tmeν WCP2018
European Workshop on Water Cherenkov Precision
Detectors for Neutrino and Nucleon Decay Physics
19-21 September 2018 - Warsaw University of Technology

Multi-PMT units for the Water Cherenkov detectors, the case of KM3Net and its evolution for E61 and Hyper-Kamiokande

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Photodetection in Water Cherenkov Detectors

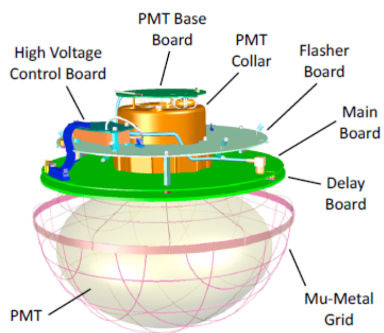
- Large area photon counting detectors
- Timing at nanosecond level to suppress backgrounds
- Synchronisation of large detector arrays at sub-nanosecond precision
- high efficiency and low cost per channel


Hamamatsu 20-inch PMT

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

Photodetectors in Water Cherenkov Detectors

Hystorical approach:
large area PMT inside a pressure vessel or with a protective cover



IceCube Coll., JINST 12 P03012 (2017)

Hamaatsu **R7081 (10 inch)**
ICECUBE, ANTARES

Hamamtsu R3600-02 (20 inch)
SUPER-KAMIOKANDE

Photodetectors in Water Cherenkov Detectors

Novel approach:
to increase the yield of the effective area of the optical system introducing intrinsic directional sensitivity

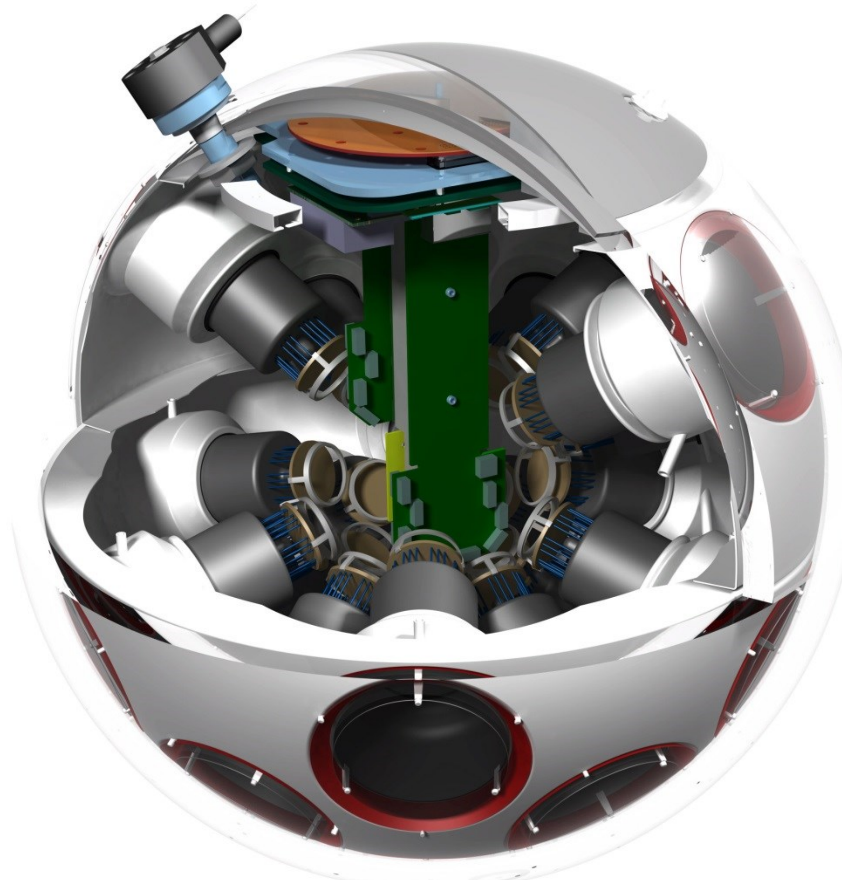
Multi-PMT
Digital Optical Module

Firstly proposed by KM3Net Collaboration

The KM3NeT Digital Optical Module

- 31x3" PMTs (Hamamatsu R12199-02) in 17" glass sphere
- Front-end electronics, digitisation, optical signal
- Single penetrator

<u>**Advantages**</u>:
- **Increase of photocathode area**
- **Superior photon counting**
- **Improved angular acceptance**
- **Extension of dynamic range**
- **Intrinsic directional sensitivity**
- **Local coincidences**
- **Cost / photocathode area**
- **Reduced risk**



The KM3NeT Digital Optical Module

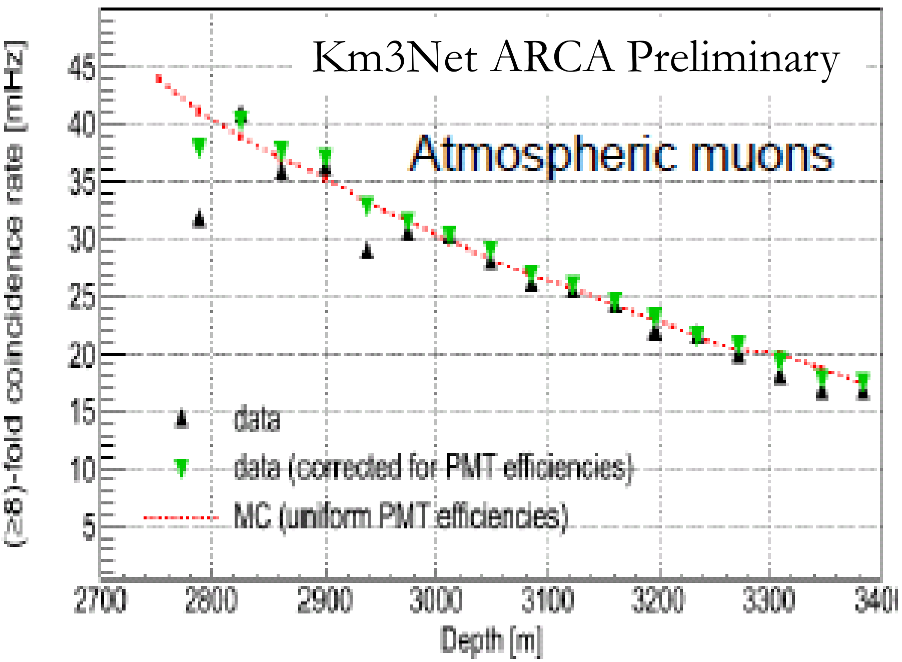
Each DOM implements a dedicated FPGA firmware for DAQ with an embedded software for slow-control

Communication is set via 1Gbps ethernet connection to shore

Time synchronisation (better than 1 ns) is achieved exploiting the White Rabbit technology

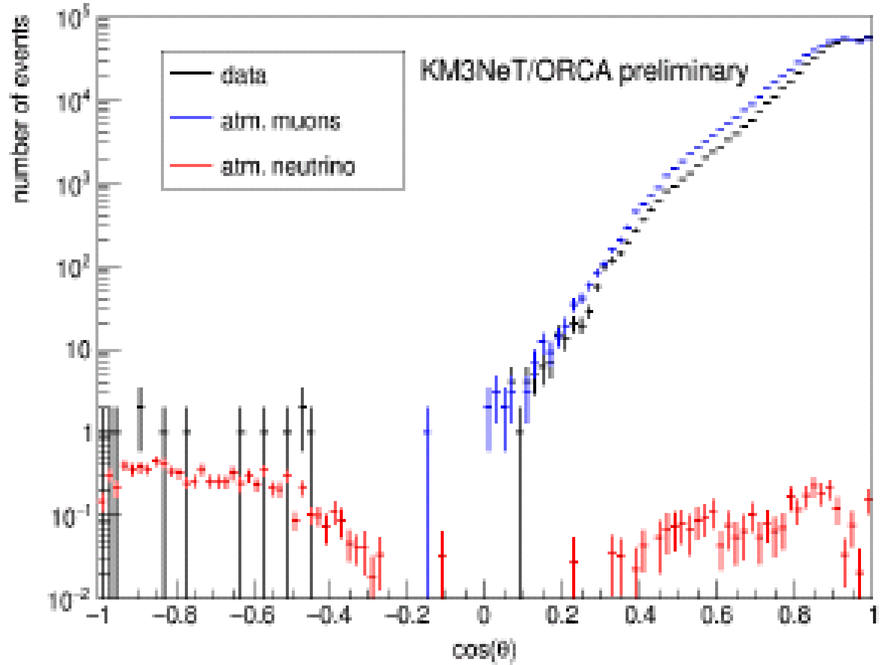
The KM3NeT Digital Optical Module

The hardware functionality and physics capability of the multi-PMT concept have been demonstrated with the deployment and operation of KM3NeT detection system in the Mediterranean



ARCA: 3 strings deployed Dec 2015 & May 2016

From U. Katz's talk: Future neutrino telescopes, Neutrino 2018, Heidelberg

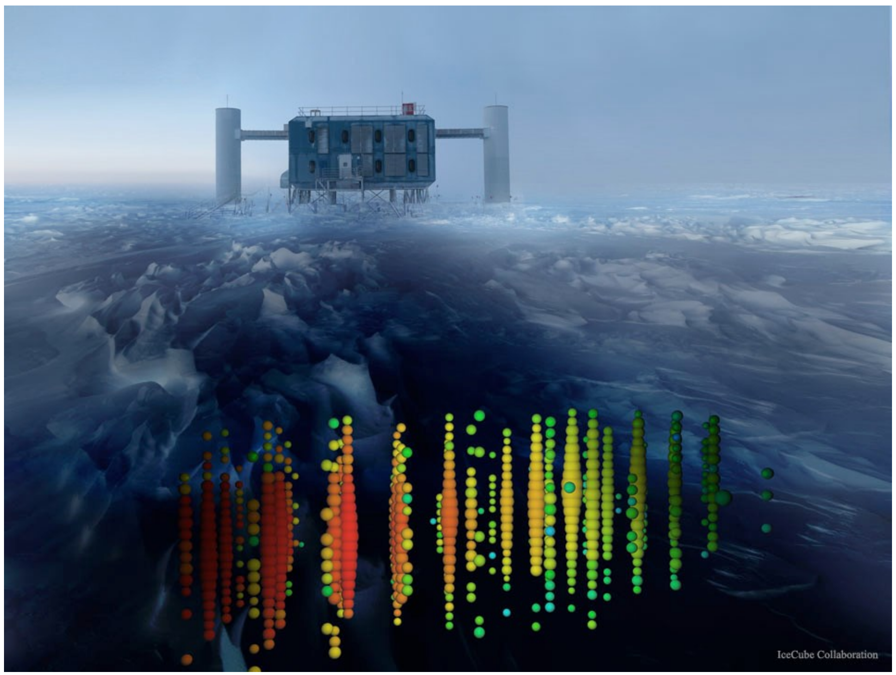


ORCA: Successful deployment & operation of first string (Sept 2017)

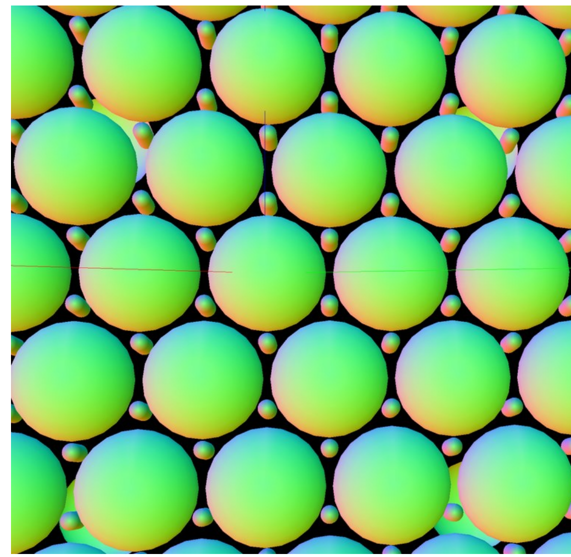
see A. Margiotta's talk for details

Multi-PMT approach for new projects

Depending on the respective implementation, the vessel in addition houses read-out, digitization electronics, auxiliary devices …



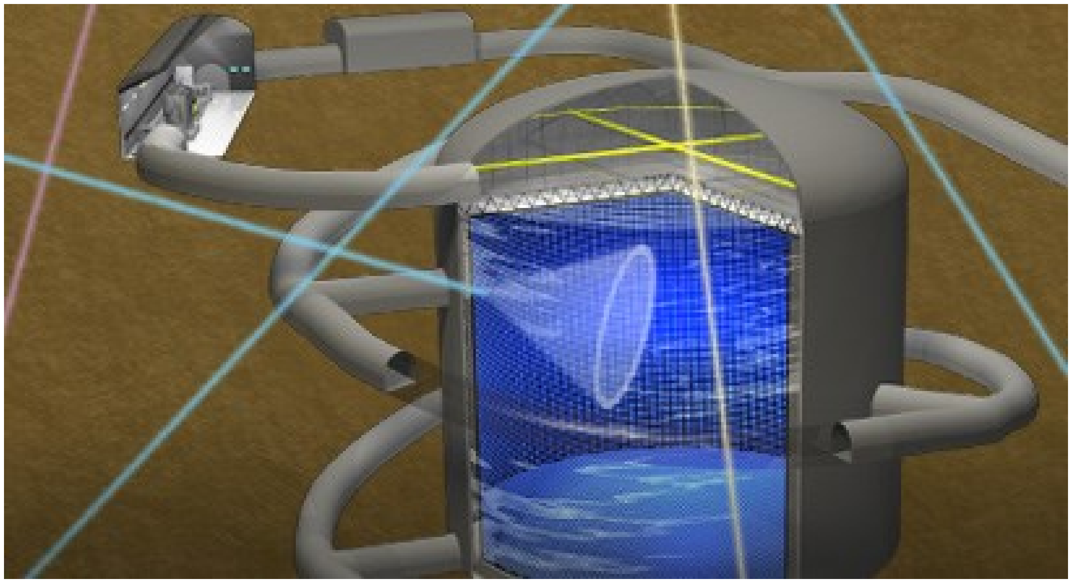
IceCube Gen2: High Energy Array



JUNO:
Large-PMT system:
20” diameter
Small-PMT system:
3” diameter

....not only WC detectors......

Multi-PMT approach for new projects



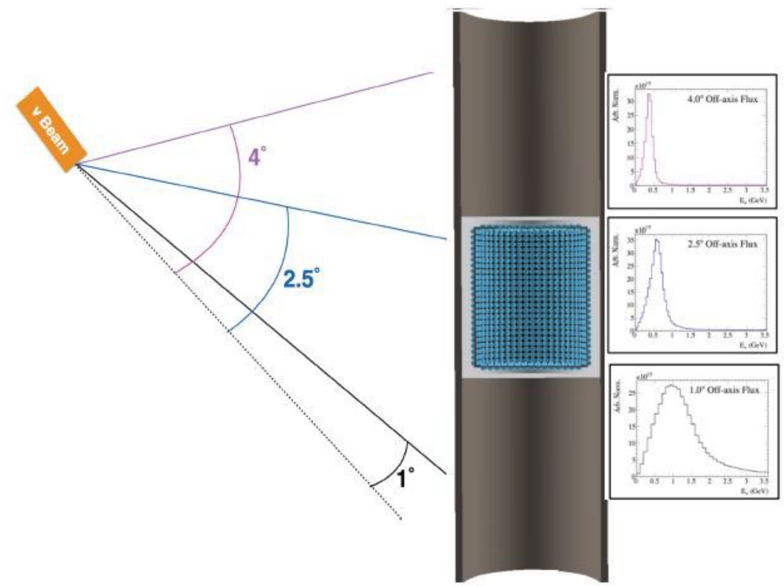
Hyper-Kamiokande Project

60 m(H)x74m(D)

Total volume 260 kt

Fiducial volume 190 kt ~10x Super-K

See S. Seo’s talks



E61 - IWCD

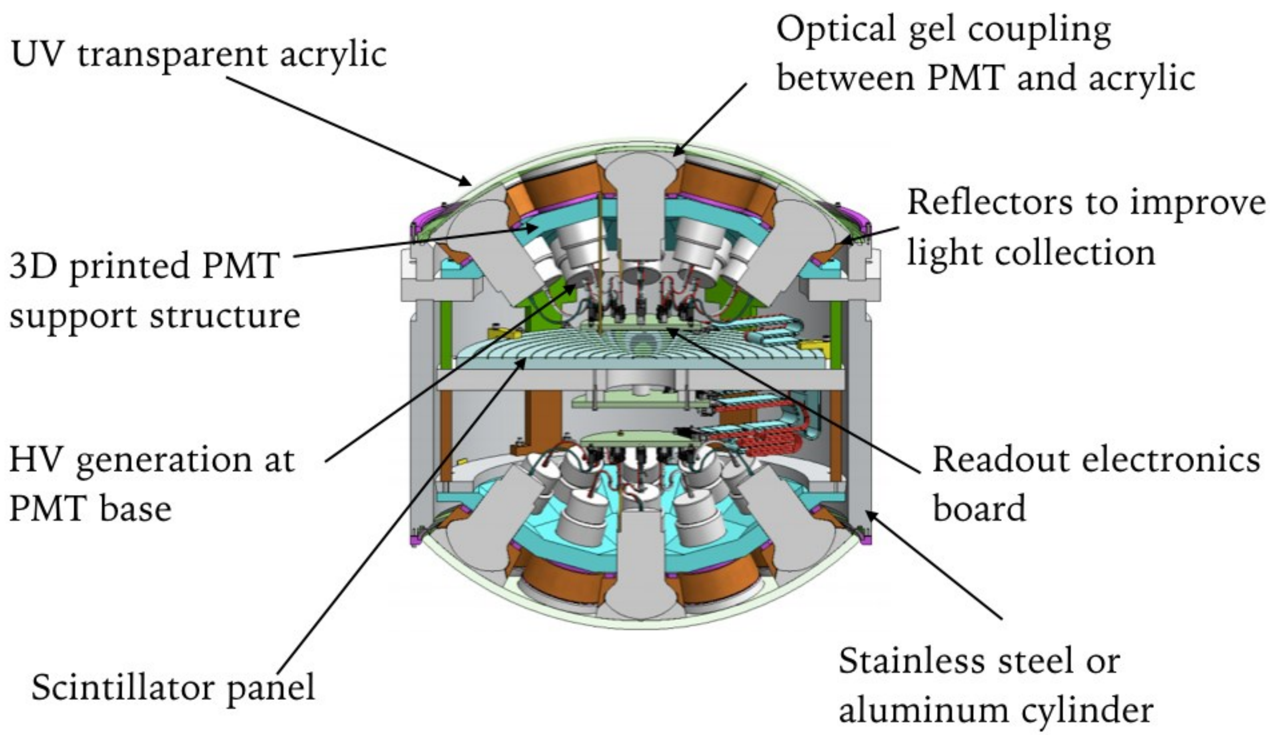
Movable Water Cherenkov detector

Inner diameter 8 m

Inner detector height 6-8 m

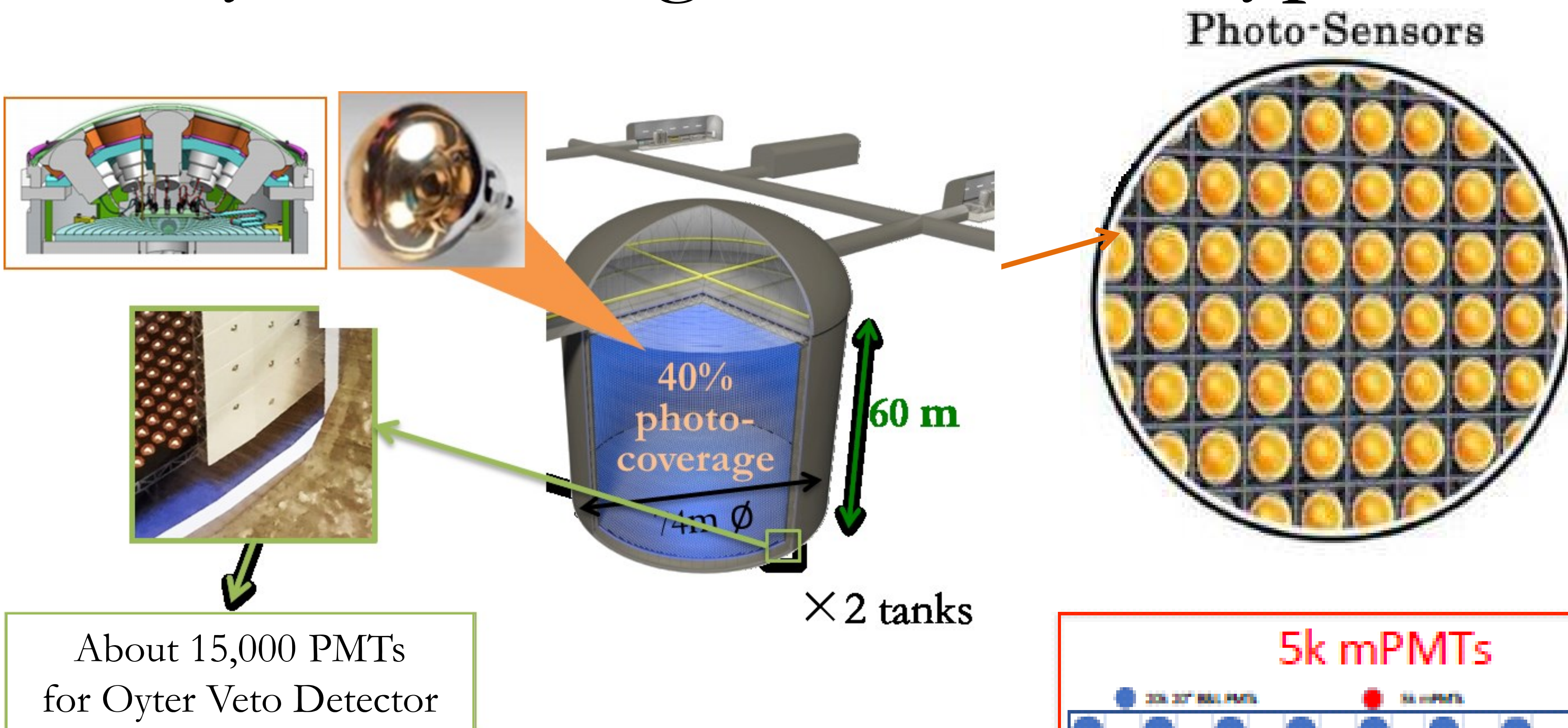
Details in C. Vilela’s talk

multi-PMTin Hyper-K and E61

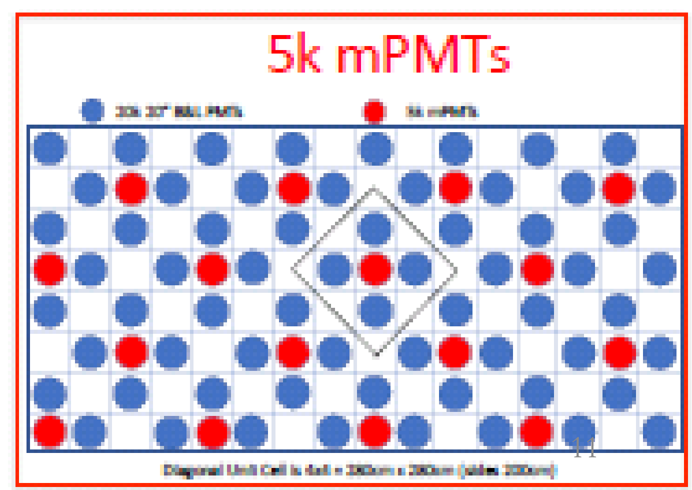


- The E61 baseline design is equipped with multi-PMT modules (mPMT) as photodetction system
- Hybrid configuration for Hyper-K: 20” + mPMT

Hybrid configuration for Hyper-K



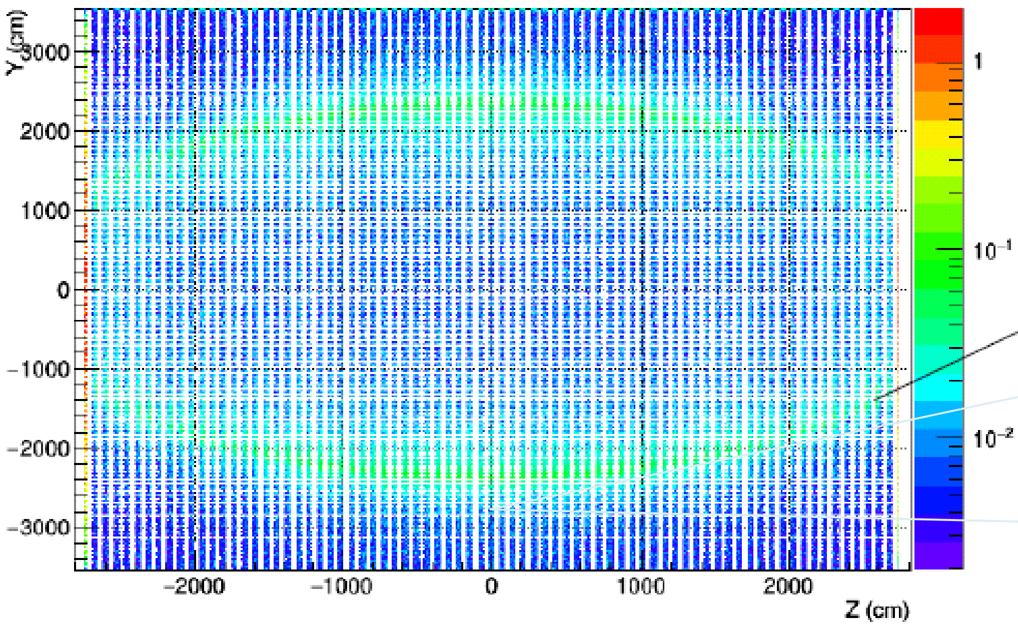
Baseline hybrid configuration:
- 20k of 20” PMTs
- 5k mPMTs



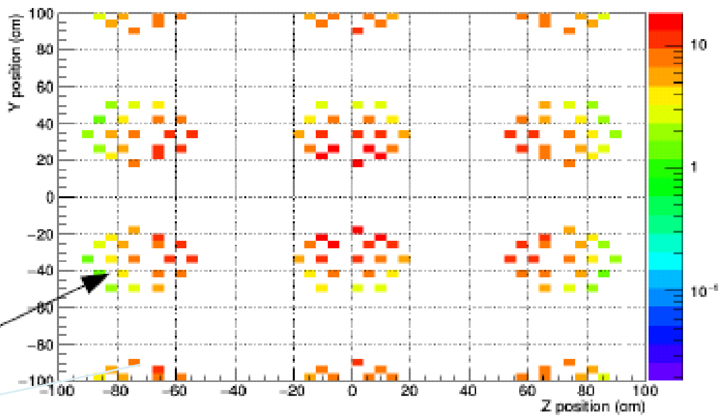
Large PMT vs mPMT?

Intermediary goal: determine capabilities of standalone mPMTs
→ Hyper-K with 40 % coverage of mPMTs: compare with 20"

e- generated at the tank center



Zoom-in



Increased granularity
enhanced event reconstruction, in particular for multi-ring events

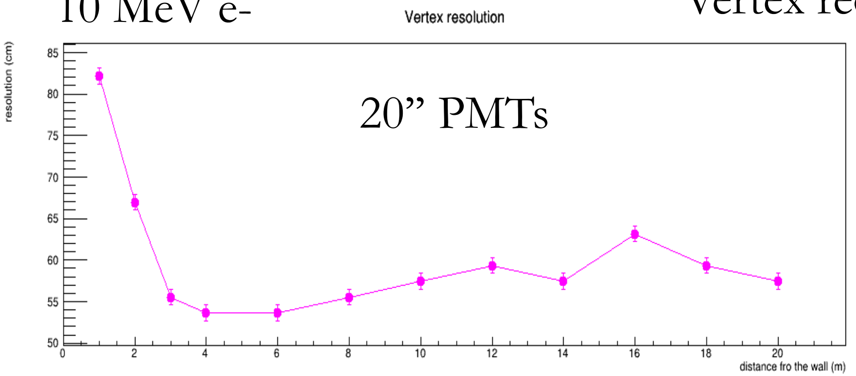
Complete simulation and reconstruction chain has been developed and validated

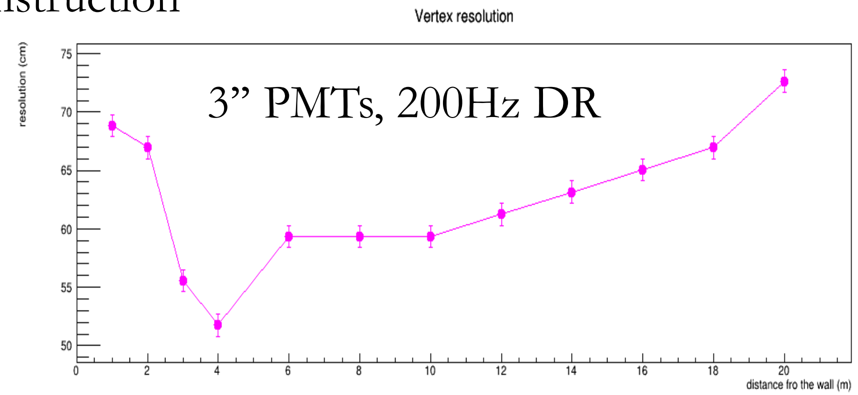
Performance Studies for mPMTs in HK

Variation of resolutions with distance to the wall

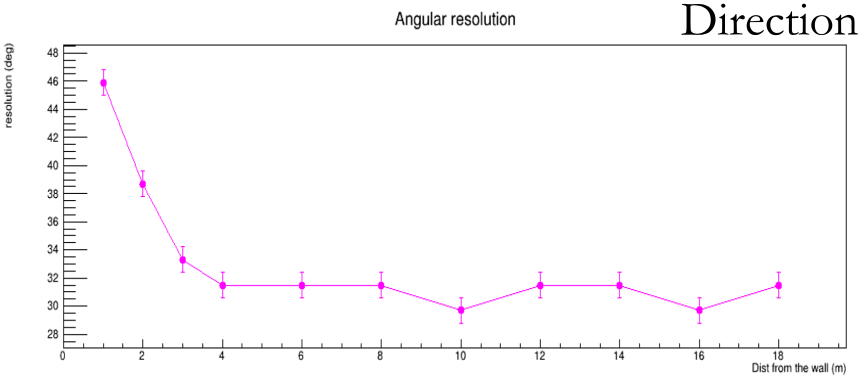
10 MeV e-

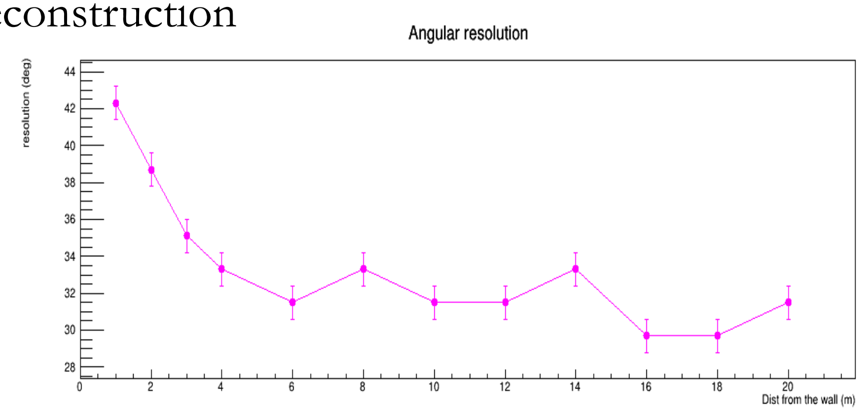
Vertex reconstruction





Direction reconstruction



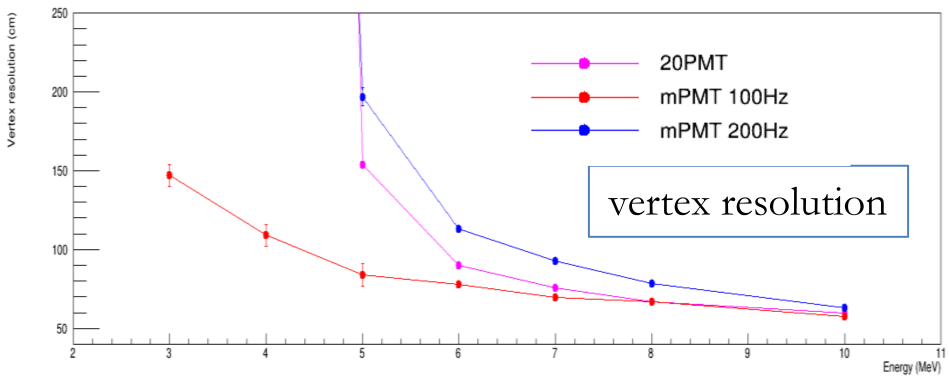


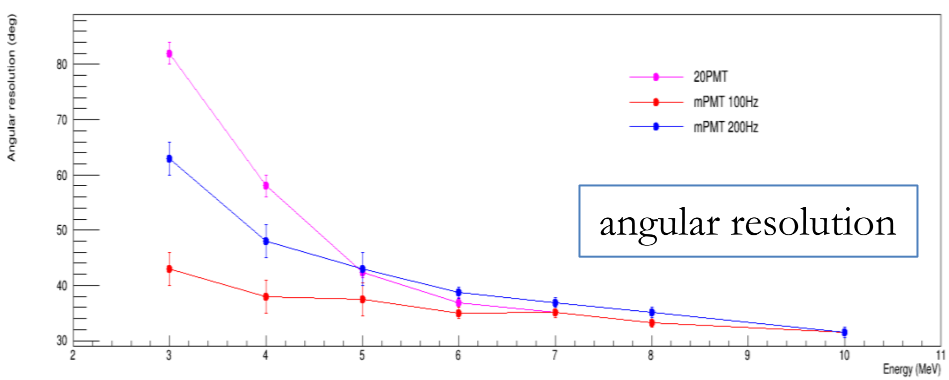
Vertex resolution improved w/ mPMT near edges of FV

Pure DR effect: improve vertex resolution 52cm (200Hz)→ 48 cm (100Hz)

Performance Studies for mPMTs in HK

Variation of resolutions with ν energy





- Vertex and angular resolution better for low energy with reduced dark rate in mPMTs
- At high energy: muon/electron separation improved near the wall; vertex resolution improved
- Improvements strongest near edges of FV
- Introduce (theta,phi) dependent efficiency functions for individual PMTs in mPMT

<u>Mixed geometry next step</u>

If operate 100Hz: improved vertex resolution and lower down the Energy threshold from 5 to 3 MeV

→ Access to low energy neutrino physics!

mPMT Prototype

Main limits of KM3NeT solution for HK project:

- Vessel:
  Km3Net experience demonstrated that glass spheres are characterized by high ^{40}K and other radioactive contamination.

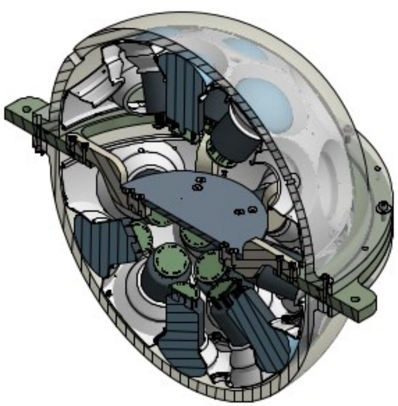
- PMT Read-Out:
  In KM3Net the time over threshold (ToT) strategy is exploited; this is not a good solution for Hyper-K project in which charge measurement is important

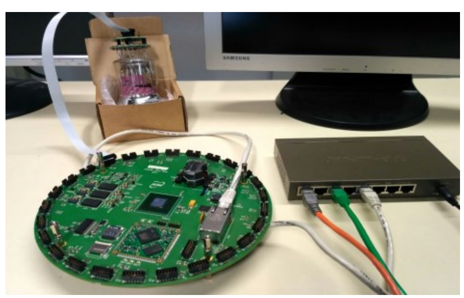
- Assembling procedure:
  mPMT production time

Prototype module design and testing

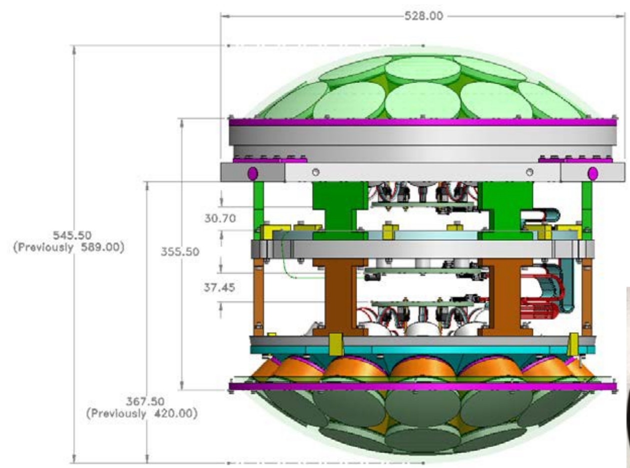
Two prototypes under construction

@INFN:
same design as Km3Net: vessel 17inch;
spherical shape;
goal:
test the acrylic vessel and new electronics





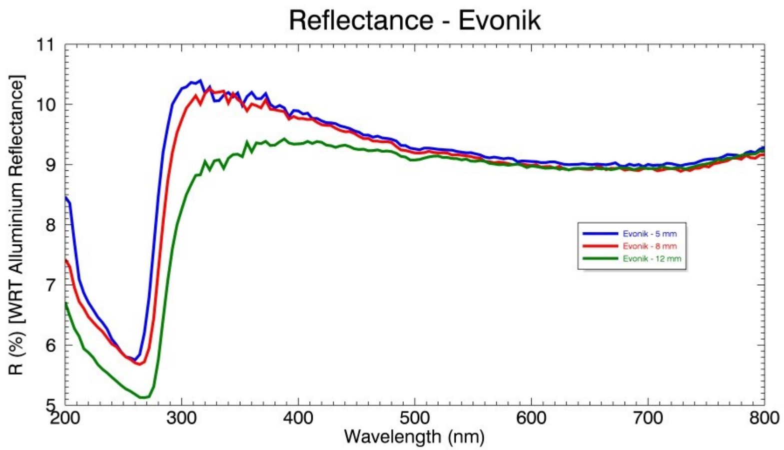
@TRIUMF:
new design and mechanics optimized for HK/E61
goal:
HK/E61 design: test mechanics and assembling procedure

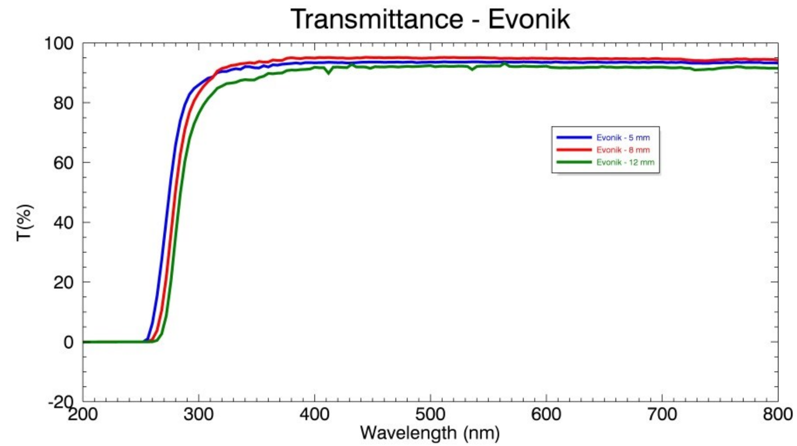


Canada, Italy, Poland, Japan groups collaborating on development of parts for the multi-PMT module

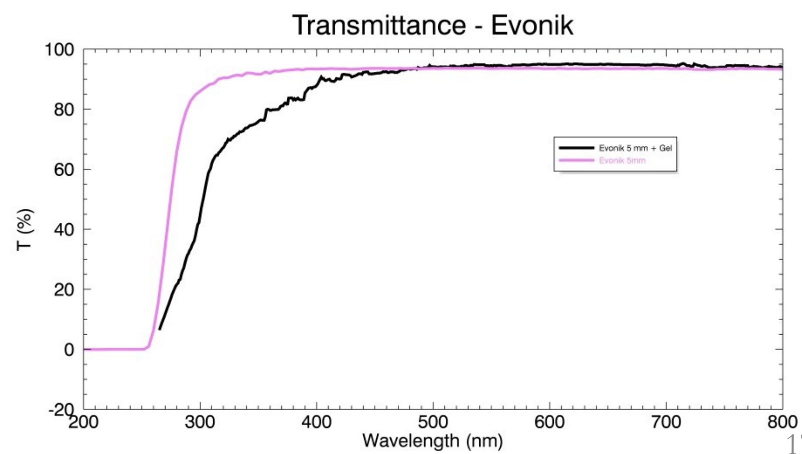
Acrylic vessel - Optical properties

Several acrylics tested: PLEXIGLAS® GS UV Transmitting by Evonik choosen for the construction of mPMT for Hyper-K and E61





Checked compatibility between optical gel and acrylic and measuread the transparency of acrylic+optical gel.



Acrylic vessel - Radioactivity

- **Radioactivity measurements** (at LNGS)
- Contamination results are here reported

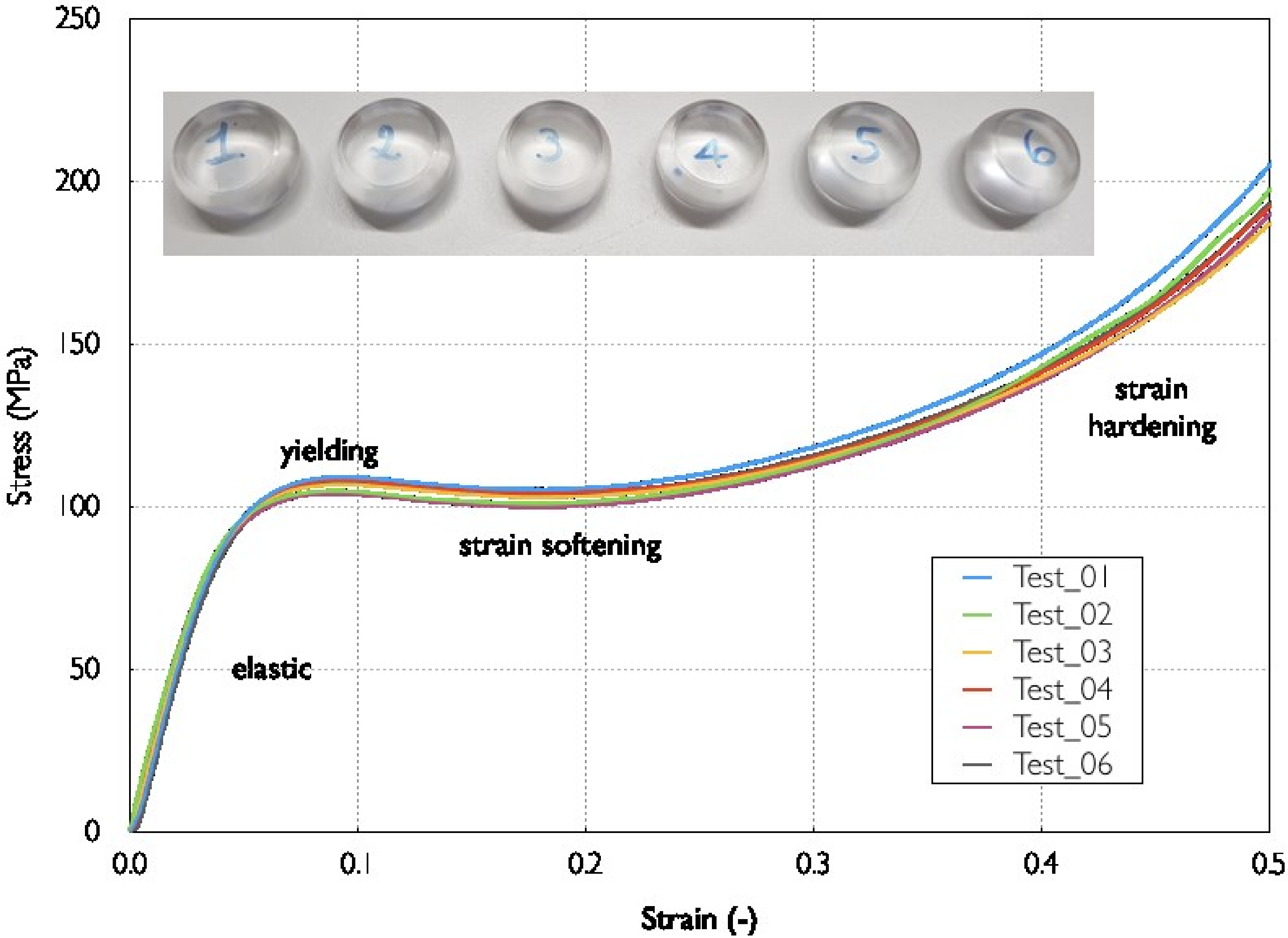
Isotope	Activity	Contamination
	^{232}Th: Thorium series	
Ra-228	< 0.11 mBq/kg	< 0.027 ppb
Th-228	< 93 μBq/kg	< 0.023 ppb
	^{238}U: Uranium series	
Ra-226	< 65 μBq/kg	< 0.0052 ppb
Th-234	< 4.6 mBq/kg	< 0.38 ppb
Pa-234m	< 2.5 mBq/kg	< 0.20 ppb
U-235	(0.15 ± 0.07) mBq/kg	$(3 \pm 1) \cdot 10^{-1}$ ppb
K-40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

Evonik acrylic.
Weight: 13.4567 kg:
Live time: 22 days

Requirements:
U-238 < 0.3 ppb
Th-232 < 1 ppb
K-40 < 0.3 ppm

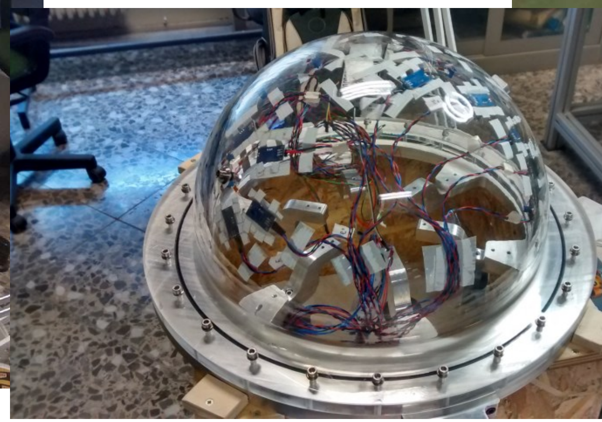
The Evonik acrylic is very clean, no radioactivity contamination

Acrylic vessel - Mechanical tests



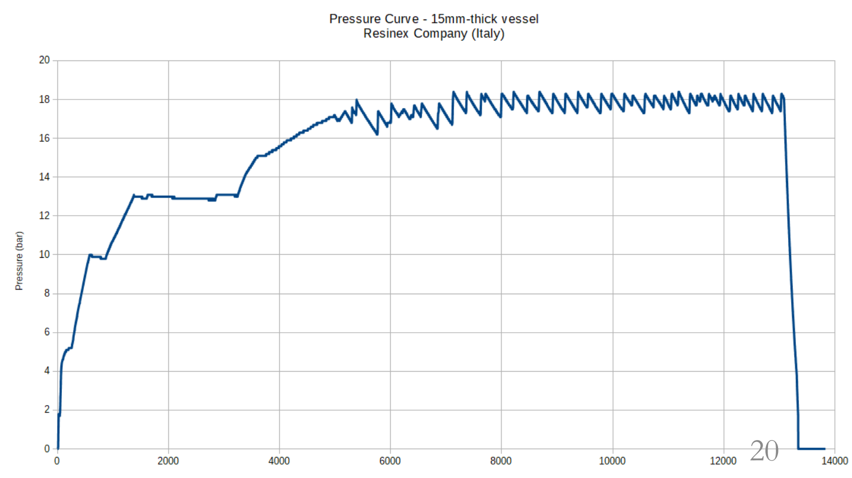
Acrylic vessel - Hydrostatic Pressure test

15mm and 20mm-thick vessels tested
Arduino pressure sensors for minitoring



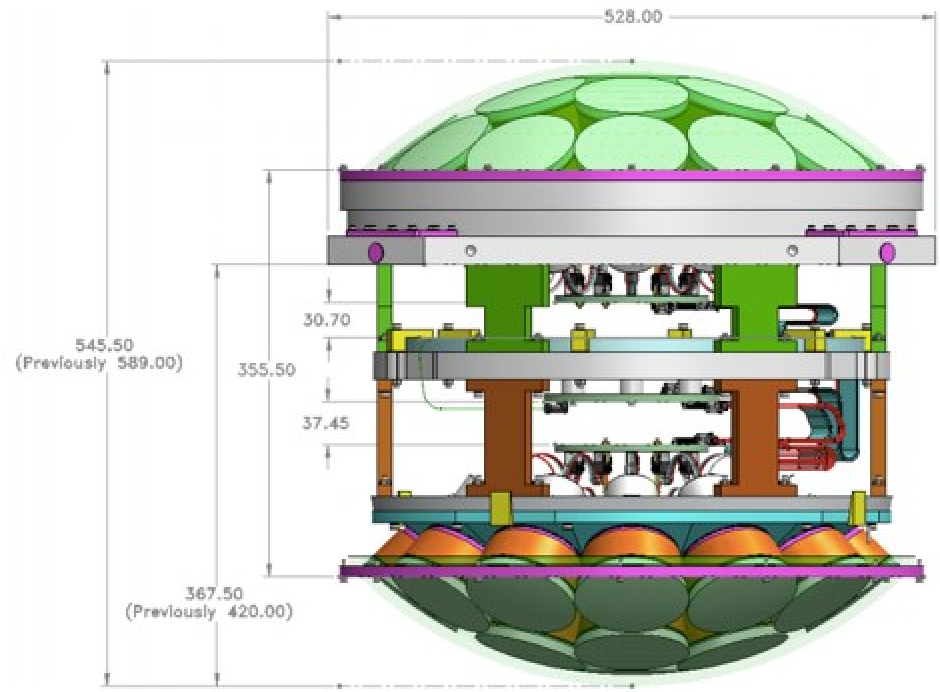
Constrain: resist up to 1.26 MPa
Pressure test results: vessel resisted to 18 bar.
No damage at the 15mm-thick vessel!
The 20mm-thick vessel was inserted into a 400-bar tank for a crash test
Implosion at 86 bar

Acrylic: PLEXIGLAS® GS, UV transmitting by Evonik



2-Sided mPMT Design

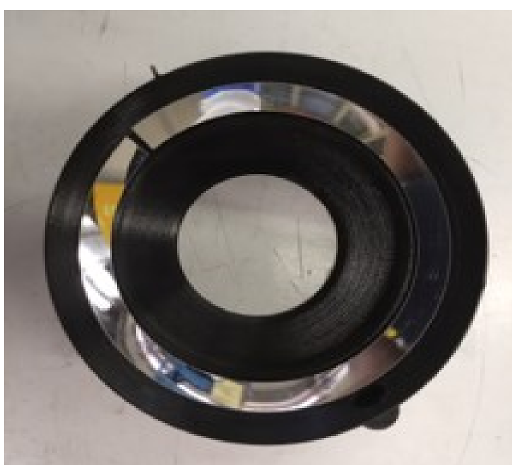
- Modular design
- Outer structure
- Inner support frame / heat transfer
- Optional scintillator disc
- 3" PMT sub-assemblies + support
- Acrylic dome
- Motherboard + daughter boards



Single PMT assembly

Single PMT assembly is challenging part of mPMT production

- Solder base onto PMT and apply conformal coating
- Assemble PMT holder and reflector
- Install PMT in holder
- Optical gel is poured and set before installation of PMT in mPMT
- PMT holder and aluminum plate form mold



Single PMT assembly

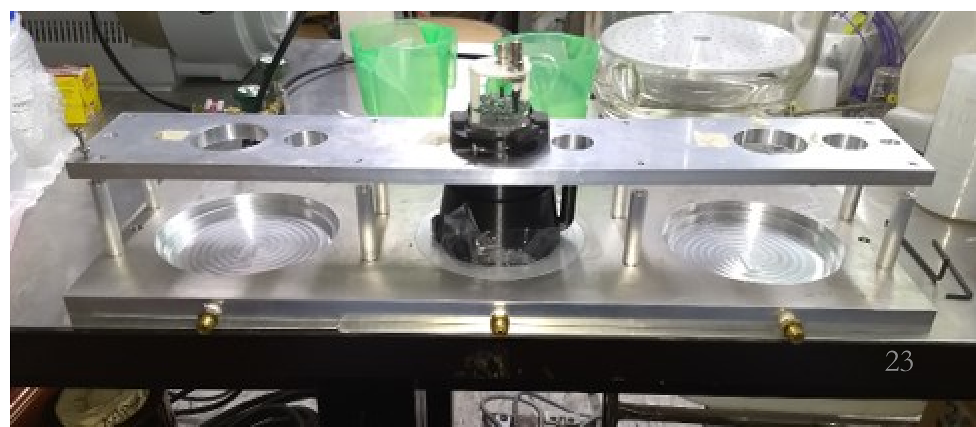
Printed with removable lip and spout

PMT and holder are placed up-side-down on porous aluminum piece

Radius of curvature matches acrylic

Gel is poured into spout through funnel

parallel production:
~25 PMTs at one time



mPMT Electronics Performance Requirements

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:

– For Hyper-K <3-4W per mPMT

Driven by water circulation requirements

– For E61 ~5-10W per mPMT

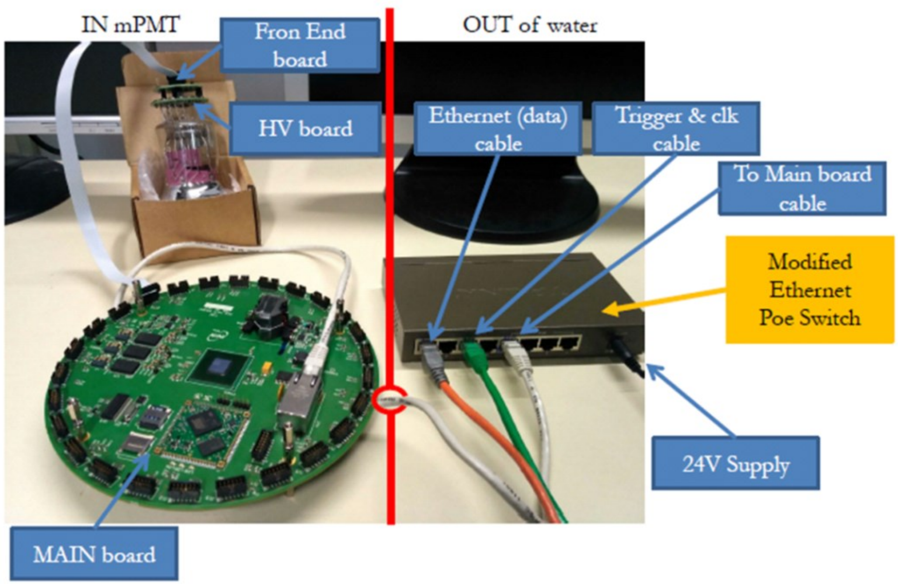
• Not as strongly constrained as Hyper-K

Moderately low cost: ideally ~$50 per channel for digitization part.

Electronics Design for mPMTs

Currently working on two different designs for the mPMT digitization

Design A:
Q/T digitization based on discrete components (INFN Naples)
Simple, low power, low cost



Design B:
FADC digitization, with on-board signal processing (TRIUMF, WUT)
Fully active during spill.
Noise suppression in FPGA.
Can export raw ADC information.
Trade off between bandwidth and power consumption

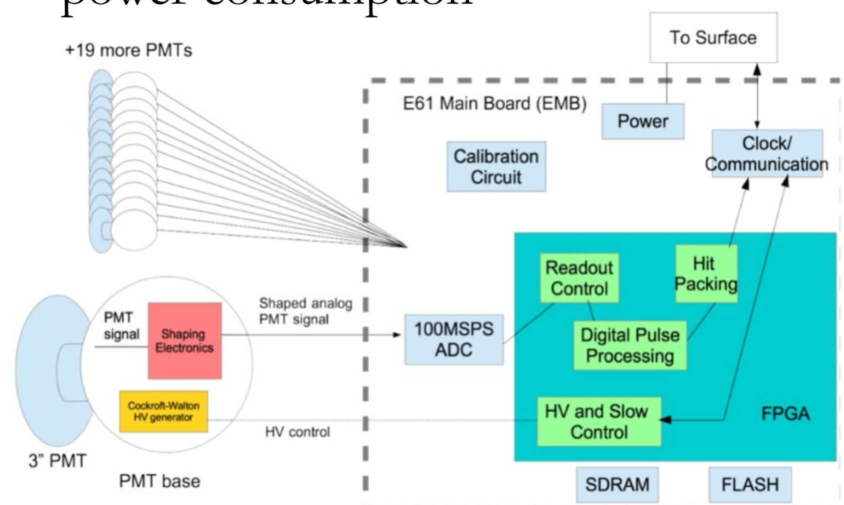
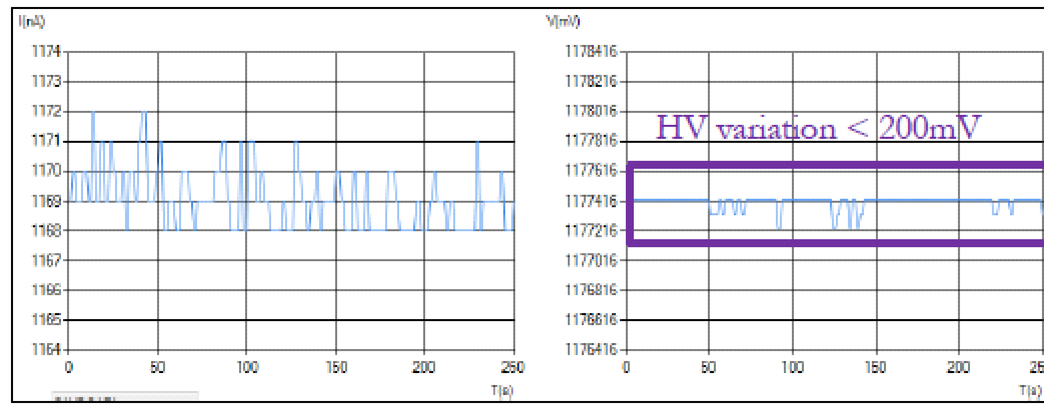


Figure 2: conceptual block diagram for the mPMT E61 Main Board (EMB).

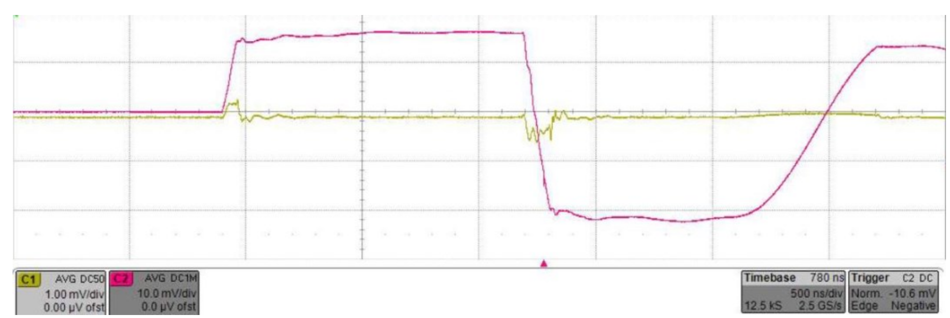
mPMT prototype: HV

Cockcroft-Walton (CW) voltage multiplier, as in KM3Net



Voltage&current monitoring: stable HV

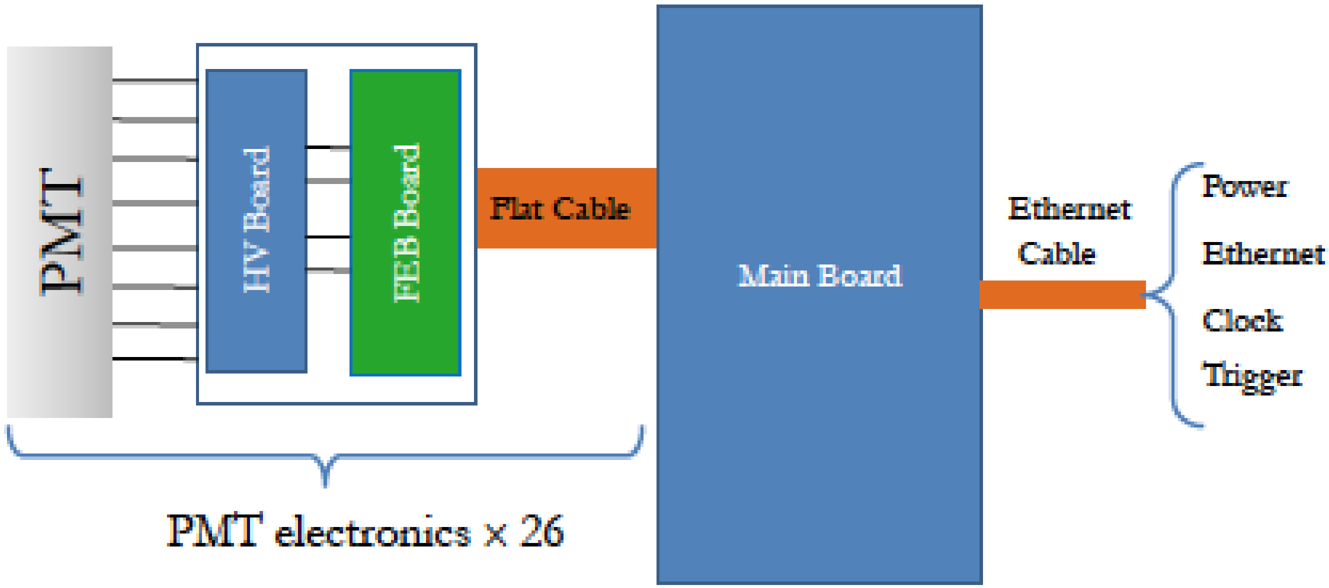
Power consumption:
-12.5 mW/ch
- ID: 19 ch → 237.5 mW



Switching noise 500µV(~1pC)

Design A: mPMT digitization

Sample&Hold
+
ADC
based on discrete components



Single channel electronic

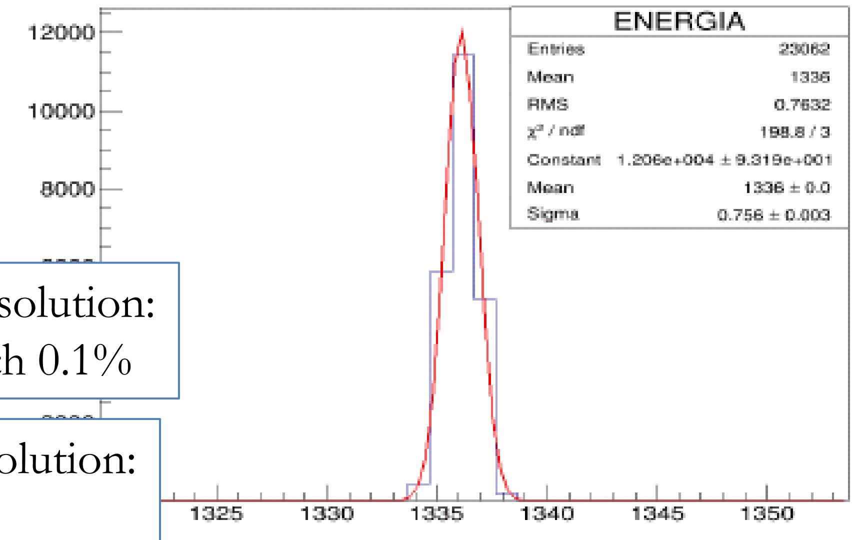
- System integrated with the HV board
- Same MCU for both boards and only one connection

Main board

Single Board Computer-Linux:
Slow control (HV and Threshold set, I/V)
Data acquisition and transmission
Power consumption and temperature
FPGA:
TDC/ADC control
Time stamp

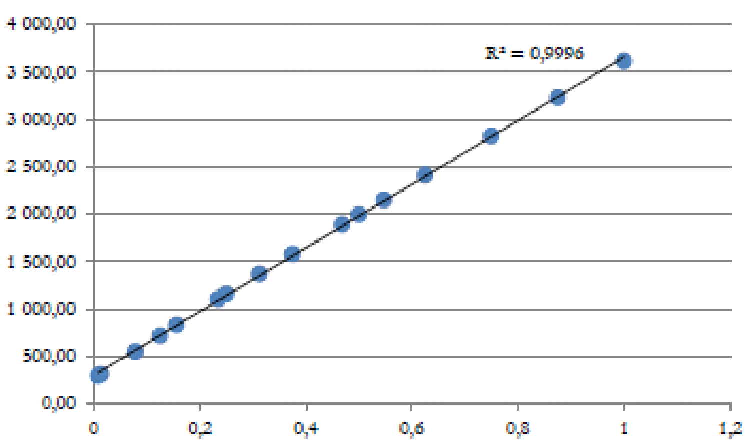
Design A: FEB

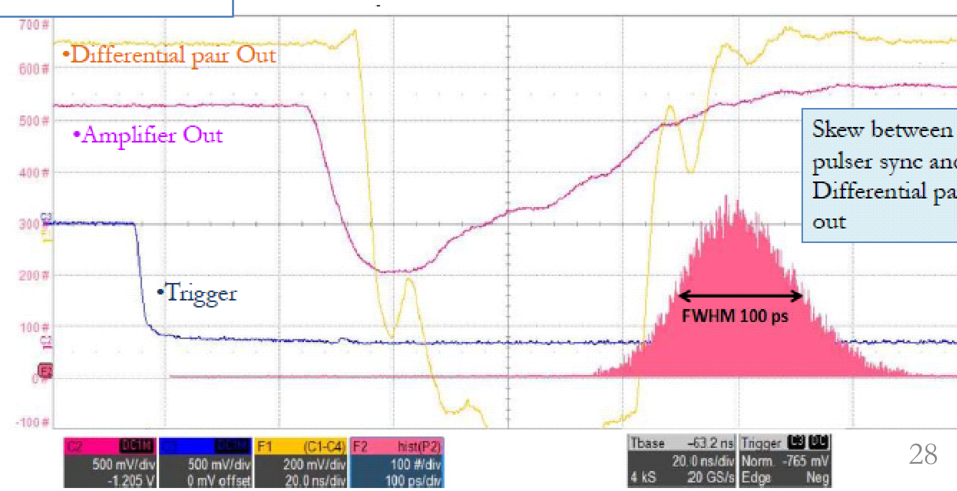
Pow DAQ circuit observed ~ 40.5 mW



Energy resolution: FWHM/ch 0.1%

Time resolution: 100ps

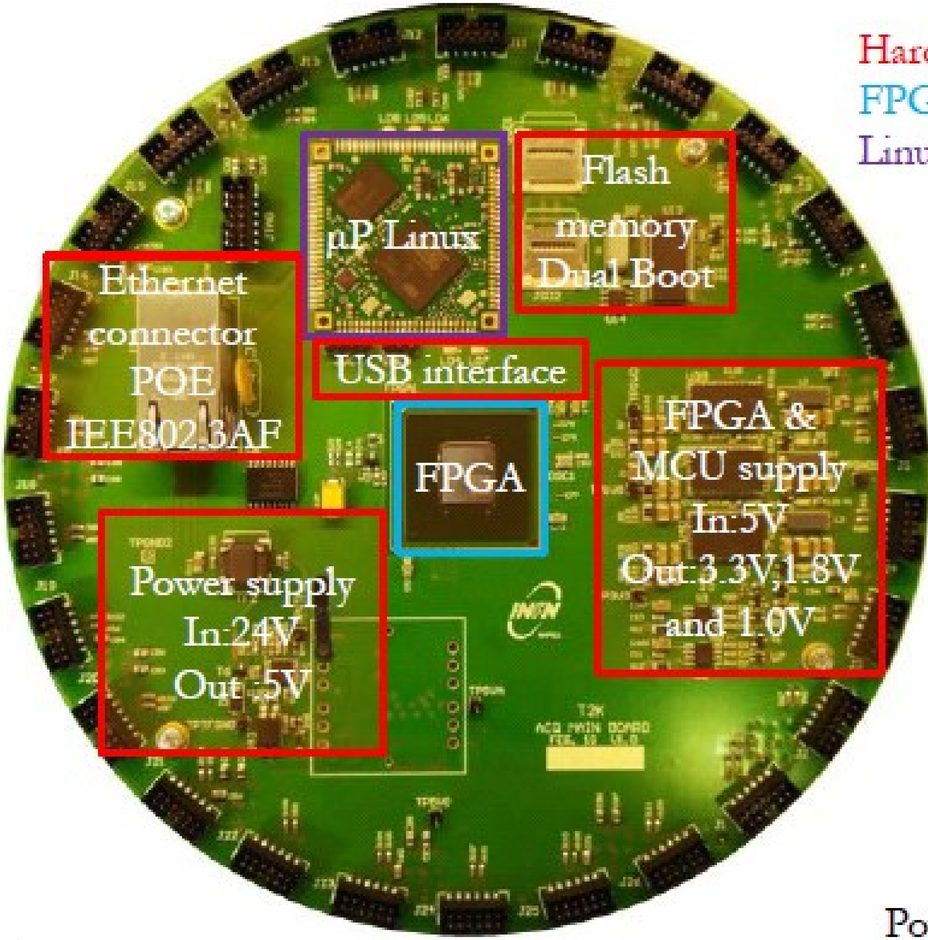




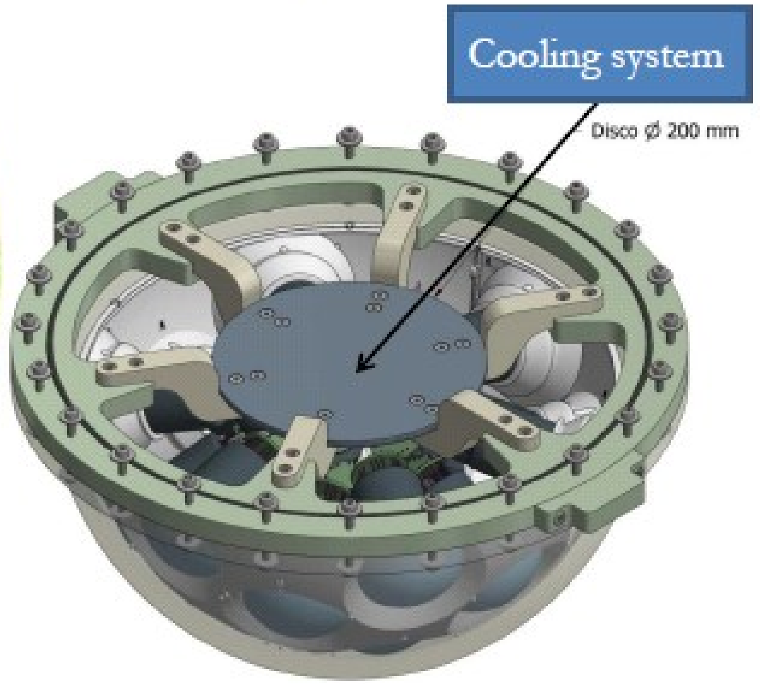
Skew between pulser sync and Differential pair out

Design A: main board

Block Diagram



Hardwere & CPU linux: Fully debugged
FPGA Firmware: To debug
Linux software: To improve



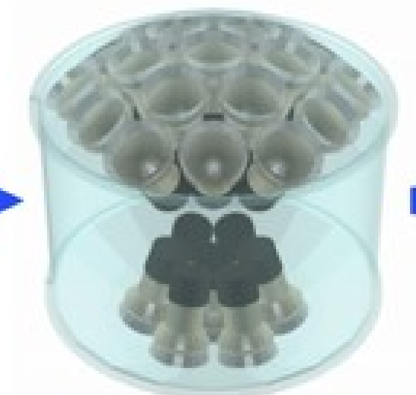
Power (1 Channel + Main board) 3.2 W

Total Power consumption:
- ID: 19 ch → ~ 4.1 W

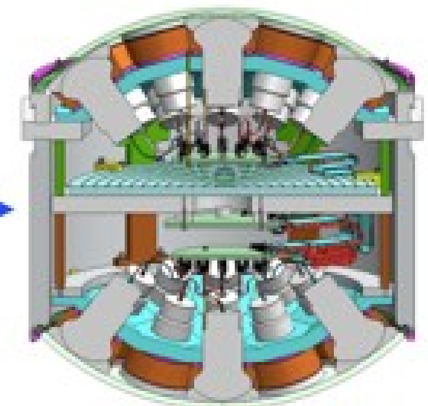
Evolution in Hyper-K and E61 design

KM3Net (31 PMTs)

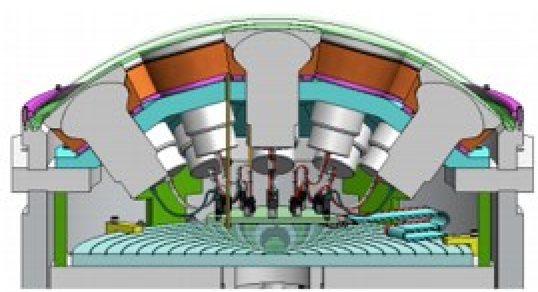
Spherical → Cylindical
19(ID)+7(OD)



Initial TRIUMF design
(26 PMTs)



ID-mPMT (19 PMTs)



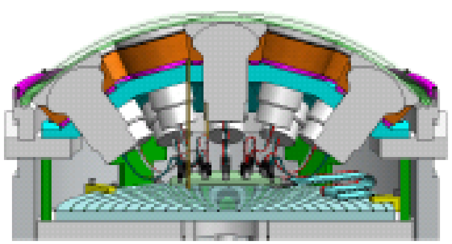
Single-sided mPMT module:

- Lighter, less dead space, simple feedthrough at back of module
- mPMT full module weight ~ 80 kg → Single-sided mPMT module weight as 20″ PMT
- only one OD photosensors system for the whole Hyper-K

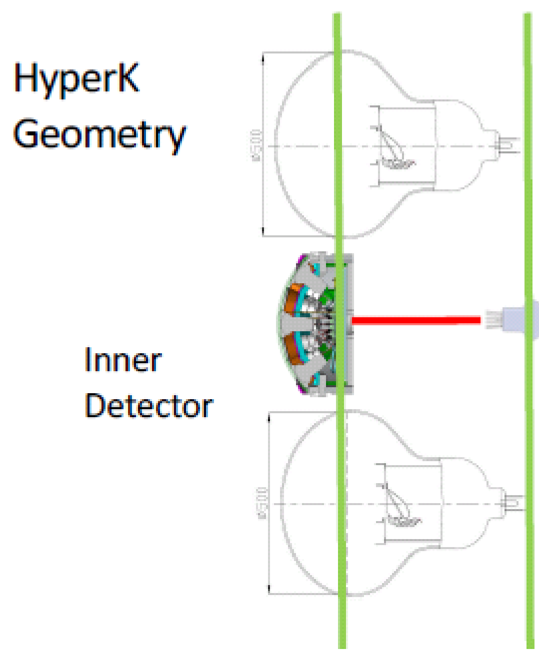
Baseline option: ID-mPMT

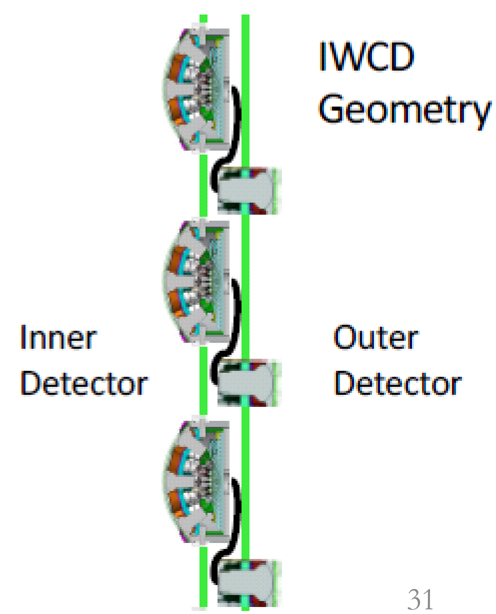
Single-sided mPMT module:

- 19 3 inch PMTs system observing the inner detector
- Lighter, less dead space
- only one OD photosensors system for the whole Hyper-K



Weight: ~44kg
Volume: ~46L
Length: ~300mm





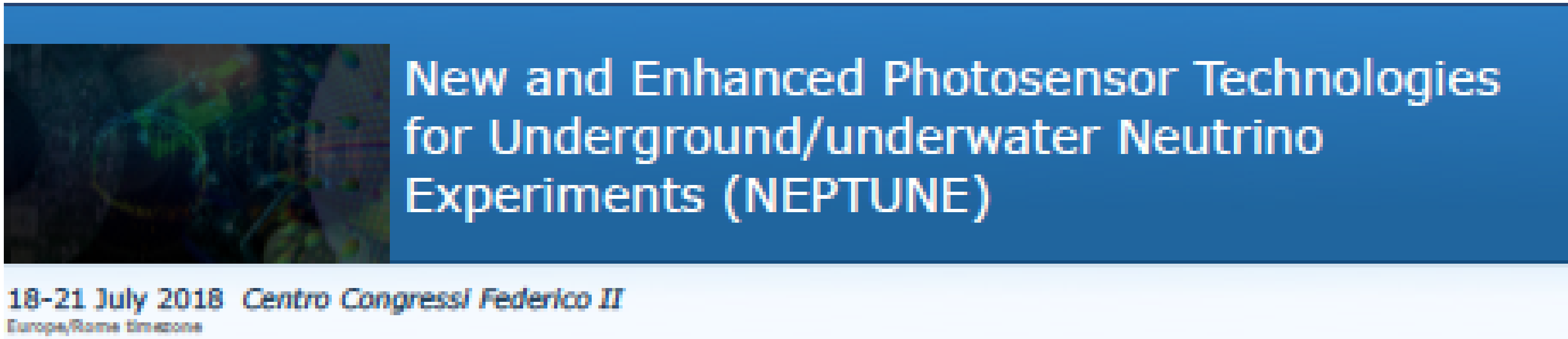
Conclusions

mPMTs offer several benefits compared to large area PMTs

- Modular construction
- Directionality
- Improved granularity
- Improved timing resolution, lower dark noise, less magnetic field sensitivity, pressure tolerance

Reconstruction studies show improvement with respect to large area PMTs for the E61 and Hyper-K detectors

- Optimisation of the design for physics underway
- Studying impact of 5000 mPMTs on Hyper-K physics



NEPTUNE workshop aims to review the state of the art and future developments in the field of photosensors, with particular attention to the high pixelation photosensor approach using small PMTs, and their applications

The workshop will be repeated annually to create a profitable synergy between the collaborations currently engaged in R & D activities for the development of systems of small photosensors

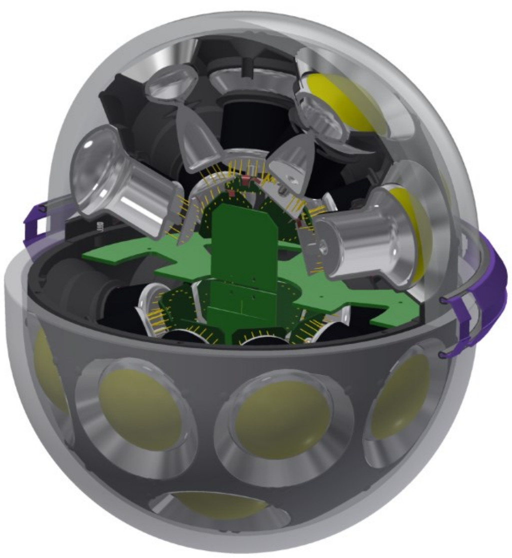
NEXT CHAPTER of this workshop in either Paris or China

Thank you!

Multi-PMT in IceCube

Multi-PMT optical module (mDOM)

- 24× 3” PMTs
- 14” borosilicate glass vessel rated @ 700 bar



Multi-PMT in IceCube

Upgrade sensor designs