J-PARC Neutrino Beam Upgrades towards 1.3 MW Beam Power for Long-Baseline Neutrino Oscillation Experiments in Japan

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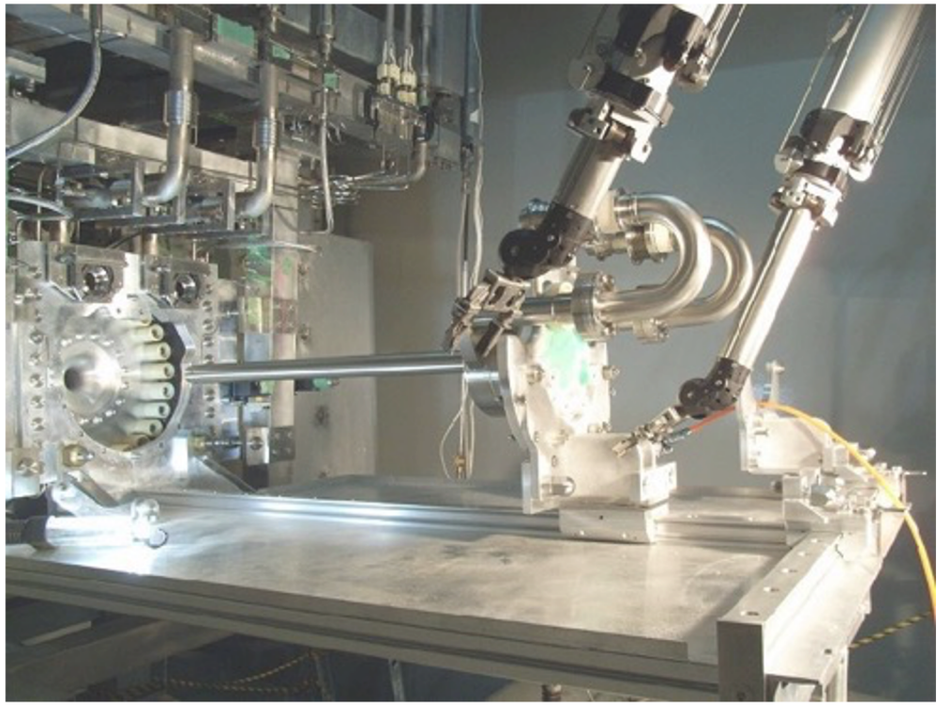
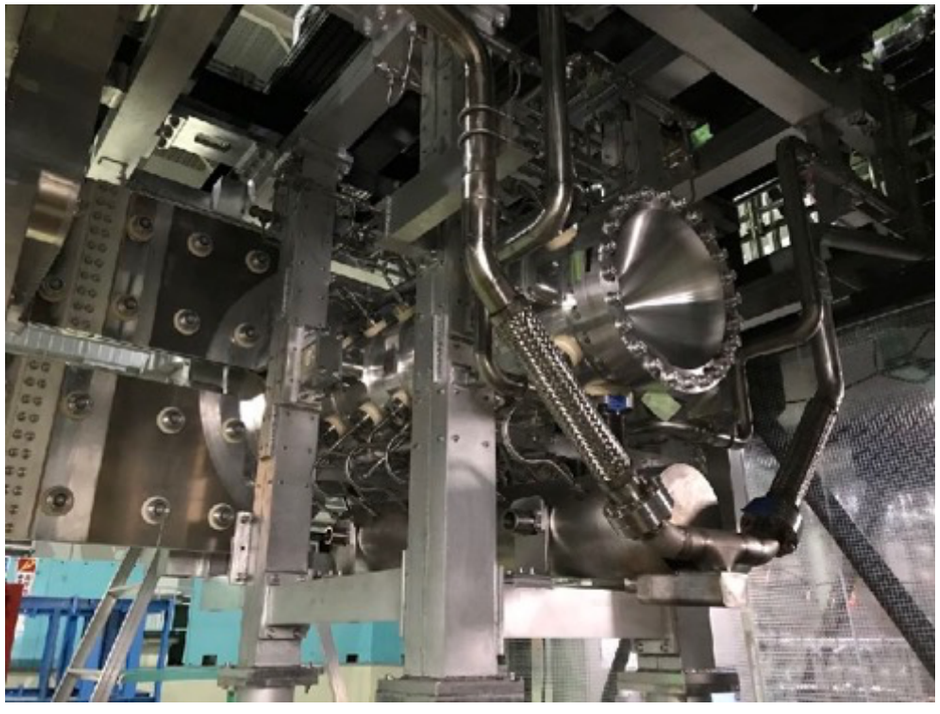
for J-PARC Neutrino Beamline Group

July 30, 2020





40th International Conference on High Energy Physics (ICHEP 2020)

Outline

- Overview of accelerator neutrino beam
- J-PARC neutrino beamline
  - Current status
  - Future upgrades
- International cooperation on high power neutrino beam
- Summary

Overview

J-PARC neutrino beam to Kamioka (T2K / Hyper-K)

- **Accelerator-based neutrino oscillation experiments are playing an important role in neutrino physics since 1999**
  - Recent T2K results showed **a hint of large CP violation** in neutrino sector
- **Next generation experiments (Hyper-K/DUNE) are aiming to reveal full picture of neutrino oscillation with precise measurements of CP and mixing parameters, and determination of mass ordering**
  - Sensitivity for CP violation 2~3σ (current) → **>5σ** (future)
  - > 10 times statistics needed
- To achieve it,
  - **~10 x larger new detectors**
  - **>1MW-class beam power needed**

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

Beam power — Detector volume

Progress on High Power Neutrino Beam

Neutrino beam facilities for long baseline experiments

Facility	Accelerator	Energy [GeV]	Curent [μA]	Experiment
KEK	PS	12	0.5	K2K
Fermilab	Main Injector	120	2.5	MINOS
CERN	SPS	450	1.1	OPERA
J-PARC	Main Ring	30	16.7	T2K
Fermilab	Main Injector	120	5.8-8.3	NOvA
J-PARC	Main Ring	30	25-43	T2K-II → HK
Fermilab	Main Injector	60-120	10	DUNE

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

6 kW

1st generation : *O*(10) kW

⇒ world-first neutrino beam for LBL experiment

NuMI 300 kW

CNGS 500 kW

2nd generation : *O*(100) kW

500 kW

NuMI 700 kW → 1 MW

3rd generation : *O*(1) MW

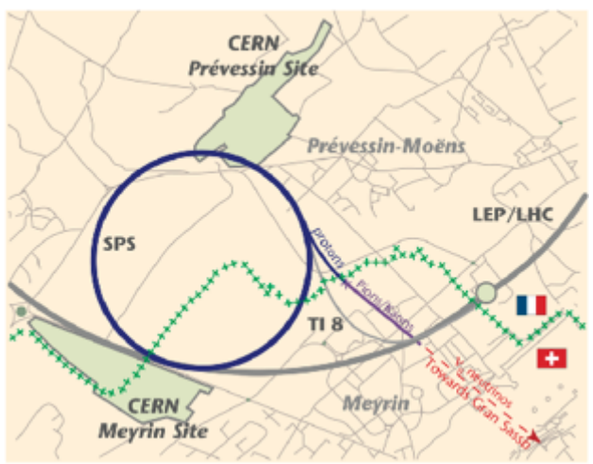
750 kW → 1.3 MW

LBNF 1.2 MW

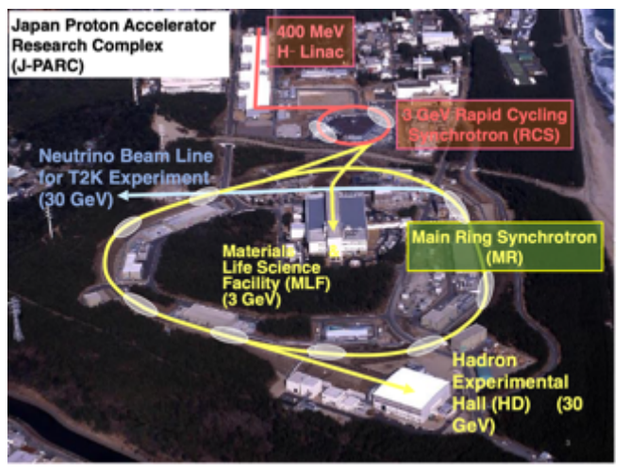
Note: Beam power (kW) = Beam energy (GeV) x Current (μA)

KEK 12GeV-PS (1999-2004)

CERN CNGS (2006-2012)



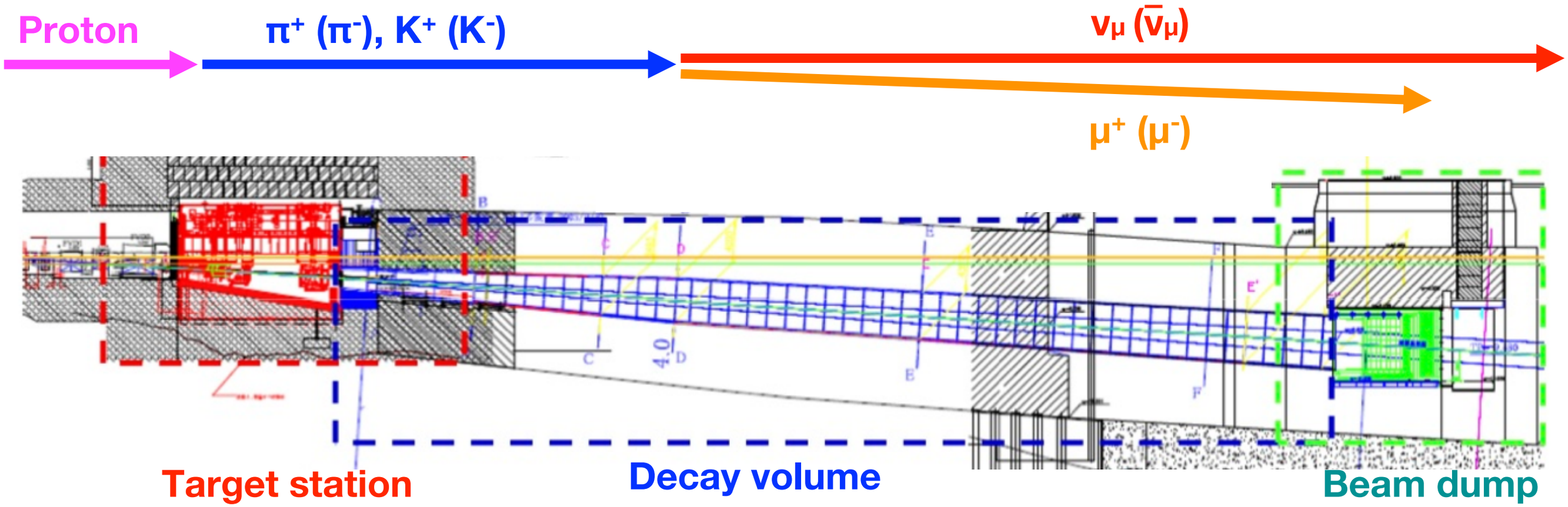
J-PARC (2009-)



Fermilab NuMI (2006-)

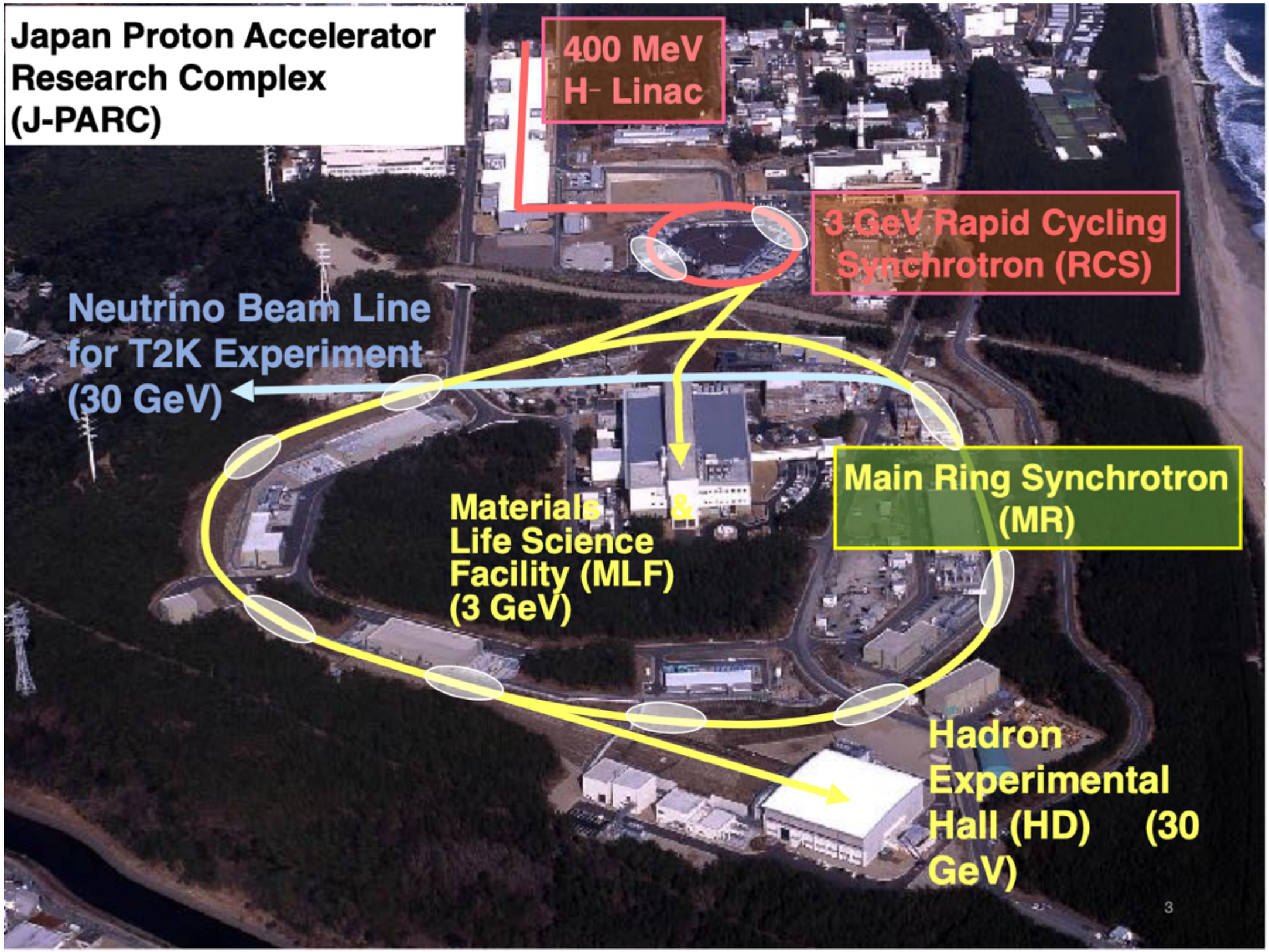
How To Produce Neutrino Beam?

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

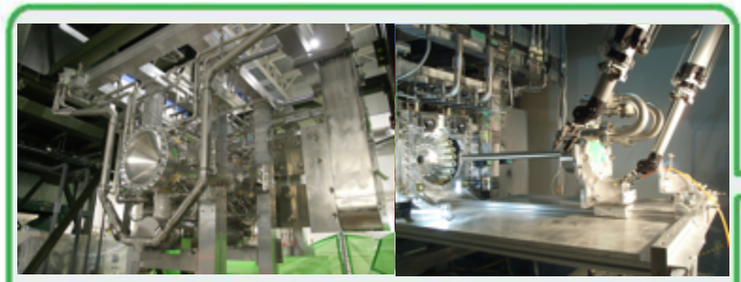


- High intensity proton beam hit a graphite target
- Secondary π/K's focused by magnetic horns and decay to neutrinos
  - Neutrino beam from $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - Antineutrino beam from $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
  - Sign-selected neutrino beam by flipping the horn polarity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

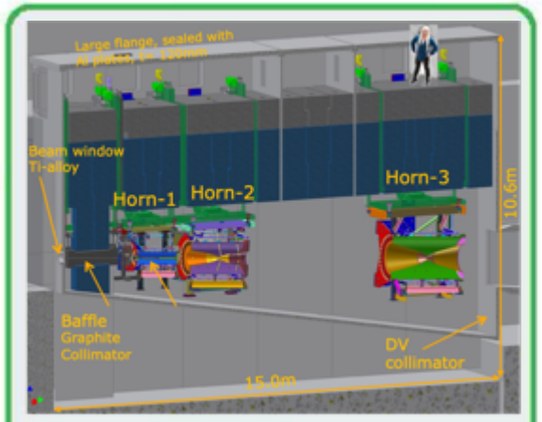
J-PARC


Japan Proton Accelerator Research Complex (J-PARC)
400 MeV H⁻ Linac
3 GeV Rapid Cycling Synchrotron (RCS)
Neutrino Beam Line for T2K Experiment (30 GeV)
Main Ring Synchrotron (MR)
Materials & Life Science Facility (MLF) (3 GeV)
Hadron Experimental Hall (HD) (30 GeV)
3

Neutrino Beamline



Target-Horn System



Target Station

Primary Beam-line

Muon
Monitoring Pit

Final Focusing
Section

295km to
Super-Kamiokande

Muon neutrino

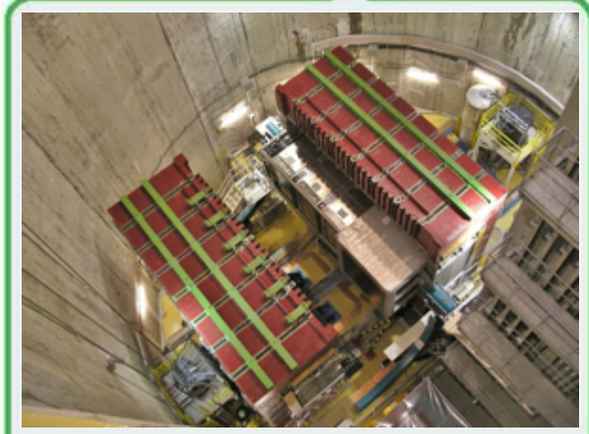
muon

π-meson

Proton

110m

280m



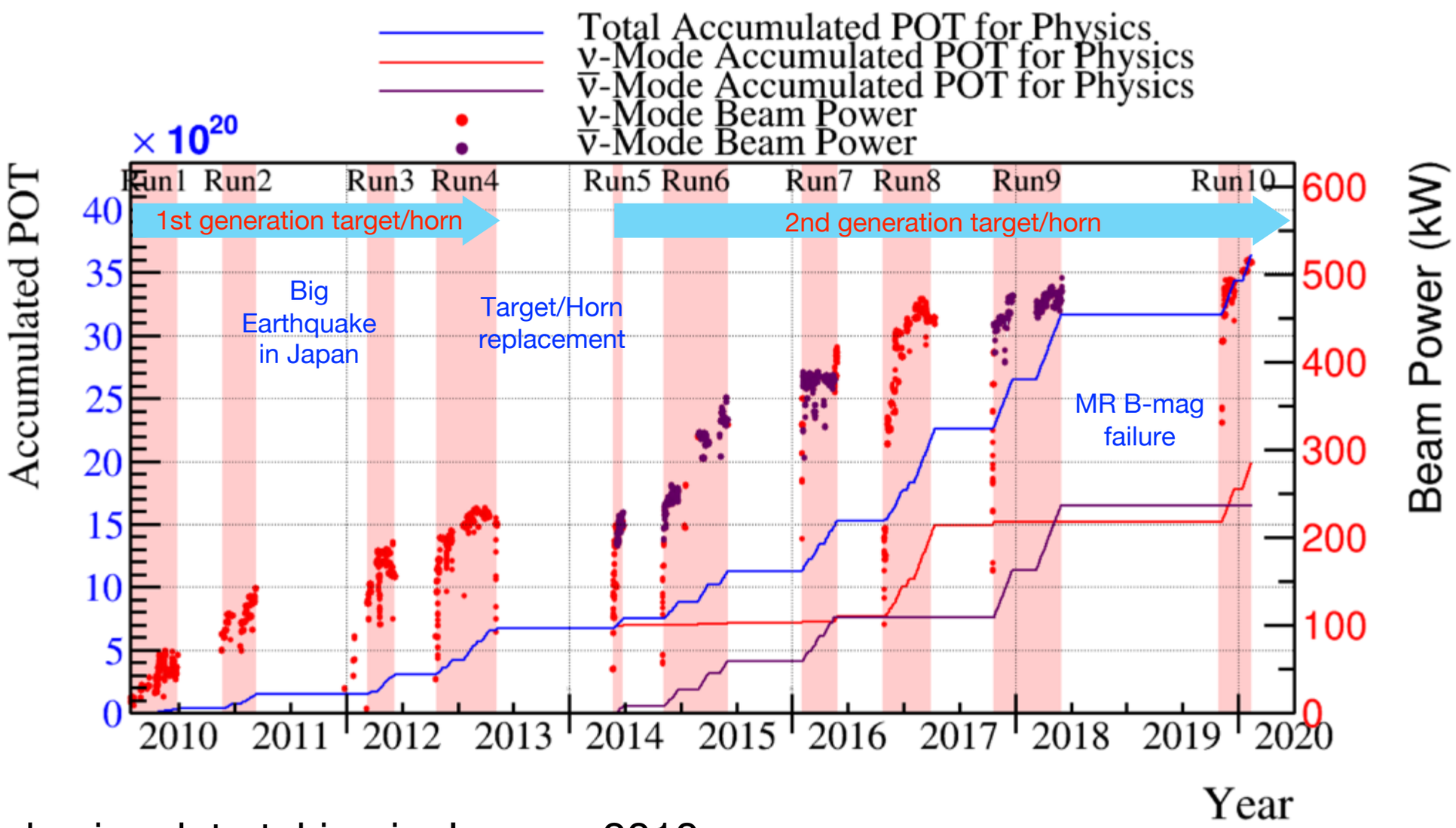
Near Neutrino Detector

Beam Dump

Decay Volume

SCFM at ARC Section

Status of J-PARC Neutrino Beam



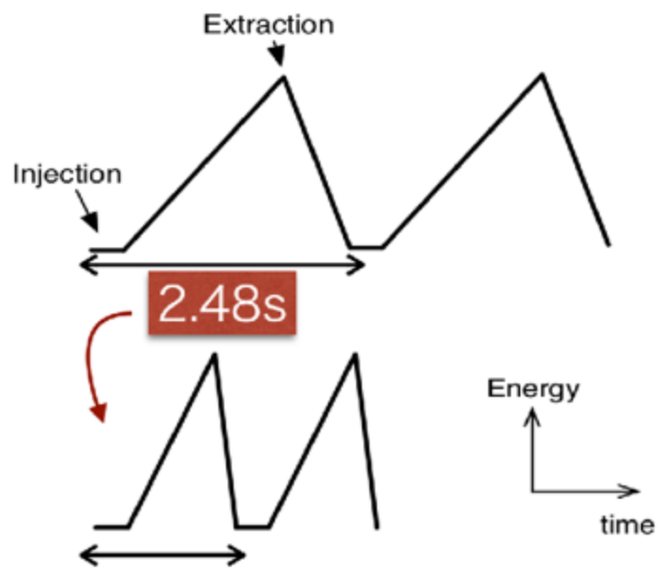
- Started physics data taking in January 2010
- **515 kW** stable operation achieved : **2.66x10^{14}** protons/pulse

  ⇒ World-highest intensity in fast-extracted beam from proton synchrotron
  - Beam power limited by space charge effect, beam instability due to insufficient RF voltage
- Provide **3.64x10^{21}** protons on target (POT) to T2K
  - ν mode POT : 1.99x10^{21} (54.7%), anti-ν mode POT : 1.65x10^{21} (45.3%)

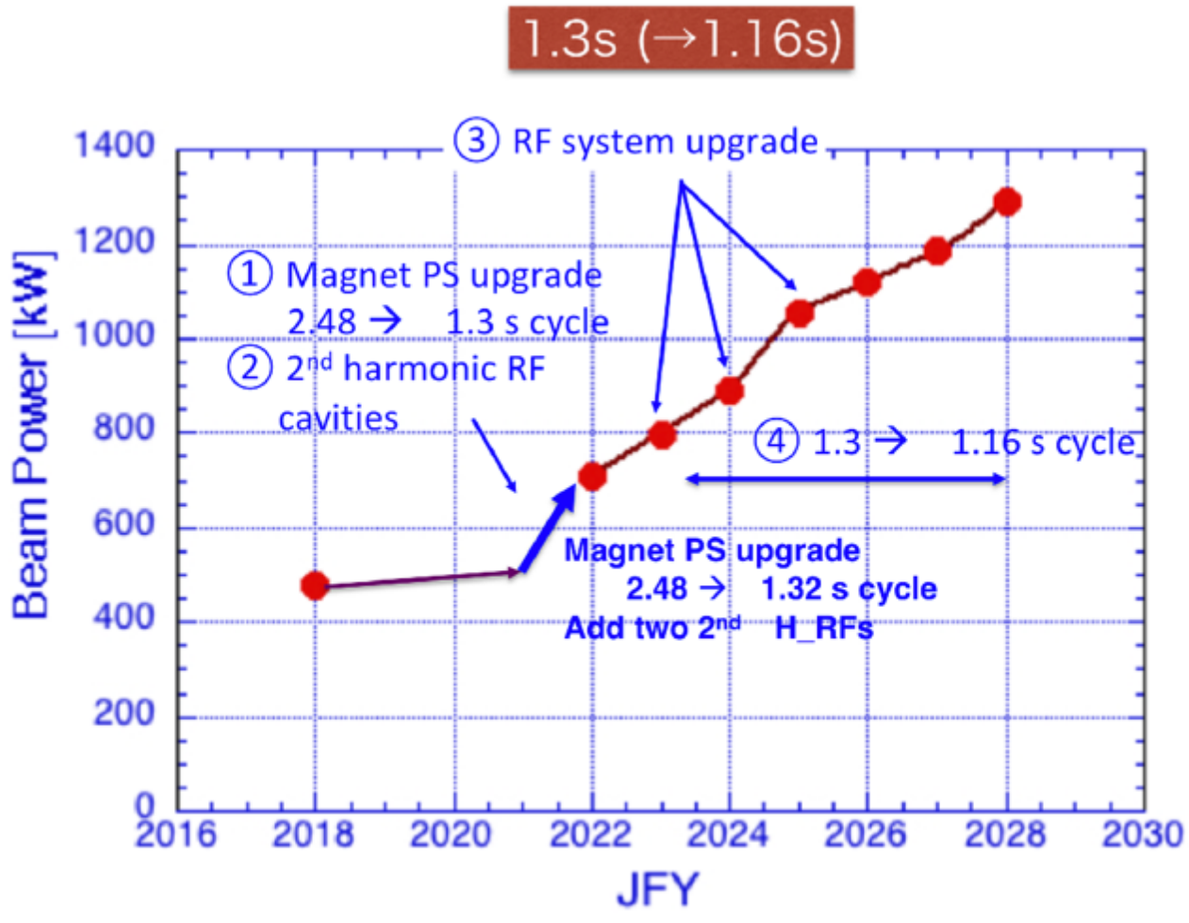
J-PARC Upgrade Toward 1.3 MW

- **Staged accelerator upgrade toward 1.3 MW**
  - **Shorter cycle** (2.48s→1.32s) for >750 kW (FY2021)
    - MR PS upgrade
    - 2nd harmonic RF cavities
  - **Higher beam intensity** for 1.3 MW (~FY2028)
    - Increase # of RF cavities (9 → 11)
    - RF anode PS upgrade
- **Upgrade of neutrino beamline is also needed**

Power ∝ E_{beam} x Intensity x 1/cycle



	Current	Upgrade
Beam power [MW]	0.5	**1.3**
Proton intensity [10^{14} / pulse]	2.7	**3.2**
Cycle [s]	2.48	**1.16**



J-PARC Neutrino Beamline Upgrade

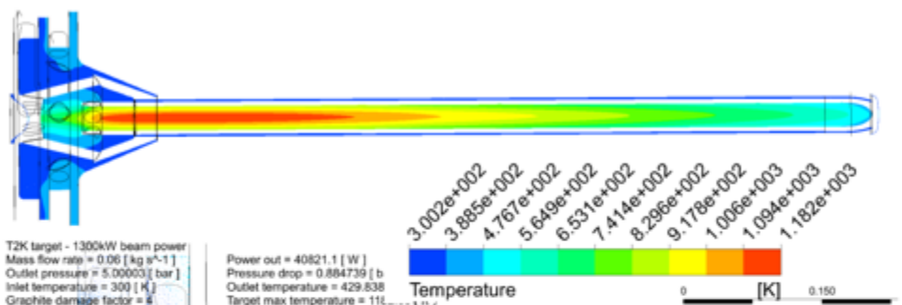
- **Baseline design**
  - Beamline components designed to accept **3.3×10^{14}** ppp
  - Replaceable components designed for **750 kW** (can be upgraded later)
  - Non-replaceable components (HV, DV, BD) designed for **3-4 MW**
- **Necessary upgrade toward 1.3 MW**
  - Improve cooling capacity to remove larger heat generated by higher power beam
    - **Target He cooling, water cooling for horn, He vessel etc**
  - Accommodate shorter cycle operation
    - **Horn operation, DAQ**
  - Accommodate larger amount of radioactivity produced by higher power beam
    - **Upgrade radioactive waste disposal facility**
  - Safe and reliable control of higher power beam
    - **Improved control system and beam monitors**

Target Upgrade

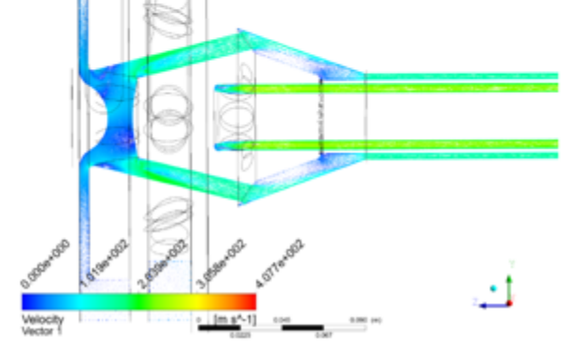
- **Original target design**
  - To survive thermal shock by **3.3x10^{14}** ppp beam ⇒ **3.2x10^{14} ppp should be OK**
  - Cooling capacity only **900 kW**
- **Improvement**
  - Higher He flow rate needed to improve cooling performance
    - 0.5 MPa pressure needed ⇒ high pressure tolerance
    - He compressor upgrade
  - Thermal analysis for 1.3 MW ⇒ max temp. **~900°C** expected
    - Further optimization to be done
  - Vacuum insulation pipes developed for higher temp. (~200°C) He flow ⇒ to

  - Prototyping of new target with high pressure tolerance ongoing ⇒ to be installed in **FY2025**
  - He circulation system upgrade scheduled in **FY2025**

Expected target temperature



Expected He velocity

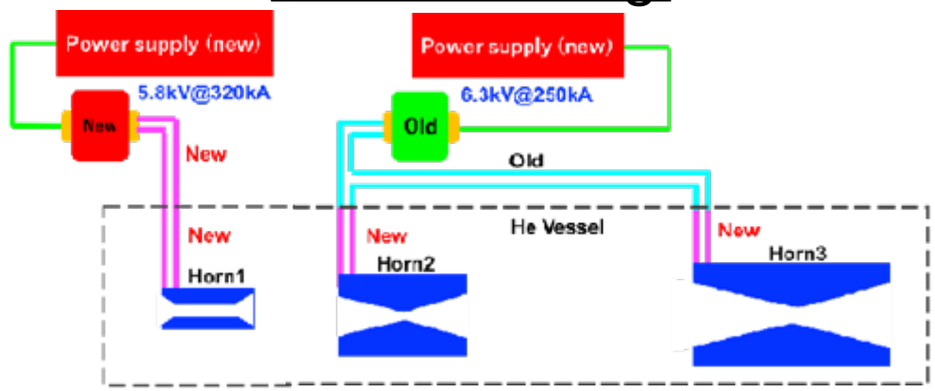


	0.75 MW	1.3 MW
Helium pressure	1.6 bar	5 bar
Pressure drop	0.83 bar	0.88 bar
Helium mass flow	32 g/s	60 g/s
Heat load	23.5 kW	40.8 kW
US window temp	105 ° C	157 ° C
DS window temp	120° C	130° C
Targe core temp	736 ℃	909 ℃

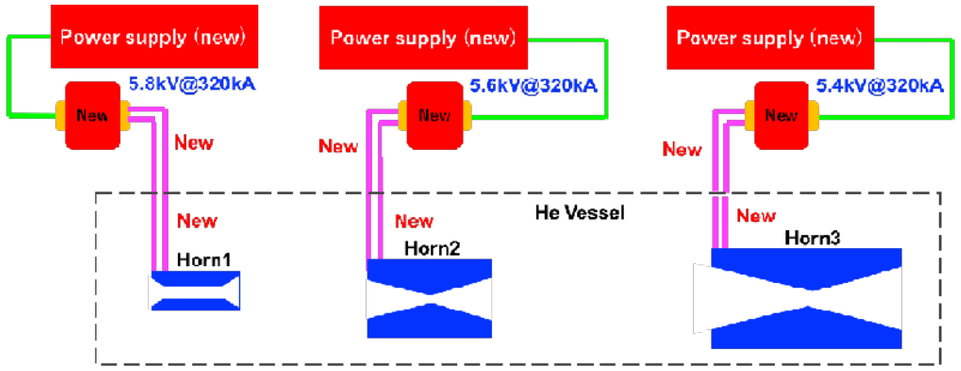
Horn Upgrade

- **Horn electrical system upgrade for 320 kA at 1 Hz**
  - Horn current 250 kA → 320 kA (design)
    - ~10% flux gain for right-sign neutrinos
    - 5~10% flux reduction for wrong-sign neutrinos
  - Three power supplies to drive three horns (one-by-one)
    - New electrical system (PS, transformer, striplines) developed
  - Staged upgrade
    - 1 Hz (@250kA) operation after FY2022
    - 320 kA operation by adding 3rd PS (FY2023~)
- **Conductor cooling improvement (for Horn2)**
  - Stripline cooling
    - Forced He flow scheme not enough for 1.3 MW
    - Water-cooled striplines established
  - Upstream conductor cooling implemented

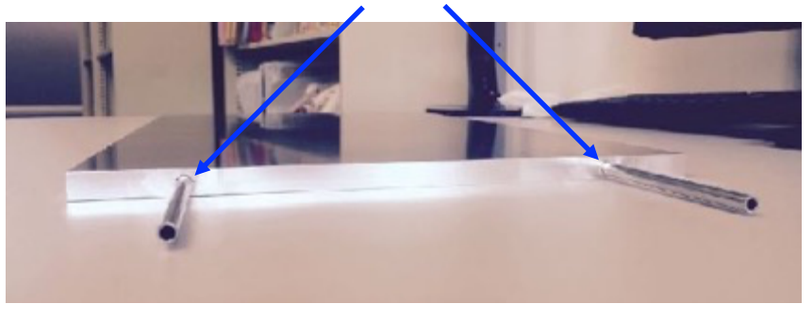
Current config.

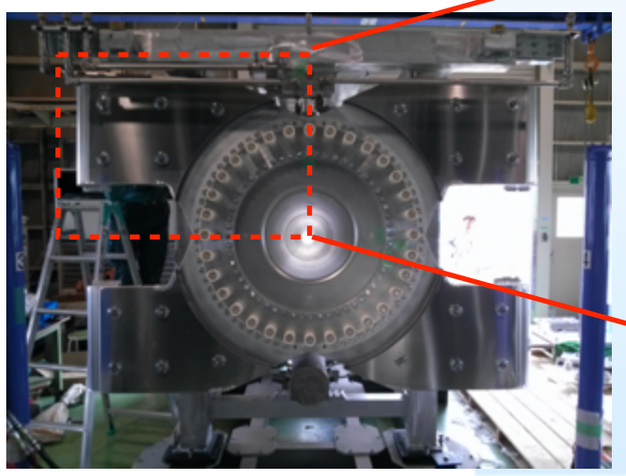


Proposed config.

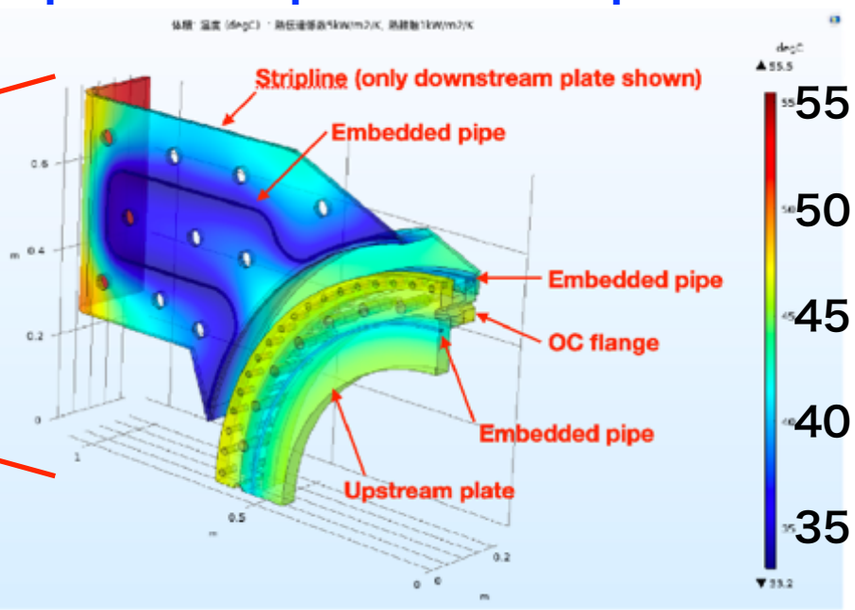


Stainless pipe embedded aluminum plate





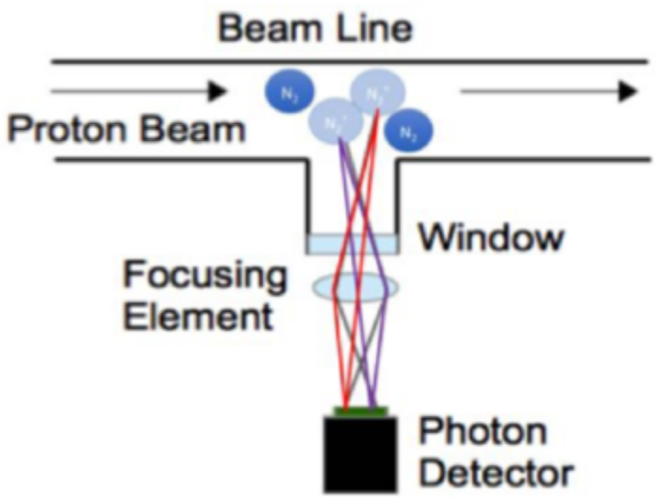
Expected temperature at striplines



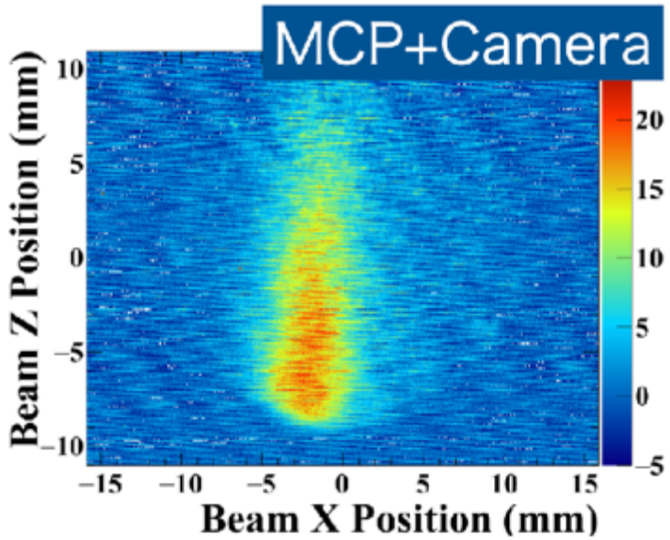
Other Upgrade Items

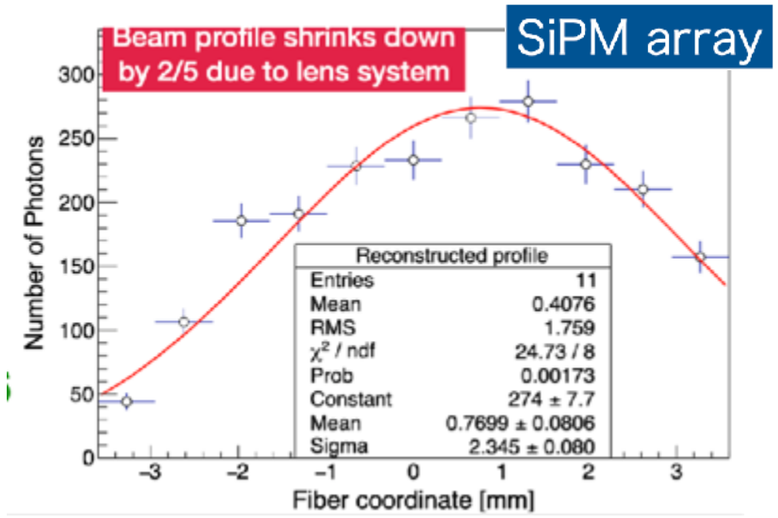
- Radio-active water disposal facility upgrade (FY2020~2021)
  - Produced tritiated water must be diluted and disposed
  - Current limitation comes from size of dilution tank 84 m^3
  - Additional 400 m^3 tank under construction
- Cooling capacity improvement for secondary beamline (FY2025)
  - Current capacity is ~1MW
  - Pumps, heat exchangers, and chillers will be replaced

- New beam profile monitor development for high intensity beam
  - Beam-induced fluorescent profile monitor
- Control/DAQ upgrade for 1 Hz operation (~FY2022)

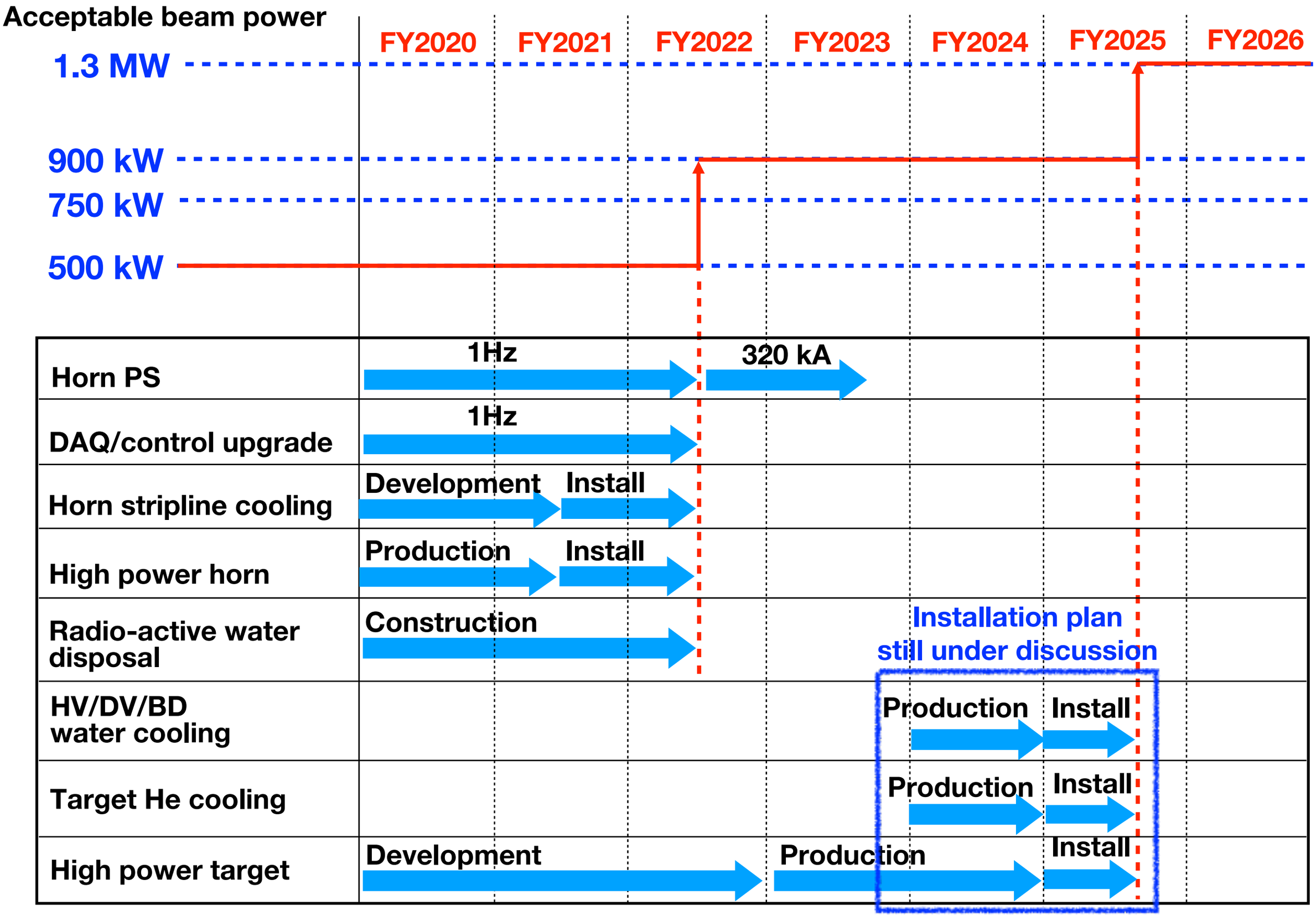


Observed signals from Beam-induced fluorescent profile monitor at first beam test





Tentative Timeline



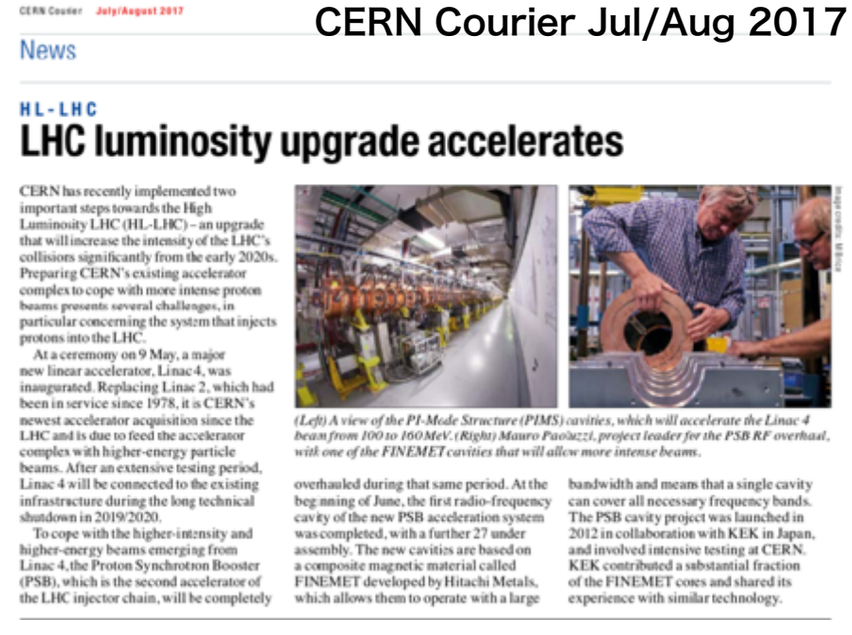
International Cooperation on High Power Neutrino Beam

- **Good relationship among KEK, Fermilab, CERN experts since 1999** (including participation from many other institutes)
  - Detailed discussions and information exchange in Neutrino Beam and Instrumentation (NBI) workshop series
    - **Many lessons learned from other facilities**
- **US-Japan Cooperative Programs in High Energy Physics**
  - 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
- **CERN-KEK cooperation for accelerator and beamline technology**
  - Accelerator technology (RF, beam monitors, etc)
  - Expanding to other fields (radiation damage, beamlines)

Most recent NBI workshop @ Fermilab

KEK contribution to LHC upgrade on RF

CERN Courier Jul/Aug 2017



CERN Courier July/August 2017

News

HL-LHC

LHC luminosity upgrade accelerates

CERN has recently implemented two important steps towards the High Luminosity LHC (HL-LHC) – an upgrade that will increase the intensity of the LHC's collisions significantly from the early 2020s. Preparing CERN's existing accelerator complex to cope with more intense proton beams presents several challenges, in particular concerning the system that injects protons into the LHC.

At a ceremony on 9 May, a major new linear accelerator, Linac 4, was inaugurated. Replacing Linac 2, which had been in service since 1978, it is CERN's newest accelerator acquisition since the LHC and is due to feed the accelerator complex with higher-energy particle beams. After an extensive testing period, Linac 4 will be connected to the existing infrastructure during the long technical shutdown in 2019/2020.

To cope with the higher-intensity and higher-energy beams emerging from Linac 4, the Proton Synchrotron Booster (PSB), which is the second accelerator of the LHC injector chain, will be completely overhauled during that same period. At the beginning of June, the first radio-frequency cavity of the new PSB acceleration system was completed, with a further 27 under assembly. The new cavities are based on a composite magnetic material called FINEMET developed by Hitachi Metals, which allows them to operate with a large bandwidth and means that a single cavity can cover all necessary frequency bands. The PSB cavity project was launched in 2012 in collaboration with KEK in Japan, and involved intensive testing at CERN. KEK contributed a substantial fraction of the FINEMET cores and shared its experience with similar technology.

(Left) A view of the PI-Mode Structure (PIMS) cavities, which will accelerate the Linac 4 beam from 100 to 160 MeV. (Right) Mauro Paoluzzi, project leader for the PSB RF overhaul, with one of the FINEMET cavities that will allow more intense beams.

Summary

- **High power neutrino beam is a key for future neutrino programs**
- **J-PARC Neutrino Beam**
  - 10-year running for T2K physics data taking since 2010
  - 500 kW stable operation achieved so far
- **Future upgrade**
  - J-PARC 1.3 MW upgrade (3.2×10^{14} protons/pulse and 1.16 s cycle)
    - Accelerator upgrades
      - Magnet PS, RF, etc
    - Neutrino beamline upgrade
      - Major upgrade during FY2021-2022 long shutdown
        - Horn replacement, Horn PS upgrade, new radio-active water disposal facility
      - Other upgrades around FY2025
        - Cooling capacity improvement, high-power target installation
- **International cooperation to realize high power neutrino beam facility**