MEG II 実験液体キセノン検出器用 VUV-MPPCの放射線耐性に関する研究

(Study on Radiation Damage of VUV-MPPC for the Liquid Xenon Detector in the MEG II Experiment)

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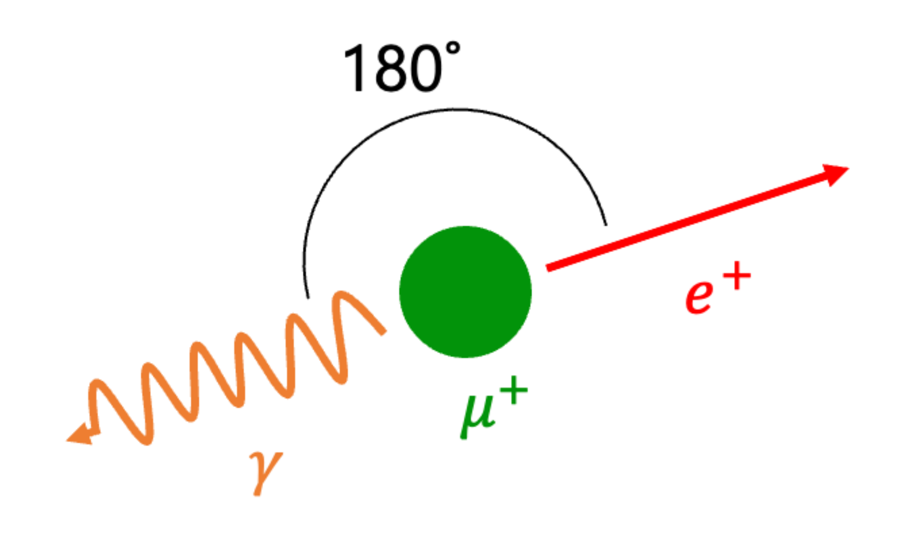
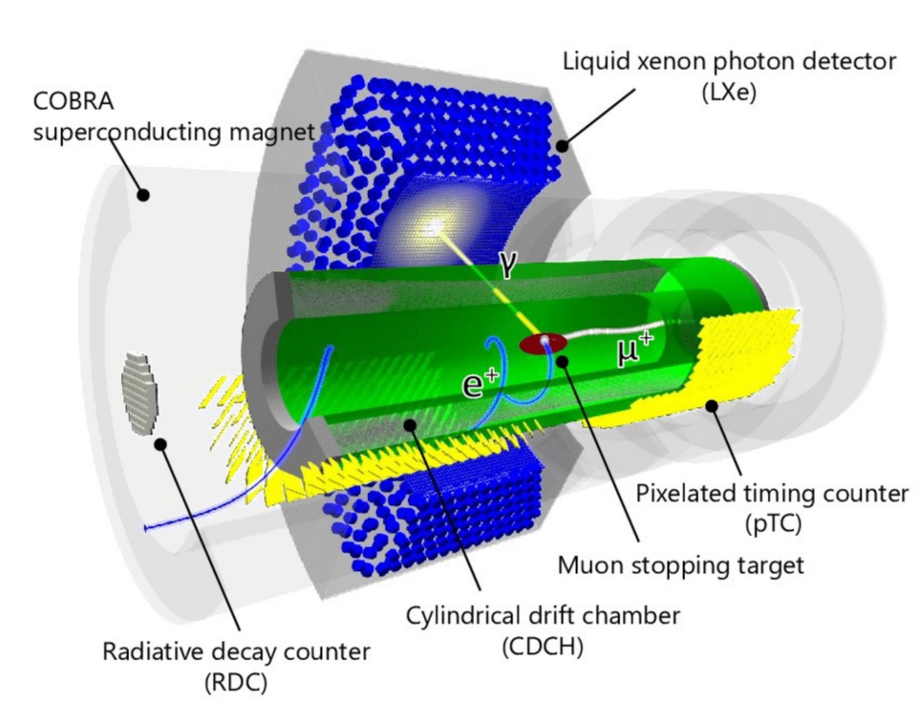
Introduction

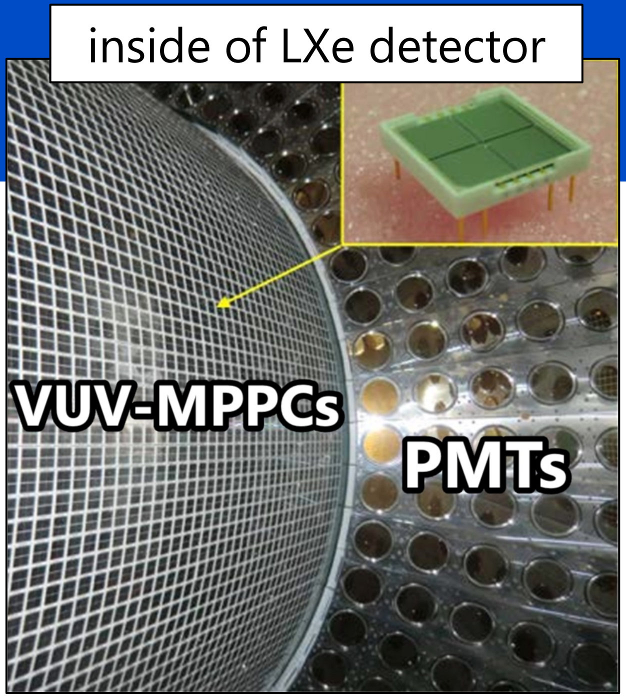
- In SM, $\mu^+ \to e^+\gamma$ decay is prohibited
- $\mu^+ \to e^+\gamma$ decay
  - Two-body decay
  - Muon decay into e^+ and γ with 52.8 MeV
  - Background limits the sensitivity of signal
    - Physics and accidental background (from $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$, $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$ and Annihilation In Flight (AIF))
  - Reconstruction of position, energy, timing for e^+ and γ is important!!
    - Searching the e^+ and γ which decayed at "*same point*", "*simultaneously*", "*opposite each other*", with "*same energy*".
- MEG II experiment
  - Searching for $\mu^+ \to e^+\gamma$ as probe of a theory beyond SM
    - with most intense muon beam (7×10^7 μ/s)
  - Sensitivity in 2021 run: 8.8×10^{-13}
    - Approaching the MEG (5.3×10^{-13}) even for several weeks



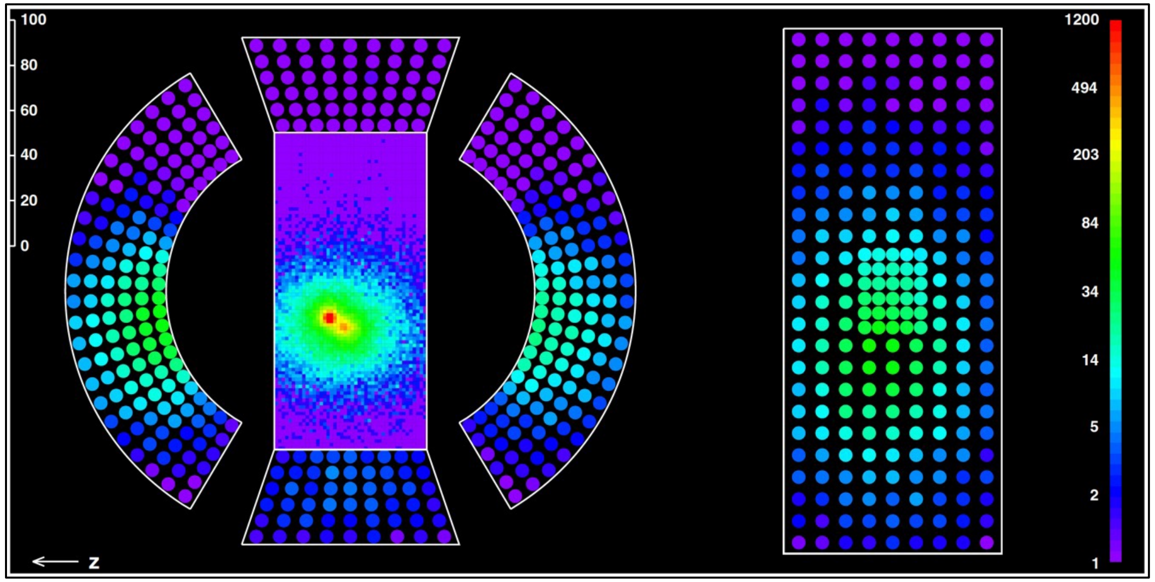


Introduction

- For gamma-ray measurement
  - LXe detector (Liquid Xenon detector)
  - measure the position, energy, timing of gamma-ray
  - Using VUV-MPPCs ← Vacuum UltraViolet (VUV) light sensitive MPPCs (Today's topic)



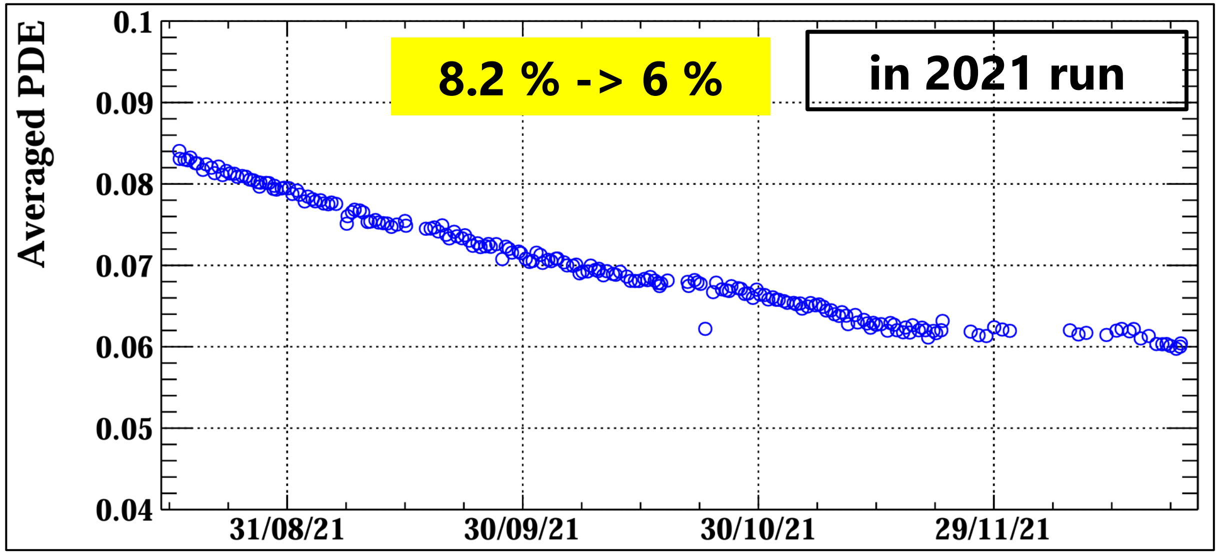
- LXe scintillator
  - Stable low temperature (~168 K) is needed
  - The scintillation wavelength is shorter than visible light (λ = 175 nm)
  - Purity of LXe affects the light yield



Background of this study

- Photon detection efficiency (PDE) for VUV rapidly decreases during physics run.
  - Found that PDE can recover by annealing (70 °C, 28h)
    - MEG II experiment was continued by annealing VUV-MPPCs (from 2021) ->not crucial for experiment
  - But we still want to understand cause

$N_{photon} = 1.1 \times 10^{11}$ photon/mm^2

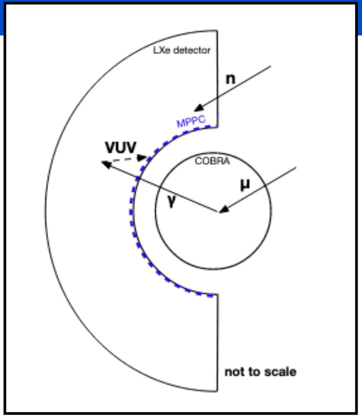


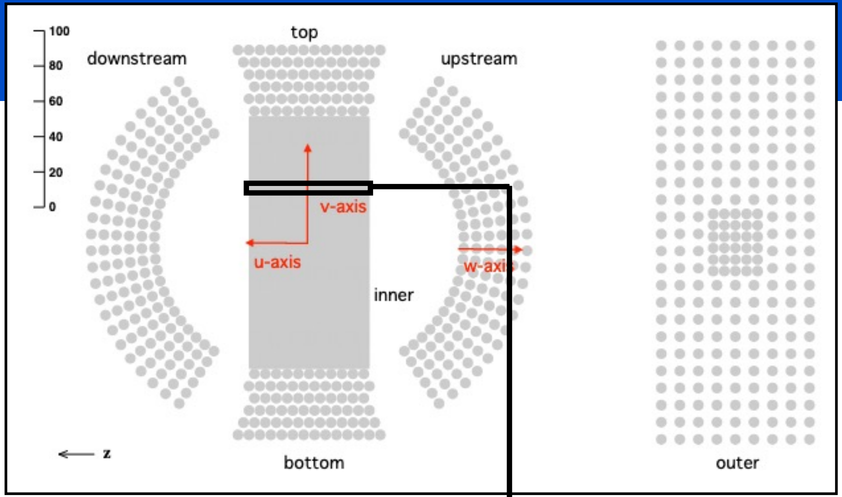
Background of this study

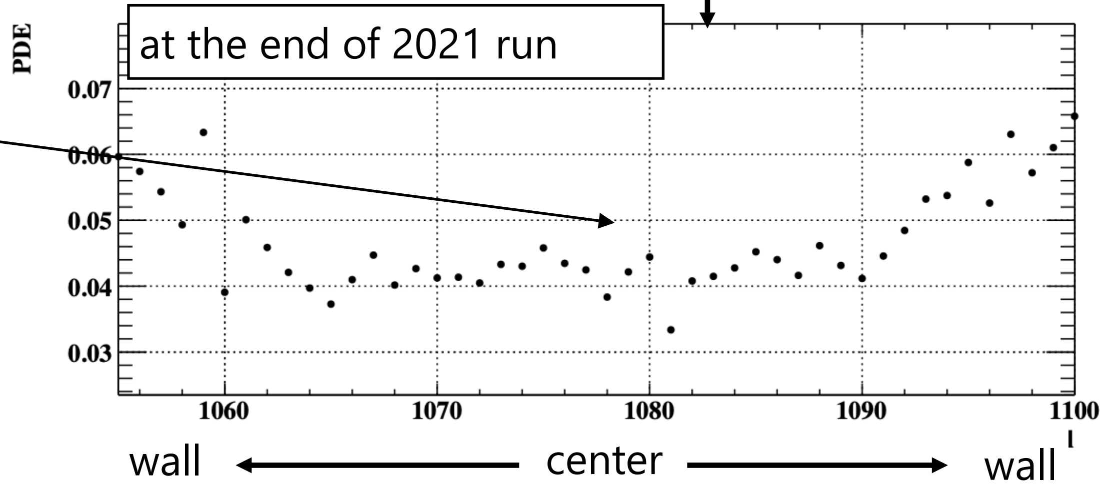
- Radiation environment
  - Radiation from the muon stopping target
    - gamma ray
    - VUV light
  - Radiation from the accelerator
    - neutron
- PDE degrease at the center is larger
- Muon stopping target is put on the center of LXe along to beam axis

→ Most likely to be caused by radiation from muon target

→ Radiation candidates: gamma-ray, ***VUV light***





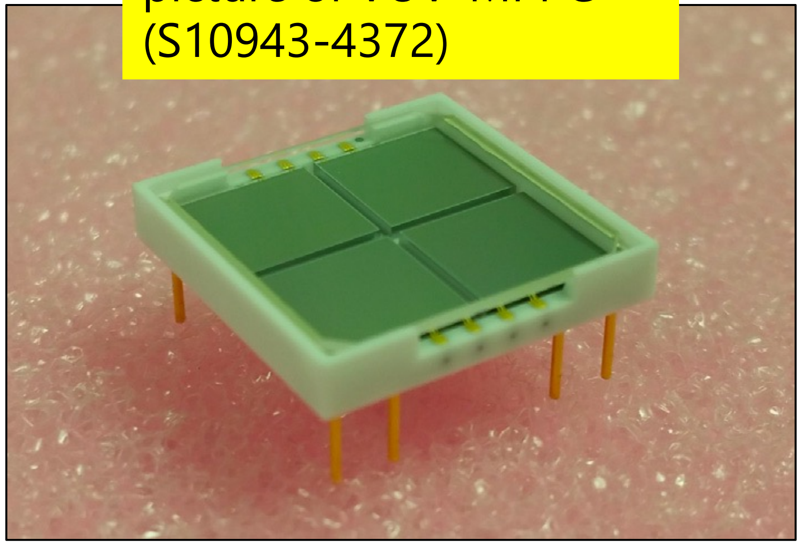


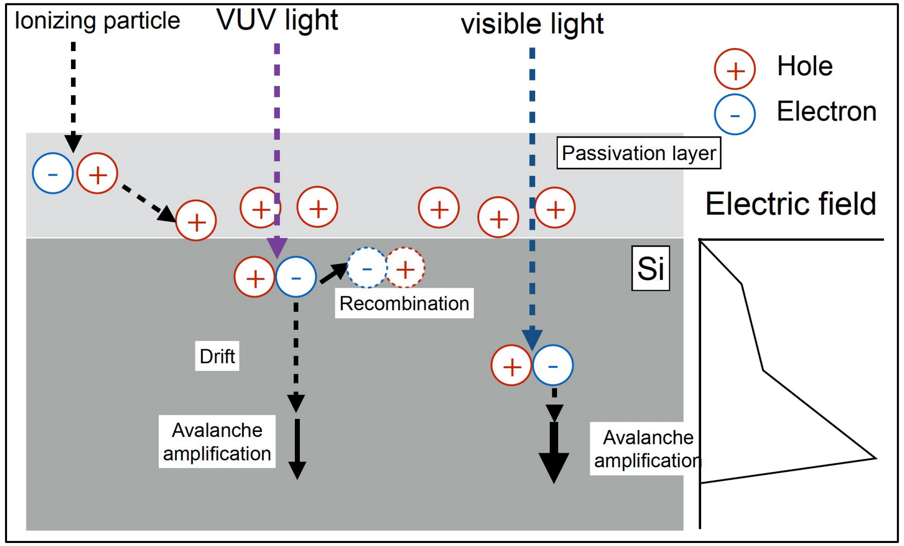
Radiation damage of VUV-MPPCs

- Candidate for radiation damage:
  Surface damage
  - occurs by irradiation of light particle (<300 keV, e.g. gamma-ray or VUV light)
- Previous studies in laboratory
  - VUV light was irradiated to VUV-MPPCs at room temperature, low temperature (~165 K), in liquid xenon
    - Humidified VUV-MPPC was irradiated with VUV light in room temperature
  - Gamma-ray was irradiated to VUV-MPPCs at room temperature, low temperature (~165 K)
- PDE degradation was not reproduced in laboratory

(PDE degradation was actually observed by VUV irradiation, but 10^4 slower)

picture of VUV-MPPC (S10943-4372)





Motivation of this study

1. It's known that VUV sensitivity of VUV-MPPC is worsened by absorbing moisture
   - Coming from VUV-MPPC has no moisture resistance layer on the surface
2. VUV-MPPCs of the LXe detecter in the MEG II were humidified during long period of storage and installation

→ Combine the above two results

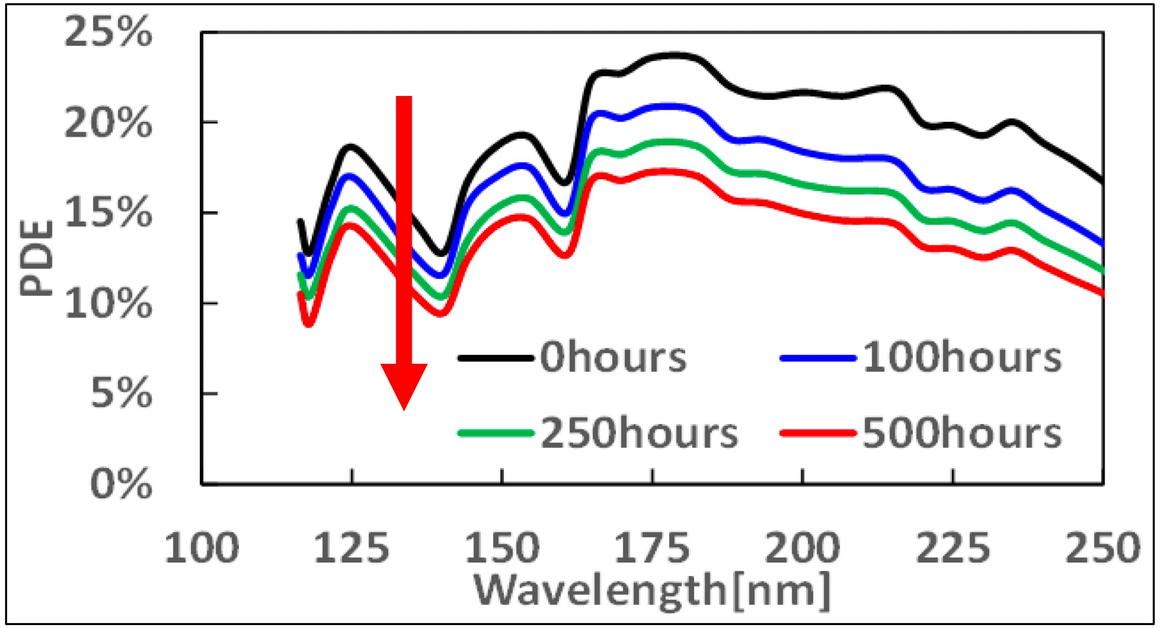
Hypothesis

→ Moisture inside VUV-MPPCs accelerate the radiation damage

- Measure PDE of humidified VUV-MPPC during VUV irradiation

Condition: temp=60 ˚C, humidity=90％

Measured by HPK



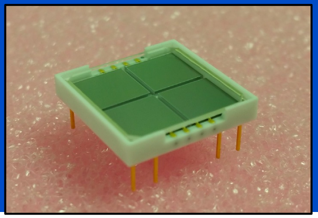
R. Yamada, et al., "Development of MPPC with high sensitivity in NUV or VUV," 2022 IEEE NSS/MIC/RTSD

(This test is accelerated test by 89 times for temperature=25 ˚C, humidity=60%)

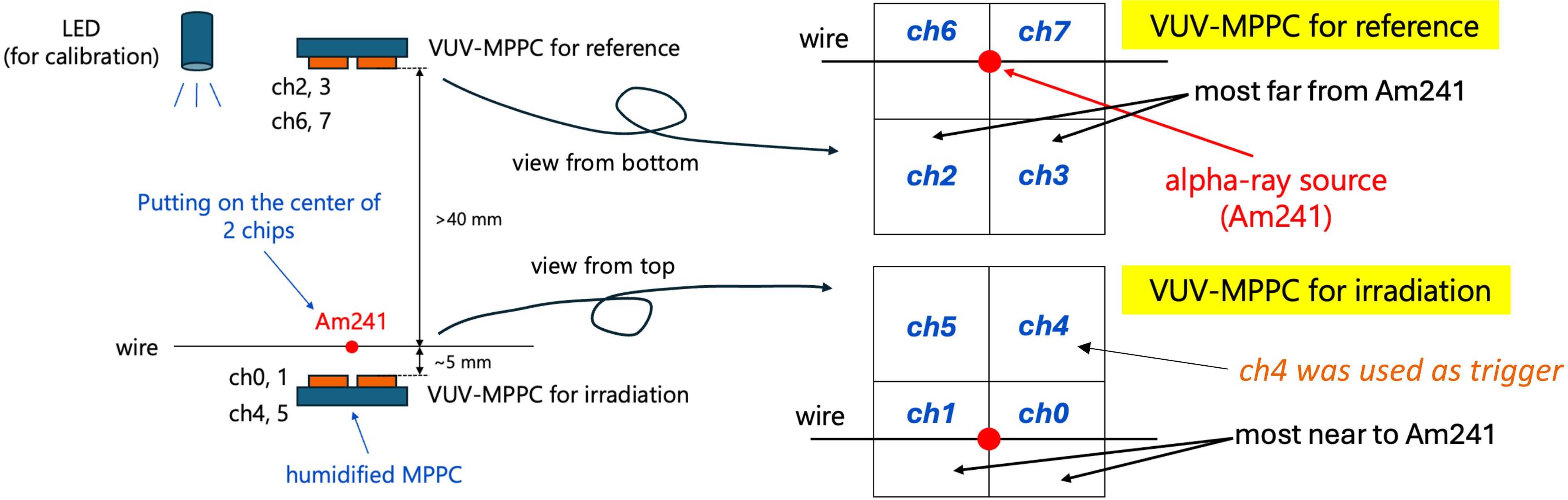
Method

- Irradiate VUV-MPPC with scintillation light (VUV light, $\lambda = 175\ \mathrm{nm}$) from LXe
  - To confirm humidified VUV-MPPC is damaged by VUV light or not
  - Irradiate same order of VUV light compare to the MEG II
    - Continued irradiation for 300 hours
- Put VUV-MPPC ,alpha ray source (Am241) and LED in LXe
  - Alpha ray is used instead of gamma ray
  - Sustain the temperature in LXe (168 K) during data taking
- DAQ
  - Measure the charge of alpha ray and MPPC gain by 1 hour

Setup – inside small chamber

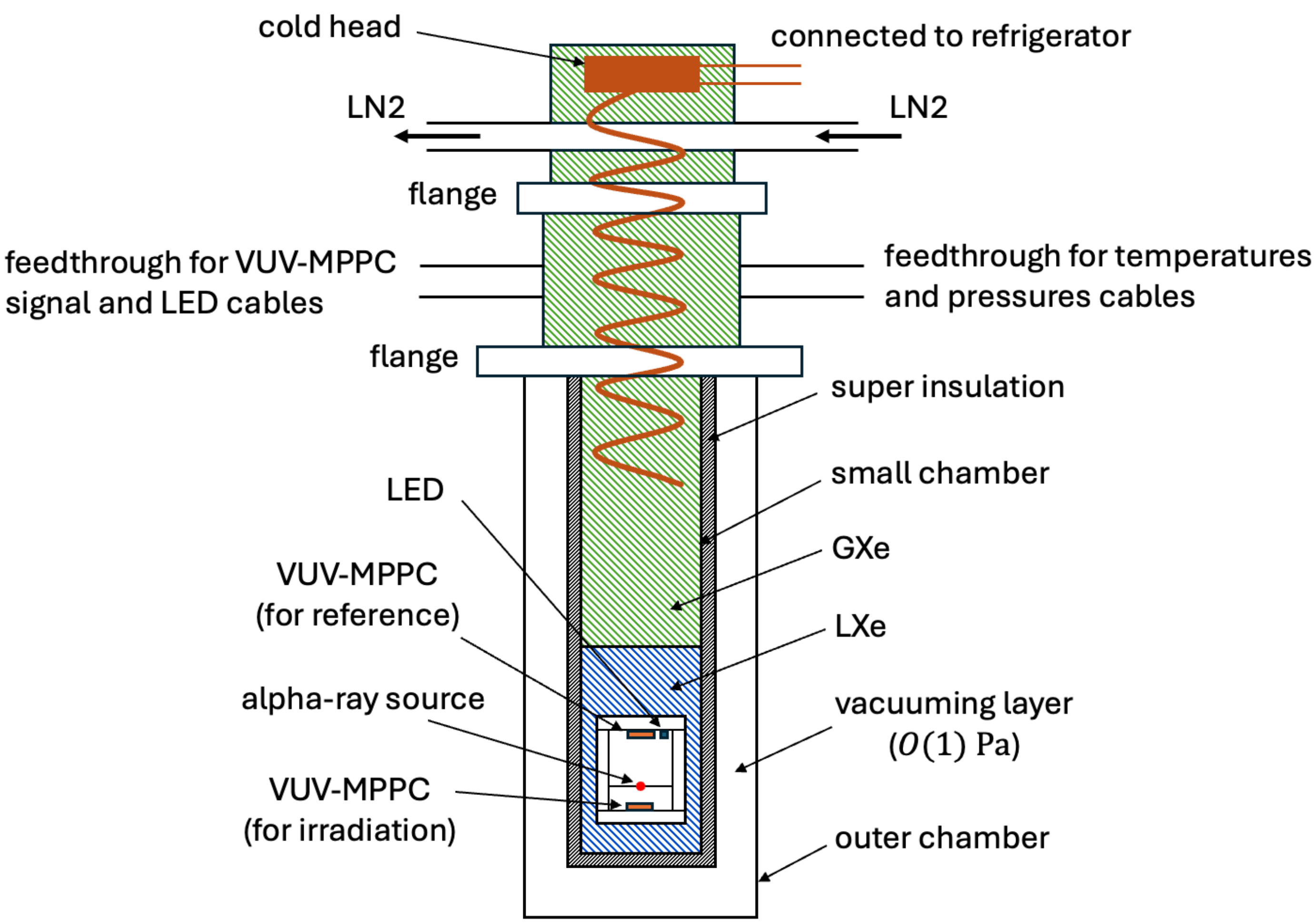


	ch0,1,4,5 (VUV-MPPC's chips for irradiation)	ch2,3,6,7 (VUV-MPPC's chips for reference)
Humidity	89 times accelarated (60 °C x 250 hours, humidity 90 %)	not accelerated
Annealing	150 °C x 16 hours baked (Assume humidities inside VUV-MPPC were removed)	not annealed
Note	for test of radiation damege	for reference of LXe stability



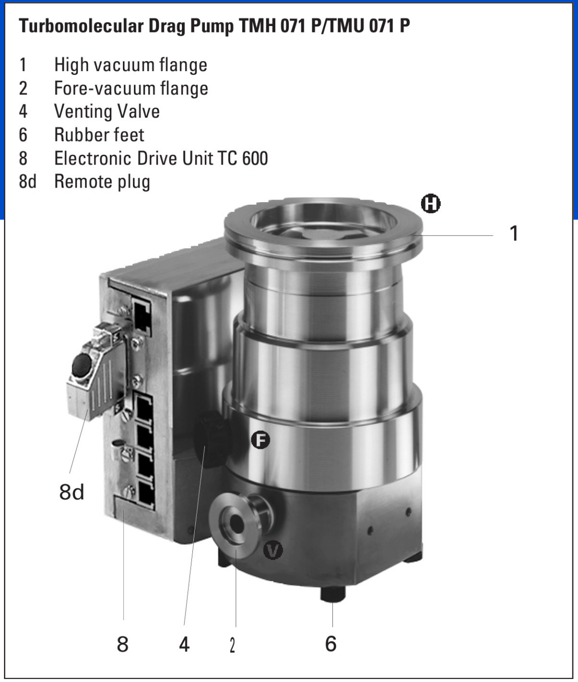
Small chamber construction

- Inside small chamber, separeted into GXe and LXe
  - By cooling, LXe accumulated in the bottom of small chamber
- Small chamber is covered by a outer chamber
  - Between the small and outer chamber is vacuumd
  - This works like "magic bottle"



Vacuuming and leak check

- Turbo pump (Pfeiffer Vacuum, TMH 071P)
  - Used for vacuuming inside the small chamber
  - Reach $O(10^{-4})$ Pa in this experiment
- Scroll pump
  - Used for vacuuming of the outer chamber
  - Reach $O(1)$ Pa in this experiment
- Helium leak detector (Alcatel, ASM 122 D)
  - Detects the leak of a flange using helium
  - There were no leak even high-sensitivity ($O(10^{-10})$ mbar $\cdot$ l/s)

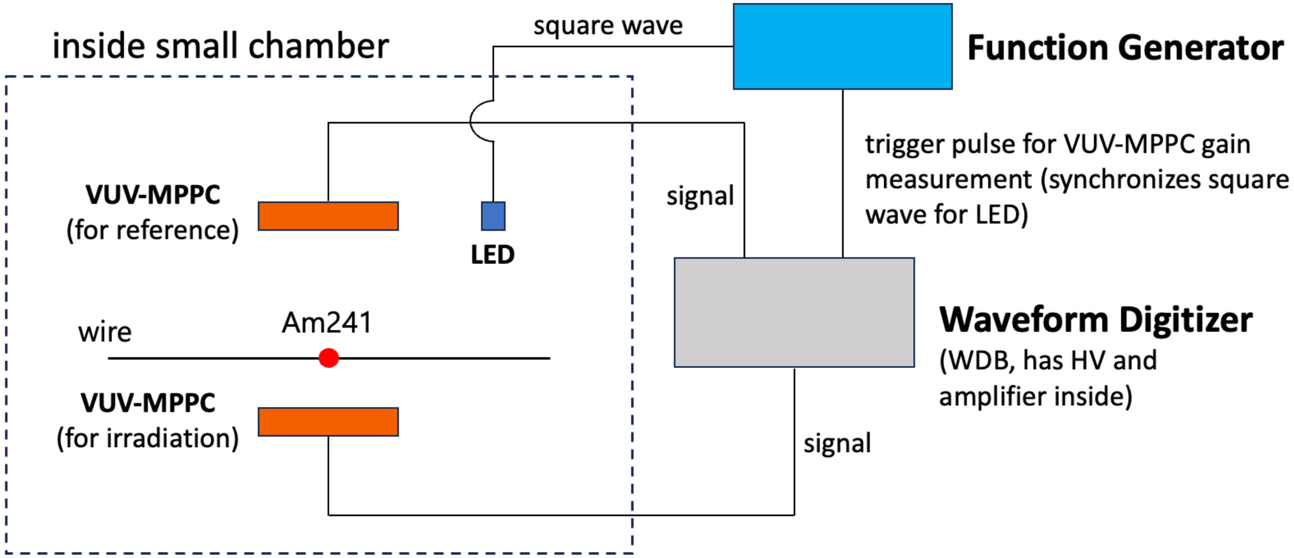


Pulification of GXe and cooling of small chamber

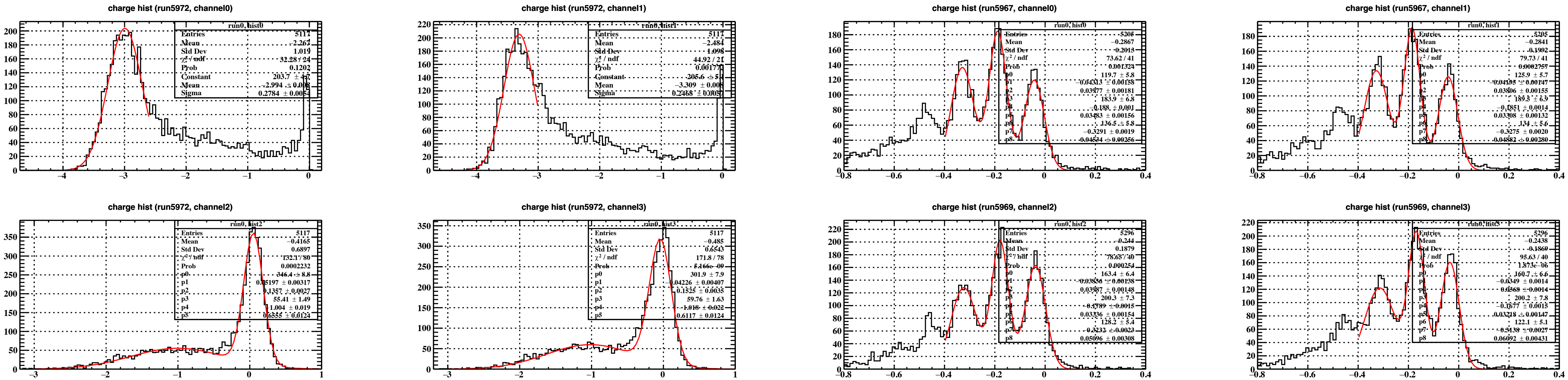
- After vacuuming, entering GXe inside the small chamber
  - Purify GXe throught the getter (impurity < 1 ppb)
- Cooling of inside the small chamber
  - Refrigerator (Iwatani, PDC08)
    - Cooling cold head inside small chamber
  - LN2
    - Helped cooling of the small chamber
    - Emergency Used (because the refrigerator didn’t work

Control of cooling system and DAQ

- SCS2000
  - Used for control of the pressure and temperature inside the small chamber "*automatically*"
    - Control LN2 flow by setting upper and lower limit of the pressure
  - Took the data of pressure and temperature inside small chamber
- WaveDREAM Board (WDB)
  - Has HV and amplifier inside
  - Took the data of VUV-MPPC signal from alpha-ray and LED light



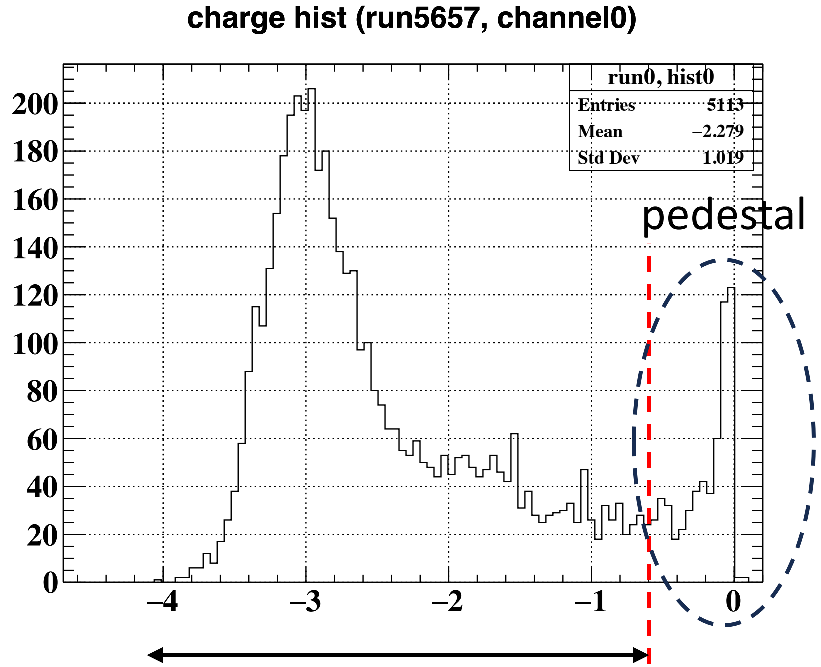
Result – Charge of alpha-ray and MPPC gain



- Charge of alpha-ray
  - ch0~7: Calculated by gaussian peak
- MPPC gain
  - ch0~7: Calculated from dividing the difference between 0 p.e. and 2 p.e. peak by 2

Result – Event rate and radiation rate

- Event rate
  - Calculated by the mean of first 10 runs
- Average charge of alpha-ray
  - Calculated by the mean of first 10 runs
    - Excluding the pedestal charge from mean calculation

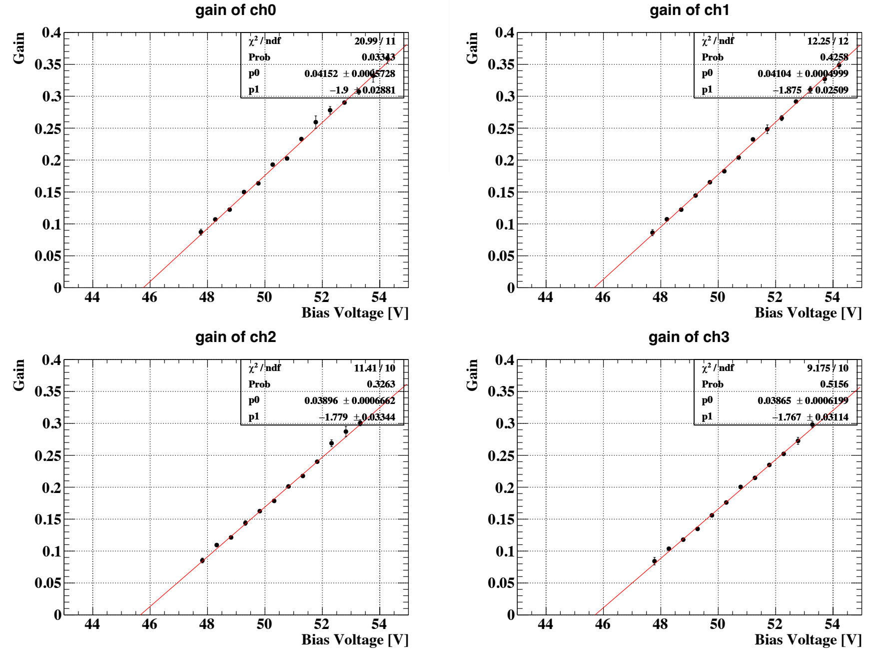


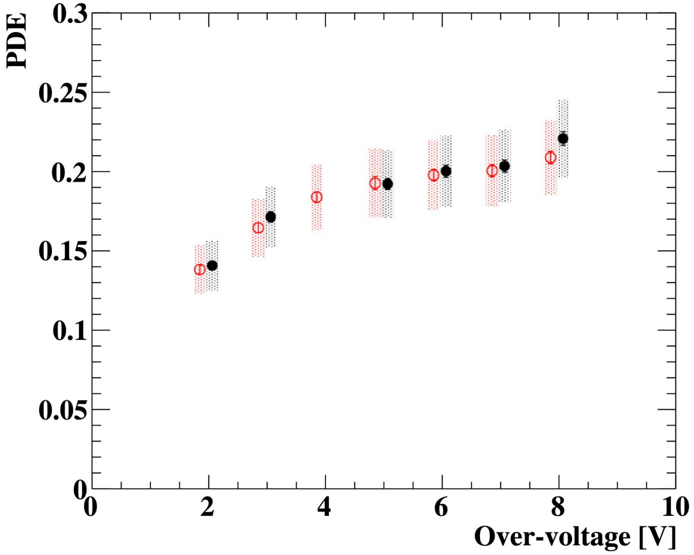
average charge of alpha-ray is calculated as the mean of this region

Result – Breakdown Voltage

	Breakdown voltage [V]	Over voltage [V]
ch0	45.76	3.51
ch1	45.68	3.53
ch2	45.66	3.66
ch3	45.71	3.57

- *Expected PDE: ~15 %*
  - Considered the effect of moisture inside VUV-MPPC





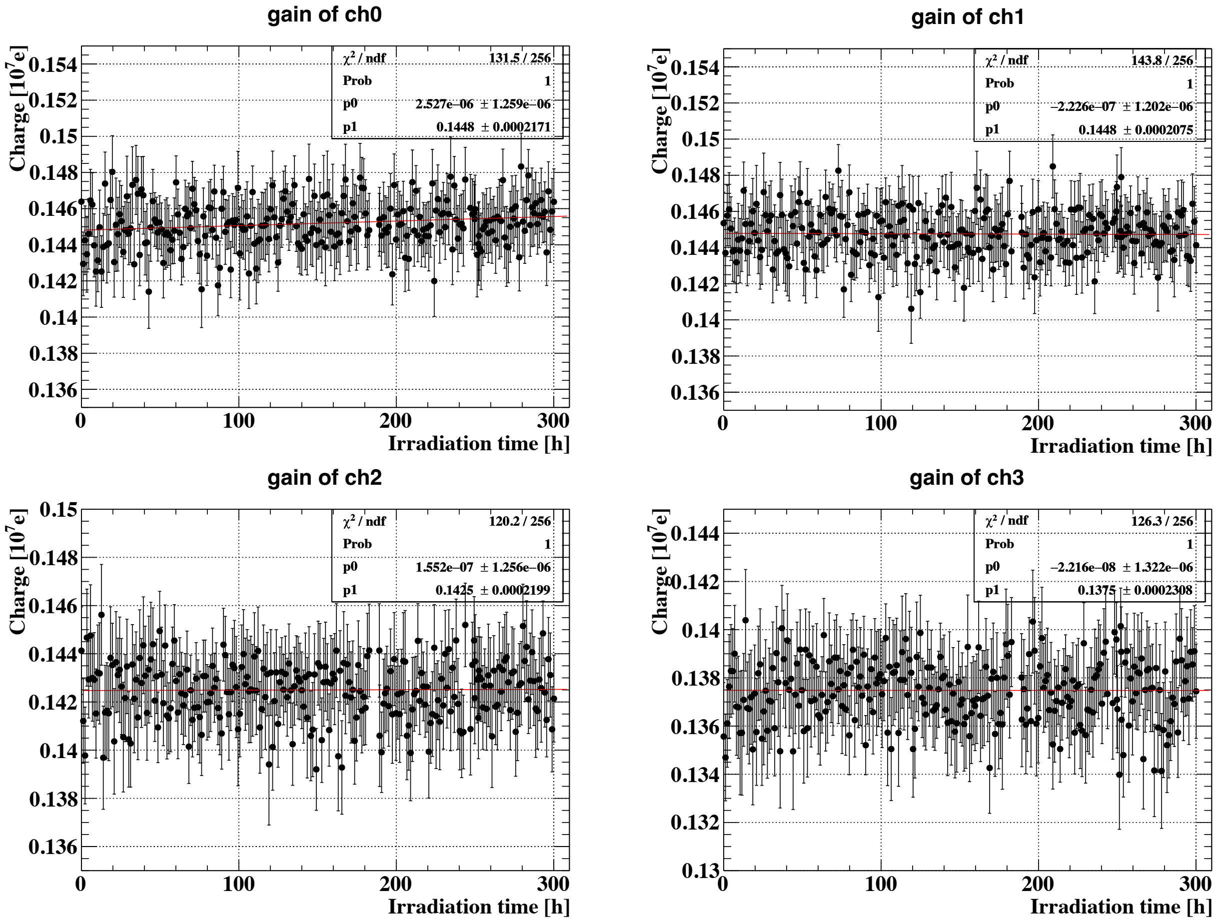
Result – Expected PDE decrease

Expecterd PDE	~15%
Event rate of alpha-ray	~38 Hz
Surface area of 1 chip on VUV-MPPC	$5.95 \times 5.85\ \mathrm{mm}^2$
Irradiation time	300 hours

⇩

Radiation dose in this experiment:	$\sim 15.8 \times 10^{12}$ stopped muons
Expected PDE decrease	>7%

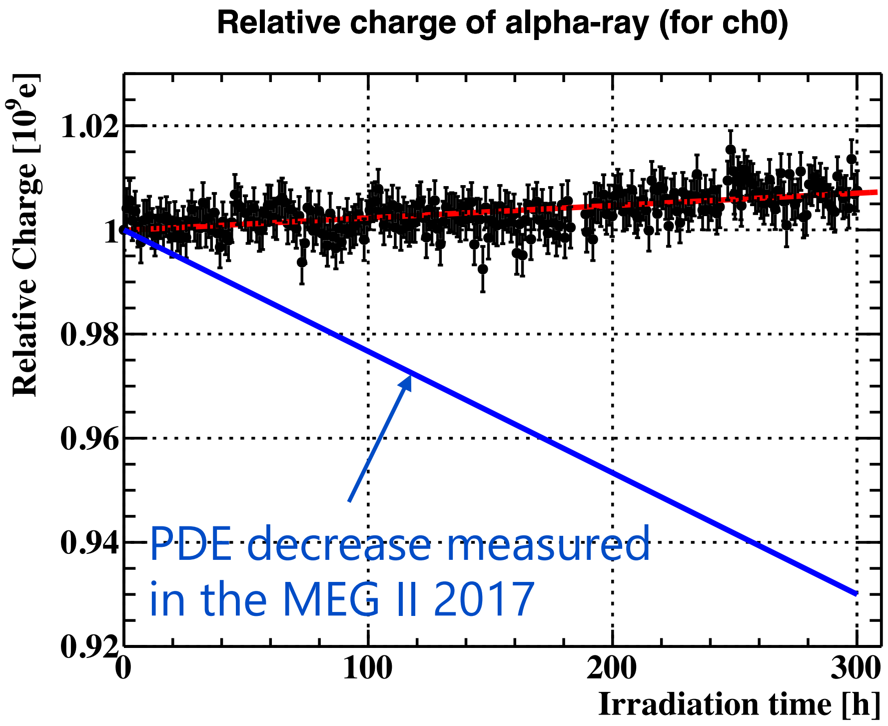
Result – Stability of LXe

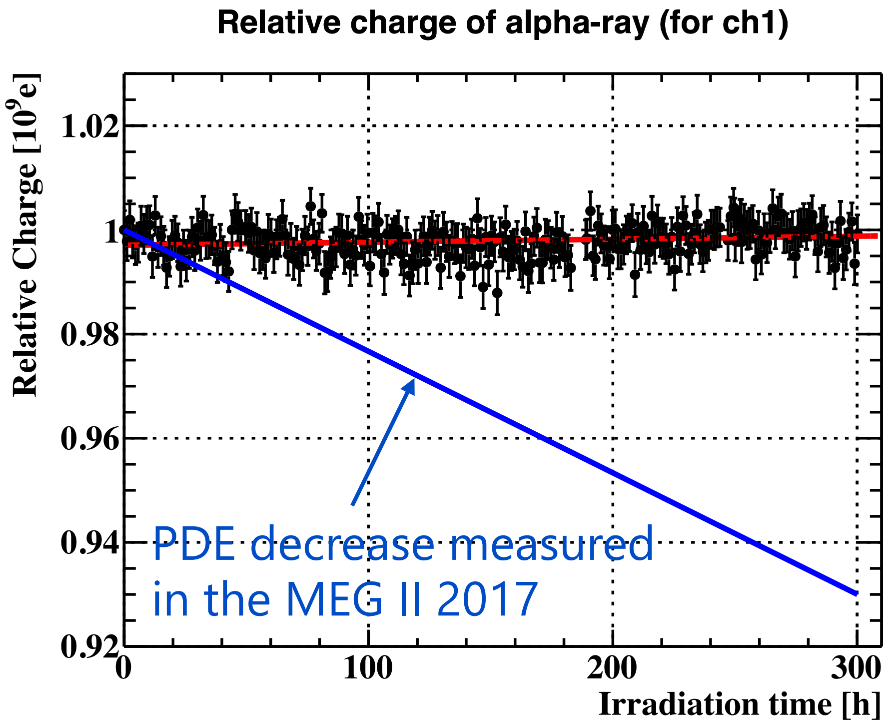


Temp: 168 ± 0.5 K

- Gain is stable during VUV light irradiation

Result – About PDE decrease





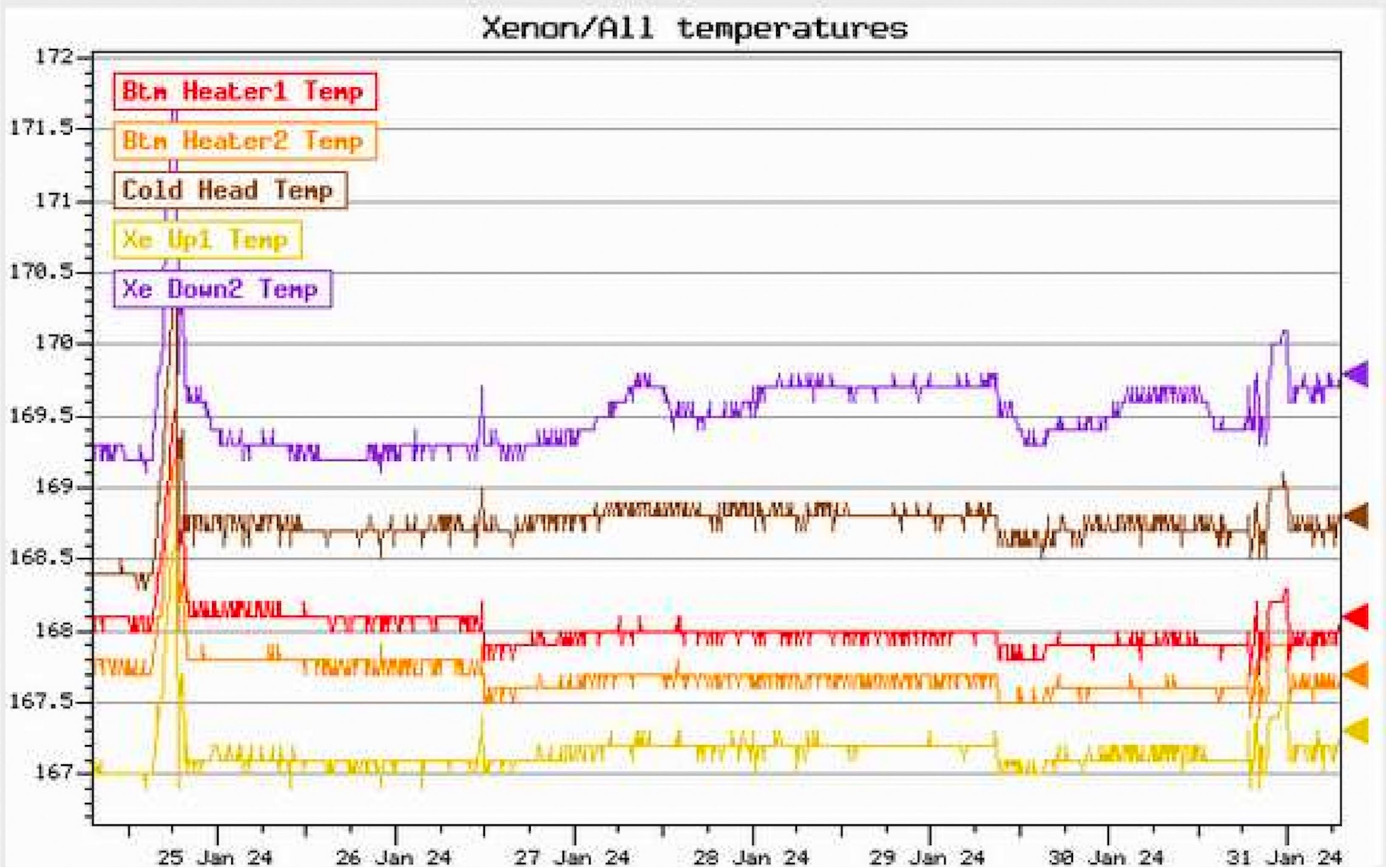
- PDE decrease by VUV irradiation was not observed for humidified MPPC.
- VUV light was excluded as the candidate of cause for the radiation damage
  - Most plausible candidate is gamma-ray

Sammary & Prospect

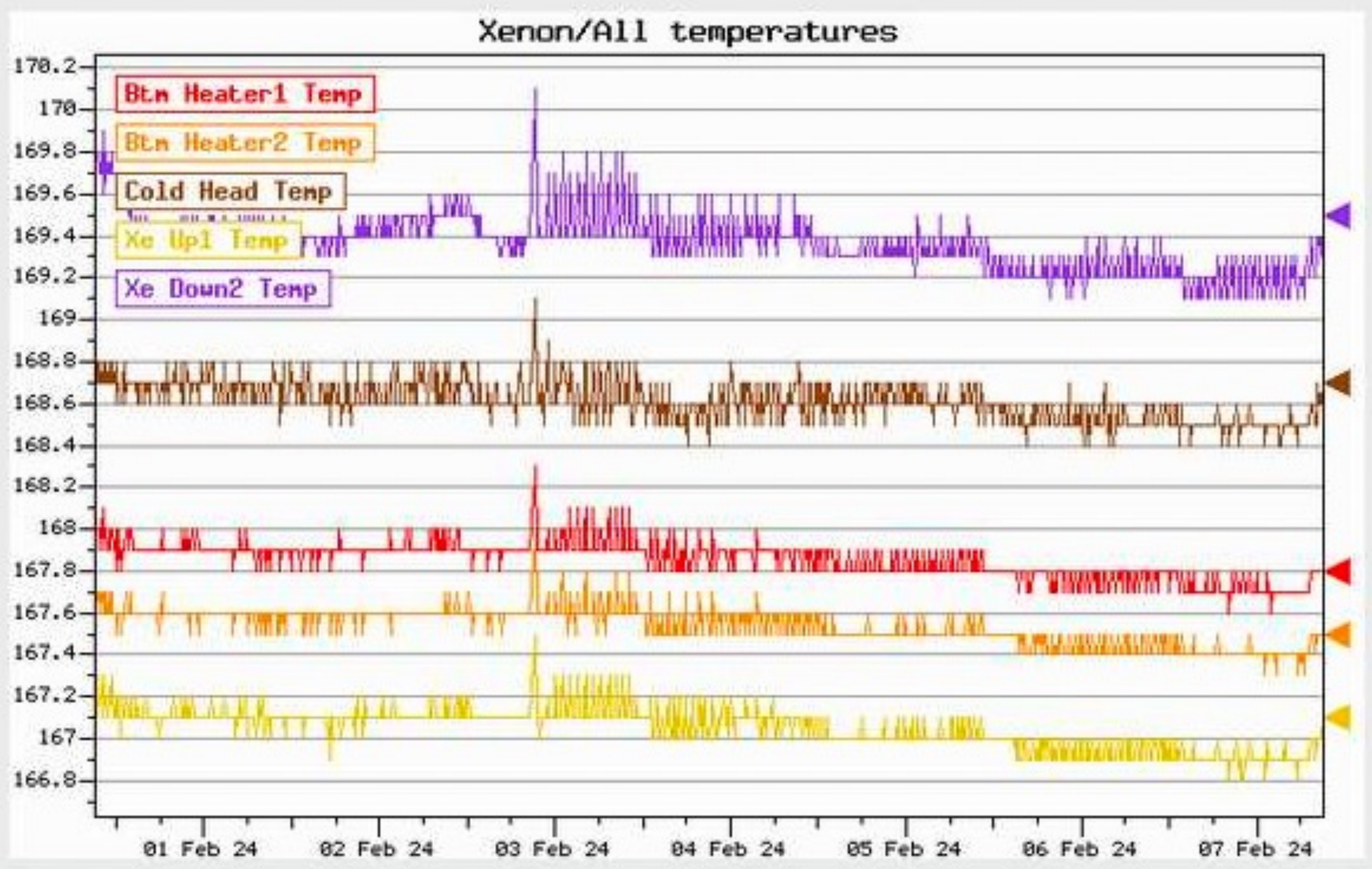
- Summary
    - Rapid decrease of VUV PDE for VUV-MPPC of MEG II LXe detector
    - Studied effect of absorption of moisture inside VUV-MPPC for VUV irradiation.
    - PDE decrease was not reproduced.
- Next step
    - Irradiate gamma-ray to VUV-MPPC
        - in LXe
        - to test the effect of moisture inside VUV-MPPC

Backup

Temperature history

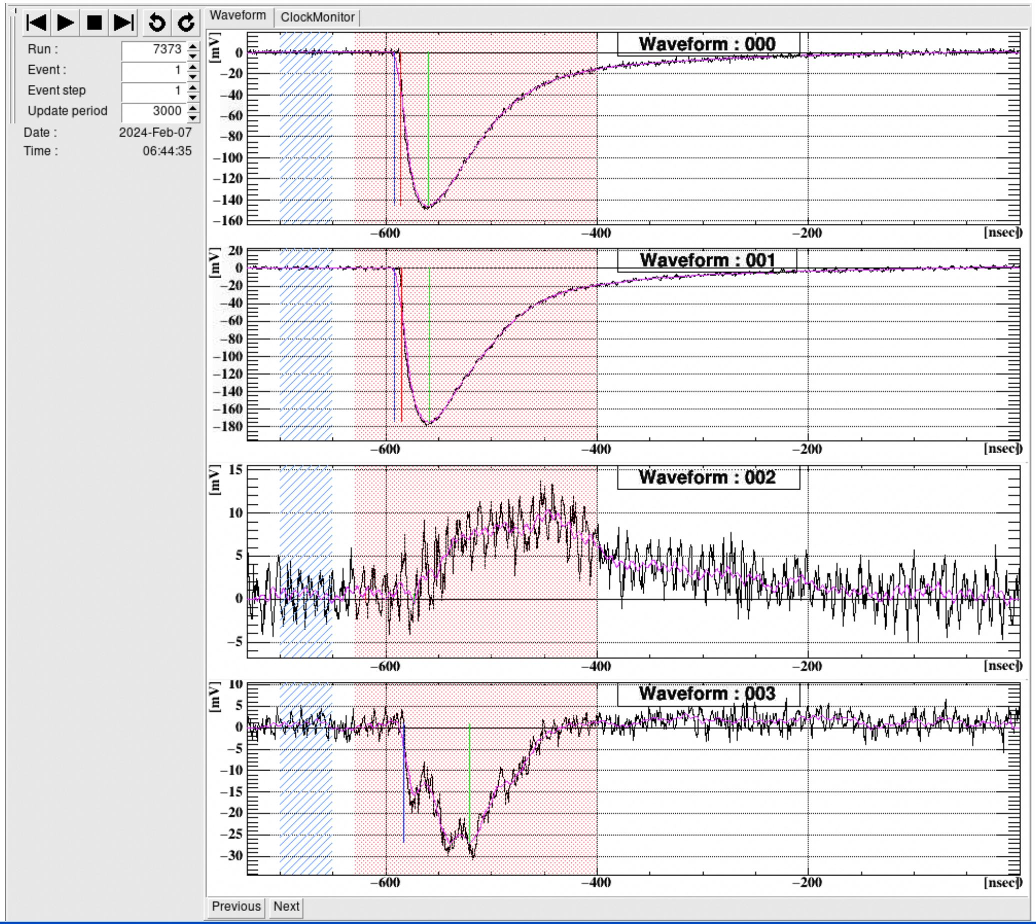


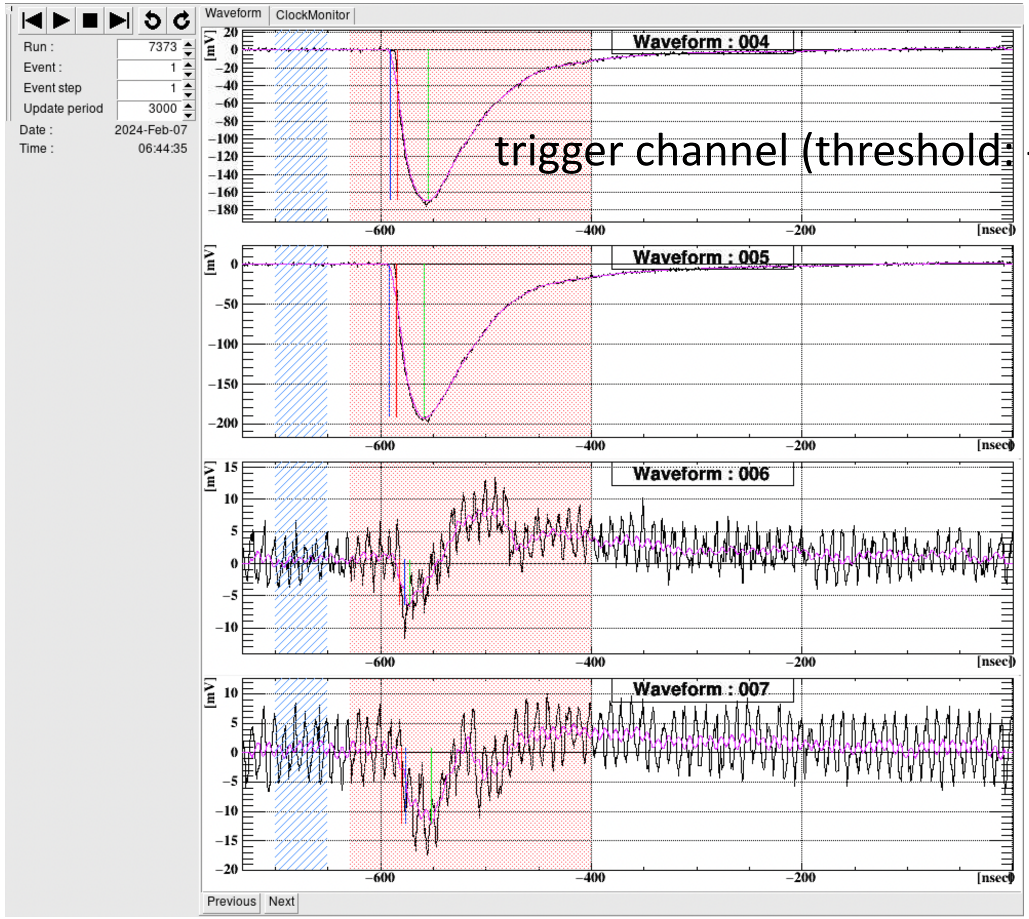
Temperature history



Result - Waveform of alpha-ray

- Mostly, the waveform of ch0, 1 were got as data.

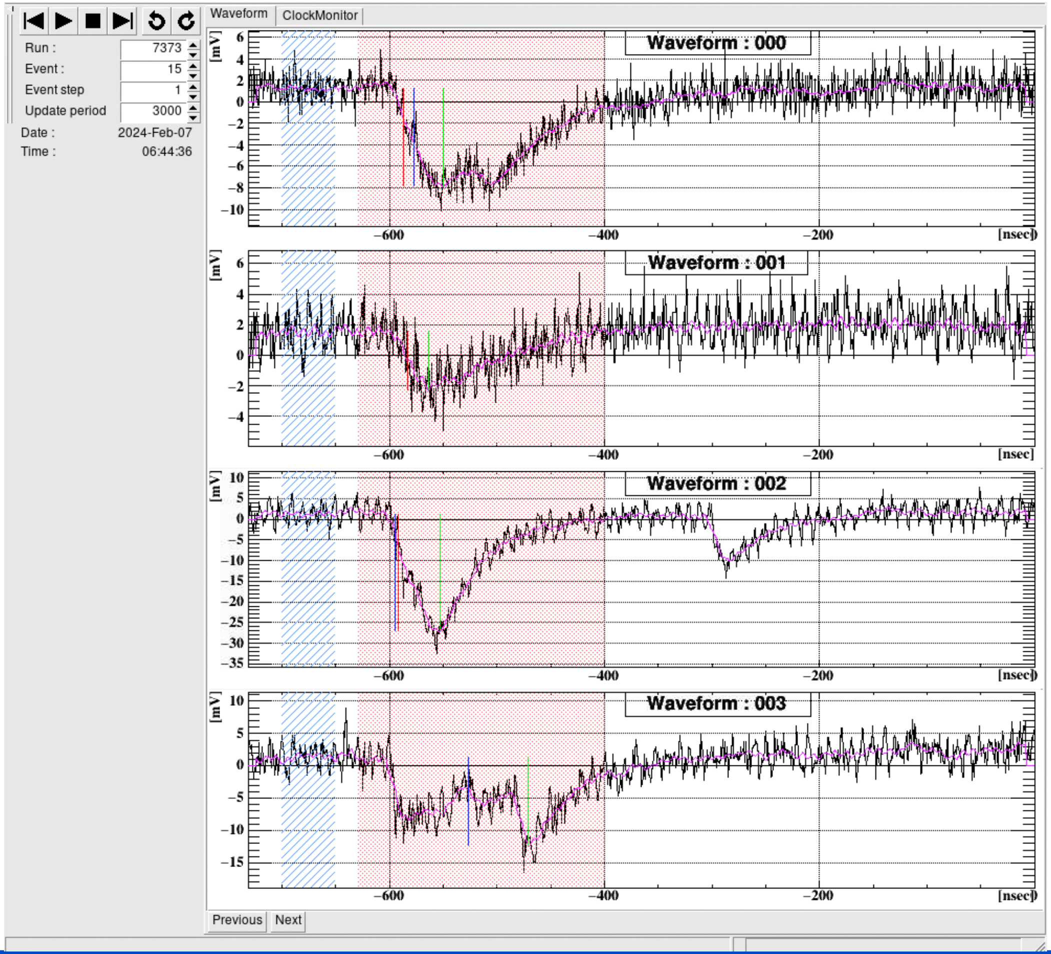


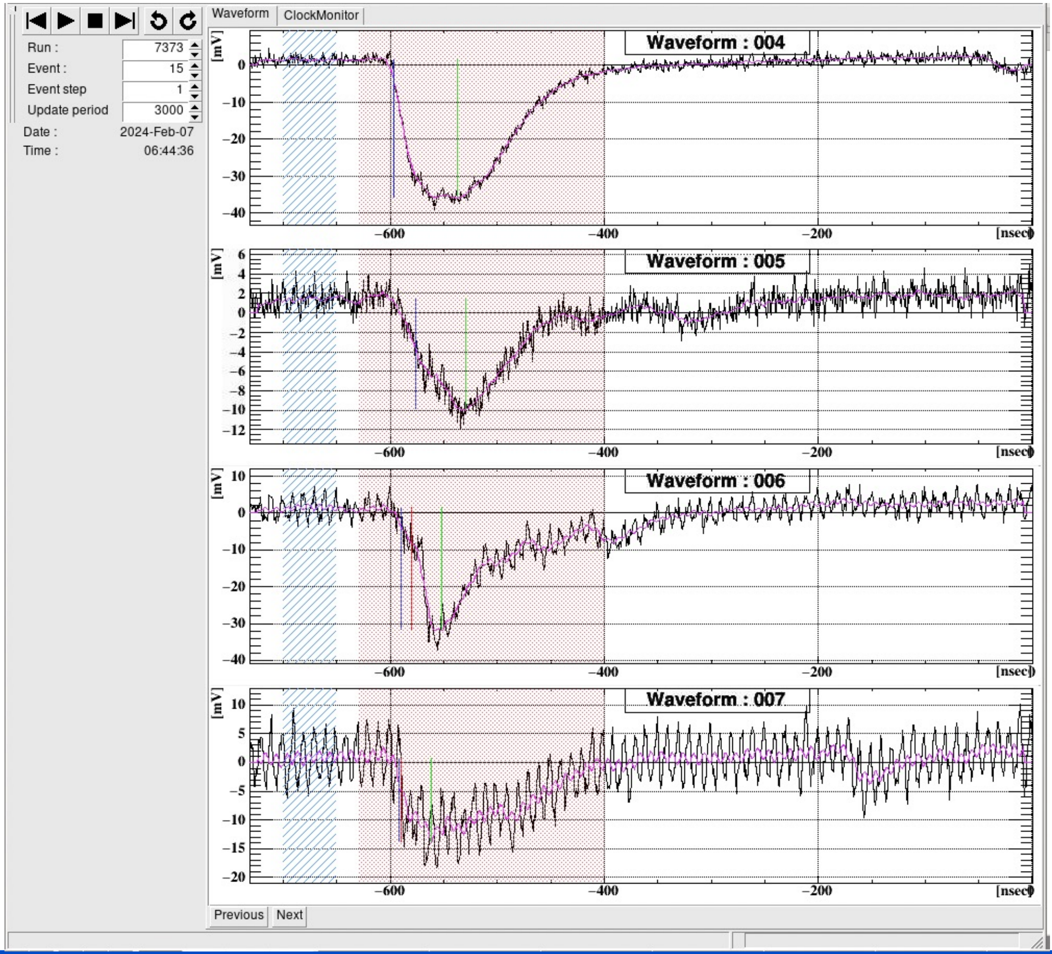


trigger channel (threshold: -20mV)

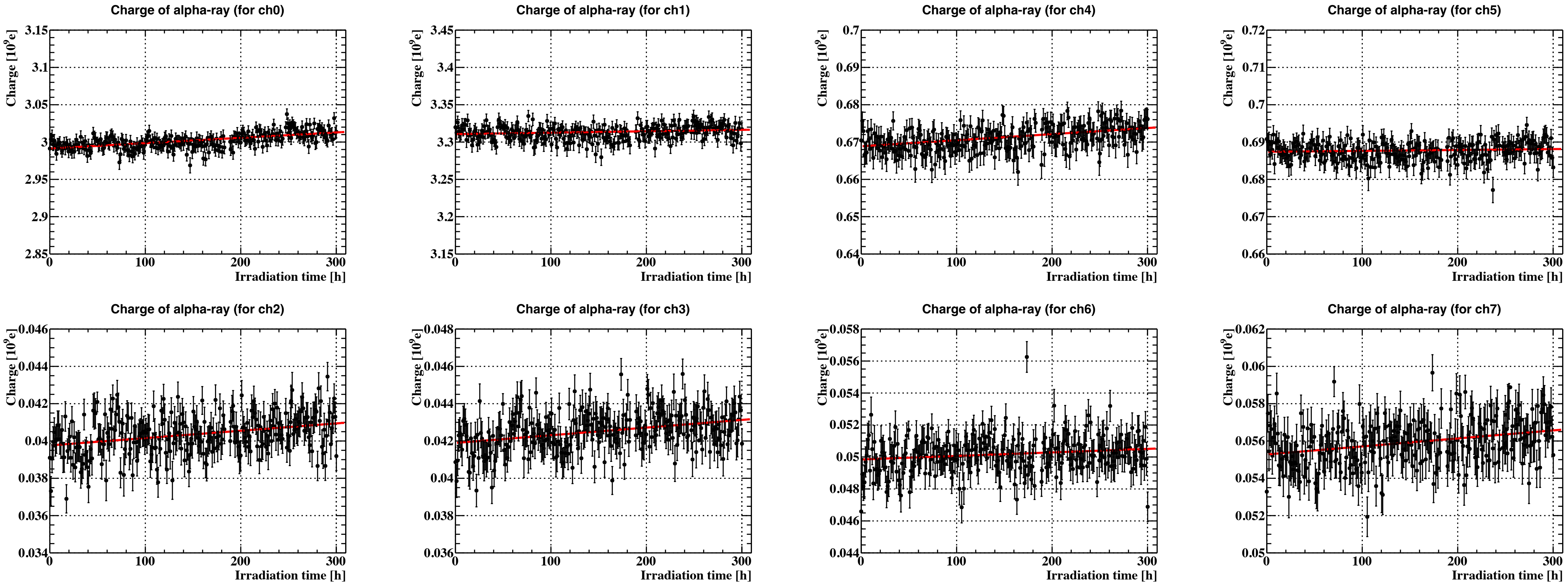
Result - Waveform of alpha-ray

- Sometimes small pulse came in ch0,1





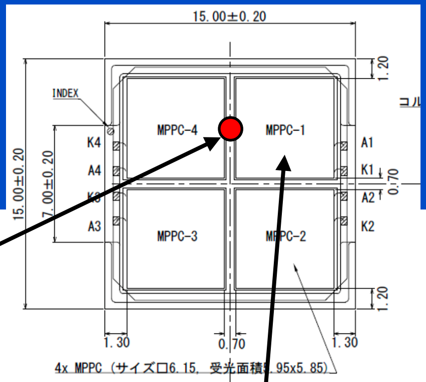
Alpha-ray charge history



Radiation rate

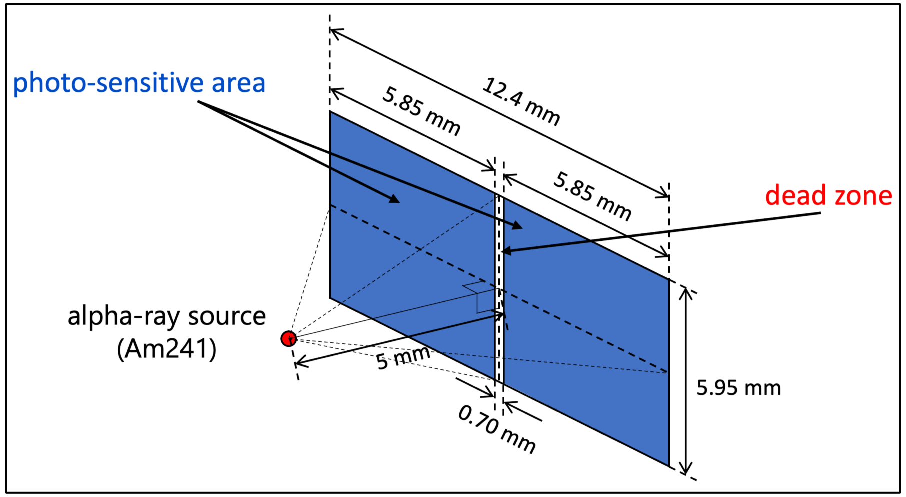
- gain of ch0 : ~$0.1448\times10^9 e$ =5.61×10^6 $(FE\ gain: 100\ (but, in\ practical: 70.15))$
  - Nphe by alpha-ray: $\frac{2.547\times70.15}{0.1448} = 1234$ photo-electron
  - Expected PDE ~ 15%
  - Npho by alpha-ray: $1234\ /\ 0.15 = 8227\ \mathrm{photon}$
  - Radiation rate: $8227\ \mathrm{photon} \cdot 37.76\ \mathrm{Hz} \cdot (5.95\times5.85\ \mathrm{mm}^2)^{-1} = 8.63\times10^3\ \mathrm{photon}\cdot\mathrm{Hz}\cdot\mathrm{mm}^{-2} = 3.21\times10^7\ \mathrm{photon}\cdot\mathrm{h}^{-1}\cdot\mathrm{mm}^{-2}$
- Irradiation time: 300.118 hour = 1.08×10^6 sec
  ->Total irradiation: $3.21\times10^7\ \mathrm{photon}\cdot\mathrm{h}^{-1}\cdot\mathrm{mm}^{-2}$ · 300.118 h=$9.634\times10^9\ \mathrm{photon}\cdot\mathrm{mm}^{-2}$
- Radiation dose in LXe detector in 2021: $1.1\times10^{11}\ \mathrm{photon}\cdot\mathrm{mm}^{-2}$
  - Radiation ratio between this experiment and 2021 run =$9.634\times10^9\ \mathrm{photon}\cdot\mathrm{mm}^{-2}\ /\ 1.1\times10^{11}\ \mathrm{photon}\cdot\mathrm{mm}^{-2}$ = 0.088
- Radiation dose in 2021 run: 180×10^{12} stopped muons
  - Radiation dose in this experiment: 180×10^{12} stopped muons · 0.088=15.8×10^{12} stopped muons
  - Absolute PDE decrease in 2017 run: ~14% -> ~13-12.5% (~1-1.5 %pt, ~7.7-12% in relative)
  - Esxpected absolute PDE decrease in this experiment: ~15 % -> lower than 14%. (>1 %pt, >7% in relative)

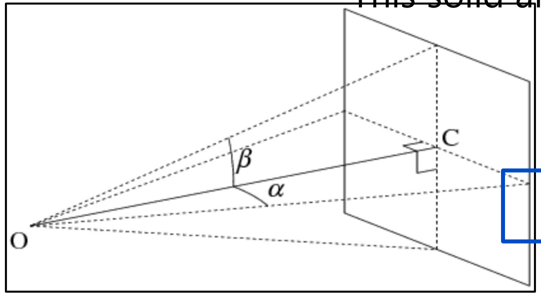
Calculation of the probability of photon entering a chip in VUV-MPPC



alpha-ray source (Am241)

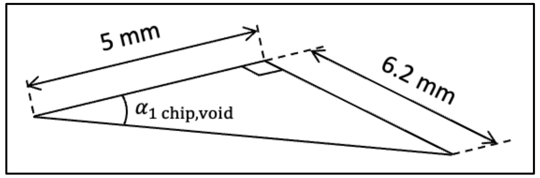
sensor chip (5.95×5.85 mm^2)

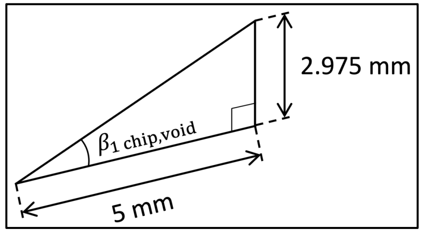


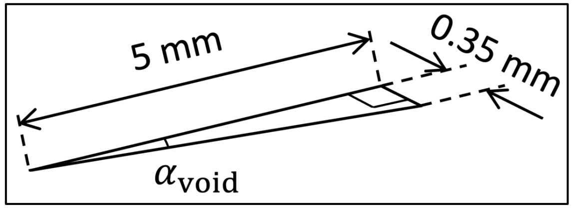


This solid angle is given by

$$\Omega = 4 \arcsin(\sin\alpha \sin\beta)$$







- The probability of photon entering a chip with including the dead zone: $P_{1\,\mathrm{chip,void}}$
  - $\alpha_{1\,\mathrm{chip,void}} = 0.892$ rad
  - $\beta_{1\,\mathrm{chip,void}} = 0.537$ rad

  -> $\Omega_{1\,\mathrm{chip,void}} = 2\arcsin(\sin\alpha_{1\,\mathrm{chip,void}} \sin\beta_{1\,\mathrm{chip,void}}) = 0.819$
- $P_{1\,\mathrm{chip,void}} = \Omega_{1\,\mathrm{chip,void}}/4\pi = 0.0652$

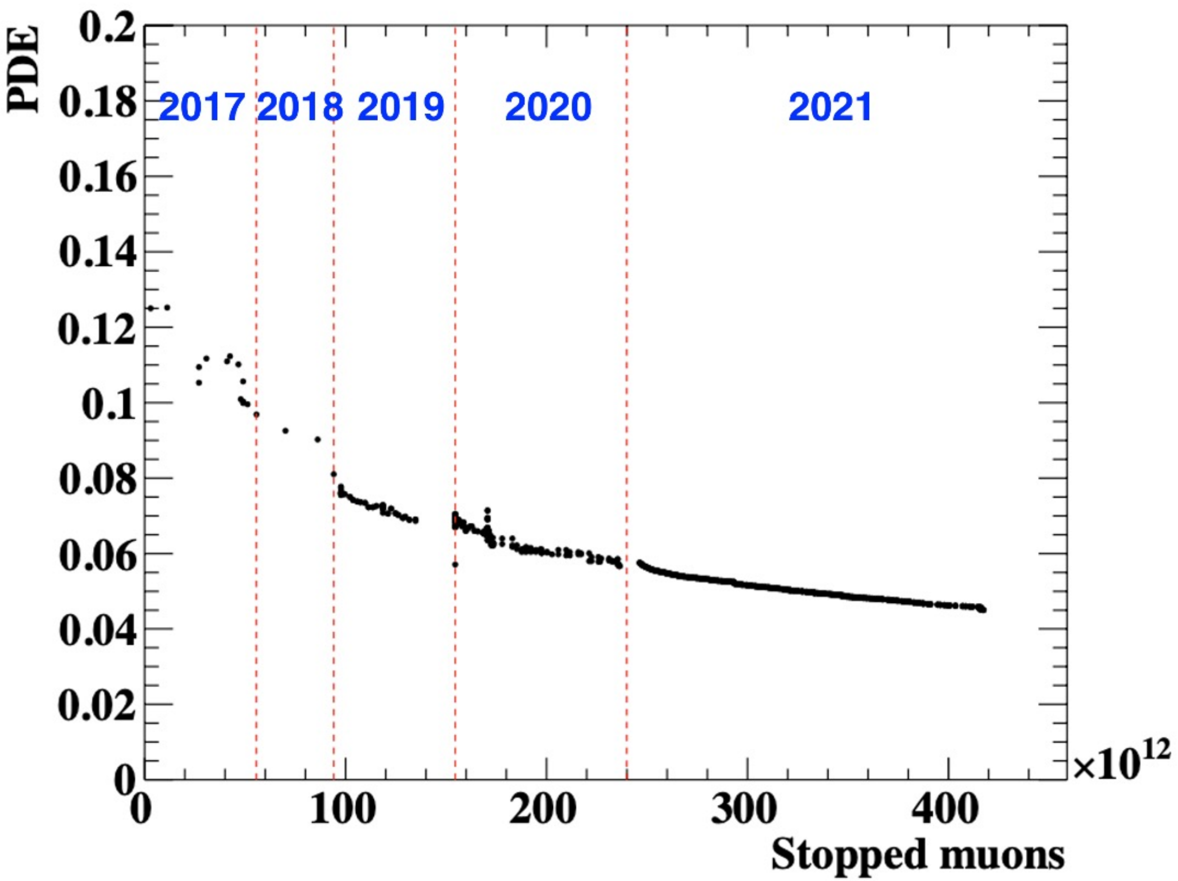
- The probability of photon entering the dead zone: P_{void}
  - $\alpha_{\mathrm{void}} = 0.0699$ rad
  - $\beta_{\mathrm{void}} = \beta_{1\,\mathrm{chip,void}} = 0.537$ rad

  ->$\Omega_{\mathrm{void}} = 2\arcsin(\sin\alpha_{\mathrm{void}} \sin\beta_{\mathrm{void}}) = 0.0714$
- $P_{\mathrm{void}} = \Omega_{\mathrm{void}}/4\pi = 0.00568$

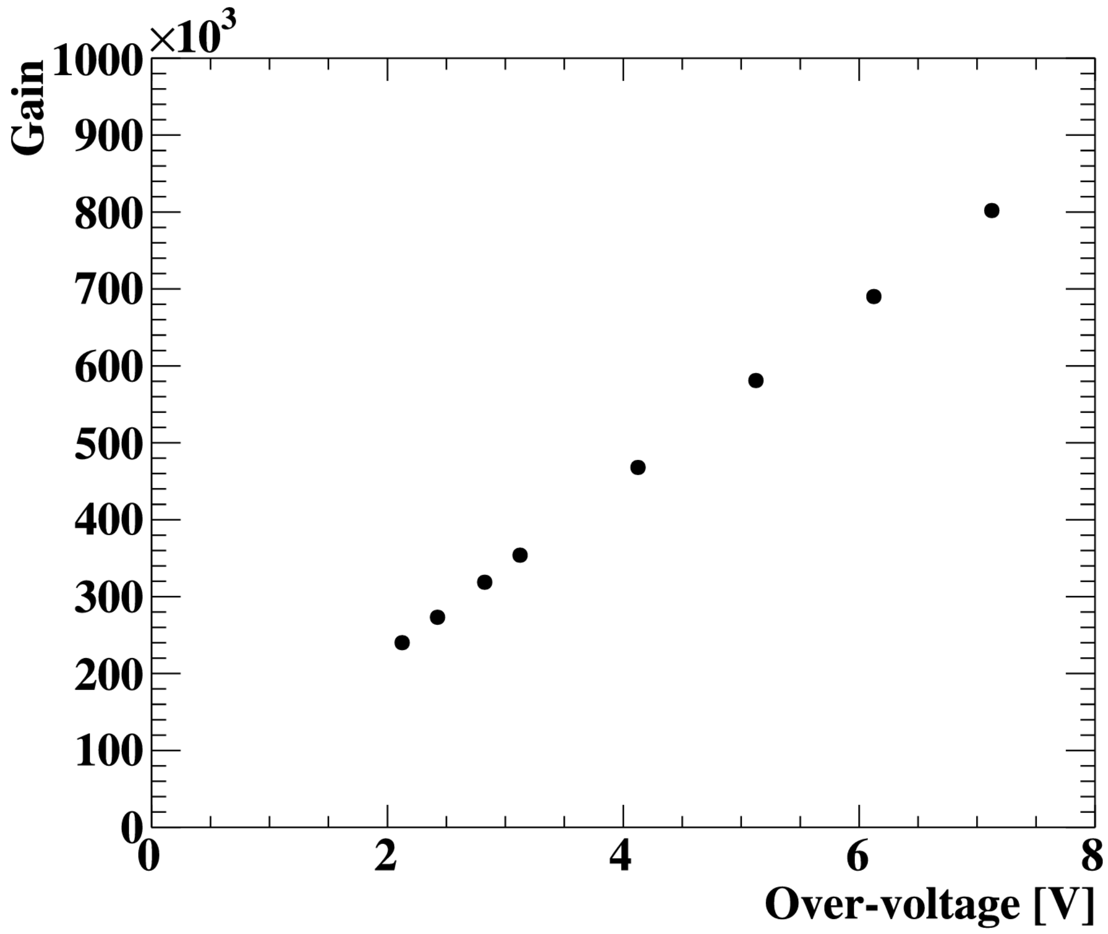
The probability of photon entering a chip without the dead zone:

$$P_{1\,\mathrm{chip}} = P_{1\,\mathrm{chip,void}} - P_{\mathrm{void}} = 0.0652 - 0.00568 = 0.0595$$

PDE degrease during run



Gain vs Over voltage



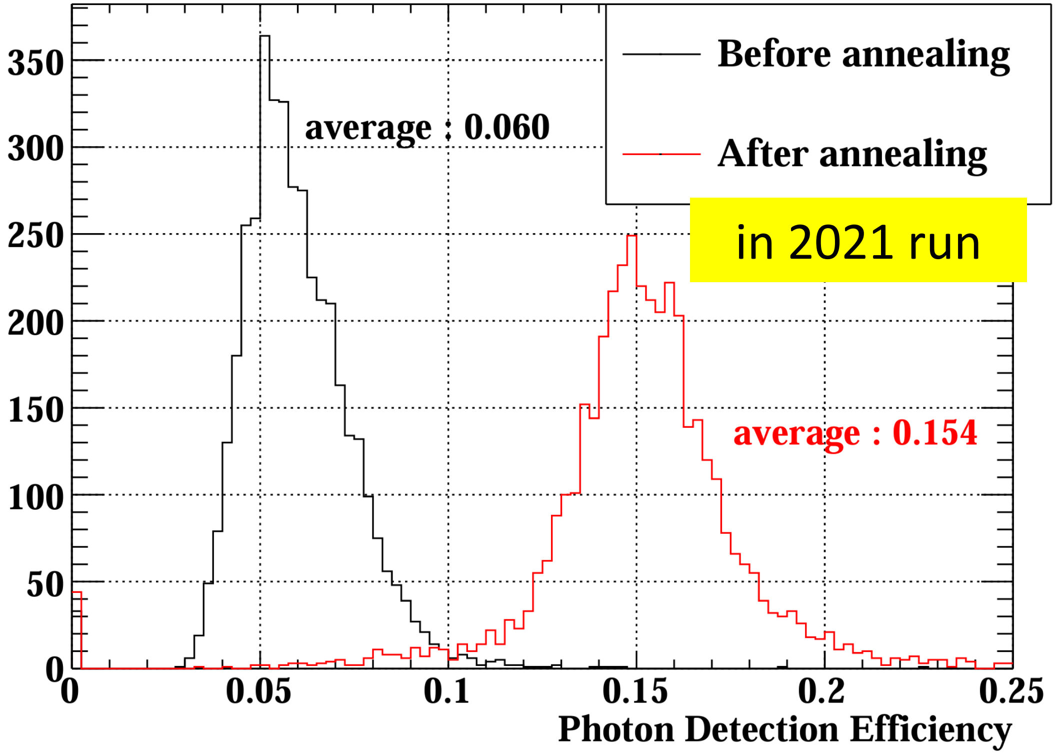
Tips

- Superinsulation
  - Multiple layer film made from alminum
- LN temperature: 77 K (196 ˚C)

Annealing

- Heating the VUV-MPPCs (at 70 ˚C)
  - to remove the accumulated positive charges
- PDE can be returned to original value by annealing.
- Sample
  - Baking condition: 150 ℃ x 16 hours

Annealing each MPPC for 28 hours (at 70 °C)



in 2021 run

Calculation of LXe height filling inside small chamber

- small chamberの容器の内径（直径）: 101 mm
  ->面積: 8008 mm^2 = 80.1 cm^2
  ->容器の底から~~20.6~~ 36 cmまで、液体キセノンに浸る
  1.65L = 1650 cm^3
  1 L = 1000 cm^3

- GXe inside high pressure tank: 750 L, 0.23 MPa
  - when the pressure is 0.12 MPa, the volume is 750×0.23/0.12 = 1438 L
- LXe volume is 500 times smaller than GXe volume
  - 1438 L in GXe -> 1438/500 = 2.88 L in LXe
- Inner diameter of small chamber: 101 mm
  - Bottom area of small chamber: $8.01\times10^3\ \mathrm{mm}^2$
- the height of LXe inside small chamber is $2.88\times10^6/\ 8.01\times10^3$ = 360 mm = 36 cm
  - 1 litre = $1\times10^6\ \mathrm{mm}^2$

Getter (PS3-MT3-R-2)

Impurities Removed	Nitrogen Outlet Purity (ppb)	Rare Gas Outlet Purity (ppb)
H_2O	<1	<1
O_2	<1	<1
CO	<1	<1
CO_2	<1	<1
CH_4	<1	<1
Other Hydrocarbons	<1	<1
H_2	<1	<1
N_2	N/A	<1