Status of the JUNO detector system

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On behalf of the JUNO collaboration

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10th workshop of the France China Particle Physics Laboratory
Jiangmen Underground Neutrino Observatory

- **JUNO**: a multipurpose neutrino experiment
  - 20kton liquid scintillator, 3%@1MeV energy resolution, 700m underground
  - A unique way to determine mass hierarchy using reactor antineutrinos by the interference between $\Delta m^2_{31}$ and $\Delta m^2_{32}$.
  - First experiment to measure solar and atmospheric mass splitting simultaneously. <1% precision to $\theta_{12}, \Delta m^2_{21}$ and $\Delta m^2_{31} (\Delta m^2_{32})$.
  - Large detector volume, good resolution and low background allow rich physics goals: supernova, geo-, solar ... neutrinos
  - Long term possibility under consideration: accelerator neutrino, $0\nu\beta\beta$ ...

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Status of the JUNO detector system
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JUNO detector

Calibration room
Pure water room

Central detector
- SS latticed shell
- Acrylic sphere

Liquid scintillator
- 20 kton

Acrylic sphere: \( \Phi 35.4 \text{m} \)
Stainless steel latticed shell: \( \Phi 40.1 \text{m} \)
Water pool: \( \Phi 43.5 \text{m} \)

Top Tracker

PMT
- \( \sim 18,000 \) 20” PMTs
- \( + \sim 36,000 \) 3” PMTs: coverage >75%

Water Cherenkov
- 35 kton pure water
- 2,000 20” veto PMTs

LS Filling room

Pure water room

Status of the JUNO detector system
Final design approved in July 2015: Acrylic sphere + Stainless steel latticed shell

- Acrylic sphere: ID35.4m, thickness: 120mm. >200 pieces of 3m × 8m panels bonded on site.
- Stainless steel: ID40.1m, OD41.1m, divided into 30 longitudes and 23 layers
- Weight of acrylic sphere: ~600 t.
- Weight of stainless steel: ~590 t.
- No. of connecting bars: 590
- No. of shell’s pillars: 60

Acrylic panel  Onsite assembly  Bonding machine  Node test
Central detector progress

• **An international review in Sep. 2016**
  – 11 committee member: 4 SNO members, 2 Daya Bay US engineers, as well as Italy, UK, China on material, mechanics and physics
  – The committee feels the detector has the big challenges on technical, schedule…close collaboration and coordination is necessary

• **Finished bidding of acrylic sphere in Feb. 2017**
  – Donchamp acrylic company (汤臣新材料) won the bid and got the contract of acrylic production and building, due to the better production capacity, equipment, management, preparation for our project.

• **Bidding of SS shell in a few months**

• **1:10 scale prototype is in preparation**
Preparation for acrylic production

- Cleaning production center for thicker acrylic panel
- Pure water treatment
- Water pool for polymerization
- Water circulation to keep the temperature uniform
- Heating room
- CNC machining center

- Built the new workshop for producing acrylic panel according to our special requirement
- Prepare the equipment for acrylic forming and machining
Liquid scintillator

- Requirements for JUNO LS
  - Lower background for $\bar{\nu}_e$ physics: $^{238}\text{U}<10^{-15}\text{g/g}$, $^{232}\text{Th}<10^{-15}\text{g/g}$, $^{40}\text{K}<10^{-17}\text{g/g}$
  - High light yield: concentration of fluor need to be optimized
  - Long attenuation length: $>20\text{m@430nm}$

- LS Purification methods
  - Distillation, column purification, filtration, water extraction, stripping…

- Preliminary LS recipe (based on DYB experiment)
  - 3g/L PPO, 15mg/L bis-MSB in LAB
  - PPO: 2,5-Diphenyloxazole
  - Bis-MSB: 1,4-di-(2-methylstyryl)benzene, p-bis(o-methylstyryl)benzene
  - LAB: linear alkyl benzene

Status of the JUNO detector system
LS pilot plant at Daya Bay

- Study of JUNO liquid scintillator with one of Daya Bay detector, led by INFN and IHEP
  - Pre-study of 20t mass production
  - Optimization of fluorescent materials
  - Study of radioactivity background
  - Test of purification methods

Status of the JUNO detector system
20-inch PMT

A new design of large area MCP-PMT by Chinese team

- Higher QE: transmissive photocathode at top + reflective photocathode at bottom
- High CE: less shadowing effect
- Easy for production: less manual operation and steps

Design

5”(8”)
Prototype

20”
Prototype

Production

2009

2010~2013

2013~2015

2016~2019

Contracts were signed in 2015
15k MCP-PMT (75%) from NNVT
5k Dynode(25%) from Hamamatsu

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (NNVC)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Efficiency (QE<em>CE</em>area)</td>
<td>%</td>
<td>27%, &gt; 24%</td>
<td>27%, &gt; 24%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>3.5, &gt; 2.8</td>
<td>3, &gt; 2.5</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>~12, &lt; 15</td>
<td>2.7, &lt; 3.5</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2, F</del>12</td>
<td>R<del>5,F</del>9</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>20K, &lt; 30K</td>
<td>10K, &lt; 50K</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, &lt;2</td>
<td>10, &lt; 15</td>
</tr>
<tr>
<td>Radioactivity of glass</td>
<td>ppb</td>
<td>238U: 50</td>
<td>238U: 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>232Th: 50</td>
<td>232Th: 400</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40K: 20</td>
<td>40K: 40</td>
</tr>
</tbody>
</table>

Status of the JUNO detector system
Mass Production at NNVT

- Production equipment all in hands
- Training workers, tuning equipment
- All parts in hand
- A few hundreds of products

first batch by workers

Radioactivity of glass

Gain vs HV

Status of the JUNO detector system
PMT instrumentation

- Characterization, installation and protection of ~50,000 PMTs with largest optical coverage in the neutrino world, under up to 45m pure water and running for 20-30 years.

- Mass testing: four test facilities were built and reviewed in Hamburg, on the way to China. System integration and testing near JUNO site.

- Waterproof potting: target failure rate <0.5% for the first 6 years. Designed as multiple waterproof layers: putty + glue + pouring sealant.

- Implosion protection: acrylic + stainless steel protection covers. >50 prototypes and several underwater tests. Thickness optimizing.

- Installation: module was designed to achieve 75% coverage. Installation in parallel to acrylic sphere is preferred.

Status of the JUNO detector system
Readout electronics

- Front part under-water, encapsulated on back of PMT with HV module and divider.
- Transmission of data, hit, clock, power and trigger by ~100m CAT5+ cable
- Integration of prototype in 2017

Status of the JUNO detector system
Muon veto system

- **Goals of veto**
  - Fast neutron background rejection
  - Help muon tracking and cosmogenic isotopes study
  - Gamma background passive shielding
  - Earth magnetic field shielding

- **Water cherenkov detector**
  - ~2000 20” PMT
  - 35 kton ultrapure water with a circulation system
  - Detector efficiency is expected to be > 95%
  - Fast neutron background ~0.1/day.

- **Top tracker (details in Marcos’ talk)**
  - Re-using the OPERA’s Target Tracker
  - Cover half of the top area
Water Cherenkov detector

• **Mechanical structure**
  – A “bird cage” structure was designed for support veto PMTs, tyvek films, cables and water pipes.

• **Water system**
  – Employ a circulation/polishing water system (~2 week one volume circulation).
  – Keep a good water quality including radon control (<0.2 Bq/m³).

• **Earth magnetic field (EMF) shielding system**
  – Use double coils system for EMF shielding.
  – A prototype of compensation coils system was built in IHEP.
  – The theoretically calculation and prototype data are consist with each other. It’s a good validation for compensation coils design of JUNO.
The Small PMT (SPMT) system

- Consists of up to 36,000 3-inch PMTs and readout electronics
- Physics concept was approved in 2015.07
- Detector system was established in 2016.01
- A joint FCPPL project started in 2016, now led by Anatael CABRERA in France and Miao HE in China.
Small PMT physics

- Double-calorimetry: calibration of non-linear response of LPMT (primary), increase optical coverage by ~3% (secondary)
- Solar parameters measurements with *partly independent* systematics
- Help reconstruction for high energy physics: muon, atmospheric $\nu$…
- Help detection of supernova neutrino

**Double calorimetry**

- Large-PMT (LPMT): measure energy via “charge integration”, increase photon statistics $\rightarrow$ stochastic effect
- Small-PMT (SPMT): measure energy via “photon counting”, control systematics $\rightarrow$ non-stochastic effect
Small PMT simulation

- Implementation of two PMT systems with Geant4 in the JUNO offline software framework.
- With realistic geometry and photon detection efficiency, \(~45\) PEs/MeV for \(36,000\) SPMTs, \(3\%\)\(~4\\%\) of LPMTs.

Implementation of a single small tube in Geant4.

A simulated event with PMT responses, \textcolor{red}{
\textbf{color}
\textbf{corresponds}}
\textbf{to number of PEs in a PMT.}
Small PMT hardwares

128 SPMTs  

128 SPMTs = Items common to both LPMT & SPMT systems

Status of the JUNO detector system
SPMT specification and bidding

- Close contact with suppliers: Hamamatsu, HZC and ETL.
- Sample tubes basically meet JUNO’s requirements.
- Specification is finalizing.
- Bidding in April.

<table>
<thead>
<tr>
<th>NO.</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Diameter of Bulb</td>
<td>&lt;82mm</td>
</tr>
<tr>
<td>2</td>
<td>Effective Diameter of Cathode</td>
<td>&gt;72mm</td>
</tr>
<tr>
<td>3</td>
<td>QE×CE@420nm</td>
<td>Minimum&gt;22%, Average&gt;24%</td>
</tr>
<tr>
<td>4</td>
<td>TTS (FWHM)</td>
<td>&lt;6ns</td>
</tr>
<tr>
<td>5</td>
<td>HV@ 3 × 10^6 gain</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>P-V Ratio</td>
<td>Minimum&gt;2, Average&gt;2.5</td>
</tr>
<tr>
<td>7</td>
<td>Resolution of SPE (σ)</td>
<td>&lt;35%</td>
</tr>
<tr>
<td>8</td>
<td>Dark Rate @ 0.25 PE</td>
<td>&lt;1.5kHz</td>
</tr>
<tr>
<td>9</td>
<td>Dark Rate @ 0.3 PE</td>
<td>&lt;5Hz</td>
</tr>
<tr>
<td>10</td>
<td>Uniformity of QE</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>11</td>
<td>Prepulse Ratio After Pulse Ratio</td>
<td>&lt;5%, &lt;5%</td>
</tr>
<tr>
<td>12</td>
<td>Spectral Response Range</td>
<td>300-650 nm</td>
</tr>
</tbody>
</table>
| 13  | Stability                                     | Gain fluctuate(1 week): 5%  
Gain fluctuate(1 year): 10% |
| 14  | Glass radiation level(ppb)                    | 238U: < 400ppb,  
232Th: <400ppb,  
40K: <200ppb |
| 15  | Minimum compressive                           | 1.0MPa                 |
| 16  | Lifetime (Working @JUNO)                      | >20 years              |
| 17  | Working current of base                       | <9μA                   |
| 18  | Nonliner                                      | <10%@1-100p.e.         |

Status of the JUNO detector system: Under optimization
Electronics

- HV unit and GCU: same as LPMT
- HV splitter study to start soon
- ASIC Battery Card (8 × CatiROC) being designed, prototypes (v0+v1) in 2017. Test board on hand. Good timing and charge resolution.
- CatiROC (OMEGA & APC)

Dual-Data Stream output with no dead time

@SPMT

1 PMT → 4 channels (appears a single-channel)

preamp

\[ g = [10,50] \times \]

analogue 2-fold pipeline ("ping-pong")

• ping-LowGain
• ping-HighGain
• pong-LowGain
• pong-HighGain

if \( q \geq q(\text{threshold}) \)

if \( q \geq q(\text{threshold}) \)
CatiROC @ Dual-Data Stream output

Status of the JUNO detector system

Δt = time-over-threshold ("tot")

NOTE: Δt proportional to #PE

ADC-DS (deadtime-ful)
FPGA (via serial bus)

discriminator-DS (deadtime-less)
FPGA (via 1ns sampling)

Δt

No deadtime!
Underwater box

An organization now in FR
- CENBG - Bordeaux to conduct prototyping
- CPPM - Marseille as support experts
- PUC - Chile for production

Some engineers working on

2 options under consideration:
- Home made SS box filled with oil or potted
- Direct contact with companies providing junction boxes (50-300m depth with electrical feedthrough)

First prototype in July
PDR by end of 2017
FDR by mid-2018
Mass testing and integration

Status of the JUNO detector system

**Candidates:** Dongguan, Zhongshan

**Potting+cabling**
- All tubes will have a simple (TBD) testing @ production
- A sub-sample (TBD) of them will be fully characterized
- Test setup specified by JUNO
- Manpower company + JUNO supervision

**INTEGRATION SITE**
- Acceptance test for the tubes (ON/OFF→signal)
- Assembly and verification test of the electronics in the UWB
- Assembly of the Medusas
- Medusa’s commissioning

**@PMT Vendor site**

Fully tested @ production
Summary

- JUNO was approved in 2013, and started civil construction in 2015.
- The detector design was finalized, and the construction of each system is in good progress.
- Plan to start operation in 2020, with 20-30 years life time.
- France and China work in close cooperation on the Top Tracker and the Small PMT system.
Underwater connector

- An additional connector may simplify a lot the installation
- Issues:
  - Specifications (HV, Crosstalk, Water-proofing)
  - Price/channel

R&D in France and China

- 4 types of connectors have been developed for 20” PMT;
- The reliability of the connector have to be verified;

Start contact with companies

Status of the JUNO detector system
Installation

- Two scenarios
- No connector: install PMT one by one on the platform
- With connector: install PMT and UWB on surface