A multi-PMT detector for the Hyper-Kamiokande experiment

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on behalf of the
Hyper-Kamiokande Collaboration

JENNIFER2 – General Meeting, November 17-18th 2022

Outline…

1. Cherenkov-detector PMT concepts

2. Overview of the Hyper-Kamiokande experiment

3. The multi-PMT photosensors for Hyper-K

Photodetectors in Water Cherenkov Detectors

Initially, Cherenkov neutrino experiments used the following concepts:

- Large-area photon counting detectors
- Timing at nanosecond level to suppress background
- Synchronisation of large detector arrays at sub-nanosecond precision
- High efficiency and low cost per channel
- Large-area PMT naked, either inside a pressure vessel or with a protective cover

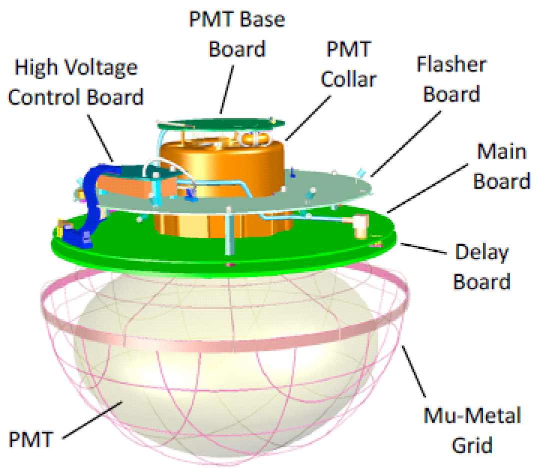
Currently, vacuum technology achieves the large areas while maintaining high gains and photon-counting capability

Hamamatsu 20-inch PMT

Photodetectors in Water Cherenkov Detectors

Convetional approach:
Large-area PMT can be naked, either inside a pressure vessel or with a protective cover

Hamamatsu **R7081 (10'')**
ICECUBE, ANTARES



IceCube Coll., JINST 12 P03012 (2017)

Hamamtsu R3600-02 (20'')
SUPER-KAMIOKANDE

Photodetectors in Water Cherenkov Detectors

New approach:
Using small PMTs to cover as much as possible effective area of an optical system and to introduce intrinsic directional sensitivity

multi-PMT (Digital Optical Module)

Firstly proposed by the **KM3NeT** Collaboration

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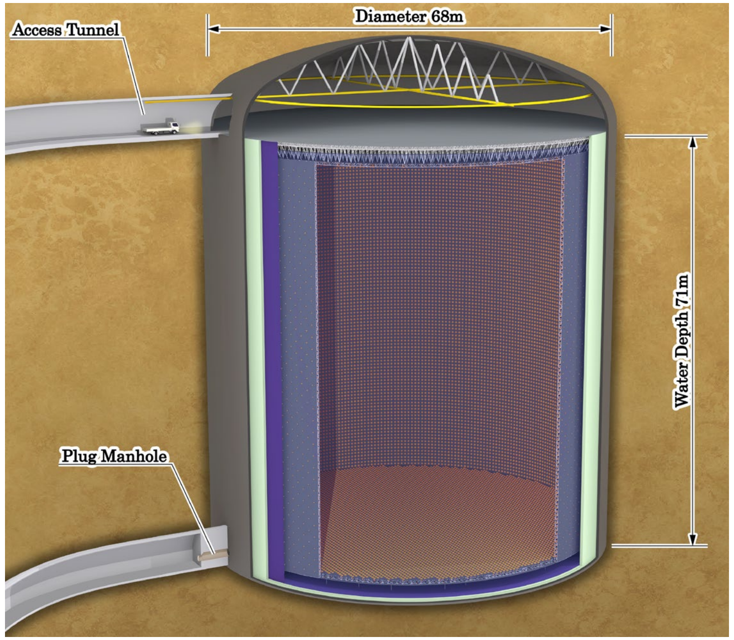
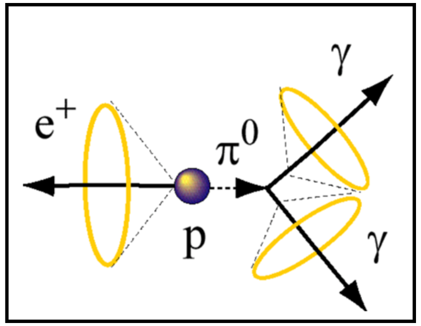
Hyper-K overview



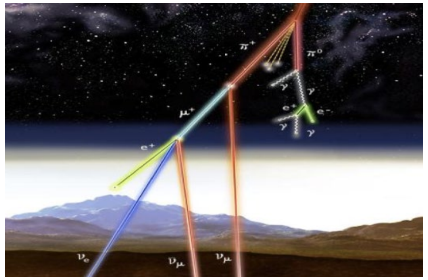
Hyper-Kamiokande (Hyper-K, HK) is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

✧ Neutrino oscillations and CP violation
(by atmospheric, accelerator and solar ν)
✧ Neutrino astrophysics
✧ Proton decay
✧ Non-standard physics

Proton decay



Atmospheric ν

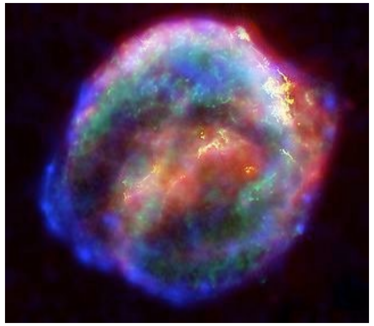


Accelerator ν

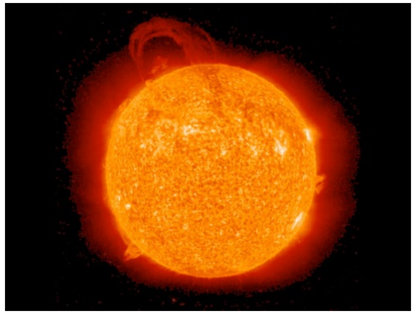
Hyper-K Far Detector (HK-FD)

- Cylindrical tank: Φ 68 m and H 71 m
- Filled with 0.25 Mtons of ultra-pure water
- Fiducial volume: 0.19Mtons (~8 times SuperK)

Today, Hyper-K is under construction and its operation will begin in 2027!



Supernova ν

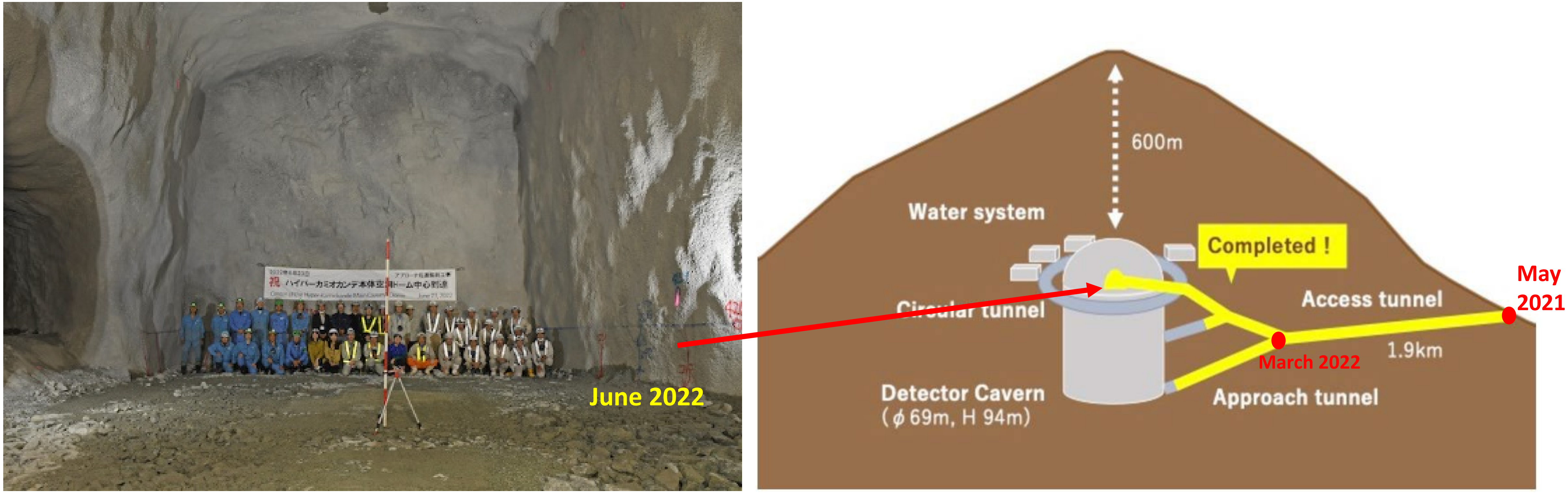


Solar ν

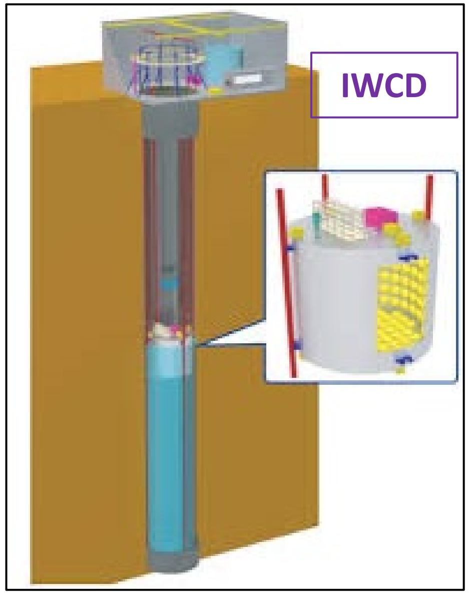
Hyper-K – Overview and its placement

The HK location is in the Kamioka area, 600 metres underground.
The access tunnel works started on the 6 May '21 and the center of the cavern dome was reached in the last June.

News and detail can be read here: https://www-sk.icrr.u-tokyo.ac.jp/en/hk/report/

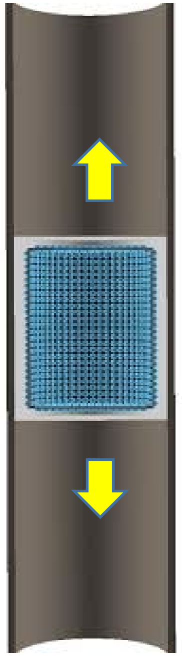


Hyper-K overview – The IWCD



Intermediate Water Cherenkov Detector (IWCD)

- ➢ 1 kilo-ton scale water Cherenkov detector
- ➢ It will be like an elevator, placed at ~ 1 km from the J-PARC accelerator
- ➢ mPMTs will be installed inside.

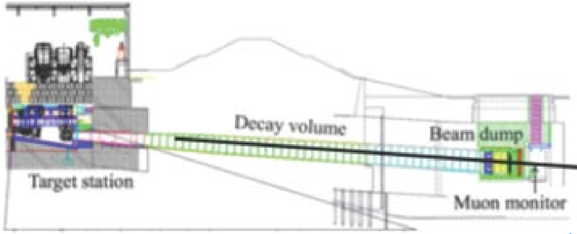


The Hyper-K IWCD
The instrumented portion will span a range of angles wrt the neutrino direction.

Inner detector:

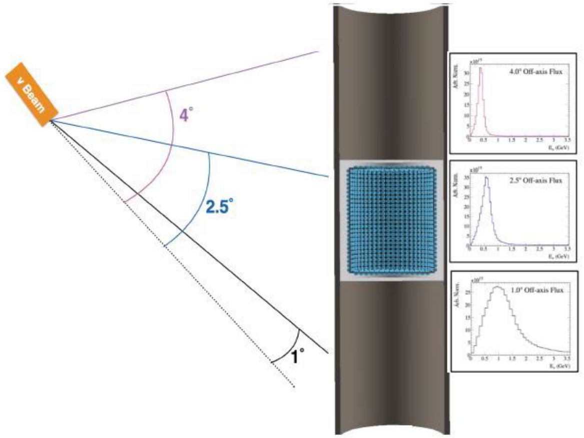
- 8 m diameter and 6 m tall
- Planned to populate with ~**500 mPMT** modules.

Position of the IWCD



~1 km baseline

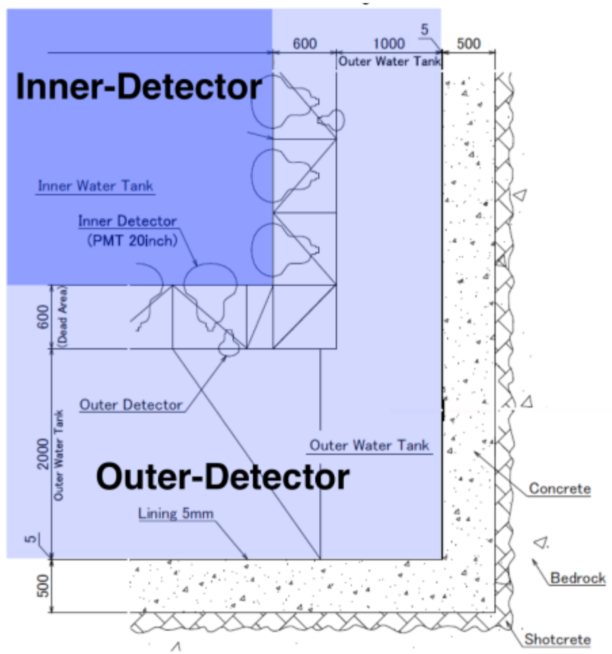
Phase-1
1-4° off-axis angle



Credit by: https://www.uvic.ca/science/physics/vispa/research/projects/neutrino/

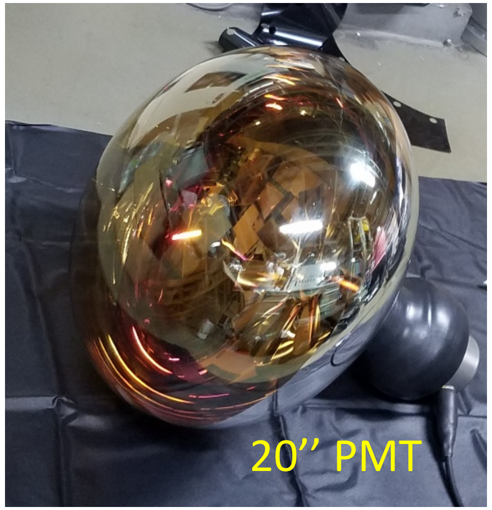
Hyper-K Far Detector inside

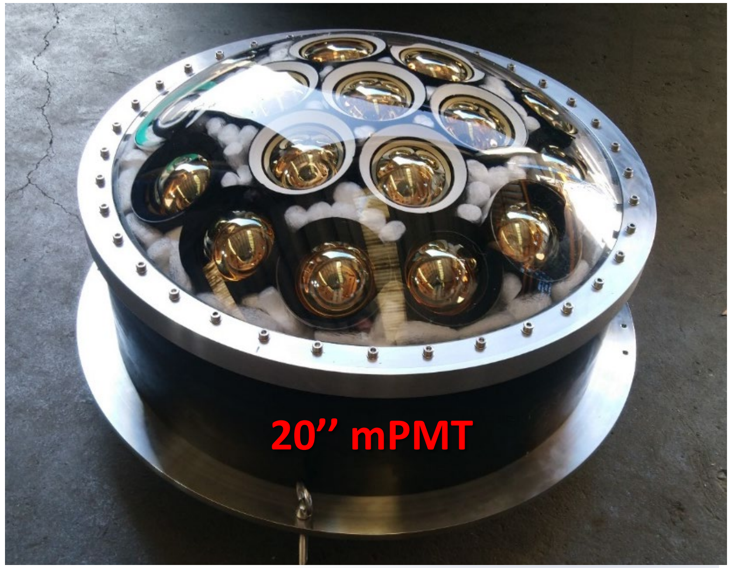
The **FD** will consist of a hybrid configuration of detectors to observe the inner and outer parts: a structure frame supports all detectors and divides the water volume into two regions.



Inner detectors (IDs):

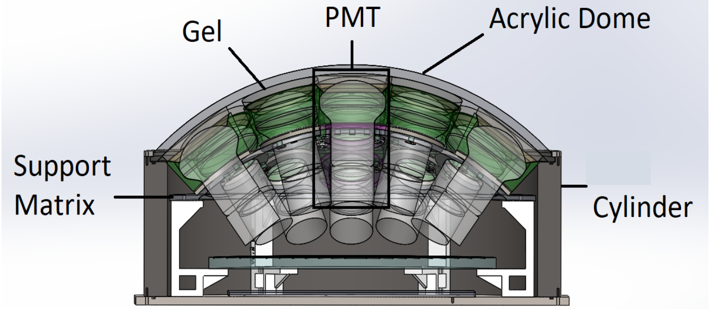
- ❖ 20'' PMTs (#20'000)
- ❖ 20'' mPMTs (->19 3'' PMTs inside) (#thousands)
  - ❖ [Photo-coverage (PC) 20%)]





New high-QE 50-cm Box&Line PMT

If compared to the Super-K PMT:
× 2 higher pressure bearing for 60-m depth
× 2 higher detection efficiency
and half time&charge resolutions



Outer detectors (ODs):

- ❖ 3'' PMTs + Wave Length Shifter (WLS) plates

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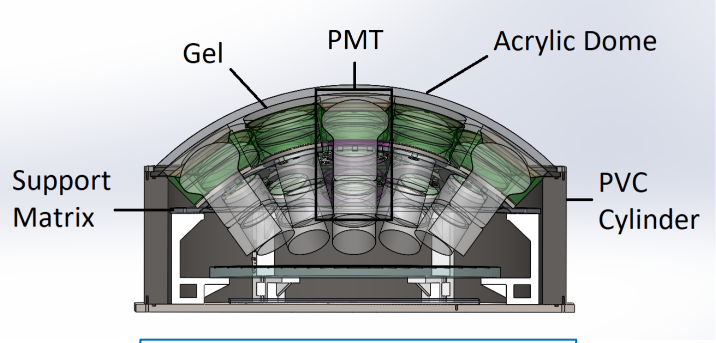
multi-PMT for Hyper-K

Based on the KM3NeT Digital Optical Module

Photodetectors and electronics are arranged inside a pressure resistent vessel

<u>Advatenges:</u>

- Superior photon counting
- Smaller transit time spread
- Extension of dynamic range
- Improved angular acceptance
- Intrinsic directional sensitivity
- Local coincidences
- Negligible effects due to magnetic fields
- Better cost/photocathode-area ratio
- Reduced risk (failures)

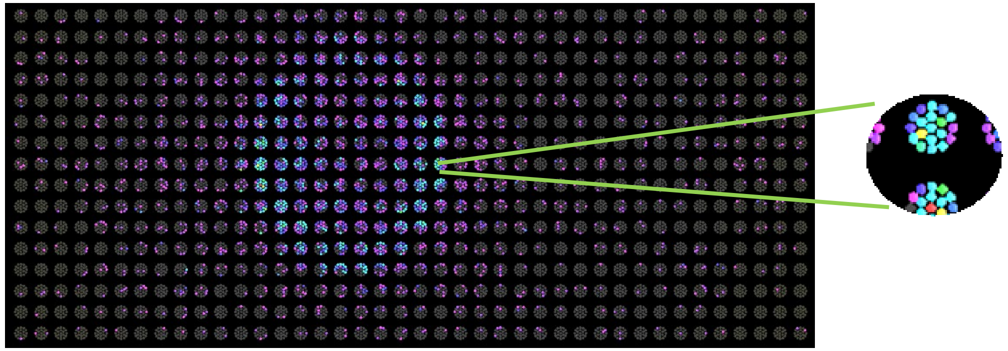


ID-mPMT (19 PMTs)

But, the main limits of KM3NeT solution for HK project are:

- ✓ Vessel
  - ➢ KM3NeT experience demonstrated that glass spheres are characterized by high ^{40}K and other radioactive contamination.
- ✓ PMT Read-Out
  - ➢ In KM3NeT the time over threshold (ToT) strategy is exploited; this is not a good solution for Hyper-K project in which charge measurement is important
- ✓ Assembly procedure
  - ➢ mPMT production time

multi-PMT for Hyper-K



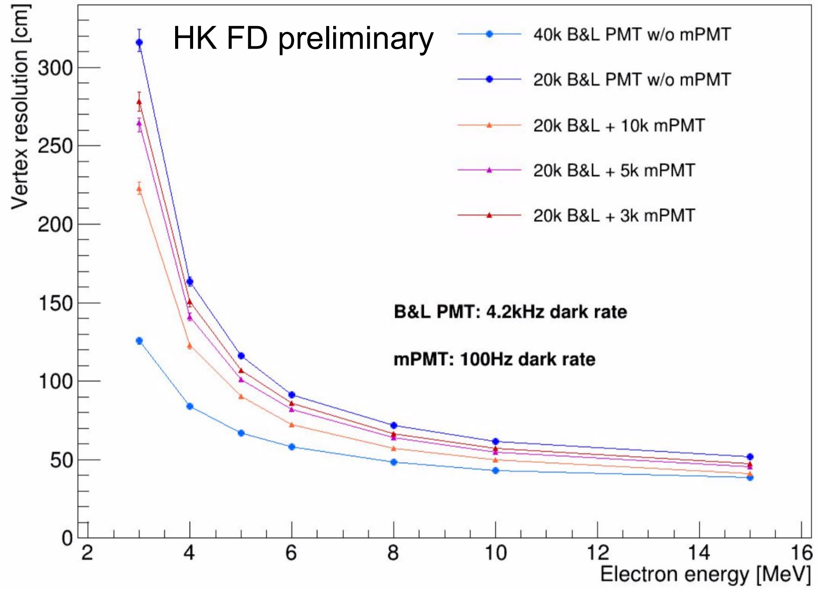
Increased granularity

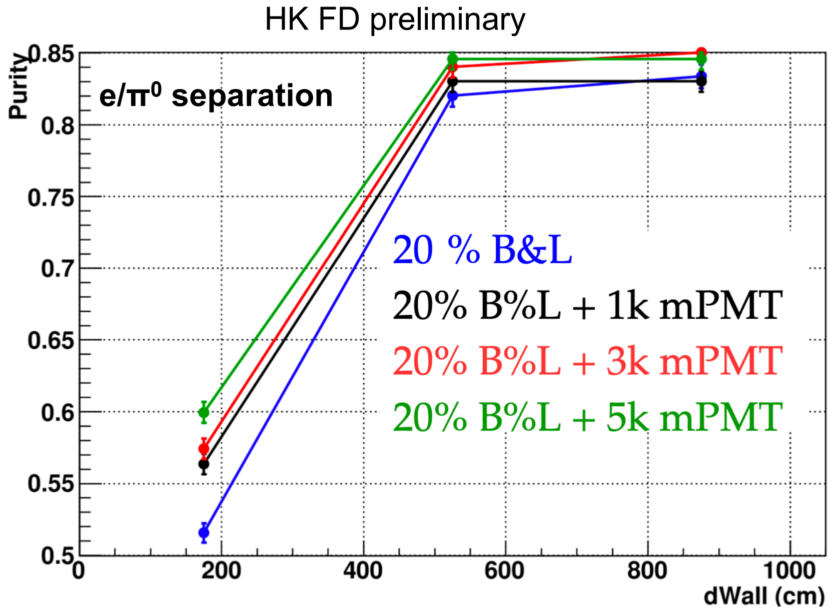
Enhanced event reconstruction, in particular for multi-ring events

HK FD simulation studies

Preliminary results:

- Vertex and angular resolution are better at low energy
- At high energy: muon/electron separation improved near the wall; vertex resolution improved
- Improvements strongest-near edges of fiducial volume





Further advantages by mPMT:

- To reduce costs
- To improve reliability for long term experiments
- To improve physics sensitivities of Hyper-K experiment

The multi-PMT designs

The mPMT is a vessel which houses and protects an array of 19 3" PMTs, and the original concept was realized for the **KM3NeT** experiment.
WRT single 20'' PMTs the mPMT configuration:

- ✓ improves the granularity and timing response over larger number of photo-sensors
- ✓ has got an additional intrinsic directional information

This detector is a common effort from Italy, Canada, Czech Republic, Mexico and Poland.
Two mPMT designs are planned, but very similar each other ⟹ Same assembly, similar components where possible.

Different constrains for the IWCD and FD mPMTs:
- in the FD a higher resistance to pressure is required (in comparison with IWCD)
- in the IWCD mPMT electronics needs to be able to distinguish between different hits in different bunches

- ➢ Currently, the number of the mPMT for the HK FD is under discussion.

Principal mPMT componets	Characteristic for the FD	Caracteristic for the IWCD
Dome	UV-transmitting acrylic	UV-transmitting acrylic
3'' PMT	19 items	19 items
Vessel cylinder	POM-C material (TBC)	PVC material
Back plate	AISI-304 stainless steel (SS)	AISI-304 SS
Optical gel	For an optical connection between the acrylic dome and the PMT photo-cathode	For an optical connection between the acrylic dome and the PMT photo-cathode
Clamping ring	AISI-304 SS	AISI-304 SS
Electronic board	Q/T digitization based on discrete components	FADC digitization, with on-board signal processing

The multi-PMT – About its tests

Many tests on the mPMT prototype and its material/components:

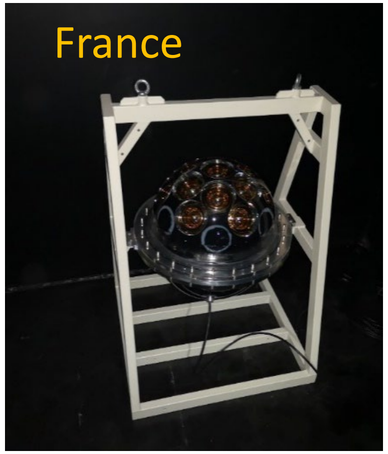
- Optical, mechanical and nuclear contamination tests on the UV-transmittance acrylic material
- Water absorption into acrylic sample
- Pressure tests of the external-component vessel
- Functional test of the first prototype in MEMPHYNO lab (a second test is scheduled soon with the last design)
- A preliminary installation into a mock-up frame in Hokkaido
- An anti-implosion test where the detector survived with no external damages and connections resisted
- Assembly tests
- ...

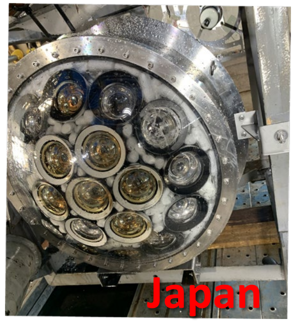
The mPMT is ready for some last verifications and final assemblies checks with the updated components.

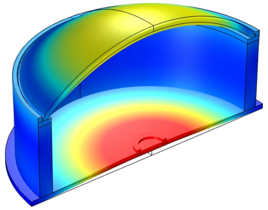
Nuclear contamination analysis at the National Gran Sasso Laboratories of INFN

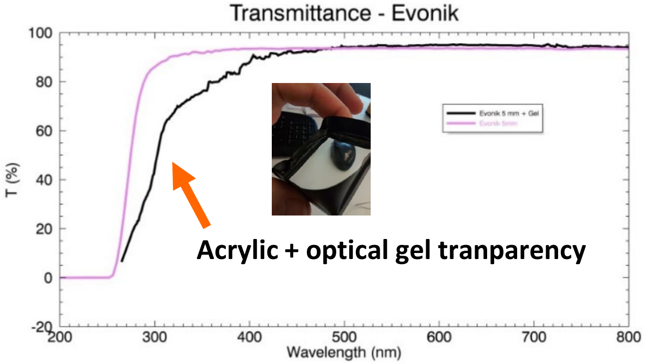
Isotope	Activity	Contamination
	^{232}Th: Thorium series	
Ra-228	< 0.11 mBq/kg	< 0.027 ppb
Th-228	< 93 μBq/kg	< 0.023 ppb
	^{238}U: Uranium series	
Ra-226	< 65 μBq/kg	< 0.0052 ppb
Th-234	< 4.6 mBq/kg	< 0.38 ppb
Pa-234m	< 2.5 mBq/kg	< 0.20 ppb
U-235	(0.15 ± 0.07) mBq/kg	$(3 \pm 1) \cdot 10^{-1}$ ppb
K-40	< 0.69 mBq/kg	< 0.022 ppm
Cs-137	< 25 μBq/kg	-

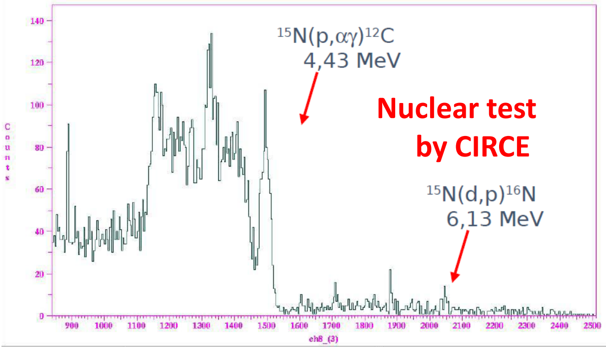
Table 5: Results of nuclear contamination of Evonik samples.

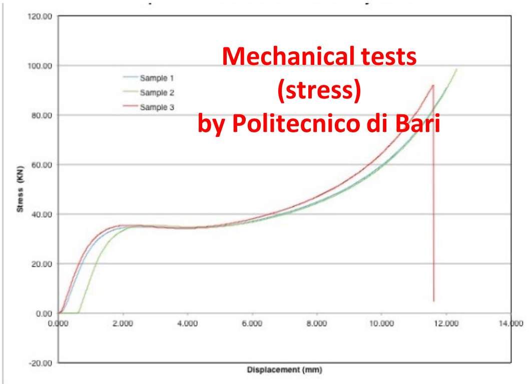


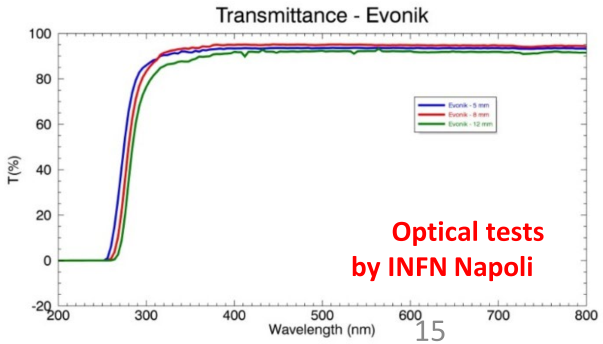




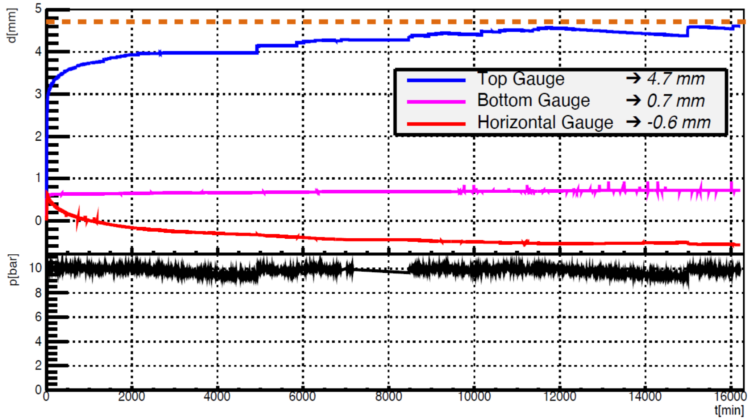


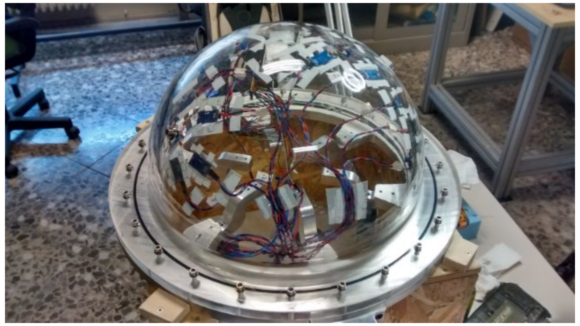




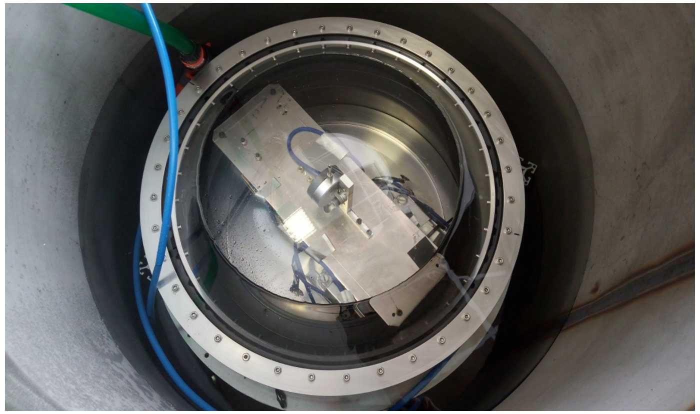


The multi-PMT – About its tests

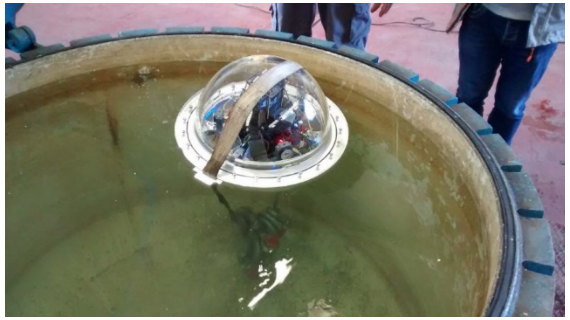


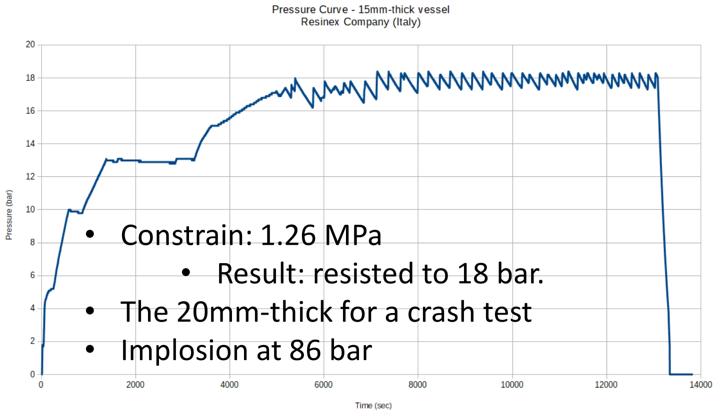


15mm and 20mm-thick vessels tested
Arduino pressure sensors for monitoring
At Resinex Company (2018)



New mPMT prototype, new Arduino monitoring system
At IPNP at Charles University (Prague) (2022)





- Constrain: 1.26 MPa
  - Result: resisted to 18 bar.
- The 20mm-thick for a crash test
- Implosion at 86 bar

mPMT Electronics

Performance requirements

– Timing resolution: better than 3" PMT TTS

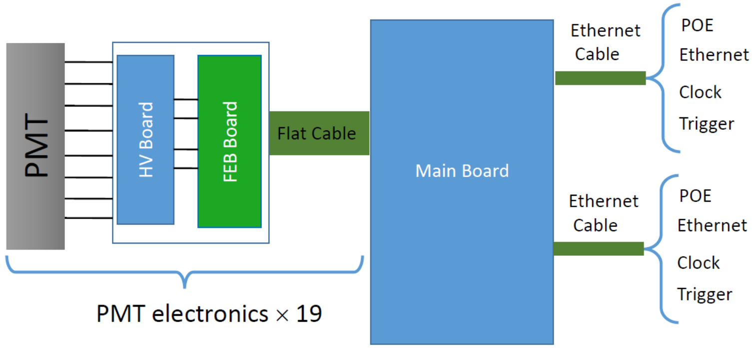
- ~300-500ps timing resolution from electronics for 1PE.
- Better timing resolution (100-200ps) for large PE pulses

– Charge resolution ~0.05PE up to 25PE.

Power-consumption requirments:

- For HK FD <3-4W per mPMT
  - Cooling driven by water circulation requirements
- For HK-IWCD ~5-10W per mPMT
  - Not as strongly constrained as Hyper-K

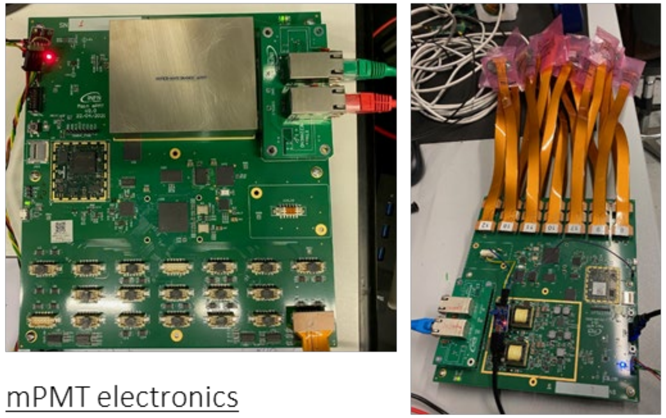
The multi-PMT – PMTs and electronics



Requirement : Total Power consumption <4 W

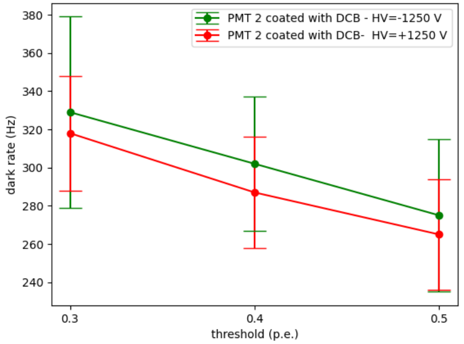
HV board

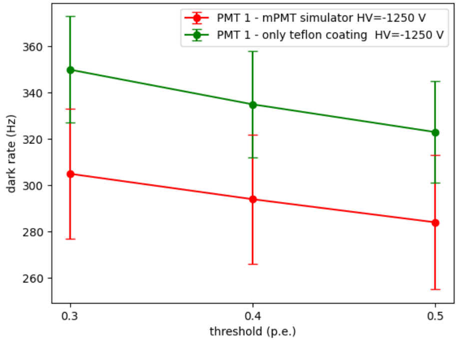
Basic Cockcroft-Walton voltage multiplier circuit designed for HV up to 1.5 kV

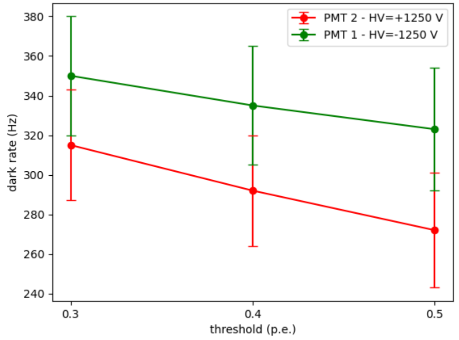


mPMT electronics

Ready to start reliability validation:
Contract started with company
Automatic testing procedure defined
Installed in INFN mPMT prototype
LED calibrator card integration started





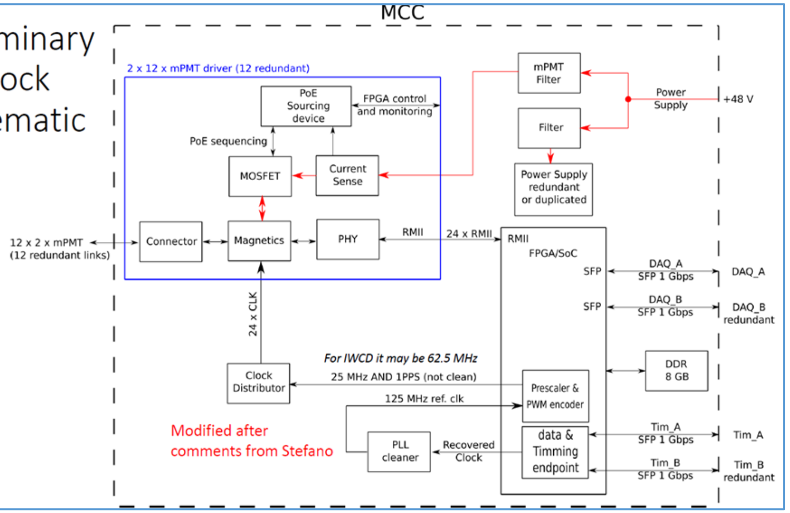


MCC Electronics

Started writing the MCC specification document
Estimating board size for MCC vessel design

Checking critical components aviability for prototypes

Preliminary block schematic



Some information:
- mPMT electronics is ready for realibility validation;
- Cables and feedthrough: prototypes ready for testing
- MCC: started writing specification document for electronics; studies for vessel started
- PMT tests and their charaterization are ongoing

Conclusions

Further technical details:

- Design Report is available (https://arxiv.org/abs/1805.04163).
- Technical Report will be published soon.

Project status:

- Japanese construction budget was approved by MEXT in Japan, in 2020.
- We are in construction phase:
    - Cavern excavation is ongoing
    - Mass production of new 20-inch PMTs started
- Basic design of tank, mPMT, electronics, etc., will be finalized soon.
    - Their mass production is scheduled at the end 2023
- PMT installation is foreseen in 2025-2026
- Hyper-K observation will start in 2027.

Thank you!!!