PROCEEDINGS OF SCIENCE

Calibration Subsystems of the JUNO Detector

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The Jiangmen Underground Neutrino Observatory (JUNO), a 20-kiloton liquid scintillator detector equipped with 17612 20-inch photomultiplier tubes (PMTs) and 25600 3-inch PMTs, is under construction currently, aiming to detect reactor, solar, atmospheric, geo neutrinos and neutrinos produced by a supernova collapse. To accurately achieve these multi-purpose physics goals, the detector energy resolution better than 3% at 1 MeV and the uncertainty of the absolute energy scale below 1% are required. In order to meet these stringent requirements, a comprehensive calibration system comprising the Automatic Calibration Unit, the Cable Loop System, the Guide Tube Calibration System and the Remotely Operated Vehicle is under development to calibrate the energy non-linearity and non-uniformity of the Central Detector (CD). This proceeding will summarize the design and development of the calibration subsystems, and report on their installation status.

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1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) will determine the neutrino mass ordering by detecting the inverse beta decay of reactor neutrinos. Achieving this key physics goal depends critically on the detector energy resolution and the uncertainty of the absolute energy scale, which is required better than 3% at 1 MeV and within 1% respectively [1–4]. To meet these challenging requirements, a comprehensive calibration system, as shown in Fig. 1, has been designed to calibrate the energy non-linearity and detector non-uniformity. This system includes the Automatic Calibration Unit (ACU) [5], the Cable Loop System (CLS) [6], the Guide Tube Calibration System (GTCS) [7] and the Remotely Operated Vehicle (ROV) [8].

The JUNO detector is under construction in Jiangmen, China. Alongside the development of the central detector, the progresses of the calibration subsystems are equally vital. The tests in the laboratory for these subsystems were complete, and on-site installation is partially finished.

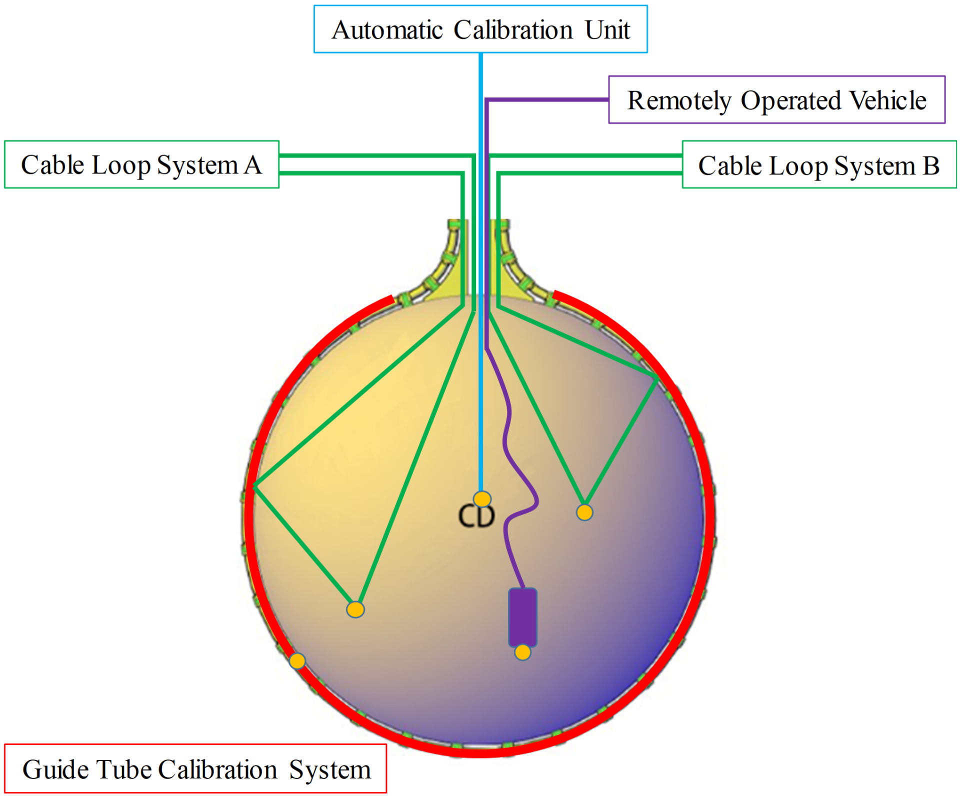

Figure 1: The layout of the subsystems in the JUNO calibration system

2. The Calibration System

The JUNO calibration system, comprising the ACU, CLS, GTCS and ROV, faces the challenge of calibrating both energy non-linearity and detector non-uniformity. As shown in Fig. 1, these four subsystems address different detector parts: the one-dimensional central axis, two-dimensional vertical plane, two-dimensional boundary longitude and three-dimensional area respectively.

The ACU is responsible for calibrating energy non-linearity and central axis non-uniformity, with a positioning accuracy better than 10 mm [5]. According to [9], after the energy non-linearity calibration (Fig. 2 (left)), the residual bias is shown in Fig. 2 (right): when combined with the instrumental non-linearity from the 20-inch PMTs, the systematic uncertainty on the energy scale is approximately 0.7%, meeting the 1% goal.

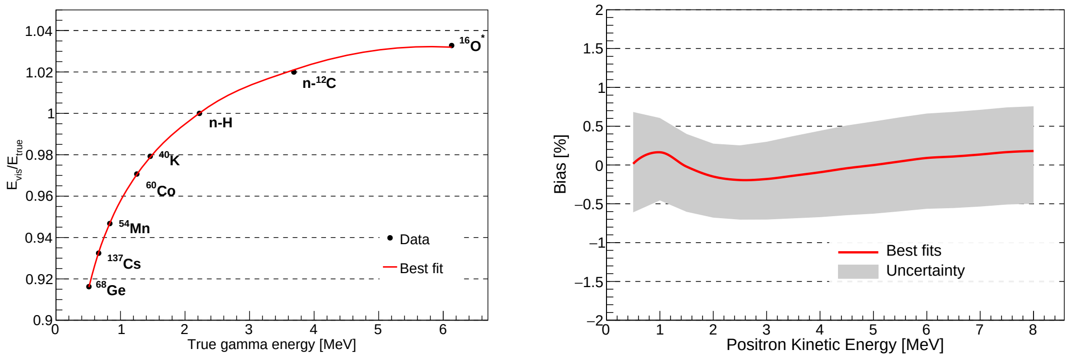

Figure 2: γ energy non-linearity (left) and non-linearity residual bias (right) [9]

The CLS calibrates detector non-uniformity within a vertical plane. Due to its structure, cable length calculation is insufficient for positioning, so the CLS employs the UltraSonic positioning System (USS) [10] and CCD camera to ensure the positioning accuracy within 30 mm [6].

The GTCS addresses boundary longitude non-uniformity, with a positioning accuracy better than 30 mm [7]. Installed on the detector's outer surface, the GTCS experiences significant Compton smearing in the energy spectrum. As shown in Fig. 3 (left), the full absorption peak can be isolated through fitting to determine the energy response at the specific positions. By combining these results, a boundary non-uniformity correction map is generated, as illustrated in Fig. 3 (right).

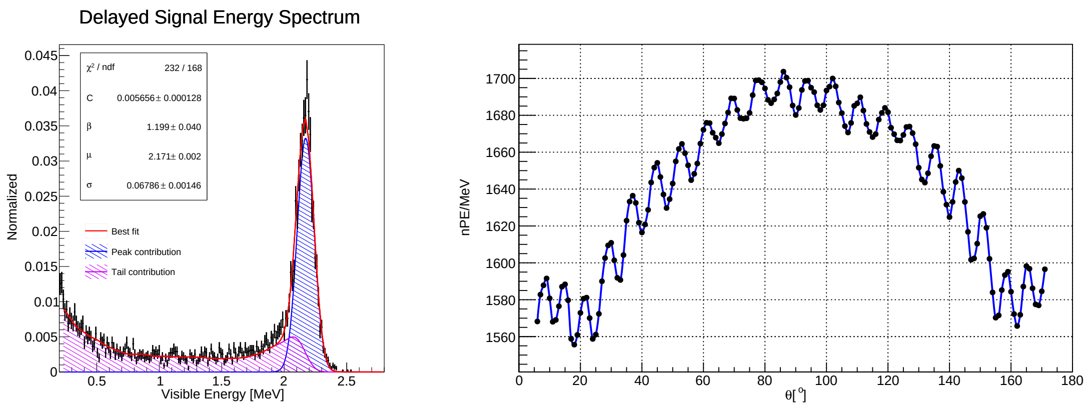

Figure 3: GTCS energy spectrum at θ=53 degree (left) and boundary non-uniformity correction map (right)

The ACU, CLS and GTCS will each perform spatial calibration to map the energy response at specific points to optimize the overall energy resolution. Once the overall γ non-uniformity correction map is obtained, it will be used to predict the positron energy resolution based on the

Birks law and the Frank-Tamm formula, achieving a resolution 2.95% at 1 MeV [11], meeting the requirement.

As a backup, the ROV provides three-dimensional calibration of detector non-uniformity, using the USS to achieve a positioning accuracy of 30 mm within 5 min [8].

3. Calibration Subsystems Status

The on-site installation of the calibration system is progressing well, involving all the subsystems.

The ACU features a turntable for selecting radioactive sources and the laser deployment, which will be used to calibrate the energy non-linearity. The source replacement and positioning have been successfully tested in the laboratory, as shown in Fig. 4 (left). The on-site assembly is currently in progress and is expected to be completed before the end of the year.

The motion control for both sets of the CLS has also been successfully tested in the laboratory, as shown in Fig. 4 (right). The CLS will utilize anchors on the inner surface of the acrylic vessel as fixed points. The cables have already been secured, and the on-site installation is underway, with completion anticipated by the end of this year.

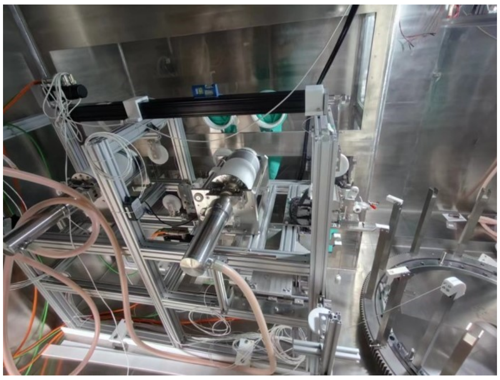

Figure 4: ACU laboratory test (left) and CLS laboratory test (right)

The GTCS motion test in the laboratory was successfully completed using C# control software, as shown in Fig. 5 (left). The GTCS requires 10 position sensors along the longitude to reduce positioning bias, as shown in Fig. 5 (middle), 9 sensors have already been installed. The installation of guide tubes on the outer surface of the acrylic vessel is nearing completion, as illustrated in Fig. 5 (right). The next step will involve assembling the GTCS motion control system on-site.

For the ROV, the tests in the laboratory have been completed. Its on-site installation will take place after the other subsystems are installed.

4. Summary

The JUNO calibration system, designed to calibrate energy non-linearity and detector non-uniformity, is currently under construction. The tests in the laboratory has been successfully completed, and the on-site installation is progressing as planned. We look forward to the first data from the calibration system.

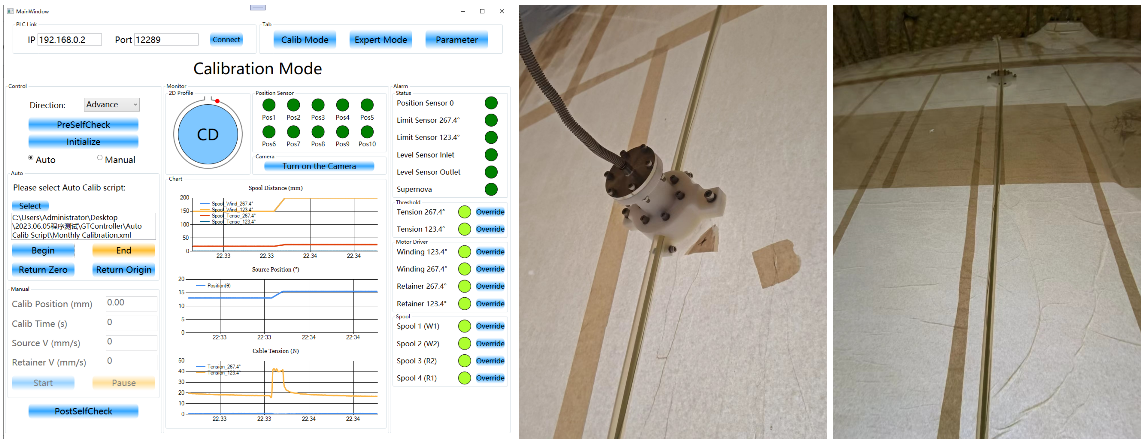

Figure 5: GTCS motion control test (left), positioning sensor (middle) and on-site installation (right)

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