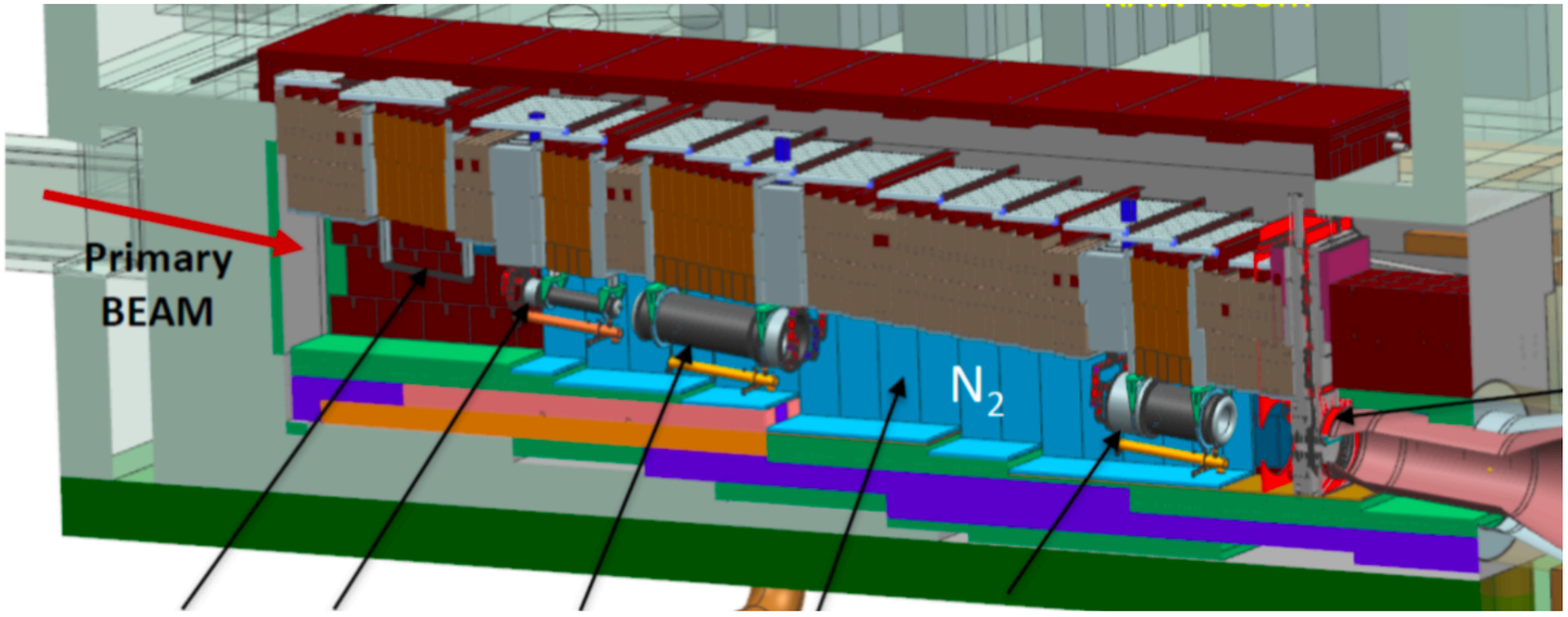
Development and Technical Design of neutrino beamline components for the Long Baseline Neutrino Facility (LBNF) at Fermilab

Tetsuro Sekiguchi (KEK, IPNS)

May 23, 2023



45th meeting of the US-Japan Science and Technology Cooperation Program in High Energy Physics

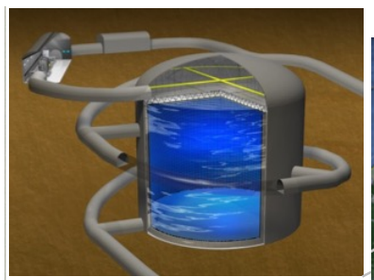
Imin International Conference Center at East West Center

Outline

- Overview
- LBNF Beamline
- KEK contribution to LBNF
- Summary

Overview

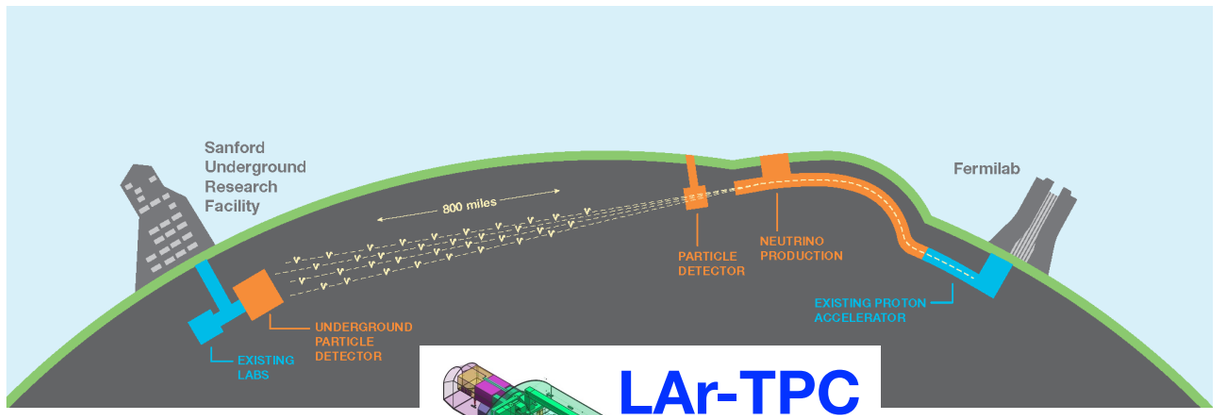
J-PARC / Hyper-Kamiokande



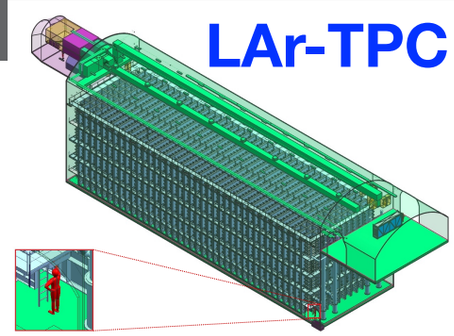
Hyper-K
(Water Č)

J-PARC
Accelerator Complex

LBNF / DUNE



LAr-TPC



- **Next generation experiments are aiming to reveal full picture of neutrino oscillation with precise measurements of CP and mixing parameters**
  - Sensitivity for CP violation ~2σ (current) → **>5σ** (future)
  - > 10 times statistics needed
- To achieve it,
  - **~10 x larger new detectors**
  - **>1MW-class beam power needed**

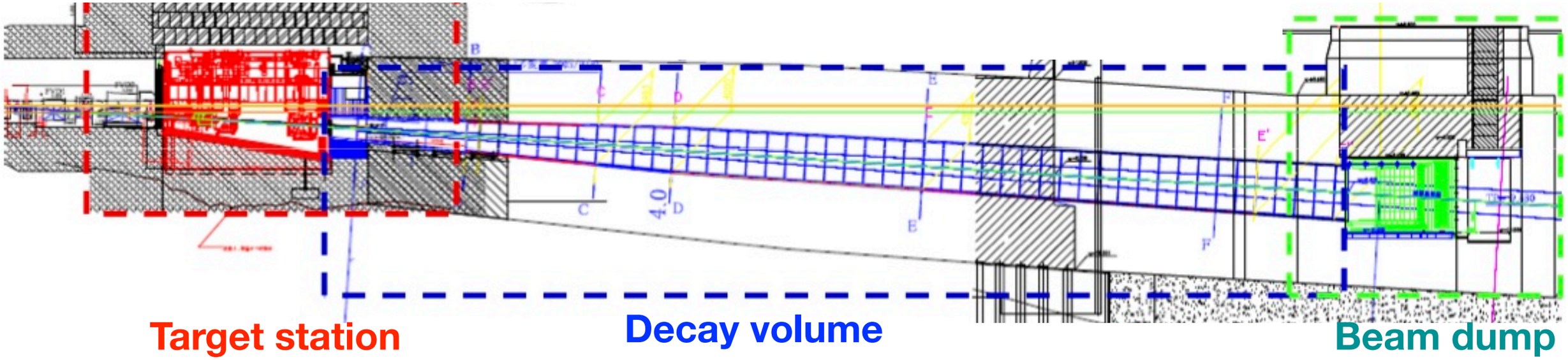
$$N_\nu \propto \boxed{\Phi_\nu(E)} \times \sigma_\nu(E) \times \boxed{\text{target}}$$

Beam power **Detector volume**

How To Produce Neutrino Beam?

Conventional neutrino beam from pion decay (since 1960's)

Proton → π^+ (π^-), K^+ (K^-) → ν_μ ($\bar{\nu}_\mu$) + μ^+ (μ^-)



- High intensity proton beam hit a graphite target
- Secondary π/K's focused by magnetic horns and decay to neutrinos
  - Neutrino beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Antineutrino beam from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - Changing neutrino beam mode by flipping the horn polarity
- All hadrons absorbed by beam dump
- High energy muons penetrating beam dump measured by muon monitors

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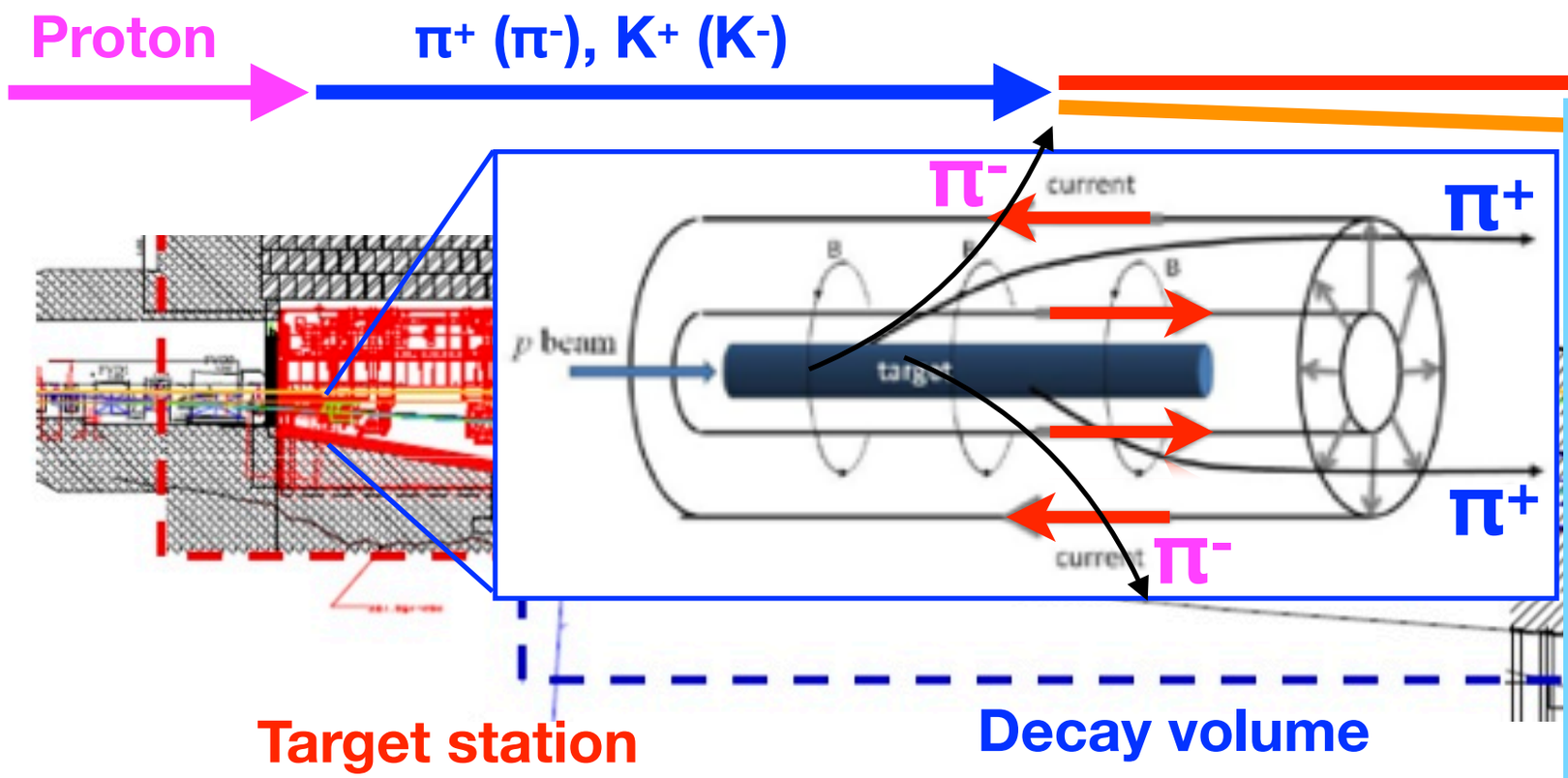

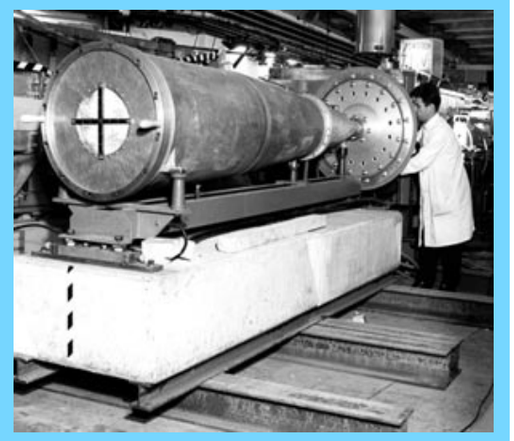

The 1st Neutrino Horn – Van den Meer, CERN, 1961

Horn-focused beam developed at CERN by Simon van der Meer (1984 Novel Prize)

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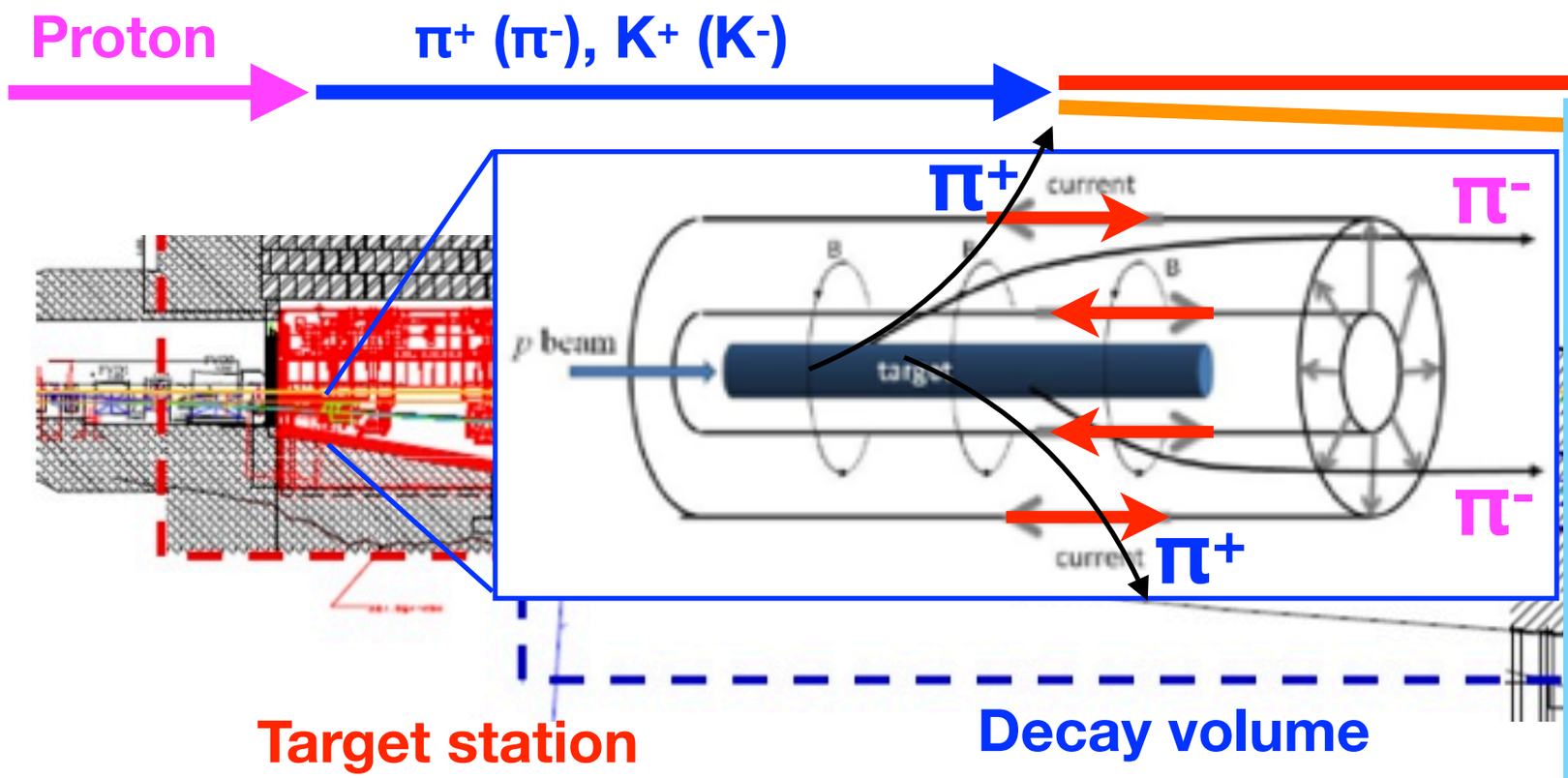

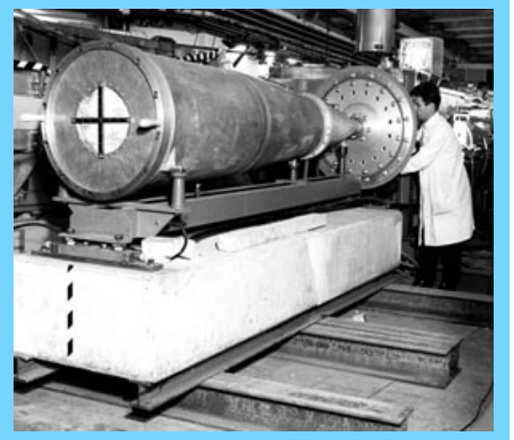

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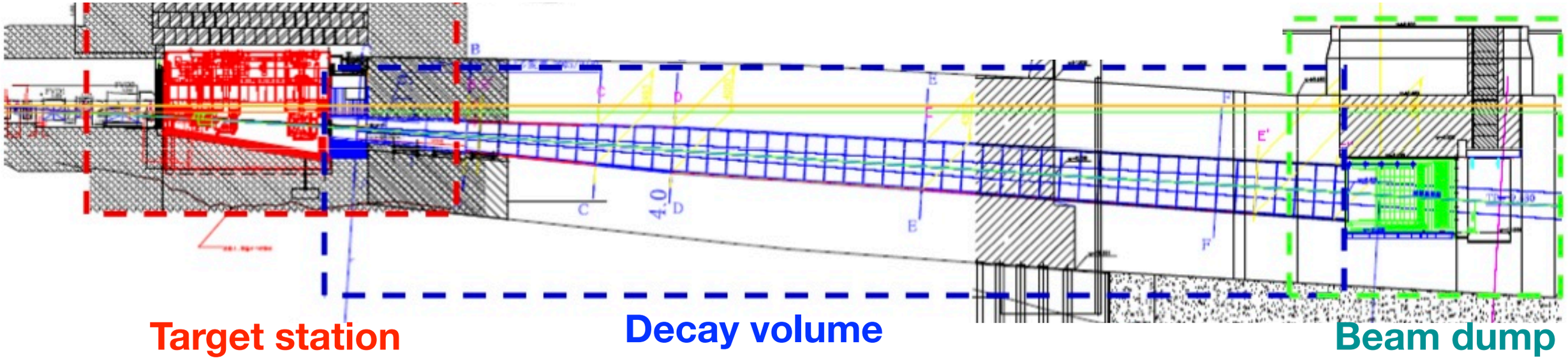

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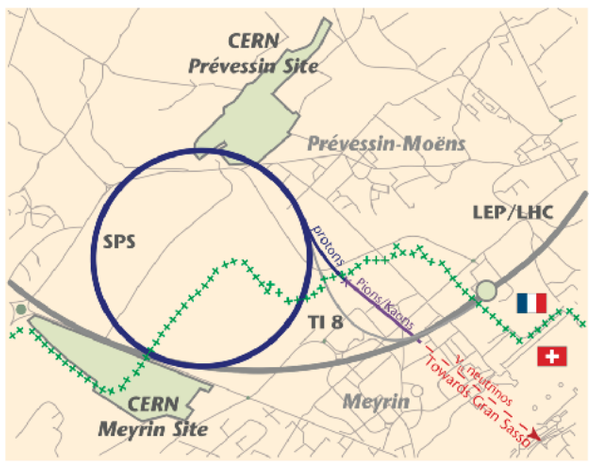
Progress on High Power Neutrino Beam

Neutrino beam facilities for long baseline experiments

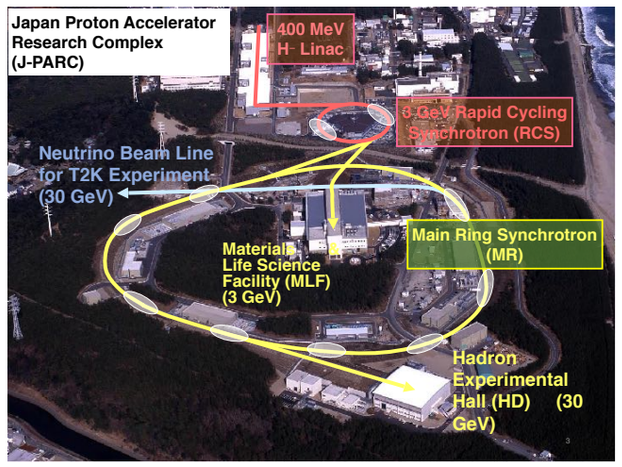
Facility	Accelerator	Energy [GeV]	Experiment	99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
KEK	PS	12	K2K	6 kW — 1st generation : *O*(10) kW ⇒ world-first neutrino beam for LBL experiment
Fermilab	Main Injector	120	MINOS	NuMI 400 kW
CERN	SPS	450	OPERA	CNGS 500 kW — 2nd generation : *O*(100) kW
J-PARC	Main Ring	30	T2K	500 kW
Fermilab	Main Injector	120	NOvA	NuMI 700 kW → 1 MW
J-PARC	Main Ring	30	T2K-II → HK	750 kW → 1.3 MW — 3rd generation : *O*(1) MW
Fermilab	Main Injector	120	DUNE	LBNF 1.2→2.4 MW

KEK 12GeV-PS (1999-2004)

CERN CNGS (2006-2012)



J-PARC (2009-)



Fermilab NuMI (2006-)

International Cooperation on High Power Neutrino Beam

High power neutrino beam is quite challenging

⇒ Inter-facility cooperation is very important

- **Good relationship among KEK, Fermilab, CERN experts since 1999**
  - Detailed discussions and information exchange in Neutrino Beam and Instrumentation (NBI) workshop series
    - **Many lessons learned from other facilities**

- NBI2022 (UK)

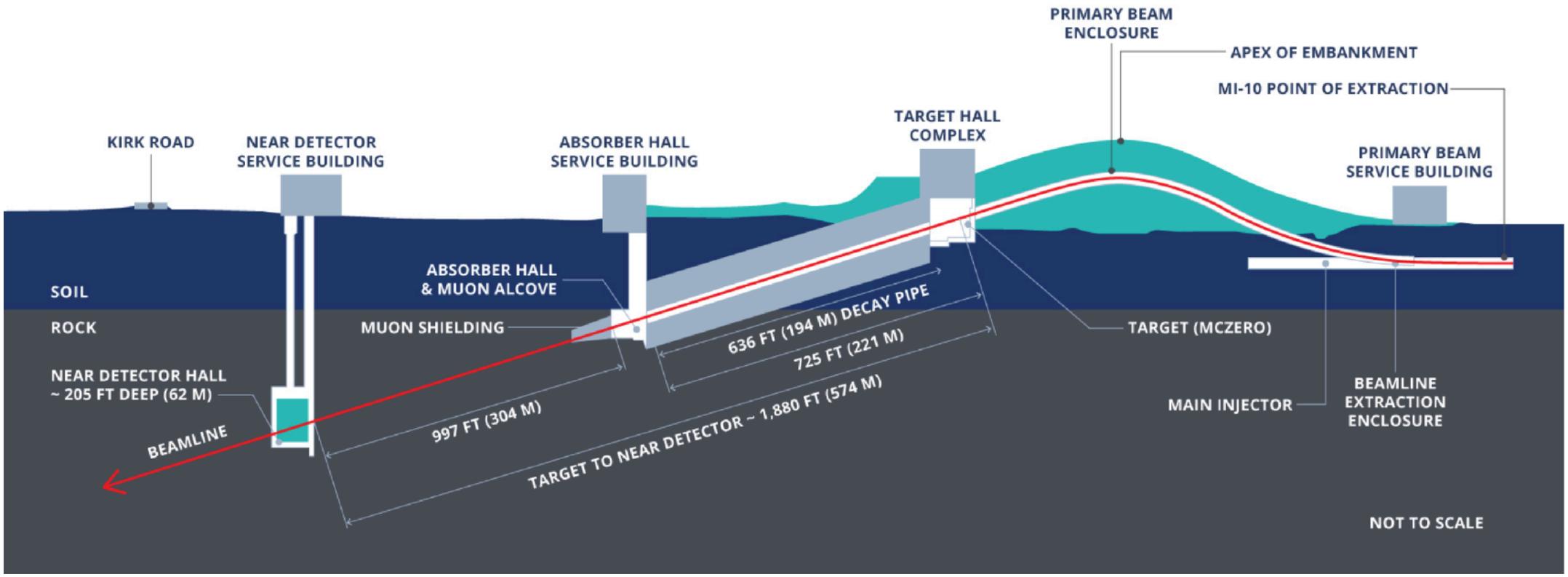
https://indico.stfc.ac.uk/event/260/

- **US-Japan Cooperative Programs in High Energy Physics**

- NBI2024 (Japan)

  - Accelerator and beamline R&D for high power neutrino beam since 2014
    - KEK-Fermilab collaboration in accelerator and neutrino beamline development
  - LBNF-specific program launched since 2018
    - KEK-Fermilab collaboration for LBNF

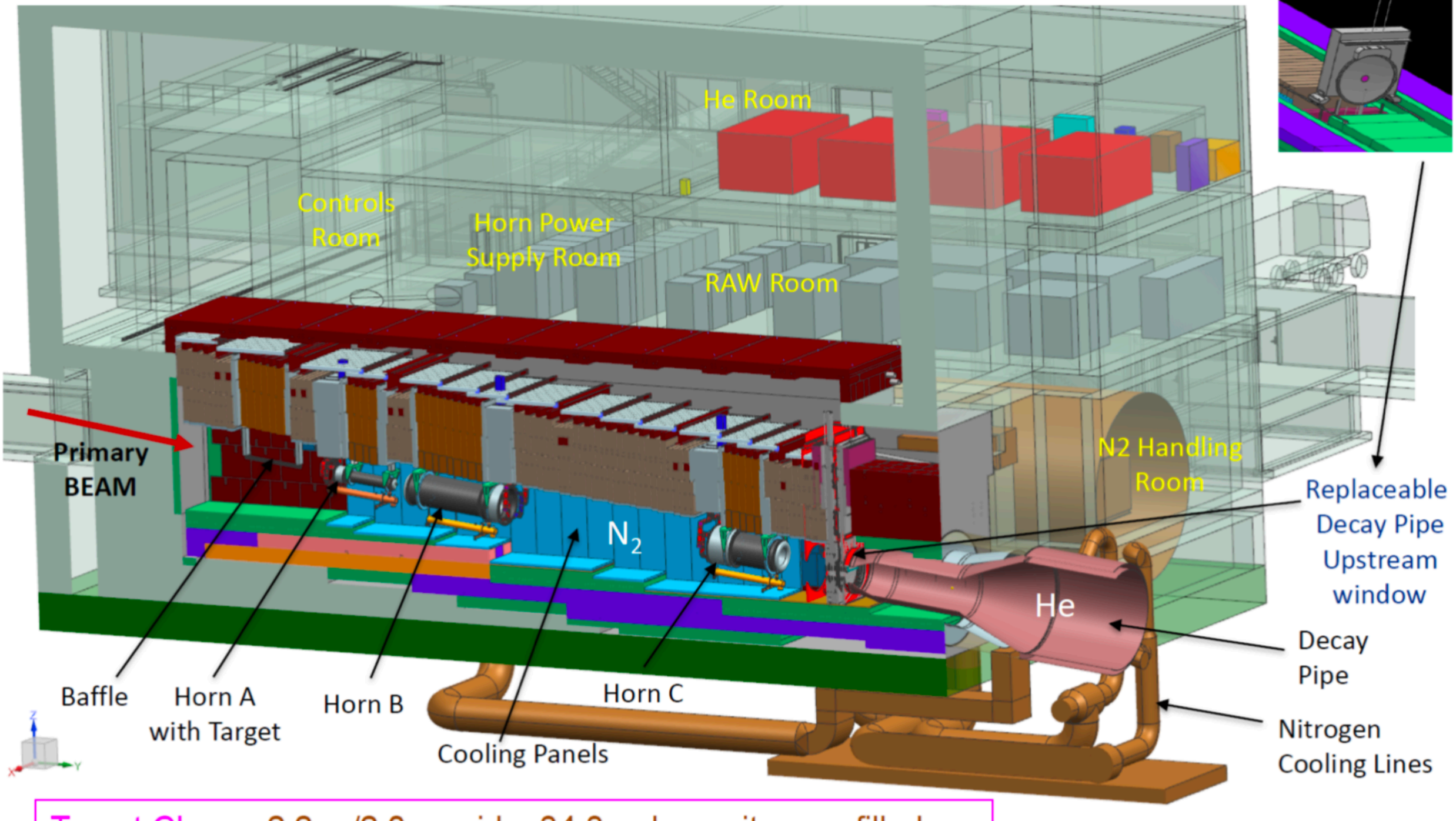
Long Baseline Neutrino Facility (LBNF)



- PIP-II : Accelerator upgrade 400MeV Linac → 800MeV SC Linac
- LBNF : New neutrino beamline for DUNE
- 120 GeV primary protons to LBNF target
- All systems designed for 1.2 MW initial proton beam power.
  Facility upgradable to 2.4 MW proton beam power.
- Aim to start beam operation from 2031

LBNF Target Hall Design

Air-filled target chase (NuMI) ⇒ N_2-filled hermetic vessel + He-filled Decay pipe



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

KEK Contribution to LBNF

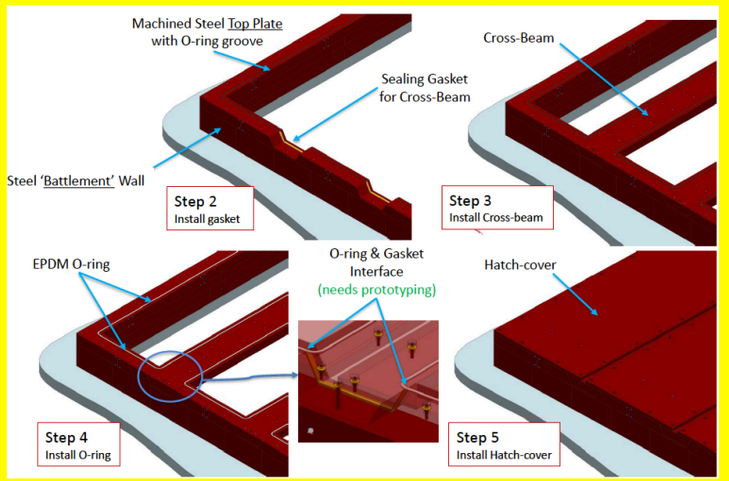
- KEK neutrino group is contributing to R&D activities for LBNF neutrino beam since 2018
- KEK has strong expertise from J-PARC operation experience for 10 years
- KEK is carrying out J-PARC 1.3 MW upgrade
- These activities are common to both Fermilab and KEK

- Strong support from KEK Director General
  - ~1M USD in total so far since 2018
- Support from US-Japan program : ~120k USD since 2018

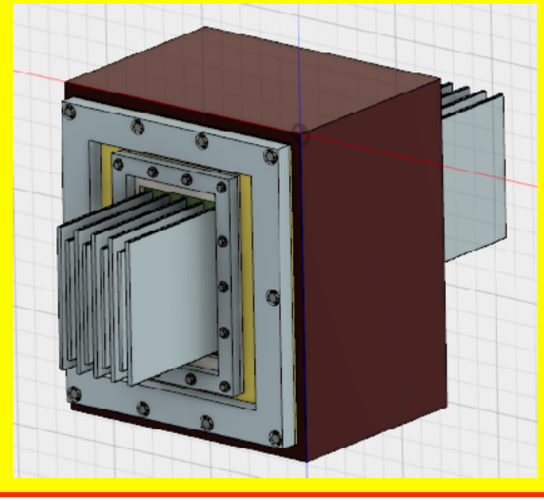
KEK Contribution to LBNF

- So far, KEK is contributing to the following components
  - Hatch cover and stripline feedthrough for hermetic vessel
  - He cooling for target
  - Hydrogen removal for horn cooling water

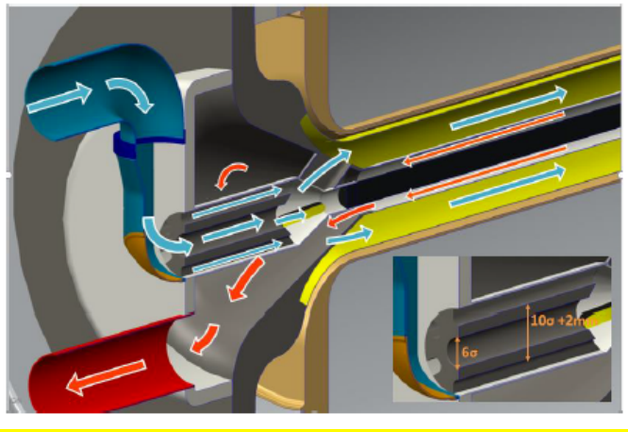
Hatch cover for hermetic vessel

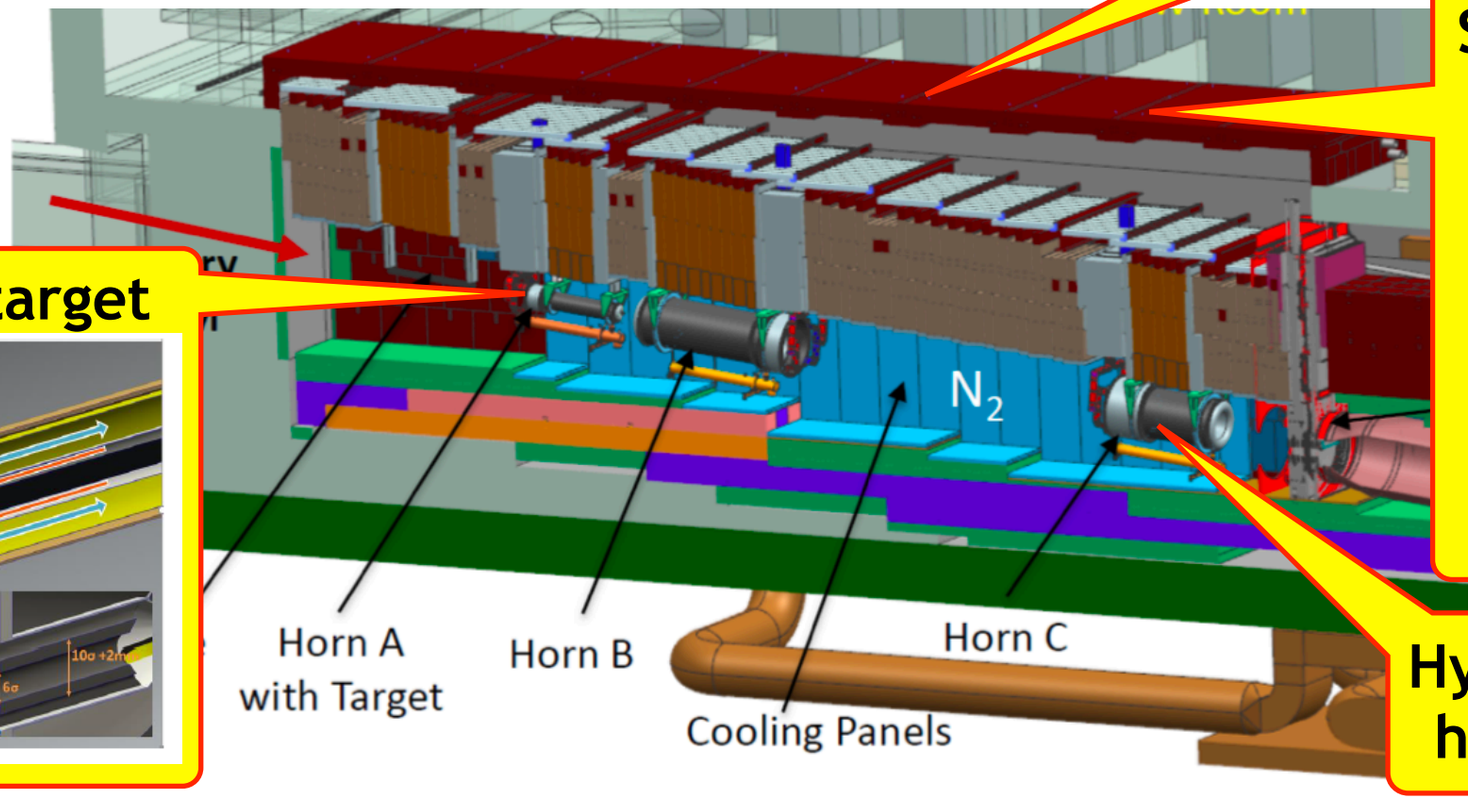


Stripline feedthough



He cooling for target

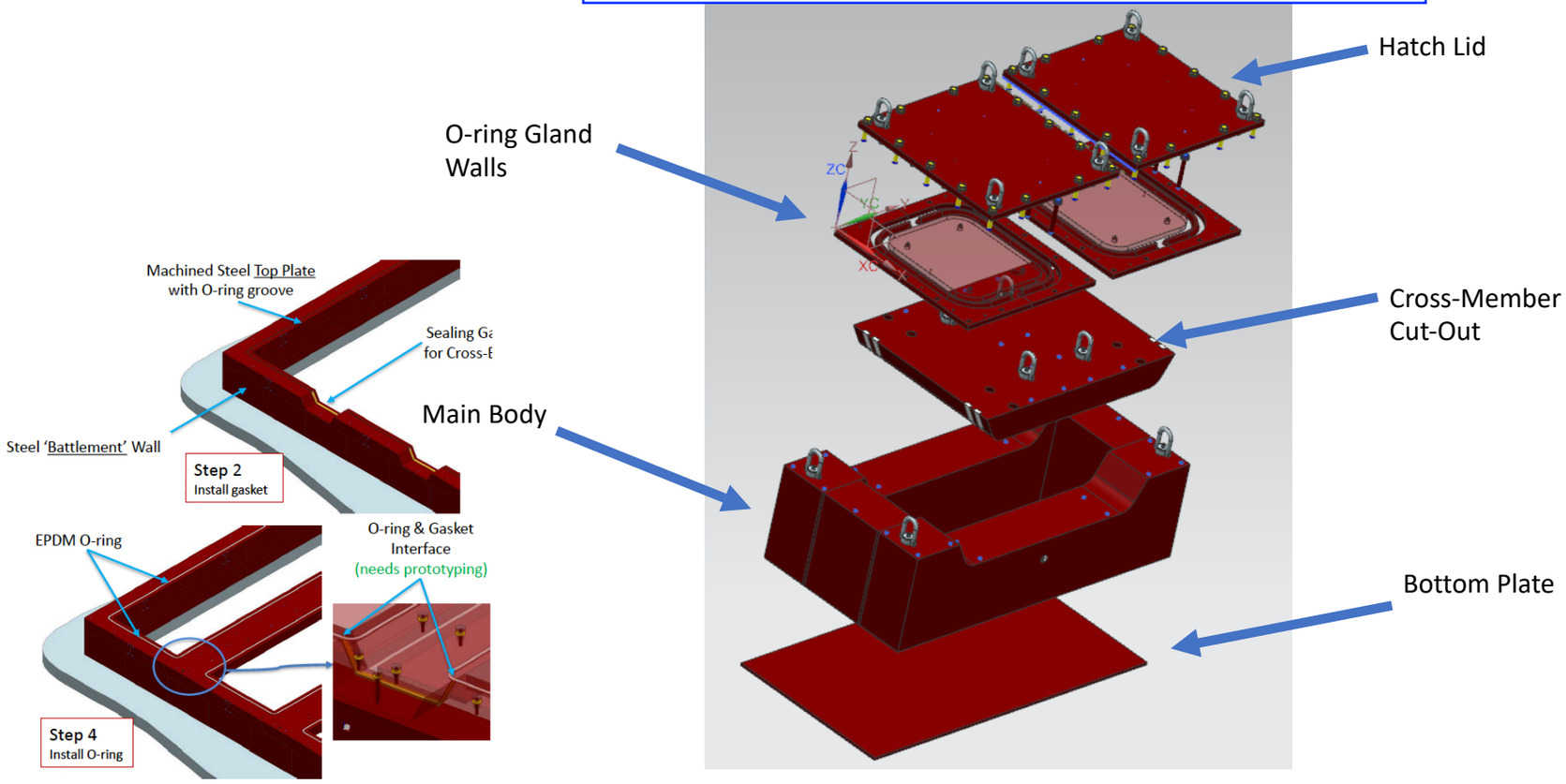




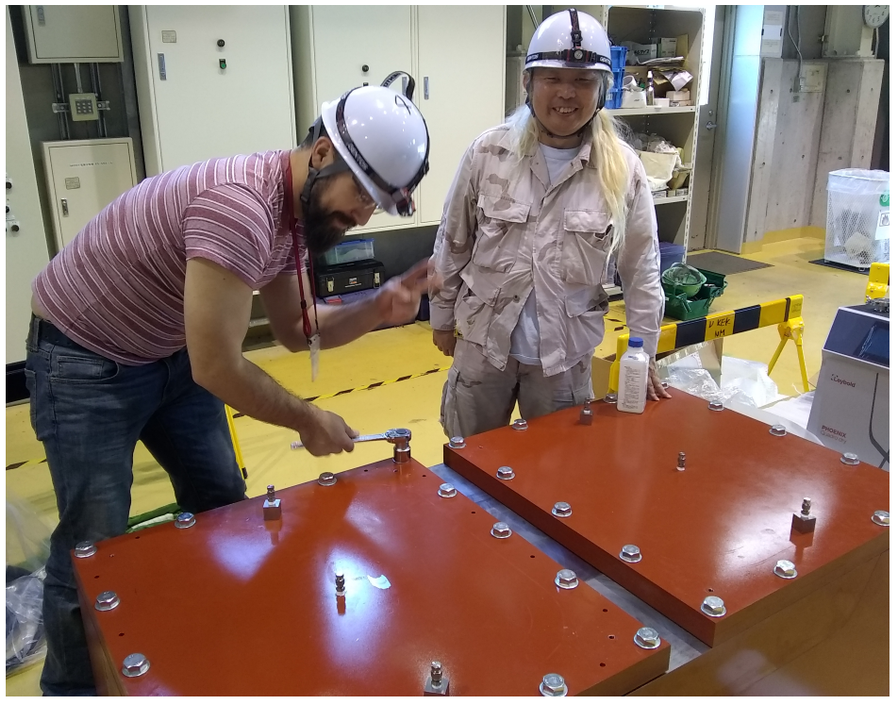
Hydrogen removal for horn cooling system

Prototyping of Hatch Cover (2018~19)

3D model of prototype hatch cover



Validation test in J-PARC



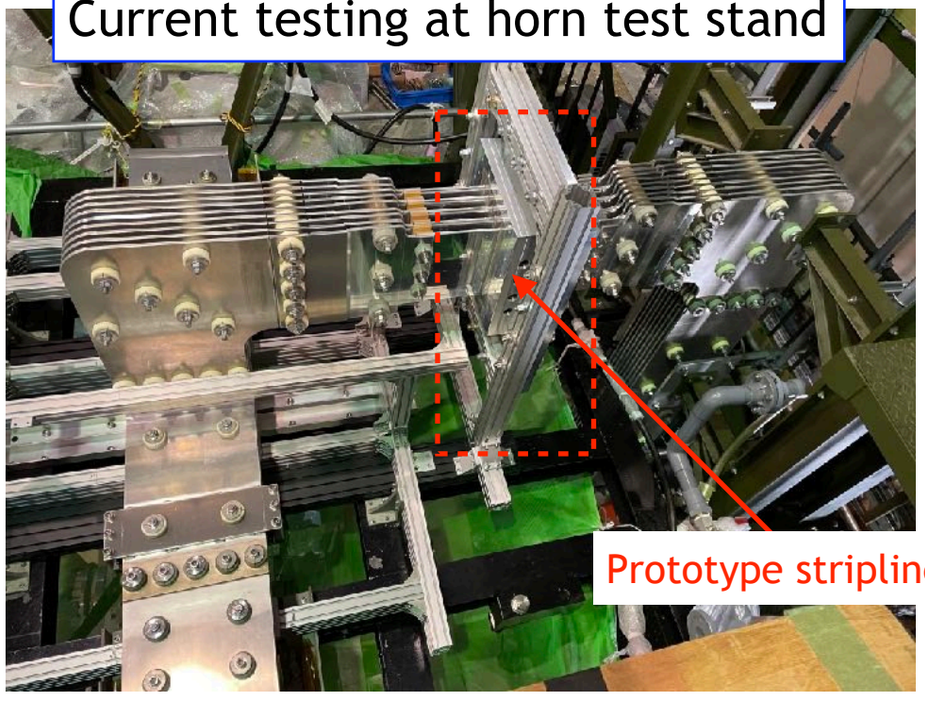
- Hatch cover of hermetic vessel has complicated structure
  - Sealing performance should be confirmed by prototype test
- KEK produced a prototype hatch cover in 2018
- Two Fermilab engineers visited J-PARC for a prototype test in 2019
  - Achieved sealing performance of $>10^{-6}$ Pa·m^3/s (spec.)
- The prototype was sent to Fermilab for further tests

Prototyping of Stripline Feedthrough (2018~)

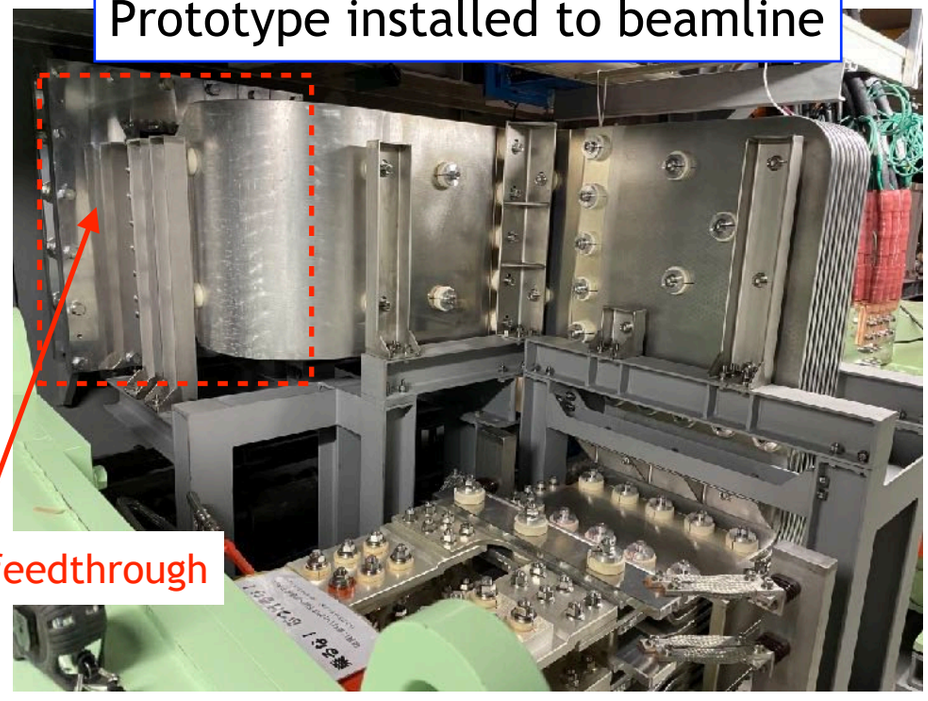
- **Stripline feedthrough must withstand 300kA pulsed current for magnetic horns**
  - Sealing performance should be kept even in long-term operation
- **Prototype stripline feedthrough production**
  - Satisfactory sealing performance of 10^{-10} Pa·m³/s (↔ spec. 10^{-6} Pa·m³/s)
  - Current testing to measure vibration at various points ⇒ No critical problem
  - Continuous operation test with 50k pulses (several days) ⇒ No problem
  - Longer term performance should be confirmed
  - One prototype installed into J-PARC beamline to check sealing performance over 10 million pulses under radiation environment
  - Long-term test will be started soon

He leak test

Current testing at horn test stand



Prototype installed to beamline



Hydrogen Removal for Horn Cooling System (2019~)

- **Water radiolysis in horn cooling water**
  - Excitation/ionization of H_2O molecule

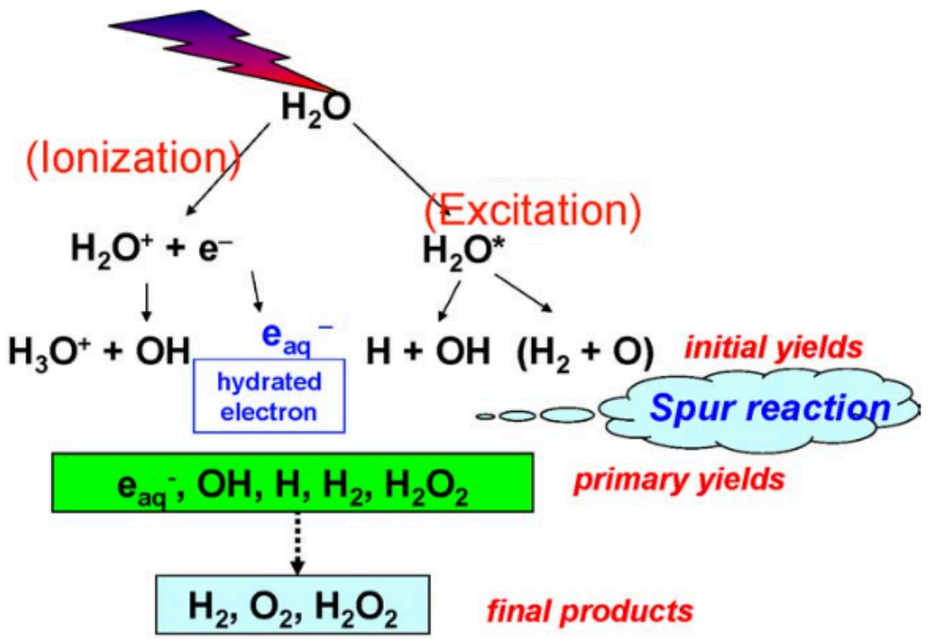
    ⇒ H_2, H_2O_2, O_2 as final products

    $H_2O_2 \rightarrow H_2O + \frac{1}{2}O_2$
- **J-PARC is developing H_2 removal system using H_2 recombination ($H_2+O_2 \rightarrow H_2O$)**
  - Great reduction of H_2 concentration :
    - 260 L (5%) / 10^{19} POT → 5 L (0.1%) / 10^{19} POT

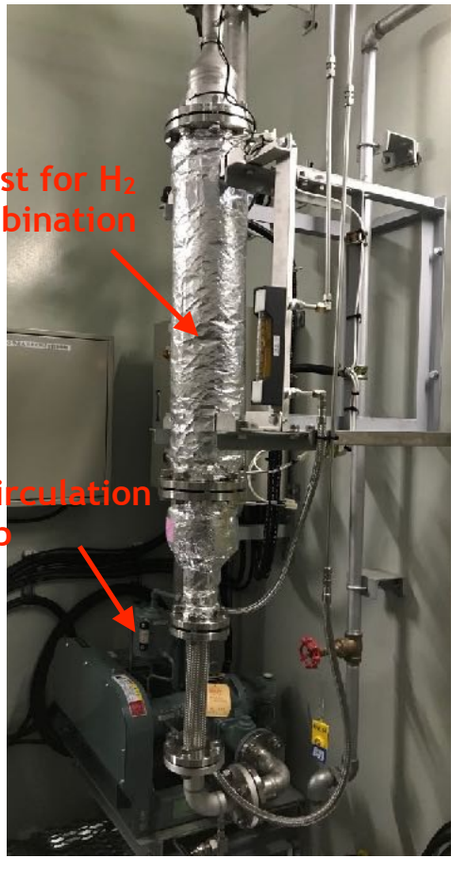
      (without recomb.) (with recomb.)
  - Critical system for safe operation with high power beam
- **Issues and measures**
  - Dissolved O_2 in water accelerates radiolysis

    ⇒ O_2 degasifier system under preparation
  - Degradation of ion-exchanger (IE) resins by H_2O_2

    ⇒ Installed new H_2O_2-tolerant IE resins
- **Information exchange with Fermilab people**
- **Consider to adopt this system to LBNF beamline**



Y. Katsumura, Radiation Chemistry, No.81, 2-7 (2006)

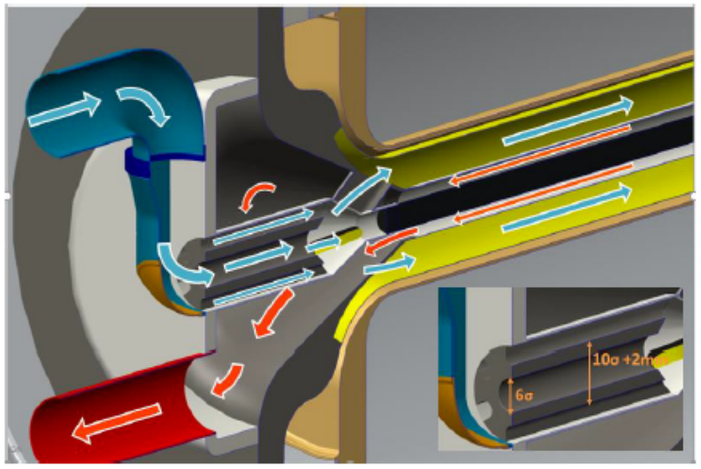


He Cooling System for Target (2019~)

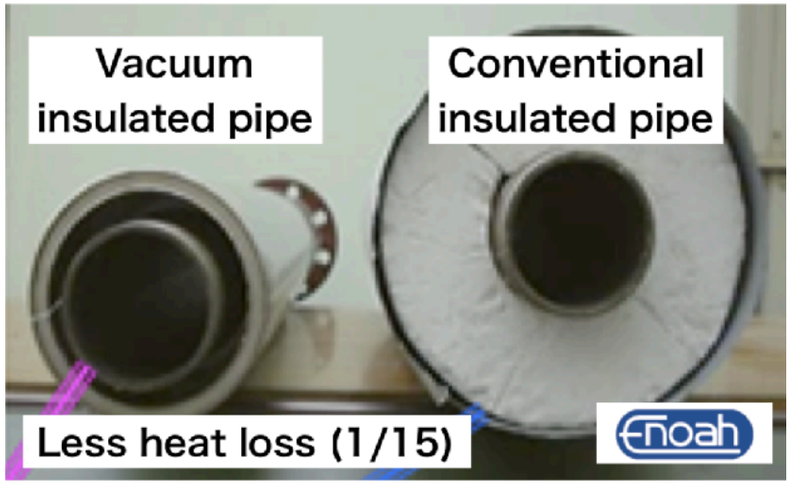
He cooling for target

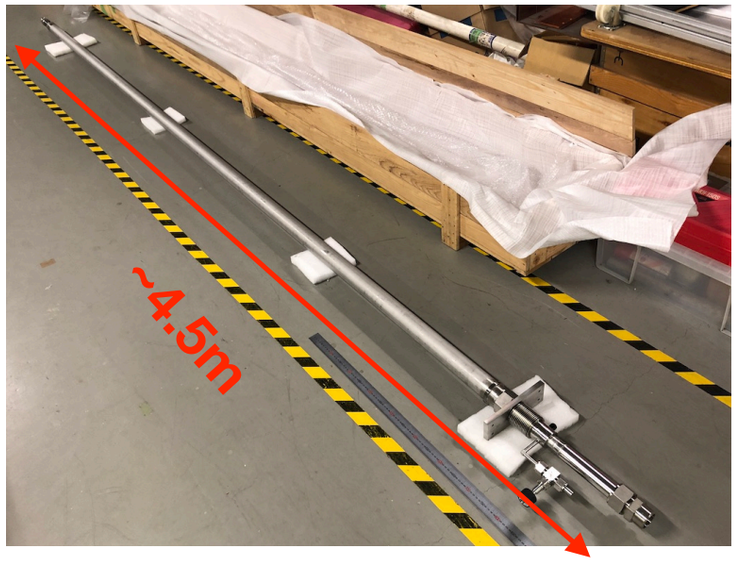
- He cooling system upgrade needed for J-PARC 1.3 MW beam
- LBNF will also use He cooling scheme
- High temperature He gas (~200°C) must be circulated

  → heat insulation is an issue
- Vacuum insulated pipe developed

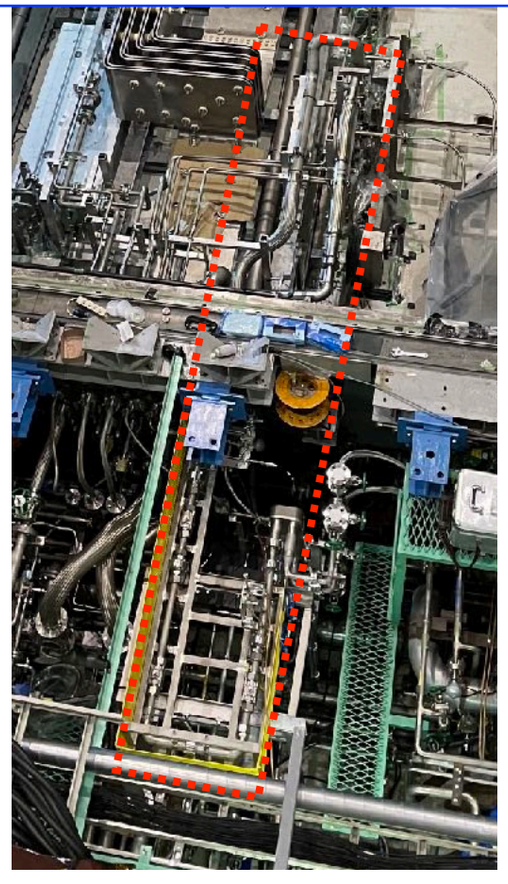


- Thermal insulation test with 200°C air → temperature on outer surface is comparable to outside temperature
- Installed to J-PARC beamline to check long-term performance





New vacuum insulated pipes



Summary and Prospect

- High power neutrino beam is key for future neutrino programs
- International cooperation to realize high power neutrino beam facility
- LBNF : facility for DUNE (1.2 MW → 2.4 MW)
    - New neutrino beamline will be built
- KEK contribution to LBNF since 2018
    - Hatch cover
    - Stripline feedthrough
    - He cooling for target
    - H_2 removal for horn cooling water
- Japanese PI visited Fermilab in last March (after 3-year COVID-19 break)
    - Many fruitful discussions for future contributions
    - Future discussion will be made for next US-Japan application