Status of the Hyper-Kamiokande Experiment

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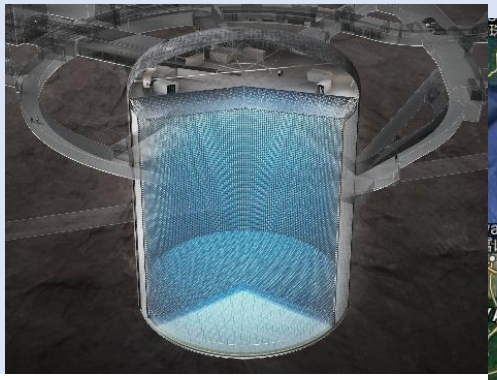
on behalf of the Hyper-Kamiokande Collaboration

The 22nd international workshop on
Next Generation Nucleon Decay and Neutrino Detectors (NNN23)

Oct 11 – 13, 2023 @ Procida, Italy

Hyper-Kamiokande Project

- The Hyper-Kamiokande project includes a far detector, a neutrino beam, and a neutrino near detector complex
  - Construct the Hyper-Kamiokande detector at Kamioka
  - Upgrade the J-PARC neutrino beam
  - Construct the Intermediate Water Cherenkov Detector (IWCD) at Tokai



Hyper-Kamiokande detector
(Far detector)

ν

295 km

J-PARC

Three Generations of Water Cherenkov Detector in Kamioka

- **Kamiokande (1983 - 1996)**
  - Atmospheric and solar neutrino “anomaly”
  - Supernova 1987A

  Birth of neutrino astrophysics

- **Super-Kamiokande (1996 - ongoing)**
  - Proton decay: world best-limit
  - Neutrino oscillation (atm/solar/LBL)
    - All mixing angles and Δm^2s

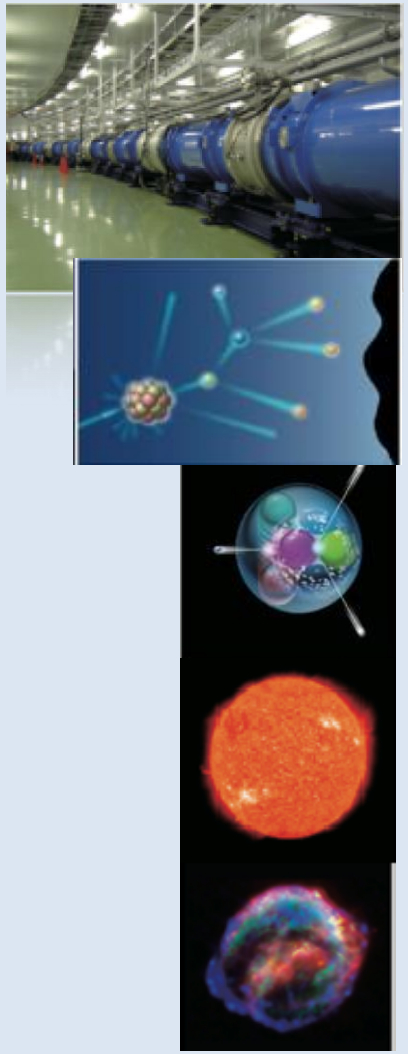
  Discovery of neutrino oscillations

- **Hyper-Kamiokande (2027 -)**
  - Extended search for proton decay
  - Precision measurement of neutrino oscillation including CPV and MO
  - Neutrino astrophysics

  Explore new physics

Hyper-K Observation Target

Target sensitivity

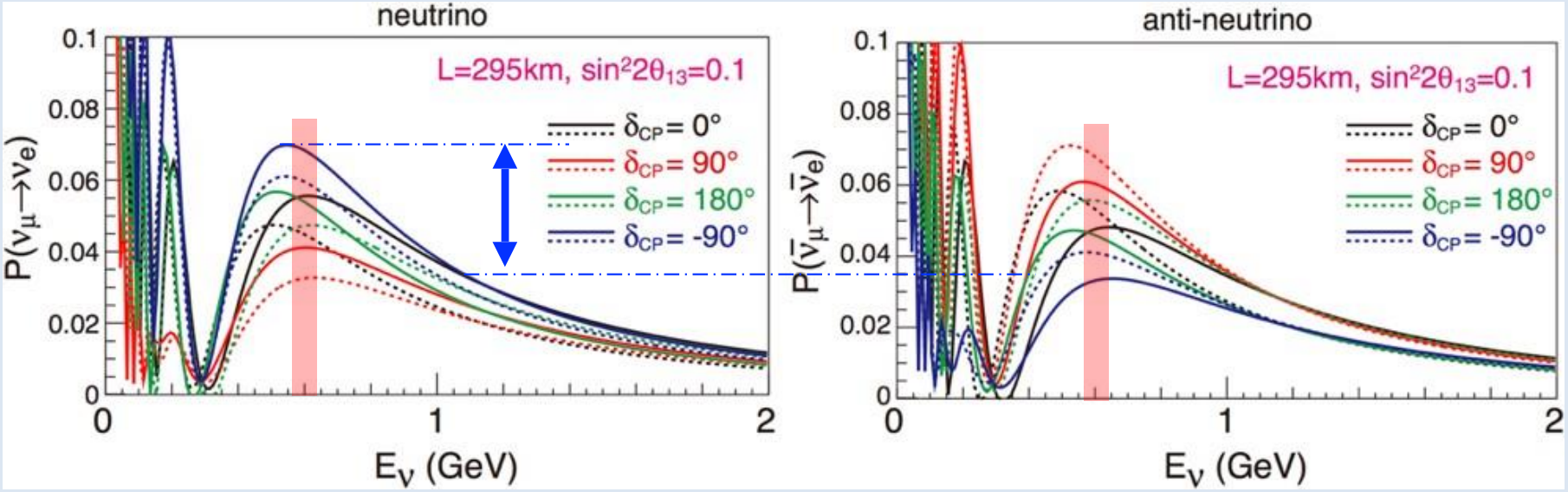


Physics category	Parameters	Sensitivity
LBL (1.3MW×10years)	δ precision	7°-20°
	CPV coverage (3/5σ)	76%/58%
	$\sin^2\theta_{23}$ error (for 0.5)	±0.017
ATM+LBL (10 years)	MO determination	>3.8σ
	Octant determination (3σ)	$\lvert\theta_{23}-45°\rvert>2°$
Proton Decay (20 years)	τ for $e^+\pi^0$ (3σ)	1×10^{35} years
	τ for νK (3σ)	3×10^{34} years
Solar (10 years)	Day/Night (from 0/from KL)	8σ/4σ
	Upturn	>3σ
Supernova	Burst (10kpc)	54k-90k
	Relic	70ν's / 10 years

Long-baseline program with the J-PARC neutrino beam

Experimental setup

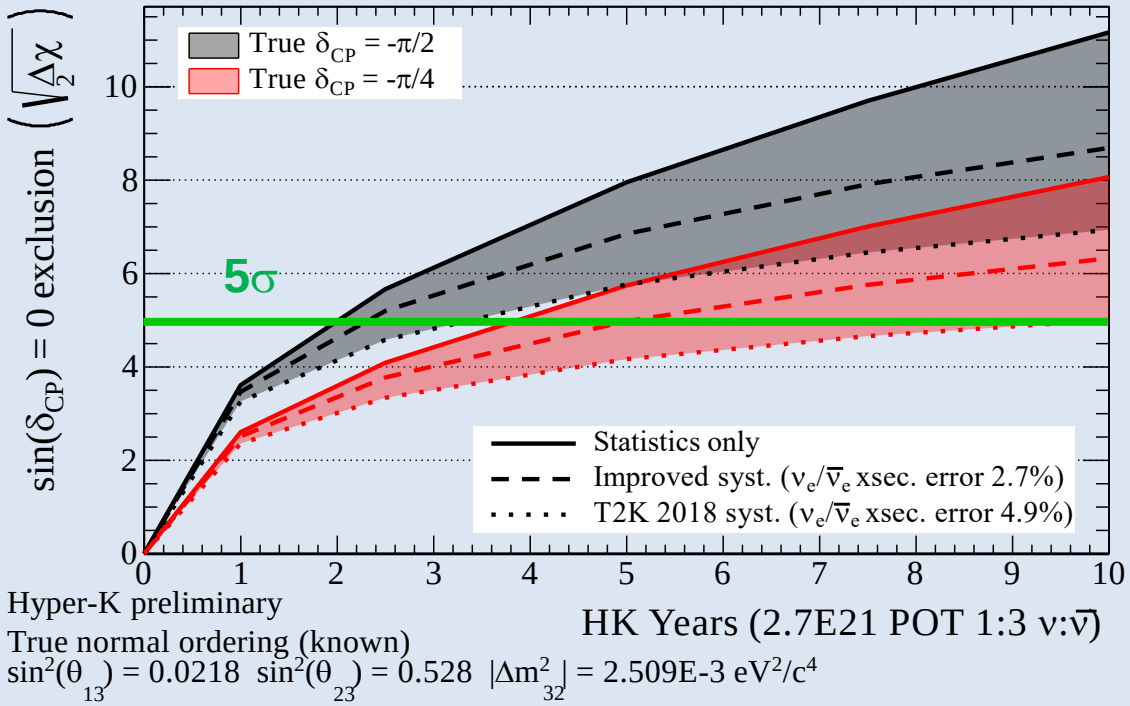
- 2.5° off-axis ν_μ and $\bar{\nu}_\mu$ beam peaked at 0.6 GeV (oscillation maximum at 295km)
  - Major interaction is QE: E_ν determined from (p, θ) of charged lepton
- Measures CP violation in neutrinos by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

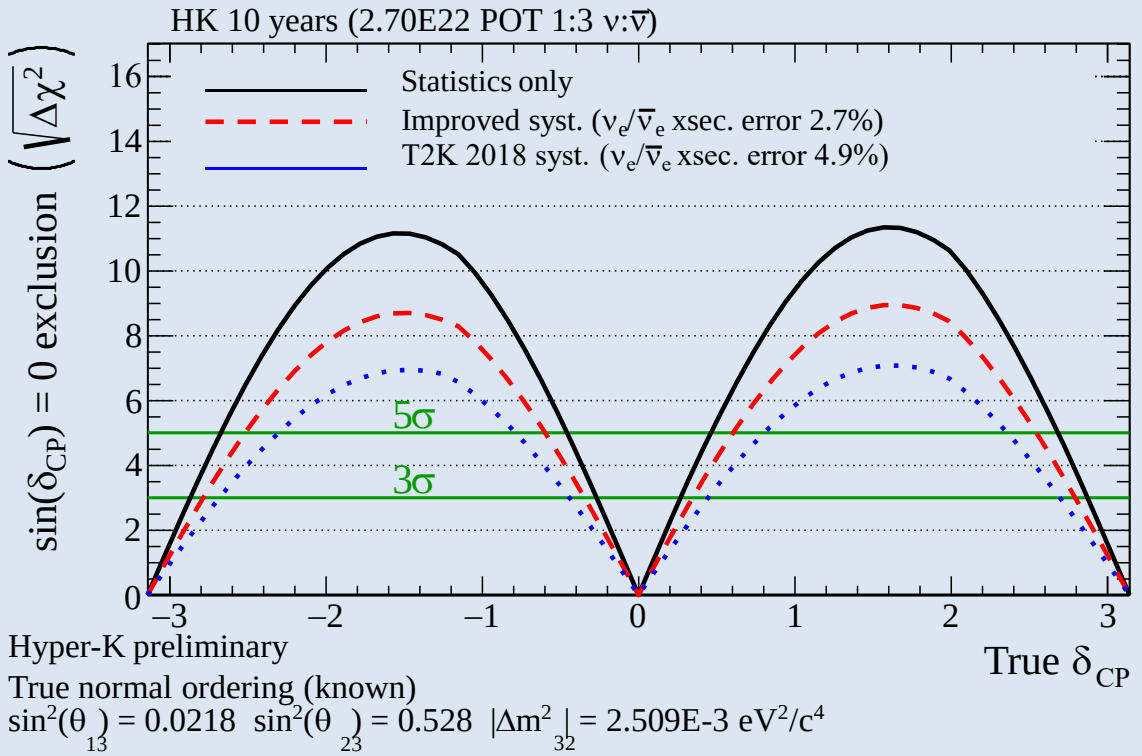


- A few % statistical uncertainties after 10 years operation with >1000 ν_e and $\bar{\nu}_e$ signals

CP violation sensitivity

- Sensitivity CP violation with 1:3 ν: $\bar{\nu}$ beam





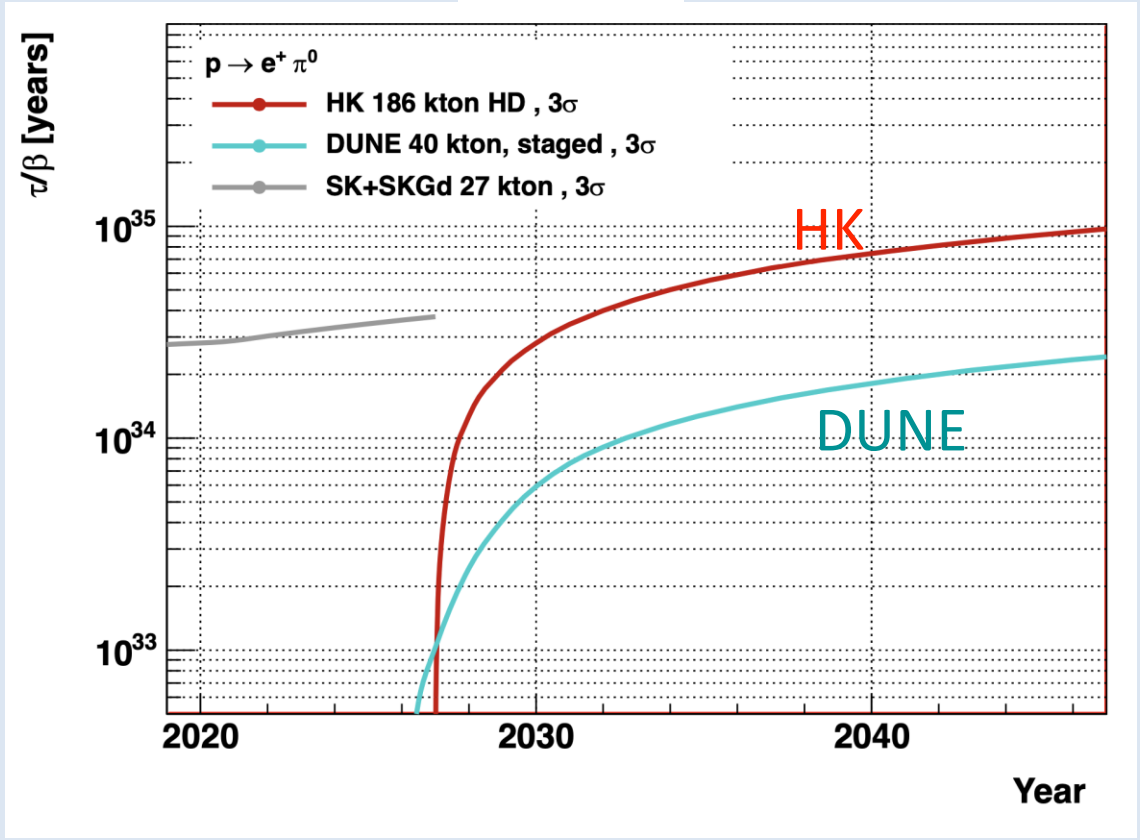
- With optimistic systematics and known mass ordering (MO): 2-3 years for 5σ sensitivity to exclude CP conservation for true $\delta CP = -\pi/2$.
- After 10 years of operation, 60% of δCP values excluded at > 5σ

Nucleon decay search

- Nucleon decay is evidence of Beyond Standard Model (BSM) and Grand Unified Theories (GUT)
- Examples of proton decay sensitivity in two modes:

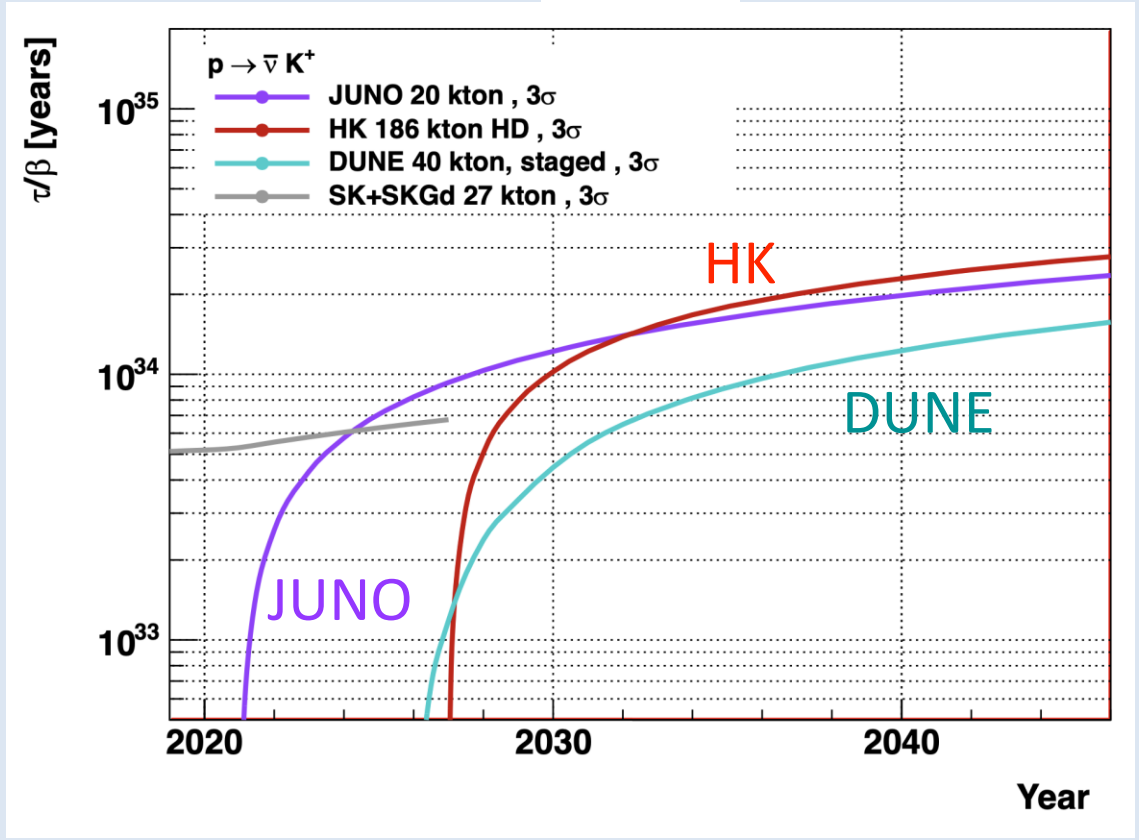
[HK] arXiv:1805 04163
[DUNE] arXiv:2002.03005
[JUNO] arXiv:1508.07166

$p \rightarrow e^+\pi^0$



$\tau \sim 10^{35}$ years (3σ)

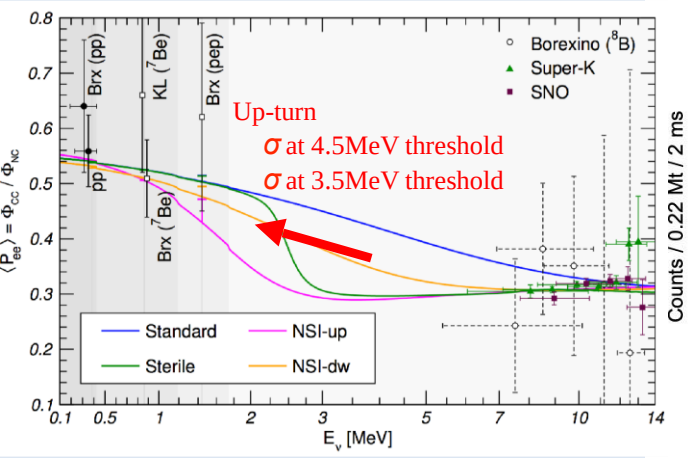
$p \rightarrow \bar{\nu}K^+$

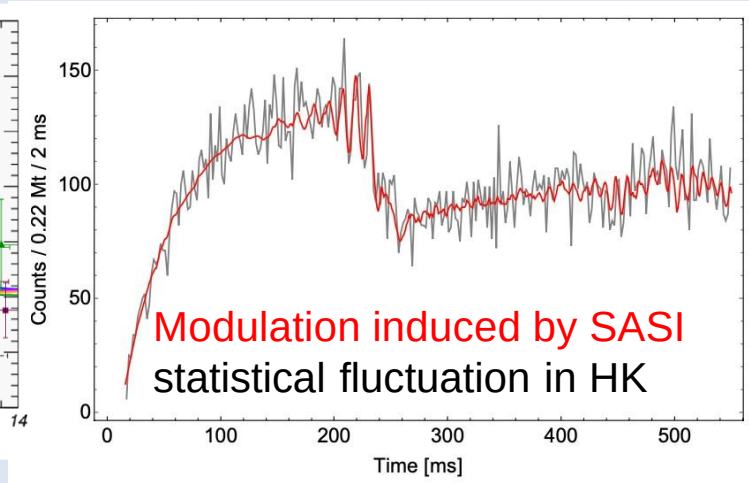


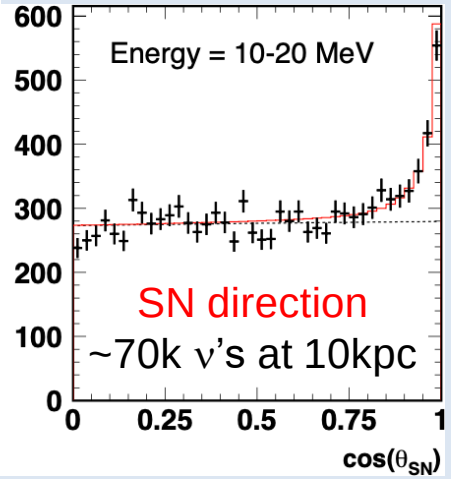
$\tau \sim 3 \times 10^{34}$ years (3σ)

Neutrino astrophysics

- Observation of a few~10MeV neutrinos with time, energy and direction information
  - Unique role in multi-messenger observation
- **Solar neutrinos:** up-turn at vacuum-MSW transition, Day/Night asymmetry, hep neutrino observation
- **Supernova burst neutrinos:** explosion mechanism, BH/NS formation, alert with ~1° pointing
- **Supernova Relic Neutrinos (SRN):** stellar collapse, nucleosynthesis and history of the universe

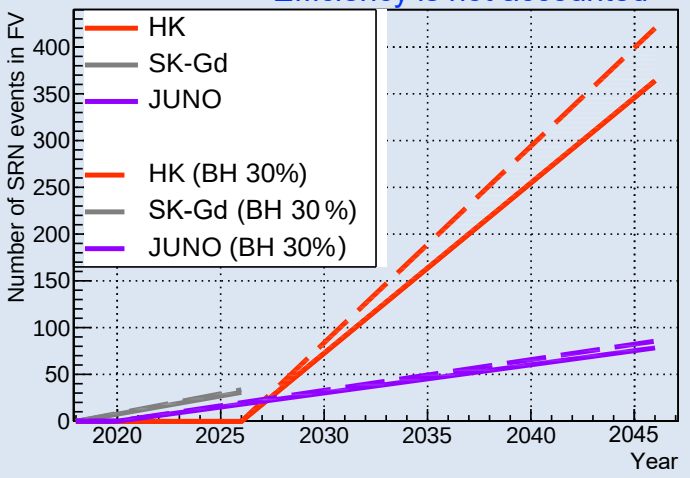






SRN rate

Calculation from FV and E_{th}
Efficiency is not accounted

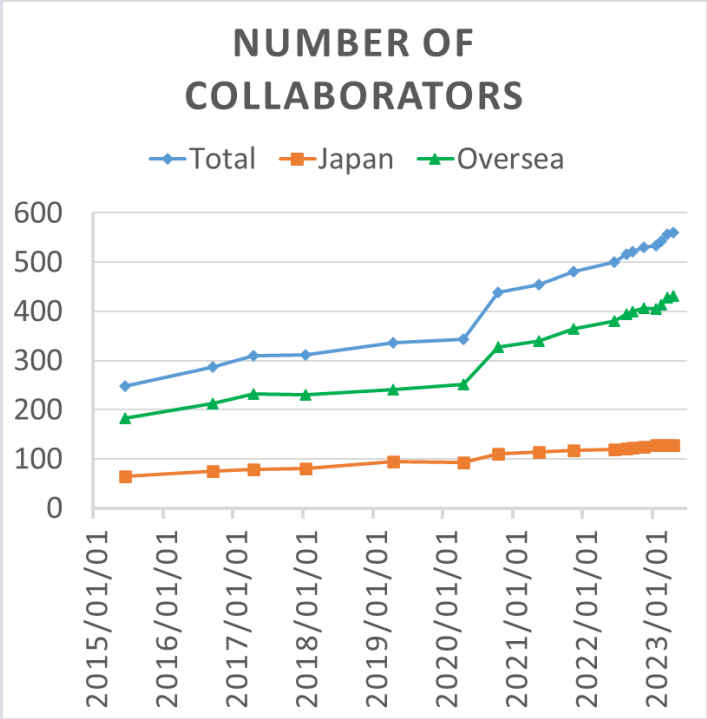


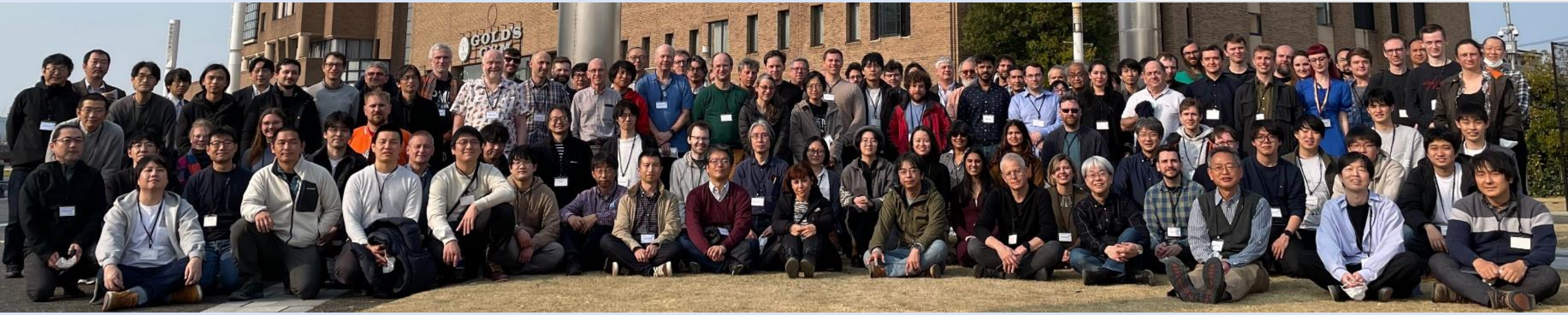
M. Maltoni et al., Phys. Eur. Phys. J. A52, 87 (2016)

Hyper-Kamiokande Collaboration

- ~600 members located in 102 institutes from 22 countries
  - 25% Japanese / 75% non-Japanese
- Recently approved as a recognized experiment (RE45) at CERN

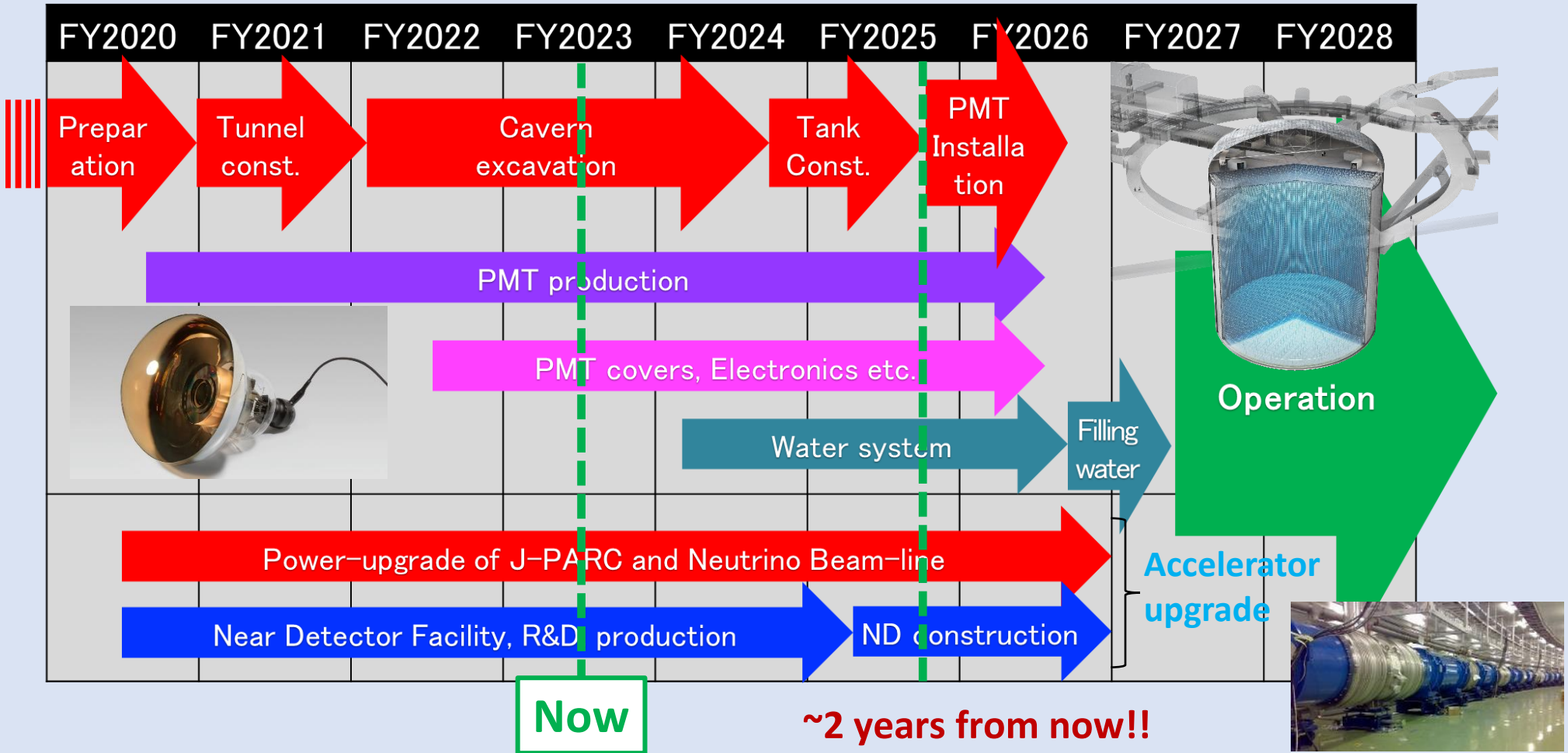
- <u>March 2023:</u>
  our very 1st Collaboration meeting in person after COVID!



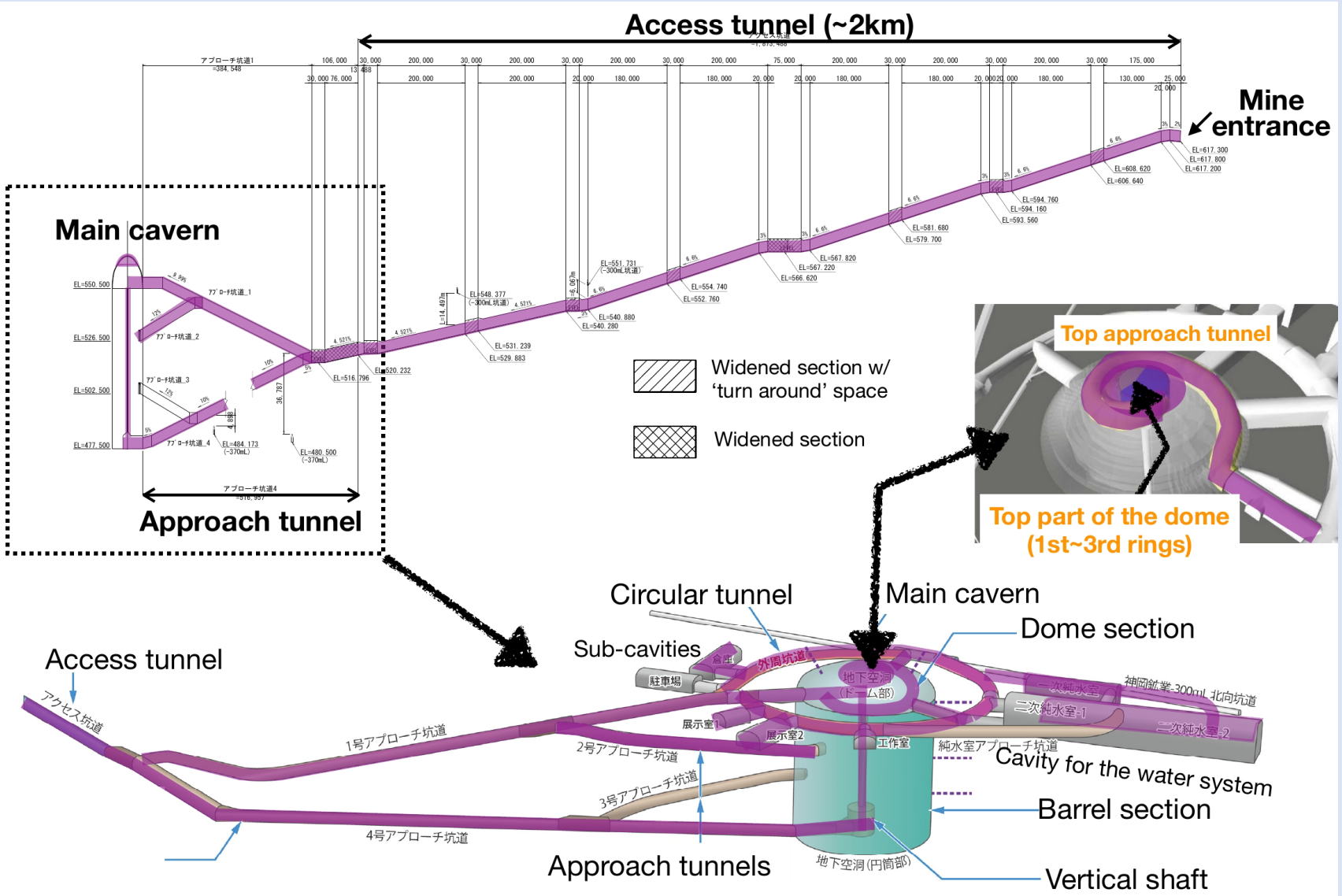


Hyper-K construction schedule

- The Hyper-K construction started in 2020 and will start operation in 2027.
- We are in the middle of the civil construction and starting to produce detector components.

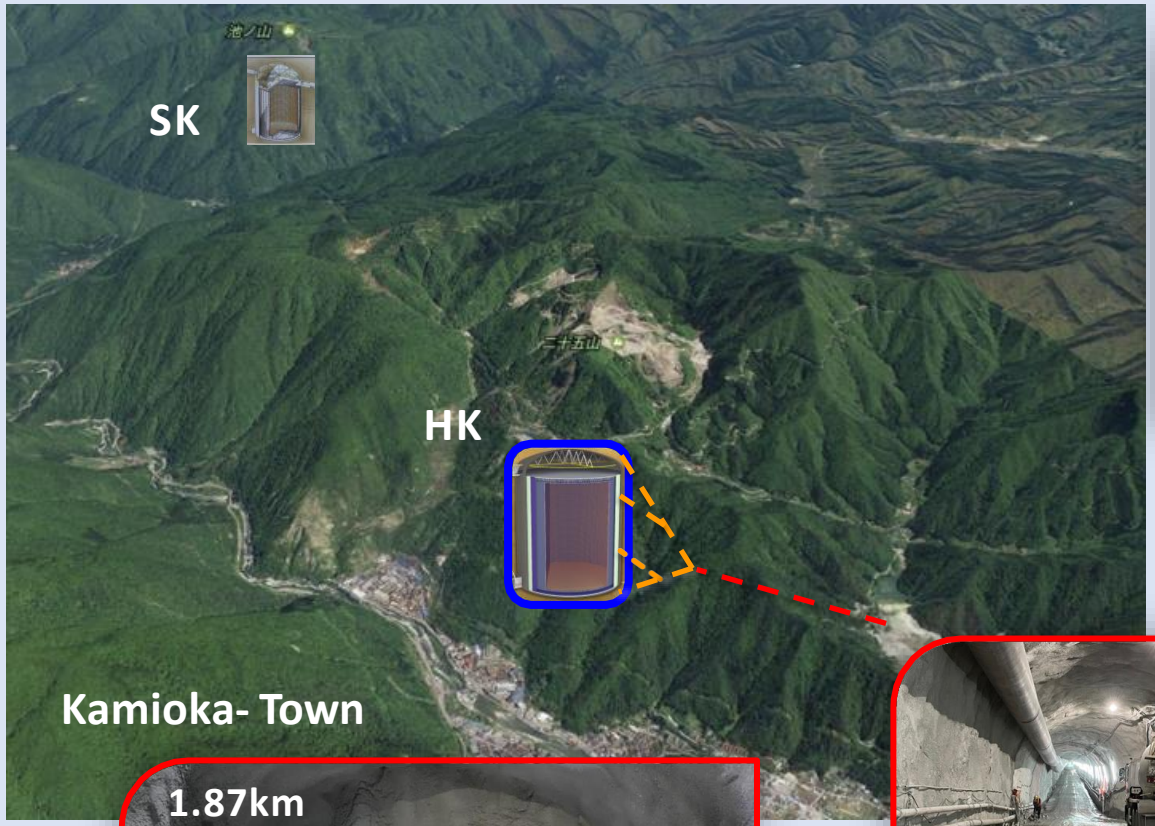


Hyper-K caverns excavation



- Access tunnel excavation completed.
- Approach & circular tunnel excavation completed.
- Main cavern excavation has started ! → On-time !

Access tunnel excavation



2021.5.28

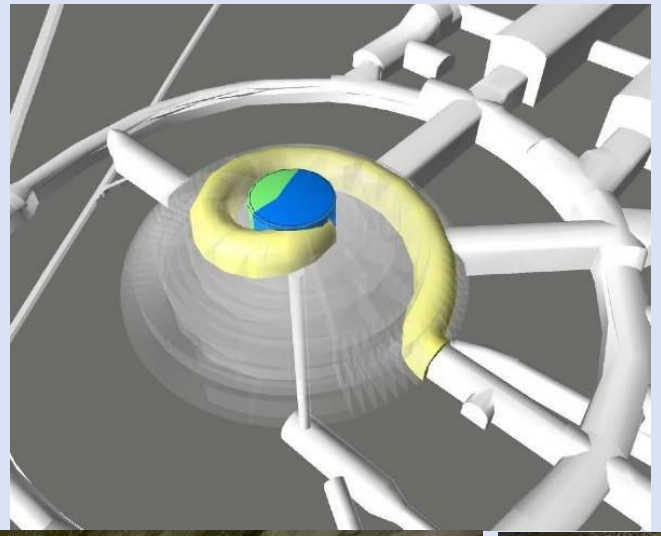
2022.2.25

Access tunnel excavation completed on schedule.

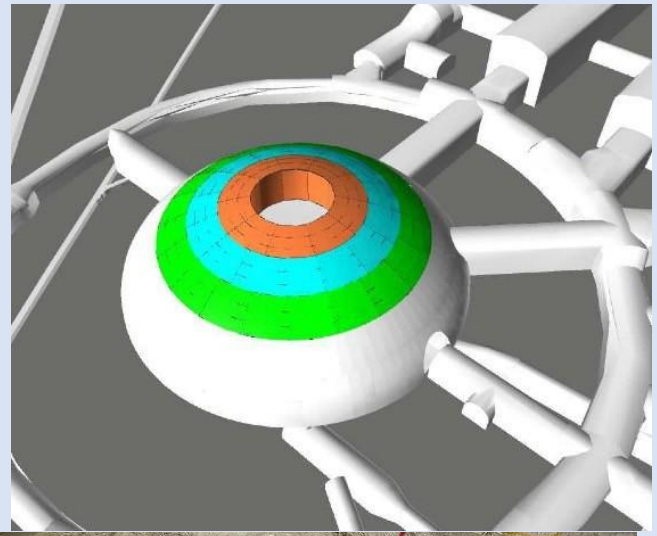
Center of the future Hyper-K Main Cavern's Dome reached in June 2022

Hyper-K main cavern excavation

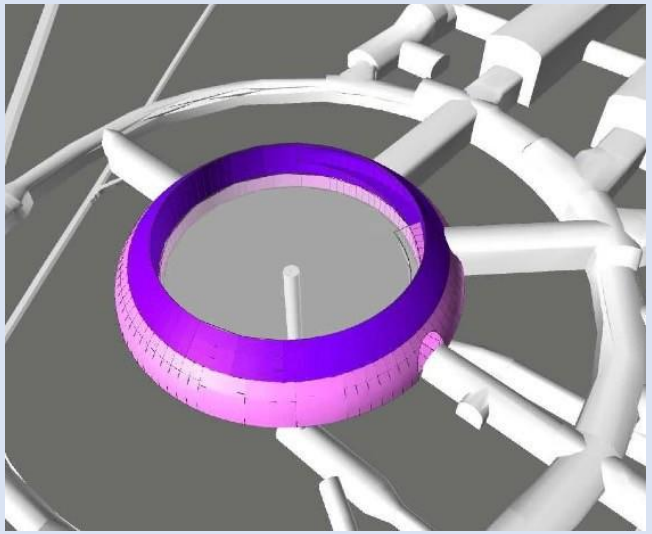
First ring

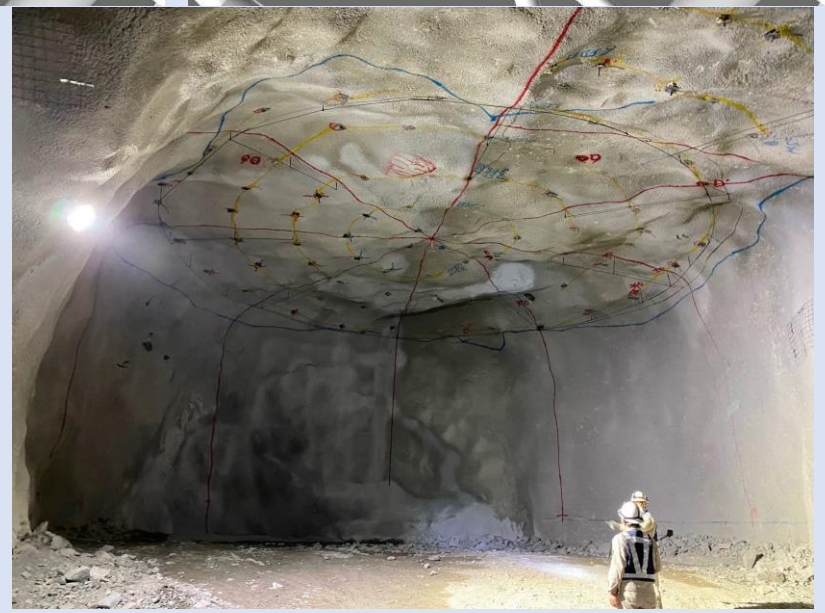


2nd - 4th rings



5th - 6th rings





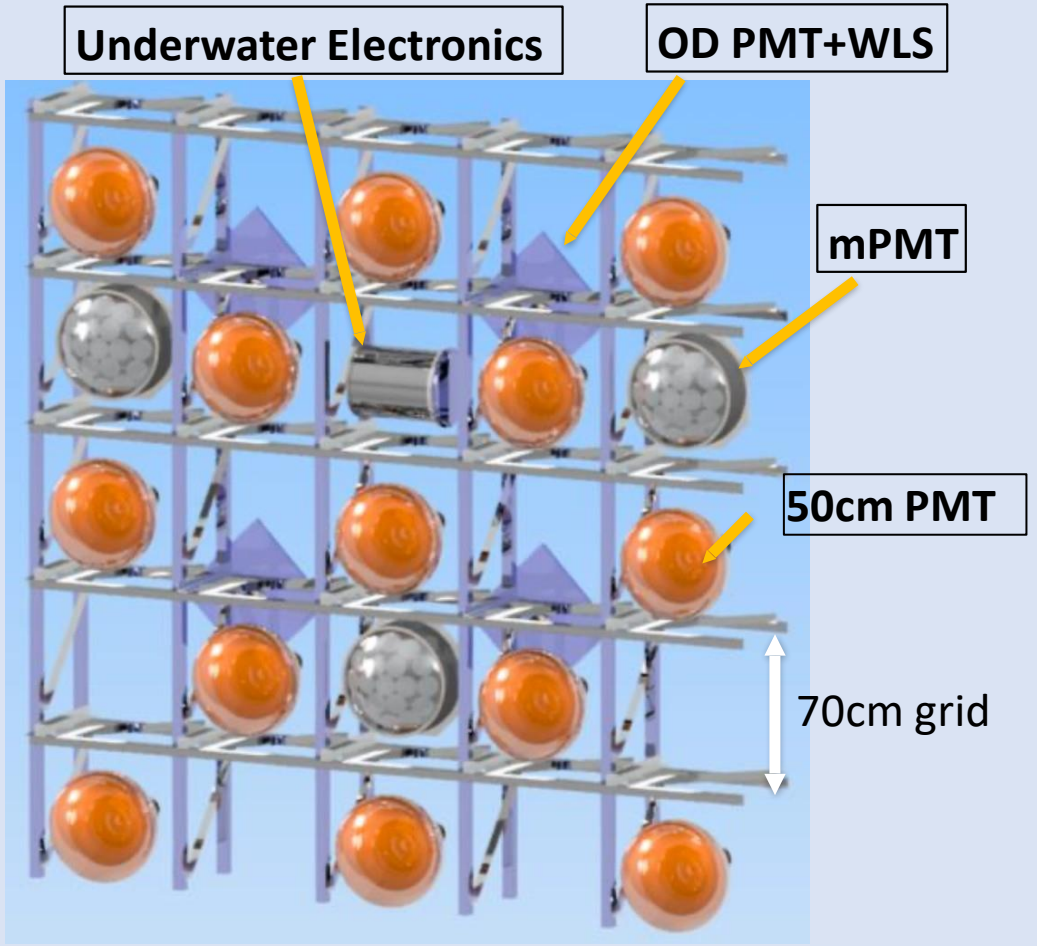
Cavern dome constructed in consecutive rings

Hyper-K main cavern excavation

- **<u>October 3, 2023:</u>** Excavation of the dome section completed.
  - 69m diameter, 21m height
  - One of the largest human-made underground space.
- Now, the excavation of the barrel section is ongoing.

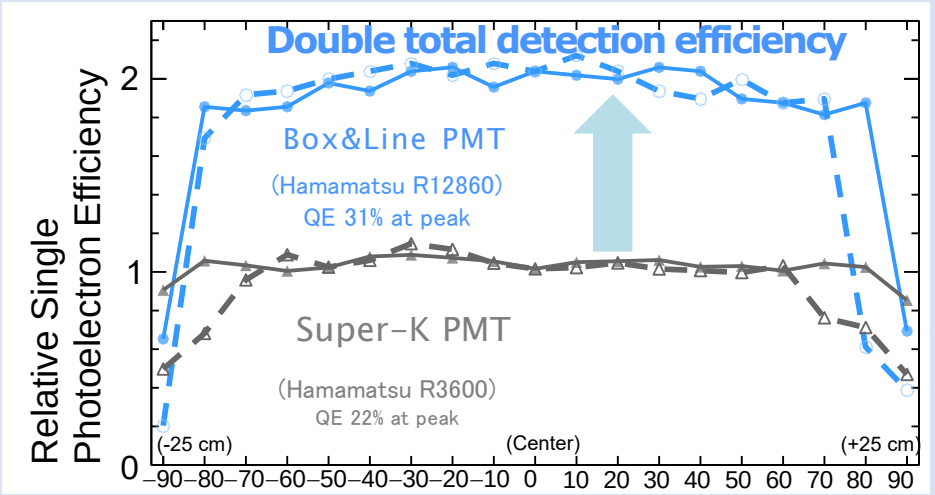
Hyper-K detector configuration

- **Inner Detector (ID)**
  - 64.8m diameter, 65.8m height
  - 50cm PMTs will be installed
  - Multi-PMT (mPMT) modules will be integrated as hybrid configuration
- **Outer Detector (OD)**
  - 1m (barrel) or 2m (top/bottom) thick
  - 3-inch PMT + WLS plate
  - Walls are covered with high-reflectivity Tyvek sheets
- **Under-water electronics**
  - Mitigate disadvantage of long cables



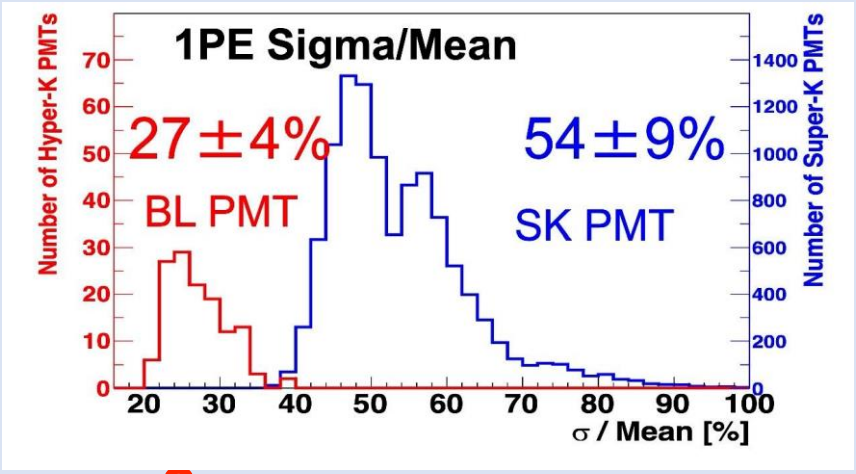
Hyper-K 50cm PMT performance

×2 better photodetection efficiency (QE×CE)

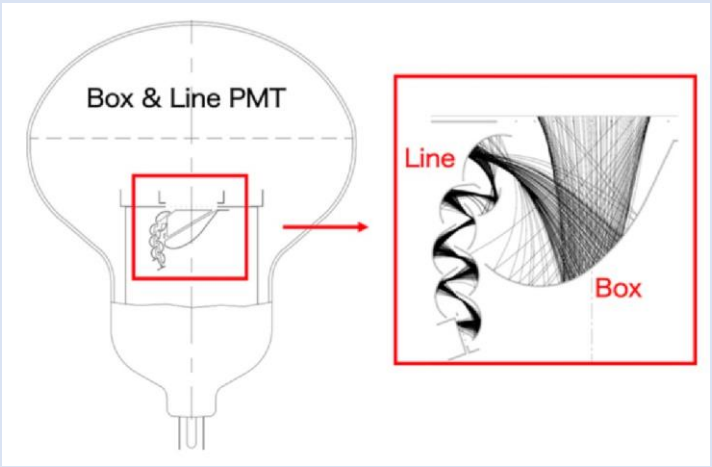


(Performance in SK tank, 1.7e7 gain)

×2 better charge resolution



Box&Line dynode

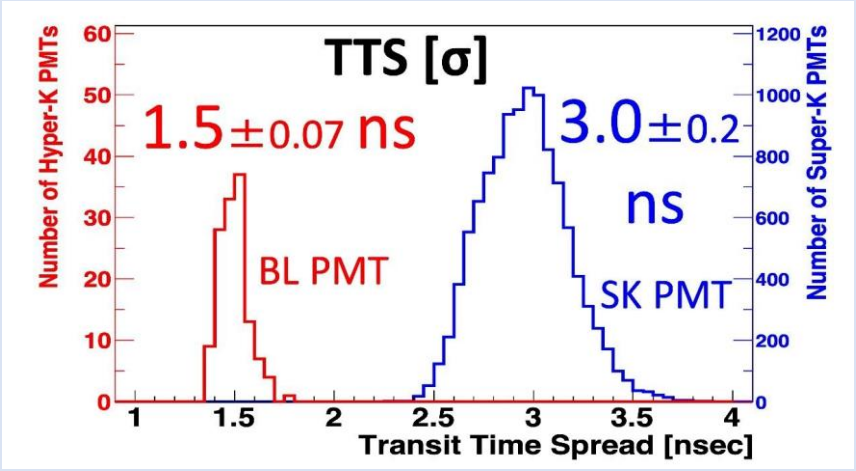


×2 better pressure tolerance
→ enable deeper tank design, project cost reduction

All PMTs will be tested >0.85MPa

Low dark rate (4kHz) and RI

×2 better timing resolution



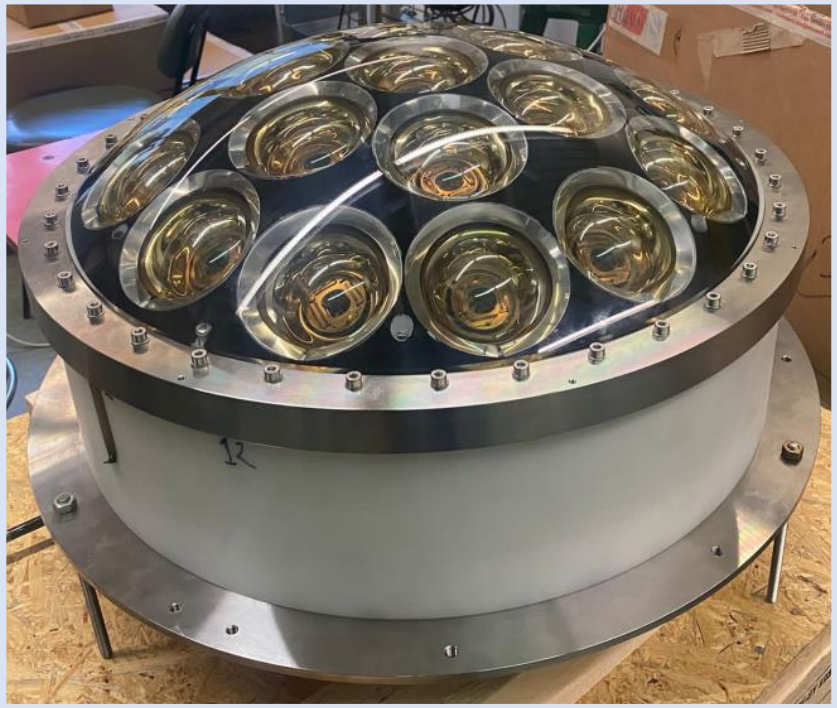
Hyper-K 50cm PMT production

- Mass production started in Dec. 2020.
- Production was suspended to investigate their defect rate in April 2022.
- From May 2023, production resumed after improvement and screening by manufacturer.
- Delivery completion remains unchanged as originally scheduled.
- Constant quality inspections at Kamioka are ongoing.

Hyper-K Photosensors

Multi-PMT (mPMT) modules

- 19 3-inch PMTs and electronics arranged inside a pressure resistant vessel
- Improvements for Cherenkov ring reconstruction and reference for detector calibration



OD PMT+WLS units

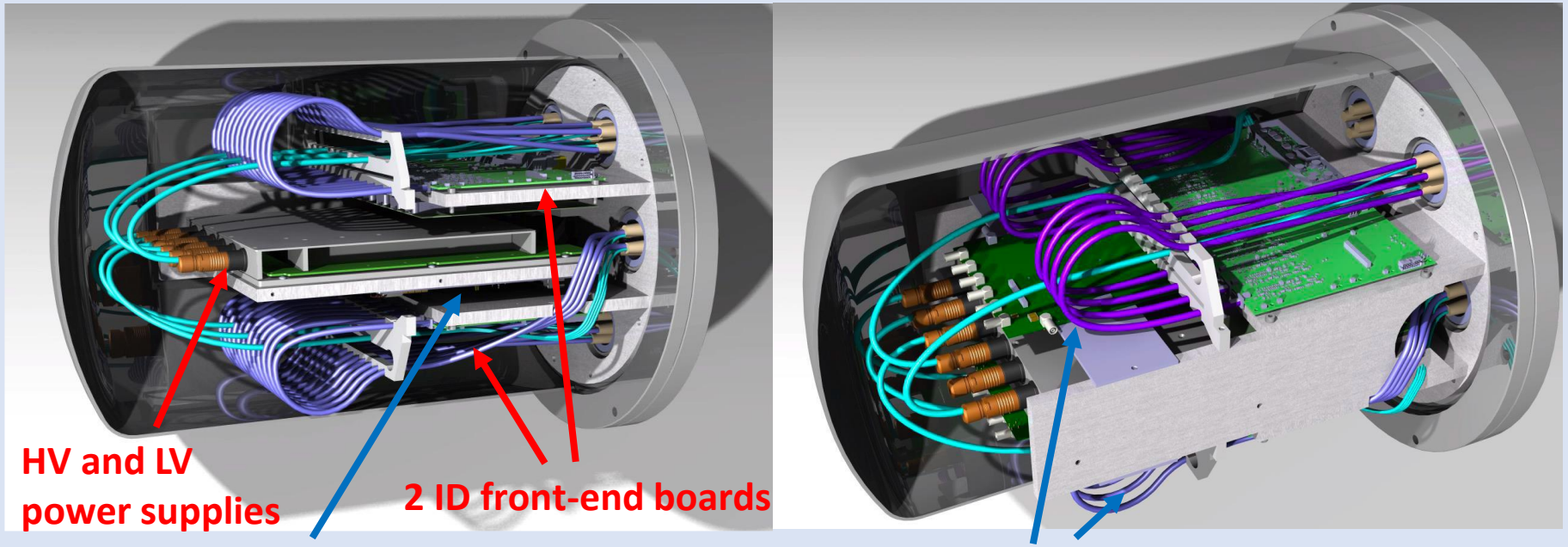
- 3-inch PMT attached to wavelength shifting plate
- To veto cosmic-ray muons

Design finalization ongoing

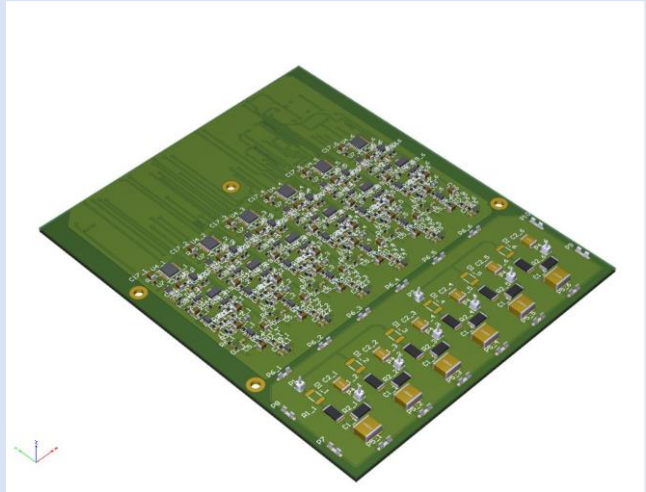
Hyper-K Electronics

- Front-end electronics placed in underwater vessels
- Two types of underwater electronics vessels
  - Inner detector vessels: 24 ID channels read out by two PCBs
  - Hybrid outer + inner detector vessels: 20 ID + 12 OD channels

Preliminary



ID 12-channel
front-end board



OD 6-channel FE board

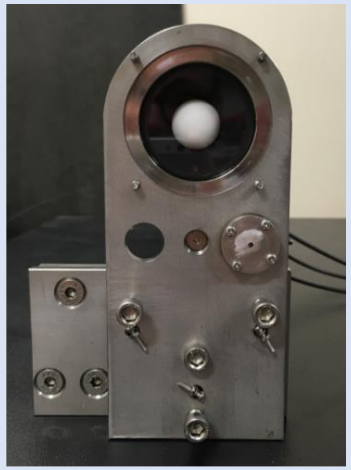
Hyper-K Calibration

- Various programs to determine detector parameters and measure systematics

- Pre-calibration of photosensors
- Photogrammetry
- Light Injection
  - Diffusers and collimators
  - mPMT system
  - OD injectors
- Electron LINAC
  - 3-24 MeV electrons
- Radioactive Sources
  - DT Source - 16N
  - AmBe + BGO – tagged neutrons
  - Ni/Cf - 9 MeV g cascade

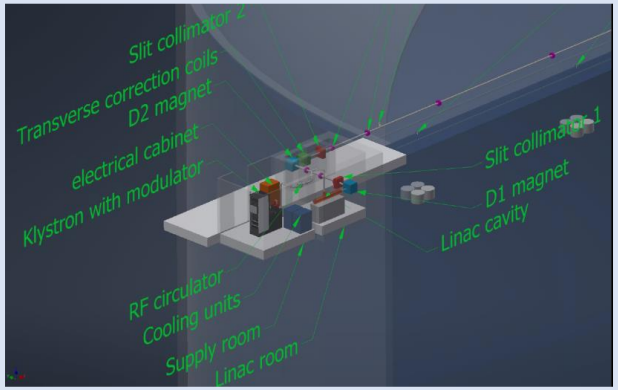
Photosensor Test Facility

Photogrammetry testing

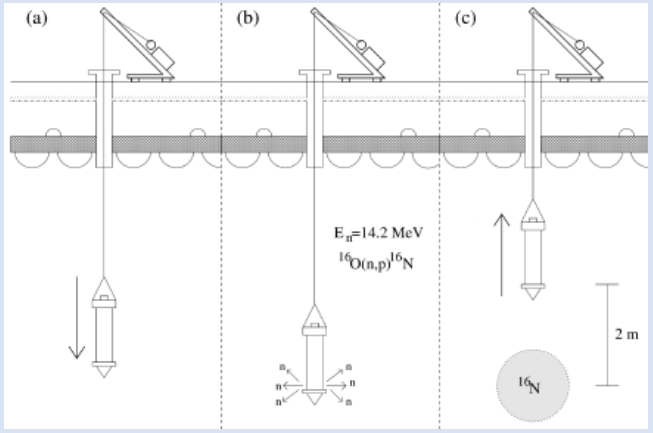


Light injectors

LINAC beam simulation



Ni/Cf source

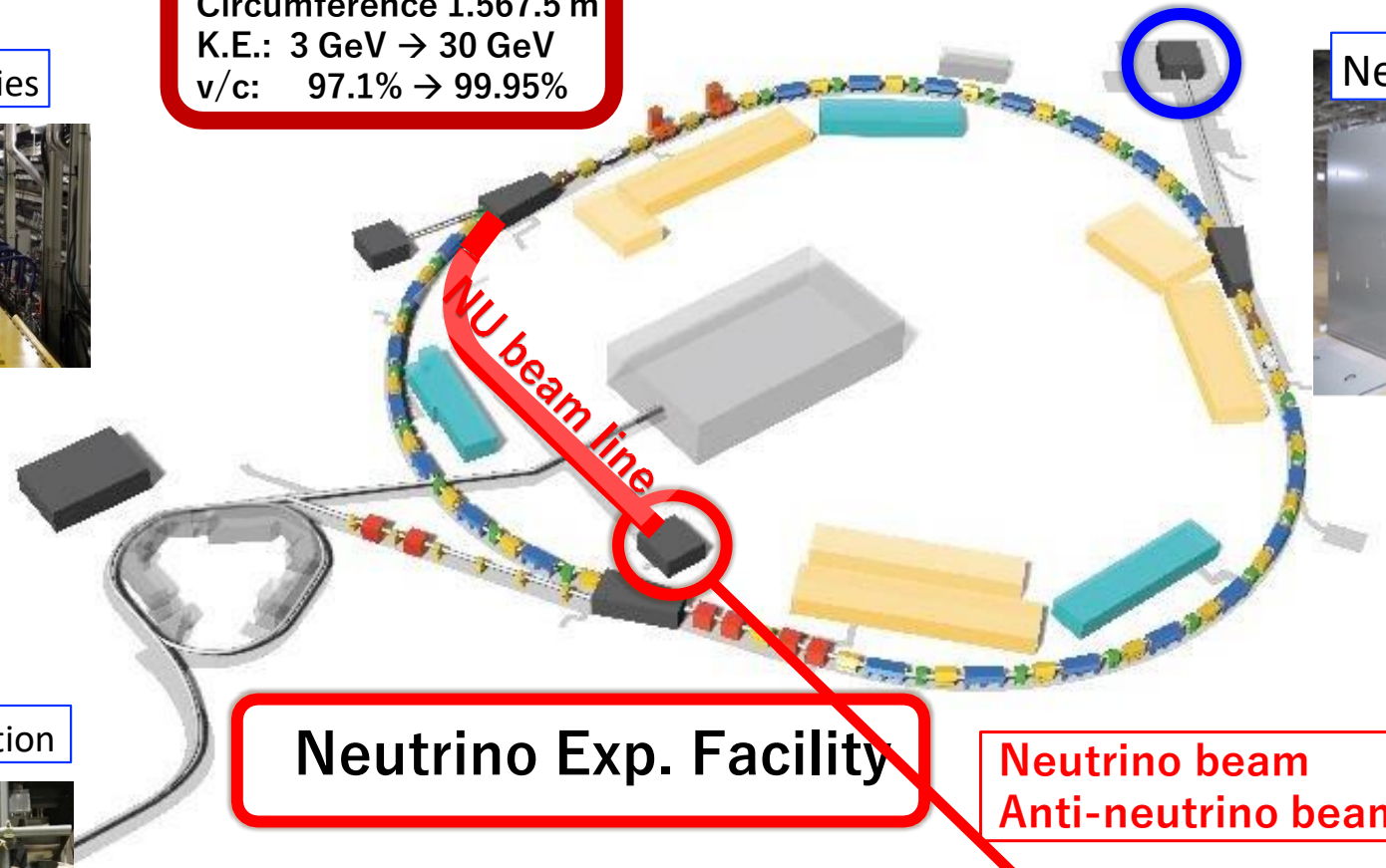


DT operation

J-PARC Upgrade

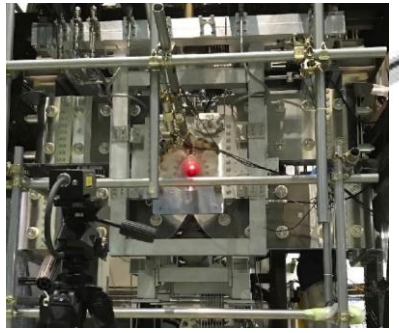
Main Ring
Circumference 1.567.5 m
K.E.: 3 GeV → 30 GeV
v/c: 97.1% → 99.95%

MR-RF cavities

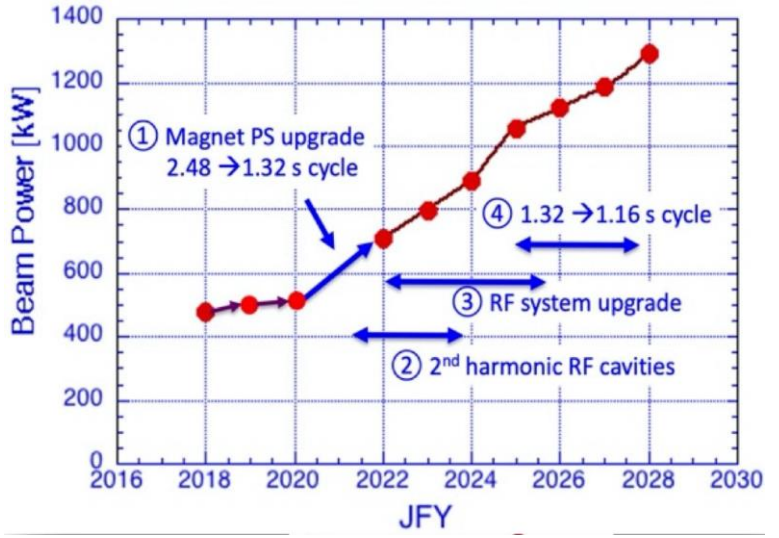


New main magnet PS for high rep. rate

320kA horn operation

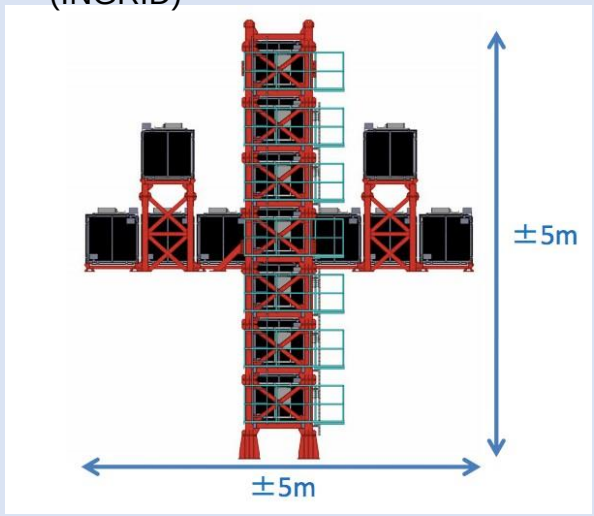


Achieved 515 kW in JFY2020
Aiming 1.3 MW by JFY2028

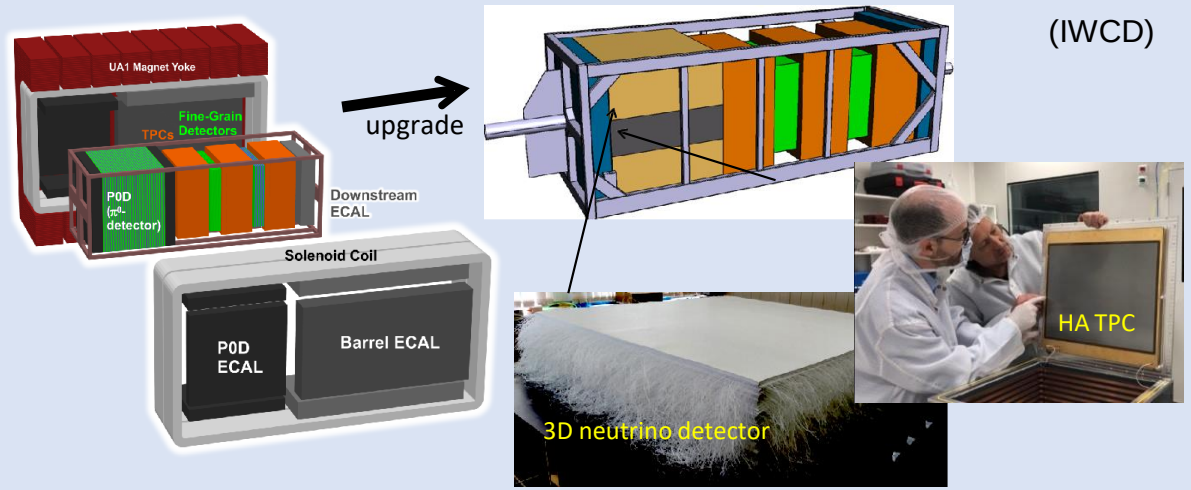


Neutrino detectors at J-PARC

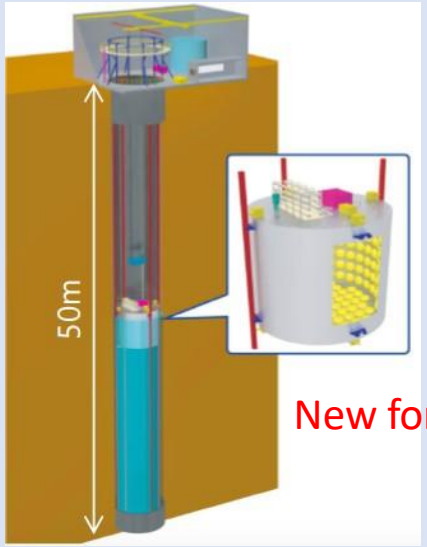
On-axis Detector
(INGRID)



Off-axis Magnetized Tracker
(ND280→Upgrade for T2K →Upgrade for HK)



Off-axis spanning Intermediate water Cherenkov detector
(IWCD)



New for HK

Critical components to precisely understand J-PARC beam and neutrino interactions:

- **On-axis detector:** Measure beam direction and event rate
- **Off-axis magnetized tracker:** Measure primary (anti)neutrino interaction rates, spectrum, and properties. Charge separation to measure wrong-sign background
  → Upgrade by T2K experiment and Intensive discussion for further upgrade in HK-era is on-going.
- **Intermediate WC detector:** H_2O target with off-axis angle spanning orientation.
  → Detector site investigation and conceptual facility design are on-going.

Conclusions

- Hyper-Kamiokande is 3rd generation water Cherenkov detector in Kamioka
- Important physics targets
  - Neutrino CP violation: Discovery with 5 σ for ~60% parameter regions
  - Nucleon Decay Search for testing GUT: $\tau > 10^{35}$ years for $p \rightarrow e^{+}\pi^{0}$
  - Neutrino Astrophysics: Supernova neutrinos
- Hyper-Kamiokande construction on schedule
  - World's largest underground facility: 260 kton water Cherenkov detector
  - Access tunnel and cavern construction on track
  - 50cm PMT production underway
  - Other detector component designs being finalized
  - Neutrino beam upgrade to 1.3 MW
  - Near detector upgrade and design of intermediate detector being finalized
- Hyper-Kamiokande will start operation in 2027.