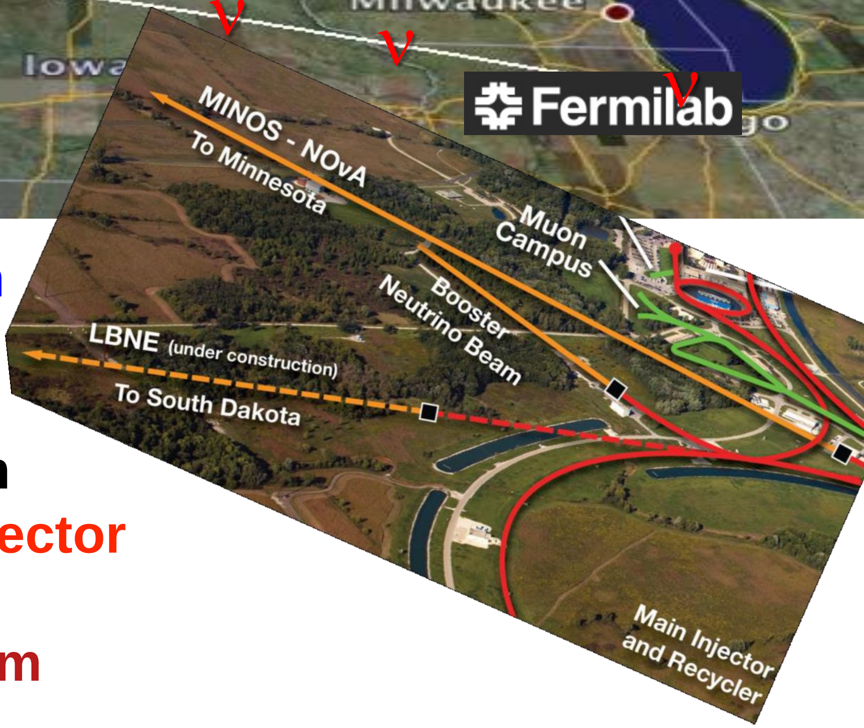
Central material held in place by less irradiated outer graphite?

Can target design be elevated to an engineering understanding of radiation damage rather than “put it in and see how long it survives?”

Can graphite be adequate, or do we need alternate target design?

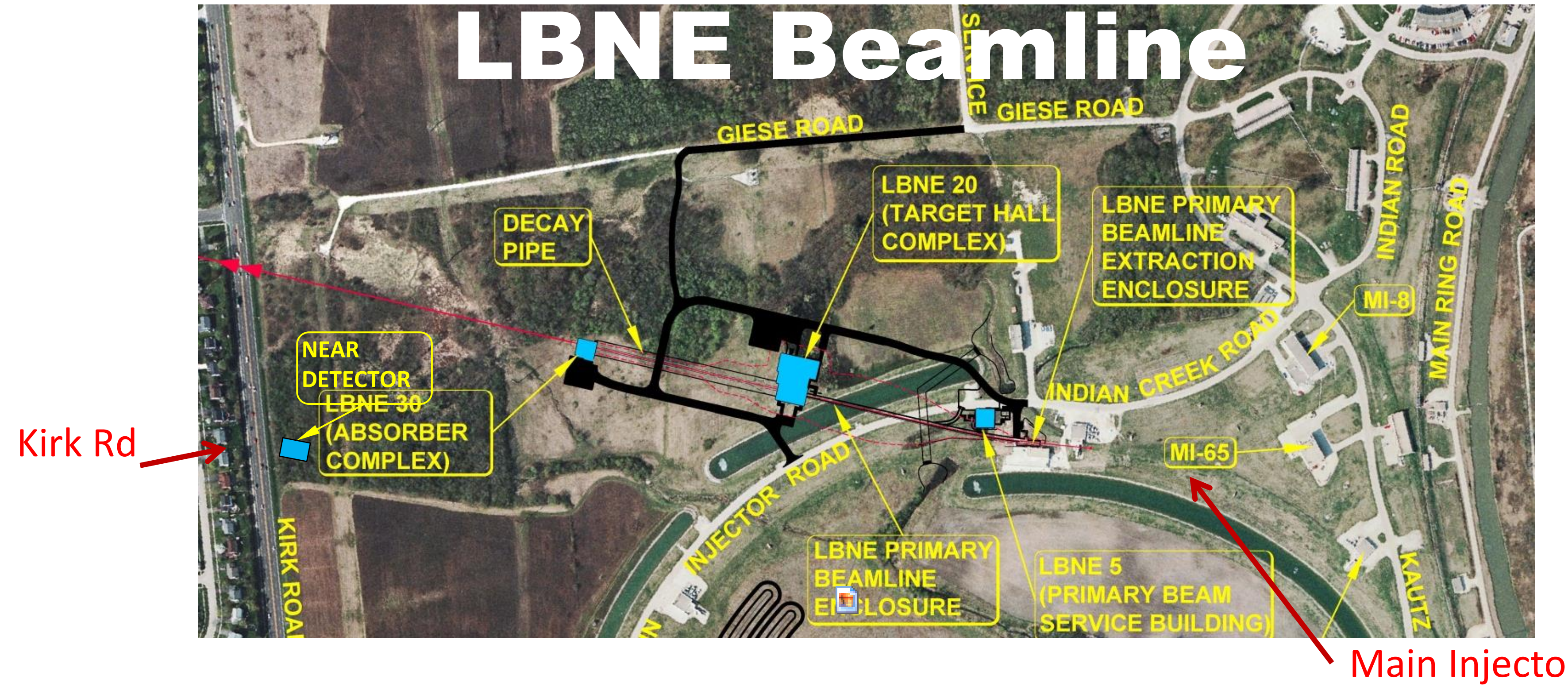
LBNE

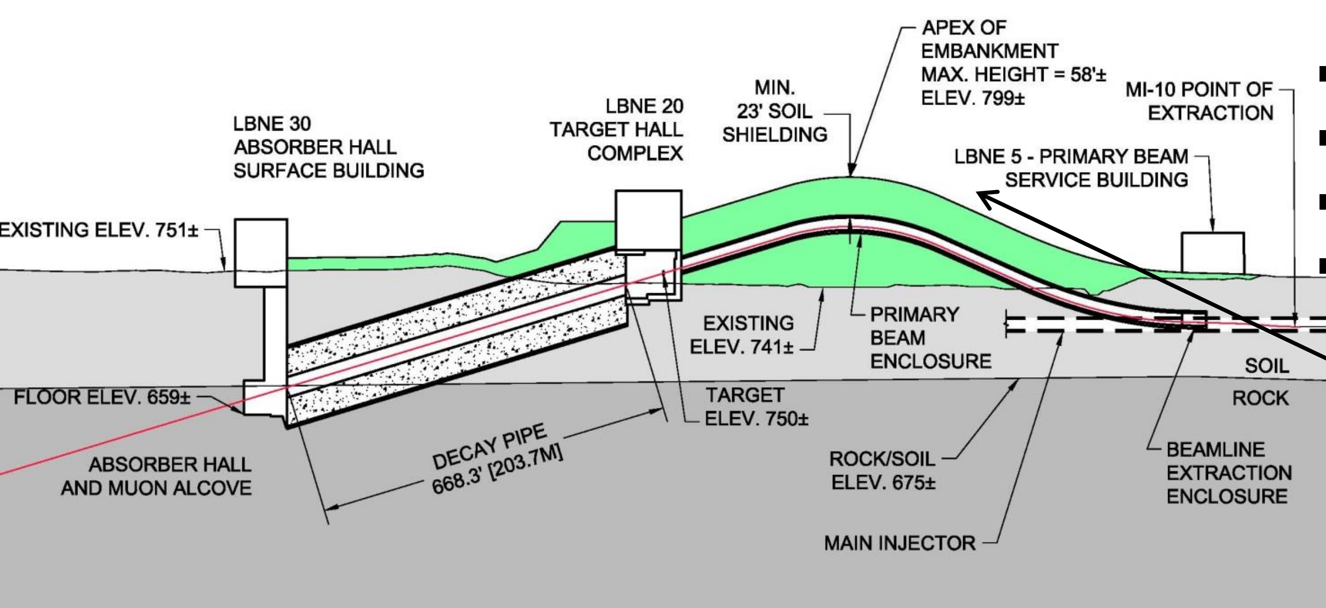
LBNE: Long Baseline Neutrino Experiment



- A new neutrino beamline over 1300 km
- Proton beam power assumption
  - 700 kW → 1.2 MW → 2.3 MW
- A highly-capable near detector system
- A ≥10 kt fiducial mass LAr TPC far detector underground at SURF
- A cavern for a full 34 kt detector system

LBNE Beamline





- $60 \leq E_{beam} \leq 120$ GeV
- 0.7 MW / 1.2 MW
- upgradeable 2.3 MW
- designed for 30 years lifetime

Accelerator proposal for LBNE

LBNE plan last October was to start at 700 kW

Now PIP-II proposal to upgrade accelerator, provide 1.2 MW by 2025

Plan A - Superconducting Linac

- 800 MeV pulsed SC linac
- Constructed from CW-capable accelerating modules
- Operated initially at low duty factor
- Sited in close proximity to Booster and to significant existing infrastructure

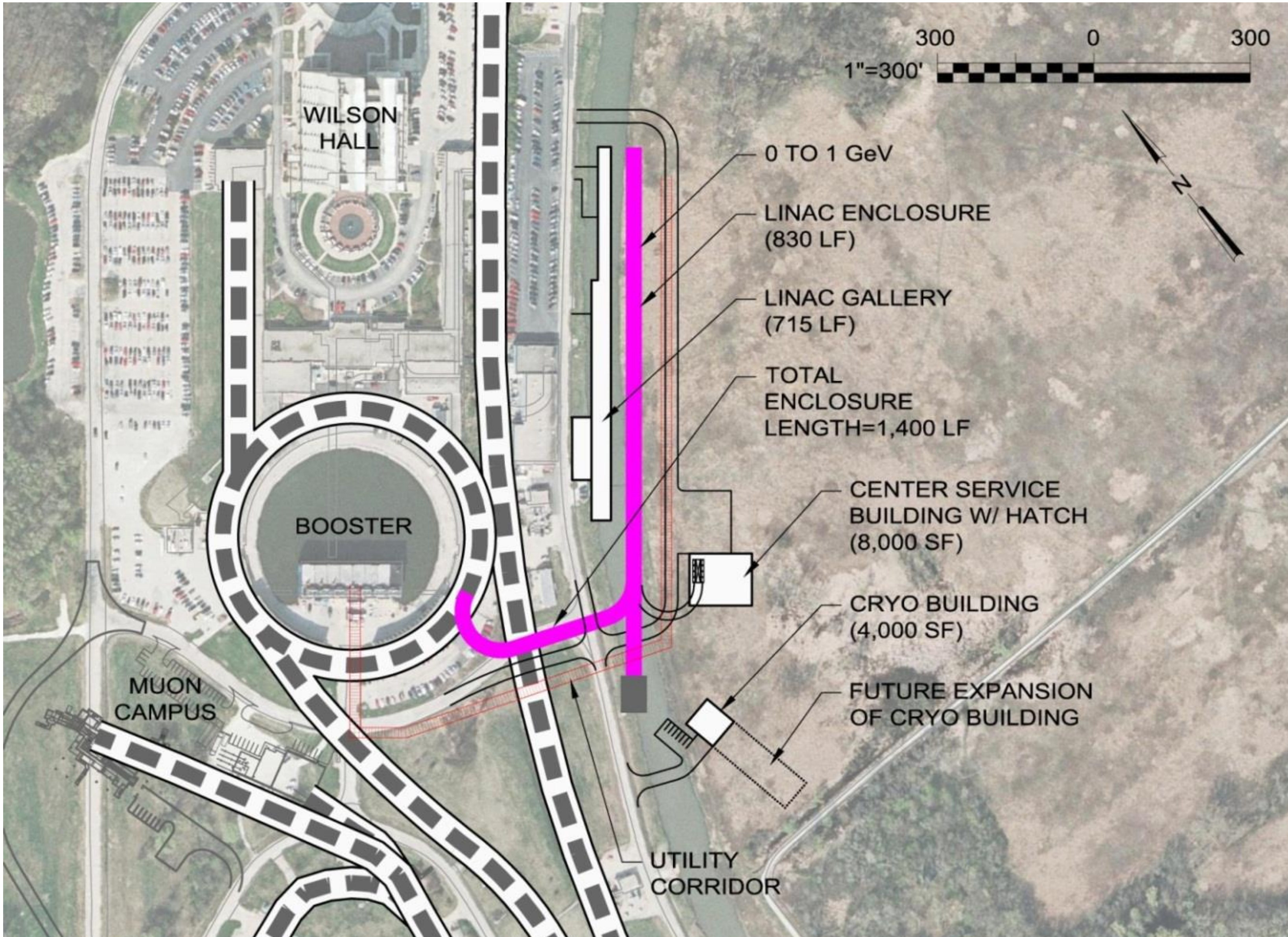
Plan B - Afterburner

- 400 MeV pulsed linac appended to existing 400 MeV linac
- 805 MHz accelerating modules
- Requires physical relocation of existing linac upstream ~50 m
- ~1 year interruption to operations
- Less expensive than Plan A

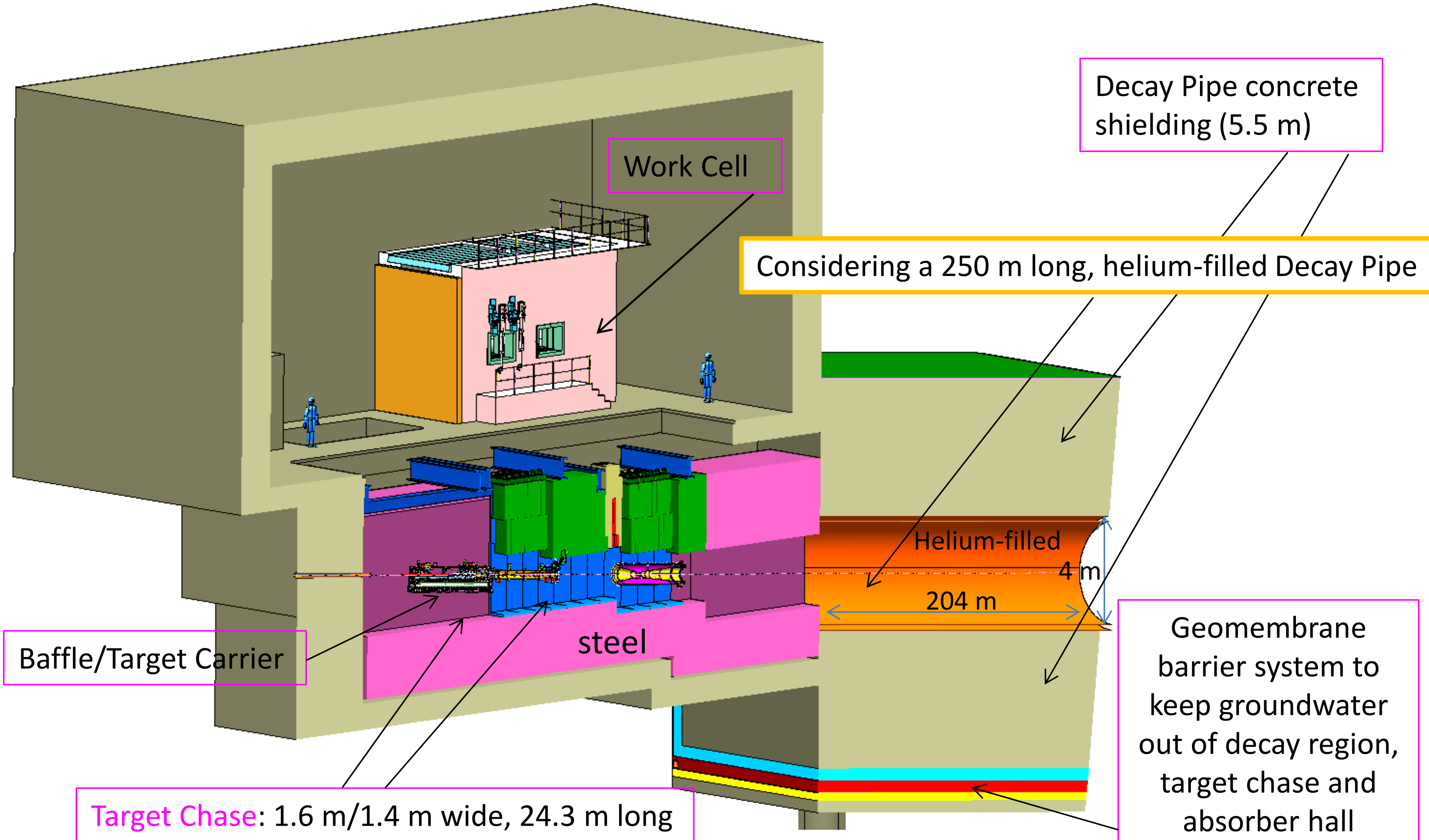
Second phase, to achieve > 2 MW beam power

- Can feed Main Injector via either a 6-8 GeV pulsed linac or rapid cycling synchrotron (RCS)

PIP-II Option A



Target Hall/Decay Pipe Layout



LBNE beamline – what is unique

- Highest power longest baseline currently approved neutrino beam
- Longer baseline means it will be on steeper slope than previous lines (10%)

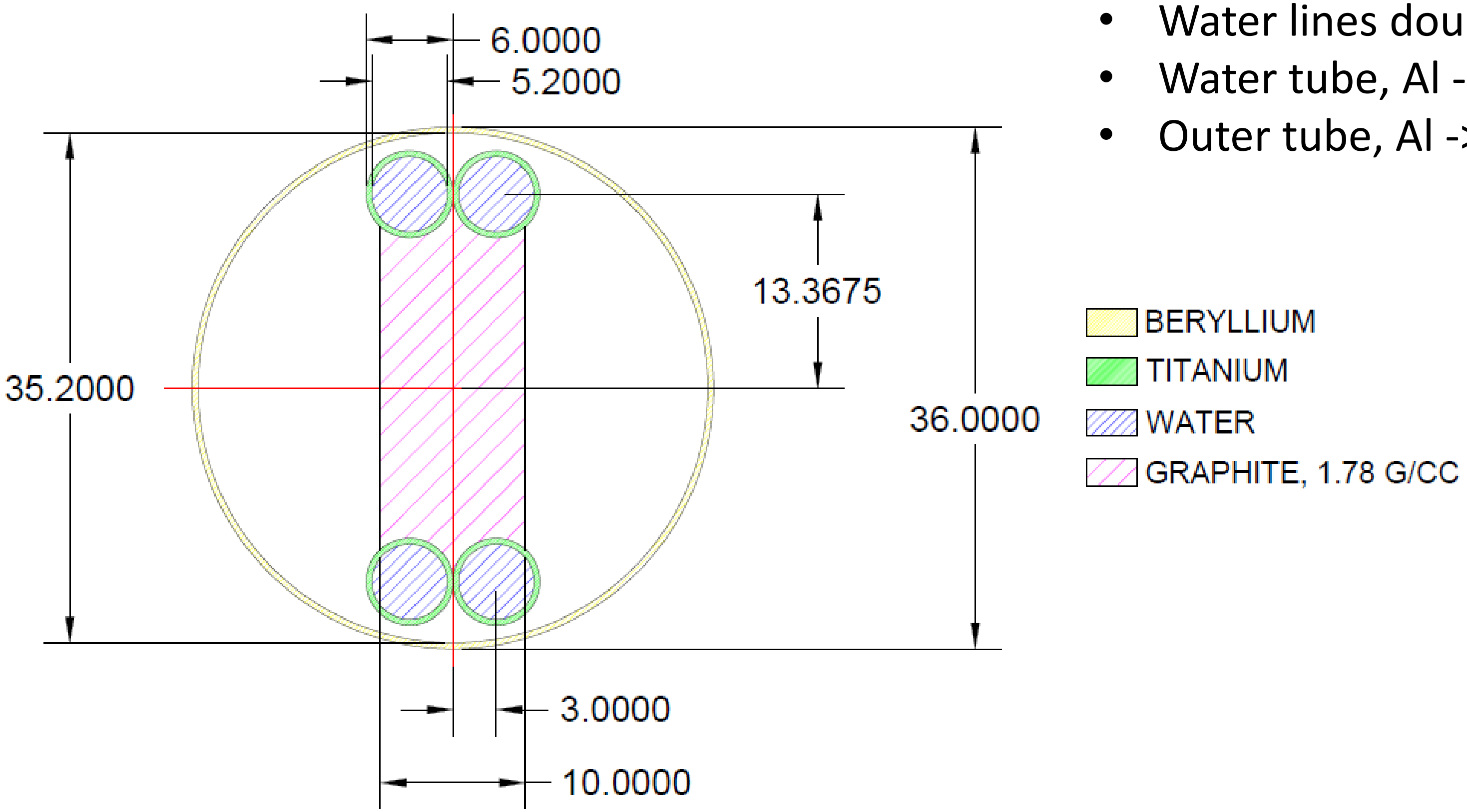
Unsurprisingly, copies much of design from NuMI. Differences:

- Built at surface instead of deep underground
- Decay pipe is twice diameter, 1/3 length
- Uses air to cool decay pipe rather than water
- Short target hall, so will not be moving horns to change spectrum
  - But can still make adjustments by moving target
- Decay pipe upstream window will be replaceable

1st phase base-line target + horns very similar to NuMI, to save project money

2nd generation target + horns expected for better optimization and higher power

“minimal change” 1.2 MW LBNE target



From NuMI LE target:

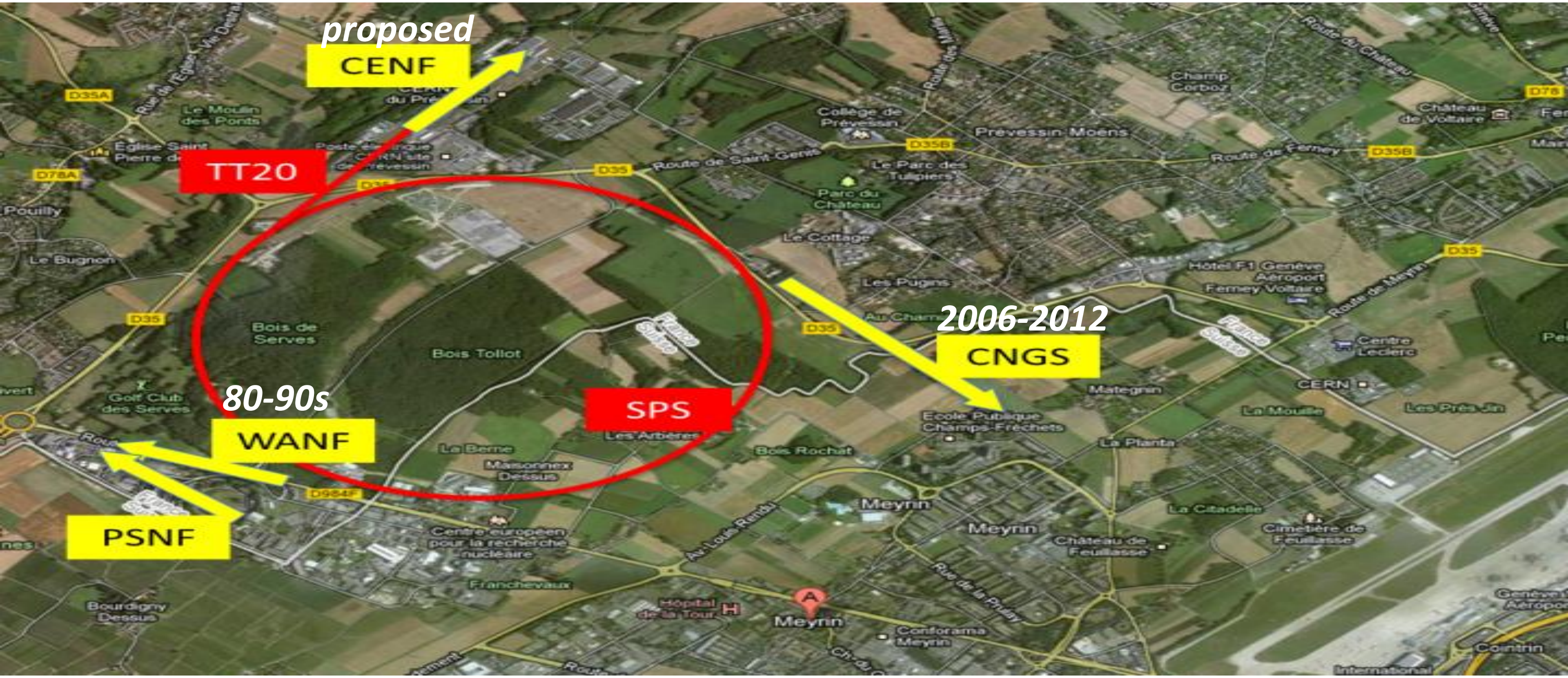
- Fin width: 6.4 mm -> 10 mm
- Beam spot: 1.1 mm -> 1.7 mm
- Water lines doubled
- Water tube, Al -> Ti
- Outer tube, Al -> Be

- **See poster: LBNE 1.2MW Target Conceptual Design**

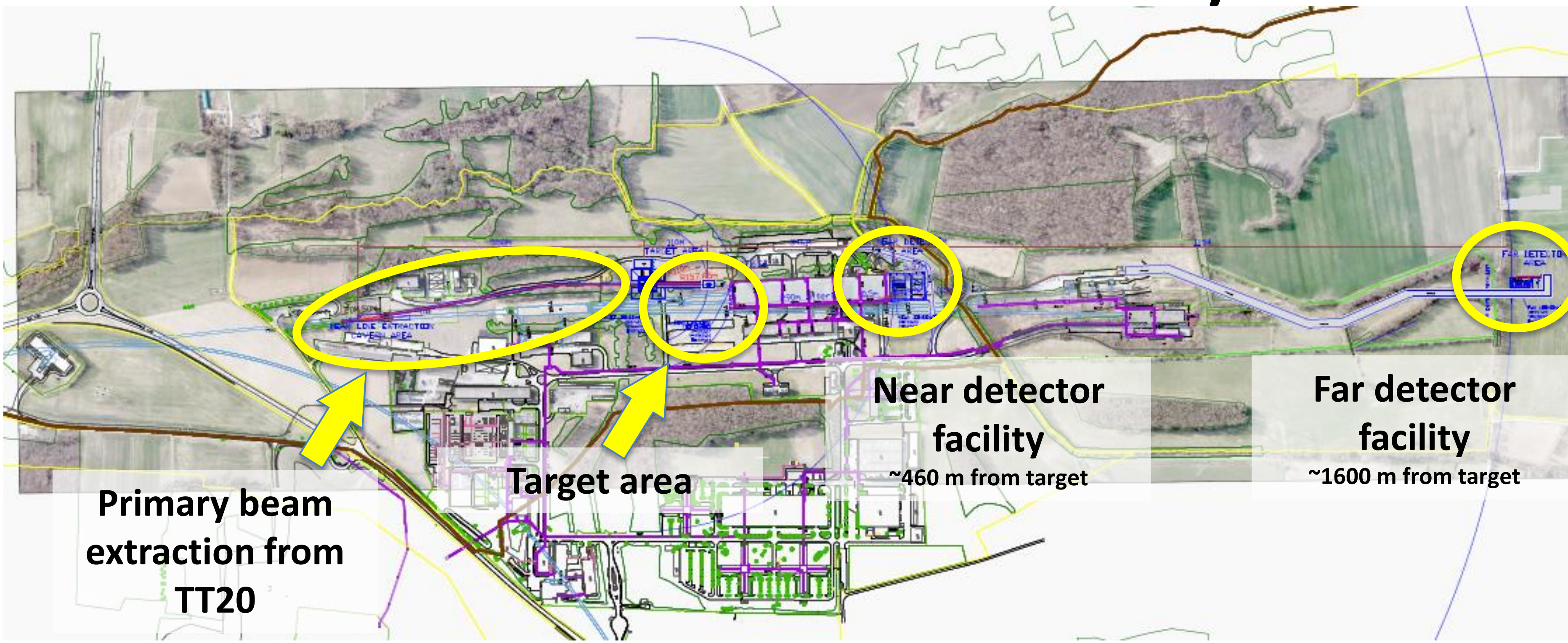
CENF

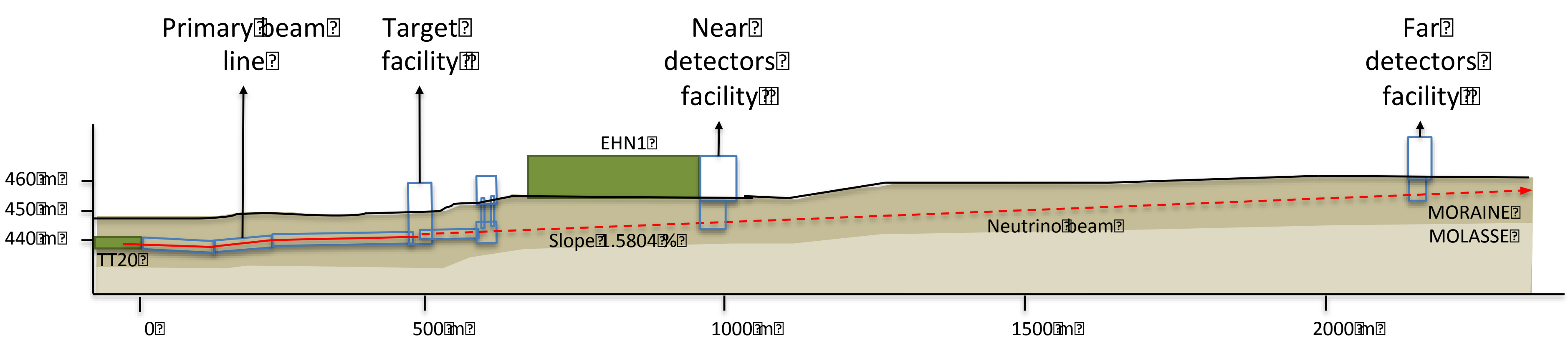
CERN Neutrino Facility

200 KW beam, short baseline
With 2 horns, order of magnitude more powerful than BNB



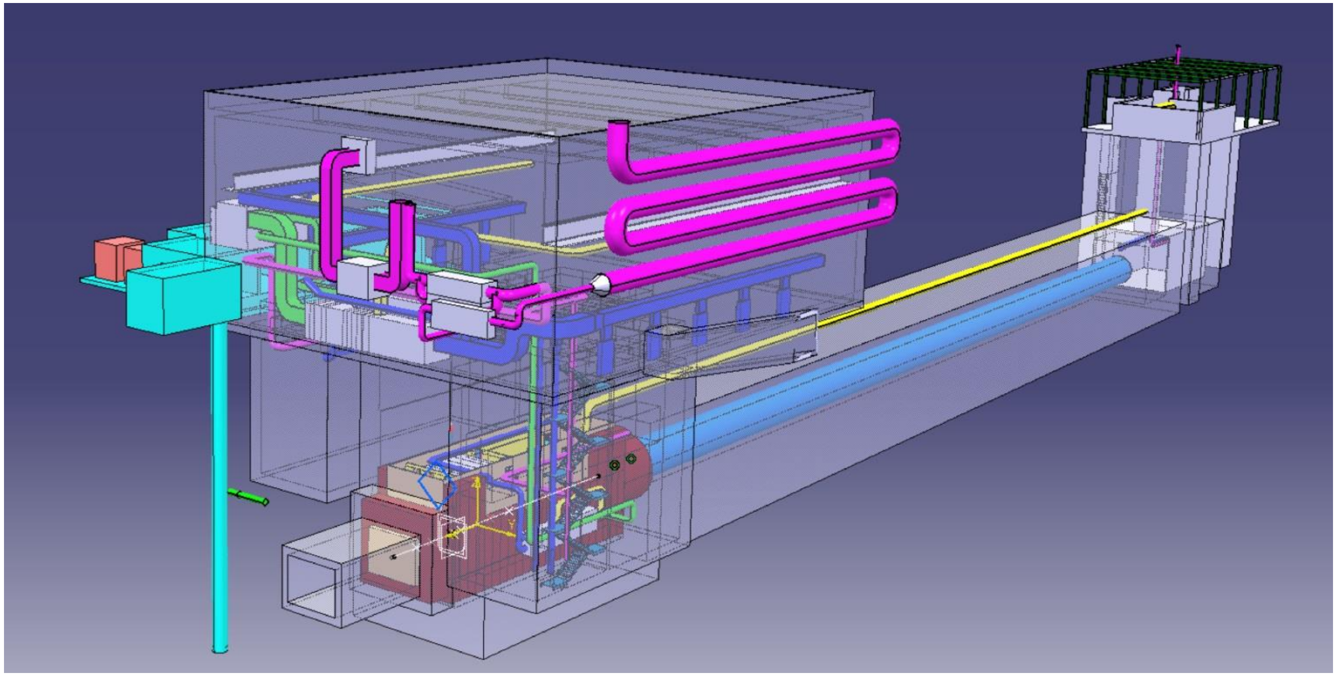
CERN Neutrino Facility





CENF – what is unique

- Near and Far detectors on a short baseline experiment
- Beam slopes up instead of down



Design is pretty far along; will finish design study this year

CN2PY

The LBNO Proposal - CN2PY LBL ν-beam

CERN Neutrinos 2 PYhasalmi beam

- **Phase 1** : proton beam extracted beam from SPS
  - **400 GeV**, max 7.0 10^{13} protons every 6 sec, ~**750 kW** nominal beam power, 10 μs pulse
- **Phase 2** : use the proton beam from a new HP-PS
  - 50(30,70) GeV, 1.33 Hz, 1.9 10^{14} ppp, **2 MW** nominal beam power, 4 μs pulse
  - alternative option: upgradedSPS
  - CN2PY also compatible with a NF option

Beam parameters

- 400 GeV protons from SPS (initial)
- Survey info:
- CERN (TCC2 target station –NA) 46°15'26.27"N, 6° 3'8.19"E
- Inmet Mine (Finland): 63°39'30.92"N, 26° 2'47.65"E
- distance: **2296 km**
- dip angle : **10.4 deg, 181 mrad**
- Neutrino beam at Pyhäsalmi ($\theta_{max} \approx$ 30 MeV/E_ν) : **14÷34 Km** for Eν 2÷5 GeV

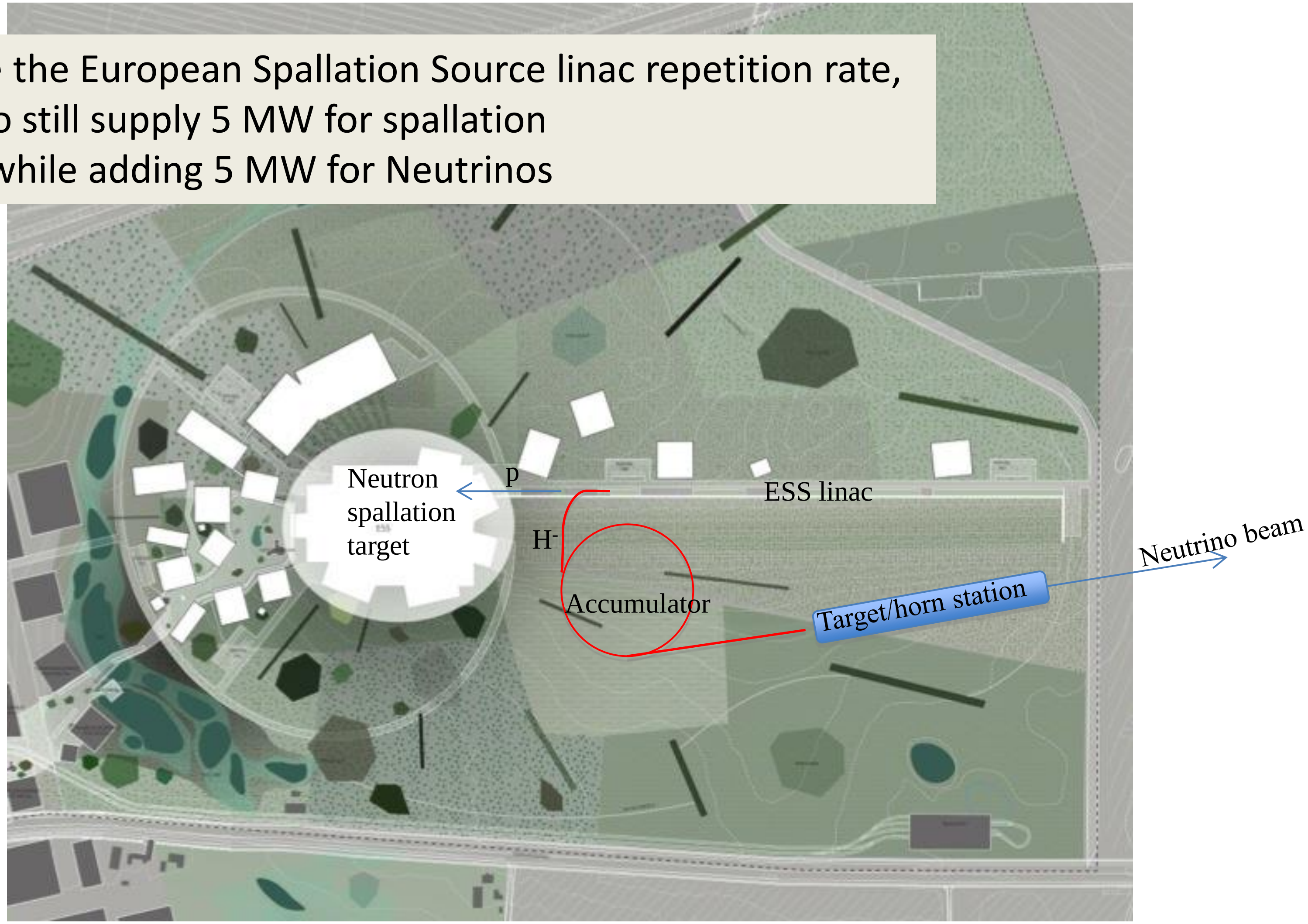
CN2PY (LBNO LAGUNA) – what is unique

- Longest proposed baseline
- Thus would be steepest slope (18%)
- Gets the 2nd oscillation maximum up to a neutrino energy that is easier to get good efficiency from a conventional neutrino beam focusing system
- Phase II (2MW) requires a new accelerator

ESSnuSB

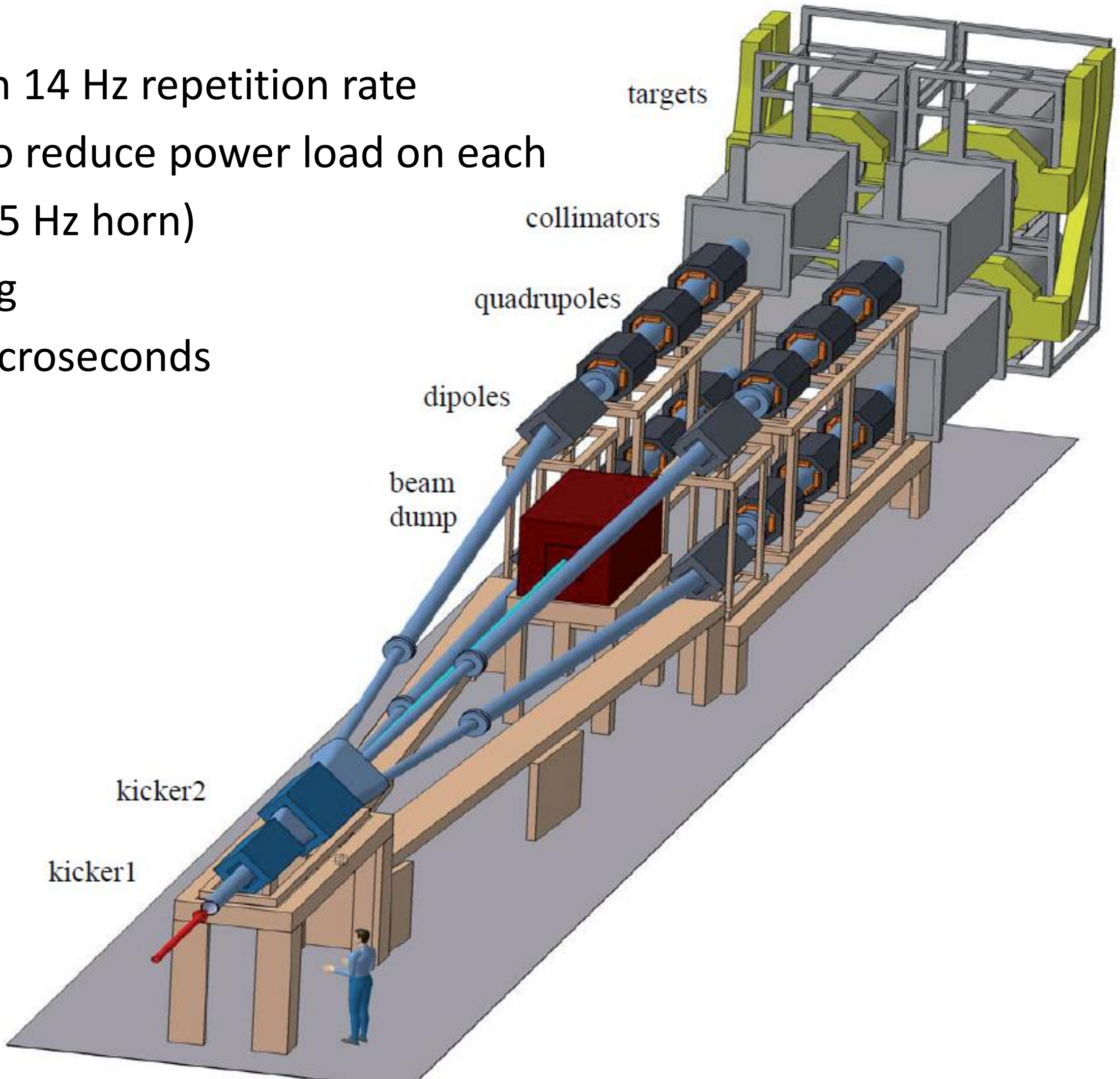
Lay-out of ESS neutrino beam

Double the European Spallation Source linac repetition rate,
to still supply 5 MW for spallation
while adding 5 MW for Neutrinos



ESSnuSB – what is unique

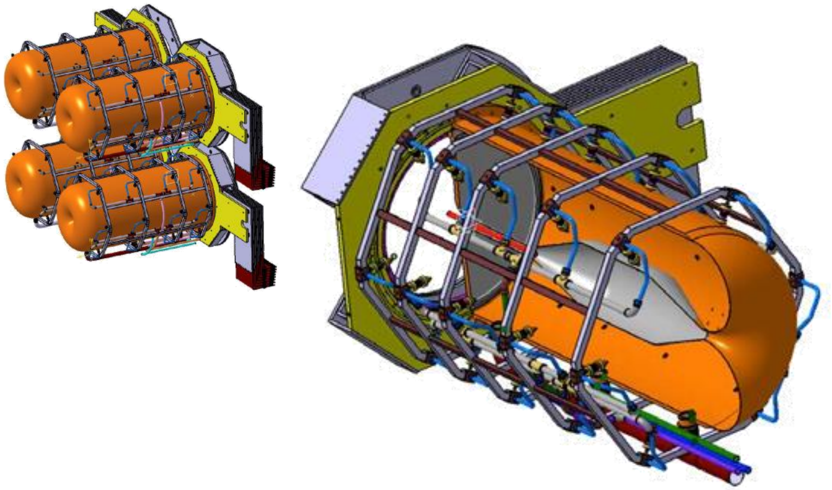
- High beam power and high 14 Hz repetition rate
- Four-target/horn system to reduce power load on each
  (1.25 MW target, 3.5 Hz horn)
- 2000 turn accumulator ring
  compress 3 ms to 1.5 microseconds



The Neutrino Horn

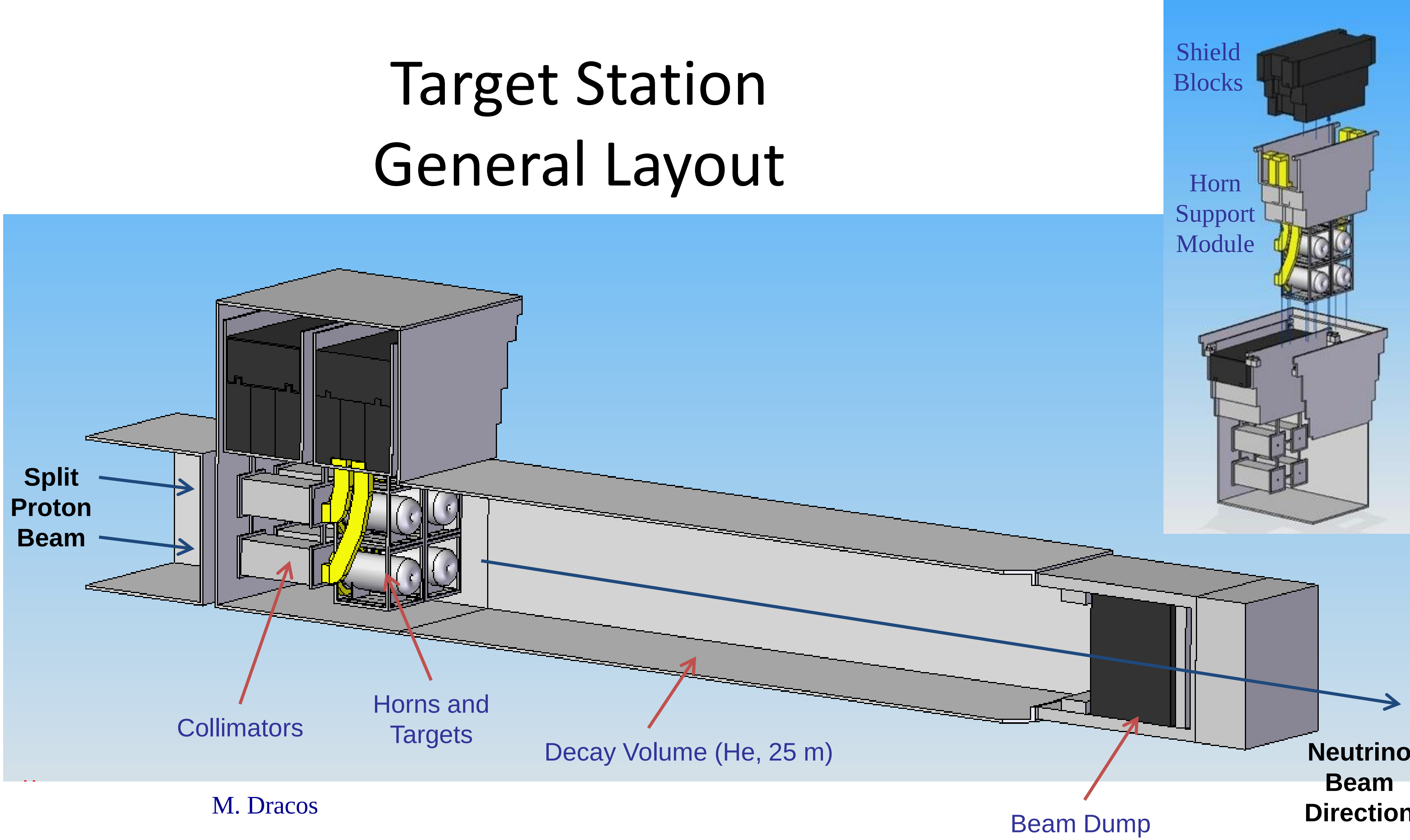
A key element for generating a neutrino beam is the hadron collector, also called neutrino horn, used to focus in the forward direction the charged pions produced in the proton-target collisions

A pulsed power supply able of providing the very high current (~350 kA) to be circulated inside the horn at the required pulse rate has not been produced so far and thus needs to be prototyped.



Furthermore, the time duration of this high current pulse can only be of a few microsecond to not overheat the horn. This implies that the ESS pulse length of ca 3 milliseconds has to be shortened by ca 2000 times using a **storage ring** in which the whole 3 ms long pulse is accumulated by multi(2000)-turn injection and then ejected in one turn. To obtain a 1.5 μs pulse the ring should have a **450 m circumference.**

Target Station General Layout



M. Dracos