The JUNO Calibration Complex and its Simulation

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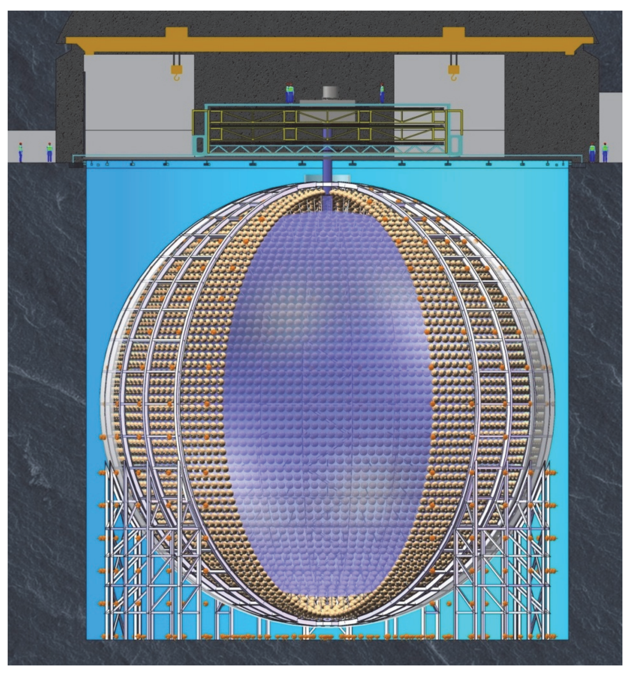
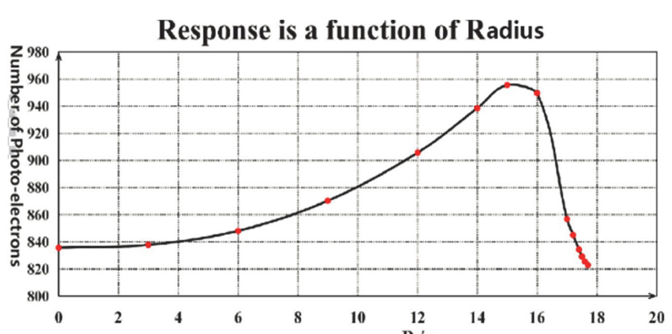
1. Introduction of JUNO

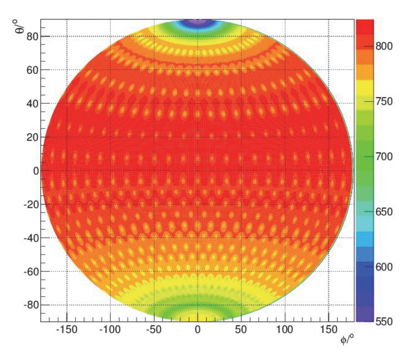
- The Jiangmen Underground Neutrino Observatory (JUNO) , which will be constructed at Kaiping, Jiangmen in South China, is designed to primarily determine the neutrino **Mass Hierarchy(MH)** by detecting reactor anti-neutrinos via inverse beta decay.
- JUNO central detector (CD) which is an **acrylic sphere with a diameter of 35.4m,** is filled with liquid scintillator(LS) and equipped with **more than 50000 PMTs** in total to measure the energy of neutrinos.
- The energy resolution should be $< 3\%/\sqrt{E}$ to determine MH in **3σ in 6 years**, so the calibration complex is very critical and has been designed.



2. Calibration Complex

□ JUNO energy response is strongly position-dependant due to the detector structure and dimension





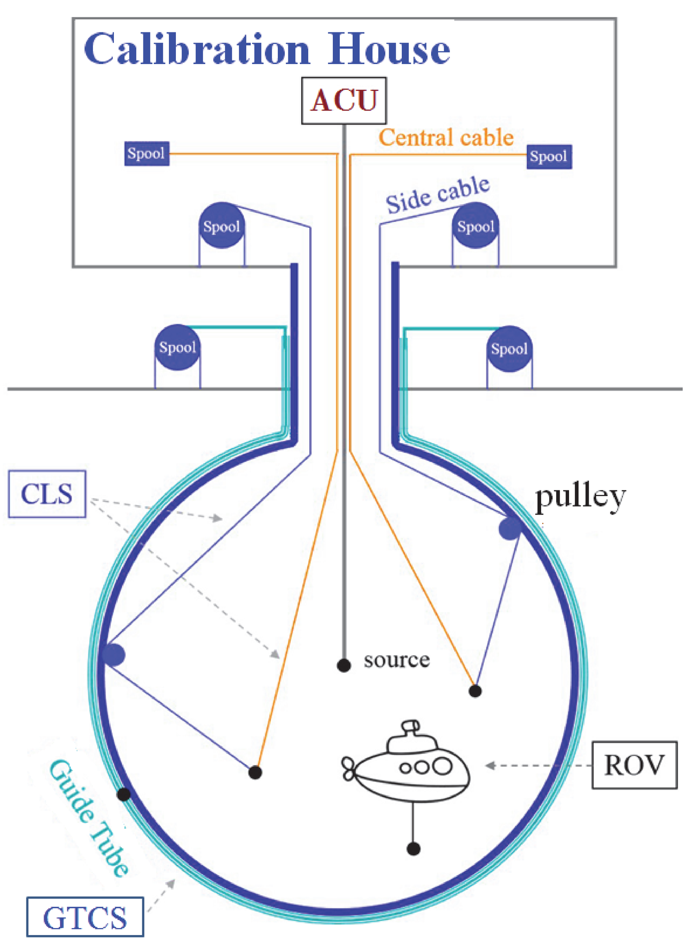
◆ Requirements

Overall energy resolution: $3\%/\sqrt{E}$
Energy nonlinearity: < 1%

◆ Calibration Sources

Source	Type	Radiation
^{137}Cs	γ	0.662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	1.173 + 1.333 MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annil 0.511 + 0.511 MeV
^{22}Na	e^+	annil + 1.275 MeV
^{40}K	e^-	0~1.31 MeV
^{90}Sr	e^-	0~2.28 MeV
^{241}Am-Be	n, γ	neutron + 4.43 MeV
^{241}Am-^{13}C or ^{241}Pu-^{13}C	n, γ	neutron + 6.13 MeV
^{252}Cf	multiple n, multiple γ	prompt γ's, delayed n's

Calibration House



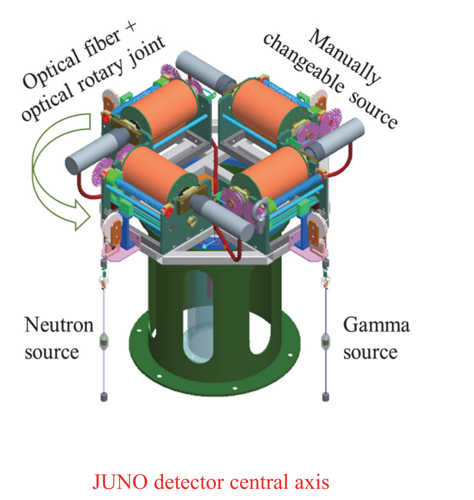
◆ Subsystems for Full-volume Coverage

1-D: Automatic Calibration Unit (**ACU**) for central axis scan
2-D: Cable Loop System (**CLS**) for one vertical plane scan + Guide Tube Calibration System(**GTCS**) for CD outer surface
3-D: Remotely Operated under-liquid-scintillator Vehicles (**ROV**) for whole CD scan

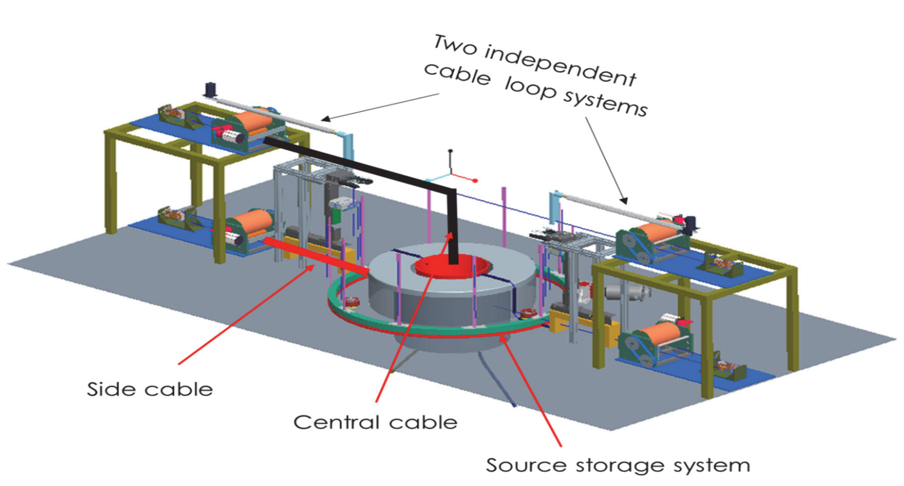
System	Frequency	Positioning	Position Control	Source change	Others
ACU	Weekly	Rope Length	Spool drive (steel wire coated with Teflon Φ1.0 mm) +Tension Control	Manual	All are critical, have to be combined
CLS	Monthly	Rope Length, CCD Ultrasonic receiver		Automatic	
GTCS	Monthly	Rope Length Metal Sensor		Manual	
ROV	When needed, seasonally or annually	Ultrasonic receiver CCD	Remotely Operated Vehicle	Manual	Redundancy

3. Introduction of Calibration Subsystems

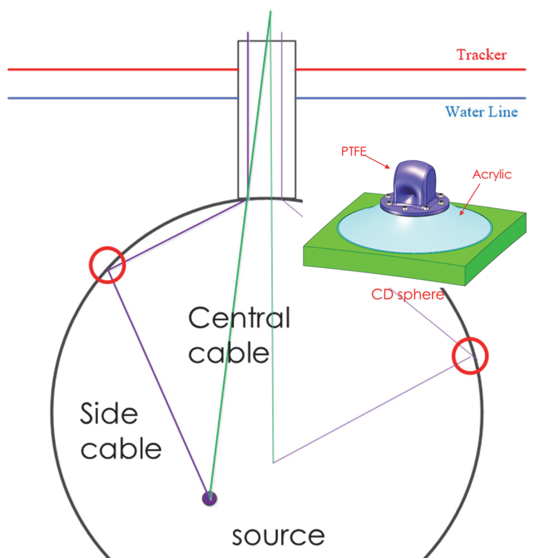
◆ Automatic Calibration Unit (ACU)



- ACU is used for calibration along central axis (1-D).
- It supports γ/neutron/laser source.
- Source positioning is a few mm.
- It provides an access for manually changing calibration source. The schema is important for non-linearity correction.



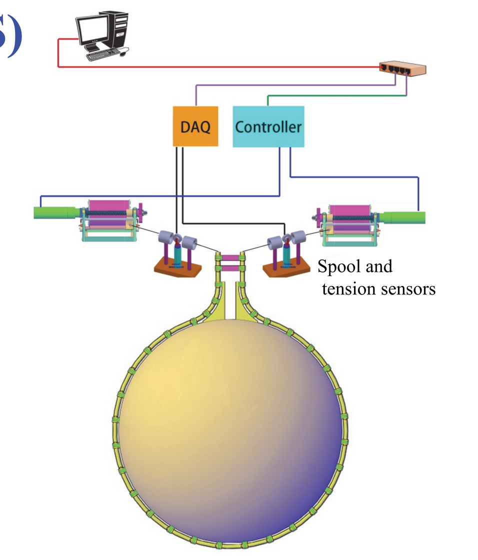
◆ Cable Loop System (CLS)

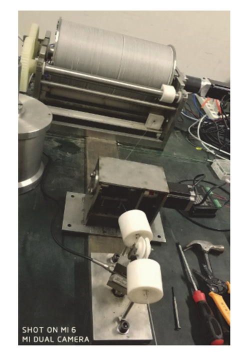


- Two cable loops will be assembled on both semisphere, source position is controlled by spools with Teflon-coated steel cable.
- Source can reach most area on one plane.
- Source position inaccuracy is controlled to be <10 cm (tested) with CLS alone.
- Independent ultrasonic system is used for the source positioning an ultrasonic emitter is attached to the radioactive source fixture.

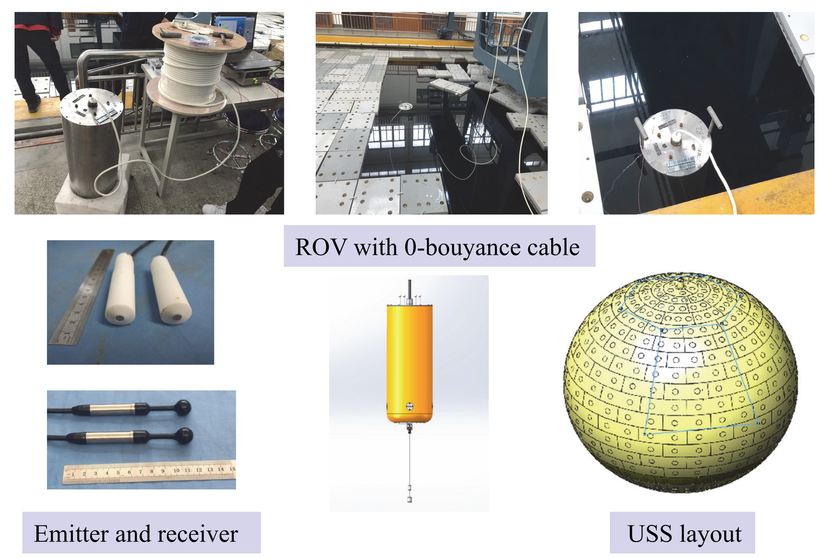
◆ Guide Tube Calibration System (GTCS)

- GTCS is used for calibration along boundary area and provides boundary condition for correction map.
- Source delivery is controlled by servomotors, Teflon tube and Teflon-coated steel cable are used to minimize the friction.
- Source position inaccuracy is < 10 cm.





◆ Remotely Operated Vehicle (ROV)



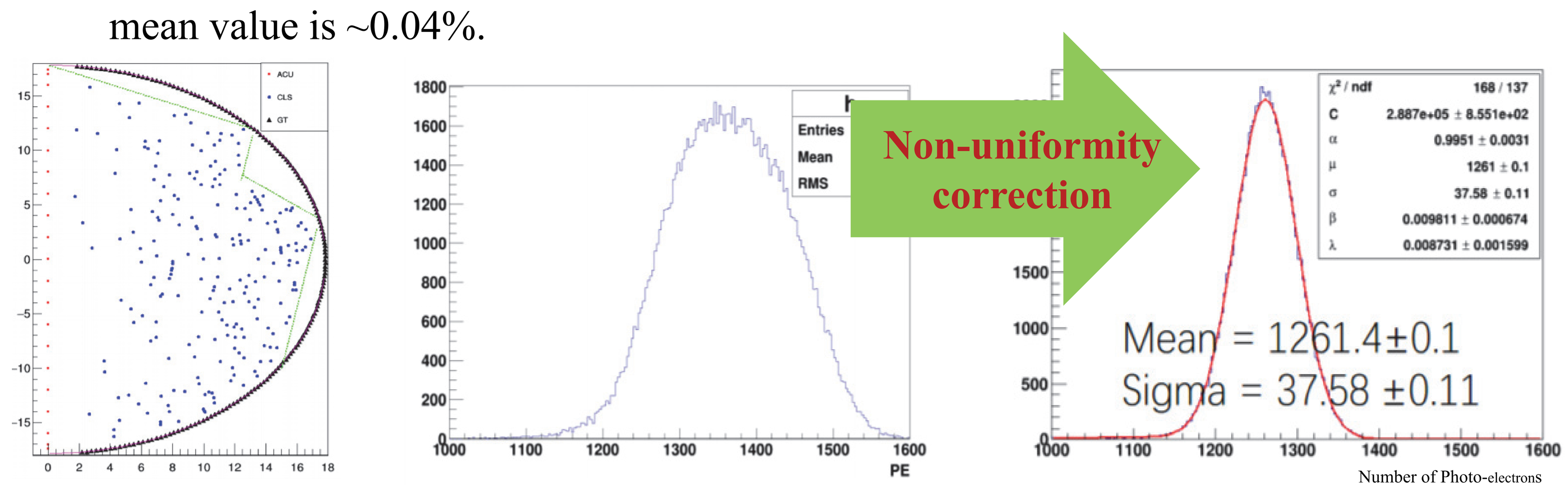
- A self-driven vehicle (Φ300 × 700 mm) .
- The body is coated with PTFE.
- Four ultrasonics emitters are attached with ROV for the source positioning. 8 ultrasonic receivers will monitor ROV`s position.
- Positioning accuracy can reach ~4cm, and ROV is designed to be stable within 3 cm in 5 minutes.

4. Simulation of Calibration Strategy

ACU+CLS+GTCS(+ROV)	^{241}Am-^{13}C in CD specified position	Non-uniformity correction	Accurate Energy Measurement
ACU	Multiple sources at the CD center	Nonlinearity correction	

4.1 Uniformity Correction

- Calibrate JUNO response function by using the data from the given calibration points.
- A simple spline function is used to predicate the "blank" region.
- The energy response uniformity would be corrected with the correction function.
- Energy resolution of 1.022MeV uniformly distributed positron is **2.98%**, bias of the mean value is ~0.04%.



231 calibration points with ^{40}K from ACU/CLS/GTCS.

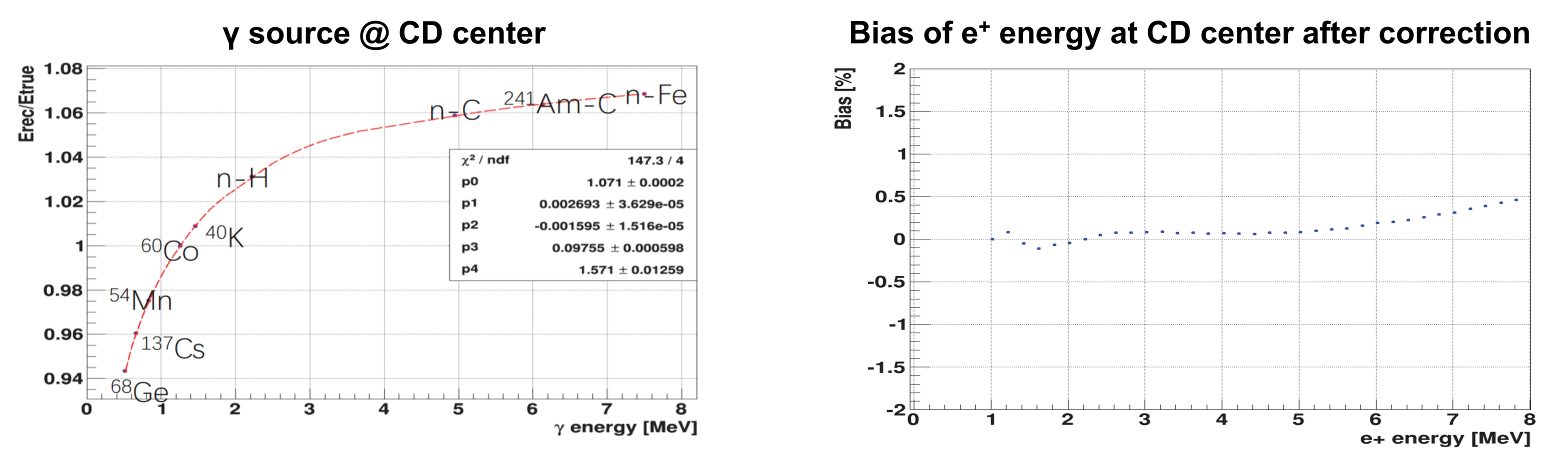
Before Correction Resolution is 5.71%

After Correction Resolution is 2.98%

Resolution is improved by correction

4.2 Linearity Correction

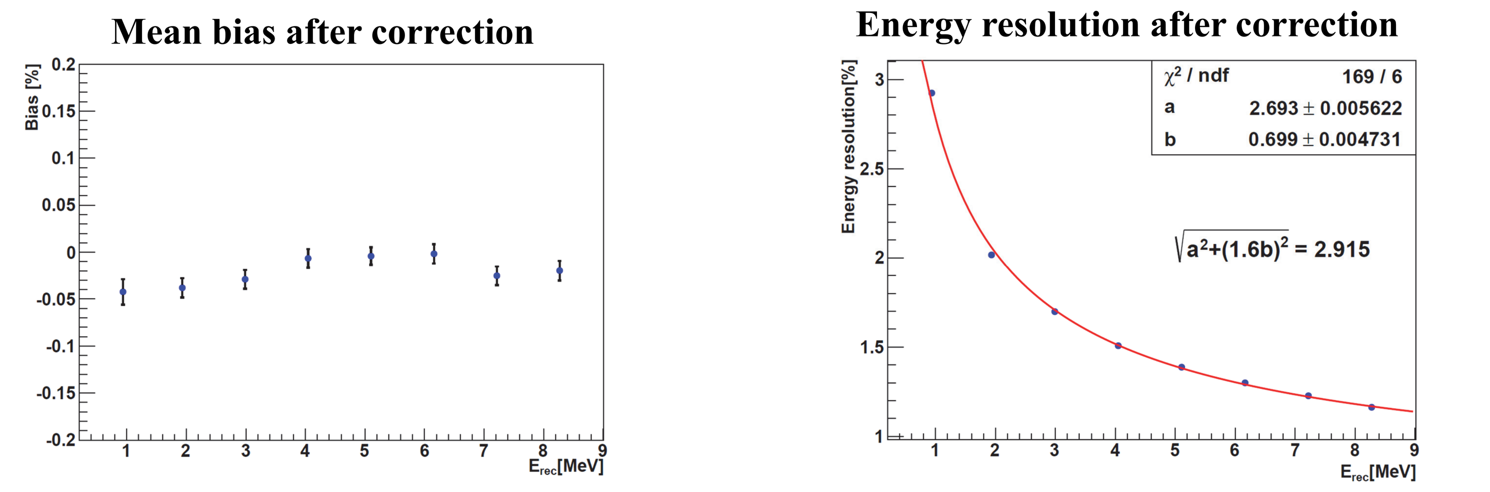
- Energy linearity is investigated by placing various sources at CD center.
- 9 gamma sources are used to study the detector`s linearity.
- As a verification test, the energy bias (non-linearity) to mono-energy positron at the CD center is < 0.5% after correction.



4.3 Overall Energy Resolution

➢The simulated mono-energy e^+ events are uniformly distributed in the CD and the non-uniformity correction (response is obtained with ^{241}Am-^{13}C) is applied .

➢**The bias <0.1% and the energy resolution <3.0%.**



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