Photodetection and electronic system for the Hyper-Kamiokande Water Cherenkov detectors

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Hyper-Kamiokande

UNIVERSITY OF SILESIA IN KATOWICE

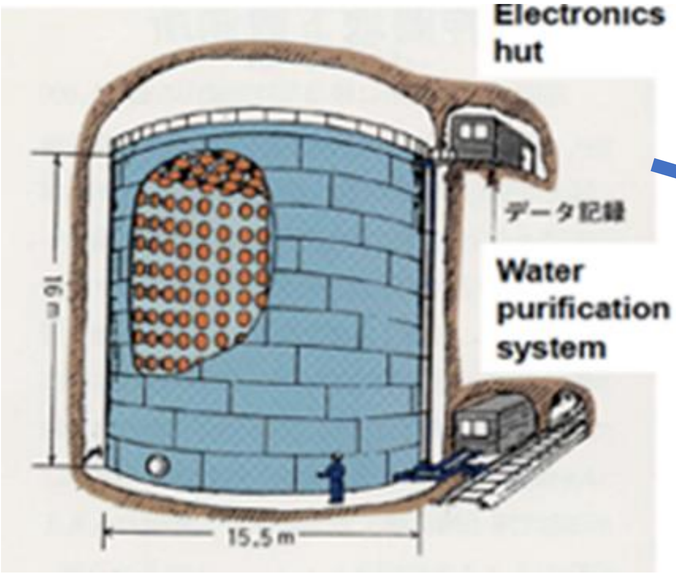
Outline

- Overview of the Hyper-Kamiokande experiment
- PMTs for Hyper-Kamiokande:
  - 20" PMTs: far inner detector,
  - 3" PMTs: far outer detector,
  - multi-PMTs: far inner detector and also Intermediate Water Cherenkov Detector (IWCD)
- Front-end electronics for Hyper-Kamiokande water Cherenkov detectors
- Outlook

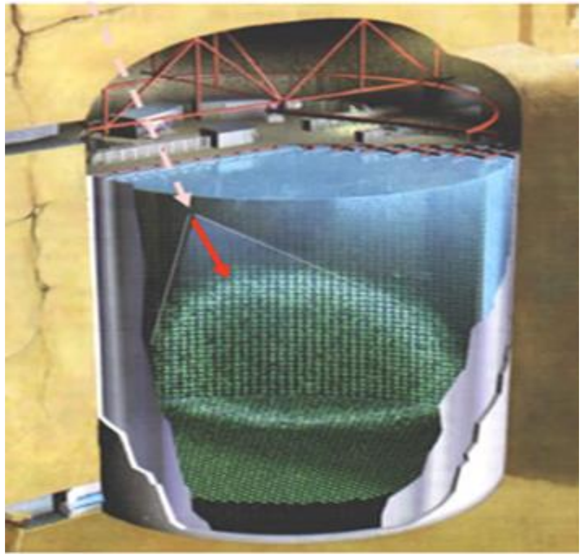
Water Cherenkov detector development (in Japan)

- Kamiokande (1983-1996), 3 kton, 20% PMT coverage:
  - SN1987a neutrinos,
  - ν_{atm} deficit,
  - …

M.Koshiba
(for the detection
of cosmic neutrinos)



20x

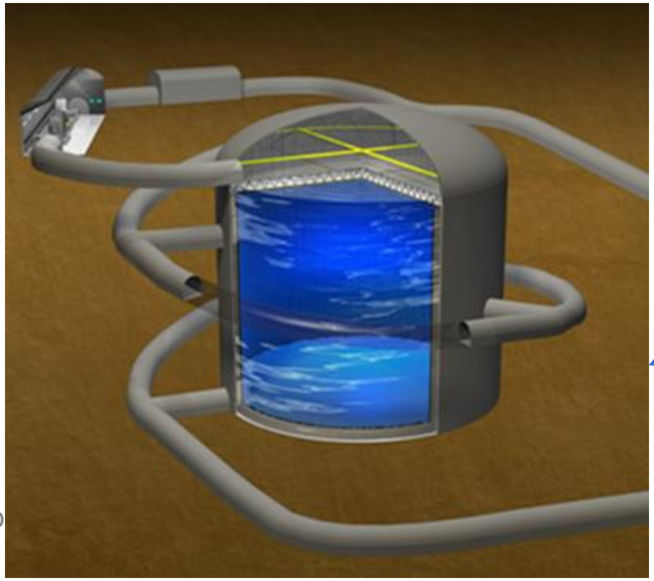


- Super-Kamiokande (1996-…), 50 (22.5 FV) kton, 40% PMT coverage:
  - ν_{atm} and ν_{solar} oscillations,
  - proton decay,
  - far detector for T2K exp.,
  - …

T. Kajita
(for the discovery
of neutrino oscillations)

- Hyper-Kamiokande (2027-…), 258 (187 FV) kton, 20% PMT coverage:
  - CP violation and proton decay (most sensitive channel: $p \rightarrow e^{+} + \pi^{0}$): elucidation of the matter dominance in the Universe,
  - neutrino oscillation (beam, atmospheric, solar)
  - neutrino mass hierarchy (combined fit of the beam and atmospheric data),
  - neutrino astrophysics (supernova, …),
  - …

8.4x

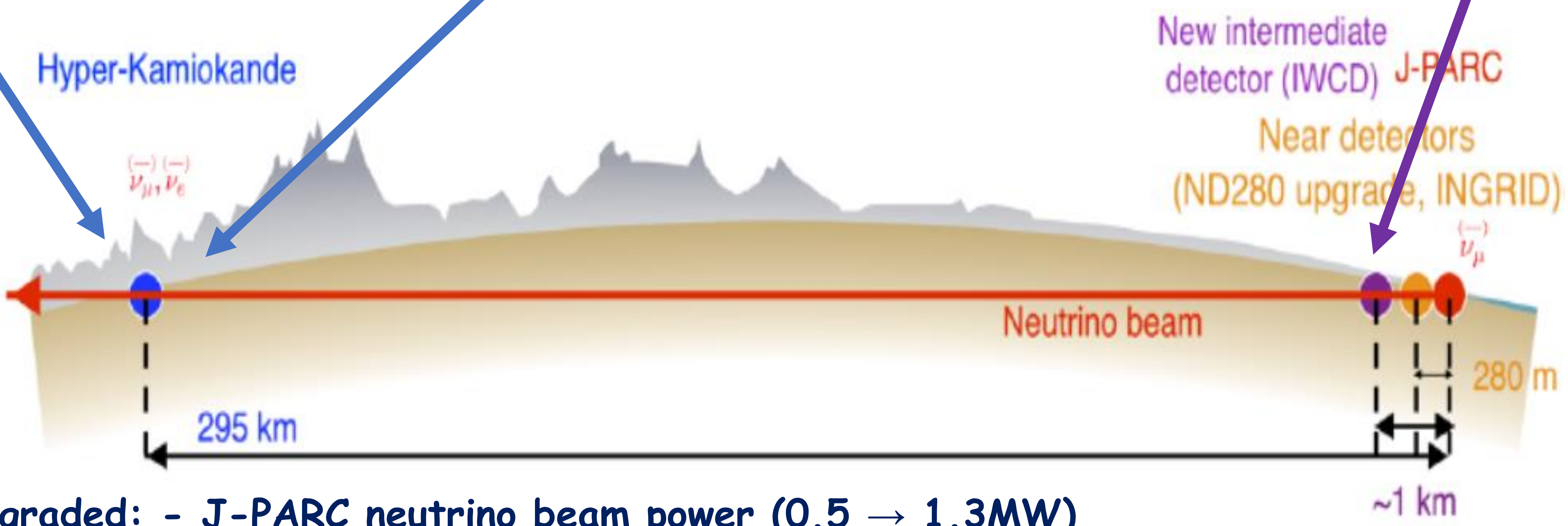


Hyper-Kamiokande (HK) experiment (1)

HK Inner Detector (ID)
- 20% photocoverage
- ~20000 20" PMTs and
- ~1000 multi-PMTs

HK Outer Detector (OD)
- ~8000 3" PMTs
- mounted on Wave Length Shifter (WLS) plates

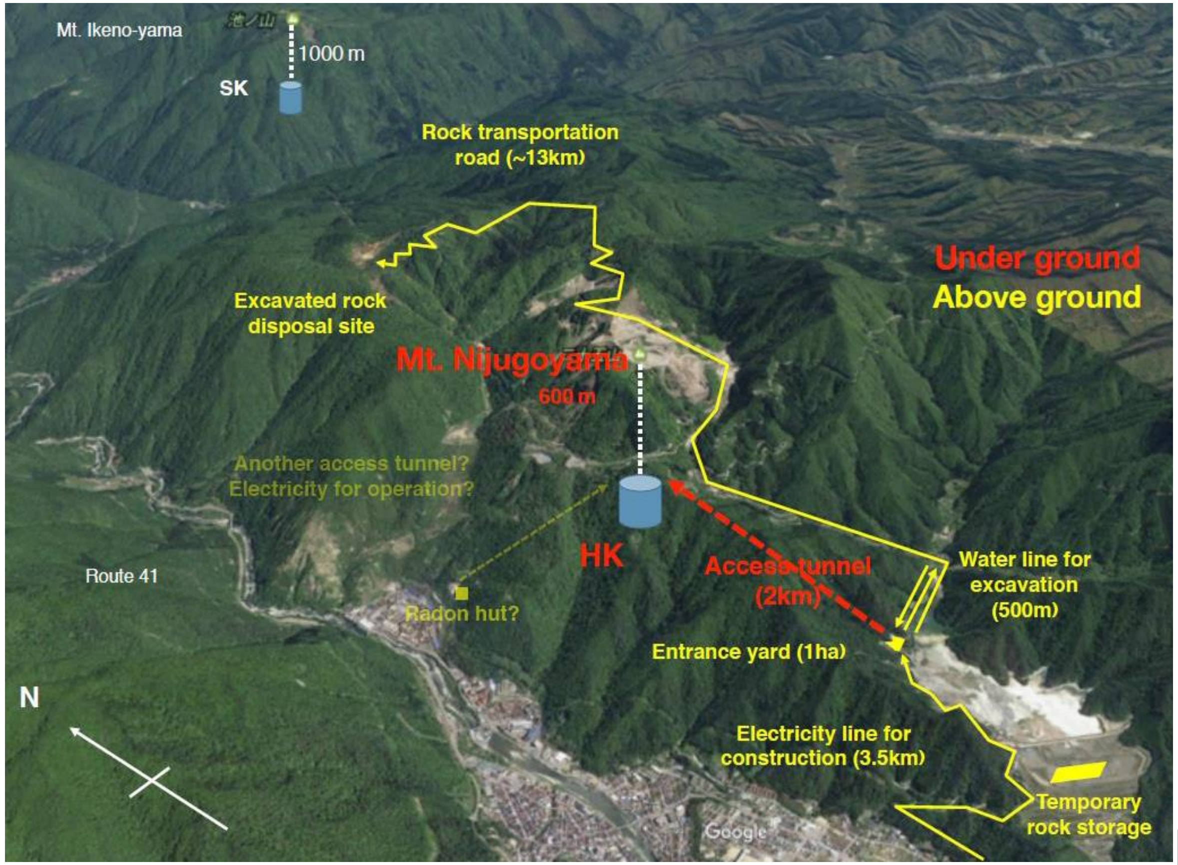
Intermediate Water Cherenkov Detector (IWCD)
- ~500 multi-PMTs



Also upgraded: - J-PARC neutrino beam power (0.5 → 1.3MW)
- ND280 detector (new Super-FGD and High Angle TPC)

New IWCD and upgraded near detectors to control systematic error in oscillation analysis.

Hyper-Kamiokande (HK) experiment (2)



20 countries, 99 institutes, ~500 people as of Jan 2022, and growing

Collaborating Institutes

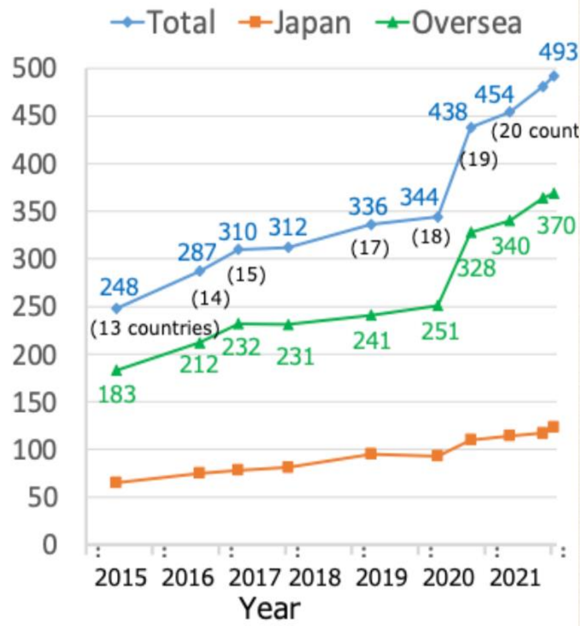
Europe	281 members
Armenia	3
Czech	4
France	27
Germany	1
Italy	55
Poland	38
Russia	22
Spain	35
Sweden	5
Switzerland	13
Ukraine	4
UK	74

Asia	149 members
India	8
Korea	18
Japan	123

Americas	52 members
Brazil	3
Canada	32
Mexico	8
USA	9

Africa	11 members
Morocco	11

Number of Collaborators



- **Towards detector construction:**

✓ Access tunnel (~ 2km) excavation completed, as scheduled Feb. 2022

✓ Approach and circular tunnels excavations 2022/3 – 2022/10

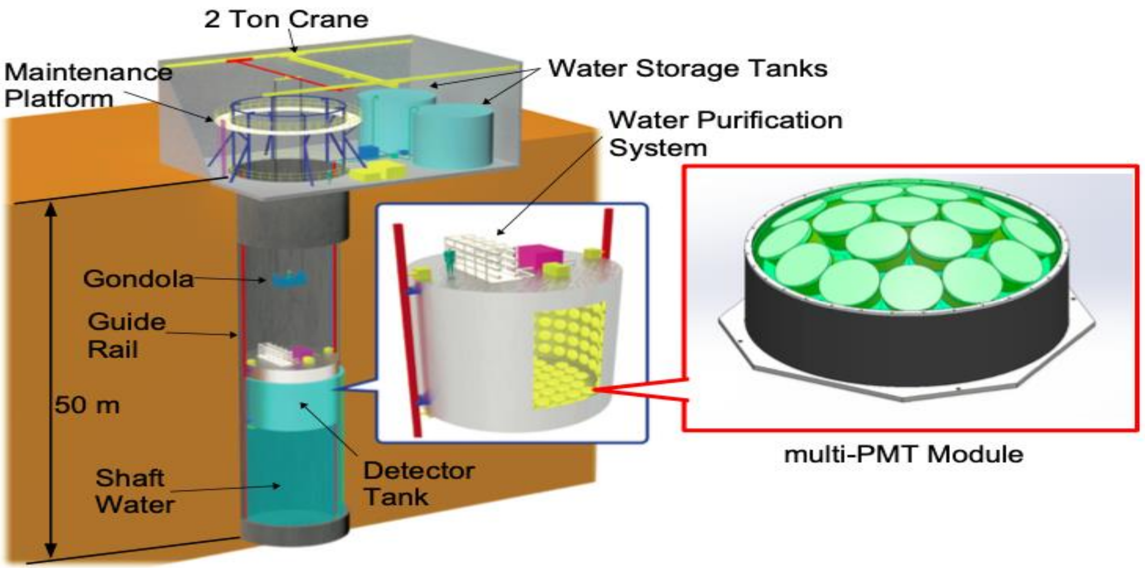
✓ Start of cavern dome excavation in Oct. 2022

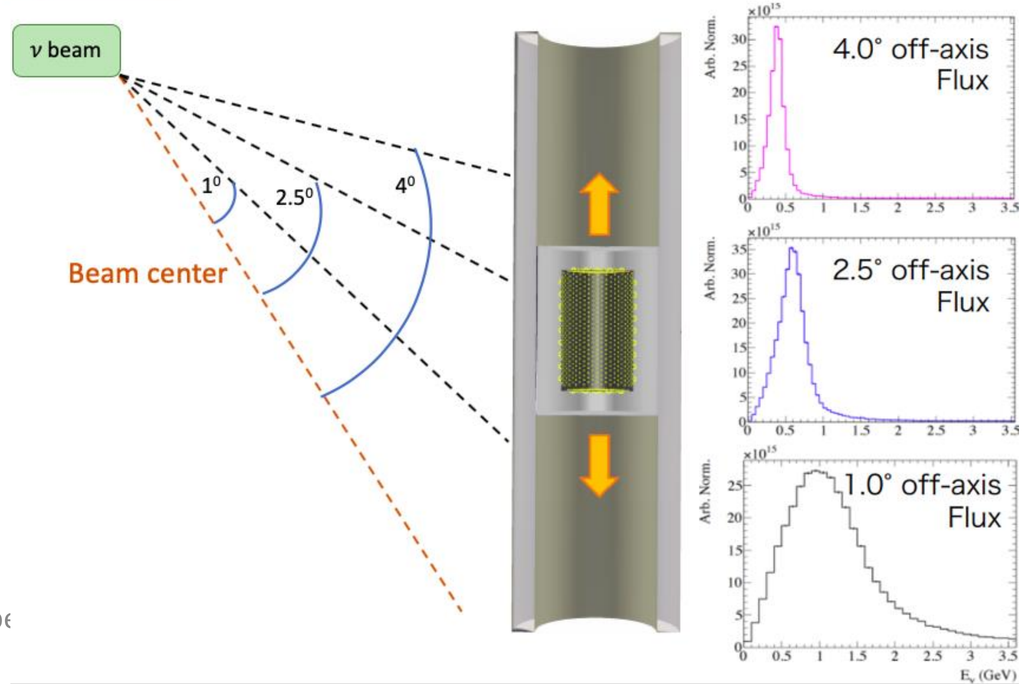
Access tunnel straight section

2022.6 Center of the main cavern dome

Intermediate Water Cherenkov Detector

- HK will study the CP violation (CPV) by comparing ν_e and anti-ν_e event rates, i.e. ν_e and anti-ν_e cross-section uncertainties will dominate systematic error. For far detector, (HK) relevant for CPV is region of neutrino energies 0.3÷0.9 GeV. Due to complicated nuclear effects, uncertainties need to be constrained by data (not by theory).
- Measurements at different neutrino beam off-axis angles (1°–4°) by moving detector filled with ~600 tons of water.
- A linear combination of the results for different off-axis angles will allow the reconstruction of the neutrino energy corresponding to an almost monochromatic neutrino spectrum without using neutrino interaction models.
- Very high event rate (~1km from neutrino source) compared to far detector event rate → different requirements for the electronics.

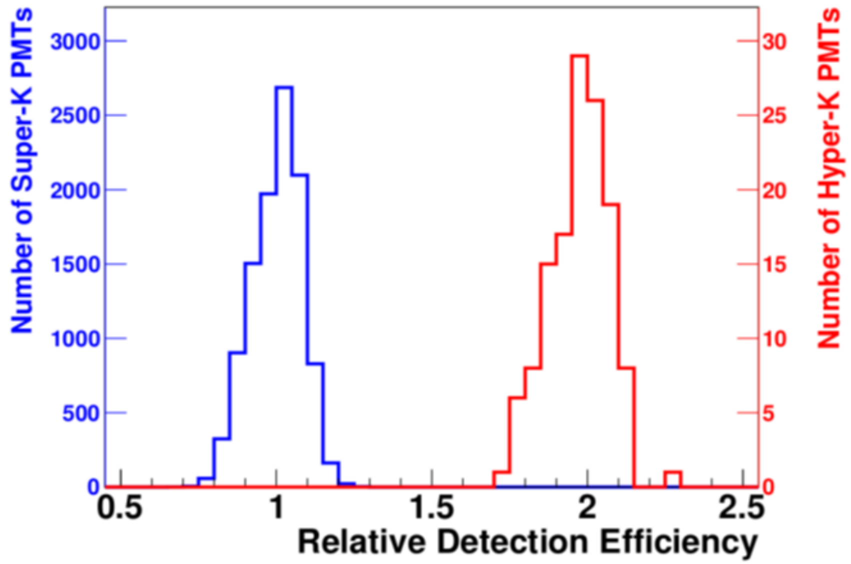




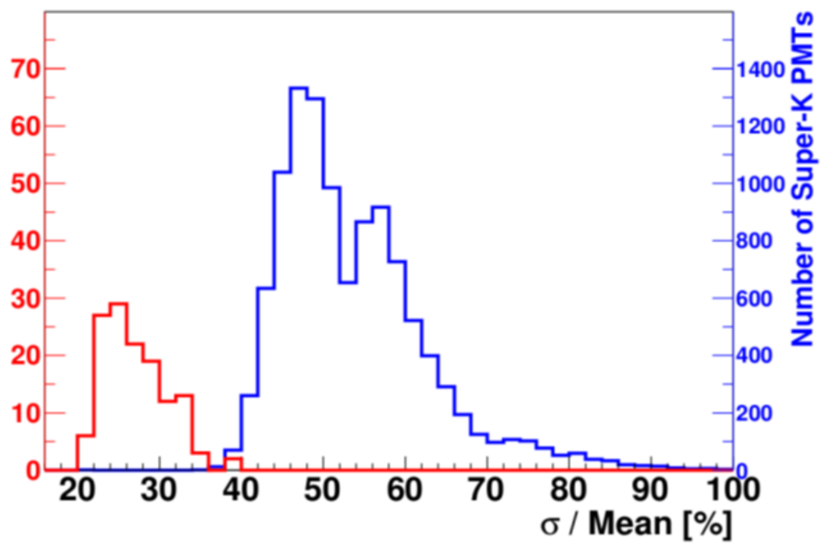
HK ID: Hamamatsu R12860 20" PMTs

- Hamamatsu R12860 (Box and line dynode) – twice better performance than Hamamatsu R3600 (Venetian blind dynode) used in Super-Kamiokande detector. Photo detection efficiency: ~2x, TTS(FWHM): 6.7ns → 2.6ns, charge resolution: ~60% → ~30%.
  - Higher detection efficiency thanks to higher QE and more electrons hits the first dynode
  - Better charge and time resolution thanks to more uniform electron drift path
- 136 new R12869 were installed (replaced dead PMTs) in the SK during 2018 refurbishment: improved detection eff., charge and time resolution - confirmed
  - Successful tests before the installation
  - Provide data for long term stability tests in real Hyper-K conditions

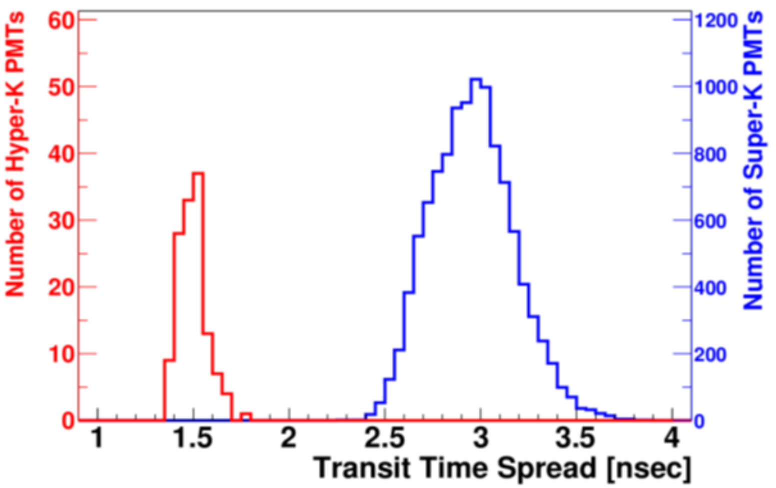
Detection efficiency



Charge resolution

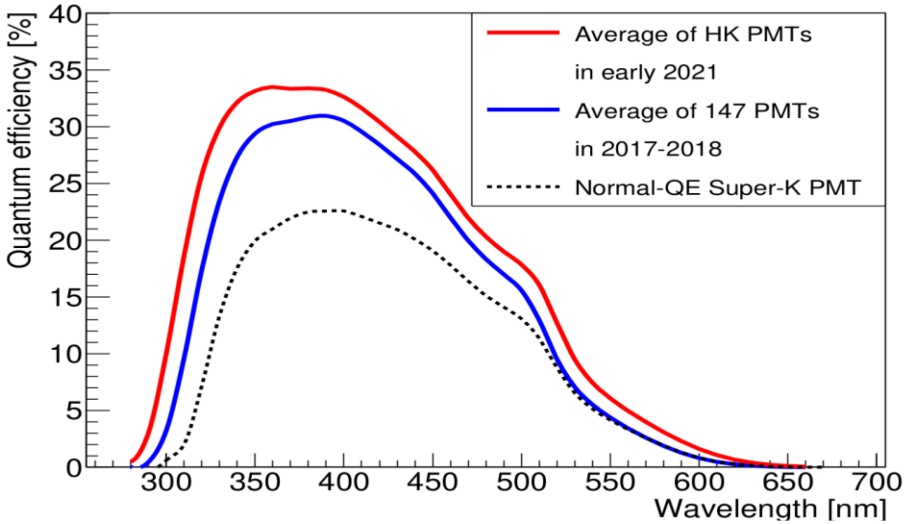


Time resolution

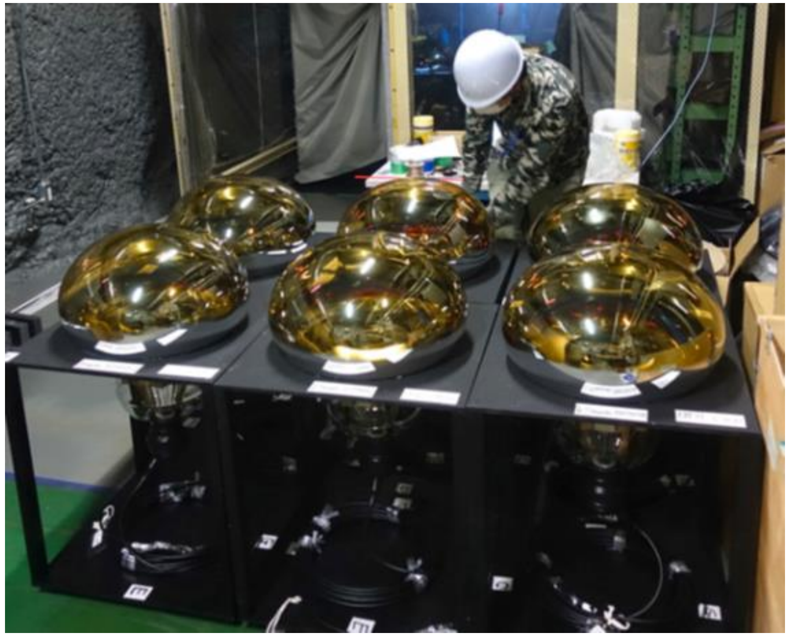


R12860: improvement since 2018 and present

- Reduced radioimpurities in glass (source of scintillations)
- Improved glass transparency
- Reduced radon content in cables: from 1.4 mBq/m down to <0.1 mBq/m
- Dark noise reduction down to 4 kHz



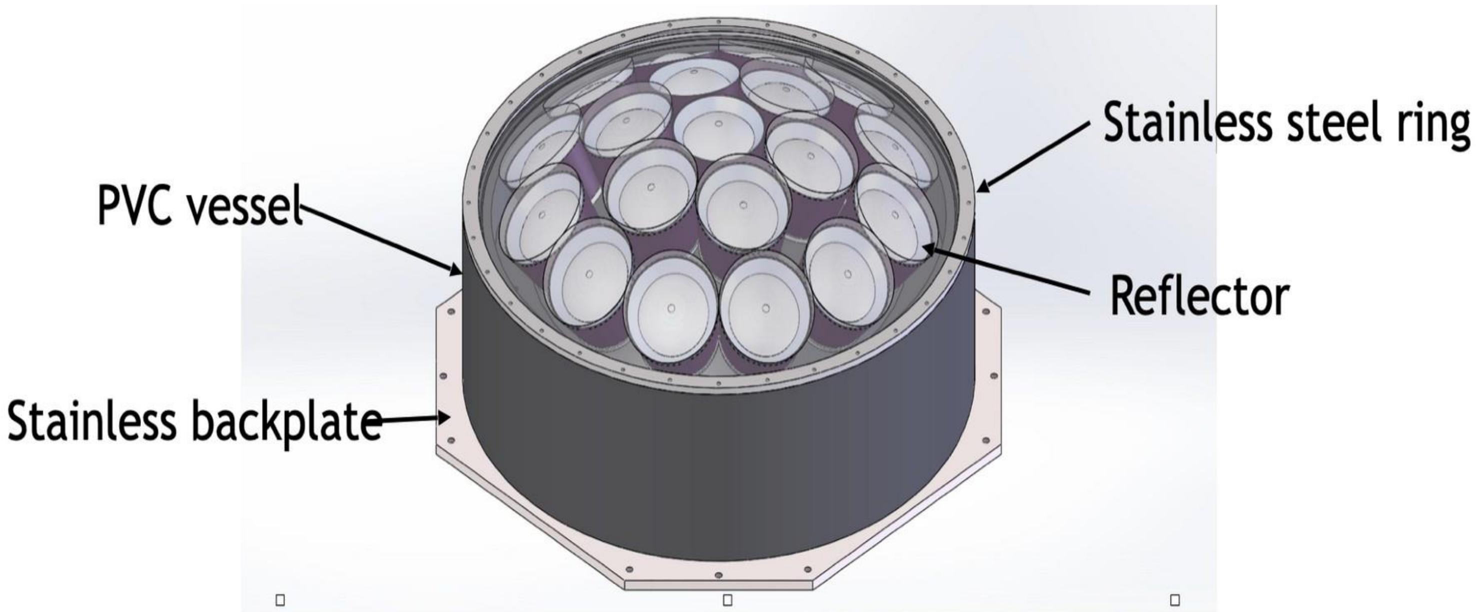
(C. Bonner 22nd Int. Workshop on Neutrinos from Accelerators, 2021)

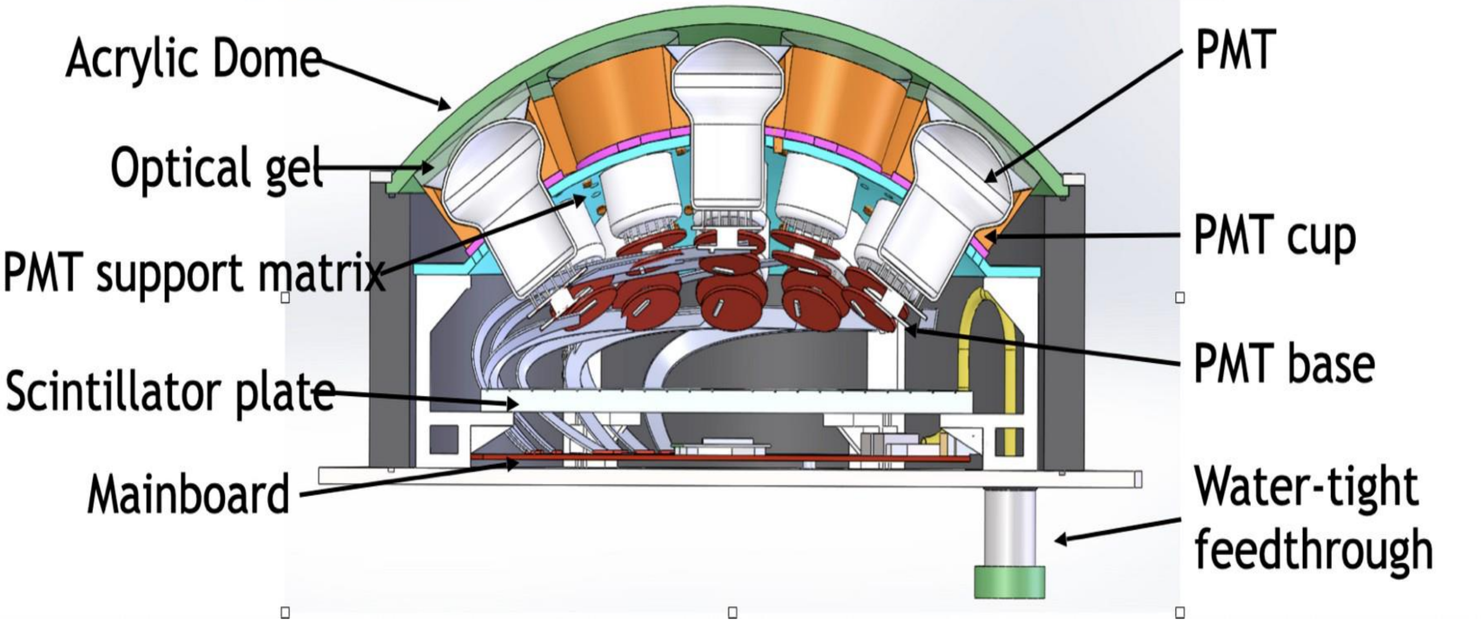


- Mass production started (~4 years to complete)
- ~3772 PMTs (18% of 20k) delivered by April 2022,
- Production suspended to investigate rate of PMTs not passing quality checks
- *Ongoing work on: PMT covers including implosion tests, installation method, validation under water pressure, etc.*
- *Assembly and installation from 2025*

Multi-PMTs for Hyper-Kamiokande

- Multi-PMT = 19 3" PMTs in a pressure vessel.
- Inspired by modules developed for the KM3NeT experiment.
- ~1000 will complement 20" PMTs in FD.
- ~500 will fully equip IWCD.
- Multi-PMT module includes: 19 PMTs, high voltage based on Cockcroft-Walton multiplier, DAQ electronics, and mechanical components.
- Optical gel used to couple PMTs to transparent, UV-transmitting (UVT) acrylic dome.
- Single twisted-pair cable to connect power supply and transmit data & clock.
- Development of 2 variants with different front-end electronics: for far detector (optimized of pressure resistance and low-power consumption) and for IWCD (higher pulse rates).

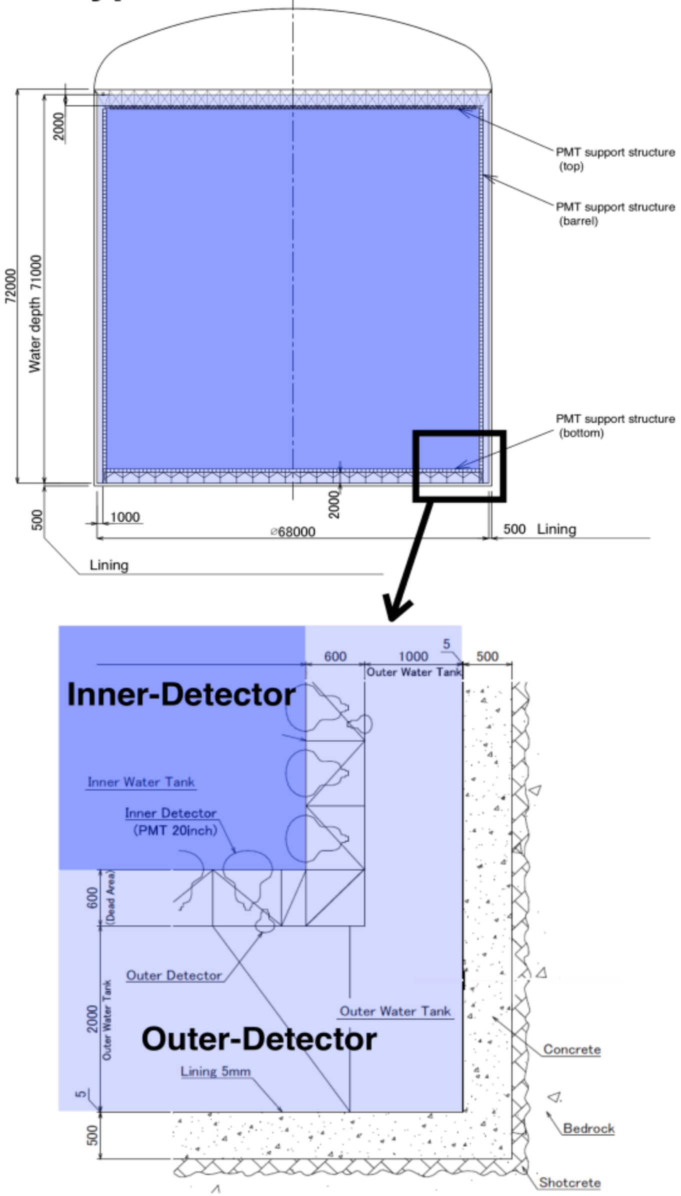




Hyper-Kamiokande Outer detector

- Purpose: the rejection of the background by identification of interactions originating from particles outside the ID
- ~8000 outward-looking 3" PMTs mounted on wavelength-shifting plates (WLS), mounted behind the ID PMTs and facing outwards to view the outer tank shell
- Reflective material on the tank wall (Tyvek).
- Present WLS design as a result of so far tests at Oxford Univ. and INR:
  - 0.6×30×30 cm^3 PMMA (base material + 50mg/l POPOP + 3g/l PPO (fluors).
  - 78 mm diameter cylindrical hole for PMT

Cross section of Hyper-Kamiokande detector



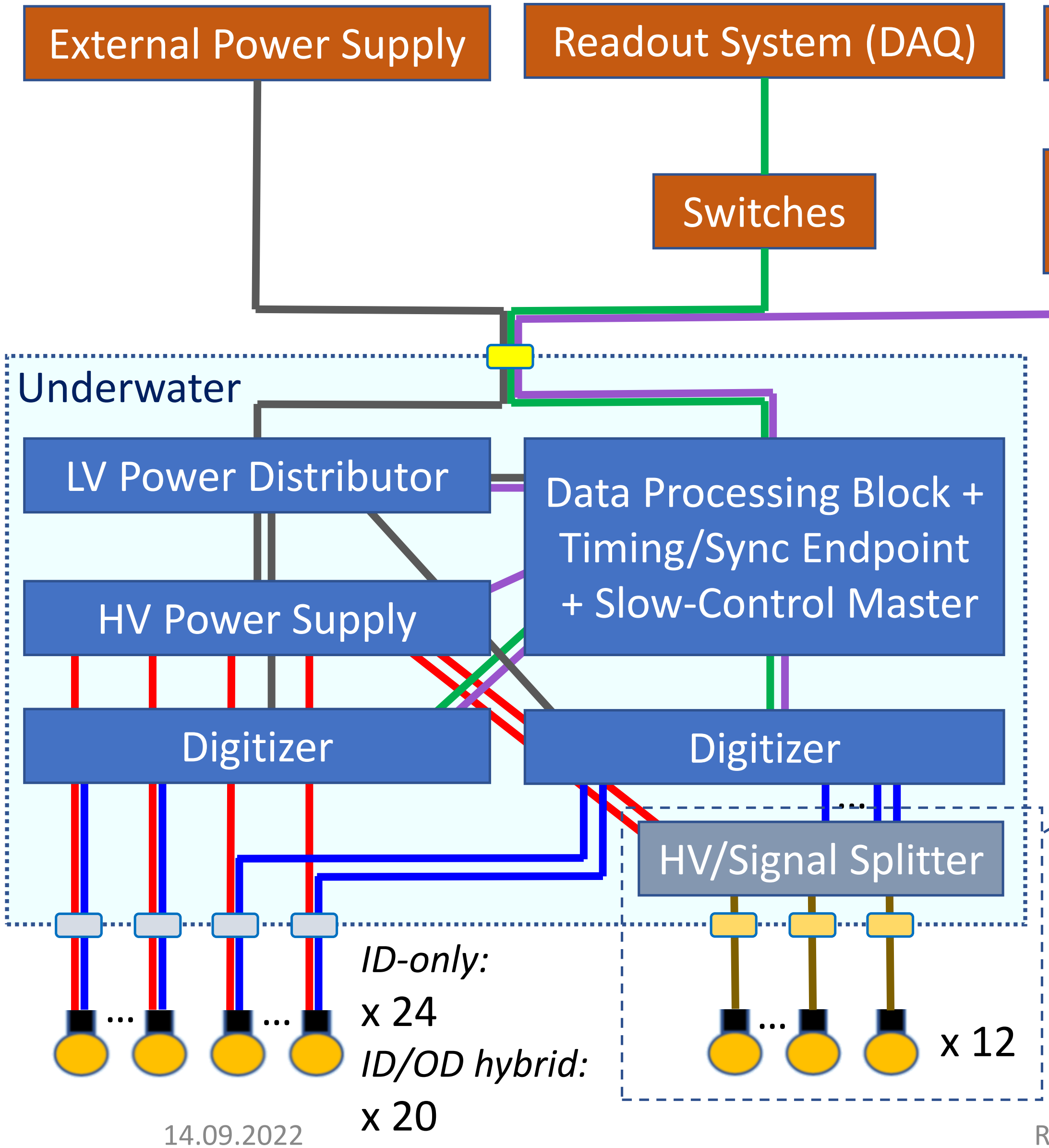
OD water thickness:

1m barrel

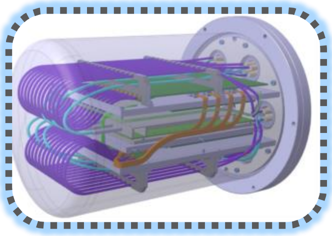
2m top

2m bottom

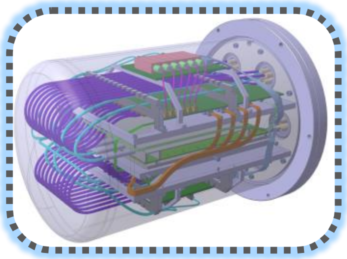
HK electronics: Block Diagram



ID-only vessel
(≈ 250 pcs.)



ID/OD hybrid vessel
(≈ 700 pcs.)

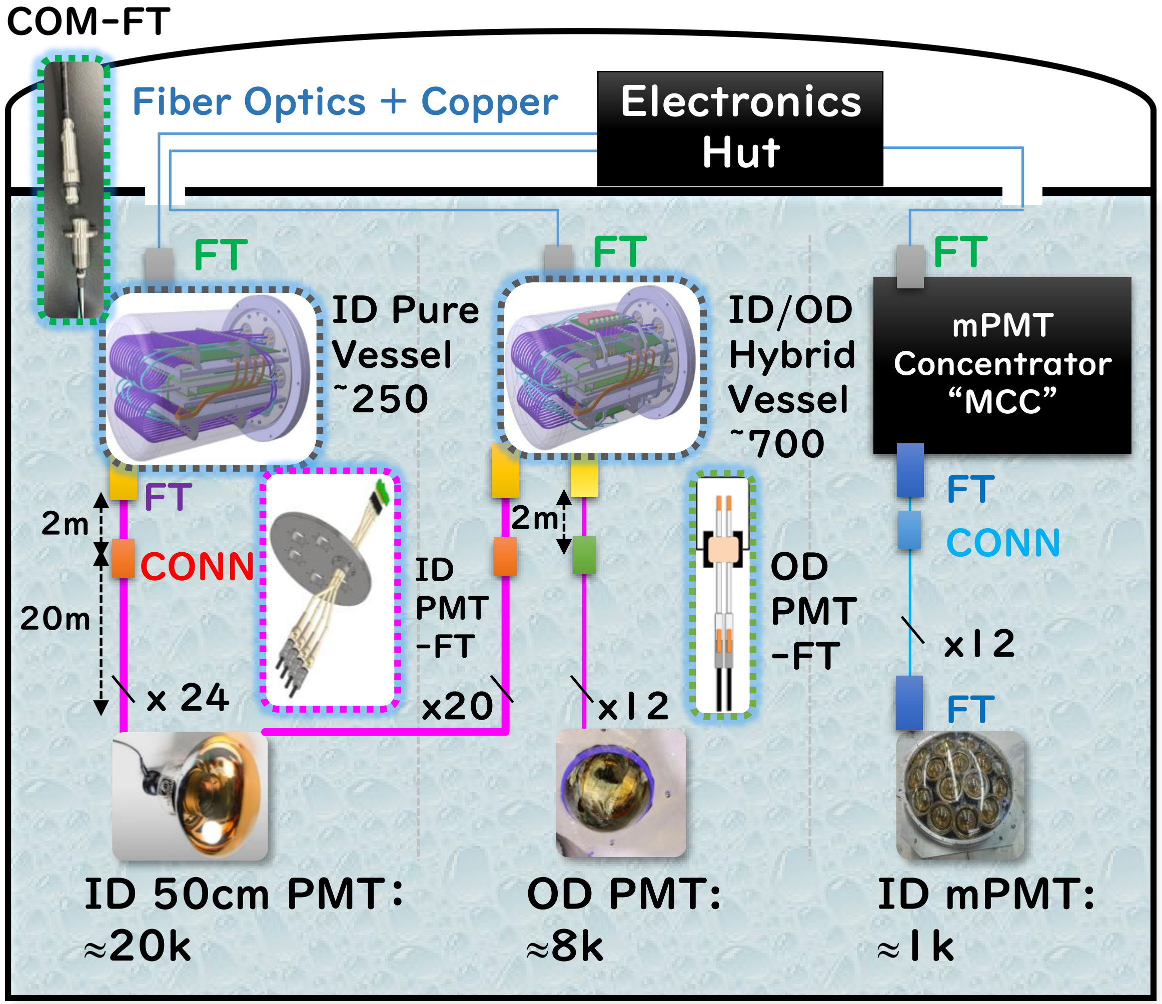


- **Measure and digitize:**
  - ✓ Charge from photosensors
  - ✓ Photon(s) arrival time
- **Requirements:**
  - ✓ Self-triggering
  - ✓ Time synchronization system
  - ✓ Absolute time stamp for neutrino beam – GPS
  - ✓ Stable HV power supply for PMTs
  - ✓ System monitoring
  - ✓ Environment monitoring
  - ✓ Continuous underwater operation without failure for > 20 years

Must preserve PMT performance

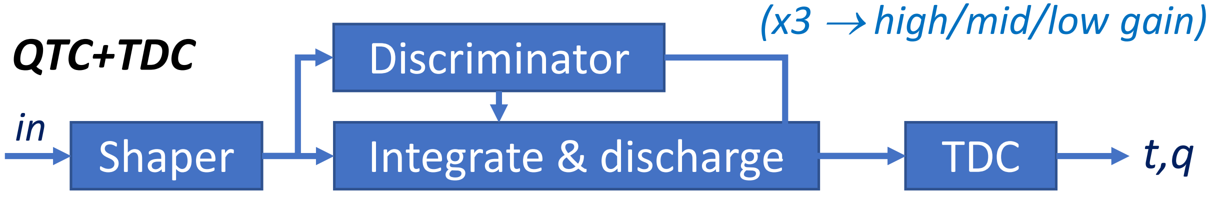
HK electronics: major challenges

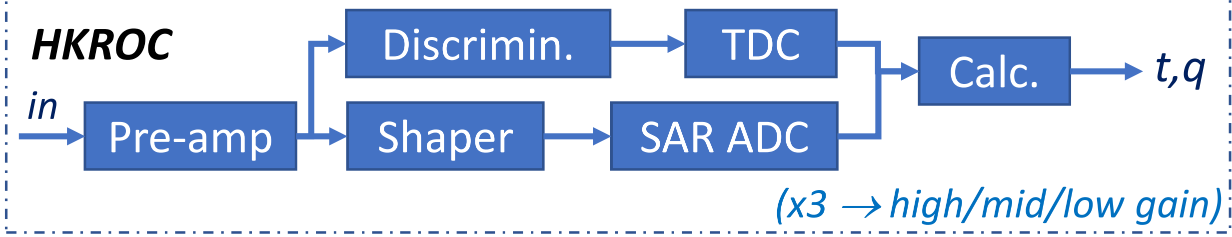
- Zero-serviceability once flooded
  - Need high reliability (>20 years of operation)
  - Redundancy (where needed)
    → Need to prevent the loss of the whole vessel
- Limits to power consumption but maintain perform.
  - <100W for the whole vessel
    (digitizer, synchronization, communication, power supplies)
  - ID -> 24 channel/3 ranges
    ID/OD -> 20 channels/3 ranges, 12 channel/1 range
  - Need to minimize disruption to water circulation
- Electromagnetic compatibility
  - Have sensitive analog circuits and DC/DC supplies + HV supplies in close proximity
  - So far conducted emission tests are encouraging
- Major R&D program related to underwater parts
  - Critical elements – feed-throughs, underwater cables, vessel
  - Material checks -> pressure & water resistance, compatibility with ultra-pure and gadolinium-doped water, radon emanation, fluorescence from material structure, soak test to check if material can release some substance into water.
  - Electrical & transmission checks

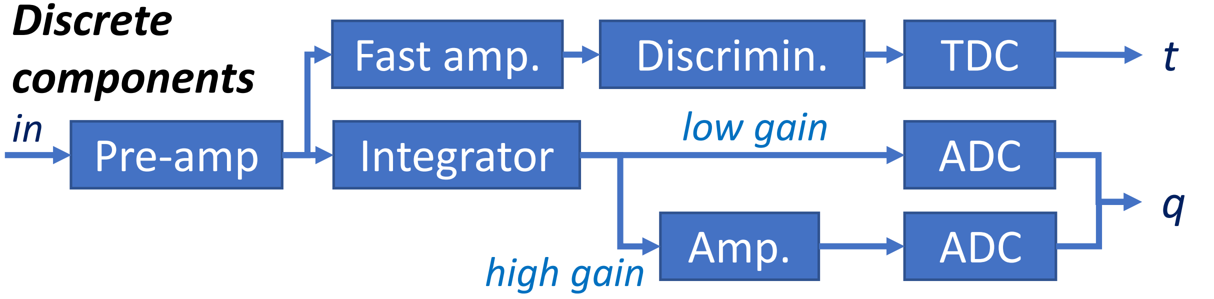


HK electronics: prototype status

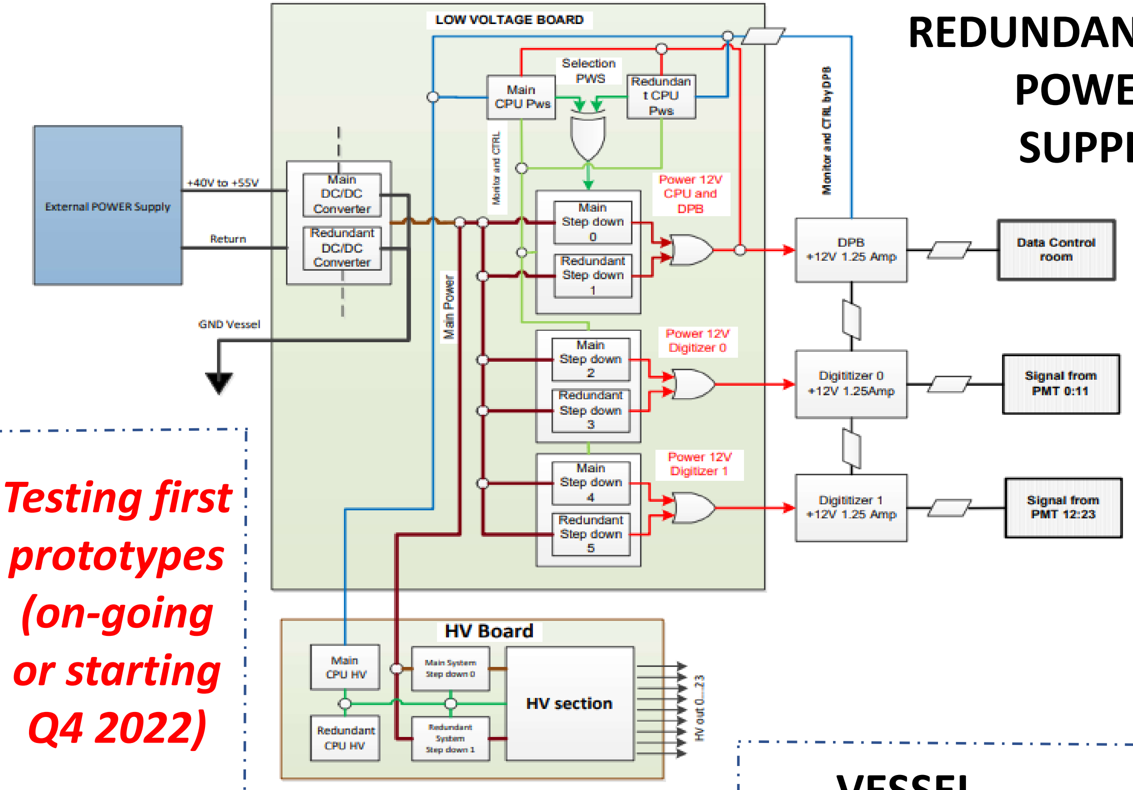
DIGITIZER OPTIONS ID+OD (decision soon)





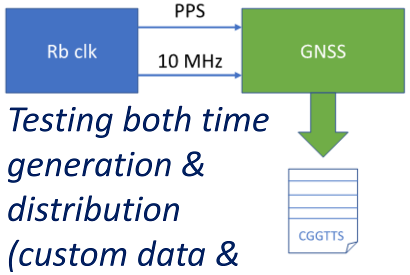


REDUNDANT POWER SUPPLY



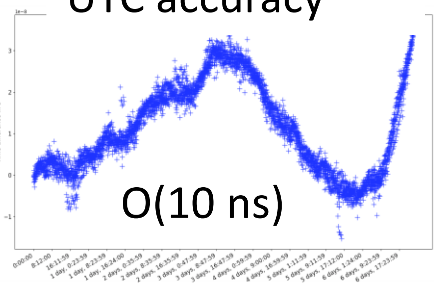
Testing first prototypes (on-going or starting Q4 2022)

TIMING SYSTEM

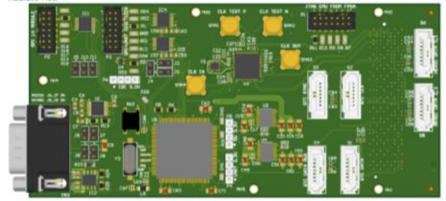


Testing both time generation & distribution (custom data & clock link)

UTC accuracy



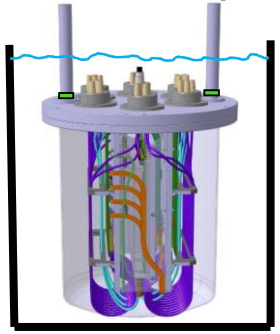
DATA PROCESSING BLOCK
(mezzanine for devkit)



VESSEL

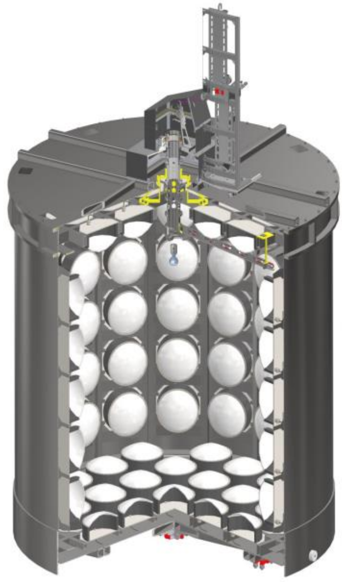
Prototype

Test setup



Multi-PMTs tests at WCTE@CERN

- **Water Cherenkov Test Experiment @ CERN** (http://cds.cern.ch/record/2712416/files/?ln=en)



✓ 50-ton scale detector (~4m×4m cylinder) to study detector calibration and response with known p, e, π, μ fluxes of 0.2-1.1 GeV/c and develop percent level calibration of water Cherenkov detector.

✓ Movable detector that can use secondary/tertiary beam of particles produced by target upstream of the detector.

✓ Measurements with ultra-pure and 0.2% gadolinium sulphate-doped water (to capture neutrons produced in CCQE antineutrino interaction and in secondary protons/pions interactions).

✓ About 100 multi-PMTs arranged in 16÷18 columns and 4÷5 rows; installed on the bottom and top endcaps and barrel region.

✓ Approved by CERN Research Board in March 2022, detector assembly from November 2023, commissioning and operation: April-June 2024.

- **Apart from physical results, tests of:**

✓ New photo-sensors – multi-PMTs and their calibration with embedded LEDs.

✓ Electronics based on commercial components (design for pre-production prototype was completed this summer).

Outlook

- Wide and ambitious Hyper-Kamiokande physics program requires a new generation of Water Cherenkov Detector.
- Hamamatsu R12860 20" PMTs and Multi-PMTs will instrument Inner Detector, whereas Multi-PMTs will collect Cherenkov light in the Intermediate Water Cherenkov Detector.
- 3" PMTs mounted on Wavelength Shifter plates with high reflective Tyvek on the walls will compose Outer Detector for the rejection of entering background.
- Various PMTs tests are ongoing.
- R&D works on electronics are nearing completion – new prototypes are being tested on an ongoing basis.
- Construction is proceeding on schedule to start operation in 2027.