The JUNO Water Cherenkov Veto system

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Experiment location

- Location: Jiangmen, Guangdong Province, China
- Powerful source: 8 nuclear reactors
  - All six $2.9 \text{ GW}_{th}$ cores in Yangjiang NPP and two $4.6 \text{ GW}_{th}$ cores in Taishan NPP are in operation now.
- Baseline: 53 km
- Background reduction: Under $\sim650\text{ m}(1800\text{ m.w.e.})$ deep underground for muon flux reduction.
Detector overall

- **Central detector:**
  - Acrylic vessel with liquid scintillator
  - 17612 large PMTs (20-inch)
  - 25600 small PMTs (3-inch)
  - ∼ 78% PMT coverage
  - PMTs in water buffer
- **Water Cherenkov Detector (veto):**
  - 2400 20-inch PMTs
  - 35 ktons ultra-pure water
- **Compensation coils:**
  - Resident earth magnetic field <0.05Gs
  - Necessary for 20” PMTs
- **Top Tracker (veto):**
  - 3 plastic scintillator layers
  - Covering half of the top of the water pool
  - Precision muon tracking
Detector challenging

- Detector requirement:
  - 3% @ 1 MeV energy resolution, very high energy resolution
  - High transparency Liquid Scintillator (>20m@430nm)
  - High coverage of PMTs (>75%)
  - Low backgrounds (reactor neutrinos, solar neutrinos)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Daya Bay</th>
<th>Borexino</th>
<th>KamLAND</th>
<th>JUNO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target mass [tons]</td>
<td>8 x 20</td>
<td>~300</td>
<td>~1,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Photo electron[p.e./MeV]</td>
<td>~160</td>
<td>~500</td>
<td>~250</td>
<td>&gt;1345</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>~8.5%</td>
<td>~5%</td>
<td>~6%</td>
<td>~3%</td>
</tr>
<tr>
<td>Photocathode coverage</td>
<td>12%</td>
<td>34%</td>
<td>34%</td>
<td>~78%</td>
</tr>
<tr>
<td>Energy calibration uncertainty</td>
<td>0.5%</td>
<td>1%</td>
<td>2%</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>

The most challenging design in the reactor neutrino experiments throughout the world.
Rich physics program of JUNO

Event Rate (after selection)

Mass ordering and oscillation parameters

Cosmogenic background

- Reactor neutrinos detected via inverse beta decay (IBD)
- Cosmic muons
  - Mean muon energy at experiment hall ~207 GeV;
  - Rate in central detector 4 Hz.
- Muon related background
  - $^9$Li/$^8$He unstable isotopes produced by muon spallation on $^{12}$C and decay beta-neutron;
  - Untagged muon induced fast neutron background.

By good veto detector design and veto strategy, muon induced background anticipation as shown in the following table (red square frame).

<table>
<thead>
<tr>
<th>Background</th>
<th>Rate (day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geoneutrinos</td>
<td>1.2</td>
</tr>
<tr>
<td>World reactors</td>
<td>1.0</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.8</td>
</tr>
<tr>
<td>$^9$Li/$^8$He</td>
<td>0.8</td>
</tr>
<tr>
<td>Atmospheric neutrinos</td>
<td>0.16</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.1</td>
</tr>
<tr>
<td>$^{13}$C(α, n)$^{16}$O</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Digitalized mountain profile of JUNO site
Two veto systems for cosmic muon detection and background reduction.

- **Water Cherenkov Veto:**
  - Muon event tagging.
    - Outer of the detector;
    - 35 kton ultrapure water as medium;
    - Fast neutrons background rejection
      - Muon tagging + passive shielding
  - Radioactivity from rock
    - Passive shielding by water
- **Top tracker:**
  - On top of water pool, cover ½ of pool;
  - A precise muon track reconstruction;
  - Cosmogenic muon induced isotopes reduction ($^9$Li/$^8$He).
Water veto sub-systems/components

- Sub-systems/components
  - PMTs: 2400 20 inch PMTs
  - Water system: 100 ton/h water system
  - EMF coils: shielding the detector to ensure the 20 inch PMT performance
  - Pool lining: covering the pool wall as Rn barrier
  - Tyvek reflector: increase light collection for PMT
  - Cover: gas tight cover for the detector
  - Support structure

Pure water system, flow rate: ~100 t/h

- PMTs & Tyvek reflection film
- Bird cage & Tyvek reflection film
- EMF coils
- Cover & rail
- Pool liner
PMTs

- Three types of PMTs used in JUNO
  - Central detector
    - 17612 large PMTs (20-inch)
    - 12612 MCP-PMTs from NNVT
    - 5000 dynode PMTs from Hamamatsu
  - 25600 small PMTs (3-inch) from HZC
  - Water veto
    - 2400 MCP-PMTs from NNVT

All PMTs are produced, tested, and instrumented with waterproof potting.
Compensation coils system

- Earth Magnetic Field (EMF) intensity at JUNO site
  - Intensity ~0.45Gs
    - Big negative affect on the 20 inch PMT performance;
  - Need a shielding system for compensation EMF.

- Use one set of coils to generate the opposite direction of the geomagnetic field to compensate.
  - 16 pairs shielding coils scheme;
  - Coils’s uniformity in CD<0.05G.
- EMF direction change effect
  - The EMF direction change every year(<0.2deg/y).
  - Set a compensation angle when the coils are installed.
  - Make the angle change < 1 degree within 10 years.
- Coils and sensors production were finished.
PMT placement in water veto

- 2400 20 inch MCP-PMT used for veto system;
  - PMTs put on the surface of the sphere and facing outside;
- No PMT on the bottom and side of the wall.
  - Positions are too close to the compensation coils/outside the coils;
  - The PMT will be affected by the magnetic field by the coils/EMF;
  - Move PMTs on the sphere of the stainless frame to get better performance.
- Trigger & efficiency
  - Divide the detector into 10 pieces for local trigger;
  - Detector efficiency is expected to reach 99.5%.
- Fast neutron background
  - With the high muon tagging efficiency, the fast neutron background is anticipated to be <0.1/day.
The ultrapure water production and circulation system

**Water system**
- Keep water quality with good transparency for detector performance
- Flow rate: ~100 t/hour
- Ground system:
  - Water production
- Underground system:
  - Purification and circulation;
  - Connection ground and underground system by 1300 stainless steel pipe in slope tunnel;
- Water circulation
  - 2-3 weeks one volume.

**Status:**
- The slope tunnel pipe installation and construction were finished.
- The underground system is under construction.
Detector temperature control

• Keep temperature control within (21±1)℃ around the acrylic vessel
  • Important for acrylic safety;
  • Keep the detector’s mechanical stability.
• A lot of studies and optimizations were done to achieve this goal.
• The circulation schema:
  • Top and bottom of the pool have inlet pipes;
  • Outlet pipes at the equator of the detector;
  • Top and bottom pipes have distributors to make the circulation more uniform;
  • The temperature distribution around the acrylic vessel is anticipated: 20℃< T <22℃.
Radon/radium removal in water

- Water buffer between the central detector acrylic vessel and PMTs.
  - Requirement for radon concentration in water $< 10 \text{ mBq/m}^3$
- Liquid-cell degassing membrane is used to remove radon from water.

- Micro-bubble device used
  - The Rn removal efficiency is correlated with the gas content in water;
  - Generate bubbles at a scale of nm/μm to greatly increase the gas content in water;
  - Installed after the first stage of degasser to load gas into the water.

- Micro-bubble device + degassing membrane
  - The radon concentration in water was reduced to ~5mBq/m$^3$;
  - These devices will be combined into water system.
The Rn/Ra concentration measurement system

• Rn concentration:
  • By detecting the αs from $^{214}$Po and $^{218}$Po decay with a Si-PIN (Hamamatsu S3204-09);
  • The sensitivity is $\sim 0.7\text{mBq/m}^3$ for one day measurement.

• $^{226}\text{Ra}$
  • The progenitor of $^{222}\text{Rn}$;
  • Mn-fiber extract radium from water;
  • A radon emanation measurement system to measure the activity of $^{226}\text{Ra}$;
  • The sensitivity of the radium concentration in water $\sim 0.1\text{mBq/m}^3$. 
Pool lining

- **High Density Polyethylene (HDPE)**
  - To separate pure water from the rock
  - To prevent rock radon from diffusing into the pool.
  - Two kinds of HDPE plate, with and without nails.
    - Thickness 5 mm.
  - The side wall lining installation was finished.

- Dimension: 43.5 m diameter * 44 m height;
- >6000 m² lining.
Tyvek reflector

Tyvek reflection film

To be installed on

- Surface of the SS latticed shell;
- Pool wall, bottom and top;
- Cover the whole inner surface of the pool to improve light collection.
- Tyvek reflector production finished.

Reflectivity larger than 95% for wavelengths > 300nm
JUNO experimental site

Pumping amount in m³/hour

Water Level Monitoring

Vertical tunnel: 563 m

Overburden ~650 m (1800 m.w.e.)

Slope tunnel: 1265 m @ slope of 42%

Civil construction finished in Dec, 2021
JUNO Timeline

2014
- International collaboration established
- Conceptual design

2015
- PMT production line setup
- CD parts R&D
- Civil construction start

2016
- PMT production start
- CD parts production start
- Yellow book published

2017
- PMT testing start
- TT arrived

2018
- PMT potting
- Start delivery of surface building
- Start production of acrylic sphere

2019-2021
- Electronics production starts
- Civil construction and lab preparation completed
- Detector construction

2022 — 2023
- Complete detector construction
- Data taking

Neutrino detected
Summary

• JUNO will measure neutrino mass ordering (3 σ with 6 years data taking ) and three oscillation parameters to <1% level.
• JUNO also has a rich physics potential with supernova neutrinos, geo-neutrinos, solar neutrinos, atmospheric neutrinos and other oscillation physics such as searches for proton decay, etc.
• JUNO water Cherenkov detector is designed for muon detection and background reduction.
• The sub-systems production/installation are well underway.
• The experiment is expected to start data taking in 2023.
Thanks!