CATIROC

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

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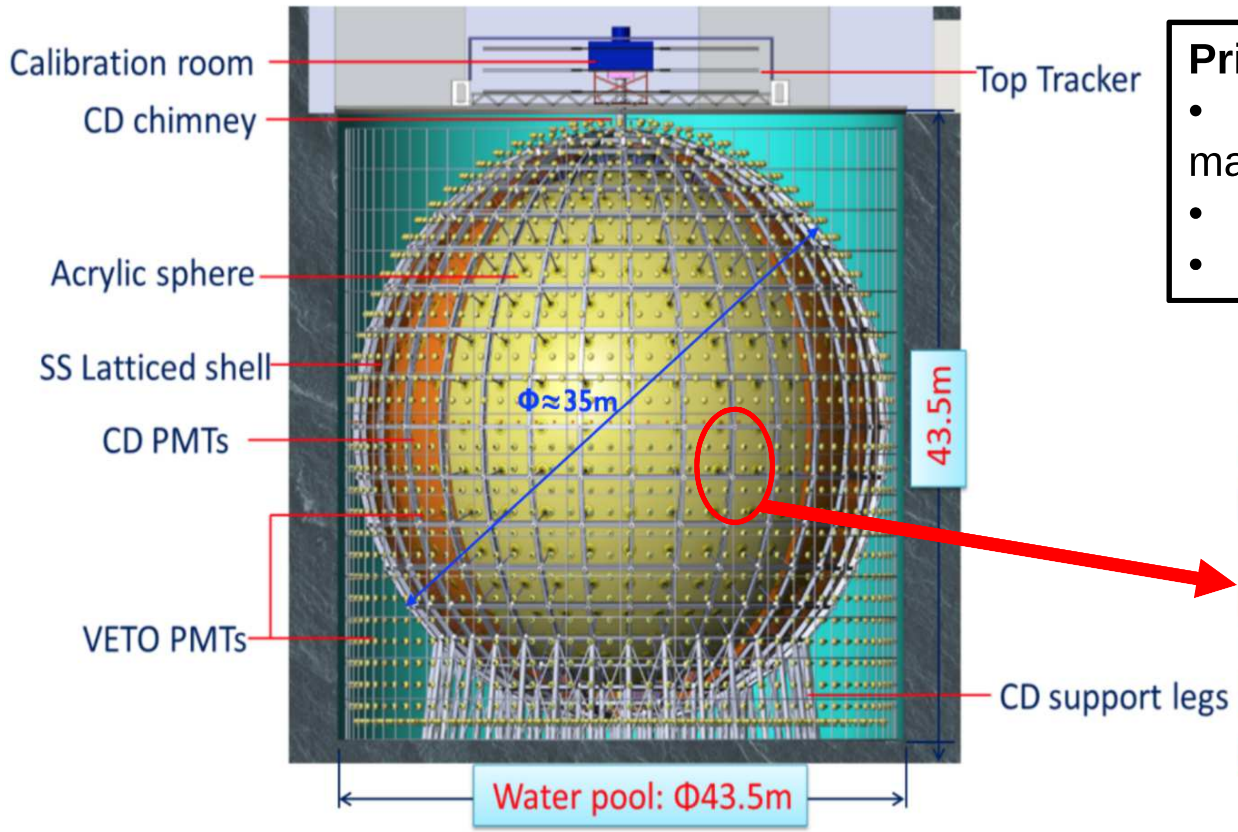
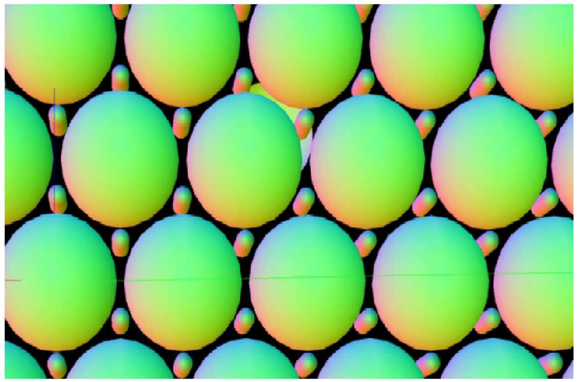
Organization for Micro-Electronics desiGn and Applications

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

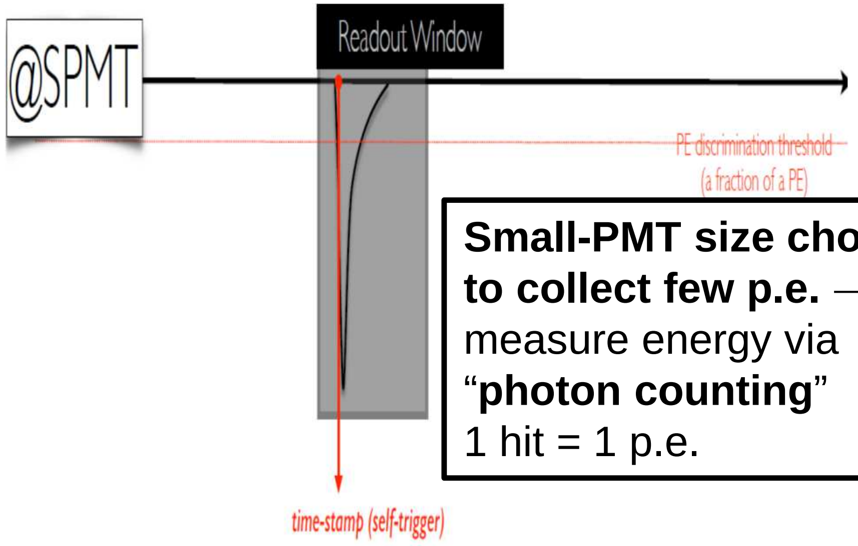


Primary goal:
- Determination of the neutrino mass hierarchy
- 3 %/√E energy resolution
- 1200 pe/MeV

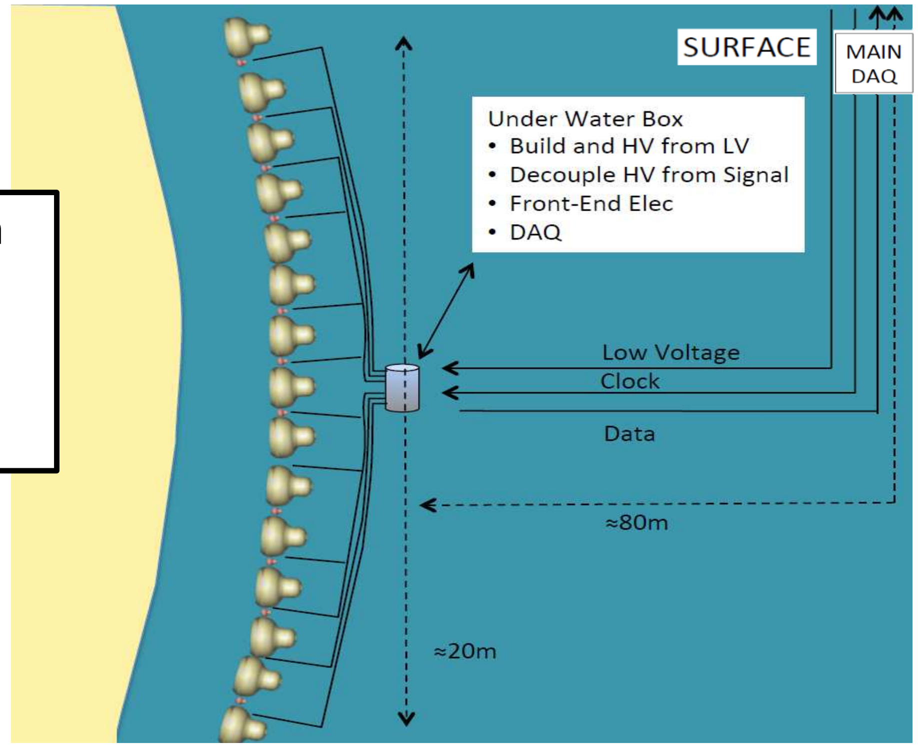


~ 18,000 PMTs (20” diameter) → Large-PMT system (LPMT) → **75 % of the inner surface**
~ 25,000 PMTs (3” diameter) → Small-PMT system (SPMT) →
- Increase coverage of the surface → Improve energy reconstruction
- Cross calibration

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:

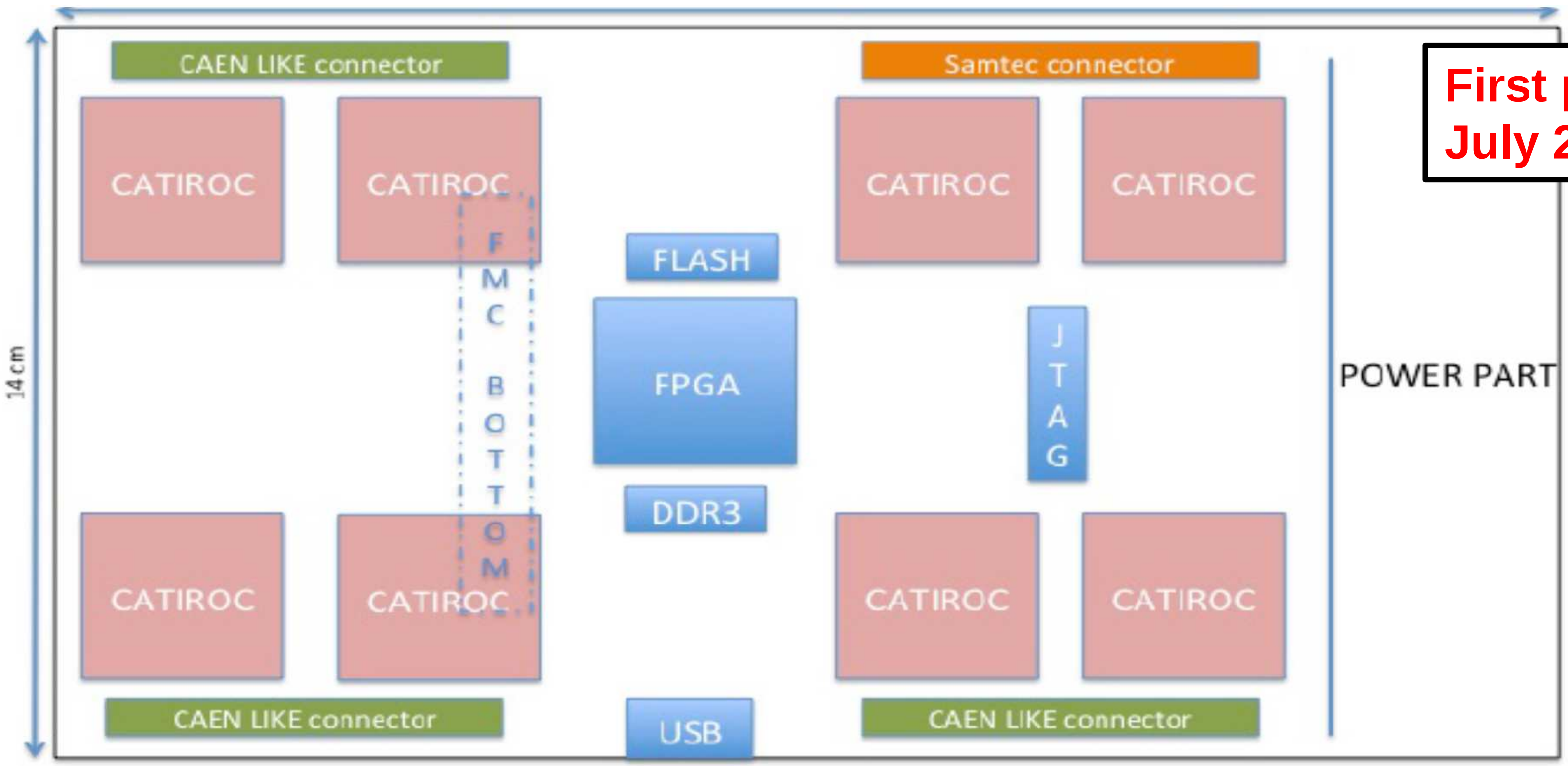
- Independent electronics
- Multichannel read-out
- Trigger efficiency @ 1/3 p.e.
- Time-stamp (< 1ns resolution)
- Charge information (few p.e.)

- **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 for JUNO

A complex System on Chip (SoC). Technology: 0.35 µm SiGe AMS

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

CATIROC schematic

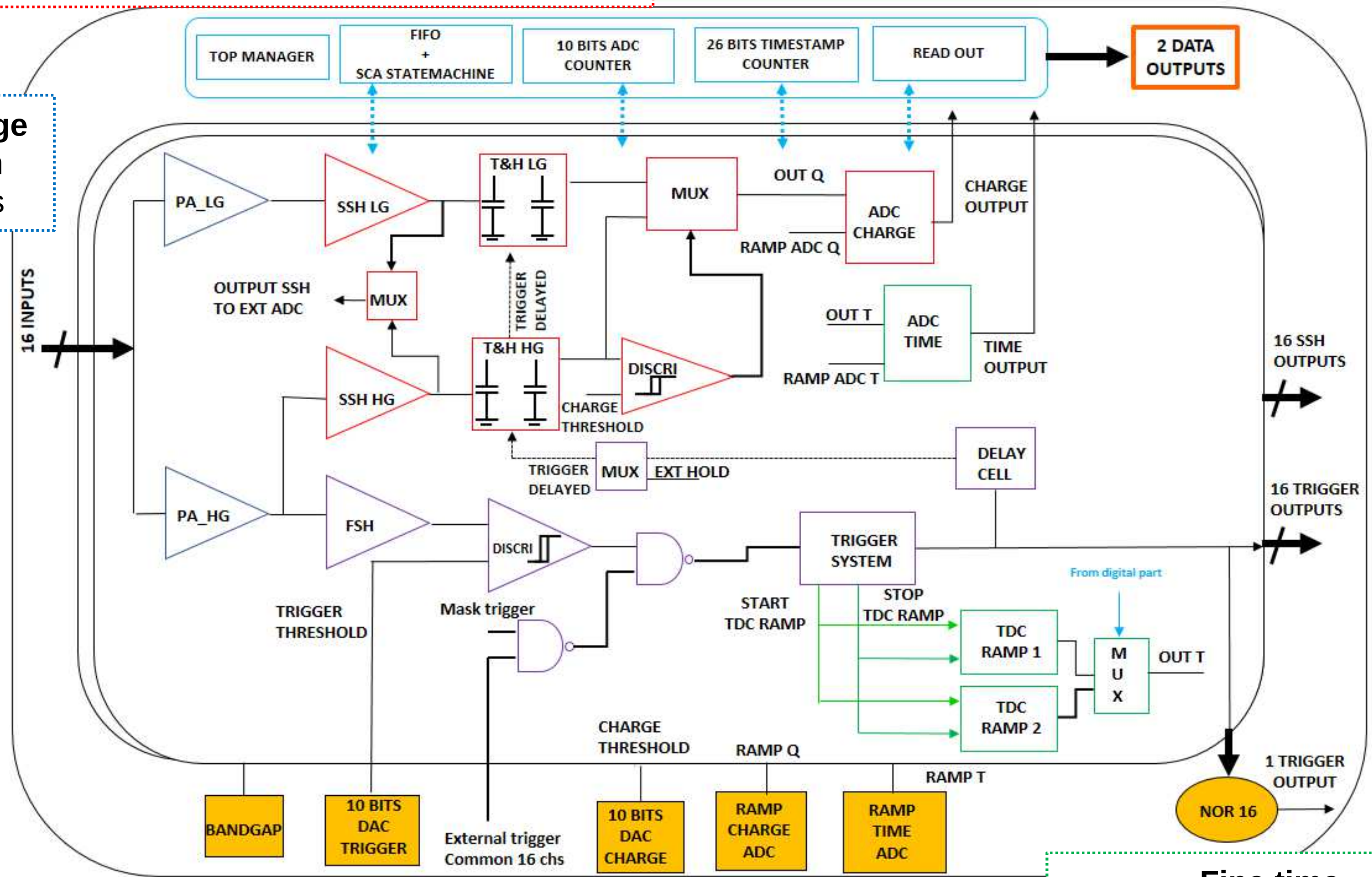
Charge path

- Shaping (variable shaping time)
- Switched capacitor array (**2 Capacitors: ping-pong mode**)
- 10 bits ADC conversion @ 160 MHz
- **50 fC ÷ 70 pC (PMT gain 10^6)**

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

Amplification stage
with variable gain
ch by ch on 8 bits

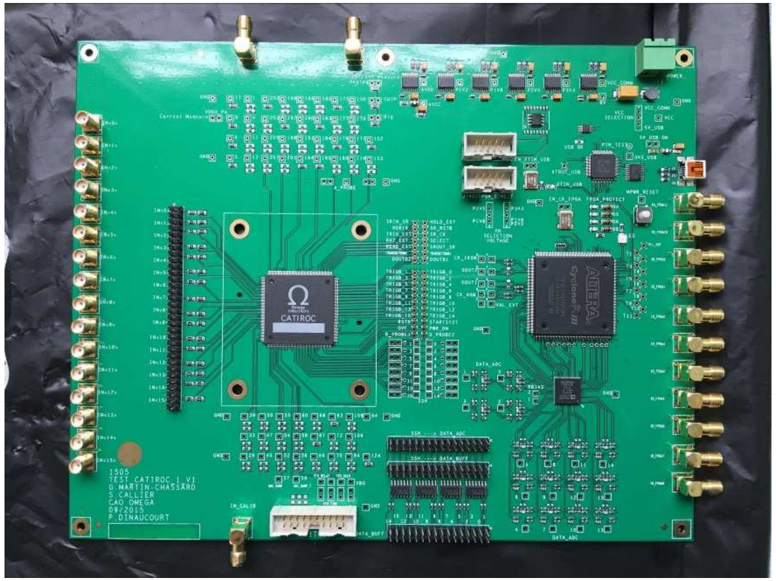
16 negative inputs

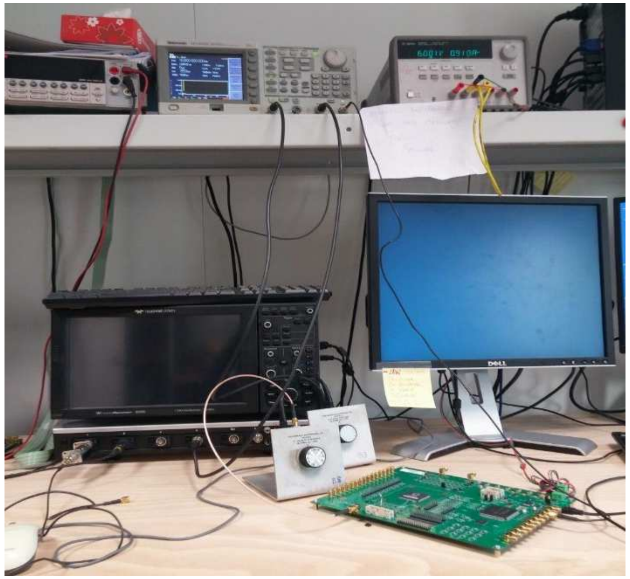


Trigger path: AUTO TRIGGER DESIGN

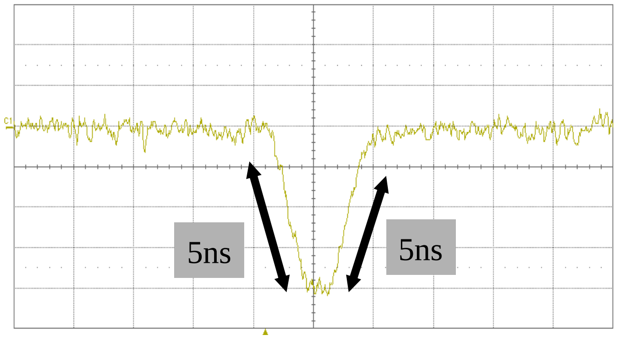
Fine time
Time to Digital Converter (TDC)
25 ns dynamic rang
Time resolution: 170 ps
Non linearity: +/- 500 ps

CATIROC performances





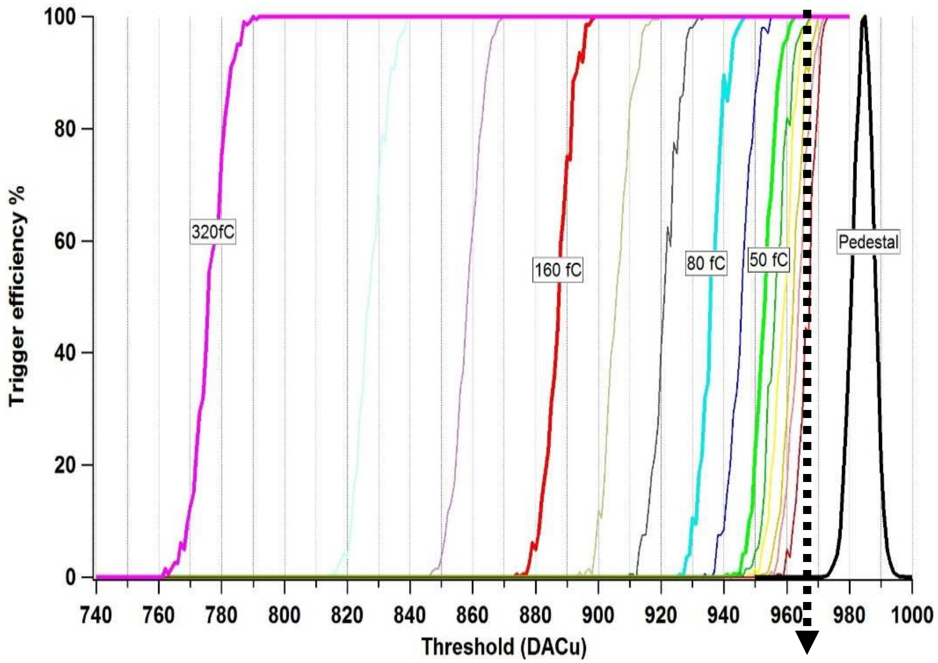
The input signal is made by a pulse generator signal: a negative voltage pulse (rise time= 5ns, fall time= 5ns, width= 10 ns, Amplitude @1 p.e.~ 0.8 mV).
The M.I.P. is 1 p.e.= 160 fC @ PMT gain 10^6

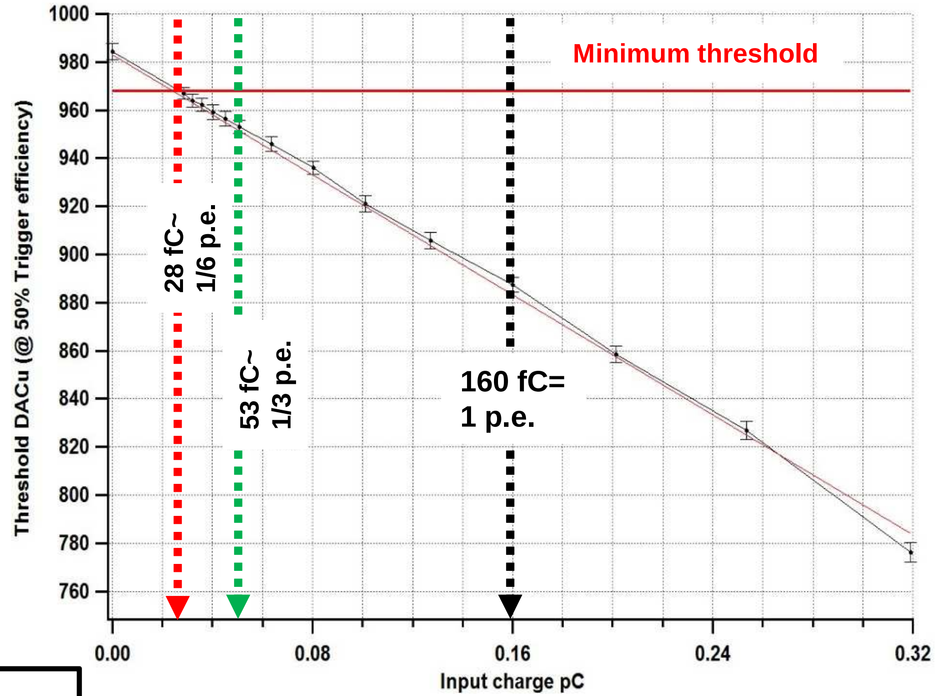


Chip status:
Submission: **February 2015**
Received: July 2015
Process: **AMS 0.35 µm SIGe**
Die dimensions: 3.3 mm x 4 mm (13.2 mm²)
Packaging: **TQFP208**
Power Supply: 3.3V
Dissipation: **20mW/ch** on 3.3 V
Clocks: 40 MHz (Coarse time) and 160 MHz (Conversion)

Trigger efficiency

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





Minimum Threshold
@ 968 DACu ~ 28 fC **< 1/3 of pe**

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

DAC resolution: 0.6 DACu/fC

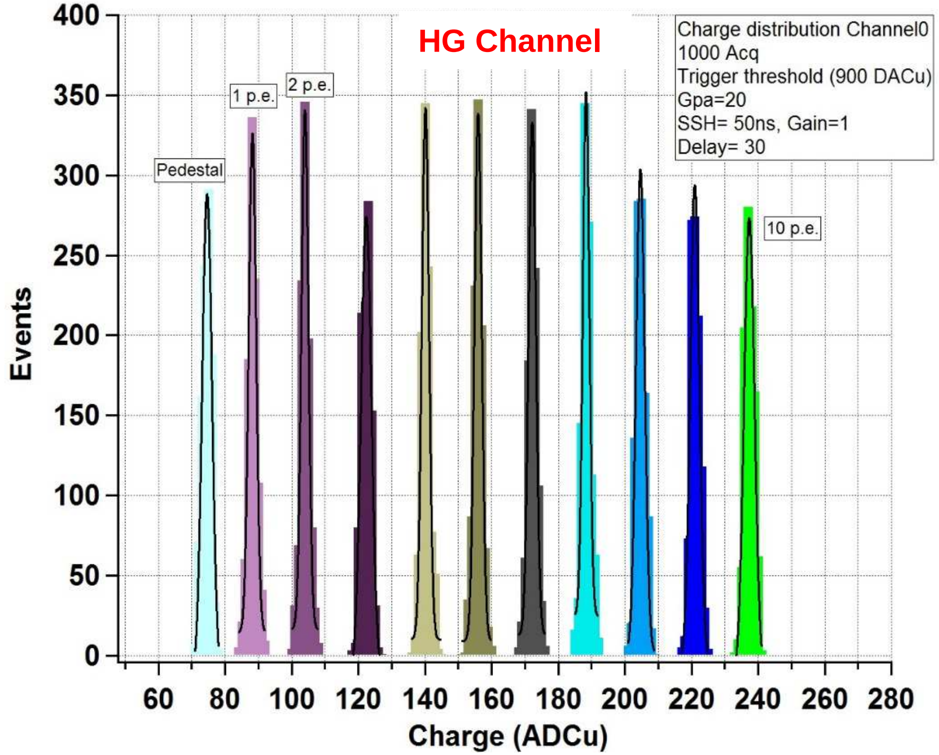
Sensitivity ~ 100 DACu/ p.e.

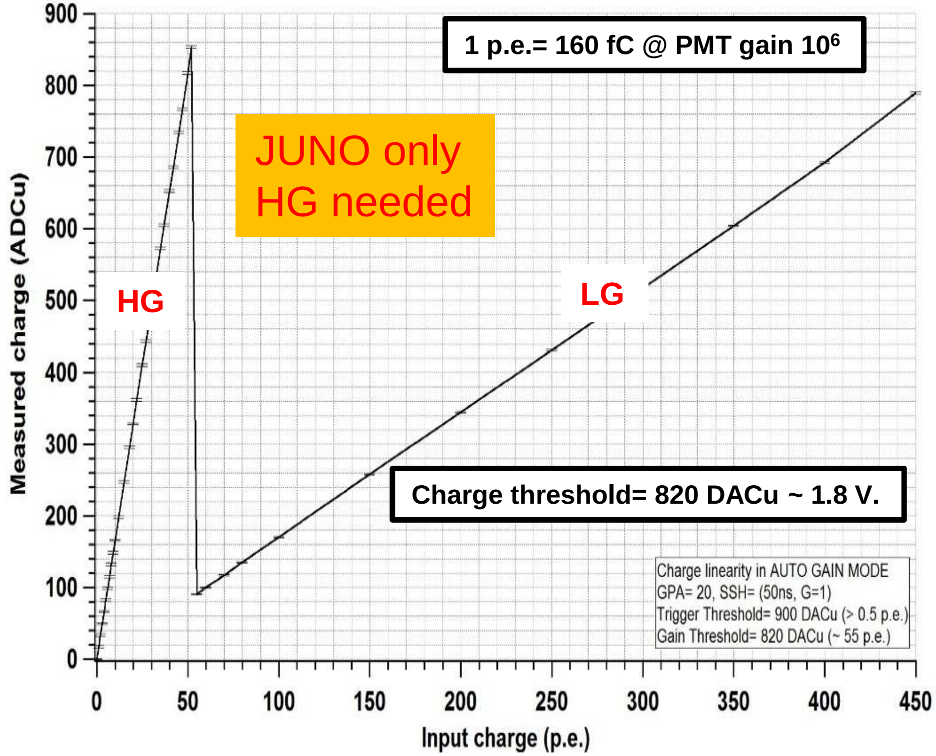
σ (noise)= 3.5 DACu= 5.6 fC

Mean= 984 DACu

Minimum threshold= Pedestal mean value (DACu)- 5 σ (DACu)= 968 DACu (~ 28 fC)

Charge resolution and linearity

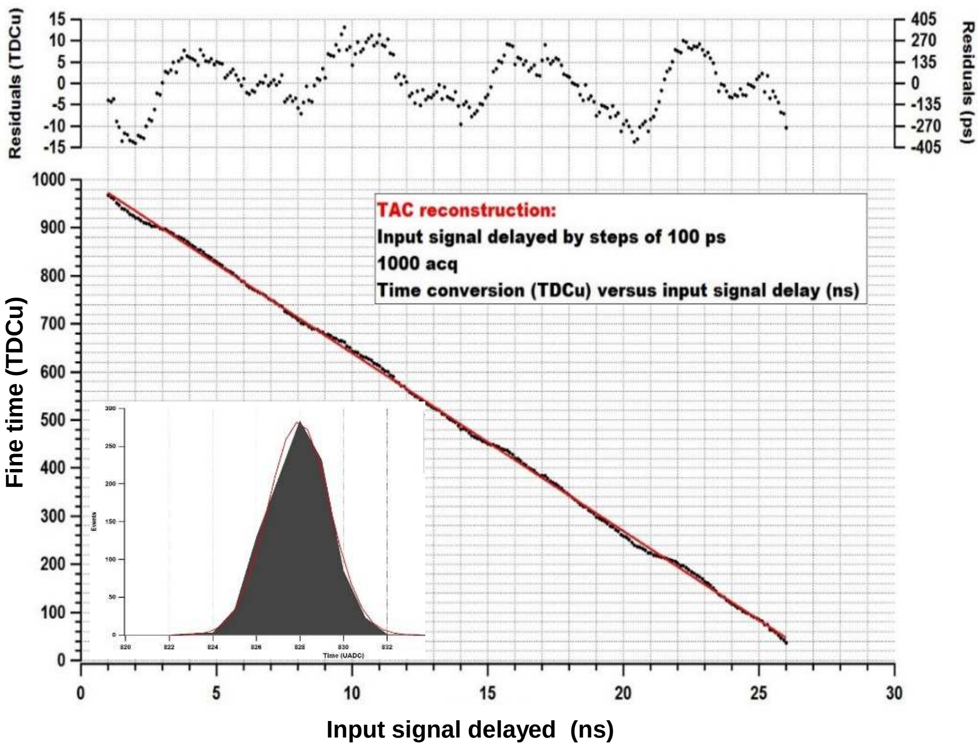




	HG charge performance	LG charge performance
Linearity residuals	< 0.7 % Up to 50 p.e.	< 1 % up to 400 p.e.
LSB	10 fC/ADCu → 16 ADCu/ 1 p.e.	80 fC/ADCu
Charge resolution	1.5 ADCu (HG) ~ **15 fC**	1.2 ADCu (LG) ~ 100 fC

Time resolution

Injection 1 channel: fine time versus input signal delayed



TDC measurements: fine time (10 bits)

INL: [-375.3, 356.4] ps

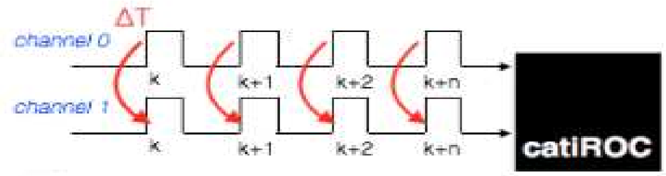
TDC bin= 27 ps

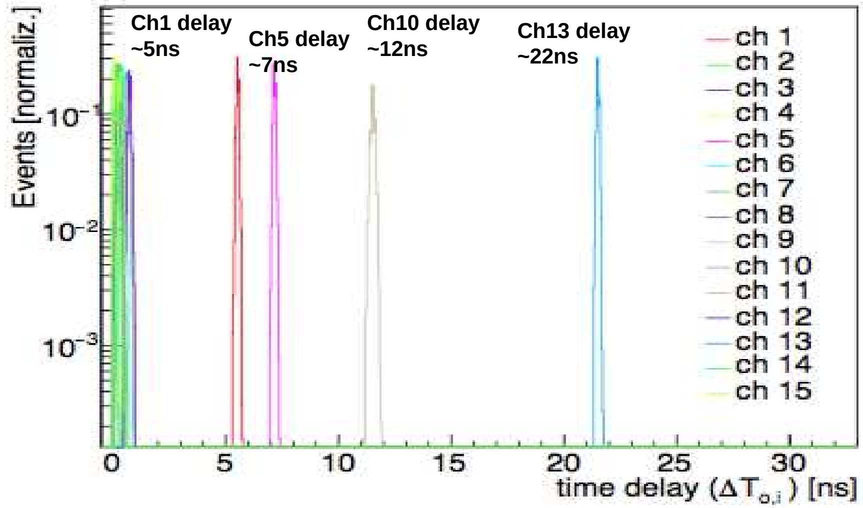
TDC non linearity= 167 ps rms

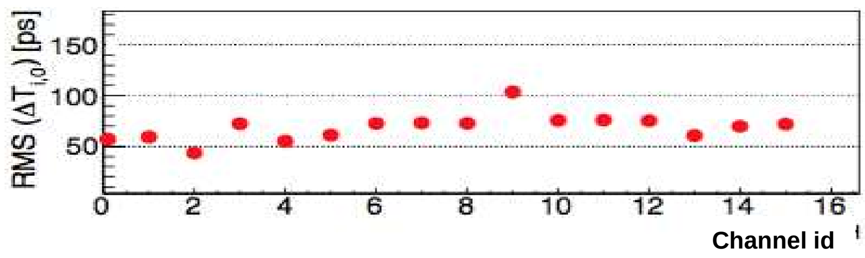
TDC resolution= 38 ps

Clock coupling seen on the TDC (residuals)

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







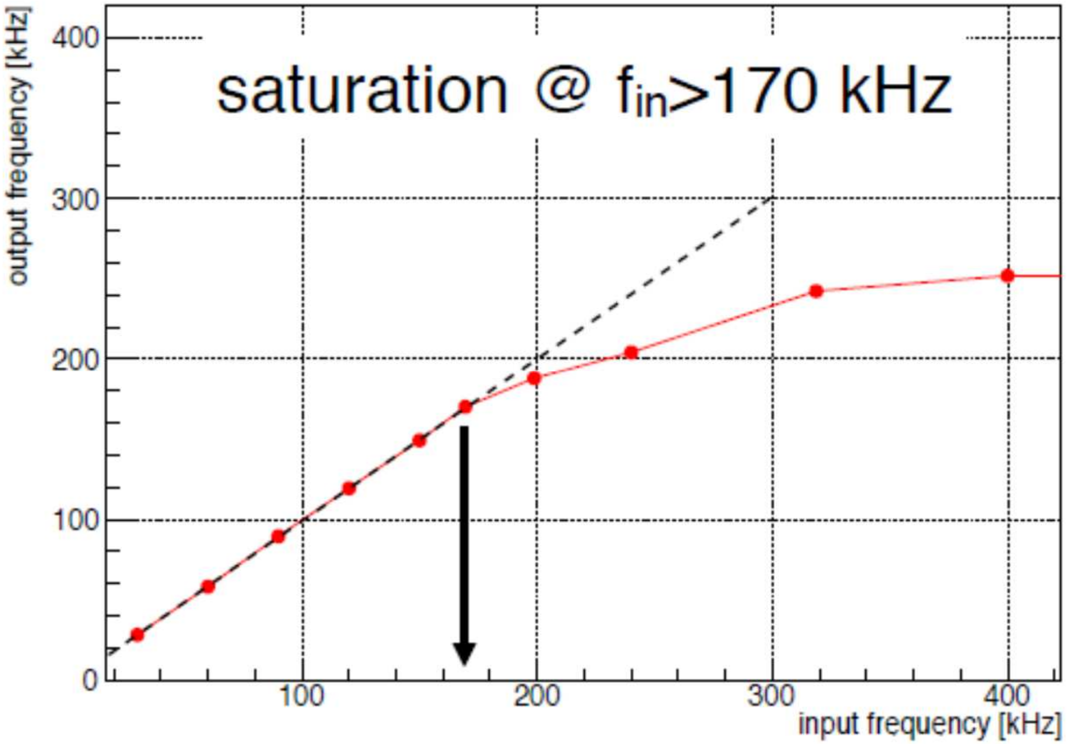
Coincidence time resolution: [50 ps; 100 ps]

Hit rate measurements

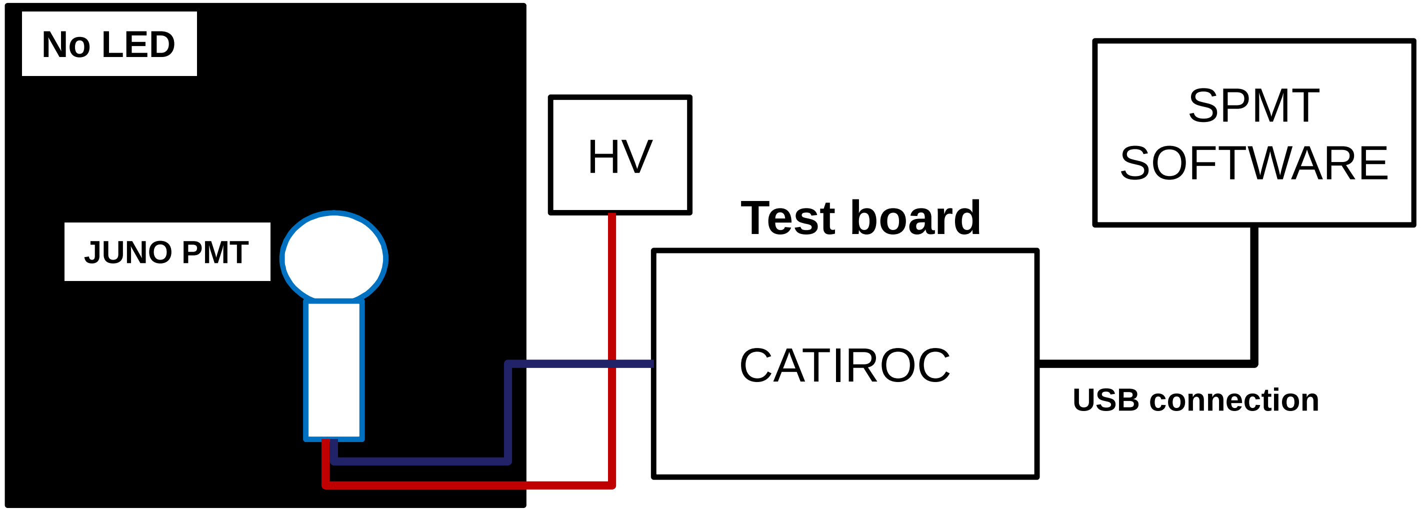
HIT RATE			
Tconv (1 ch)	6.4 μs	Tconv (16 ch)	6.4 μs
Tread-out (1 ch)	0.36 μs	Tread-out (16 ch)	3 μs
Tcycle (1 ch)	6.8 μs	Tcycle (16 ch)	9.4 μs
Hit rate (1 ch)	150 kHz	**Hit rate (16 ch)**	100 kHz

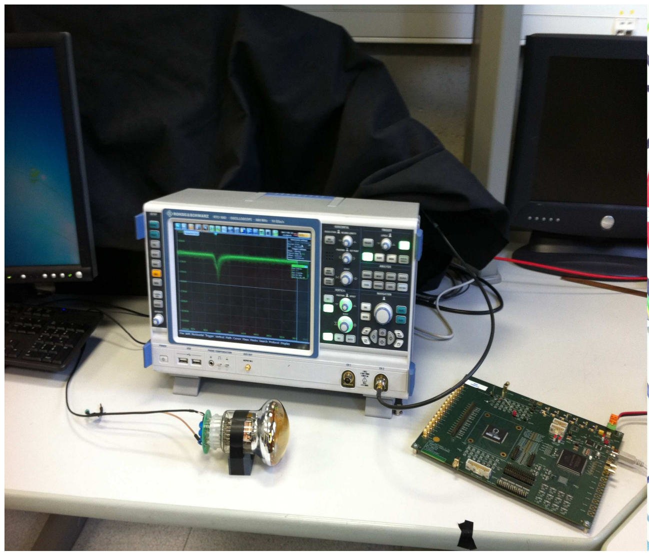
$$Tconv = \frac{2^n}{F_{conv}} = 6.4\ \mu s$$

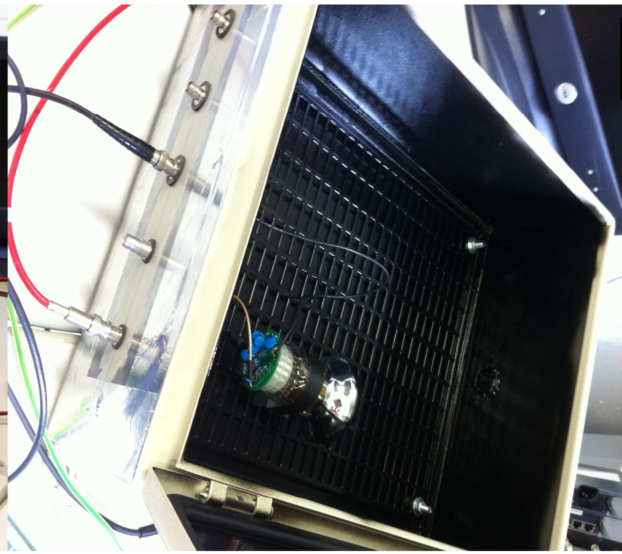
$$TRO = \frac{n^\circ\ of\ channels * number\ of\ bit}{F_{RO}}$$



Charge measurements with PMT

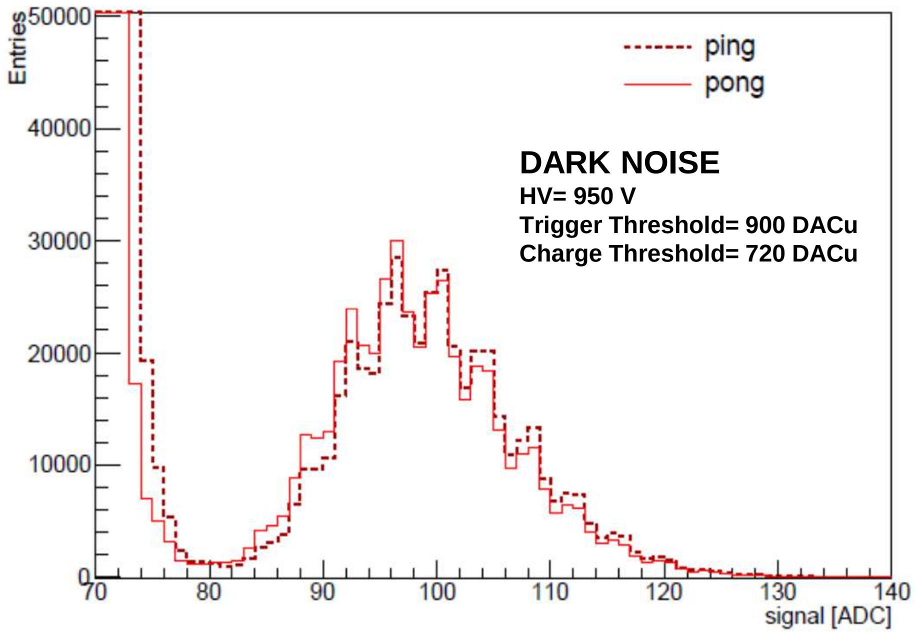


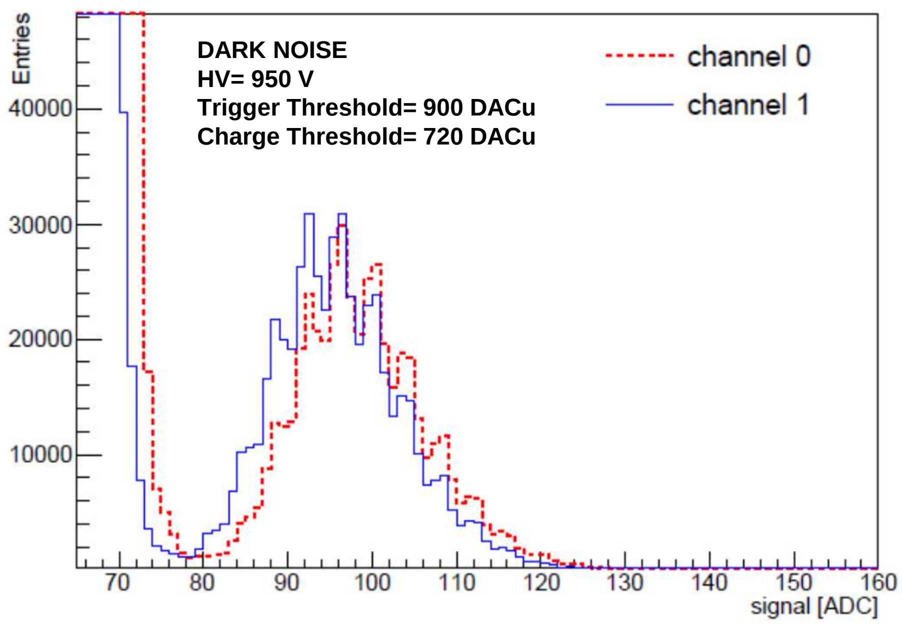


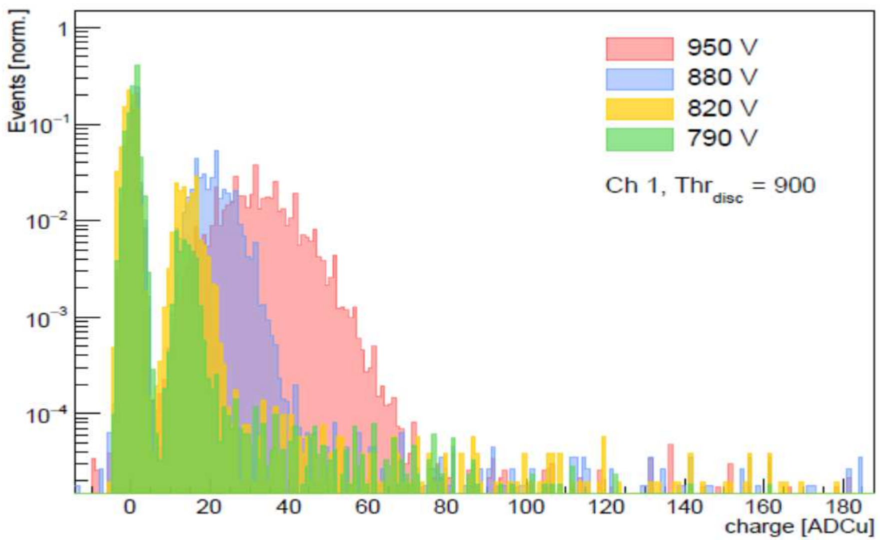


JUNO 3” PMT HZC

1 p.e. distribution







Charge resolution: σp.e./ µ p.e**.= 30%**

Ping-pong: charge difference < 5 %

Good **charge uniformity** (only 2 chs)

Wiggles due to the clock coupling

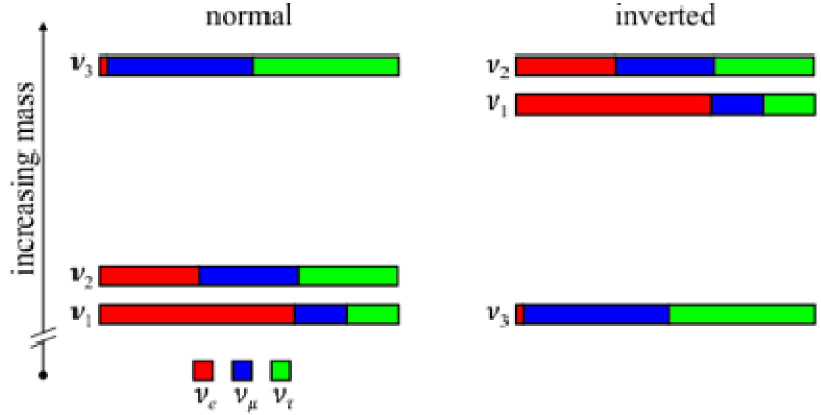
Preliminary results

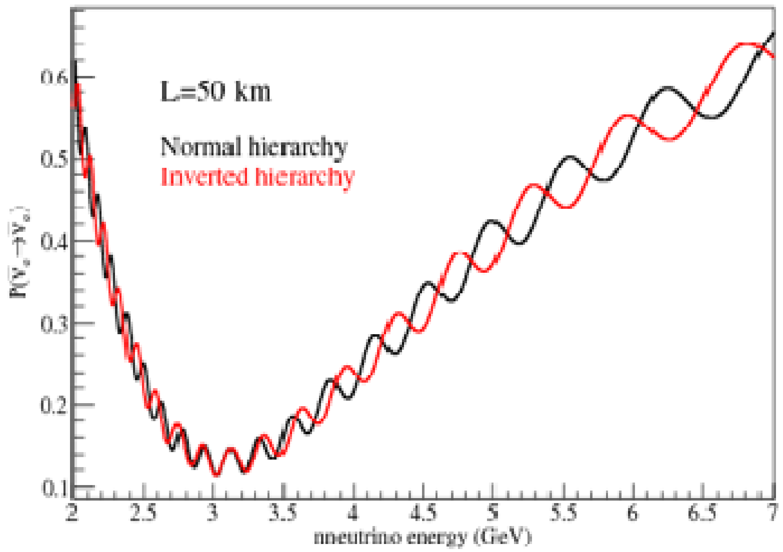
Conclusions

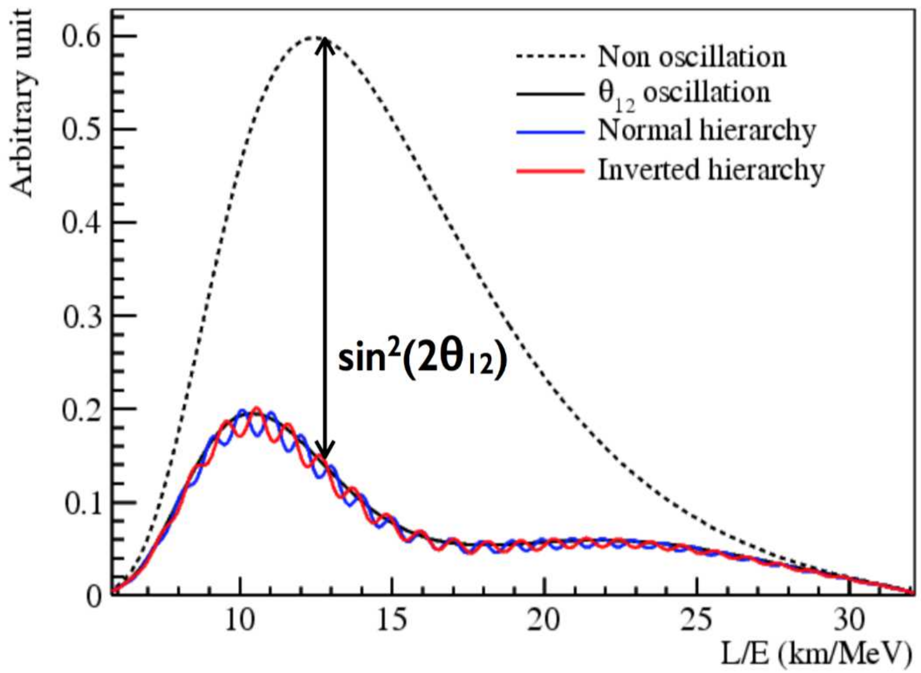
- CatiROC performance fits very well for JUNO-SPMT:
  - 100% trigger efficiency @ **1/3 p.e.** (50 fC @ PMT gain 10^6)
  - Charge resolution (**only HG used**) : 1.5 ADCu ~ **15 fC** (50 fC @ PMT gain 10^6)
  - Time resolution= **167 ps rms**
- Tests with the HZC 3” PMT shows
  - **Good p.e. spectrum**
  - 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

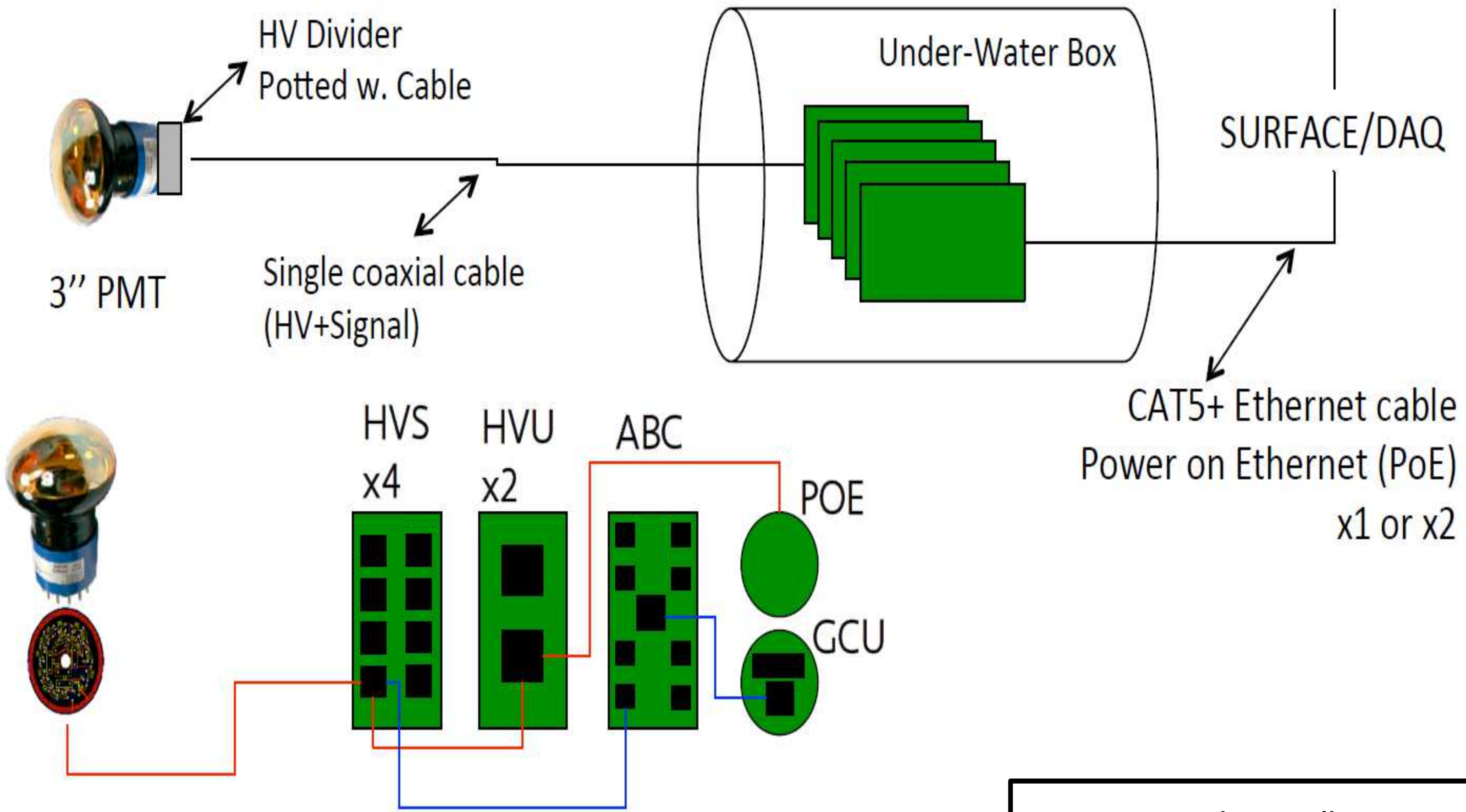
CATIROC Datasheet on http://omega.in2p3.fr

Neutrino energy spectrum









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

CATIROC main features

CATIROC
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 2^{nd} serial link) Max: 40 Mbits/s 16 chs 8,3 Mbits/s 1 ch

Digital part

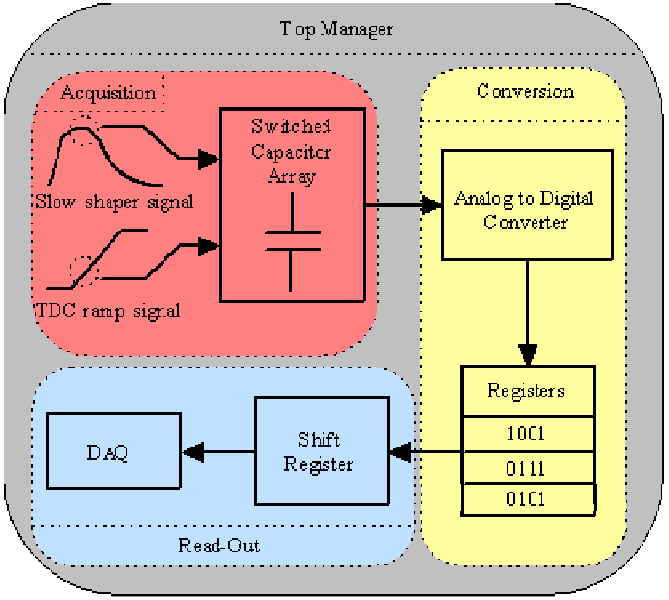
All channels are handled independently

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**= 3bits; **fine time**=10 bits, **charge**=10 bits, **gain**=1 bit

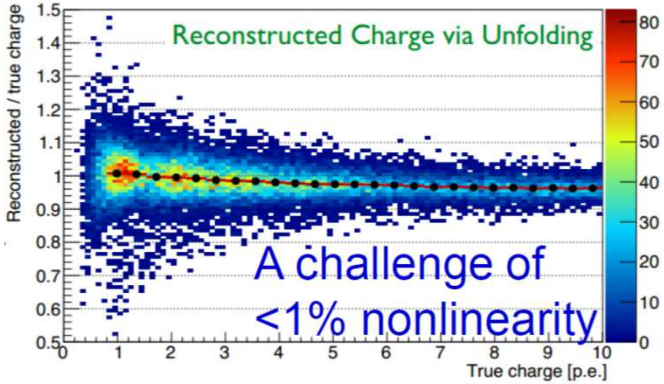
JUNO: the Small PMT (SPMT) system

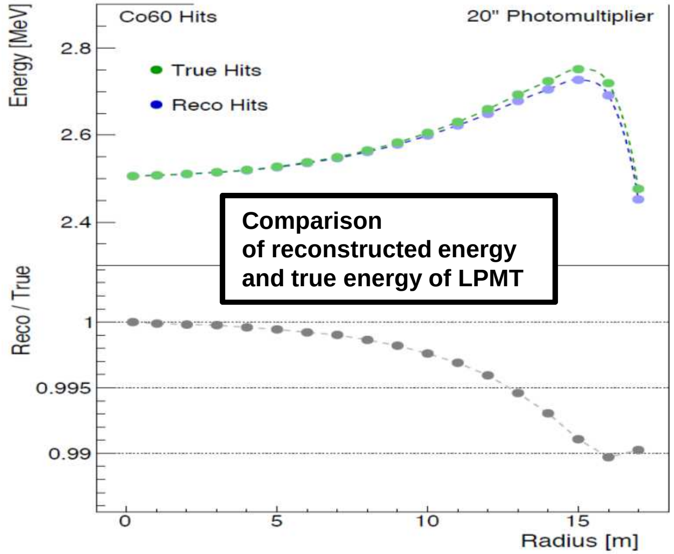
36.000 3” PMTs

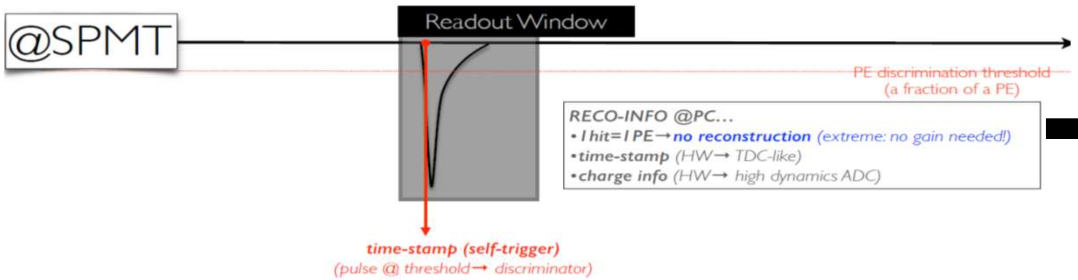
Double-calorimetry:

- 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 ν…
- Help detection of supernova neutrino

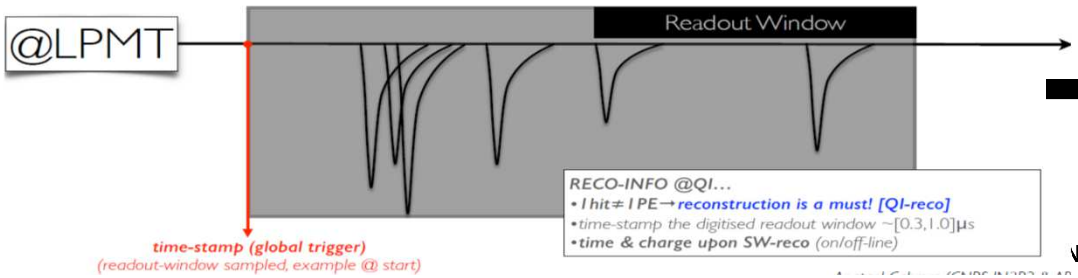
Nonlinear response of LPMT due to the distortion of output waveform





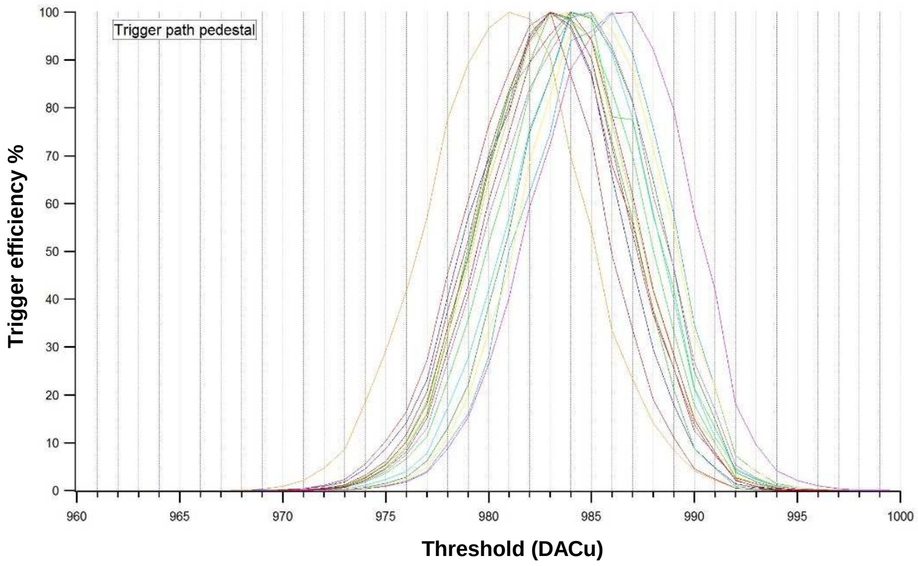


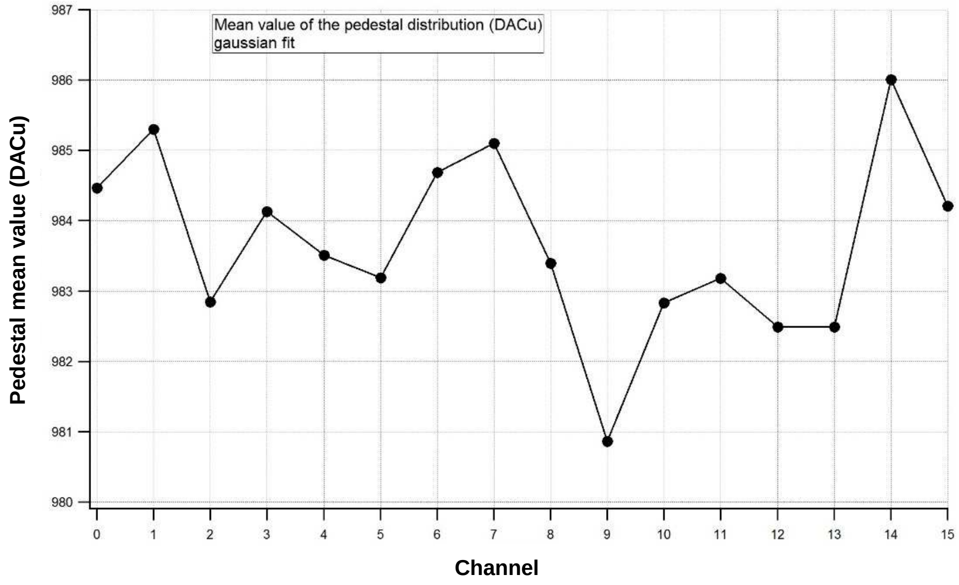
Small-PMT (SPMT):
measure energy via “**photon counting**”,
control systematics →non-stochastic effect

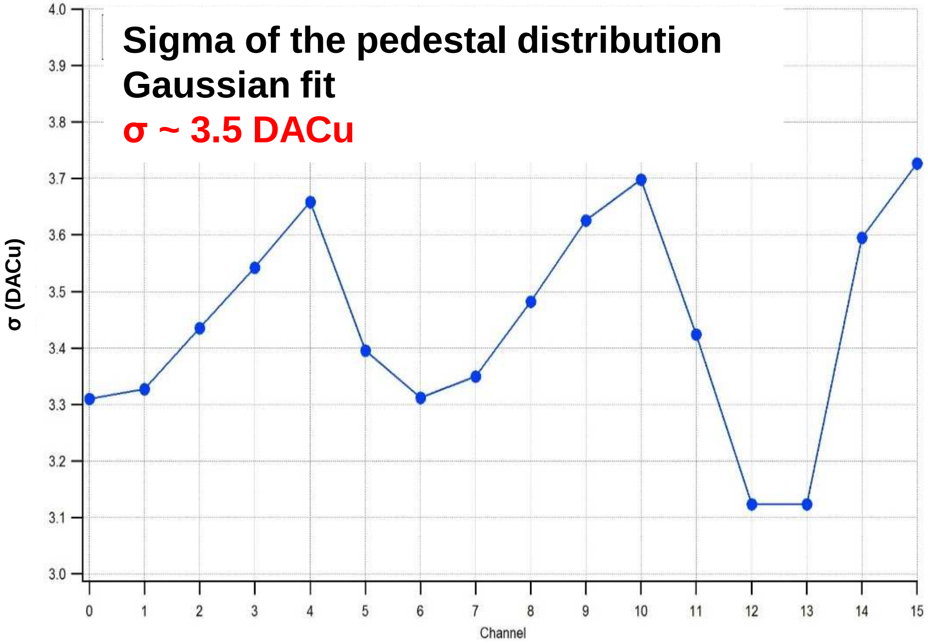


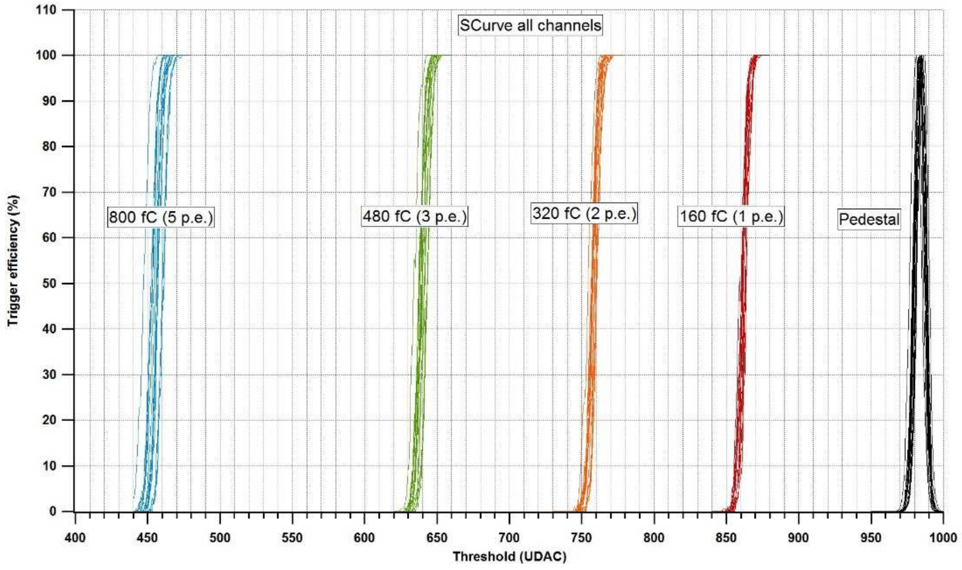
Large-PMT (LPMT):
measure energy
via “**charge integration**”,
increase photon statistics →stochastic effect

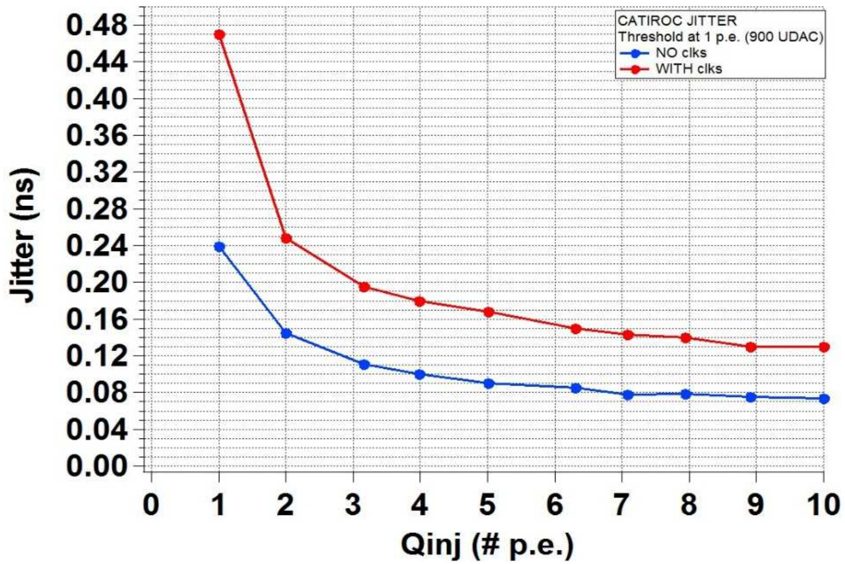
Autotrigger efficiency

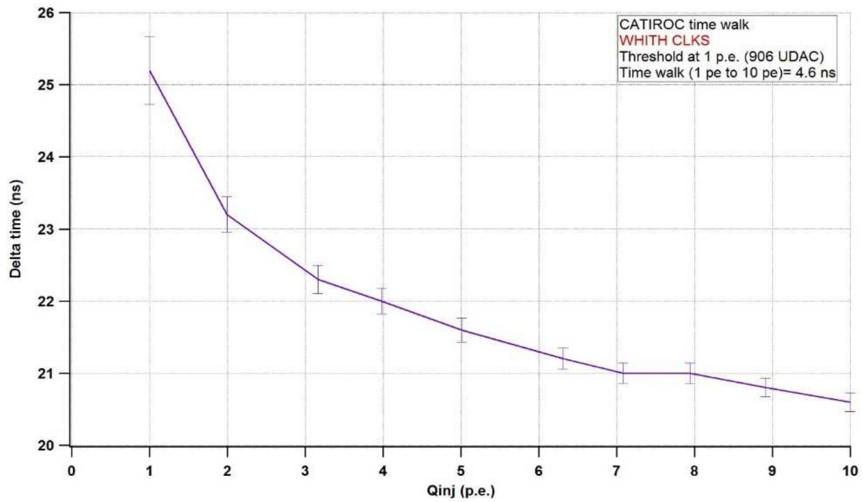


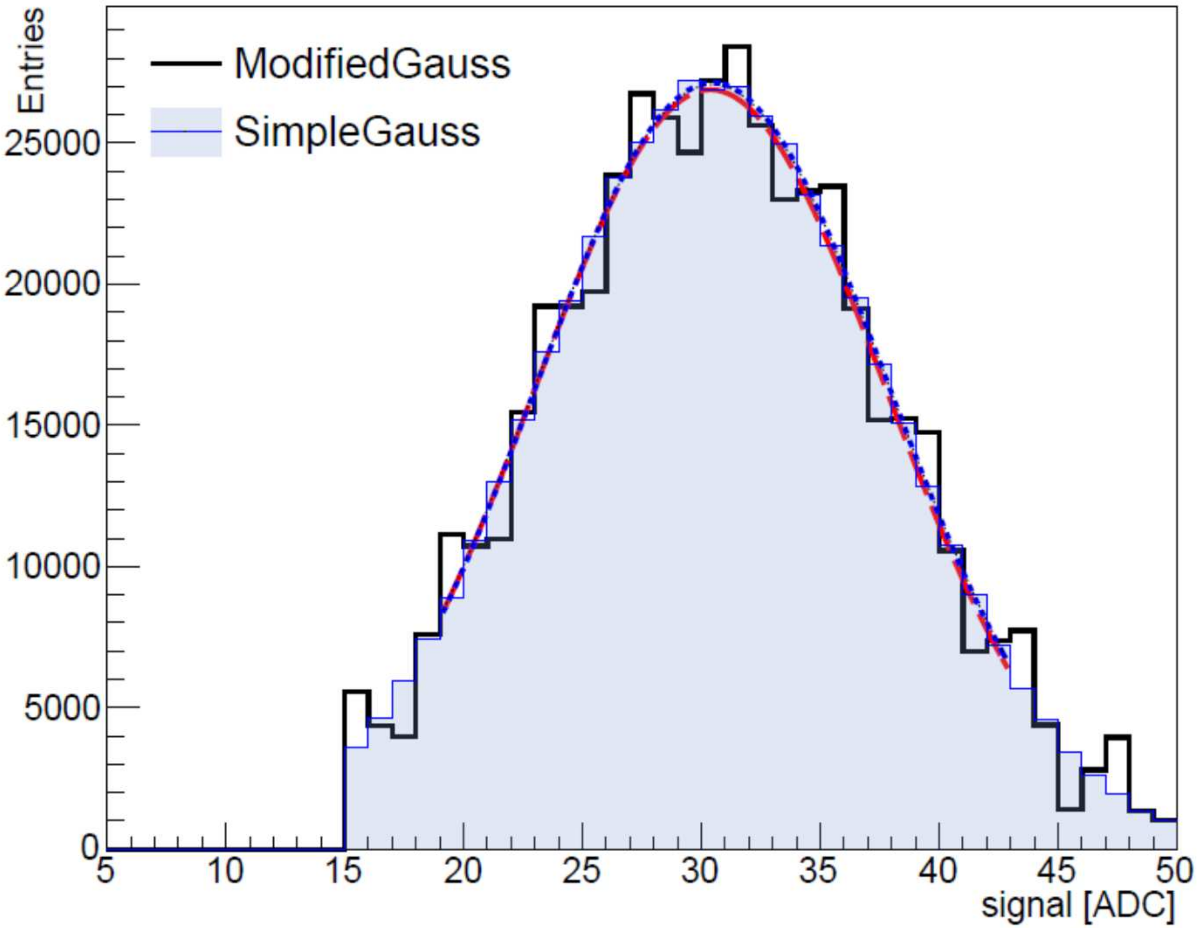





SCurve all channels
800 fC (5 p.e.)
480 fC (3 p.e.)
320 fC (2 p.e.)
160 fC (1 p.e.)
Pedestal
Trigger efficiency (%)
Threshold (UDAC)


CATIROC JITTER
Threshold at 1 p.e. (900 UDAC)
NO clks
WITH clks
Jitter (ns)
Qinj (# p.e.)


CATIROC time walk
WHITH CLKS
Threshold at 1 p.e. (906 UDAC)
Time walk (1 pe to 10 pe)= 4.6 ns
Delta time (ns)
Qinj (p.e.)



Impact of CatiROC features

- σ_{pe}/μ_{pe} ~ 30%
- **ping-pong:** charge difference < 5%
- **wiggles effect** (distorsion on p.e. < 1%)

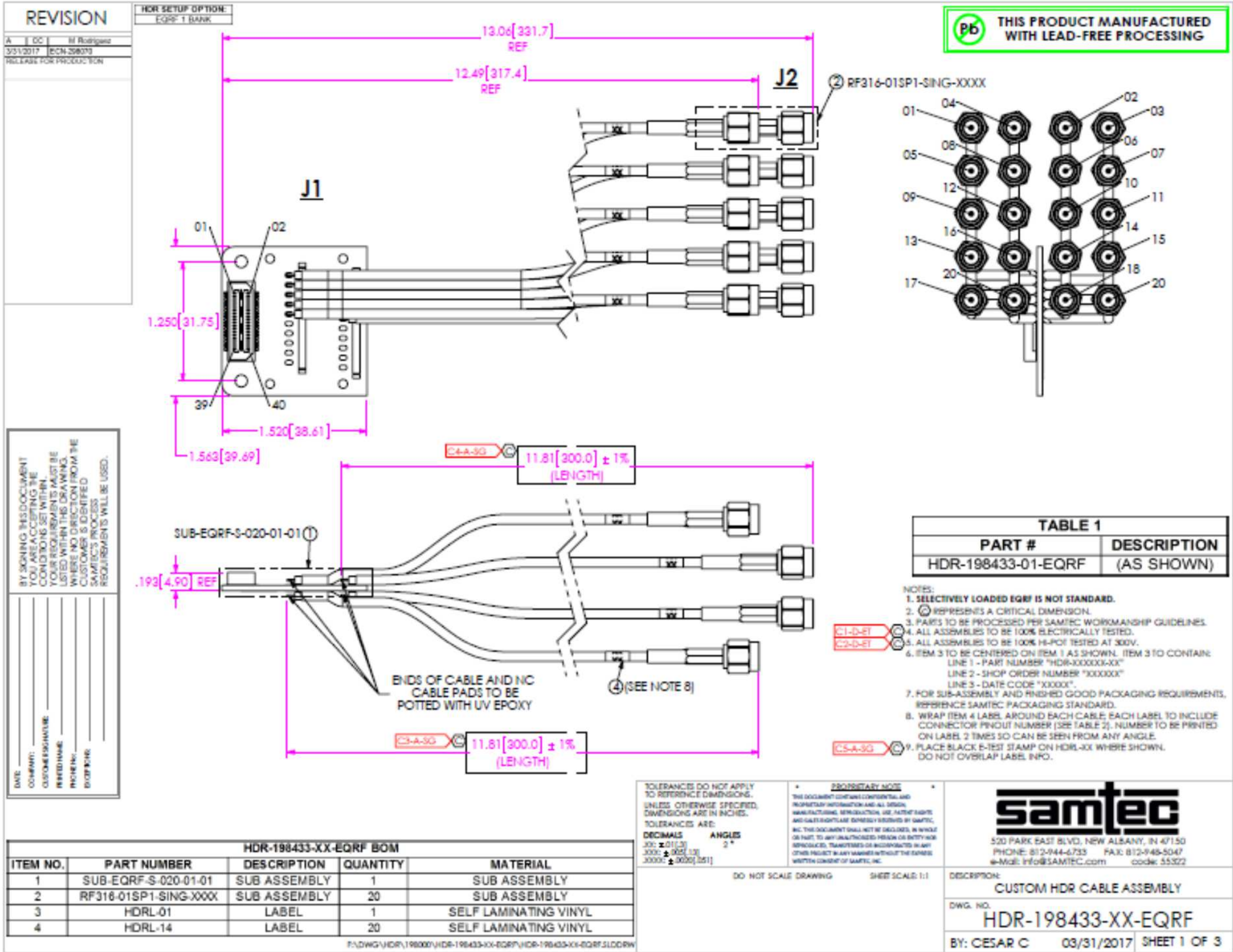


TABLE 1

PART #	DESCRIPTION
HDR-198433-01-EQRF	(AS SHOWN)

HDR-198433-XX-EQRF BOM

ITEM NO.	PART NUMBER	DESCRIPTION	QUANTITY	MATERIAL
1	SUB-EQRF-S-020-01-01	SUB ASSEMBLY	1	SUB ASSEMBLY
2	RF316-01SP1-SING-XXXX	SUB ASSEMBLY	20	SUB ASSEMBLY
3	HDRL-01	LABEL	1	SELF LAMINATING VINYL
4	HDRL-14	LABEL	20	SELF LAMINATING VINYL

Interface planned to test

- For CAEN LIKE connectors