Enhanced search for CP violation in leptons with the new Intermediate Water Cherenkov Detector and improved J-PARC neutrino beam in the Hyper-Kamiokande Experiment.

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High Energy Accelerator Research Organization (KEK)
for
Hyper-Kamiokande Collaboration

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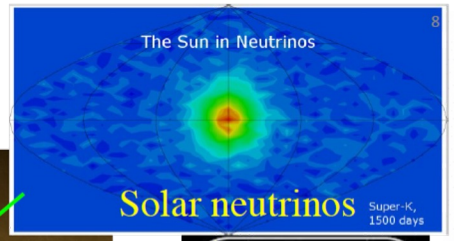
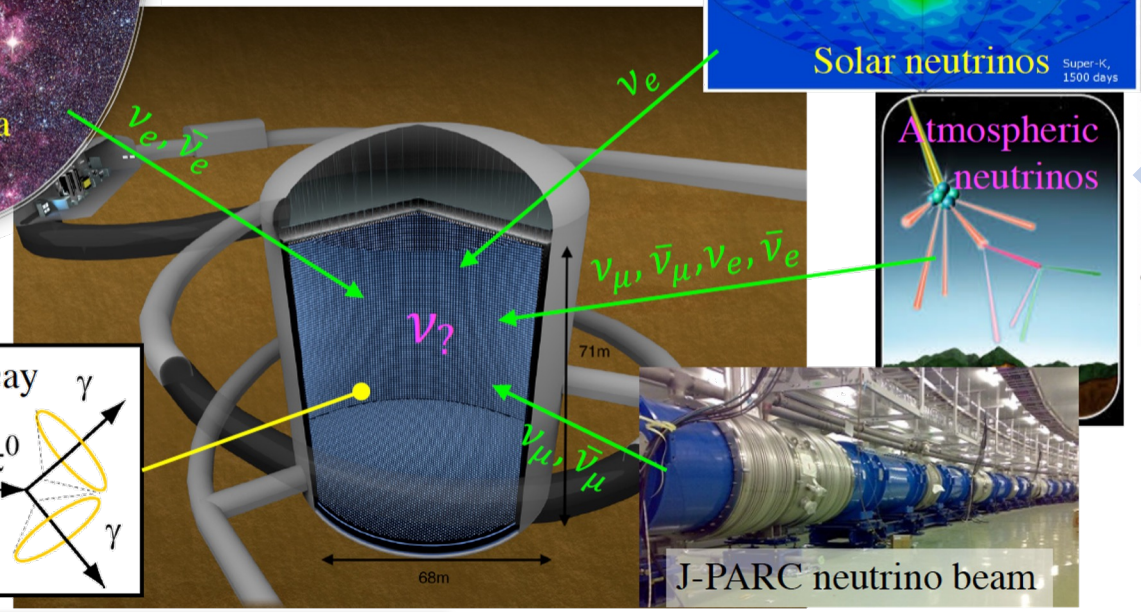
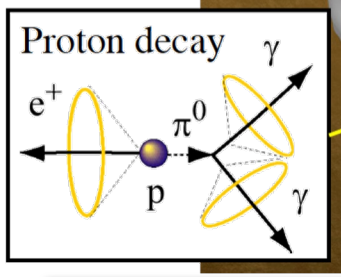
Hyper-Kamiokande Overview

Physics in
Hyper-Kamiokande







New Huge Water
Cherenkov Detector
(Fiducial mass = 190kt)

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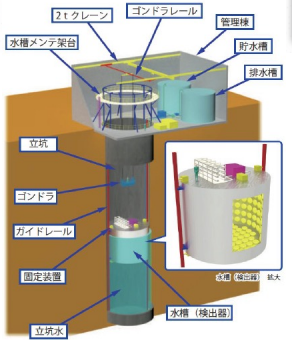
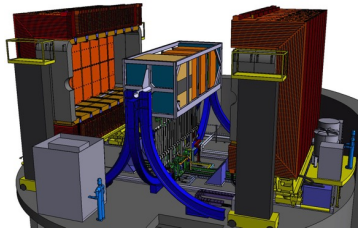
THE UNIVERSITY OF TOKYO

J-PARC
ν-beam
upgrade
(1.3MW)

Near Detector
upgrade





KEK

Under construction from 2020,
Data taking in 2027~.

Civil construction at Kamioka and PMT mass production is in progress.

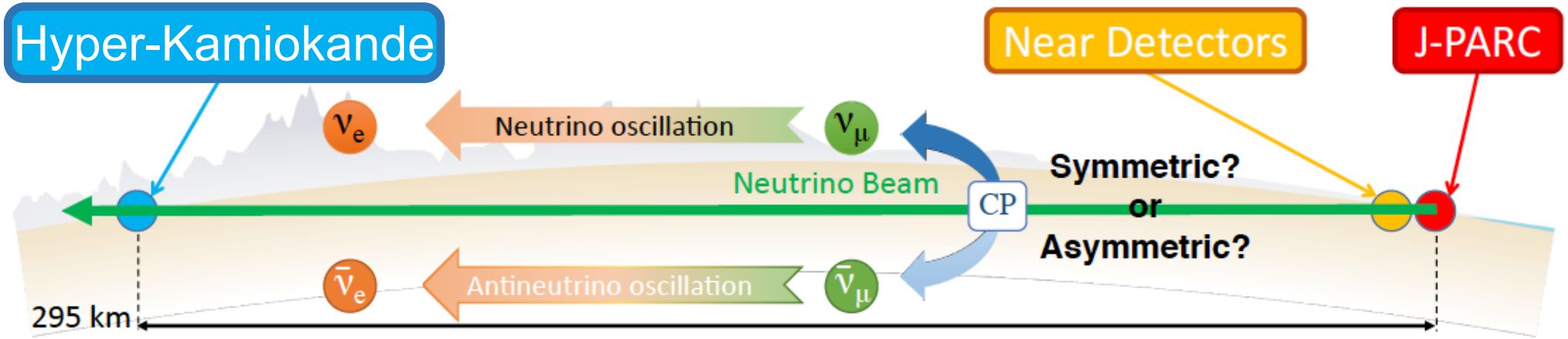
Physics goal of Long-baseline program in HK

- Search matter - anti-matter difference (“CP violation”) in leptons by precise measurement of neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\Sigma U_{\alpha i} U_{\beta i} U_{\alpha j}\, U_{\beta j} \sin^2\left(\Delta m^2_{ij} L/4E\right)$$

$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{-i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

→ Approach the fundamental question;
“Why anti-matter is disappeared in early Universe? ”

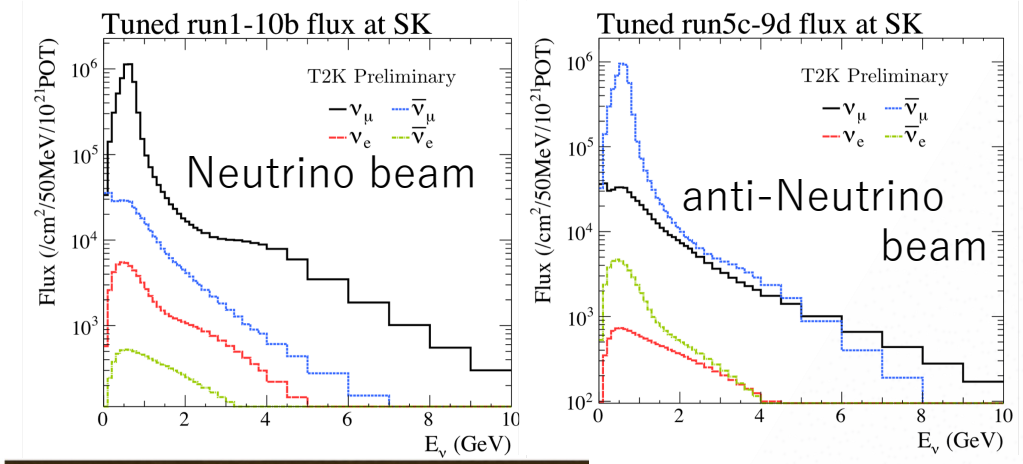


Long baseline experiment using J-PARC ν-beam

T2K : J-PARC 750kW (Orig. Design) + SK (50kt) : 2009~ Running

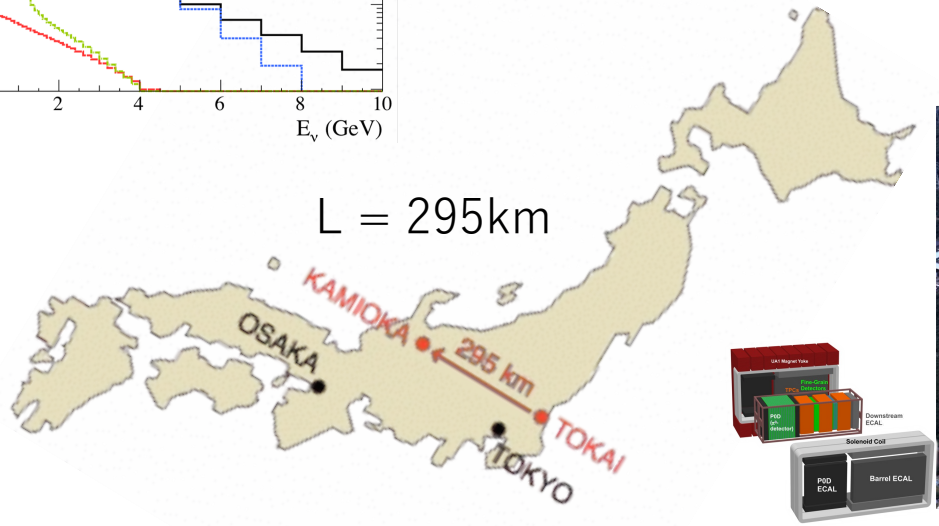
→ **Hyper-K: J-PARC 1.3MW + HK (260kt)**: Under Construction

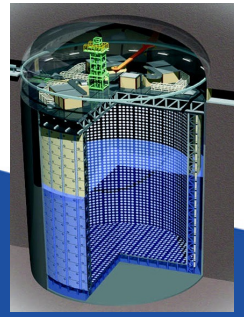
- 2.5° Off-axis Narrow band beam → Eν~600MeV : Ocsi. Max. @300km

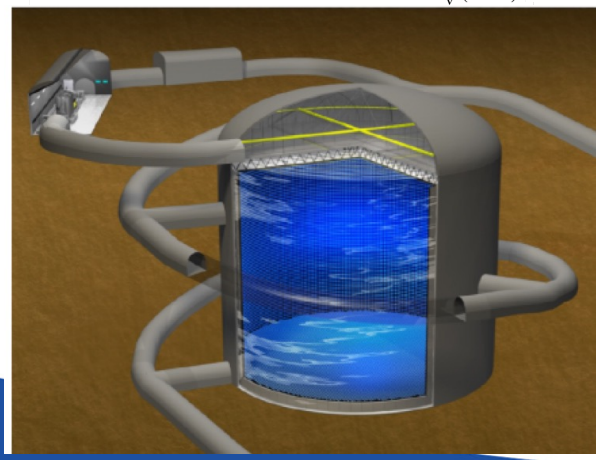


T2K Results

- 2013: **First observation of νe appearance**
- 2014~: Lepton CPV search
  → 2021: **First 3 σ constraint for δ_{CP}**







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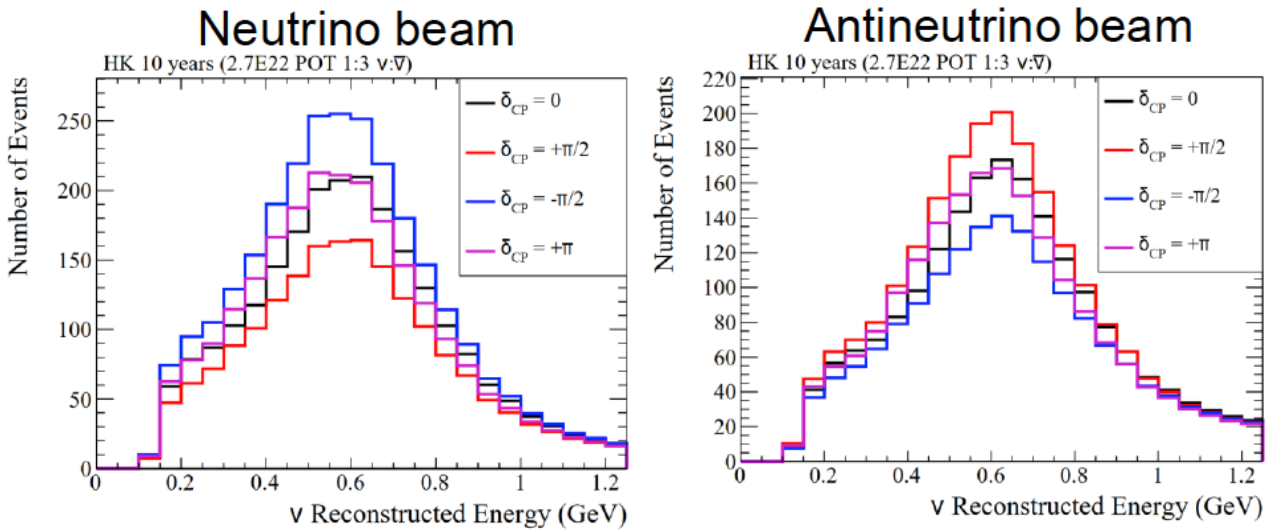
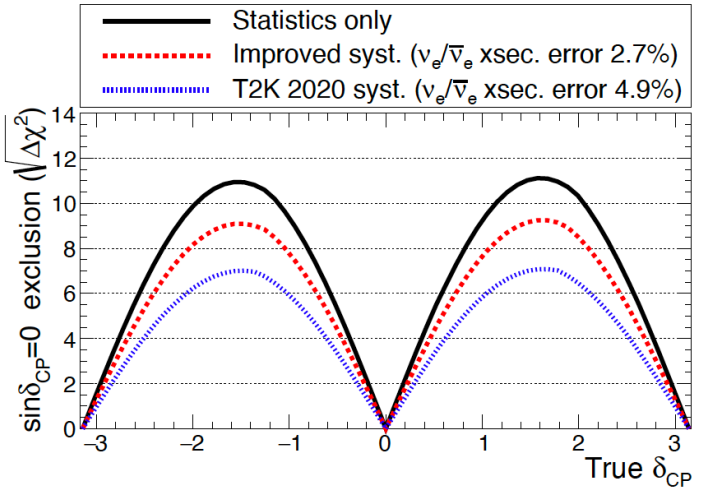
Expected sensitivity for CP violation search

- High statistics samples:
  ~2300 $\nu_\mu \rightarrow \nu_e$
  ~1900 $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  are expected in 10 years.
  : Max. 27% effect by CPV
  (standard 3-flavor model)

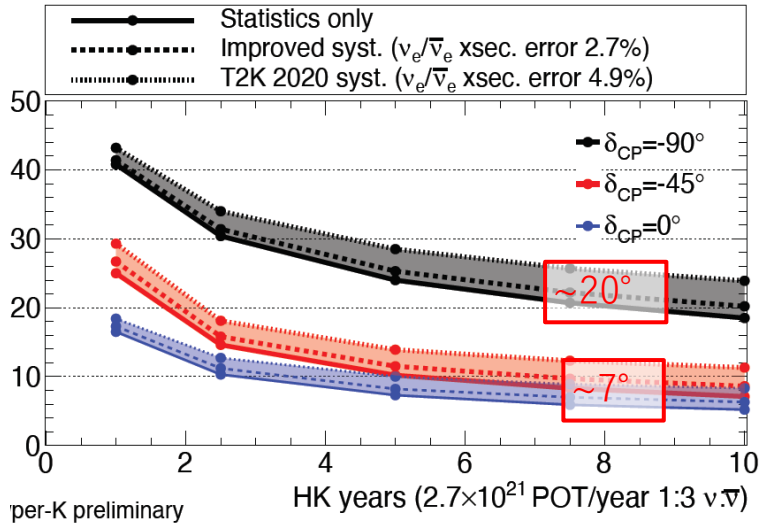
➔ Discovery potential for ~60% of parameter space.

➔ Measure the size of CPV effect with good precision.





Hyper-K preliminary
True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 ν:ν̄)
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4



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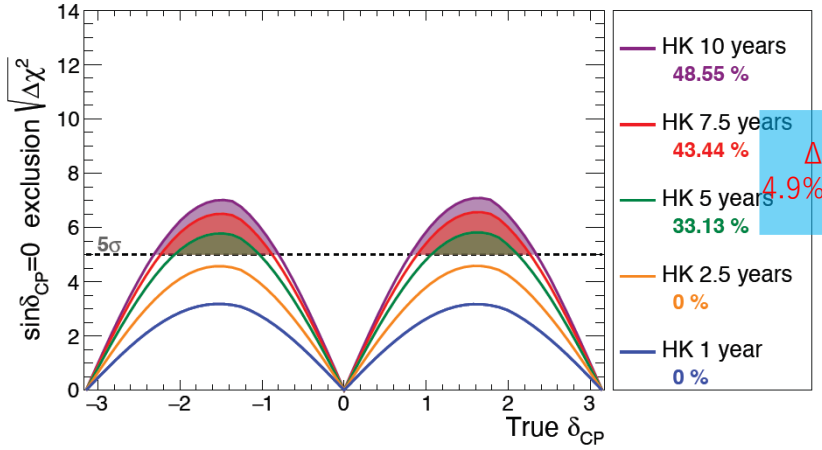
Hyper-Kamiokande
J-PARC
KEK
IPNS Institute of Particle and Nuclear Studies

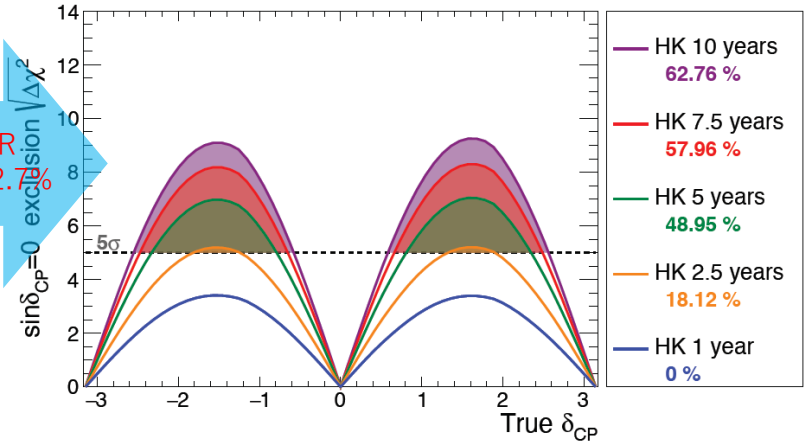
Challenges for precision measurement of ν-oscillation

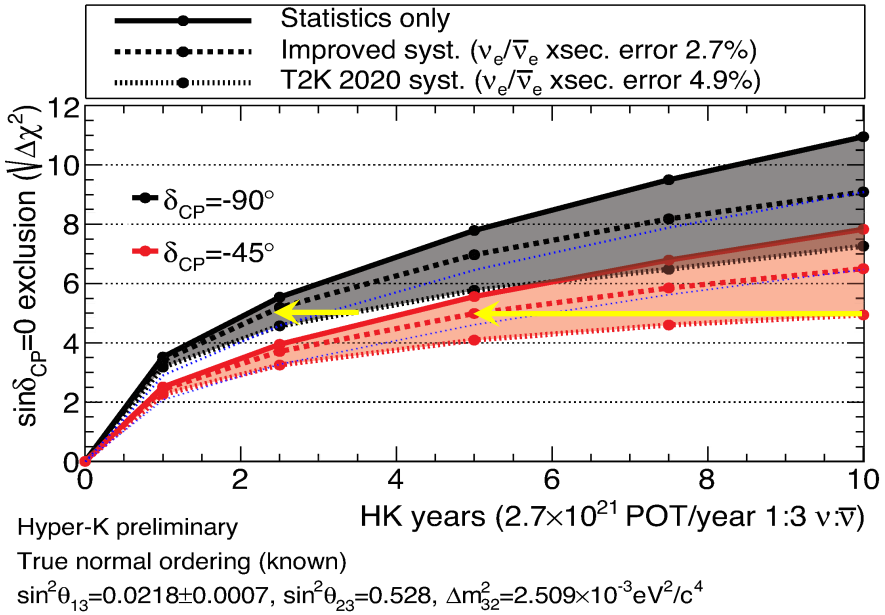
- **Stable intense neutrino beam** : Aiming ~6 month/year for 10 years.
- **Control systematic uncertainty** :

Major source: (relative) ν-N interaction cross-section $\mathbf{R} \equiv \left[\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}\right]$

- Current experiment (T2K) : $\Delta R/R \sim 5\%$ (using on theoretical models)
  → HK goal : Control $\Delta R/R \leqq 2.7\%$ based on the measurement → IWCD







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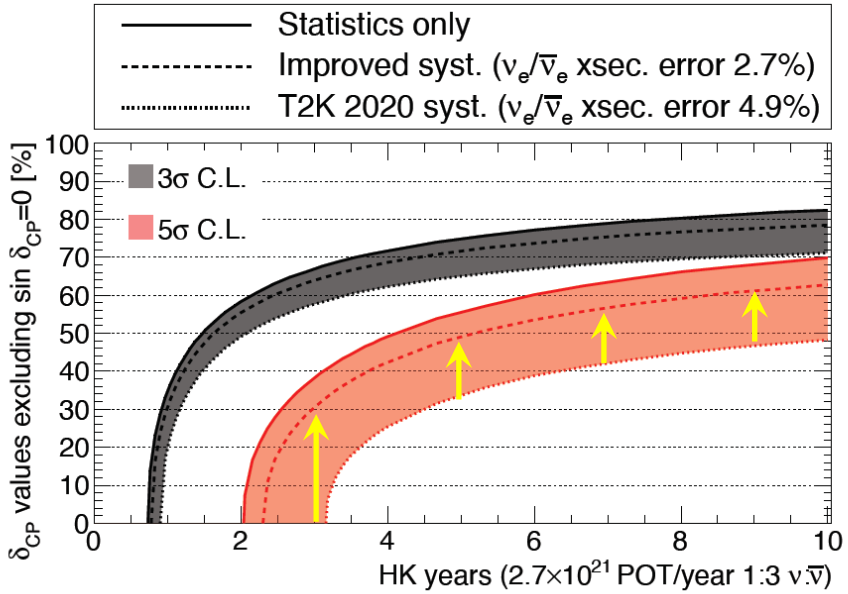

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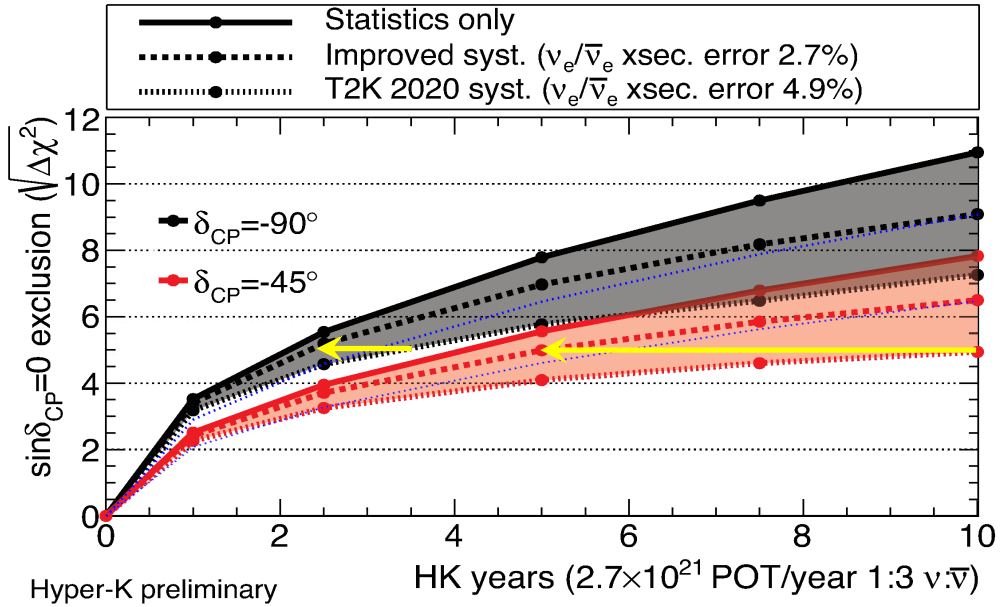

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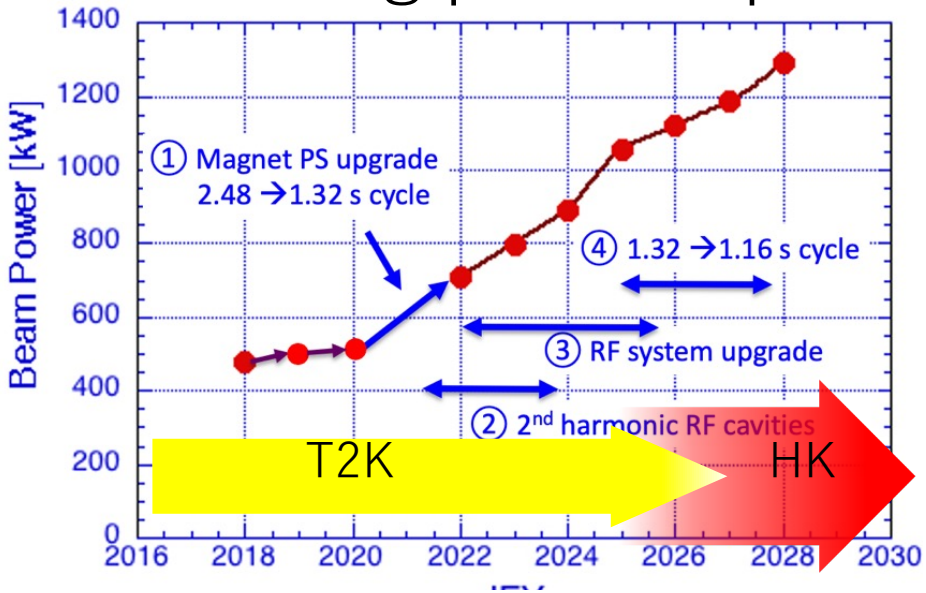
J-PARC Accelerator (MR) upgrade plan

- MR Power upgrade by higher repetition + increasing protons/pulse.

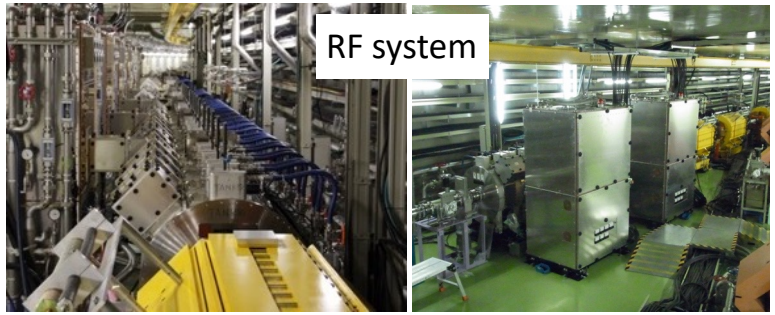
JFY	2020	2021	2022	2023	2024	2025	2026	2027	2028
Event		Long Shutdown							
FX power [kW] SX power [kW]	515 55	- 60–70	>700 >80	800 >80	900 >80	>1000 >80	>1100 ~100	>1200 ~100	1300 ~100
Cycle time for Fast Extraction New Magnet PS	2.48s	Mass Production Installation/Test		1.32s	1.32s	1.32s	<1.32s	<1.32s	1.16s
RF system upgrade 2nd RF system upgrade									
Collimator system		Add.colli. (3.5kW)							
Injection system FX system		Kicker PS improvement Septa manufacture Test							
Beam Monitors (BPM circuits)									

JFY2023~: User Beam operation resumed with new configuration.

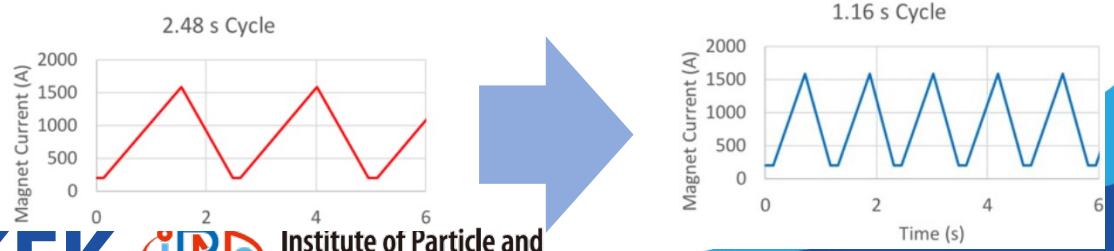


	Beam Power	Cycle Time	Number of accelerated protons
Achieved ~ 2021	500 kW	2.48 s	2.6×10^{14} ppp
Original Design	750 kW	1.36 s	2.1×10^{14} ppp
New Plan	1.3 MW	1.16 s	3.3×10^{14} ppp

New main magnet PS for ~1Hz op. are installed in LS (2021-2022)



Reinforcement of RF and etc. is on-going



By courtesy of Y. Sato (J-PARC Accelerator)

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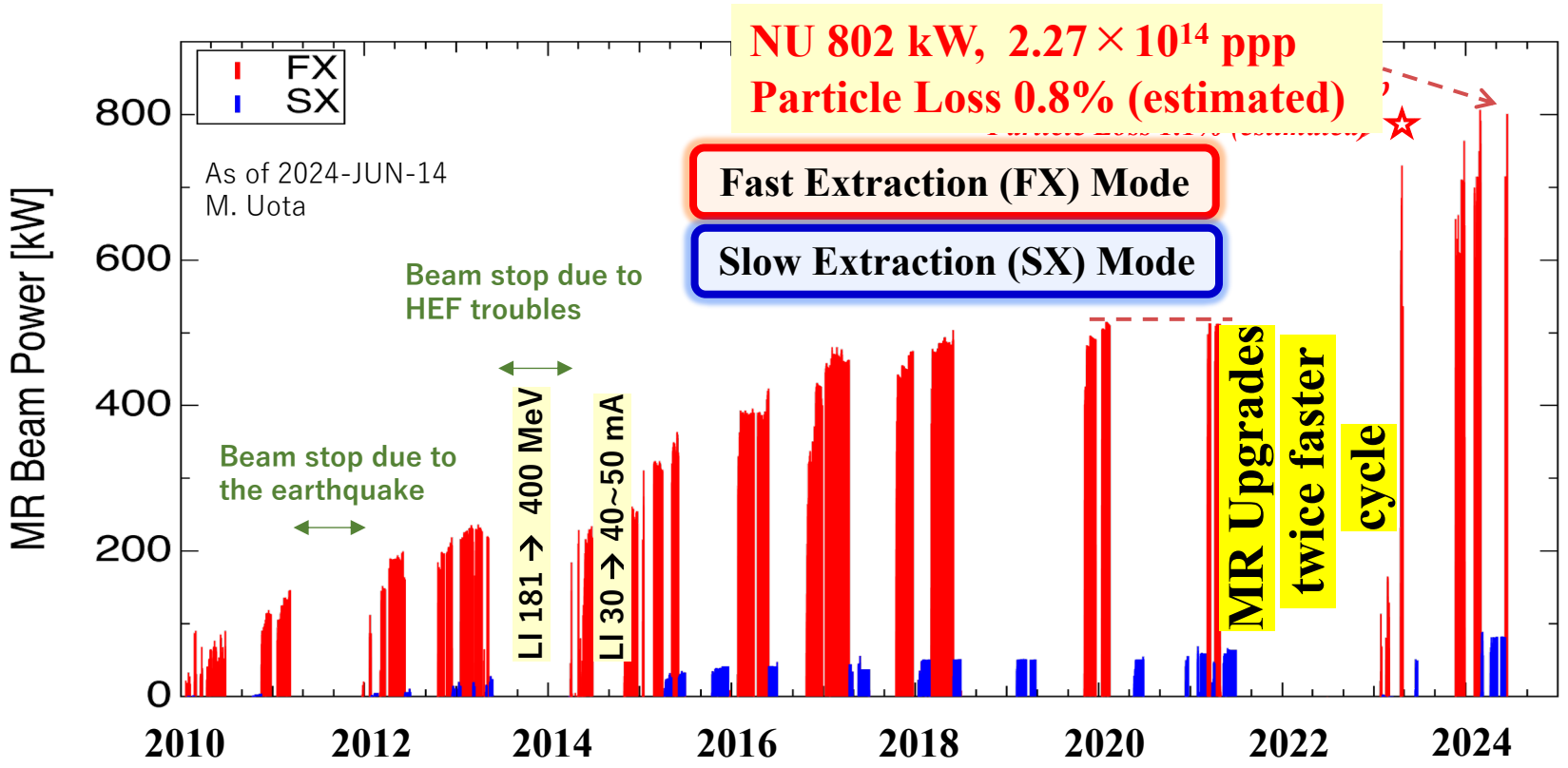
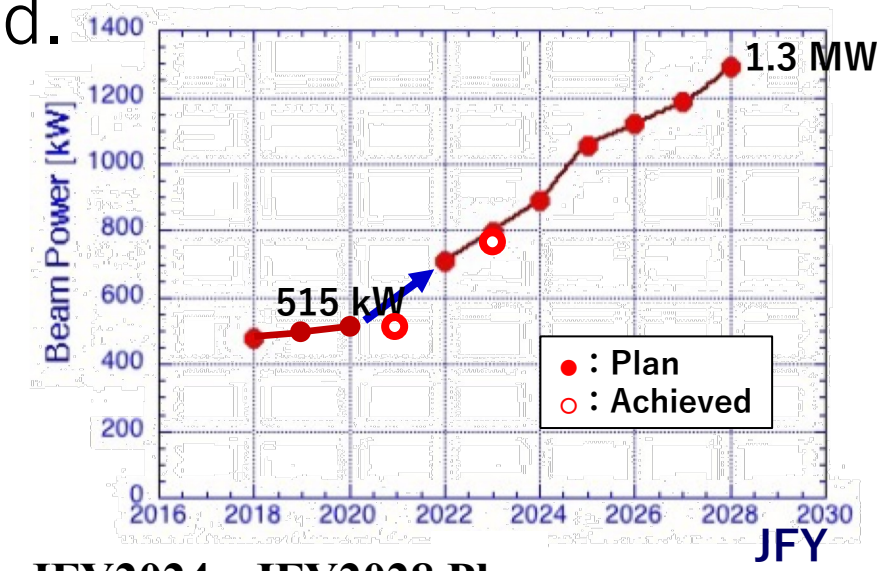
J-PARC Accelerator (MR) upgrade status

- Stable continuous **~800kW** (FX) operation for users is established!
  : MR power is being improved almost as planed.





JFY2024 - JFY2028 Plans

- RF system upgrade (continued)
- More magnet power supplies for beam correction
- Reinforcement of the main magnet PSs
- Upgrade MR-Abort-Dump

3.52s 3.04s 2.56s 2.48s → 1.36s → FX operation cycle for NU

6.00s → 5.52s → 5.20s → 4.24s → SX operation cycle for HD

By courtesy of Y. Sato (J-PARC Accelerator)

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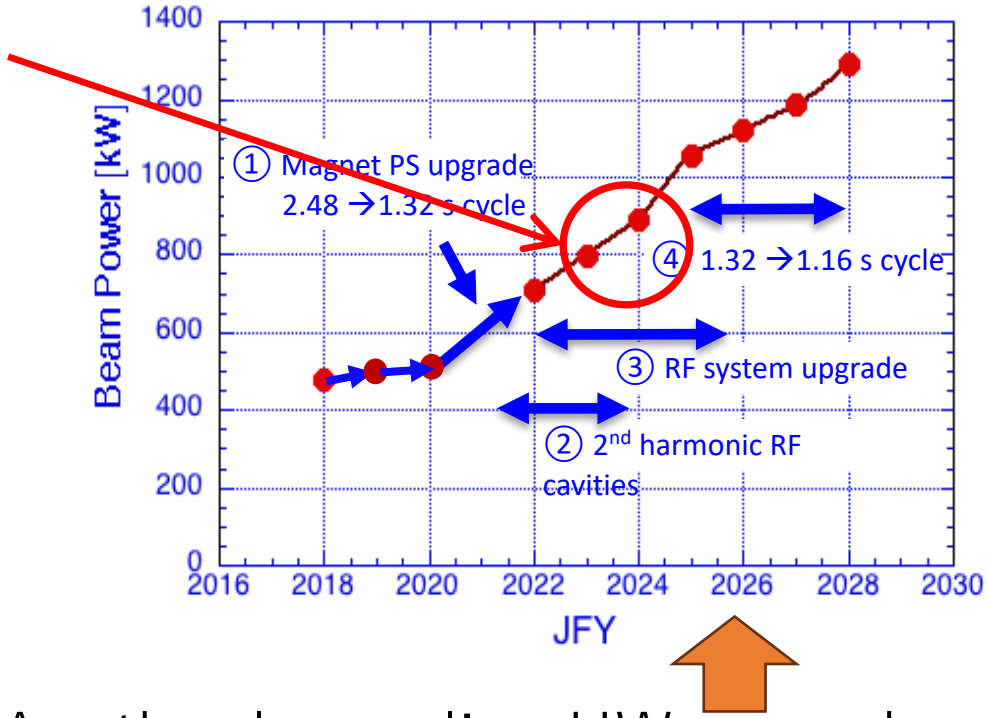
J-PARC neutrino beam-line upgrade

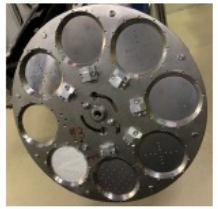
- HW modification for MR 1Hz op. was done in 2021-2022 LS.
  - Horn current reinforcement: +10% yields/protons.
    → acceptable beam power ~900kW
  - Radiation protections in Target Station are reinforced.
    → Government approval for 1.3MW has been obtained.



New Horn PS/trans/ strip-lines for 320kA & 1Hz

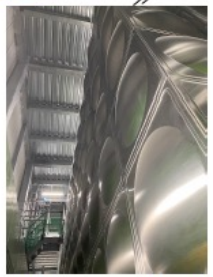
New Horn1 & 2 w/ upgraded cooling capability

New OTR



New FVD2 magnet for better maintainability

New MUMON Si (half of sensors)

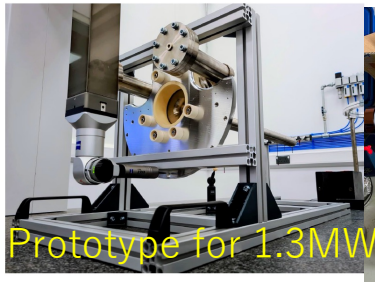


New water tank for radio-active waste handling improvement

New target cooling system

New target

Another beam-line HW upgrade for 1.3MW in JFY2026.

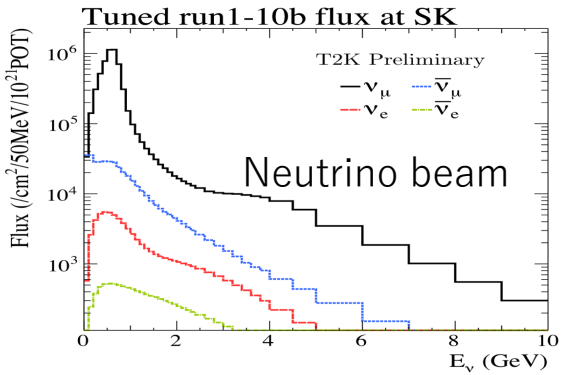


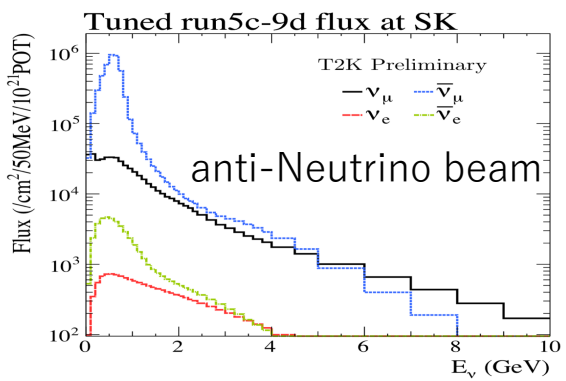
Prototype for 1.3MW target (RAL)

Institute of Particle and Nuclear Studies

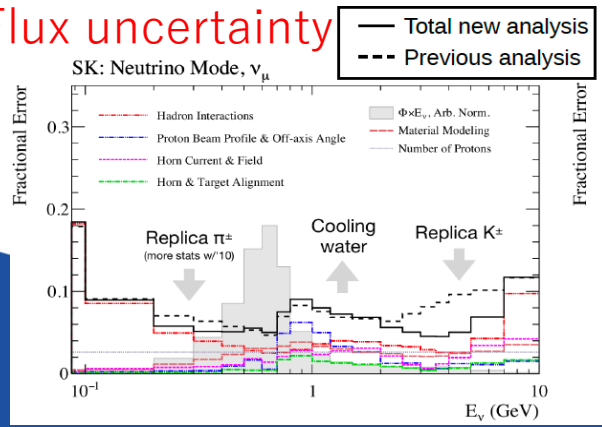
For precise neutrino beam flux predictions

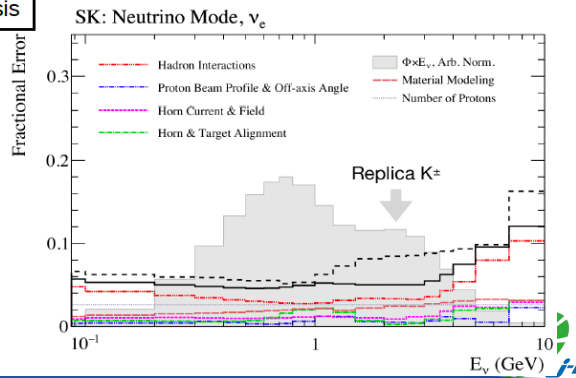
- Precise neutrino flux estimation is important to understand the neutrino interaction cross-section measurement at Near Detectors.
  - Additional NA61/SHINE data for T2K in 2022. → Further improvement is expected.
- Secondary interaction of hadrons become non-negligible error source.
  - Hadron production for 2ndary $\pi^{\pm}$ + C / Al / Fe / H_2O / ⋯ → Dedicated measurements are proposed.
    → EMPATIC @ FNAL (running), NA61 low-E beam-line (proposed)
  - More precise implementation of MC simulation is needed.



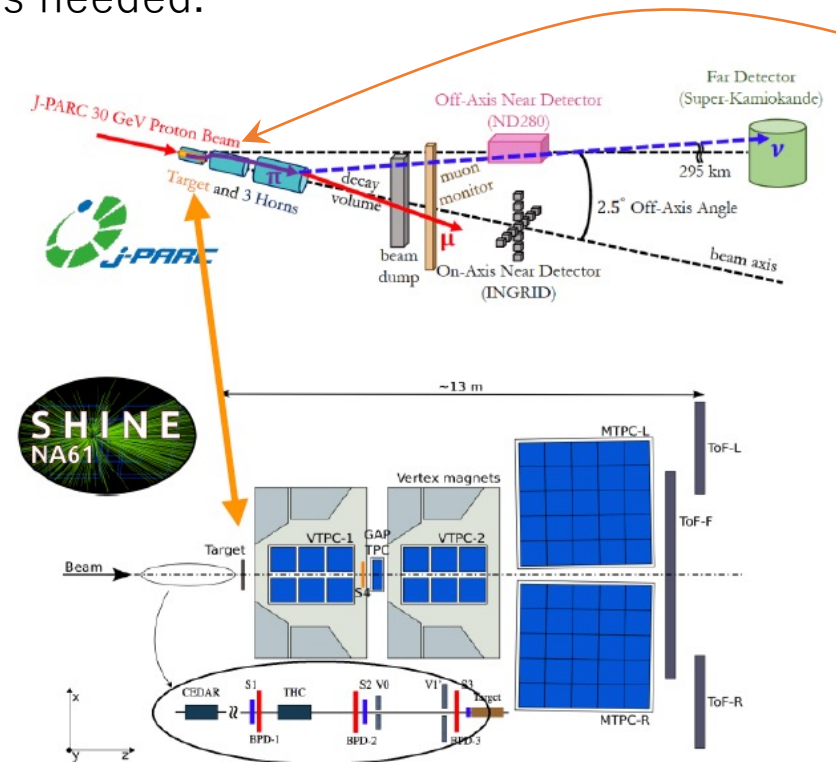


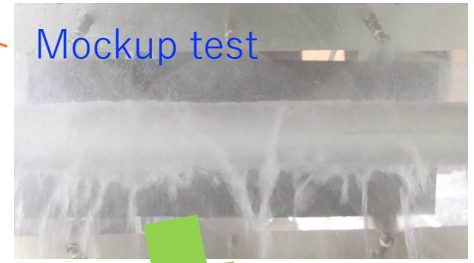
Flux uncertainty

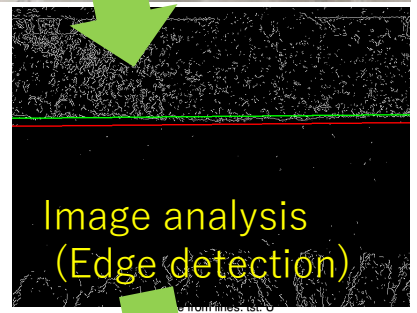


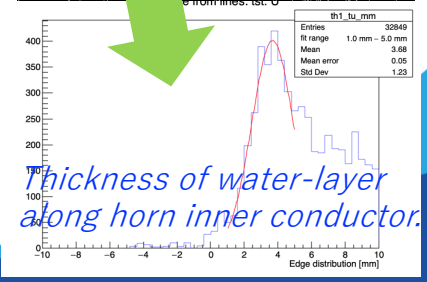


Improvement of material modeling in flux simulation (MC)









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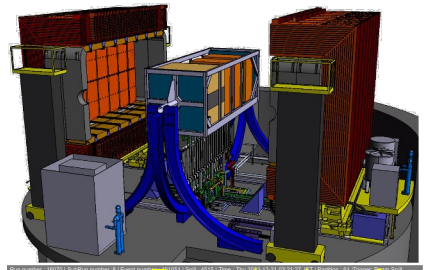
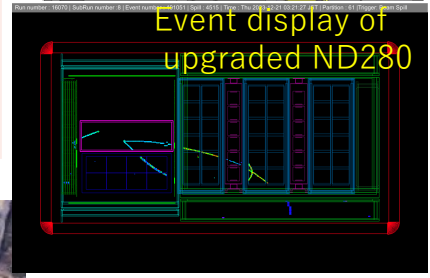
Near Detectors for Hyper-Kamiokande

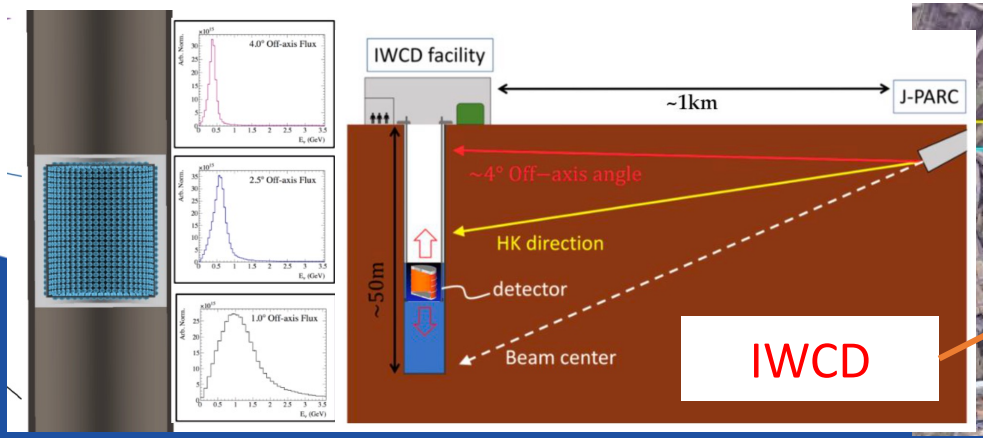
- Key to achieve the aimed systematic error reduction

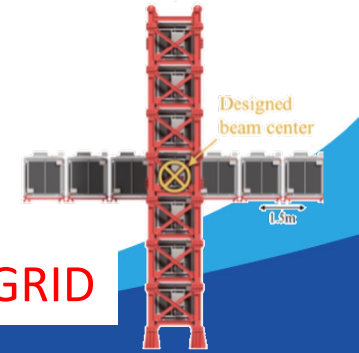
New IWCD	Upgrade ND280 (On-site)	INGRID (On-site)
HK-direction, ~900m	SK-direction, 280m	280m
OA 1.7° — 4.0°	OA 2.5° (fixed)	On axis
---	**Mag. Field (0.2T)**	---
H_2O Target	CH (+H_2O) Target	Fe
Water Cherenkov	Tracker	Tracker
• ν_μ / $\bar{\nu}_\mu$ beam flux/cross section • ν_e / $\bar{\nu}_e$ cross section→ "R" • Beam ν_e / $\bar{\nu}_e$ contamination • "Feed-down" BG.	• ν_μ / $\bar{\nu}_\mu$ beam flux/cross section • "Wrong-sign" contamination	• Beam Direction • Beam stability

ND280







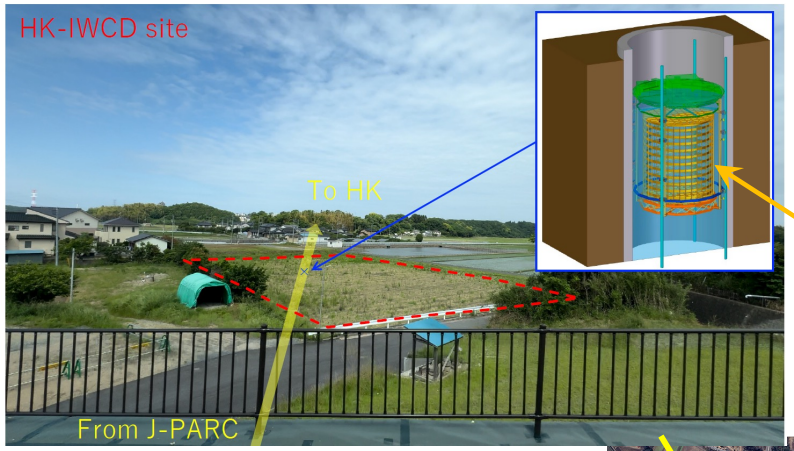


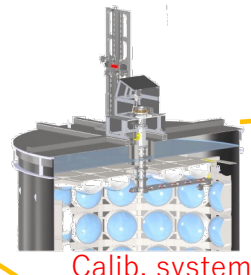
Intermediate Water Cherenkov Detector (IWCD)

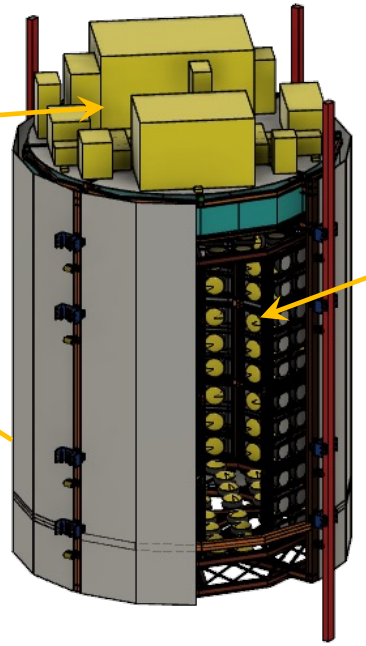
- Novel **Movable** Water Cherenkov Detector (ϕ~9m × H~12m) using mPMT.

  →Key to achieve the 2.7% systematic uncertainty on $\mathrm{R} \equiv \left[\frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}\right]$ with same detection principal (CC-QE) with HK Far detector.

- Development of detector components are on-going.
- Progress in securing the detector site! → Civil construction from JFY 2025~.
  - Detailed facility design based-on the geological survey is in progress.







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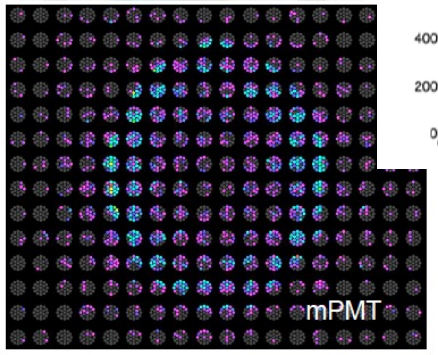

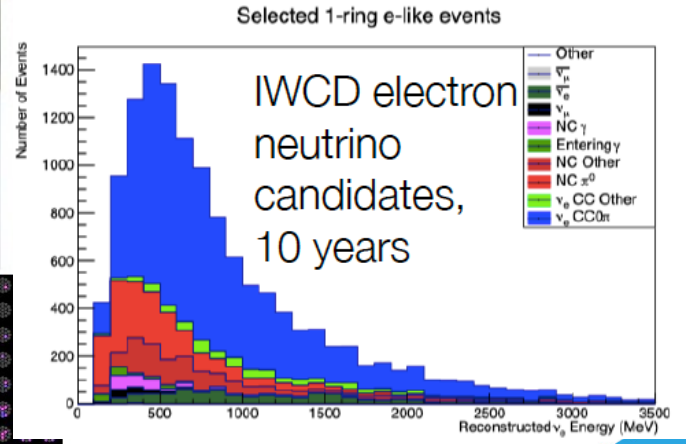

Summary

- Long-baseline program of HK will search CPV in leptons by precise measurement of $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation.
- HK construction is on-going from 2020, and HK physics data taking will start in JFY2027.
  - J-PARC neutrino beam power is improving as expected!
    → >800kW stable beam with higher repetition rate is established.
  - New novel Water Cherenkov Detector (IWCD) will plays key roles to achieve the required systematic error reduction.
    → IWCD facility construction is about to start.

New participants for J-PARC neutrino-beam improvement and IWCD project are very welcome!

Related presentations in ICHEP2024

- "Likelihood and Deep Learning Analysis of the electron neutrino event sample at Intermediate Water Cherenkov Detector (IWCD) of the Hyper-Kamiokande experiment", T. Mondal, 7/19/24, Poster Session 2
- "Low-Energy Calibration of the Hyper-Kamiokande Detector Utilizing a Deuterium Tritium Neutron Generator", R. Er-Rabit, 7/19/24, Poster Session 2
- "The Intermediate Water Cherenkov Detector for the Hyper-Kamiokande long-baseline neutrino oscillation program", R Akutsu, 7/19/24, Poster Session 2
- "Enhancing Event Reconstruction for Hyper-Kamiokande's Water Cherenkov Detectors through Machine Learning", N. Prouse, 7/20/24, Parallel session (Computing, AI and Data Handling)
- "Hadron Production Measurements at NA61/SHINE for Neutrino Oscillation Experiments", K. Allison, 7/19/24, Parallel session (Neutrino Physics)
- "Significant upgrades of magnetic horn system for J-PARC neutrino beamline towards 1.3 MW beam power", T. Sekiguchi, 7/18 Parallel session (Accelerator: Physics, Performance, and R&D for Future Facilities)