Calibration System of the JUNO Experiment

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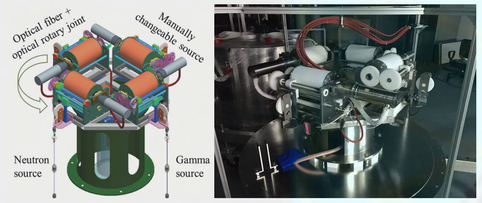
A comprehensive multiple-source, multiple-position calibration program is developed for a JUNO central detector(CD) to achieve a better than 1% linear energy scale and a superior effective energy resolution of 3% between 1 MeV and 8 MeV in order to determine neutrino mass hierarchy, measure solar neutrino, detect supernova neutrino, etc.

Automatic Calibration Unit (ACU)

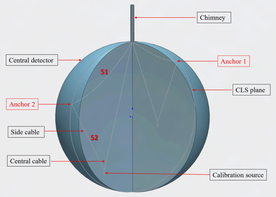
- 1D central axis scan with gamma sources, neutron sources and laser automatically



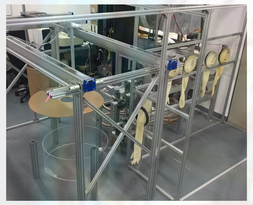
ACU prototype

Cable Loop System (CLS)

- 2D plane source scan with cable loops assembled on both semisphere sides



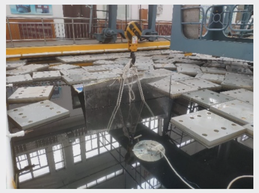
CLS layout



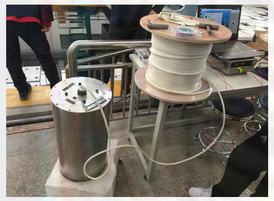
CLS motor prototype

Remotely Operated Vehicle (ROV)

- 3D source scan with a self-driven vehicle unit



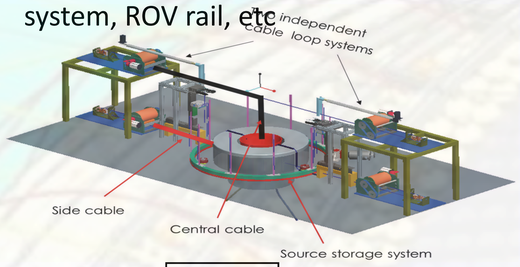
ROV water test

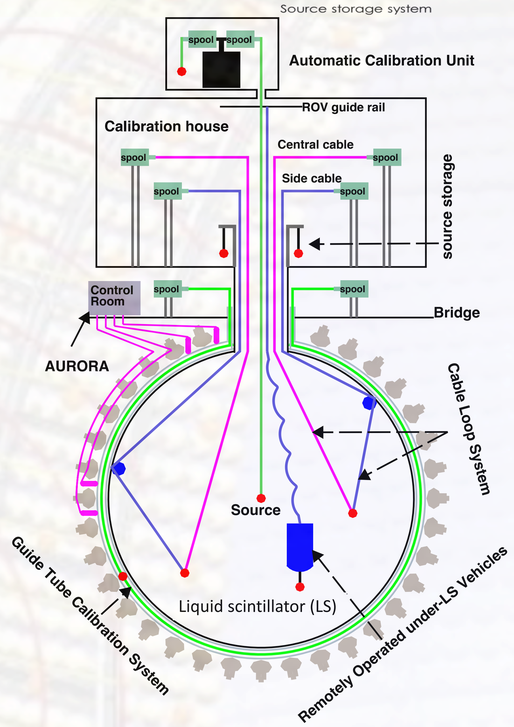


ROV

Calibration house

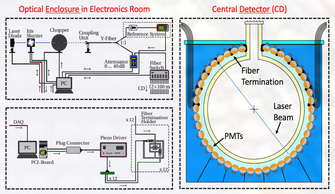
- Source storage, motors to control CLS system, ROV rail, etc





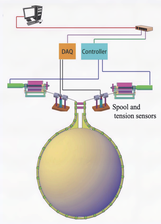
AURORA (A Unit for Researching Online the LSc tRAnsparency)

- Monitor and determine LS attenuation length, scattering length and absorption length with laser system



Guide Tube Calibration System (GTCS)

- Calibrate boundary area and provide boundary condition for the CD

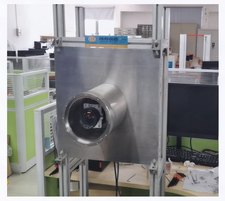


1:1 GTCS prototype

Ultrasonic sensor system (USS) and CCD

- positioning ROV and CLS

USS prototype



CCD prototype

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
^{241}Am-Be	n, γ	neutron + 4.43 MeV
^{241}Am-^{13}C	n, γ	neutron + 6.13 MeV
(n,γ)p	γ	2.22 MeV
(n,γ)^{12}C	γ	4.94 MeV or 3.68 + 1.26 MeV

Energy resolution

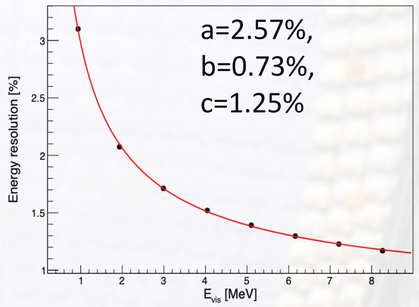
- Energy resolution

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

Effective energy resolution

$$\tilde{a} \equiv \sqrt{(a)^2 + (1.6\times b)^2 + \left(\frac{c}{1.6}\right)^2}$$

- a term is the statistical term, about 2.7%
- b is a constant term independent of the energy, and in the case of JUNO, dominated by position non-uniformity
- c term represents the contribution of a background noise term, c is estimated to be 1.0%



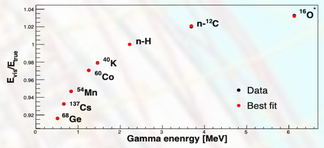
Positron energy resolution vs. E_{vis} after the ideal non-uniformity correction

Physics nonlinearity

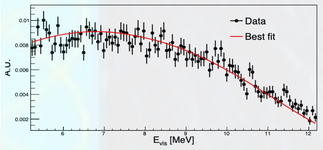
- Caused by scintillating and Cerenkov photons in LS

$$f_{\rm nonlin} = \frac{p_0 + p_3 E^e}{1 + p_1 e^{-p_2 E^e}}$$

- Multiple gamma sources and cosmogenic background are used to corrected physics nonlinearity



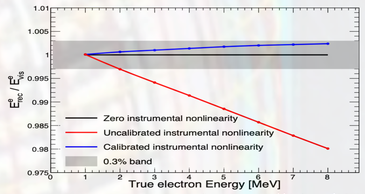
(a) Gamma nonlinearity



(b) Boron Spectrum

Instrumental nonlinearity

- Combine dual calorimetry including LPMTs and reference SPMT whose response is linear in charge by design and tuneable laser source to calibrate channel nonlinearity

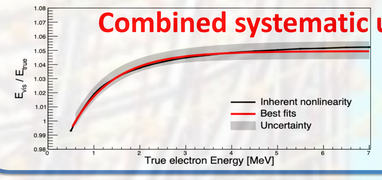


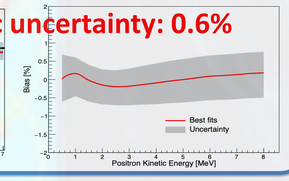
Refer to https://doi.org/10.1007/s41605-017-0022-2

Systematic uncertainties

- Shadowing effect: < 0.15%
- Energy loss effect: < 0.1%
- High energy gamma uncertainty: 0.4%
- Instrumental nonlinearity: <0.3%
- Position dependent effect: 0.3%
- Statistics: 0.01%

Combined systematic uncertainty: 0.6%





- **The bias in the reconstructed energy is less than 0.6% over the entire range of the inverse beta decay energy, which is significantly better than the 1% requirement.**
- **The effective energy resolution is less 3.0% between 1 MeV and 8 MeV.**