OSIRIS – The Online Scintillator Internal Radioactivity Investigation System of JUNO

16.06.2022 | **Moritz Cornelius Vollbrecht** for the JUNO collaboration |

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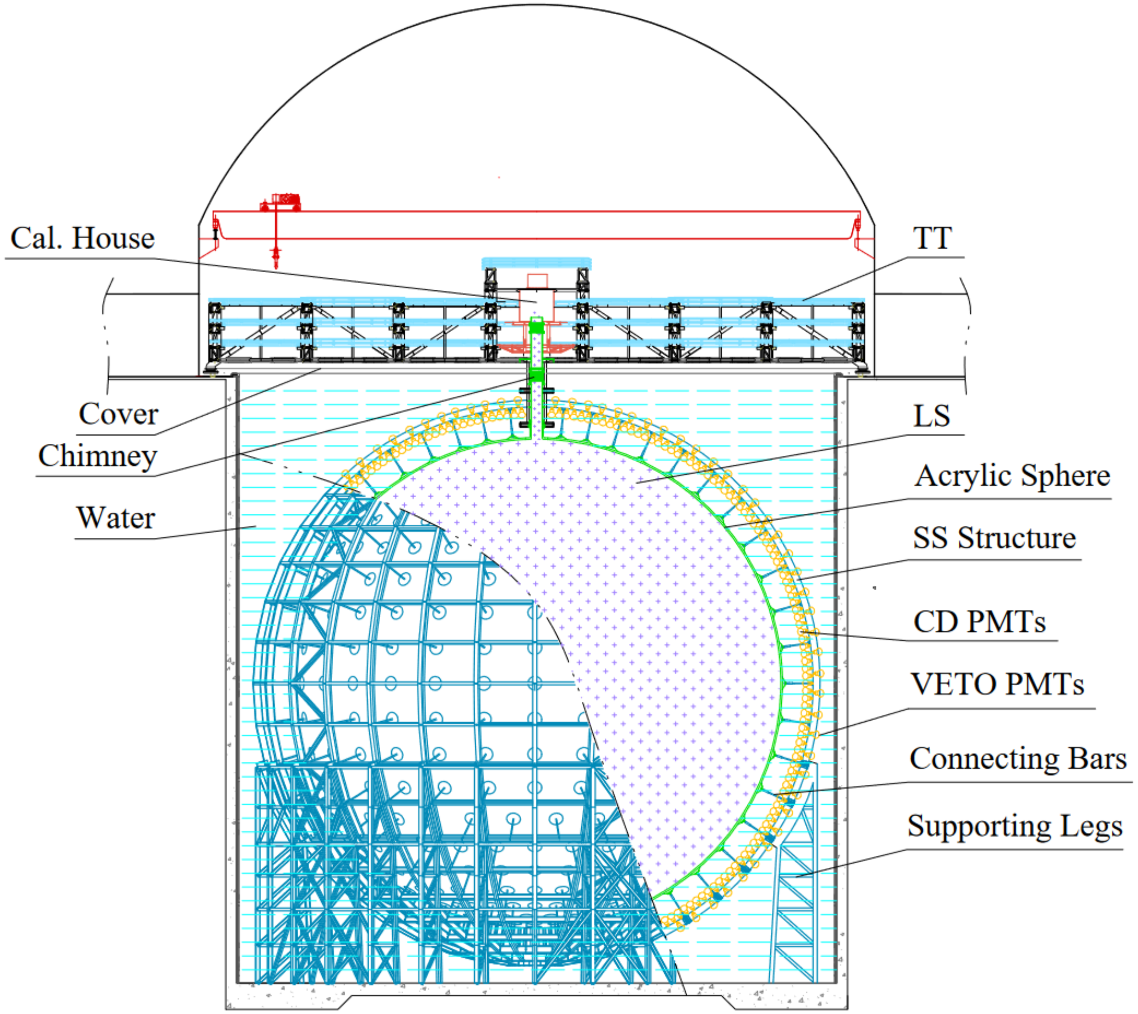
JUNO

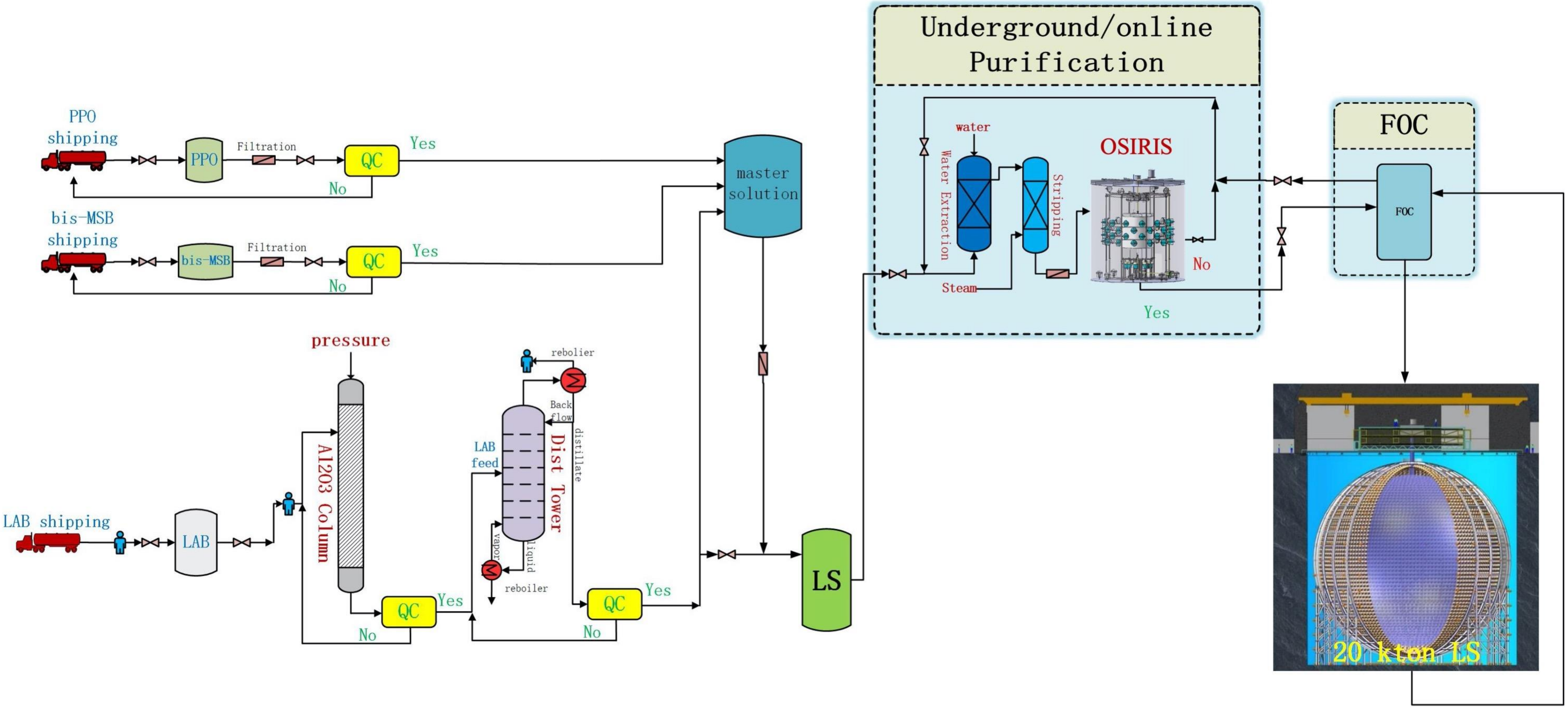
Jiangmen Underground Neutrino Observatory

- Currently under construction in Southern China, first data taking in 2023
- 20 kton liquid scintillator (LS) detector
- Central detector: 17612 20"- and 25600 3"-PMTs
- Excellent energy resolution of 3% at 1 MeV
- Main goal: determination of neutrino mass hierarchy via reactor anti-neutrino measurements (53 km baseline)
- Huge potential for other fields in (astro-)particle physics
- Radiopurity requirements of JUNO LS for ^{238}U / ^{232}Th:
  - 10^{-15} g/g reactor measurements
  - 10^{-16} g/g solar measurements
- Ensuring these limits during the months-long filling of JUNO crucial to achieve physics goals



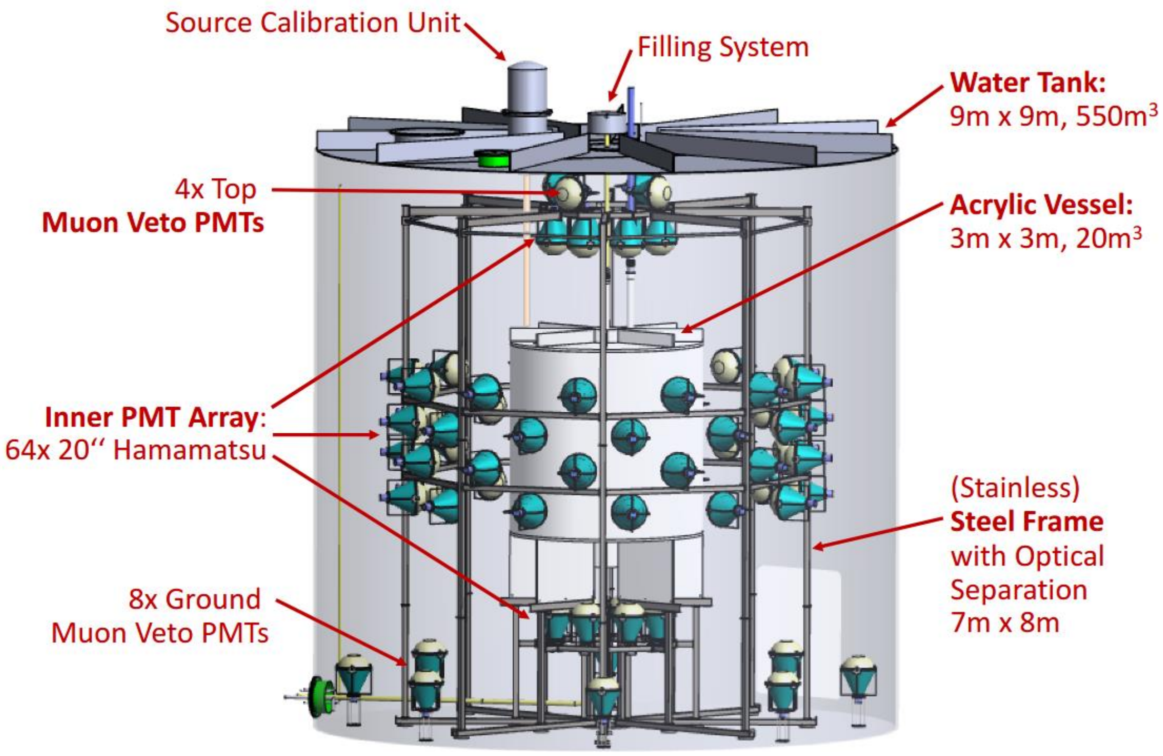
JUNO Physics and Detector
(arXiv:2104.02565)

JUNO LS purification and filling system



OSIRIS

Online Scintillator Internal Radioactivity Investigation System



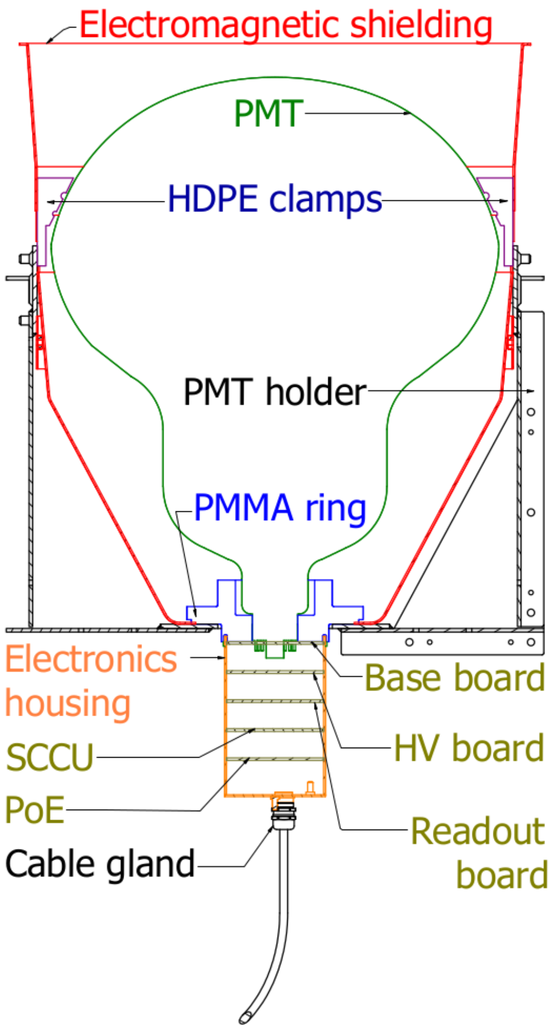
- Monitoring of LS radiopurity during JUNO filling via measuring Bi-Po coincidences in ^{238}U / ^{232}Th decay chains
- Levels of ^{14}C, ^{210}Po and ^{85}Kr also measurable
- Trigger alarms in case of contaminations and air leaks

- Main components of OSIRIS:
  - 9m x 9m cylindrical steel tank filled with ultra pure water
  - 18 t LS target in 3m x 3m cylindrical acrylic vessel
  - Stainless steel frame for mounting measurement devices and optical separation of veto
  - Two calibration systems (Light / Source Injection System)
  - 76 intelligent PMTs (64 instrumenting LS target, 12 for muon veto)

Intelligent PMT

Mechanical structure

- Novel design combining 20“-PMT with readout electronics
  → reduced noise, higher signal quality
- Single Cat5e cable sufficient for power and data transfer
- In total five boards per iPMT:
  - Base board (PMT pin connections, voltage dividers for HV)
  - HV board (high voltage for PMT)
  - Readout board (data processing and analysis)
  - SCCU: Slow-Control and Configuration Unit
  - PoE-board (supply voltages)
- Electronics sealed in oil-filled housing (cooling)
- PMMA ring as central support structure, glued to PMT neck
- Electromagnetic shielding for reducing earth magnetic field and electronic noise
- iPMT holder to mount full assembly in detector



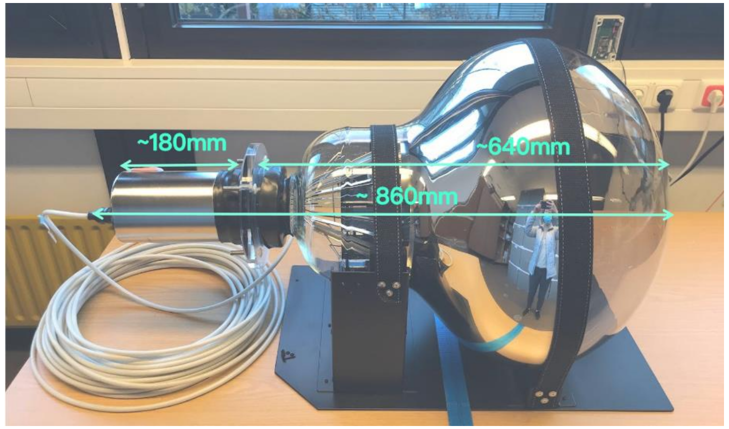
Intelligent PMT

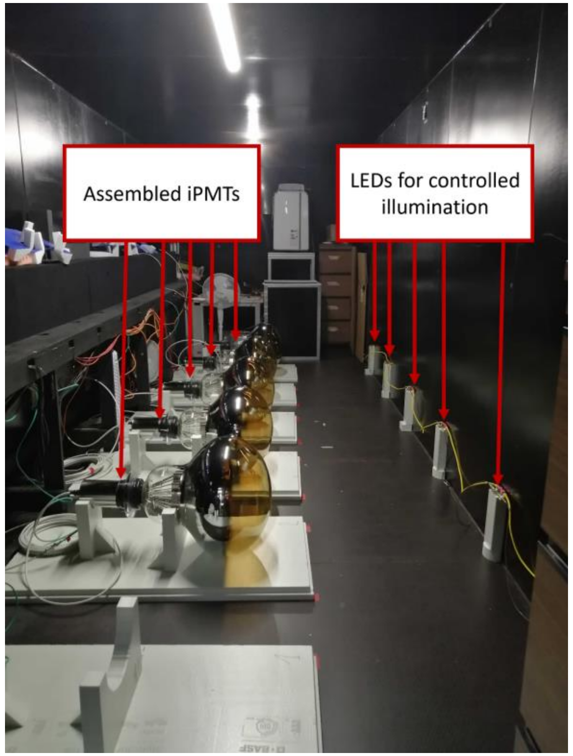
Why „intelligent“?

- Digitisation and waveform reconstruction algorithms directly on iPMT hardware → „intelligent“ PMT („iPMT“)
- Self-triggered during normal operation
- Digitisation chip: VULCAN (ZEA-2, Forschungszentrum Jülich)
- Sampling rate: 500 MSps
- FPGA and ARM combination (Xilinx ZYNQ) for data handling
- Highly configurable electronics, also after assembly
- Power consumption: < 15W
- iPMTs connected to SurfaceBoards

  → Clock and synchronisation

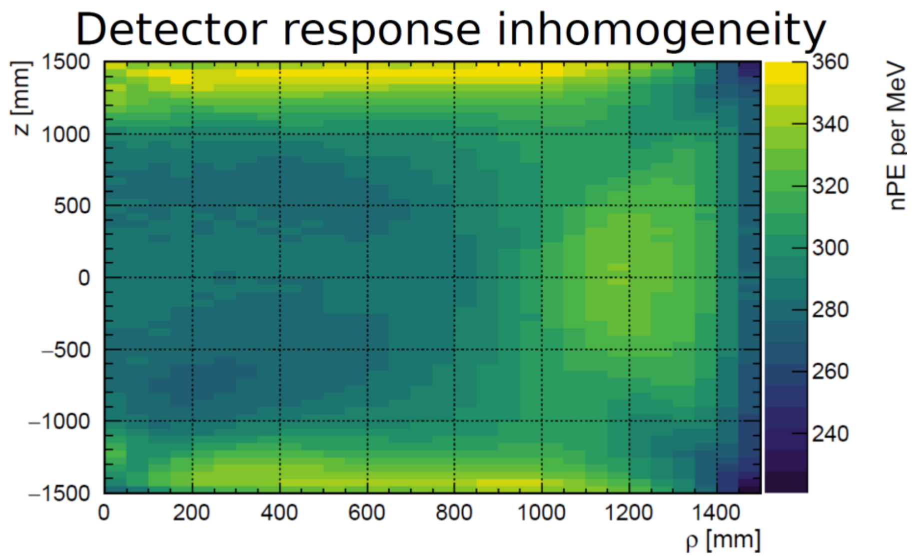
  → Uplink and determination of cable lengths
- (Regular) Calibration of iPMTs needed

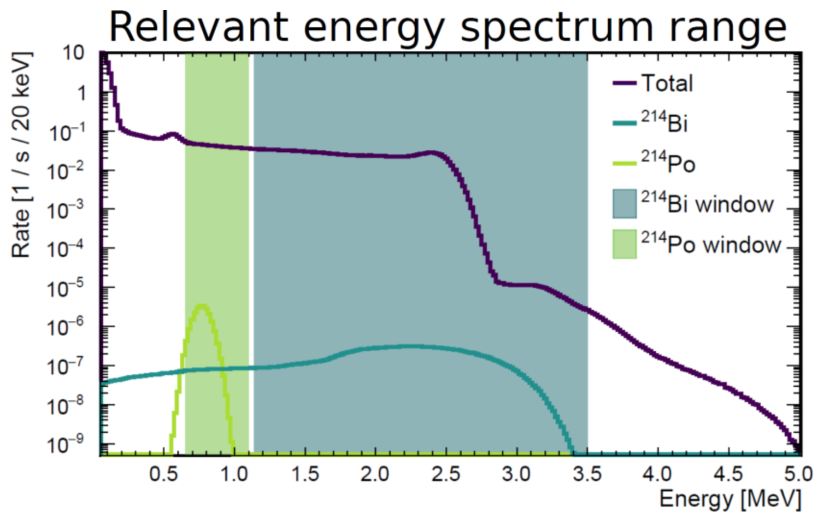




Calibration goals

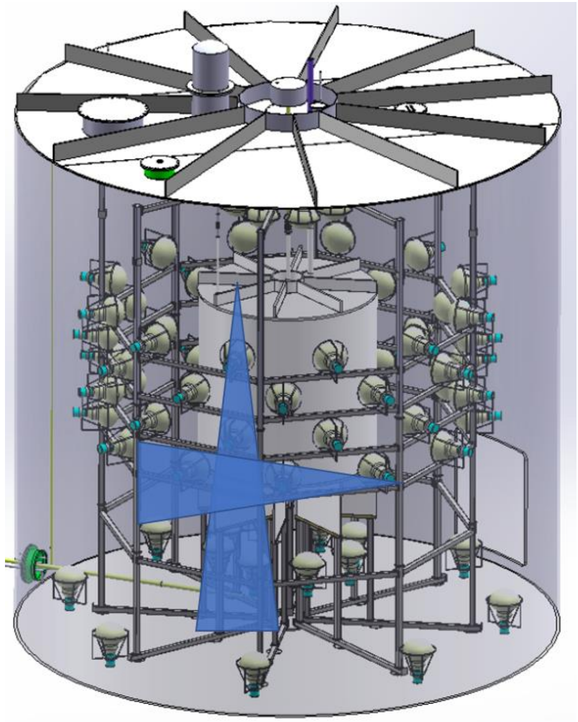
- **Vertex and energy reco calibration**
  - High-activity γ-sources (≈ 3 kBq)
  - Calibration of FV energy non-uniformity
  - Sources cover crucial energy range for Bi-Po detection (0.66 MeV – 2.5 MeV)
- **PMT timing and charge calibration**
  - Timing: Relative alignment of iPMT timings
  - Charge: single p.e. to saturation
- **Liquid scintillator monitoring**
  - Low-activity ^{40}K source (< 1 Bq)
  - < 1% LS light yield changes within a day

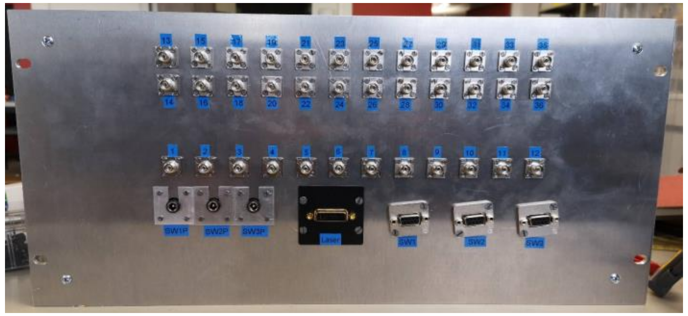




Calibration systems – Light Injection System

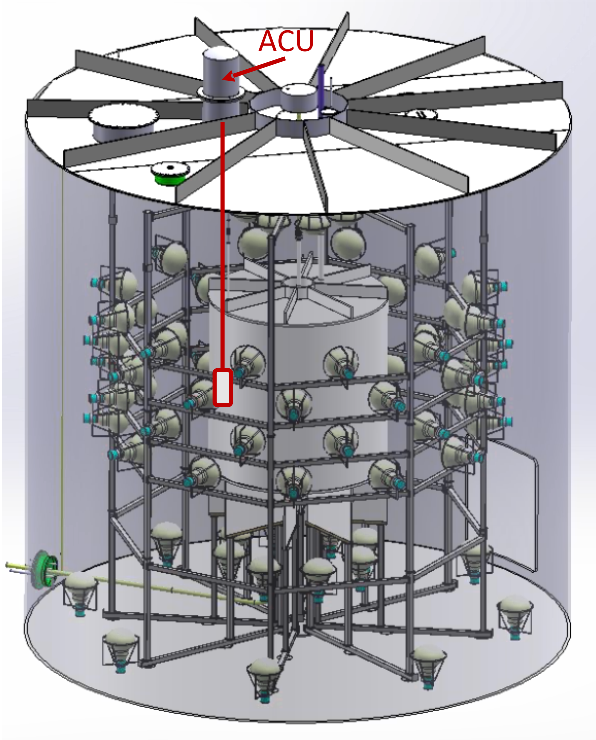
- Laser system with 24 diffusors in OSIRIS
- System parameters:
  - 420 nm wavelength
  - 80 ps pulse width
  - Pulse frequency: 10 kHz
  - Light output: 0.01 p.e.
- Controlled via LabView / EPICS
- Daily PMT charge and timing calibrations
- Simultaneous calibration of inner and veto iPMTs possible
- Total daily calibration time: ≈ 10 minutes

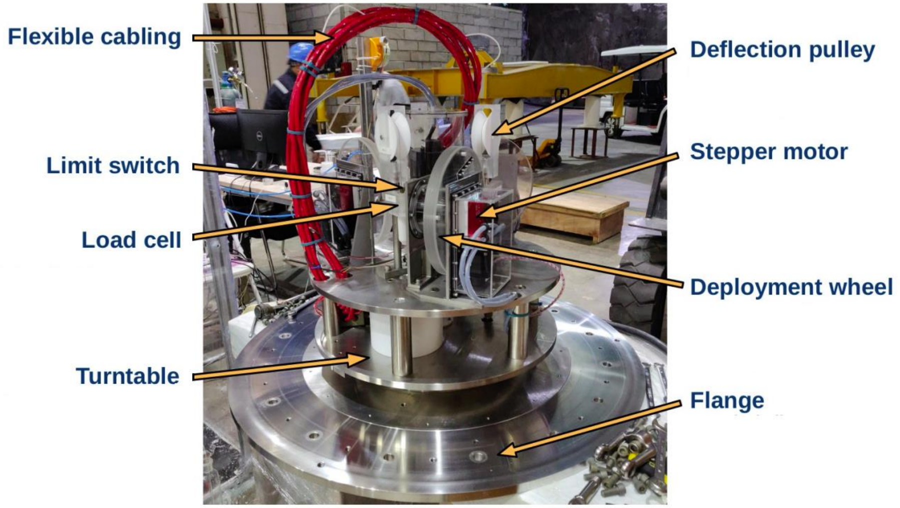




Calibration systems – Source Injection System

- Refurbished Automated Calibration Unit (ACU) of Daya Bay collaboration
- Positioned at off-center axis in OSIRIS (121.5 cm, vessel radius 150 cm)
- Three sources: multi- γ, ^{40}K, LED
- Source capsules lowered directly into LS
- Limit switches and load sensors for safe operation
- Accuracy of source positioning: cm level
- Calibration durations:
  - Weekly: multi-γ ≈ 30 min, LED ≈ 1.5 h
  - Initial: multi-γ ≈ 1 h, LED > 3 h





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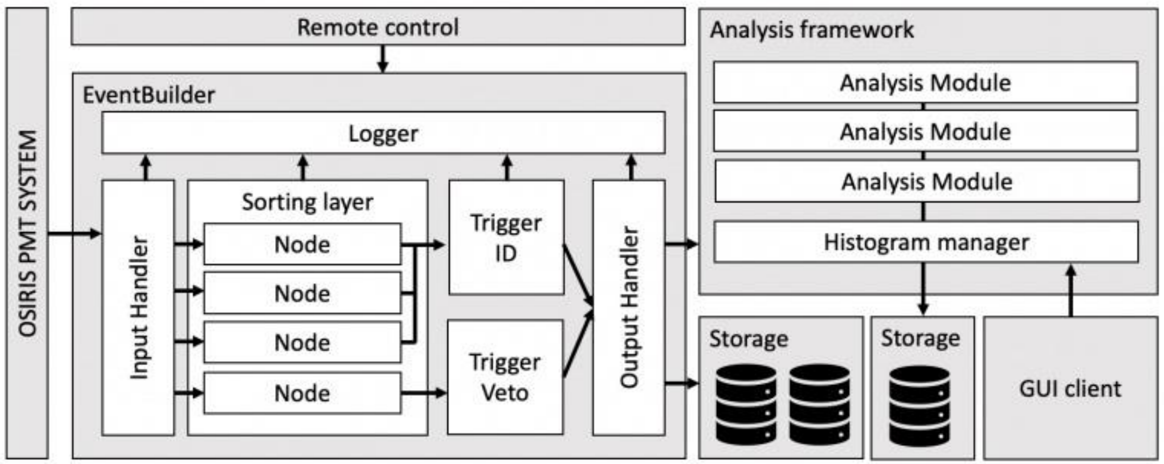
Online data acquisition

- iPMT data digitised directly on iPMTs

  → No detector-wide analog trigger possible

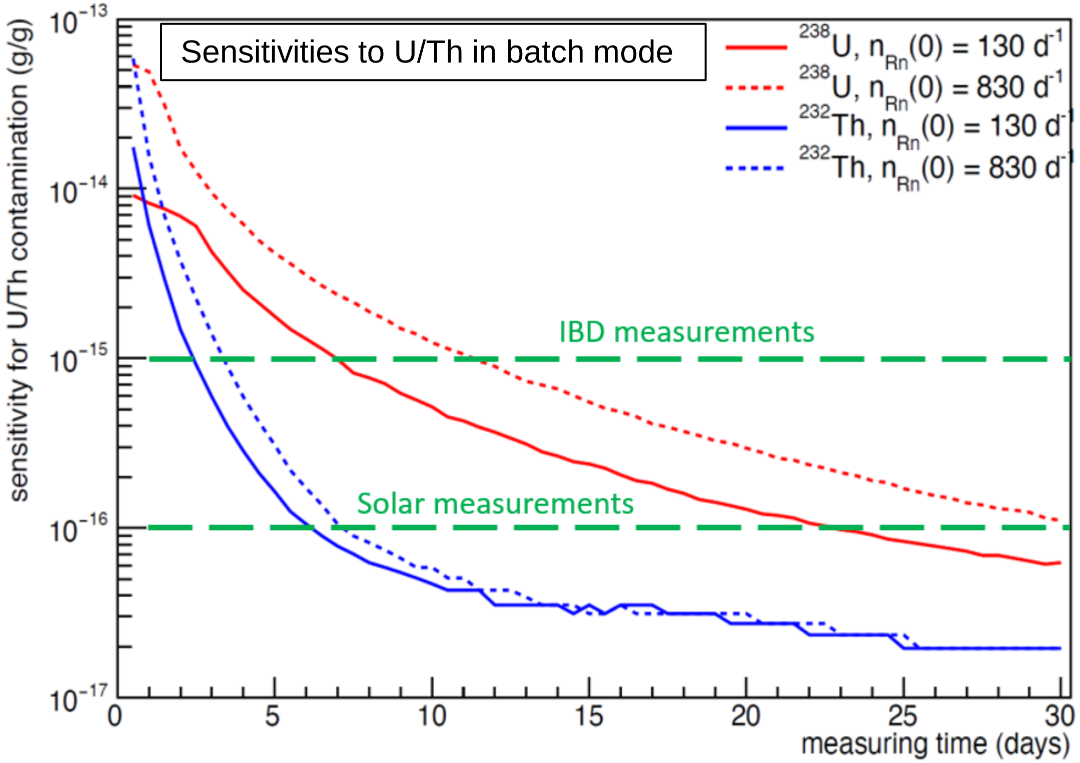
  → Online trigger needed
- Single consumer-grade computer („EventBuilder“) triggering and combining iPMT data streams into events for further analysis
- Incoming data rate: 230 MB/s (dark count rate ≈ 15-18 kHz, expected event rate: ≈ 40 Hz)
- Trigger on timing information only (14 of 230 MB/s)
- Expected data volume: ≥ 5 TB / year (excluding calibrations)
- Online Monitor for live Bi-Po rate analysis

  → Sudden rises in rate indicate problems in filling / purification chain → fast reactions possible



Sensitivity of OSIRIS

- Sensitivity influenced by Radon (Rn) contaminations from:
  - Surfaces in contact with LS
  - N2 blankets
  - Gas leaks in connections (small)



- Detailed study of Rn influence during commissioning phase

  → „Batch mode“: LS batch stays in OSIRIS for longer time (e.g. for a month) → not practical during JUNO filling

- During JUNO filling phase: „Continuous mode“

  → Scintillator flows through OSIRIS (passage time ≈ 1 day)
  → Partial decay of Rn contamination during passage → height-dependent determination of Bi-Po rate
  → Batch-mode results included in Bi-Po rate calculation
  → Expected: U/Th sensitivity close to IBD level, triggering of contamination alarms within few hours

Summary and Outlook

- Much work already done by many different groups!
- OSIRIS installations started beginning of 2022
- Construction of tank structures ongoing
- Commissioning phase starting around July, experts planned to be on-site
- First data taking in autumn

Talk by Andrea Barresi: „Radiogenic background control strategy for the JUNO experiment“
June 17, 14:15

Thank you for your attention!

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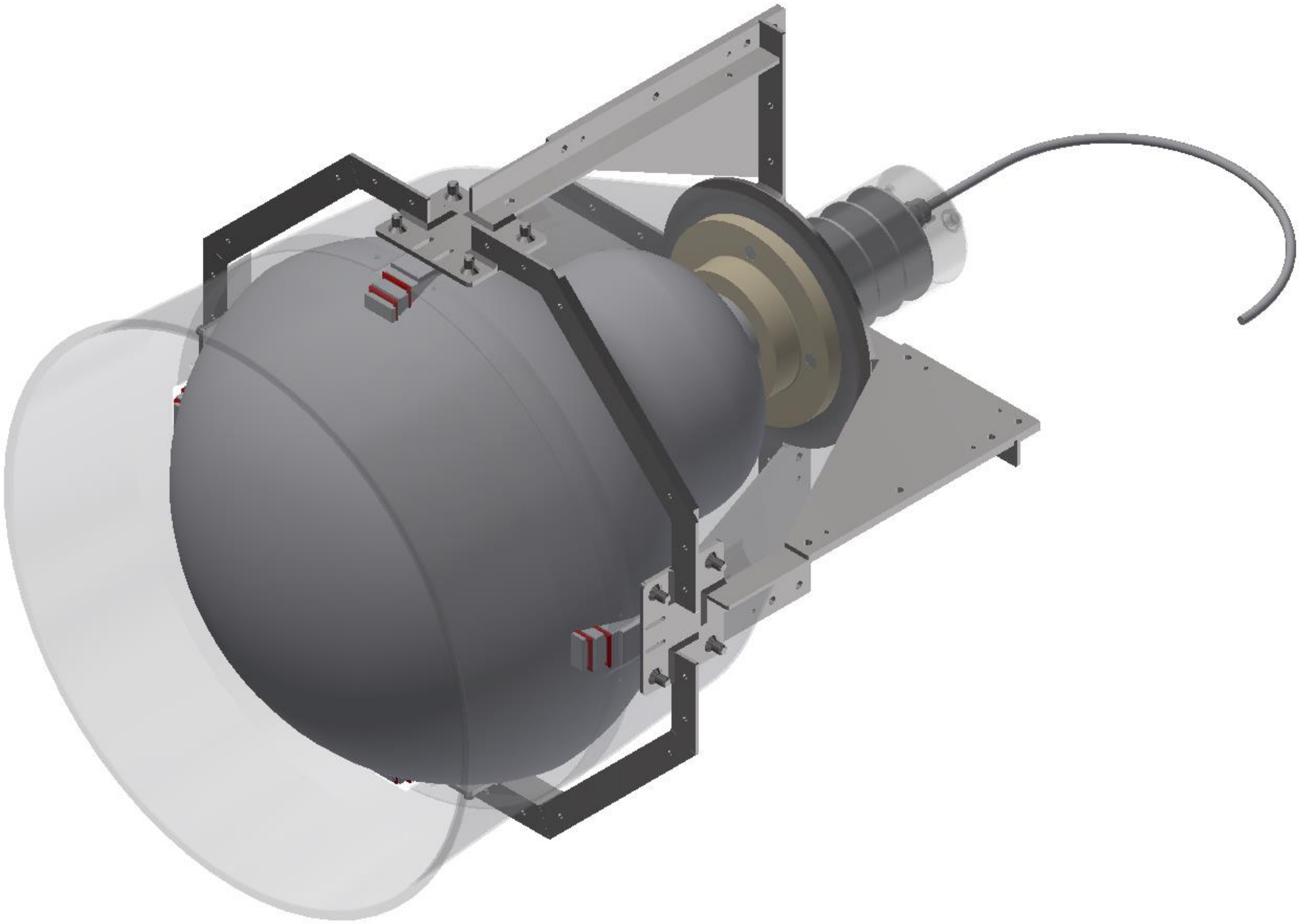
BACKUP

iPMT assembly

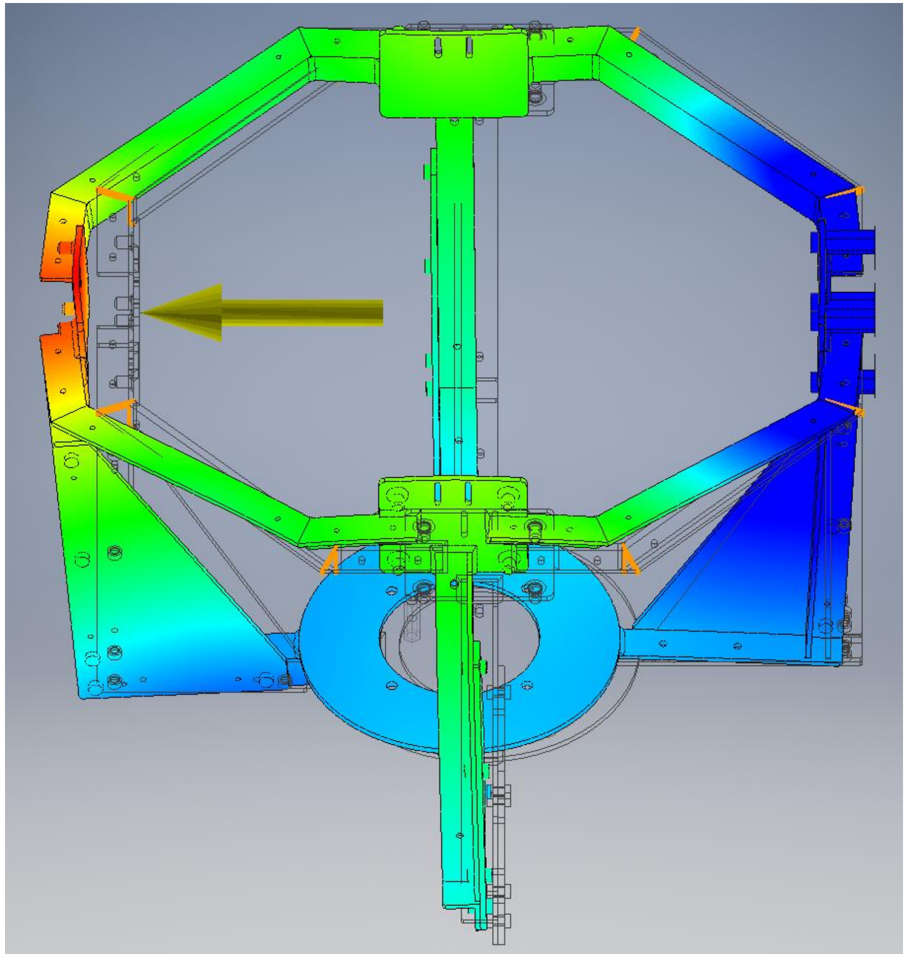


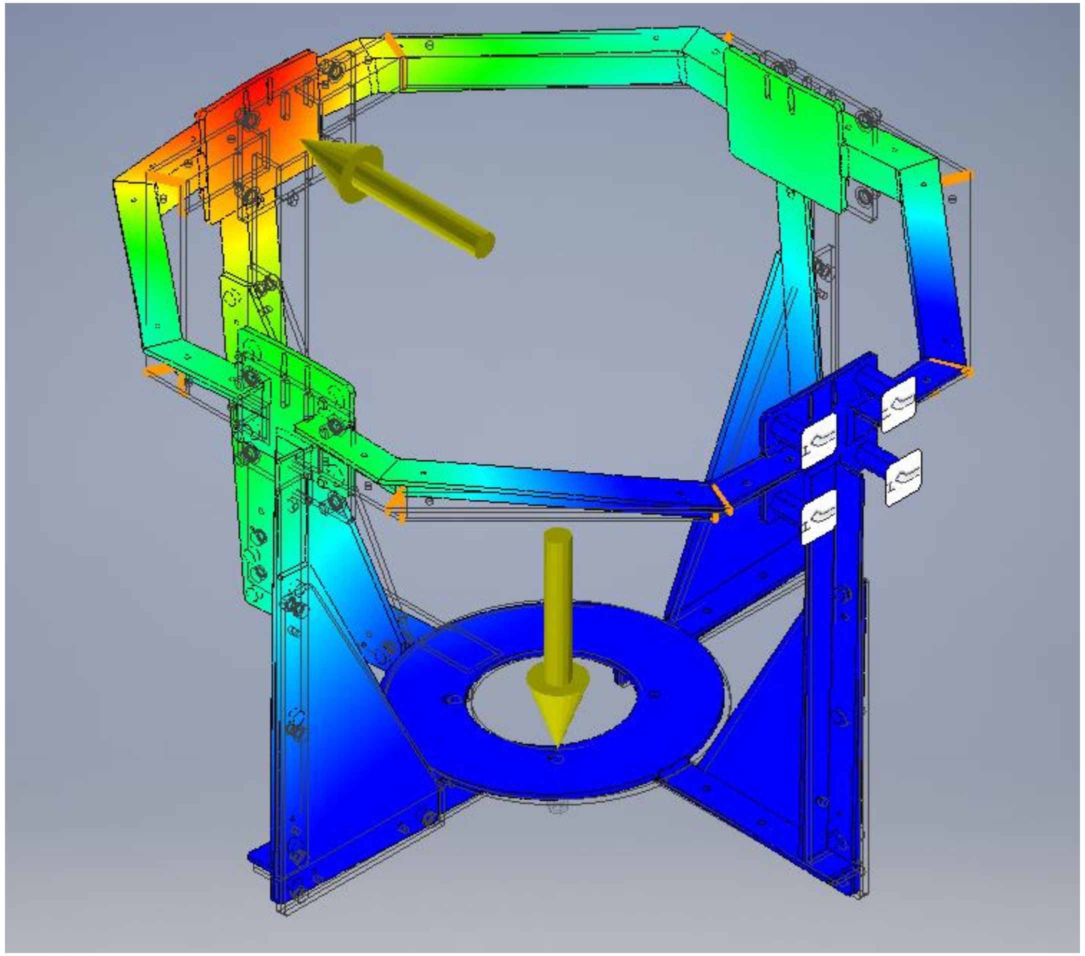
iPMT assembly

iPMT, magnetic shielding, holder

iPMT assembly

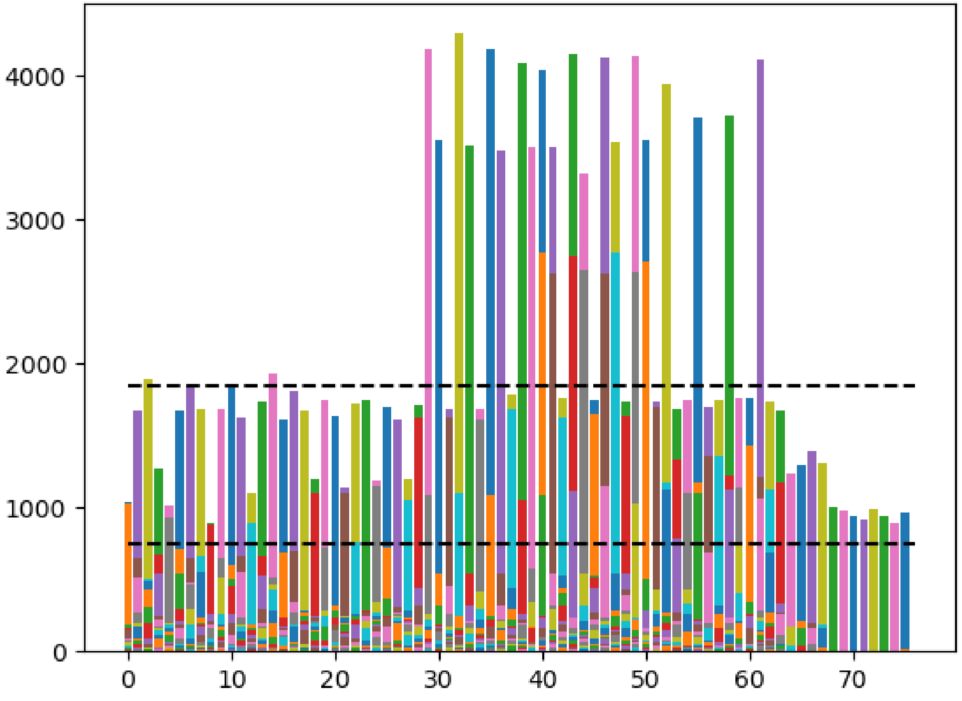
Mechanical simulations, max deflection < 1.5 mm



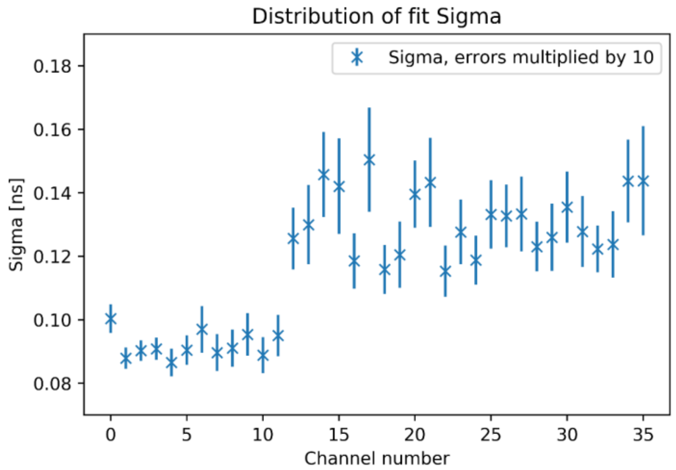


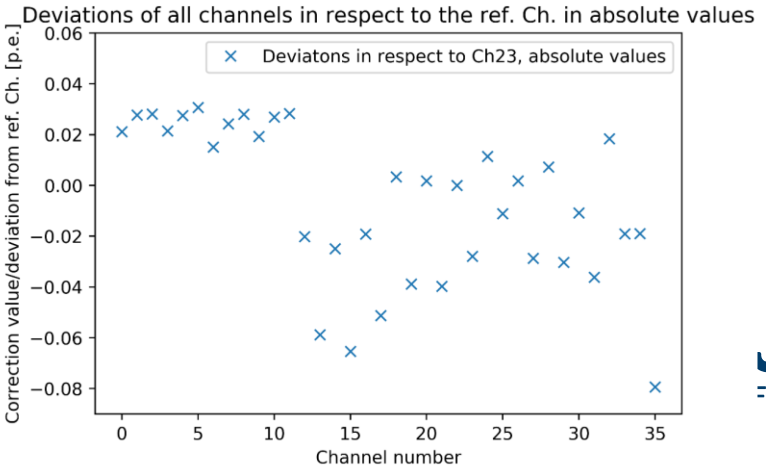
Calibration – Light Injection System

- Simulations on PMT occupancies to optimise diffusor positions



- Calibration results of LIS (mean jitter 70 ps, PMT TTS ~1.2ns), deviating channels can be avoided by excess of channels





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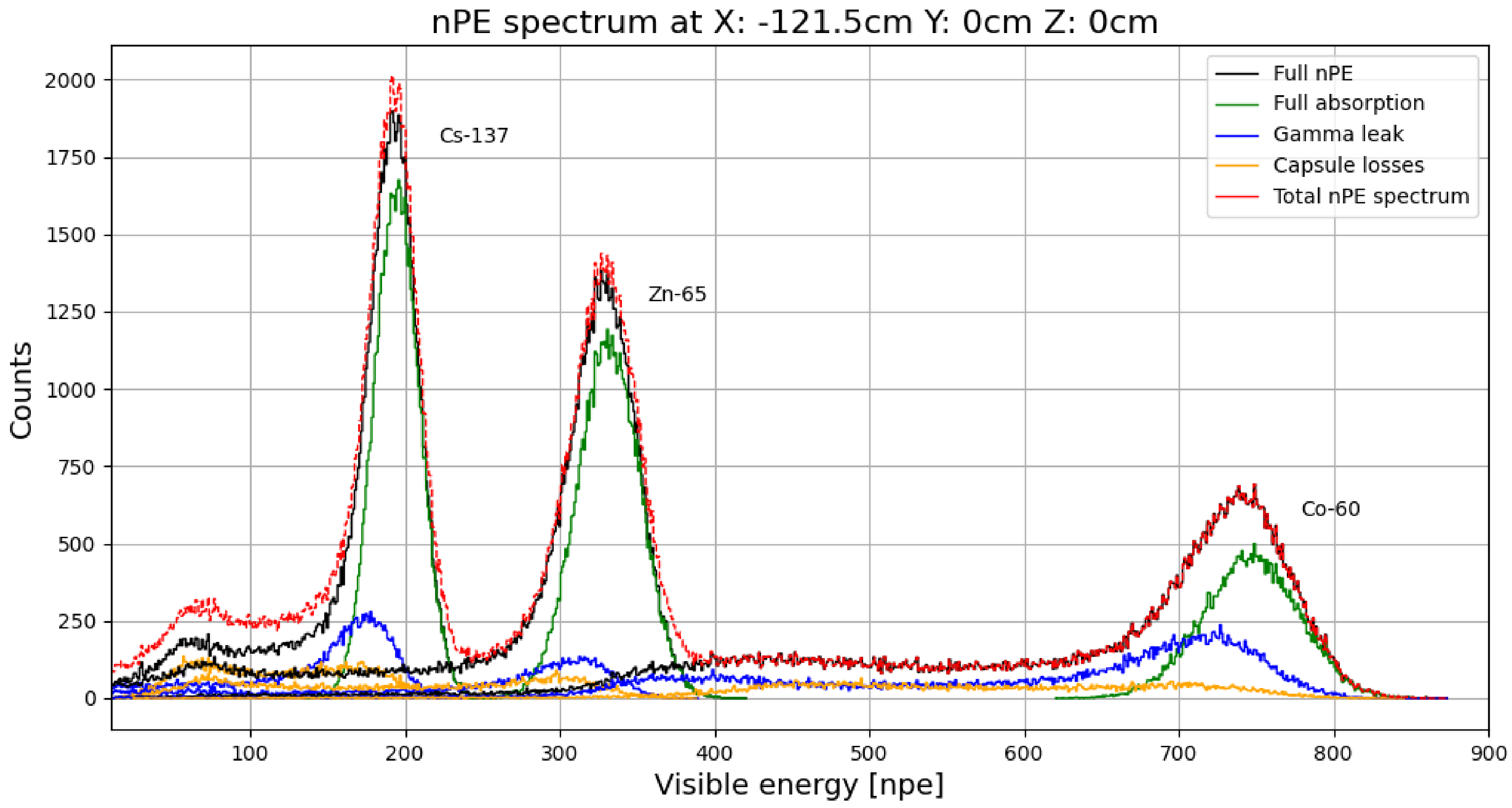
Calibration – Source Injection System

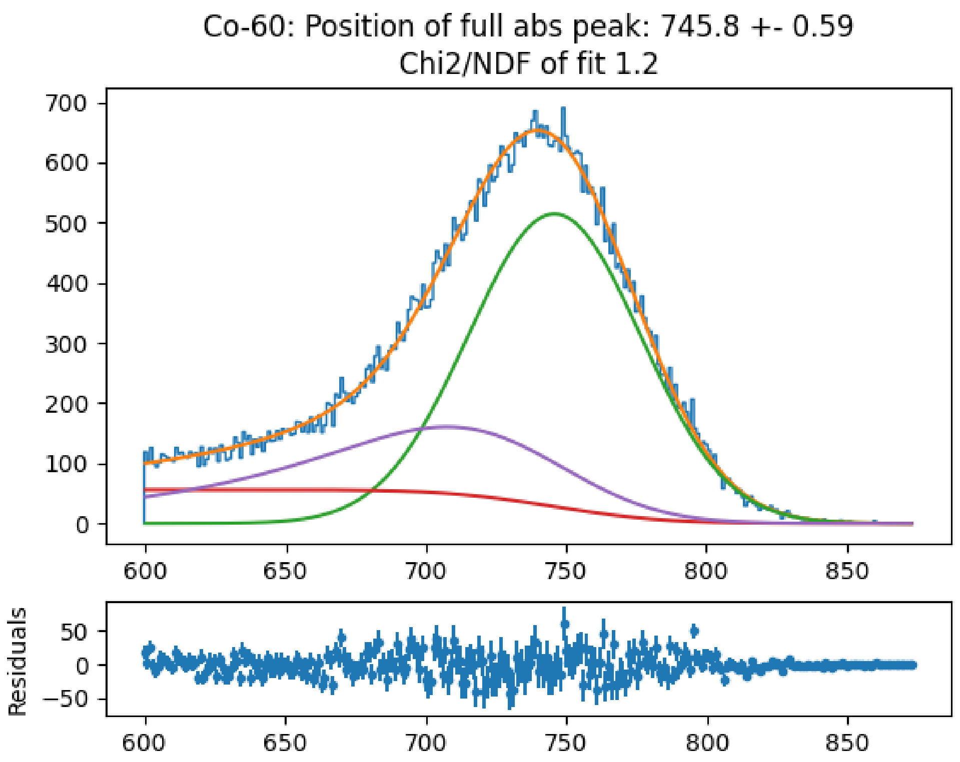
Calibration spectrum



Calibration – Source Injection System

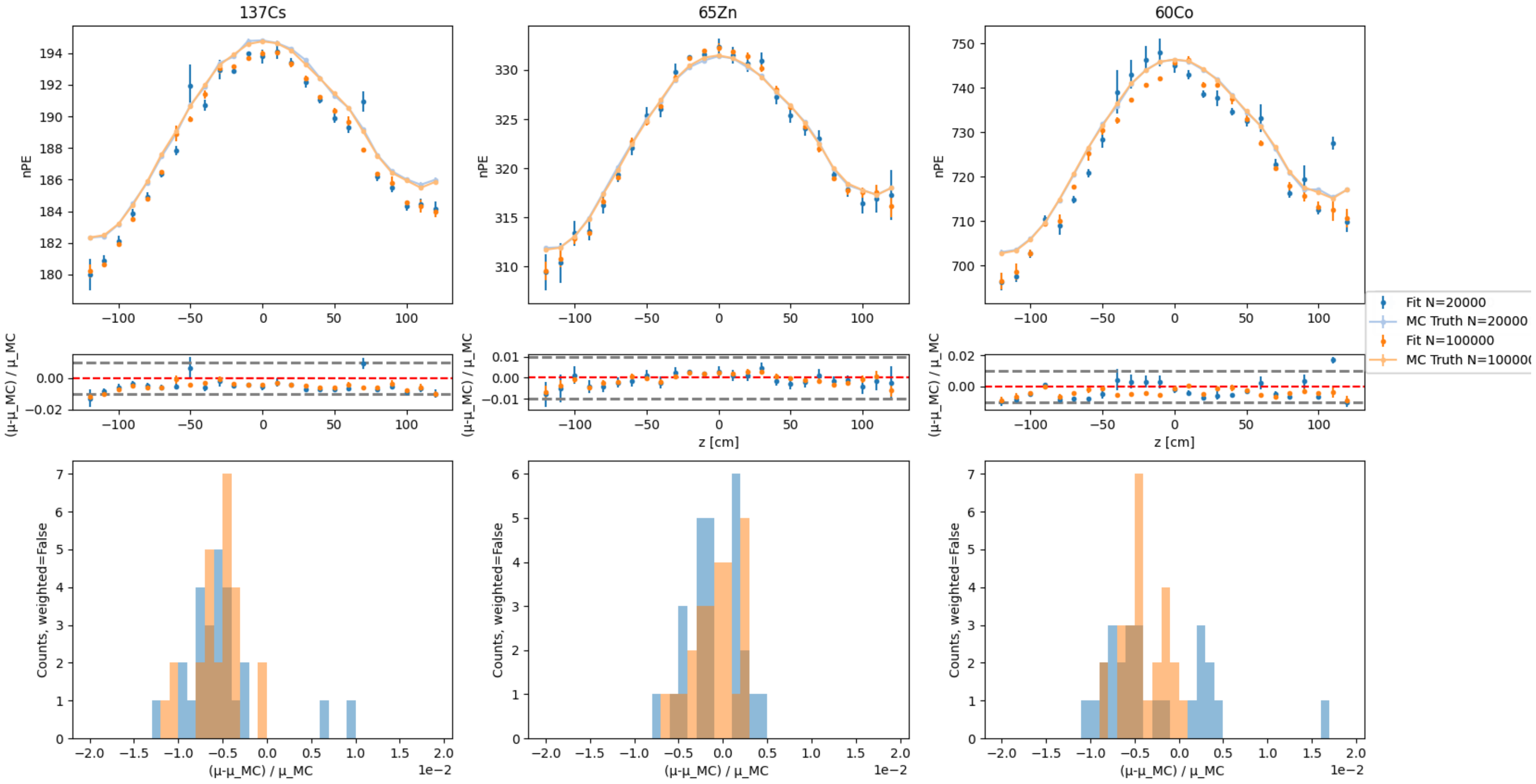
Peak fitting

- Wanted: position of full absorption peak (green curve)
- Fitfunction with three components:
  - Gaussian (line in spectrum convoluted with Gaussian)
  - Exponential (Light leakage out of small detector)
  - Constant (capsule losses)
- All components convoluted with Gaussian
- Crossover from neighboring peaks possible



Calibration – Source Injection System

Bias of peak fitting – work in progress!



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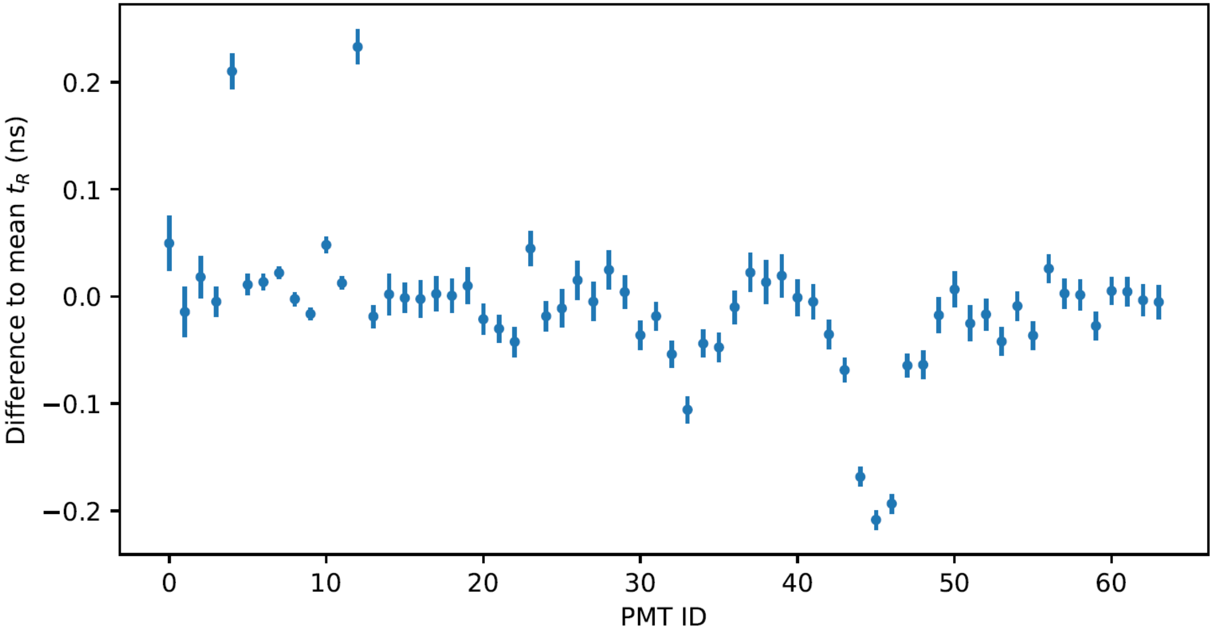
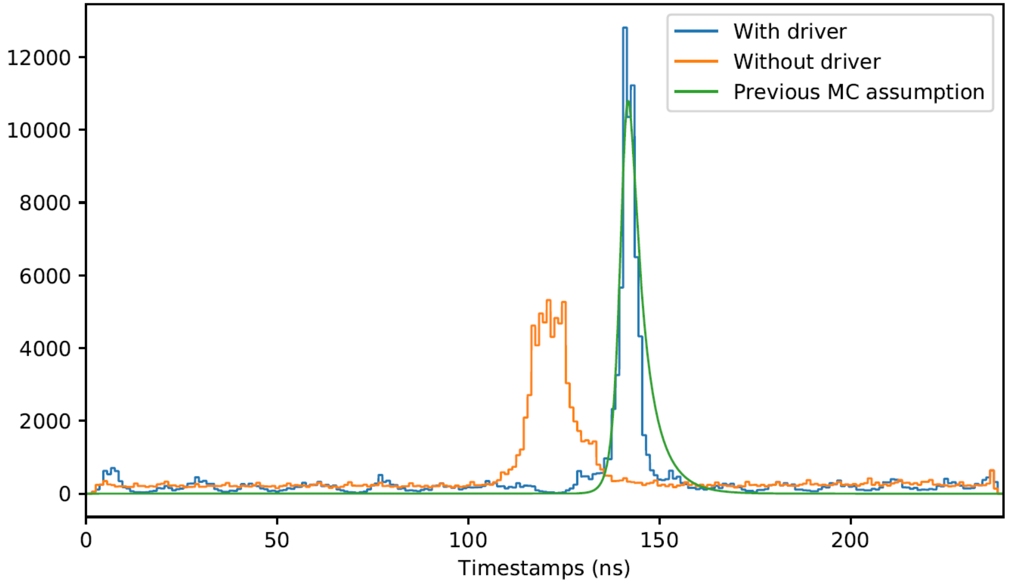
Calibration – Source Injection System

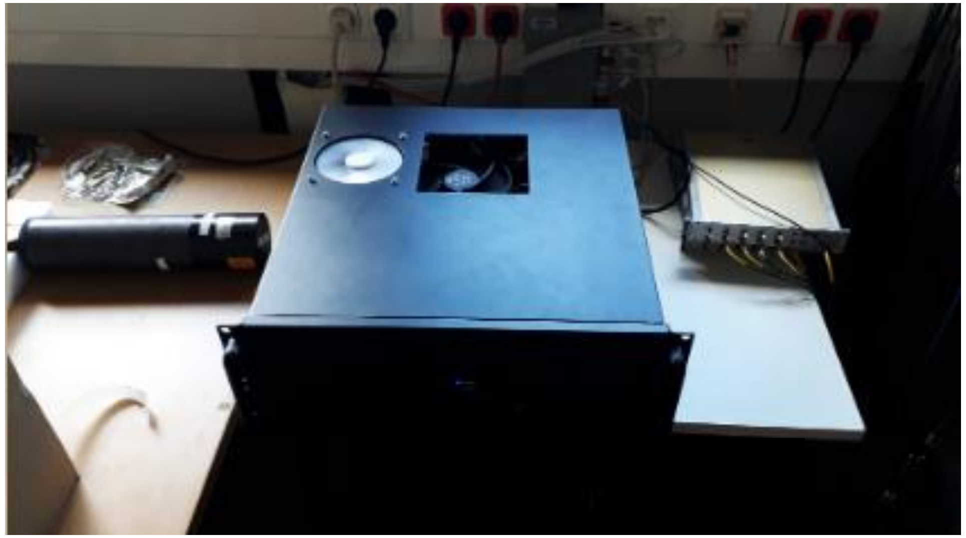
LED – average relative PMT timing uncertainty <= 0.1 ns





Online Data Acquisition

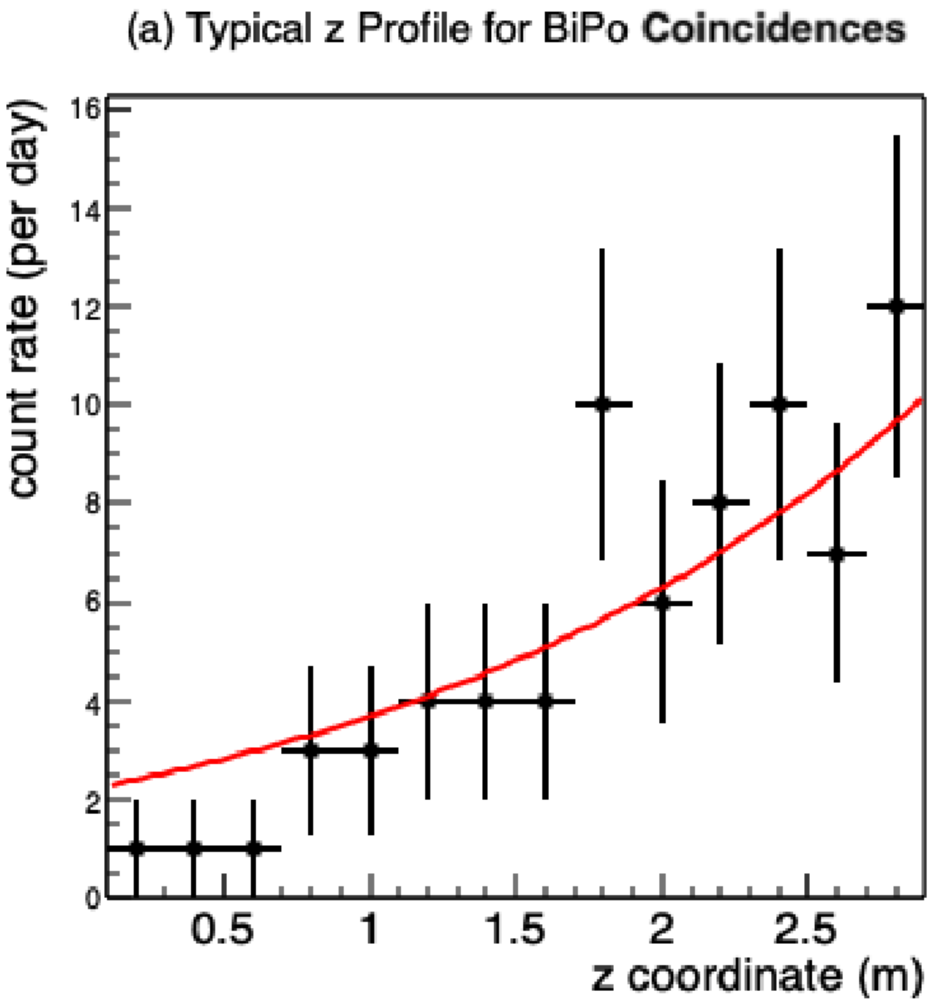
- EventBuilder
  - Intel i9-9900KF @ 5GHz
  - 128 GB RAM
  - 2 x 1 TB NVME-SSDs (RAID-1)
  - 10 Gbit-Ethernet card to Online Monitor
  - Rack-mountable



- Tested with EventGenerator
  - Simulates full iPMT data stream
  - AMD Threadripper 3970x (32 cores, 64 threads)
  - 128 GB RAM
  - 1 TB SSD
  - 10 Gbit-Ethernet card to EventBuilder

Sensitivity of OSIRIS -- Layers

- Constant flow speed of liquid scintillator (1m3 / h → 2mm / min)
- Dividing LS volume into 14 layers of 20 cm width
- Fresh scintillator entering detector at 3m
- Determination of
  - Height-independent Bi-Po rate contribution by U/Th
  - Height-independent Bi-Po rate contribution by Rn
- Fit of exponential function plus constant and known flow speed
  → time-dependent decay rate



Sensitivity of OSIRIS to Rn spikes

- Biggest contributor to Rn rates in JUNO: surface storage tank (shifting Rn levels due to volume variation of N2 blanket & stainless steel surfaces)
- Improved filling: adjusting refilling times of LS surface tank
- Pure-N2: Improvement of Rn purity
- Curve differences mainly due to:
  - Beginning: Lower overall Rn rate
  - Long times: expected Rn rate variation

- Large contaminations easily detectable within few hours
  → LS not in FOC tank then = not in central detector