OSIRIS – An online scintillator radiopurity monitoring pre-detector of JUNO

NUCLEUS 2021

09.2021 I Runxuan Liu [1, 2], on behalf of the JUNO collaboration

[1]Forschungszentrum Jülich - Institute for Nuclear Physics, IKP-2, Jülich, Germany

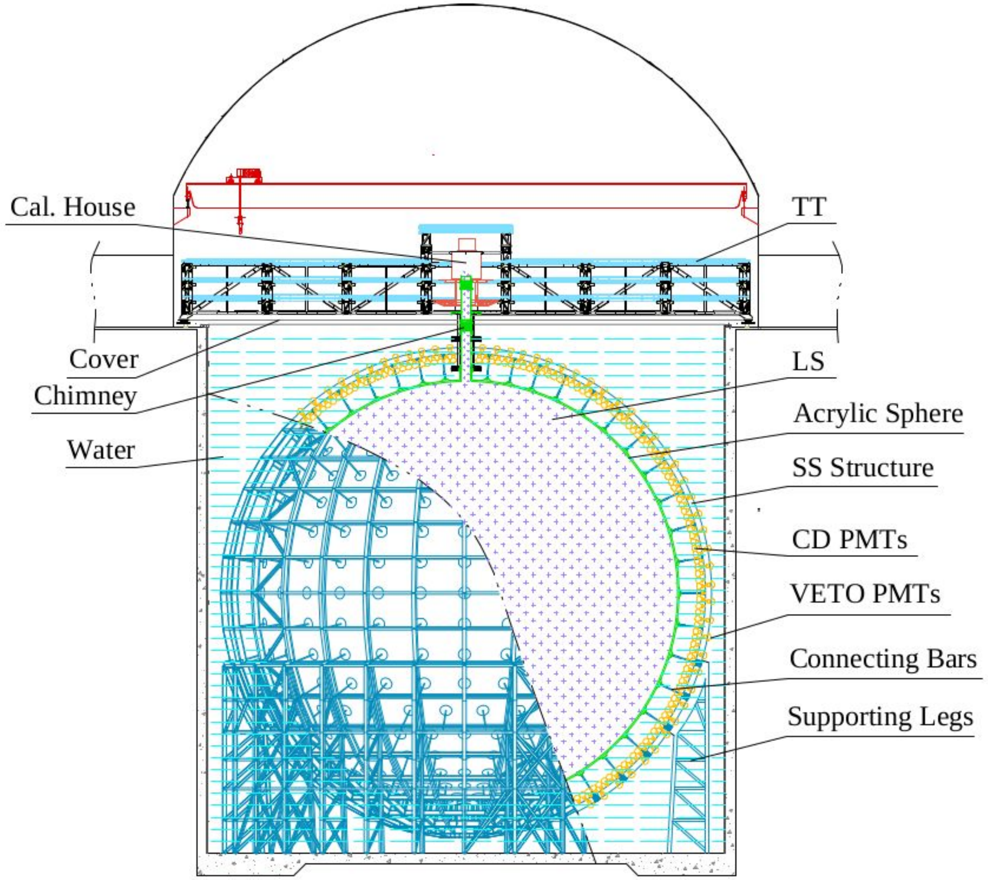
[2]RWTH Aachen University - Physics Institute III B, Aachen, Germany

JUNO Experiment

See more about JUNO in Yury Malyshkin's plenary talk

- JUNO (Jiangmen Underground Neutrino Observatory) is a next-generation multi-purpose experiment.
- Under construction in Jiangmen, China.
- Expected to start data taking in 2023.
- The primary goal: to determine the neutrino mass hierarchy via oscillation pattern of reactor antineutrinos at 53 km baseline.
- There are several other (astro-) particle physics goals like detection of solar neutrinos, geo-neutrinos, atmospheric neutrinos, supernova neutrinos, DSNB neutrinos.

- ➢ 20 kton liquid scintillator (LAB)
- ➢ 17,612 large 20“-PMTs
- ➢ 25,600 small 3“-PMTs
- ➢ 3% energy resolution at 1 MeV



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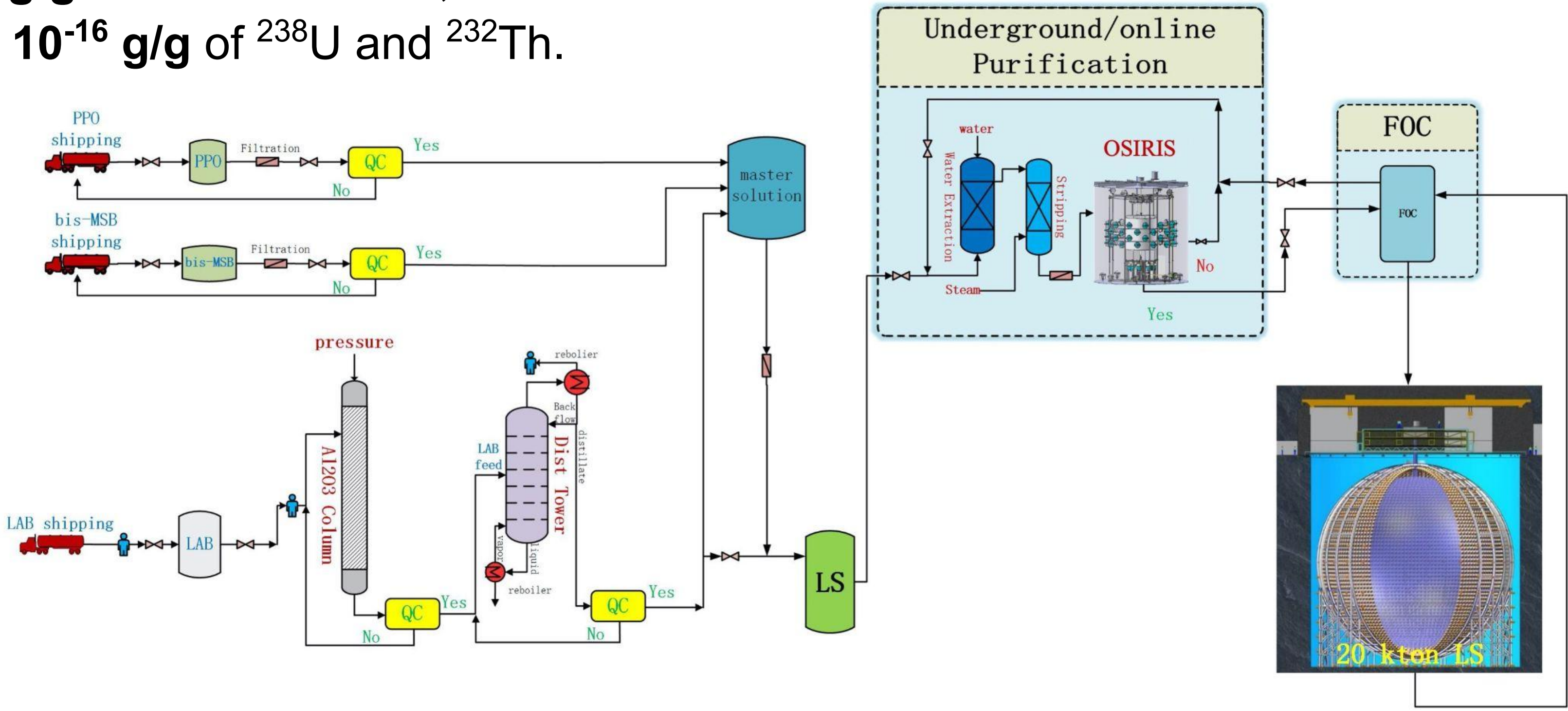
JUNO Scintillator System

- The radioactivity in LS may trigger events that mimicking the IBD (inverse beta decay) coincidence signals, or cause pile-up to the single events.
- For solar neutrino detection, β-decaying isotopes can form a background to elastic neutrino scattering events.
- So stringent requirements on the radiopurity of the LS is set as:
  - For **IBD-based** physics: **≤ 10^{-15} g/g** of ^{238}U and ^{232}Th;
  - For **solar neutrino** detection: **≤ 10^{-16} g/g** of ^{238}U and ^{232}Th.

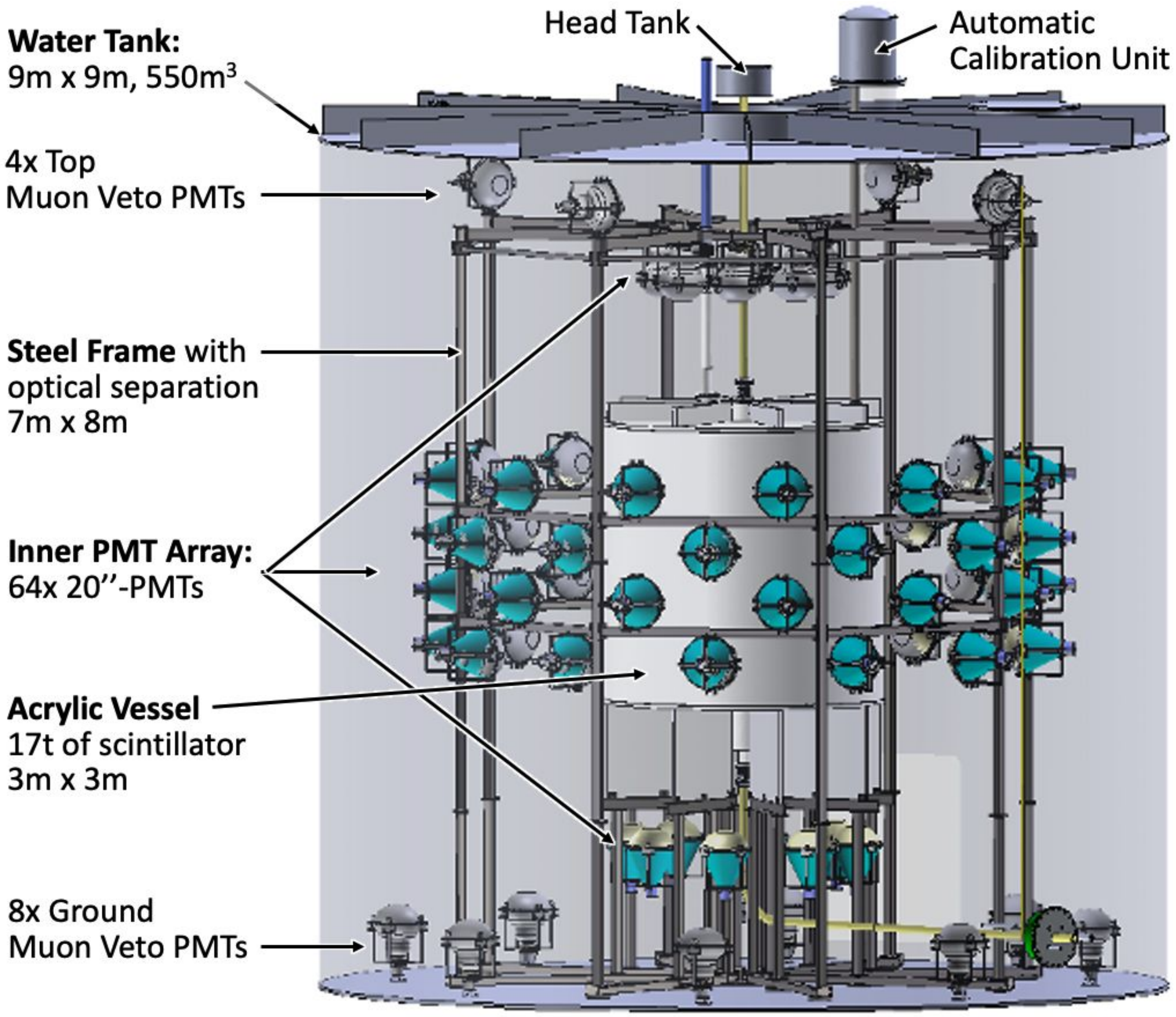
- A chain of specialized purification plants is designed to set up at JUNO site.
- After purification, mixing, and storage, the LS will finally enter **OSIRIS** (Online Scintillator Internal Radioactivity Investigation System) pre-detector during several months of filling process.
- Only a fraction of each purification batch will be tested by OSIRIS.



OSIRIS Experiment

- The OSIRIS setup has been optimized for the purpose to detect the residuals of natural U/Th contamination of the LS.
- OSIRIS can hold 18 ton LS in the acrylic vessel.
- OSIRIS consists of
  - Inner detector (ID): LS volume with 64 inner PMTs
  - Outer detector (OD): 12 outer PMTs face towards the water shielding as a Cherenkov muon veto.

- Searching for the fast coincidence decays of ^{214}Bi - ^{214}Po and ^{212}Bi - ^{212}Po in the decay chains of ^{238}U and ^{232}Th, respectively.
- Determination of the ^{14}C and ^{210}Po concentrations in the JUNO LS.
- Fast detection of air leaks at vales and connections via fast coincidences from ^{222}Rn and ^{85}Kr.



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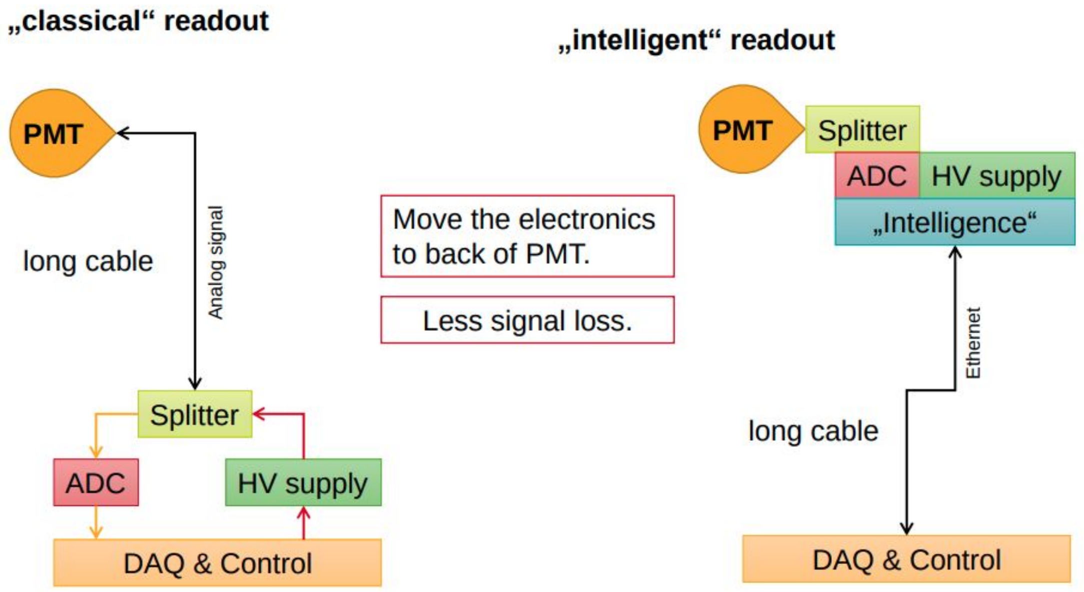
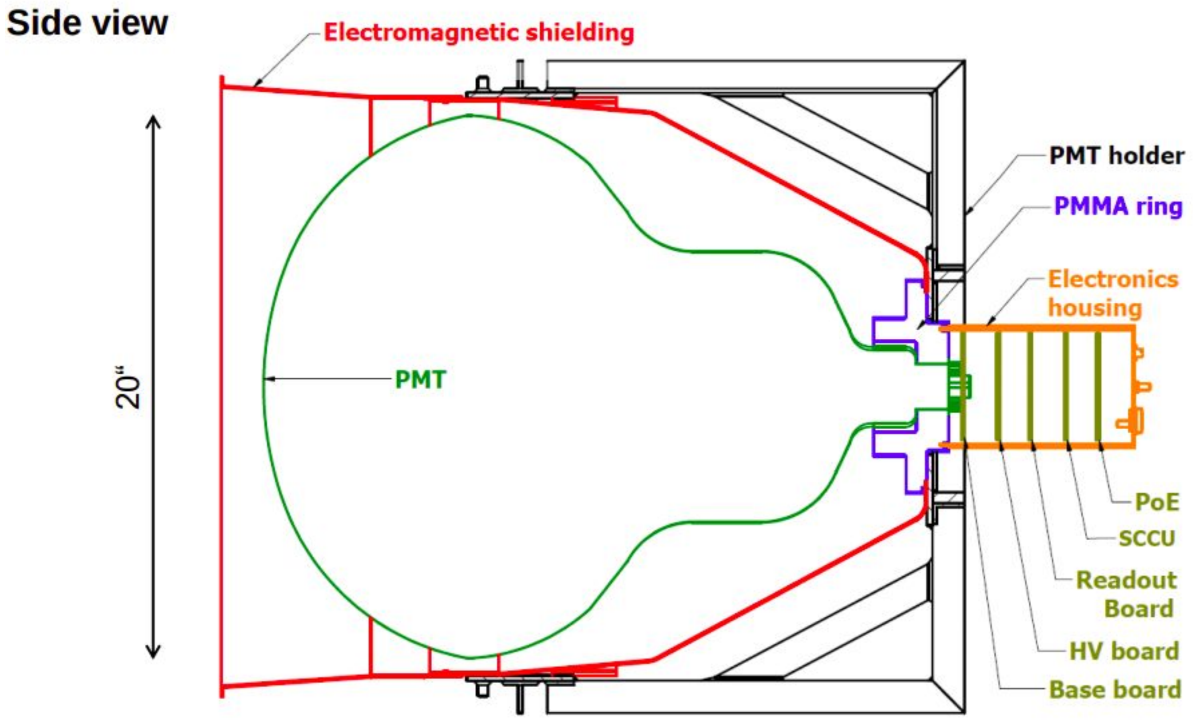
iPMTs (intelligent PMTs)

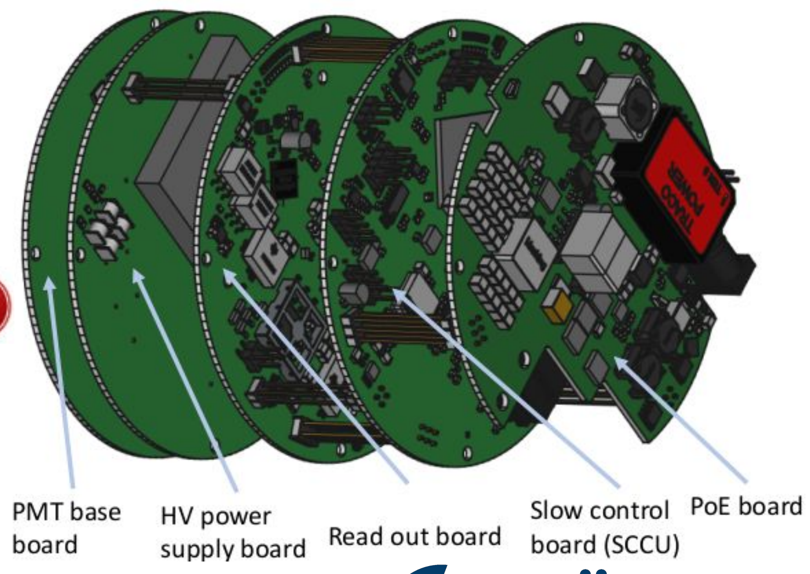
- OSIRIS uses 20’’-Hamamatsu PMTs .
- Dark count rate is 15.4 ± 2.6 kHz per PMT.
- All required electronics (high voltage supply, digitizer and control) are mounted at the PMT bases.





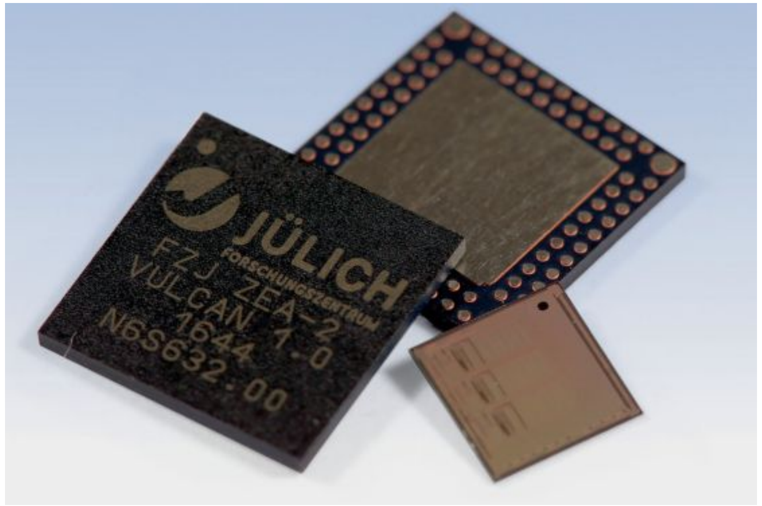
iPMT assembly

iPMT electronics stack

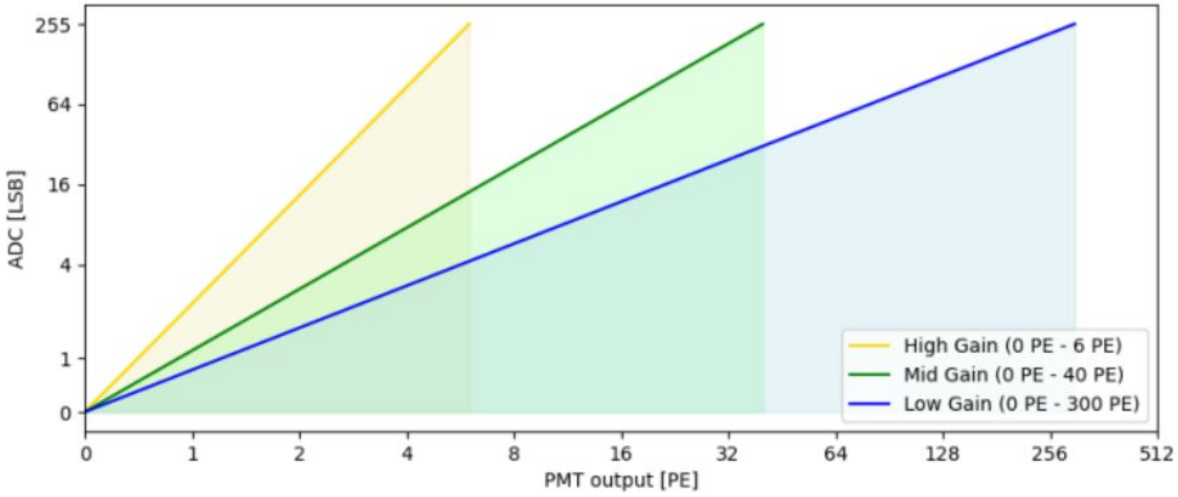


iPMT

VULCAN ASIC (Application-Specific Integrated Circuit)



- The VULCAN chip was developed by ZEA2, FZ Juelich, Germany.
- It has three individual identical receivers.
- Each receiver has an ADC with sampling rate 500 MSps.
- All three receivers are sampled in parallel.
- They cover different signal amplitude ranges.
- The ASIC selects the one with the highest resolution and no saturation.



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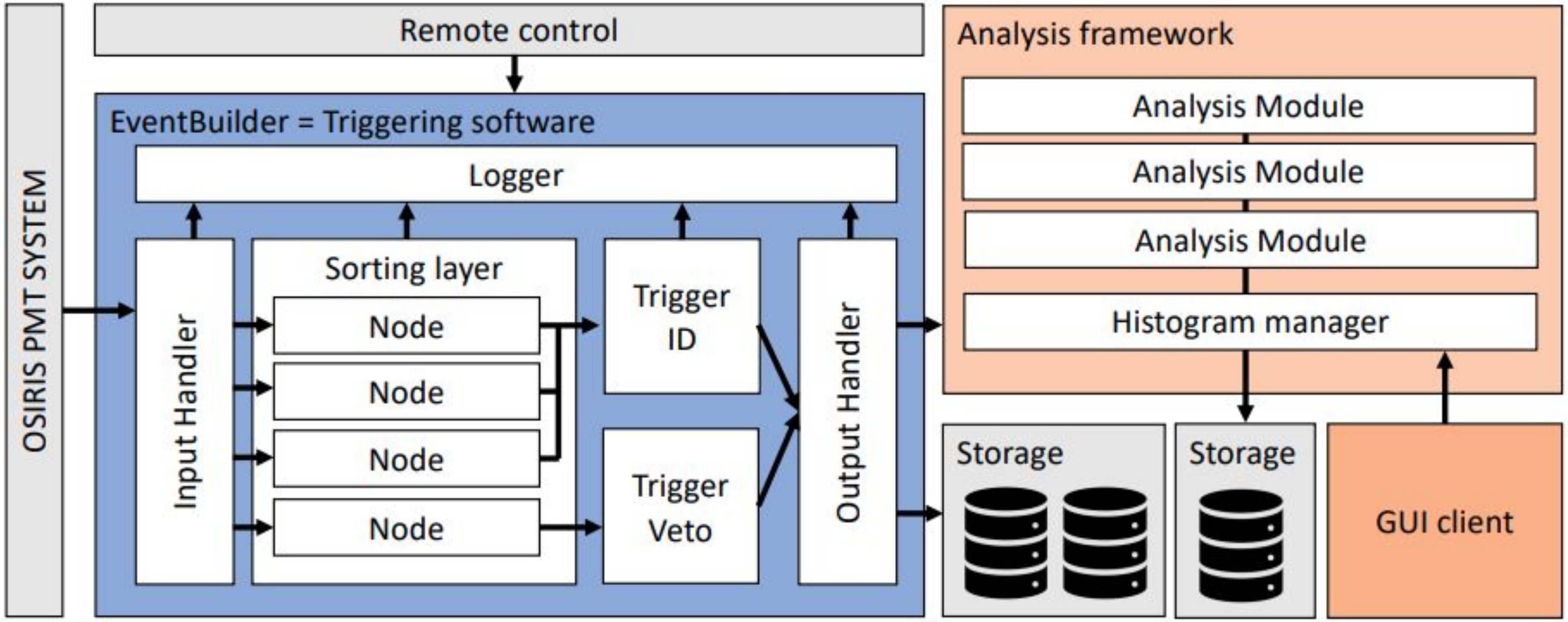
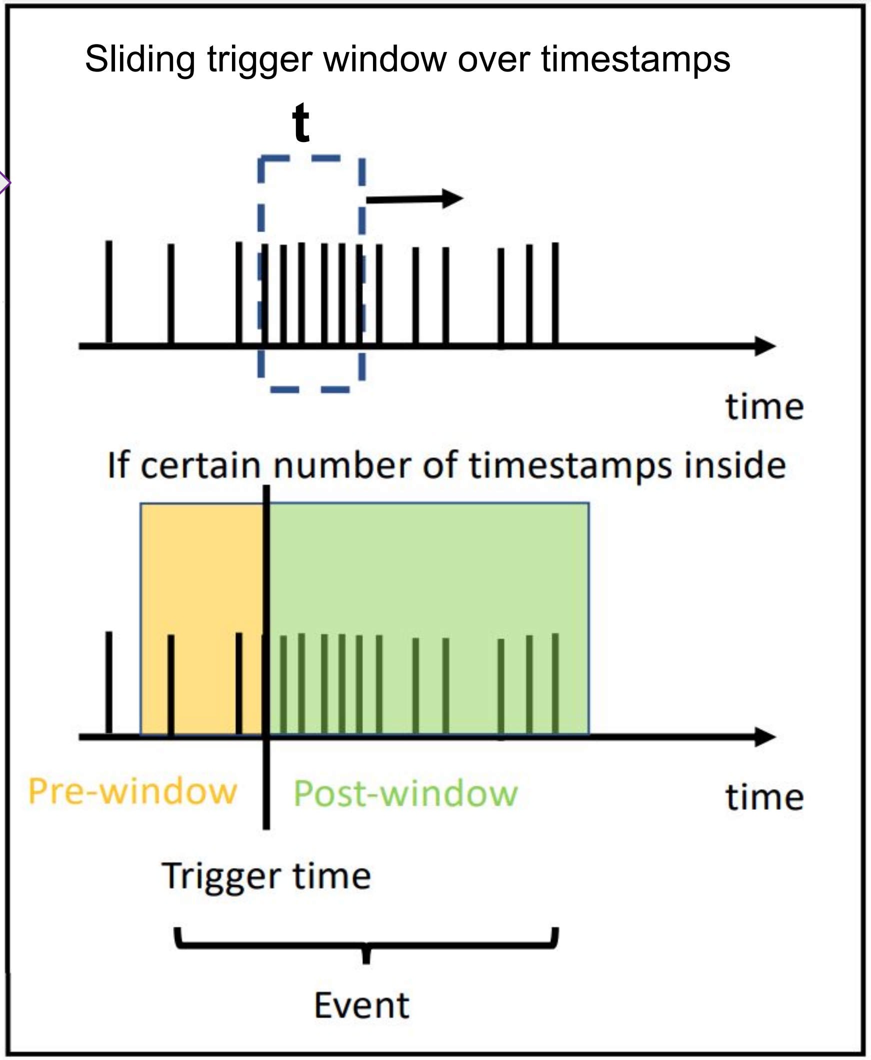
Online DAQ

- Each PMT will provide a data-stream composed of the digitized PMT pulses, each contains a timestamp.
- The event builder software will build events in ID and OD with optimized trigger conditions.
- Change of the event rates (especially Bi-Po coincidence) needs to be monitored in real time.
- Therefore, event reconstruction and analyses have to be performed online.



Trigger Conditions Optimization

- Trigger condition (**t**, **n**) is defined as a minimal multiplicity of timestamps **n** in a time window **t**.
- For ID and OD, we will apply different pairs of trigger conditions.
- The ID&OD triggered events will merge as one if their timestamps are within 200 ns.
- Optimize ID trigger conditions assuming ^{14}C contamination in the LS of 30.0 Bq and dark noise in ID of 15.3 kHz.
- Applying (**t**, **n**) = (70 ns, 5) for ID, we have:
  - ^{14}C event rate of 22.5 s^{-1}
  - pure dark noise event rate of 2.9 s^{-1}
  - Trigger efficiency reaches 90% at 36.0 keV.
- For OD, multiplicity n > 4: to have darknoise event rate < 10 times smaller than the muon rate in OSIRIS (0.39 s^{-1}).
- Trigger conditions **ID (70 ns, 5)** and **OD (150 ns, 5)** give muon trigger efficiencies:
  - **OD = 94.7%; ID||OD = 95.1%.**

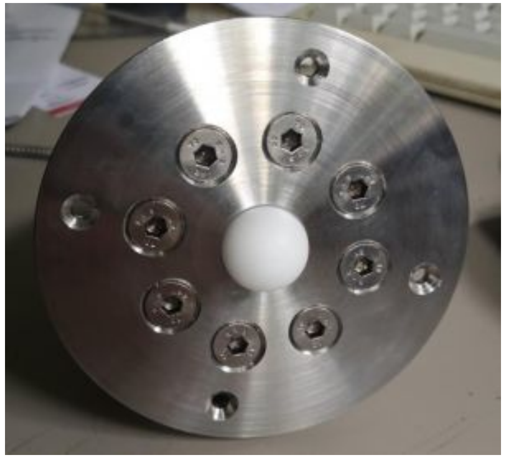


Calibration Systems

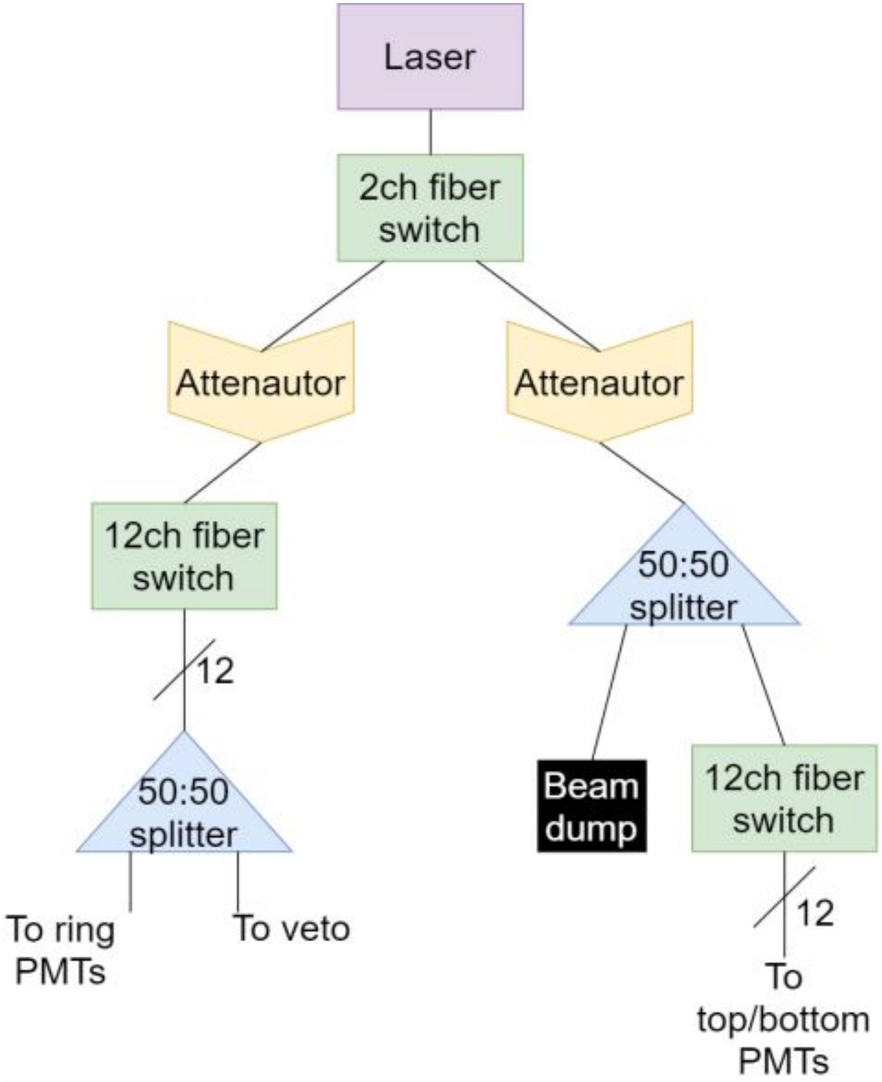
Laser Fiber System

- Precise relative timing and single photoelectron (s.p.e.) charge calibration of all PMTs.
- Picosecond laser (pulse length ≈ 80ps).
- 24 light insertion points with diffusers (showing below) to create homogeneous light field.
- Their positions are optimized according to uniform illumination of all PMTs (light intensities varying ≤ a factor of 2).
- A light distribution system (LDS) is applied (showing on the right).
- Required pulses: 2×10^5.
- Measurement time per diffuser:

  20 s @ 10 kHz.



Diffuser Capsule



Light routing scheme of the Laser calibration system

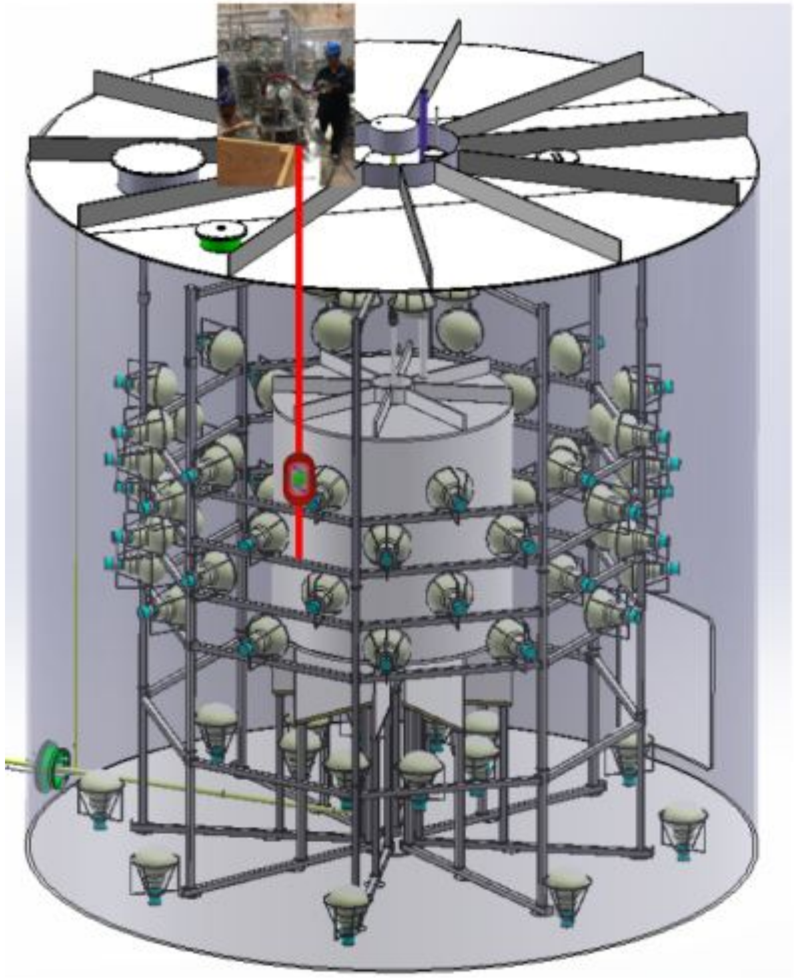
Calibration Systems

Source Insertion System

- Use gamma sources to calibrate the energy and the position reconstruction.
- And LED for time and charge calibration.

- Based on an Automated Calibration Unit (ACU), provided by the Daya Bay collaboration.
- Mounted on the roof of the water tank.
- 1.2 m from the central detector axis, to maximize the variation of the detector response at different height.

- One capsule carries LED (435 nm) with tunable intensity to investigate the PMT response to higher p.e. occupancies, also used for iPMT timing calibration at low intensities.
- One capsule with ^{137}Cs, ^{60}Co, and ^{65}Zn, for initial and regular calibrations, combined several kBq.
- One capsule with ≤ 1 Bq of ^{40}K, for continuous monitoring of the LS.



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Calibration Systems

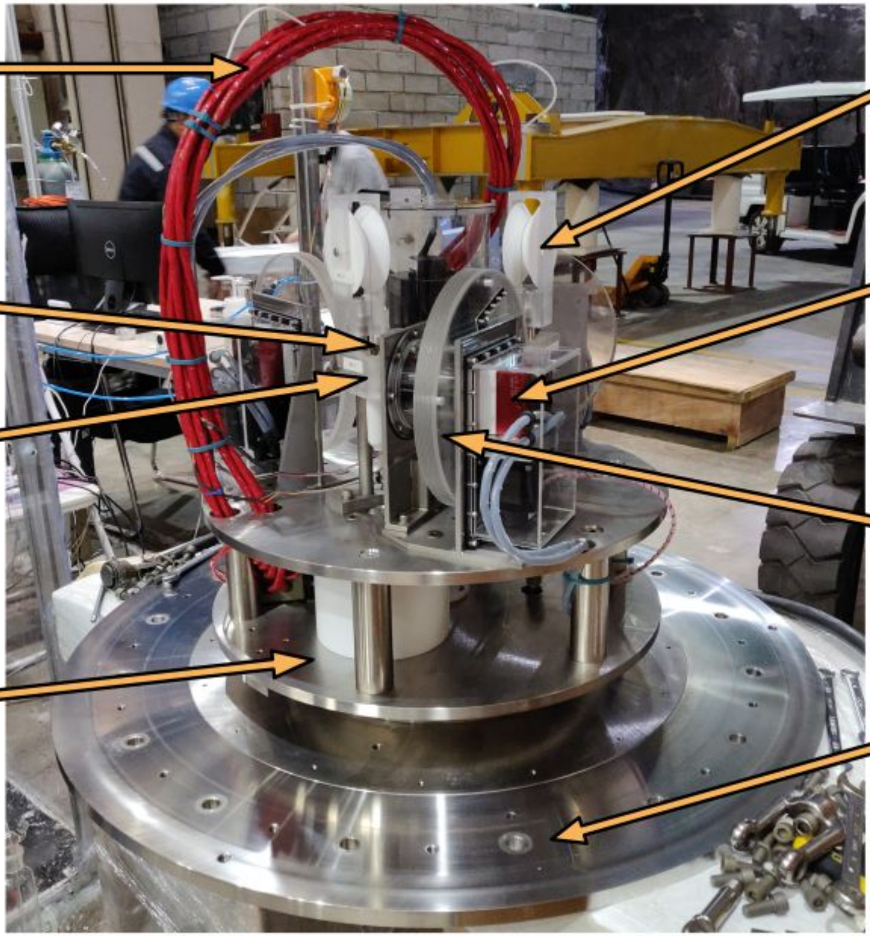
Automated Calibration Unit, Provided by the Daya Bay Experiment

Flexible cabling
- Bundles all incoming cables
- Designed to withstand moving turntable

Limit switch
- Automatic termination of wheel movement at fixed point

Load cell
- Montoring of cable tension
- Allows emergency shutoff before tearing of cable

Turntable
- Turns the whole structure
- Choice of three deployment wheels
- Limit switches in both directions



Deflection pulley
- Absorbs lateral displacement of the cable unwinding from the wheel

Stepper motor
- Moves the wheel to lower the source
- Worm gear box
- Control and feedback through software

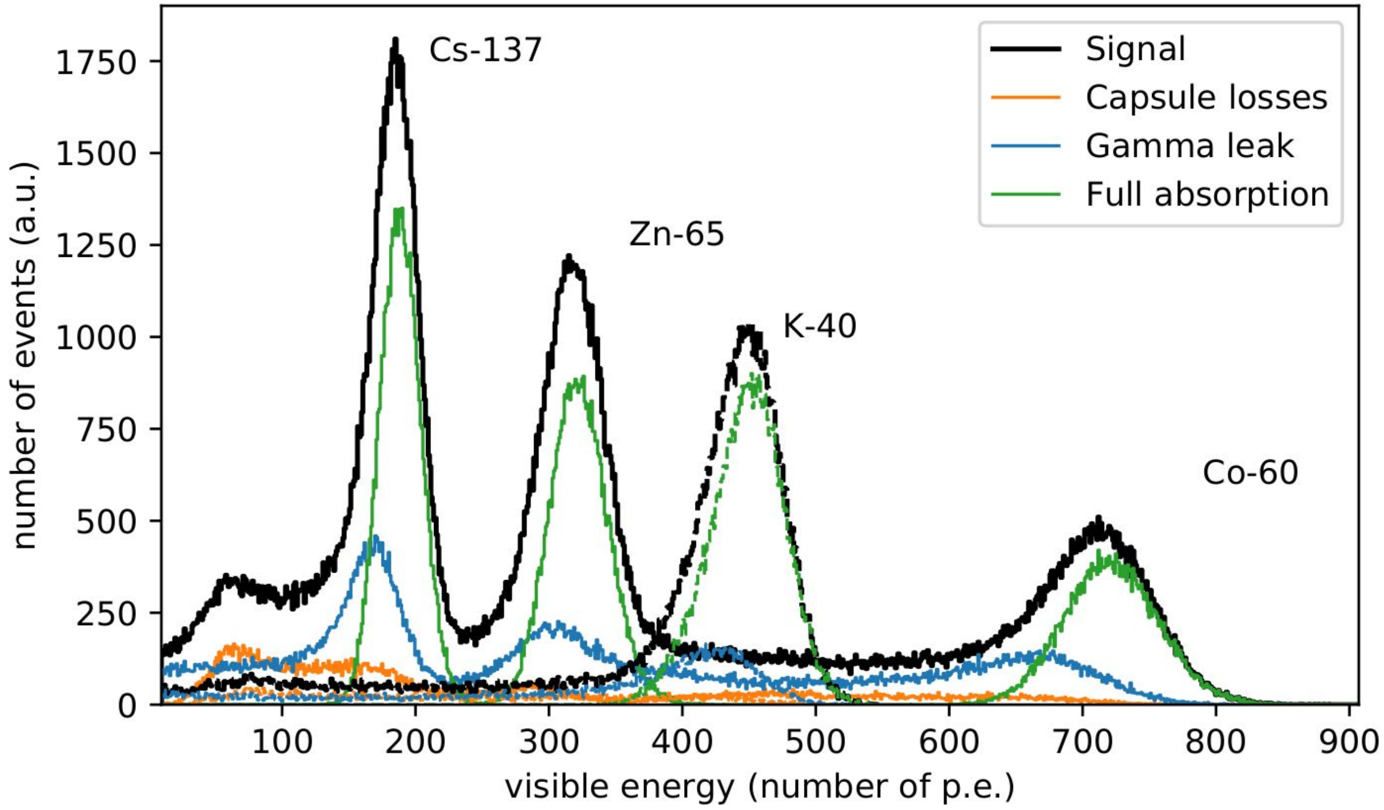
Deployment wheel
- 9 inch diameter
- 10 groves
- Tota of ~7 m cable deployable

Flange
- 35 inch diameter
- Connection to bell jar on top and detector on bottom

Calibration Systems

ACU Energy calibration

Monte Carlo simulation of the visible energy spectra
Source position: x = 120 cm; y = 0 cm; z = 120 cm



- Solid lines: weekly calibration with ^{137}Cs, ^{60}Co, and ^{65}Zn of several kBq.
- Dashed lines: continuous source with $^{40}K \leq 1$ Bq.

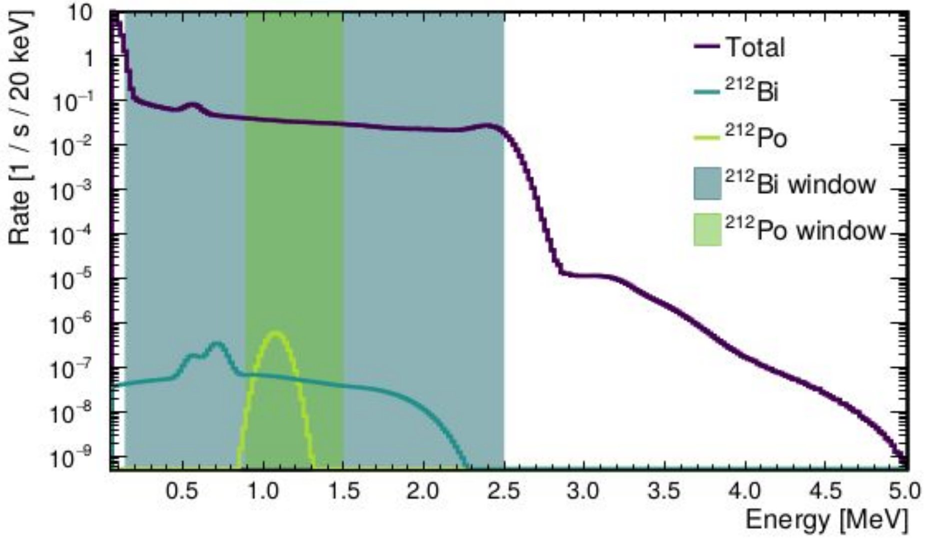
Sensitivity[1] (to ^{238}U and ^{232}Th contamination)

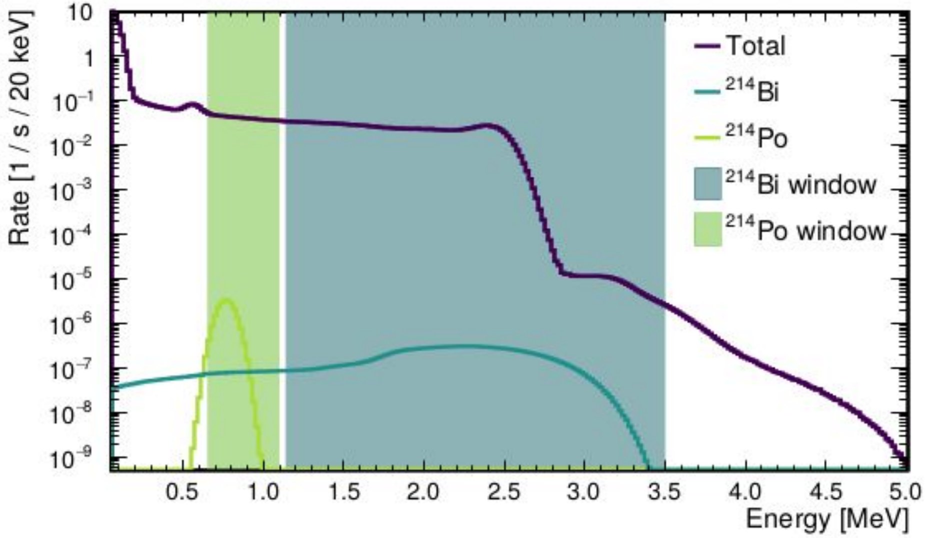
Selection Cut of Bi-Po Coincidence events

Decay chain	Mass limit (IBDs)	β-α-coincidence	Activity limit	Po lifetime
^{238}U	10^{-15} g/g	^{214}Bi-^{214}Po	1.2×10^{-8} Bq/kg	237 µs
^{232}Th	10^{-15} g/g	^{212}Bi-^{212}Po	0.4×10^{-8} Bq/kg	0.5 µs

- To select Bi-Po coincidence events:
  - The fiducial volume is defined as a cylinder of 2.8 m height and diameter;
  - $E_{Bi, Po}$ are the energy windows selected for prompt and delayed decays;
  - Δt and Δr are time distance cuts.
- For distance cut, the numbers in brackets represent the rejection efficiencies for accidental coincidence.

	^{212}Bi–Po		^{214}Bi–Po	
Cut	Range	Efficiencies (%)	Values	Efficiencies (%)
FV	<140 cm	-	<140 cm	-
E_{Bi}	0.14 MeV to 2.5 MeV	98	1.4 MeV to 3.5 MeV	83
E_{Po}	0.9 MeV to 1.5 MeV	100	0.7 MeV to 1.1 MeV	99
Δt	0.2 µs to 2 µs	62	0.2 µs to 711 µs	95
Δr	<72.5 cm	98 (94)	<45 cm	88 (98)
Total		60		69





[1, Fig.16]

[1] : Based on arXiv:2103.16900 (published on European Physical Journal C)

Sensitivity (to ^{238}U and ^{232}Th contamination)

Bi-Po Sensitivity in Batch Mode

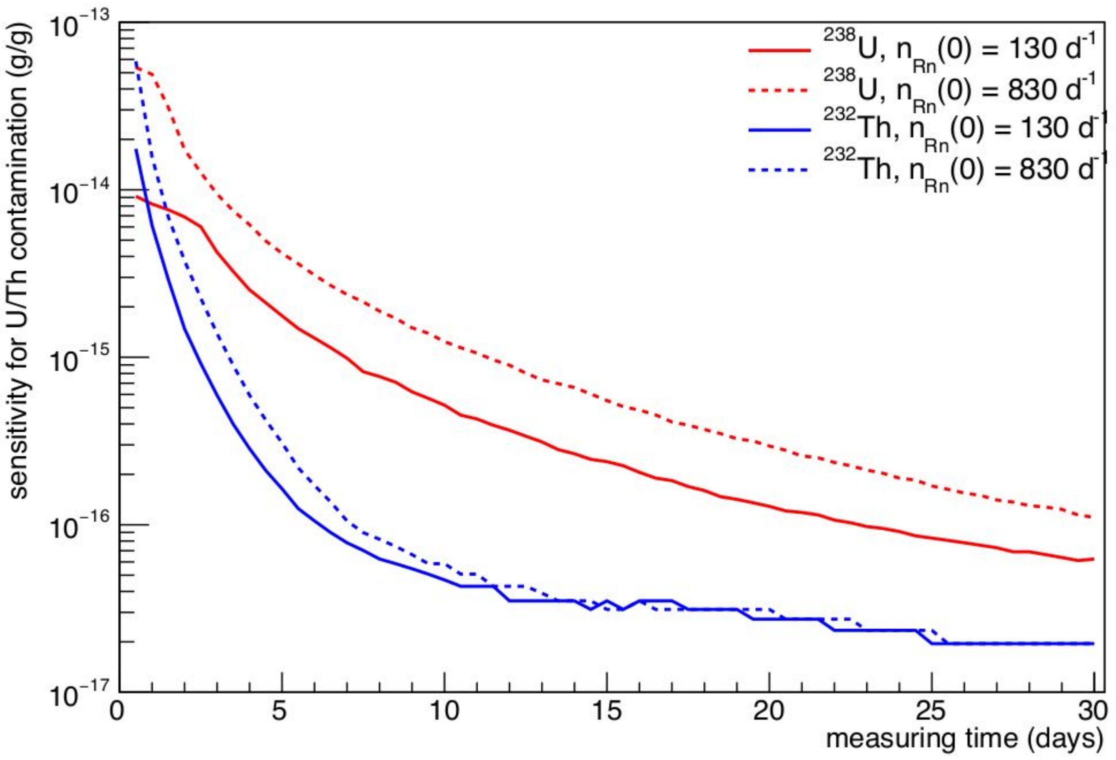
- OSIRIS is designed to have two operation modes:
  - Batch mode: a single 18-ton sample of LS will be monitored over days or weeks.
  - Continuous mode: constant exchange of LS during JUNO filling phase.

- Assuming presence of an initial radon contamination:

  $\dot{n}_{Rn}(0) = 130 - 830$ counts per day

- The strategy for sensitivity determination of a counting experiment (Cowan et al., 2011) is used.
- The sensitivity curves of ^{212}Bi-Po and ^{214}Bi-Po for a 90% confidence level are shown in the plot.

- OSIRIS can verify the JUNO IBD-level requirement within days
- For JUNO solar requirement, a measurement of 2-3 weeks is needed.



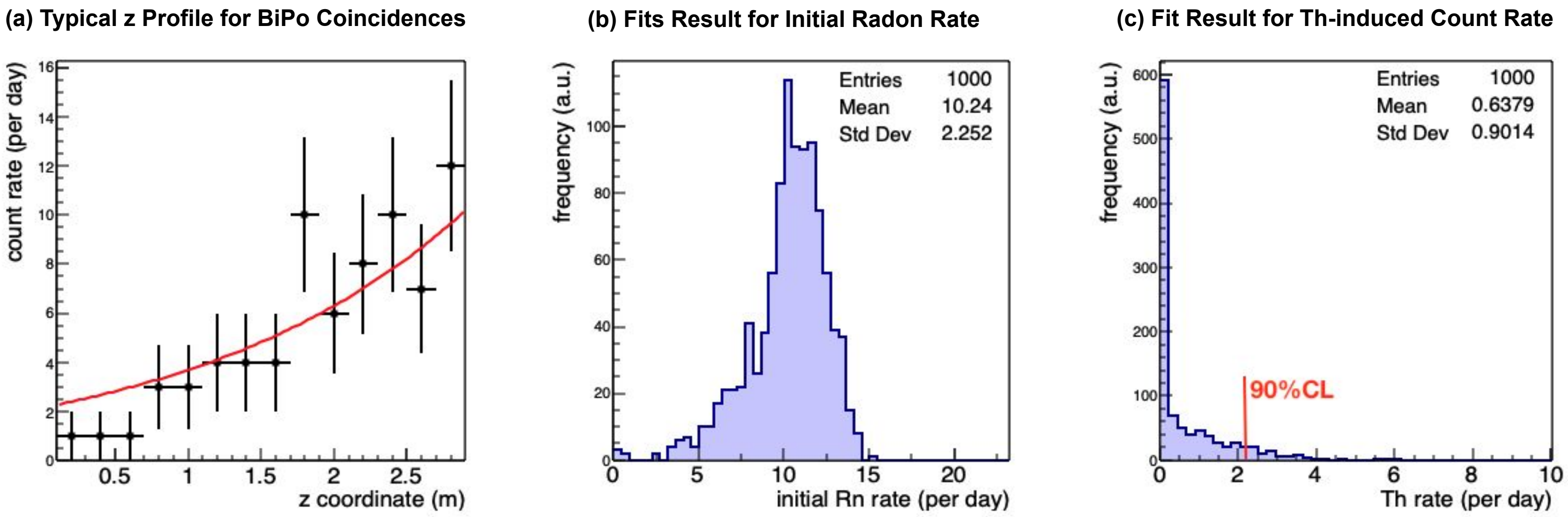
[1, Fig.18]

Sensitivity (to ^{238}U and ^{232}Th contamination)

Bi-Po Sensitivity in Continuous Mode

- The Bi-Po rate supported by radon will partially decay while LS traveling from top to bottom of the acrylic vessel. A reduction by 17% (80%) is expected for ^{222}Rn (^{220}Rn).

- The height (z) is equivalent to a time coordinate.
- Assuming 830 /day initial Rn rate, an exponential fitting (plus constant) is applied in plot (a) that reflects the ^{212}Pb lifetime and LS flow speed.



[1, Fig.19]

- Plot (b) and (c) show the results for Rn and Th-induced Bi-Po rates.
- The expected corresponding upper limit on the ^{232}Th contamination for 90% C.L. translates to $1.4 \cdot 10^{-14}$ g/g.

- In this continuous mode, OSIRIS can provide a timely warning to in case a sudden air leakage increases the amount of Rn.

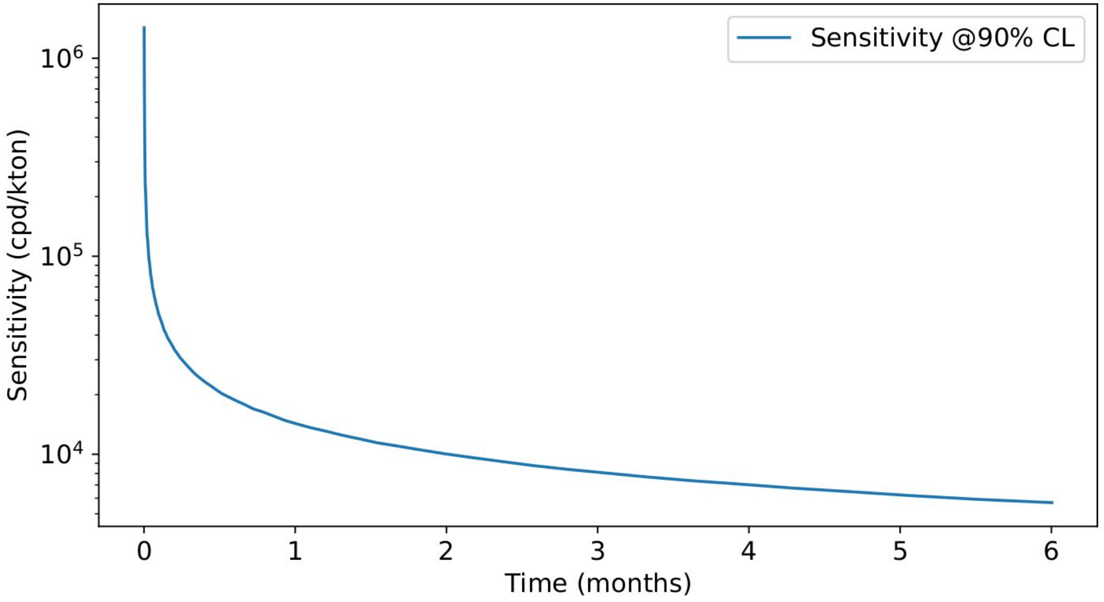
Sensitivity

^{85}Kr

- ^{85}Kr contamination is a measure of air leak in the LS filling process.
- The main decay branch of ^{85}Kr is β decay with endpoint energy of 687 keV.
- Its spectral shape and the expected rate is similar to the electron recoil spectrum of solar ^{7}Be neutrino.
- So it is an important background in JUNO solar analysis.

- Pre-window time in trigger study was optimized to catch the coincidence in ^{85}Kr decay, it is 5000 ns.

- The 90% C.L. sensitivity of OSIRIS to a contamination by ^{85}Kr in dependence of the measurement time is shown in the plot.
- The expected ^{85}Kr rate is much lower than the sensitivity.
- But it will be helpful if we have air leakage problem.

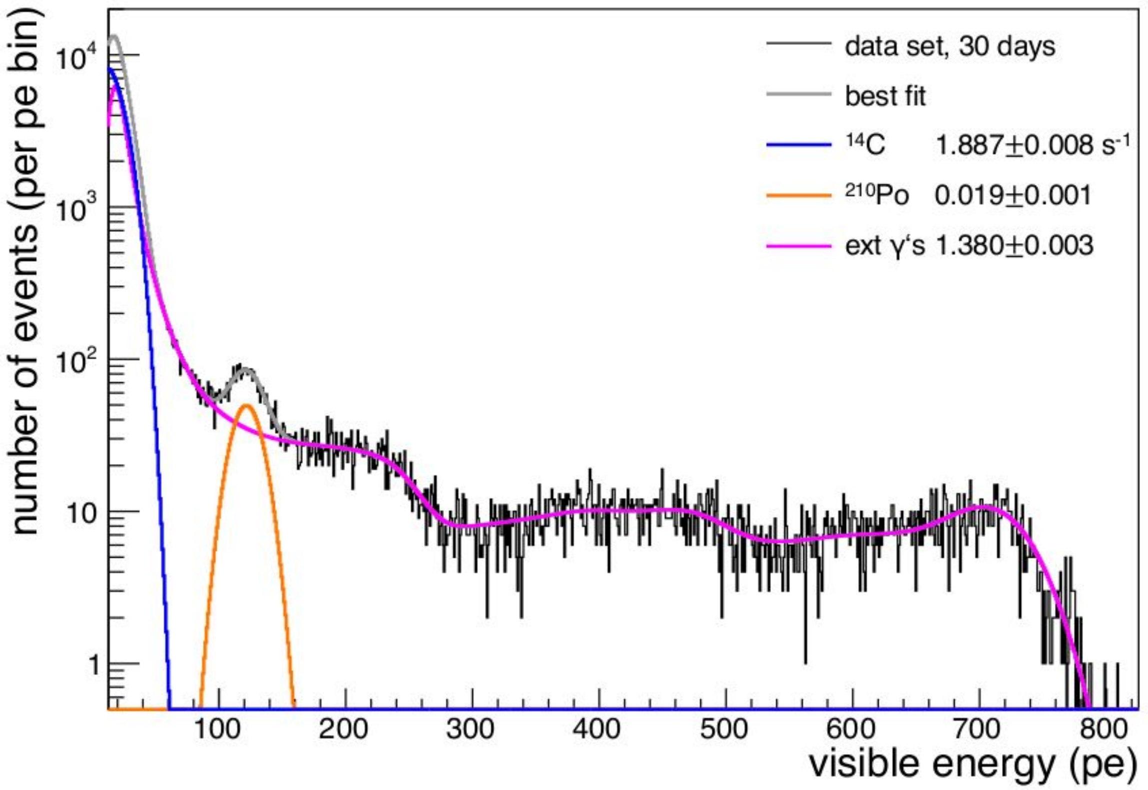


[1, Fig.20]

Sensitivity

^{14}C and ^{210}Po

- Restrict fiducial volume cut of 1 m height and diameter. Choose measuring time of 30 days.
- The baseline limit of ^{14}C for JUNO is: 10^{-17}.
- Assume ^{14}C abundance of 10^{-18} (*abundance level of Borexino*) and ^{210}Po decay rate at 80 /(day·ton).
- We got the sample photoelectron (p.e.) spectrum for OSIRIS.
- The spectral contributions of ^{14}C and ^{210}Po emerge above the otherwise dominant external γ background level.
- The ^{210}Po decay rate could be determined at 4% precision in a long batch-mode run.
- ^{14}C background will be easily measured in OSIRIS.



[1, Fig.21]

Summary

- Technical design of iPMT system, online DAQ system, and calibration systems are discussed.
- OSIRIS will provide valuable information on the efficiency of the purification chain and issue a timely alert in case problems occur with the radiopurity of the LS during filling of the JUNO main detector.
- OSIRIS has been optimized to screen the LS to the required radiopurity levels of U/Th.
- The final sensitivity and required measurement time depend on the level of radon emanation.
- OSIRIS will be able to trace air leaks in the JUNO filling system based on ^{85}Kr and ^{222}Rn.
- Excellent sensitivity will be achieved for the distinctive ^{14}C and ^{210}Po backgrounds.

Thanks for your attention!

If you have any questions or comments,
Runxuan Liu
r.liu@fz-juelich.de

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Back up

Decay chain of U/Th