Introduction of Photodetector System in TAO

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- **Taishan Antineutrino Observatory (TAO), a satellite experiment of JUNO.**
  - **Taishan Nuclear Power Plant, 30 – 35 m from one of the 4.6 GW_{th} reactor cores**
  - **Total cost, 4-5 M$**

- **Measure reactor neutrino spectrum w/ sub-percent E resolution (< 2% @ 1MeV)**

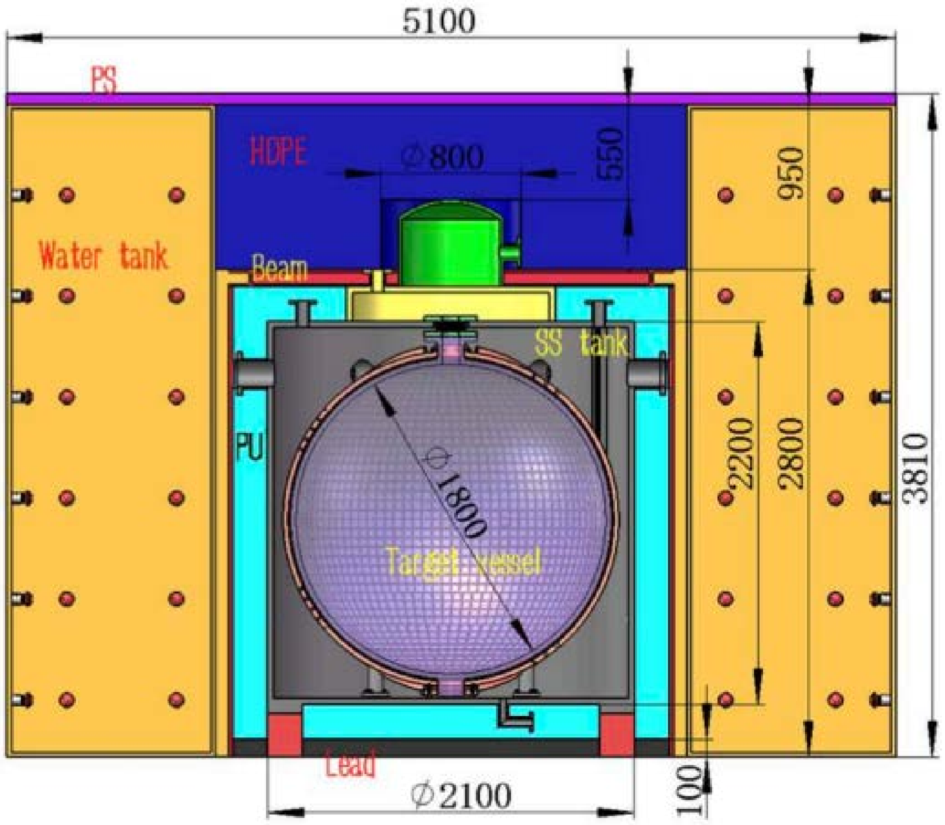
- **Ton scale Gd-doped Liquid Scintillator (Gd-LS)**

- **95% coverage of SiPMs w/ PDE > 50%**
  - **$2.5\%/\sqrt{E(MeV)}$ energy resolution with PMTs of PDE 24%**

- **Operate at -50 °C to suppress SiPMs' dark noise**

- **4500 p.e./MeV**

- **Online in 2023**



Location of JUNO and JUNO-TAO

Yangjiang	Taishan
17.4 GW	9.2 + 9.2 GW

JUNO-TAO detector

❄ **Laboratory in a basement at -10 m, 30-35 m from Taishan core (4.6 GW_{th})**

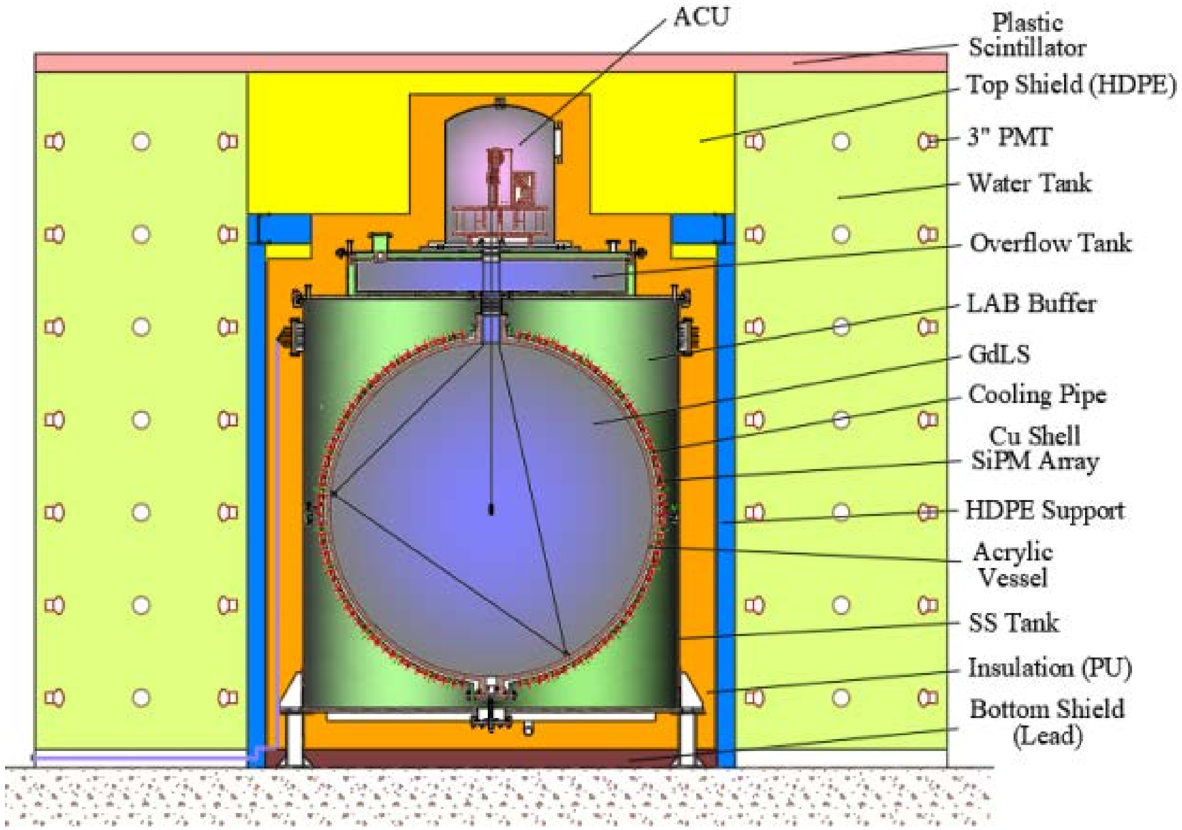
❄ **2.6 ton Gd-LS in a spherical vessel**

- ➢ **1-ton FV, ~4000 IBDs/day**
- ➢ **10 m^2 SiPM of 50% PDE Operate at -50°C**

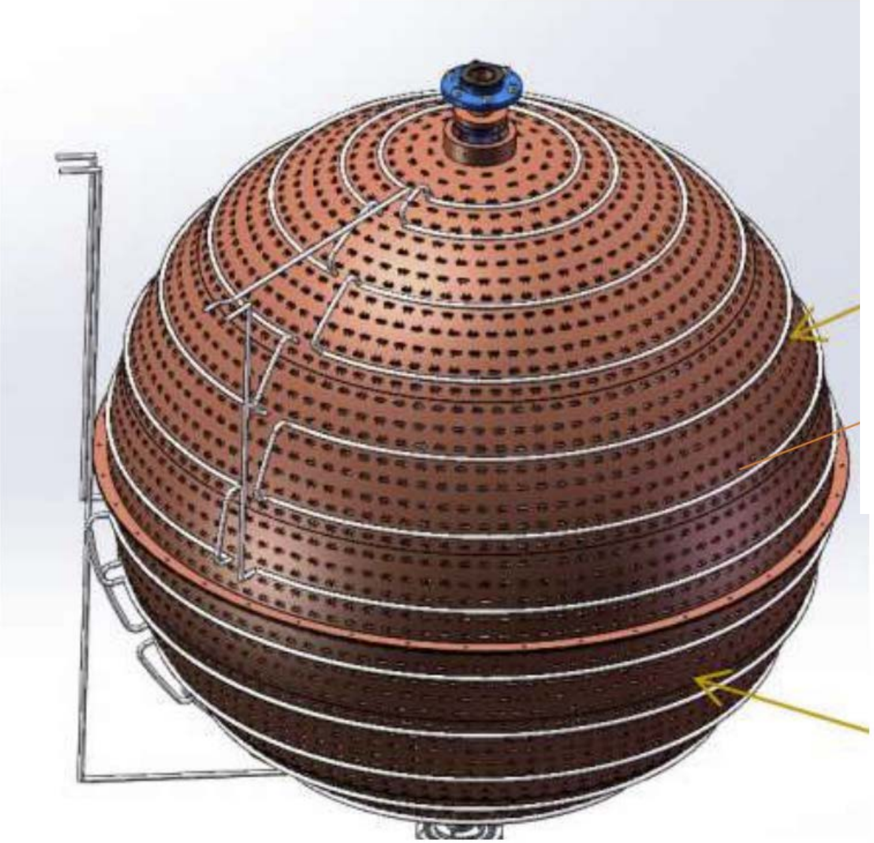
TAO CDR ready in 2020
arXiv:2005.08745

❄ **From Inner to Outside**

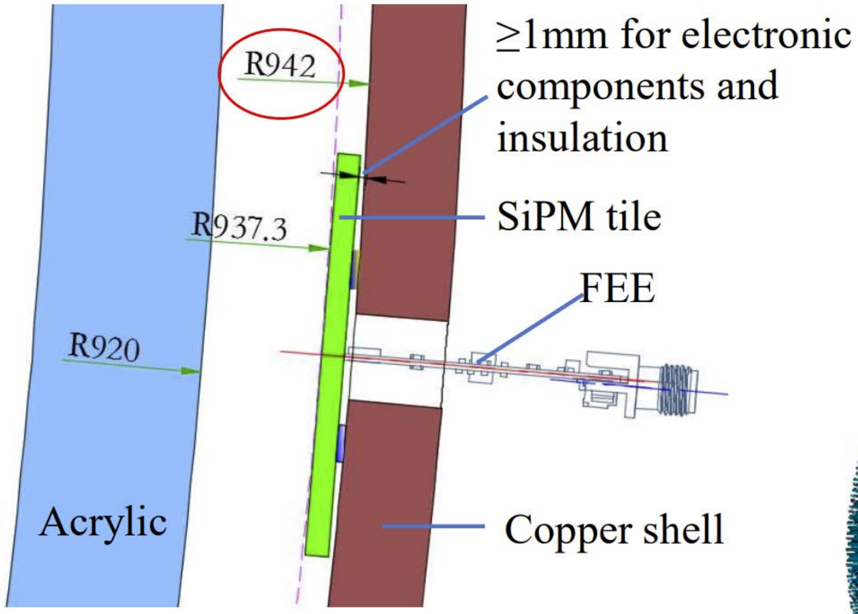
- ➢ **Gd-LS**
- ➢ **Acrylic vessel**
- ➢ **SiPM and support (Cu shell)**
- ➢ **LAB buffer**
- ➢ **Cryogenic vessel (SS + insulation)**
- ➢ **Veto detector**
  - **Water Cerenkov detector**
  - **PS + SiPM on the top**

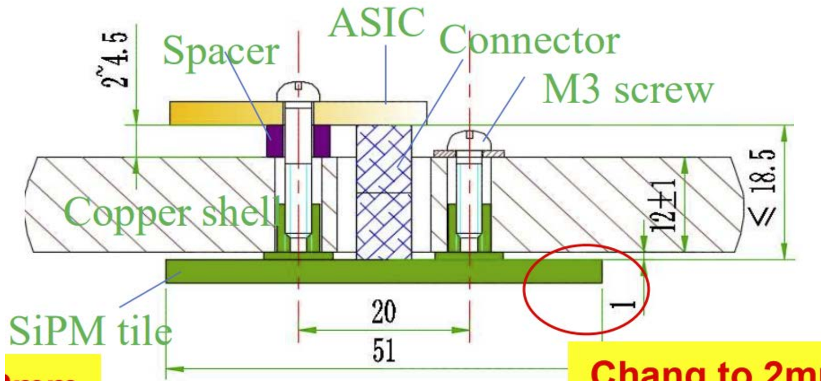


Photodetector



Chang to R943mm





2mm

Chang to 2mm

4024 tiles

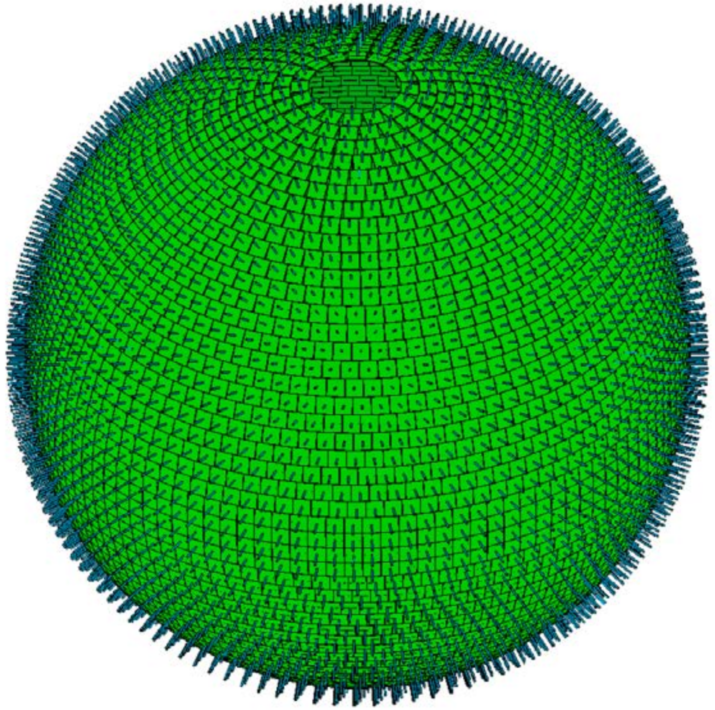
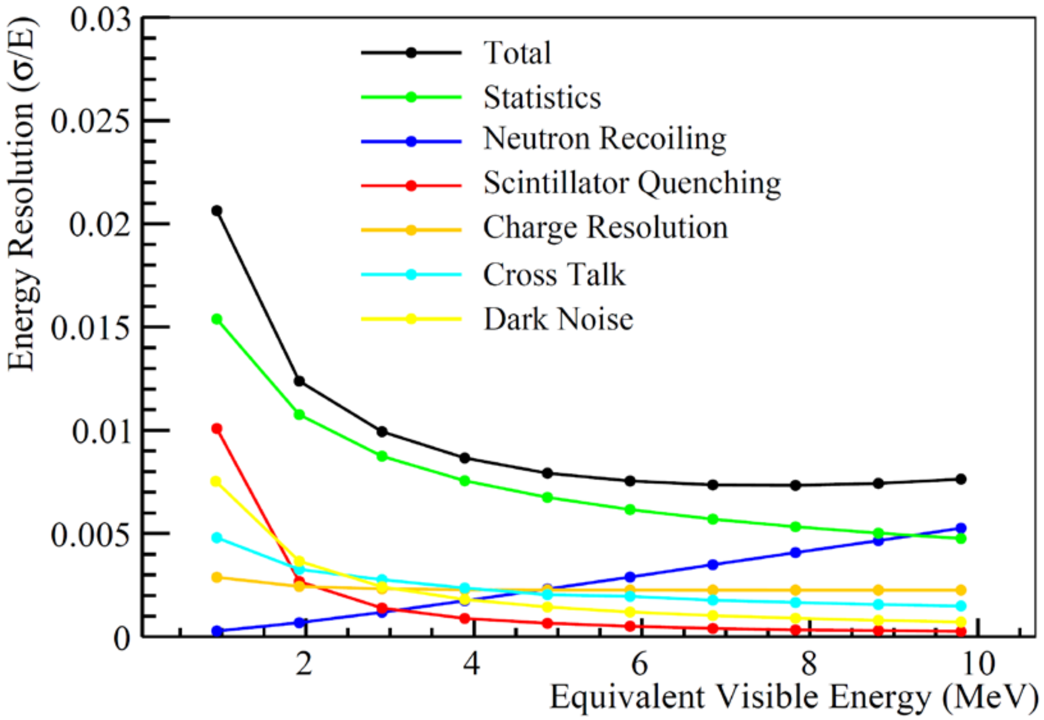


Table 6-1: Requirements on the SiPM parameters.

Parameters	Specification	Comments
PDE	$\geq 50\%$	at 400 nm, not including correlated noise
Dark count rate	$\leq 100\ \mathrm{Hz/mm^2}$	at -50°C
Probability of correlated noise	$\leq 10\%$	including cross talk and afterpulsing
Uniformity of V_{bd}	$\leq 10\%$	to avoid bias voltage tuning
Size of the SiPM device	$\geq 6 \times 6\ \mathrm{mm^2}$	for easy handling
SiPM coverage within tiles	$\geq 94\%$	not included in SiPM's PDE



PDE, DCR and correlated noise strongly depend on bias voltage applied on SiPMs.

So, for any given SiPMs, the optimal operating voltage should exist.

94% SiPM coverage within tiles assumes to use TSV. Now the wire bonding is also fine because of low cost and feasibility.

SiPMs in market

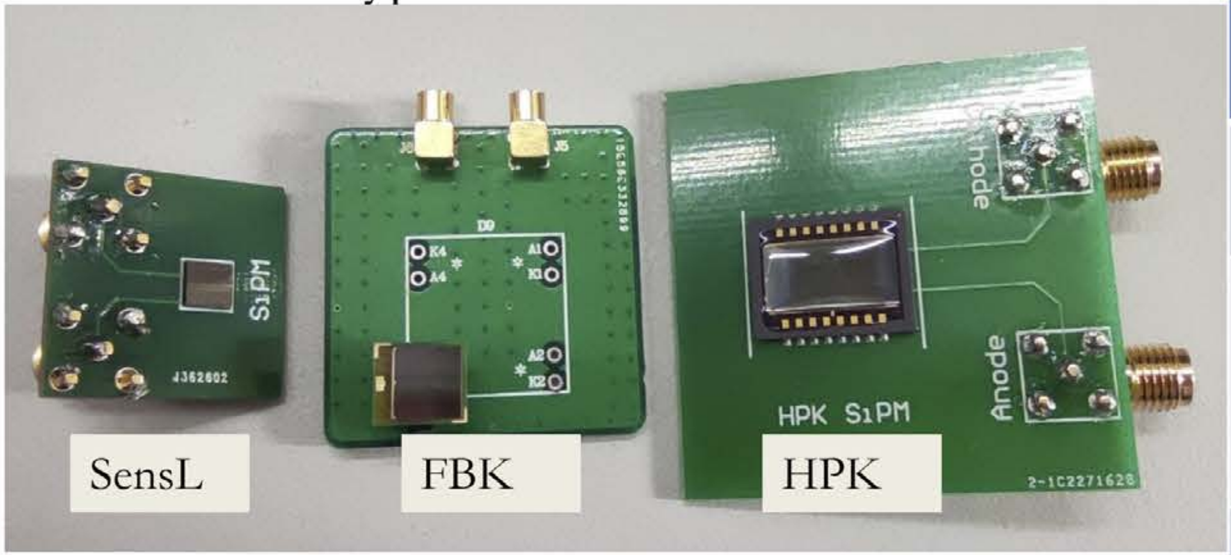
May not be up-to-date!	**SensL**	**Hamamatsu**	**FBK**
Type	**MicroFJ-60035**	**S14160/S14161**	**NUV-HD**
Cell size (μm)	35	50	40
Cell Fill factor (%)	76	74	81
PDE (%)	**51**	**50**	**56**
Peak wavelength (nm)	420 (250-900)	450 (270-900)	410 (280-700)
Dark count rate (kHz/mm^2)	70	166	150
Gain	6.0 x 10^6	2.5 x 10^6	3.5 x 10^6
Crosstalk probability (%)	20	7	10

The performance of some SiPMs looks promising.

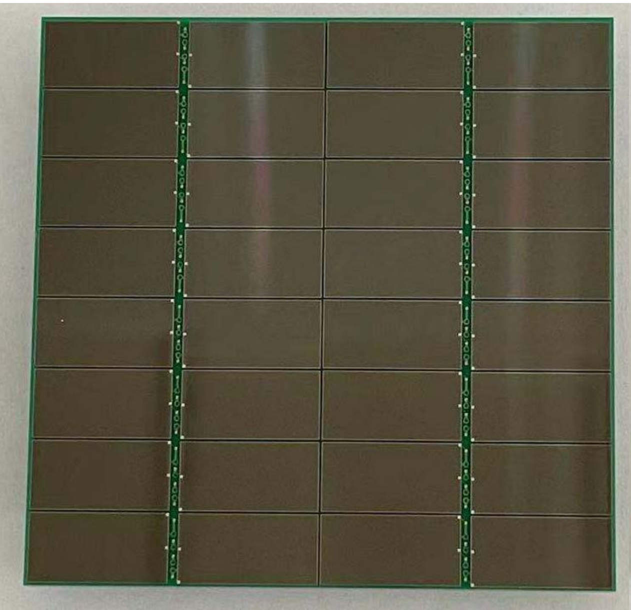
TAO starts R&D work with FBK and HPK in 2020.

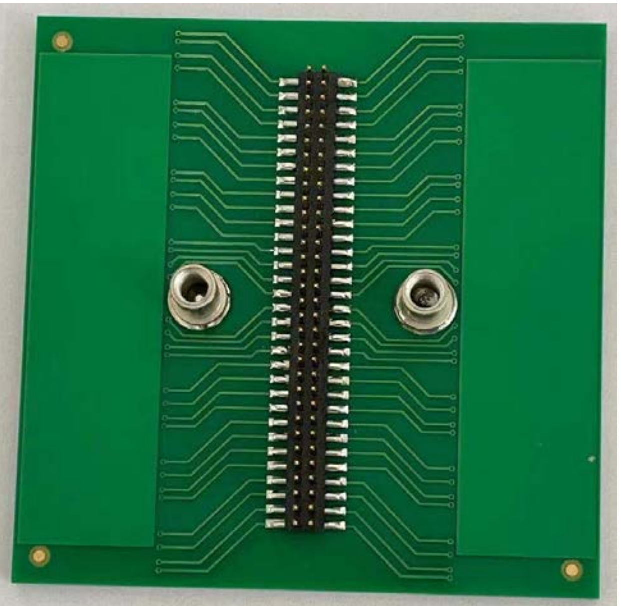
Samples from different vendors

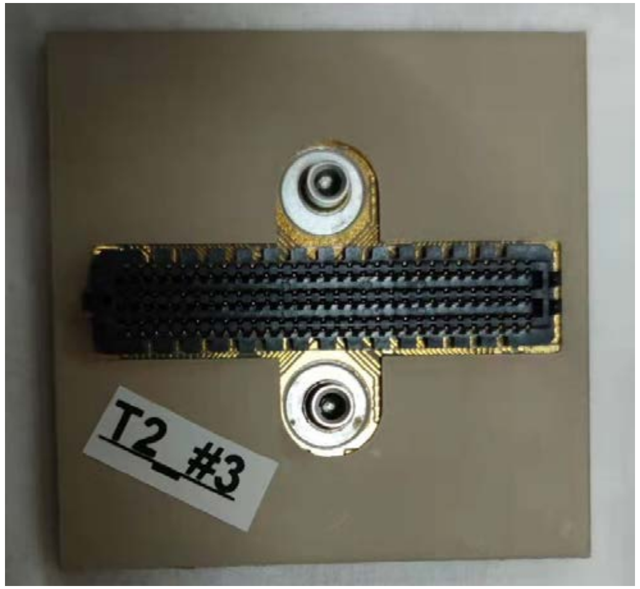
SiPMs: three types from different vendors



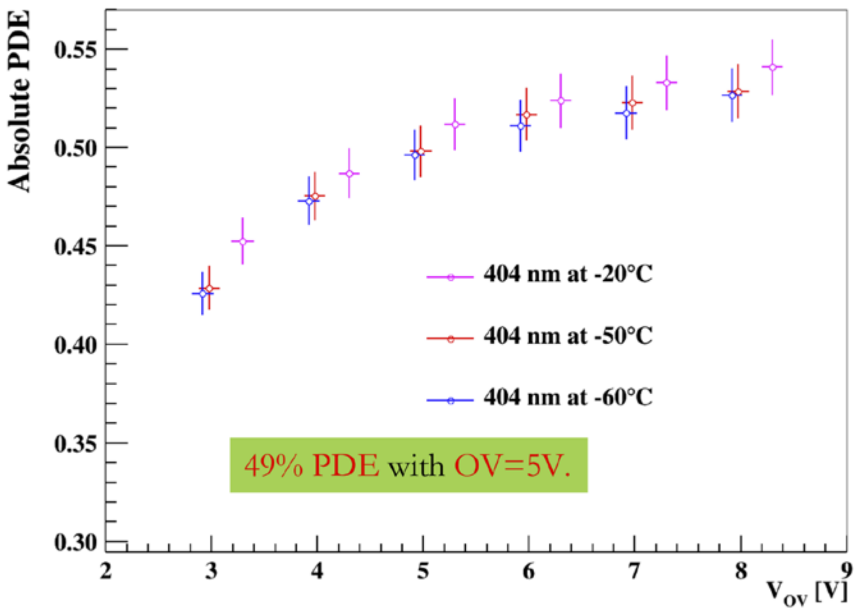
Vendor	Type	Pixel size (μm*μm)	Total size (mm*mm)
SensL	MicroK-40035-E715	35*35	4*4
FBK	NUV-HD LowCT_v2 (Double/Triple trenches)	50*50 (75*75)	6*6
HPK	S16080	75*75	6*12



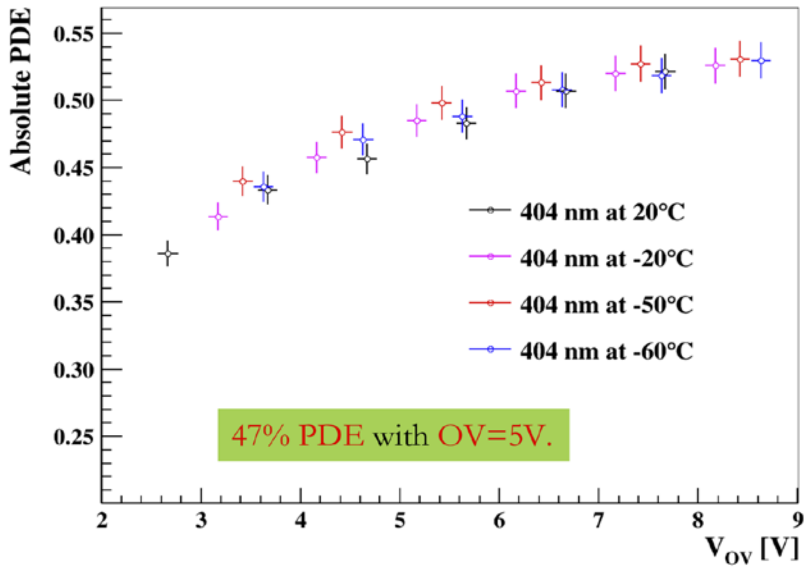




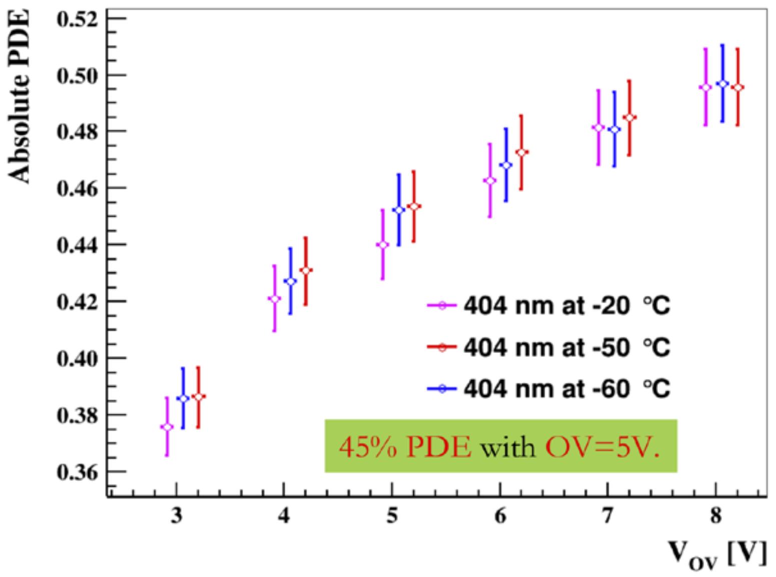
Preliminary PDE



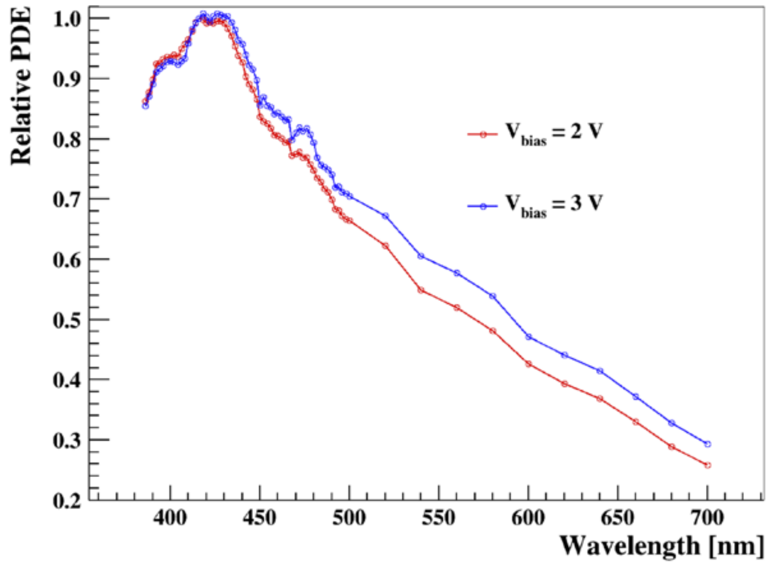
Absolute PDE of HPK SiPM at 404nm

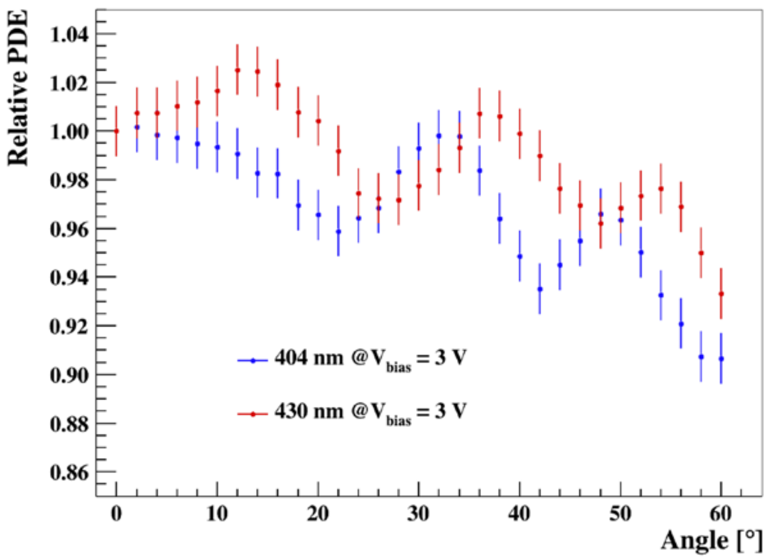


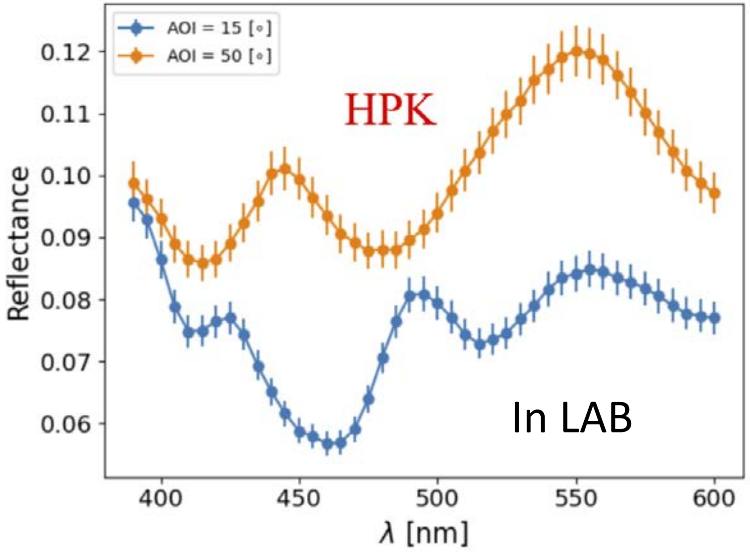
Absolute PDE of SensL SiPM at 404nm



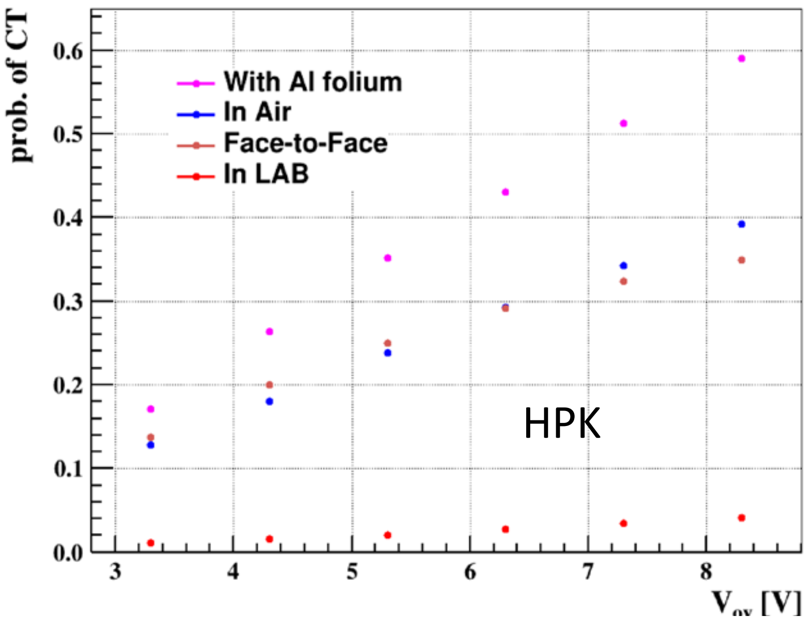
Absolute PDE of FBK SiPM at 404nm

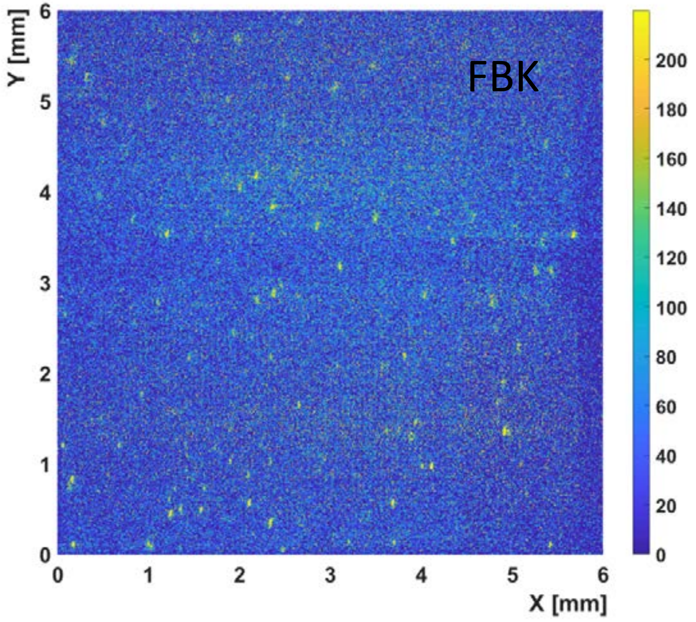


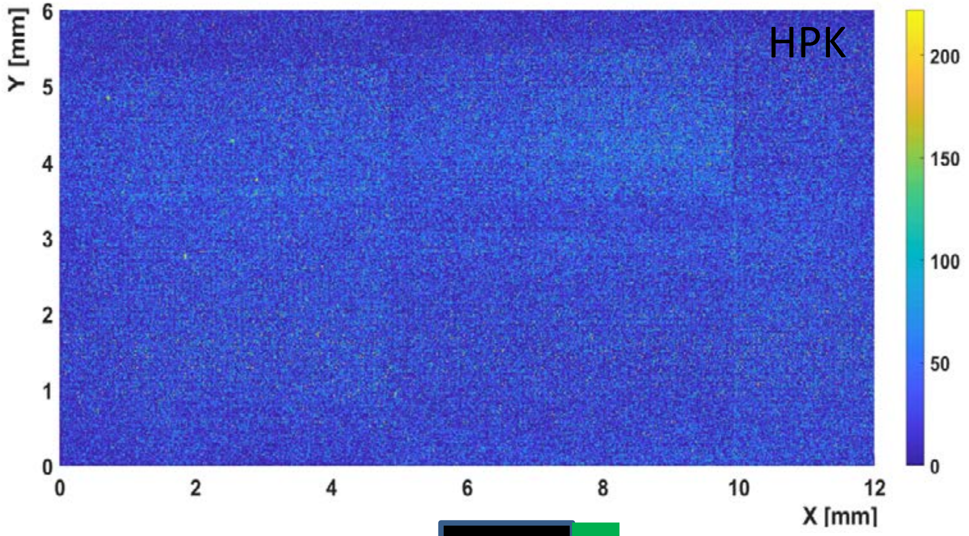


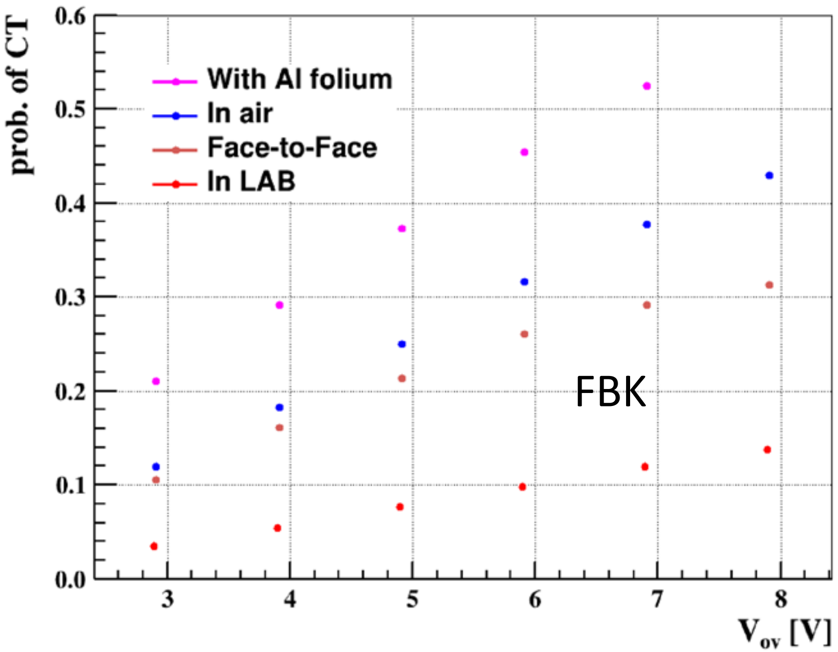


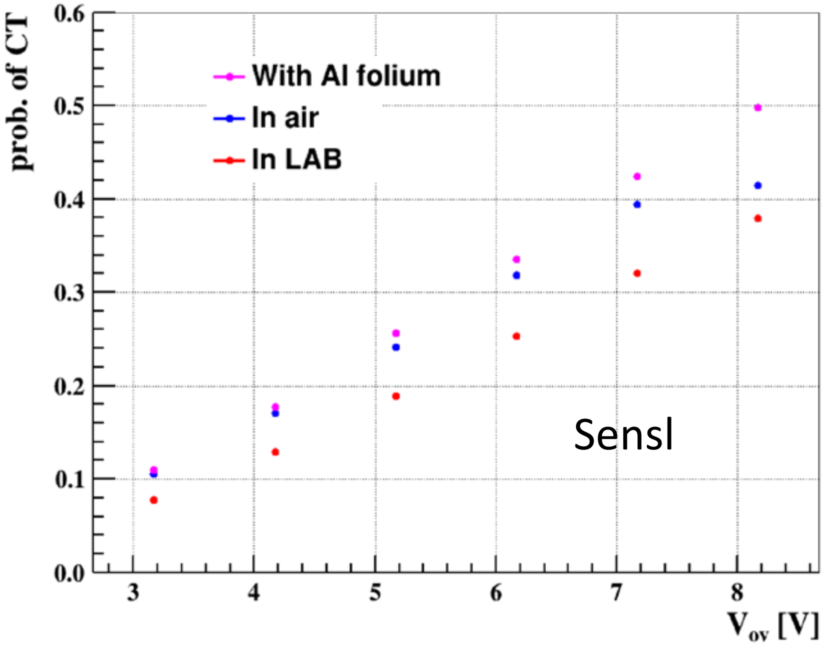
Optical cross talk

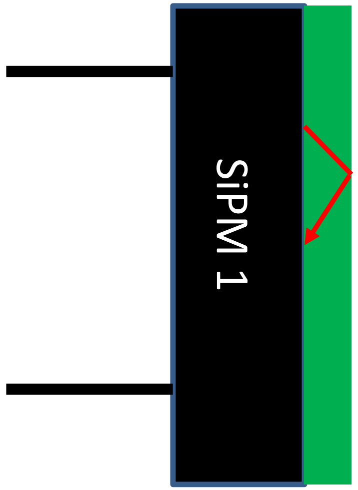








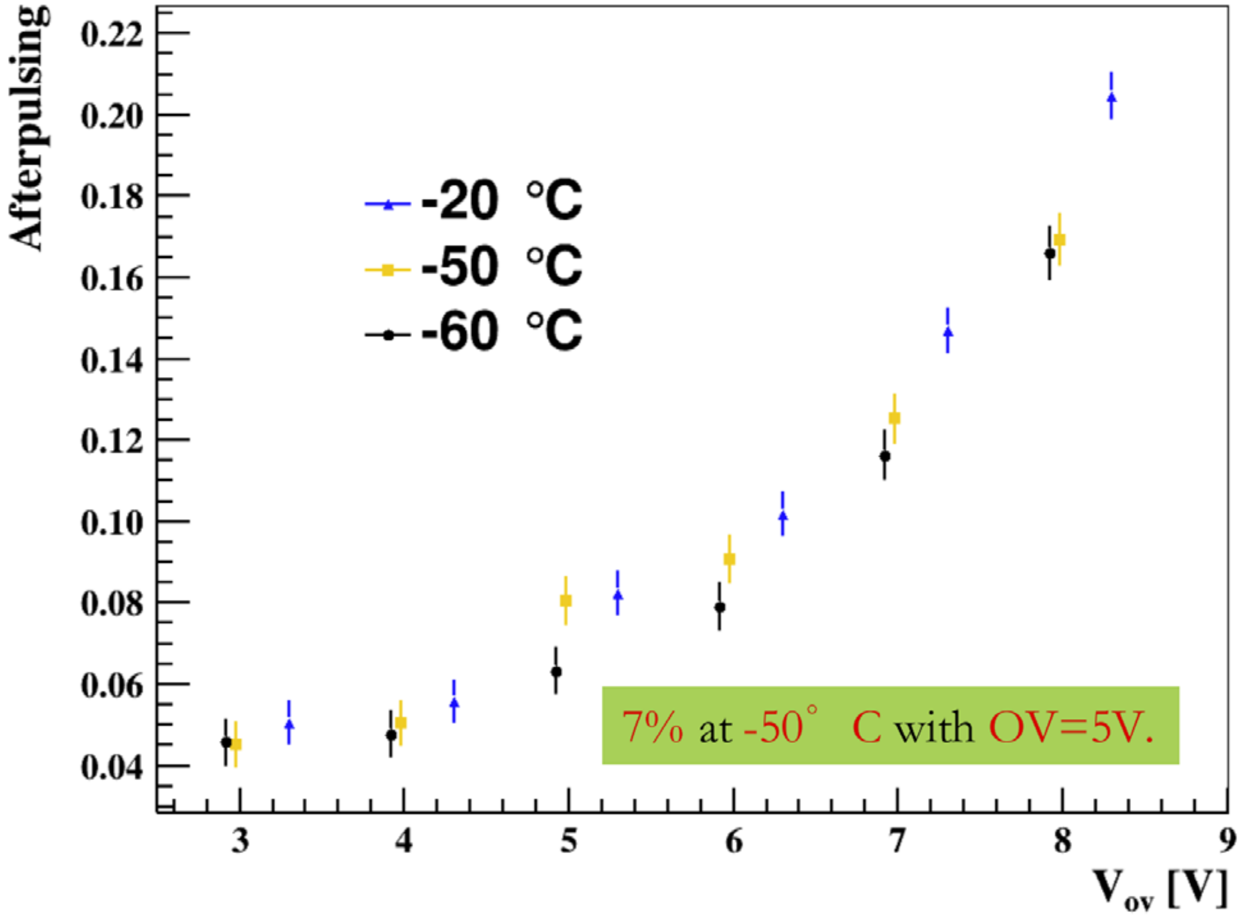




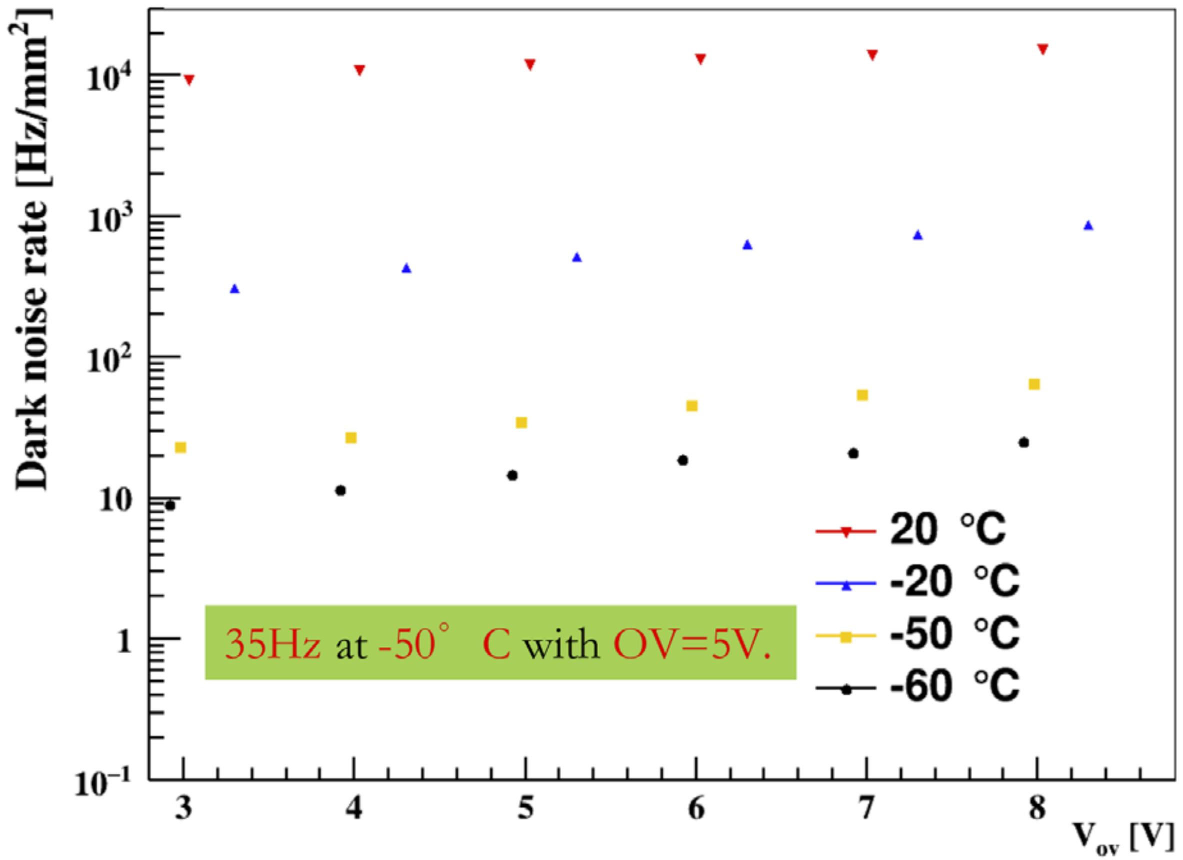
CT includes internal and external CT.

TAO is sensitive to both.

After pulse and DCR



After pulse prob. of HPK at low temperature



Dark noise rate of HPK SiPM at different temperature

- ❄ **The vendors should response the technical parameters of SiPMs at -50 °C, which is the operating temperature of the TAO detector.**
  - ➢ **It is well known that the DCR strongly depends on temperature**
  - ➢ **We did not observe strong temperature dependence for other parameters, like PDE, cross talk and after pulse**

- ❄ **The acceptance check will be performed at -50 °C**

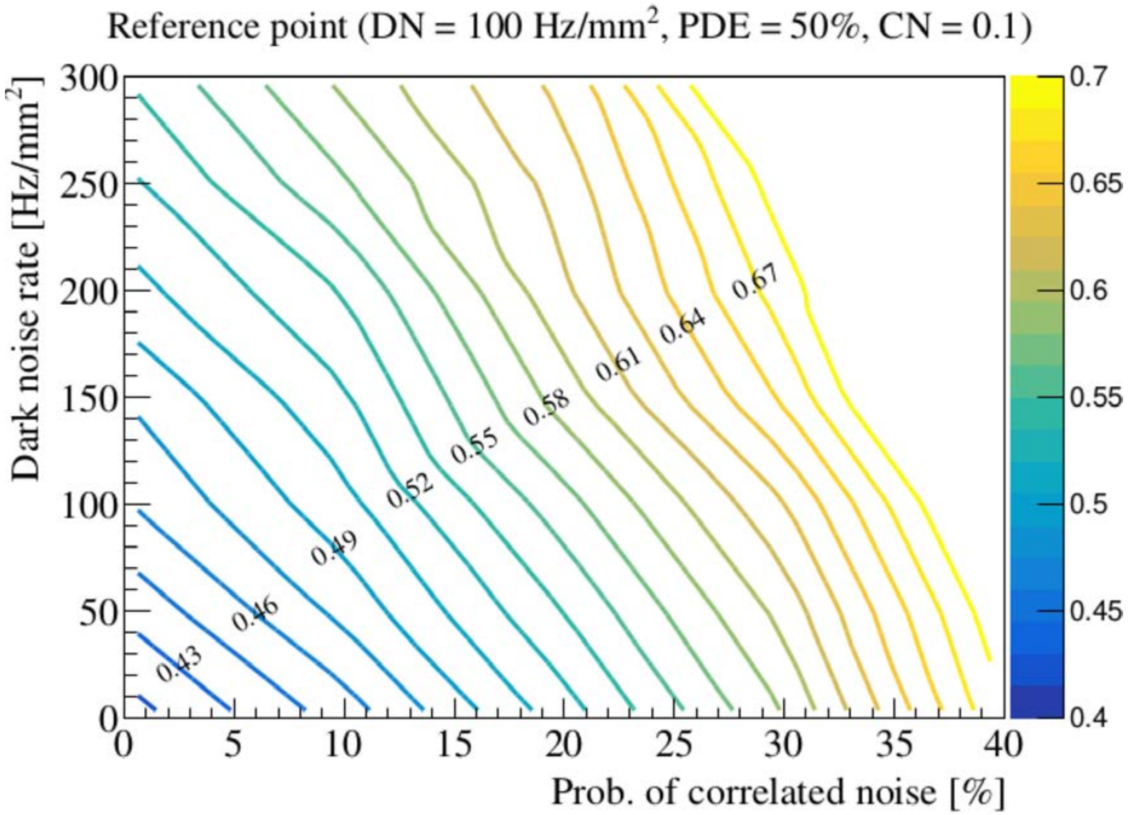
$\boldsymbol{PDE_{Eff}}$ **can be calculated based on DCR and correlated noise of SiPM:**

$$PDE_{Eff} = 0.51 + 0.35 \times P_{cn} + 0.84 \times P_{cn}^2 + (4.2 \times 10^{-4} + 2 \times 10^{-4} \times P_{cn}) \times DCR$$

$\boldsymbol{P_{cn}}$ **is correlated noise, including CT + AP**

DCR **is dark count rate, units:** ***Hz/mm²***

CT includes both internal and external cross talk!



Δ_ε **is the difference between the measured (real) PDE of SiPM at 420 nm and the effective PDE calculated from DCR and CN, in which the SiPM coverage on the tile is also taken into account.**

$$\Delta_\varepsilon = PDE \times \frac{C}{0.9} - PDE_{Eff}$$

PDE **is the absolute PDE of SiPMat 420 nm**

C **is the coverage of SiPM cells in one tile**

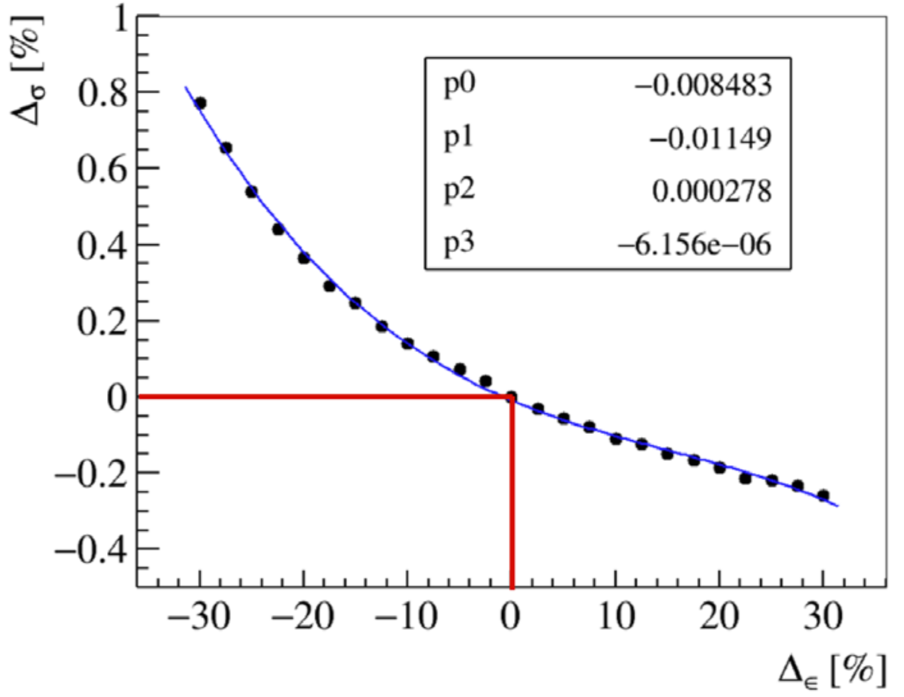
PDE_{Eff} **is the effective PDE defined in previous slide**

Then, impacts on energy resolution can be achieved:

$$\Delta_\sigma = -0.0115 \times \Delta_\varepsilon + 0.0278 \times \Delta_\varepsilon^2 - 0.0616 \times \Delta_\varepsilon^3$$

*** Δ_ε > -25%**

 # Δ_ε converted to Δ_σ to calculate scores



From resolution (Δ_σ) to score

- ❈ **If we use PMTs in the TAO detector, the expected energy resolution is about 2.5% @ 1MeV, total 4000 3'' PMTs are needed, the cost is about 4M RMB.**

- ❈ **By using SiPMs in TAO, the expected resolution is 2% @ 1MeV, the cost of 10 m^2 SiPM is about 20M RMB.**

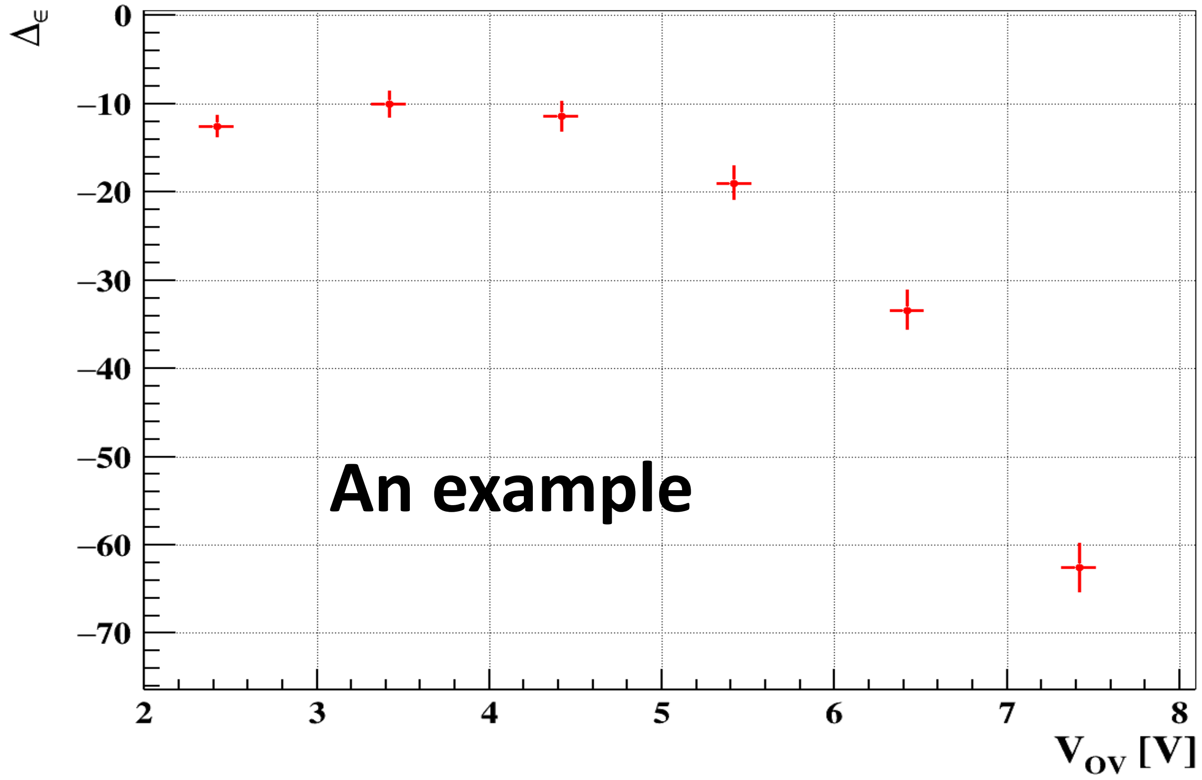
- ❈ **Therefore, 0.1% absolute change of resolution is corresponding to 3.2M RMB.**

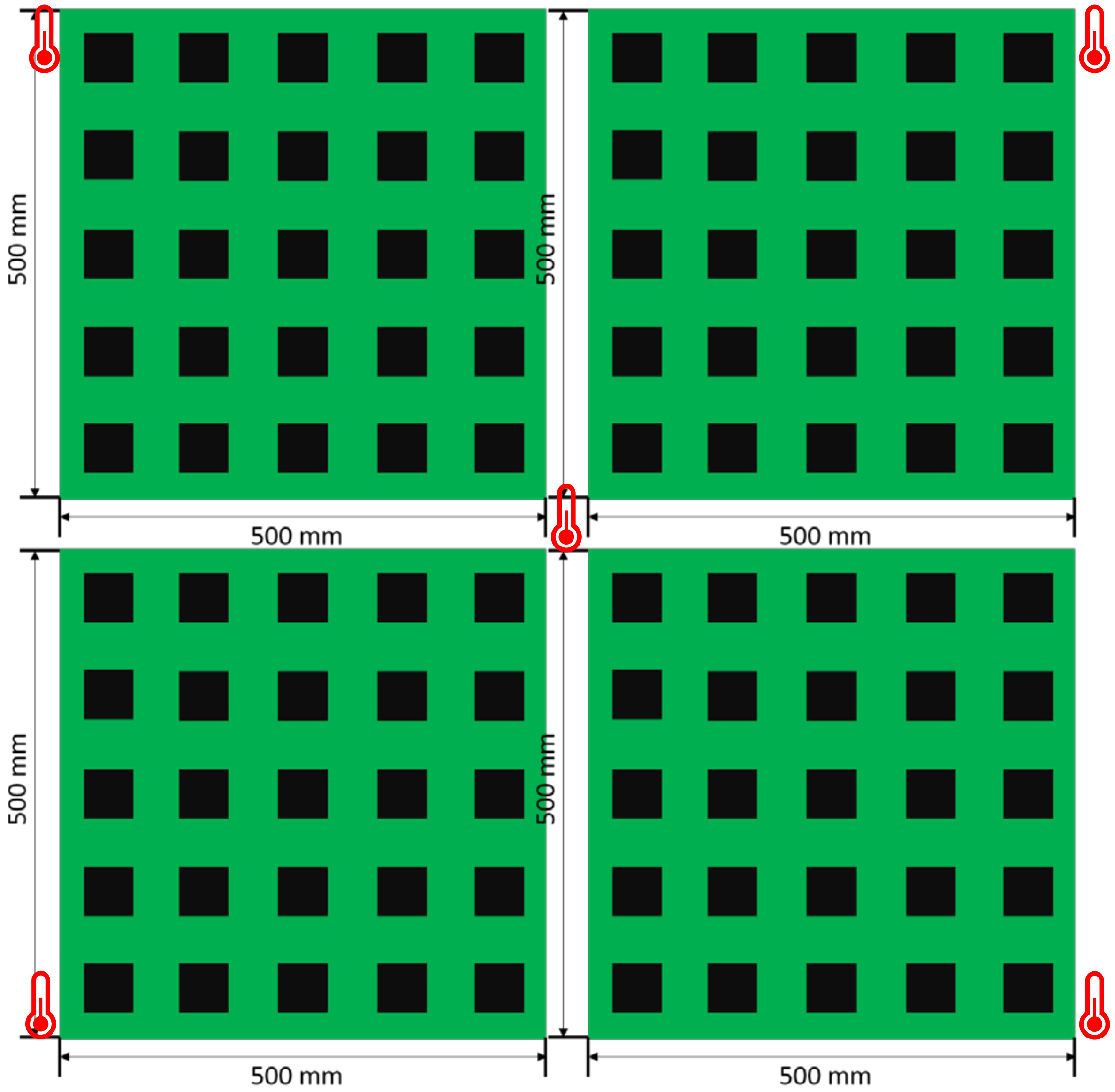
- ❈ **We know 35 scores are assigned to the price, so**

$$\boldsymbol{Technical\ score = 50 - \Delta_\sigma \times \frac{100}{0.1} \times 320 \times \frac{35}{Benchmark\ price}}$$

Examples of Δ_{ε} versus over voltage

Vendors have to scan the operating voltage and find the optimal one, then use the best numbers to response the technical items.



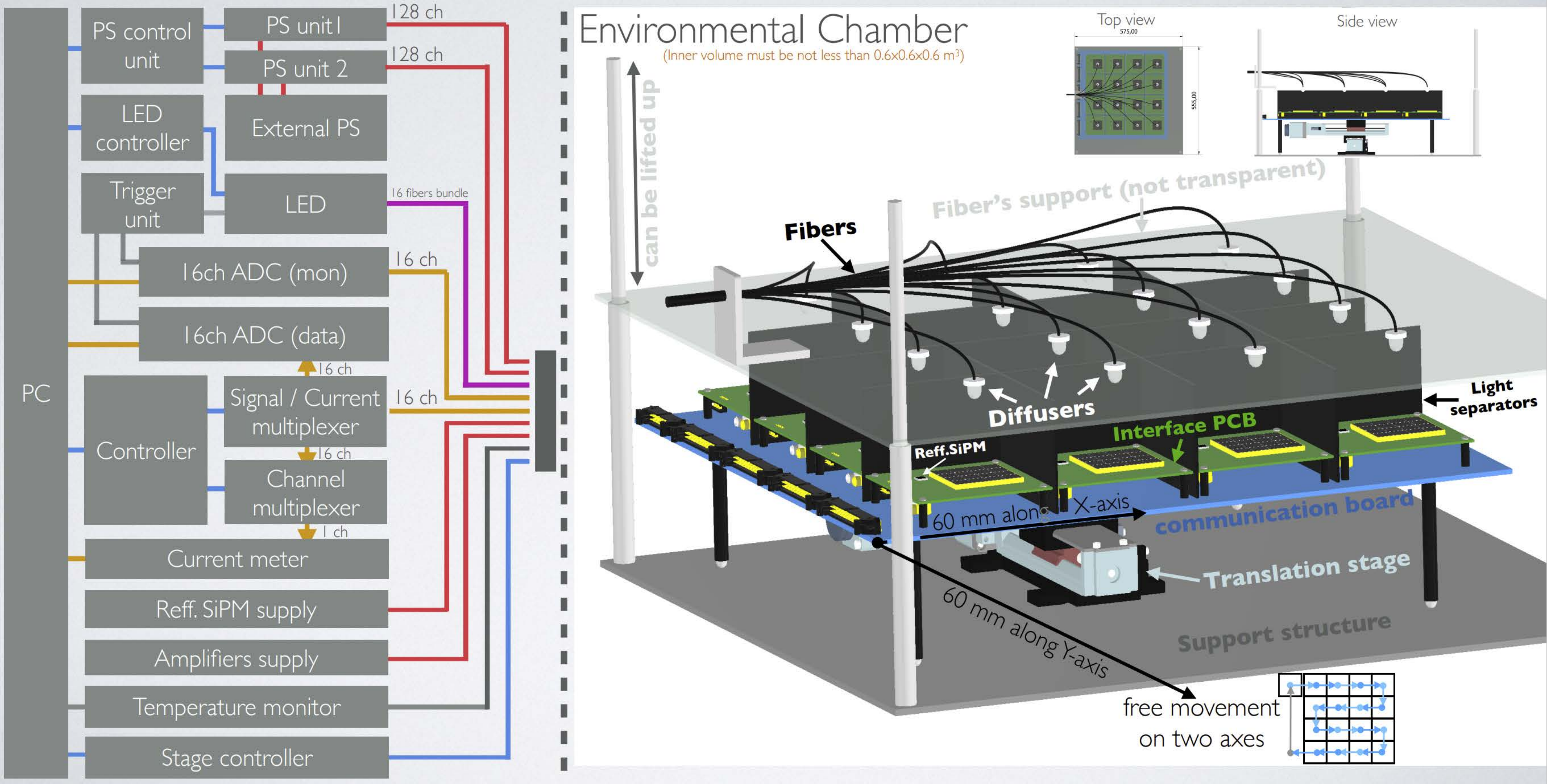


❑ Step 1: Visual check

❑ Step 2: burning test

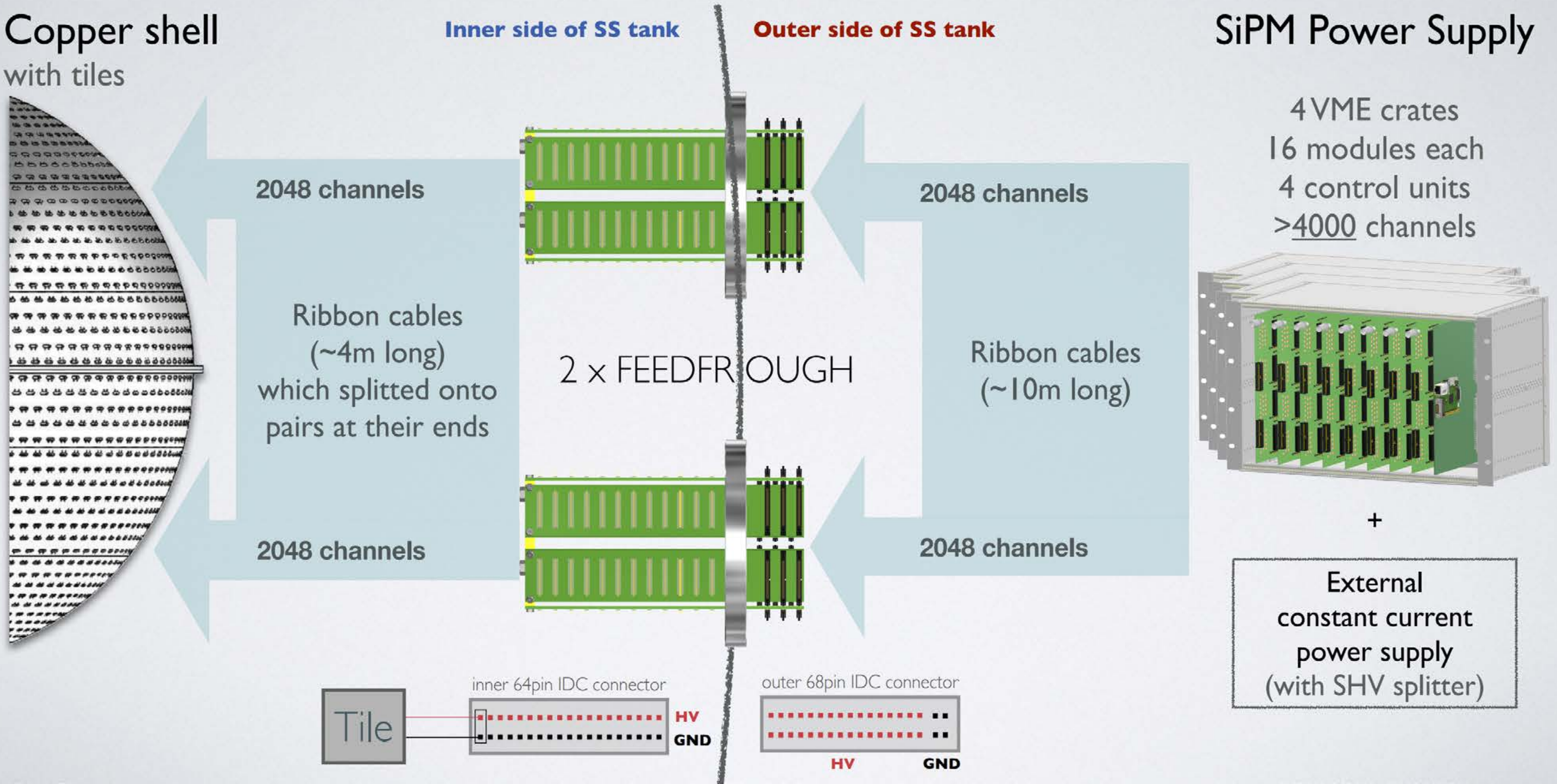
- All SiPM tiles are required to run for two weeks before the mass testing.
- 4 layers in total
- Each layer consists of 4 PCBs, each PCB is 500 x 500 mm^2, including 25 tiles.
- 5 temperature sensors in each layer, 20 sensors in total

Step 3: mass test



Action type	Studied parameters	Equipment	Timing
Tile installation	-	Environmental chamber SiPM Power Supply boards 16 Interface PCBs + ref.SiPM 16 channel ADC (data) 16 channel ADC (mon) Trigger unit XY - Translation stage (hot version) Communication board Channel multiplexer Current meter (Keithley) 1(2) Fiber distributor 1(2) LED LED controller Duffusers + Light separators	5 min
Cooling down	-		30 min
Fast charge scan (All SiPMs are biased, Gain vs V)	Average V_{bd}		10 min
Detailed charge scan over 5 points by overvoltage (Single SiPM is biased)	PDE, GAIN, CT, DCR, PDE_{eff}, V_{op}, Dark current		16 SiPMs x 1min x 5 Vpoints = 80 min
Heating	-		30 min
Light field scan	Light field distribution		20 min *it can be done once per shift for instance
Tile uninstallation	-		5 min
		Total time:	2h 40min + 20 min

Full MC timing: 4100 tiles / (16 tiles x 3 scans/day) ≈ 86 days
4100 tiles / (16 tiles x 4 scans/day) ≈ 64 days


Copper shell
with tiles
Inner side of SS tank
Outer side of SS tank
SiPM Power Supply
4 VME crates
16 modules each
4 control units
>4000 channels
2048 channels
2048 channels
Ribbon cables
(~4m long)
which splitted onto
pairs at their ends
2 x FEEDFR OUGH
Ribbon cables
(~10m long)
2048 channels
2048 channels
+
External
constant current
power supply
(with SHV splitter)
Tile
inner 64pin IDC connector
HV
GND
outer 68pin IDC connector
HV
GND

Power unit

- VME mechanics
- 128 channels
- up to 200V/ch
- up to 550uA/ch
- 1xSHV connector
- 2x 68pin IDC connectors
- Output voltage monitor (24bit ADC)
- 4x 14bit DAC chips
- CANOpen protocol

Power Unit

Control unit

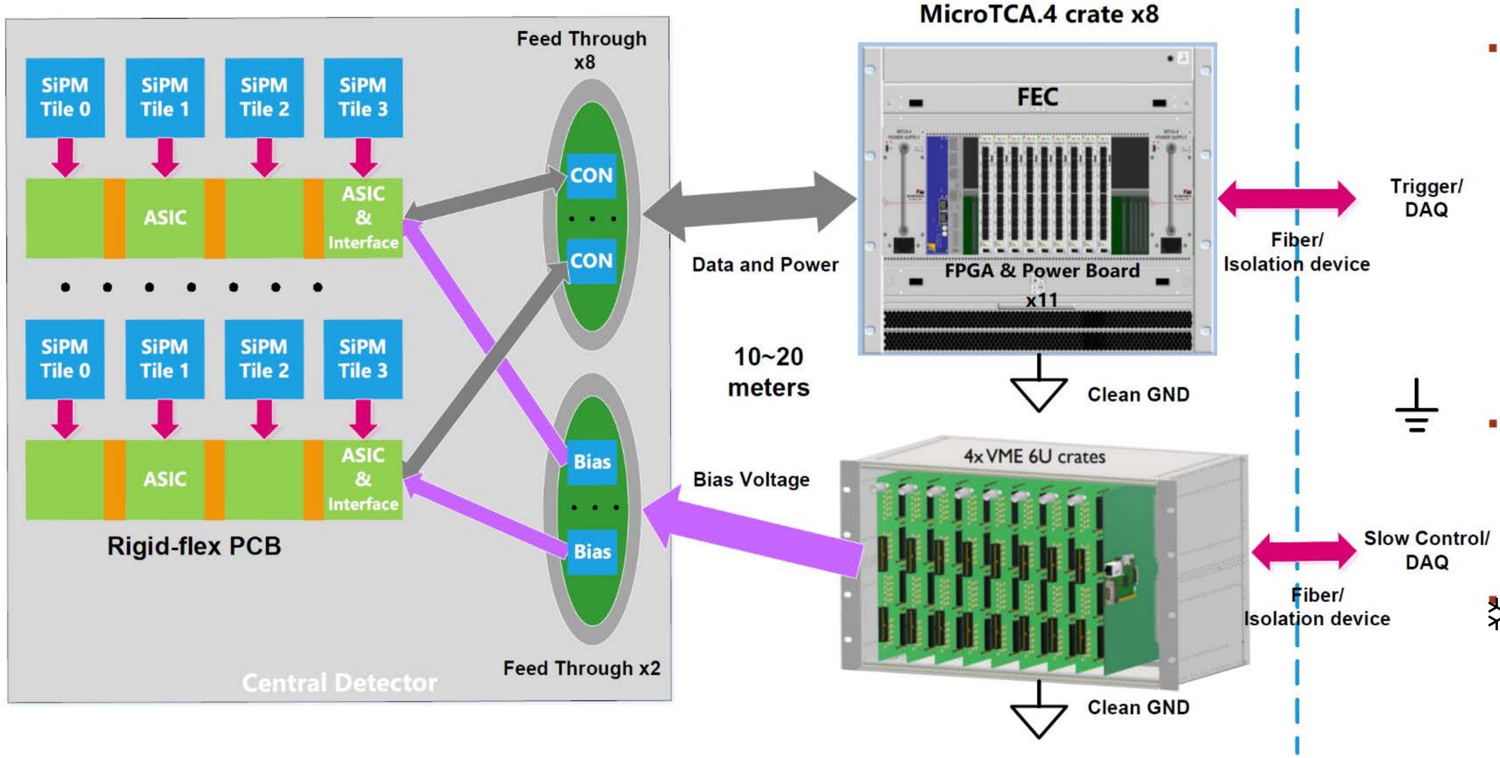
- VME mechanics
- Micro PC: phyCORE-i.MX7
- CAN-int, CAN-ext
- 2x connection interfaces: 1GBPS (SFP) and100MBPs (RJ45)
- COM port (RS232) and USB (B type) for direct access to the micro PC
- Reset button on the front panel
- 2x status LEDs (Power/Err)

Control Unit

- ❄ **Based on KLauS chip – ASIC scheme**
  - ➢ **The KLauS chip is developed by Heidelberg University, the latest version is v6.**
  - ➢ **UMC 180 nm CMOS technology**

- ❄ **Based on discrete components – discrete scheme**

ASIC scheme



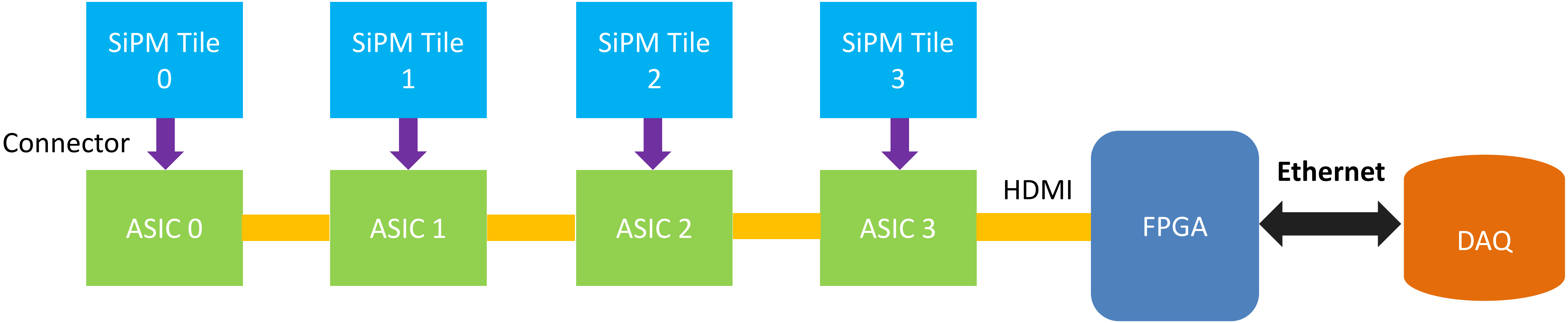
FEB

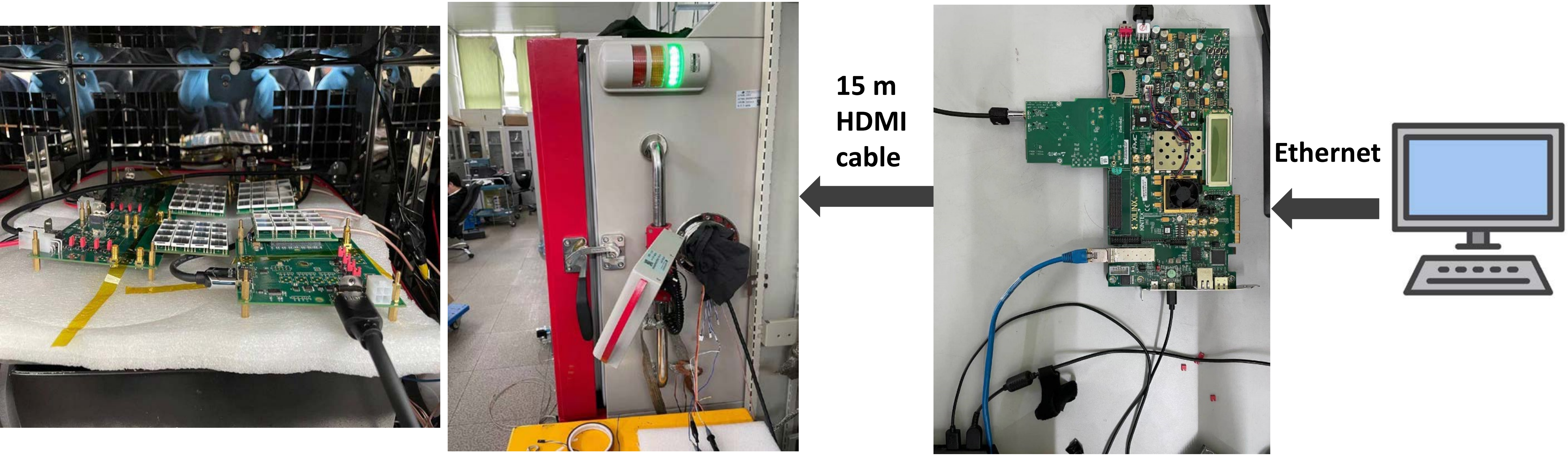
- 1 chip readout 2 tiles, 16 ch/tile
- Total 64,384 channels, 2012 chips
- Rigid-flex PCB, 4 tiles in 1 group
- Tile and FEB are connected with connectors
- Digital signals from FEB will be transferred to FEC via HDMI cables, 3-4 m inside the SS tank, ~10 m outside the tank

FEC

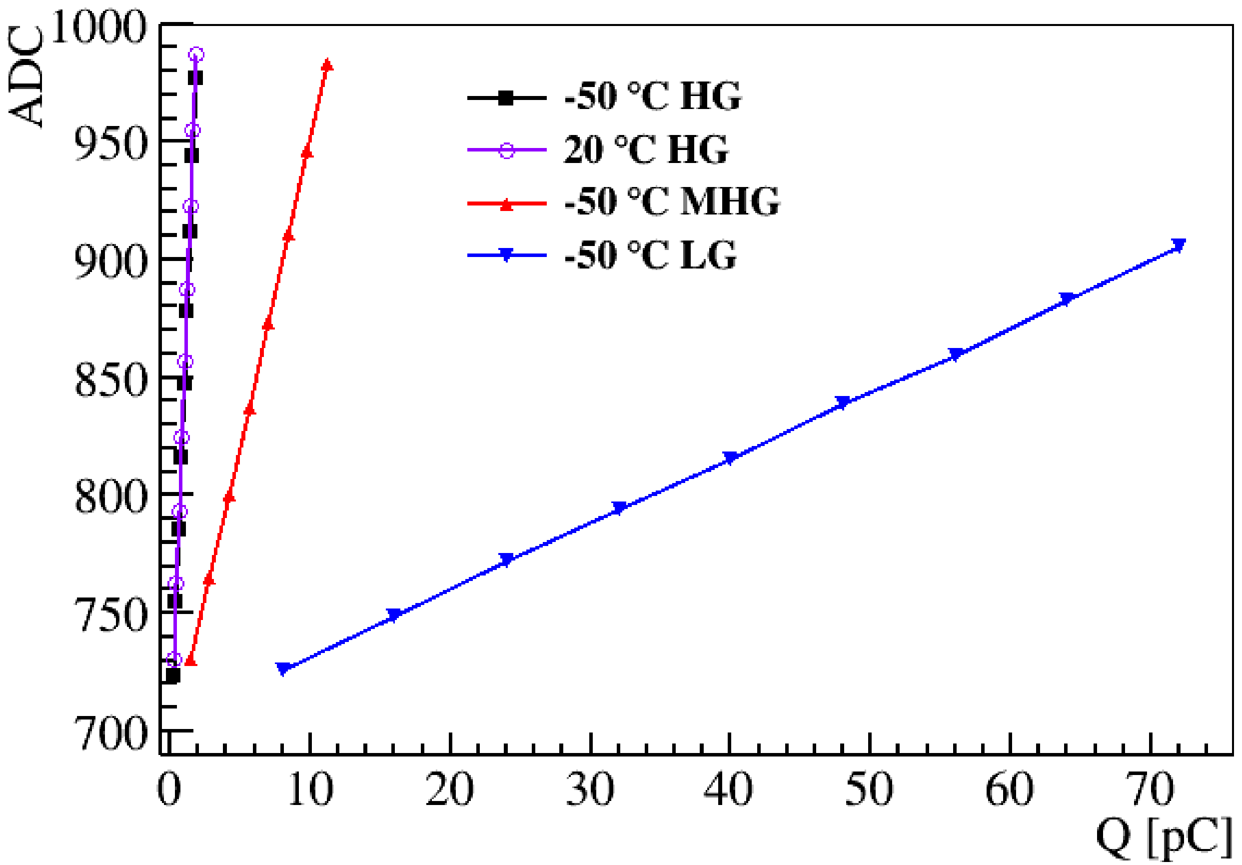
- FPGA & Power boards in MicroTCA.4 crate
- Slow control, timestamp, sending data to TDAQ

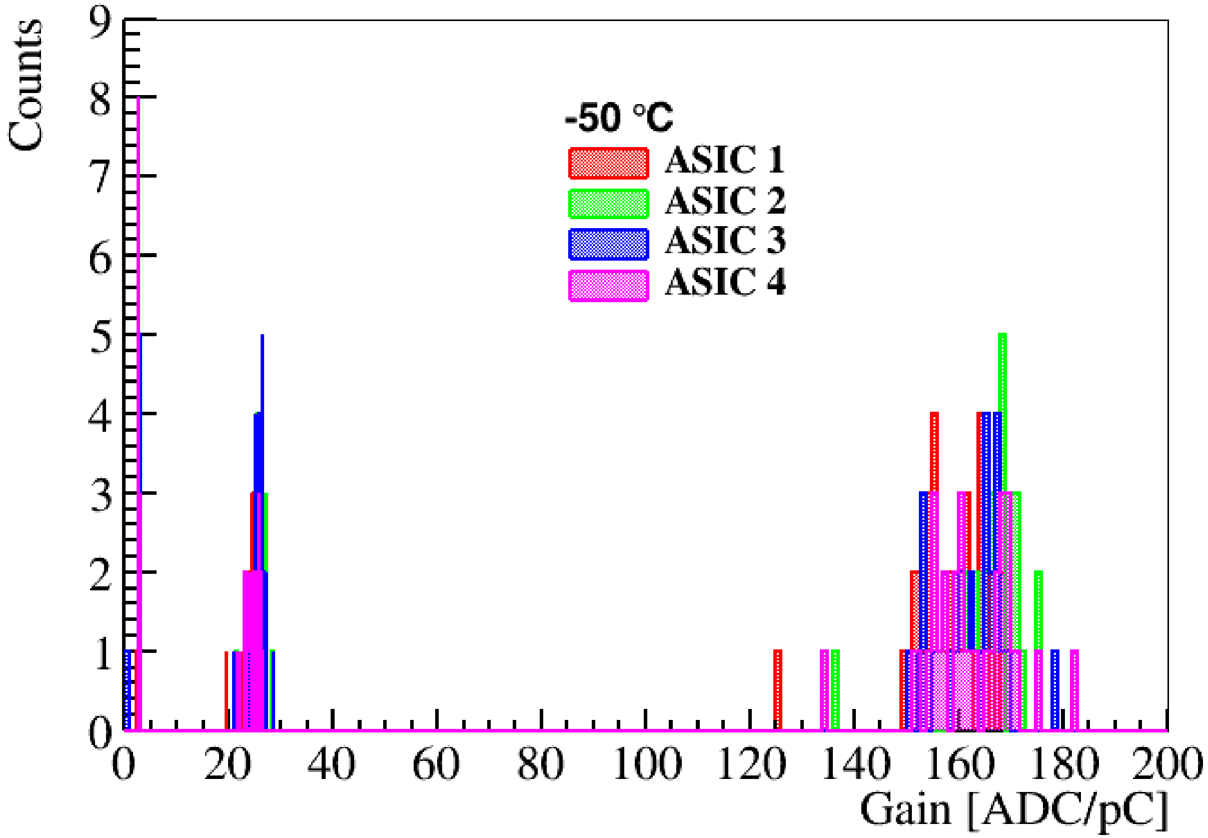
A mockup block with 1/1000 TAO readout channels



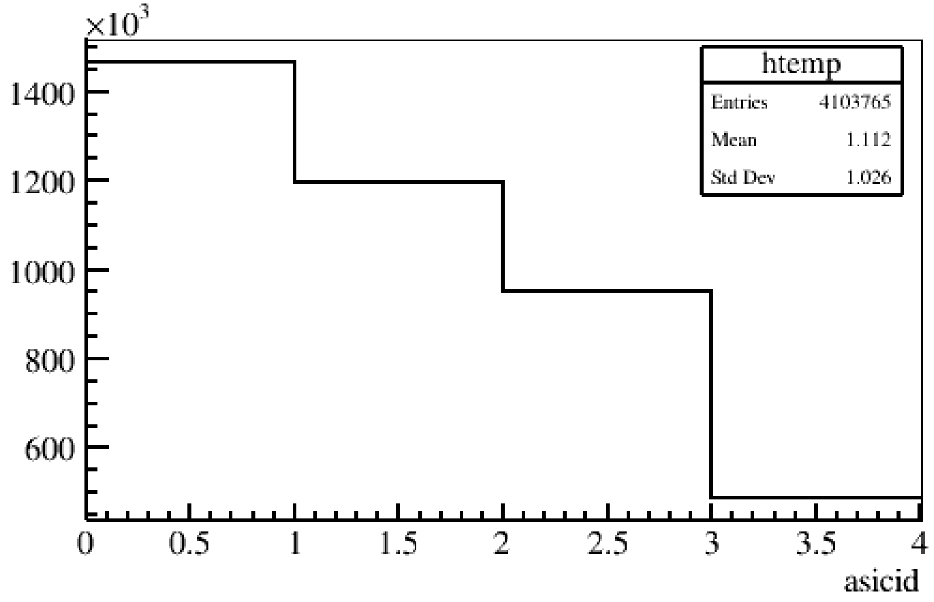


Gains in 3 branches (HG 1:1, MHG 1:7 and LG 1:40) have been characterized for 4 chips at low temperatures, which shows good linearity.

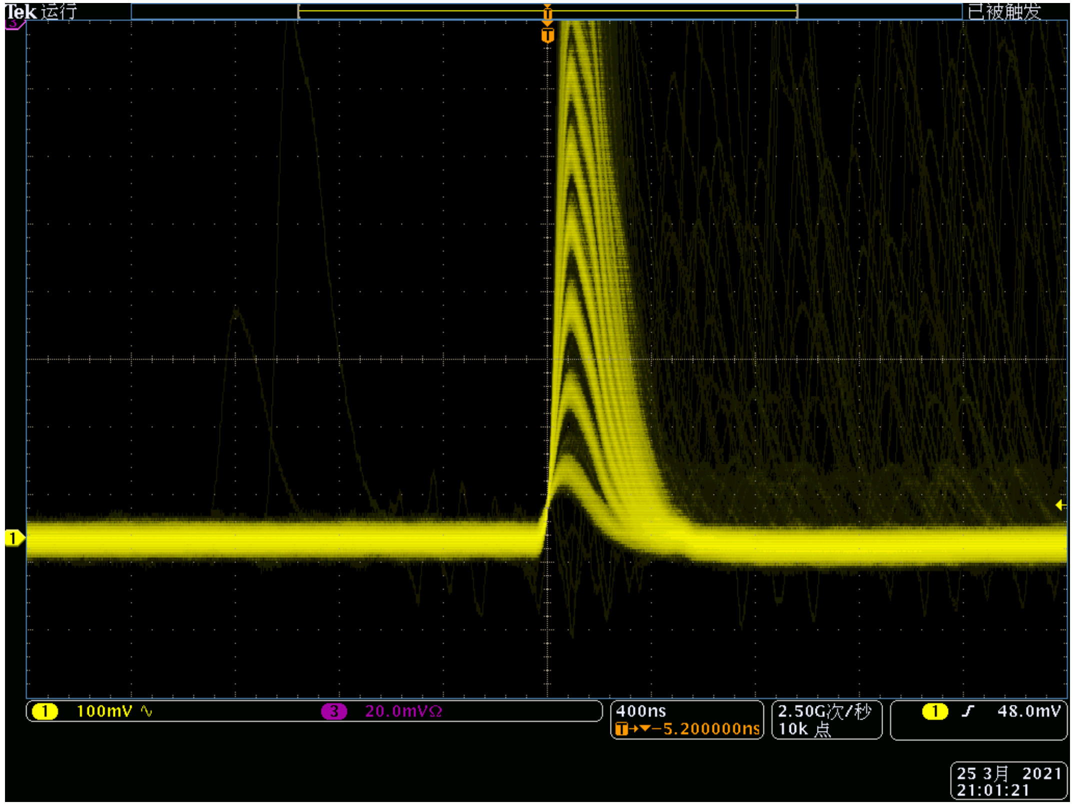




Bias voltage 53 V, break voltage 50.8V.

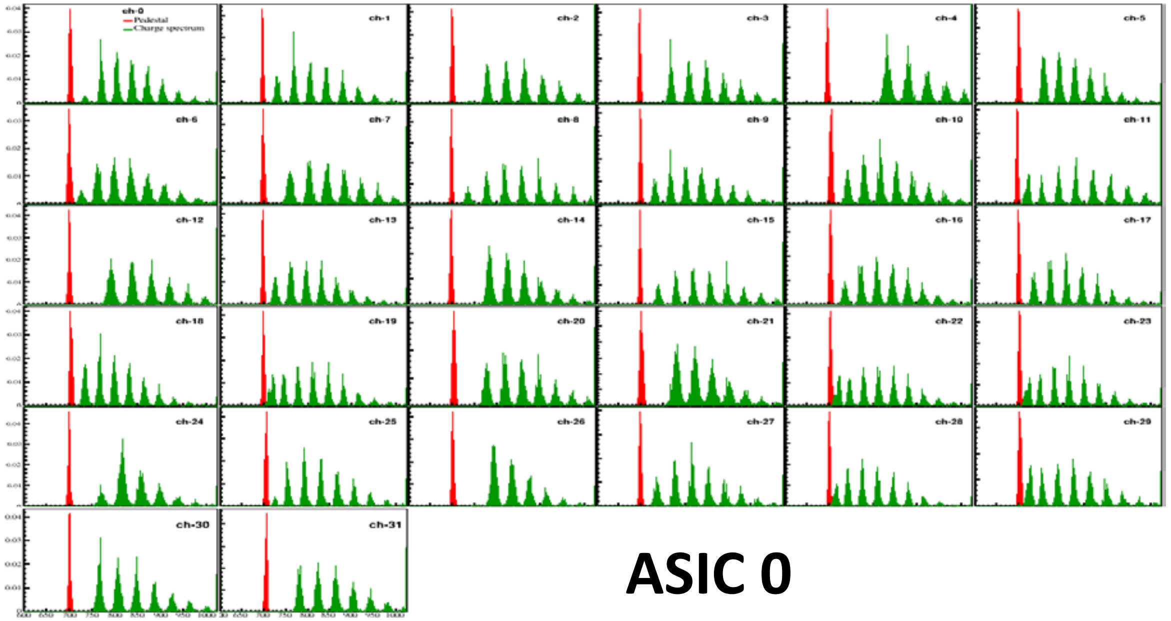


Distribution of chip ID

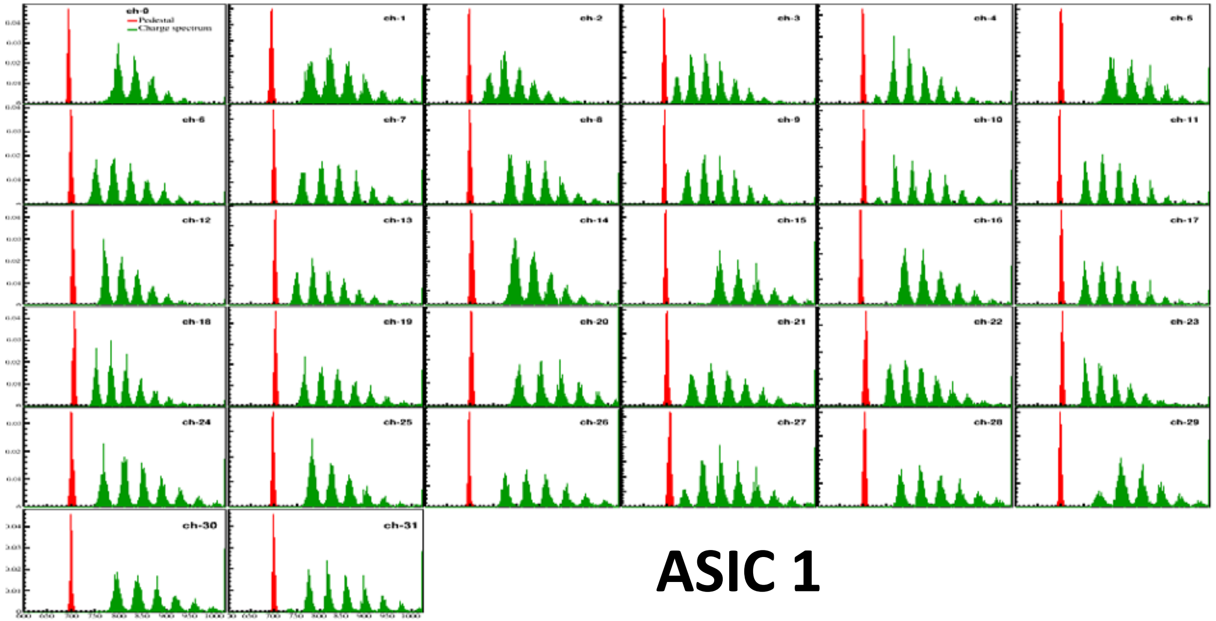


The analog signals after the shaper are monitored by an oscilloscope.

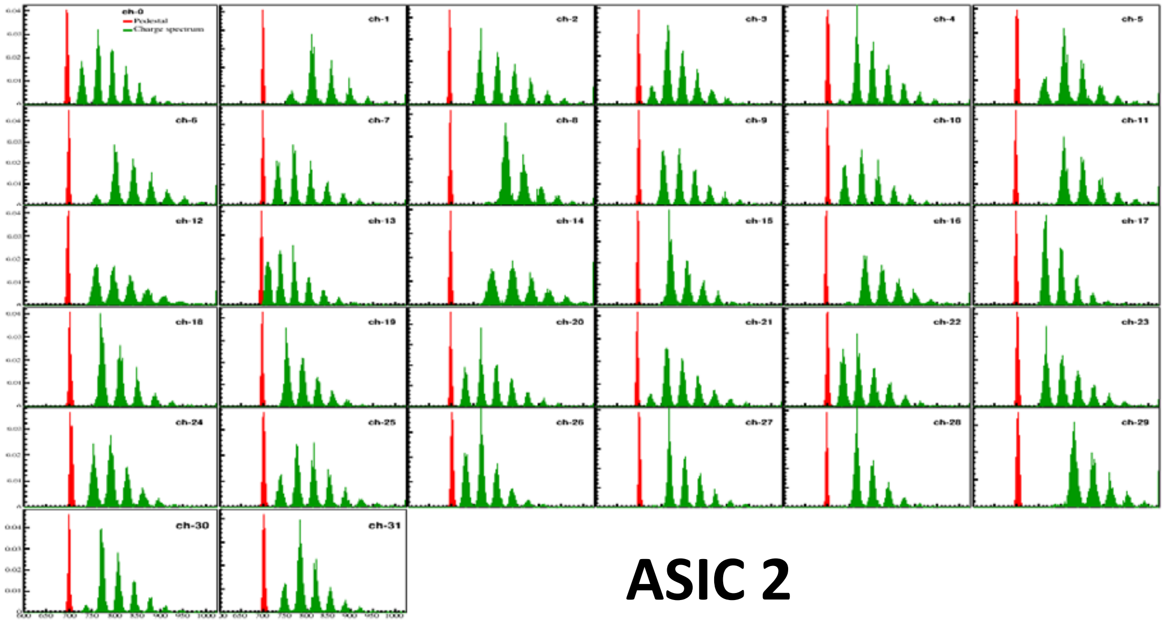
Charge spectra from 4 chips @ OV = ~2 V



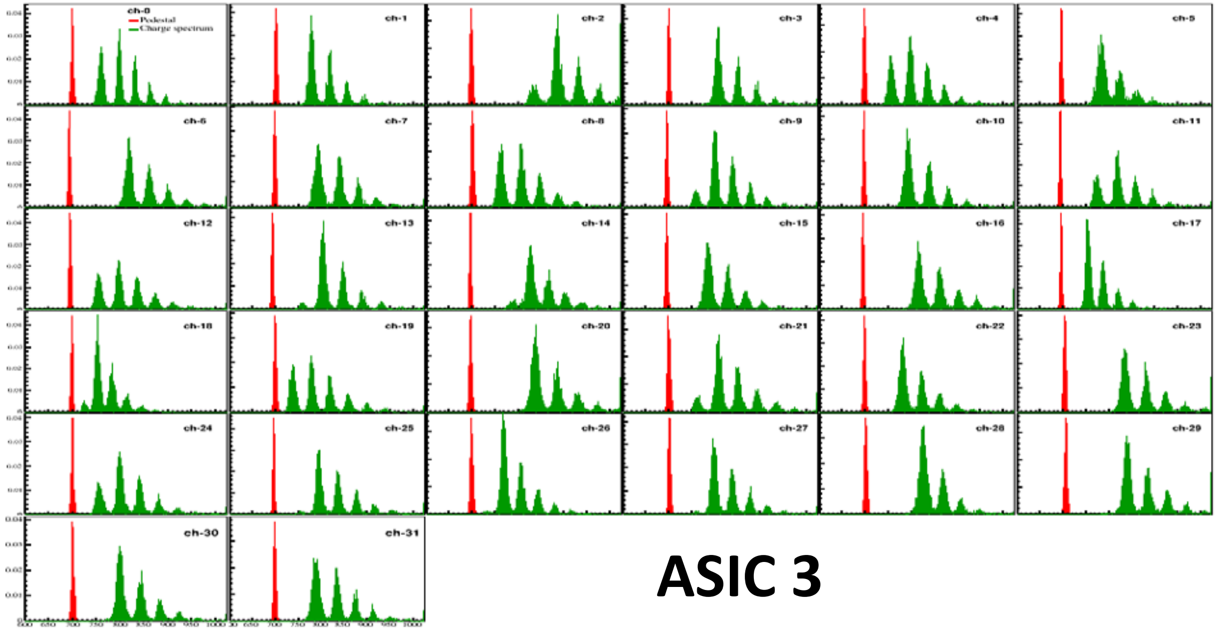
ASIC 0



ASIC 1



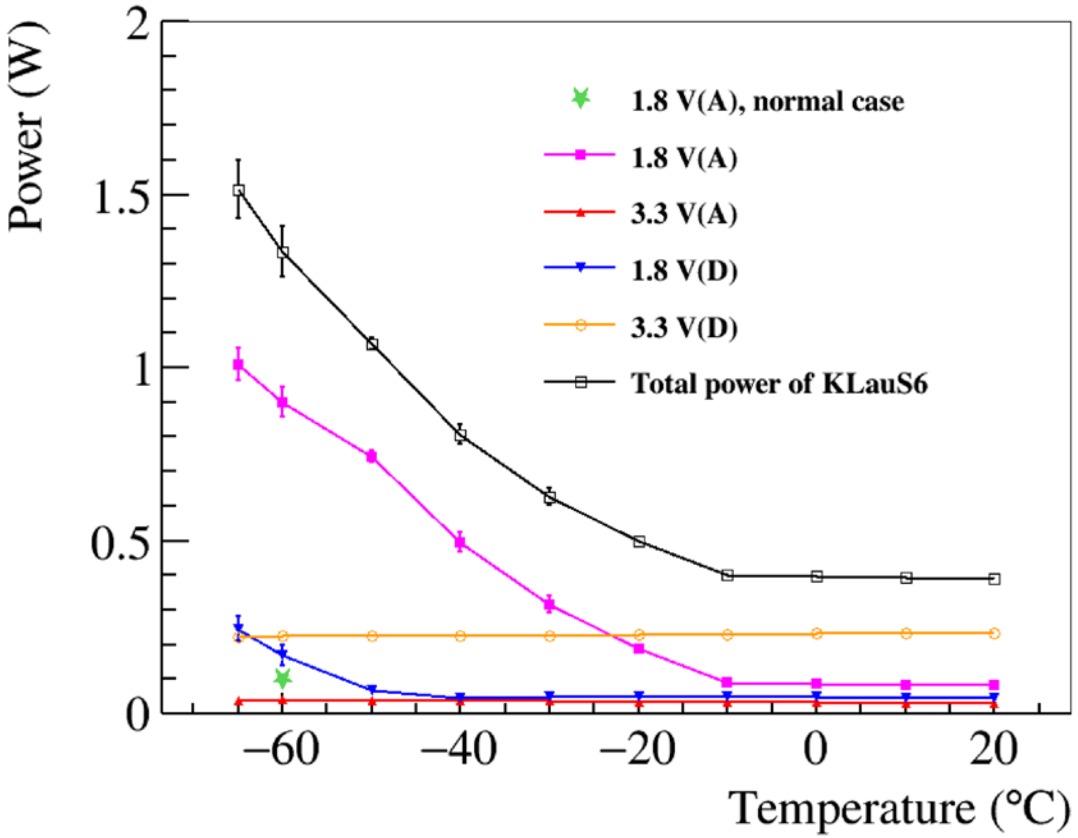
ASIC 2



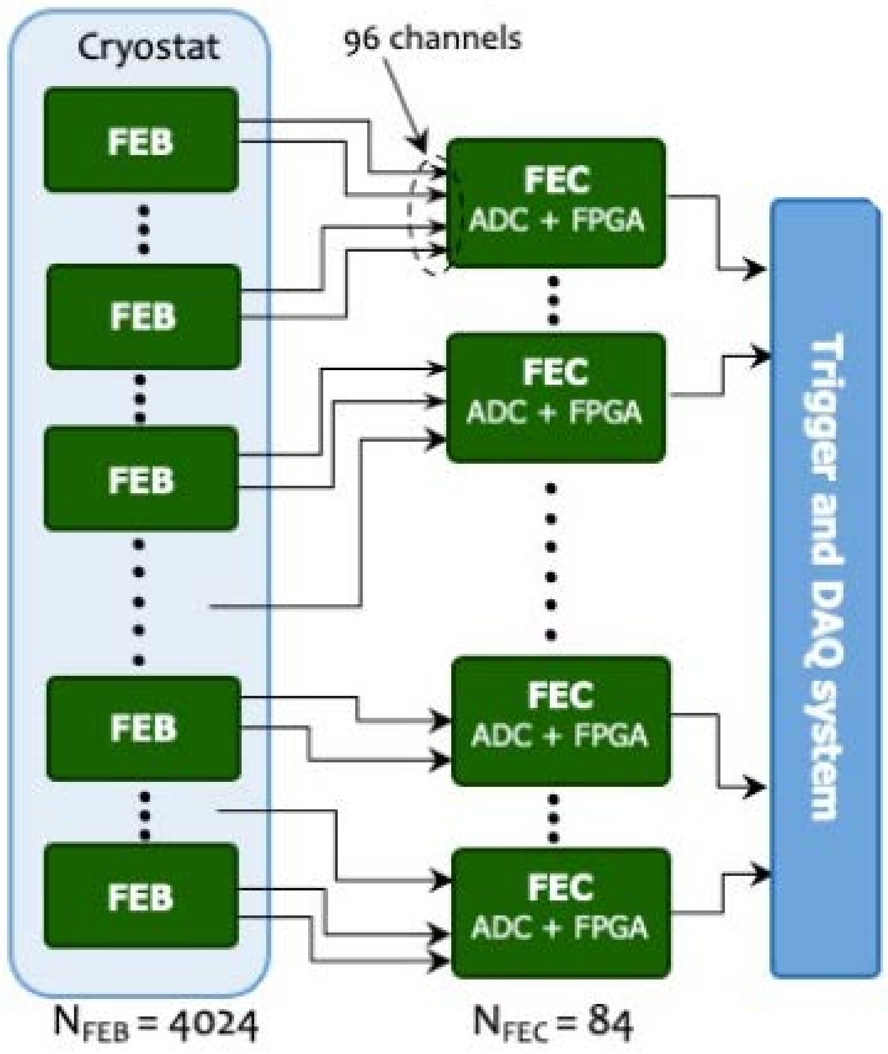
ASIC 3

❄ **Cooperating with KLauS developers, lots of efforts have been made to investigate the power issue**

➢ **No impacts on chip performance at low temperature**

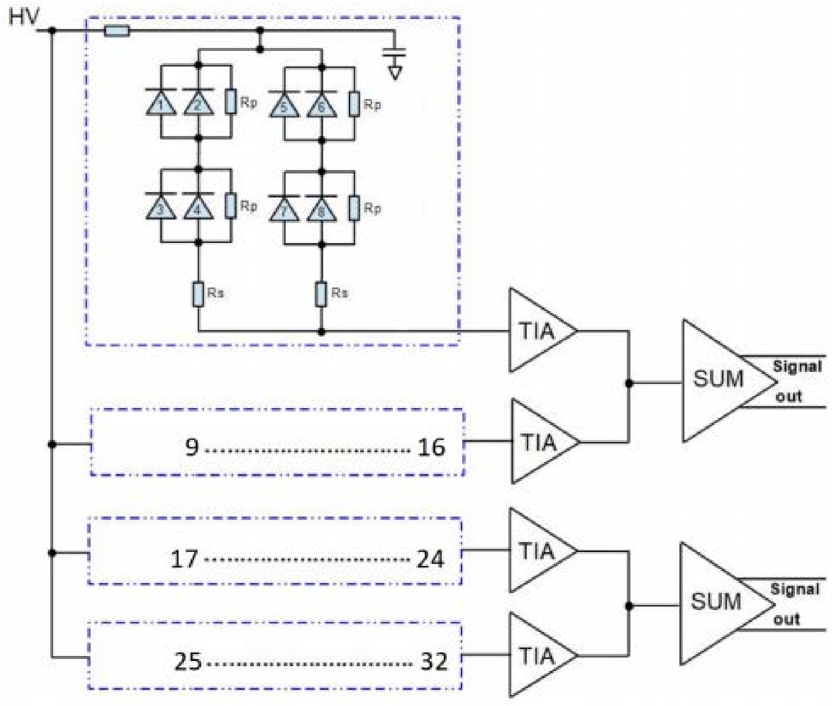


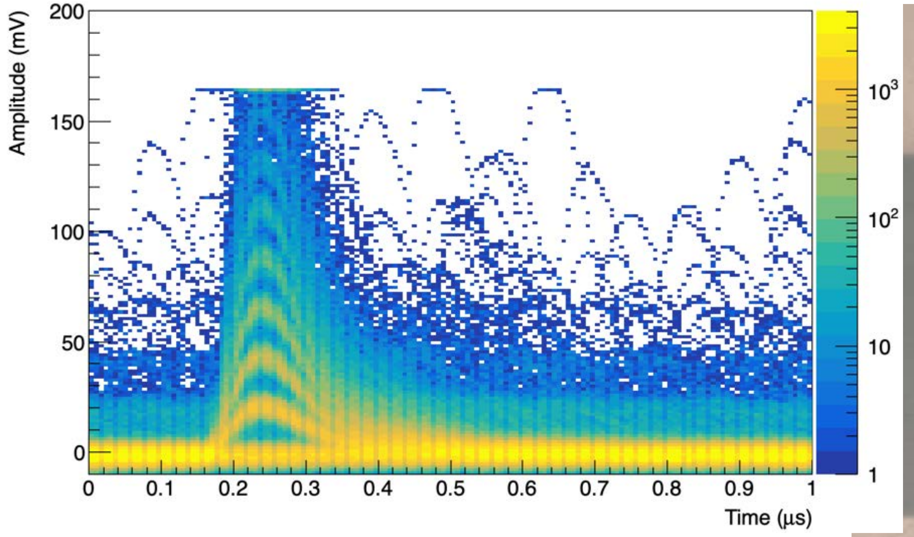
Discrete readout

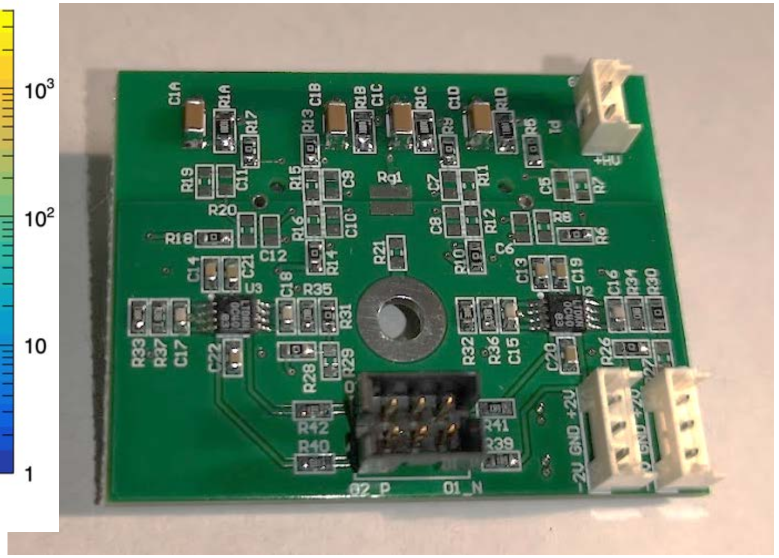


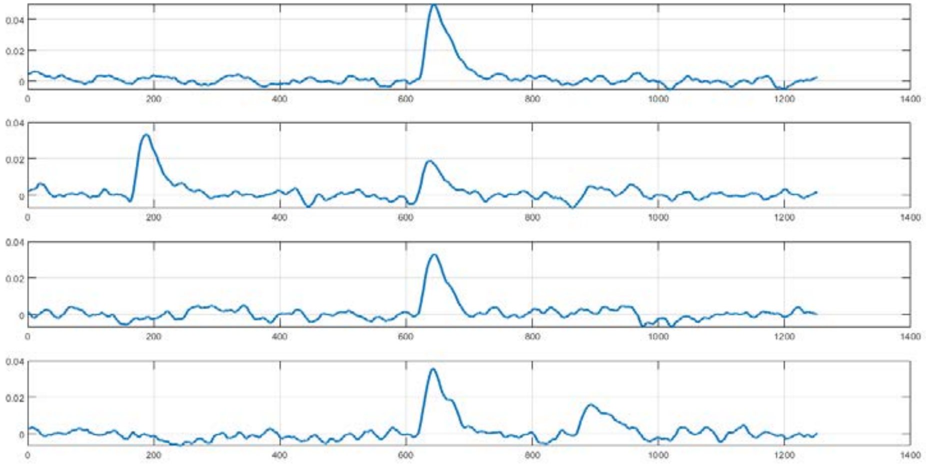
- **FEB**
  - **2 channel 1 tiles**
  - **Total 8048 channels**
  - **Tile and FEB are soldered**
  - **Analog signals from FEB will be transferred to FEC via differential pairs, 3-4 m inside the SS tank, ~10 m outside the tank**
- **FEC**
  - **ADC is on FEC, used to digitize analog signals from FEB**
  - **FPGA & Power boards in MicroTCA.4 crate**
  - **Q/T information is extracted with FPGA (waveform analysis)**

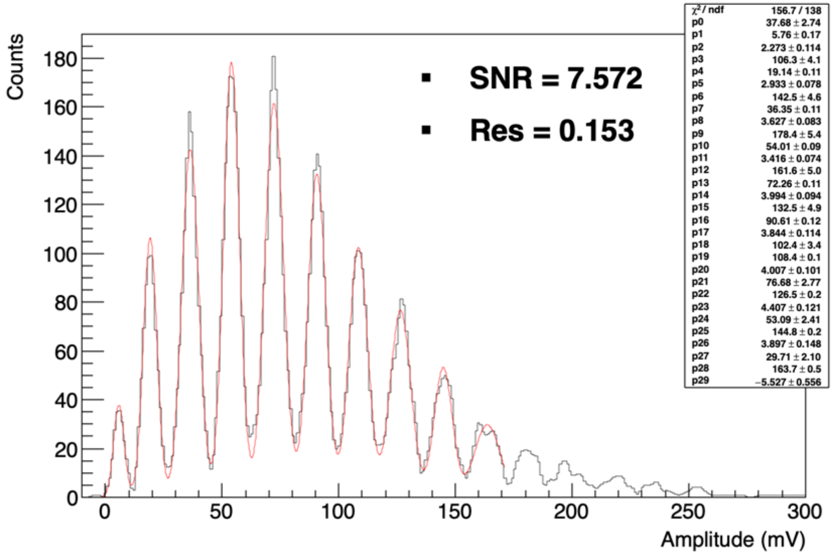
FEB

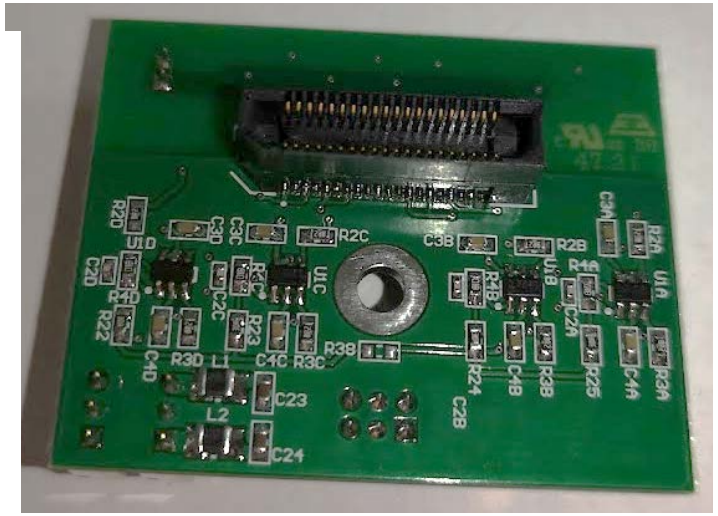

HV
Rp
Rs
TIA
SUM
Signal out
9 16
17 24
25 32


Amplitude (mV)
Time (µs)






Counts
Amplitude (mV)
▪ SNR = 7.572
▪ Res = 0.153
χ² / ndf 156.7 / 138
p0 37.68 ± 2.74
p1 5.76 ± 0.17
p2 2.273 ± 0.114
p3 106.3 ± 4.1
p4 19.14 ± 0.11
p5 2.933 ± 0.078
p6 142.5 ± 4.6
p7 36.35 ± 0.11
p8 3.627 ± 0.083
p9 178.4 ± 5.4
p10 54.01 ± 0.09
p11 3.416 ± 0.074
p12 161.6 ± 5.0
p13 72.26 ± 0.11
p14 3.994 ± 0.094
p15 132.5 ± 4.9
p16 90.61 ± 0.12
p17 3.844 ± 0.114
p18 102.4 ± 3.4
p19 108.4 ± 0.1
p20 4.007 ± 0.101
p21 76.68 ± 2.77
p22 126.5 ± 0.2
p23 4.407 ± 0.121
p24 53.09 ± 2.41
p25 144.8 ± 0.2
p26 3.897 ± 0.148
p27 29.71 ± 2.10
p28 163.7 ± 0.5
p29 −5.527 ± 0.556



- ❑ Perform waveform reconstruction and send T/Q to TDAQ

- ❑ 6 uTCA.4 crates
  - ➢ Each crate will be mounted with 11 FEC boards
    - ✓ 9 FEC with 4 ADC boards
    - ✓ 2 FEC with 3 ADC boards and 1 WR board
  - ➢ Up to 8064 ADC channels

- ❑ Interface to TDAQ
  - ➢ 66 10Gbps fibers

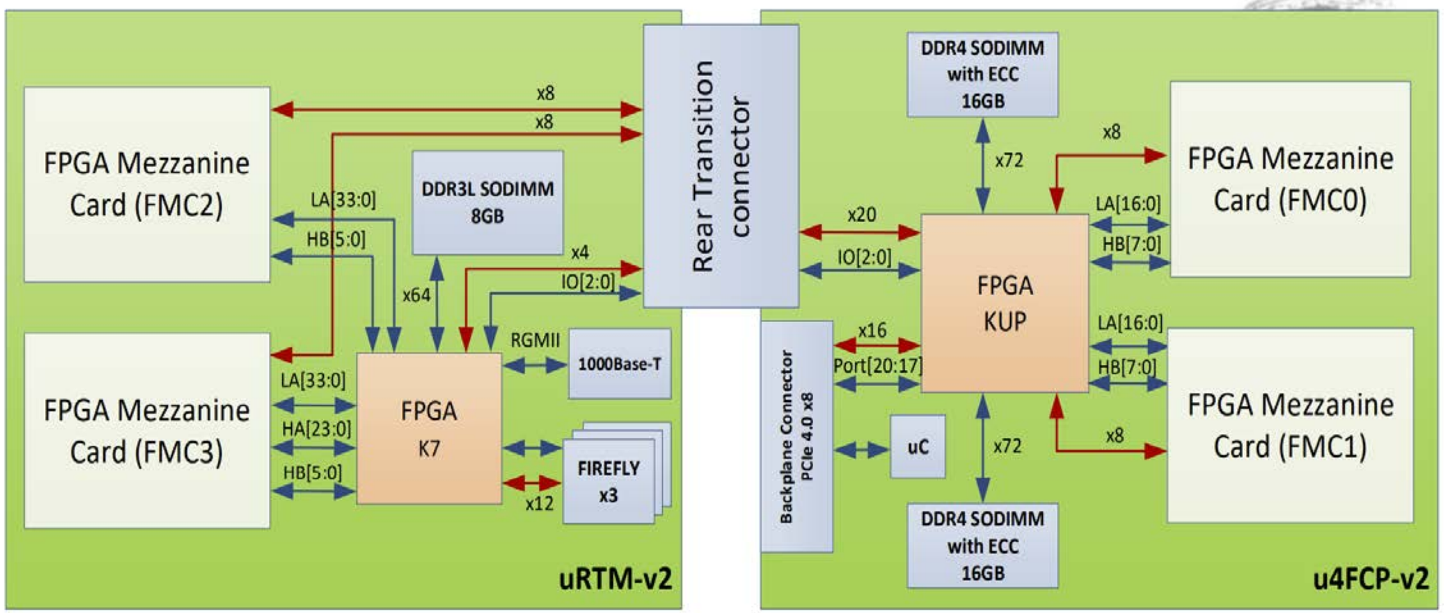
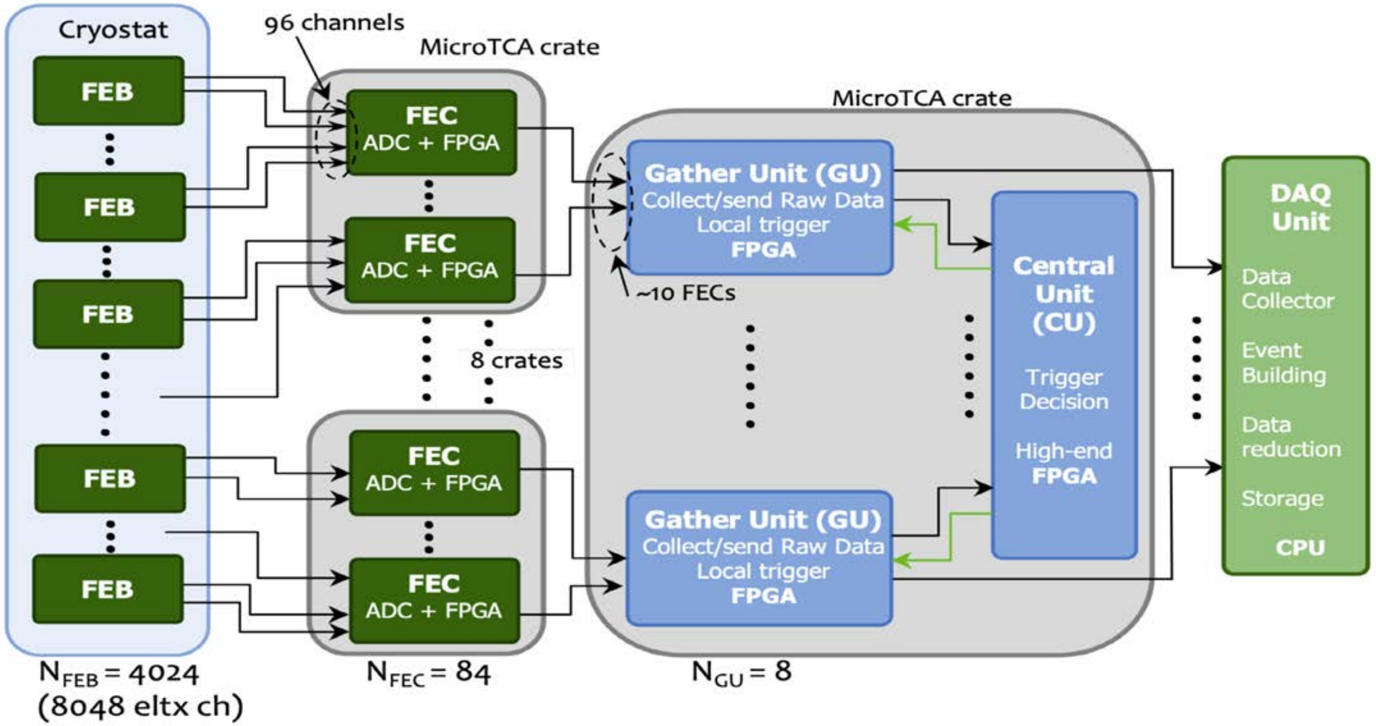


Photo of previous version (V1)

Signal	Event rate (Trigger input)	Event rate (output)	Data rate trigger input (Mbps)	Data rate trigger output (Mbps)
Reactor IBD	4000/day	4000/day	-	-
Radioactivity background	150 Hz	150 Hz	77	77
Muons [0.7, 20] MeV	36 Hz	36 Hz	19	19
Muons >20 MeV	296 Hz	296 Hz	152-304[c]	152-304[c]
Cosmogenic background [0.7,20] MeV	20 Hz	20 Hz	10	10
Cosmogenic background >20 MeV	20 Hz	20 Hz	10-20[c]	10-20[c]
SiPM dark counts	1 GHz[b]	~0	$64\cdot10^3$	-
TOTAL			**$64\cdot10^3$**	**240-400 [a]**



- **High input data rates in the trigger system is a challenge**
- **Output data rate has to be < 100 Mbps:**
- **We need to implement a logic to reduce data size for large energy events at FEC level;**
- **A local FEC logic can be implemented to reduce DCR hits rate to the TDA**

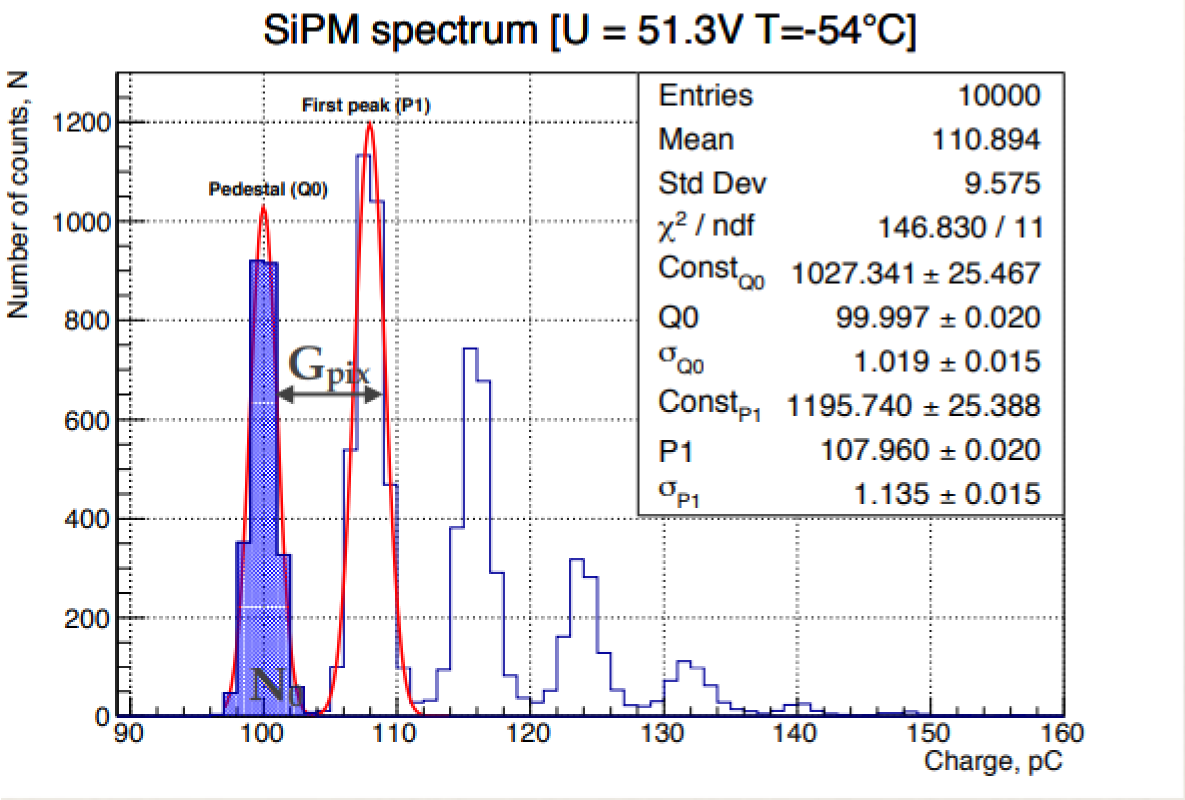
Summary

- **10 m^2 SiPMs will be deployed in the TAO experiment, proposed to precisely measure reactor neutrino energy spectrum.**

- **SiPMs bidding is done with a good price.**

- **QA/QC and readout electronics are in good shape.**

- **TAO will start data taking in 2023.**



pe number per pulse is a distribution of poisson :

$$f(k) = \frac{\mu^k}{k!} e^{-\mu}$$

By intergrating the entry of the peak(k=0):

$$f(0) = e^{-\mu} = \frac{N_{peak}}{N_{total}}$$