ICHEP 2024 | PRAGUE

Calibration of the JUNO Detector

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On behalf of the JUNO collaboration

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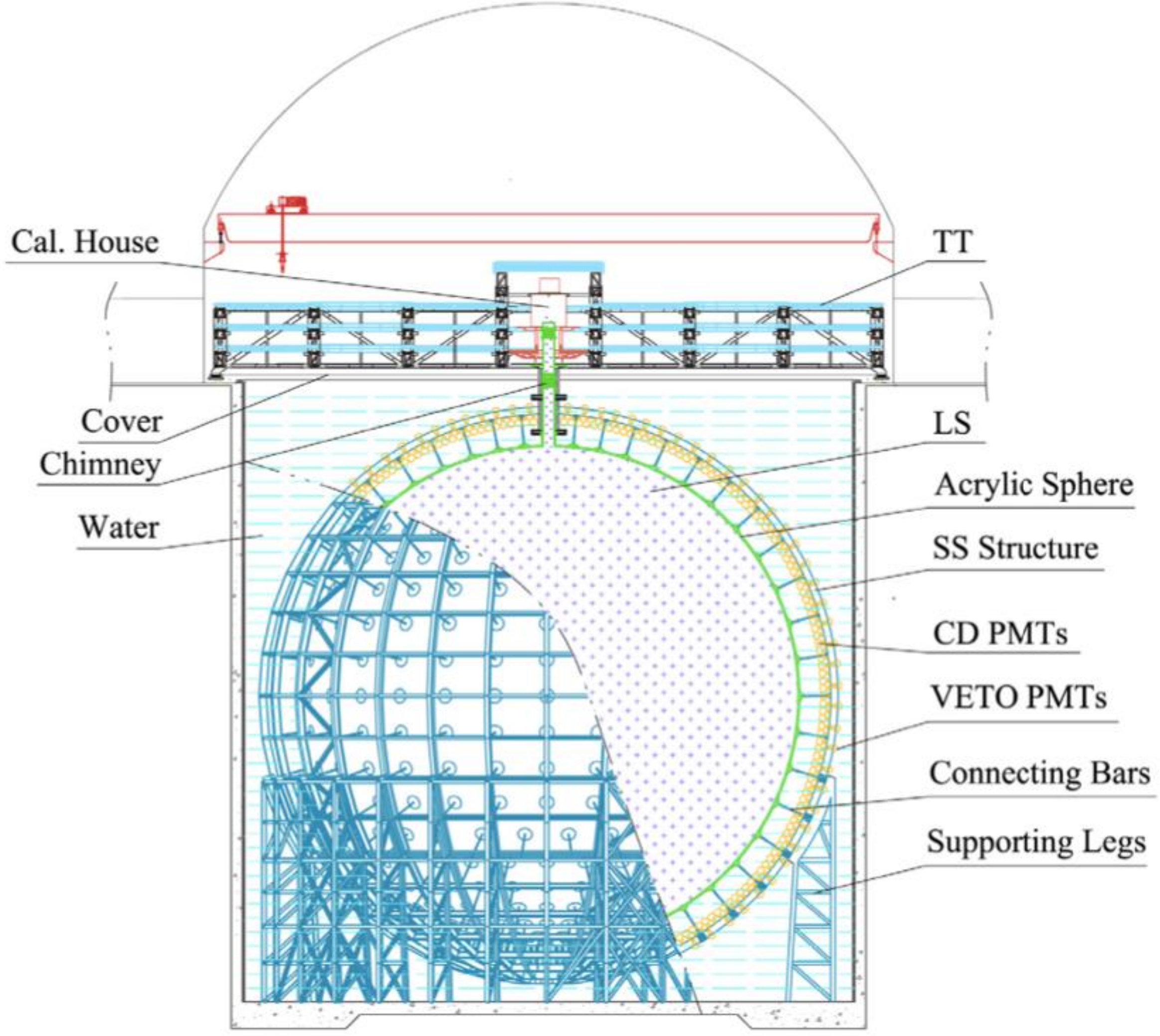
Outline

- Introduction of JUNO Calibration
- JUNO Calibration Strategy
- JUNO Calibration System Status
- Summary

Jiangmen Underground Neutrino Observatory (JUNO)

- **Primary goal is to determine the neutrino mass ordering by detecting $\bar{\nu}_e$ ($\bar{\nu}_e + p \rightarrow e^+ + n$)**
- **JUNO Structure:**
  - Diameter: 35.4 m
  - Acrylic sphere: filled with 20 kton liquid scintillator (LS)
  - PMT: ~17612 20-inch and ~25600 3-inch PMTs for central detector (CD), ~2400 20-inch PMTs for water pool (WP)
- **Challenges for calibration:**
  - Energy nonlinearity (Energy dependent)
  - Detector non-uniformity (Position dependent)



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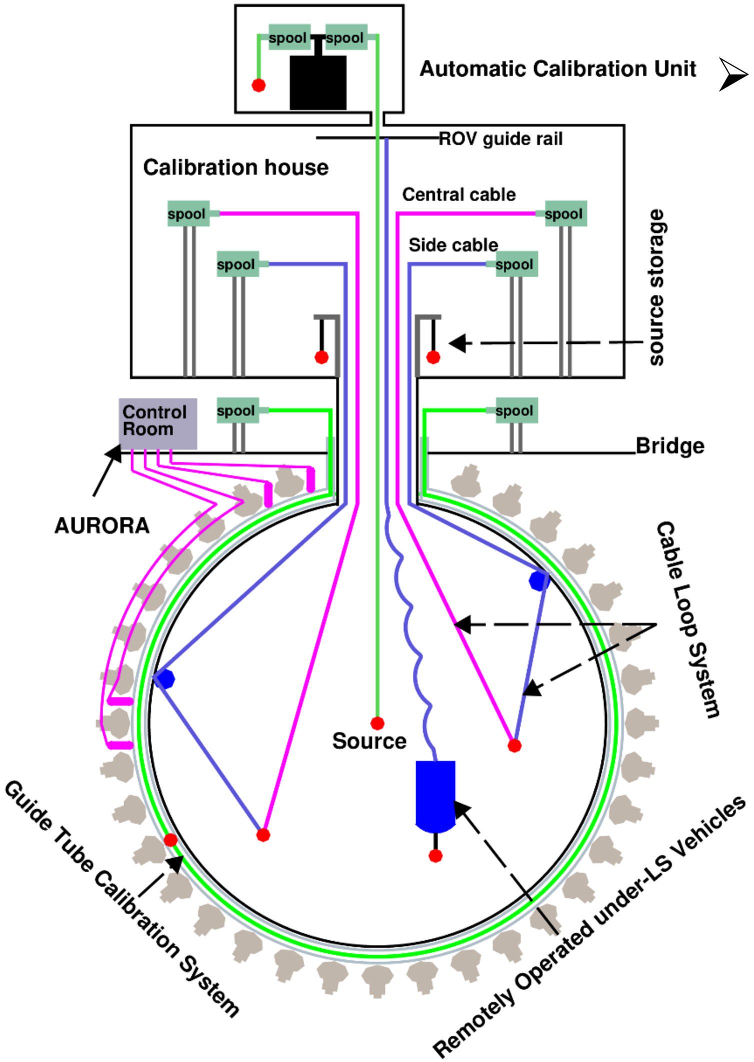
JUNO Calibration System

- **Comprehensive calibration system:**
  - 1D central axis scan:
    Automatic Calibration Unit (ACU)
  - 2D plane scan:
    Cable Loop System (CLS)
  - 2D boundary scan:
    Guide Tube Calibration System (GTCS)
  - 3D scan:
    Remotely Operated Vehicle (ROV)
- **Calibration strategy:**
  - Calibrate the energy nonlinearity
  - Calibrate the detector non-uniformity



- **Meet the stringent requirements:**
  - Energy scale uncertainty < 1%
  - Energy resolution < 3% at 1 MeV

ACU: JINST 16 T08008 (2021)

CLS: NIM A 988 164867 (2021)

GTCS: JINST 14 T09005 (2019)

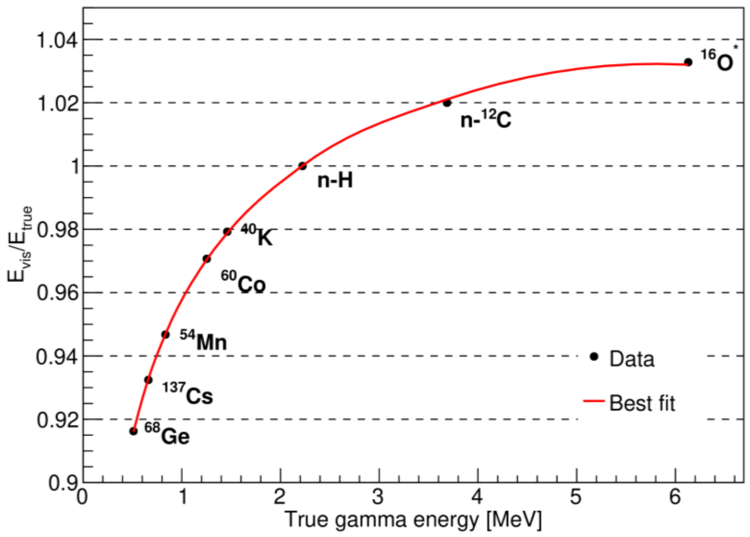
GTCS: JINST 16 T07005 (2021)

ROV: JINST 13 T12001 (2018)

JUNO Calibration Strategy

➢ **Energy nonlinearity:**

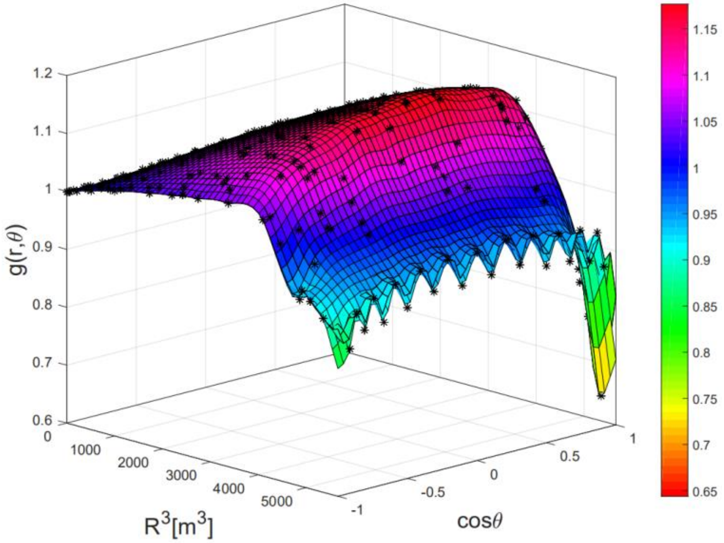
- Energy dependent
- Dominantly contain physical nonlinearity and instrumental nonlinearity
- Multiple radioactive sources calibration @ACU



Gamma energy nonlinearity

➢ **Detector non-uniformity:**

- Position dependent
- Geometrical effects and photon propagation
- Comprehensive calibration scan @ACU+CLS+GTCS



Non-uniformity correction map

Energy Nonlinearity Calibration

- **Determine the NMO by measuring $\bar{\nu}_e$ energy spectrum:**
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - $E_{\bar{\nu}} \sim E_{e^+} + 0.8$ MeV
  - The prompt signal energy range is 1-8 MeV
- **Physical nonlinearity:**
  - Quenching effect and Cherenkov photon emission
  - Different energy corresponds to different detected nPEs/MeV
  - Multiple radioactive sources calibration @ACU

Radioactive sources/Processes	Type	Energy [MeV]	Radioactivity
^{241}Am	γ	0.0595	~100 Bq
^{226}Ra	γ	0.186	~100, 500, 1000 Bq
^{137}Cs	γ	0.662	~100 Bq
^{54}Mn	γ	0.835	~100Bq
^{60}Co	γ	1.173 + 1.333	~100 Bq
^{40}K	γ	1.461	~20 Bq
^{68}Ge	e^+	annihilation 0.511 + 0.511	~100 Bq
^{241}Am-^{9}Be	n, γ	neutron + 4.43 (^{12}C*)	~30 neutrons/s
^{241}Am-^{13}C	n, γ	neutron + 6.13 (^{16}O*)	~100 neutrons/s
(n,γ)p	γ	2.22	
(n,γ)^{12}C	γ	4.94 or 3.68 + 1.26	

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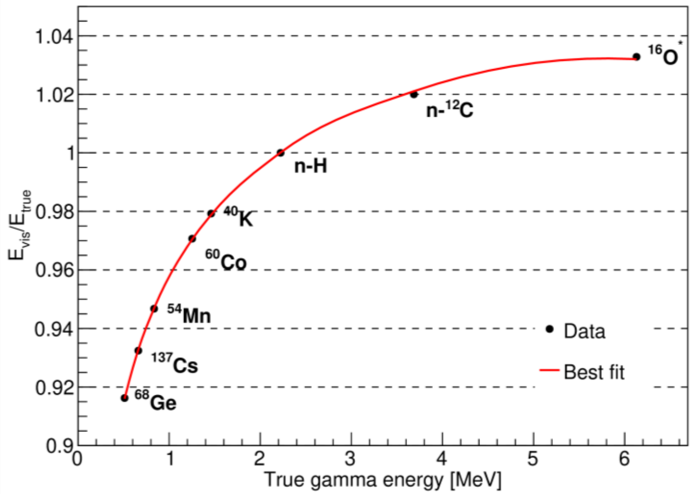
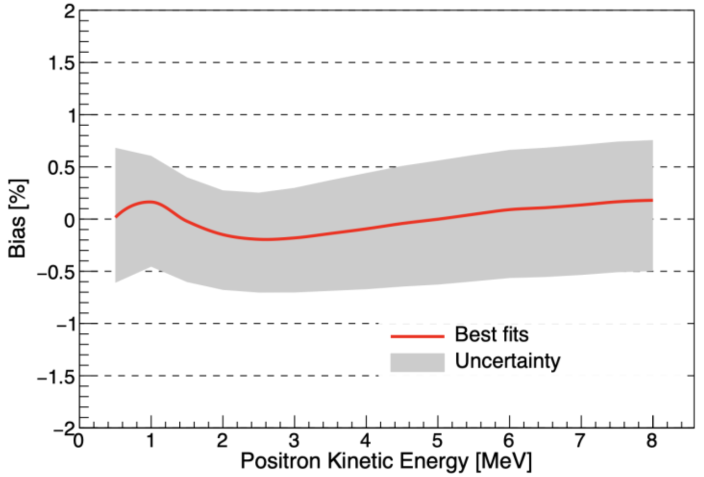


Gamma energy nonlinearity

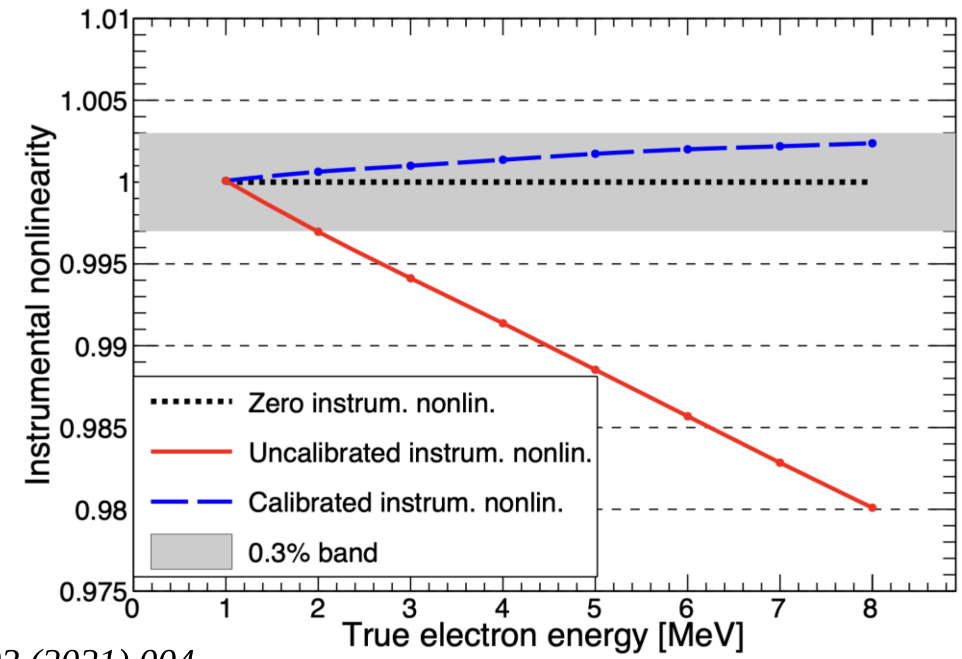


Positron nonlinearity after calibration

- **Residual bias ~0.3%**

Energy Nonlinearity Calibration

- **Instrumental nonlinearity:**
  - LPMT has nonlinearity between the received nPEs and the measured charge
  - Laser source on the detector center avoids the physical nonlinearity and non-uniformity
  - Calibration method: LPMT and SPMT dual calorimetry + tunable laser source



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Instrumental nonlinearity

- **Requirement for calibration:**
  - Energy scale uncertainty < 1%
- **Systematic uncertainty on energy scale ~0.7%:**
  - Dominant components:

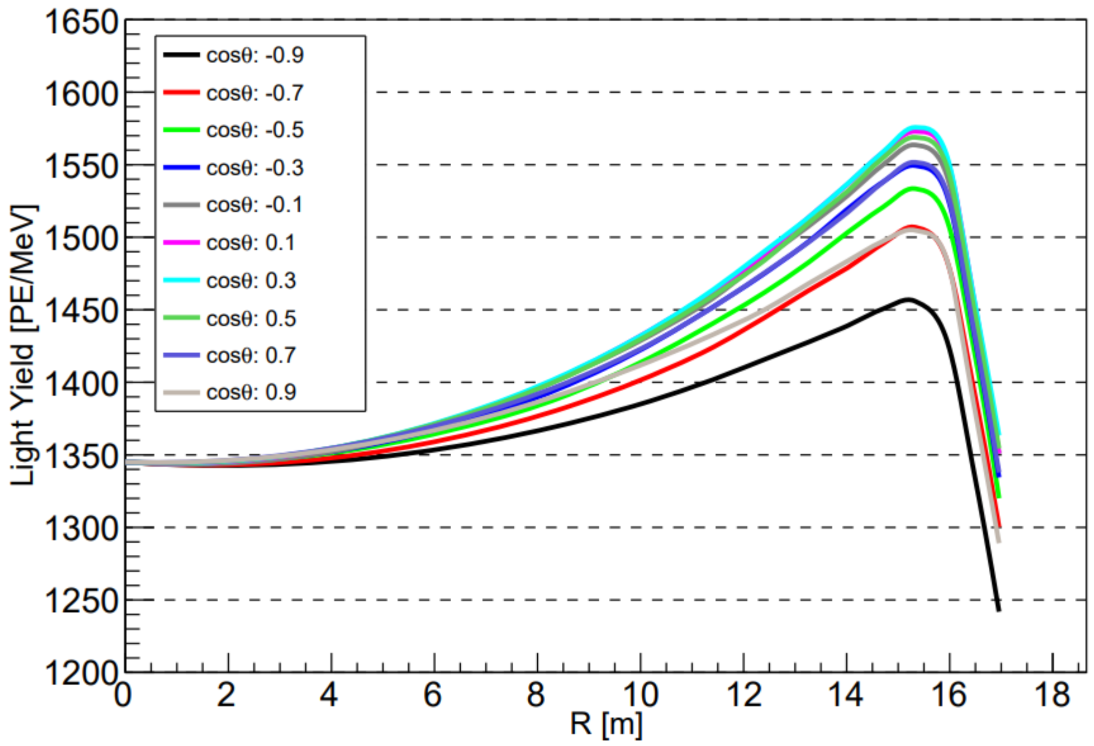
    Residual bias of positron energy nonlinearity ~0.3%

    Instrumental nonlinearity ~0.3%

- Meet the energy scale uncertainty requirement

Non-uniformity Calibration

- **Position dependent:**
  - Geometrical effects (e.g. solid angle) and photon propagation (e.g. total reflection at R = 15.7 m)
  - Calibration in different positions @ACU+CLS+GTCS
- **Requirement for calibration:**
  - Energy resolution < 3% at 1 MeV
  - $\frac{\sigma_{E_{vis}}}{E_{vis}} = \sqrt{\left(\frac{a}{\sqrt{E_{vis}}}\right)^2 + b^2 + \left(\frac{c}{E_{vis}}\right)^2}$
  - a – statistical term, ~2.7%
  - b – constant term, dominated by non-uniformity
  - c – contribution of a background noise term, ~1%



Light yield function of the radius and the polar angles θ

Non-uniformity Calibration

- **Non-uniformity function:**
  - 250 calibration points

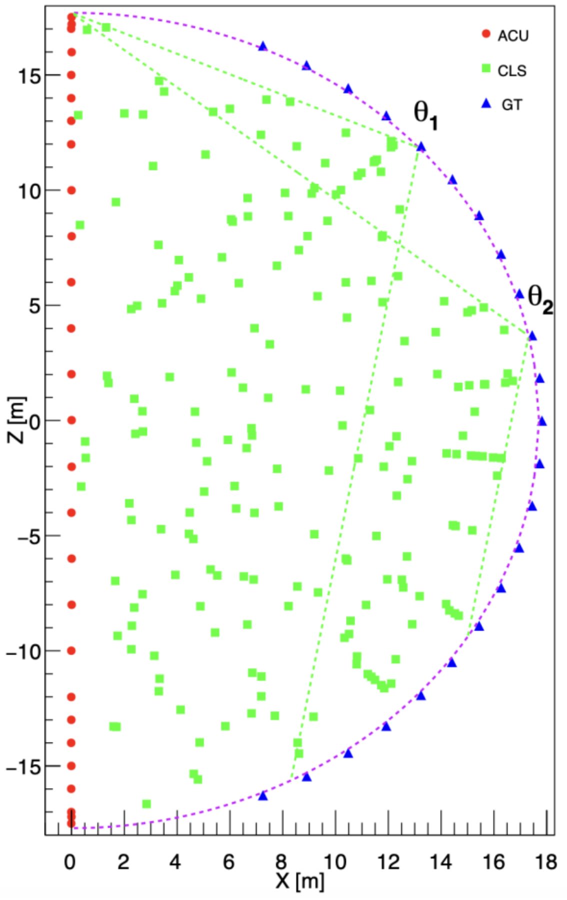
    1D central axis – ACU, Am-C

    2D plane – CLS, Am-C

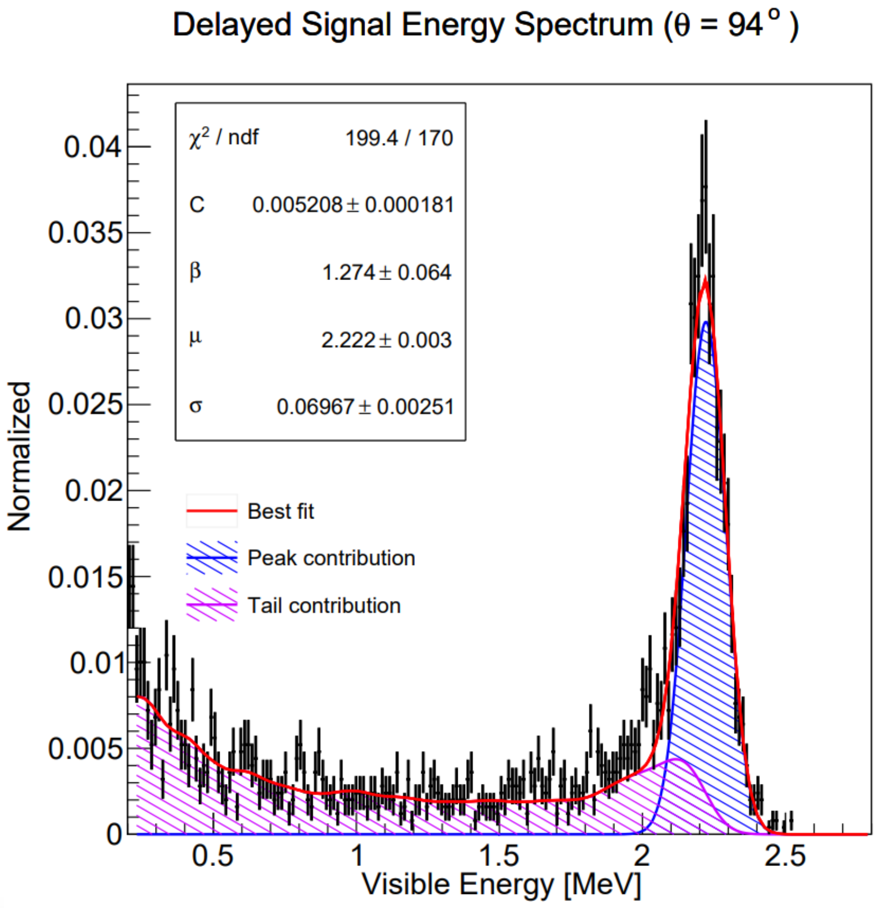
    2D boundary – GTCS, Am-Be
  - Energy spectrum fitting

    $S_{vis} = S_{edep} \otimes \text{resolution} \equiv S_{peak} + S_{tail}$

    Correction function: The light yield in different position



Calibration points distribution



Energy spectrum fitting @GTCS, θ=94°

Non-uniformity Calibration

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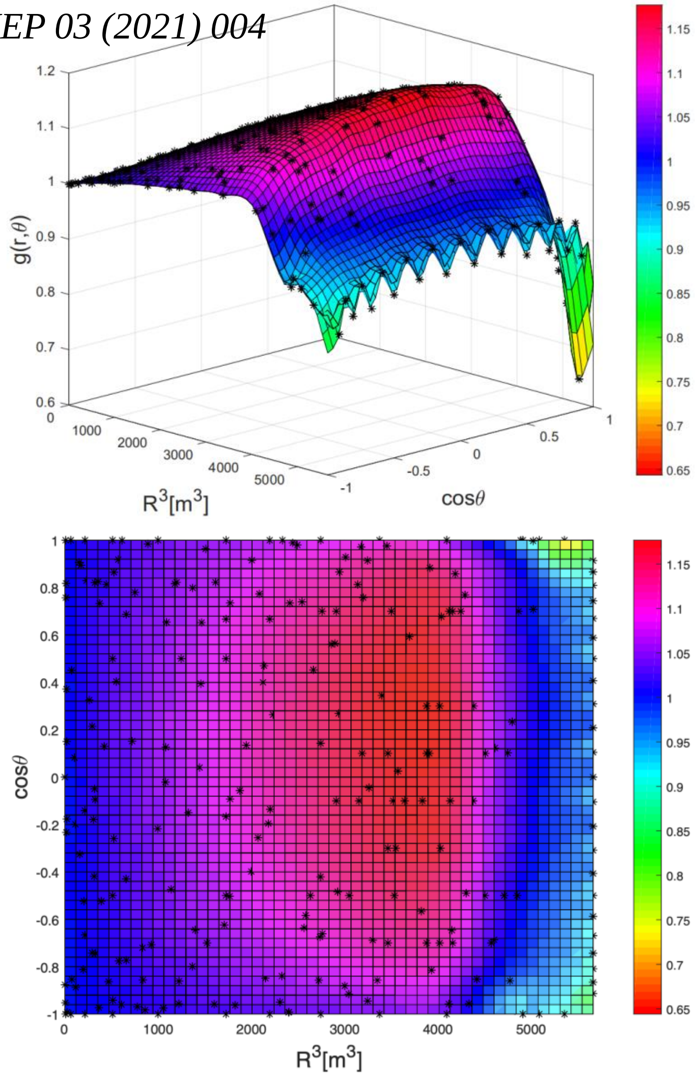
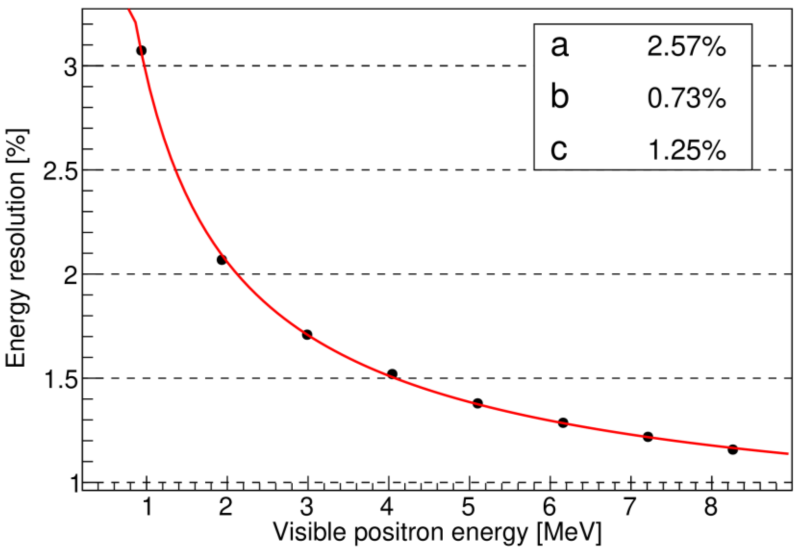


Non-uniformity correction map

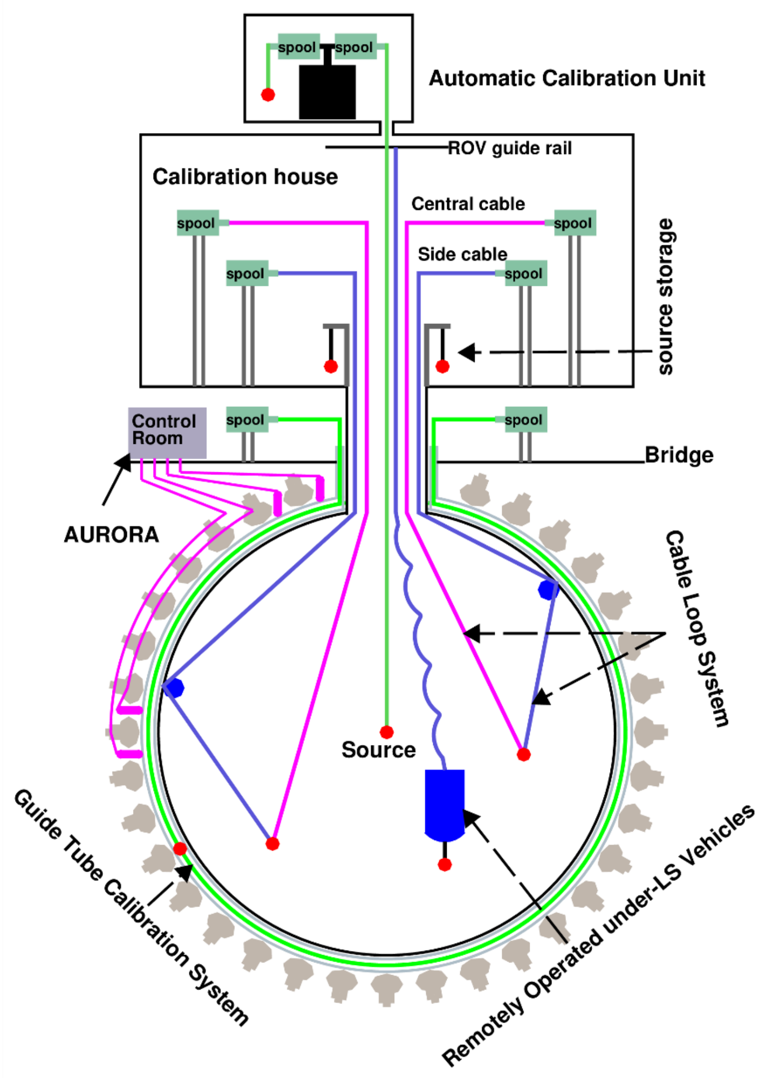
- **Non-uniformity correction:**
  - Use the gamma non-uniformity correction map to adjust the **Birks Law + Frank-Tamm Formula model**
  - Use the adjusted model to predict the positron energy resolution



Positron energy resolution after calibration

- **Requirement for calibration:**
  - Energy resolution < 3% at 1 MeV
  - b term < 1% after calibration
- **Effective energy resolution < 3%:**
  - $\tilde{a} \equiv \sqrt{a^2 + (1.6 \times b)^2 + \left(\frac{c}{1.6}\right)^2}$
- Meet the energy resolution requirement

JUNO Calibration System Status



- **Comprehensive calibration system:**
  - ACU: 1D, 100% completion in the lab, waiting for the installation
  - CLS: 2D, installation is underway, inside the CD parts are installed 100%
  - GTCS: 2D, installation is underway, outside the CD parts are installed 70%
  - ROV: 3D, waiting for the installation

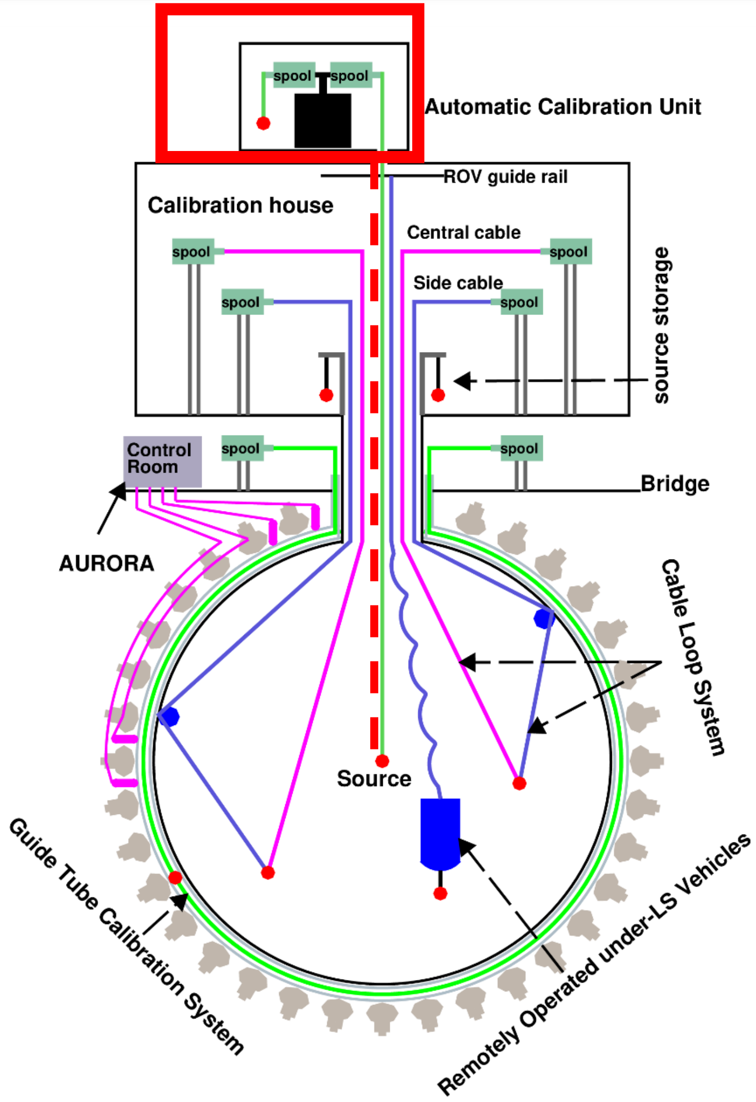

ACU


CLS

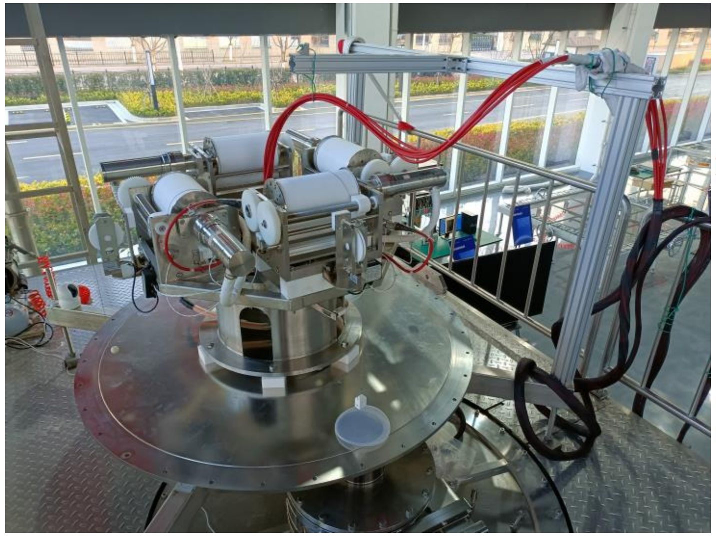

CTCS


ROV

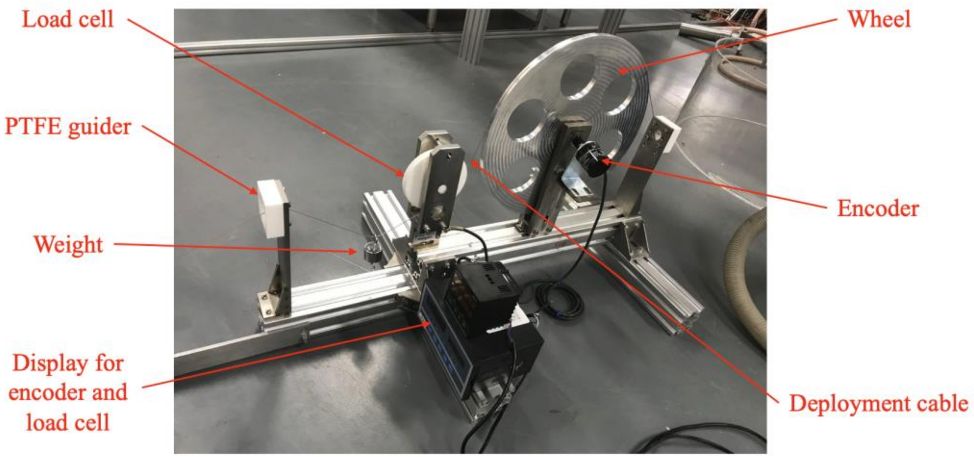
ACU Status



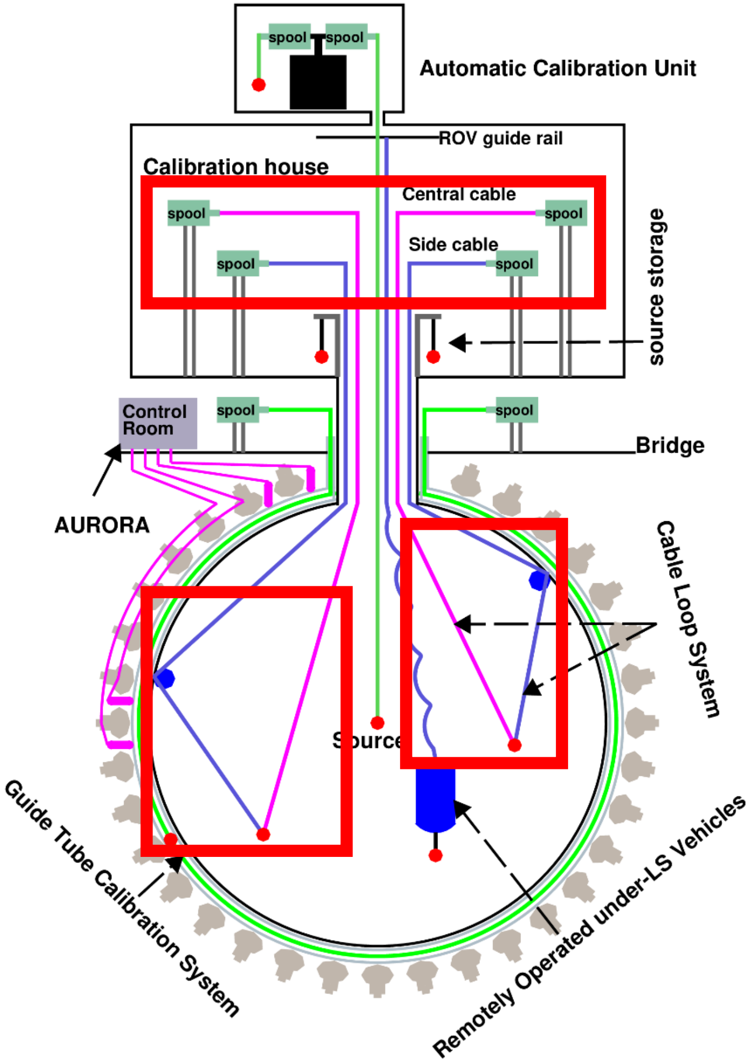
- **ACU:**
  - 1D central axis calibration system
  - Calibrate the nonlinearity and partial non-uniformity
  - Turntable for source selection as well as the laser deployment
  - Validate using a custom length recorder to measure the bias
  - Better than 10 mm positioning accuracy



ACU



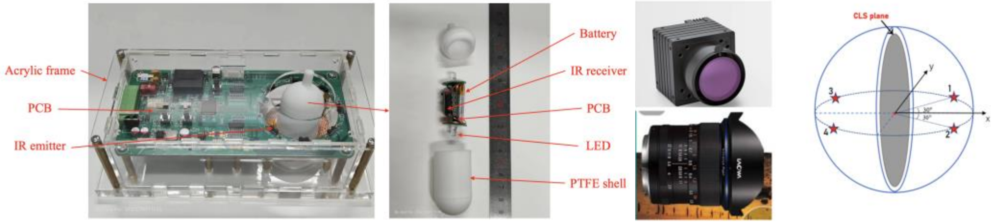
Custom length recorder



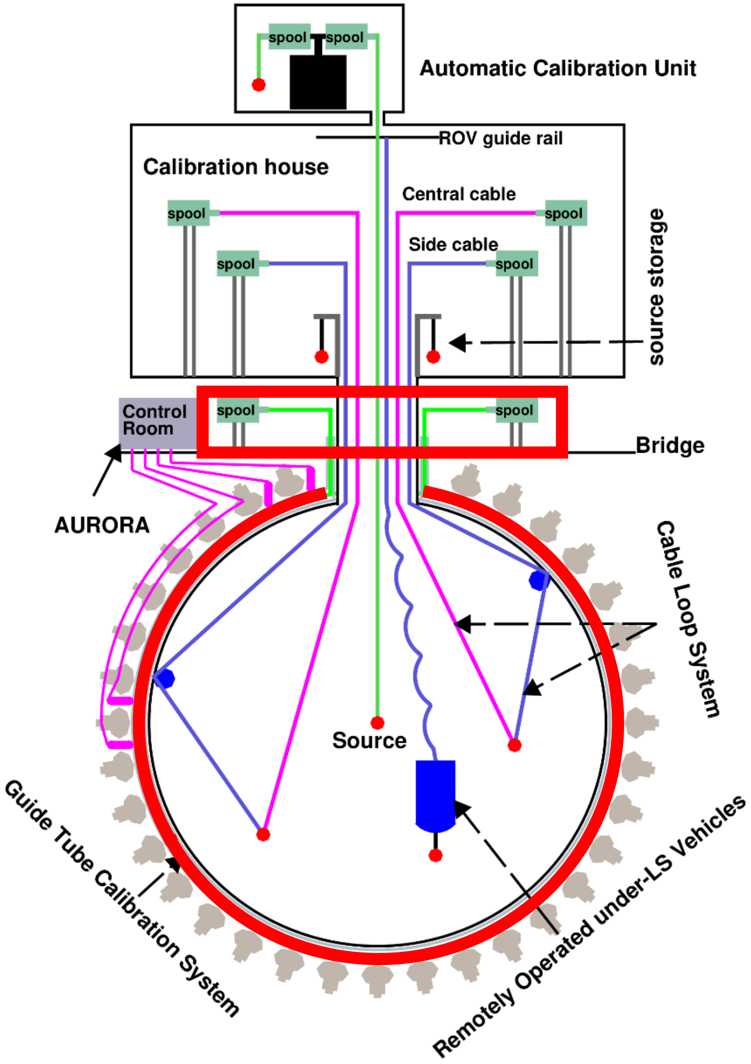
- **CLS:**
  - 2D plane calibration system
  - Calibrate the detector non-uniformity in a vertical plane
  - Can’t calculate the position by the cable length
  - Validate using USS (UltraSonic positioning System) and CCD camera
  - Better than 30 mm positioning accuracy

CLS

USS emitter (left), receiver (middle) and installation (right)



Positioning light source (left) and CCD layout (right)



- **GTCS:**
  - 2D boundary calibration system
  - Calibrate the detector boundary non-uniformity
  - Validate using positioning sensors to correct the bias
  - Better than 30 mm positioning accuracy
  - Finished 70% installation on the detector surface

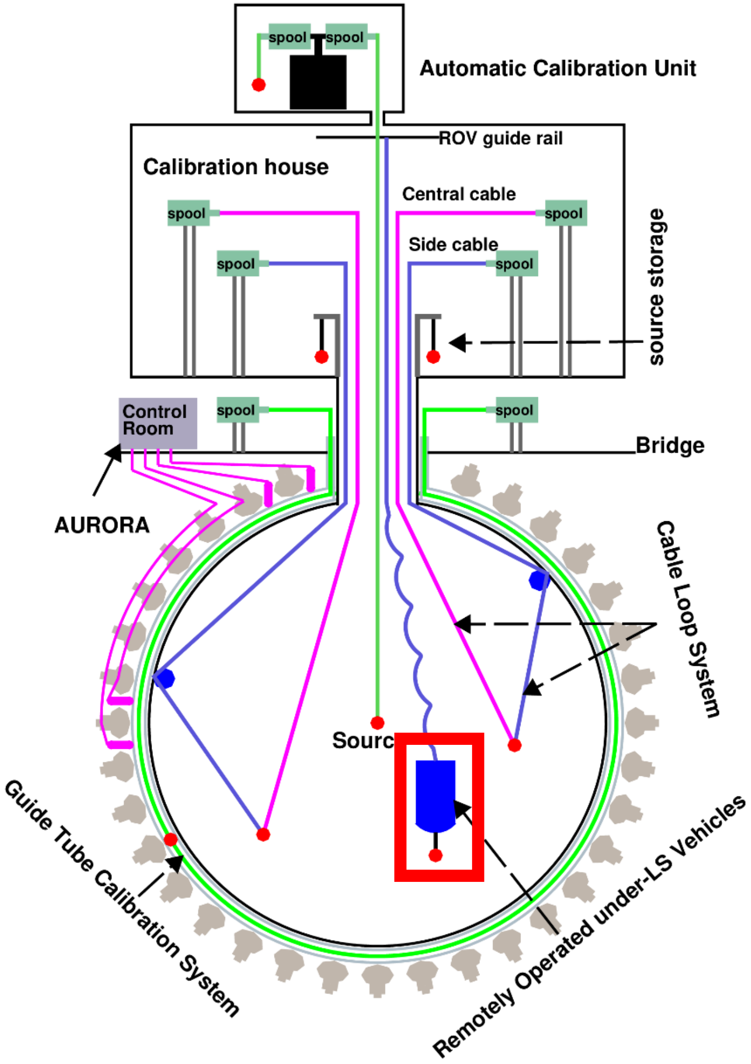
GTCS prototype

Motion control

Guide tube

Sensor

ROV Status



- **ROV:**
  - 3D calibration system calibrates the detector non-uniformity
  - Submarine with umbilical cable for radioactive source deployment
  - Validate using USS to meet the 30 mm/5 min positioning accuracy

Umbilical cable

ROV

Summary

- The calibration subsystems are produced and tested well, installed partially.
- Based on the calibration strategy, after the calibration, the energy scale uncertainty is better than 1% and the detector energy resolution is better than 3% at 1 MeV.

Thanks!