Overall status of 20-inch PMT instrumentation for the JUNO experiment

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on behalf of the JUNO Collaboration
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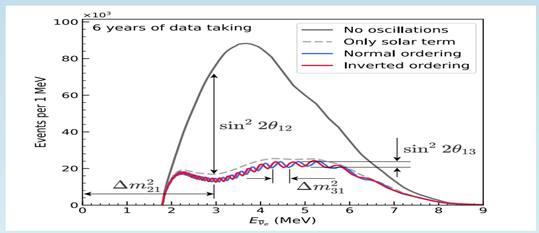
1. the JUNO experiment

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment, currently under construction and located at 700m underground in Jiangmen city, Guangdong province. The JUNO experiment is 53km from the Yangjiang and Taishan nuclear power plants, which have a total power of 26.6 GW_{th}.

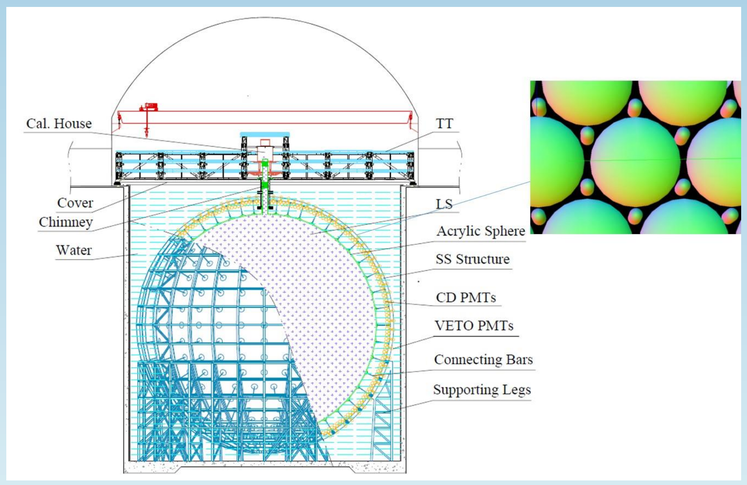
JUNO has rich physics topics as listed below[1]. The main scientific goal is determination of the neutrino mass ordering by measuring the reactor antineutrinos from those nuclear power plants.

- Neutrino mass ordering (NMO)
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geo-neutrinos
- Solar neutrinos
- Sterile neutrinos
- Atmospheric neutrinos
- Exotic searches



2. the JUNO Detector and PMT system

To reach 3%/√E(MeV) energy resolution, the JUNO detector [2] will build a 35.4m-diameter acrylic vessel and a 40.1m-diameter stainless-steel truss, which hold 20kt liquid scintillator, 20012 20-inch PMTs and 25600 3-inch PMTs. The coverage of all PMTs is 78%, with 75% for 20-inch PMTs and 3% for 3-inch PMTs. The nearest distance between two adjacent 20-inch PMTs is 3 mm.



3. JUNO requirements on the 20-inch PMTs

JUNO 20-inch PMT system includes totally 20012 PMTs, in which:

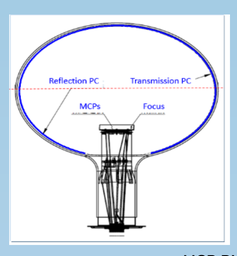
- 15012 are the MCP PMTs produced by NNVT company (China)
- The rest of 5000 are the dynode PMTs from Hamamatsu company (Japan)

The JUNO requirements:

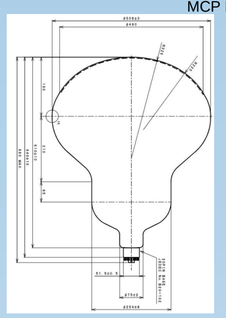
Table 1: Main acceptance criteria for JUNO 20-inch PMTs.

	HPK R12860-50	NNVT GDB-6201
Parameter	Average (Limit)	Average (Limit)
QE	30.3 % (≥ 27 %)	28.5 % (≥ 26.5 %)
CE	95.6 %	98 % (≥ 96 %)
Effective area ratio	96 % (93 %)	97 % (≥ 96 %)
Gain	10^7	10^7
HV (for a 10^7 gain)	2000 V (≤ 2500 V)	2500 V (≤ 2800 V)
QE uniformity	5 % (≤ 15 % inside 70°) 20 % (≤ 30 % inside 80°)	8 % (≤ 10 %)
TTS (FWHM)	2.7 ns (≤ 3.5 ns)	12 ns (≤ 15 ns)
P/V ratio	3 (≥ 2.5)	3.5
Pre-pulse ratio (80 ns window, main pulse ~160 p.e.)	0.8 % (≤ 1 %)	0.5 % (≤ 1 %)
After-pulse ratio (0.5~20 μs window, main pulse ~160 p.e.)	10 % (≤ 15 %)	10 % (≤ 15 %)
Dark count rate (0.25 p.e., 22°C)	10 kHz (≤ 50 kHz)	≤ 50 kHz (if 24 % ≤ PDE < 27 %) ≤ 60 kHz (if 27 % ≤ PDE < 28 %) ≤ 80 kHz (if 28 % ≤ PDE < 29 %) ≤ 100 kHz (if 29 % ≤ PDE)
Glass radioactivity	^{238}U: < 400 ppb ^{232}Th: < 400 ppb ^{40}K: < 40 ppb	^{238}U: < 75 ppb ^{232}Th: < 75 ppb ^{40}K: < 30 ppb
Pressure tolerance	≥ 0.8 MPa	> 1 MPa
Dimension tolerance	508 (±3 mm) (diameter) < 10 mm (height)	508 (±3 mm) (diameter) < 10 mm (height)
Lifetime[1]	≥ 20 years	≥ 25 years

[1] Gain decrease less than 50% in 20 years with the same HV.



MCP PMT(GDB6201)

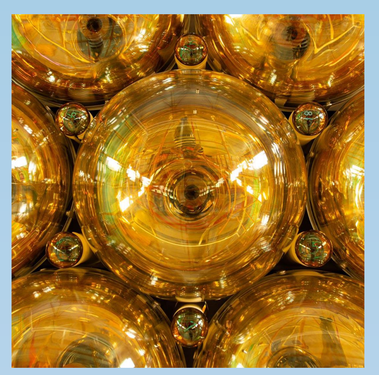


Dynode PMT(R12860)

4. the 20-inch PMT instrumentation

The goal of PMT instrumentation is to instrument all 20" PMTs, including testing, design of high voltage divider, waterproof potting, implosion protection and protective covers assembly.

- PMT testing: including acceptance test and parameter characterization.
- High voltage divider: provide the proper voltages to PMT electrodes and output the signals.
- Waterproof potting: seal the PMT external electrode pins and the high voltage divider from water.
- Implosion protecting: protect PMTs from chain implosion.
- Protective cover assembling: assemble the different parts into a PMT.



5. Receiving and testing of 20-inch PMTs

- JUNO has received all 20-inch PMTs by now, stored in a workstation near to JUNO site
- All PMTs have been tested with a test system and a defined procedure [3], the unqualified PMTs have been returned to the manufacturers
- The main parameters of the tested PMTs are shown the table [4]. In which, the photon detection efficiency (PDE) averaged for all PMTs is 29.6% , while for MCP PMT is 30.1% and for Dynode PMT is 28.5%, respectively. The dark count rate(DCR) is also measured

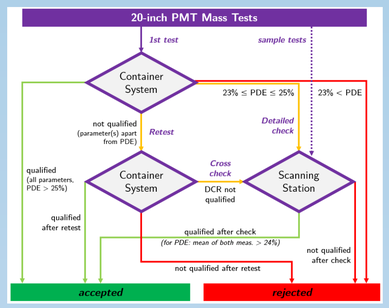
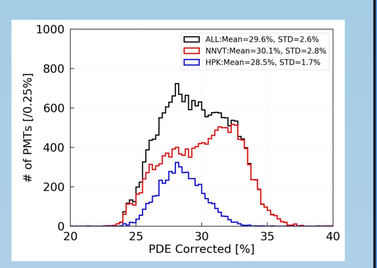
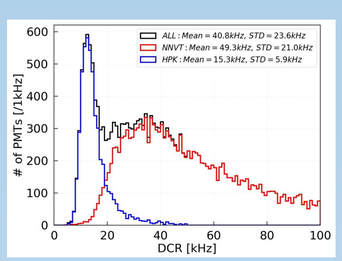


Table 3: Main parameters of qualified 20-inch PMTs

Parameters	PMT type	Bare (Mean)
Gain (× 10^7)	HPK	1.00
	NNVT	1.03
HV (V)	HPK	1863
	NNVT	1748
S/N	HPK	13.0
	NNVT	13.4
SPE amplitude (mV)	HPK	6.5
	NNVT	7.5
PDE (%)	HPK	28.5
(corrected)	NNVT (High-QE/Low-QE)	30.1 (31.3/27.3)
DCR (kHz)	HPK	15.3
	NNVT (potted)	49.3 (31.2)
P/V	HPK	3.8
	NNVT	3.9
Risetime (ns)	HPK	6.9
	NNVT	4.9
Falltime (ns)	HPK	10.2
	NNVT	17.3
FWHM (ns)	HPK	11.6
	NNVT	7.9
TTS (σ,ns)	HPK	1.3
(container laser)	NNVT	7.0

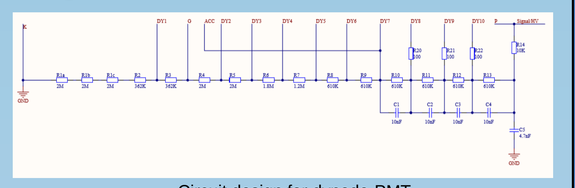




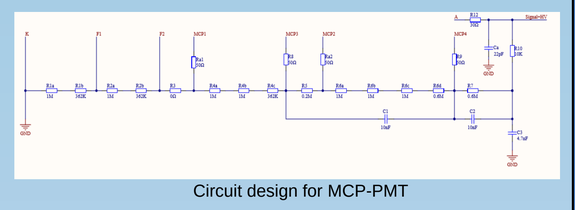
6. Design of High Voltage Divider

JUNO requirements and design:

- Two types i.e. MCP PMT and dynode PMT
- operating current &HV:
  - less than 300μA@3000V
  - gain at 10^7 and positive HV
- Dynamic range & Linearity
  - full dynamic range: 4000 p.e.
  - non-linearity: < 10% for 1000p.e.;
- Overshoot & ringing: less than 1%
- Voltage ratio is optimized, to get the best performance of the PMT;
- Reliability: failure rate < 0.1% for the first 6 years



Circuit design for dynode-PMT



Circuit design for MCP-PMT

Current status:

- All high voltage dividers have been produced and soldered to PMTs now

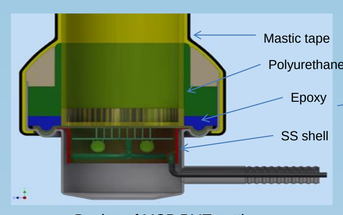
a batch of produced high voltage dividers

a HV divider under soldering

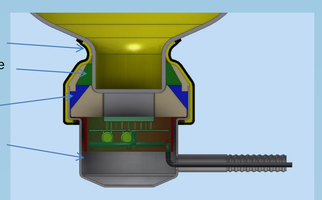
a HV divider soldered to a PMT

7. Waterproof Potting

- **The potting is designed as multiple waterproof layers;**
  - stainless-steel shell acts as a pressure-resistant house;
  - epoxy is for structural adhesion between shell and glass;
  - polyurethane is used as a filling sealant;
  - mastic tape is used as the outmost layer of sealing;
- **JUNO potting has finished**
  - A Potting Laboratory with 650m^2 area was built in the PMT workstation;
  - Potting was started in July of 2019, with 40 – 50 PMTs potted per day;
  - By now, all the 20012 PMTs have been potted, no leaks found after leakage test done by pressurized water or gas.
  - Dark count rate (DCR) of MCP PMT is decreased from 49 KHz to 31 KHz after potting.



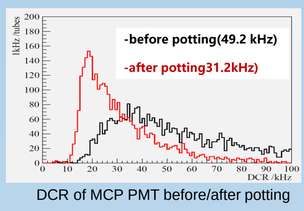
Design of MCP PMT potting



Design of Dynode PMT potting

The potting Lab.

Leakage check with SF_6 gas

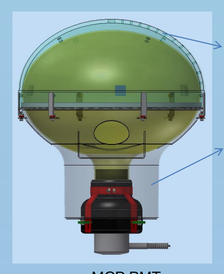


DCR of MCP PMT before/after potting

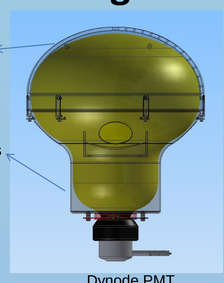
Leakage check with water tank

8. implosion Protection and cover assembling

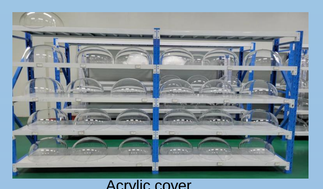
- **Final design of the PMT implosion protection has been finished**
  - top cover: acrylic, 9~11mm thickness varying from equator to top;
  - bottom cover: stainless-steel, 2mm thickness uniformly;
- **Protective cover production**
  -the acrylic cover is fabricated by injection moulding, by now all acrylic coves have been injected and ~14000 delivered to JUNO;
  -the stainless-steel cover is fabricated by stretching, production is ongoing;
- Protective cover assembling
  - the top and bottom cover will be firstly assembled to the PMT at the PMT workstation, then the PMT will be transported to JUNO site where a PMT module will be built.
  - cover assembling will start in the end of this year.



MCP PMT

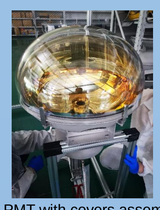


Dynode PMT

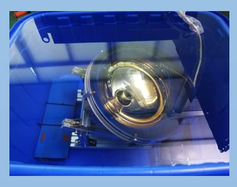


Acrylic cover

Stainless-steel cover in production



A PMT with covers assembled



A test of the assembly in water

References: **[1]** JUNO Collaboration, *Neutrino Physics with JUNO*, J. Phys. **G43**, 3, 030401 (2016) [arXiv:1507.05613]; [2] JUNO Collaboration, *JUNO Physics and Detector*, 2021, arXiv:2104.02565; [3] B. Wonsak *et al* 2021 *JINST* **16** T08001, "A container-based facility for testing 20'000 20-inch PMTs for JUNO"; [4] JUNO collaboration, Mass Testing and Characterization of 20-inch PMTs for JUNO, arXiv:2205.08629