Performance of the Mass Testing Setup for Arrays of Silicon Photomultipliers in the TAO Experiment

NUCLEUS-2024

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on behalf of the JUNO Collaboration
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OUTLINE

1. JUNO Detector overview
2. TAO Detector overview
3. Photodetectors overview
4. Scanning station design
5. SiPM Mass testing setup at IHEP
6. Mass testing procedure
7. Setup control software
8. Methods of parameter estimation
9. Results
10. Summary

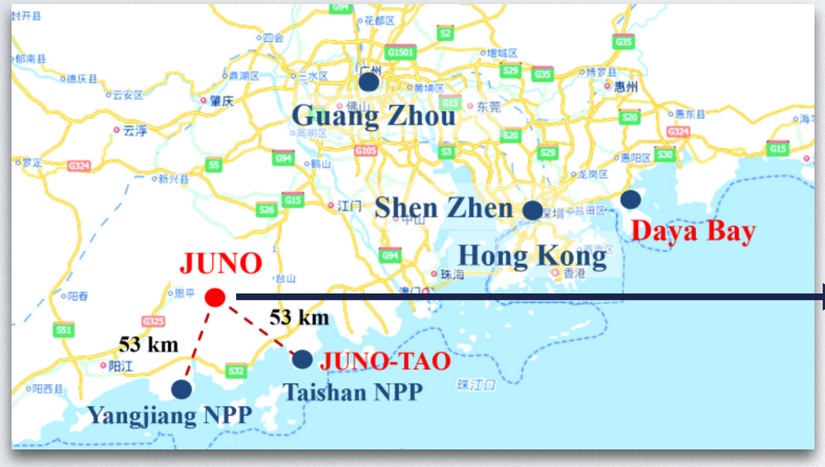
JUNO DETECTOR OVERVIEW

The Jiangmen Underground Neutrino Observatory

JUNO Physics Goals:

- Neutrino mass hierarchy measurements
- Oscillation parameters measurements
- Astrophysics and rare processes

Location:

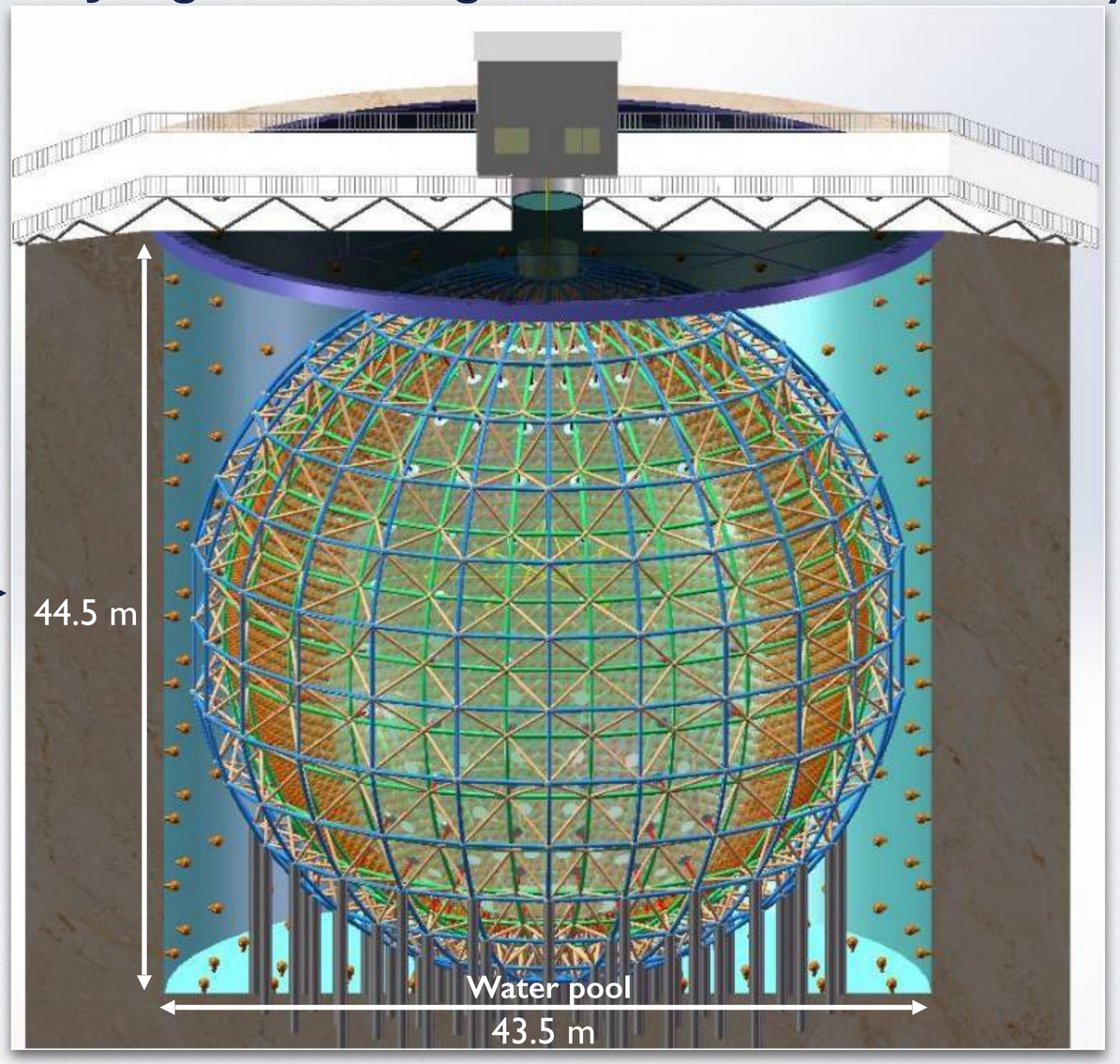


Baseline:

52.5 km

Powerful source:

Yangjiang and Taishan power plants
26.6 GWth in 2020, later 35.7 GWth



Parameters:

- ø35.4m Acrylic Vessel
- 41.1m Stainless Steell Structure
- 20 kton Liquid Scintillator
- 17’612 large 20” photomultiplier tubes (PMTs)
- 25’600 3” small PMTs
- Water Cherenkov Veto 35 kton pure water and 2400 20” PMTs
- 700 m underground

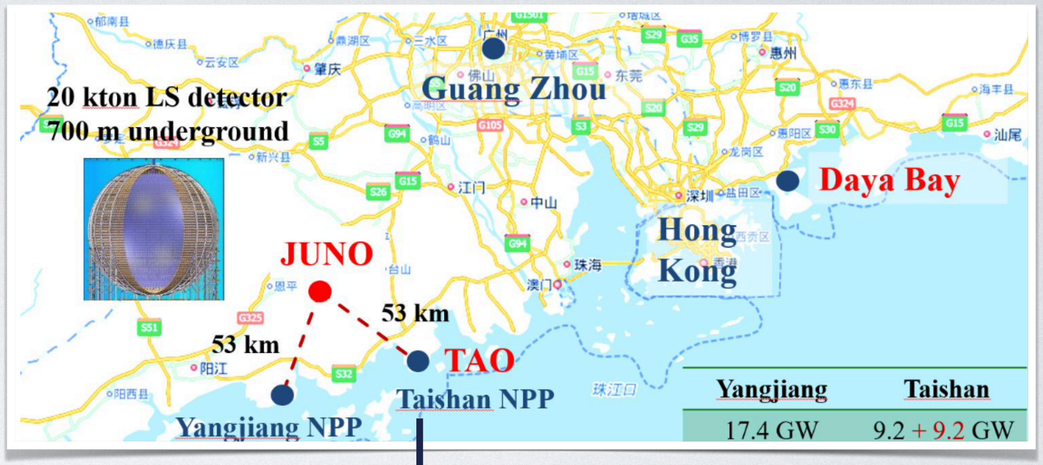
TAO DETECTOR OVERVIEW

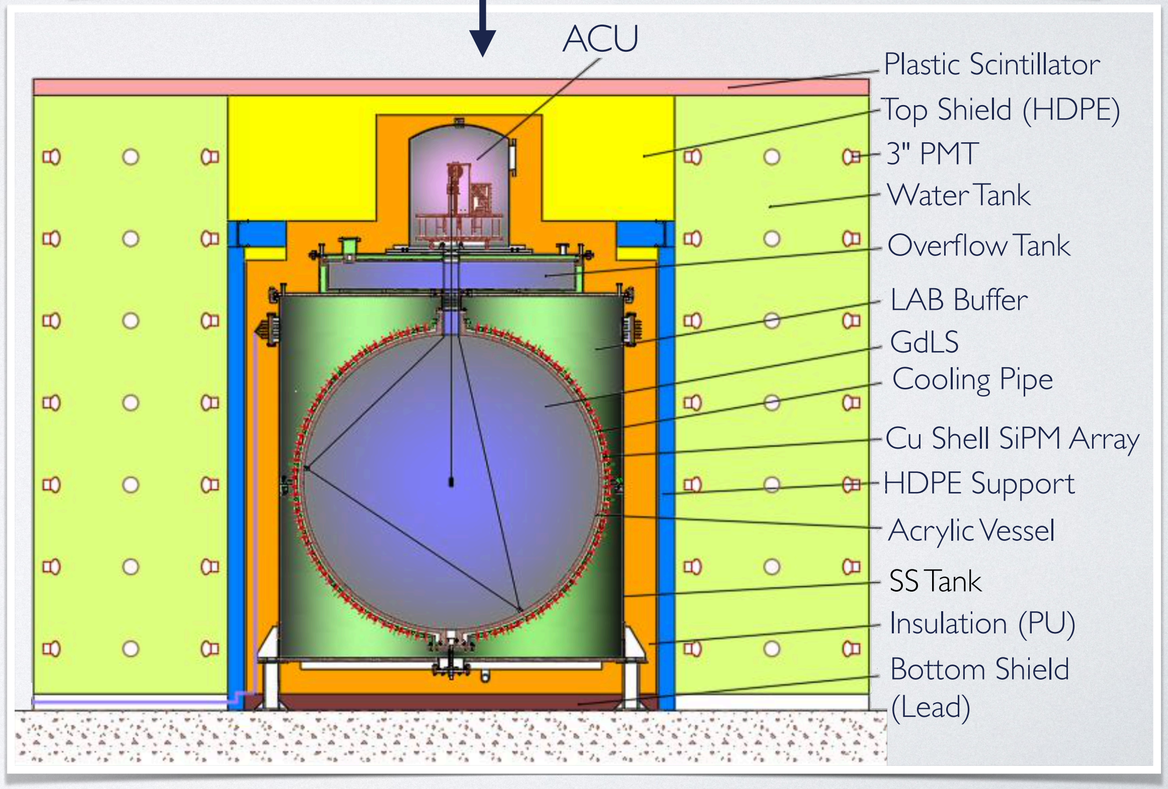
Taishan Antineutrino Observatory

- ~44m to core
- Ton-level fiducial mass
- N(p.e.) ~4500/MeV, ~85% SiPM cover
- Low dark noise: -50°C → Low T LS
- Energy resolution < 2%/MeV

TAO physics goals:

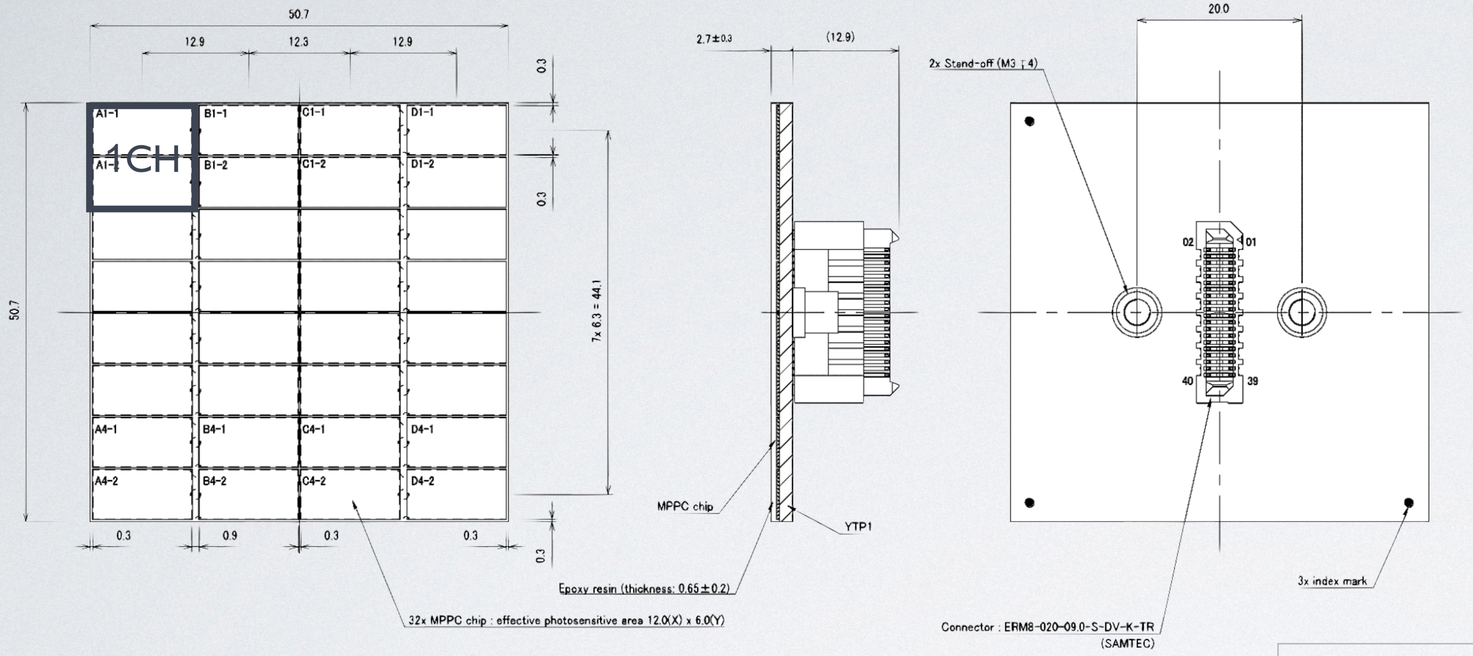
- measure reactor antineutrino spectrum with high energy resolution
- A new benchmark to test the nuclear database

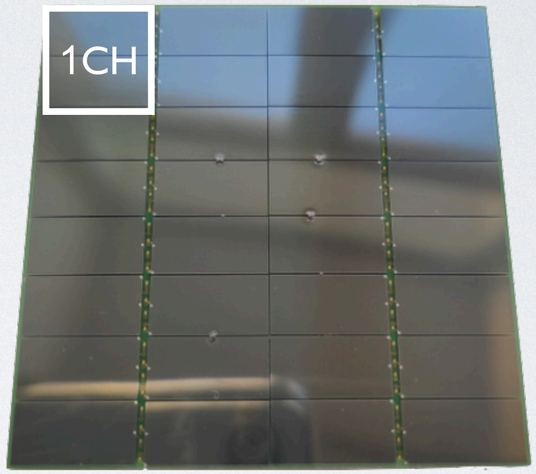


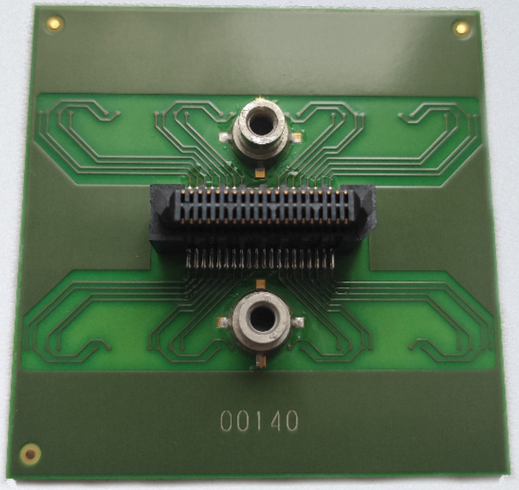


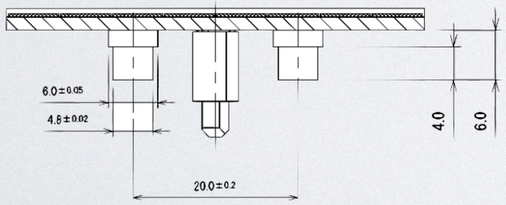
TAO PHOTODETECTOR OVERVIEW

TAO Tile - array of 32 S16088 Hamamatsu MPPCs

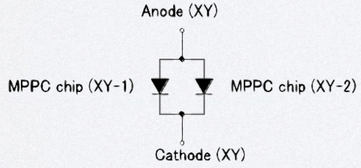








[NOTE]
1. General tolerance: ±0.1
2. Connected each of 2 chips in parallel (X: A - D, Y: 1 - 4)



Main parameters

Number of channels	16 (2 SiPMs in parallel)
Effective photosensitive area	12 x 12 mm^2/ch
Pixel pitch	75 um
PDE at 420 nm	49 %
Breakdown voltage	48 ± 2 V
Gain	4.0x10^6
Dark Count Rate at -50°C	45 Hz/mm^2
Crosstalk probability	12 %

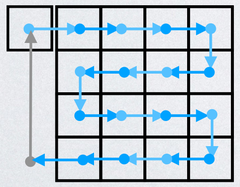
*at operating voltage

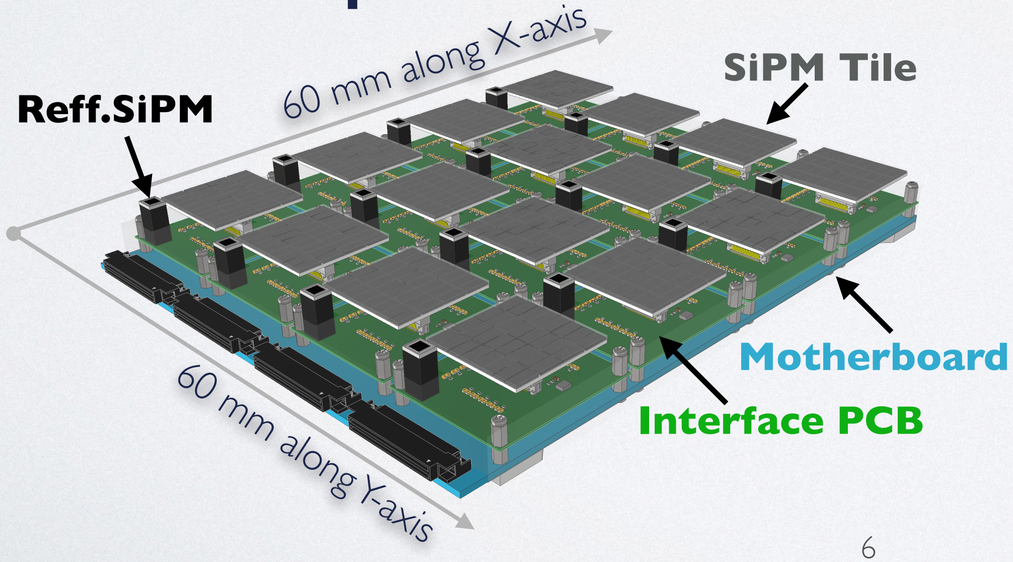
SCANNING STATION DESIGN

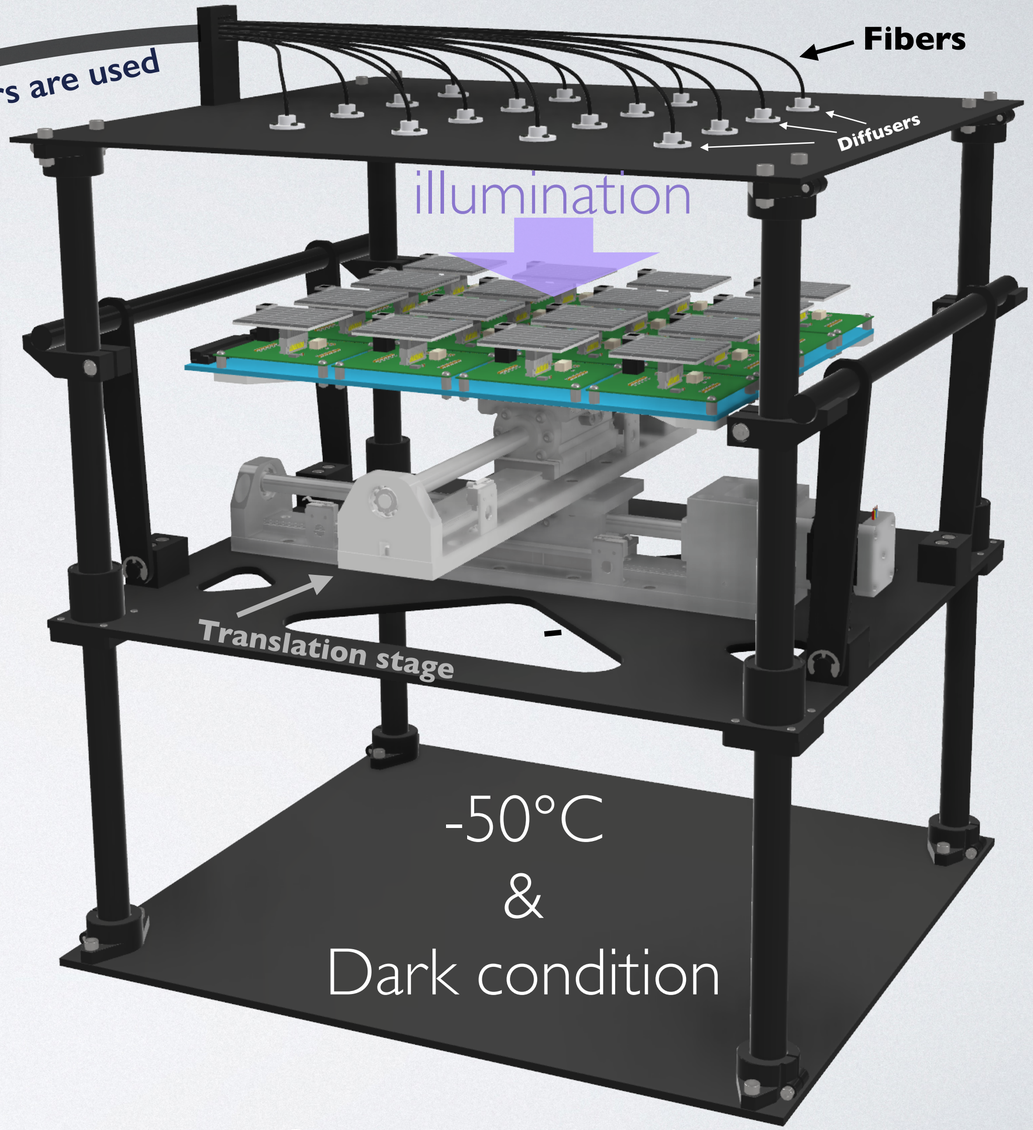
Light distribution system

Main platform

Free movement along two axes



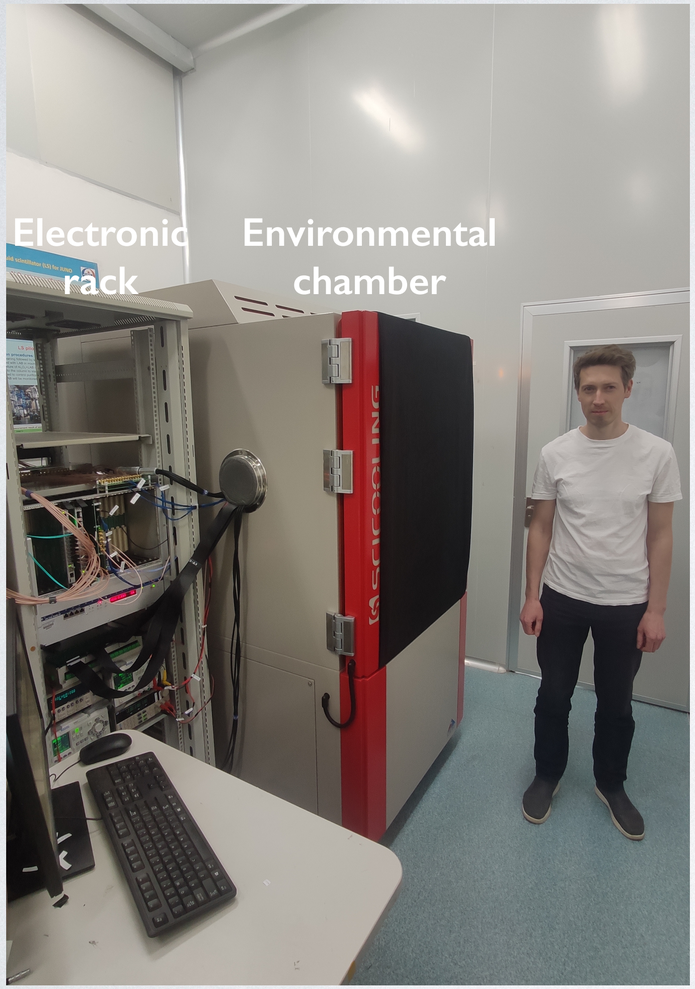




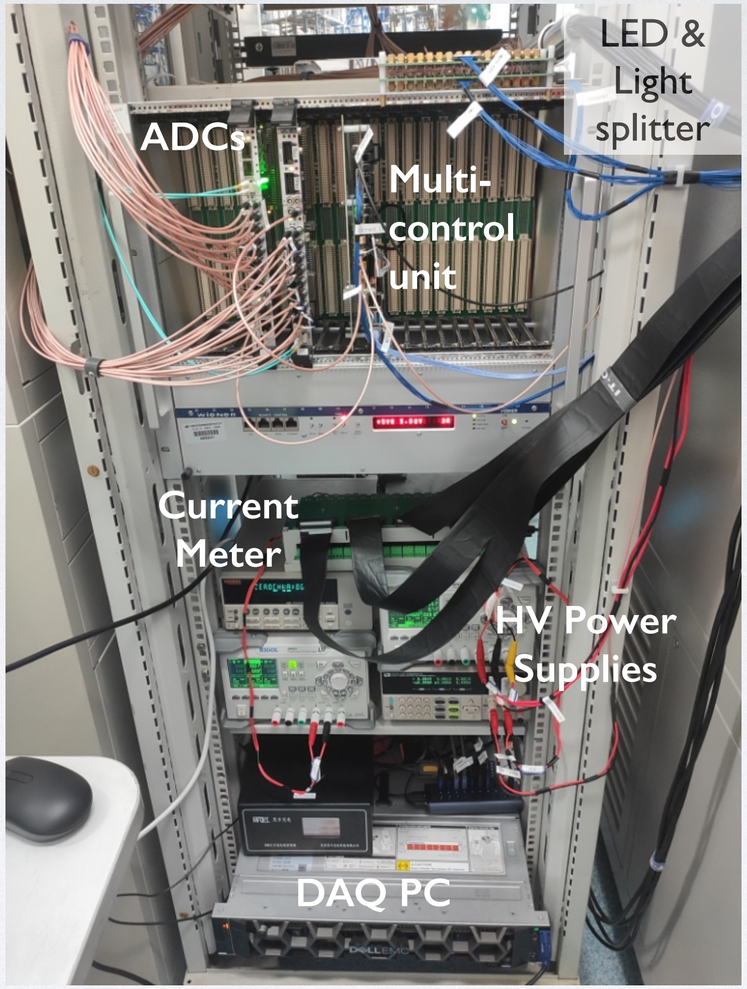
Stand mechanics

MASS TESTING SETUP (IHEP)

Outside view

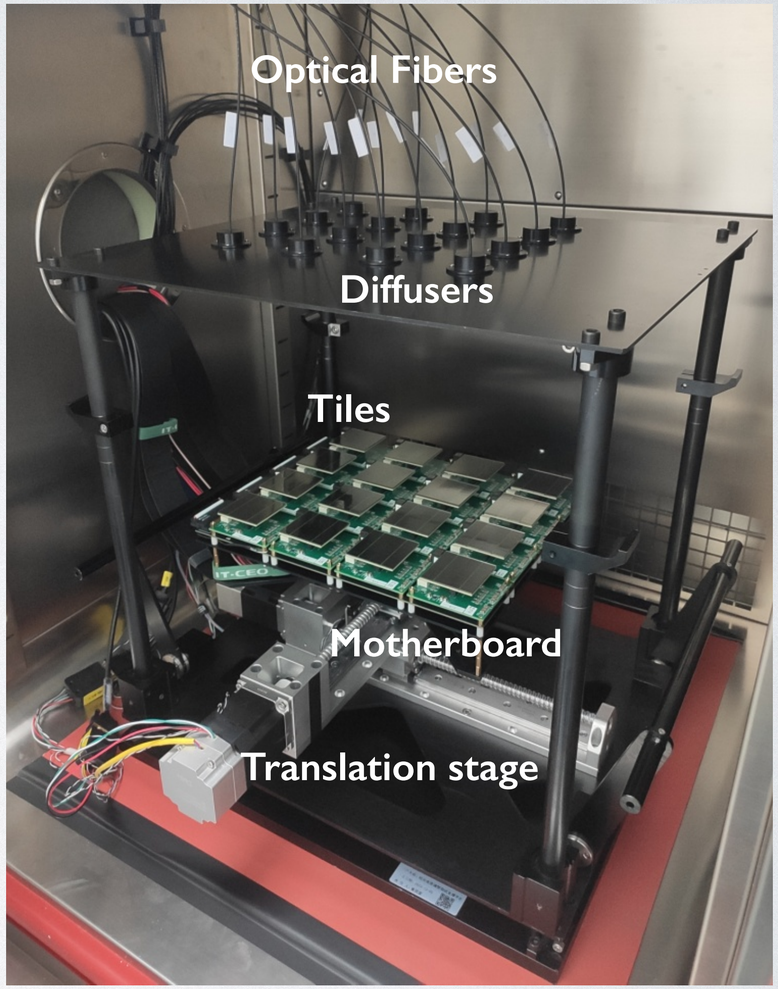


Electronics



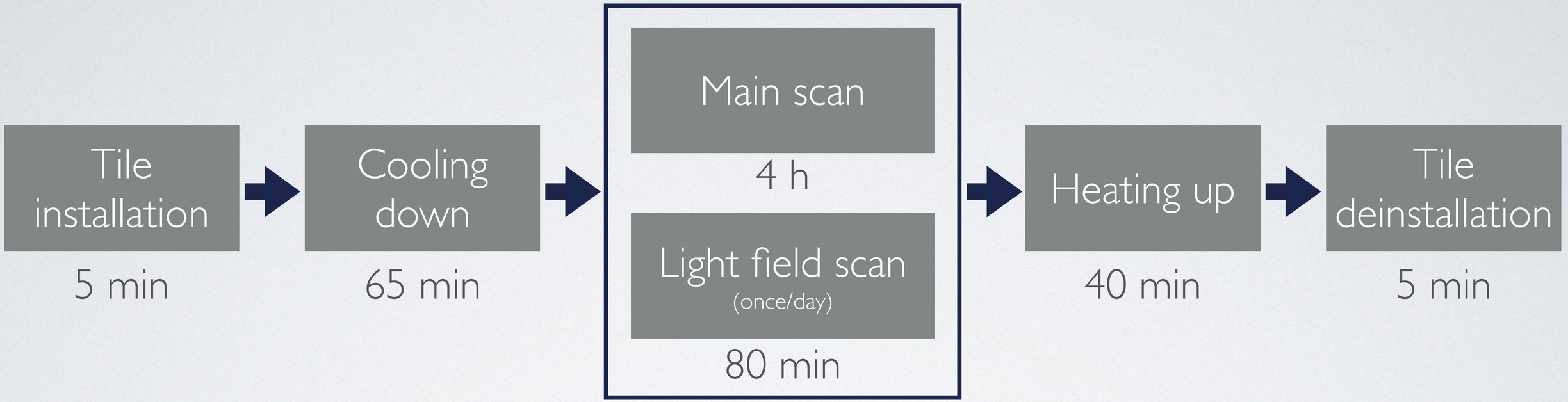
Inside electronic rack

Mechanics



Inside environmental chamber

MASS TESTING PROCEDURE



Single scan time ~6h

3 scans/day or 48 tiles/day

Total mass testing time ~90 days

SETUP CONTROL SOFTWARE

Green LAB

Monitor Settings Main-DB Light-DB

MAIN RUN | LIGHT RUN | STOP RUN | OSCILLOSCOPE

Hardware Info: Status: OK

Server status:	Web Server	Digitizers		MCUnit	SiPM Power		HV Multiplexer		LED		Current Meter		Stage Controller		Stage Decoder	
Device status:		080C-635B	0CD9-6B60		connected		/dev/ttyUSB4		/dev/ttyUSB1		/dev/ttyUSB0		disconnected		/dev/ttyUSB3	
Tile position #:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
TSensor SN:	cc705ff	4063fff	d858fff	d4b74ff	cd7e2ff	40505ff	f3f51ff	c5a72ff	cd8c9ff	d6cb7ff	cdefcff	d8890ff	d7480ff	ce2b6ff	d1a6dff	d83a6ff
Temperature: show	-48.69	-49.44	-48.81	-49.50	-47.50	-47.94	-49.00	-49.19	-47.56	-48.44	-47.25	-48.56	-47.75	-47.69	-48.88	-48.63
Tile SiPMs Voltage:	relay # 1								52.998 V							
Reff. SiPMs Voltage:	ON								52.919 V							
LED state:	OFF								0							
Measurement mode:	Spectrum								Current							
Current multiplexer CH#:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Current meter:	Tile #4								-5.943261e-9 A							
Stage position:	#home [X:0, Y:0]								Decoder X: 0				Decoder Y: 0			

Run configuration Info:

Setting:	Value:
Applied config ID:	28
LED intesity:	400
Trigger frequency:	600
Trigger type:	0
Run statistics:	30000
Start from voltage:	48
Number of voltage points:	6
First overvoltage point:	1
Voltage step:	1
Reff.SiPM voltage:	52.92

Run status:	Current Multiplexer - Set Channel: 5 - Server status code: 200 MCUnit: ok

Run progress:	**-4.0V**	**1.0V**	**2.0V**	**3.0V**	**4.0V**	**5.0V**	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8	CH9	CH10	CH11	CH12	CH13	CH14	CH15	CH16	**6.0V**

ANALYSIS CONVENTIONS

Digitizer parameters

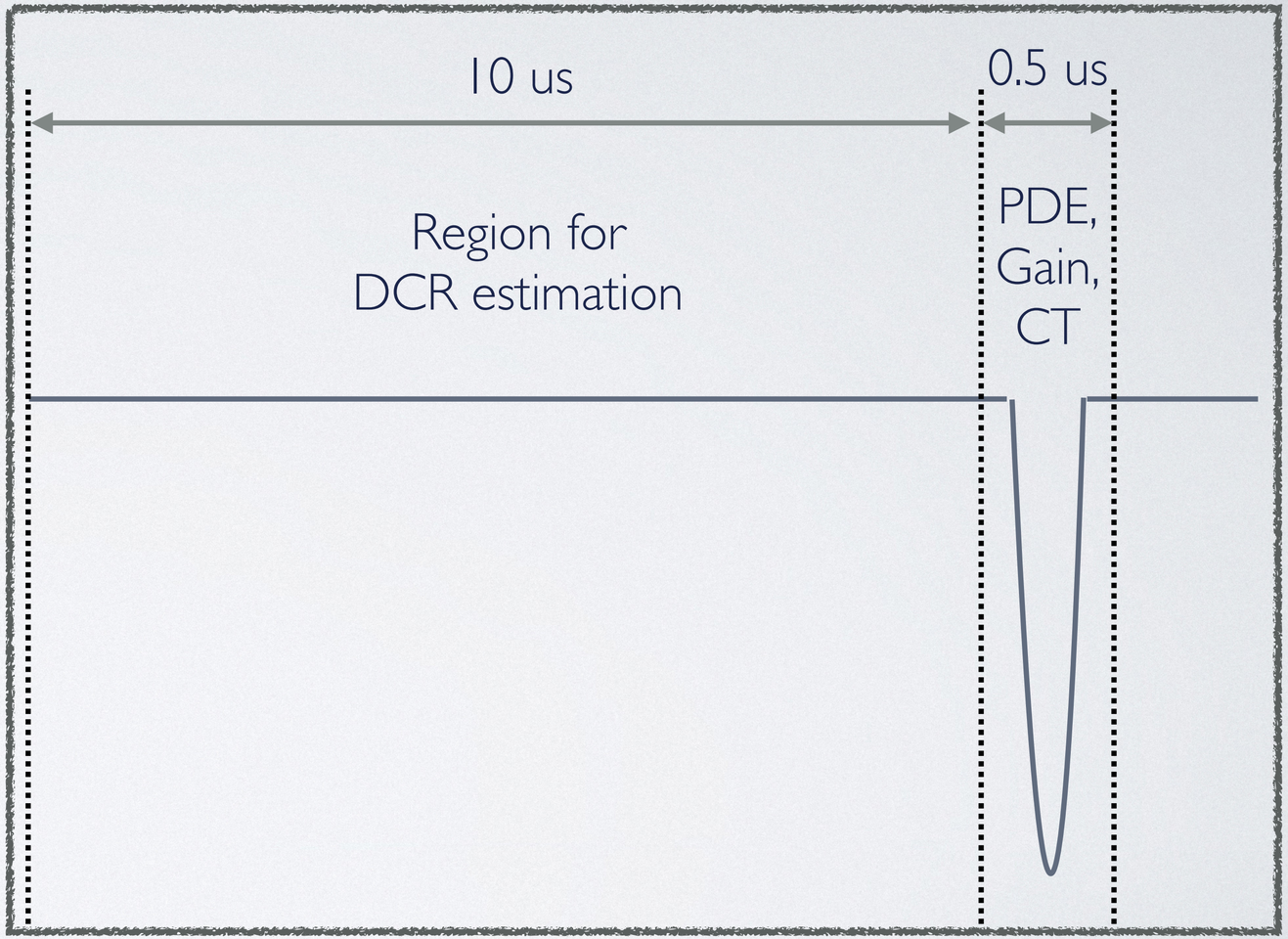
Parameters	Values
Number of channels	16
Time discretization	125 MHz
Resolution	14 bit
Voltage range	2 V
Maximum window width	16us

1 ADC - SiPM Tile data acquisition
2 ADC - continuous monitoring of LF with Reff. SiPMs

Run parameters:

Parameters	Values
Number of oscillograms	30k
Time window for light pulses	0.5 us/oscillogram
Time window for dark pulses	10 us/oscillogram
Voltage scan range	1 - 6 V
Voltage scan step	1 V

Single oscillogram

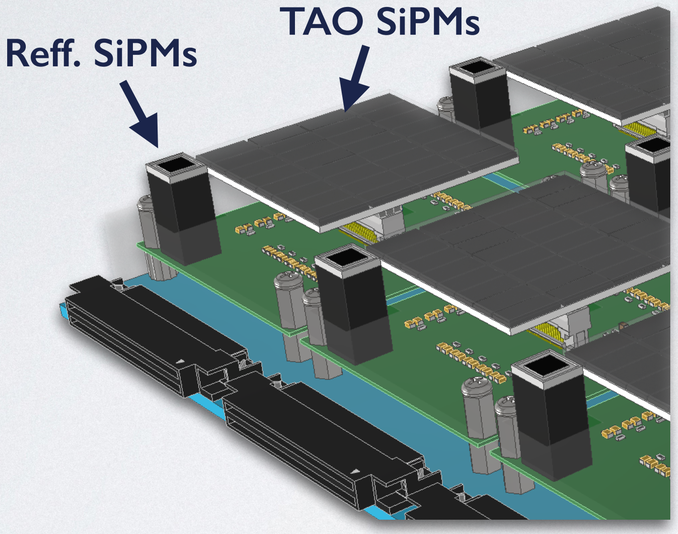


PHOTON DETECTION EFFICIENCY

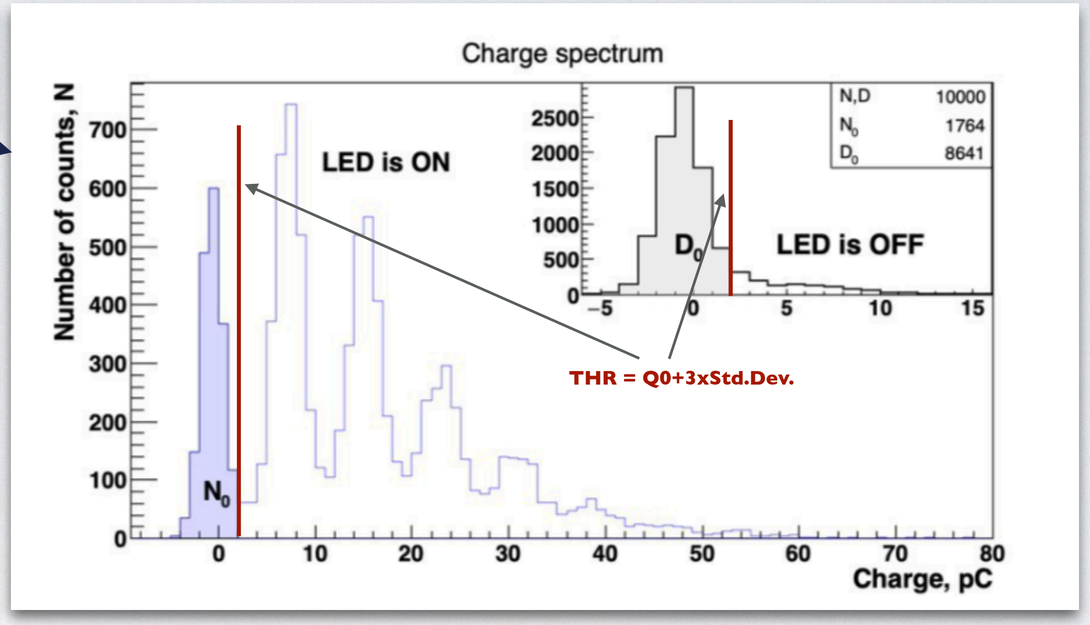
Absolute PDE value:

$$PDE_{tao\ sipm} = \frac{\mu_{tao\ sipm}}{\mu_{ref\ sipm}} \times PDE_{ref\ sipm}$$

*μ - number of photoelectrons



Estimation of the number of photoelectrons

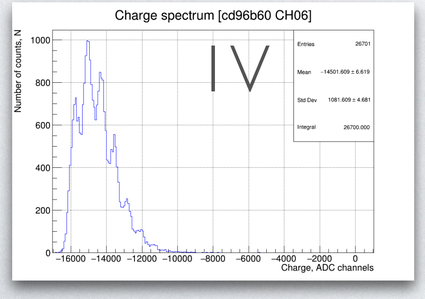


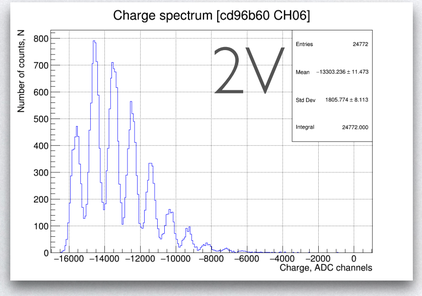
$$e^{-\mu} = \leftarrow \underline{Poisson(\mu, n=0)} \rightarrow = (\frac{N0}{N})/(\frac{D0}{D}),$$

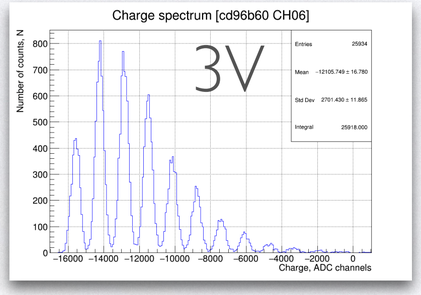
$$\mu = -\ln\left(\frac{N_0}{D_0}\right).$$

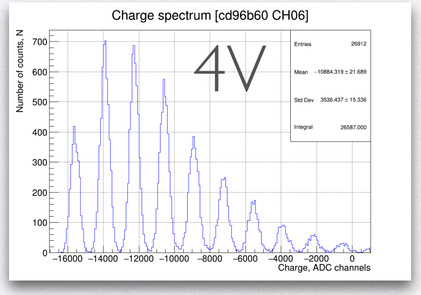
$$\sigma_\mu \approx \sqrt{\frac{D_0 + N_0}{D_0 N_0}}.$$

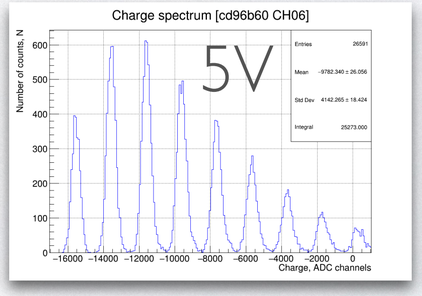
Accuracy: ±0.5%

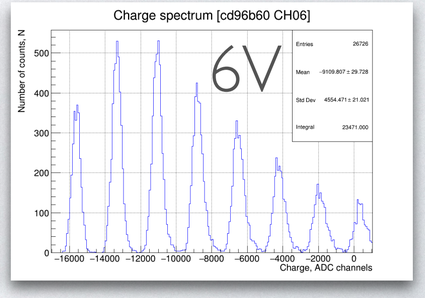




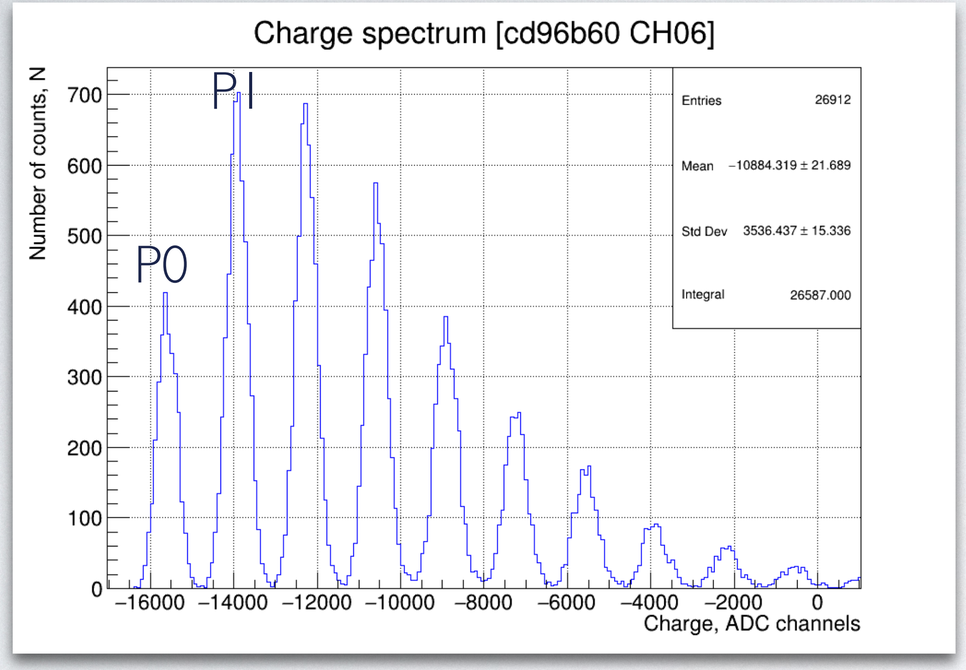








GAIN & BREAKDOWN VOLTAGE

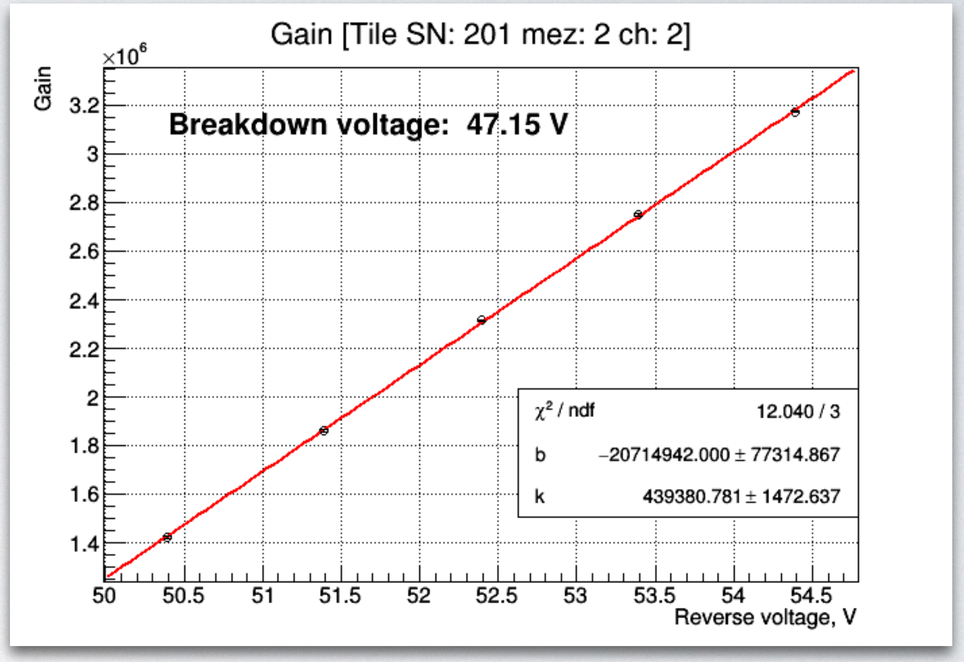


$$GAIN_{pixel} = \frac{P0 - P1}{K_{amp} \cdot q}$$

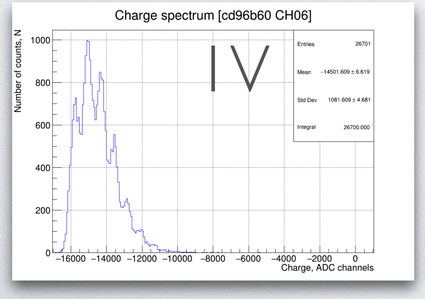
P0 - pedestal position
P1 - position of the 1st peak
K_{amp} - coeff. of the amplifier
q - elementary charge

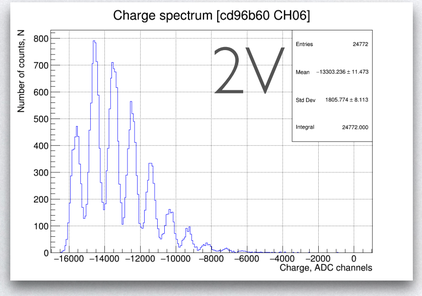
Gain Accuracy: ±0.4%

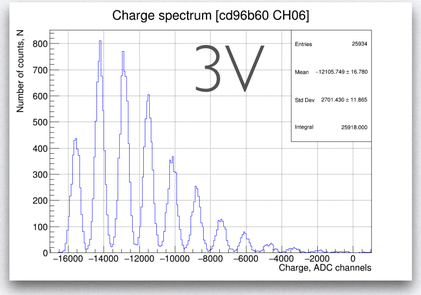
Gain-Voltage dependence

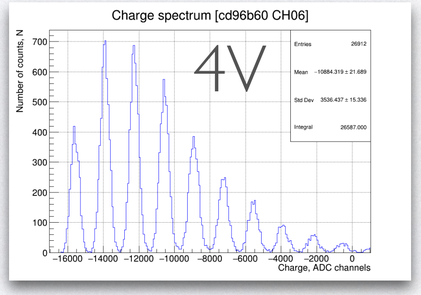


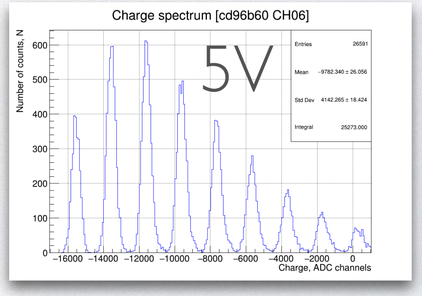
V_{bd} Accuracy: ±0.1%

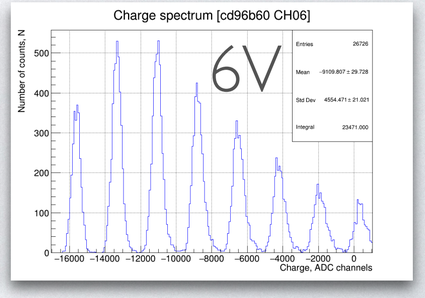






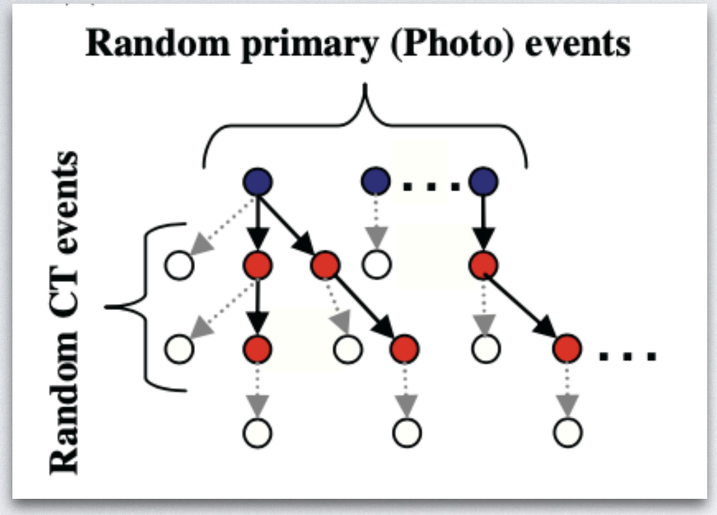






CROSSTALKS

Branching Poisson crosstalk process



Generalized Poisson distribution

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

More details in:
S.Vinogradov, (2011). Analytical models of probability distribution and excess noise factor of Solid State Photomultiplier signals with crosstalk. NIM A 695. 10.1016/j.nima.2011.11.086.

Crosstalk evaluation

- Building charge spectra
- Extracting and calculation of values:
  - Mean of spectrum
  - Pedestal position of spectrum
  - Number of photoelectrons (μ)
  - Gain of pixel (Q_1)
  - Average SiPM response

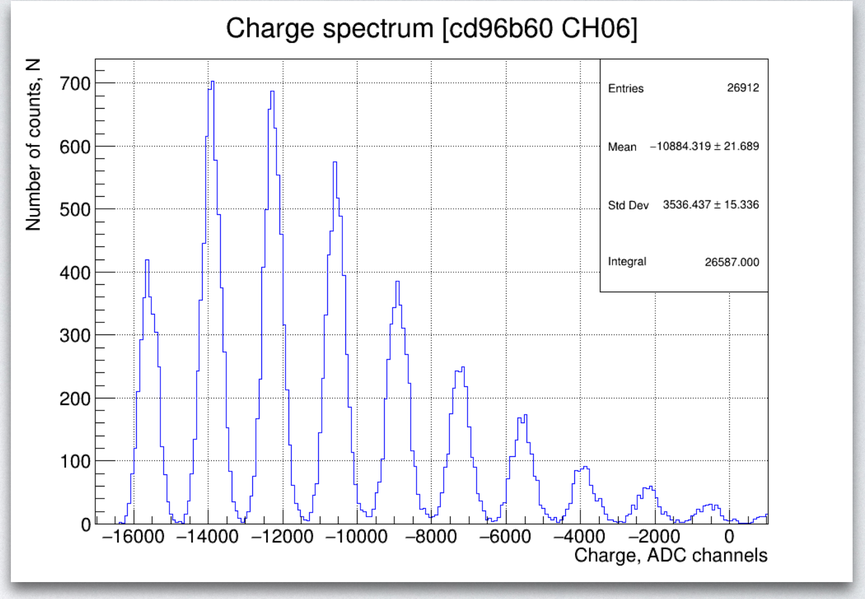
$$S = Mean_{spectrum} - Pos_{pedestal}$$

  - Crosstalk probability

$$\lambda = 1 - \frac{\mu Q_1}{S}$$

$$\delta_\lambda = \frac{1}{S}\sqrt{(Q_1\delta_\mu)^2 + (\mu\delta_{Q_1})^2 + (\frac{Q_1\mu}{S}\delta_S)^2}$$

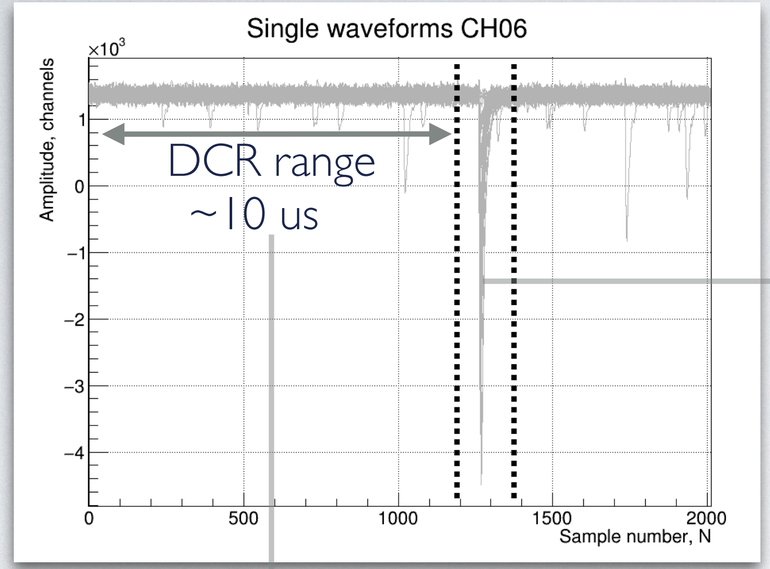
$$P_{crosstalk} = 1 - exp(-\lambda)$$

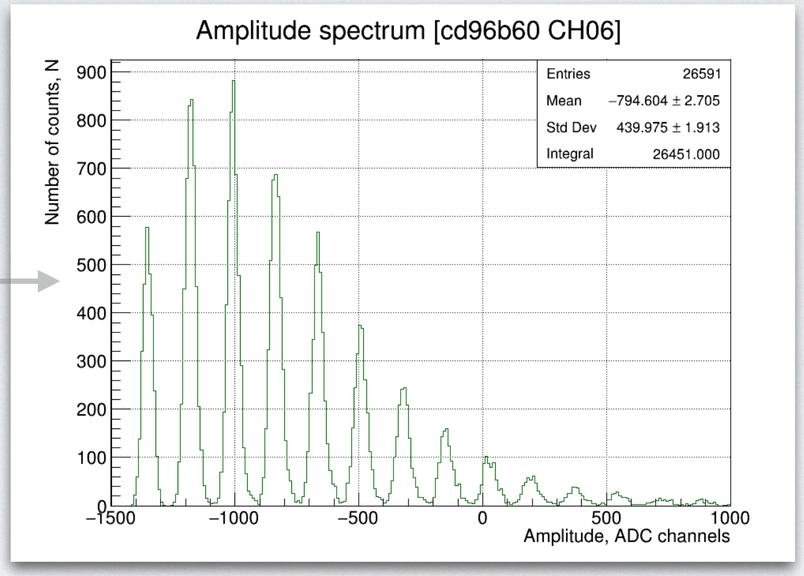


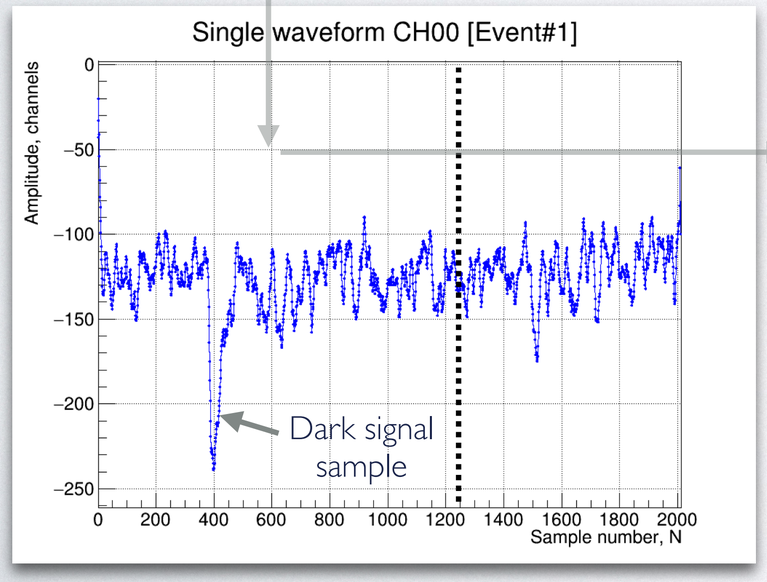
Gate window: 500ns

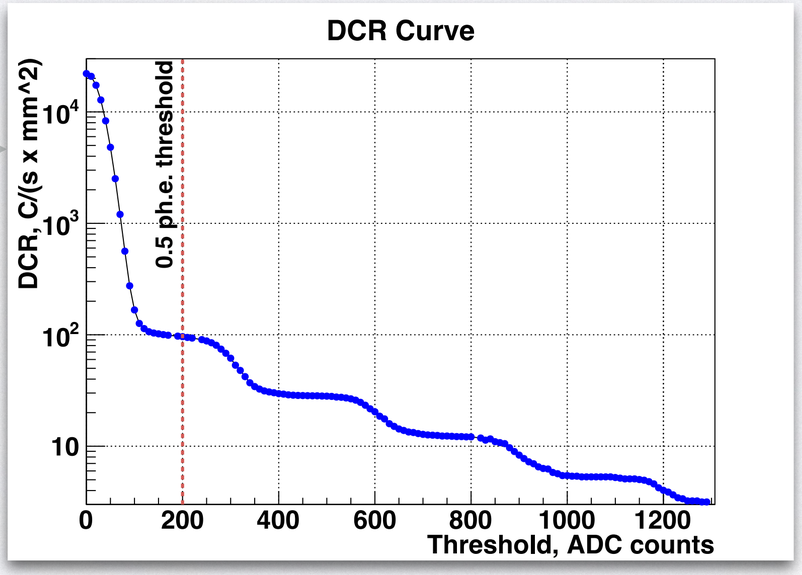
Accuracy: ±3%

DARK COUNT RATE









DCR curve reconstruction by means of software analysis ADC data file

$$\mathrm{DCR} = \frac{C}{W \times N \times S},$$

$$\sigma_{\mathrm{DCR}} = \frac{\sqrt{C}}{W \times N \times S}.$$

C - number of counts over threshold
W - width of analysis window (10us)
N - number of oscillogram (30k)
S - SiPM area (144mm^2)

Accuracy: ±1.5%

Eval. DCR @ diff.thresholds

⇩

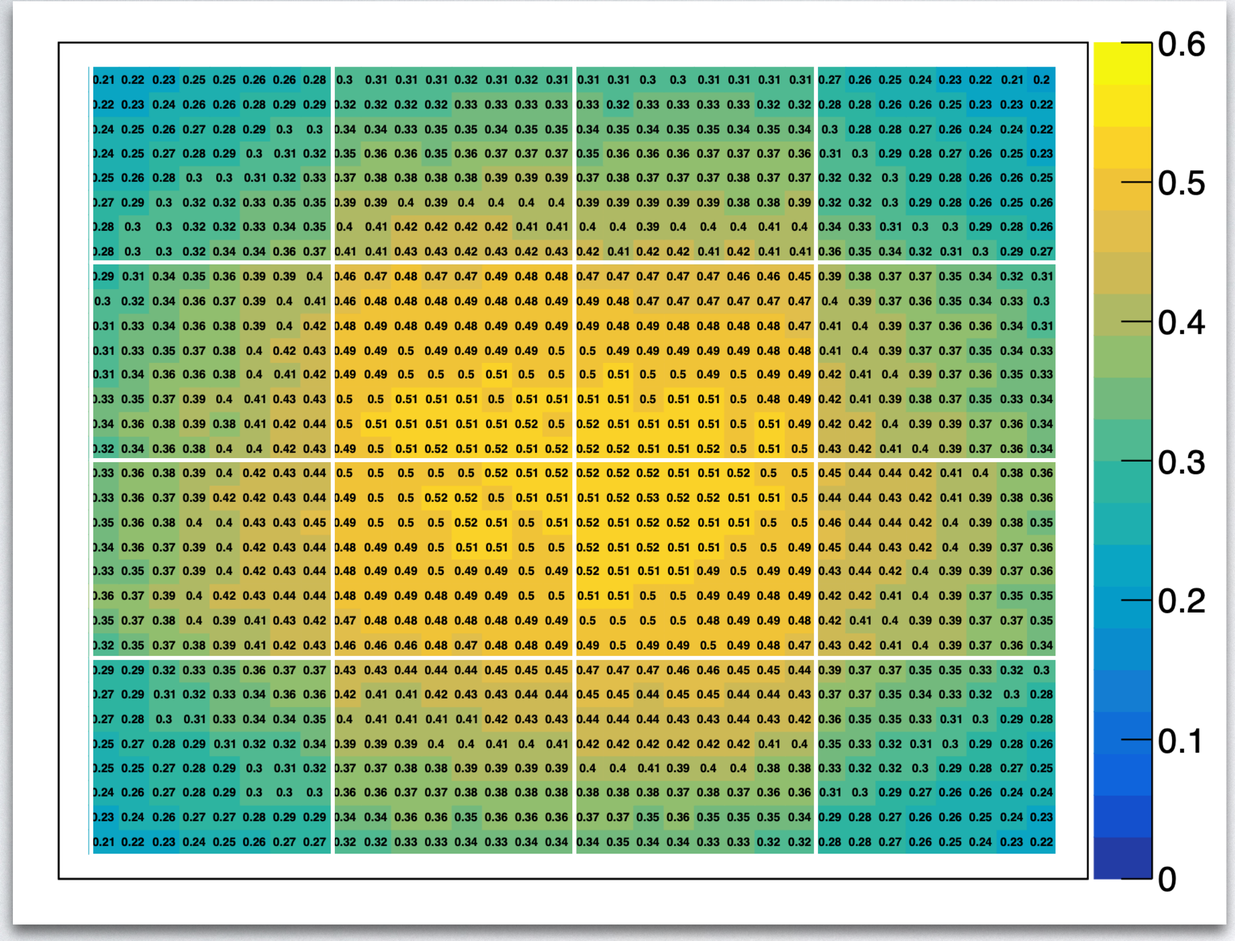
Building DCR Curve

⇩

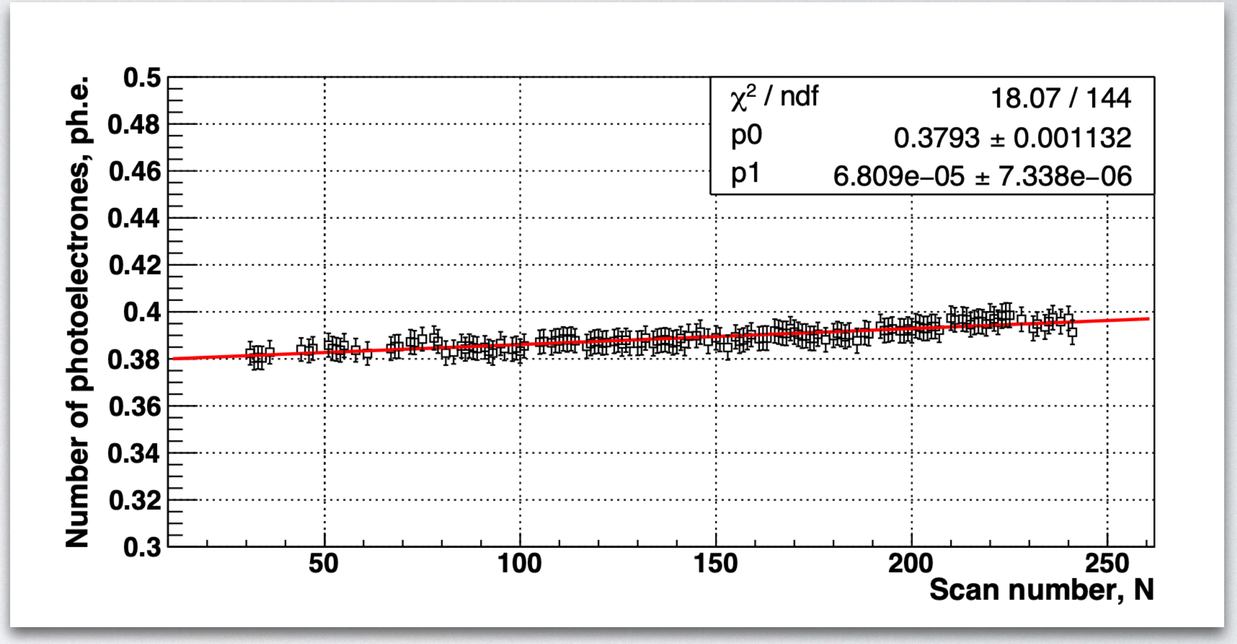
DCR Value @ required threshold

LIGHT FIELD SCAN PERFORMANCE

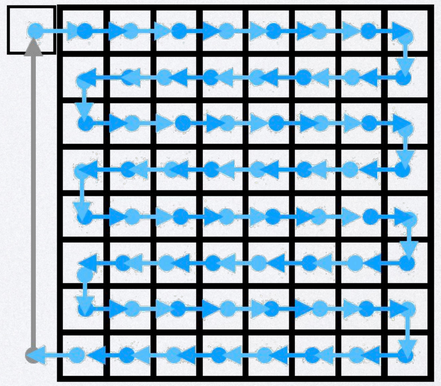
The light field map



Light stability overall scans



Scanning path

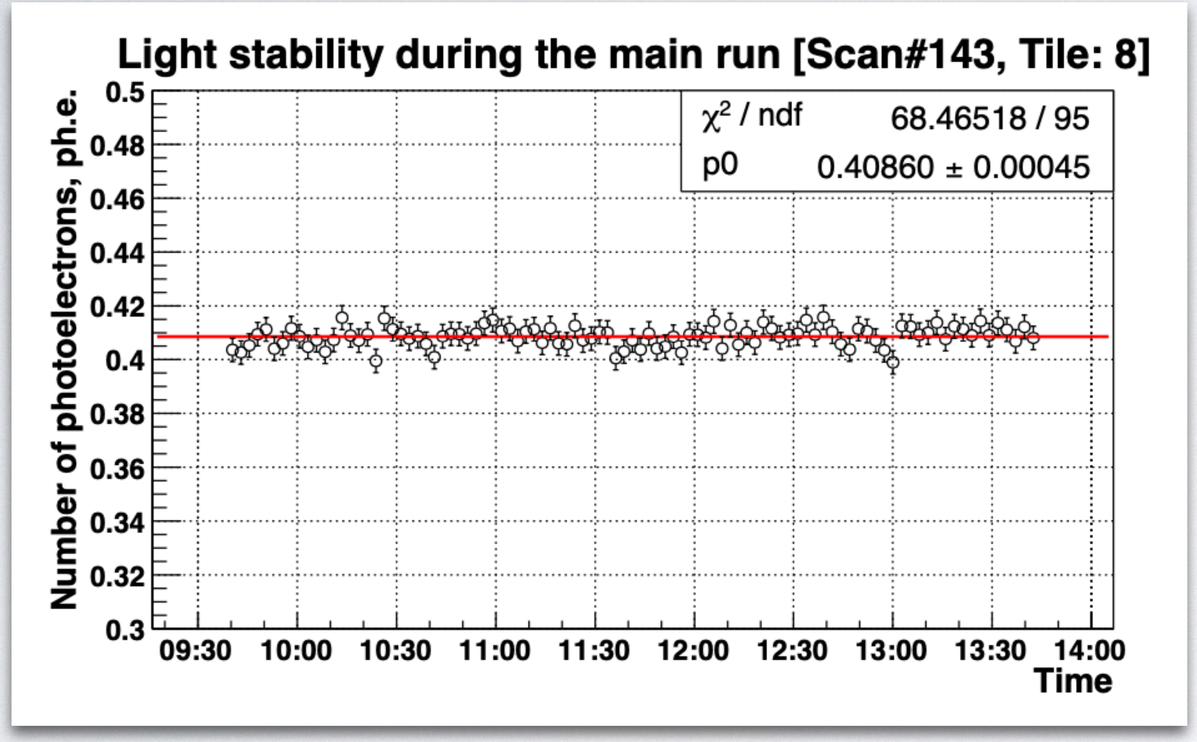


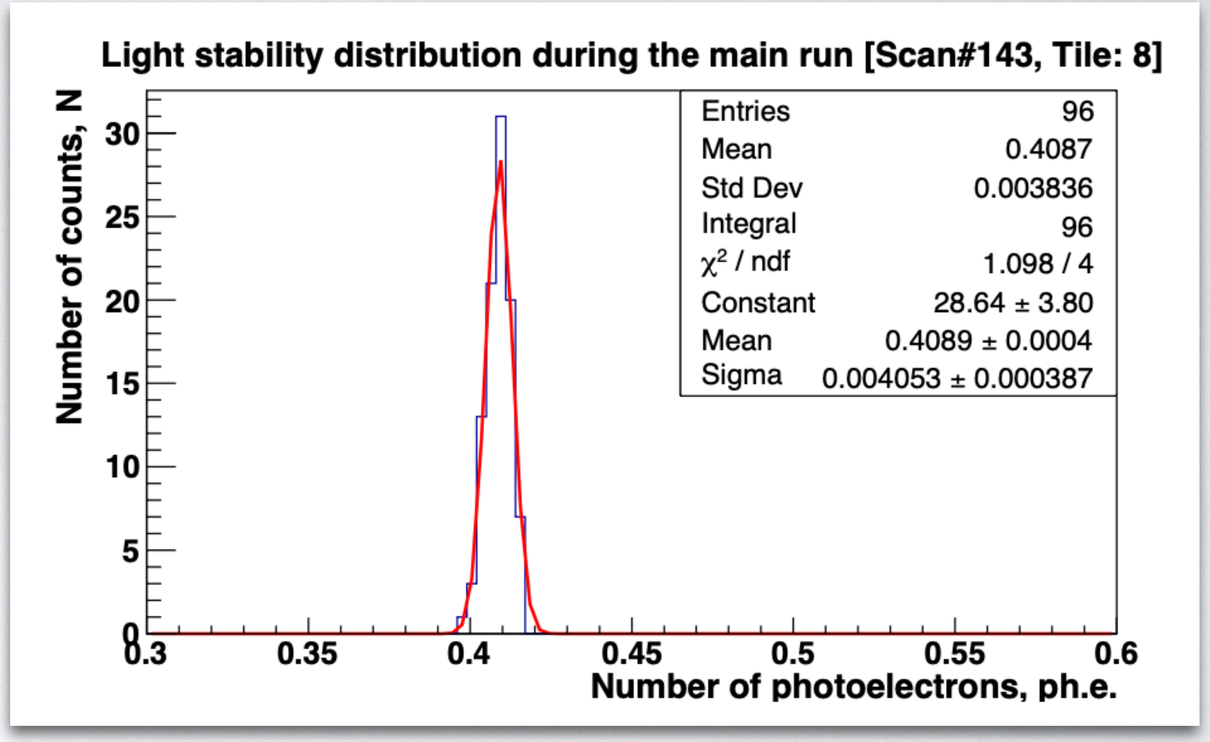
For single tile

- 64 points/single tile area
- the same for all 16 tiles

LIGHT FIELD STABILITY

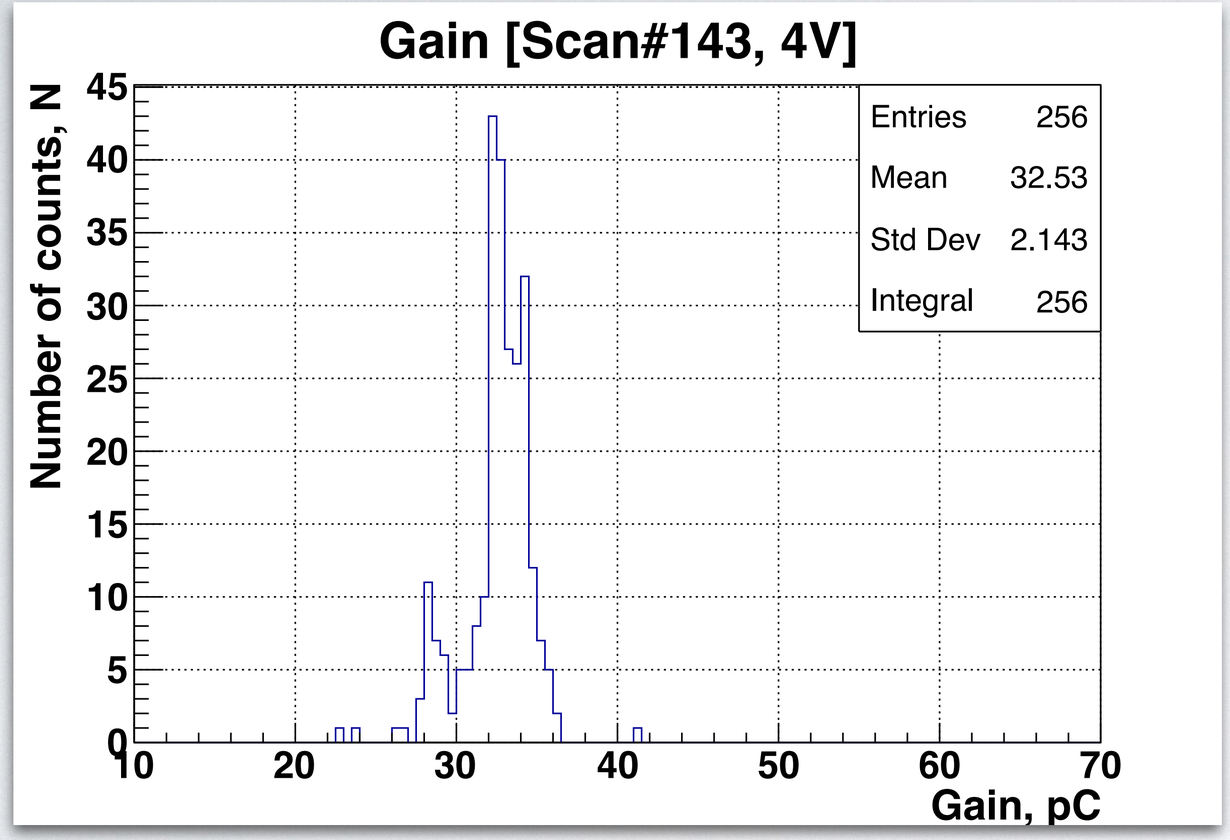
Over single scan

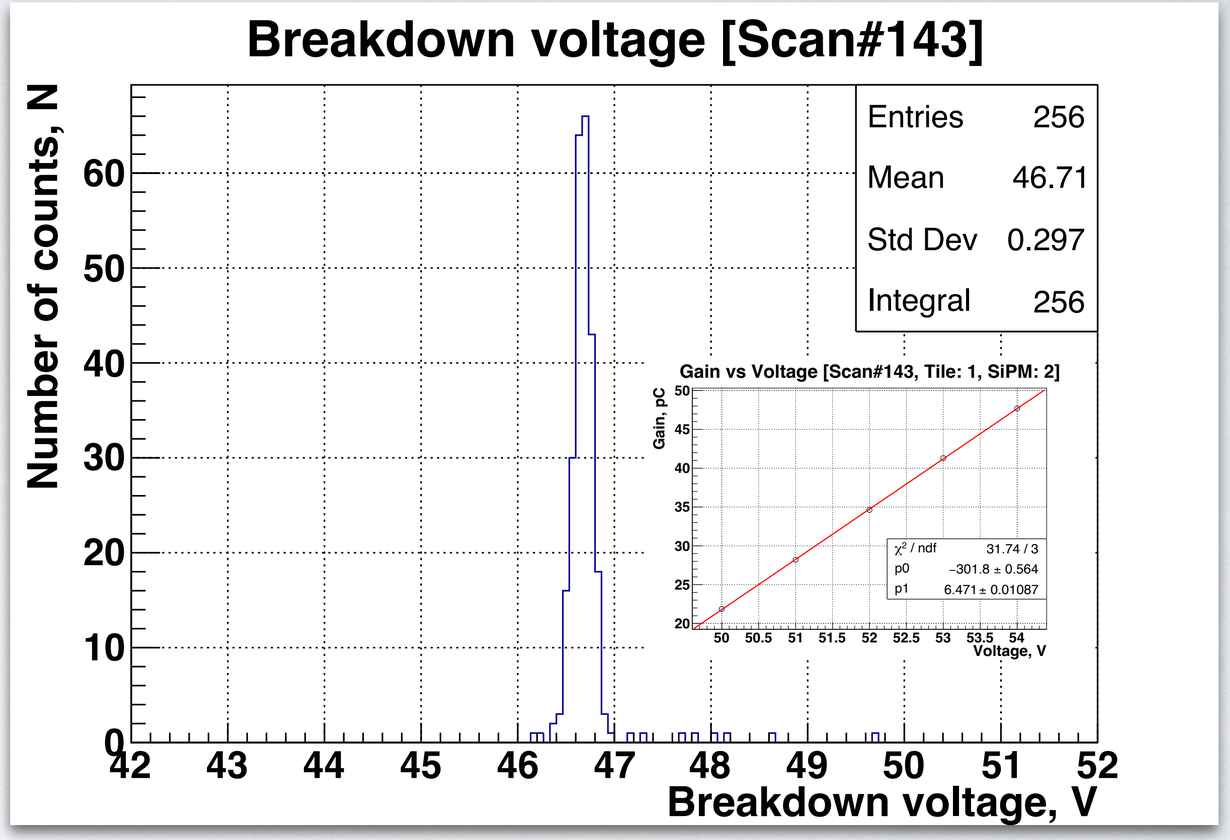




MAIN SCAN PERFORMANCE

Single scan





MAIN SCAN PERFORMANCE

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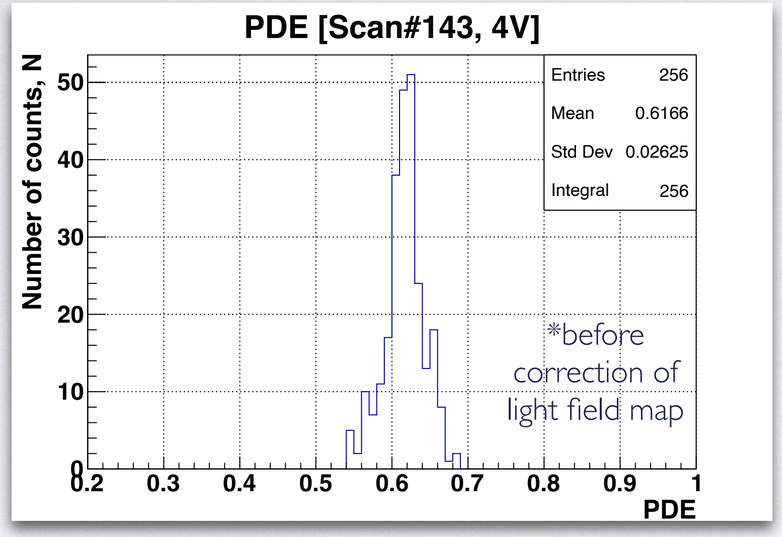

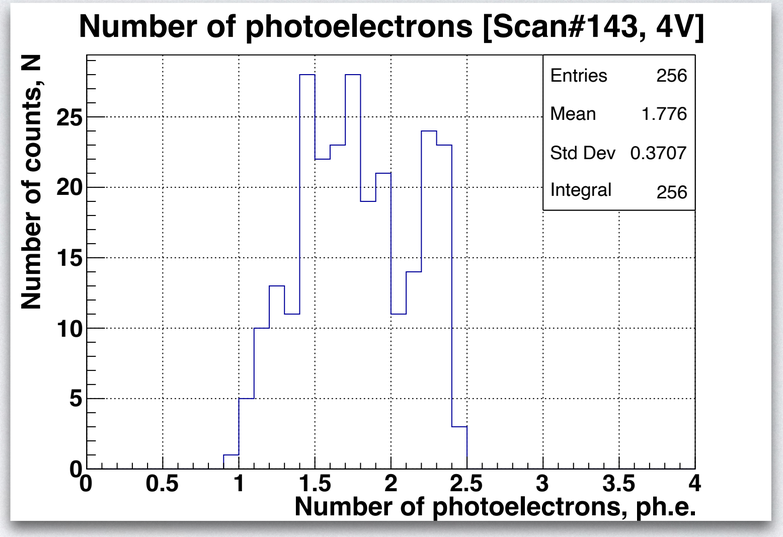

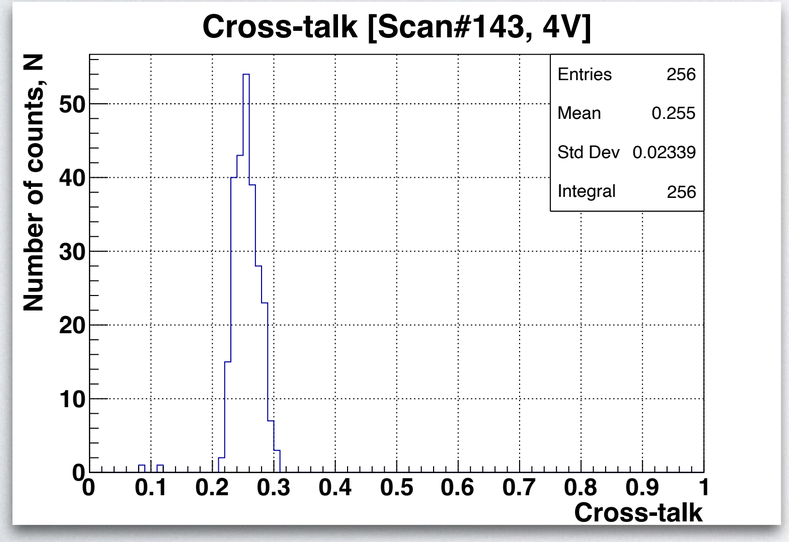

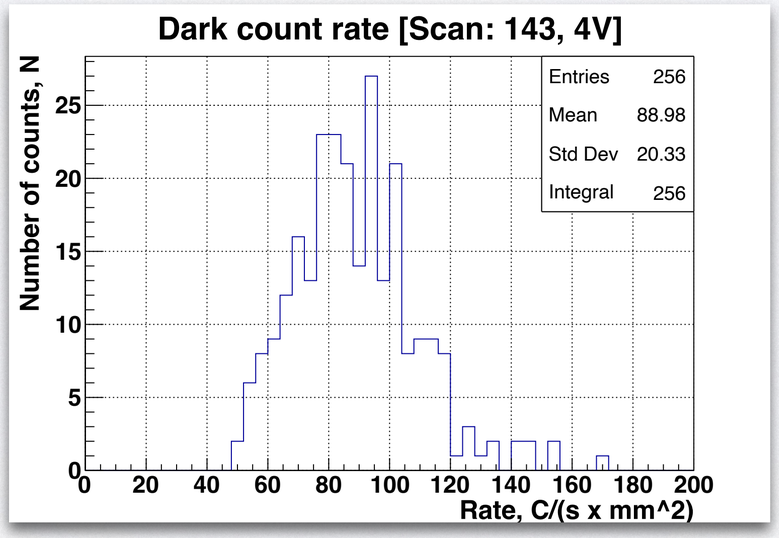

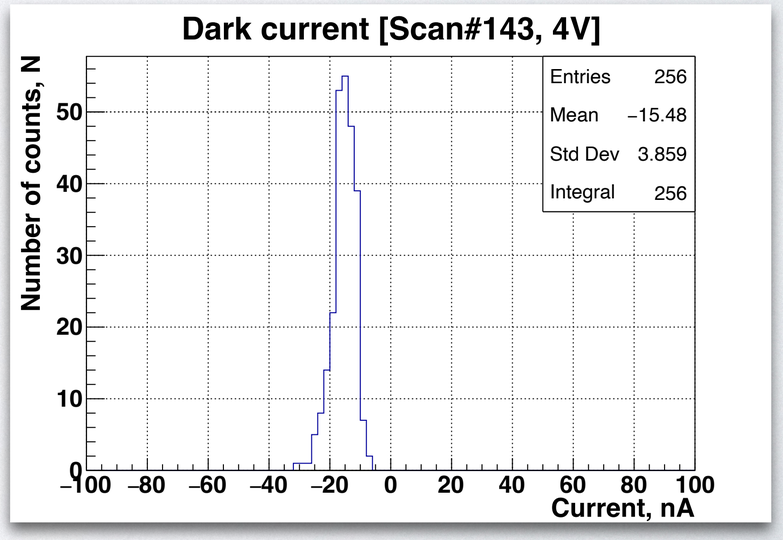

SUMMARY

- The setup design has been developed
- The testing procedures and methods have been developed and applied
- The testing setup has been produced and putt into operation in China
- Two papers related to the setup have been published in PEPAN Letters and JINST
- All tiles have already been tested
- The data analysis is in progress