A multi-PMT photodetector system for the Hyper-Kamiokande experiment

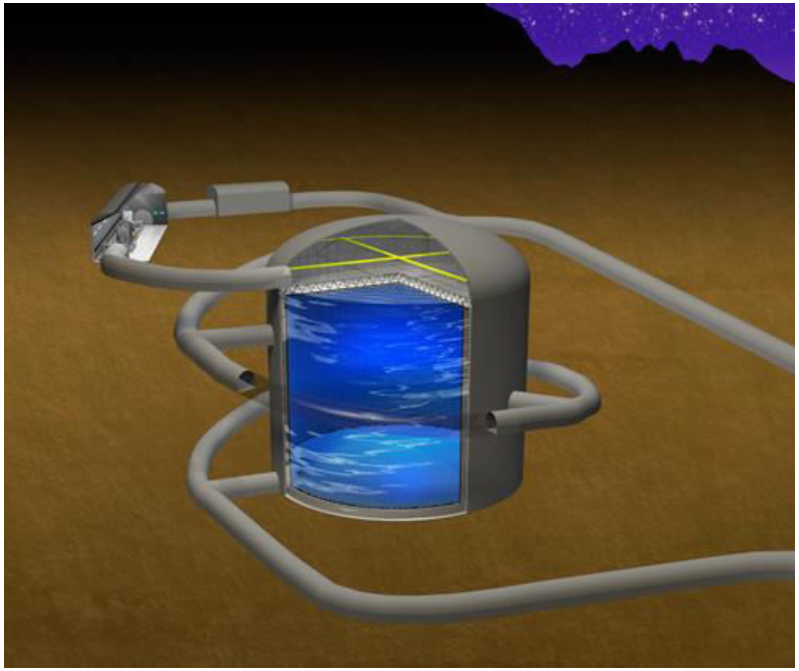
Gianfranca De Rosa

on behalf of the

Hyper-Kamiokande Proto-Collaboration

15th Vienna Conference on Instrumentation

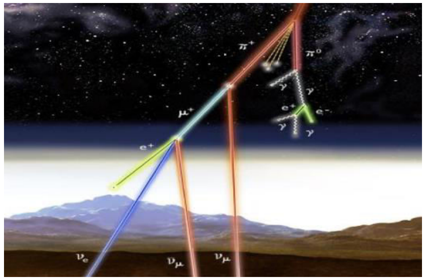
Hyper-Kamiokande: overview

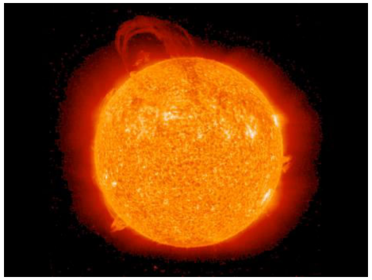


Hyper-Kamiokande (HK) is a multi-purpose **Water-Cherenkov detector** with a variety of scientific goals:

- ✧ Neutrino oscillations (atmospheric, accelerator and solar);
- ✧ Neutrino astrophysics;
- ✧ Proton decay;
- ✧ Non-standard physics.

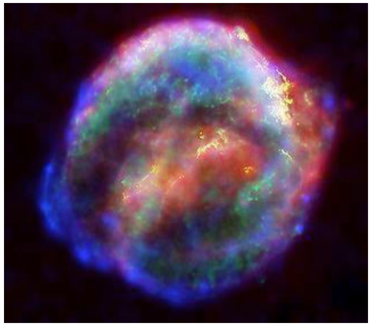
Atmospheric ν





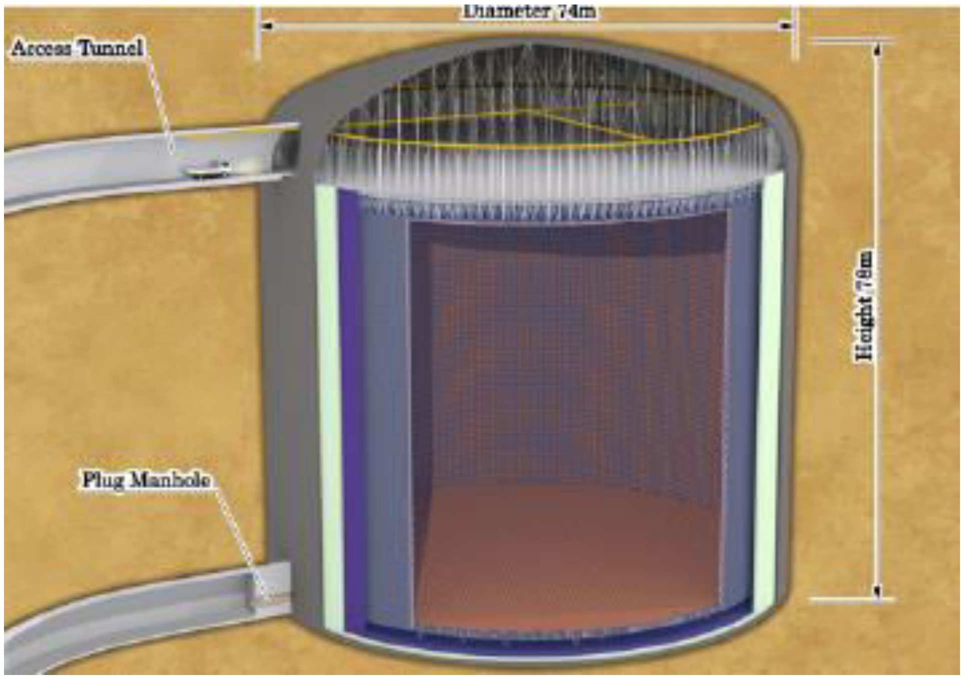
Solar ν

Supernova ν



Accelerator ν

Hyper-Kamiokande design



2 tanks with the staging construction.

- Cylindrical tank: Φ 74 m and H 60 m
- Total and fiducial volumes (for one tank): 0.26 and 0.19Mtons, resp.; ~10xSuper-K
- Photo-cathode coverage: 40%. 40,000 ID PMTs and 6700 OD PMTs per tank.

1 kilo-ton scale water Cherenkov detector located ~1 km from the neutrino source (IWCD)

HK builds on the successful strategies used to study neutrino oscillations in Super-Kamiokande, K2K and T2K with:

- Larger detector for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part

Planned time line:
Begin construction April 2020
Experiment 2026 (1st tank)
Proposals for a second tank:
- 6 years later in Japan
- as soon as possible in Korea

Photodetectors for Hyper-K

Requirements

Wide dynamic range
High time&charge resolutions, high detection efficiency, ..

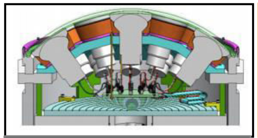
- ~nsec time resolution
- low background
- Clear photon counting,
- High rate tolerance

New high-QE 50 cm Box&Line PMT

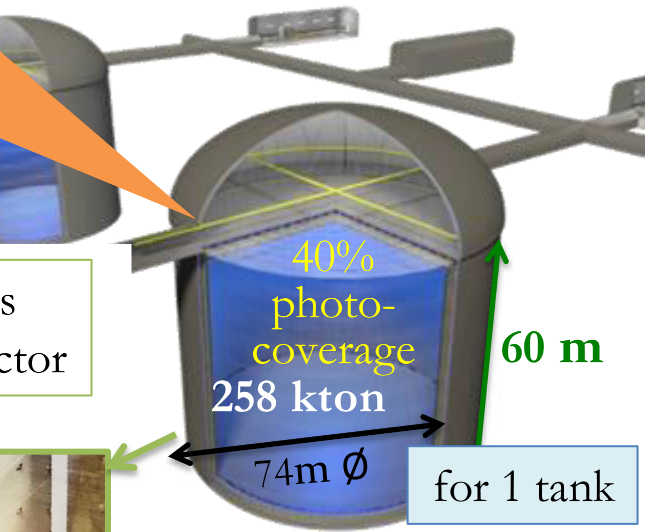
×2 high pressure bearing
for 60 m depth

×2 high detection efficiency
and half time&charge resolutions
compared to Super-K PMT
(up to ~40m depth)

see Poster ID 748 by Y. Nishimura



multi-PMT



for 1 tank

About 7,000 PMTs
for Outer Veto Detector

187 kton Fiducial Mass

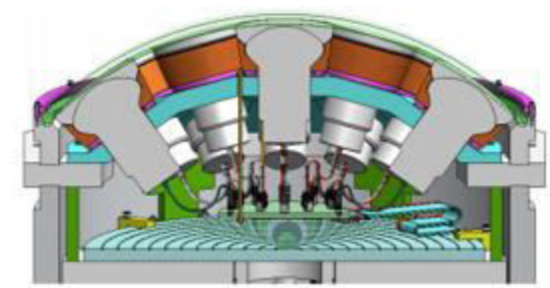
Baseline option
40,000 20” PMTs
Alternative option:
50% 20” PMTs and mPMTs

Multi-PMT Option for Hyper-K

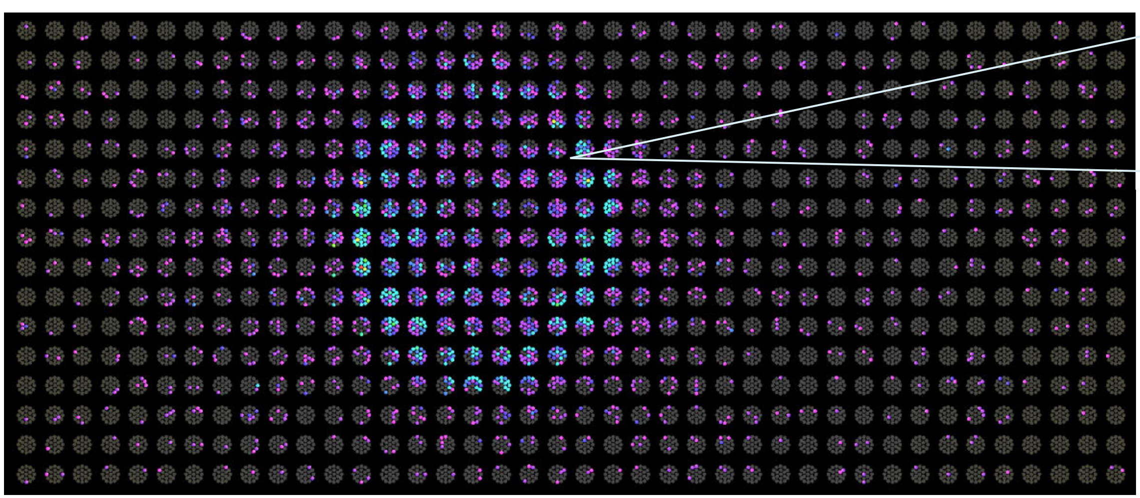
Based on KM3NeT Digital Optical Module

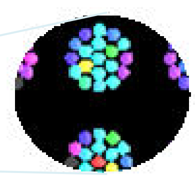
Photodetectors and electronics arranged inside a pressure resistent vessel

- **Superior photon counting**
- **Improved angular acceptance**
- **Extension of dynamic range**
- **Intrinsic directional sensitivity**
- **Local coincidences**
- **Reduced risk**



ID-mPMT (19 PMTs)

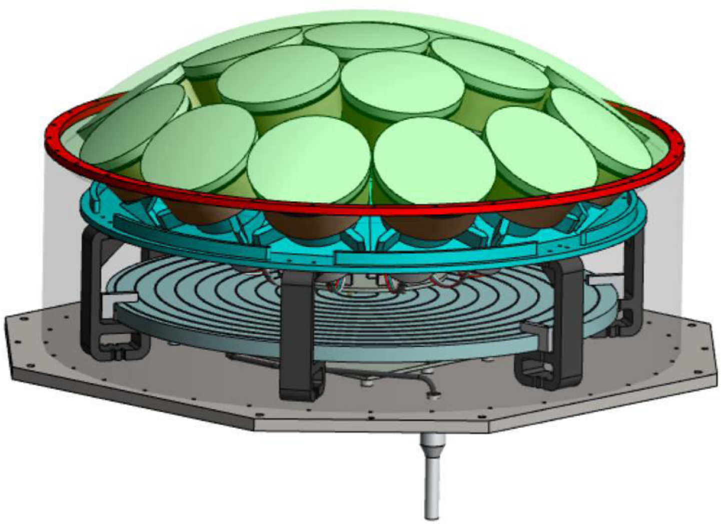


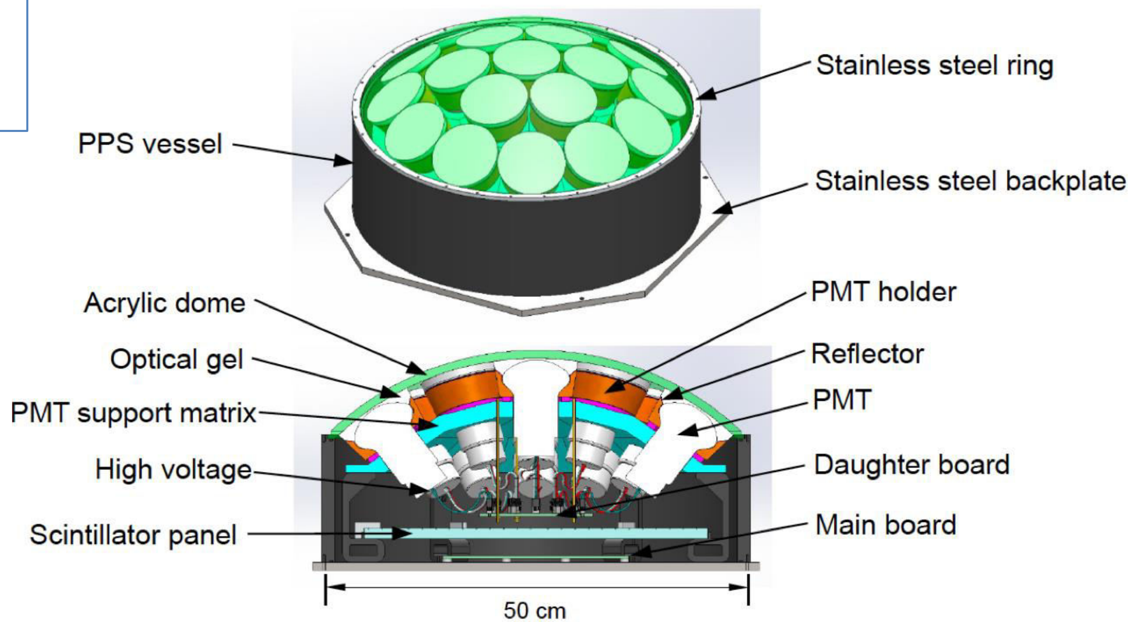


Increased granularity enhanced event reconstruction, in particular for multi-ring events

multi-PMTin Hyper-K

The HK-IWCD baseline design is equipped with multi-PMT modules (mPMT) as photodetction system





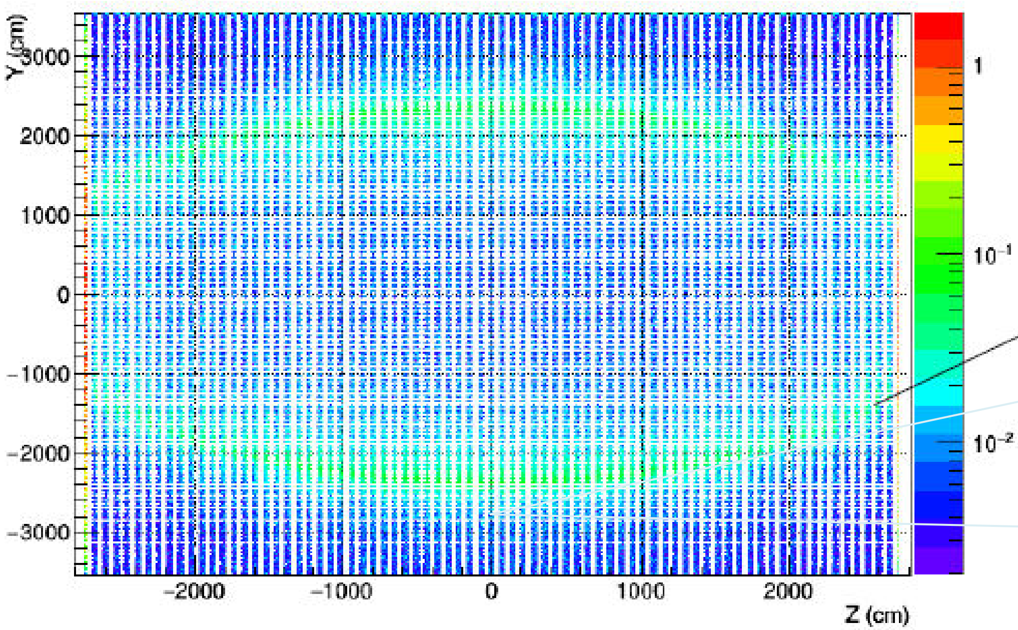
Hybrid configuration considered for Hyper-K: 20" + mPMT

Large PMT vs mPMT

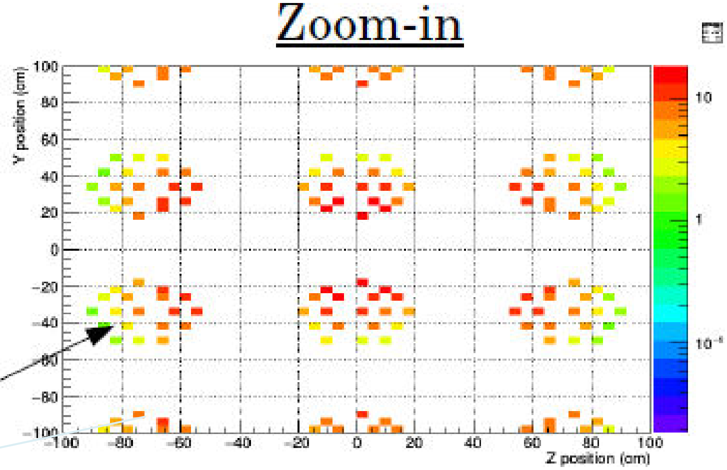
Capabilities of standalone mPMTs:

→ 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

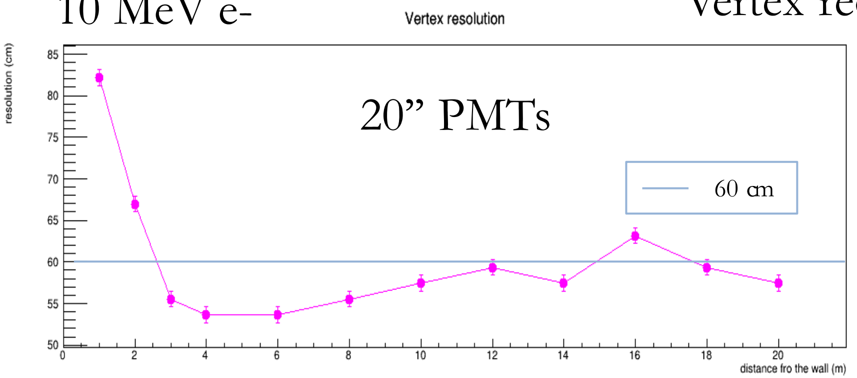
Complete simulation and reconstruction chain has been developed and validated

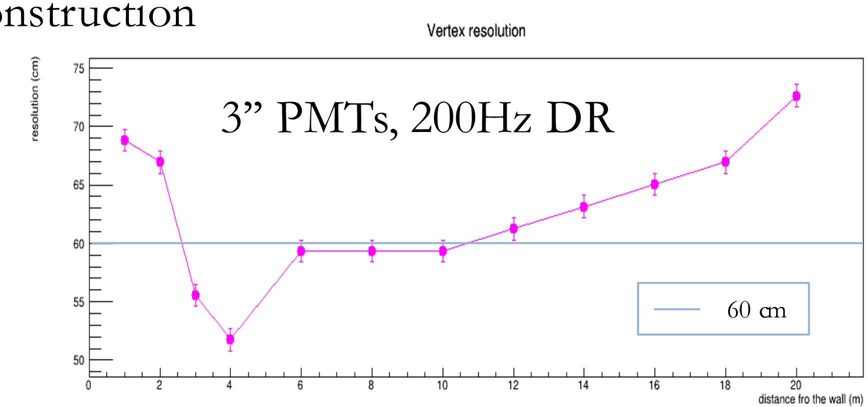
Performance Studies for mPMTs in Hyper-K

Variation of resolutions with distance to the wall: assuming 40 % coverage

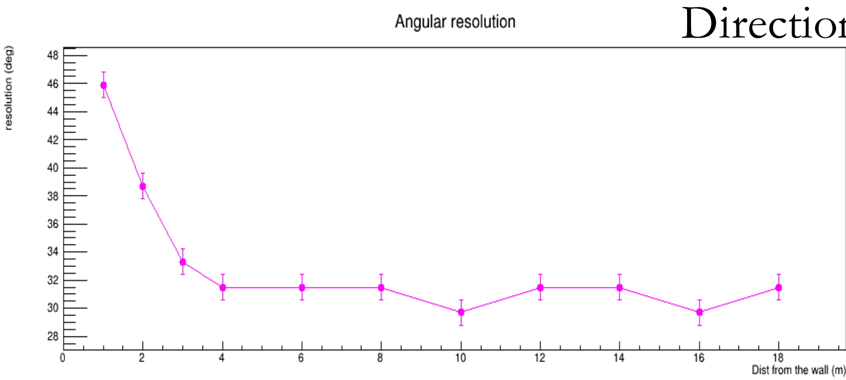
10 MeV e-

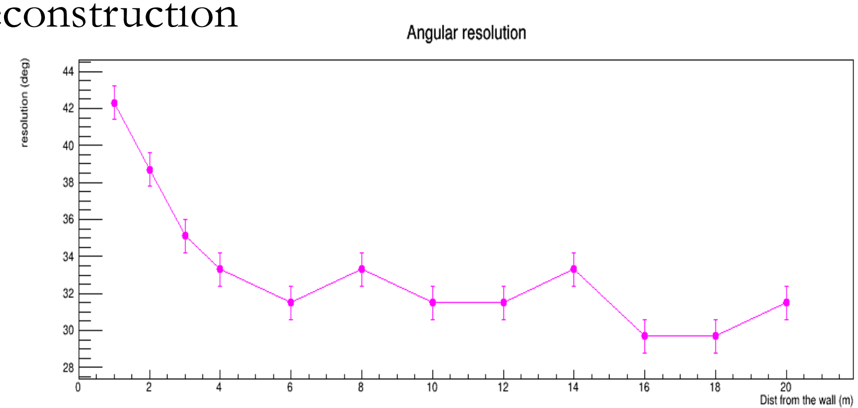
Vertex reconstruction





Direction reconstruction



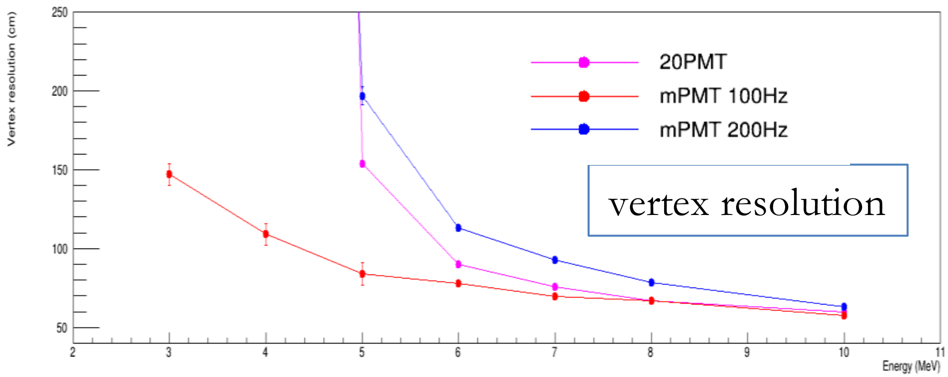


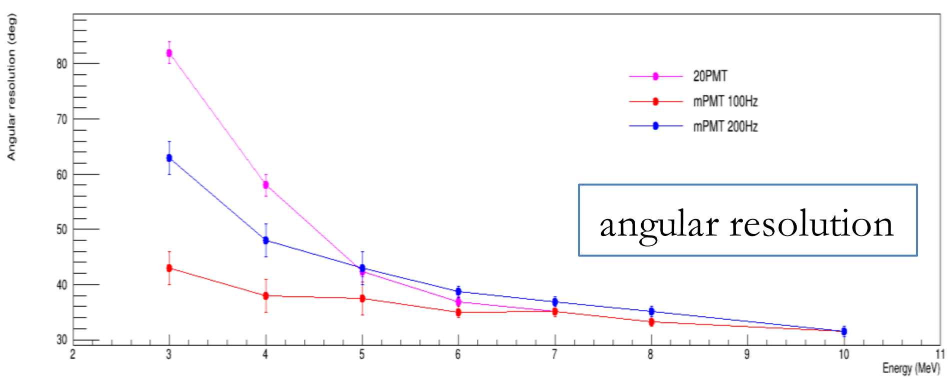
Vertex resolution improved w/ mPMT near edges of FV

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

Performance Studies for mPMTs in Hyper-K

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

Improved vertex resolution and lower Energy threshold from 5 to 3 MeV @ DR~ 100Hz
→ low energy neutrino physics!
To investigate radioactive backgrounds

Detailed investigations of possible 3" candidate PMTs
• In particular, focus on better timing resolution and reduced dark noise

mPMT Prototypes for Hyper-K

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.

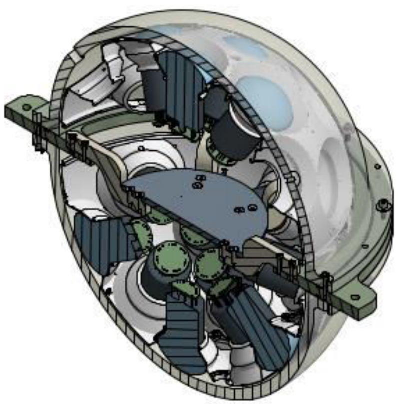
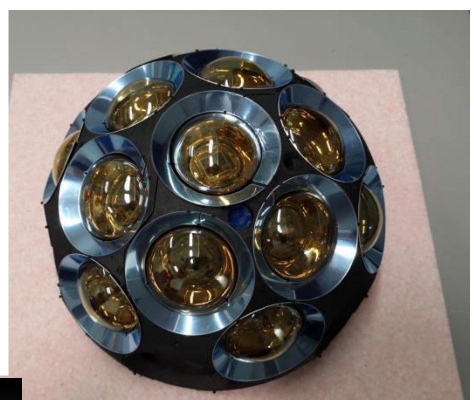
- PMT Read-Out:
  In KM3Net the time over threshold (ToT) strategy is exploited; this is not a good solution for Hyper-K project in which charge measurement is important

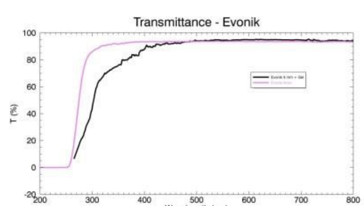
- Assembling procedure:
  mPMT production time

Prototypes and testing

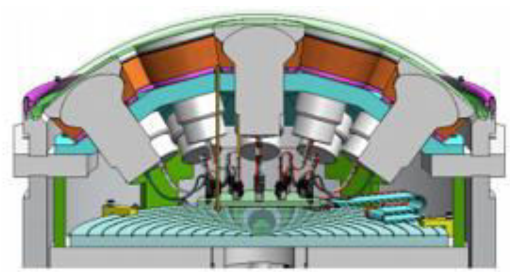
Two prototypes realized and currently under test

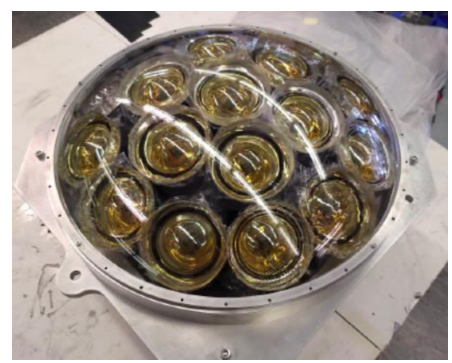
@INFN:
same design as KM3Net: vessel 17inch;
spherical shape;
goal:
test the acrylic vessel and new electronics



@TRIUMF:
new design and mechanics optimized for Hyper-Kamiokande
goal:
test mechanics and assembling procedure

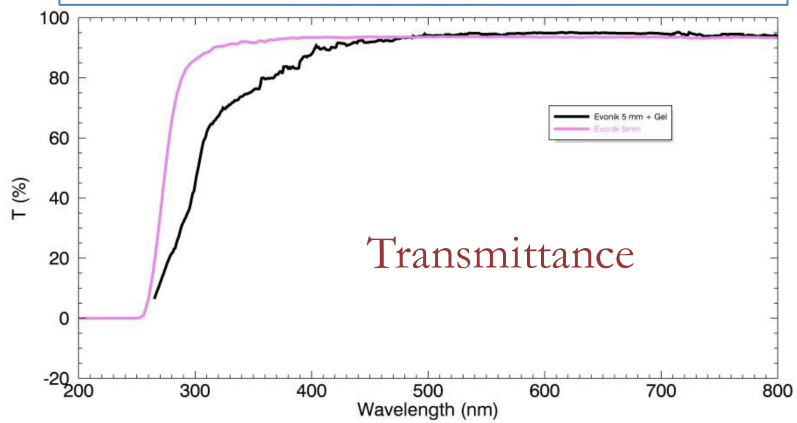





Acrylic vessel

- Optical test @ Napoli
- Radioactivity measurements@ Gran Sasso INFN labs
- Mechanical test @ Bari
- Absorption test @ Circe Lab Caserta

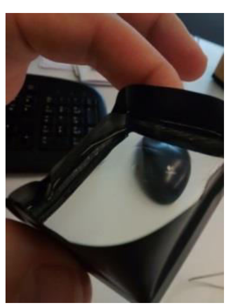
PLEXIGLAS® GS, UVT by Evonik

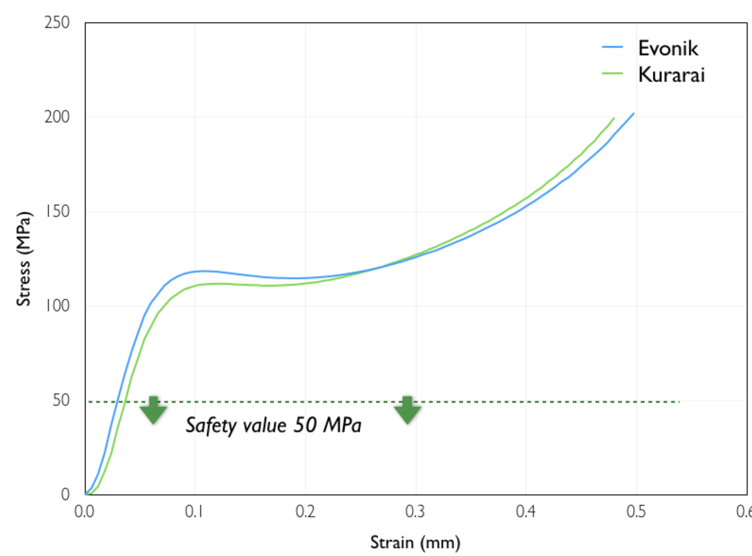


Isotope	Activity	Contamination
	^{232}Th: Thorium series	
Ra-228	< 0.11 mBq/kg	< 0.027 ppb
Th-228	< 93 μBq/kg	< 0.023 ppb
	^{238}U: Uranium series	
Ra-226	< 65 μBq/kg	< 0.0052 ppb
Th-234	< 4.6 mBq/kg	< 0.38 ppb
Pa-234m	< 2.5 mBq/kg	< 0.20 ppb
U-235	(0.15 ± 0.07) mBq/kg	$(3 \pm 1) \cdot 10^{-1}$ ppb
K-40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

Table 5: Results of nuclear contamination of Evonik samples.

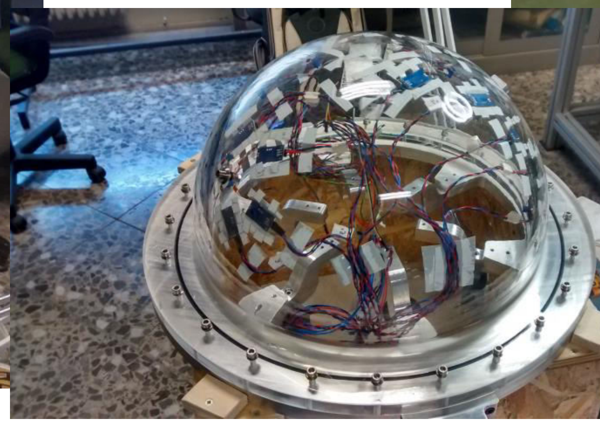
Checked compatibility between optical gel and acrylic and measuread the transparency of acrylic+optical gel:





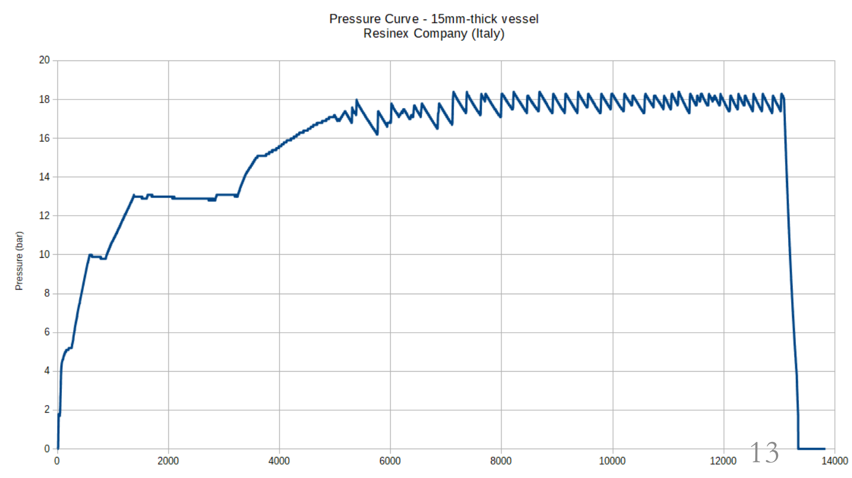
Acrylic vessel - Hydrostatic Pressure test

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



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

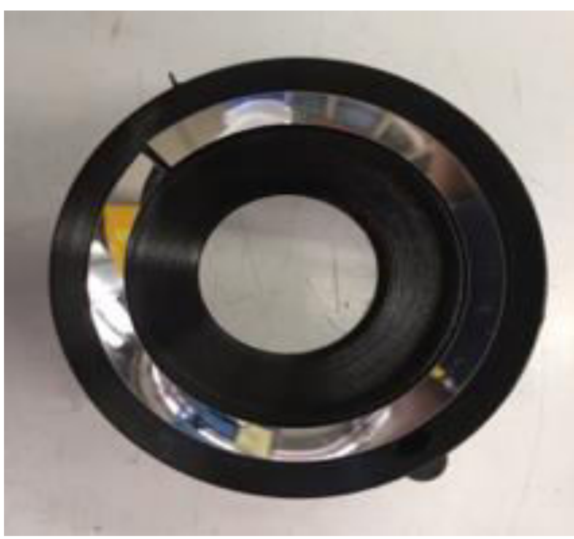
Acrylic: PLEXIGLAS® GS, UV transmitting by Evonik



Single PMT assembly

3" PMT sub-assembly with reflector ring and gel cap:

- Solder base onto PMT and apply conformal coating
- Assemble 3D printed plastic holder and reflector
- Install PMT in holder
- Pour gel through spout



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 HK-IWCD ~5-10W per mPMT

• Not as strongly constrained as Hyper-K

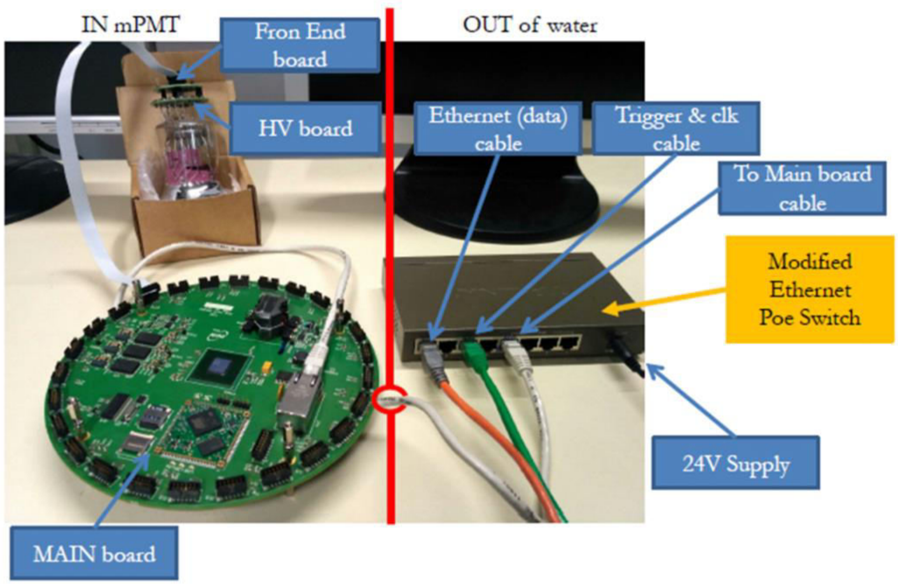
Electronics Design for mPMTs

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

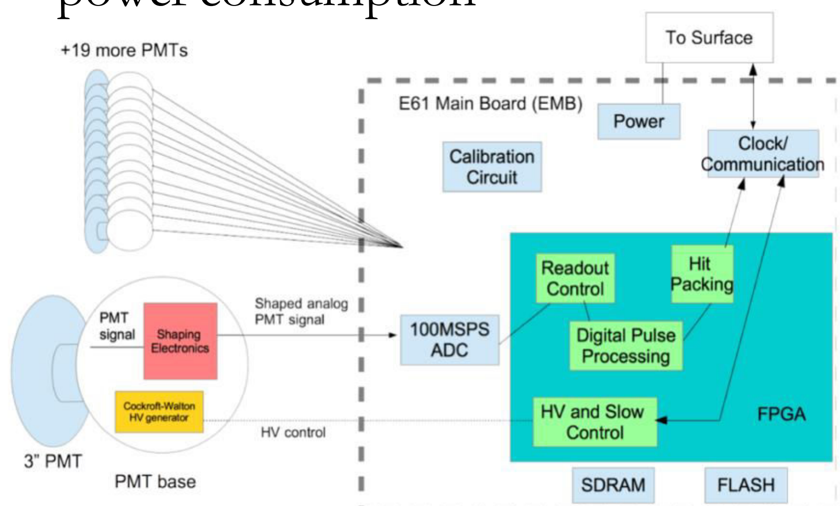
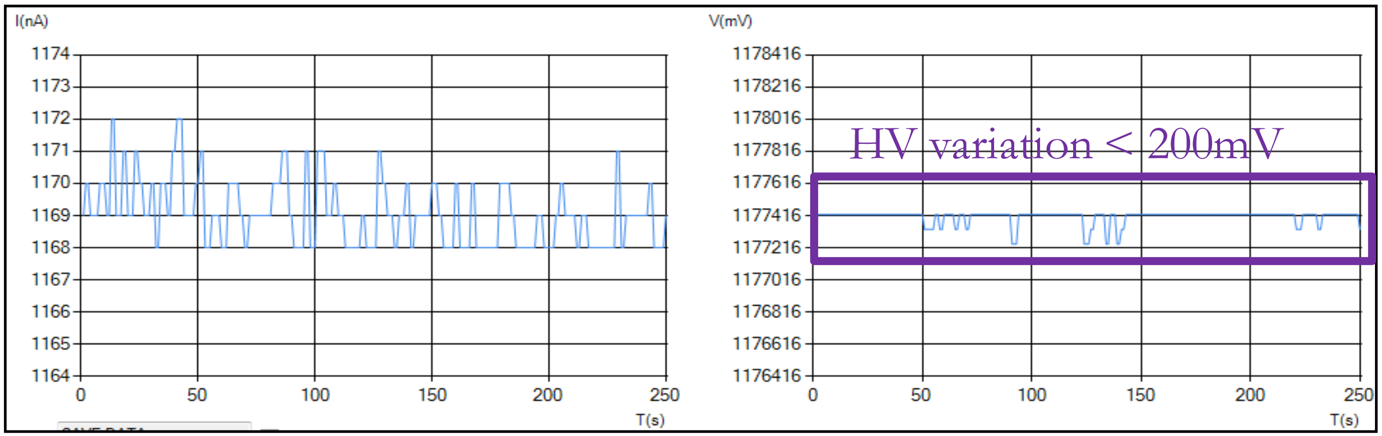
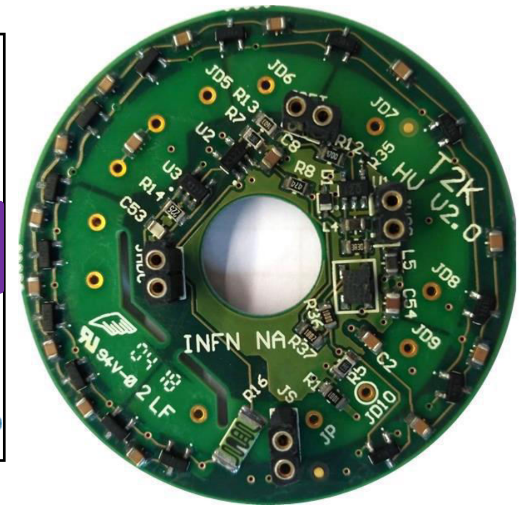


Figure 2: conceptual block diagram for the mPMT E61 Main Board (EMB).

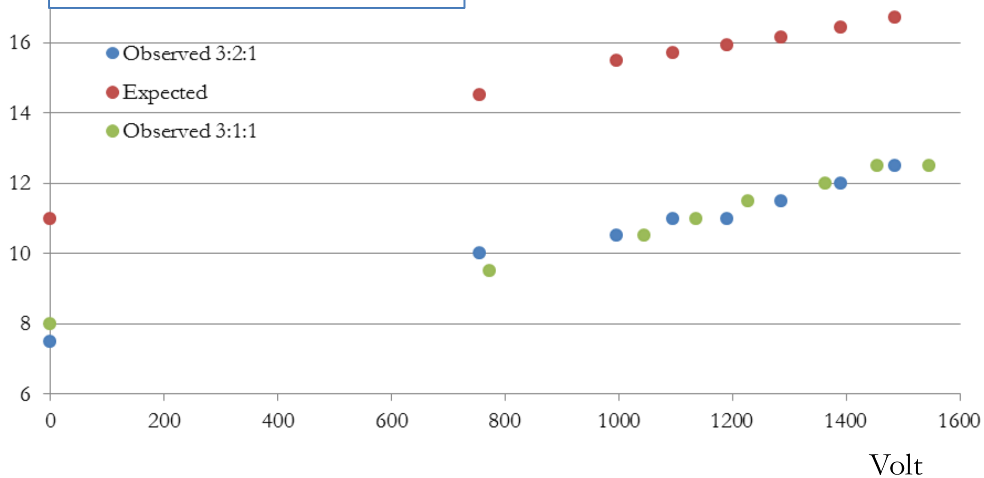
INFN mPMT electronics: HV

Basic Cockcroft-Walton (CW) voltage multiplier circuit designed for –HV up to 1500V





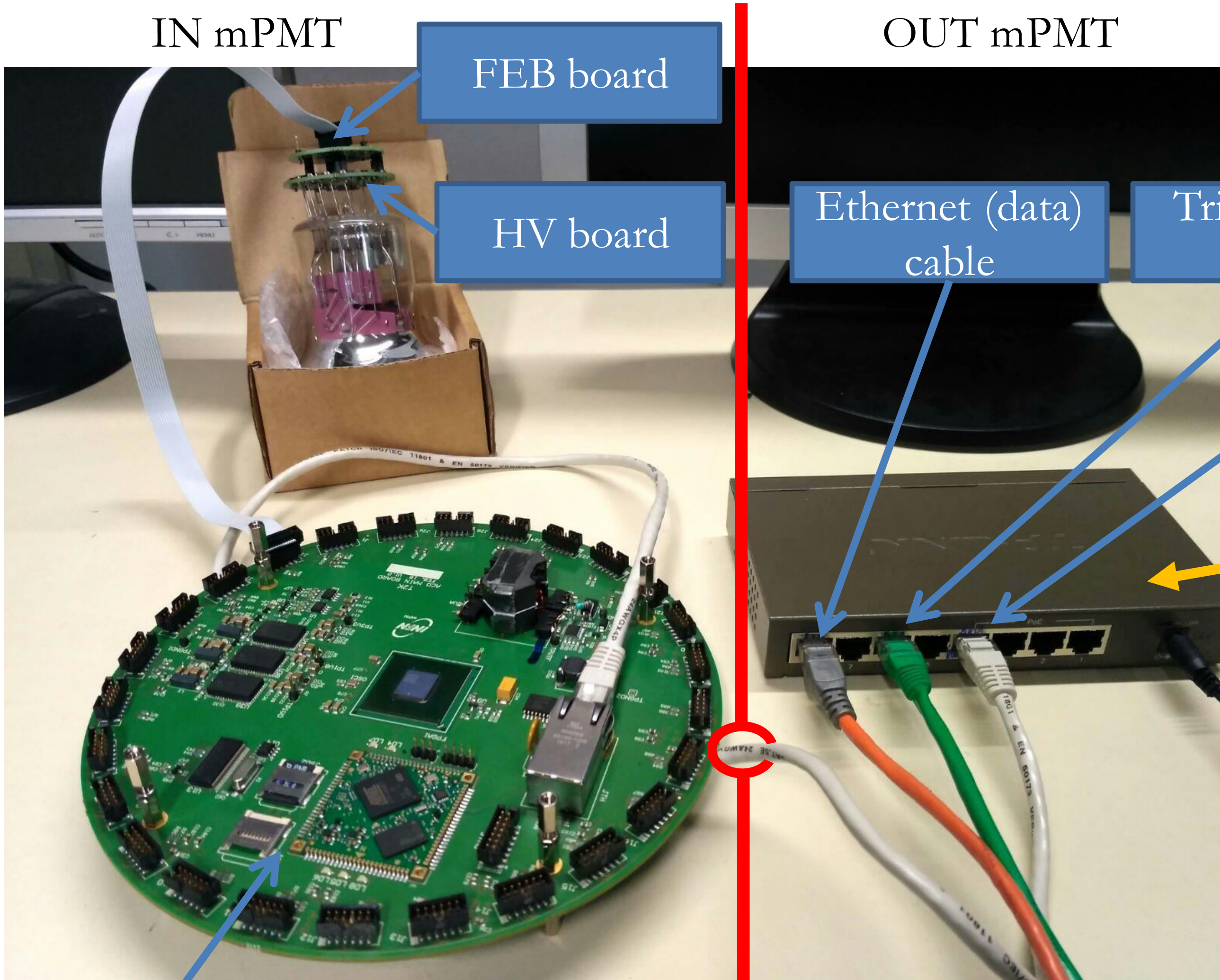
Power consumption



Voltage&current monitoring:
stable HV
HV board swithching noise :
noise subtraction circuit ~0.4pC

Power consumption:
-12.5 mW/ch @1.5kV
- ID: 19 ch → 237.5 mW

Design A: mPMT Connection

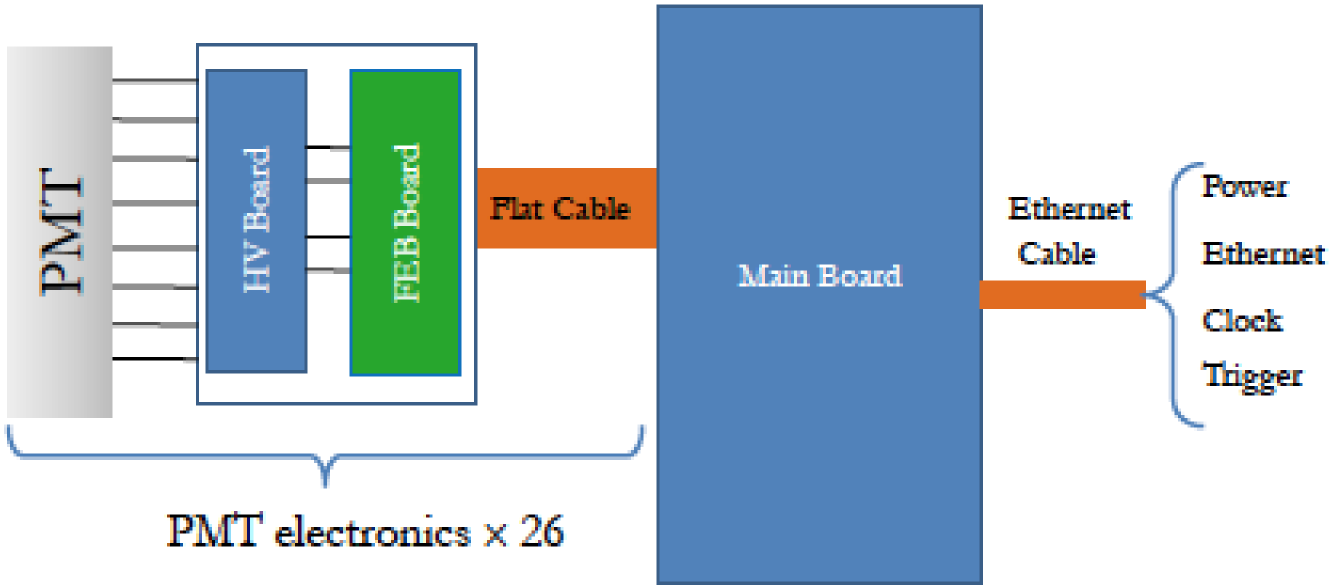


power supply. trigger, clock and data in a single cable

Only 1 Ethernet cable goes out of the mPMT

Design A: mPMT digitization

Sample&Hold
+
ADC
based on discrete components



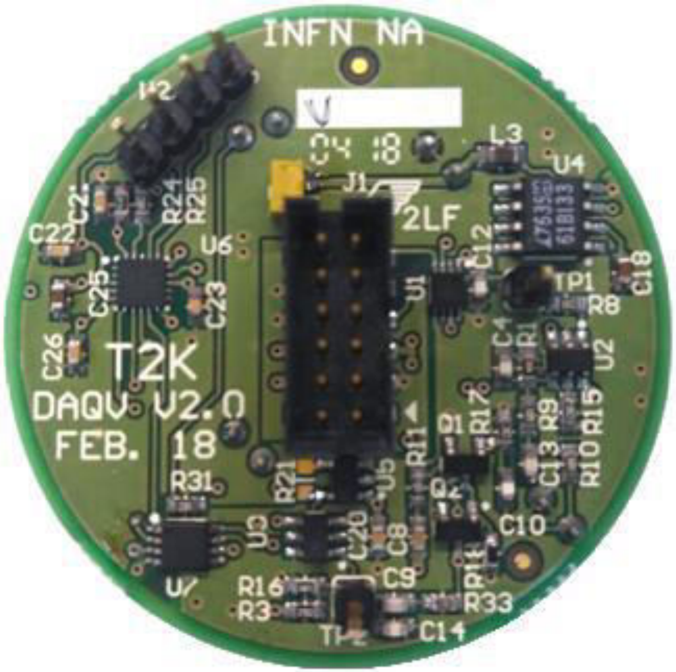
Single channel electronic

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

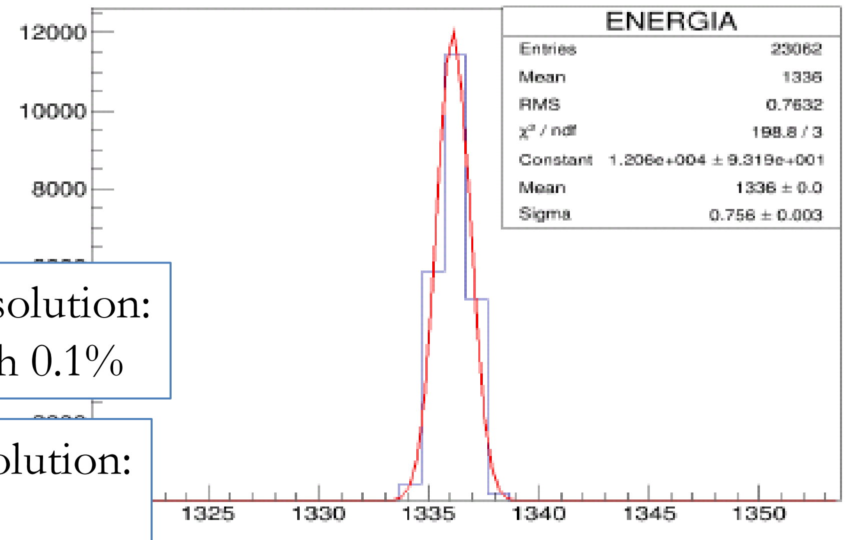
Main board

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

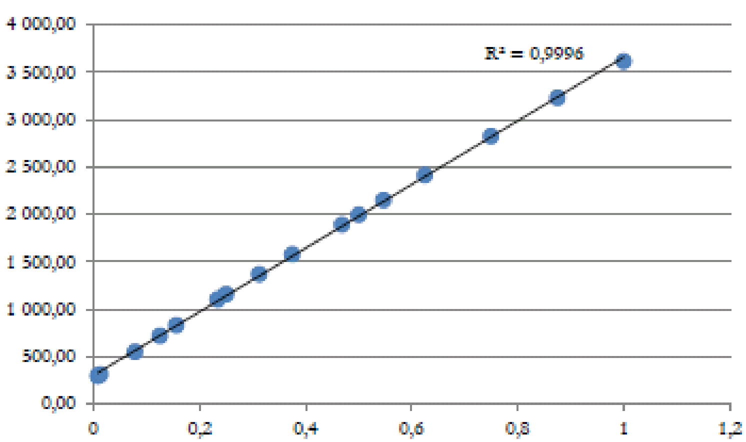


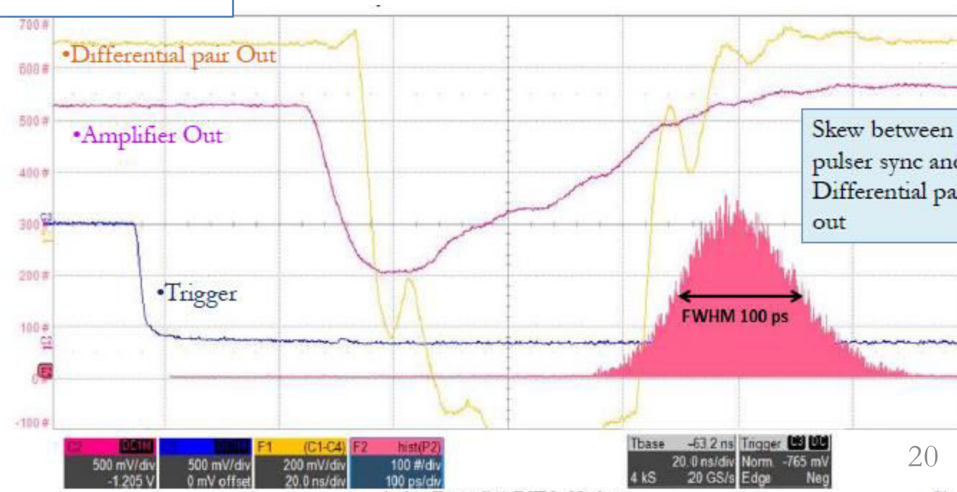
Pow DAQ circuit observed ~ 40.5 mW



Energy resolution: FWHM/ch 0.1%

Time resolution: 100ps

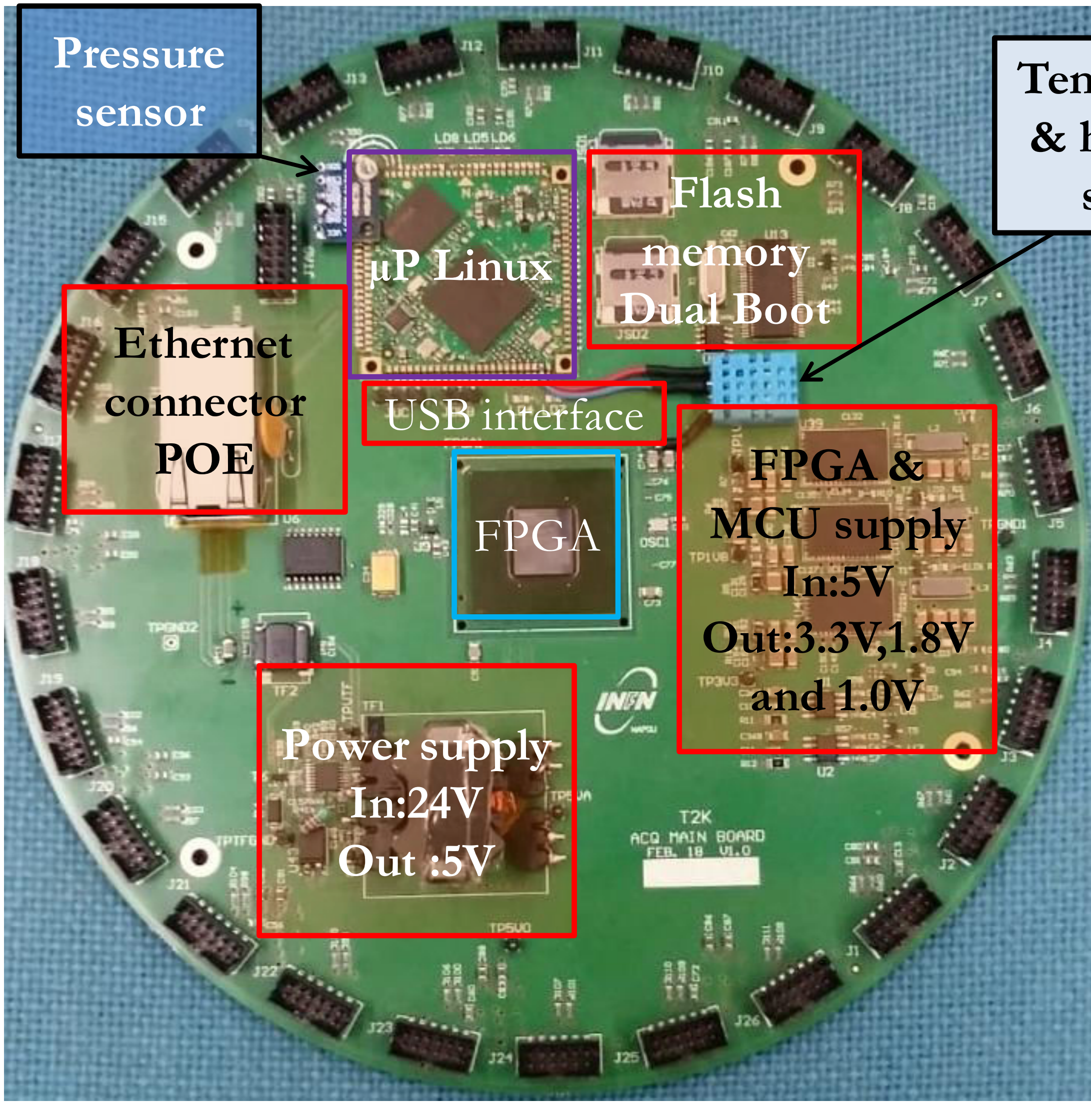




Skew between pulser sync and Differential pair out

Andrea Evangelisti, INFN - Naples

Design A: main board



FPGA Artix-7
N × Single channel TDC/ADC control
Time stamp
N × Single channel On/Off
Trigger logic

Single Board Computer (SBC)-Linux:
N × Single channel Slow control (HV and Threshold set, Current and Voltage monitor)
Data acquisition and transmission
FPGA Slow control and reset
Power consumption and temperature monitor
Remote Single channel μP and FPGA programming /debug

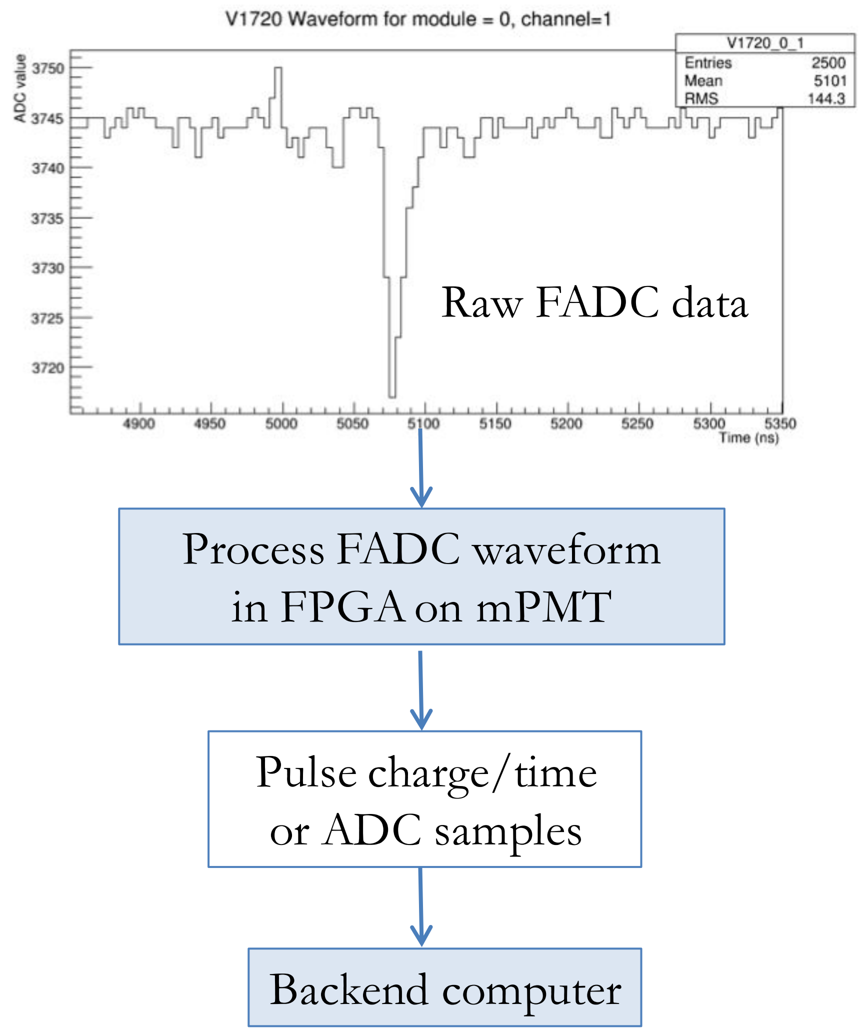
Total Power consumption: ID: 19 ch → ~ 4 W

Design B: FADC Digitization

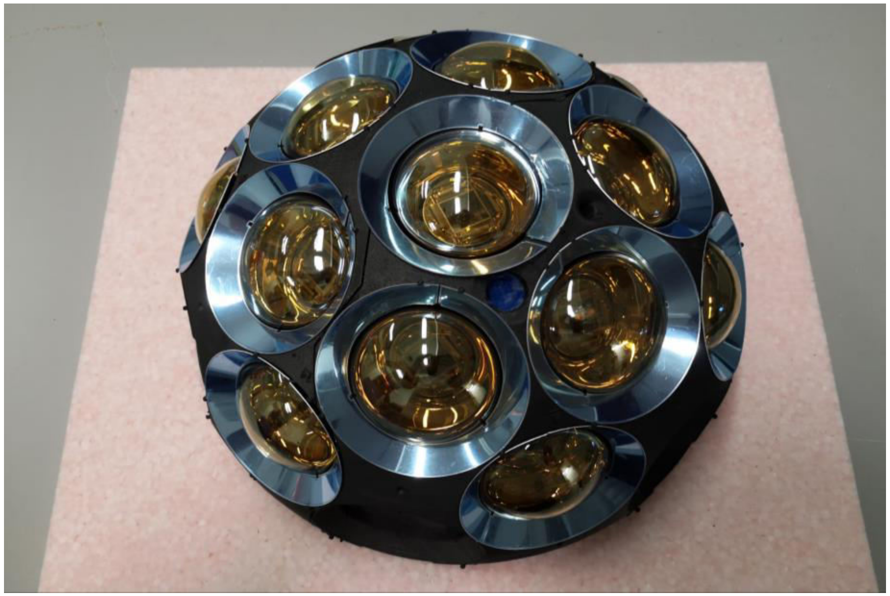
- FADC samples continuously processed with FPGA; on-the-fly feature extraction: Q/T + quality factor (QF)
  - Normally Q/T + QF is sent to backend; send a set of ADC samples in case QF is unsatisfactory

- FPGA data processing also allows for more sophisticated techniques for noise and EMI suppression

- Challenges:
  - Ensure pile-up resolution without too high power consumption and system cost



mPMT prototypes for Hyper-K



mPMT pressure prototype
- **@INFN** Acrylic vessel resisted to 18 bar.
- **@TRIUMF** Metal plate welded to cylinder:.test to 0.7MPa (70m water depth) with no problem.

mPMT Electronics prototype DesignA @INFN
- test the sHV and PMTs read-out
Tests ongoing

mPMT Optical Prototype@TRIUMF
- test the support+PMT+Gel+acrylic assembly and optical properties
Tests ongoing

Conclusion and outlook

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

Two prototypes for Hyper-Kamiokande currently under test

New prototypes with final design by end 2019

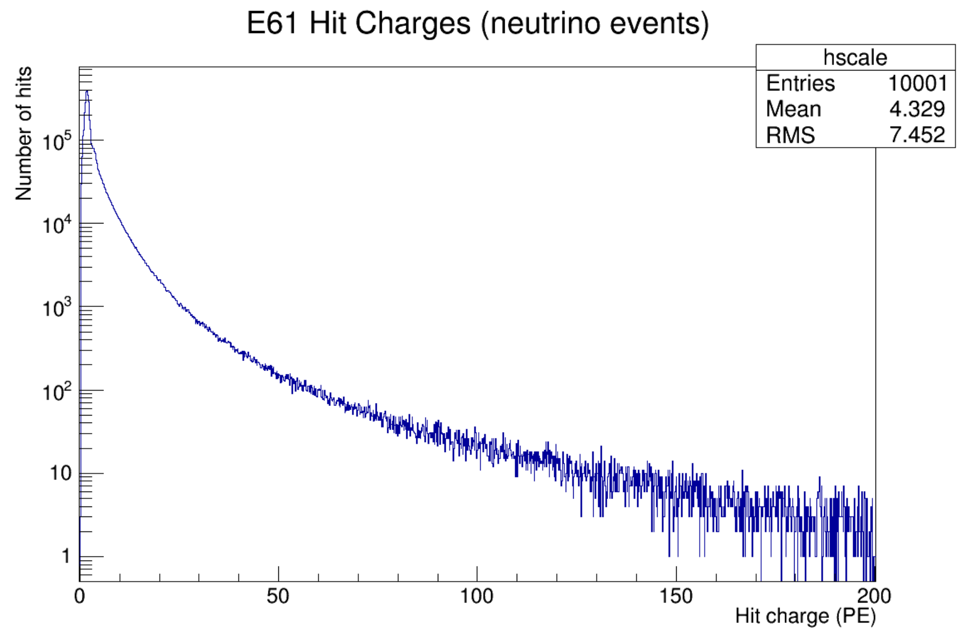
Thank you!

IWCD Dynamic Range Requirements

Dynamic range requirements: single PE up to 50-100PE

- Simulation:
  - 0.49% of hits > 50PE
  - 0.13% of hits > 100PE

Need study of how much saturated hits would effect energy reconstruction.



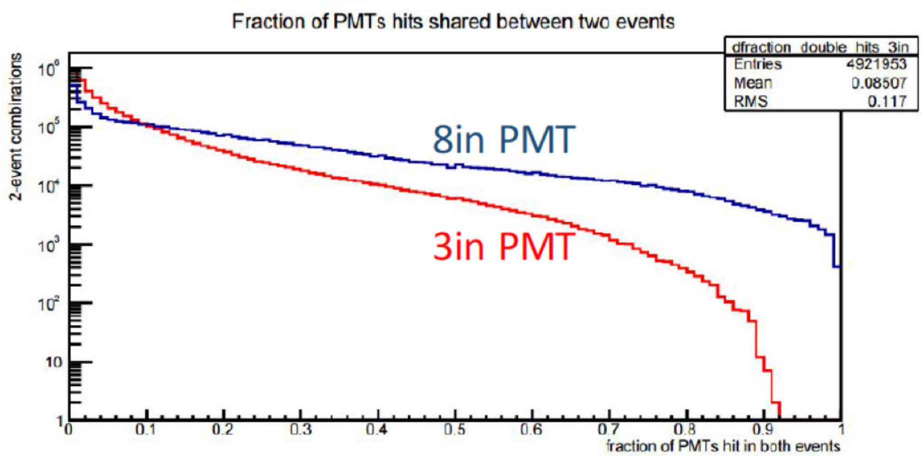
Simulated number of PE per hit for IWCD neutrino interactions
(improved higher-eff 3" PMTs)

IWCD Pile-up/Dead-time Requirements

J-PARC beam spill structure:
– 8 bunches of ~15ns width, separated by ~600ns.
– Spill every 1-2 sec.

- Up to 10% of bunches will have two fully contained events (after outer detector veto) for 10 off-axis position.
- Single PMTs will often get hit multiple times in the same spill and sometimes multiple times in the same bunch.
- Ongoing studies on separating different events in same bunch.
- At a minimum we need separate measurements for each bunch. Finer time information desired.

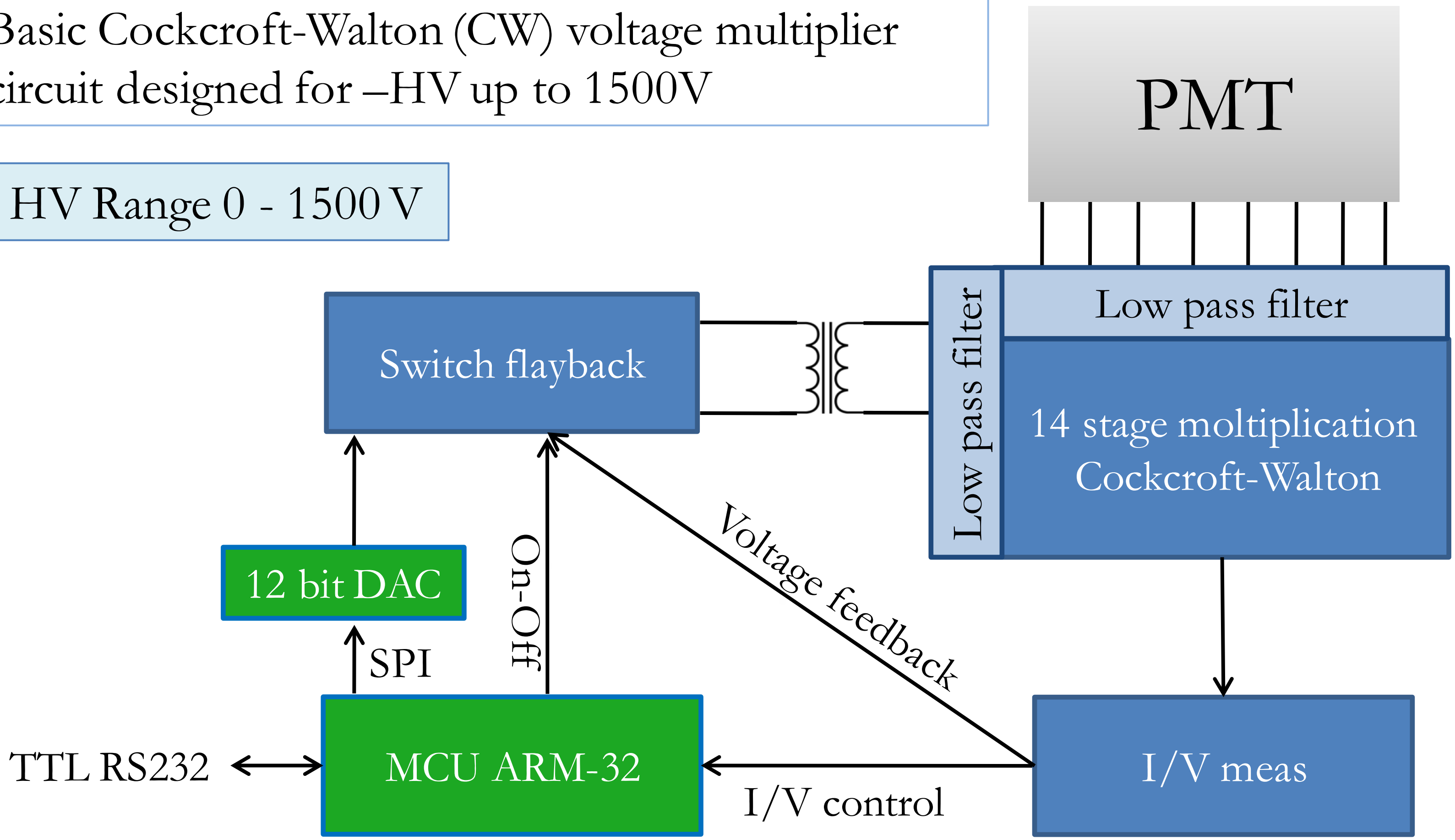
# of pmts hit twice in both events/
# of pmts hit



HV Board block diagram

Basic Cockcroft-Walton (CW) voltage multiplier circuit designed for –HV up to 1500V

HV Range 0 - 1500 V



MCU:
ARM-32 STM32L011F4U
Ultra-low-power ARM Cortex-M0+

V full scale = 1500 V (resolution 0.4V)
I full scale = 16.5 μA (resolution 4 nA)

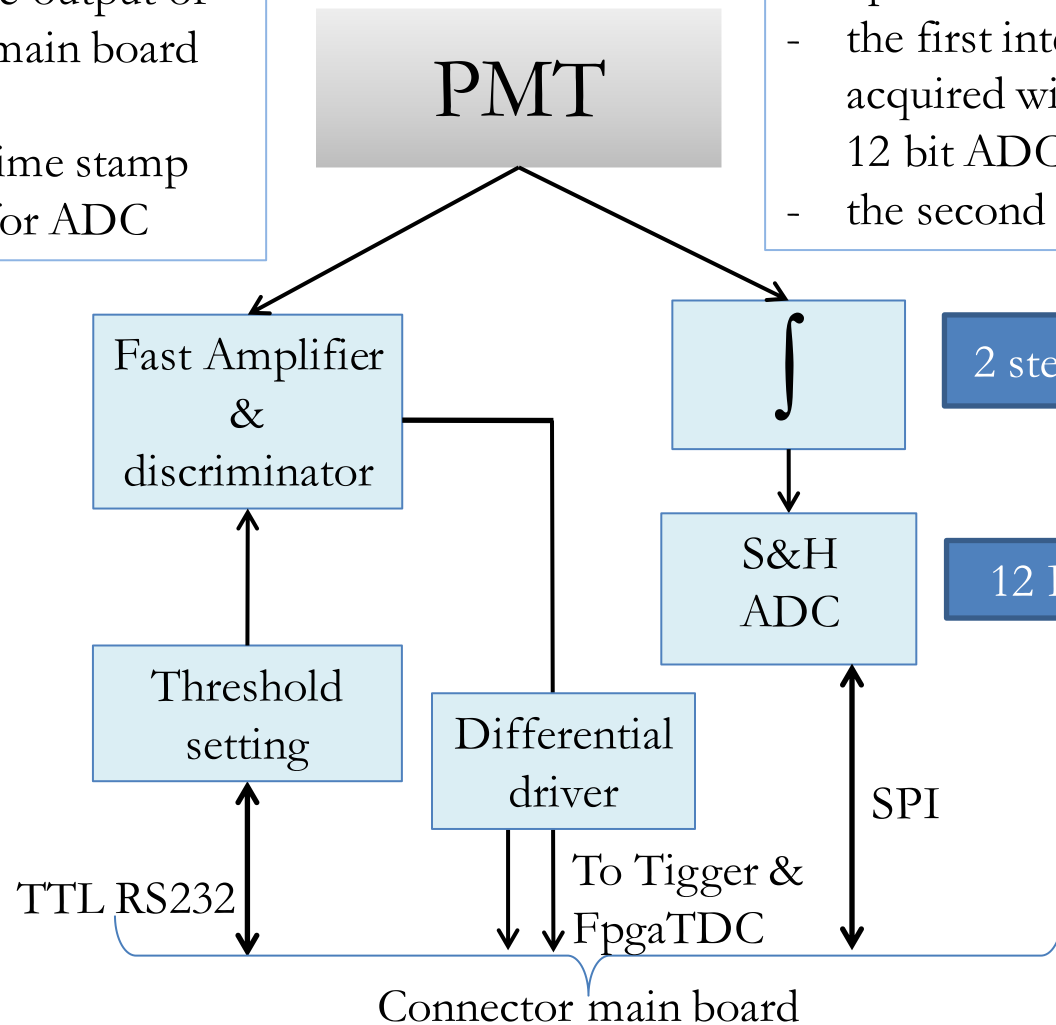
Front End Board block diagram

The amplifier output is compared with a threshold set by the DAC. The output of the discriminator sent to the main board

Time output to produce the time stamp and generate the hold signal for ADC

PMT signal is divided in two part:

- the first integrated and acquired with a 2MSPS 12 bit ADC;
- the second amplified



2 step integrator

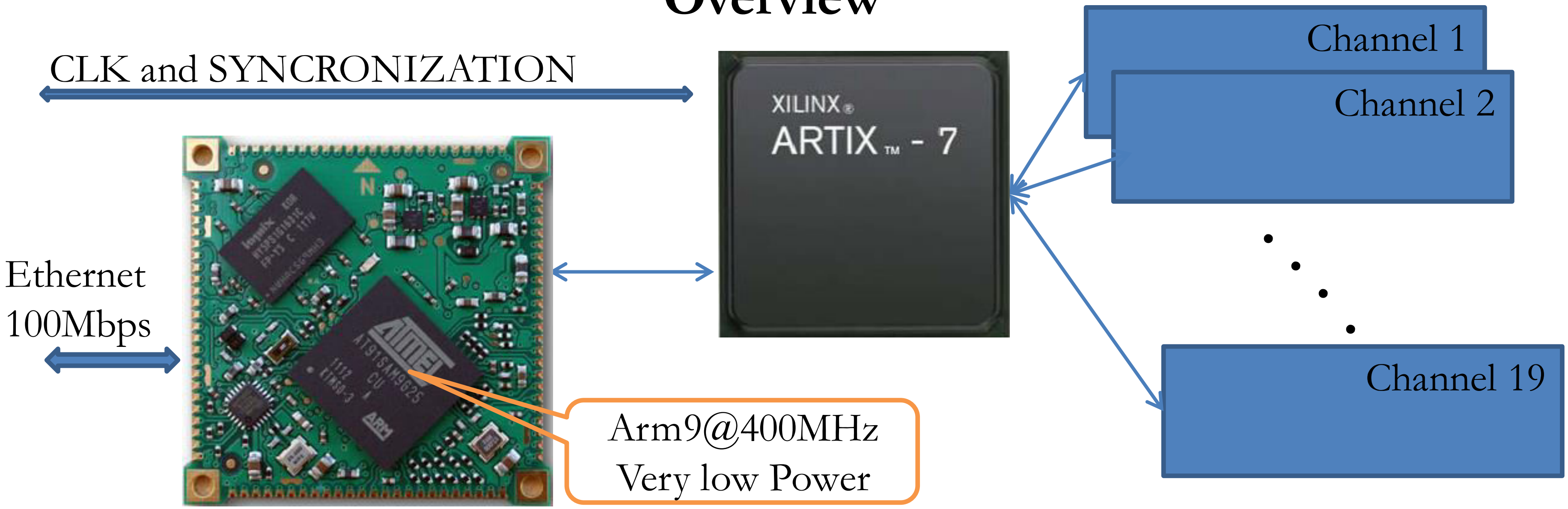
Fast comparator
4.5 ns propagation delay

12 Bit 2 MSPS

0-2.5 V Threshold
(0.6 mV step)

Main Board

Overview



Single Board Computer(SBC)-Linux:

N × Single channel Slow control (HV and Threshold set, Current and Voltage monitor)
Data acquisition and transmission
FPGA Slow control and reset
Power consumption and temperature monitor
Remote Single channel µP programming /debug
Remote FPGA programming /debug
Power (100% CPU) 700 mW

FPGA Artix-7

N × Single channel TDC/ADC control
Time stamp
N × Single channel Overcurrent control
N × Single channel On/Off
N × Single channel enable
Trigger logic
Trigger ratemeter

Time stamp and energy information → low power microprocessor → the data out of mPMT