Experience of SiPMs at TAO

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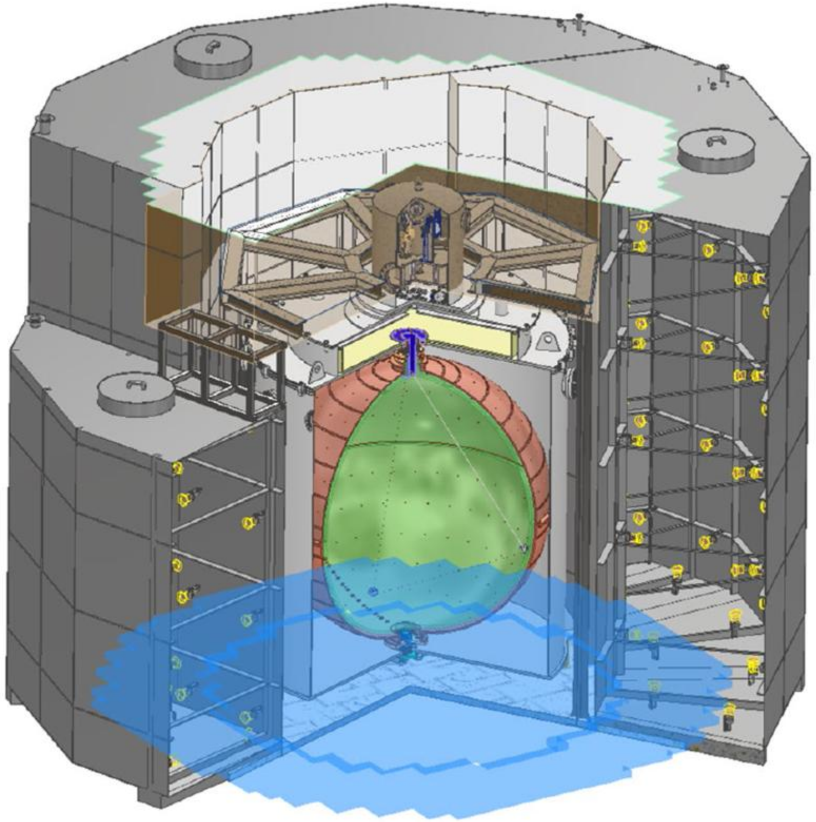
- **Taishan Antineutrino Observatory (TAO), a satellite experiment of JUNO.**
  - **Taishan Nuclear Power Plant, ~44 m from one of the 4.6 GW_{th} reactor cores**
  - **Total cost, 4-5 M$**
- **Measure reactor neutrino spectrum w/ sub-percent E resolution (< 2% @ 1MeV)**
- **Ton scale Gd-doped Liquid 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**



❄ **Laboratory in a basement at -10 m, 44 m from Taishan core (4.6 GW_{th})**

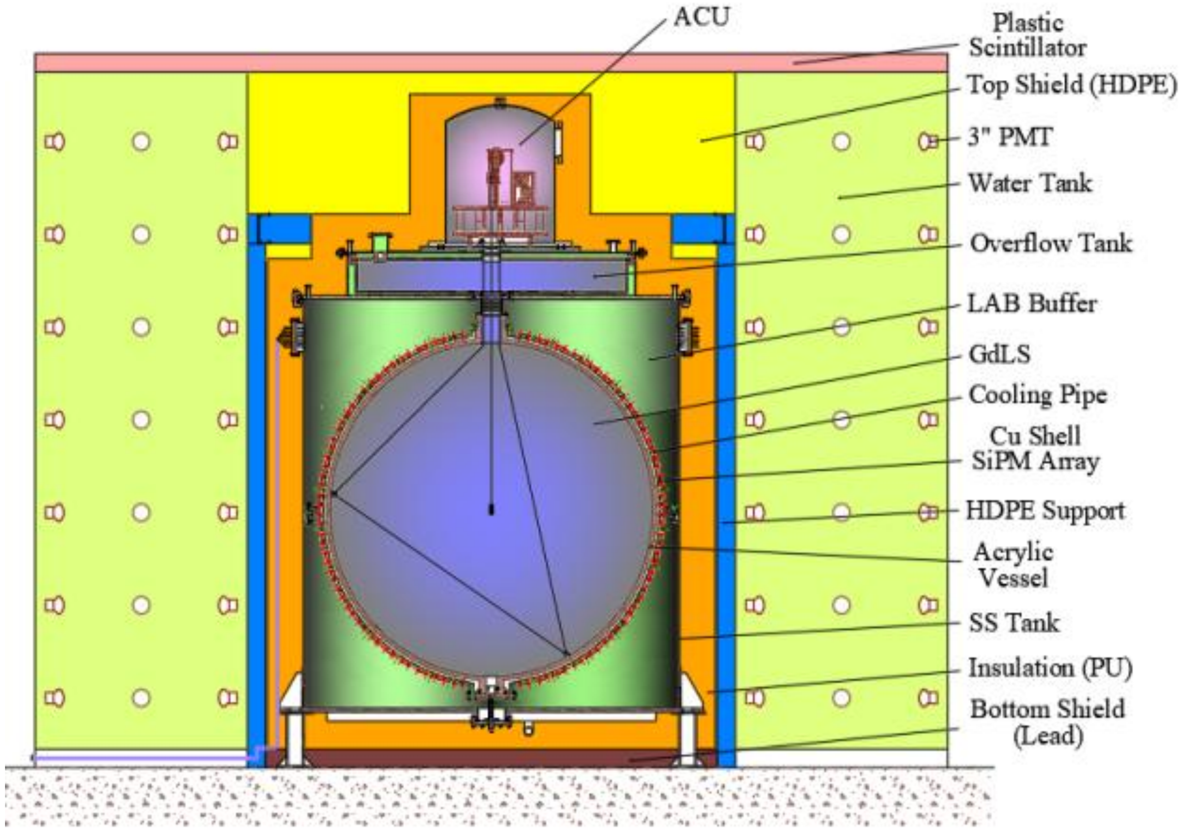
❄ **2.6 ton Gd-LS in a spherical vessel**

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

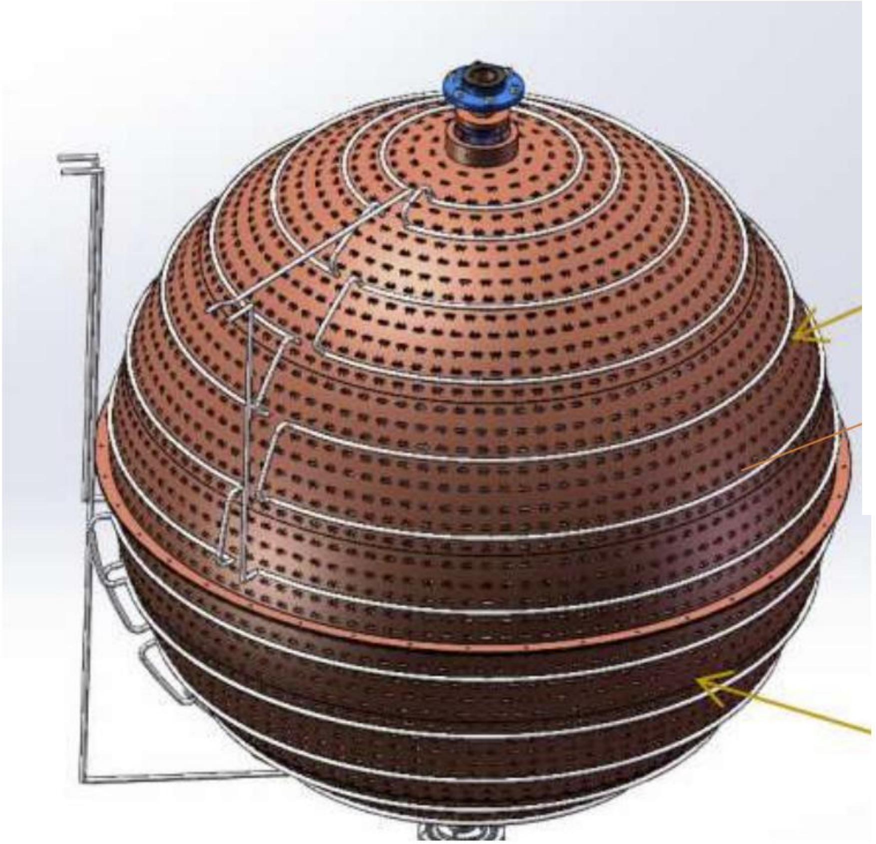
TAO CDR ready in 2020
arXiv:2005.08745

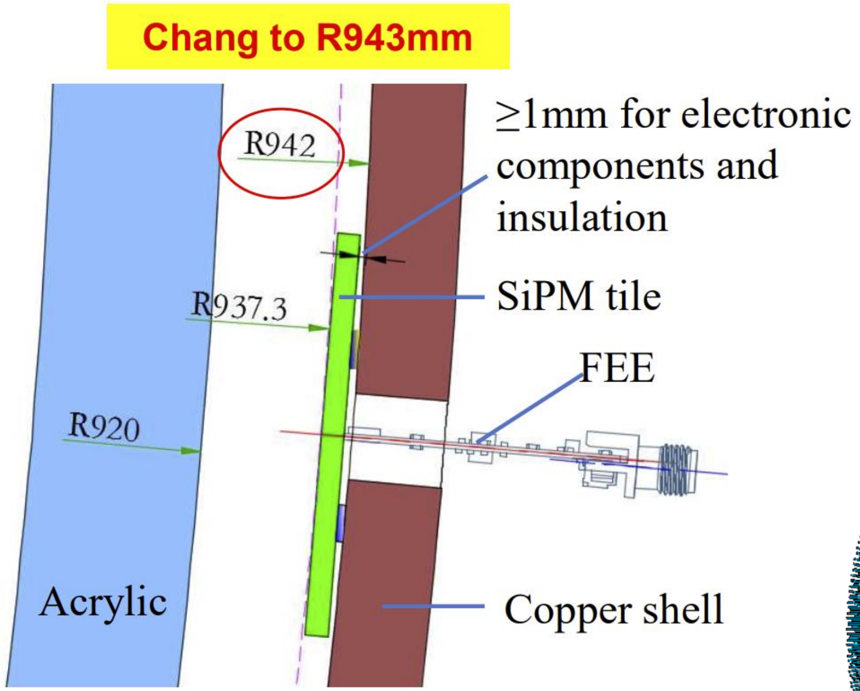
❄ **From Inner to Outside**

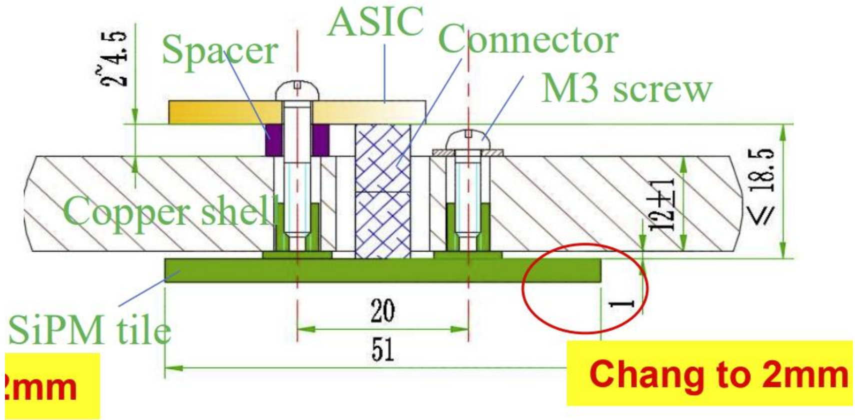
- **Gd-LS**
- **Acrylic vessel**
- **SiPM and support (Cu shell)**
- **LAB buffer**
- **Cryogenic vessel (SS + insulation)**
- **Veto detector**
  - **Water Cerenkov detector**
  - **PS + SiPM on the top**



Photodetector







4024 tiles

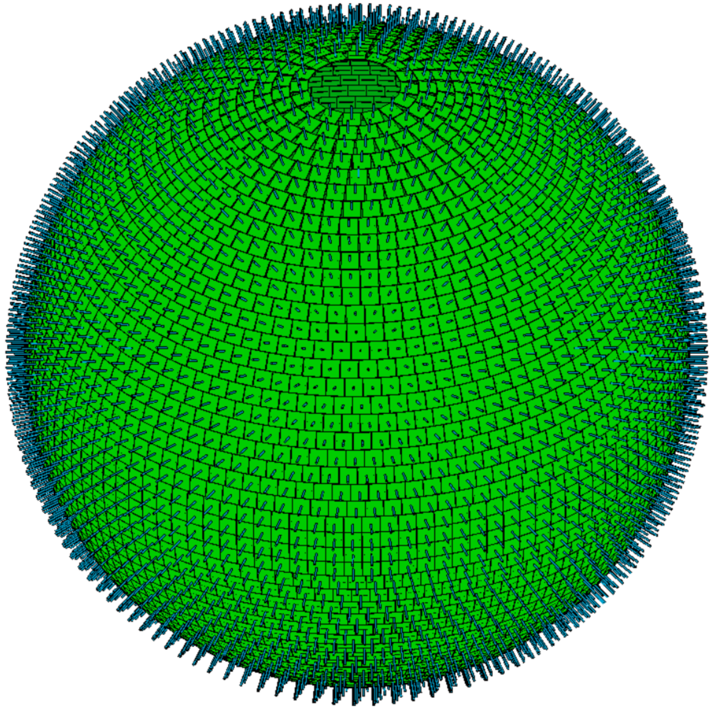
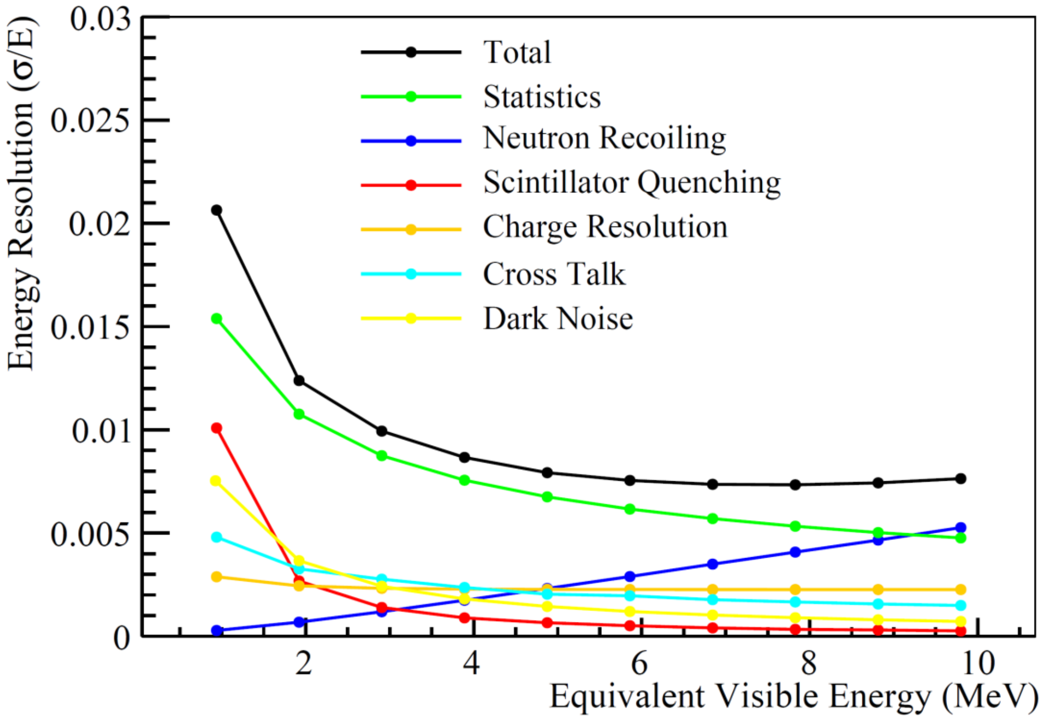


Table 6-1: Requirements on the SiPM parameters.

Parameters	Specification	Comments
PDE	$\geq 50\%$	at 400 nm, not including correlated noise
Dark count rate	≤ 100 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	$\geq 6 \times 6$ 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

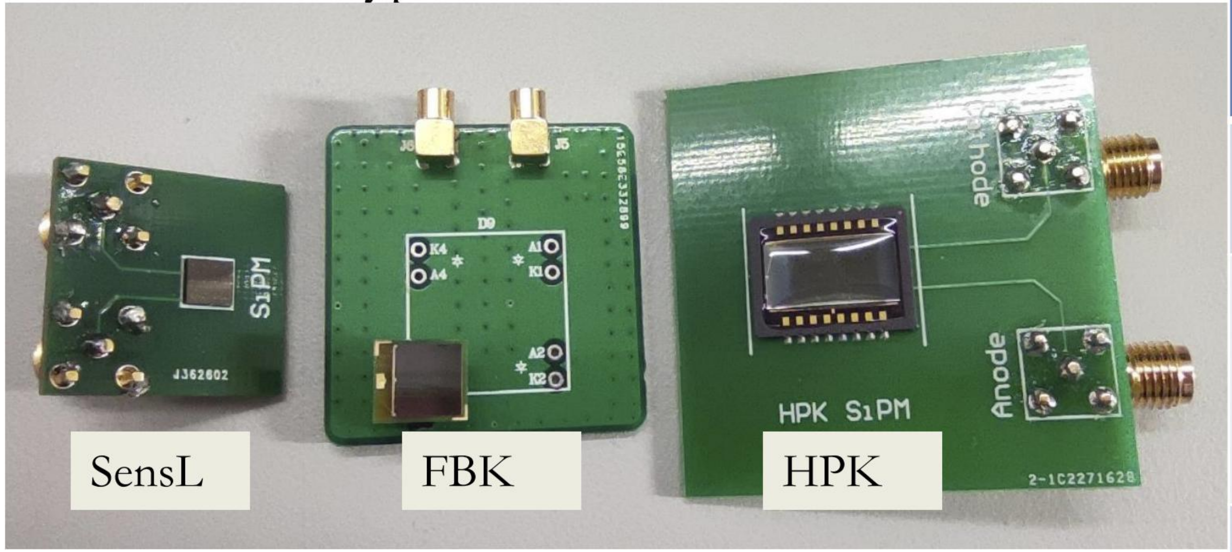
May not be up-to-date !	SensL	Hamamatsu	FBK
Type	**MicroFJ-60035**	**S14160/S14161**	**NUV-HD**
Cell size (μm)	35	50	40
Cell Fill factor (%)	76	74	81
PDE (%)	**51**	**50**	**56**
Peak wavelength (nm)	420 (250-900)	450 (270-900)	410 (280-700)
Dark count rate (kHz/mm^2)	70	166	150
Gain	6.0 x 10^6	2.5 x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

The performance of some SiPMs looks promising.

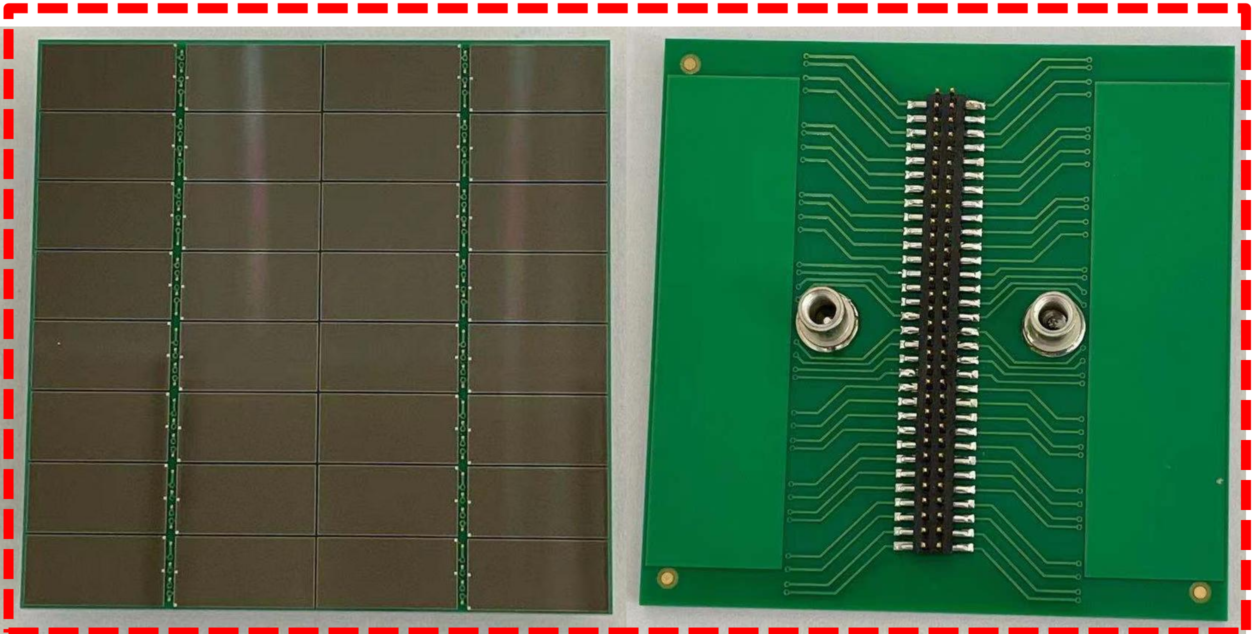
TAO starts R&D work with FBK and HPK in 2020.

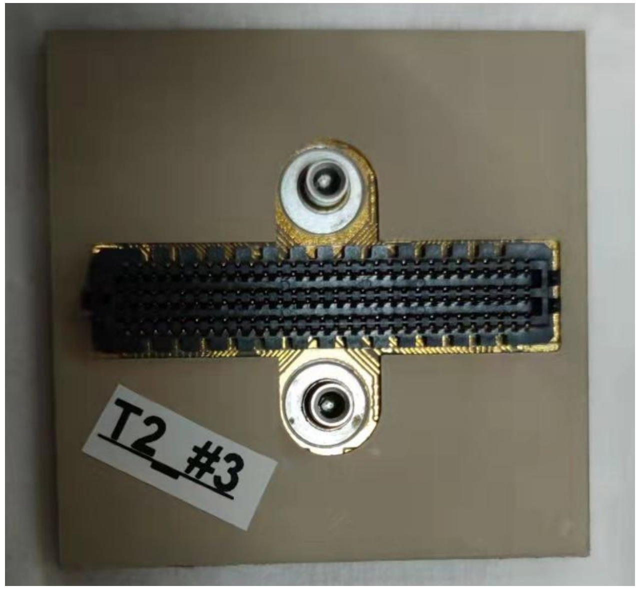
Samples from different vendors

SiPMs: three types from different vendors



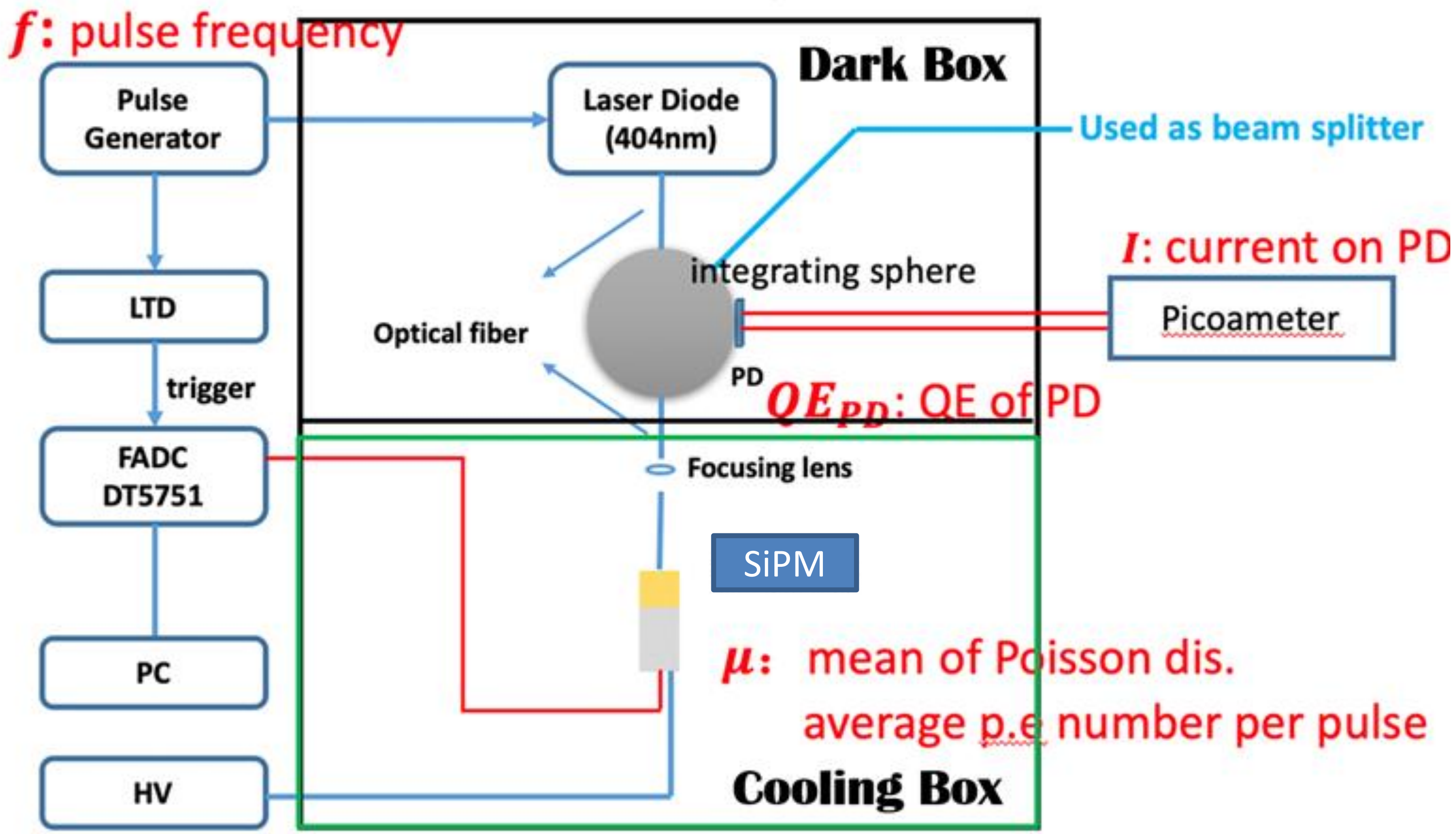
Vendor	Type	Pixel size (μm*μm)	Total size (mm*mm)
SensL	MicroK-40035-E715	35*35	4*4
FBK	NUV-HD LowCT_v2 (Double/Triple trenches)	50*50 (75*75)	6*6
HPK	S16080	75*75	6*12

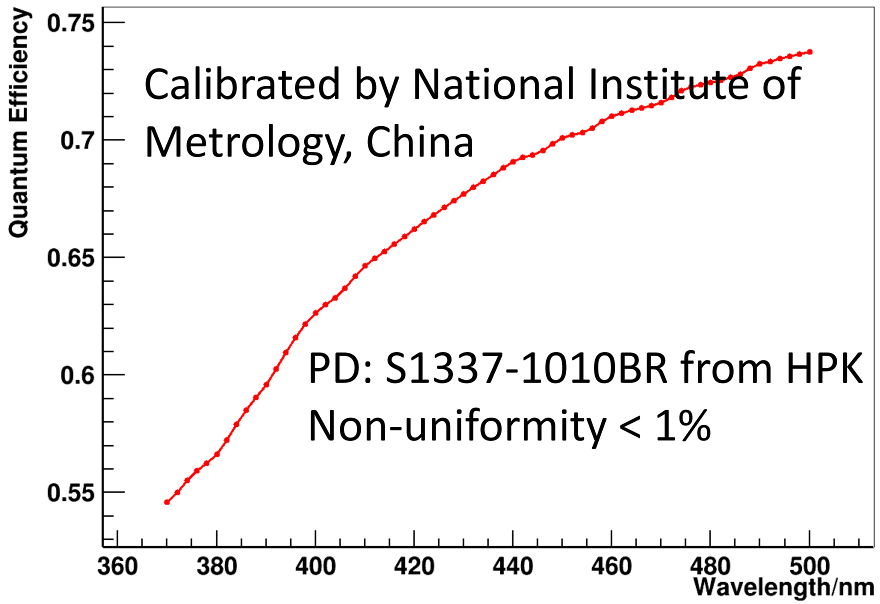


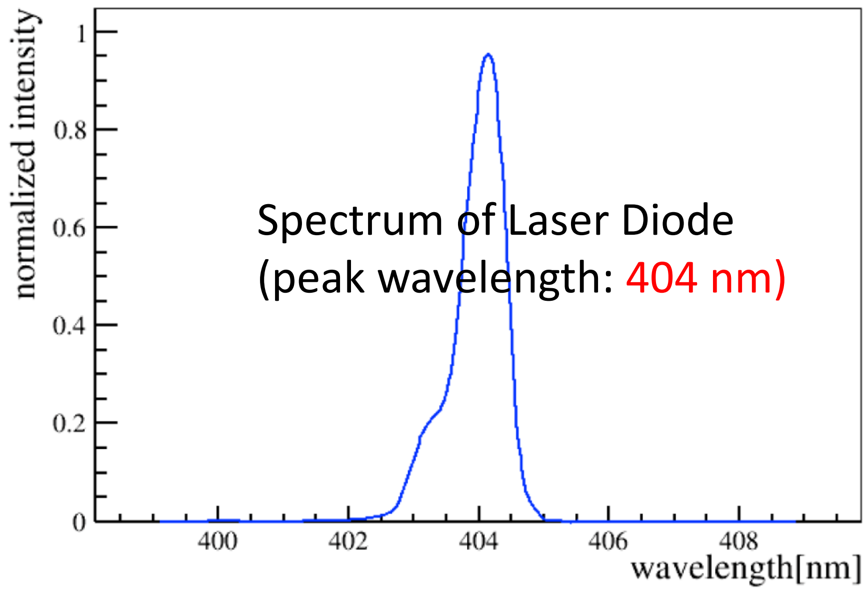


Absolute PDE from room T to -50 ℃ (IHEP)

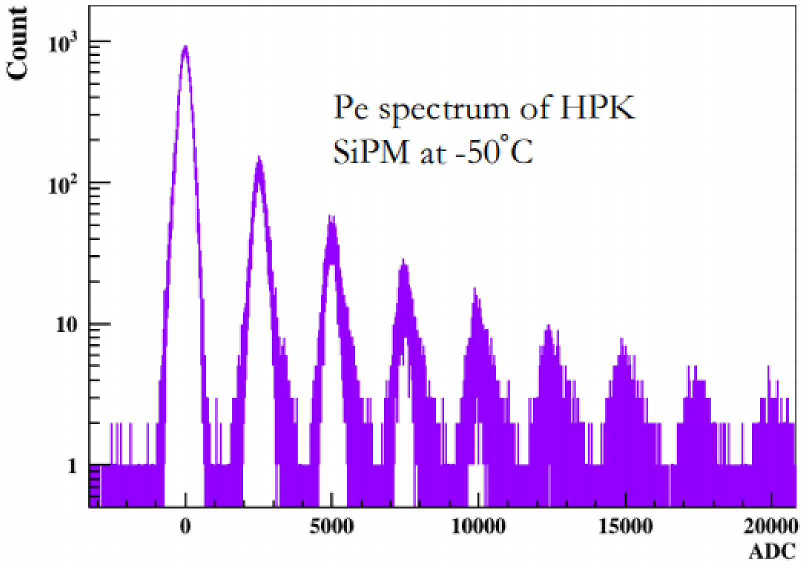
$$PDE = \frac{pe_{signal}}{pe_{incoming\ light}} = \mu * f/(\frac{I}{Q_e * QE_{PD} * R})$$







Absolute PDE

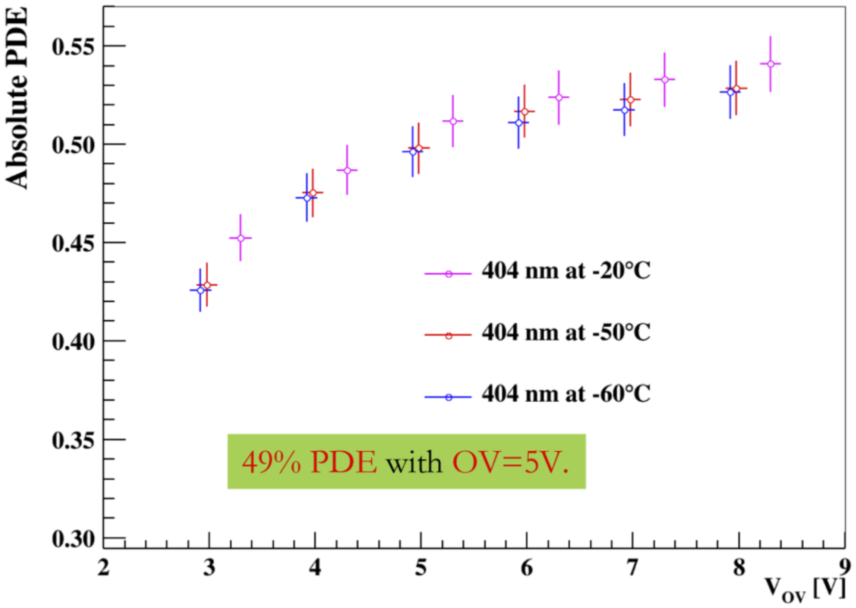


pe number per pulse is a distribution of poisson :

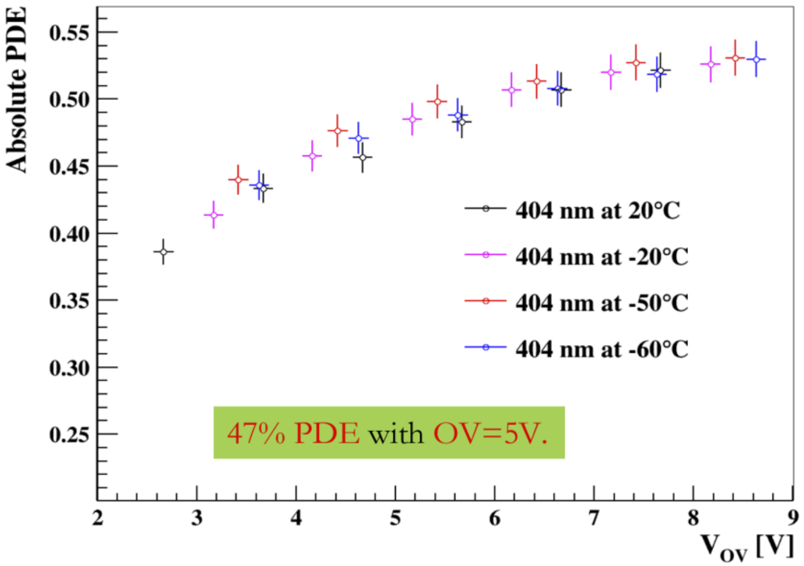
$$f(k) = \frac{\mu^k}{k!} e^{-\mu}$$

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

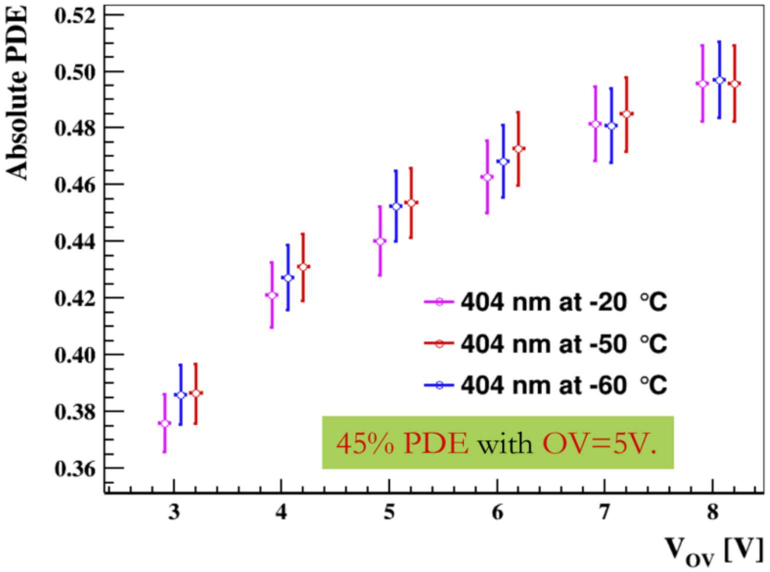
$$f(0) = e^{-\mu} = \frac{N_{peak}}{N_{total}}$$



Absolute PDE of HPK SiPM at 404nm



Absolute PDE of SensL SiPM at 404nm



Absolute PDE of FBK SiPM at 404nm

A setup built at IHEP, to measure

- ✓ Spectral response of SiPMs
- ✓ Angular response of SiPMs
- ✓ Reflectance of samples in liquid

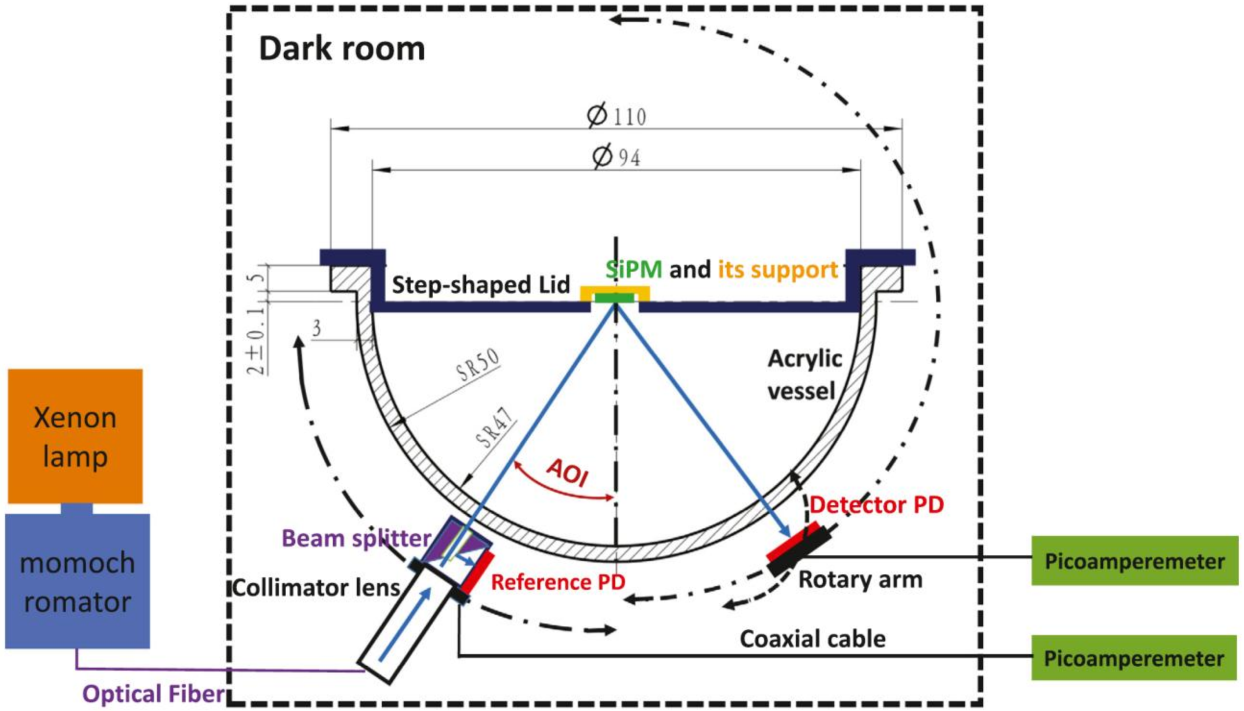
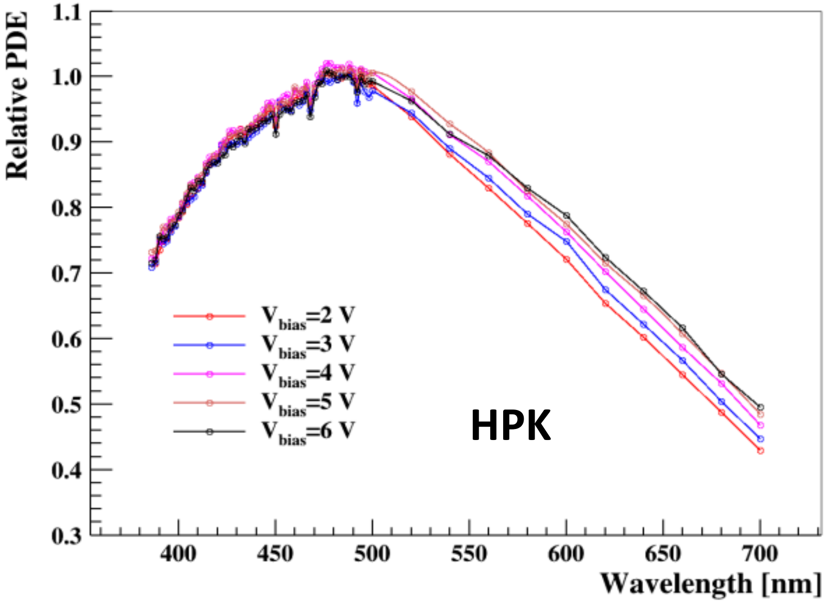
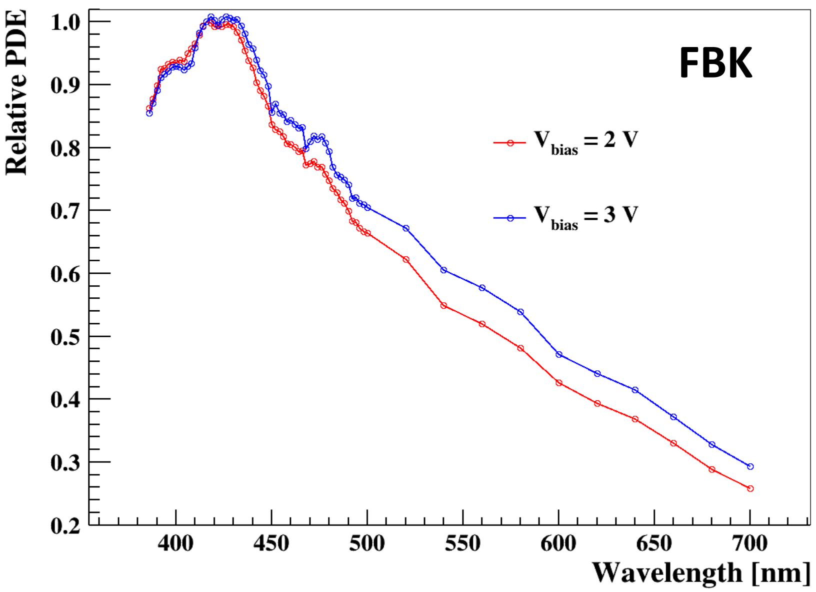
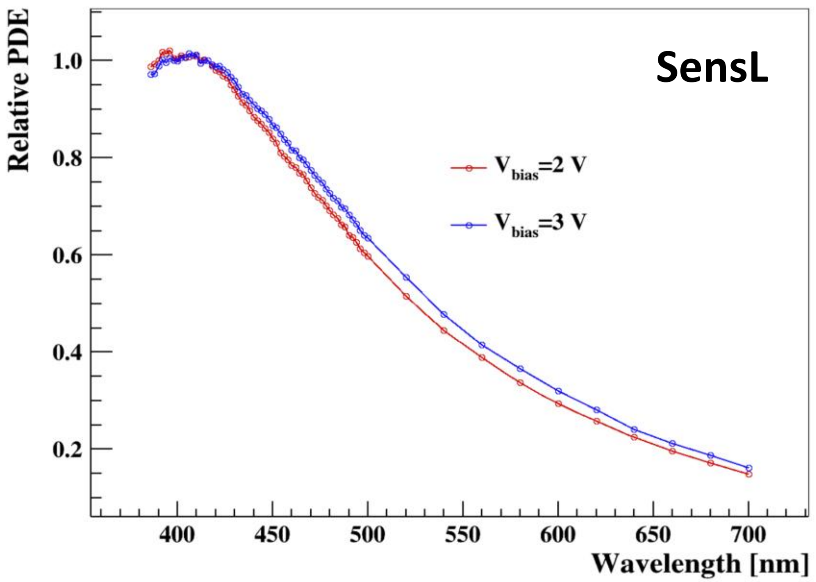


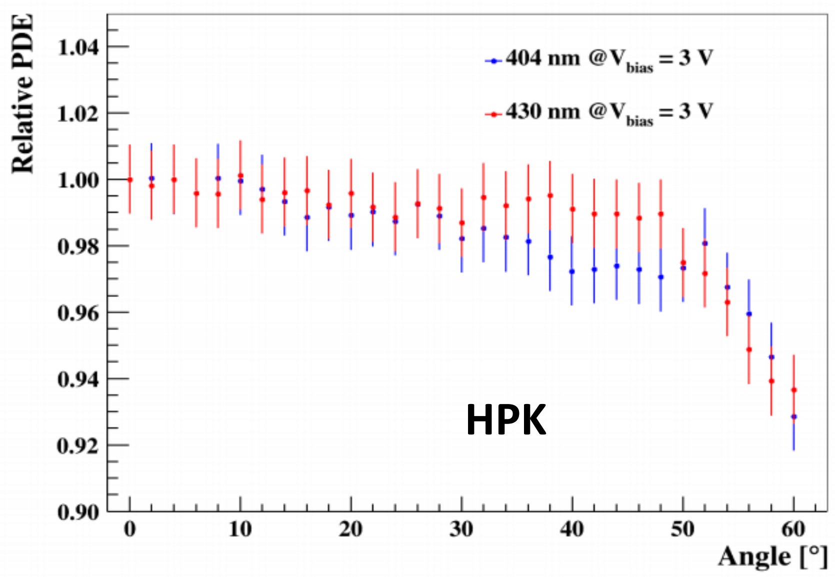
Fig. 1. Schematic diagram of the instrumentation.

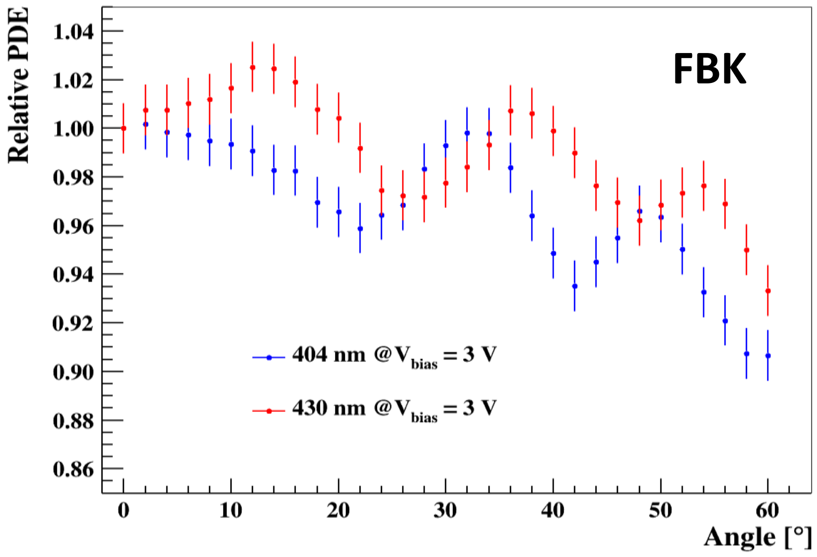
Spectral and angular responses of PDE

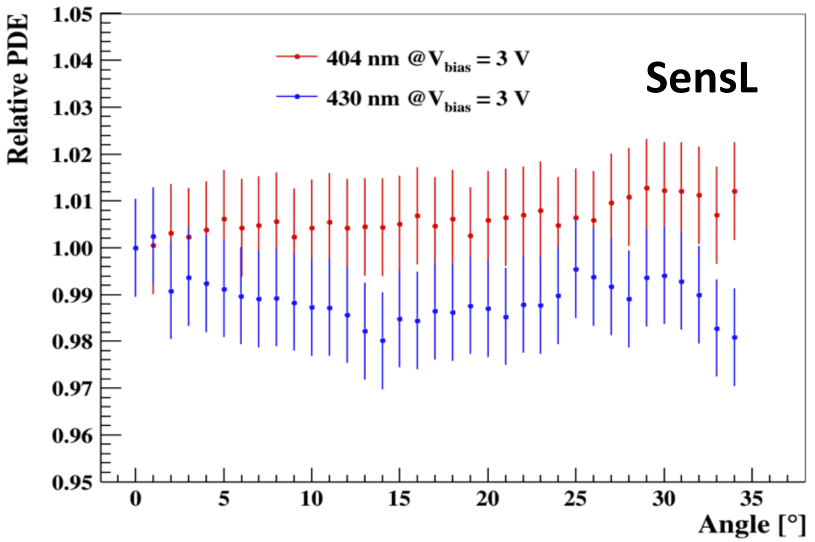






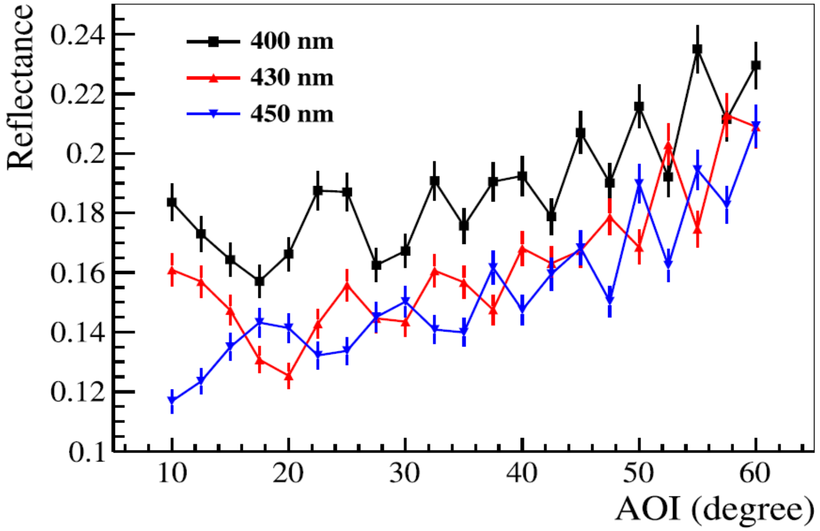




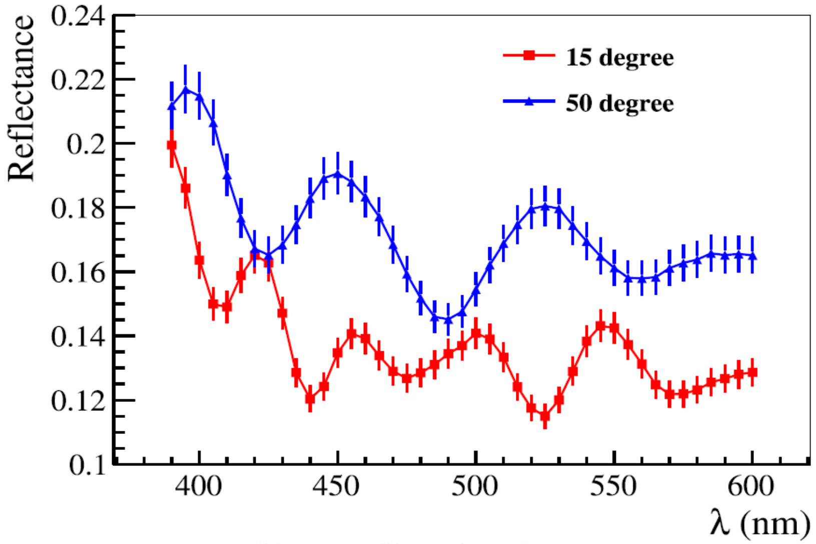


Reflectance of SiPMs

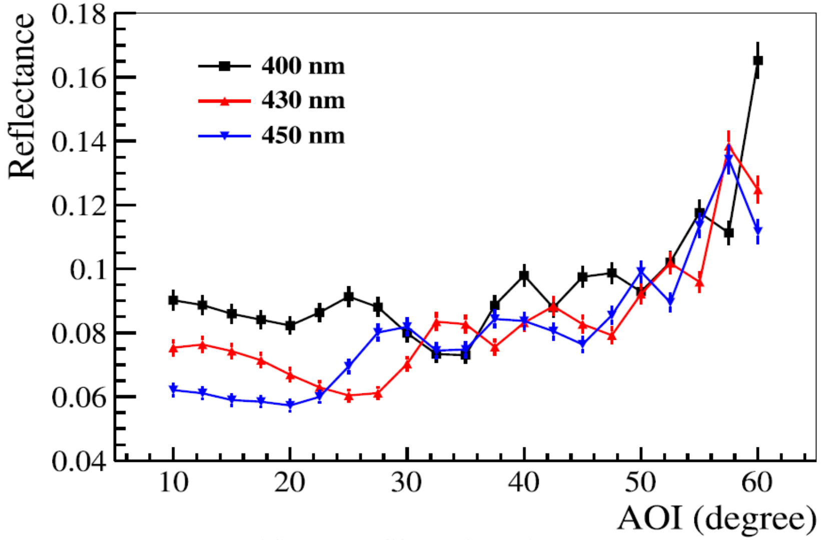
Nuclear Inst. and Methods in Physics Research, A 973 (2020) 164171



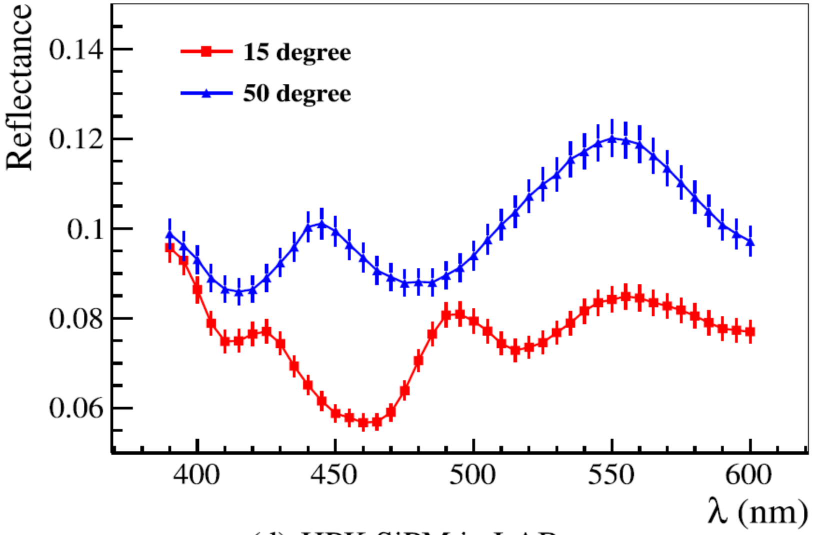
(b) FBK SiPM in LAB



(b) FBK SiPM in LAB

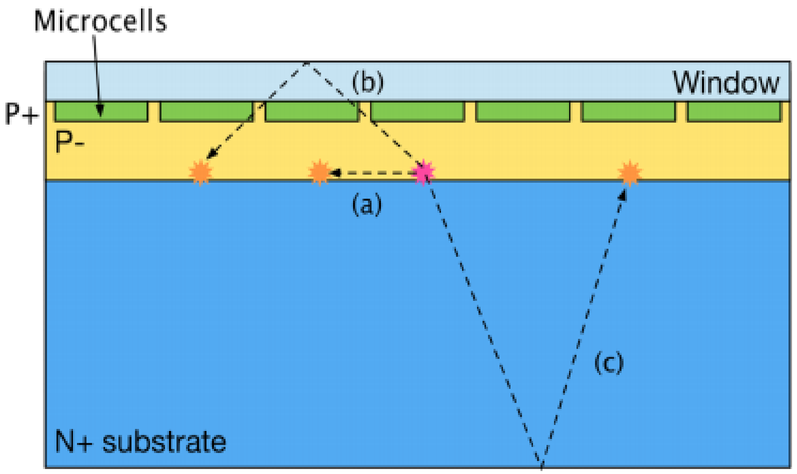


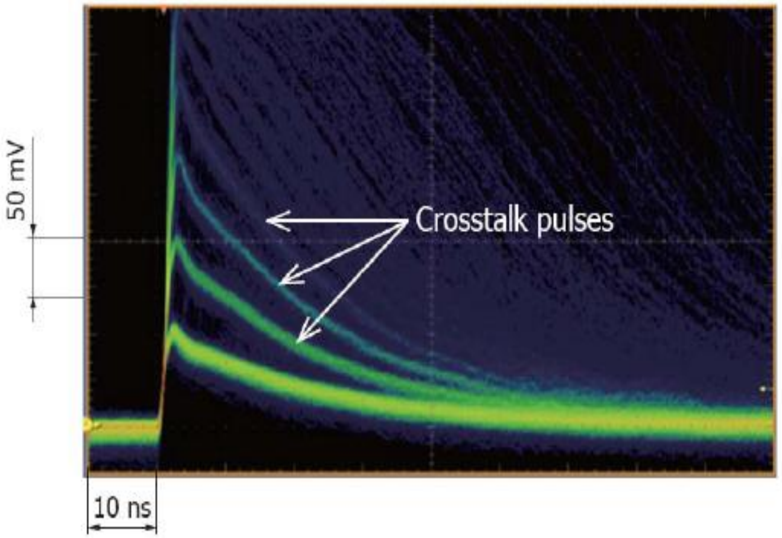
(d) HPK SiPM in LAB

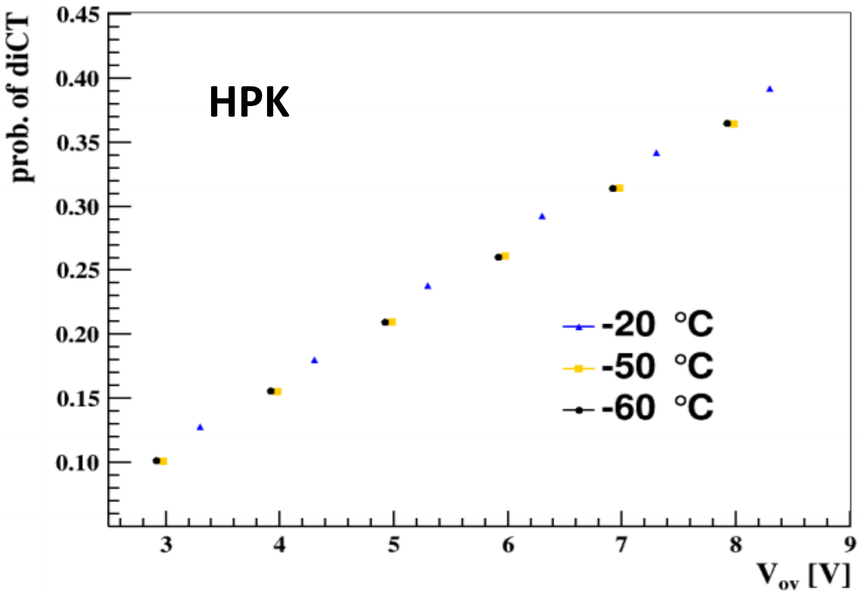


(d) HPK SiPM in LAB

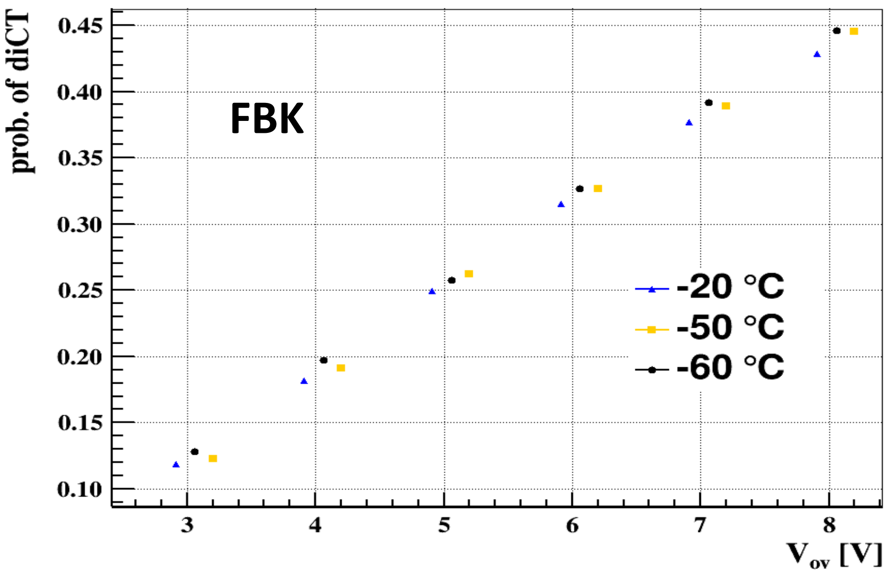
Internal optical cross talk

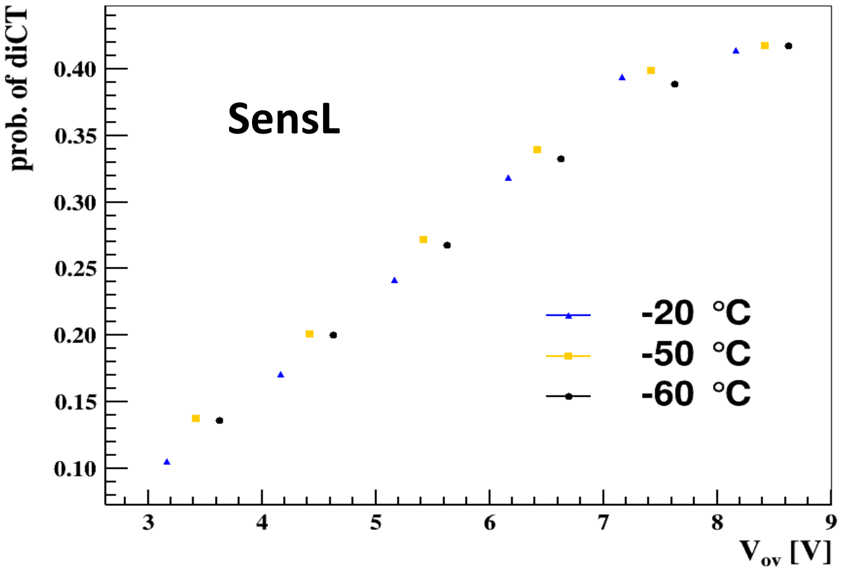






Y. Guan et al 2024 JINST 19 P06024





No strong temperature dependence observed.

Internal + external optical cross talk

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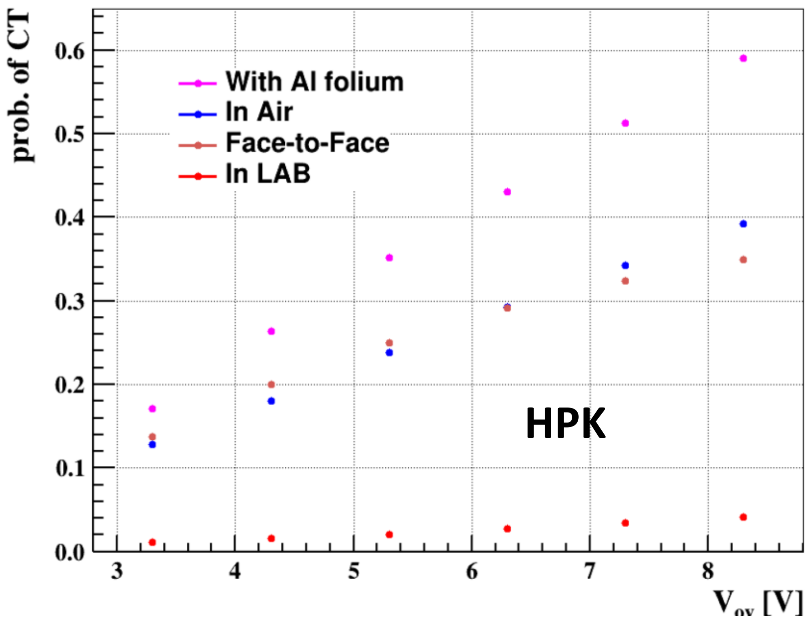
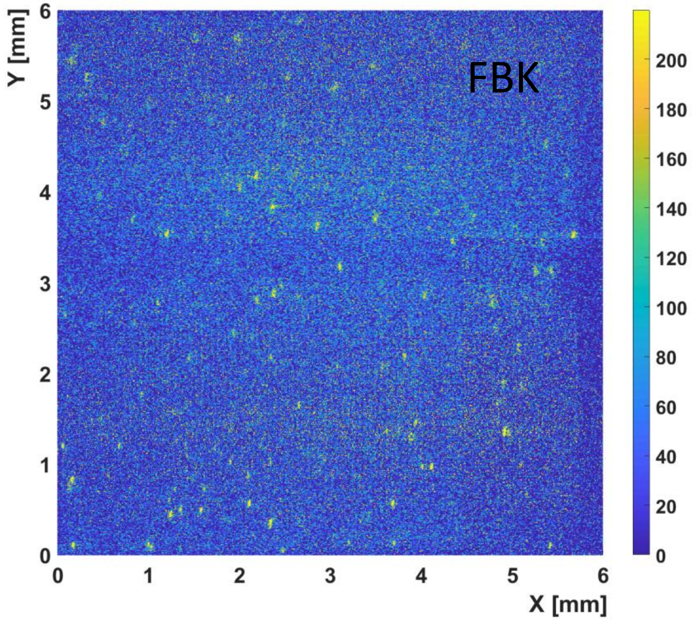
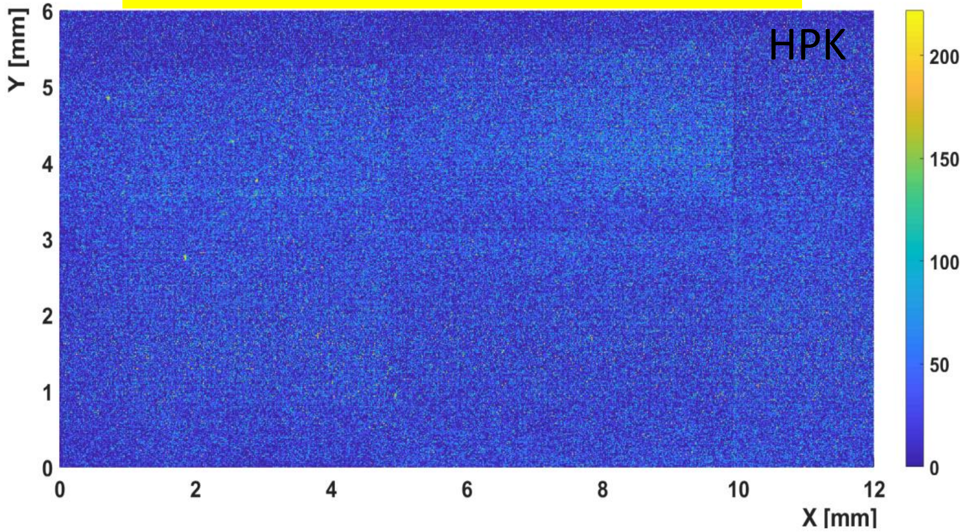
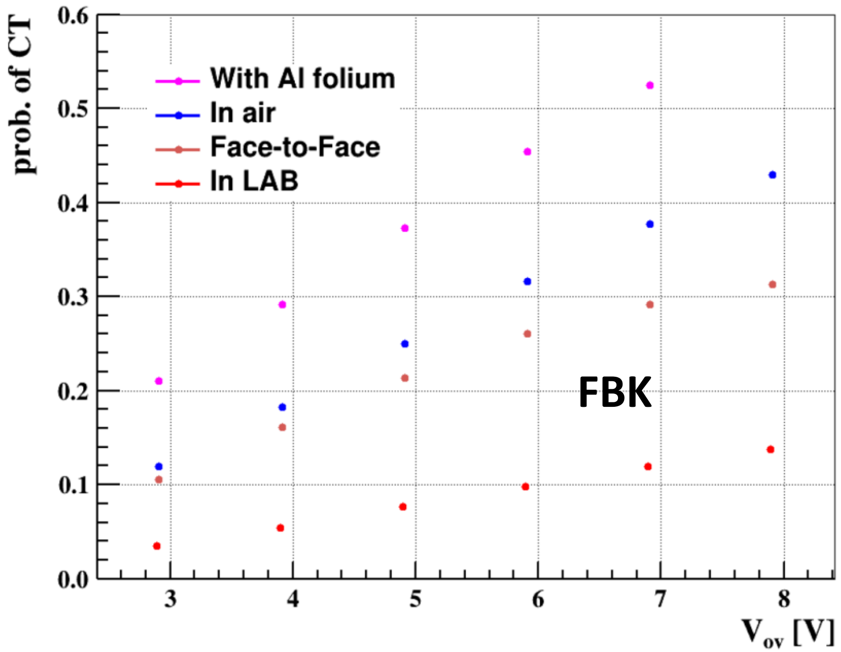
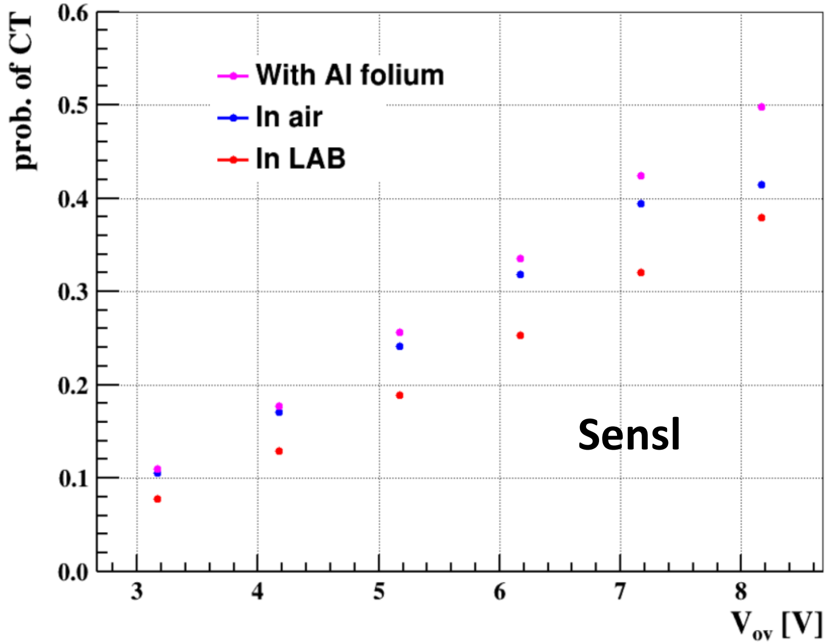
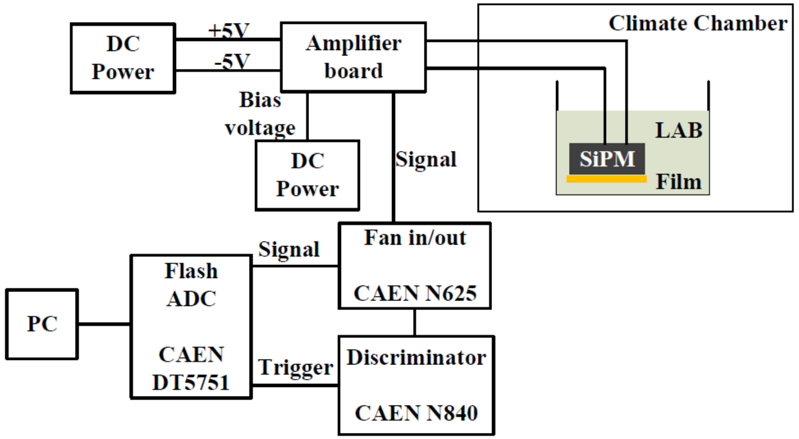






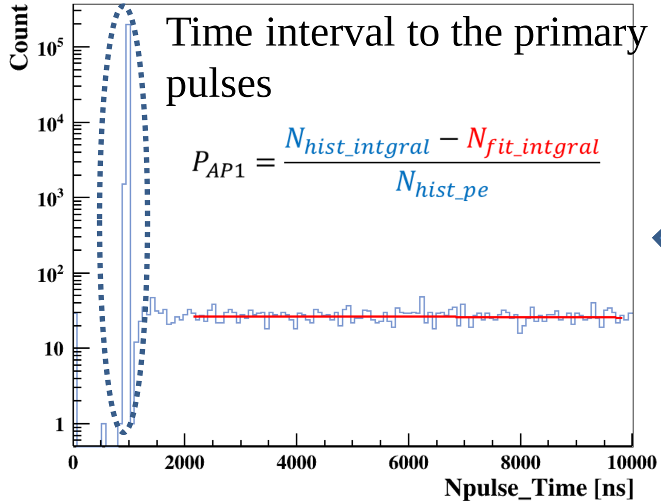


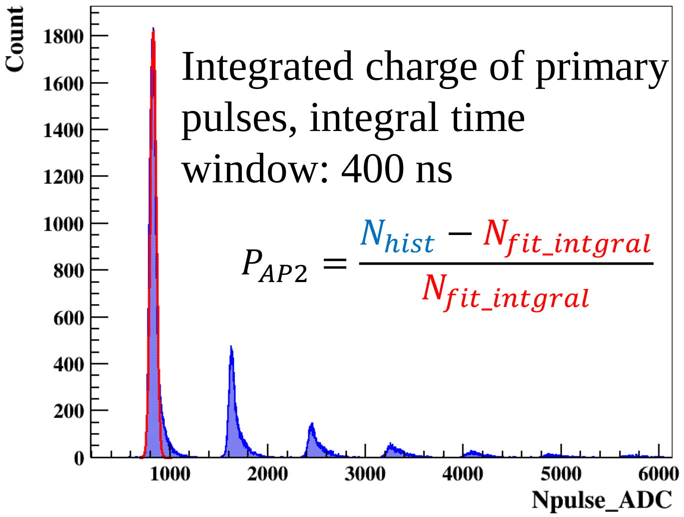




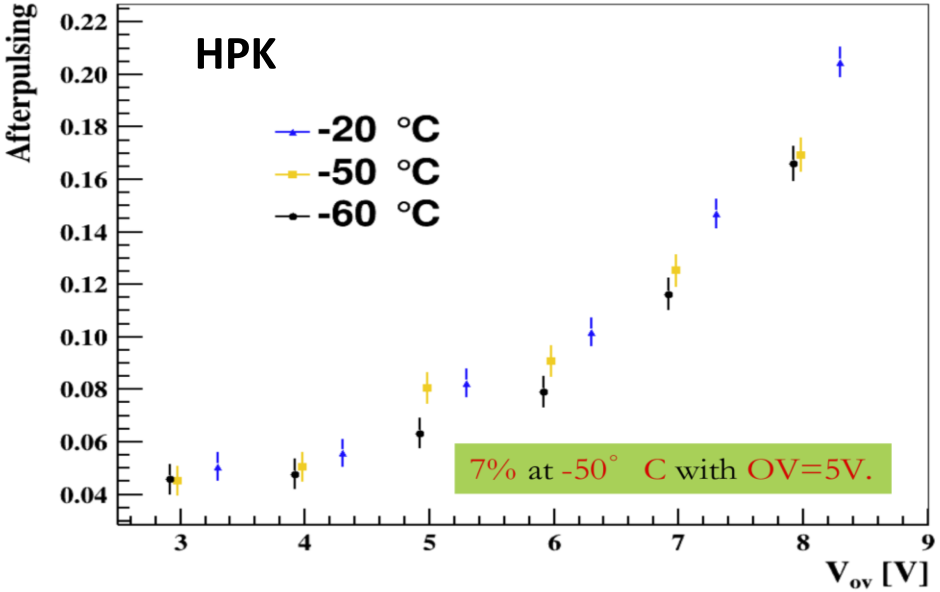
CT includes internal and external CT.

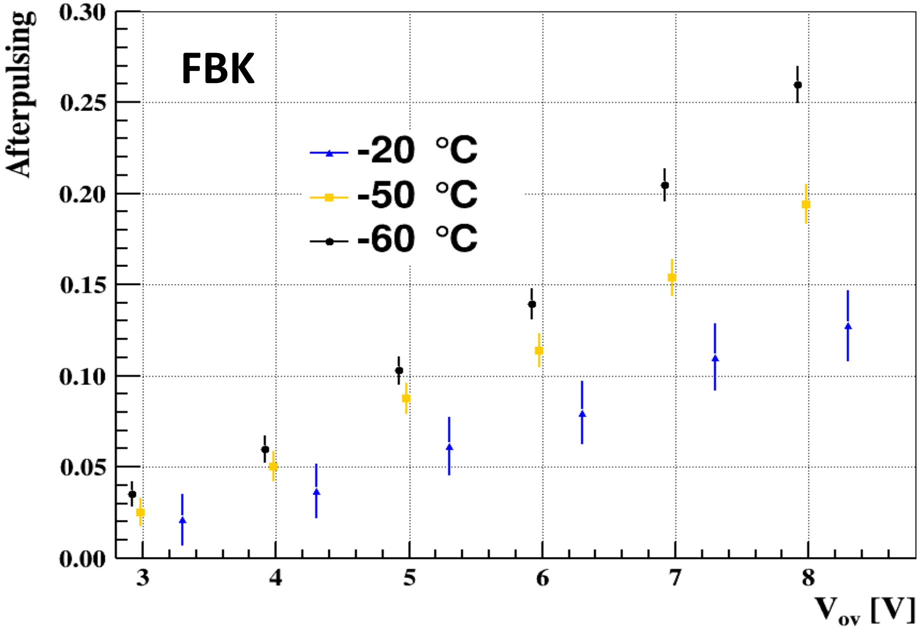
TAO is sensitive to both.



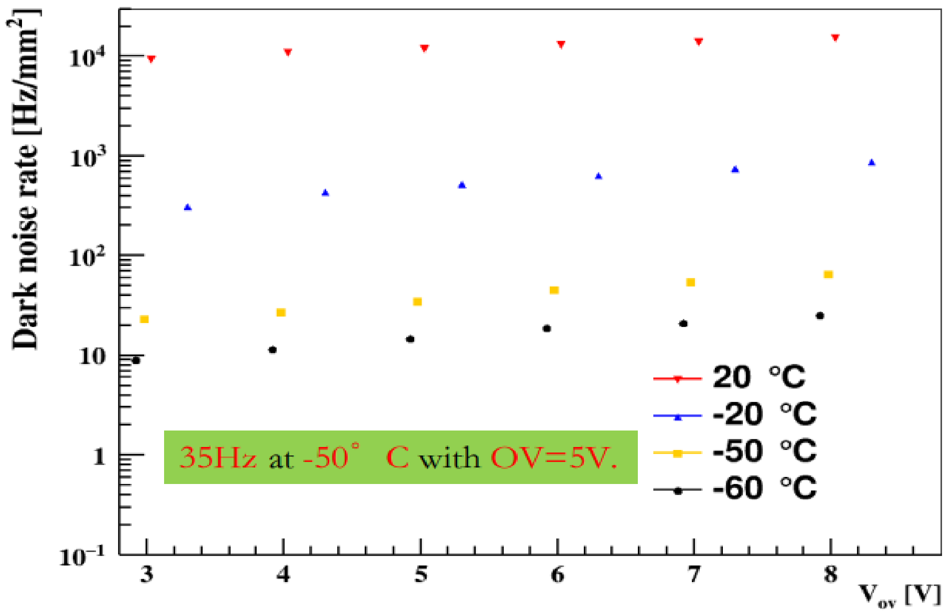


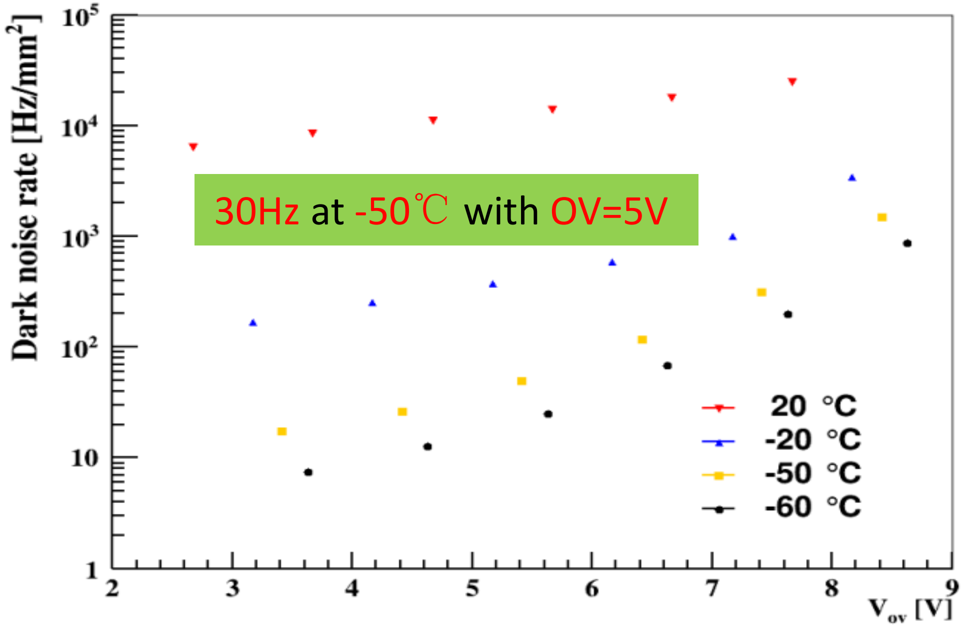
Total AP is $P_{AP1} + P_{AP2}$

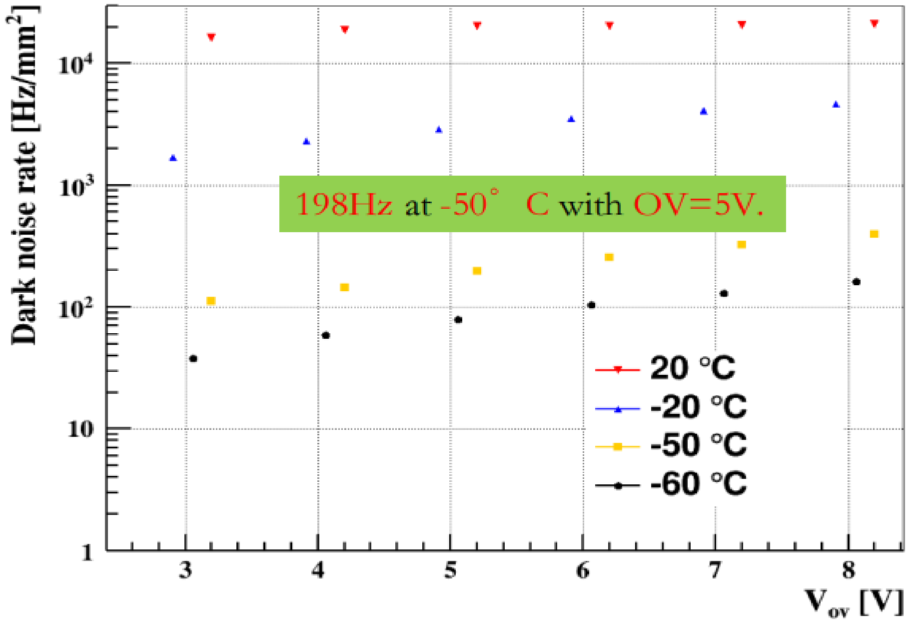




DCR


Dark noise rate [Hz/mm^2]
V_{ov} [V]
20 °C
-20 °C
-50 °C
-60 °C
35Hz at -50° C with OV=5V.


Dark noise rate [Hz/mm^2]
V_{ov} [V]
30Hz at -50℃ with OV=5V
20 °C
-20 °C
-50 °C
-60 °C


Dark noise rate [Hz/mm^2]
V_{ov} [V]
198Hz at -50° C with OV=5V.
20 °C
-20 °C
-50 °C
-60 °C

- **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 and cross talk**

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

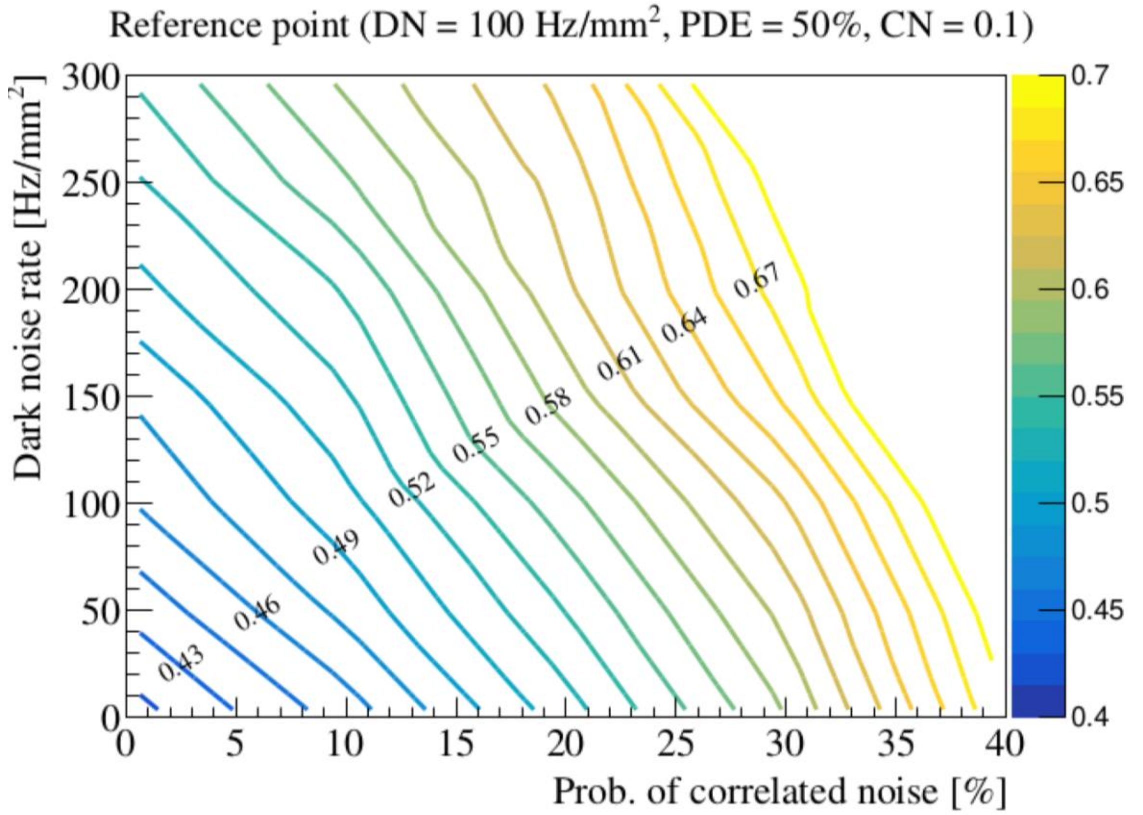
PDE_{Eff} can be calculated based on DCR and correlated noise of SiPM:

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

P_{cn} is correlated noise, including CT + AP

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

CT includes both internal and external cross talk!



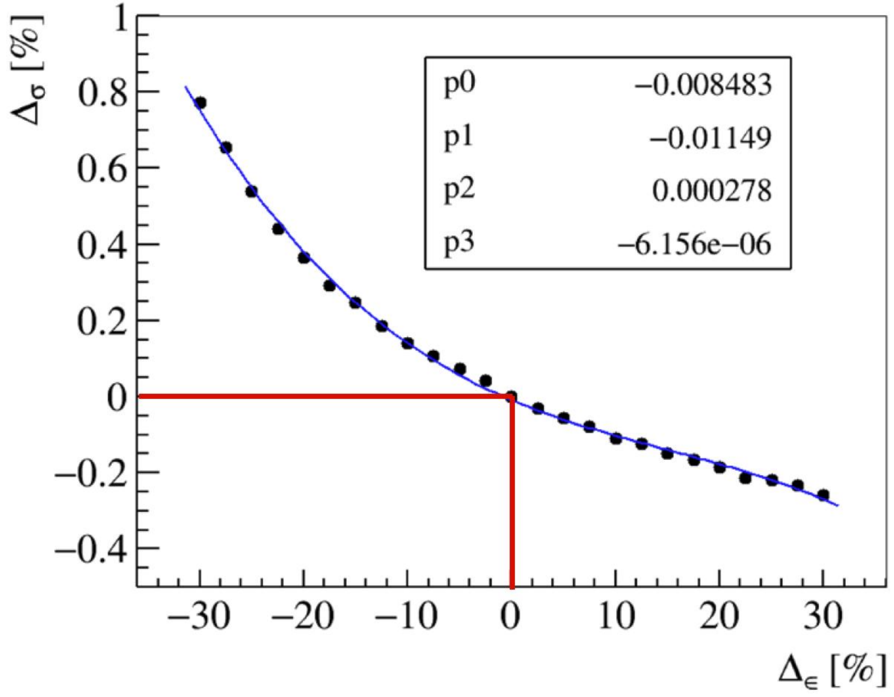
Δ_{ε} is the difference between the measured (real) PDE of SiPM at 420 nm and the effective PDE calculated from DCR and CN, in which the SiPM coverage on the tile is also taken into account.

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

PDE is the absolute PDE of SiPMs at 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:

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

*** $\Delta_{\varepsilon} > -25\%$**

 # Δ_{ε} converted to Δ_{σ} to calculate scores

❄ **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 CNY.**

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

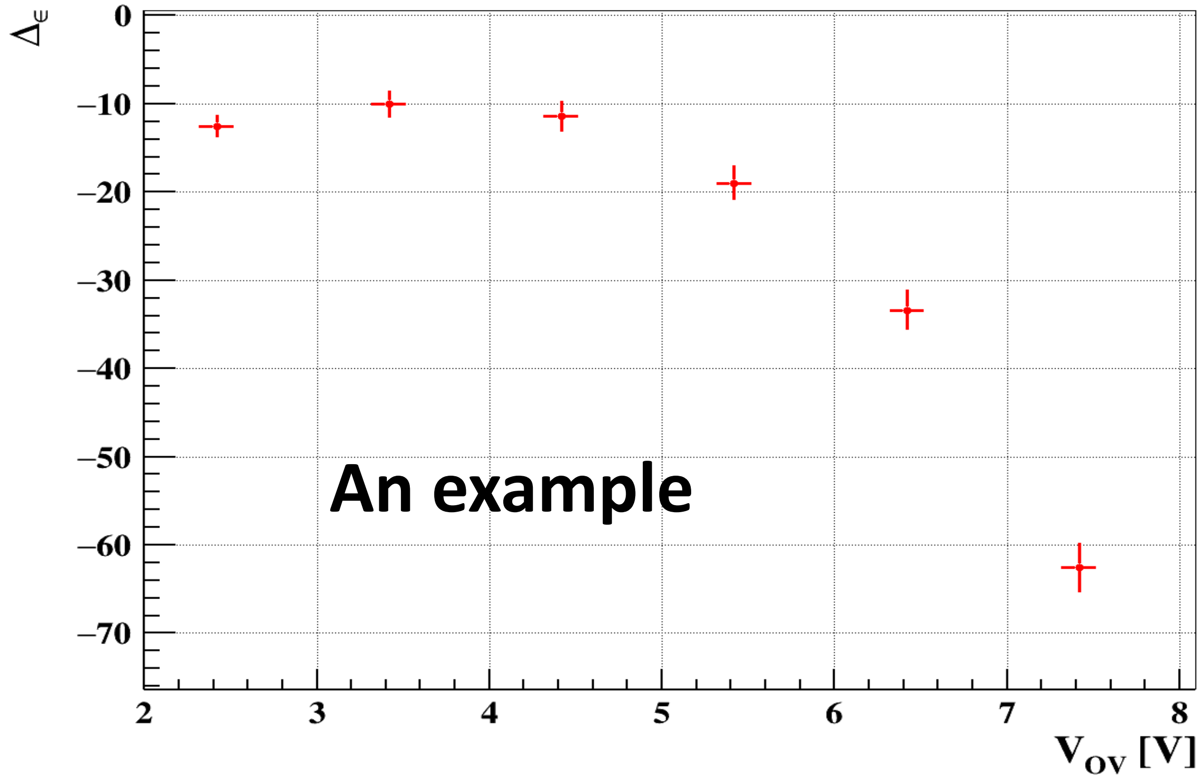
❄ **Therefore, 0.1% absolute change of resolution is corresponding to 3.2M CNY.**

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

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

Examples of Δ_ε versus over voltage

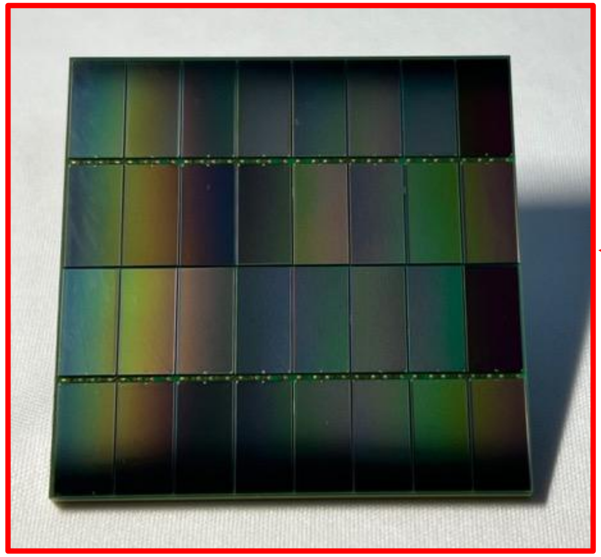
Vendors have to scan the operating voltage and find the optimal one, then use the best numbers to response the technical items.

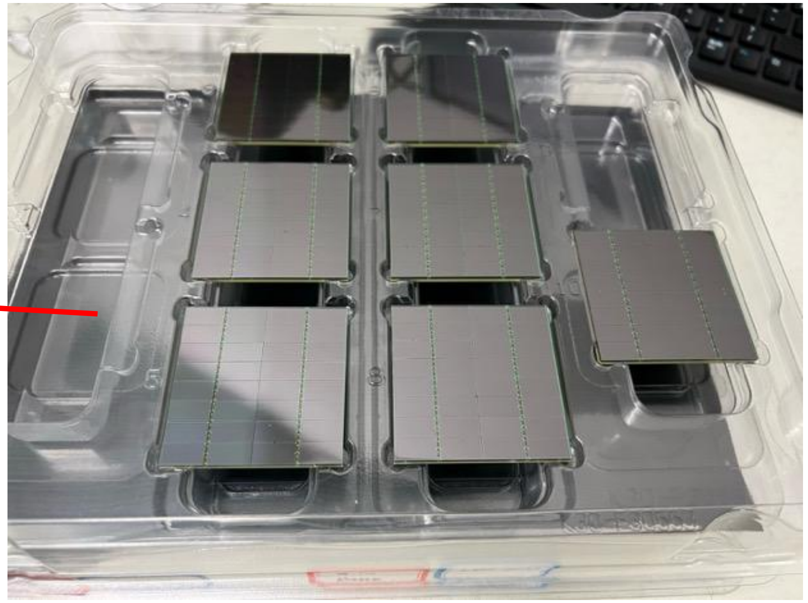


SiPM Production for TAO

- A customized type S16088 from Hamamatsu, similar to S13360-6075PE
  - Pixel size: 75 μm
  - SiPM chip size: 12 mm × 6 mm
  - Each SiPM tile holds 32 chips, with 2 chips connected in parallel per channel
- Coverage of photo-sensitive area: 89.6%
- Channel capacitance: 5,100 pF

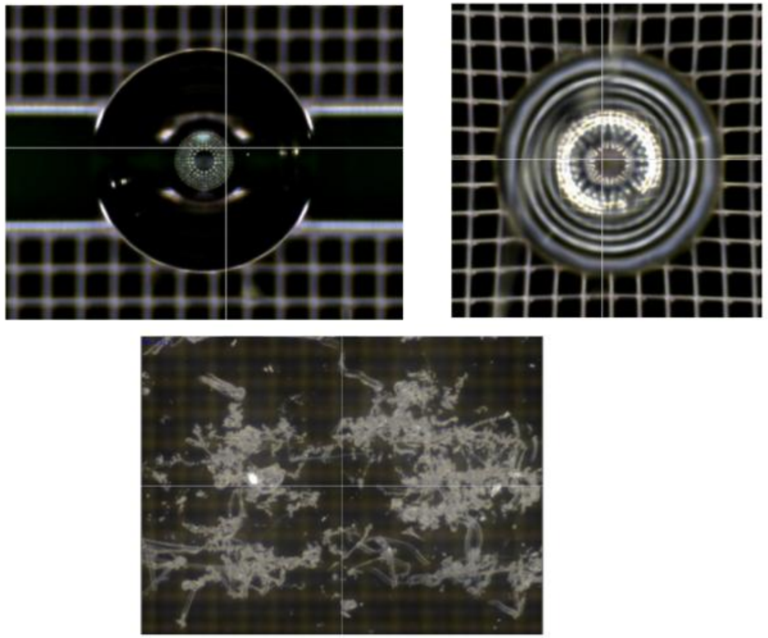
- **Received 4,100 + 298 SiPM tiles from Hamamatsu**
  - 4024 tiles mounted on the detector
  - Total area: 4024 tiles × 32 chips × 12 mm × 6 mm ≈ 9.27 m2
- **Number of Channels for QA/QC: 4398 × 16 = 70,368**

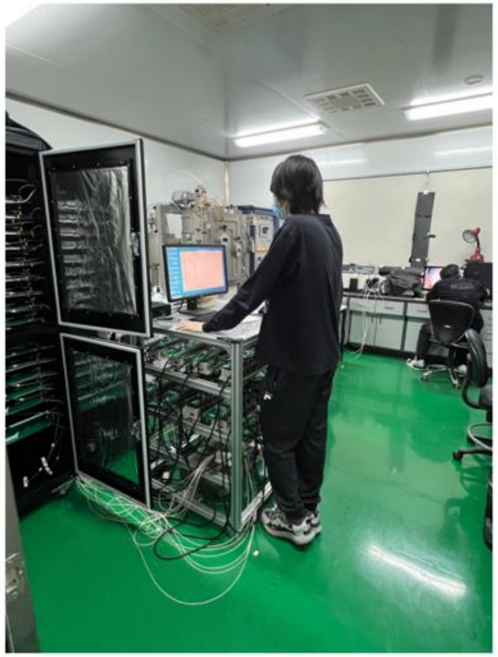


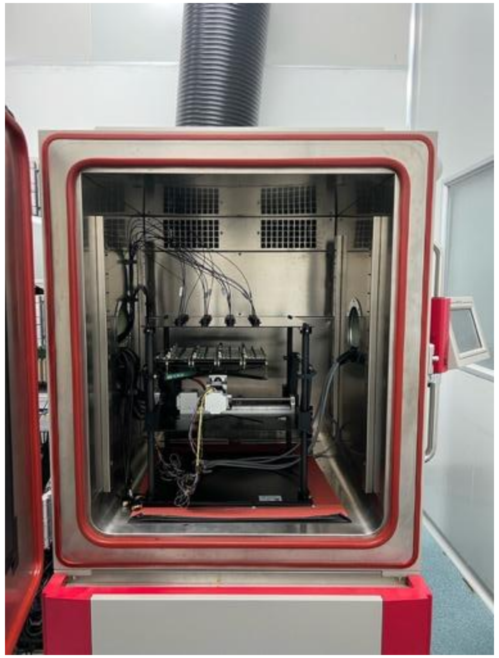


❄All SiPMs undergone three types of test

- ➢Microscopic visual inspection
- ➢Room temperature burn-in test, 2 weeks running at ~3 V OV
- ➢Waveform acquisition and characterization at -50 °C



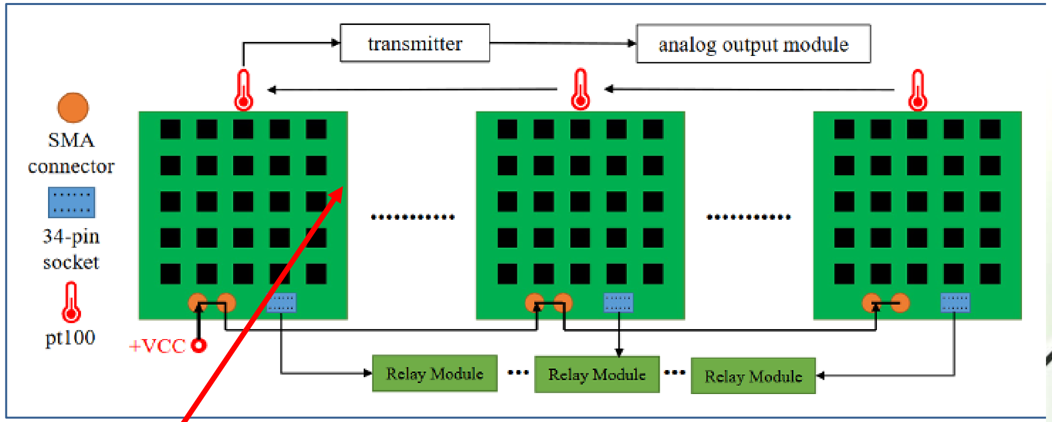


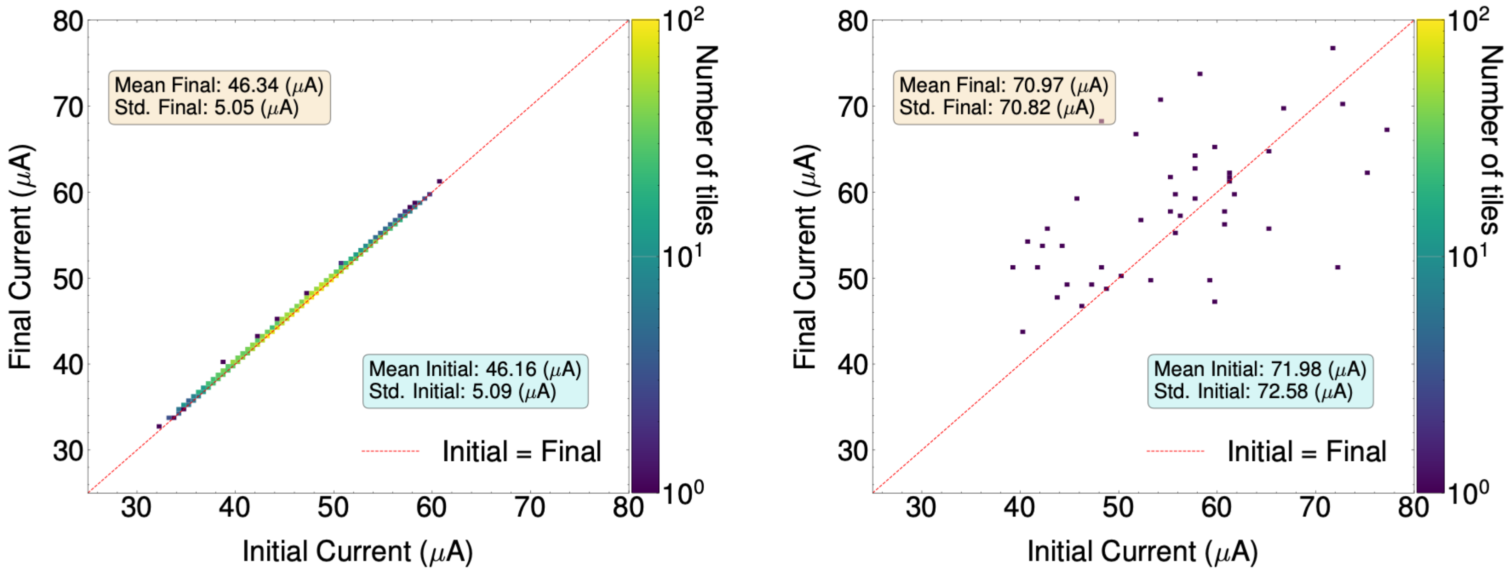


Burn-in Test

- SiPMs operated at a fixed voltage (~55V) at room temperature in the dark
- 400 SiPM tiles tested per run, each lasting two weeks
- **Dark current** and **ambient temperature** periodically recorded using a picoammeter and relay modules
- Data taking completed at the end of 2023
- A few pieces tagged as “bad”

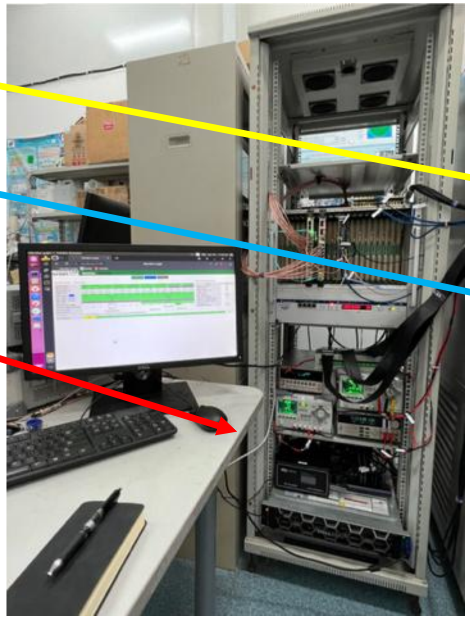
Setup developed by Sen:
RDTM 8, 1194–1201 (2024)

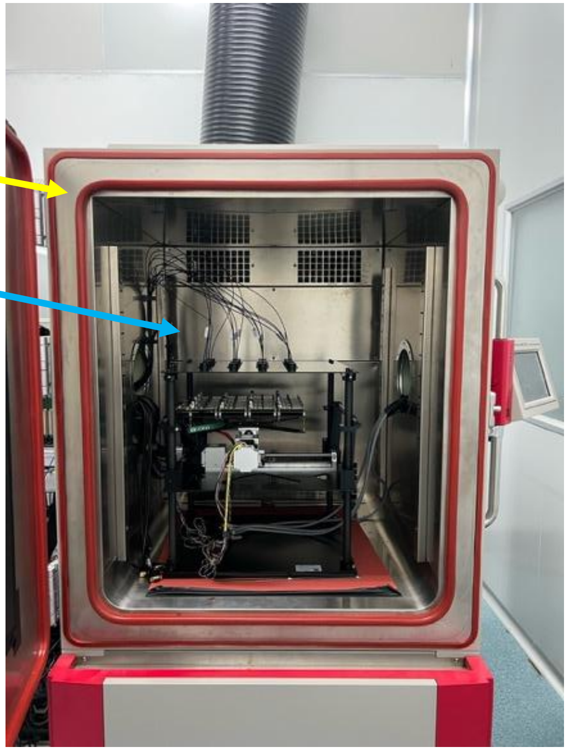




X. Chen *et al* 2024 *JINST* **19** P07028

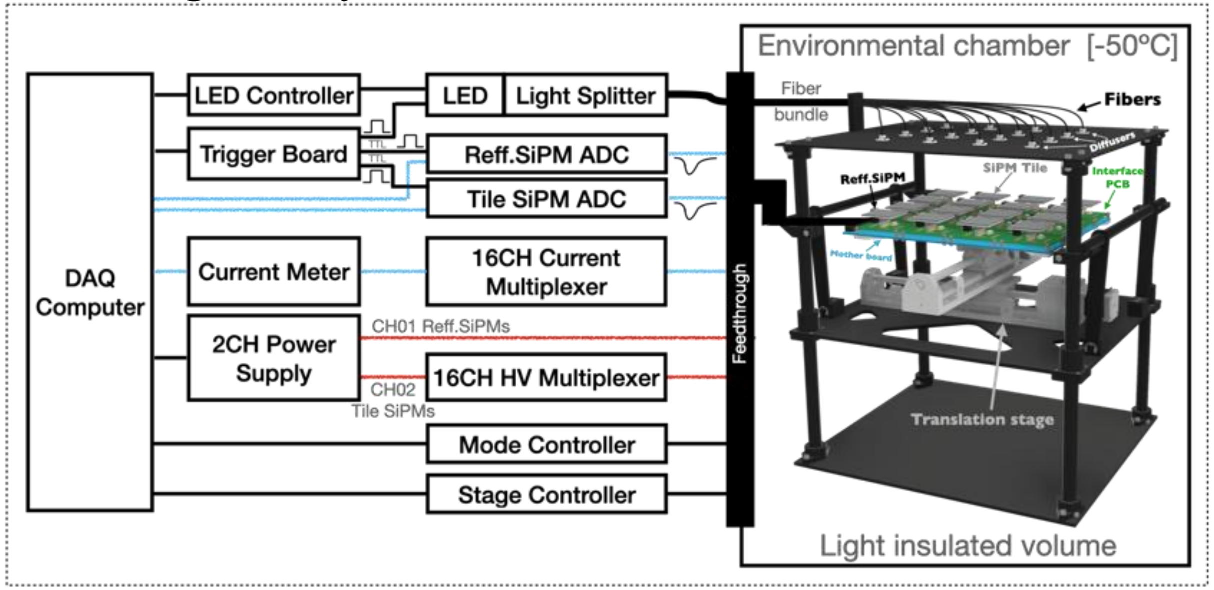
- Cryogenic chamber (dark, -50°C)
- 420 nm LED in pulsed mode, with a stable light field after optical fibers and diffusers
- Control & DAQ outside the chamber
- Dedicated design for the **absolute PDE** measurement, with calibrated reference SiPMs
- Designed by JINR and IHEP





Cryogenic chamber, providing dark and low temperature (-50℃) environment

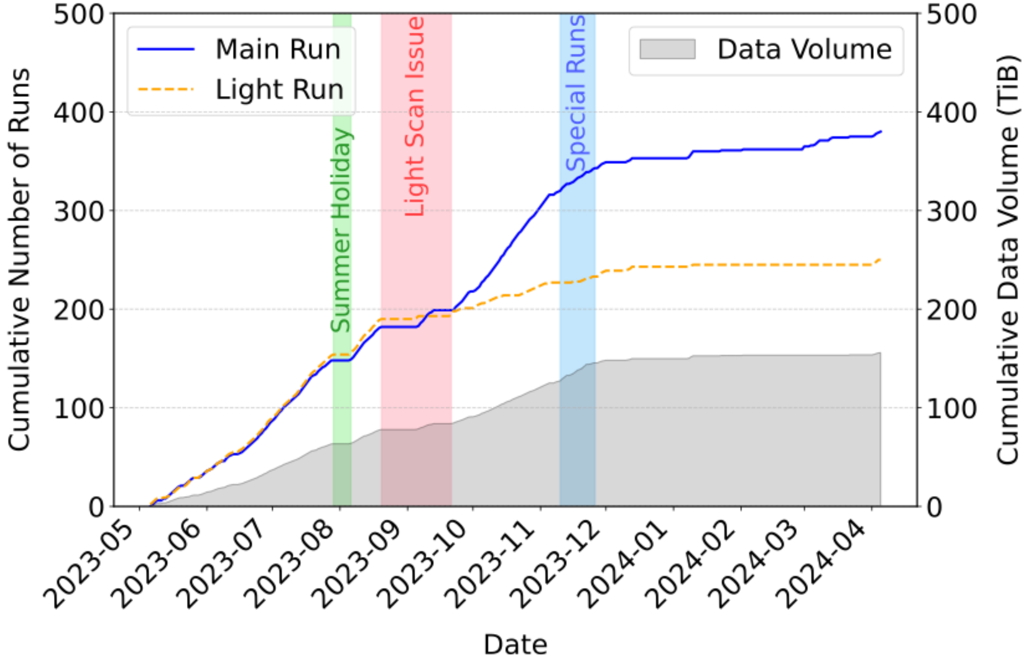
Platform with movement control for light field calibration

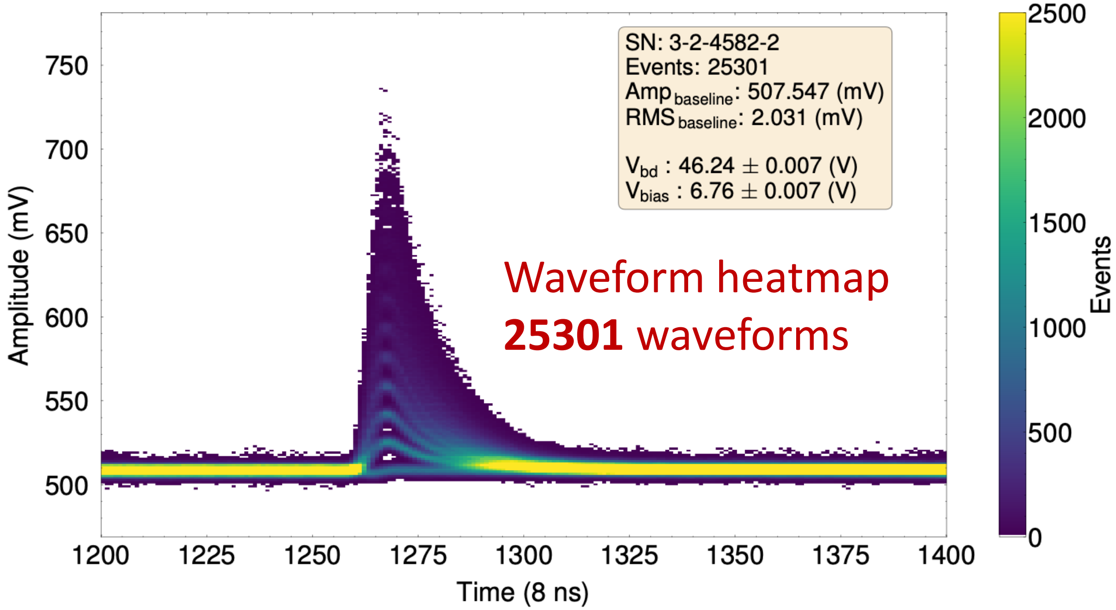


A. Rybnikov *et al* 2024 *JINST* **19** P05035

- Each data-taking run holds 16 SiPM tiles, 3 runs per day
- Record waveforms with a duration of 16 μs each
- Final disk volume for raw data: 150 TiB
- 6 pre-set voltages, step = 1 V (OV ~ 3 to 8 V)
- Each waveform:
  - Dark condition 0 ~ 10 μs
  - LED illumination 10 μs ~ 10 μs + 360 ns (charge integral window)

- Resulting in 4100 tiles × 16 channels × 6 voltages ≈ **400, 000** charge spectra





Charge Spectrum Fit

- Prompt discharges (initial detected photons + prompt crosstalk):
  - Gaussian-smeared Generalized Poisson (G.P.)
- After-pulse:
  - Gaussian-smeared geometric distribution

$$\frac{\mathrm{d}p}{\mathrm{d}Q} = GP_{0,\mu,\lambda} \cdot N\left(Q; 0, \sigma_0\right) + \sum_{n=1}^{n_{\max}} GP_{n,\mu,\lambda} \cdot \sum_{i=0}^{i_{\max}} G(i; n, \alpha) \cdot N\left(Q; n, i, \sigma_n\right)$$

$$N\left(Q; n, i, \sigma_n\right) = \frac{1}{\sqrt{2\pi}\sigma_n} e^{-\frac{(Q-(\mathrm{Ped.}+n\cdot \mathrm{Gain}+i\cdot Q_{\mathrm{ap}}))^2}{2\sigma_n^2}}$$

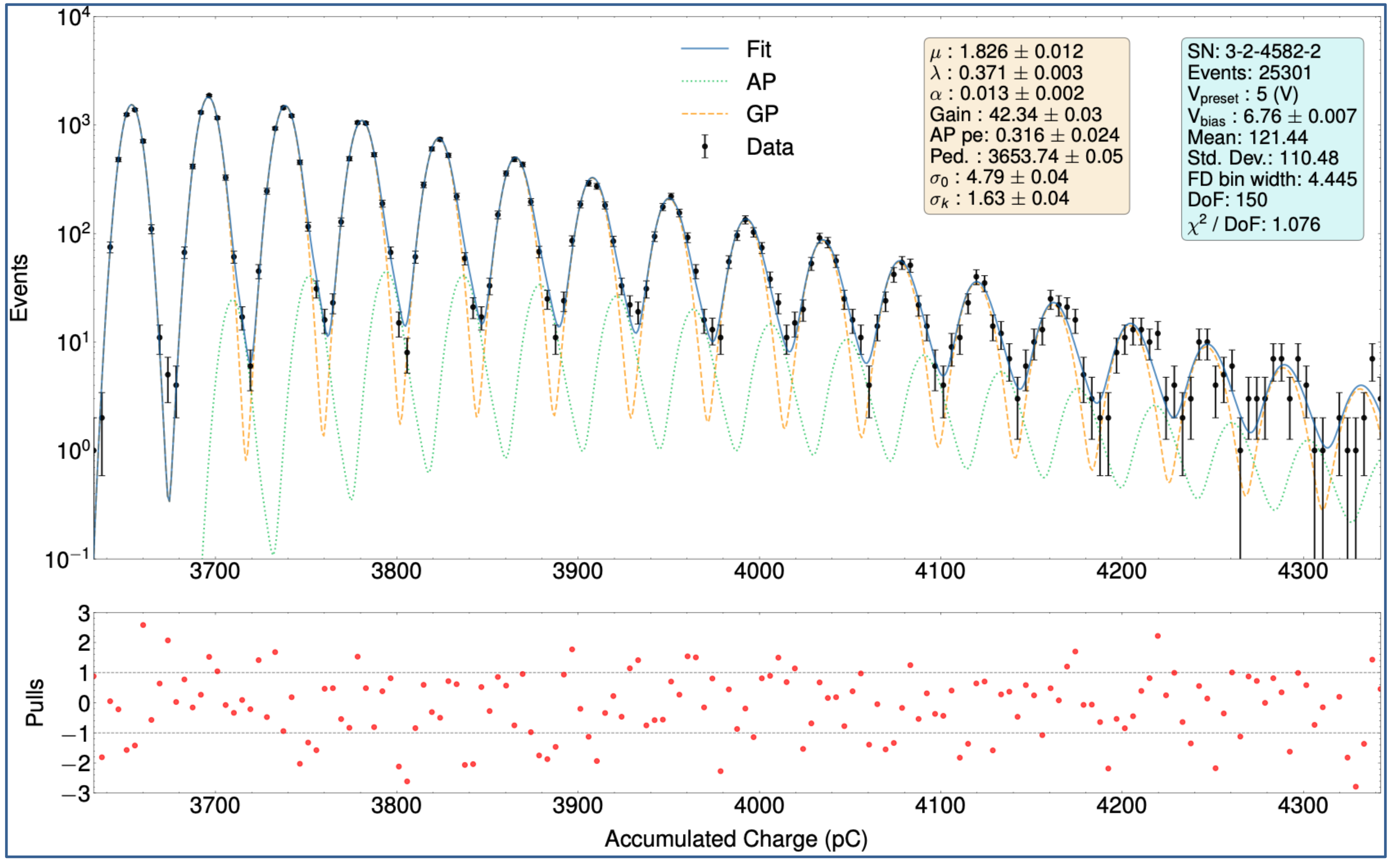
$$GP_{n,\mu,\lambda} = \frac{\mu(\mu+n\lambda)^{n-1} e^{-\mu-n\lambda}}{n!}$$

$$G(i; n, \alpha) = (1-n\alpha)(n\alpha)^i, n\alpha < 1$$

$$\sigma_n^2 = n \cdot \sigma_k^2 + \sigma_0^2,$$

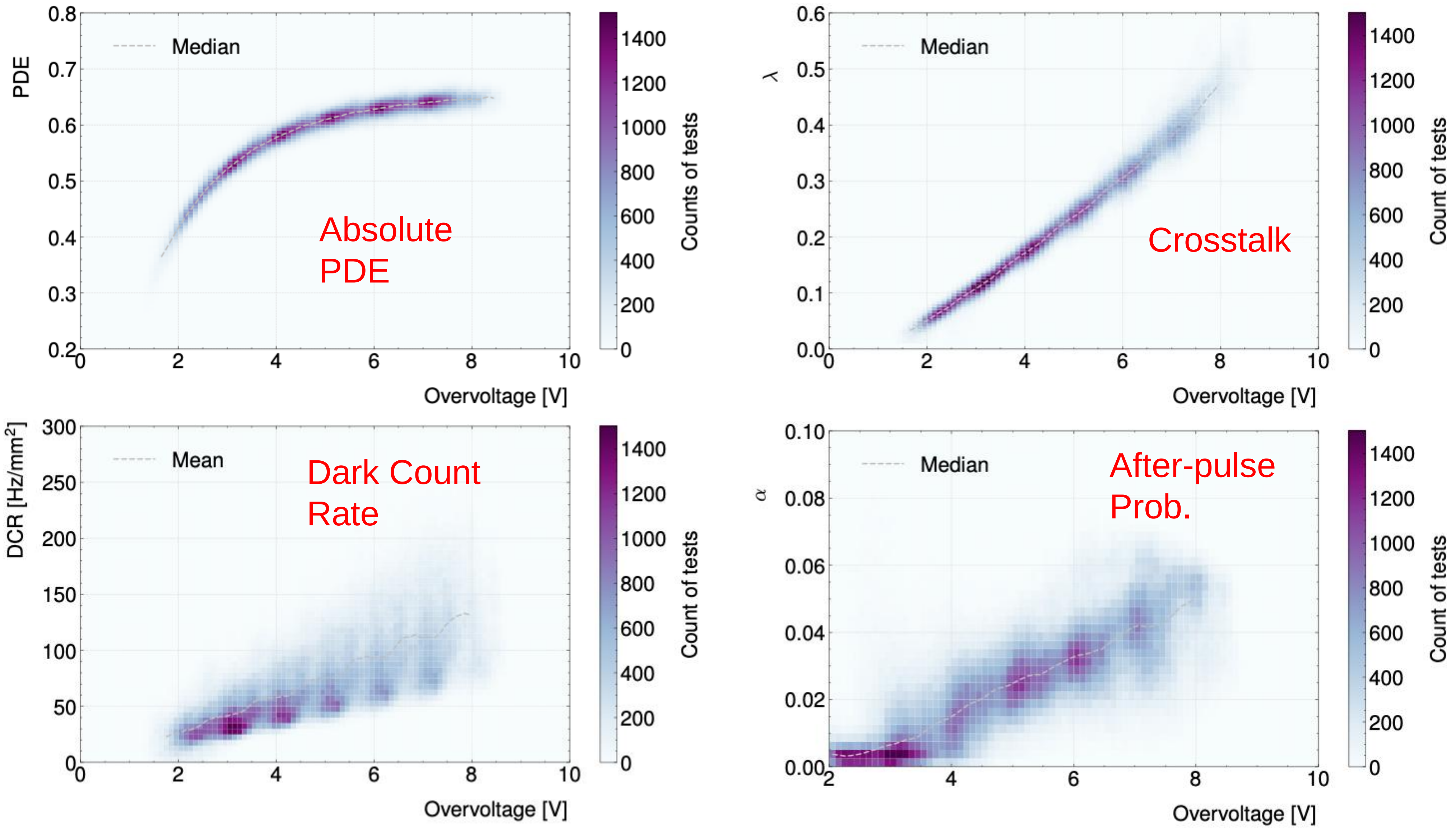
Free parameters:

- μ, λ from G.P.
- Single p.e. gain
- After-pulse charge
- After pulse prob. α
- Baseline noise σ_0
- σ_k from SiPM pixels
- pedestal



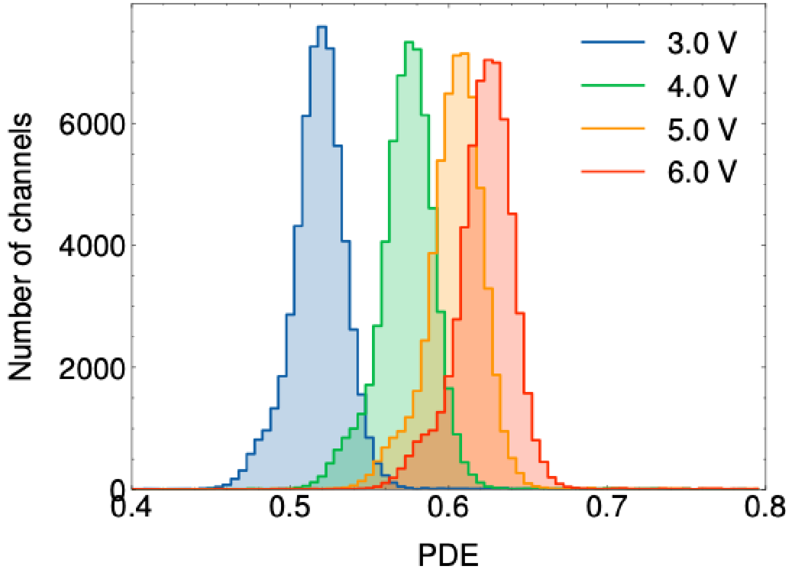
- Analysis framework developed using **C++ RooFit**
- PDF implemented with **RooGenericPDF**
- PDF TMath expressions generated by Python scripts
- Can be open source; free to use!

1 entry =
1 charge
spectrum fit

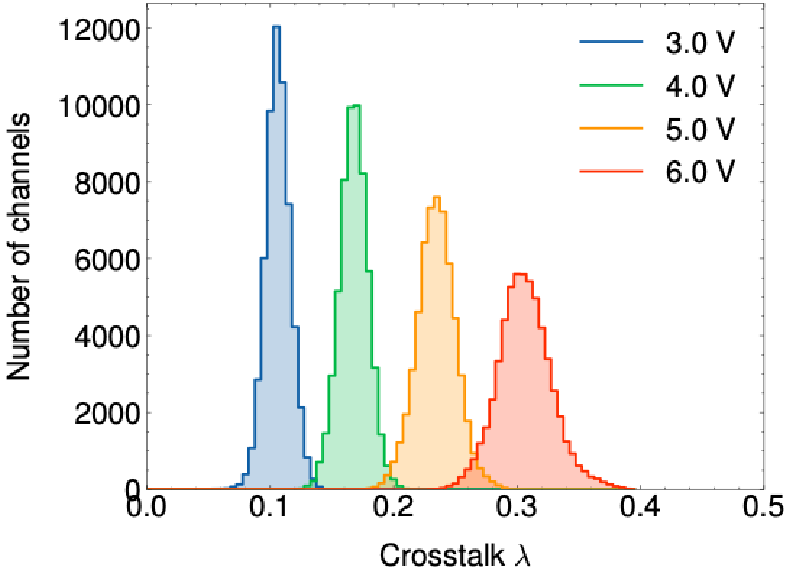


Smoothly parameterized SiPM response as a function of overvoltage, based on six pre-set measurement voltages.

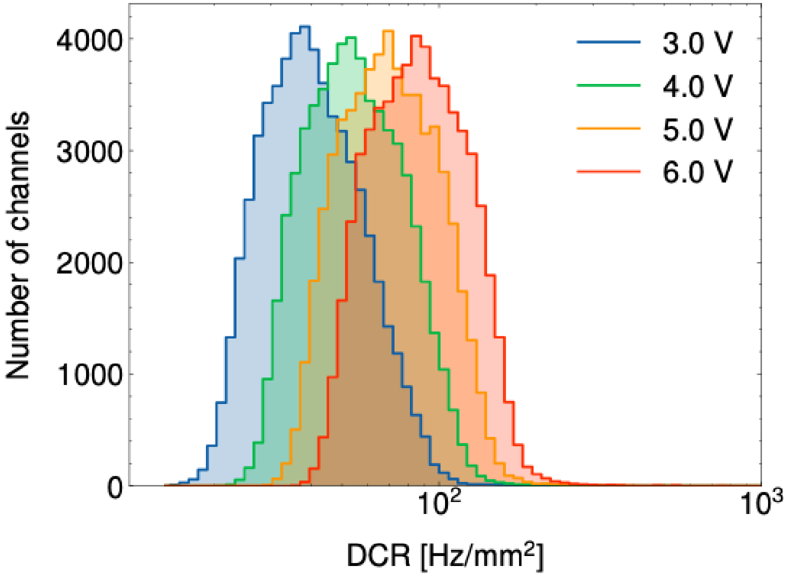
We then can evaluate the SiPM parameters at any chosen OV:



Absolute PDE

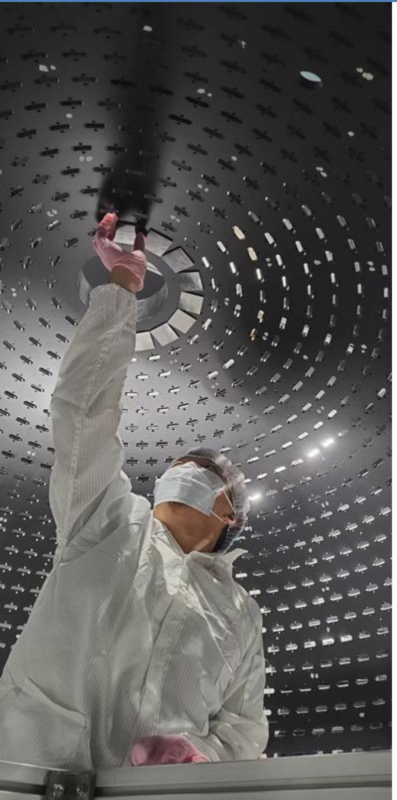


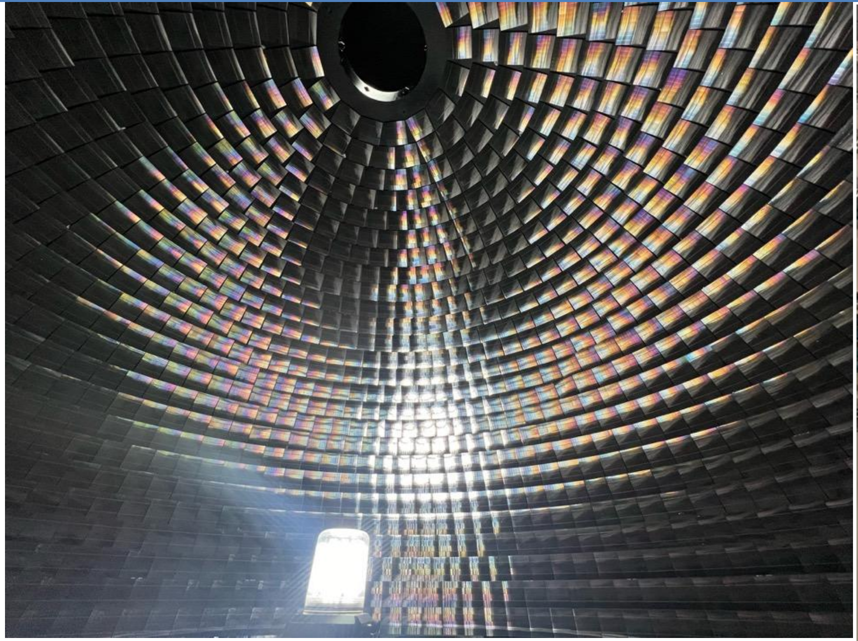
Crosstalk

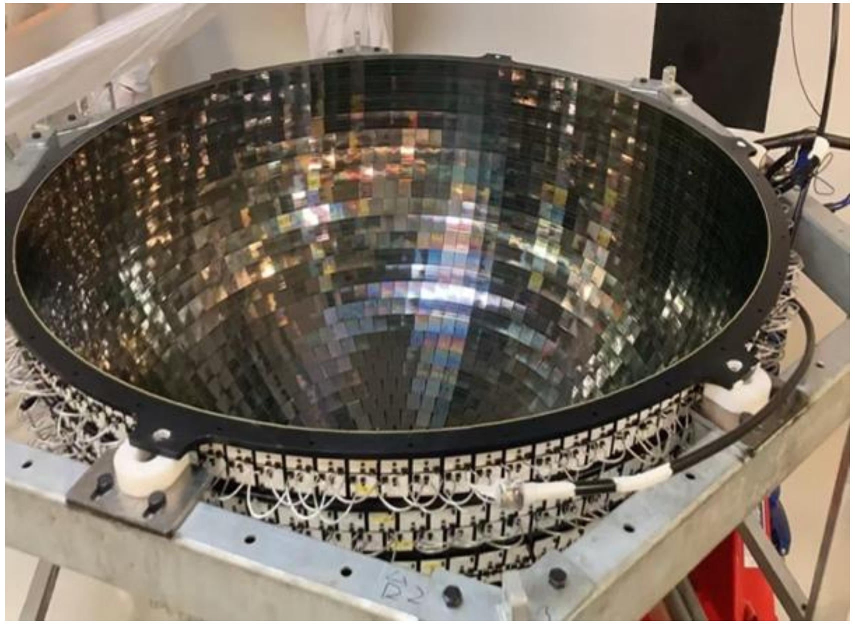


DCR

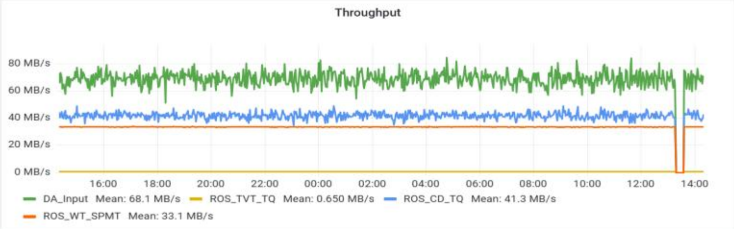
SiPM Installation

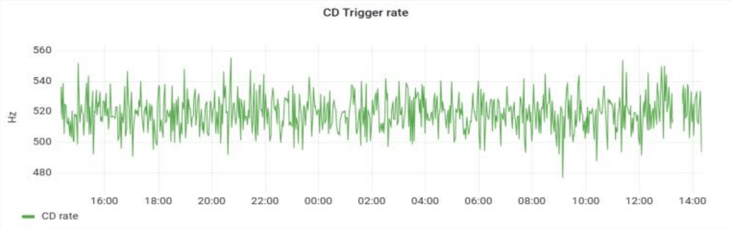


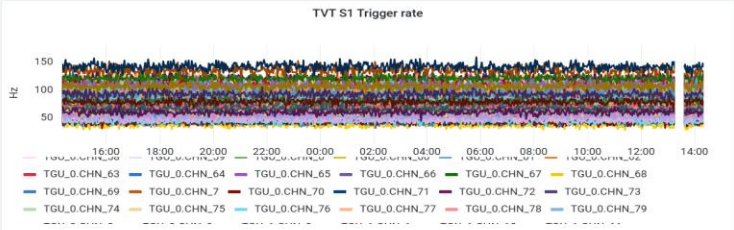


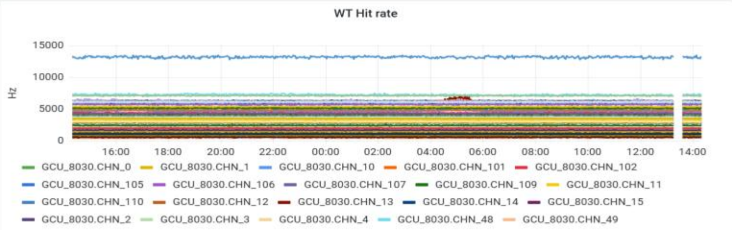


- ❄ **Installation of the TAO detector was done in September last year**
- ❄ **The detector commissioning was done at the beginning of this year**
- ❄ **The TAO detector started the data taking a few days ago**





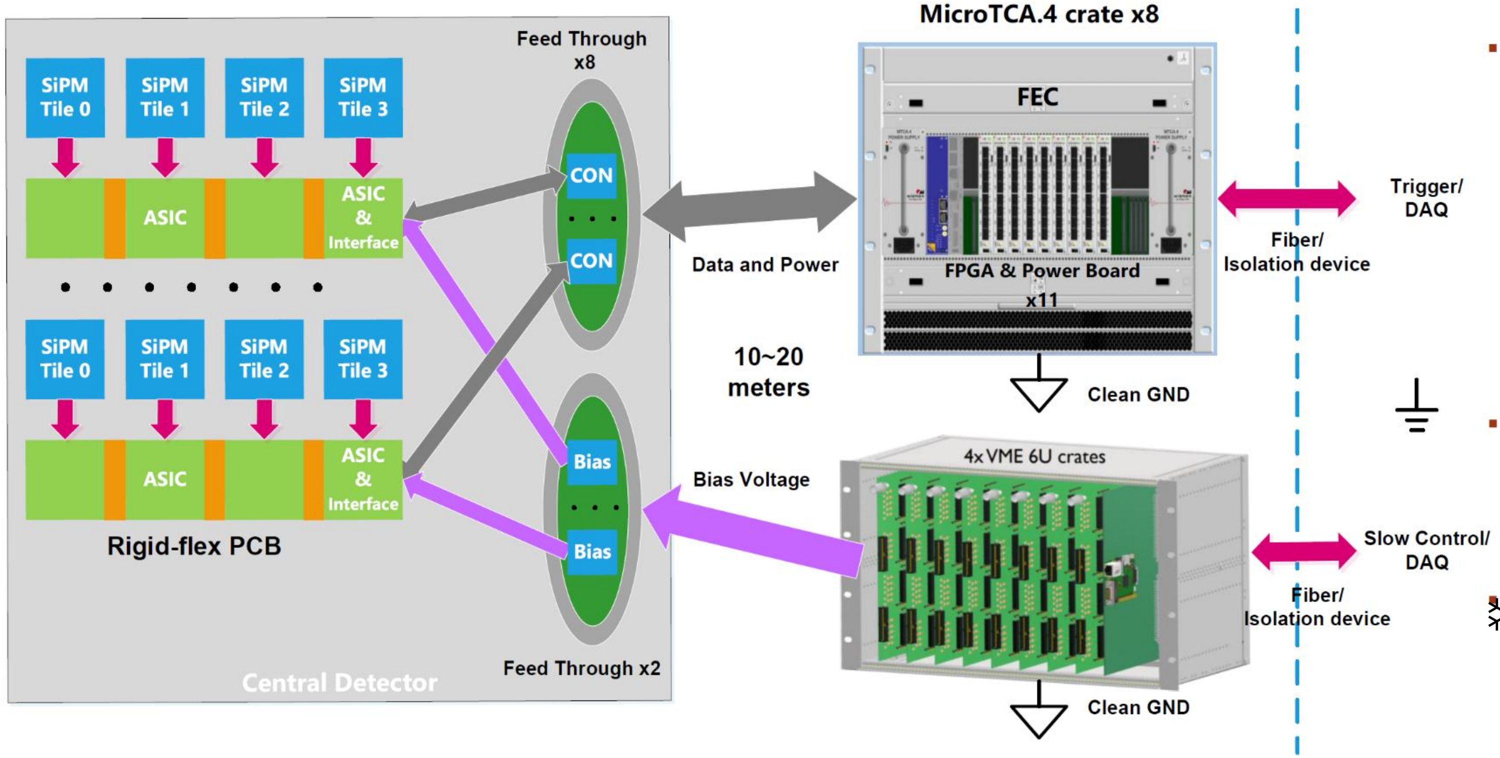




- ❄ **Based on KLauS chip – ASIC scheme**
  - ➢ **The KLauS chip is developed by Heidelberg University, the latest version is v6.**
  - ➢ **UMC 180 nm CMOS technology**

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

ASIC scheme



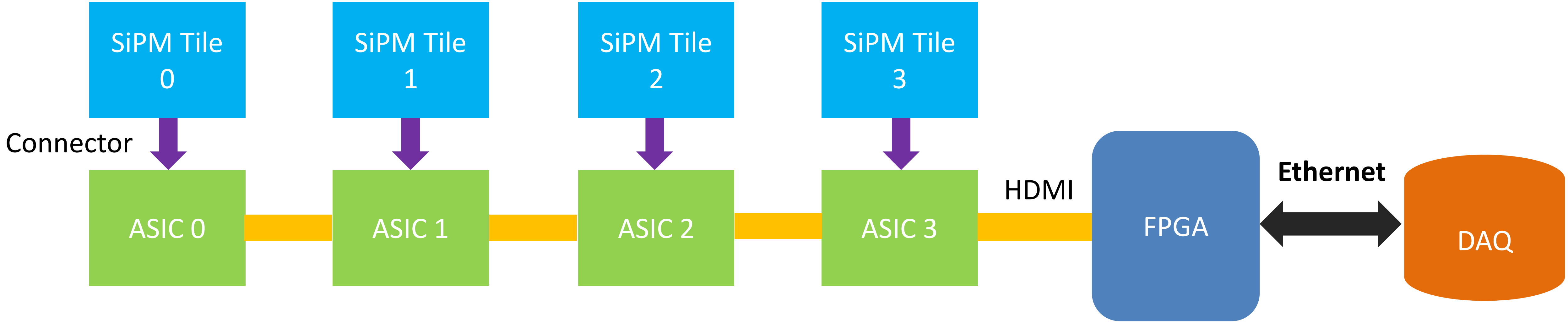
❄ FEB

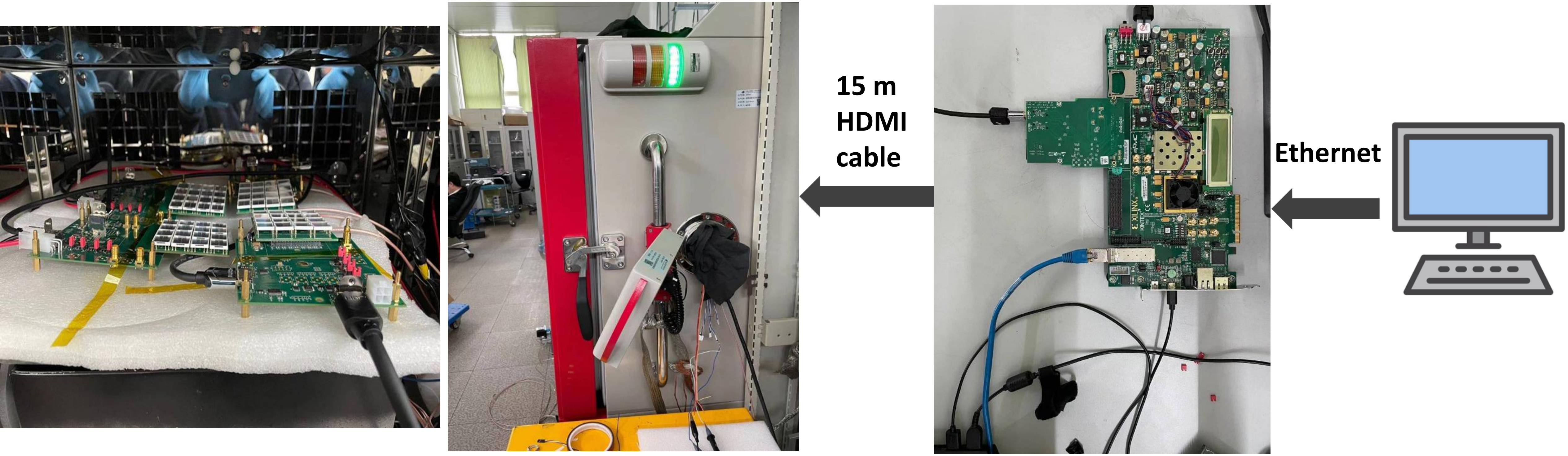
- 1 chip readout 2 tiles, 16 ch/tile
- Total 64,384 channels, 2012 chips
- Rigid-flex PCB, 4 tiles in 1 group
- Tile and FEB are connected with connectors
- Digital signals from FEB will be transferred to FEC via HDMI cables, 3-4 m inside the SS tank, ~10 m outside the tank

❄ FEC

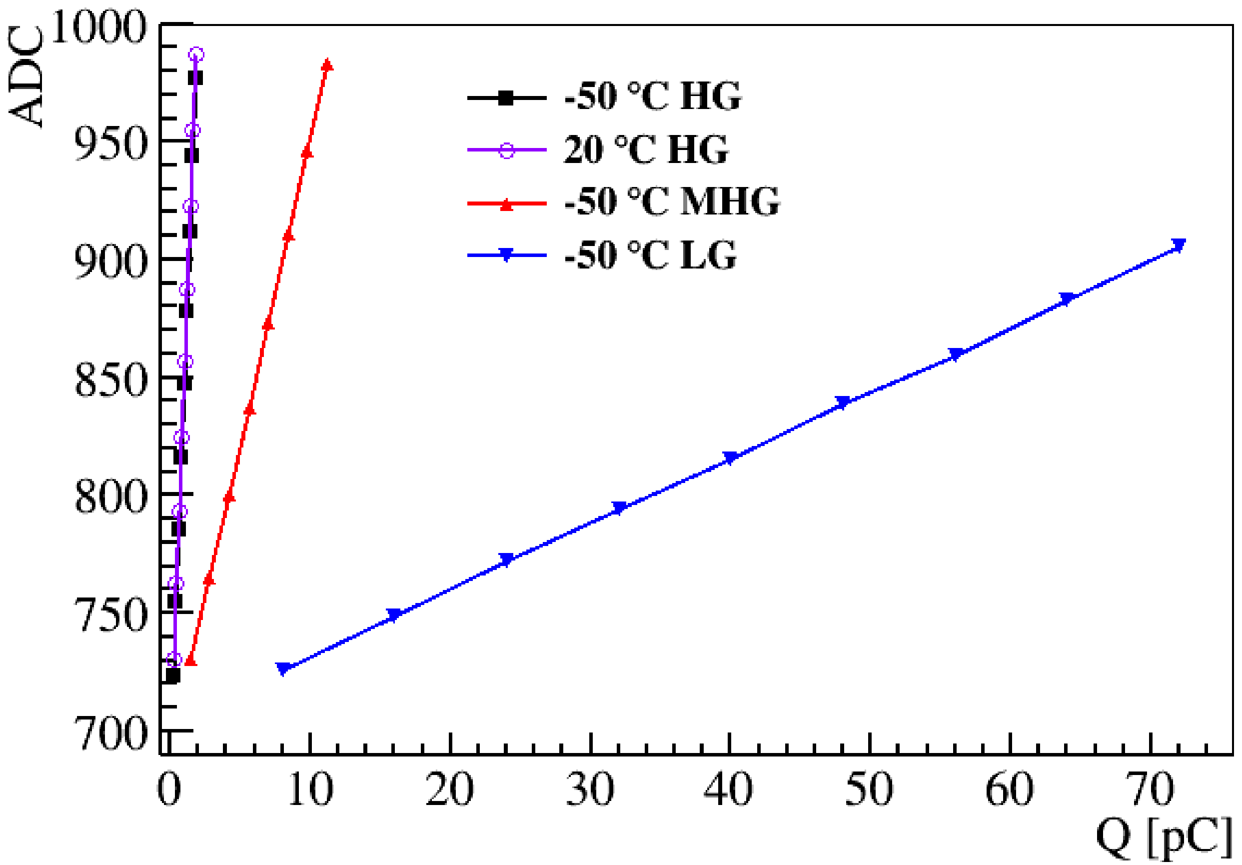
- FPGA & Power boards in MicroTCA.4 crate
- Slow control, timestamp, sending data to TDAQ

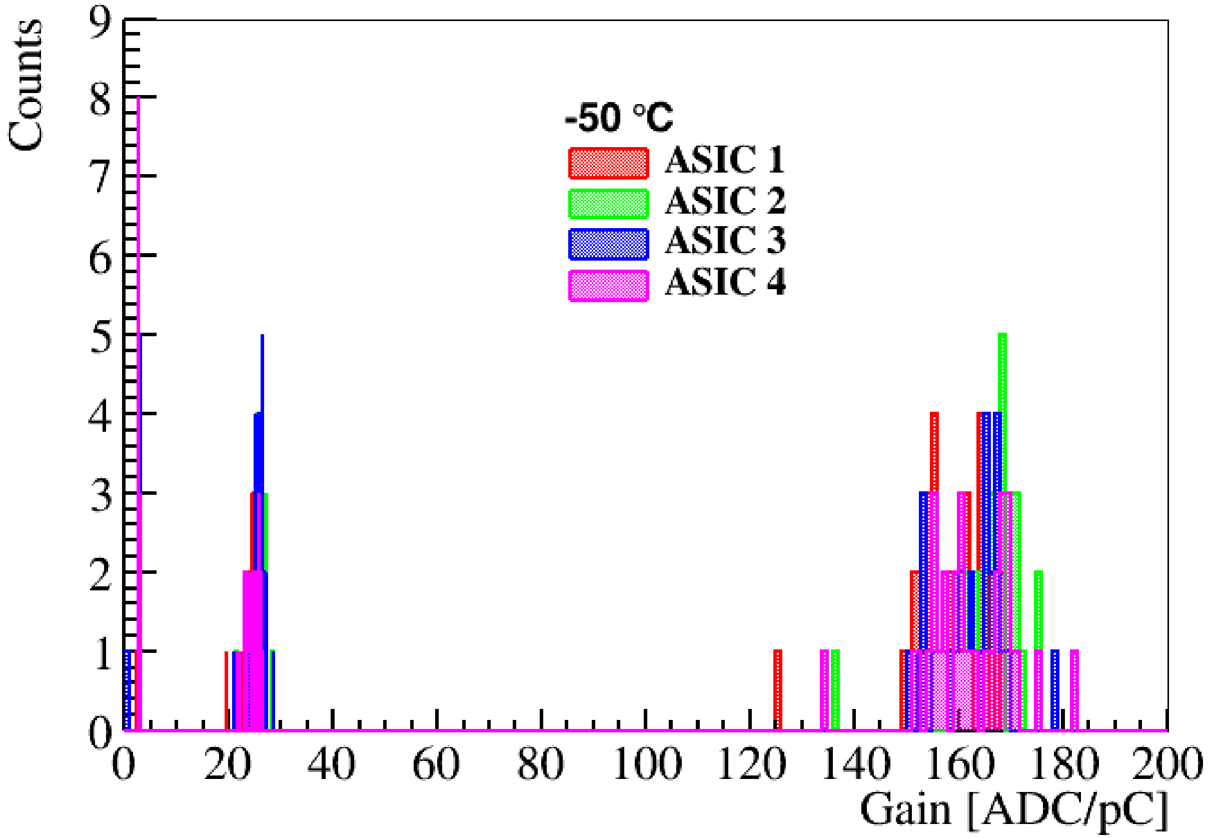
A mockup block with 1/1000 TAO readout channels





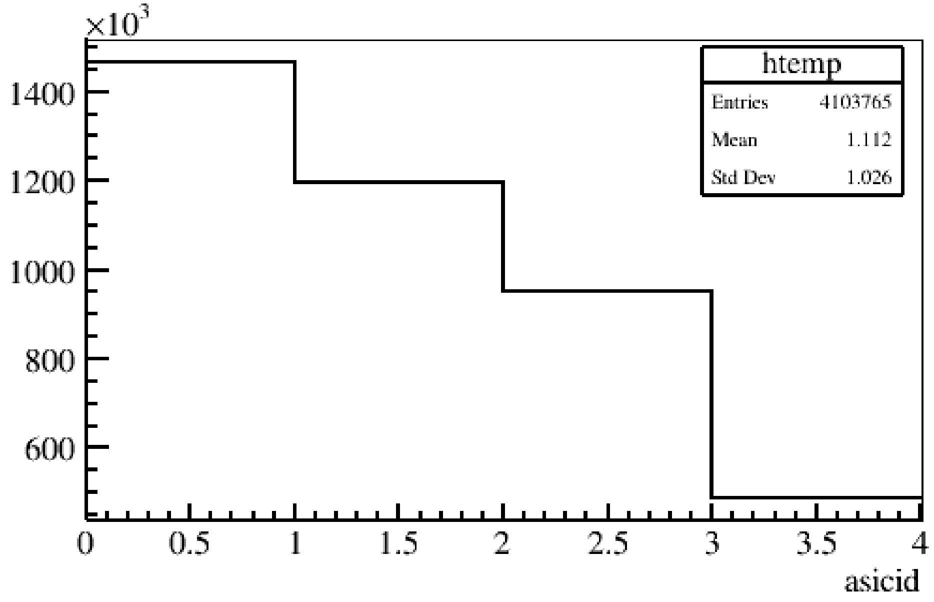
Gains in 3 branches (HG 1:1, MHG 1:7 and LG 1:40) have been characterized for 4 chips at low temperatures, which shows good linearity.



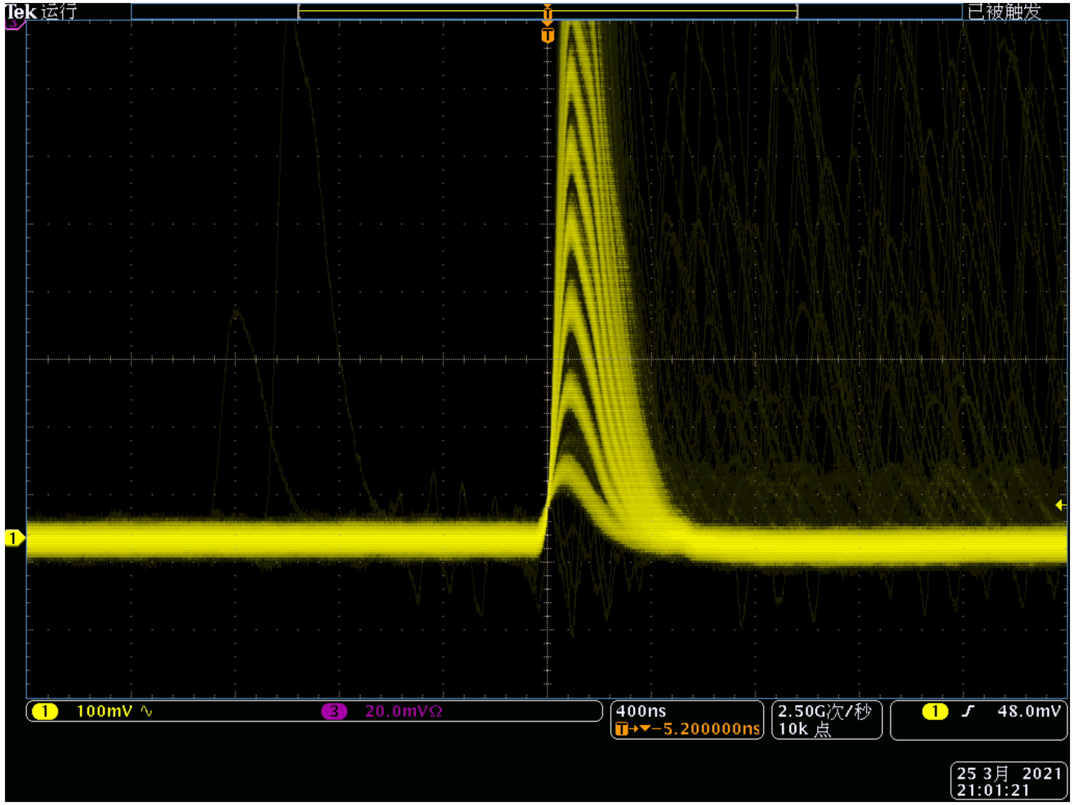


Signals from analog monitor

Bias voltage 53 V, break voltage 50.8V.

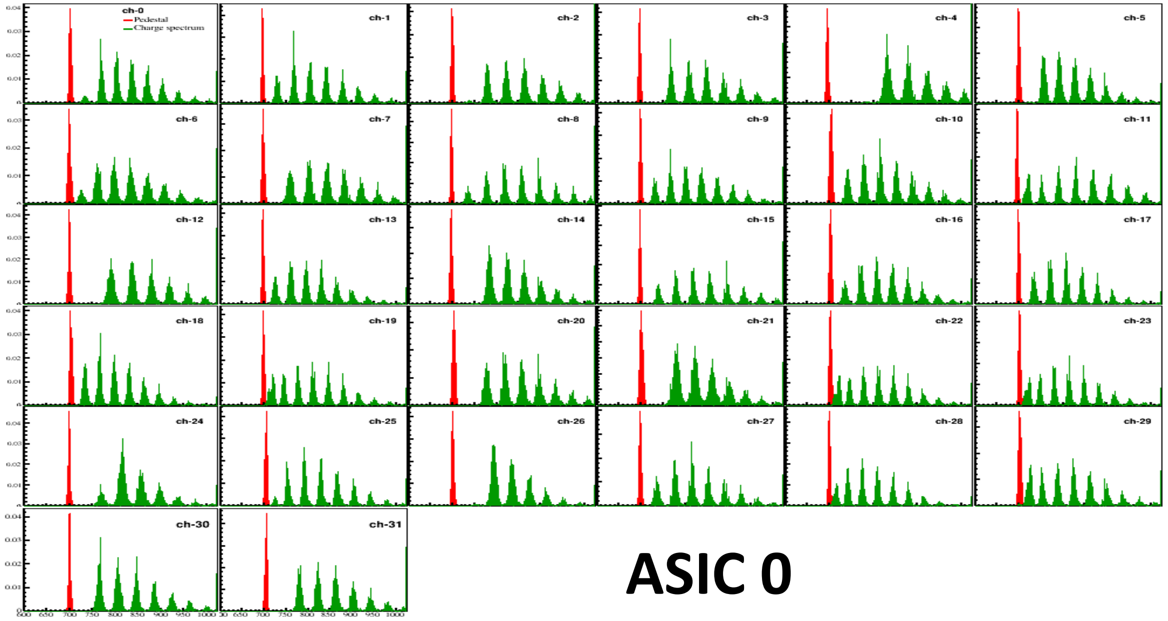


Distribution of chip ID

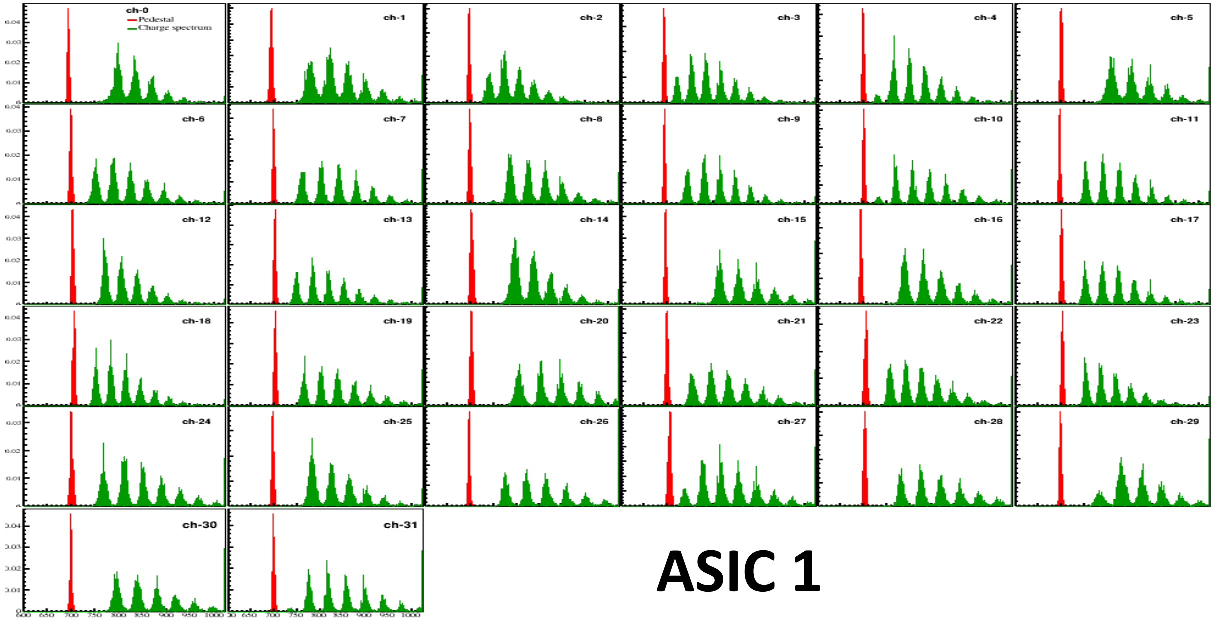


The analog signals after the shaper are monitored by an oscilloscope.

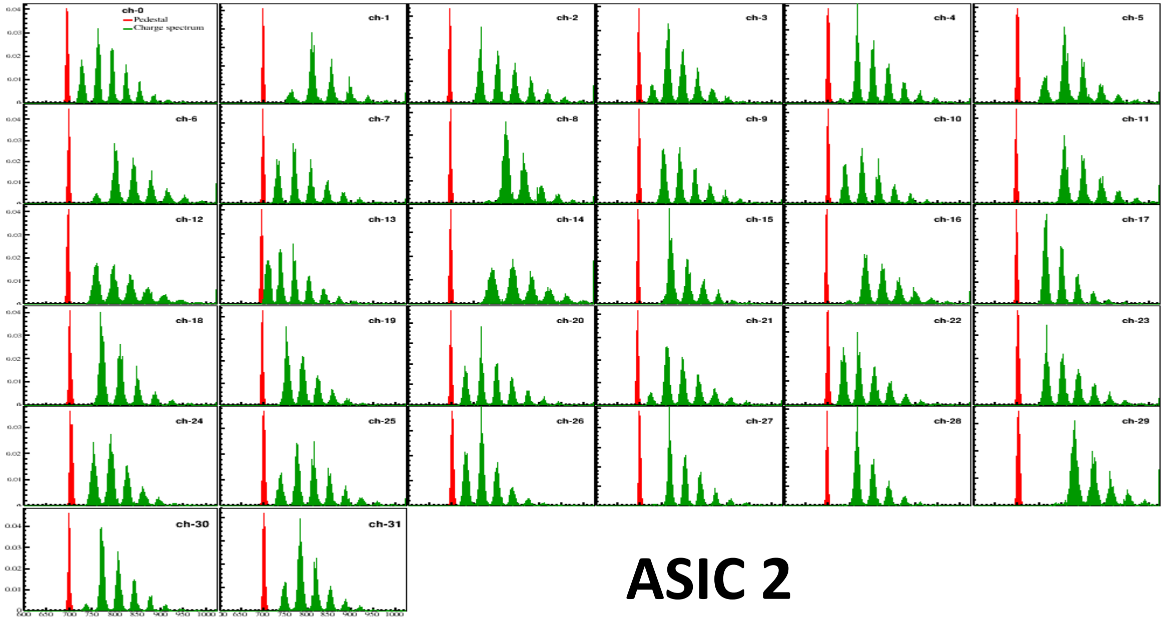
Charge spectra from 4 chips @ OV = ~2 V



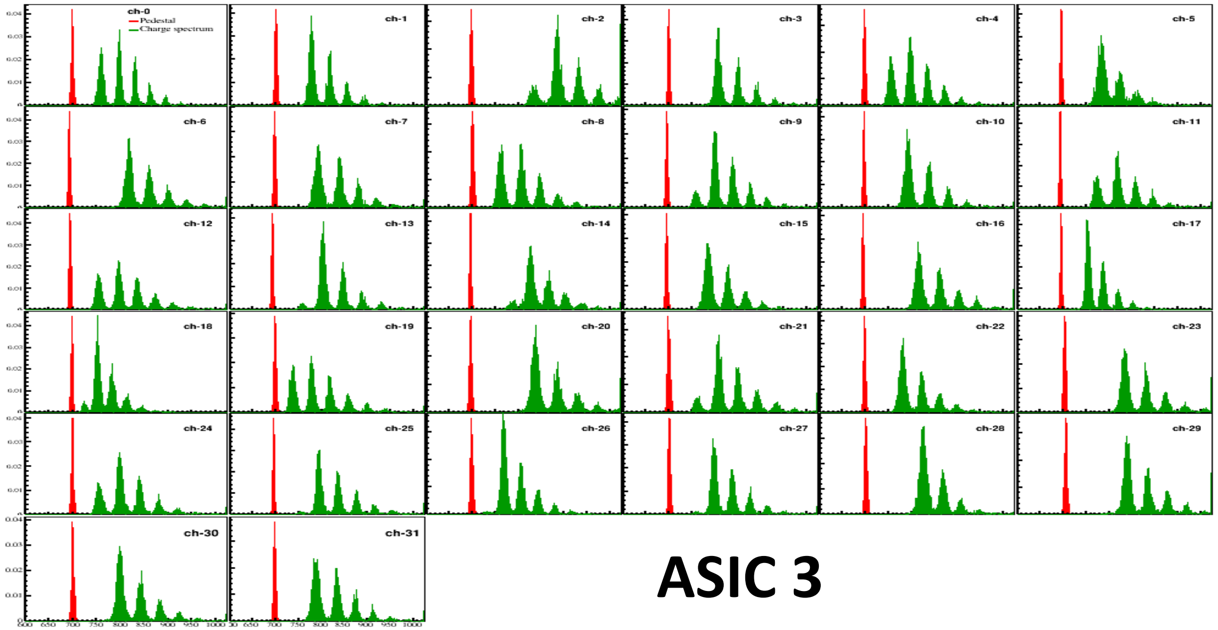
ASIC 0



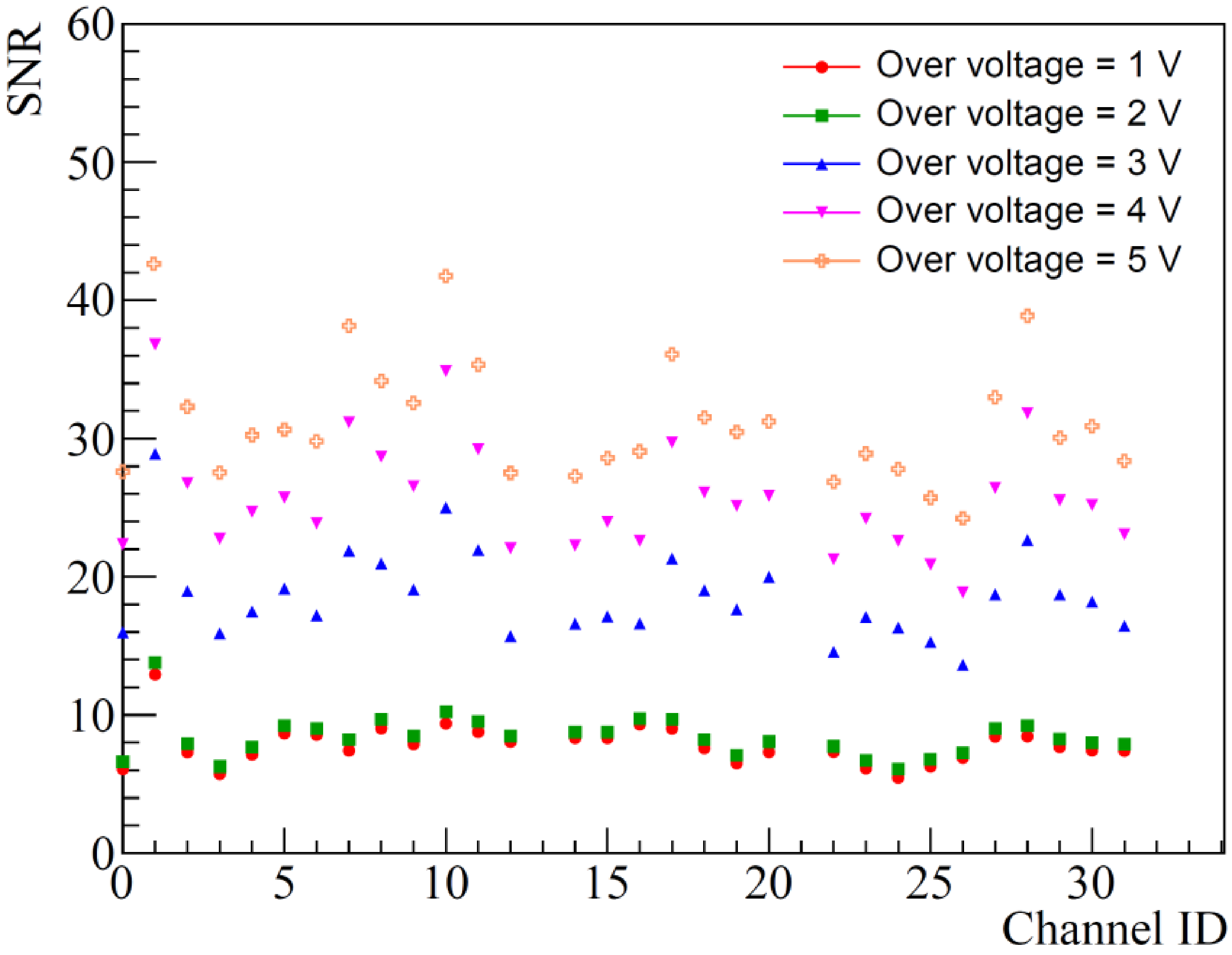
ASIC 1



ASIC 2

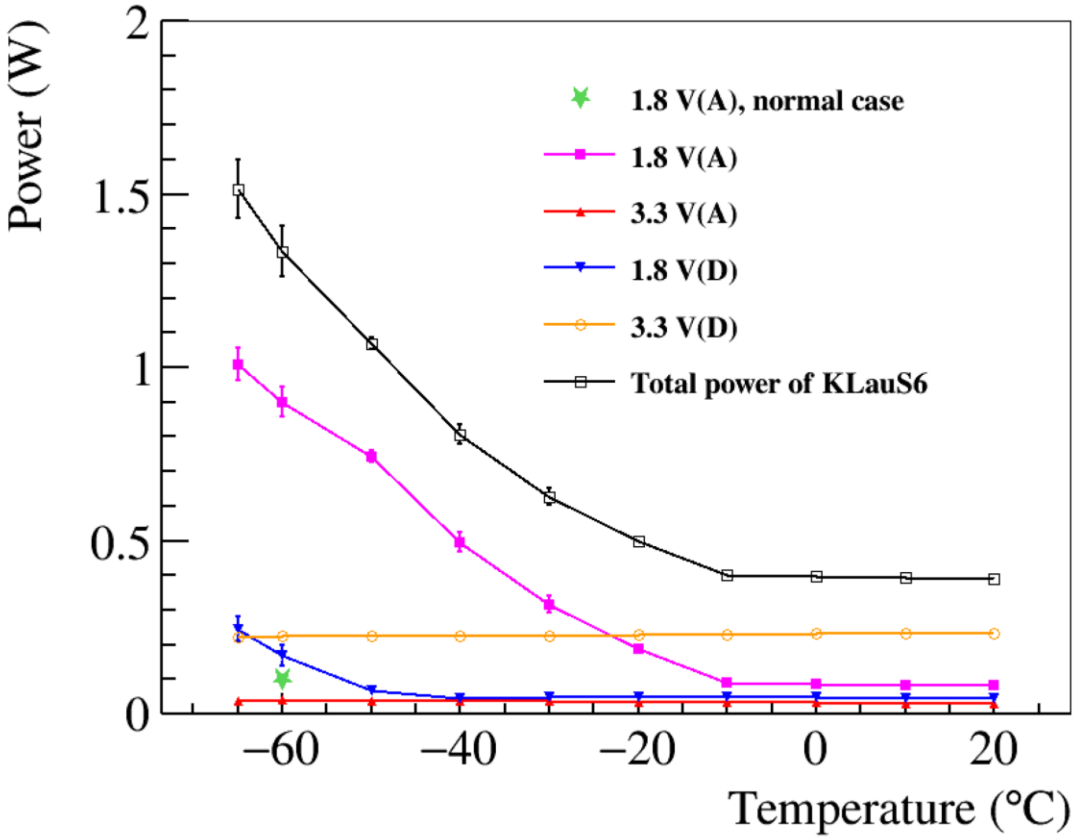


ASIC 3

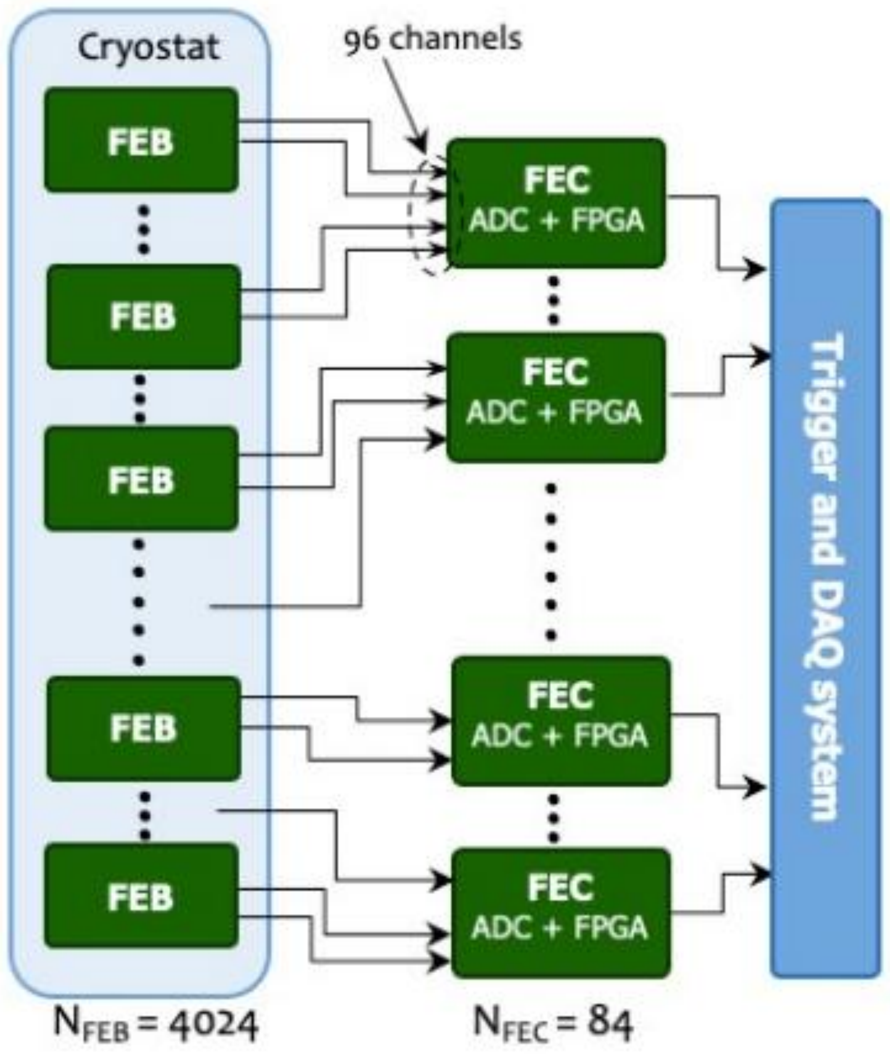

SNR
60
50
40
30
20
10
0
0
5
10
15
20
25
30
Channel ID
Over voltage = 1 V
Over voltage = 2 V
Over voltage = 3 V
Over voltage = 4 V
Over voltage = 5 V

❄ **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



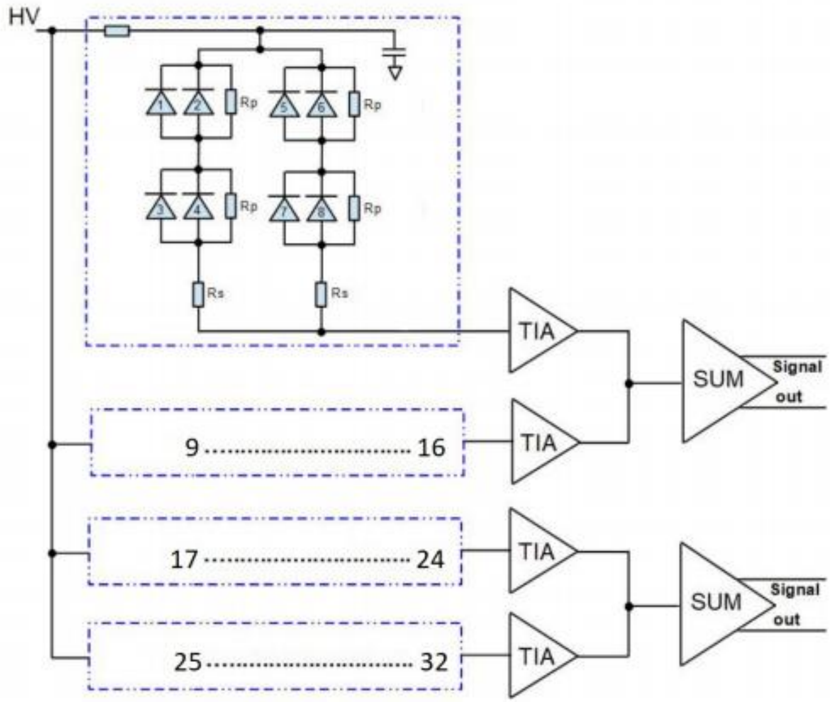
❄ **FEB**

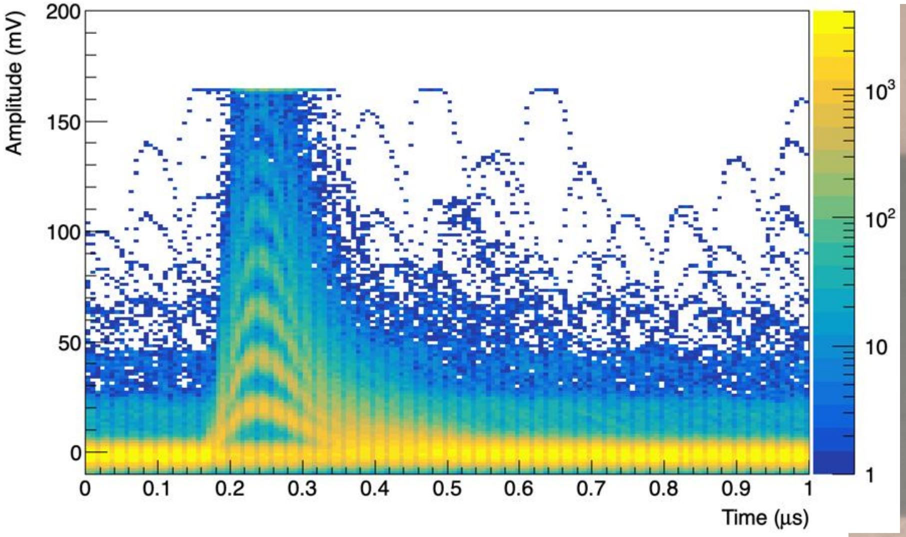
- **2 channel 1 tiles**
- **Total 8048 channels**
- **Tile and FEB are soldered**
- **Analog signals from FEB will be transferred to FEC via differential pairs, 3-4 m inside the SS tank, ~10 m outside the tank**

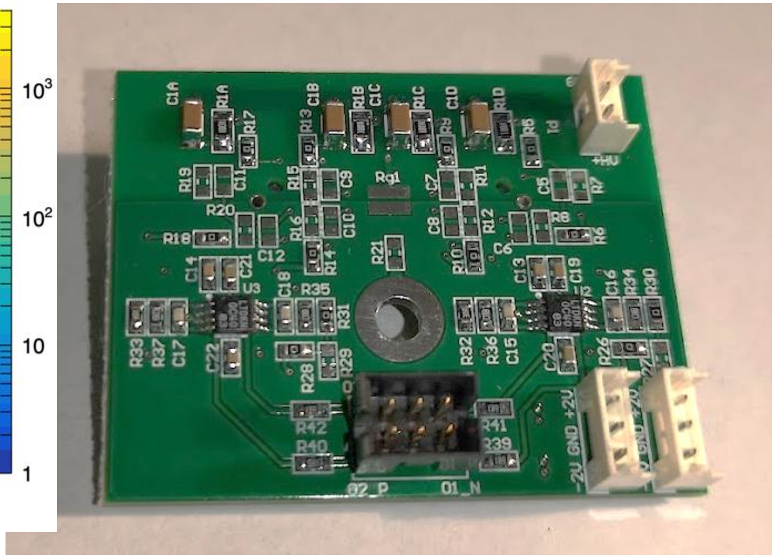
❄ **FEC**

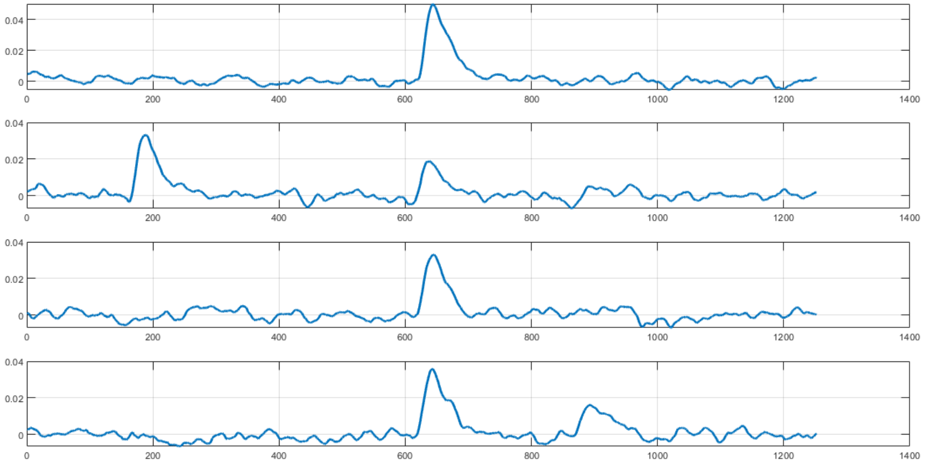
- **ADC is on FEC, used to digitize analog signals from FEB**
- **FPGA & Power boards in MicroTCA.4 crate**
- **Q/T information is extracted with FPGA (waveform analysis)**

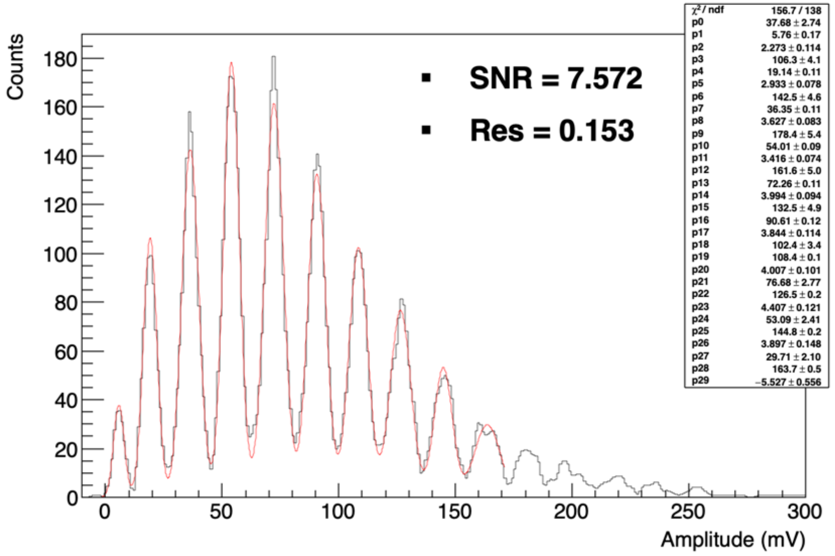
FEB

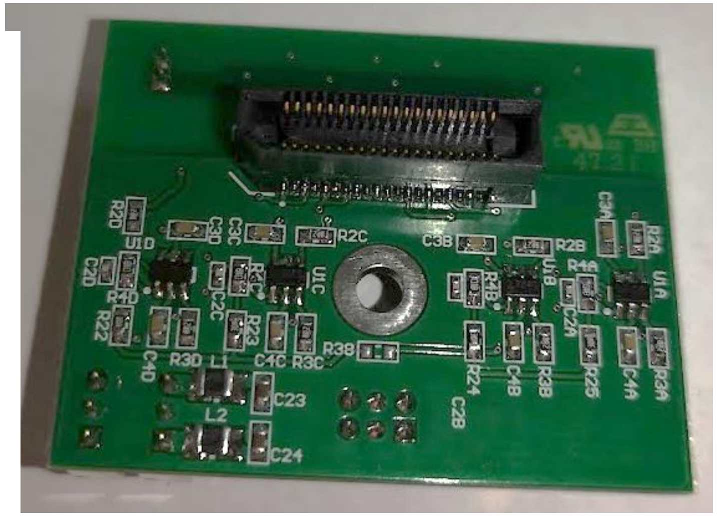

HV
Rp
Rs
TIA
SUM
Signal out
9 16
17 24
25 32


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

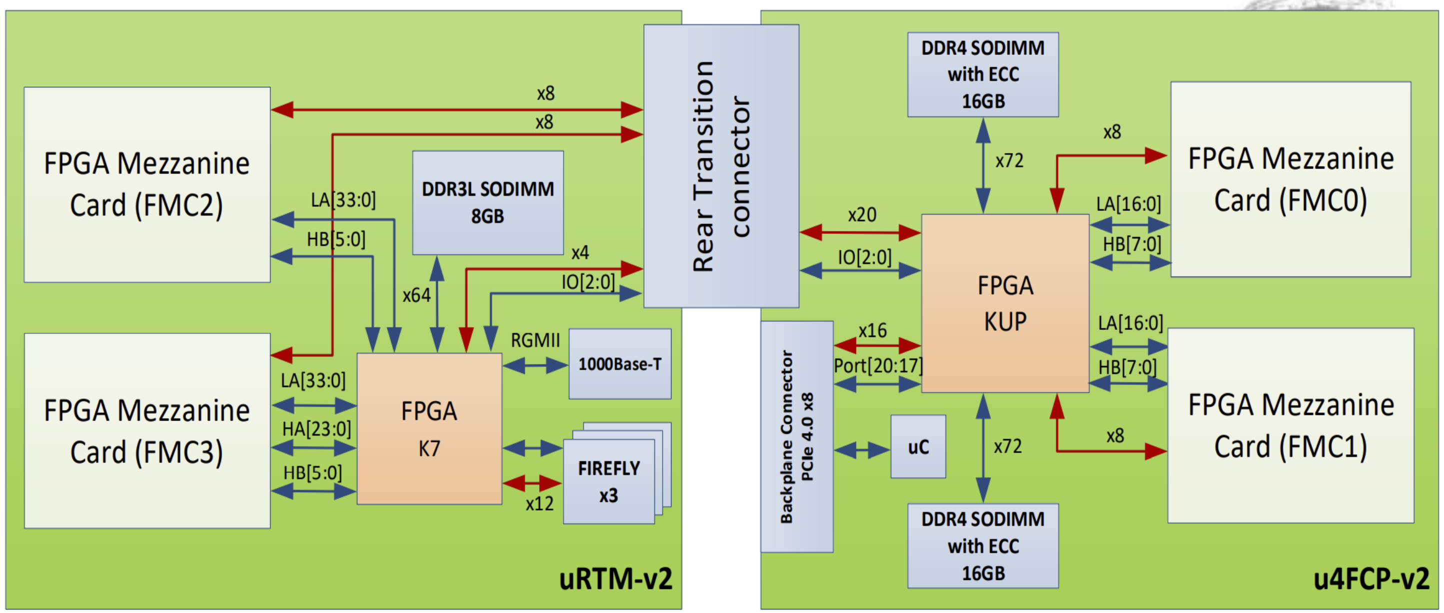
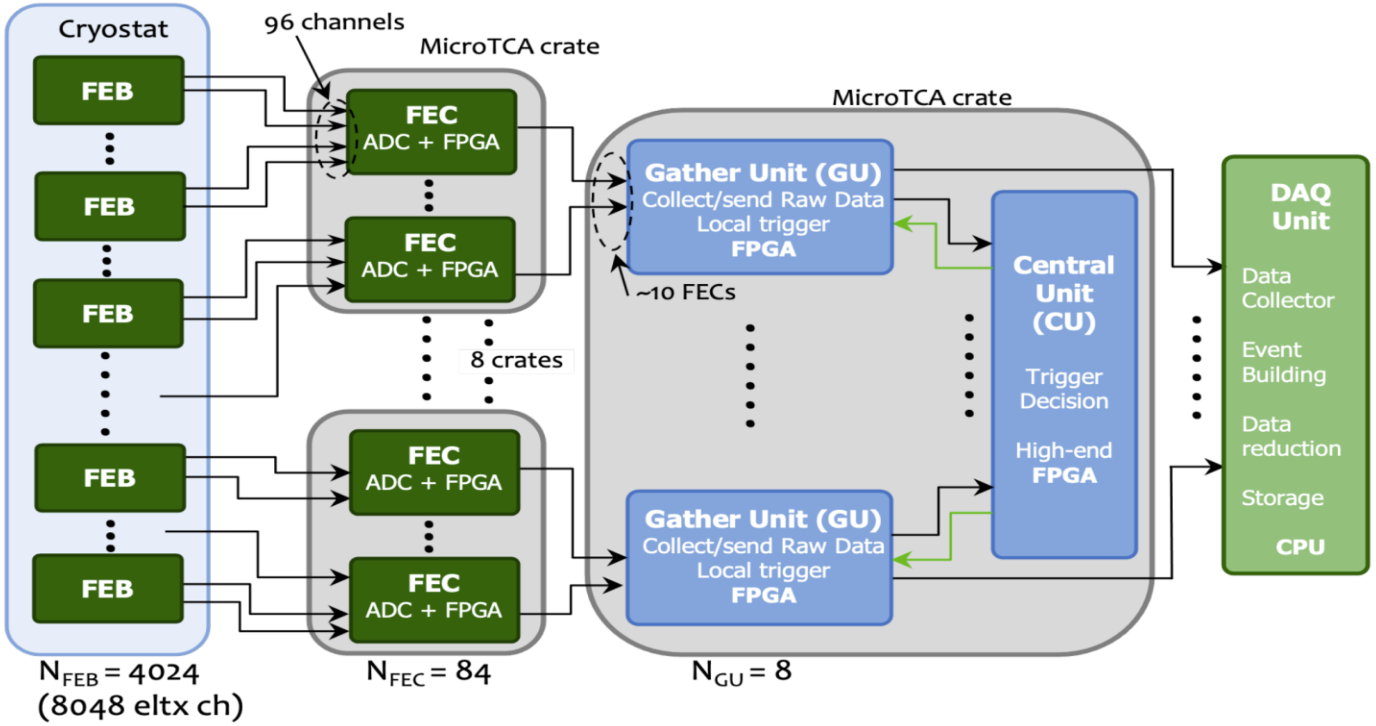


Photo of previous version (V1)

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	$64 \cdot 10^3$	-
TOTAL			**$64 \cdot 10^3$**	**240-400 (a)**

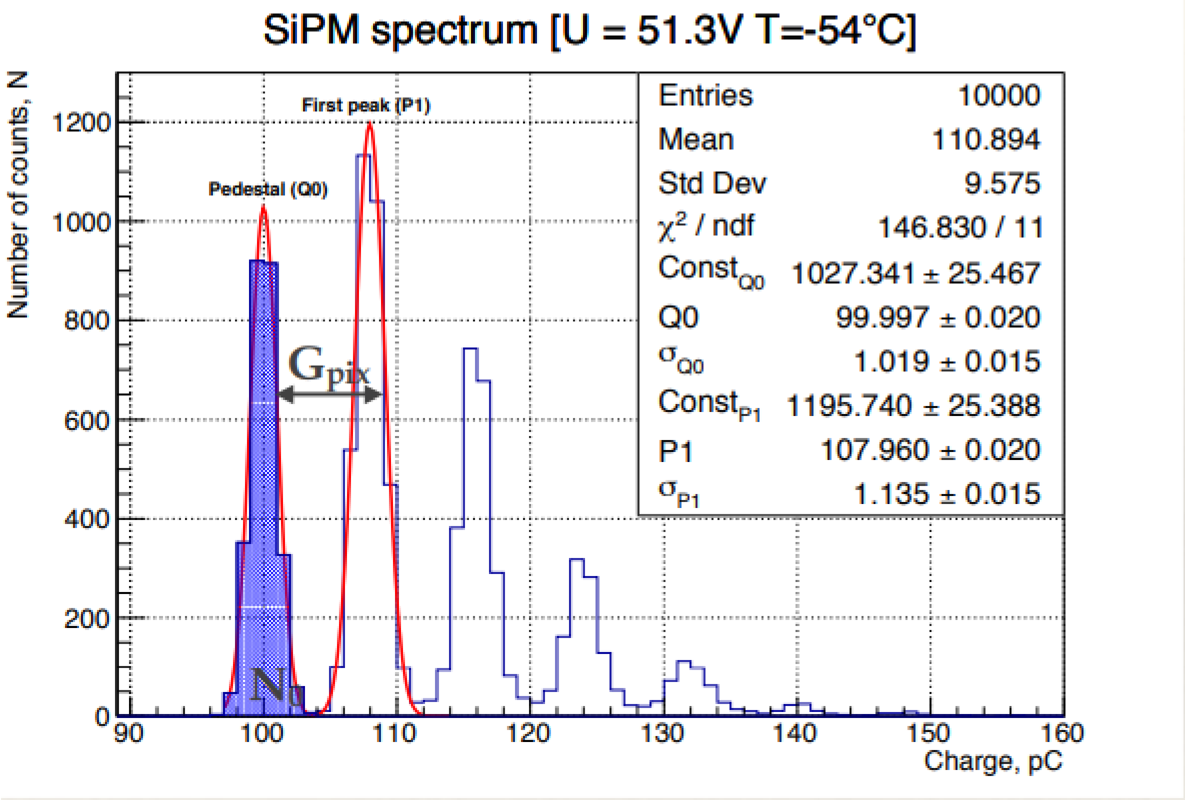


- ❄ **High input data rates in the trigger system is a challenge**
- ❄ **Output data rate has to be < 100 Mbps:**
- ❄ **We need to implement a logic to reduce data size for large energy events at FEC level;**
- ❄ **A local FEC logic can be implemented to reduce DCR hits rate to the TDA**

- ❄ **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.**



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):

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