CATIROC

a multichannel front-end ASIC to read out the SPMT system of the JUNO experiment

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JUNO (Jiangmen Underground Neutrino Observatory)

A multipurpose neutrino experiment designed to determine neutrino mass hierarchy with a 20,000 tons liquid scintillator detector at 700-meter deep underground.

Primary goal:
- Determination of the neutrino mass hierarchy
- 3 %/\sqrt{E} energy resolution
- 1200 pe/MeV

~ 18,000 PMTs (20” diameter) → Large-PMT system (LPMT) → 75 % of the inner surface
~ 25,000 PMTs (3” diameter) → Small-PMT system (SPMT) →
  - Increase coverage of the surface → Improve energy reconstruction
  - Cross calibration
Small PMT (SPMT) system

Small-PMT size chosen to collect few p.e. → measure energy via “photon counting” 1 hit = 1 p.e.

Small PMT requirements:
- Independent electronics
- Multichannel read-out
- Trigger efficiency @ 1/3 p.e.
- Time-stamp (< 1ns resolution)
- Charge information (few p.e.)

- 128 Small PMTs with a read-out system: the Under Water Box (UWB)
- A dedicated FEB based on CATIROC

Details in:
“Double Calorimetry System in JUNO Experiment”
Dr. Miao HE, May 23, Neutrino session R2
Small PMT front-end board

- SPMT front-end with **8 ASIC CATIROC** each of 16 channels
- **FPGA** (Kindex 7 425-T)+ 2GB DDR3 **RAM memory** (large storage and processing on board)
- **4 connector** x 32 signals (CATIROC inputs)
- Power supply for ASIC and FPGA
- Low cost concept (**one board**/ **128 PMTs**/ one under water cable to send out data)

First prototype July 2017
### CATIROC general features

<table>
<thead>
<tr>
<th>CATIROC general features</th>
<th>Application to JUNO</th>
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<tbody>
<tr>
<td>16 independent channels</td>
<td>Reduce the number of electronic board (only 200 boards for 25,000 SPMTs)</td>
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<tr>
<td>Analog F.E. with 16 trigger outputs +</td>
<td>Photon counting + charge and time measurements. Resolutions very good</td>
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<tr>
<td>charge and time digitization</td>
<td></td>
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<tr>
<td>Autotrigger mode: all the PMTs signals</td>
<td>Simplify online-DAQ</td>
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<tr>
<td>above the threshold (1/3 p.e.) generate a</td>
<td></td>
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<tr>
<td>trigger and are converted in digital data</td>
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<tr>
<td>100% trigger efficiency @ 1/3 p.e.</td>
<td>Good 1 p.e. detection photon counting mode</td>
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<tr>
<td>Dual gain front-end: HG and LG channel</td>
<td>Only HG actually used (only few p.e. expected)</td>
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<tr>
<td>Charge dynamic range 0 to 400p.e.</td>
<td></td>
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<tr>
<td>(at PMT gain $10^6$)</td>
<td></td>
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<tr>
<td>Time stamping (resolution ~ 170 ps rms)</td>
<td>&lt; 1ns required</td>
</tr>
<tr>
<td>Each channel has a variable gain</td>
<td>To compensate gain vs HV spread for the 16 PMTs</td>
</tr>
<tr>
<td>One output for DATA</td>
<td>Less number of cables to the surface</td>
</tr>
<tr>
<td>Hit rate 100 kHz/ch (all channels hit)</td>
<td>Very “light” data output (compared to a FADC waveform)</td>
</tr>
<tr>
<td>50 bits of data / hit channel</td>
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Charge path
- Shaping (variable shaping time)
- Switched capacitor array (2 Capacitors: ping-pong mode)
- 10 bits ADC conversion @ 160 MHz
- 50 fC to 70 pC (PMT gain 10^6)

Amplification stage
with variable gain
ch by ch on 8 bits

16 negative inputs

Coarse time
by 26-bit gray counter
(Digital part) 25 ns steps

Fine time
Time to Digital Converter (TDC)
25 ns dynamic range
Time resolution: 170 ps
Non linearity: +/- 500 ps
The input signal is made by a pulse generator signal: a negative voltage pulse (rise time= 5ns, fall time= 5ns, width= 10 ns, Amplitude @1 p.e.~ 0.8 mV).
The M.I.P. is 1 p.e. = 160 fC @ PMT gain $10^6$

Chip status:
Submission: February 2015
Received: July 2015
Process: AMS 0.35 μm SiGe
Die dimensions: 3.3 mm x 4 mm (13.2 mm²)
Packaging: TQFP208
Power Supply: 3.3V
Dissipation: 20mW/ch on 3.3 V
Clocks: 40 MHz (Coarse time) and 160 MHz (Conversion)
Trigger efficiency

The trigger efficiency is investigated by scanning the threshold (by the internal DAC) for a fixed channel and monitoring the discriminator response.

**DAC resolution**: 0.6 DACu/fC

Sensitivity ~ 100 DACu/ p.e.

σ (noise)= 3.5 DACu= 5.6 fC

Mean= 984 DACu

**Minimum threshold**= Pedestal mean value (DACu)- 5 σ (DACu)= 968 DACu (~ 28 fC)
Charge resolution and linearity

<table>
<thead>
<tr>
<th></th>
<th>HG charge performance</th>
<th>LG charge performance</th>
</tr>
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<tbody>
<tr>
<td>Linearity residuals</td>
<td>&lt; 0.7% Up to 50 p.e.</td>
<td>&lt; 1% up to 400 p.e.</td>
</tr>
<tr>
<td>LSB</td>
<td>10 fC/ADCu → 16 ADCu/1 p.e.</td>
<td>80 fC/ADCu</td>
</tr>
<tr>
<td>Charge resolution</td>
<td>1.5 ADCu (HG) ~ 15 fc</td>
<td>1.2 ADCu (LG) ~ 100 fc</td>
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</table>

Charge threshold = 820 DACu ~ 1.8 V.

1 p.e. = 160 fC @ PMT gain $10^6$

JUNO only
HG needed

Charge distribution ChannelID
1000 Acq
Trigger threshold (900 DACu)
Gain=20
SSH= 50ns, Gain=1
Delay= 30

HG Channel

LG

Charge threshold= 820 DACu ~ 1.8 V.
**Time resolution**

**Injection 1 channel:** fine time versus input signal delayed

![Graph showing TDC reconstruction and time conversion](image)

**TDC measurements:** fine time (10 bits)
- **INL:** [-375.3, 356.4] ps
- **TDC bin** = 27 ps
- **TDC non linearity** = 167 ps rms
- **TDC resolution** = 38 ps
- **Clock coupling** seen on the TDC (residuals)

**Injection 16 channels:** 4 channels delayed.
Delta [Time meas. (CH0) – Time meas. (CHi)]

![Graph showing coincidence time resolution](image)

**Coincidence time resolution:** [50 ps; 100 ps]
## HIT RATE

<table>
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<tr>
<th></th>
<th>Tconv (1 ch)</th>
<th>Tconv (16 ch)</th>
<th>Tread-out (1 ch)</th>
<th>Tread-out (16 ch)</th>
<th>Tcycle (1 ch)</th>
<th>Tcycle (16 ch)</th>
<th>Hit rate (1 ch)</th>
<th>Hit rate (16 ch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tconv</td>
<td>6.4 µs</td>
<td>6.4 µs</td>
<td>0.36 µs</td>
<td>3 µs</td>
<td>6.8 µs</td>
<td>9.4 µs</td>
<td>150 kHz</td>
<td>100 kHz</td>
</tr>
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</table>

\[ T_{conv} = \frac{2^n}{F_{\text{conv}}} = 6.4 \, \mu s \]

\[ T_{RO} = \frac{\text{no of channels} \times \text{number of bit}}{F_{RO}} \]

**saturation @ \( f_{in} > 170 \, \text{kHz} \)**
Charge measurements with PMT

No LED

JUNO PMT

HV

Test board

CATIROC

SPMT SOFTWARE

USB connection

JUNO 3” PMT HZC

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Charge resolution: $\sigma\text{p.e.}/\mu\text{p.e.} = 30\%$

Ping-pong: charge difference < 5 %

Good charge uniformity (only 2 chs)

Wiggles due to the clock coupling
Conclusions

• CatIROC performance fits very well for JUNO-SPMT:
  – 100% trigger efficiency @ 1/3 p.e. (50 fC @ PMT gain 10^6)
  – Charge resolution (only HG used): 1.5 ADCu ~ 15 fC (50 fC @ PMT gain 10^6)
  – Time resolution = 167 ps rms

• Tests with the HZC 3" PMT shows
  – Good p.e. spectrum
  – Some features (ping/pong and wiggles) that have not significant effects on the data taking

• To do:
  – test with PMT and a light source
  – Front-end board first prototype will be produced in July → test in the next Autumn

Neutrino energy spectrum

normal

\( \nu_e \quad \nu_\mu \quad \nu_\tau \)

inverted

\( \nu_2 \quad \nu_3 \quad \nu_1 \)

Increasing mass

\( L = 50 \text{ km} \)

Normal hierarchy

Inverted hierarchy

\( \sin^2(2\theta_{12}) \)

Arbitrary unit

Non oscillation

\( \theta_{12} \) oscillation

Normal hierarchy

Inverted hierarchy

L/E (km/MeV)
The SPMT system – UNDER WATER BOX (UWB)

- **HVS**: HV decoupling
- **HVU**: HV building from LV
- **ABC**: ASIC Battery Card (8 CATIROCs)
- **CGU**: DAQ = LPMT system

CAT5+ Ethernet cable Power on Ethernet (PoE) x1 or x2
CATIROC main features

<table>
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| **Read out frame:** 50 bits  
2 frames of (29+21) bits  
1 frame/8chs  
coarse time= 26  
Ch nb= 3  
Fine time converted= 10  
Charge converted= 10  
Gain used= 1 |
| **Conversion:** 10 bits ADC at **160 MHz** |
| **Two Read out:** **80 MHz** |
| **Time stamp:** 26 bits counter @ **40 MHz** |
| Triggerless acquisition  
noise= 5 fC (simulation result)  
Threshold= 25 fC (calculation 5σ) |
| Dynamic range 0 to ~400 p.e. (at PMT gain 10^6) (simulation result) |
| Time stamping : resolution < 200 ps  
A TDC ramp for each channel |
| Minimum input rate **100 kHz/ch**  
Max input rate **150 kHz/ch** |
| Output rate 1 serial link (x2 for the 2nd serial link)  
Max: 40 Mbits/s 16 chs  
8.3 Mbits/s 1 ch |
Digital part

All channels are handled independently by the digital part and only channels that have created triggers are digitized, transferred to the internal memory and then sent-out in a data-driven way.

The **digital part** manages:

**Acquisition**: Analog memory: 2 depths for HG and LG

**Conversion**: Analog charge and time into 10 bits digital values saved in the register (RAM)

**Read Out**: RAM read out to an external system

- Readout clock: **80 MHz**
- Max Readout time (16 ch hit): **3 µs**
- **50 bits of data / hit channel**
- **Readout format** (MSB first): coarse time= 26 bits; channel number= 3 bits; fine time=10 bits, charge=10 bits, gain=1 bit
JUNO: the Small PMT (SPMT) system

36,000 3” PMTs

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

Nonlinear response of LPMT due to the distortion of output waveform

A challenge of <1% nonlinearity

Comparison of reconstructed energy and true energy of LPMT

Small-PMT (SPMT):
- measure energy via "photon counting", control systematics $\rightarrow$ non-stochastic effect

Large-PMT (LPMT):
- measure energy via "charge integration", increase photon statistics $\rightarrow$ stochastic effect
Autotrigger efficiency

Trigger efficiency %

Threshold (DACu)

Pedestal mean value (DACu)

Channel

Mean value of the pedestal distribution (DACu)
Gaussian fit

Sigma of the pedestal distribution Gaussian fit

σ ~ 3.5 DACu

Minimum threshold = Pedestal mean - 5σ

σ (DACu)

Minimum threshold (DACu)

Channel

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Impact of CatिROC features

- \( \sigma_{p.e.}/\mu_{p.e.} \sim 30\% \)
- ping-pong: charge difference < 5%
- wiggles effect
  (distorsion on p.e. < 1%)
Interface planned to test

- For CAEN LIKE connectors