Megawatt targets for Neutrino Super-Beams

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LBNE study in collaboration with : Patrick Hurh, Bob Zwaska, James Hylen, Sam Childress, Vaia Papadimitriou (Fermilab)

+ T2K Beam Group

+ LAGUNA/LBNO/CN2PY Study Group

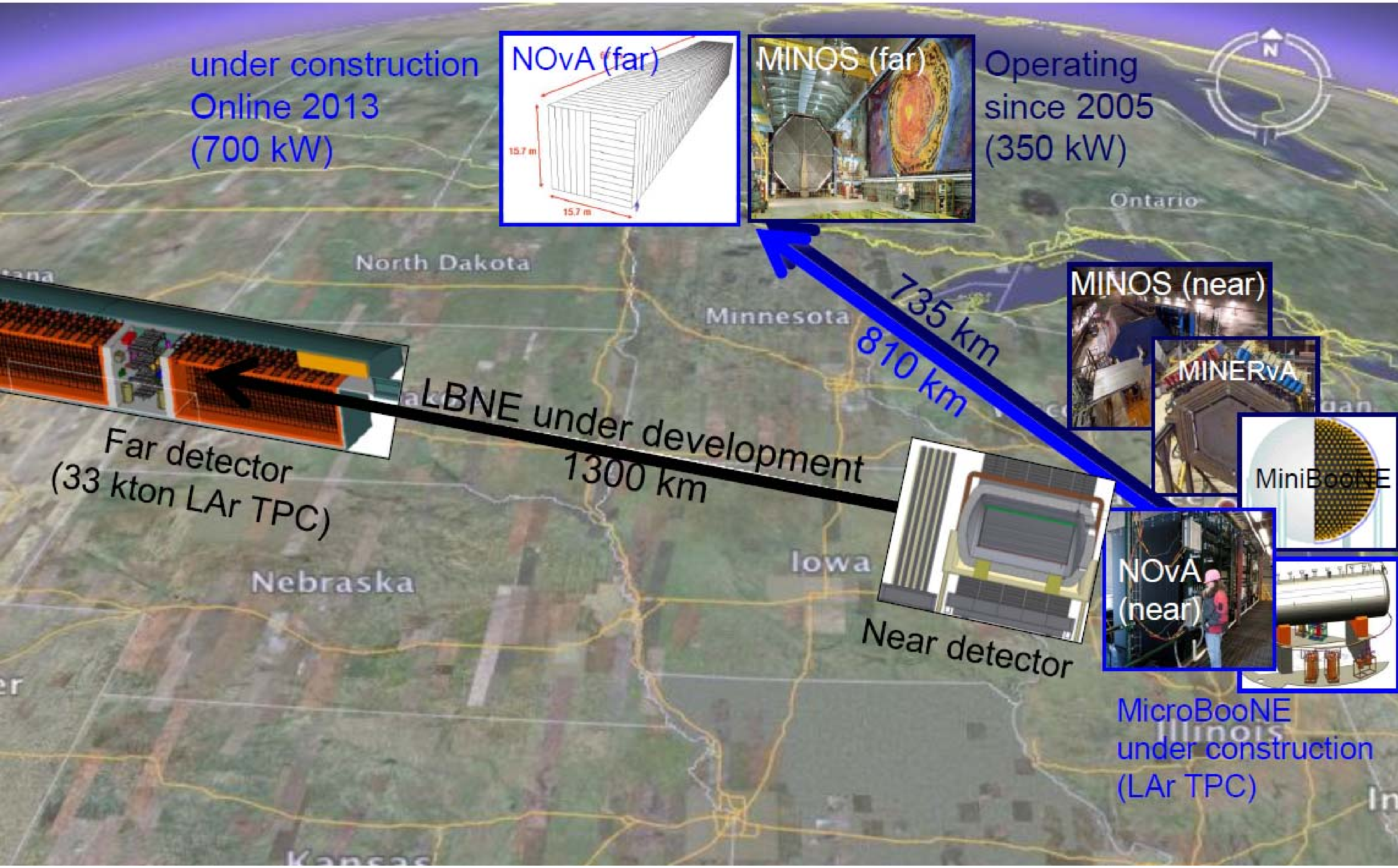
'Conventional' neutrino beams: where we are

	Fermilab NuMI/NOvA	JPARC T2K	CERN CNGS
Beam energy	120 GeV	30 GeV	400 GeV
Beam cycle	2.2 s	2.1 s	6 s
Spill length	10 μs	4.2 μs	2 x 10.5 μs
Design beam power	400 kW	750 kW	750 kW
Maximum beam power to date	375 kW	230 kW	311 kW (448 kW over 30s)
Beam size (rms)	1.1 mm	4.2 mm	0.5 mm
Physics	ν_μ disappearance	$\nu_\mu \rightarrow \nu_e$ appearance, ν_μ disappearance	$\nu_\mu \rightarrow \nu_\tau$ appearance
First beam	2005	2009	2006

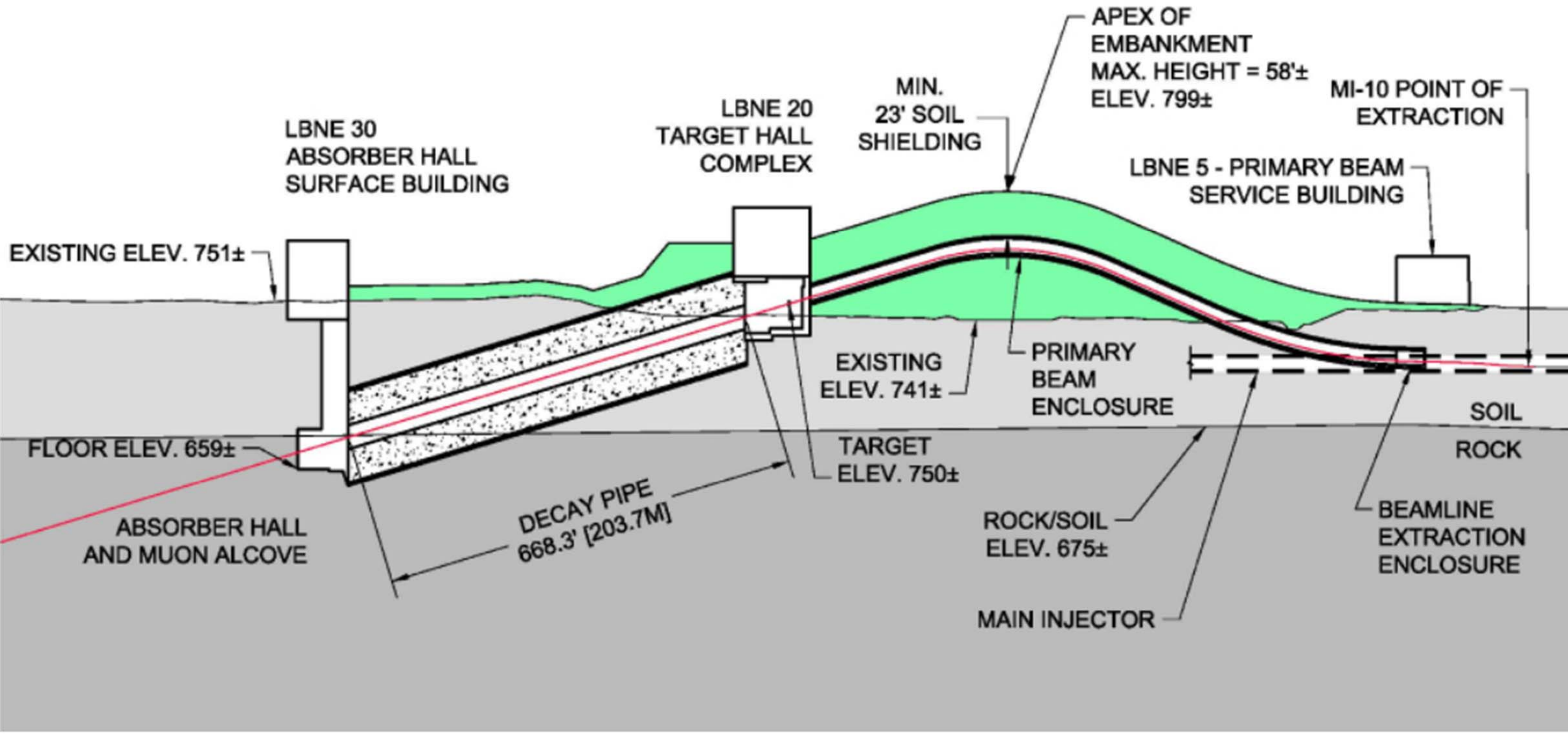
Neutrino 'Superbeams' : where we want to go

	Fermilab LBNE (/Project X)	JPARC T2K Long term plan (2018-)	CERN CN2PY/LBNO (Phase 2)
Design beam power	2.3 MW	3.2 MW	2 MW
Beam energy	120 GeV	50 GeV	50 (70)GeV
Rep rate	0.75 Hz	1 Hz	1.33 Hz
Beam sigma (range)	1.5 – 3.5 mm	4.2 mm	
Heat load in: C Be Ti pebble bed	 10.5 – 23.1 kW	~100 kW	

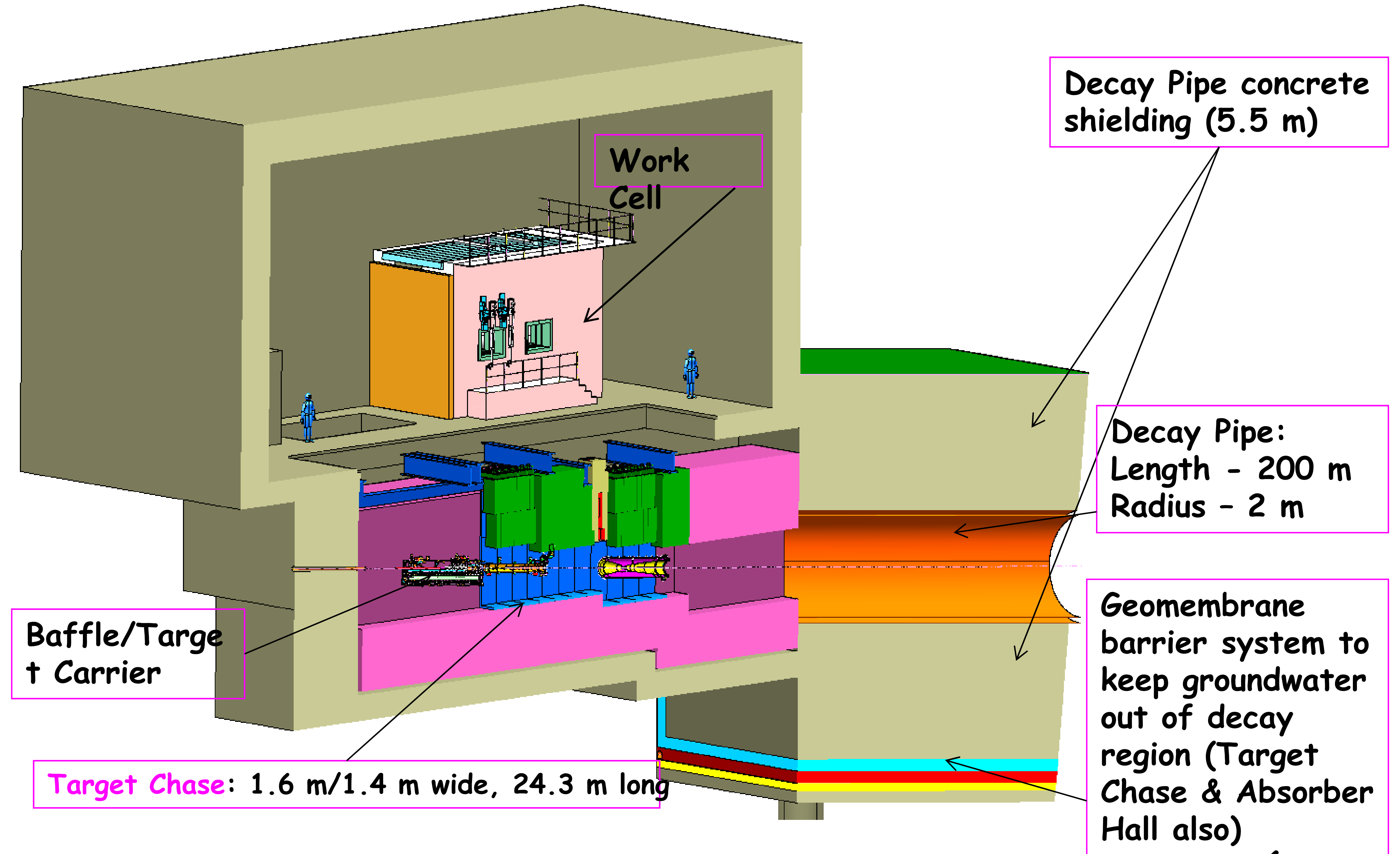
Neutrino Program at Fermilab



LBNE Overview

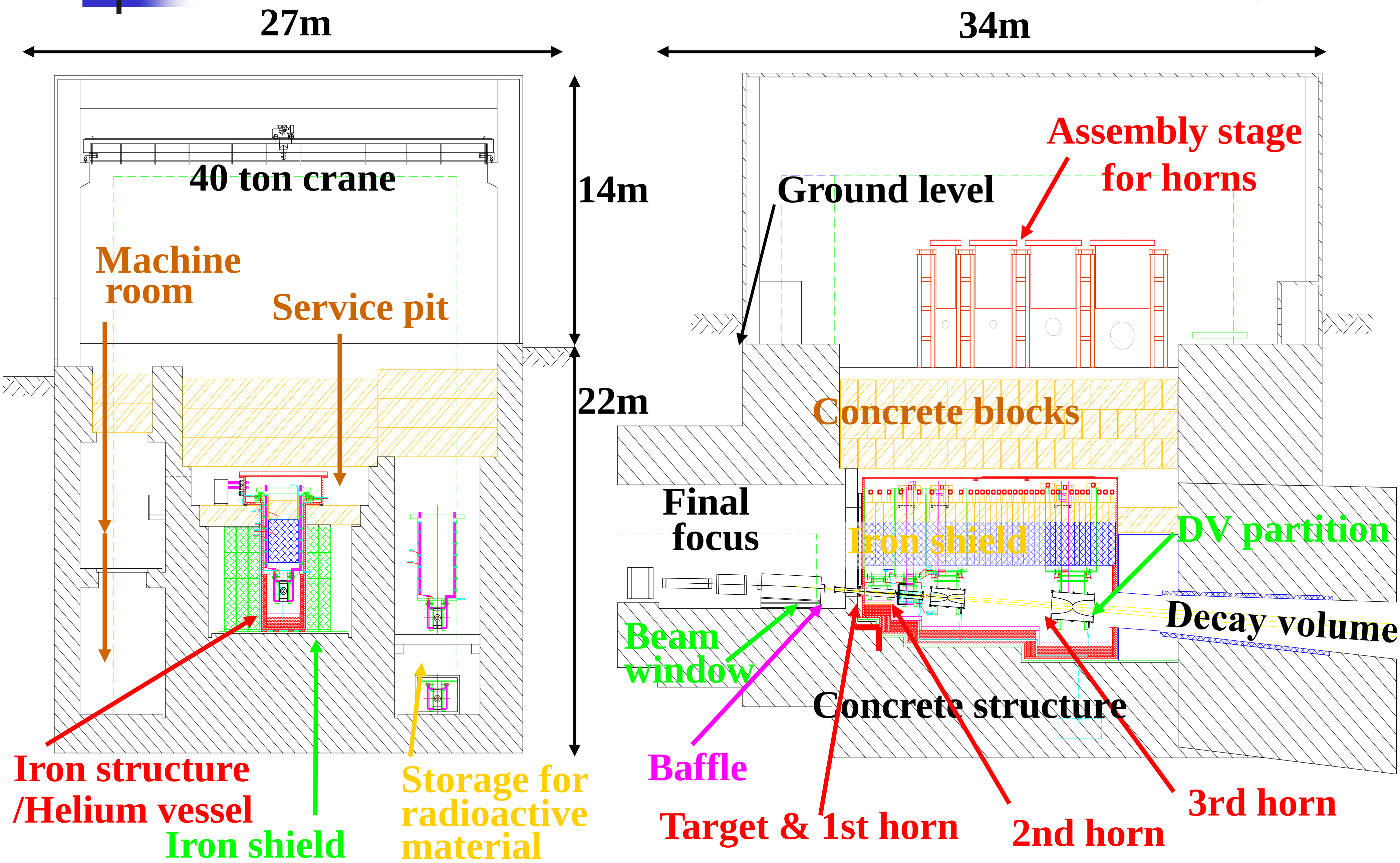


LBNE Target Facility – for 2.3 MW operation

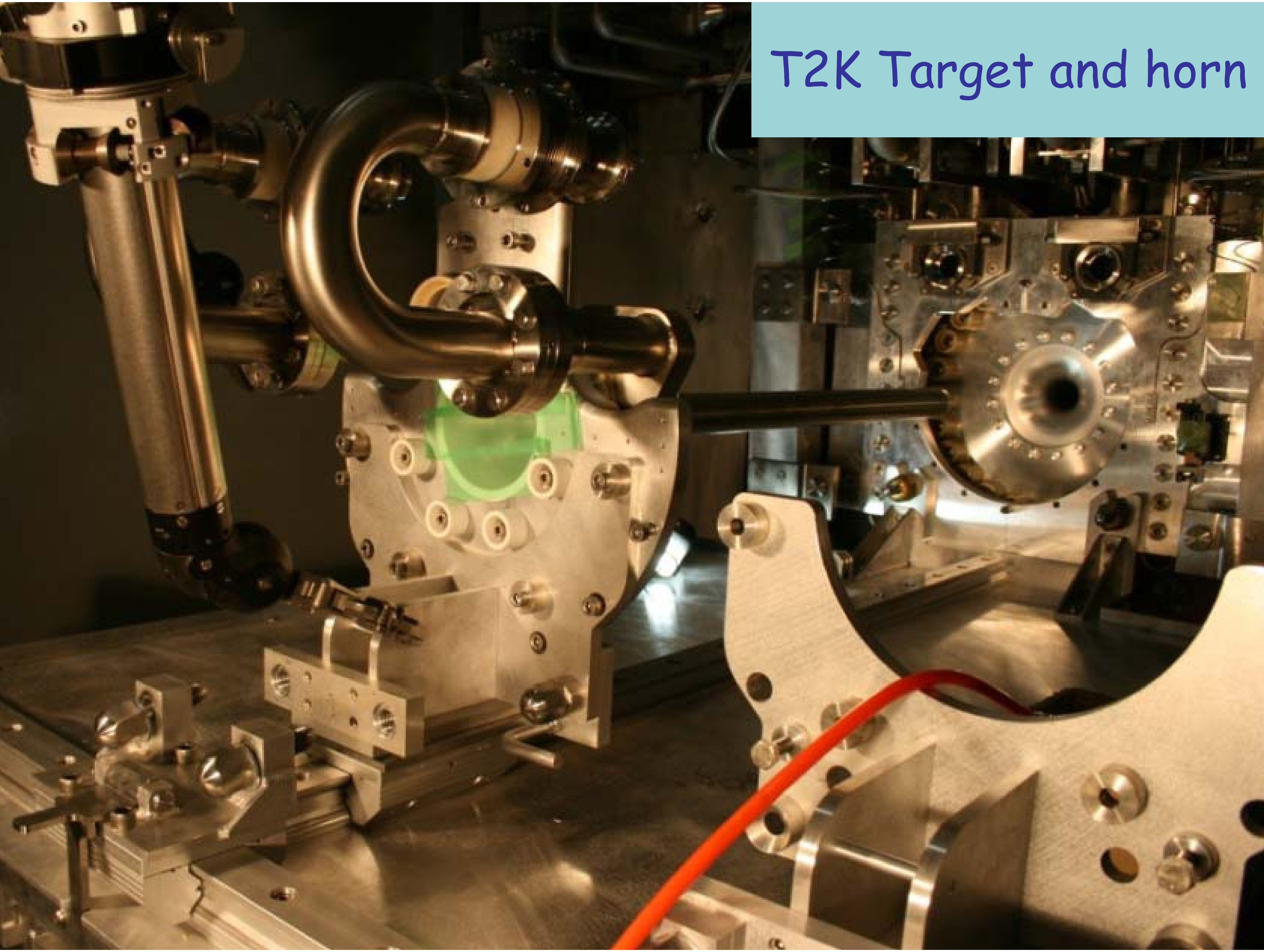


T2K Target Station for 4 MW

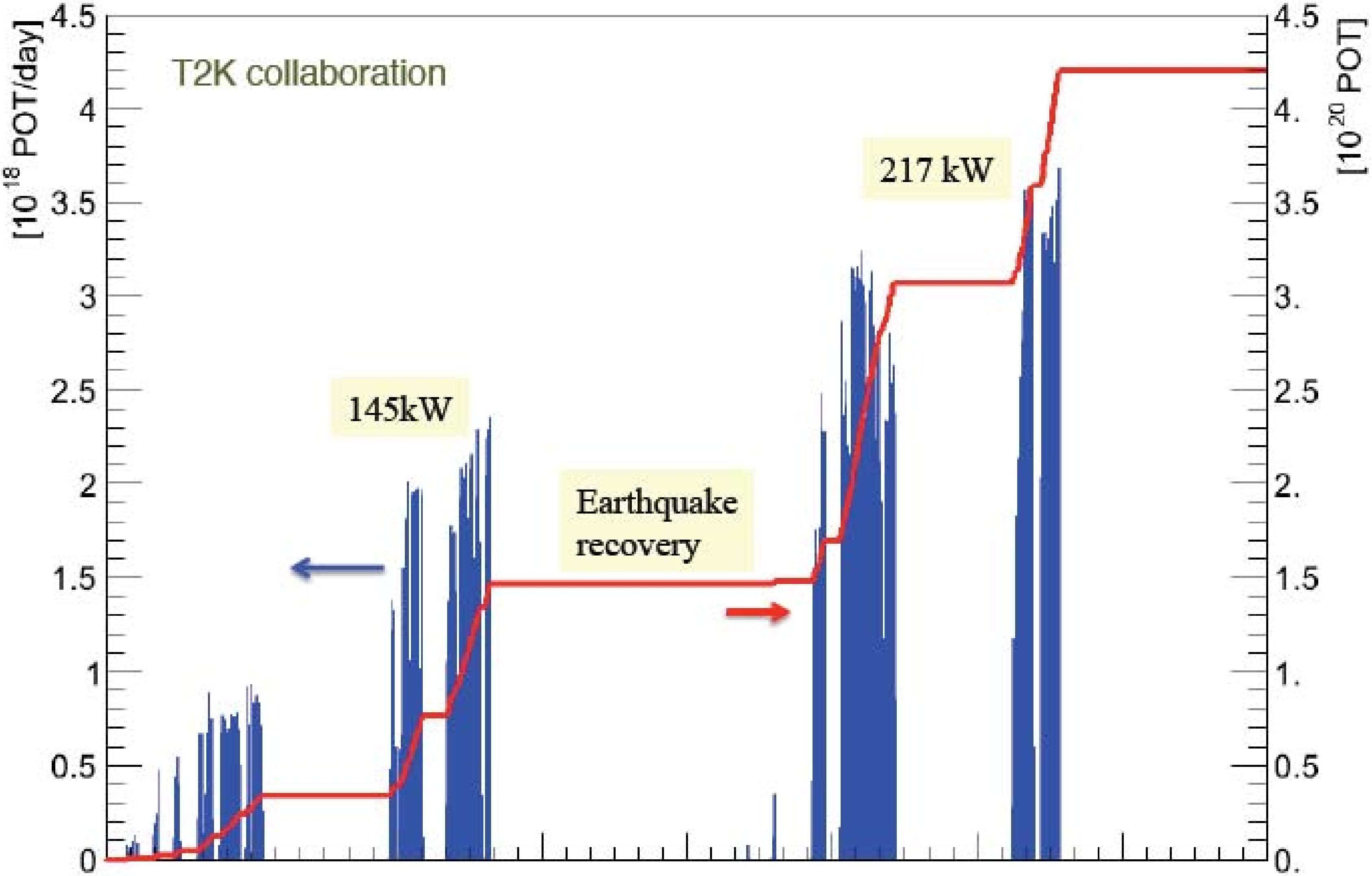
Y.Yamada



T2K Target and horn



History of delivered beam to the T2K experiment



Beam delivery to the T2K experiment in 2012 finished on Dec. 14.
Accumulated number of proton ~4.2 x10^{20} POT.

T2K: Plans for 8 GeV Booster Ring for 2-3 MW

Tadashi Koseki (KEK)

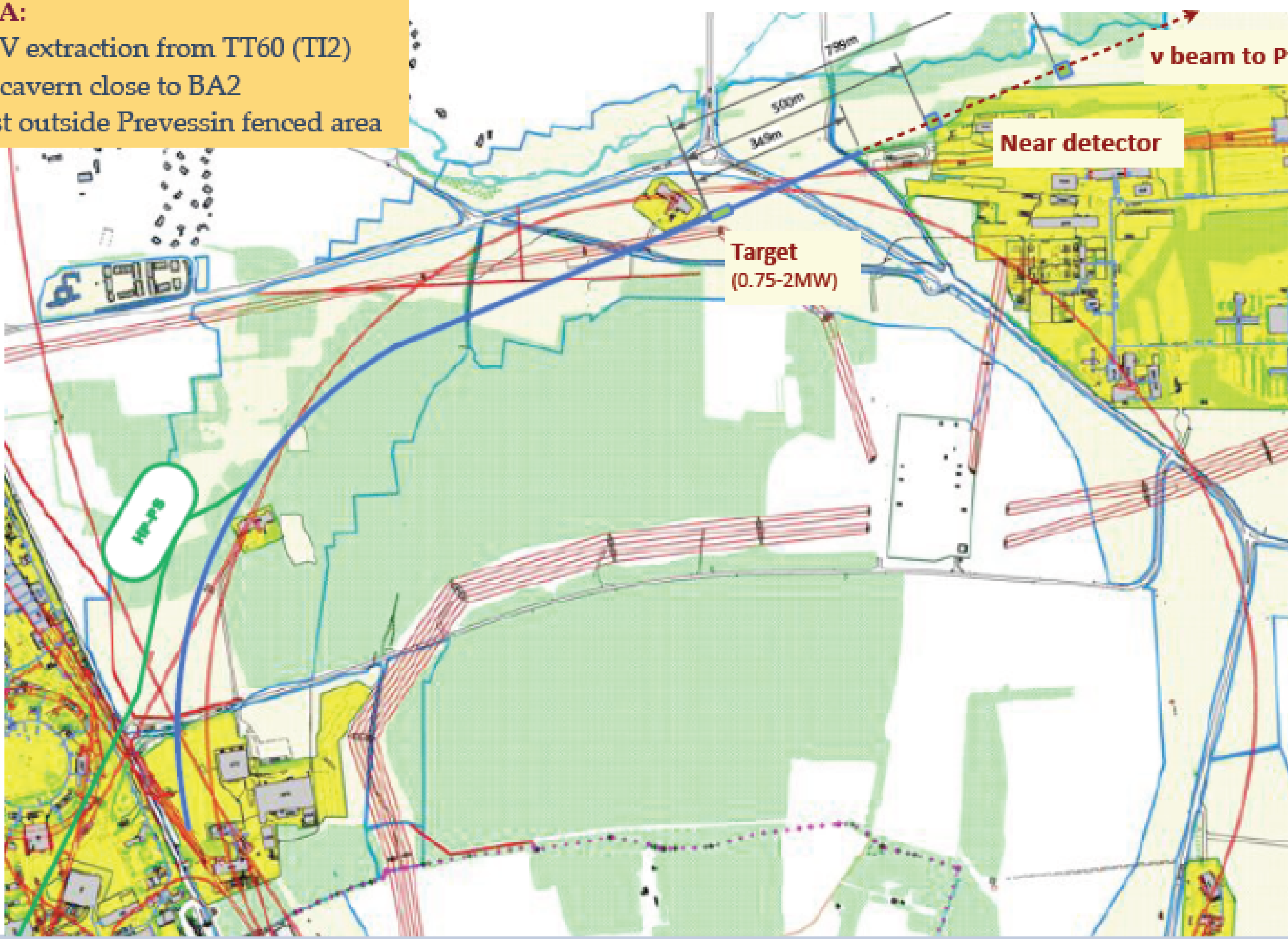
CN2PY – Layout Options

Update since CERN Meeting – October'12

For the **WP4 Layout Study Group**:
M. Calviani, I. Efthymiopoulos, B. Goddard, A. Kosmicki, J.Osborne, Y. Papaphilippou, R. Steerenberg, P. Velten. H.Vincke

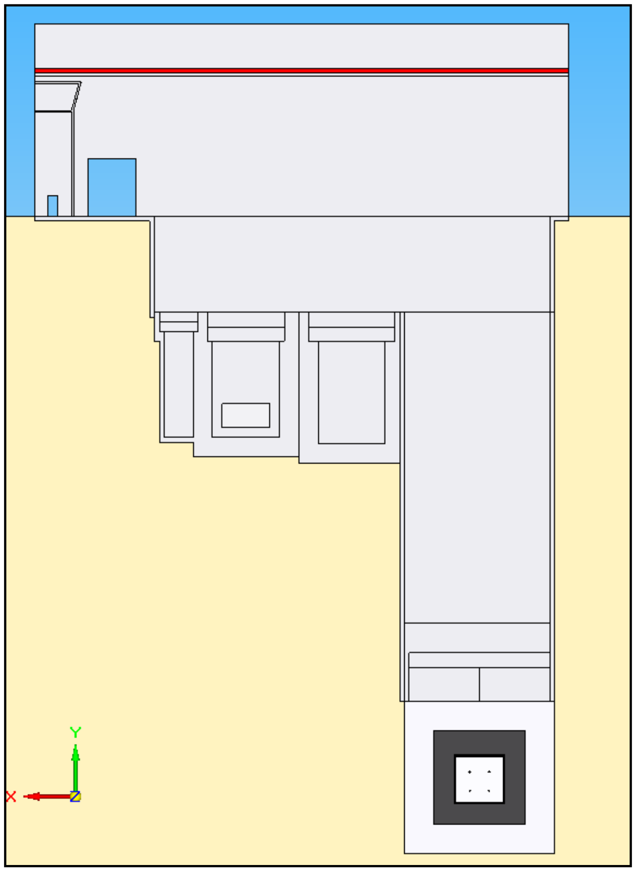
CERN ν-beam to Pyhäsalmi - CN2PY : Option-A

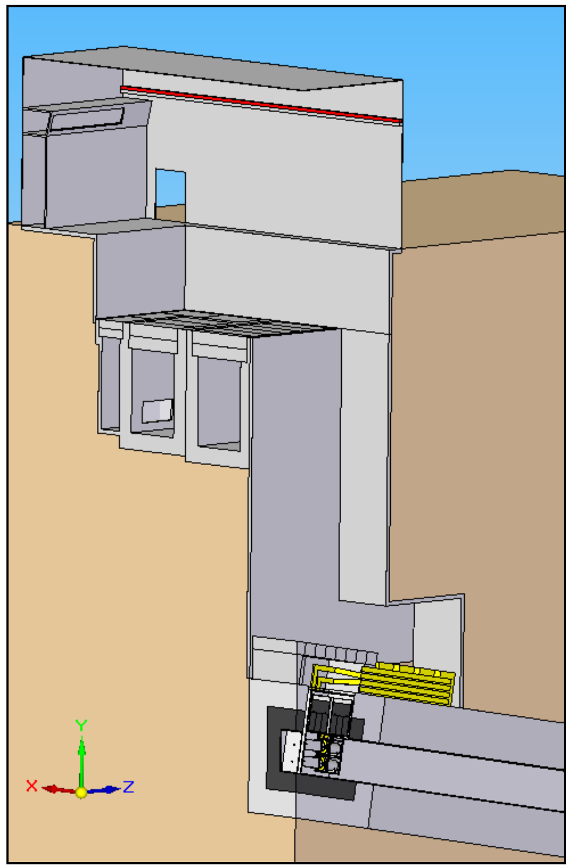
Option A:
- 400 GeV extraction from TT60 (TI2)
- Target cavern close to BA2
- ND just outside Prevessin fenced area

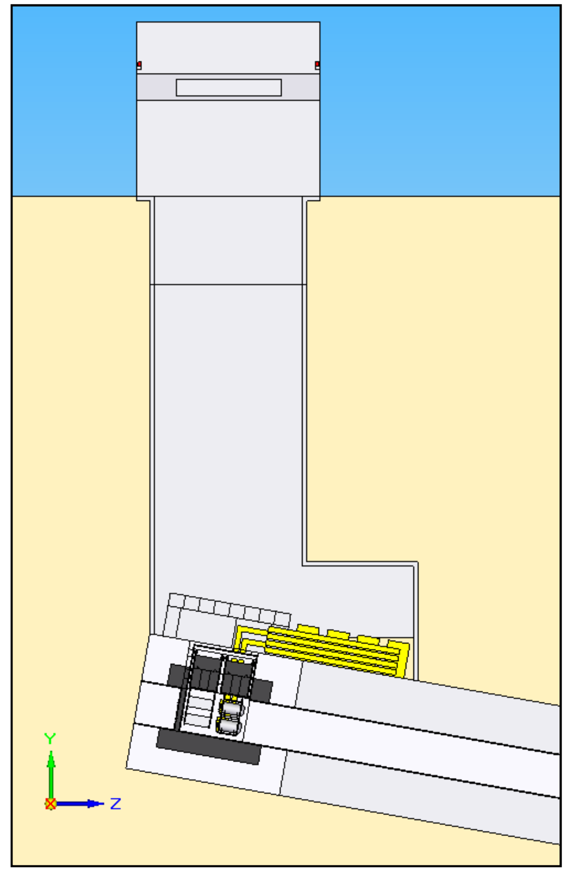


Preliminary Concept for CN2PY

- Keep as many buildings as possible at the surface to keep construction costs down
  - Must have a shaft to access the horns and targets
  - Power supplies (or transformers) must be underground, close to the beamline
  - The pump house may also be underground, depending on the acceptable pressure drop







Drawings not to scale: number and layout of horns will be different in practice, as will beamline dimensions

Dan Wilcox

CERN ν-beam to Pyhäsalmi - CN2PY

CN2PY beam

- **Phase 1** : use the 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 the new HP-PS
  - **50**(70) GeV, 1.33 Hz, 1.9 10^{14} ppp, **2 MW** nominal beam power, 4 μs pulse

Requirements - layout

- Use the same secondary beam elements for both beams
  - sufficient shielding to contain the produced radiation
    - including muons, water and soil activation (H3 and NA22 production)
  - target and focusing elements (horns) with similar parameters
    - same layout or allow variations already from the design phase
    - don't have to be identical since anyhow are to be exchangeable
- Use the same beam decay volume, dump and near detector
  - deposited energy in target, shielding and dump would be × 2.7 higher for the Phase-II beam

- The facility layout is driven by the 400 GeV beam
- The target cavern layout (shielding) is driven by the 50(70) GeV beam and the 2MW of power

Target Basics (J.Hylen)

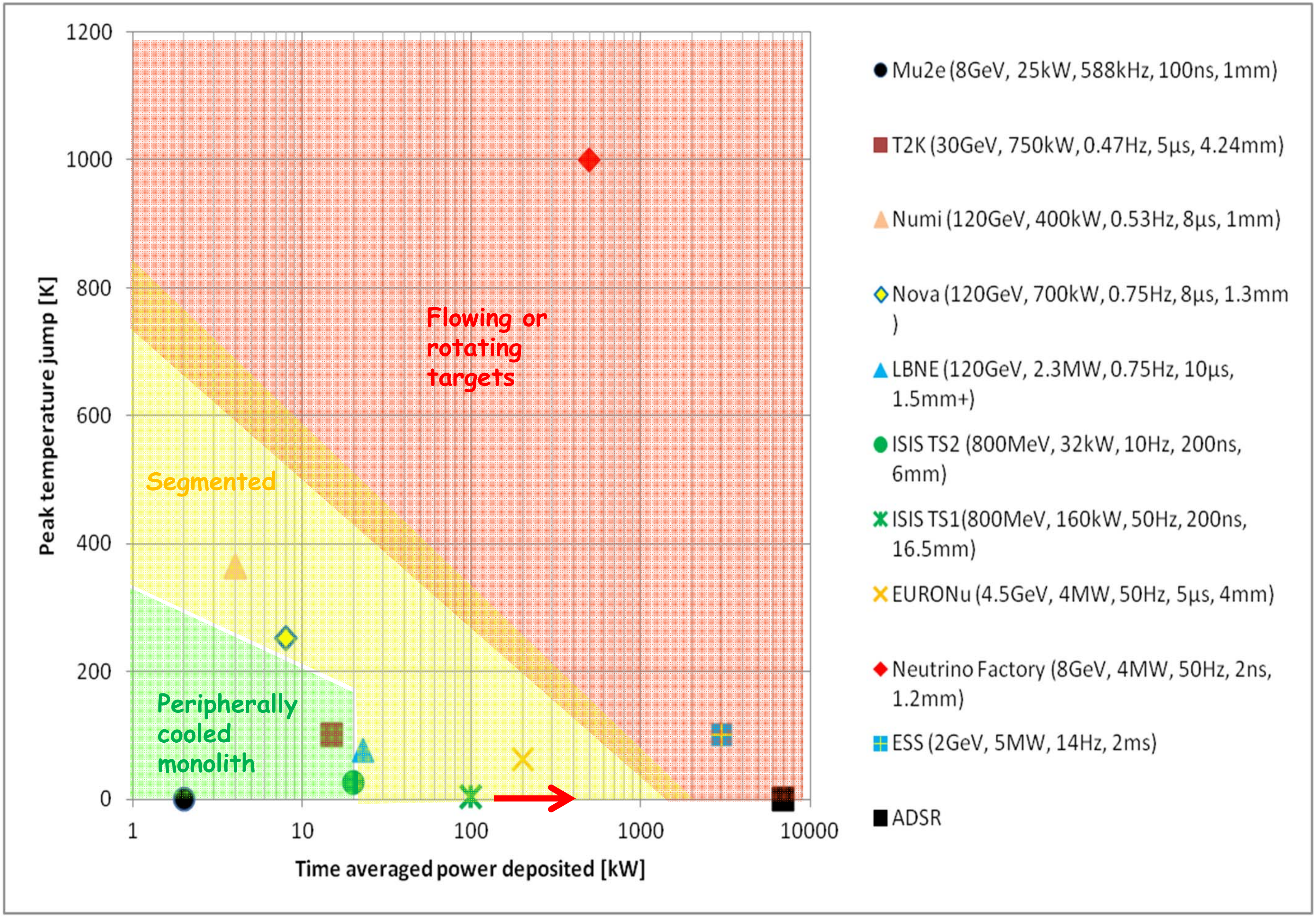
Long enough (2 interaction lengths) to interact most protons
Dense enough that 2 λ_{int} fits in focusing system depth-of-field
Radius: R_{target} = 2.3 to 3 R_{beam} (minimize gaussian tails missing target)
Narrow enough that pions exit the sides without re-absorption
(but for high E_{proton} and low E_{ν}, secondary shower can help)
High pion yield (but to first order, ν flux α beam power)
Radiation hard
Withstand high temperature
High strength (withstand stress from fast beam pulse)
Low density (less energy deposition density, hence less stress; don't re-absorb pions)
Low dE/dx (but not much variation between materials)
High heat capacity (less stress induced by the dE/dx)
Low thermal expansion coefficient (less stress induced by the dE/dx)
Low modulus of elasticity (less stiff material does not build up stress)
Reasonable heat conductivity
Reasonable electrical conductivity (monitor target by charge ejection)

CNGS, NuMI, T2K all using graphite

Existing target technologies

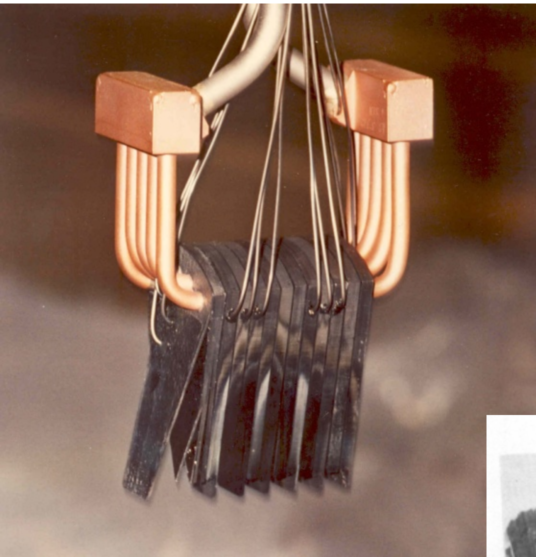
	NuMI/NOvA	CNGS	T2K
Target material	Graphite: POCO ZXF-5Q	Graphite and Carbon-carbon	Graphite: IG 430
Target arrangement	Subdivided	subdivided	monolithic
Cooling	Water (forced convection)	Helium (natural convection)	Helium (forced convection)
Limitations for higher power operation	•Radiation damage •Water hammer, cavitation •Hydrogen + tritium + water activation	• Only possible for low deposited heat loads	•Heat transfer •Radiation damage •High helium volumetric flow rate (and high pressure or high pressure drops)

Limitations of target technologies



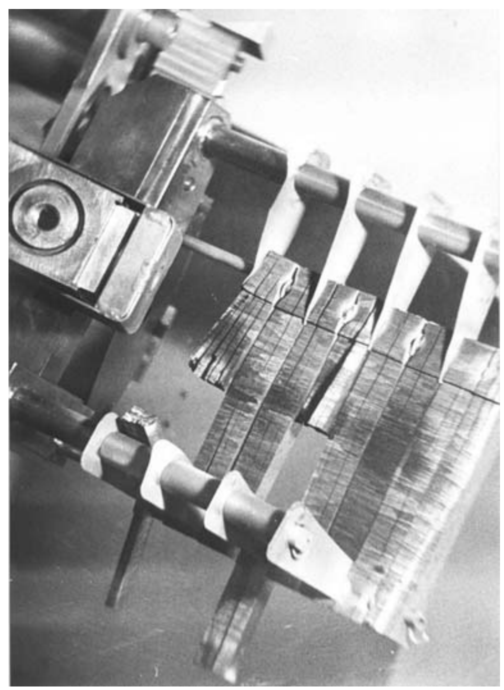
Ashes to ashes, dust to dust...

Effect of proton beams on some graphite targets

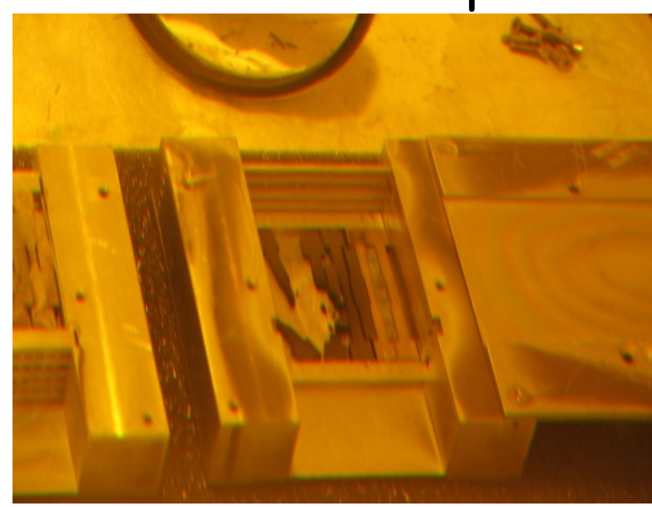


LAMPF fluence 10^22 p/cm2

PSI fluence 10^22 p/cm2



BNL tests: fluence ~10^21 p/cm2



Physics vs Engineering Optimisation ? Target and Beam Dimensions

- For pion yield – smaller is better
  - Maximum production and minimum absorption (shown by FoM)
- For target lifetime – bigger is better
  - Lower power density – lower temperatures, lower stresses
  - Lower radiation damage density
- For integrated neutrino flux, need to take both neutrino flux and lifetime factors into account
  - Want to make an assessment of trade off between target lifetime vs beam and target dimensions
  - Answer will depend on Target Station engineering (time to change over target and horn systems)

Target configurations considered for Superbeams

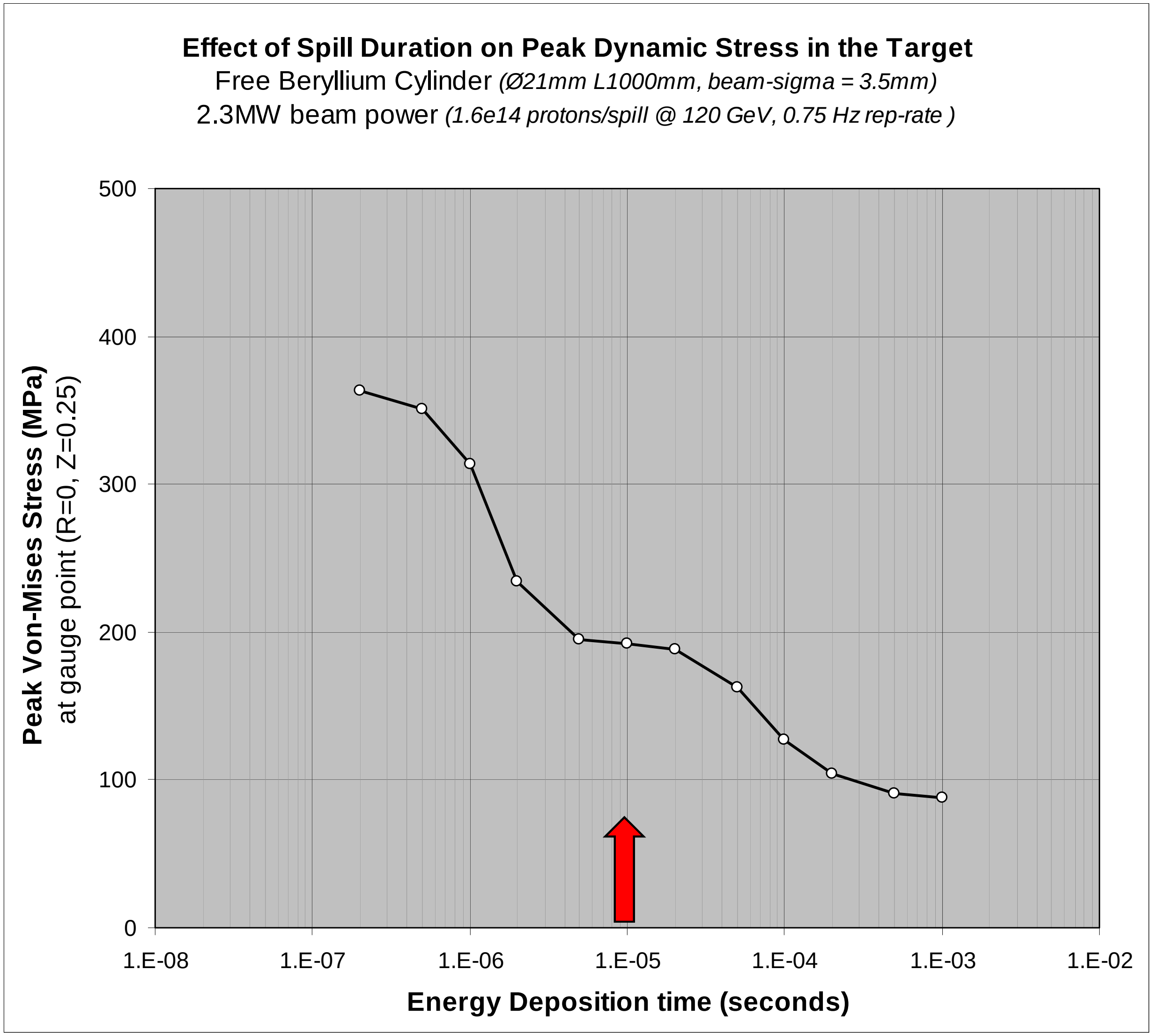
1. LBNE at Fermilab

- Integral target and horn inner conductor
  - Solid Be rod
  - water spray cooled
- Separate target installed inside bore of horn inner conductor
  - Graphite, water cooled (IHEP study (baseline))
  - Be: subdivided in z, water cooled
  - Be: spheres, helium cooled

2. EUROnu SuperBeam using high power SPL at CERN
   4-horn system (4 x 12.5 Hz)

- ‘Pencil’ shaped beryllium rod
- ‘Packed bed’ of titanium beads
- Integral target and horn inner conductor
- (Graphite excluded due to radiation damage concerns)

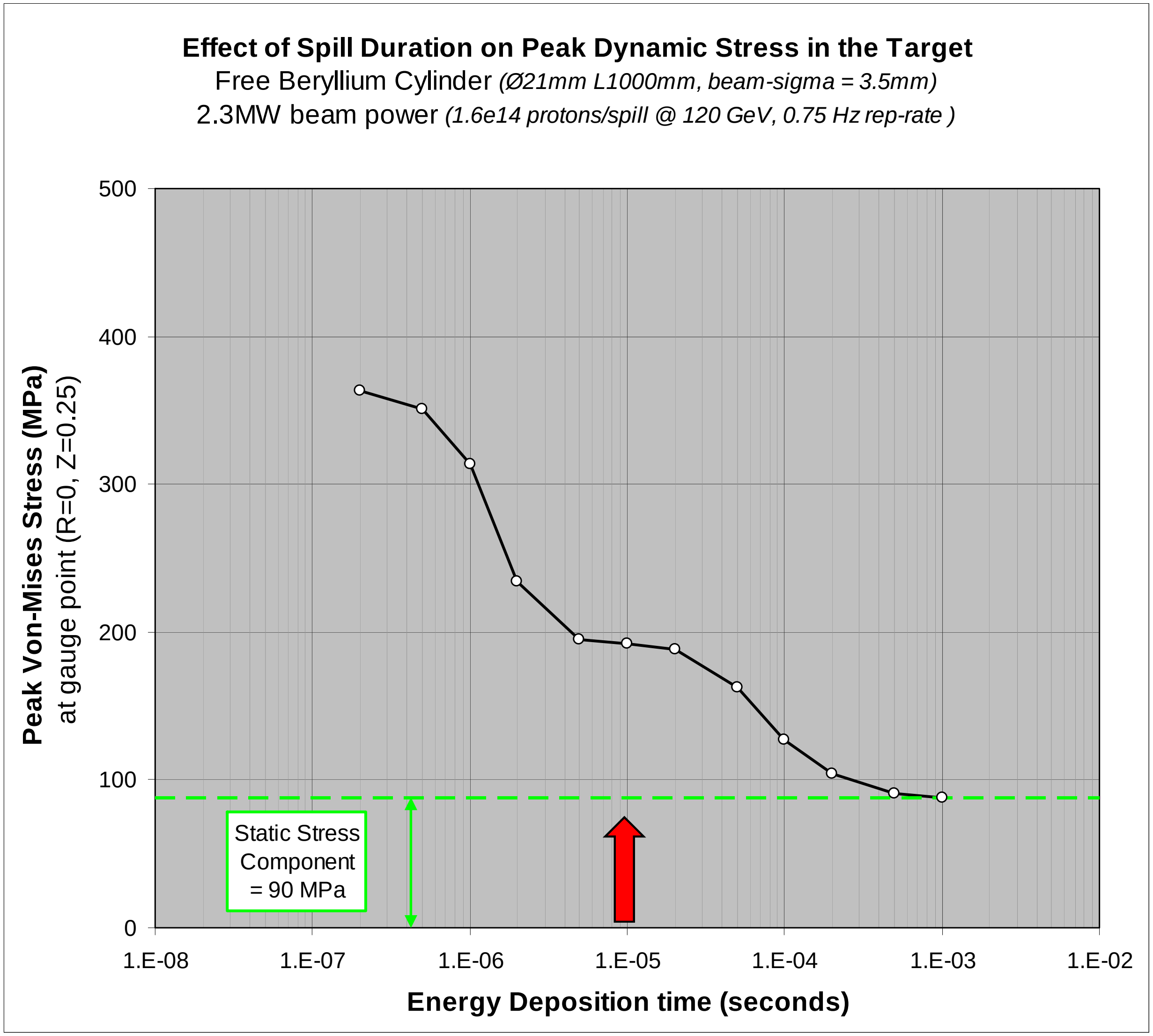
LBNE Beryllium rod target: Stress-Waves



Effect of beam spill time on the peak dynamic stress in the target

LBNE Beryllium rod target: Stress-Waves

- “static” stress component is due to thermal gradients
  - Independent of spill time



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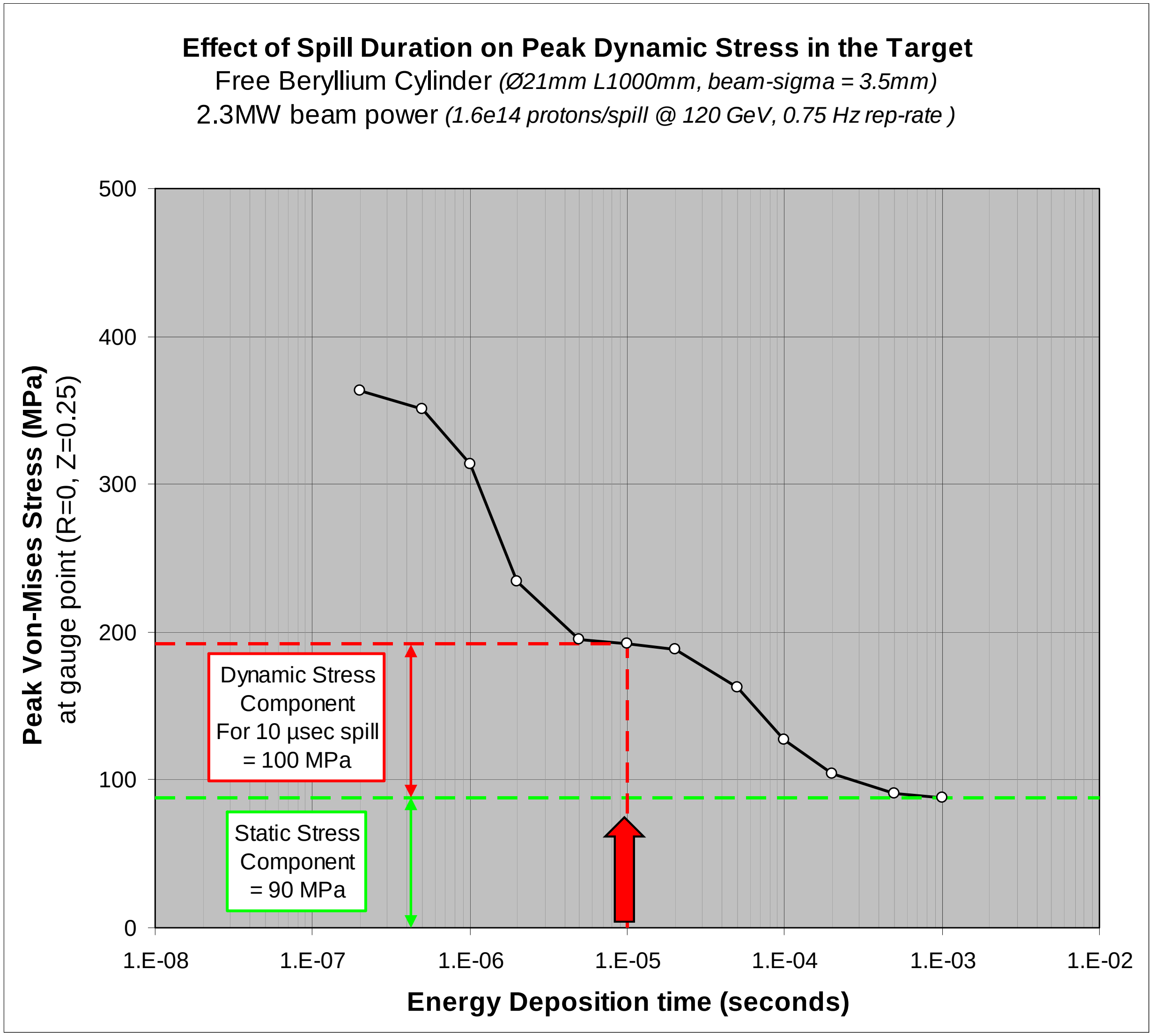

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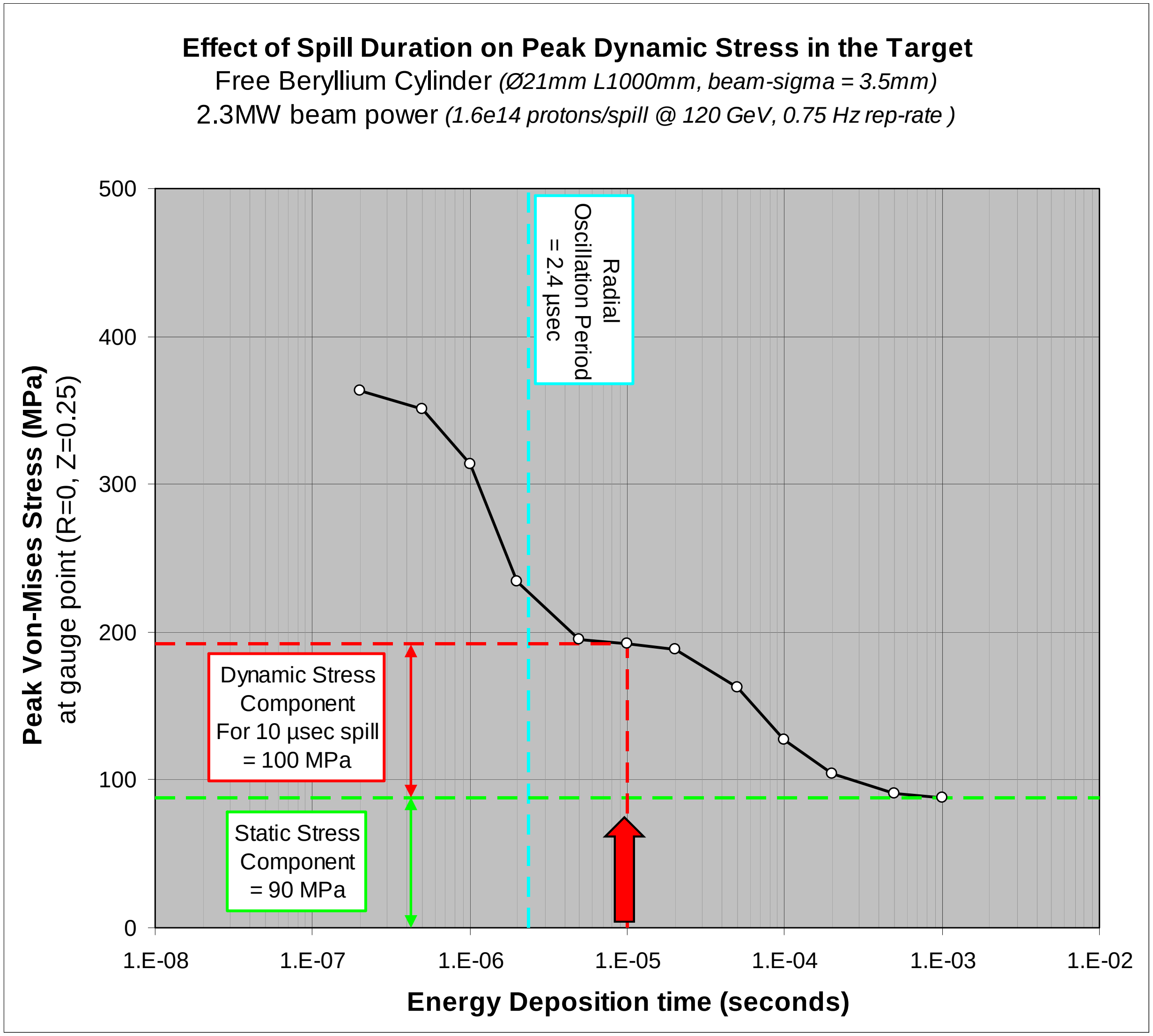
- “dynamic” stress component is due to stress waves
  - Spill time dependent
- Tspill > Radial period
  - Radial stress waves are not significant



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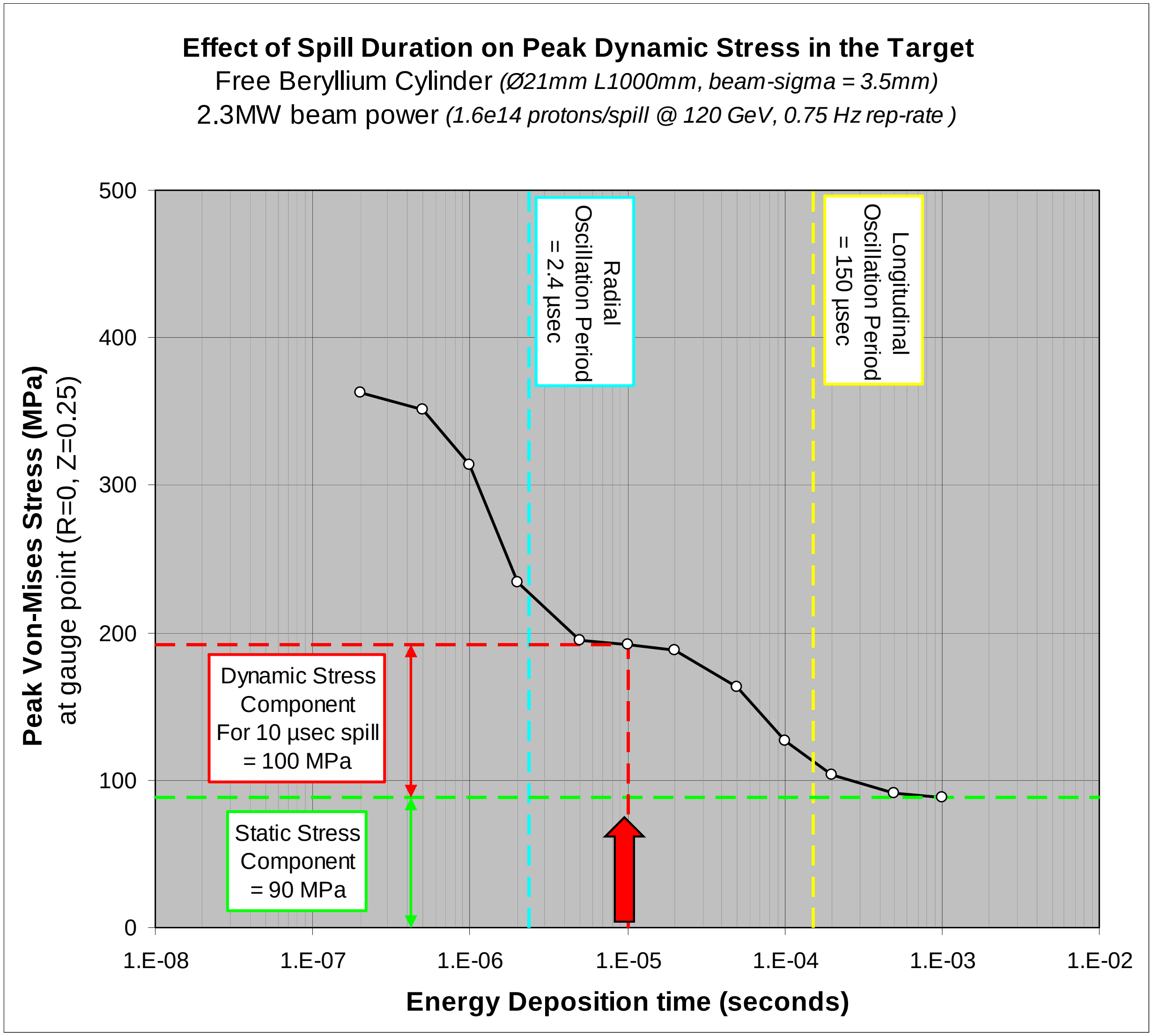
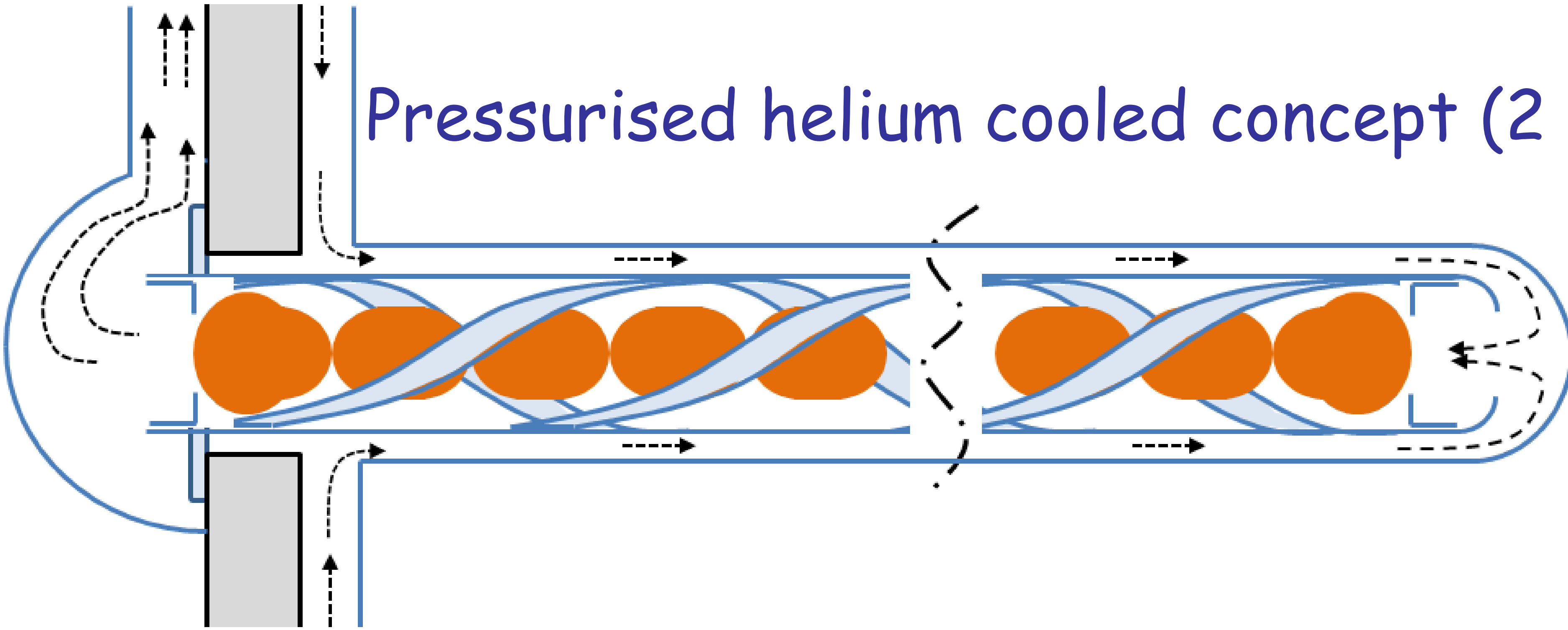
LBNE Beryllium rod target: Stress-Waves

- "static" stress component is due to thermal gradients
  - Independent of spill time
- "dynamic" stress component is due to stress waves
  - Spill time dependent
- Tspill > Radial period
  - Radial stress waves are not significant
- Tspill < Longitudinal period
  - Longitudinal stress waves are important!



Effect of beam spill time on the peak dynamic stress in the target

Pressurised helium cooled concept (2 MW)



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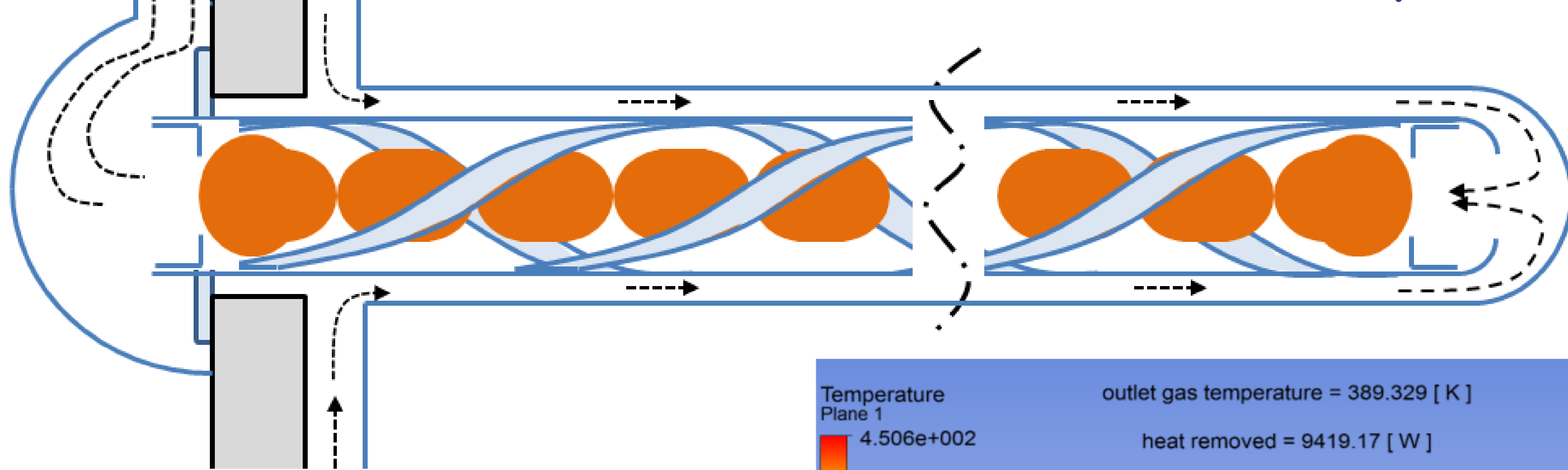
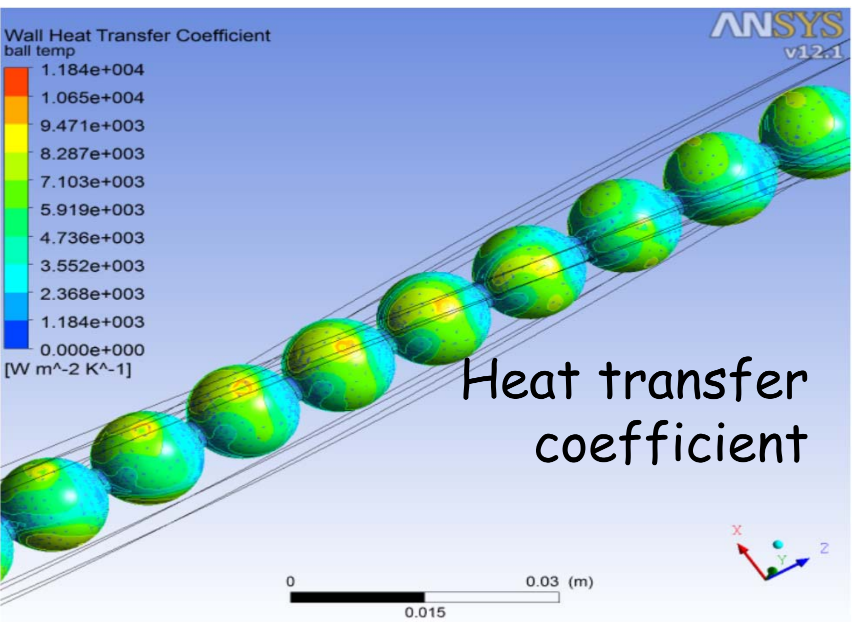
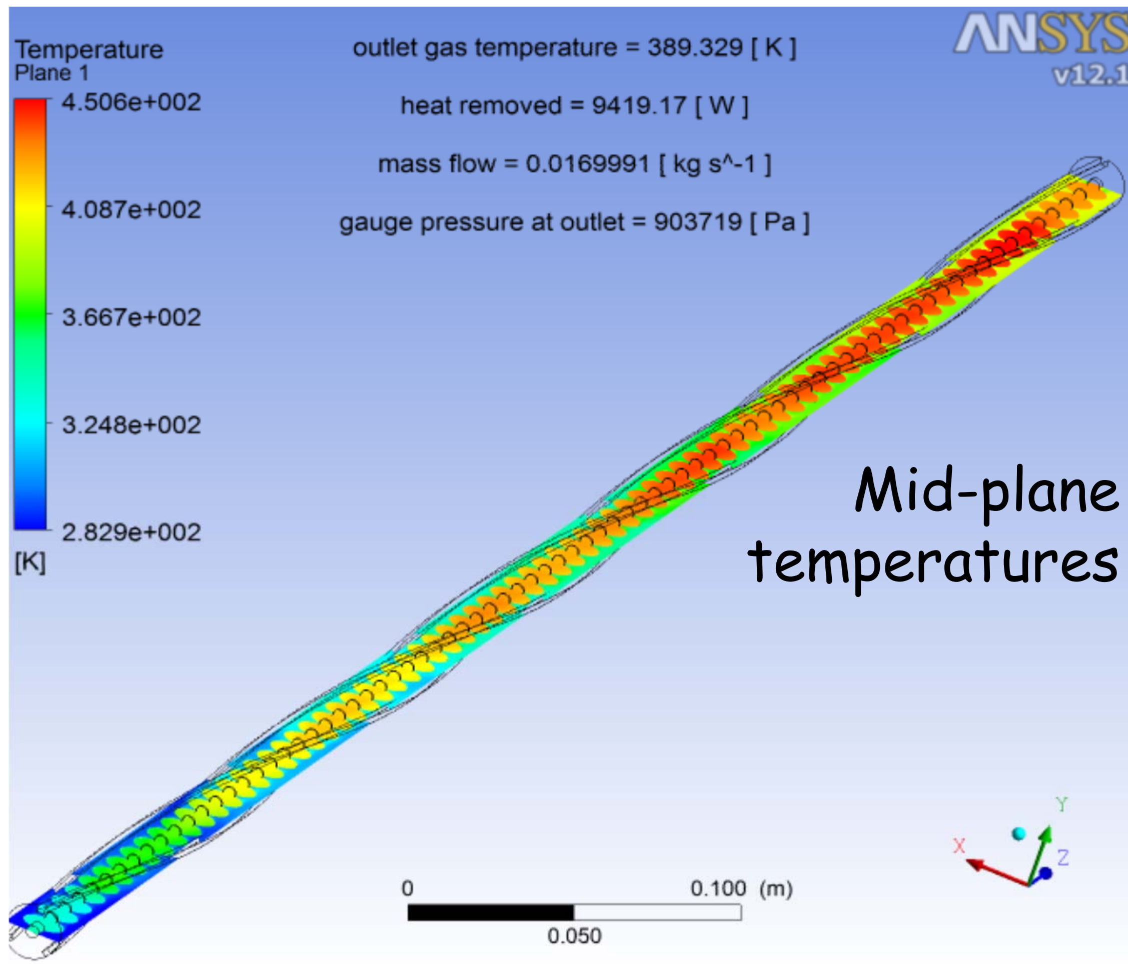






Otto Caretta & Tristan Davenne

Pressurised helium cooled concept (2 MW)

Beryllium sphere diameter	13 mm
Beam sigma	2.2 mm
Helium mass flow rate	17 g/s
Inlet helium pressure	11.1 bar
Outlet helium pressure	10 bar
Inlet velocity	40 m/s
Maximum velocity	185 m/s
Total heat load	9.4 kW
Maximum beryllium temperature	178 C
Helium temperature rise, ΔT (T_{in}-T_{out})	106 C

Otto Caretta & Tristan Davenne

Conclusions: ‘Divide and Rule’ for increased power

Dividing material is favoured since:

- Better heat transfer
- Lower static thermal stresses
- Lower dynamic stresses from intense beam pulses

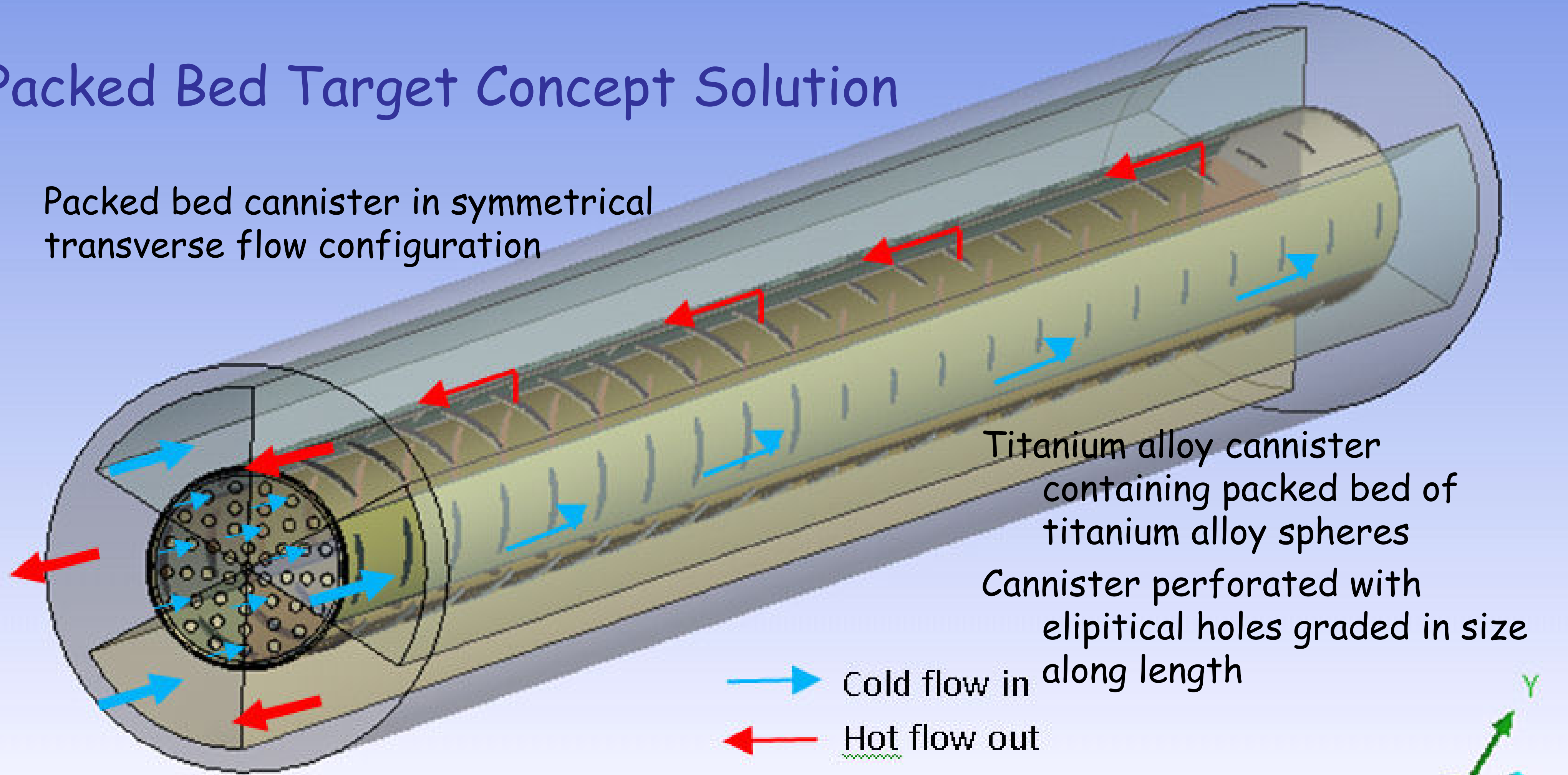
Helium cooling is favoured (cf water) since:

- No ‘water hammer’ or cavitation effects from pulsed beams
- Lower coolant activation, no radiolysis
- Negligible pion absorption – coolant can be within beam footprint
- For graphite, higher temperatures anneal radiation damage

Static, low-Z target concepts proposed

Packed Bed Target Concept Solution

Packed bed cannister in symmetrical transverse flow configuration



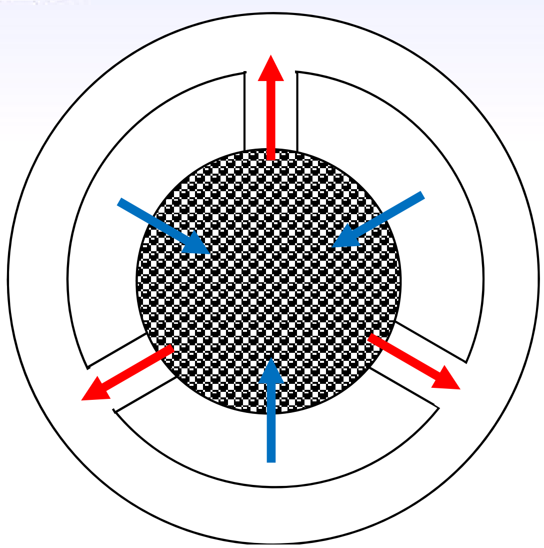
Titanium alloy cannister containing packed bed of titanium alloy spheres

Cannister perforated with elipitical holes graded in size along length

Cold flow in

Hot flow out

T.Davenne



Model Parameters

Proton Beam Energy = 4.5GeV

Beam sigma = 4mm

Packed Bed radius = 12mm

Packed Bed Length = 780mm

Packed Bed sphere diameter = 3mm

Packed Bed sphere material : Titanium Alloy

Coolant = Helium at 10 bar pressure

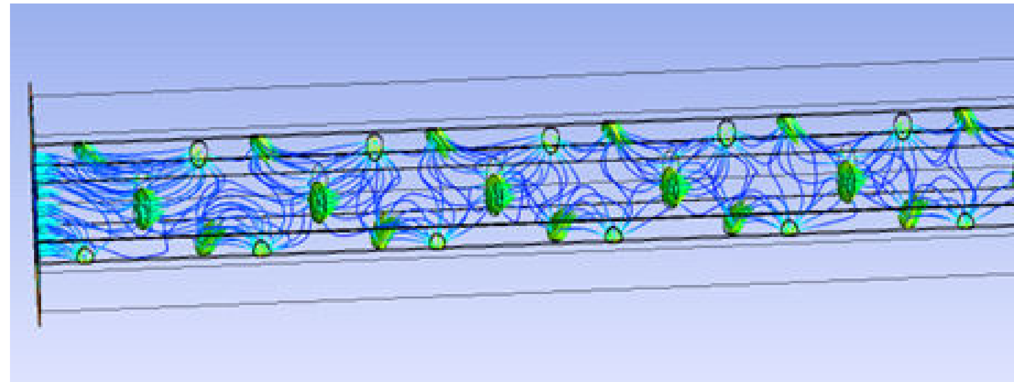
Particle bed advantages

- Large surface area for heat transfer
- Coolant can pass close to maximum energy deposition
- High heat transfer coefficients
- Low quasi static thermal stress
- Low dynamic stress (for oscillation period <<beam spill time)

... and challenges

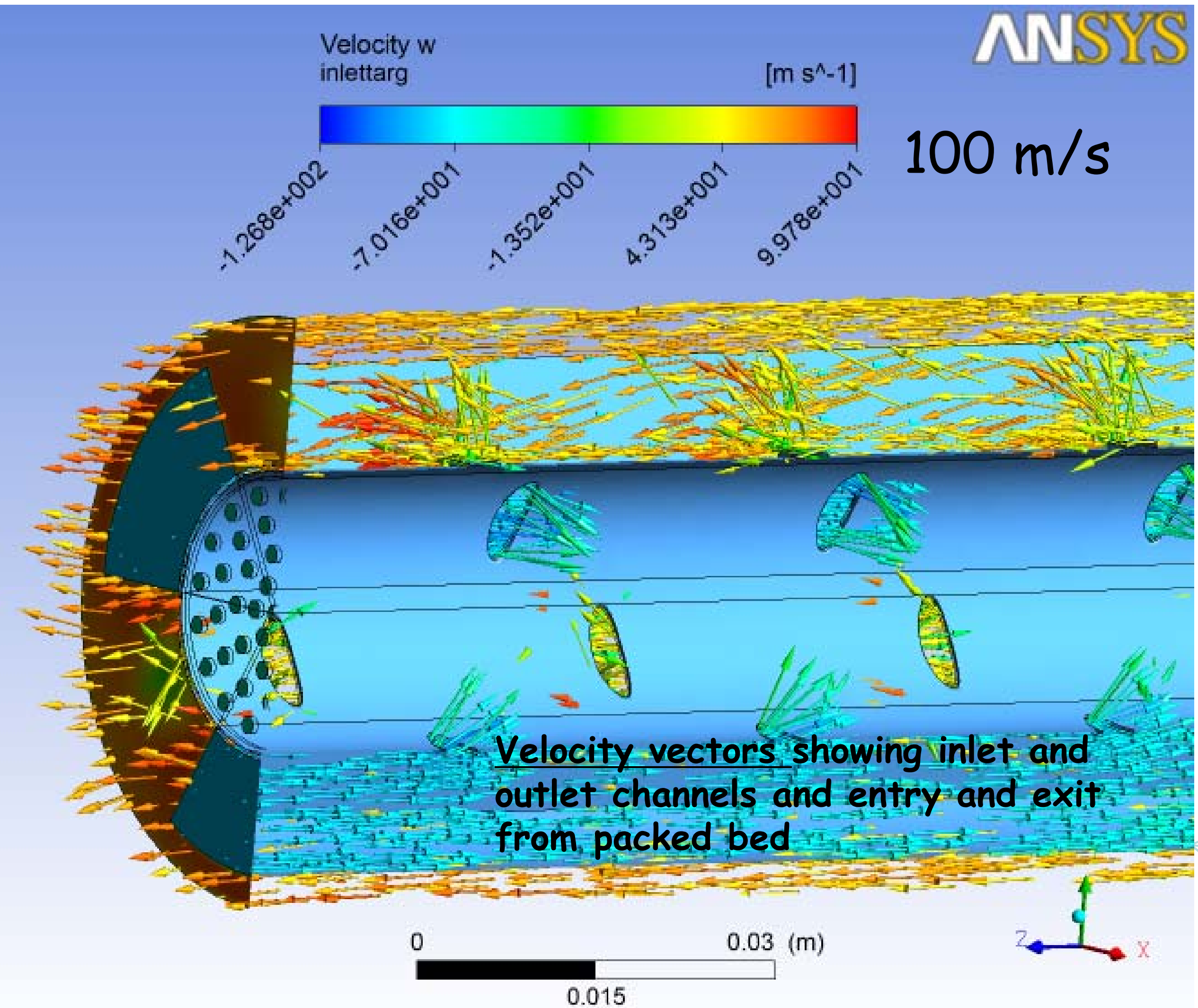
- High pressure drops, particularly for long thin superbeam target geometry
  - Need to limit gas pressure for beam windows
- Transverse flow reduces pressure drops – but
  - Difficult to get uniform temperatures and dimensional stability of container

Packed Bed Model (FLUKA + CFX v13)



Streamlines in packed bed

- Packed bed modelled as a porous domain
- Permeability and loss coefficients calculated from Ergun equation (dependant on sphere size)
- Overall heat transfer coefficient accounts for sphere size, material thermal conductivity and forced convection with helium
- Interfacial surface area depends on sphere size
- Acts as a natural diffuser flow spreads through target easily



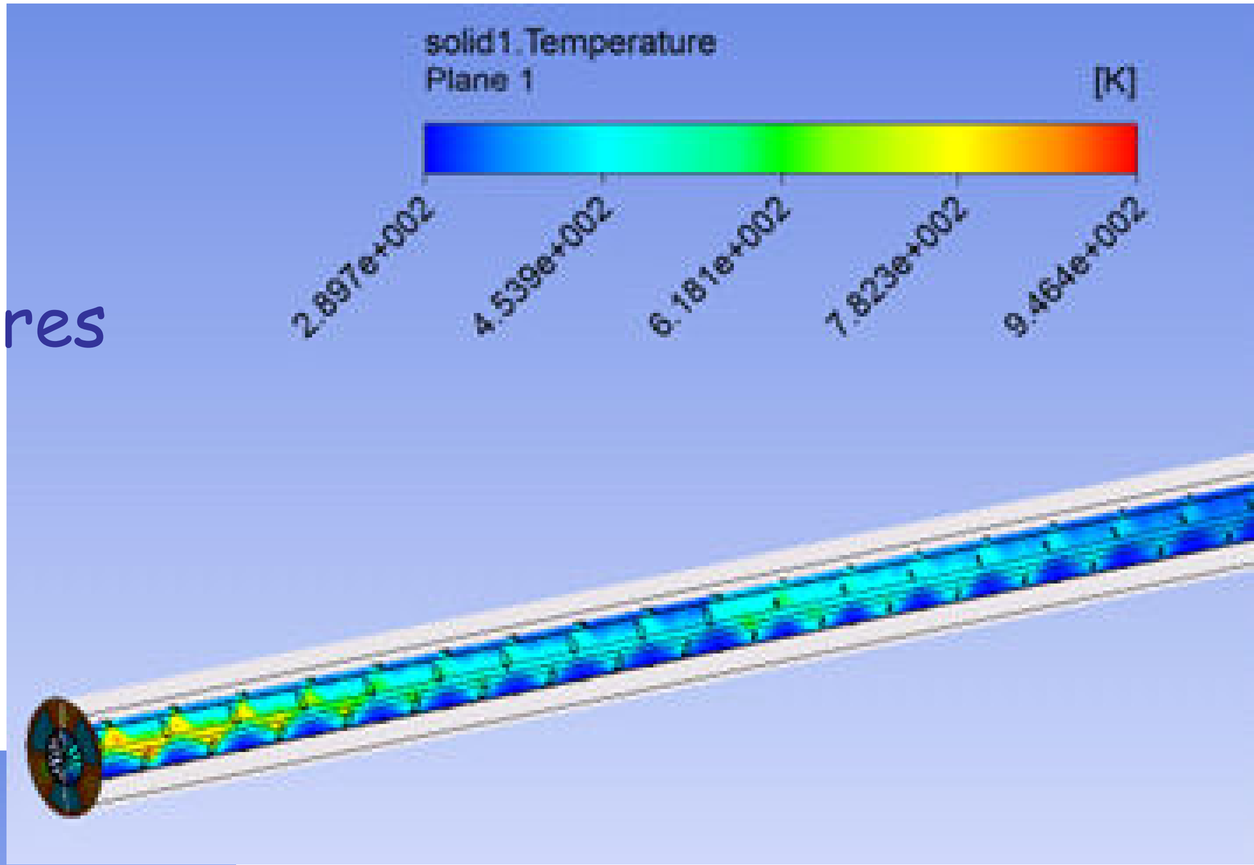
100 m/s

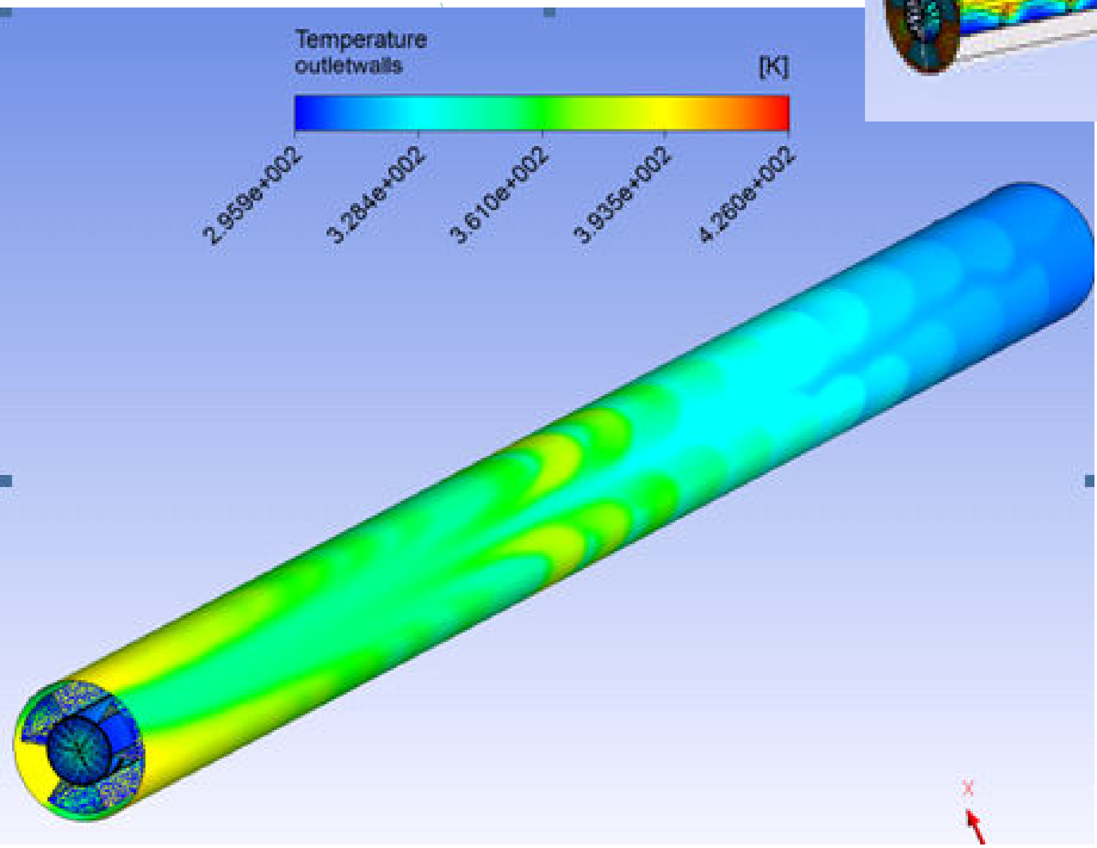
Velocity vectors showing inlet and outlet channels and entry and exit from packed bed

T.Davenne

High Power Targets

Packed Bed temperatures





<u>Outer Can Surface Temp</u>

Almost Symmetric Temperature contours

Maximum surface Temperature = 426K = 153° C

<u>NB windows not included in model yet</u>

<u>- Double skin Be should withstand both heat and pressure loads</u>

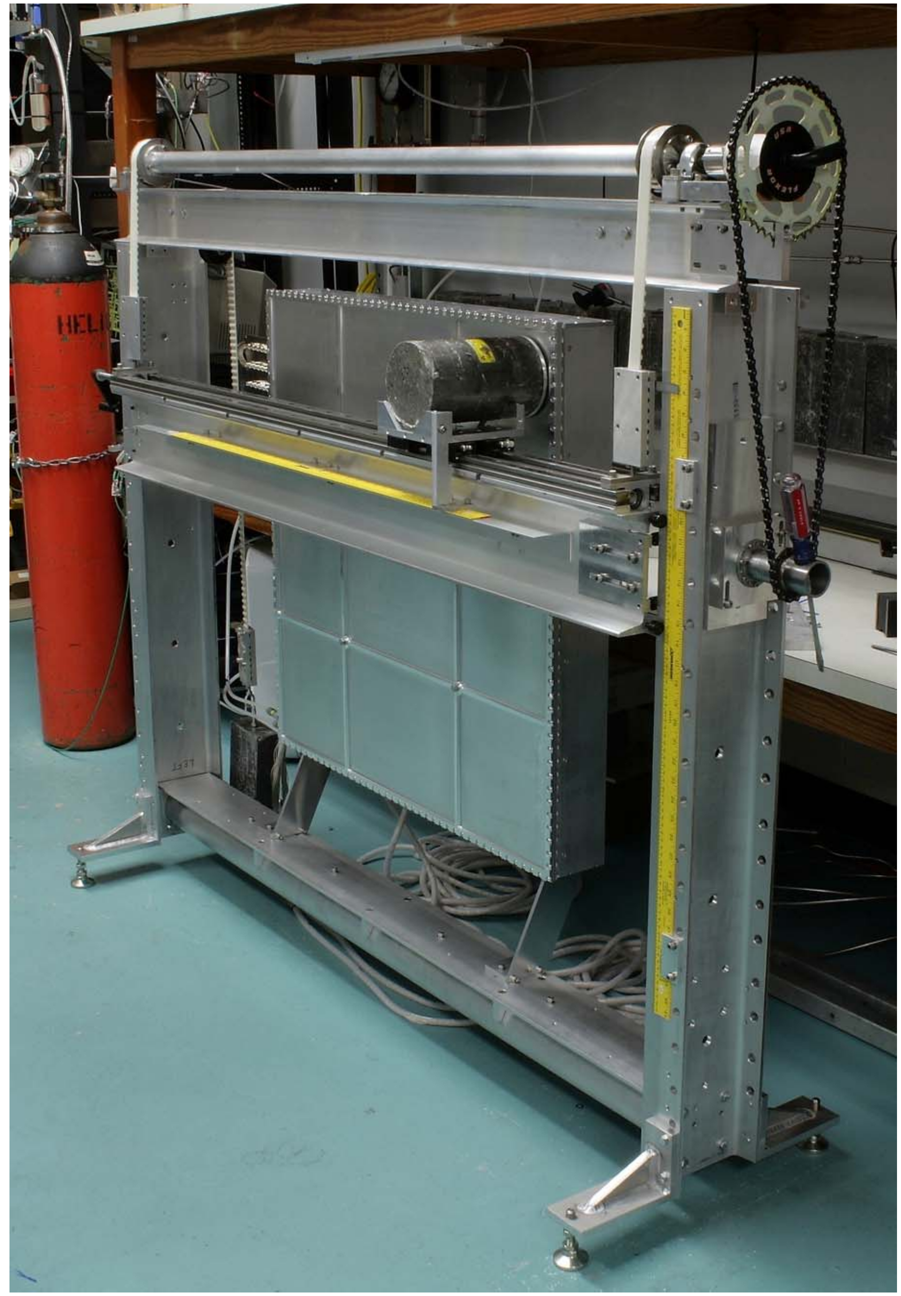
High Power Targets

Future LBNE Collaborative Opportunities?

- Further prototyping on LBNE 700 kW target (Be or Ti outer tube replacing Al)
  - Eventual manufacture of spare target?
  - Requires good design/analysis and manufacturing capabilities
- Pre-conceptual scoping of 2.3 MW target (graphite or Be)
  - Requires good design/analysis capabilities
- Conceptual design and prototyping of LBNE beam windows:
  - Especially for 2+ MW beam power
  - Possibility of Decay Pipe windows (challenge even at 700 kW)
  - Requires good design/analysis capabilities
- Hadron Monitor design and prototyping (eventual manufacture?)
  - Need new radiation hardened version for LBNE
  - Requires good design/analysis and manufacturing capabilities

Hadron Monitor

- Measures position and intensity of secondary particles at the end of the decay pipe (in absorber shield pile)
- LBNE has shorter decay pipe than NuMI
  - More heating
  - More radiation damage
  - 5x better resolution
- Current conceptual design is parallel plate ionization chambers with low pressure helium
- Used during beam/target/horn alignment & diagnostic scans and monitoring degradation of target material
- Good project to take from design to construction



NuMI Hadron Monitor being calibrated at University of Texas

Target collaboration for the first Neutrino Superbeam

- Whichever facility – LBNE/LBNO/T2HK – is first to be approved for construction/upgrade to operate in the MW region, there will be little time to develop a target system
- There is very significant commonality/synergy between the target/horn system and target station for all proposed facilities
- Now is a good time to get ready by collaborating over the necessary research and development
- Common challenges/areas for collaboration:
  - Target station design (T2K already constructed for 3-4 MW)
  - Beam window
  - Low Z target, 1-3 λ long
    - heat transfer, stress waves, lifetime - radiation damage effects, performance optimisation
  - Integration of target with horn to capture low energy pions
  - Horn – lifetime, radiation damage effects
  - Instrumentation – OTR, beam