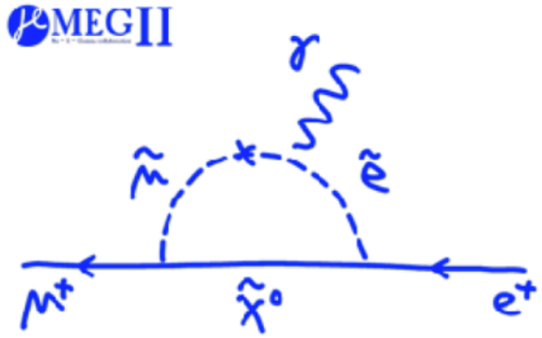
東京大学
素粒子物理国際研究センター
International Center for Elementary Particle Physics
The University of Tokyo



MEG II experiment
and
Liquid xenon detector

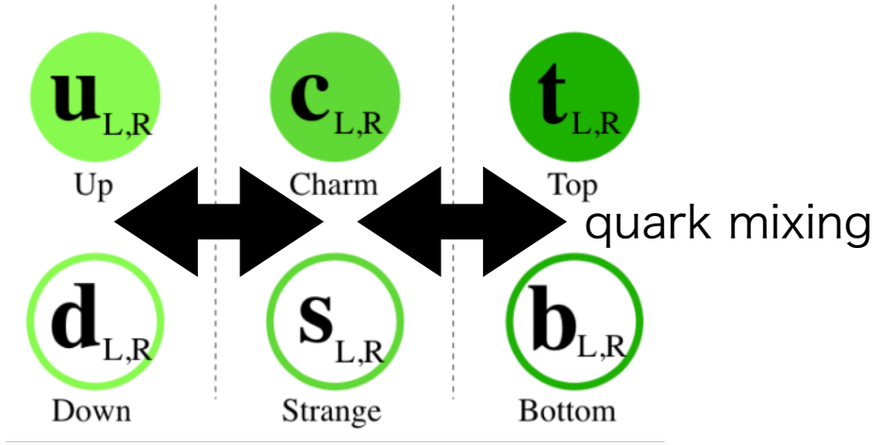
Sei BAN (ICEPP), for the MEG II collaboration
24th May. 2022, XeSAT2022 at Coimbra, Portogul

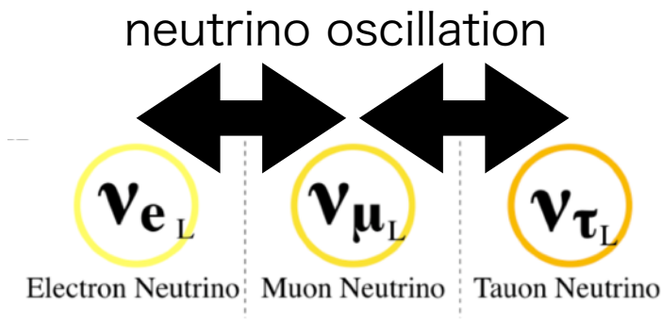
Contents

Contents

Charged Lepton Flavor Violation

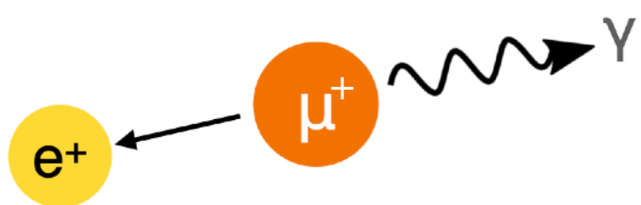
- In quark and neutrino (neutral lepton) sector, the flavor violates in SM+ν mass



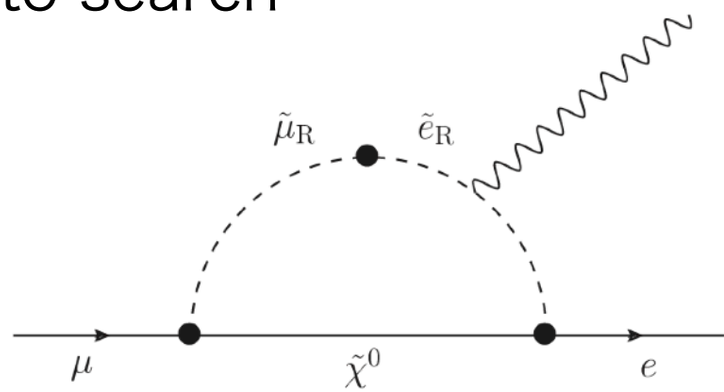


- Some theories BSM predict flavor violation in the charged lepton sector
  - In the Standard Model, it is practically prohibited : Br(μ→eγ)=10^{-54}
  - In BSM, Br(μ→eγ) ~ O(10^{-14}) is predicted : large enough to search

- Signal : Gamma-ray and positron with 52.8 MeV (=$m_\mu/2$)



back-to-back
the same timing

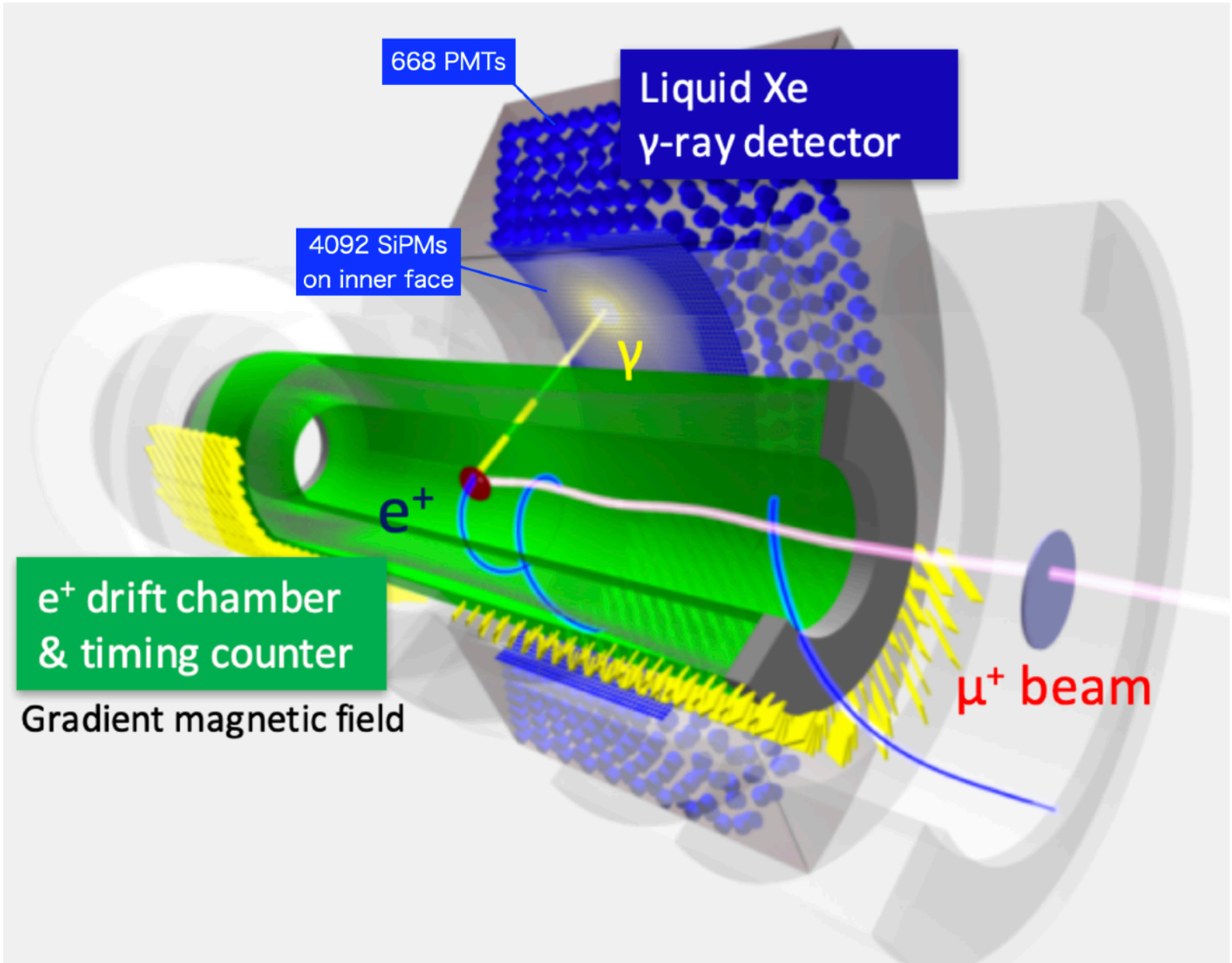


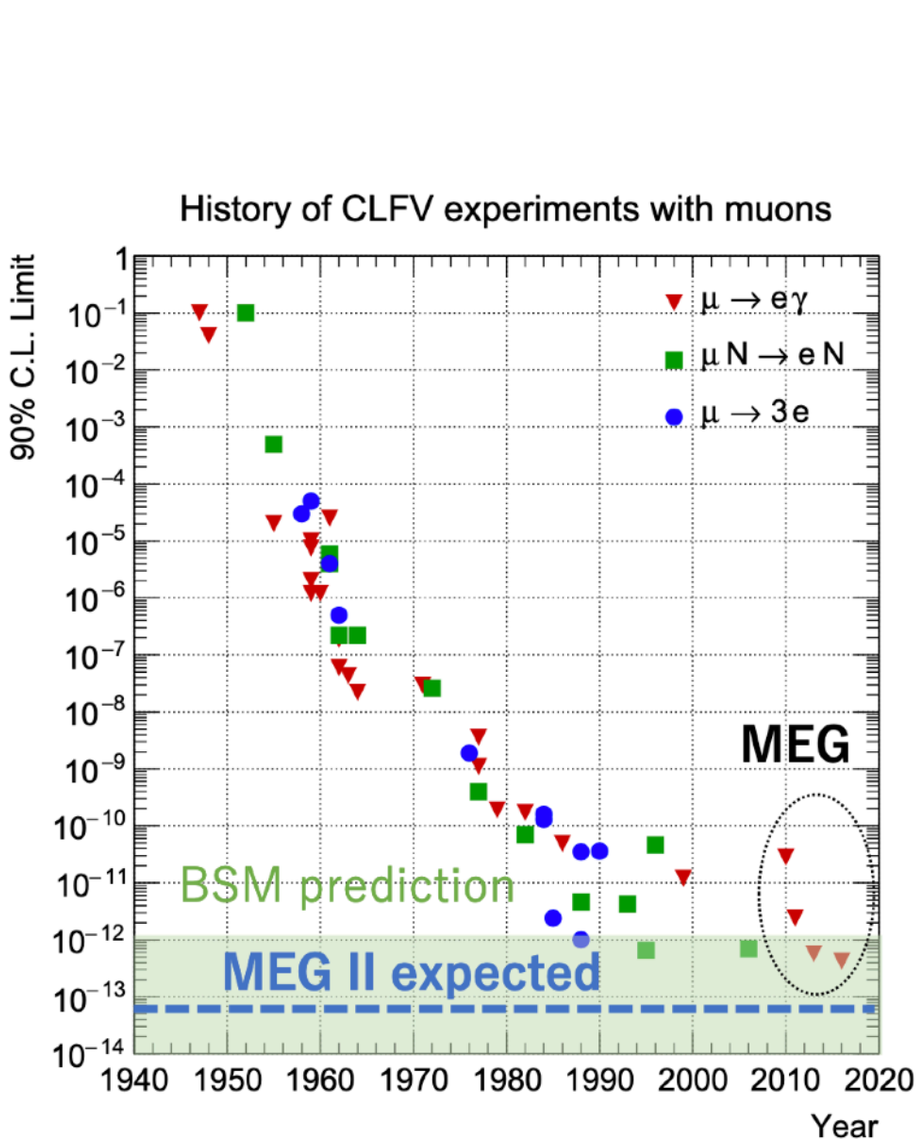
Possible diagram
in SUSY-GUT senario

- N_{signal} ∝ [beam rate]x[time]
- N_{BG} ∝ [beam rate]^2 x [time] x [Detector resolutions]
  - Good resolutions (energy, timing) are required
  - DC beam is prefer than AC (pulsed) beam

MEG II experiment

- MEG II experiment aims to search for charged lepton flavor violation : $\mu^+ \rightarrow e^+\gamma$
  - with higher sensitivity by one order of magnitude compared to the MEG
- Consists of LXe detector for γ-ray, drift chamber & timing counter for e^+
- Engineering run and physics run with full number of readout channels were conducted in 2021





Contents

Timeline in 2021

Assigned beam time

May. | Jun. | Jul. | Aug. | Sep. | Oct. | Nov. | Dec.

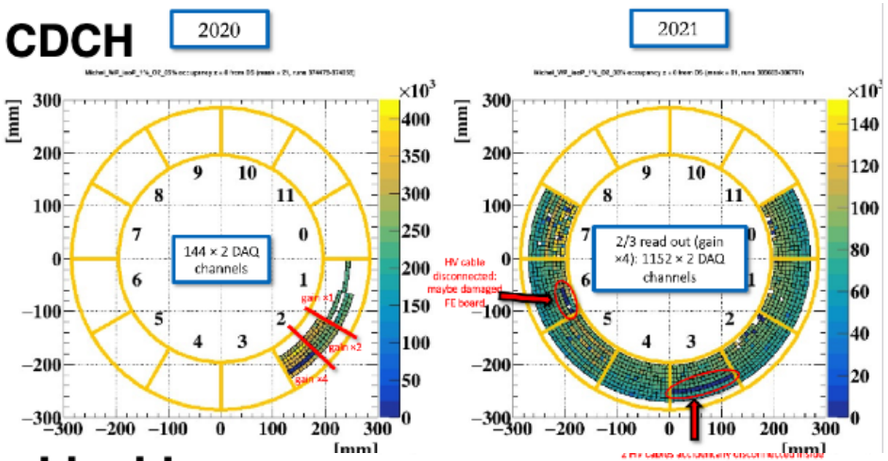
Sub-detector preparation with full channel readout

Trigger setup

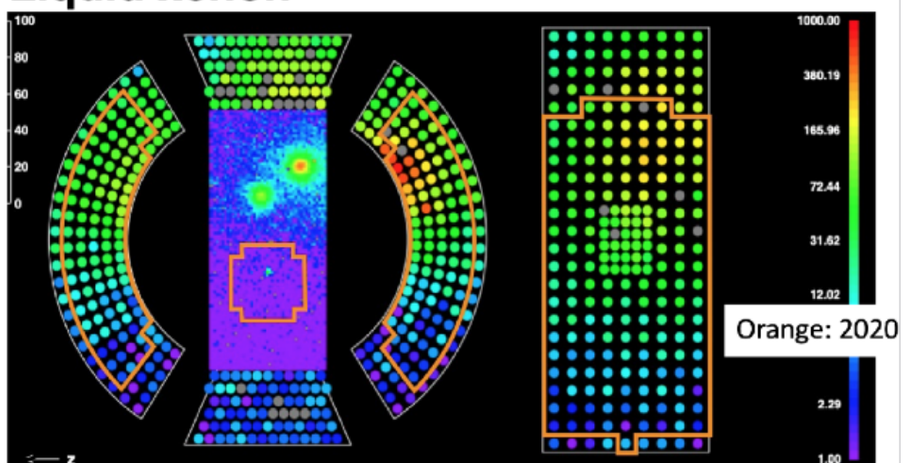
Physics run

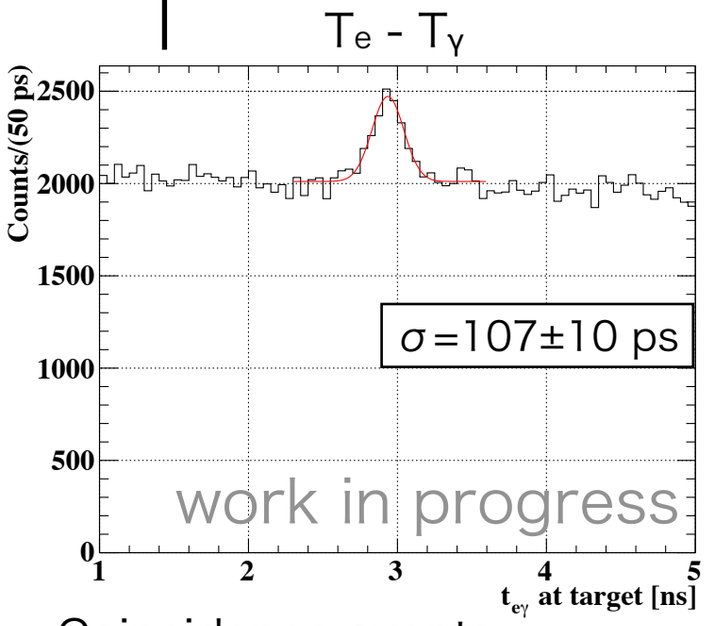
Calibration run with pion CEX

CDCH



Liquid xenon



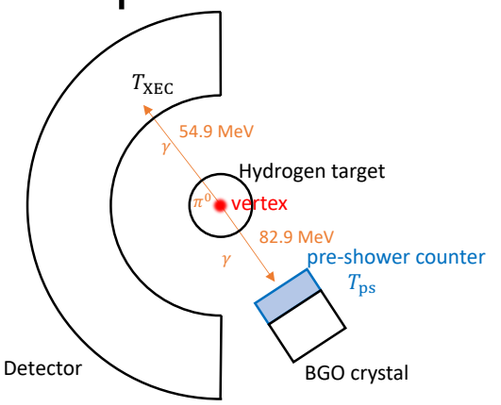


Coincidence events between γ and e are obtained

: Radiative Muon Decay

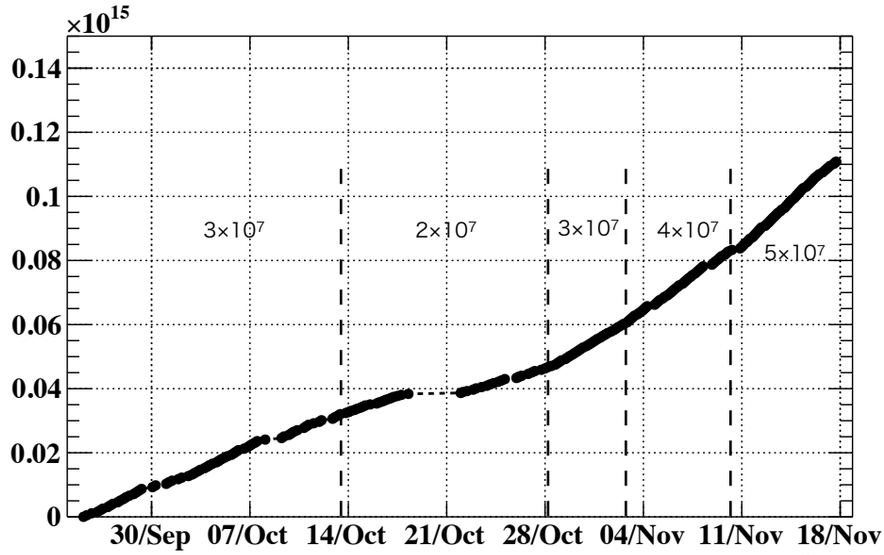
$\mu \rightarrow e\nu\nu\bar{\gamma}$

→ Trigger works as expected



Period : 25th Sep. — 17th Nov.

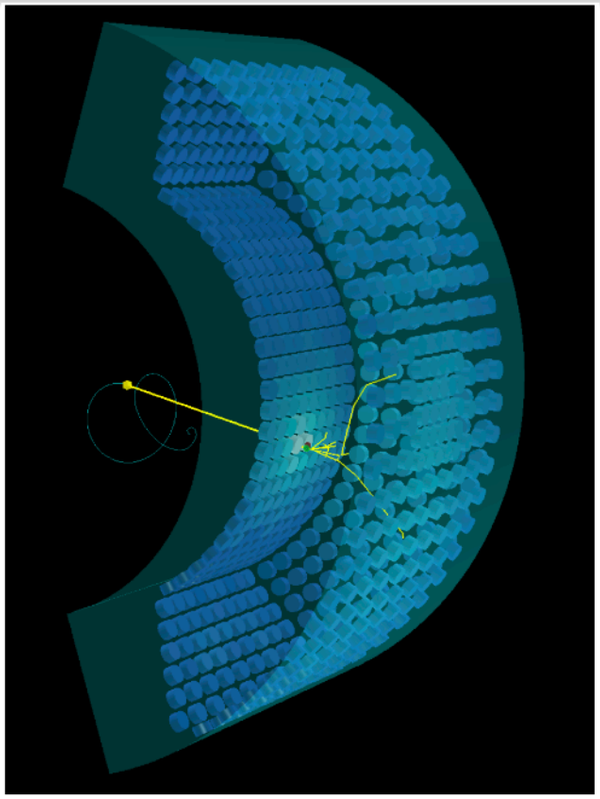
Stopped muon in target : 8e+13

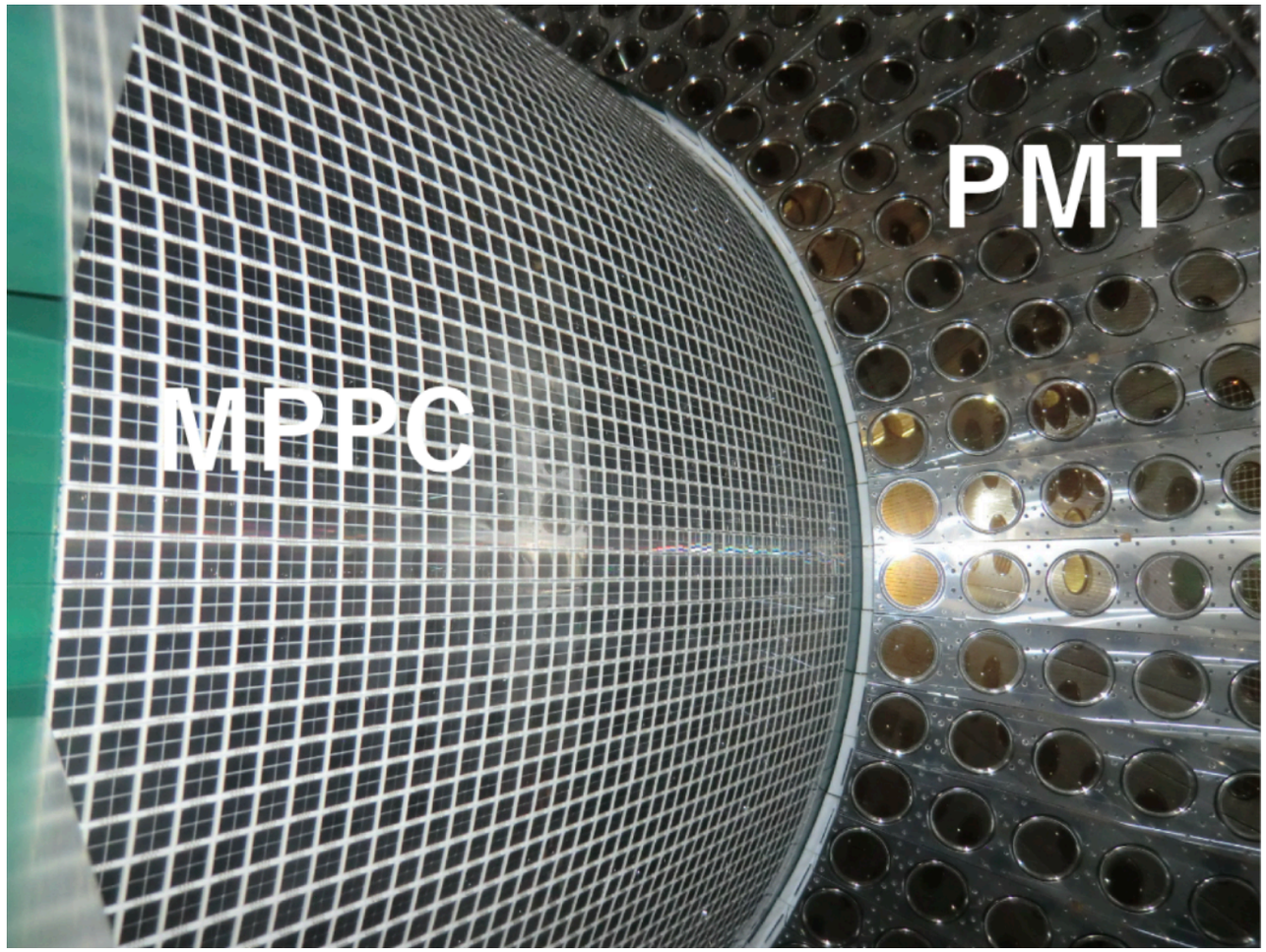


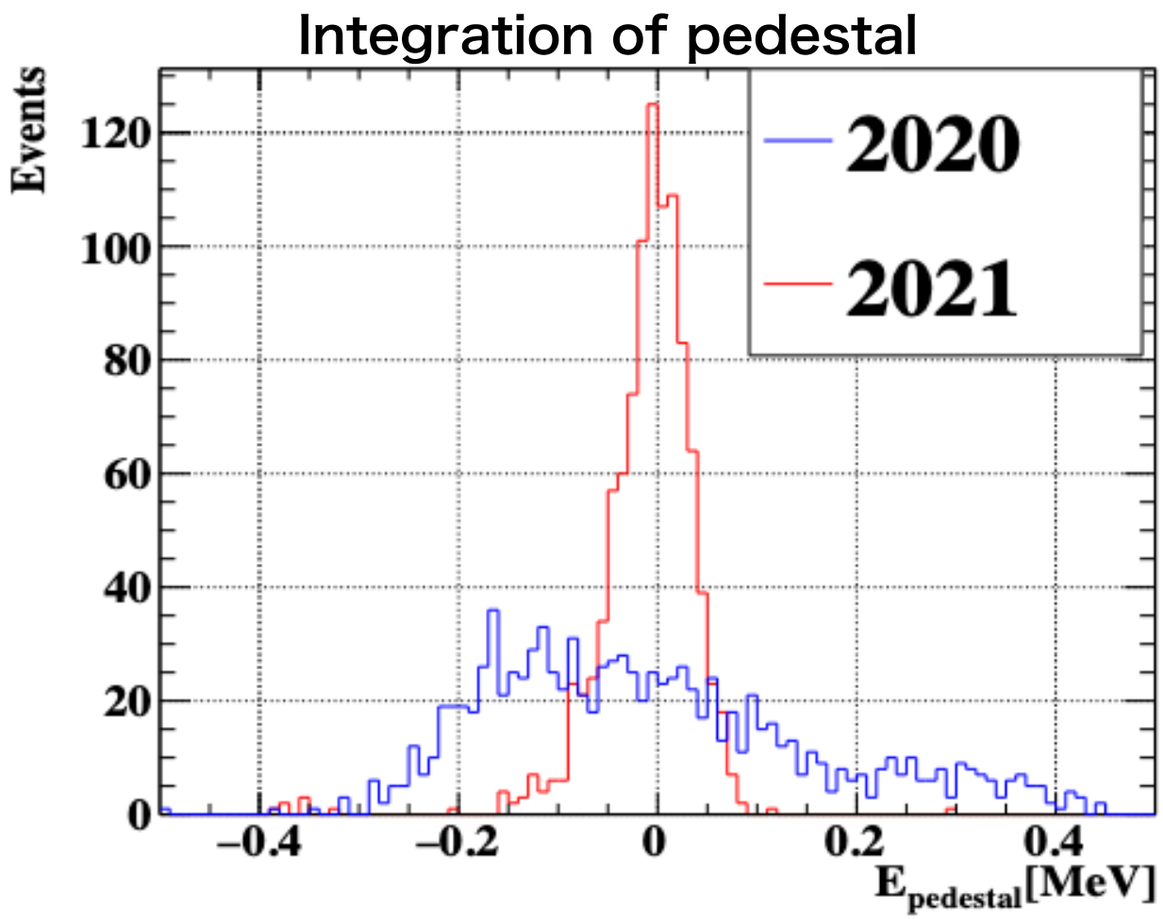
Contents

Operation of the liquid xenon detector in 2021 run

- The liquid xenon detector consists of 4092 VUV-sensitive MPPCs on the inner face and 668 VUV-PMTs on the other faces
  - Measuring the energy, position and timing of incoming gamma-rays
- First operation of the full number of readout in 2021
- Noise is reduced by improvement of electronics and analysis



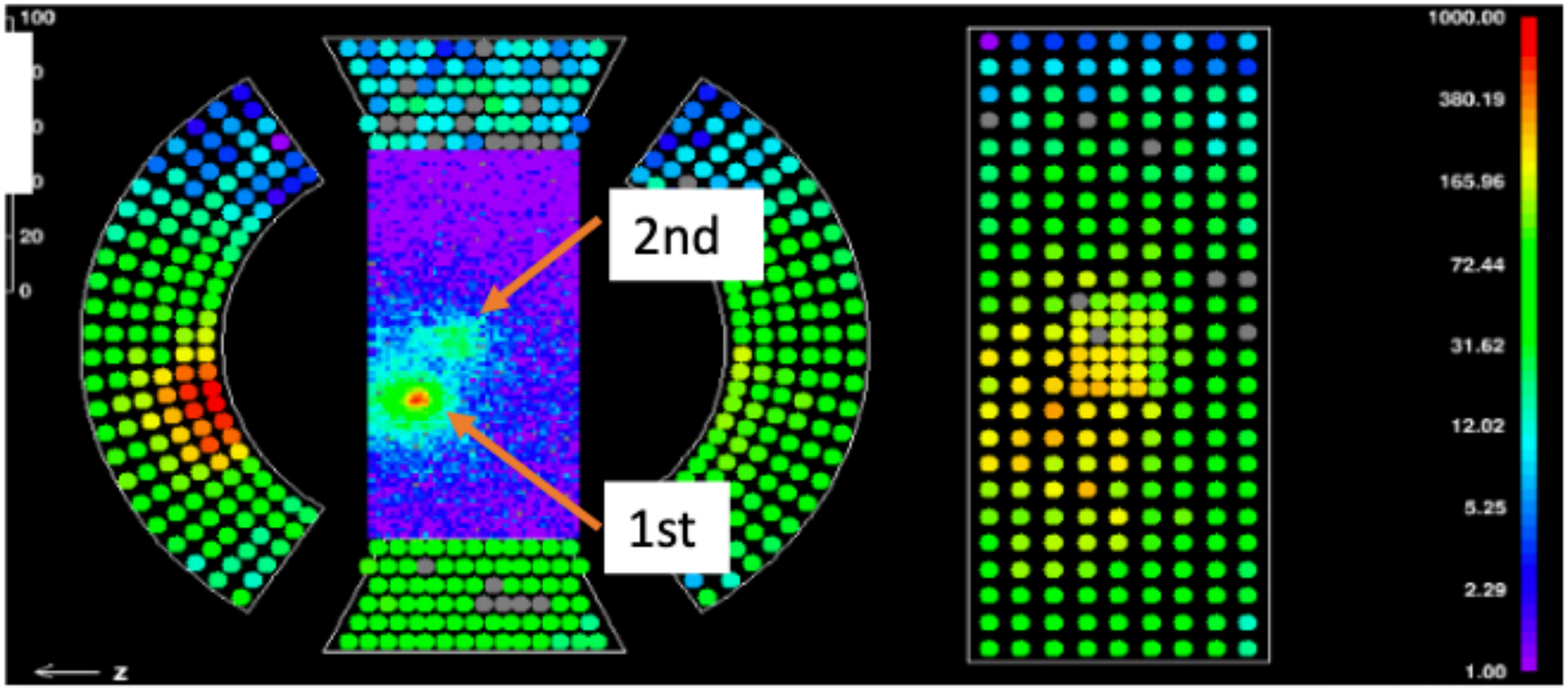




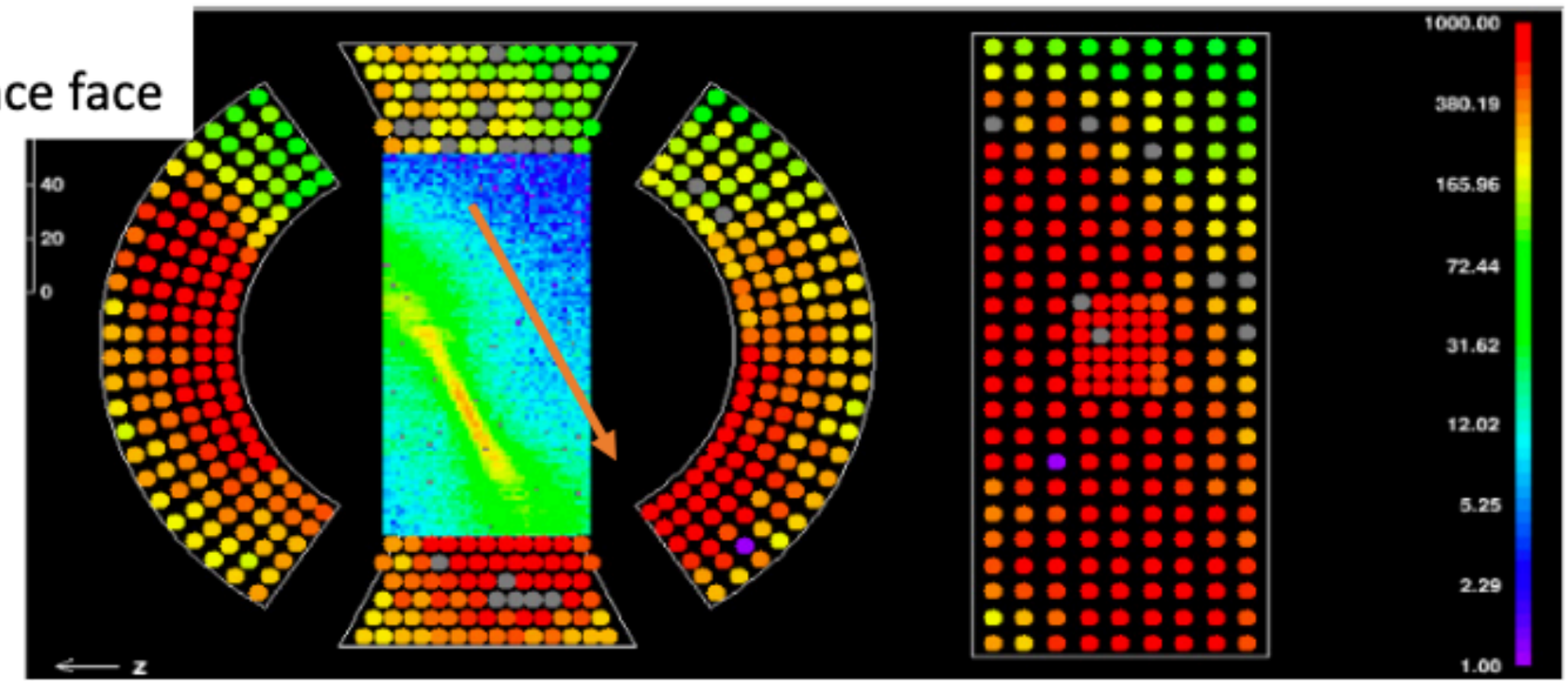
Operation of the liquid xenon detector in 2021 run

- Event display with full number of readout channels

Pileup
gamma-rays



Cosmic-ray
Close to entrance face



Stability of the energy scale

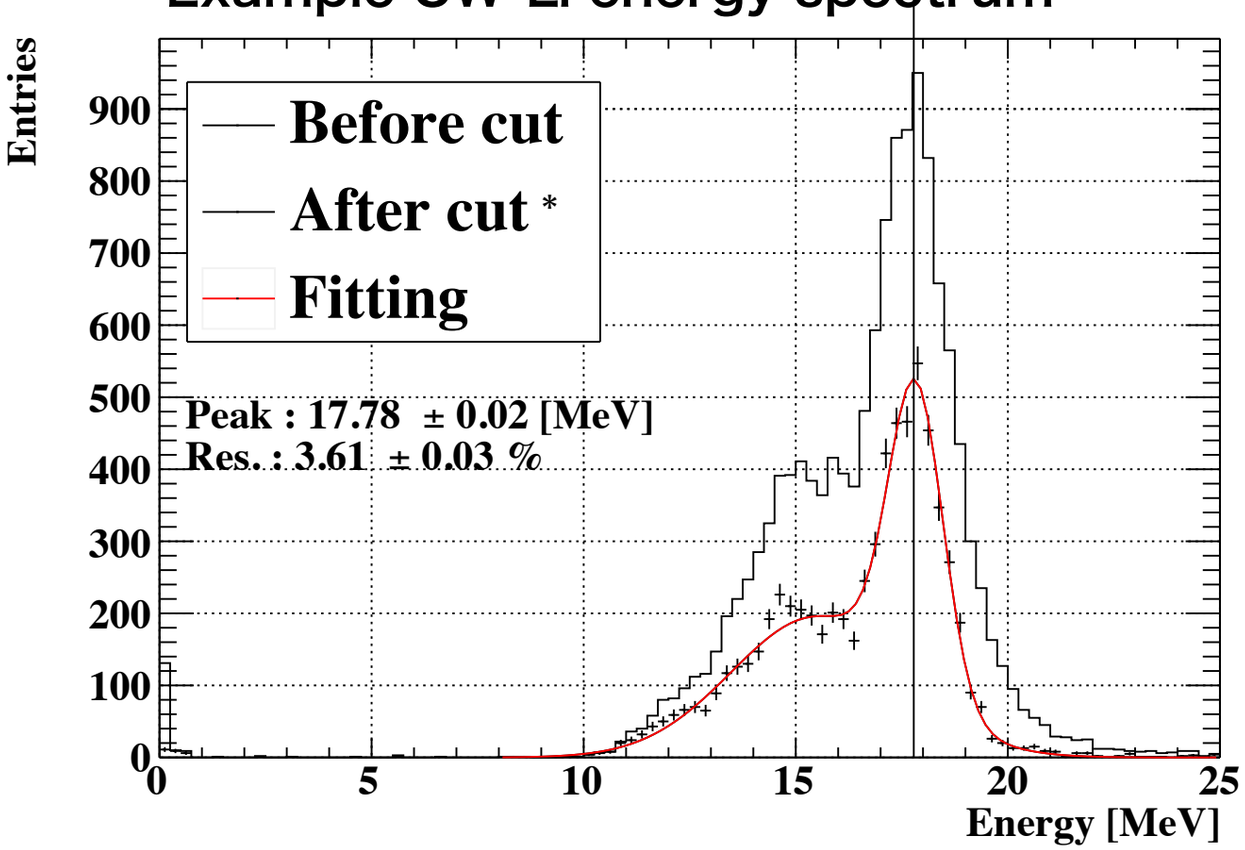
- Performance of the liquid xenon detector was monitored and evaluated using various calibration sources during the beam time
  - LED light, Alpha-ray, Mono-energy Gamma-ray (9 MeV, 17.6 MeV)

- 17.6 MeV gamma-ray from CW accelerator and Li target

  p (CW acc.) + Li (target) → Li(p,γ)Be → γ (17.6 MeV)

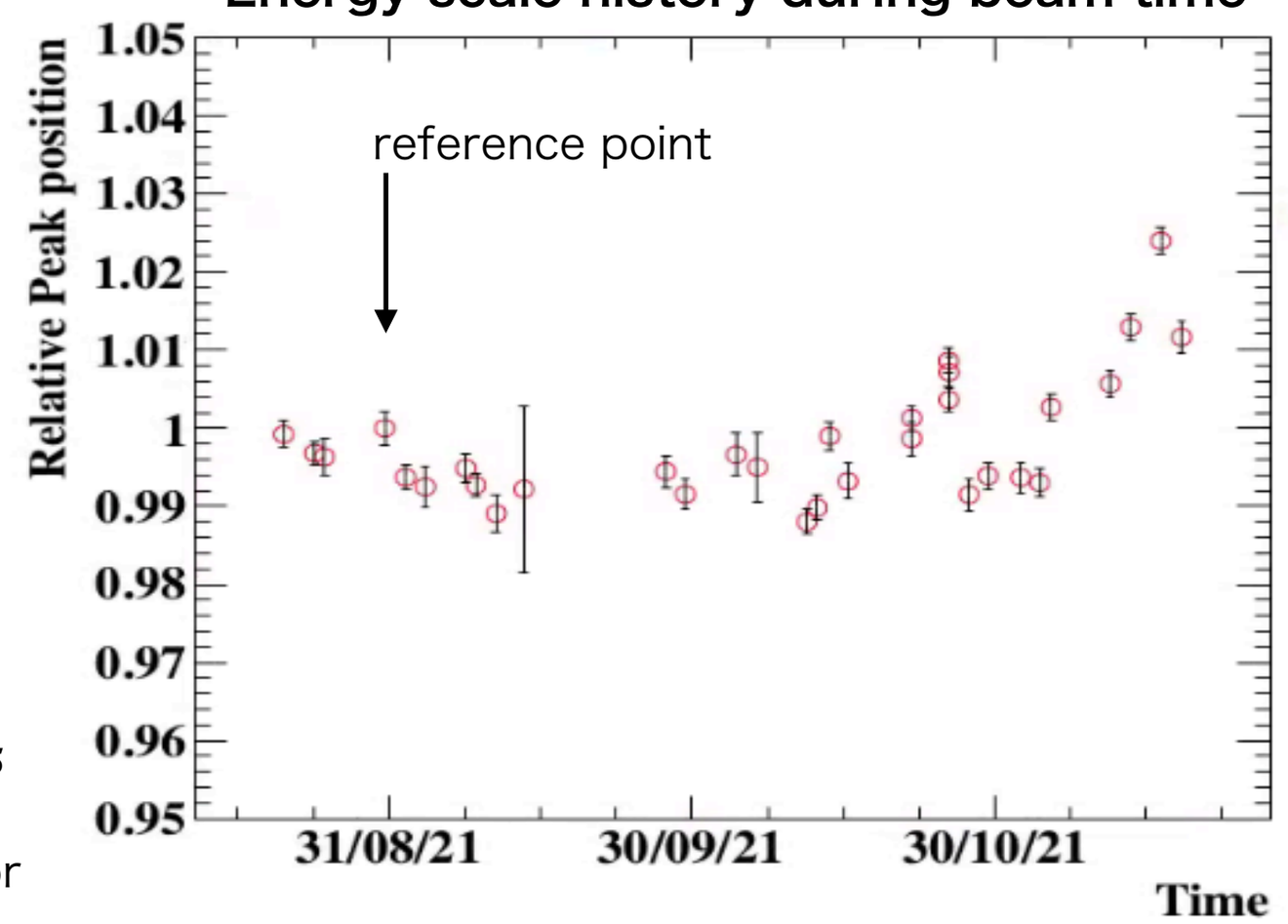
- For some reason, energy scale increased gradually (~2%)

Example CW-Li energy spectrum



* Event selection : central region of the detector

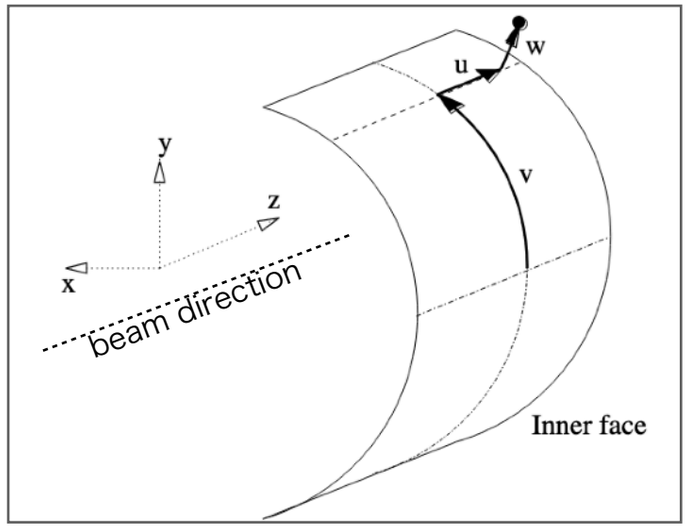
Energy scale history during beam time

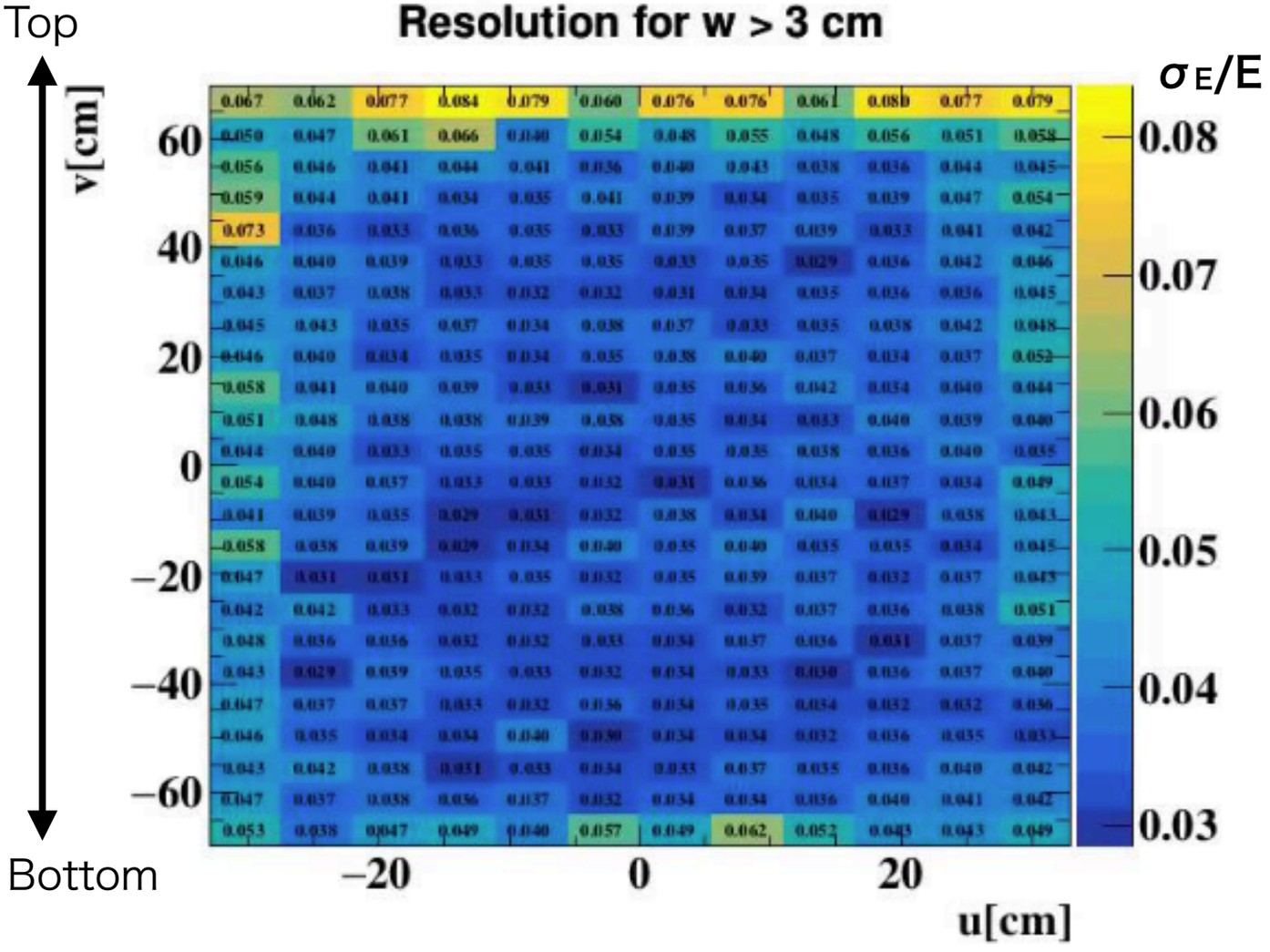


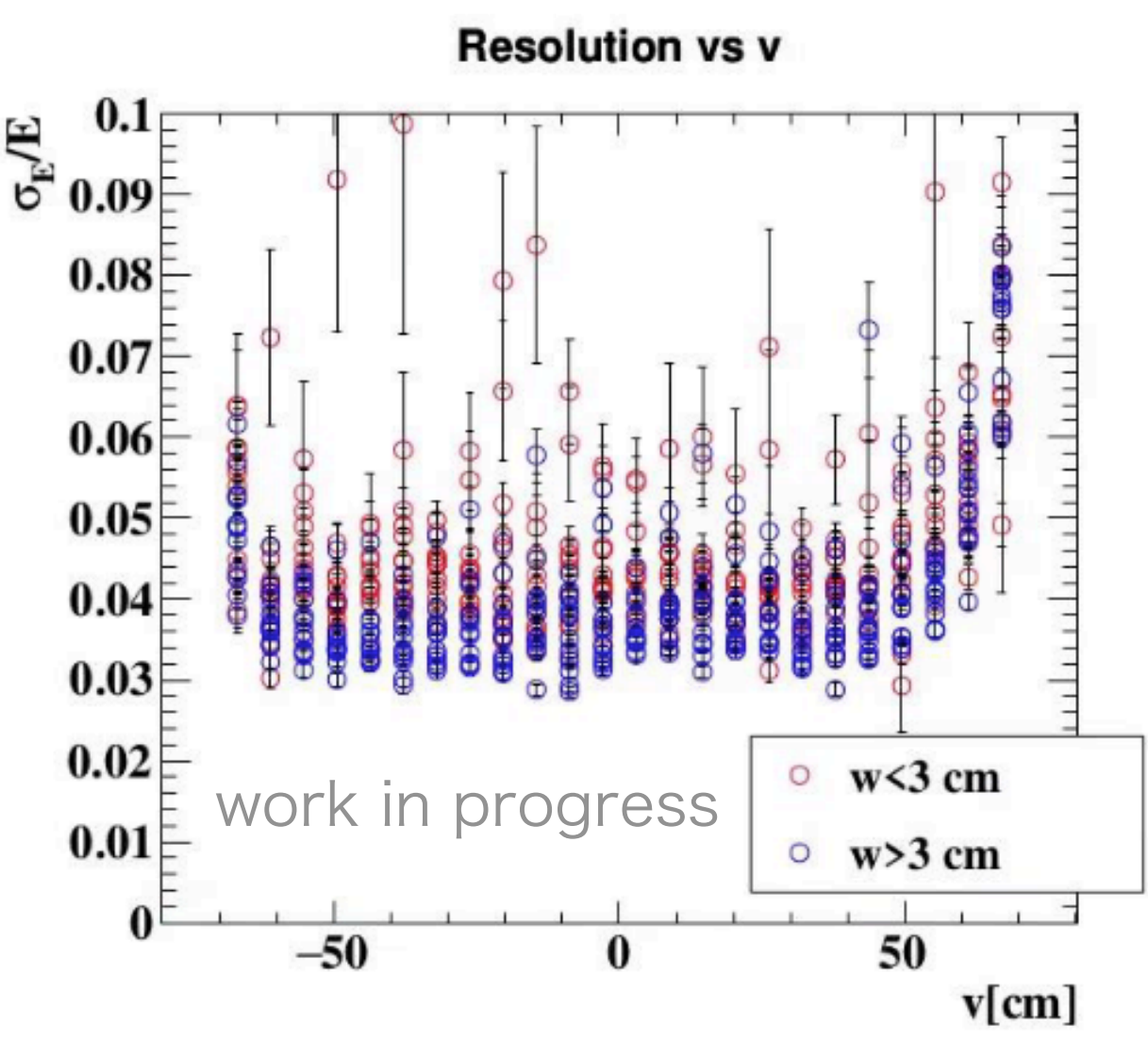
Energy resolution

- Energy resolution is also evaluated using 17.6 MeV gamma-ray
  - Depth dependence is observed
    - Better E resolution for w > 3.0 cm
  - Energy resolution is worse at the top/bottom region
- Almost uniform response is observed except for edges

Definition of the coordinate system

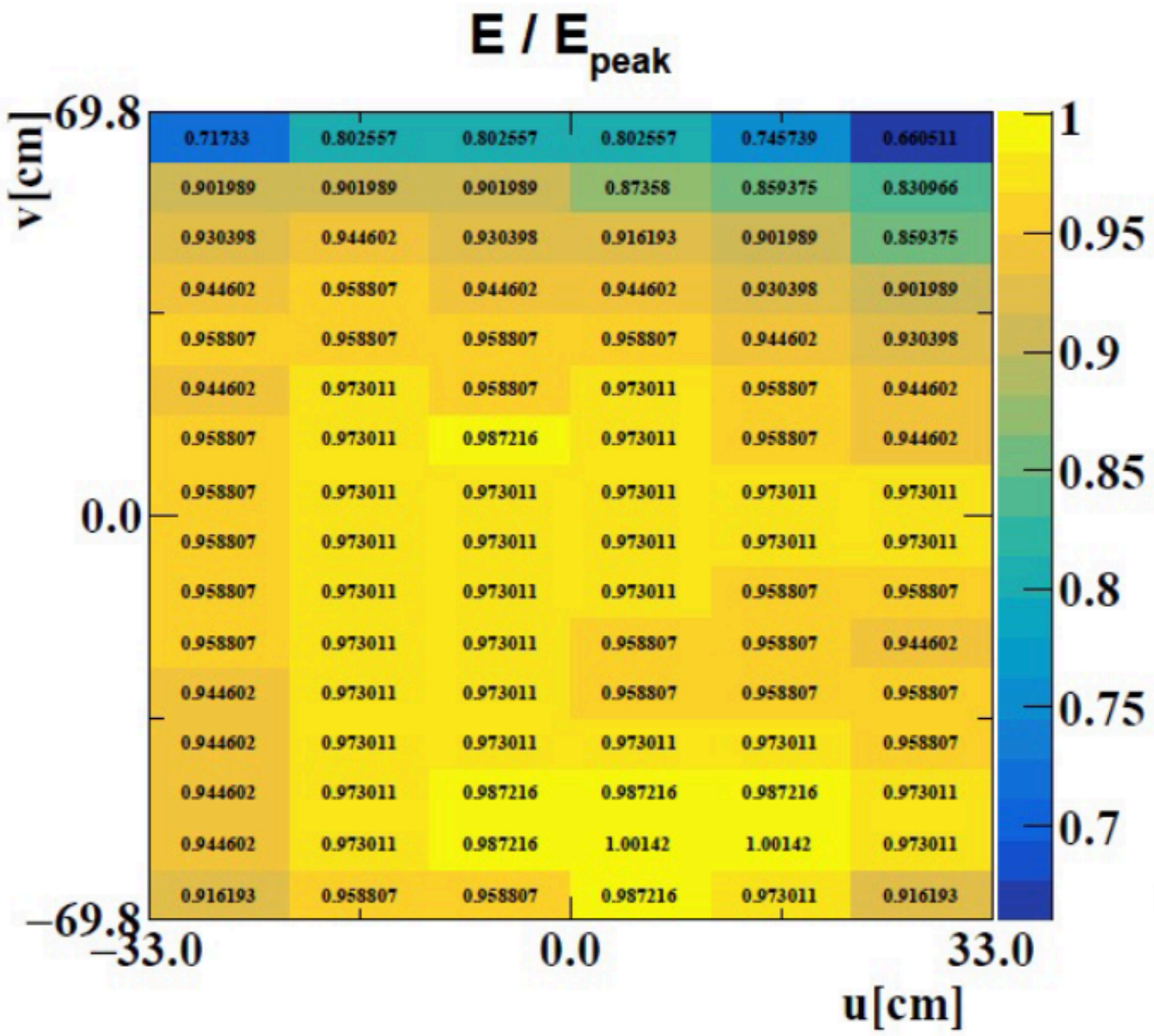






Uniformity of energy scale

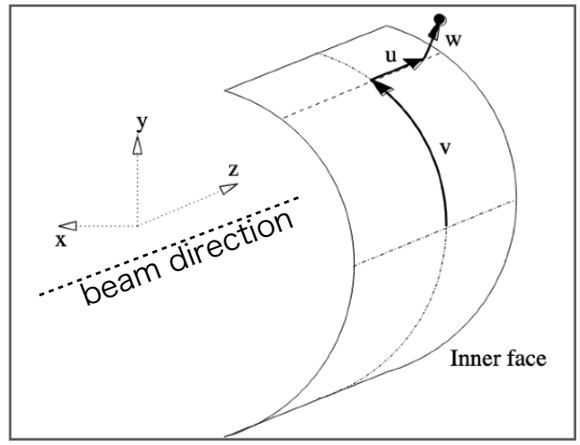
- Large non-uniformity, in particularly along v-direction again, is observed
  - Larger than the prediction of MC simulation
- Possible reasons :
  - Liquid xenon may not be filled up to the top of detector region
  - Systematic bias of detection efficiency measurement with alpha-sources



Detector top
(+v direction)

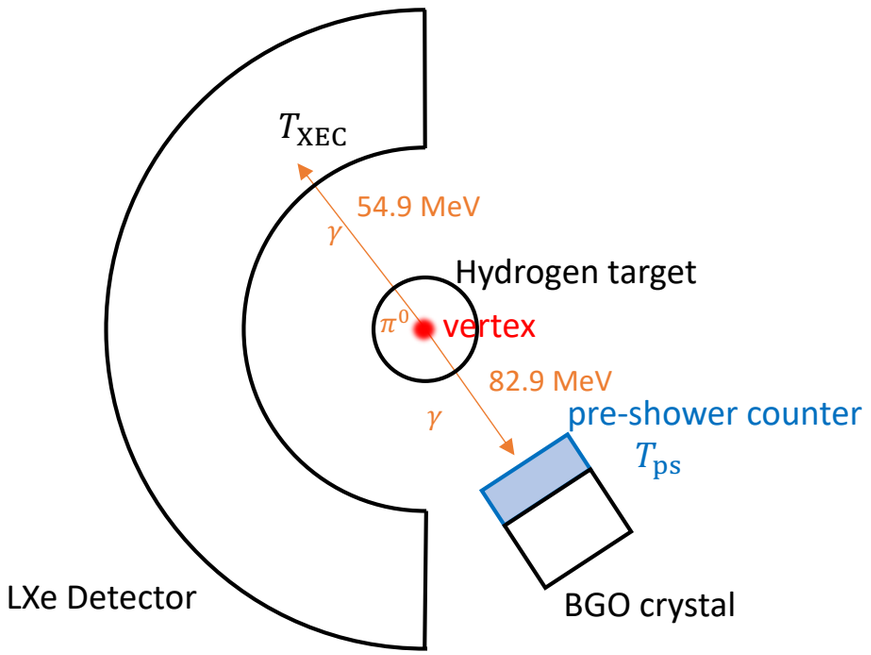
Detector bottom
(-v direction)

- Energy scale and resolution should be evaluated by CEX run in 2021
  (at E=55MeV)
  - Analysis is ongoing



Timing resolution

- Timing resolution of the liquid xenon detector was evaluated using back-to-back gamma-rays from pion charge exchange reaction
  - $\pi^- \rightarrow \pi^0$ (in Hydrogen) $\rightarrow \gamma + \gamma$
  - Gamma-ray at the opposite side is detected by Pb+plastic scintillators and BGO crystals



- Absolute timing resolution is calculated as follow:

$$\sigma_{\mathrm{abs}} = \sigma\left(T_{\mathrm{XEC}} - T_{\mathrm{ps}} - T_{\mathrm{TOF}}\right) \ominus \sigma_{\mathrm{ps}} \ominus \underline{\sigma_{\mathrm{vertex}}}$$

70.0ps
→corresponding to 10.5mm vertex size

xec-ps time dif (TOF correction, 55MeV)

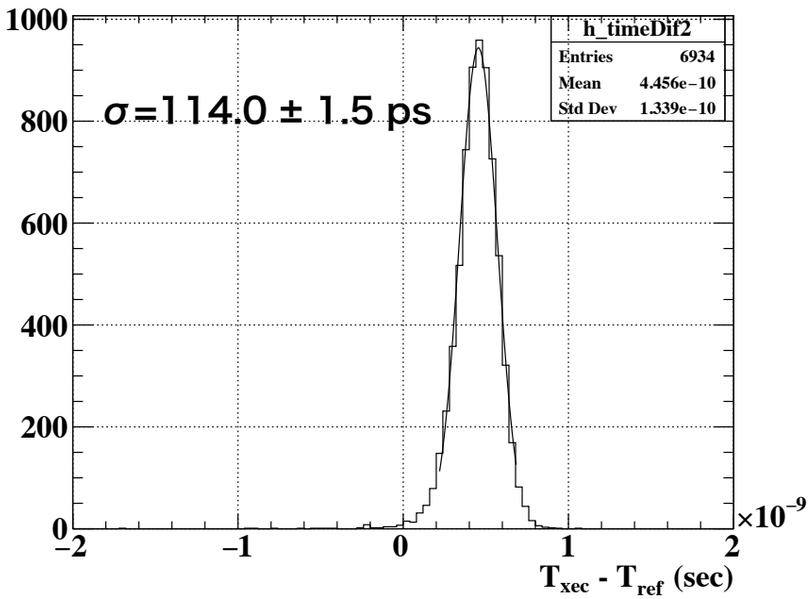
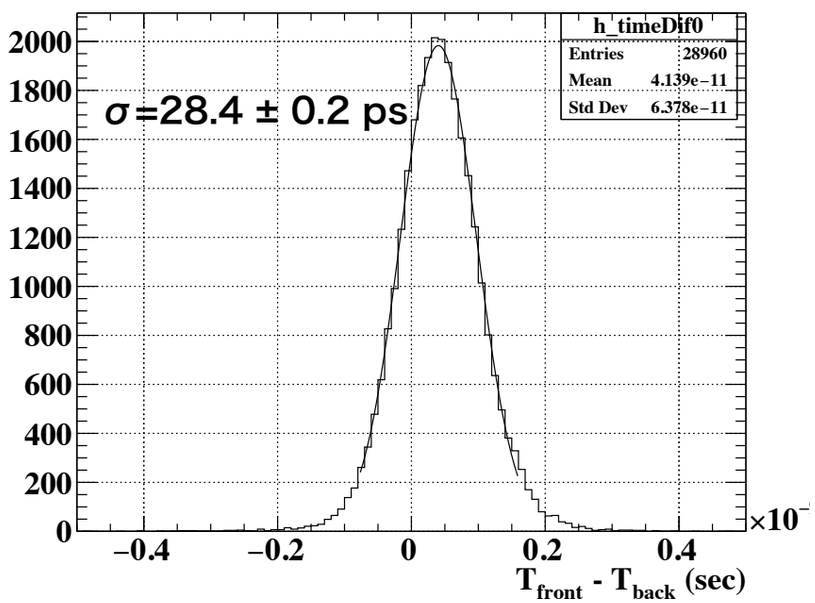
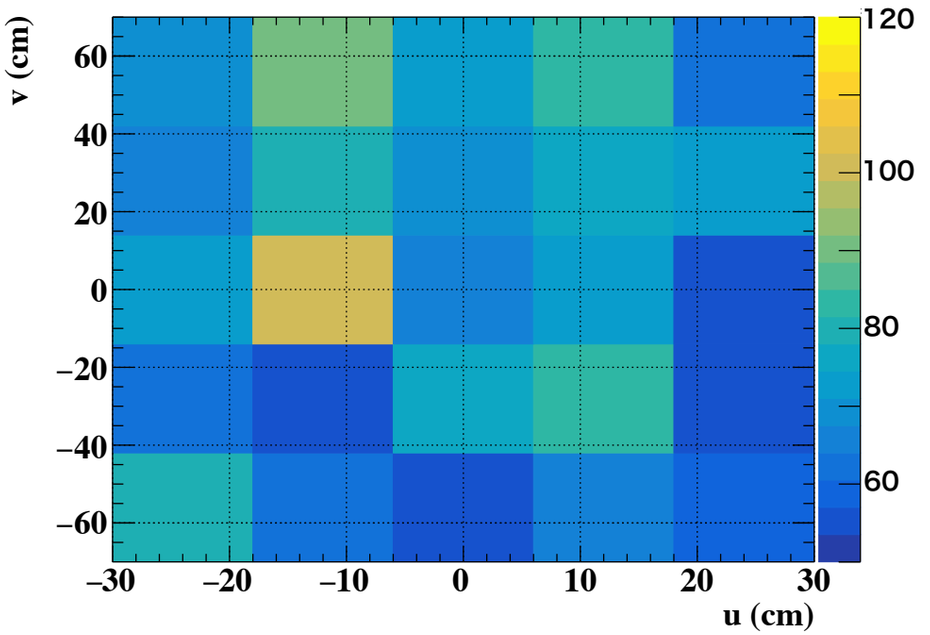


plate time dif



Position dependence of timing resolution [ps]



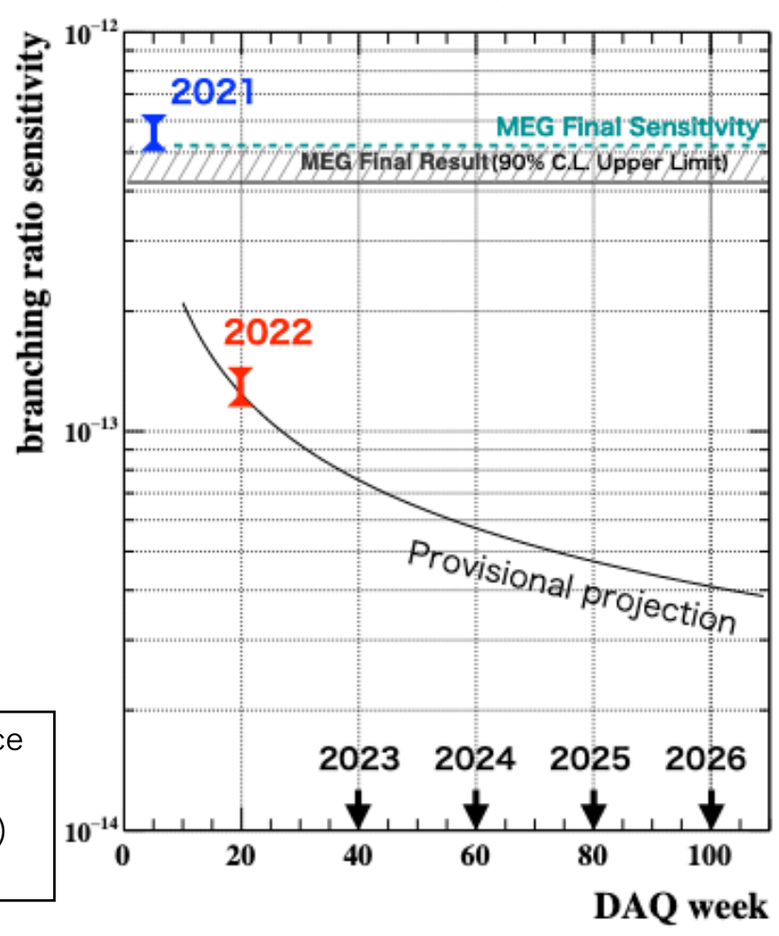
- Absolute timing resolution of the liquid xenon detector : **85.4±5.1 ps**

Detector performance and sensitivity

- Summary of the detector performance (including positron side)
  - These values will be improved more by detailed analysis

	ΔE_γ	ΔX_γ	ε_γ	ΔP_e	$\Delta\theta_e$	ε_e	$\Delta T_{e\gamma}$
MEG	1.7% w>2cm	5mm	63%	380keV/c	9.4mrad	30%	122ps
MEG II goal	1.7% w>2cm	2.4mm	69%	100keV/c	6.7mrad	65%	70ps
MEG II achieved	1.8% w>2cm measured in 2020	2.4mm measured in 2018	69% by simulation	<150keV/c	7.2mrad	>47%	<100ps

- Expected sensitivities
  - Data 2021 : **(5.3 – 6.1)×10^{-13}**
    - Already approaching MEG sensitivity (5.3×10^{-13})
- Prospect of the sensitivity,
  - Data 2021+2022 : (1.3 – 1.4)×10^{-13}
  - Well beyond MEG

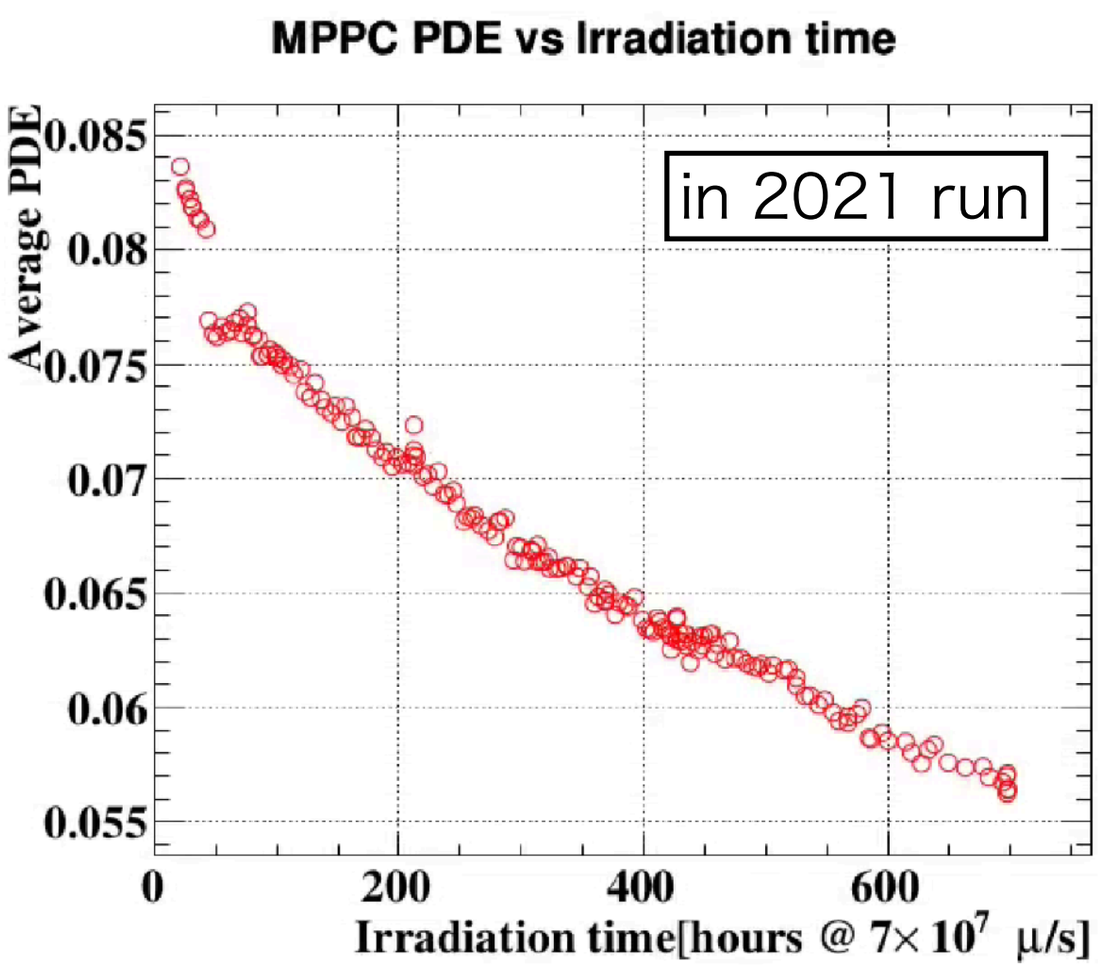


- Provisional projection curve based on expected detector performance (“MEG II goal” in the summary table)
- Assume 20 DAQ weeks per year, (6 month beam time for every year)
- DAQ time 2021 with correction for fraction of physics run

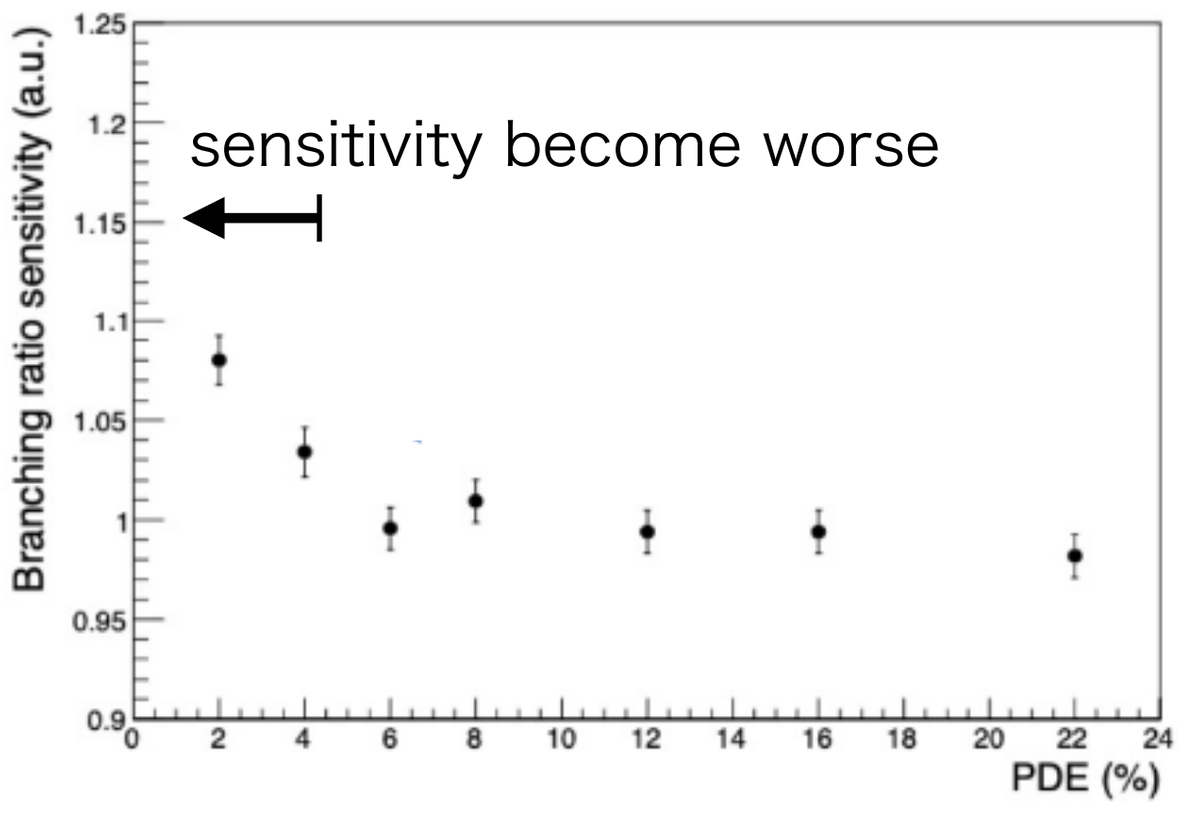
Contents

Liquid xenon detector / PDE decrease

- Photon Detection Efficiency (PDE) decrease was observed in 2021 run
  - known problem since 2017
  - Averaged PDE : 8.4% → 5.6%
  - The cause of PDE decrease is under investigate (radiation damages?)
- PDE < 2-4%, reachable in 2022, will worse the sensitivity
  - Recovery of PDE is essential task to make the experiment sustainably
- By previous works, we know **“annealing” (heating) process recovers PDE**
  - PDE of 11% is required to stand 4e+7 μ/s beam in 2022 (14% for 5e+7)



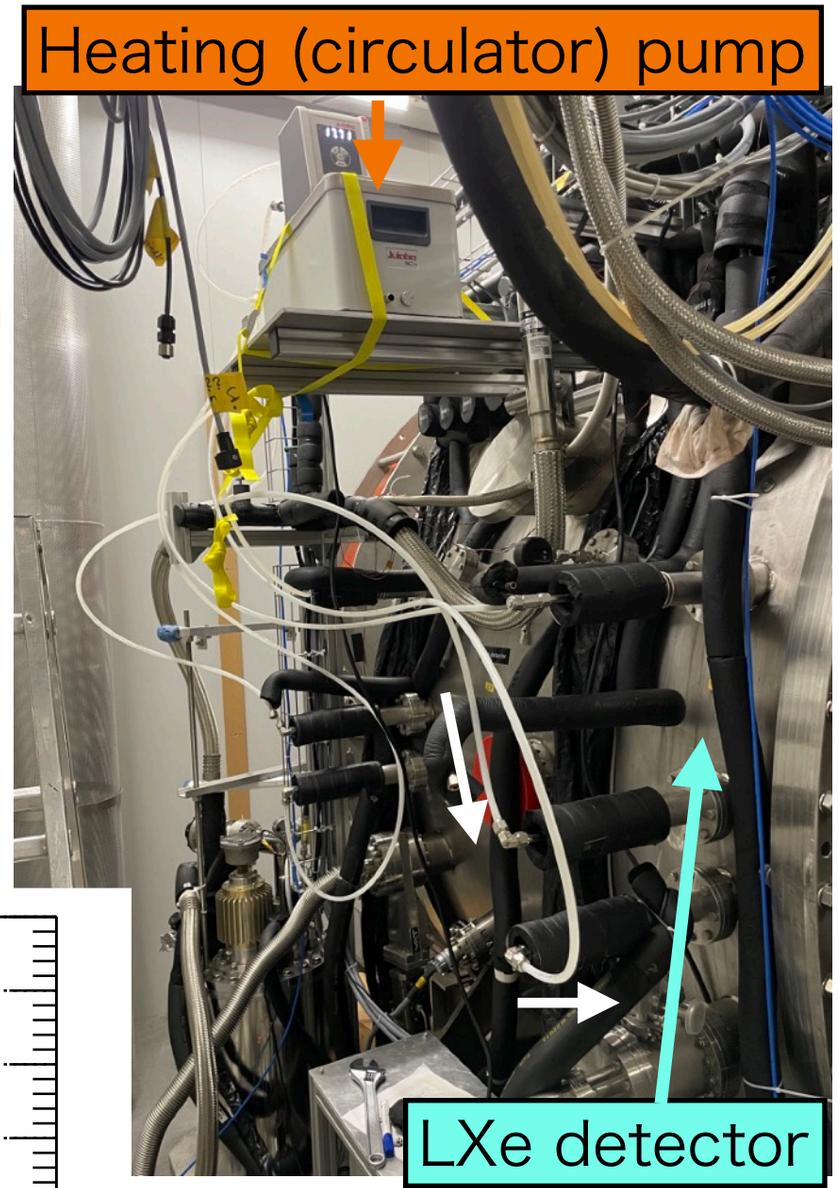
by simulation work



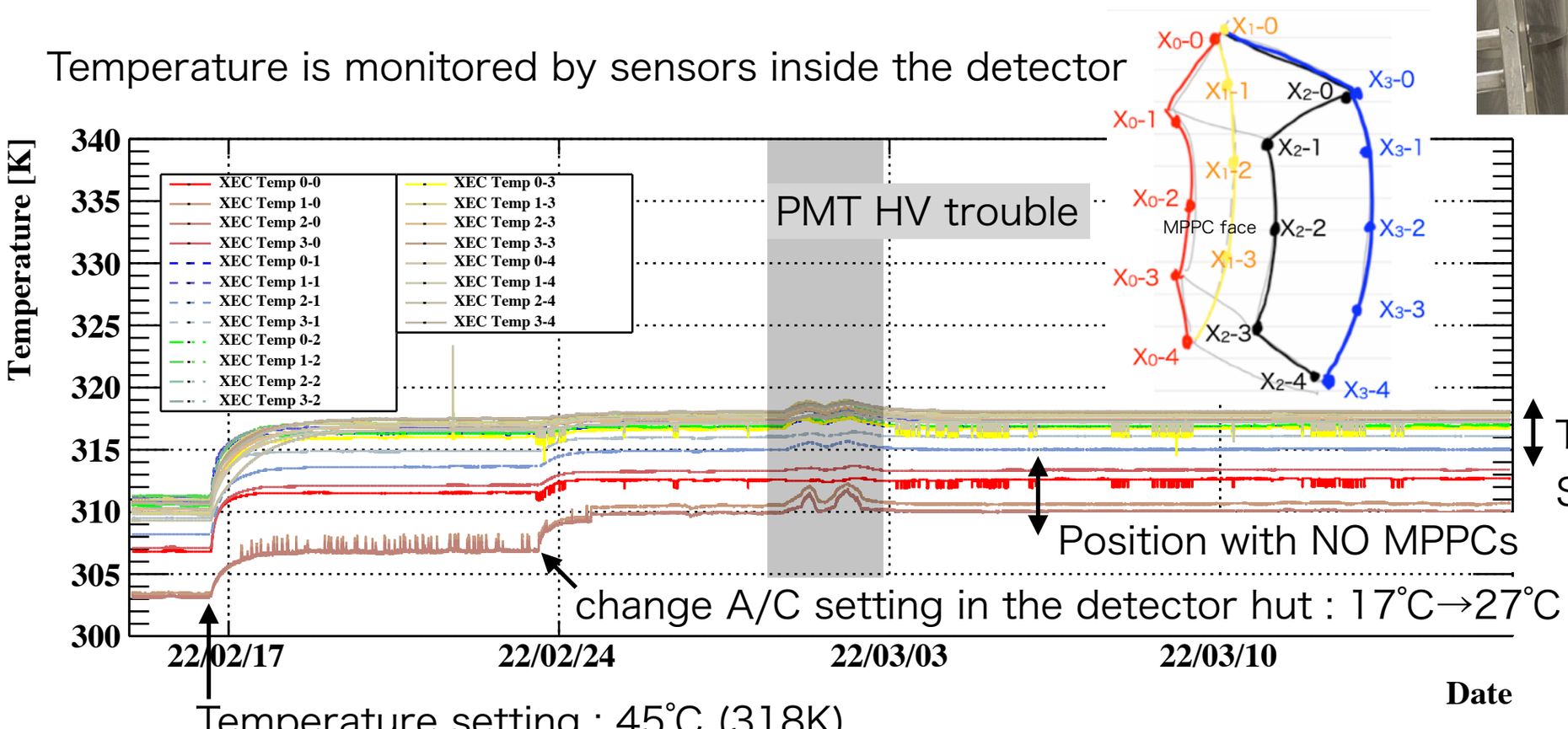
Annealing with hot water circulation

- Circulating hot water through the cooling pile that surrounds the detector
  - Be able to heat up entire of the detector easily
  - The temperature of hot water is limited up to 45℃ because of the limitation from detector components
- Annealing with hot water was conducted for one month

- Recovery of PDE is monitored and estimated with visible LED light
  - Strong correlation with PDE for VUV light



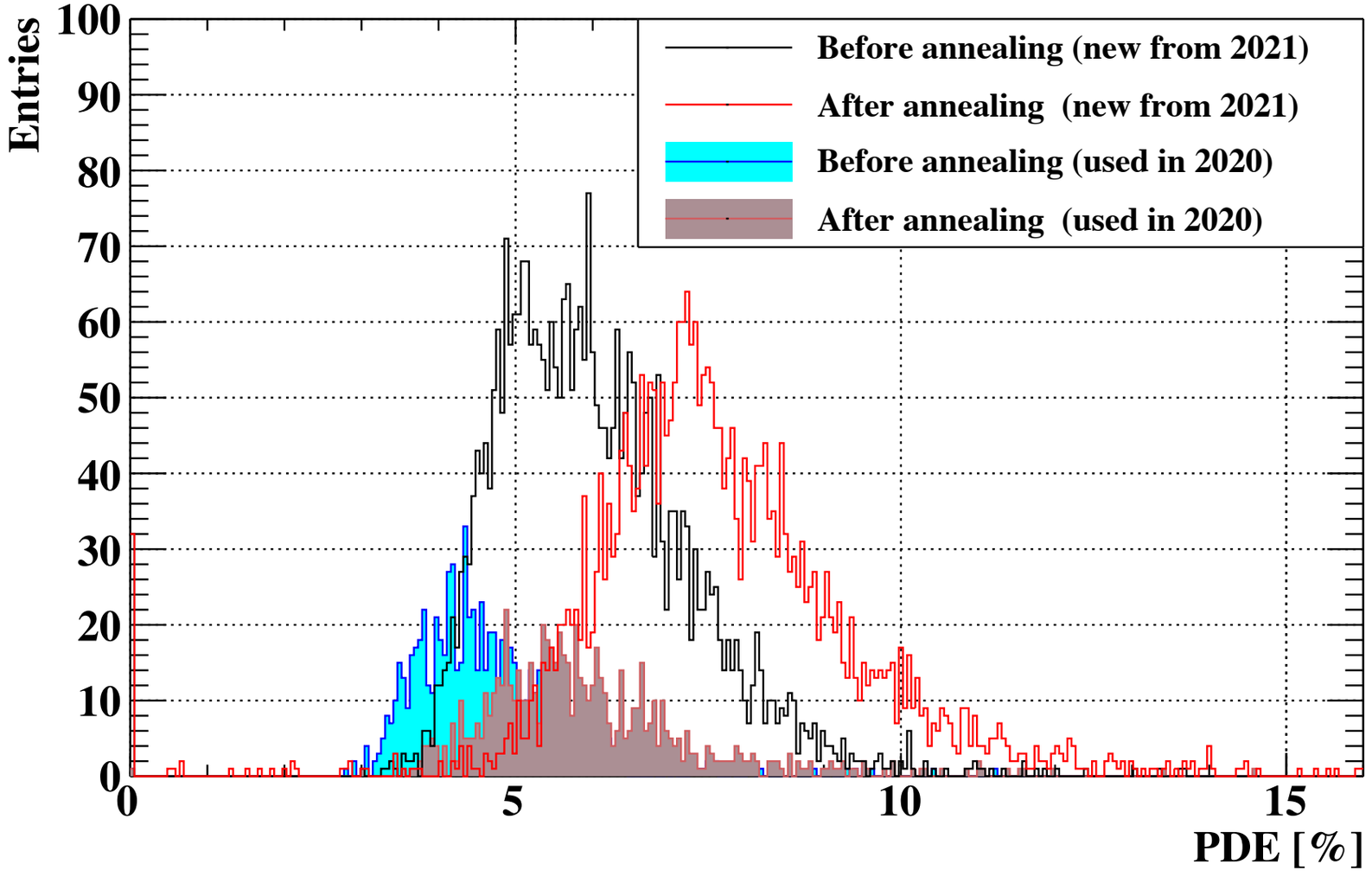
Temperature is monitored by sensors inside the detector



Temp. are within 3℃ range
Stable within 0.1℃

Annealing with hot water circulation

- Absolute PDE value (for VUV) before/after the hot water annealing
  - Average PDE value of MPPCs used before 2020 : 4.56% → 5.98% (x1.31)
  - Average PDE value of MPPCs used since 2021 : 6.02% → 7.79% (x1.29)
- Slower than the expected recovery speed : 30 %/month < ~145 %/month(expected)
- Note that the PDE value is not fixed
  - “Before” value contains large uncertainty : still continuing to improve analysis
  - “After” PDE value is estimated value using visible LED

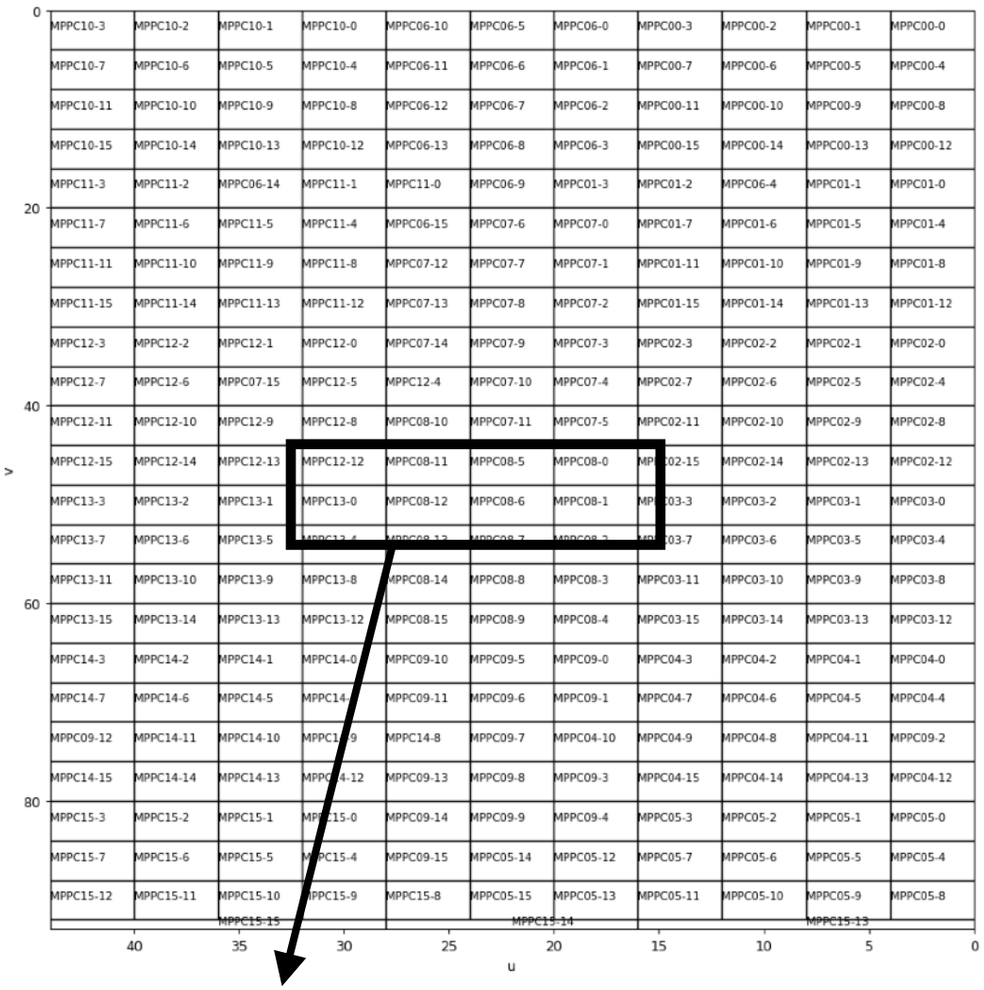


Annealing by Joule heating

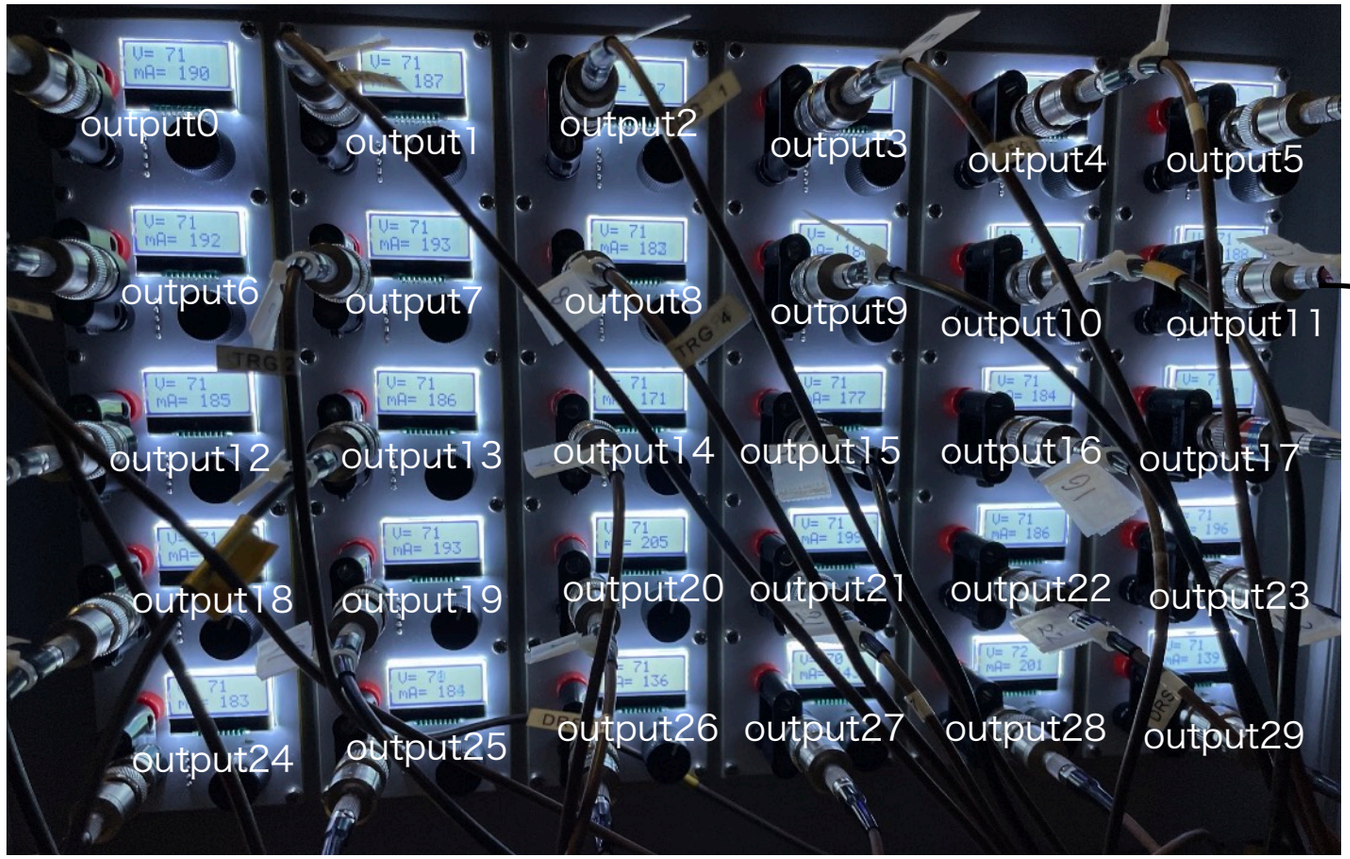
- MPPC is annealed by Joule heating using a high current source and LED light
  - Heated with ~1.7W per MPPC
- MPPCs with an interval of 4 are annealed at once
  - Avoid over heating of the detector
  - 240 MPPCs are annealed at once

    → 17 set of annealing is required (30h/set)

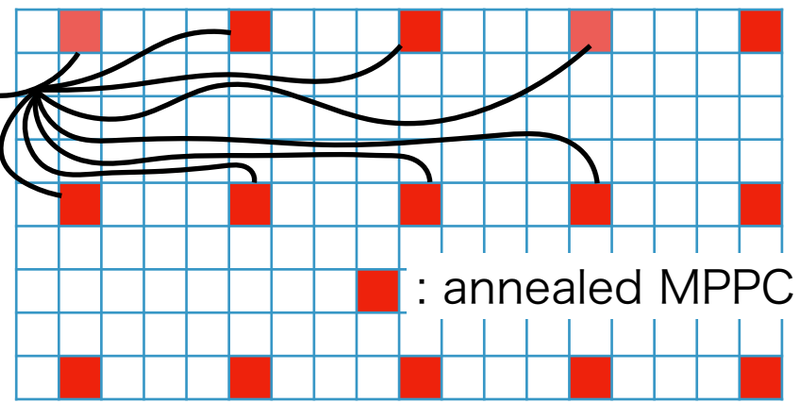
Readout electronics on the MPPC face



Power supply with large current : 250 mA/output, 60~80 V



8 MPPCs per output



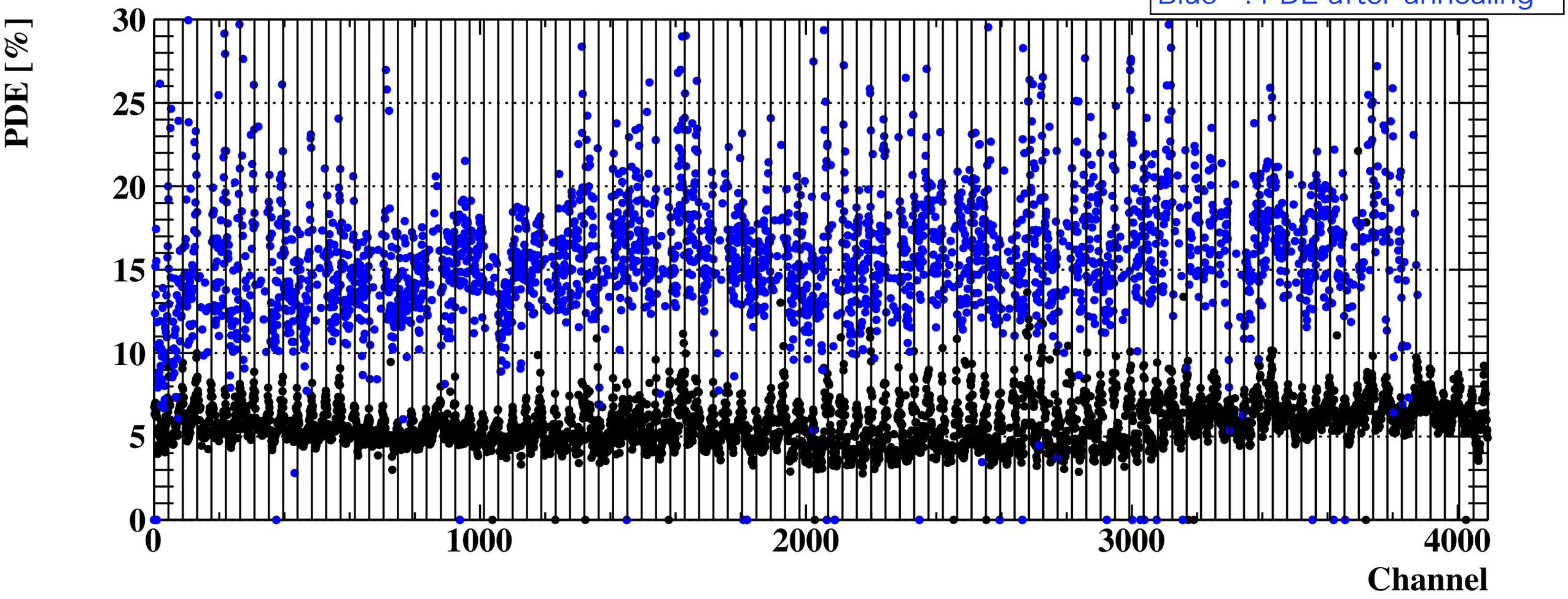
Blue LED light

Annealing by Joule heating

- Current status of Joule heating annealing
  - ~3300 MPPCs have been annealed
  - the remaining MPPCs will be annealed within this week (～ 28th May. 2022)
- **We are (almost) ready for the beam time this year : PDE more than 11%**
  - The method for PDE recovery by Joule heating annealing is established
    → annealing will be conducted every year (after beam time)

- Note that the PDE value is not final value (contains large uncertainty)
  - “Before” value contains large uncertainty : still continuing to improve analysis
  - “After” PDE value is estimated value using visible LED, not be measured by VUV light

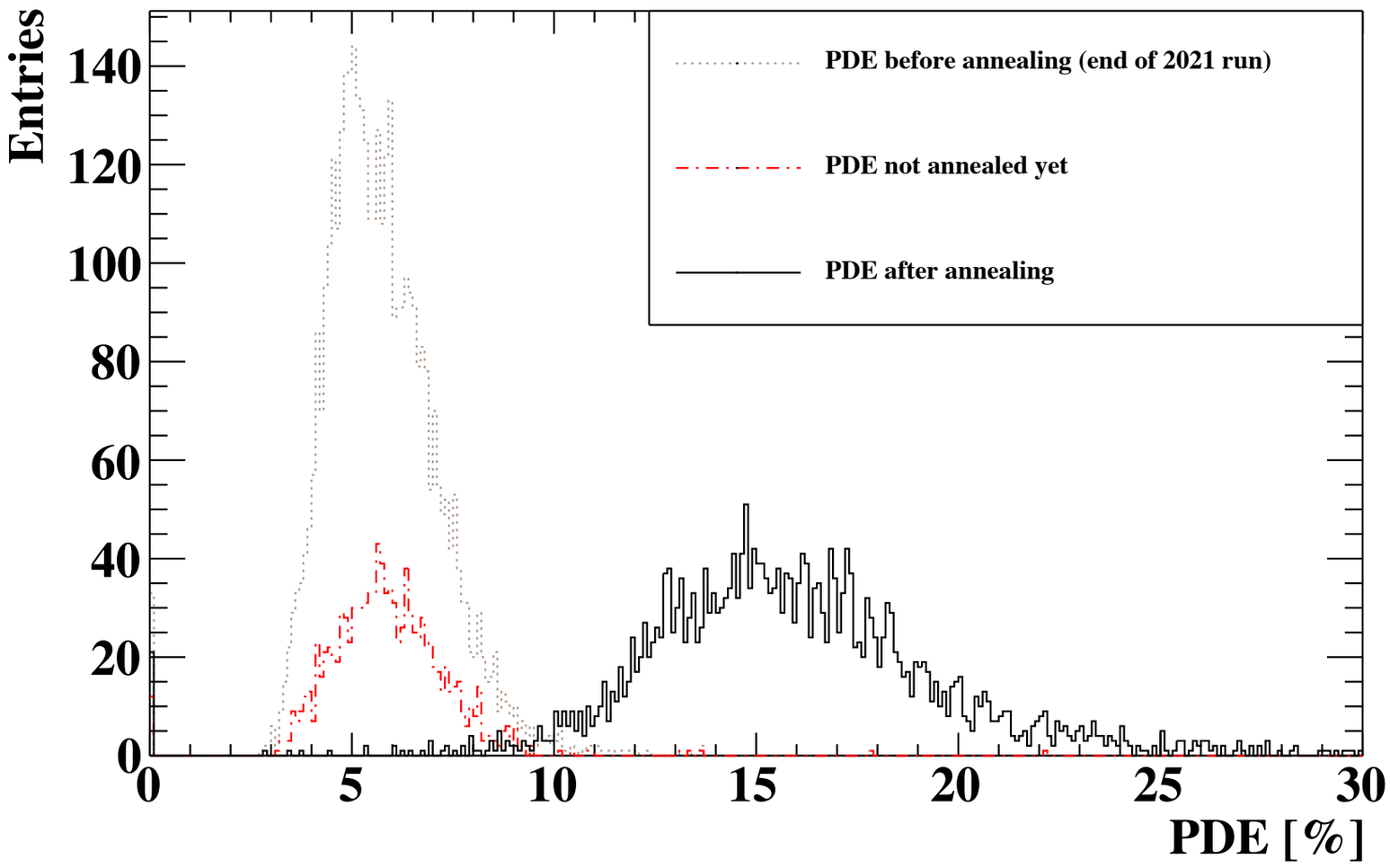
Black : PDE before annealing
Blue : PDE after annealing



Annealing by Joule heating

- Current status of Joule heating annealing
  - ~3300 MPPCs have been annealed
  - the remaining MPPCs will be annealed within this week (～ 28th May. 2022)
- **We are (almost) ready for the beam time this year : PDE more than 11%**
  - The method for PDE recovery by Joule heating annealing is established
    → annealing will be conducted every year (after beam time)

- Note that the PDE value is not final value (contains large uncertainty)
  - “Before” value contains large uncertainty : still continuing to improve analysis
  - “After” PDE value is estimated value using visible LED, not be measured by VUV light directly



Contents

Summary

- MEG II experiment searches for charged lepton flavor violation : $\mu^+ \rightarrow e^+\gamma$

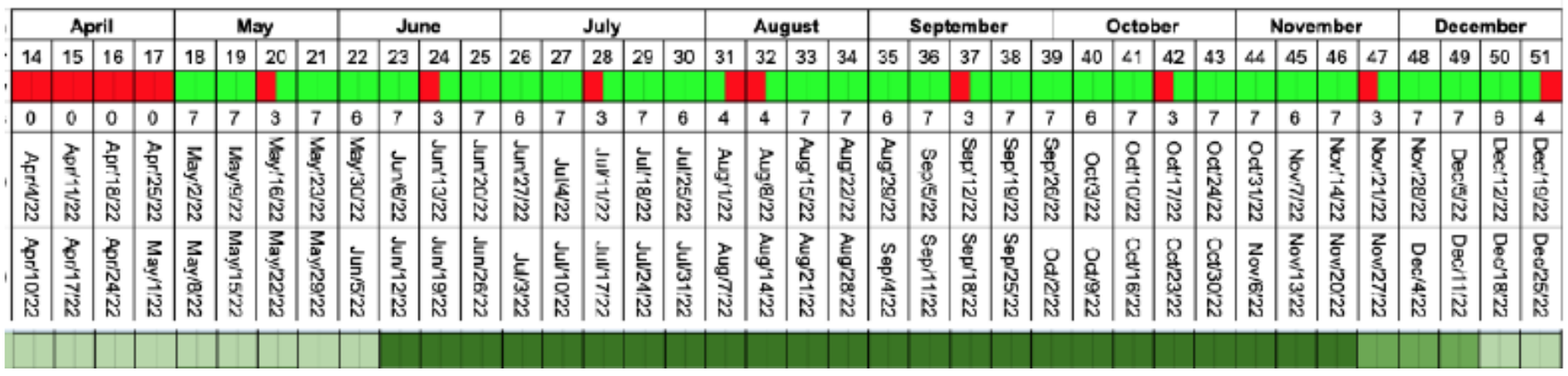
- Full channel operation was conducted in 2021
- Detector commissioning, Trigger setup, Physics run were successfully done
- Expected sensitivity with 2021 data (for branching ratio) : **$(5.3 - 6.1)\times10^{-13}$**

- PDE decrease of MPPCs (liquid xenon detector) is an issue
- Annealing process was (is being) conducted to recover PDE
  - Annealing with hot water circulation recovered relatively ~30% PDE
    - Recovery speed is slower than expected
  - Annealing with Joule heating is ongoing
    - PDE of Annealed MPPCs became ~10-20% : **sufficient for this year's run**
    - Annealing of whole MPPCs (4092) will finish by 28th May. 2022

MEG II beam time in 2022

6th Jun. — 20th Nov.

(21st Nov. — 11th Dec is suspended)



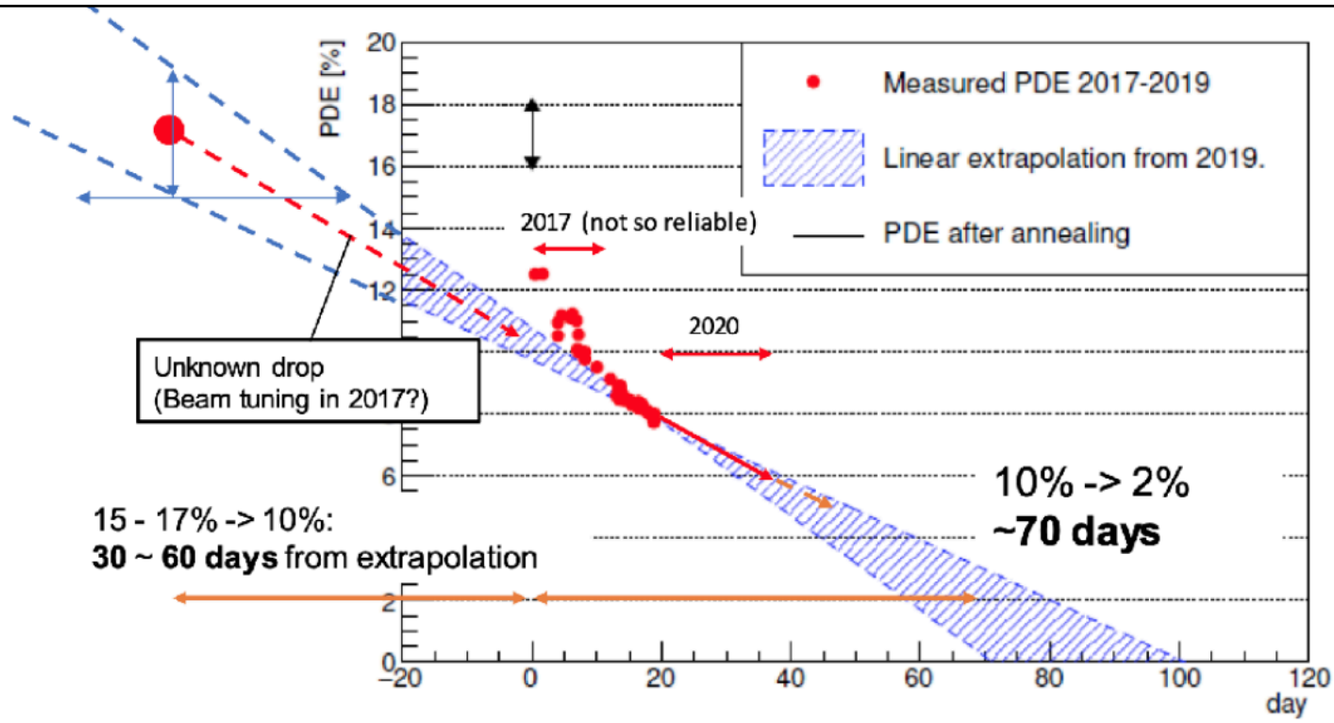
Back up

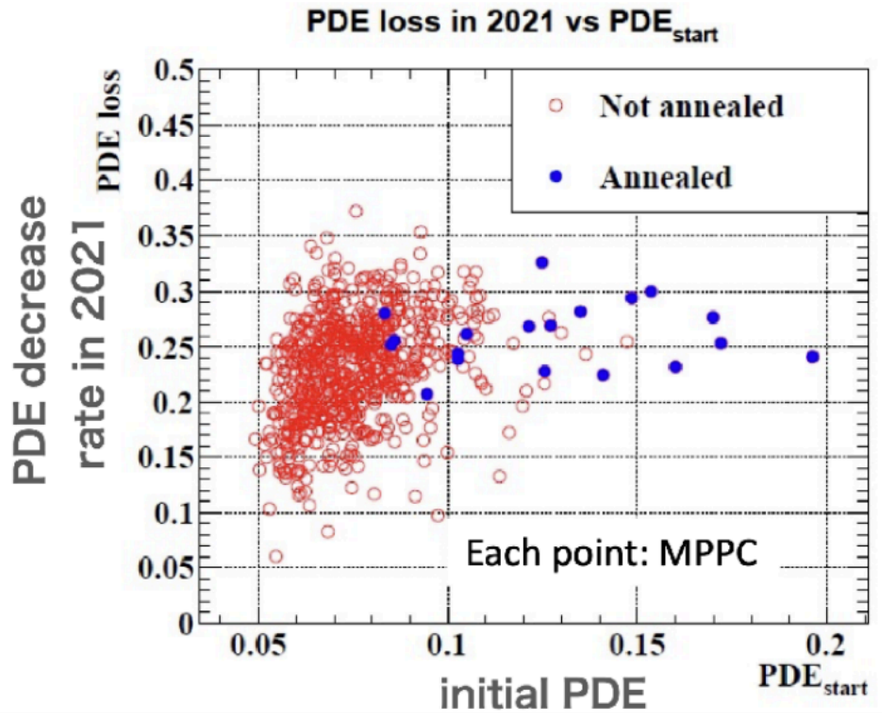
PDE decrease

Slide from T. Iwamoto (JPS Mar. 2021, talk: 15aA562-4)

γ detector (LXe) Issue

- MPPC PDE decrease
  - observed in 2017 under muon beam
  - The cause to be investigated
  - Based on 2021 operation, PDE will change from 16% to 2% in ~100 days MEG II intensity
  - Annealing recovers PDE fully
- Strategy for run 2022
  - LXe MPPC can sustain ~ 120 days with 5×10^7 μ/s
    - Beam intensity optimization necessary
  - Annealing for all MPPCs during accelerator winter shutdown period



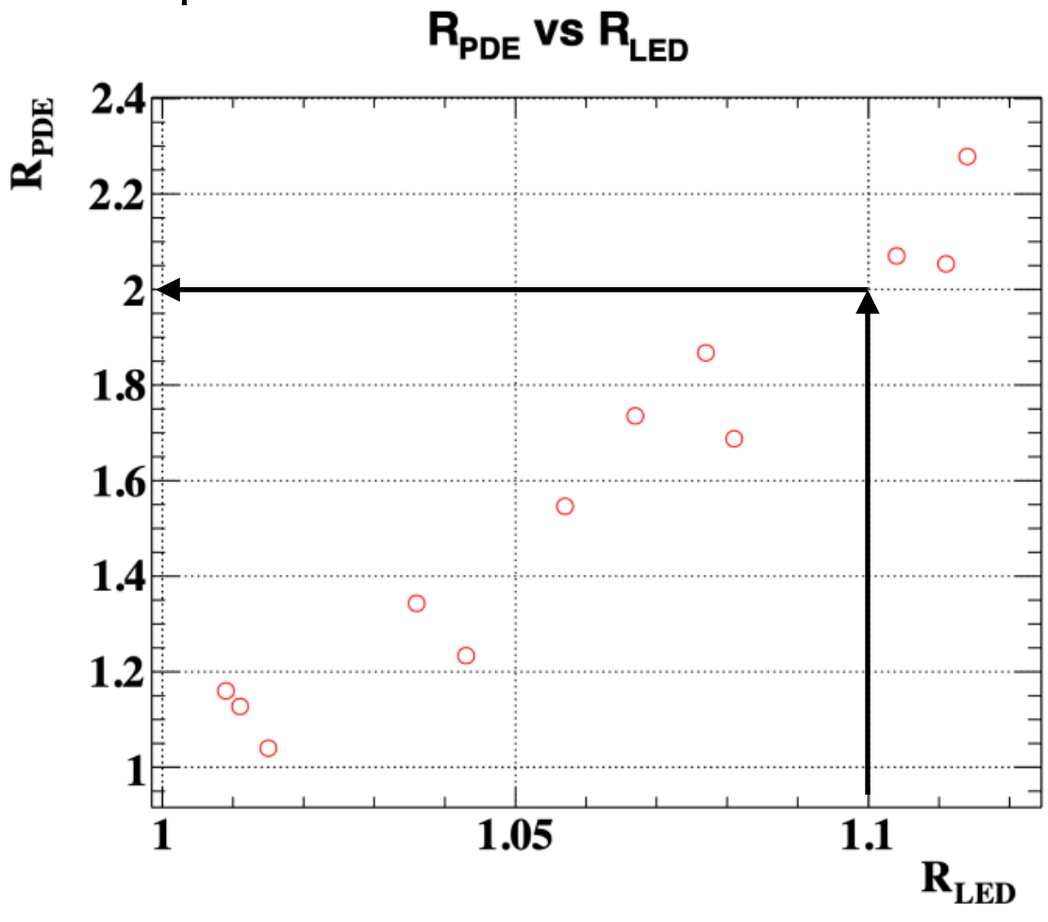


Goal of annealing this year

- Goal of Annealing this year
  - Recovered amount of charge (PDE) for LED can be translated into that for VUV
    - $\Delta R_{PDEforVUV} = 10 \times \Delta R_{PDEforLED}$
      - relatively 10% recovery for LED light corresponds to relatively 100% recove VUV-light

- Required PDE value is (absolute) 14% for 120 days beam time with 5e+7 intensity
  - In average, (absolute) ~5.5% at the end of 2021 run (before annealing)
  - → Relatively 15% charge recovery for LED is required

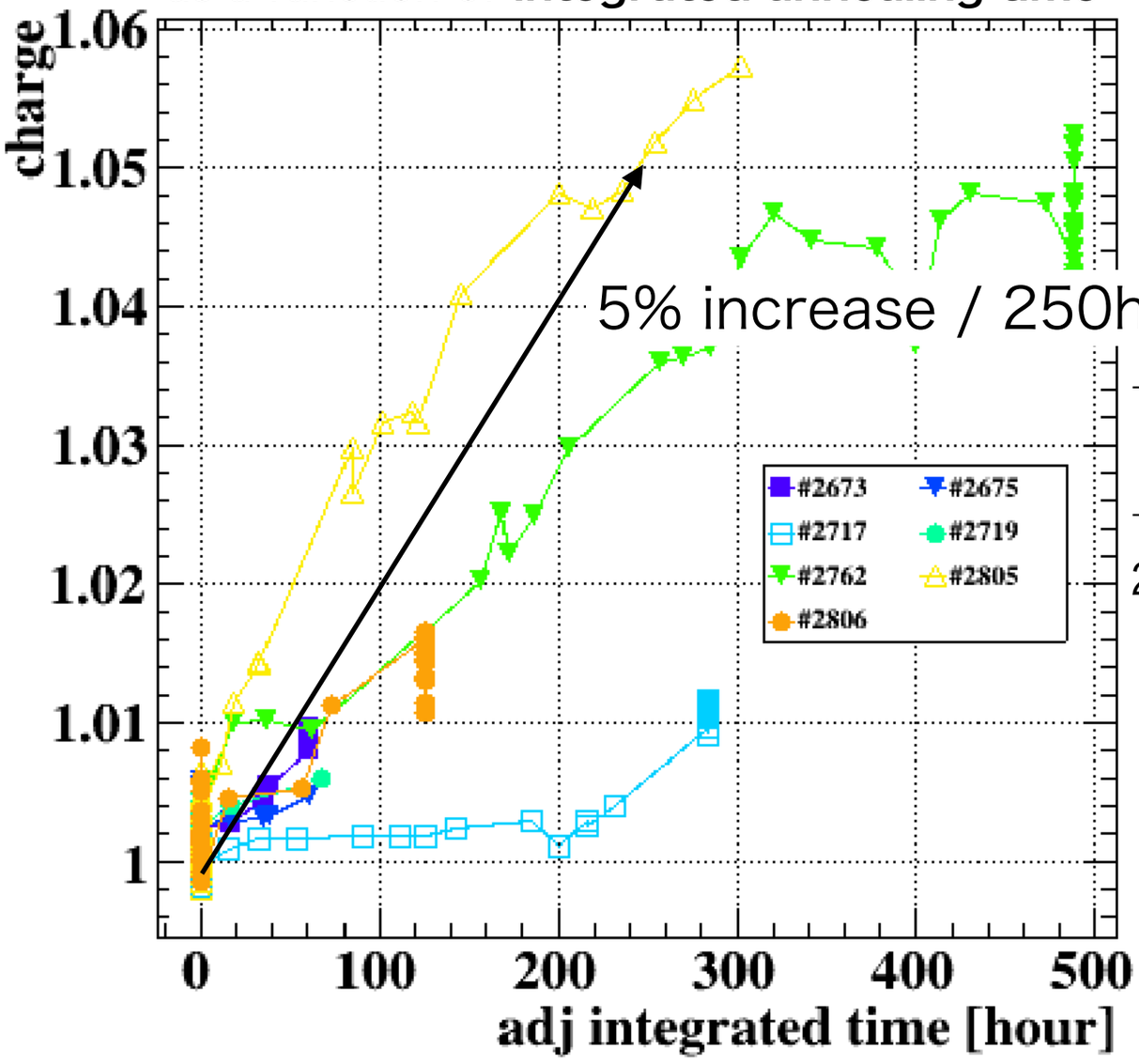
- In principle, absolute PDE value will recover to 20% (initial value at manufactured)



Estimation of charge recovery by hot water annealing

- Estimation based on 2019 Joule annealing
  - The neighboring channels of annealed MPPC were also warmed to ~40℃
    - Because of heat conductivity through PCB, measured in Lab. test

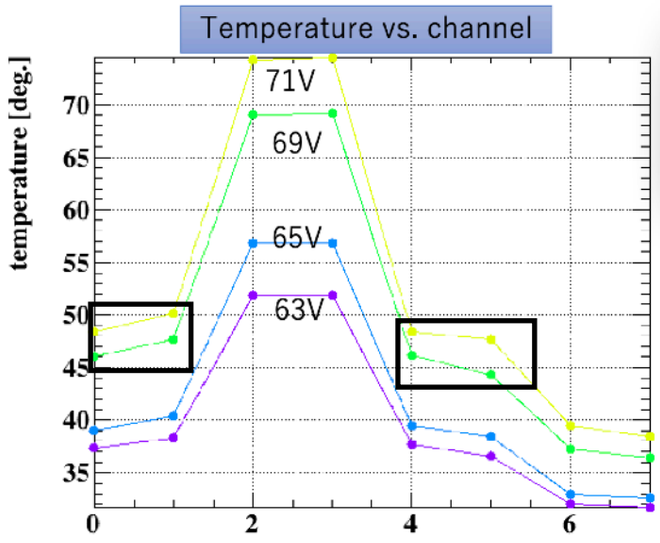
Monitored charge using LED (adjacent MPPCs)
as a function of **integrated annealing time**

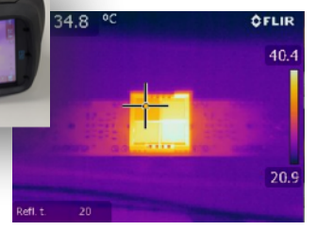


5% increase / 250h : if it is extrapolated linearly

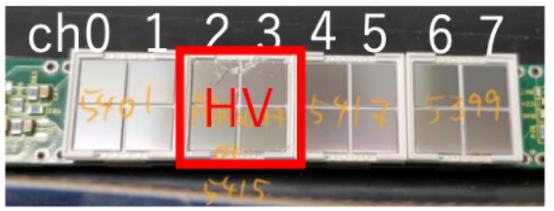
→ It will take 500 h = **20.8 days** to recover (relatively) 10% charge for LED light

→ 1000 h = **41.6 days** are required to recover (relatively) 20% charge for LED light





FLIR E50
thermometer

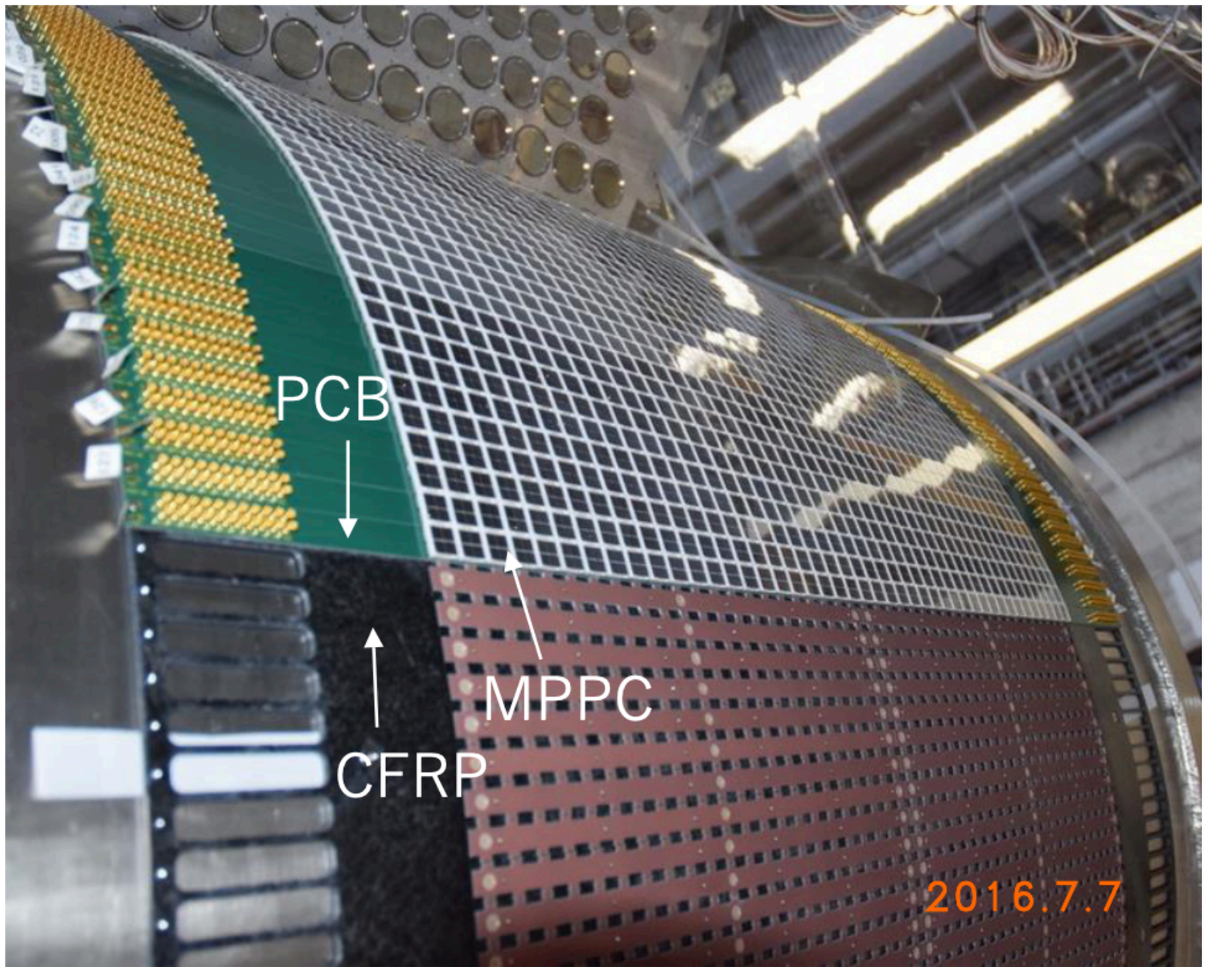


- NOTE that this estimate is just obtained just extrapolating the previous trial
  → **There is no guarantee that the PDE recovers to the target value at ~45℃**
  → one of what we have to study by this year's trial

Temperature limitation

CFRP should not exceed 45℃

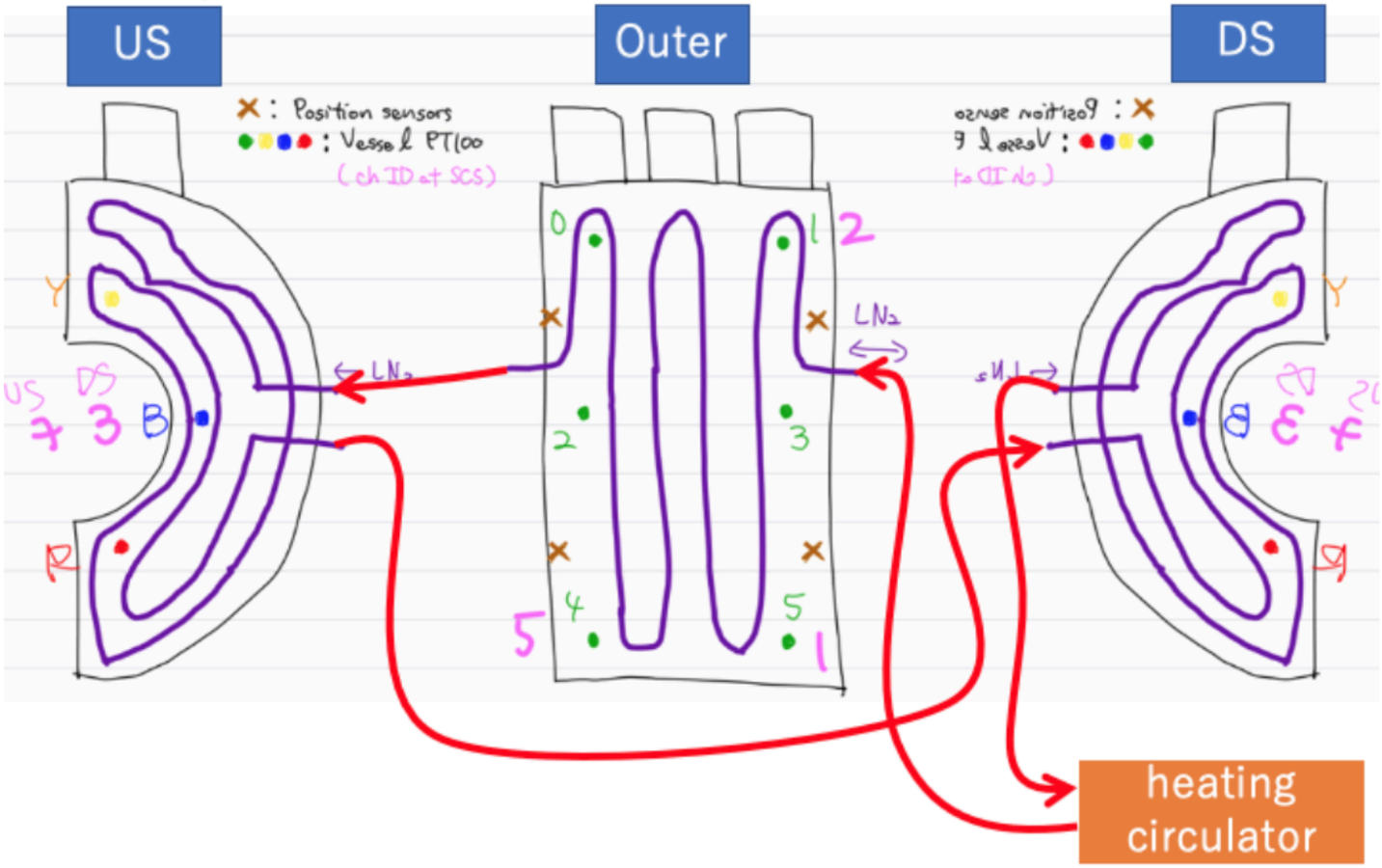
→ the maximum temperature setting in hot water annealing must be 45℃

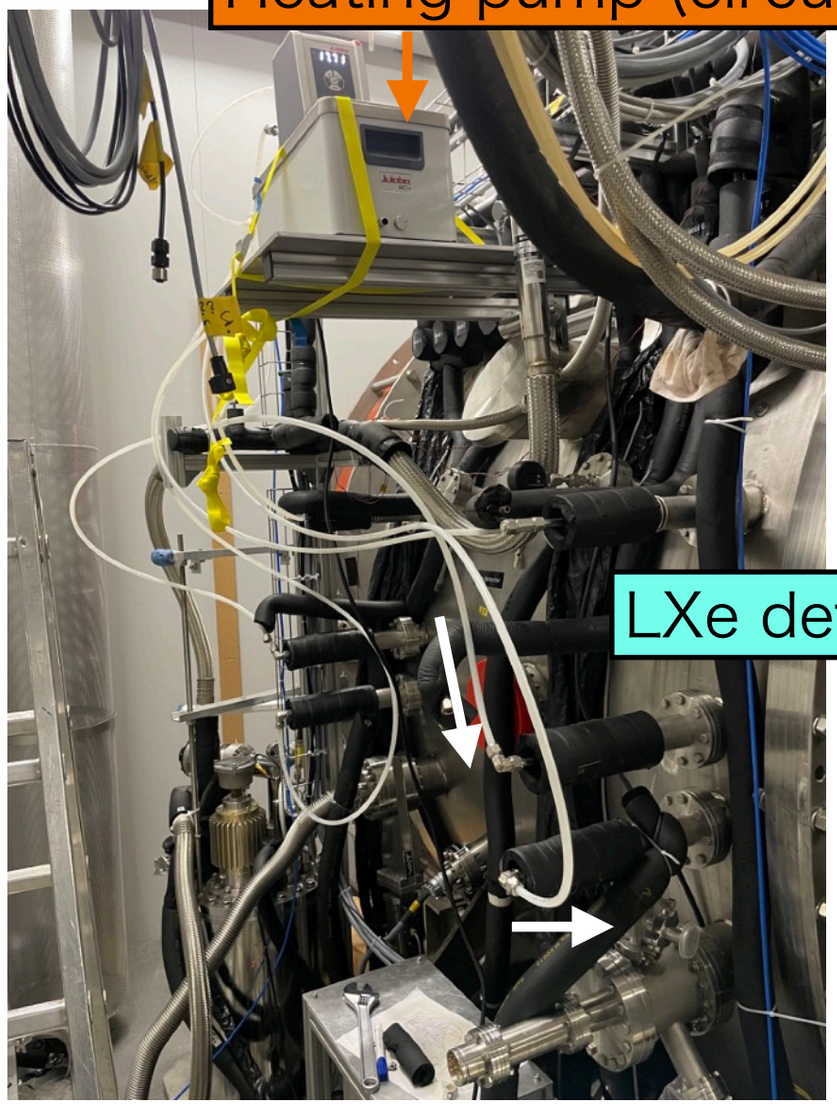


- Temperature limit
  - MPPC: 100°C
  - PCB: 120°C
  - **CFRP: 45°C**
  - Glue: 65°C

Annealing with hot water circulation

- Circulating hot water through the cooling pile that surrounds the detector
  - Be able to heat up entire of the detector easily
  - The temperature of hot water is limited up to 45℃ because of the temp. limitation of detector components



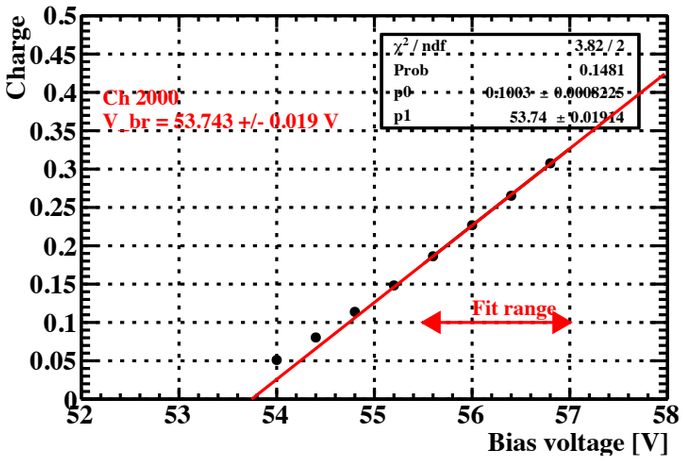


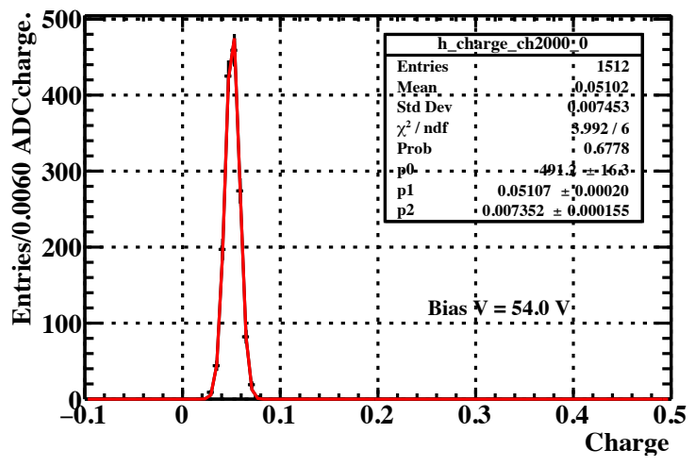
(by previous work)

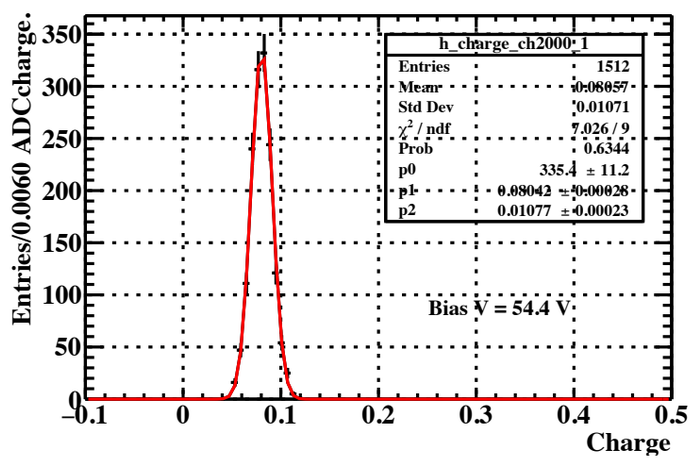
- PDE recovery can be estimated from the PDE for blue LED (installed in the detector)
  - Correlation exists between PDE_{VUV} and PDE_{LED} : $PDE_{LED} \sim 0.1 \times PDE_{VUV}$
- The expected value of charge increase is 1~5% for one month annealing at 45℃

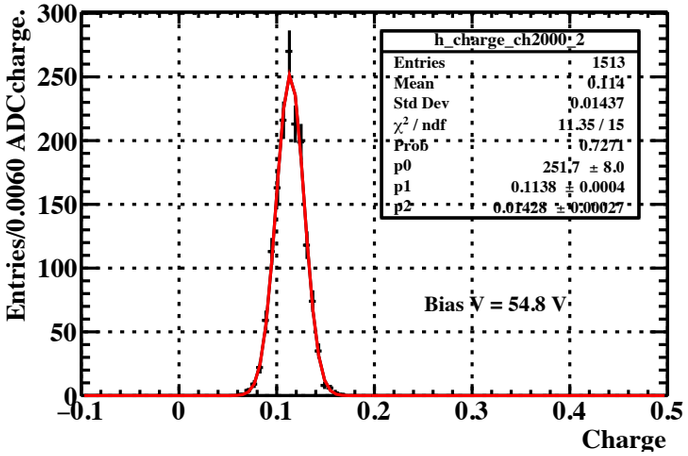
Annealing with hot water circulation / MPPC charge

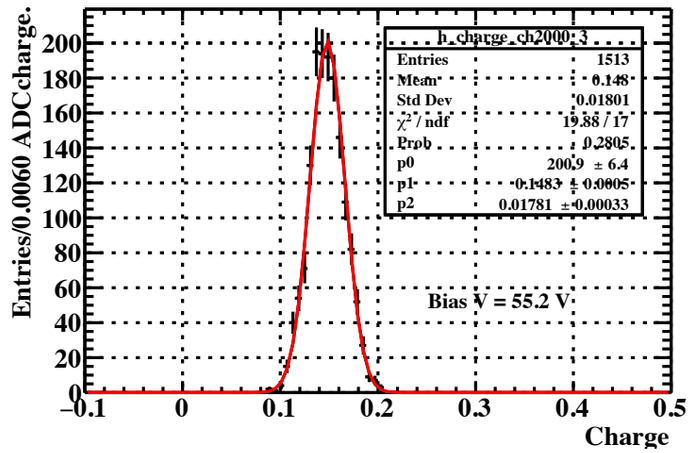
- LED data with various bias voltages are taken for monitoring the PDE_{LED}
- Breakdown voltages are estimated by extrapolating the gain curve with linear fit
- Example charge distributions and gain curve of an MPPC at the central region

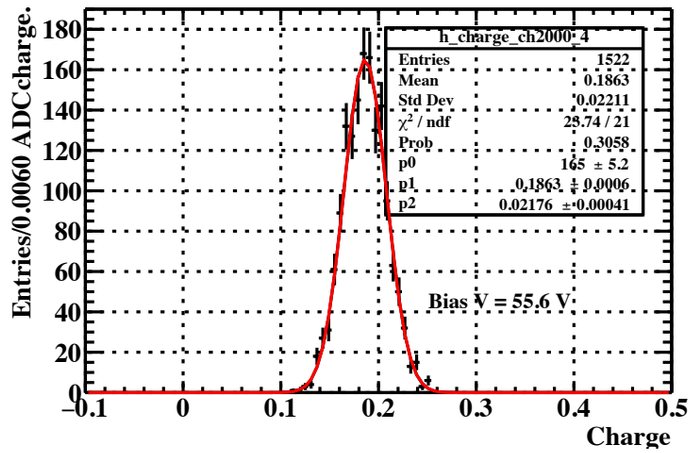


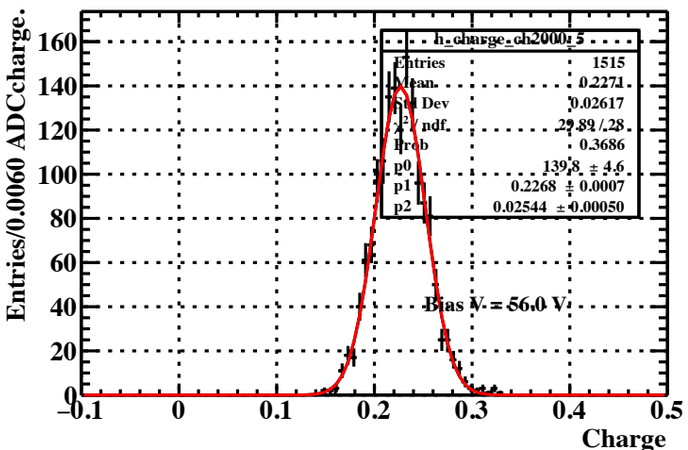


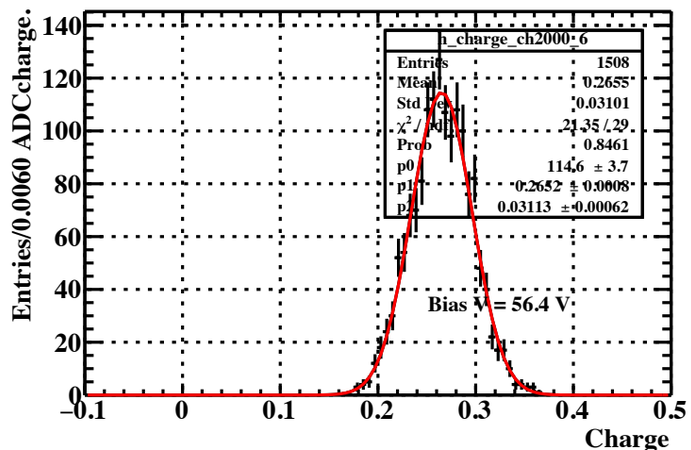


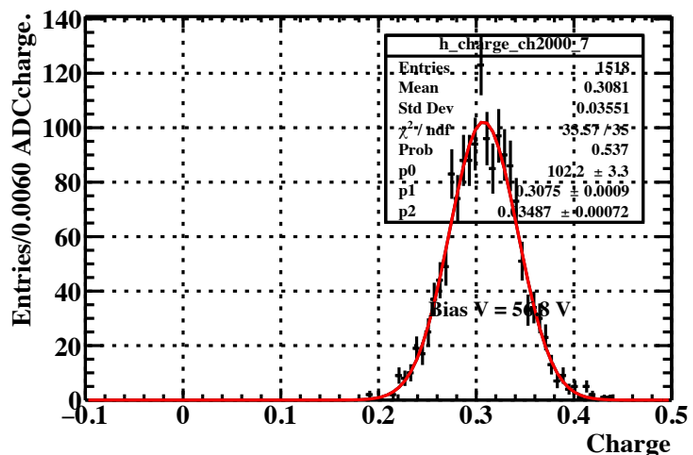








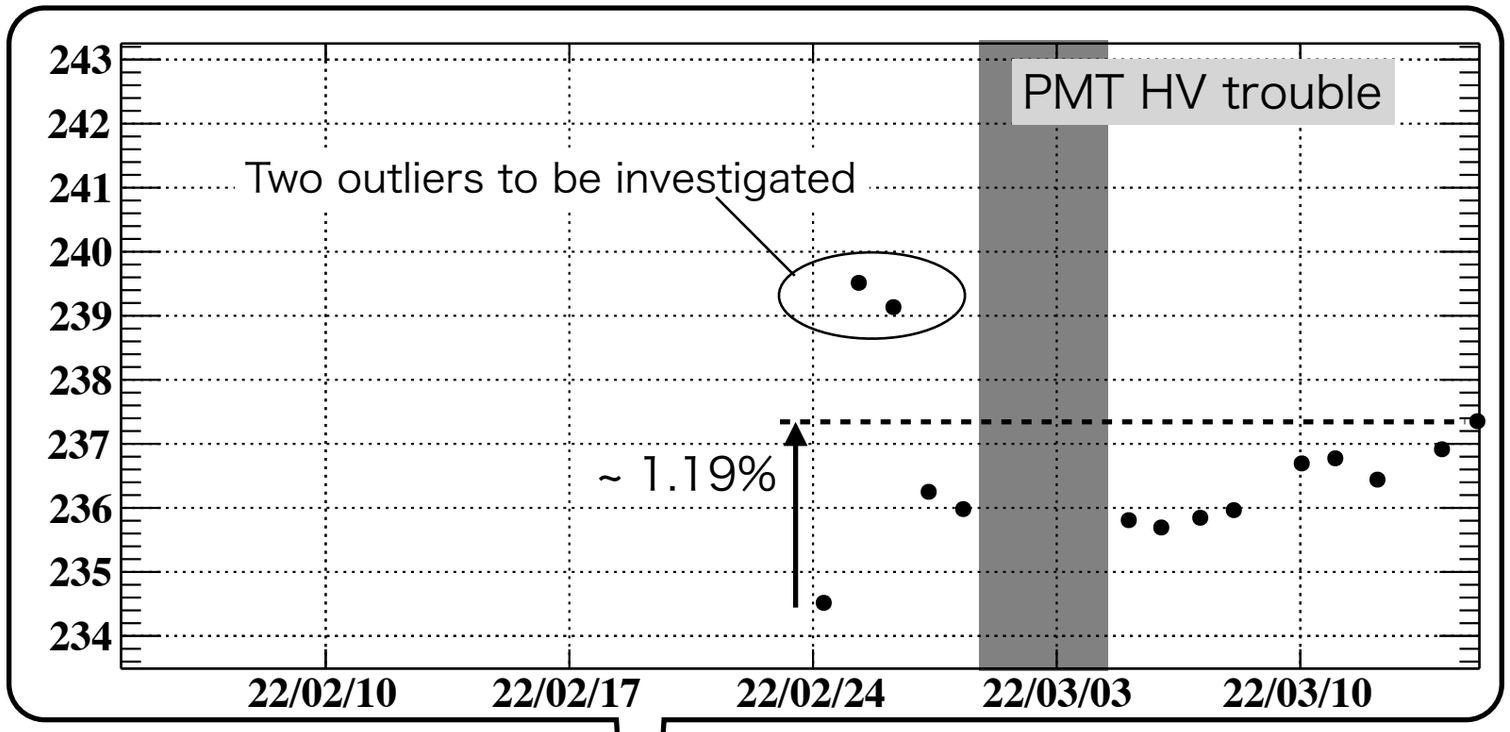


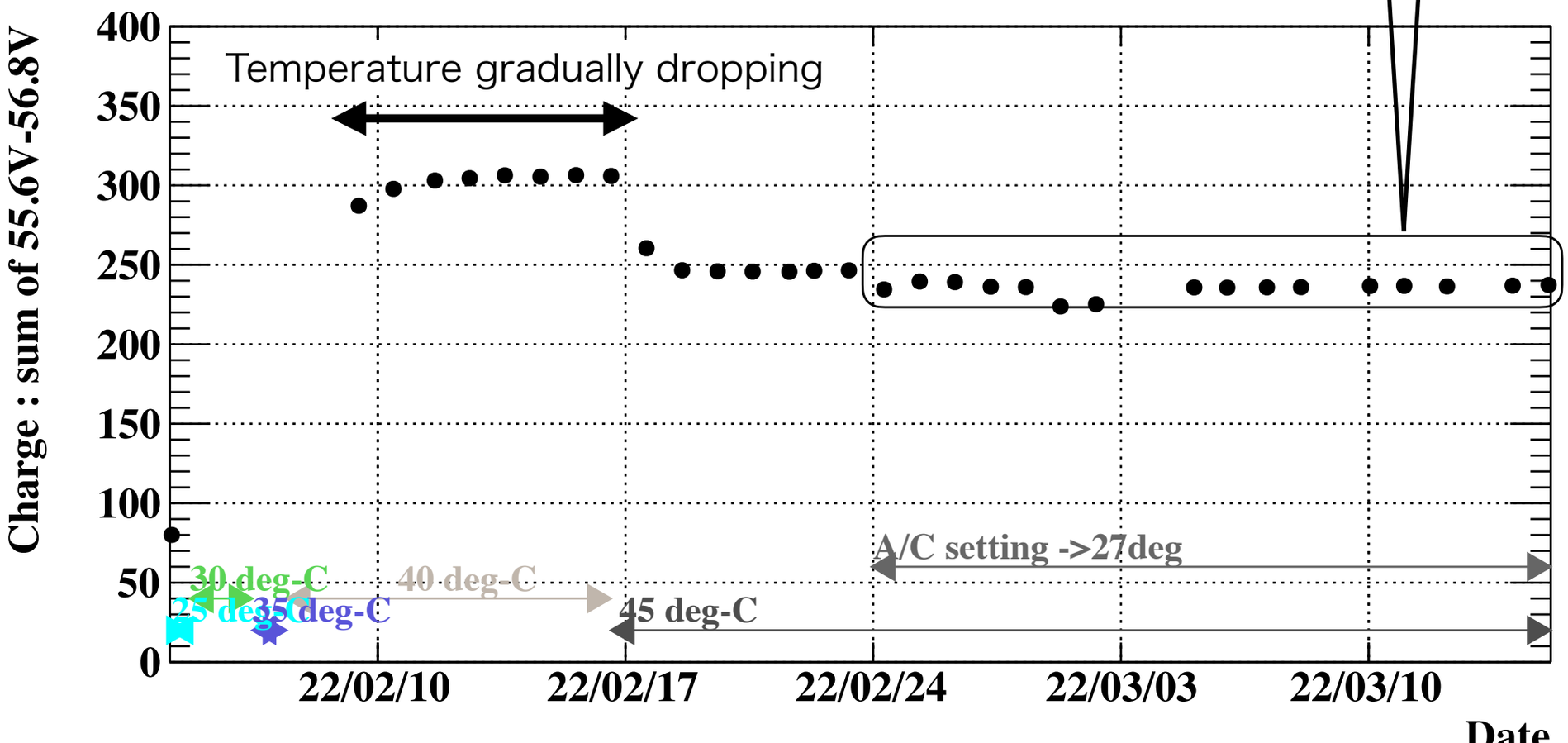


Annealing with hot water circulation / MPPC charge

Charge at constant bias voltage
(sum of 55.6, 56.0, 56.4, 56.8 V)
- sum charge of ~400 MPPCs
- NOT normalized by PMT charge

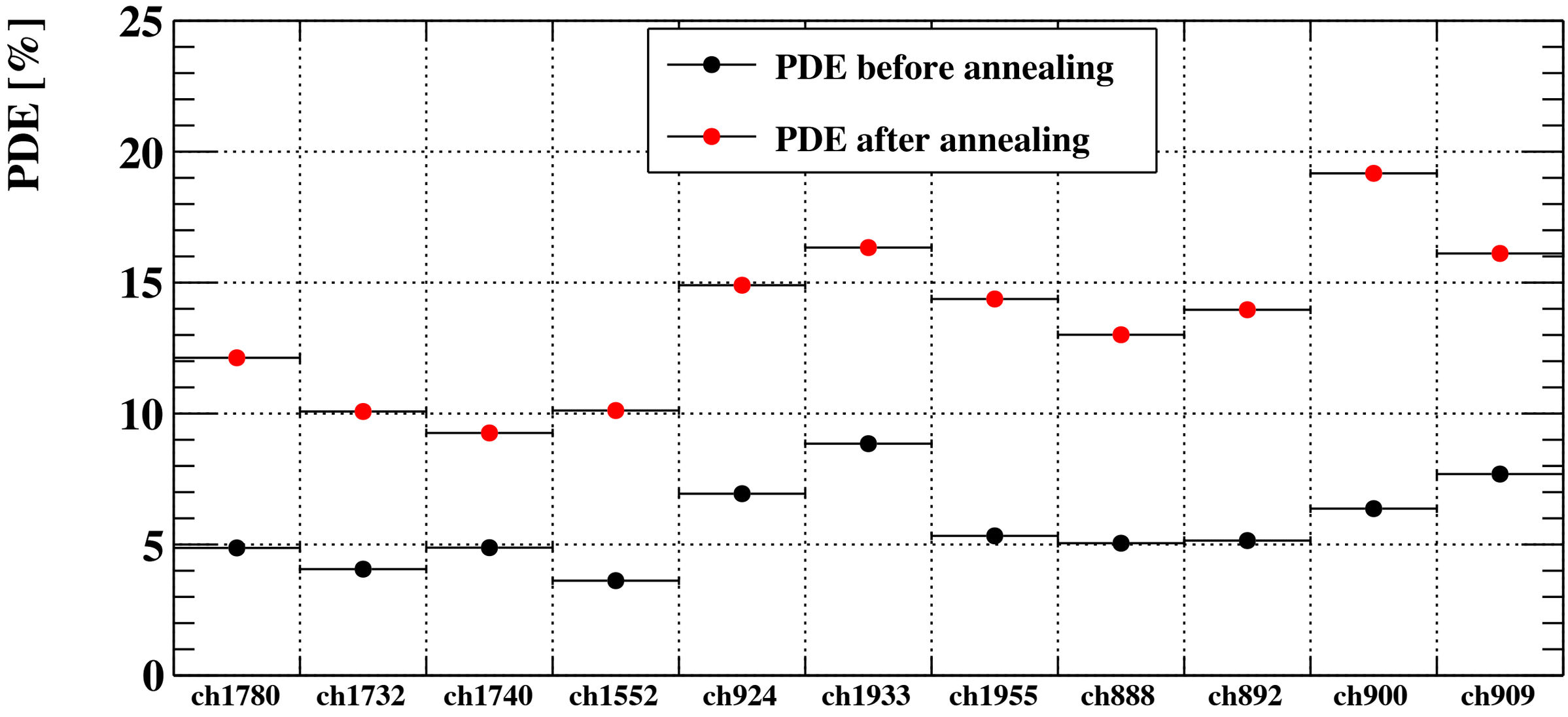
Slight charge increase can be seen
- ~1.2% after the temperature becomes constant
- Should be monitored carefully more





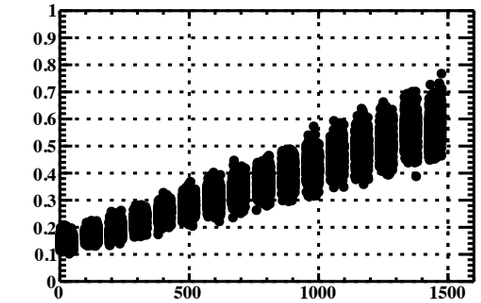
Summary of Joule annealing (small num. test)

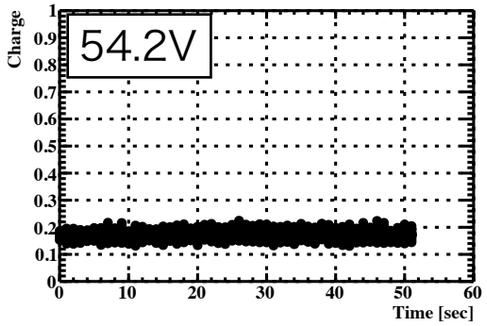
- Summary of small number test
- PDE after annealing is estimated by charge ratio both of the hot water annealing and Joule annealing

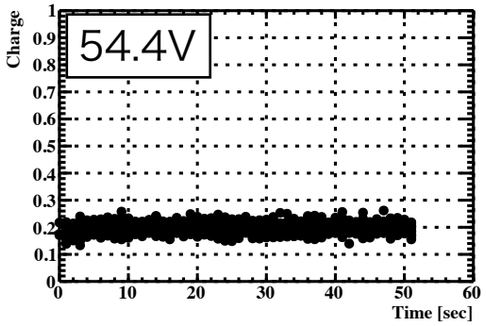


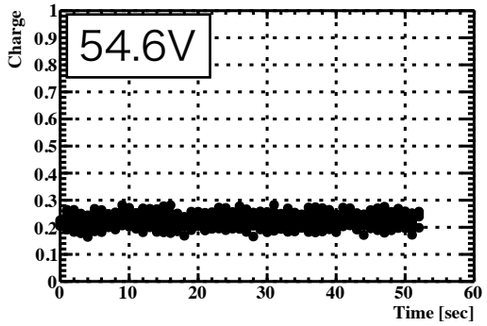
Charge vs time : effect of temperature decrease

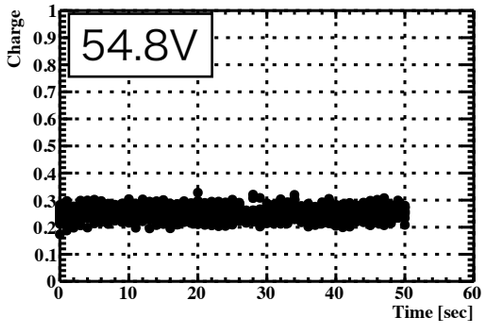
- Charge vs time
  - Dataset : run421165 - 421181 (after annealing of ch4), ch1000
  - No time dependence is observed

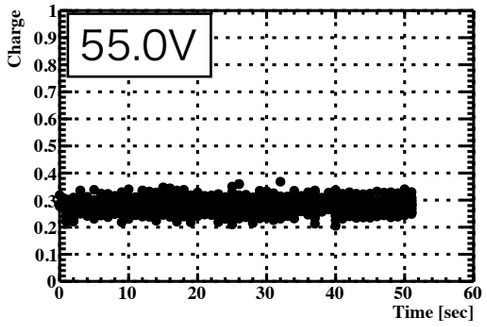


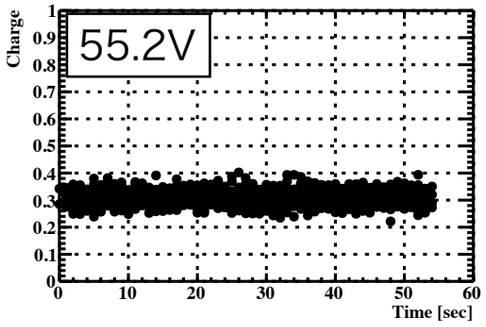


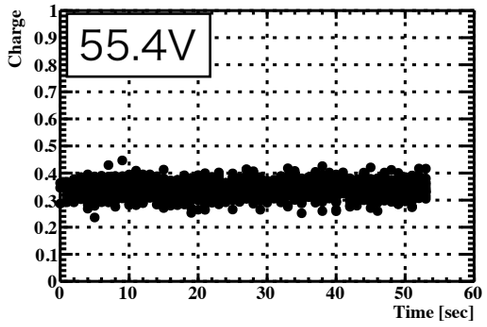


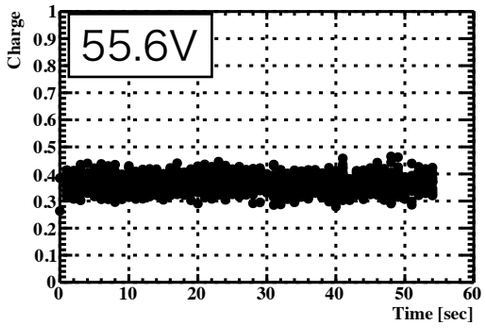


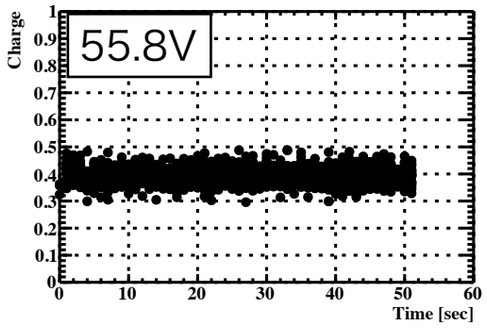


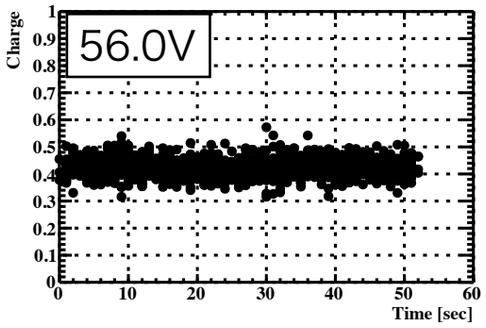


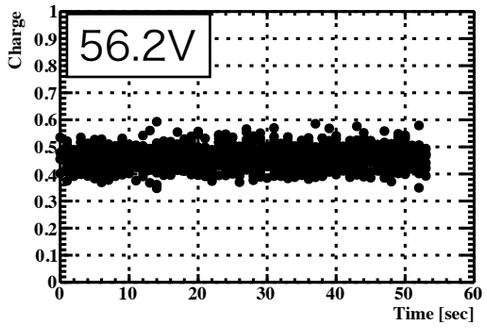


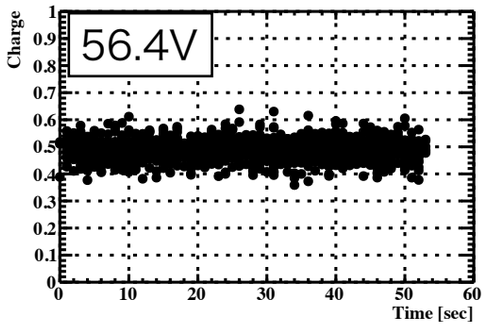


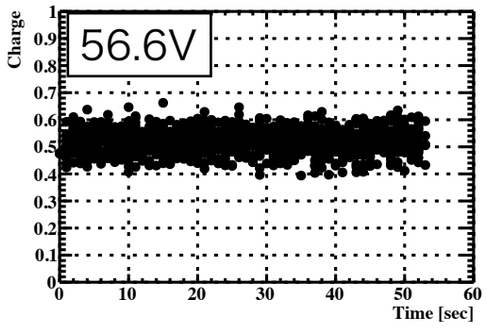


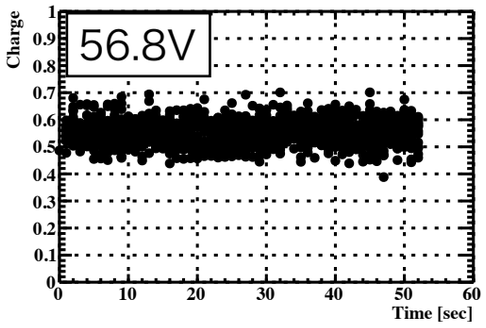


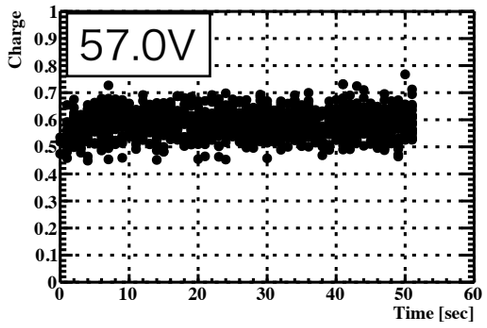












Calculate breakdown voltage and charge

- Charge vs time
  - Dataset : run421165 - 421181 (after annealing of ch4), ch1000
  - Example of how to calculate $V_{breakdown}$ and its result
    - Charge at over voltage : 3.0 V is used to evaluate the annealing effect