The JUNO SPMT system

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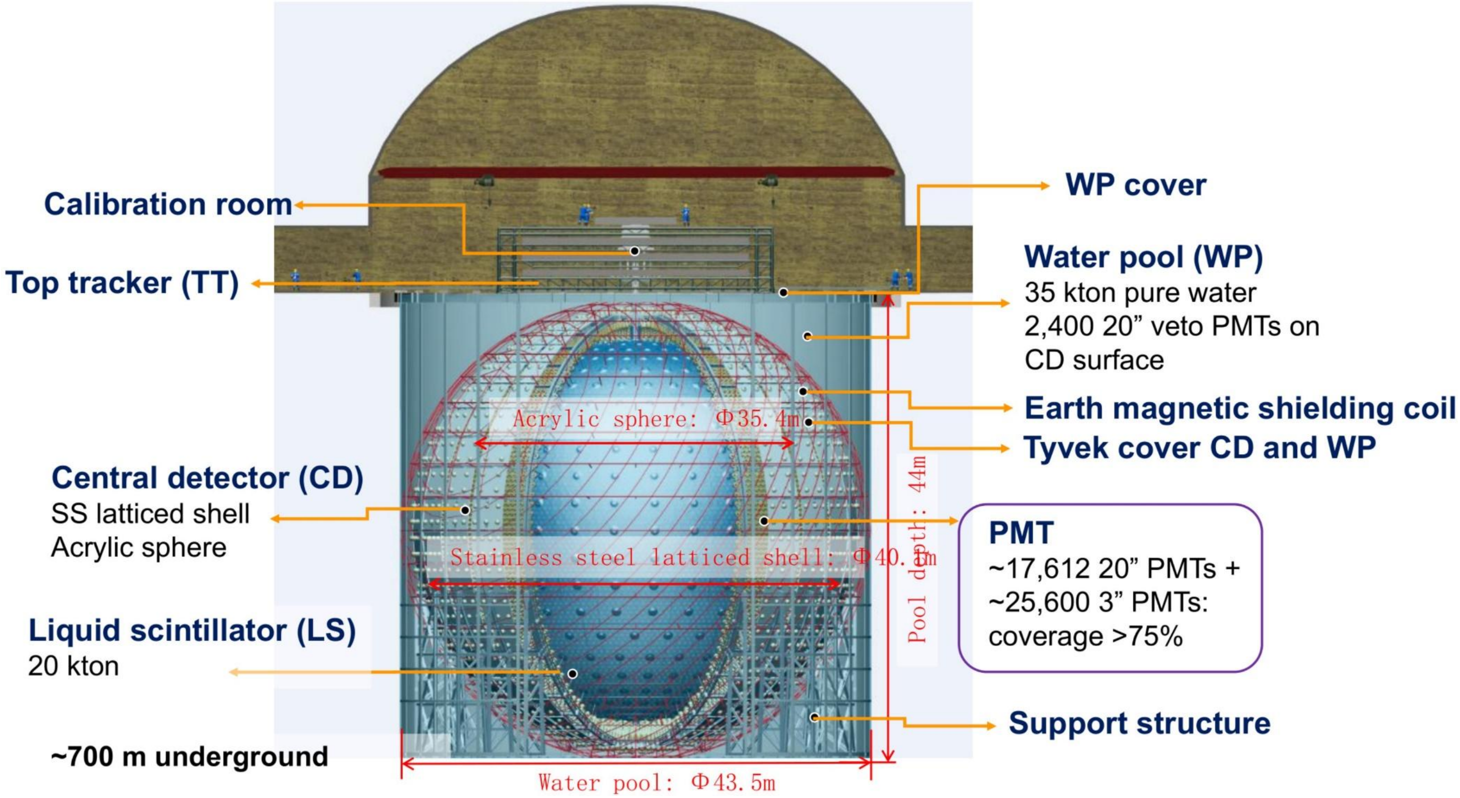
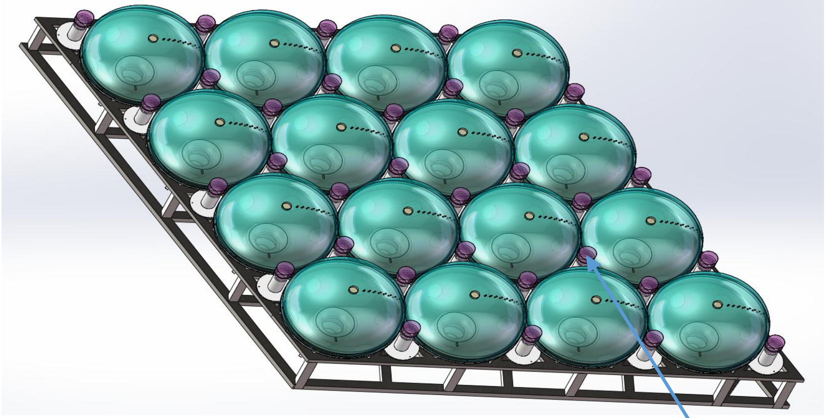
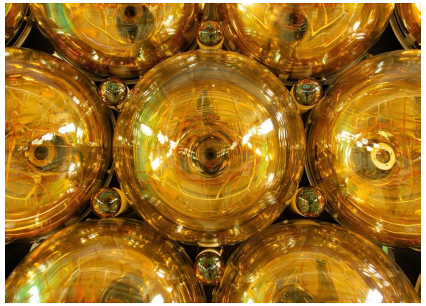
On behalf of the JUNO collaboration

FCPPL2023, Nov. 6-10, 2023, Zhuhai

JUNO Detector



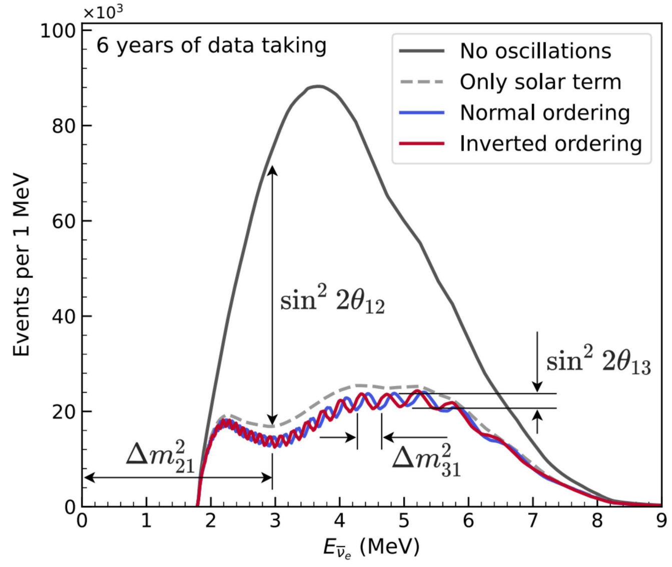




3” PMT(25600)
Dynode PMT from
HZC Photonics

- 25,600 3-inch “small” and 17,612 20-inch “large” photomultiplier tubes (SPMTs and LPMTs, respectively) detect the light produced by neutrino interactions in the CD

Detection requirements and characteristics

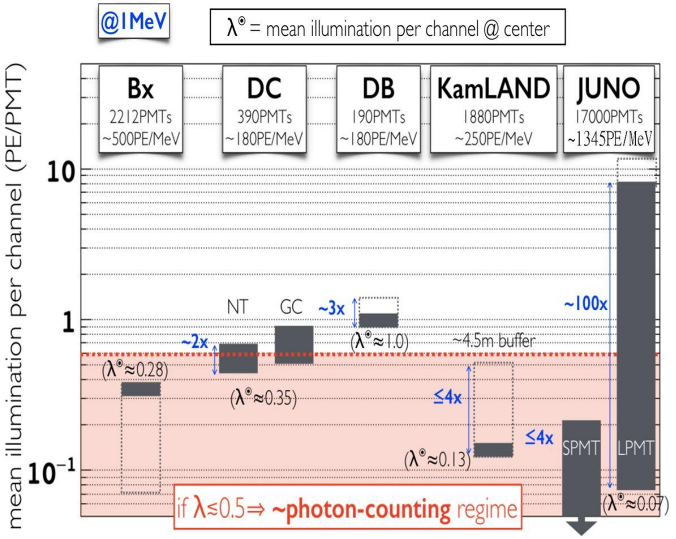


- **Energy scale uncertainty < 1%**
- **Effective energy resolution < 3% @ 1MeV**

$$\frac{\sigma_{E_{\mathrm{vis}}}}{E_{\mathrm{vis}}} = \sqrt{\left(\frac{a}{\sqrt{E_{\mathrm{vis}}}}\right)^2 + b^2 + \left(\frac{c}{E_{\mathrm{vis}}}\right)^2}$$

Stochastic term~1345 p.e./MeV (Light yield, Transparency, Photo-coverage, QE…)

Non stochastic terms (Non-uniformity, background noise)



LPMT (20 inch):

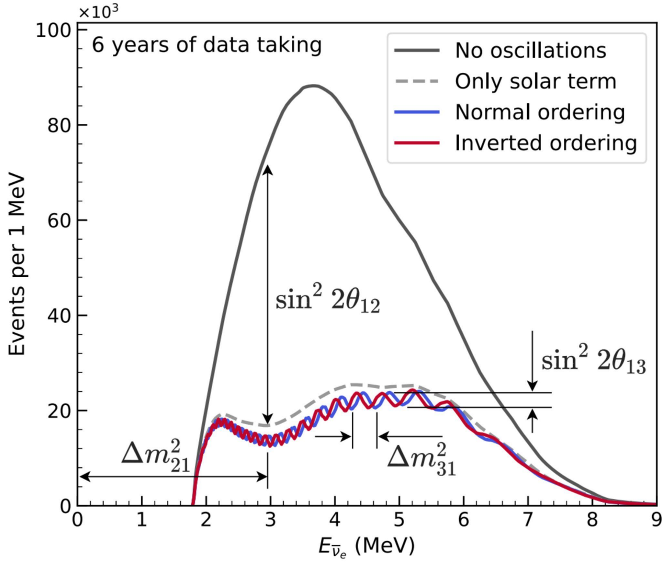
- Works over a large dynamic range
- Energy information is obtained by reconstructing the charge
- With large photon statistics which can reduce the statistical items

SPMT (3 inch):

- Work in single-photon counting mode for reactor neutrino detection
- Photons can be counted directly (1 hit = 1 p.e.)
- Control systematic uncertainties and reduce the non-statistical items

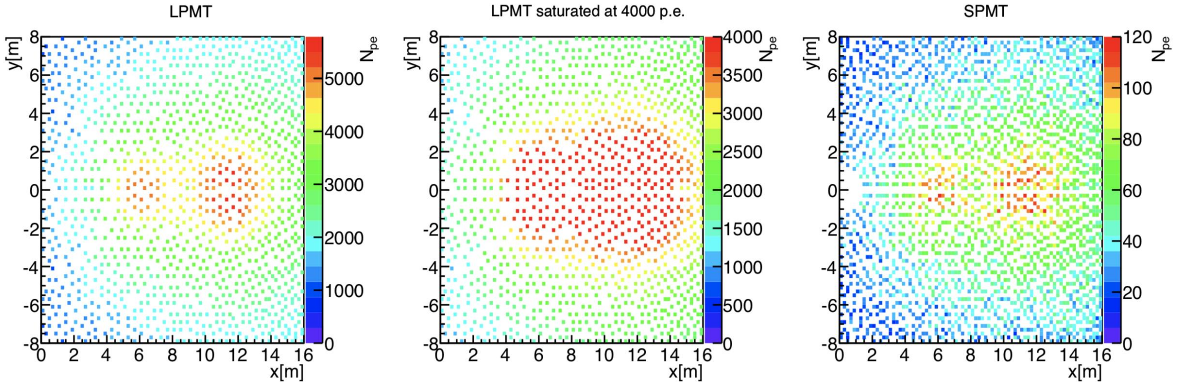
Why SPMT ?

- Improve the energy scale precision and energy resolution
  - Slightly increase detected light yield (~3%)
  - Calibrate charge non-linearity of LPMTs and their electronics
  - Reduce the non-statistical items of energy resolution
- Two independent systems make Stereo Calorimetry
- Enhanced physics capabilities
  - Semi-independent measurement to θ_{12}, Δm^2_{21}
  - Muon reconstruction
  - High-rate supernova detection

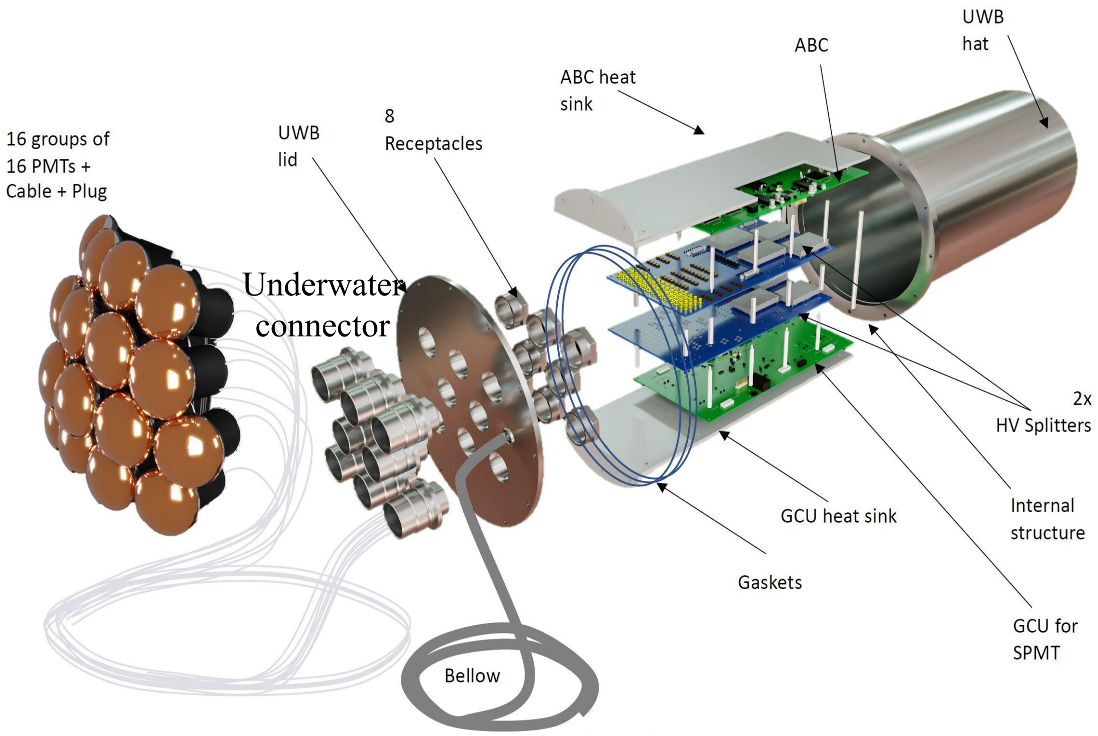


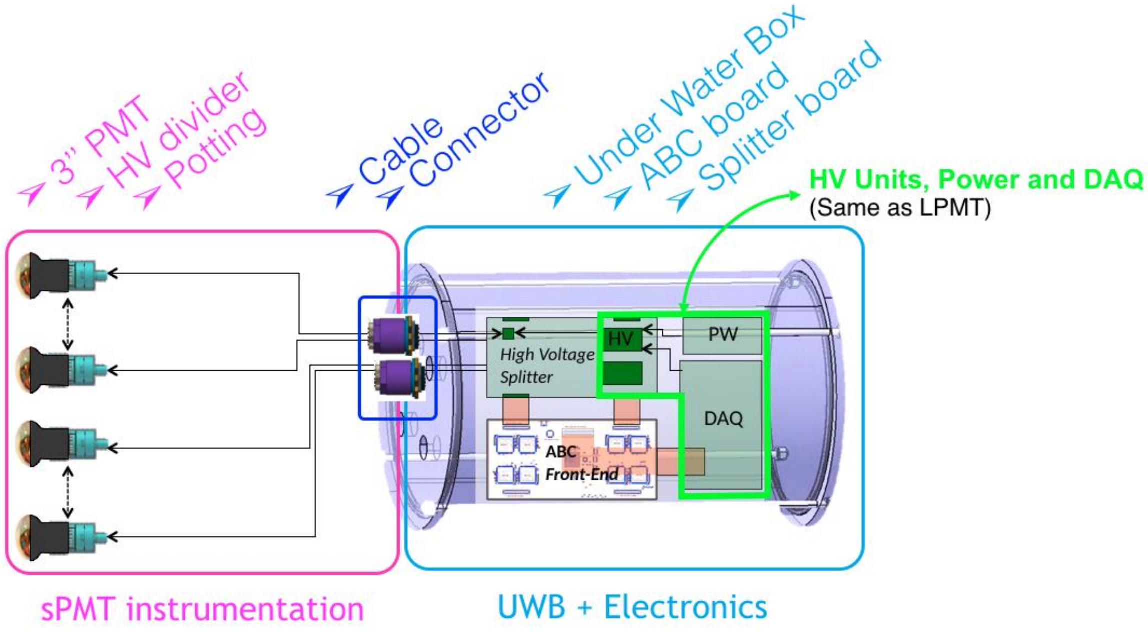
Ideal antineutrino spectrum without oscillations and with oscillations for JUNO

Example of double muon hit pattern seen by LPMTs without saturation, LPMTs saturated at 4000 p.e. and SPMTs, respectively



SPMT system

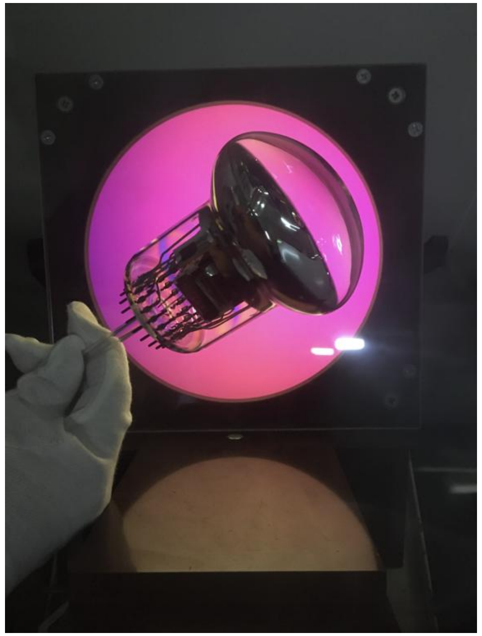




200 Underwater boxes (UWBs) → **× 8 groups (128 PMTs) per UWB** → 1600 groups → **× 16 PMTs per group** → 25600 SPMTs

Bare PMT test

Nucl.Instrum.Meth.A 1005 (2021) 165347



Summary of the 3-inch PMTs acceptance criteria and test results for different parameters. Results for class A parameters were from 26,000 PMT mean value of vendor data after acceptance measurement introduced in Section 4.2, and other results were from acceptance measurement only. Unless specified, all of the parameters were measured at 3×10^6 gain.

Parameters	Class	Requirement (limit)	Requirement (mean)	Test fraction HZC	Test fraction JUNO	Tolerance of diff.	Results (mean)	Rejection number
Φ (glass bulb)	A	(78, 82) mm	–	100%	10%	–	OK	0
QE@420 nm	A	>22%	>24%	100%	10%	<5%	24.9%	1
High Voltage	A	(900,1300) V	–	100%	10%	<3%	1113 V	1
SPE resolution	A	<45%	<35%	100%	10%	<15%	33.2%	0
PV ratio	A	> 2	> 3	100%	10%	–	3.2	0
DCR@0.25 PE	A	<1.8 kHz	<1.0 kHz	100%	10%	–	512 Hz	1
DCR@3.0 PE	A	<30 Hz	–	100%	10%	–	7.2 Hz	1
TTS (σ)	B	<2.1 ns	–	–	3%	–	1.6 ns	0
Pre-pulse	B	<5%	<4.5%	–	3%	–	0.5%	0
After-pulse	B	<15%	<10%	–	3%	–	3.9%	11
QE non-uniformity	B	<11%	–	–	3%	–	5%	0
Φ (eff. cathode)	B	>74 mm	–	–	3%	–	77.2 mm	0
QE@320 nm	C	>5%	–	–	1%	–	10.2%	0
QE@550 nm	C	>5%	–	–	1%	–	8.6%	0
Aging	D	>200 nA years	–	–	3 PMTs	–	OK	0

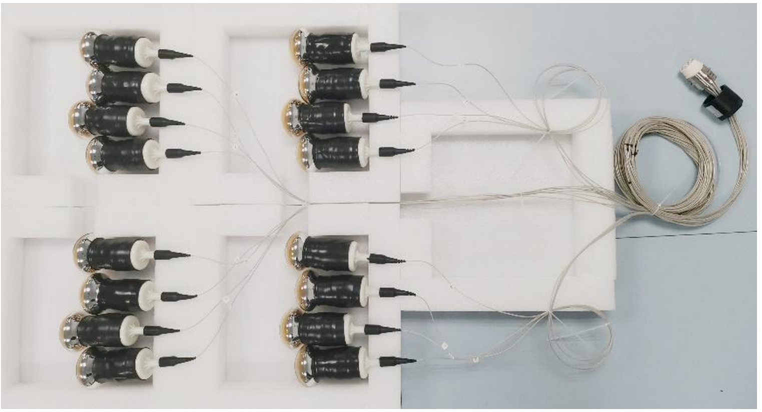
- 26,000 XP72B22 3-inch PMTs were produced and characterized at Hainan Zhanchuang Photonics Technology Co., Ltd (HZC) under JUNO's supervision
- 15 parameters have been characterized
- Only 15 PMTs were found to be unqualified and thus rejected

Connector

- Integration of PMTs (after HV grouping) with HV dividers, frontend cable and connector with water proofing
- **Connector:**
  - **Customized design for JUNO by Axon-France**
  - **Optimized design and mass production by Axon-China**

Instrumentation

- **Integration** of PMTs (after HV grouping) with HV dividers, frontend cable and connector with water proofing
- Supply **same HV to 16 PMTs** through a multi-channel connector
- Partnership with industry was key to completing this process



Production and test of bare PMT
@HZC

Plug and Receptacle
@Axon

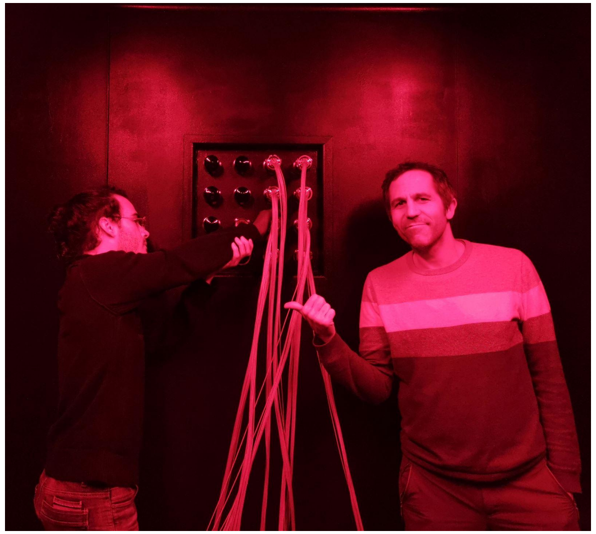
Cable sealing
@Pan Asia

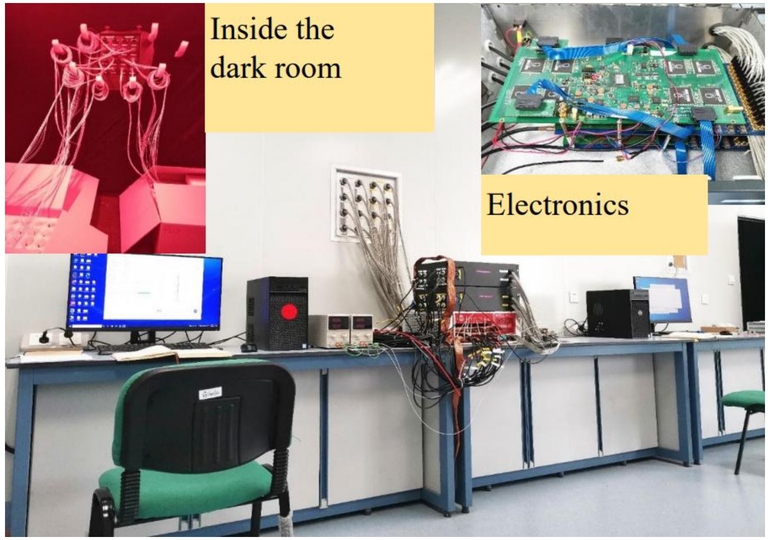
Potting and Leakage test
@HZC

Acceptance Testing
@Guangxi University

Acceptance tests of water proofing potting PMTs

- Tasks: test all 26k SPMTs and check
  - PMT alive
  - Gain, SPE resolution, DCR
- **Two test benchs were provided by French working group and they contributed a lot to operate the system**

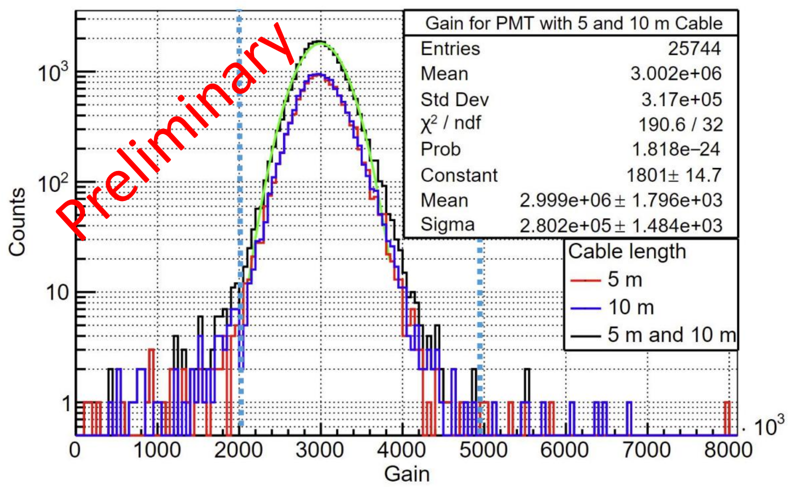


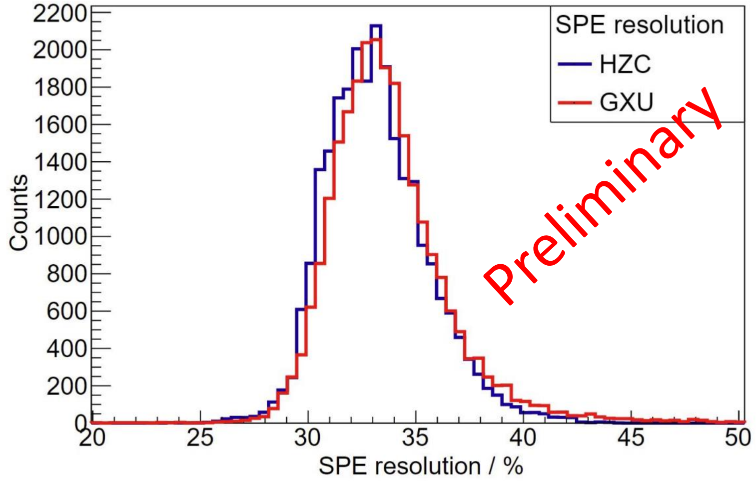


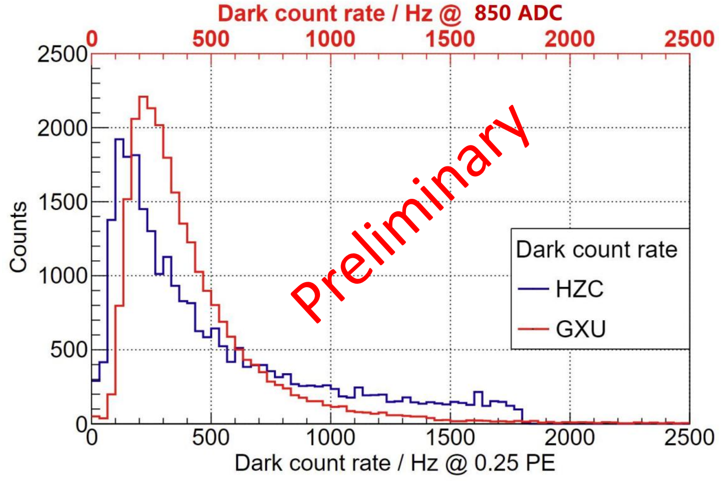
Test station at GXU

Acceptance tests of water proofing potting PMTs

- Acceptance of SPMTs after waterproofing was finished in Guangxi University (GXU).
- Unqualified ratio < 0.7%
- Gain spread ~ 10%, mean SPE resolution ~33%, mean dark rate ~400 Hz

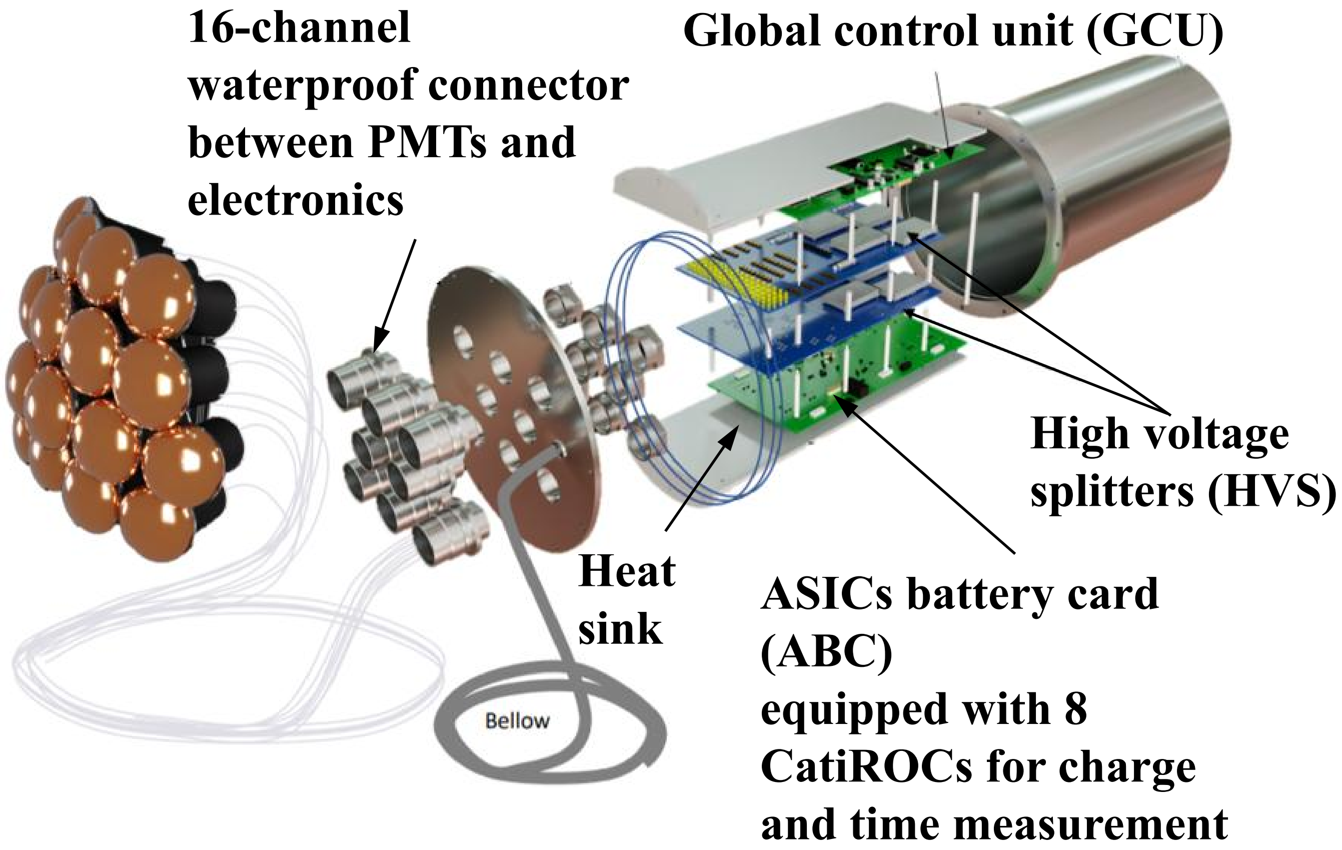




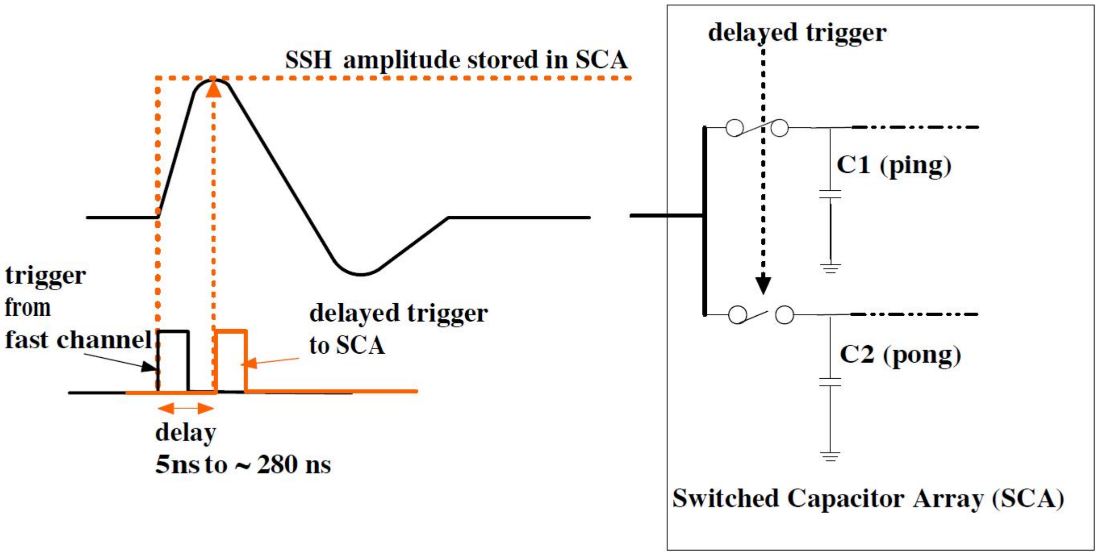


SPMT electronics

- The whole system will be installed underwater at a maximum depth of ~40 m
- Each group of 16 PMTs shares the same HV and threshold

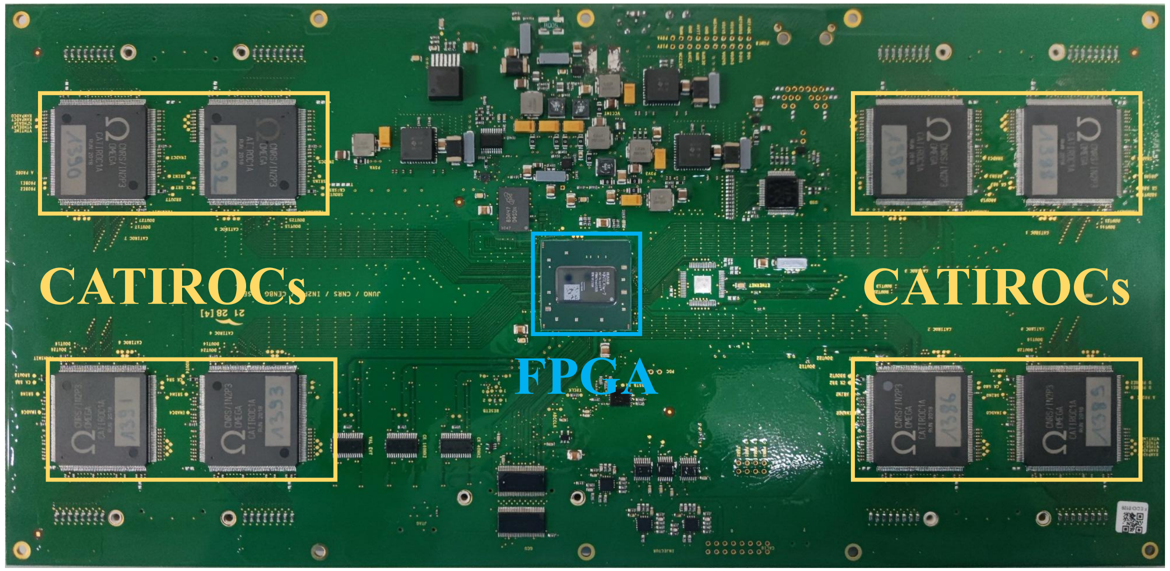


CATIROC and ABC



Charge measurement method of CATIROC

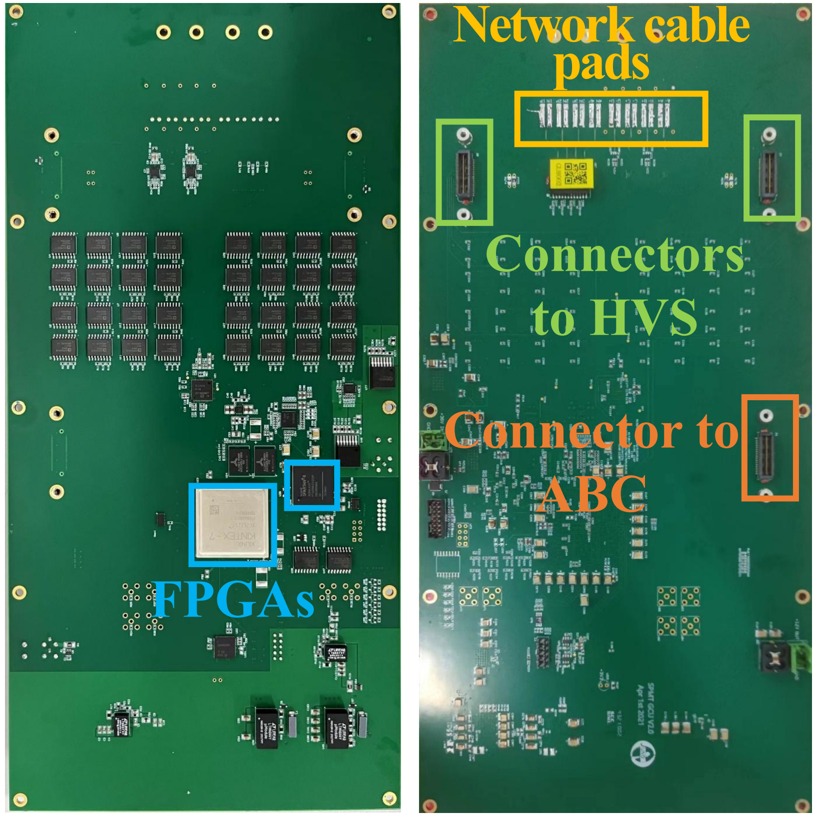
JINST 16 (2021) 05, P05010



ABC board

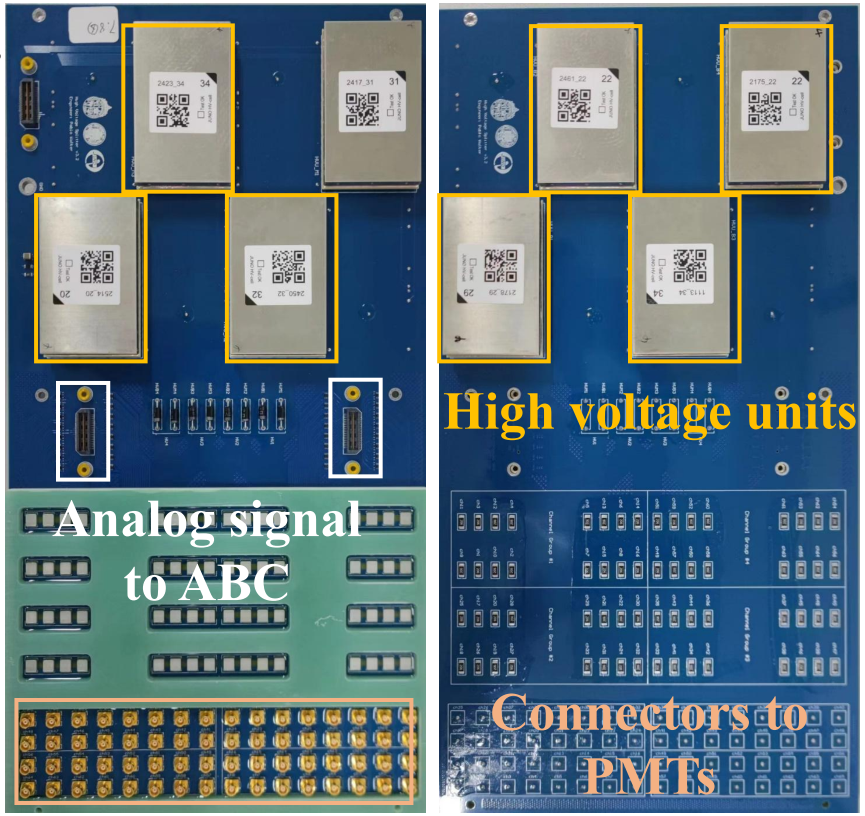
- **CATIROC and ABC (ASICs Battery Card) board are designed and producted by French working group**
- 8 CATIROCs on one ABC for 8 groups of PMTs
- CATIROC is an ASIC to analyze signals from PMTs and output time and charge data.
- The dynamic range using both the low and high gain regimes is from 0 to ~120 PE.
- Noise of high gain is about 2 ADCu, which correspond to 0.015 pC and 0.03 p.e. for a gain of 3×10^6

HVS and GCU



GCU board

Connector to GCU

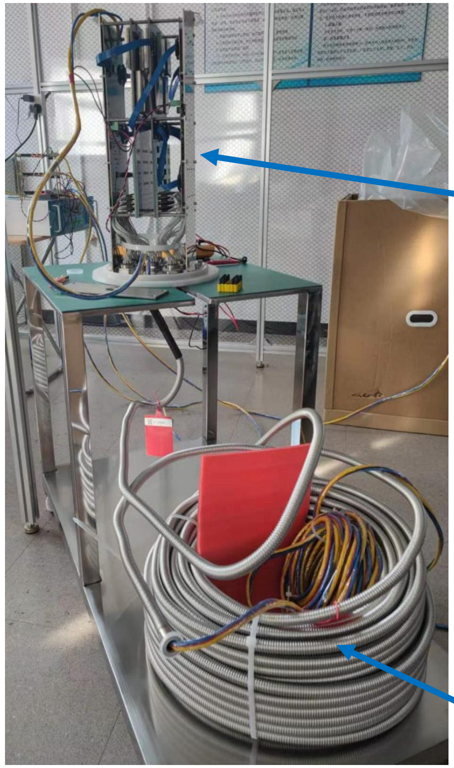


HVS board

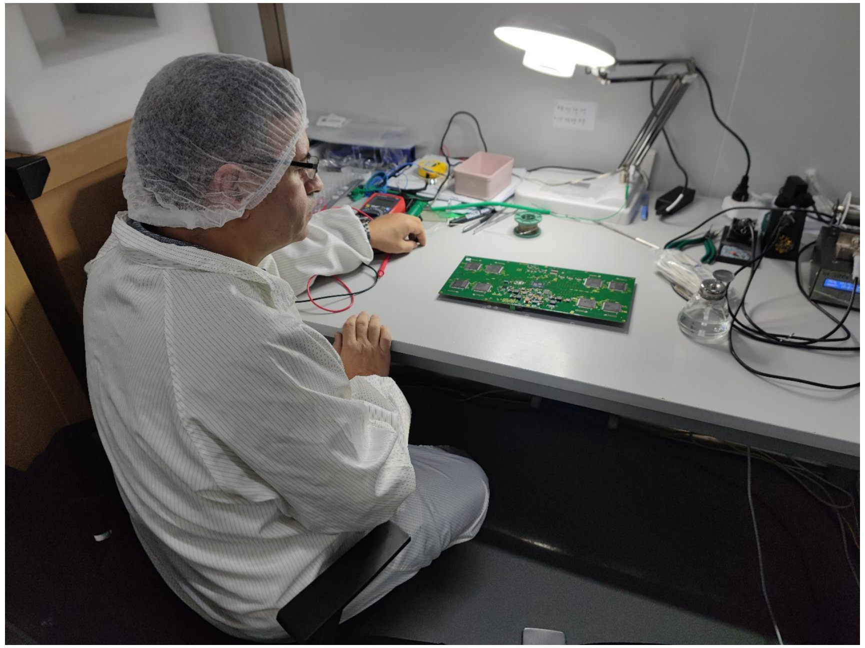
- ➢ High Voltage splitter (HVS): supply high voltage and split signal
- ➢ Global Control Unit (GCU): control and transfer data to DAQ

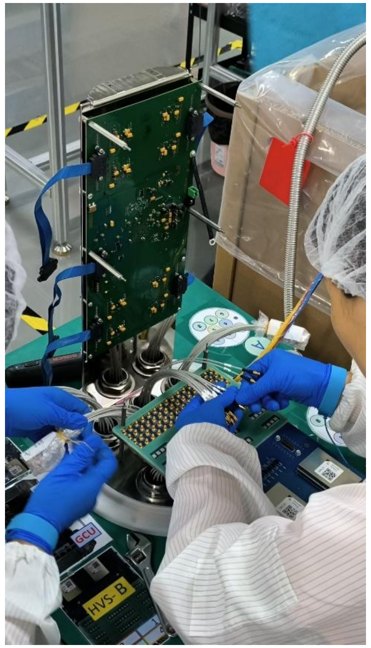
Mechanical structure

- ➢ Network and power cables run inside bellows to electronic rooms in the surface
- ➢ Heat sink to support electronic boards and dissipate heat through the front lid
- ➢ UWB sealed with 3 redundant O-rings
- ➢ Custom-made Axon waterproof connectors between HVS and SPMTs



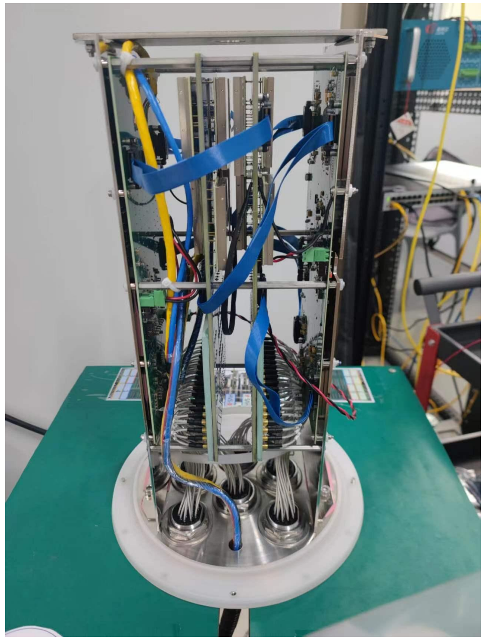
Electronics integration



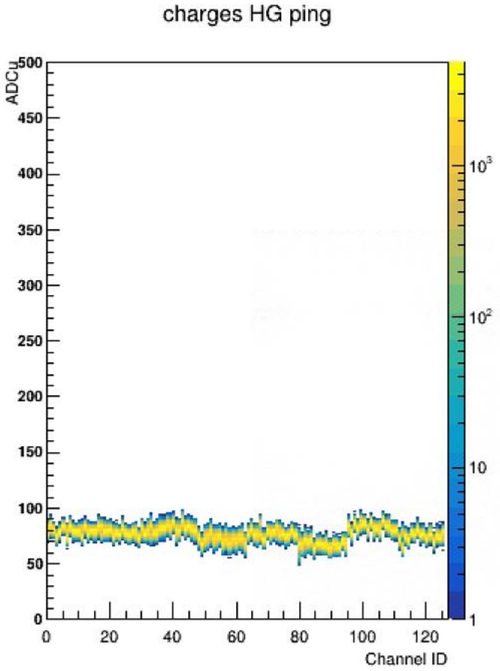


- 204 sets of electronics have been integrated at JUNO site
- 2 electronics per day at first → 3 ~ 4 electronics per day

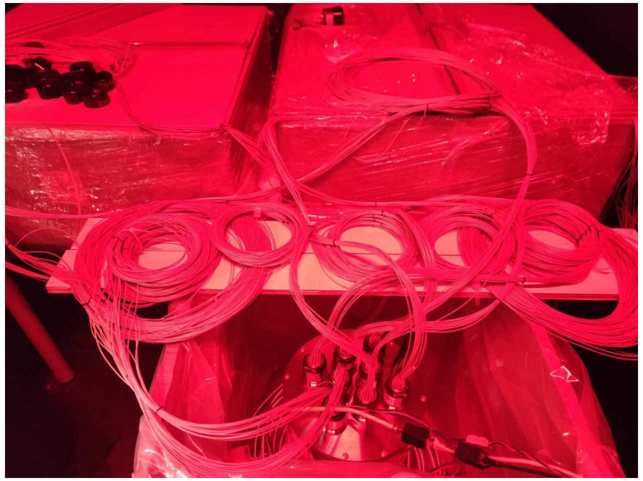
Tests during integration



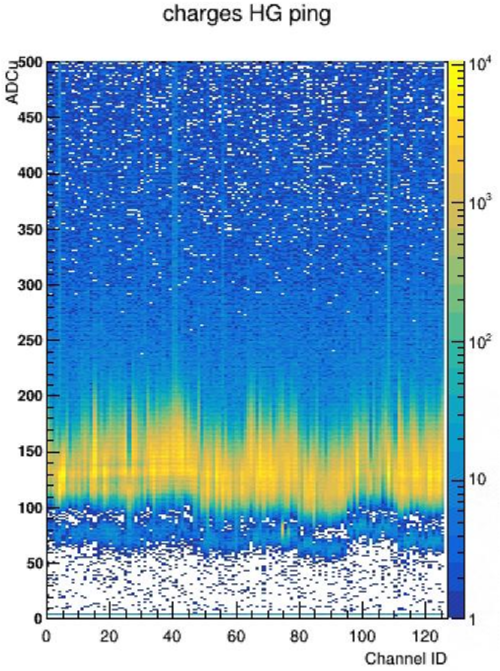
Pedestal test before closing UWB



Pedestal of one set of electronics



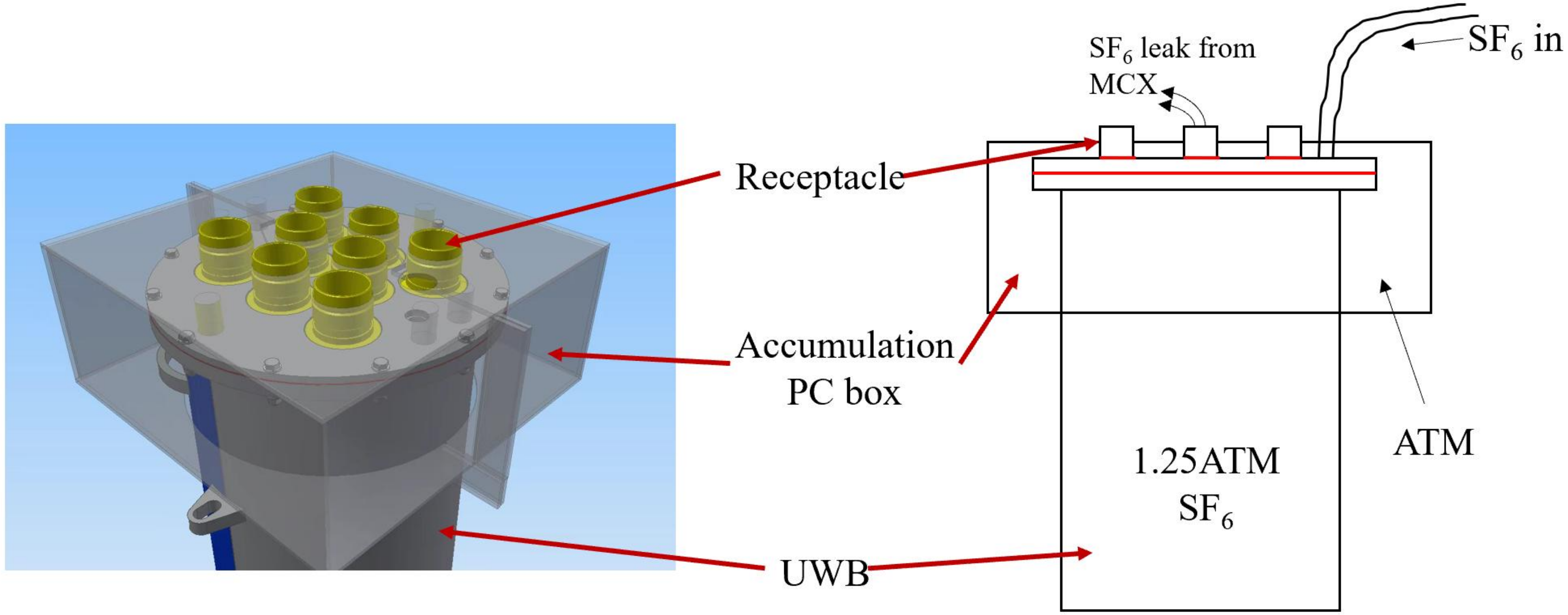
Test with SPMTs in dark room



SPE signals read by one set of electronics

- RMS of pedestal is about 0.04 p.e. consistent with result tested with single ABC
- All electronics finished integration and passed tests!

Leakage test

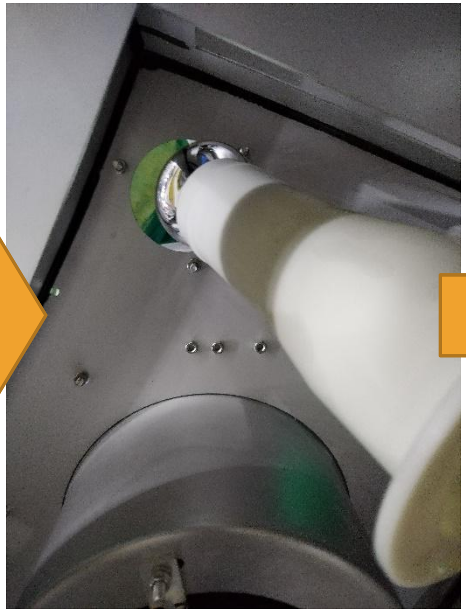


Leakage test system

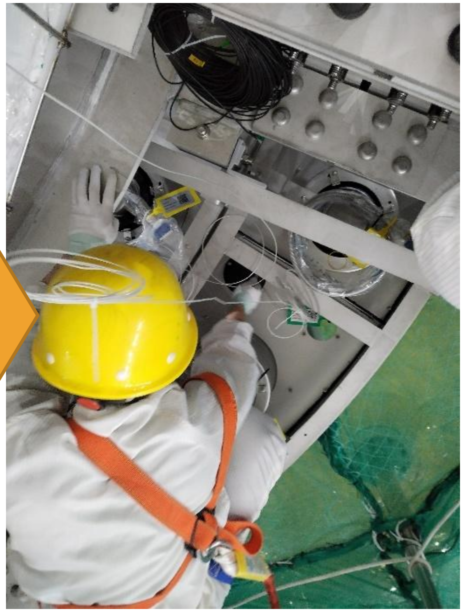
- A SF6 based leakage test system was designed for UWB
- Sensitivity is ~ 10^{-8} Pa · m^3/s
- Leaky receptacles were identified and sealed with epoxy

PMT installation

Install support



Install PMT



Install Light Barrier

Module
MID:
GJ-N57-06(3/6)
PID:
N-057-020.5-U
CID: 12

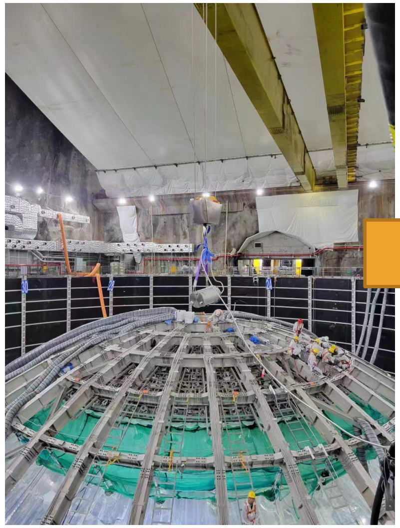
QR code on installation position

SPMT
MID:
GJ-N57-06(3/6)
PID:
N-57-020.5-U
CID: 12 Type: L

QR code on PMT

- Starts in November 2022
- One group of 3 workers can install 60 ~ 80 PMTs per day on the stainless steel truss
- 9265/25600 (~36%) PMTs were installed
- QR codes to make sure correct installation position

Electronics installation

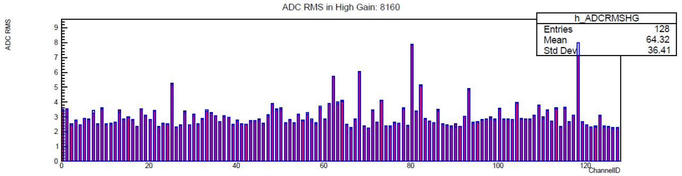


Install UWB

Connect SPMTs to UWB

QR code on installation position

QR code on UWB



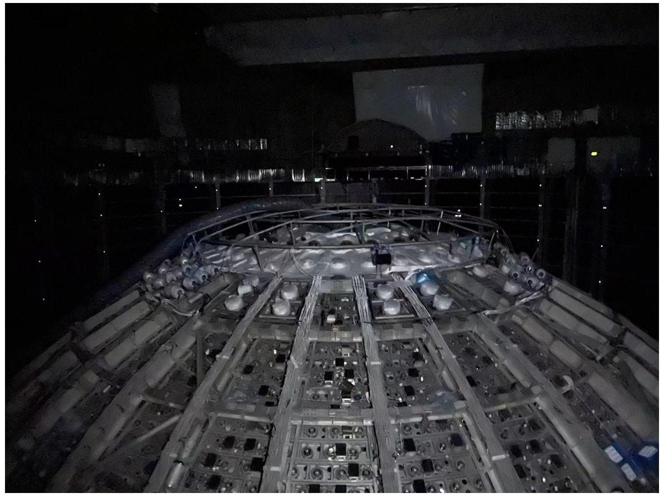
Pedestal test after installation

Leakage test after installation

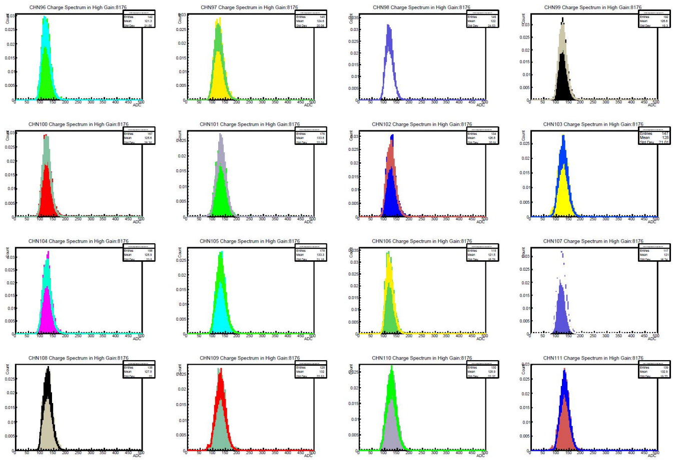
- Starts in March 2023.
- 26 UWBs per day if only the SPMT UWBs are installed.
- 86/200 (~43%) UWBs were installed.

Lights-off tests

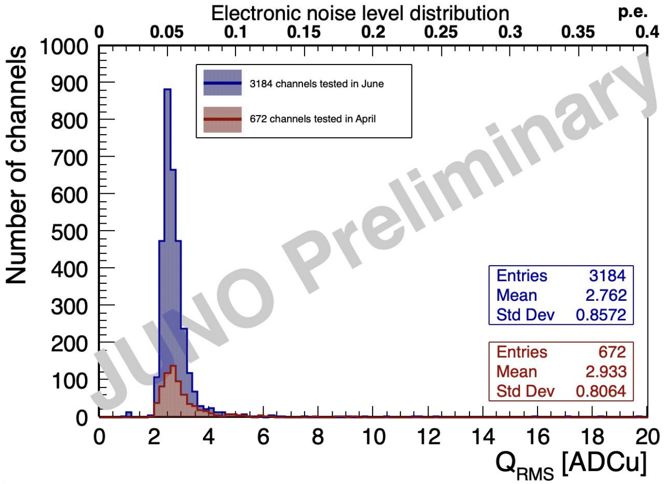
Operate in electronics room



JUNO detector with lights off



Charge spectra of one group of 16 SPMTs



Noise on detector

- **56 UWBs with 6976 PMTs were tested during four dedicated lights-off tests**
- Electronics noise of SPMT is 2.8 ADC counts, ~5% of SPE

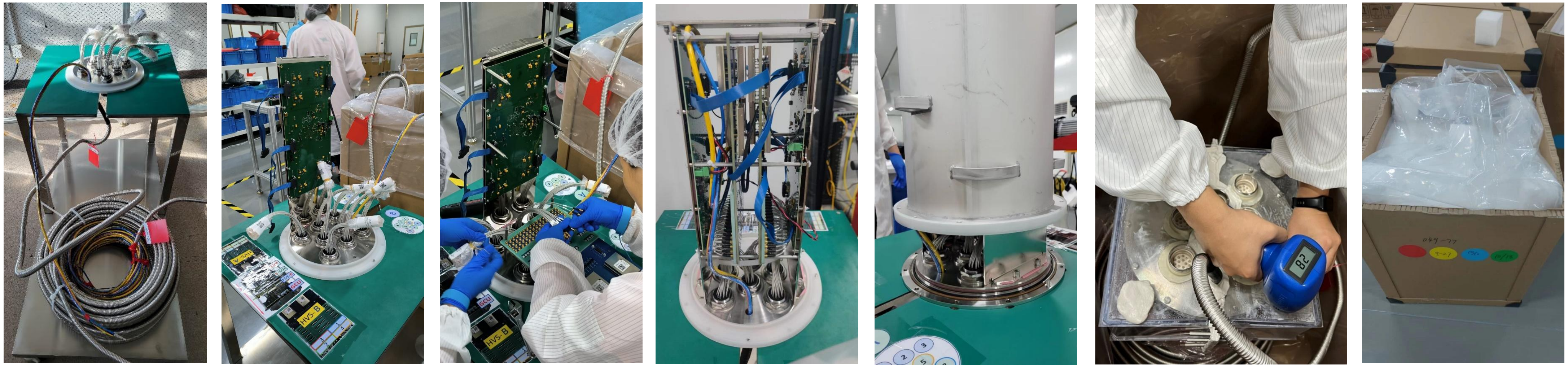
  → Much lower than the trigger threshold of 1/3 p.e.
- Problematic cables (~1/1000) were identified and repaired

Summary and Prospects

- 26k 3-inch PMTs and electronics were produced and integrated
- 9293 (~36%) PMTs and 86 (~43%) electronics have been installed in the detector
- PMTs and electronics are connected through 16-channel underwater connectors
- Four times lights-off tests have been conducted with ~0.1% problematic channels identified and repaired
- Installation of PMTs and electronics to be completed by early 2024

Back up

Electronics integration

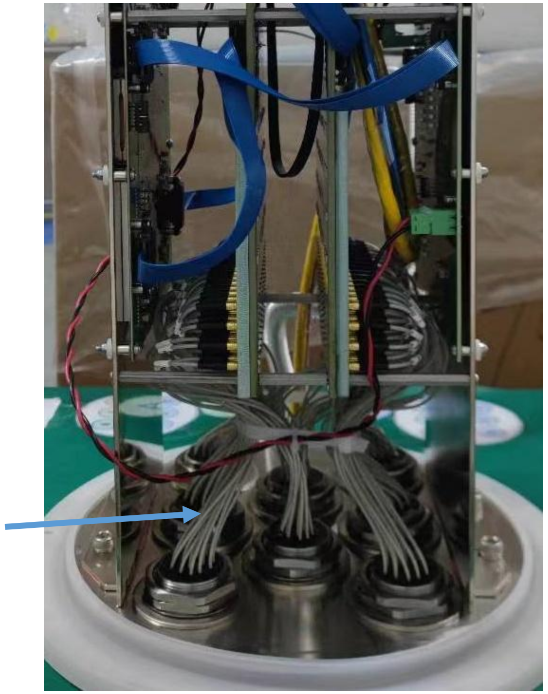


Assembly of receptacles → Assembly of ABC → Assembly of two HVS boards → Assembly of GCU → UWB closing → Leakage test → Packaging

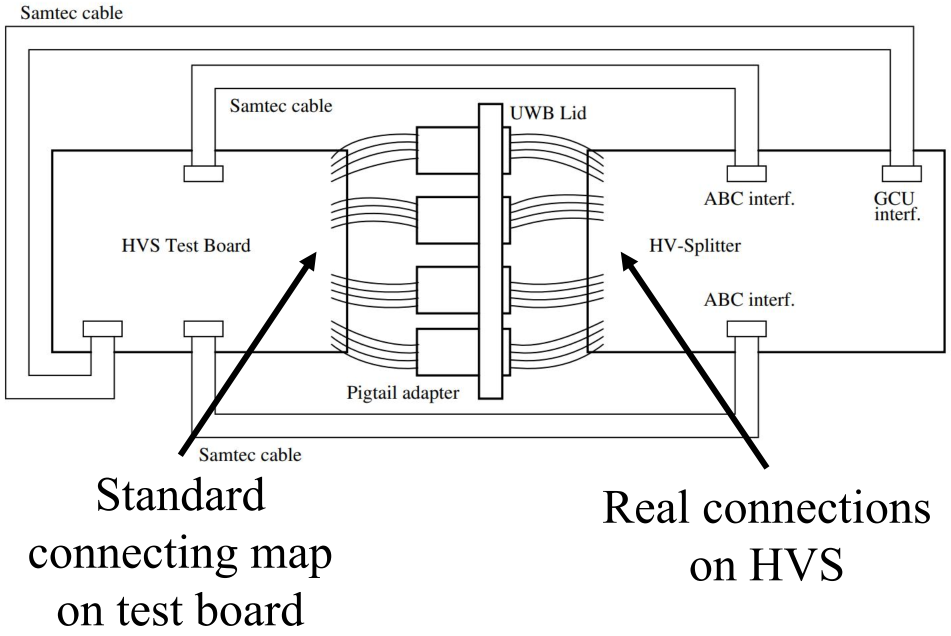
SPMT electronics integration procedure

- 204 sets of electronics have been integrated at JUNO site
- Mass integration starts in September 2022 and ends in April 2023
- 2 ~ 4 workers worked together with 2 ~ 4 JUNO collaborators
- 2 electronics per day at first → 3 ~ 4 electronics per day

Connection check



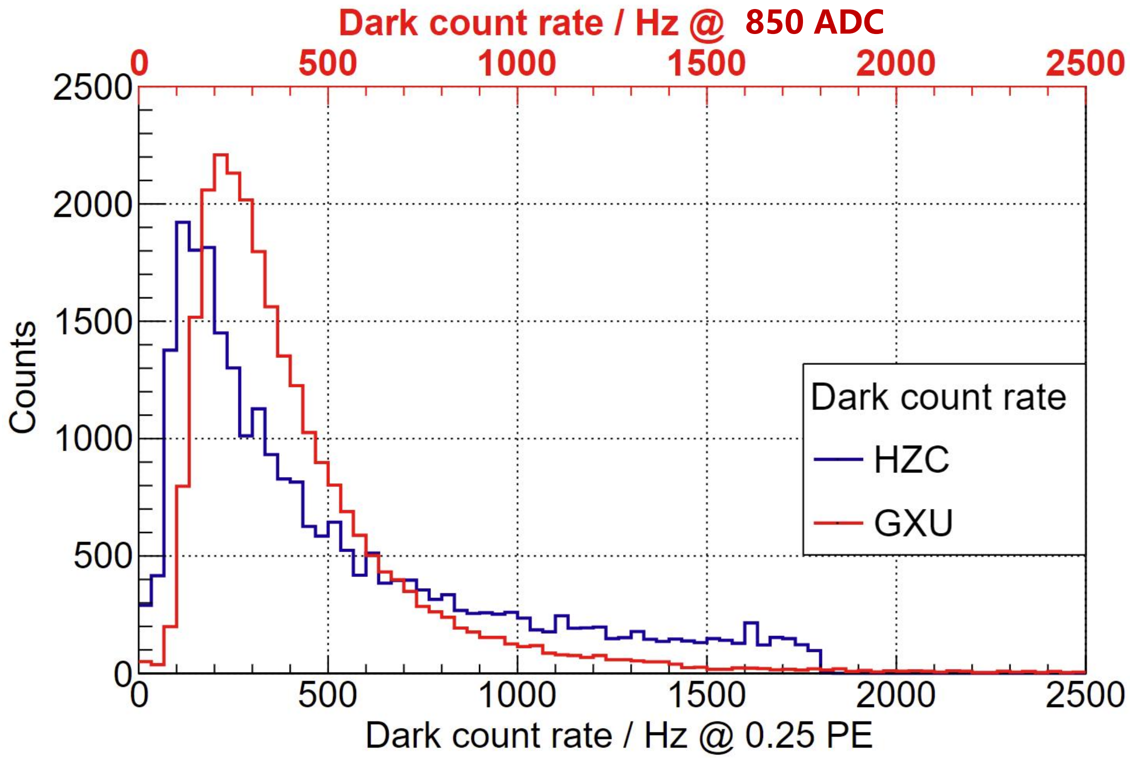
HVS test board system



- Use series of known pulses to ensure correctness of 128 cable connections
- Make sure HVS is working

Dark count rate

Dark count rate > 3 kHz : 82 PMTs → 0.3%

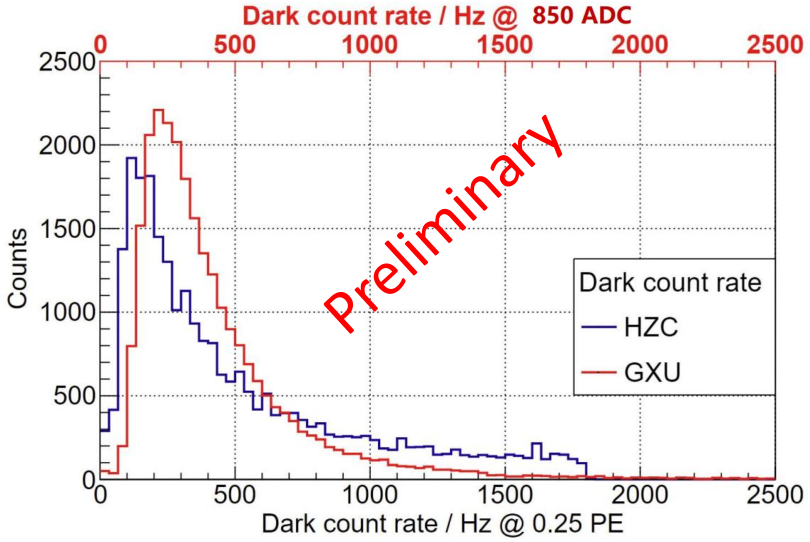


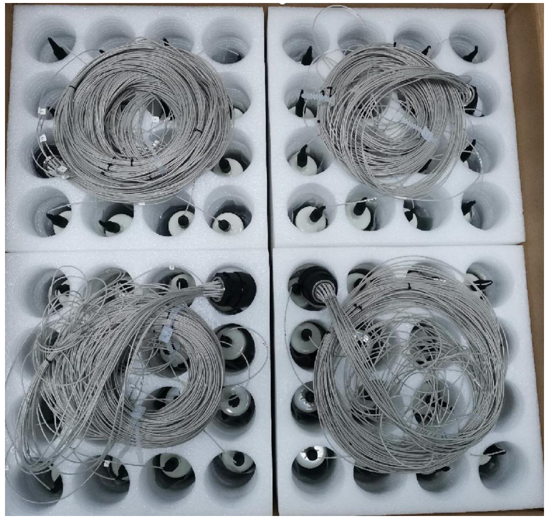
The long tail of HZC:

- It’s because HZC without enough cooling time
- In HZC, if dark rate < 1.8 kHz, then stop the measurement

How to understand GXU has a larger peak position?

Dark count rate





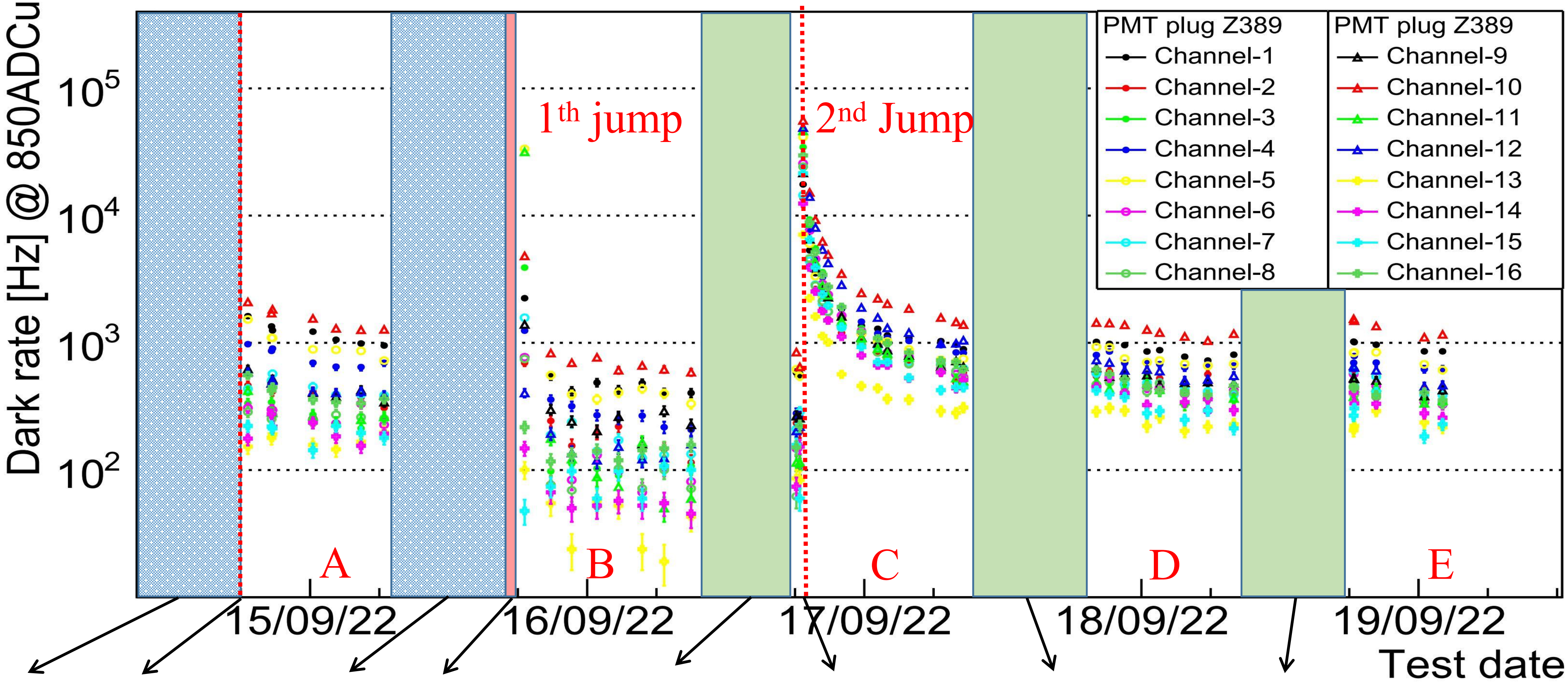
The long tail of HZC:

- It's because HZC without enough cooling time
- In HZC, if dark rate < 1.8 kHz, then stop the measurement

Investigation - Foam material

- ➢ Many foam materials are used for packaging and protection
- ➢ Could it be the source of larger dark rate?

How to understand GXU has a larger peak position?



In dark room for more than 20 days, with foam material, HV off

HV on

Night, HV off

Remove foam material, red light exposure for 10 mins, then HV on

Night, HV on

HV off, add foam material, red light exposure for 4 mins, then HV on

Night, HV on

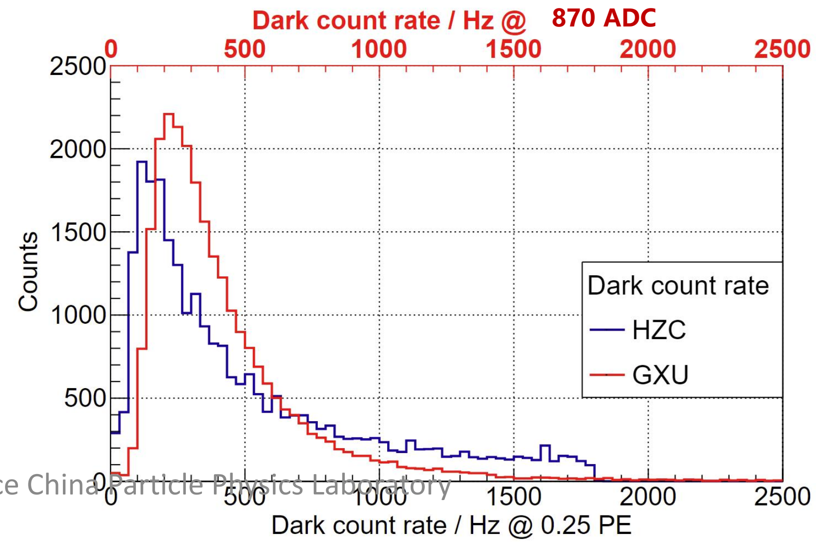
Night, HV on

Foam material with room light exposure after removed

Comparing period A, B and E: fluorescence introduces fake DR (100~300 Hz) in PMT DR measurement

Dark count rate

- How to understand GXU has a larger peak position?
  - Fluorescence from foam materials introduces fake DR (100~300 Hz) in PMT DR measurement
  - The true dark rate is better (the current criteria of 3 kHz is strict for some PMTs)
- Any modification of our test is needed?
  - No, we found this explanation until Sep. 2022, testing is finished and retesting seems unnecessary
  - It requires a lot of work if we want to remove the foam materials during the test, and it has a big risk for SPMTs



How to understand GXU has a larger peak position?