MEG II Experiment;
to Search for Lepton Flavor Violation ($\mu \to e\gamma$)

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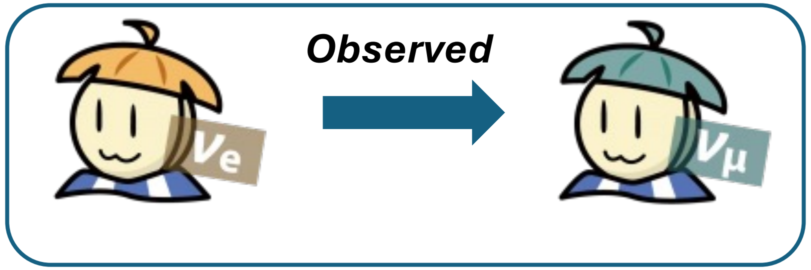
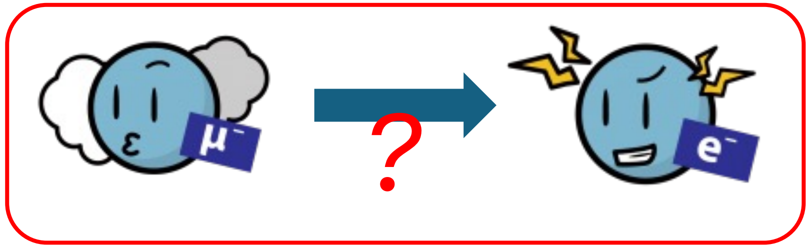
Introduction

- Motivation of search for charged Lepton Flavor Violation (cLFV)
    - Neutrino oscillation was ***observed*** by Super Kamiokande Experiment in 1998
    - Does charged Lepton Flavor Violation also exist?

- Search for $\mu^+ \rightarrow e^+\gamma$ (MEG II Experiment)
    - Br($\mu^+ \rightarrow e^+\gamma$) < 7.5×10^{-13} (90 % CL, published in 2024)
    - Prospect Sensitivity: $\mathcal{S}_{90}$~6.0×10^{-14} by 2026
    - Standard model: Br<10^{-55} ?

neutral Lepton

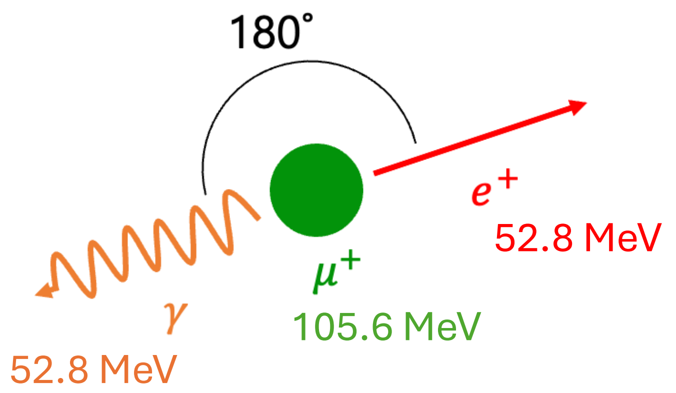




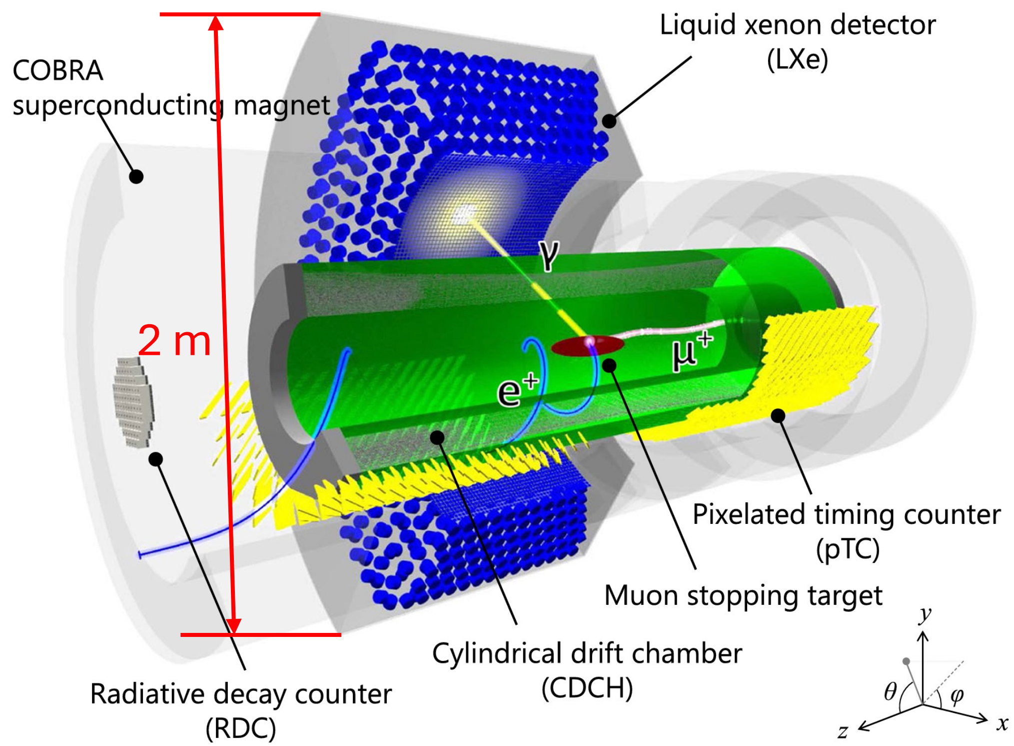
charged Lepton

MEG II Experiment

- Signal Event
  - e^+ and γ moving back to back with half energy of the muon mass (52.8 MeV)



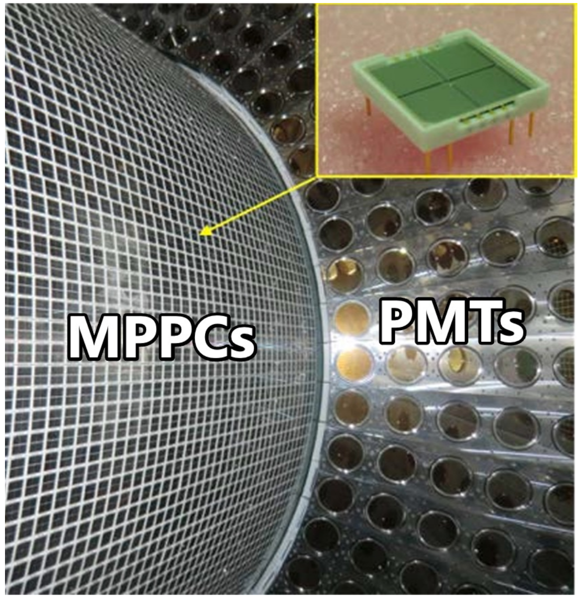
- Background Event
  - Decay contributing background;
    - Michel Decay: $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$
    - Radiative Muon Decay (RMD): $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$
  - Accidental Background;
    e^+ (from Michel Decay) +
    γ (from RMD or annihilation in flight of e^+ from Michel Decay)



- Detector
  - pTC and CDCH: measure time and position, energy of e^+
  - LXe Detector: measure time, position and energy of photon

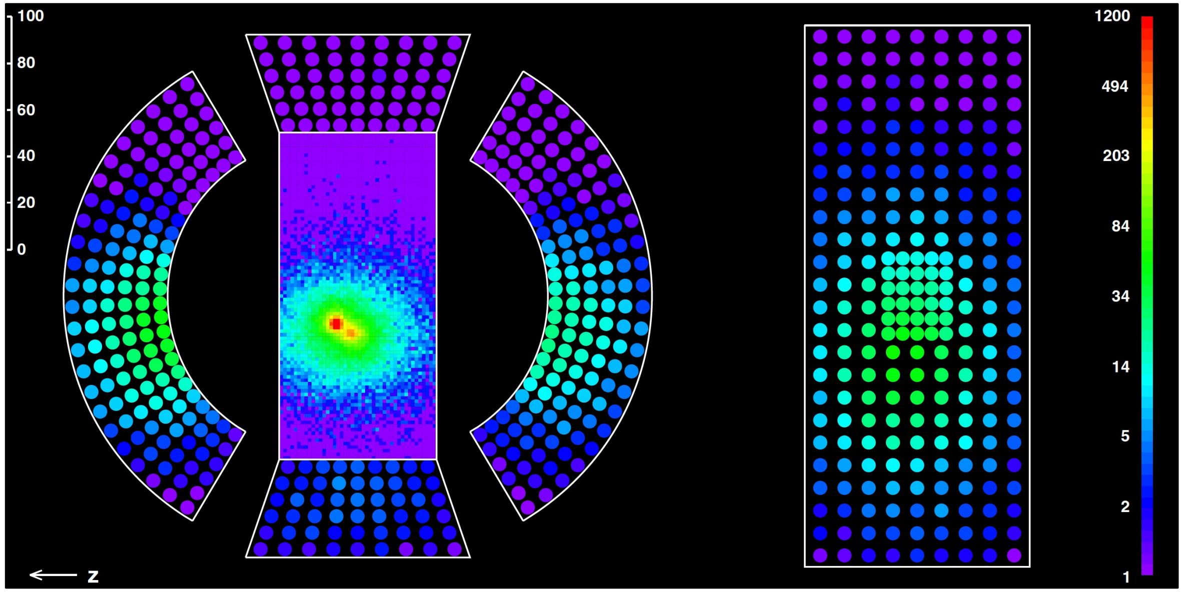
Liquid Xenon (LXe) Photon Detector

- LXe Photon Detector
  - Measure position, time, energy of photon by detecting scintillation light of xenon
    - Scintillation light of xenon is in VUV (Vacuum UltraViolet) range ($\lambda = 175$ nm)
    - 2.7 t LXe inside



- Photomultiplier (PMT) and silicon photomultiplier (SiPM) are used as photo-sensors
  - PMT
    - Number: 668
    - Diameter: 2-inch
  - MPPC (a kind of SiPM)
    - Number: 4092
    - Size: 15 × 15 mm^2

- The PMT and MPPC are sensitive to VUV light



Xenon Leak Check for the LXe Photon Detector

Xenon Leak

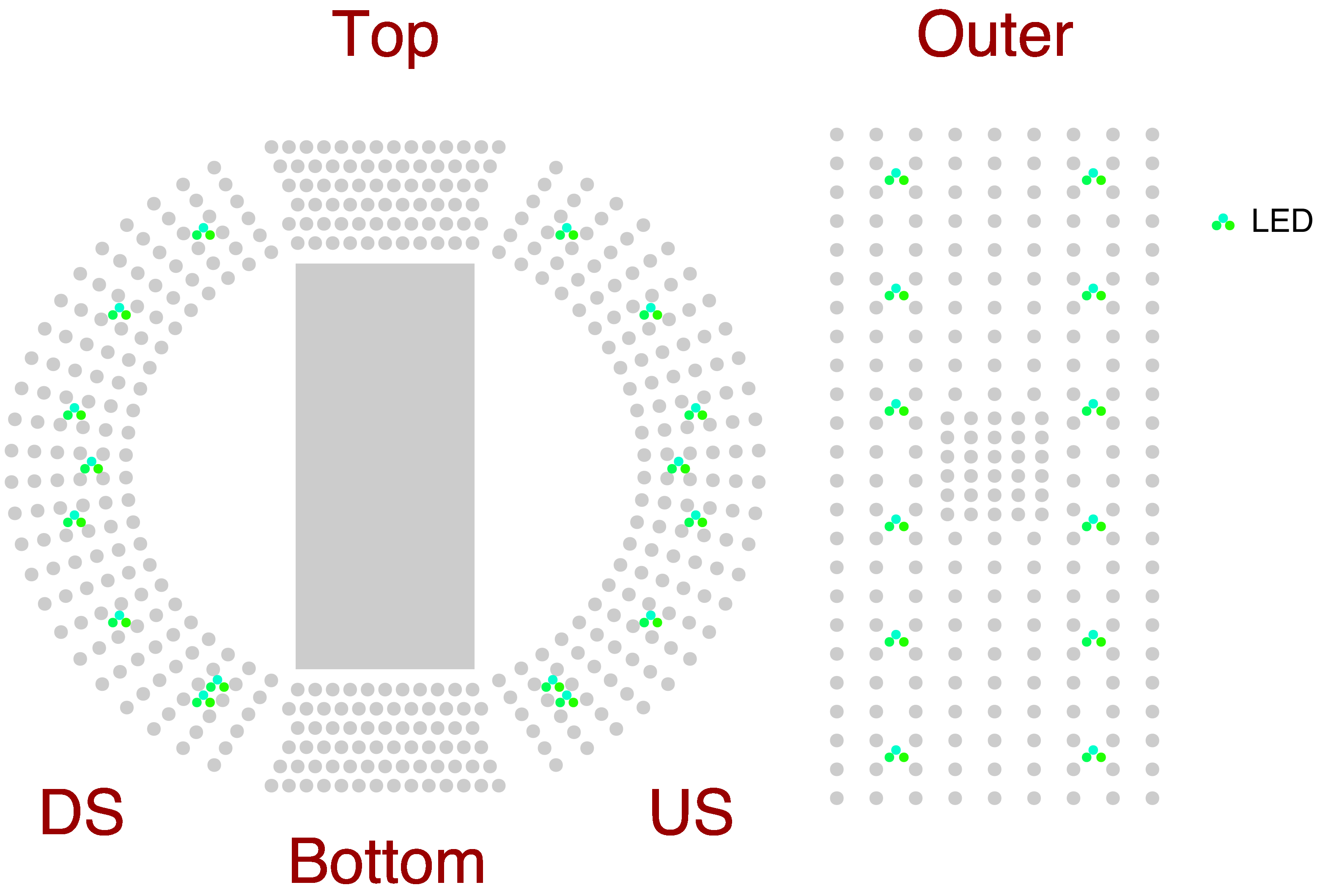
- A Xenon leak was found in the LXe detector in 2024
  - Leak rate: 0.32 ± 0.16 kg/day
  - Possible cause: Distortion of gasket joined parts

- Xenon collection undergoing
  - Collect leaked xenon in a LN2 trap, purify later
  - Return these xenon to the LXe detector in the future

- Gasket: mechanical seal to prevent leakage from joined objects while under compression

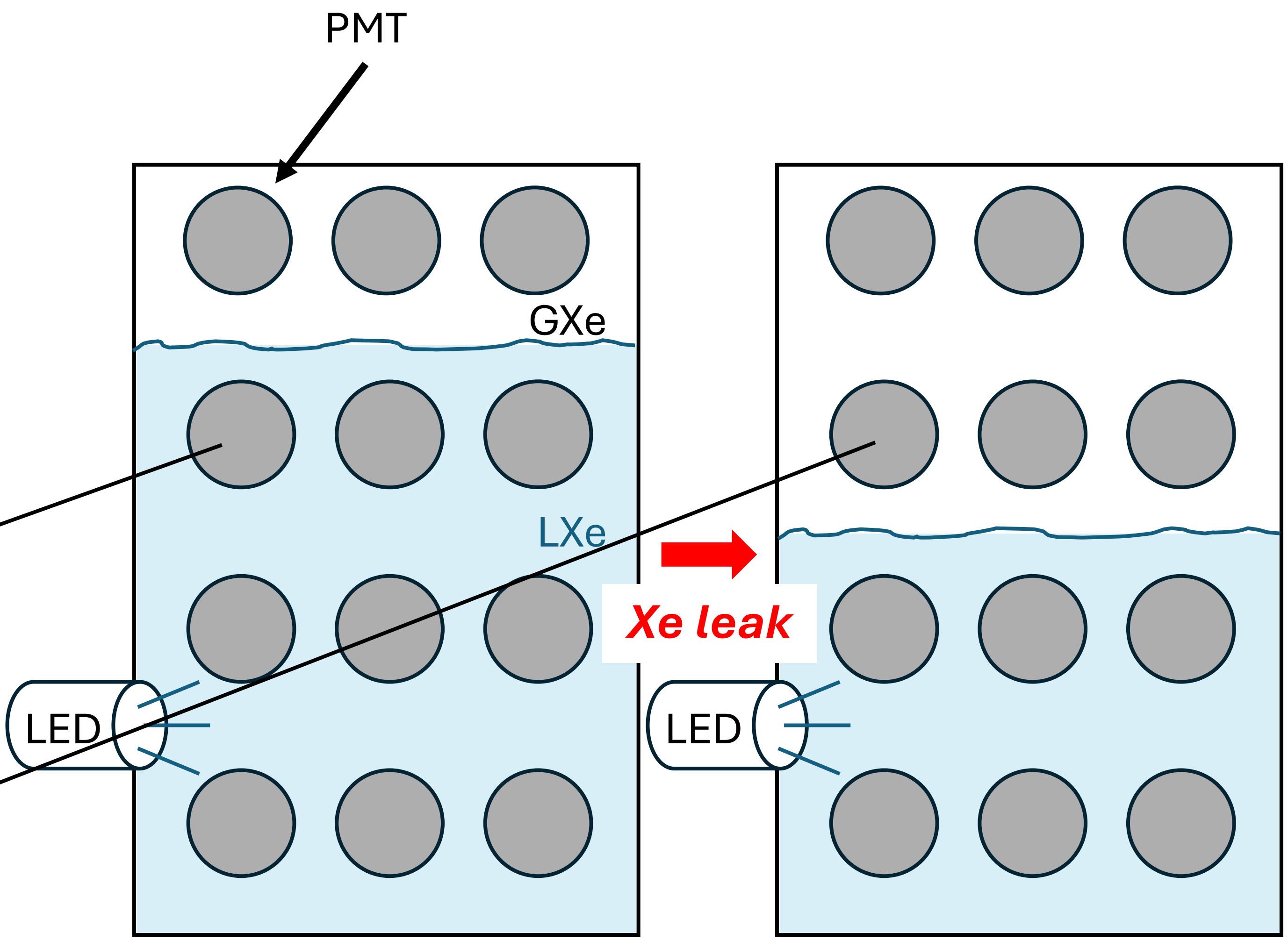
LEDs inside LXe Photon Detector to Estimate Liquid Level

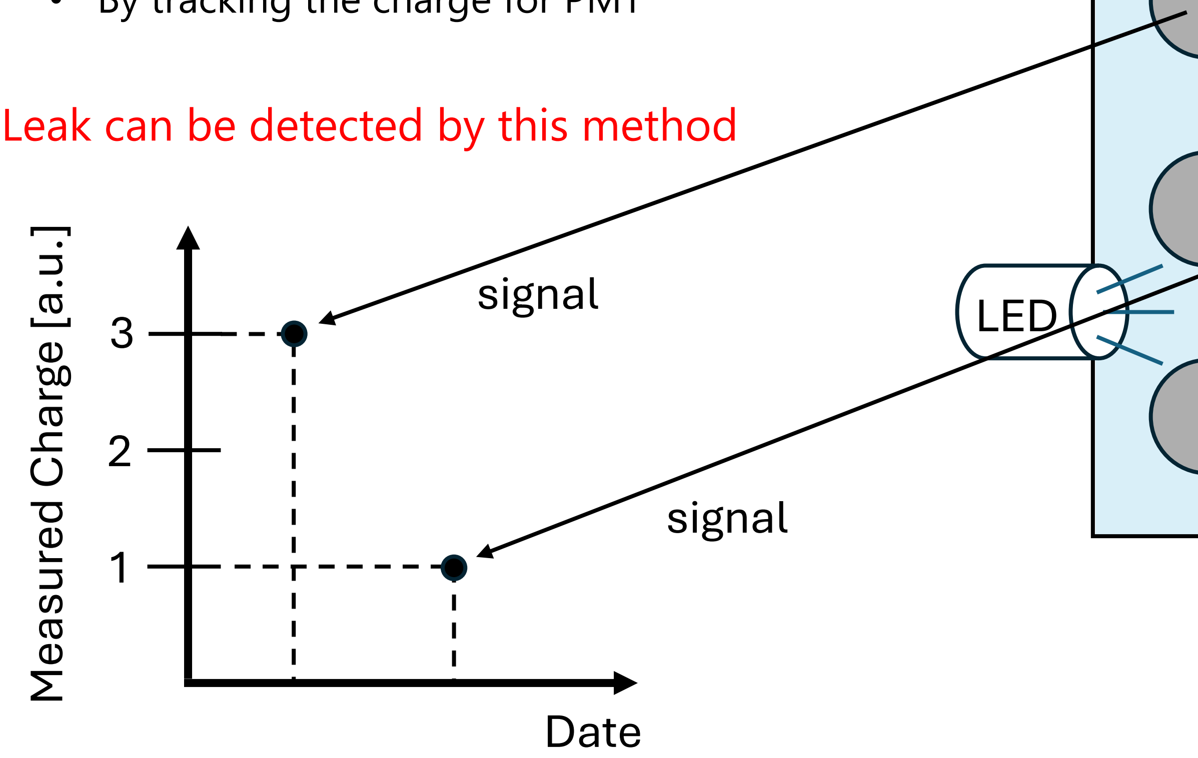
- LEDs inside LXe detector are used for the calibration of the photo-sensors



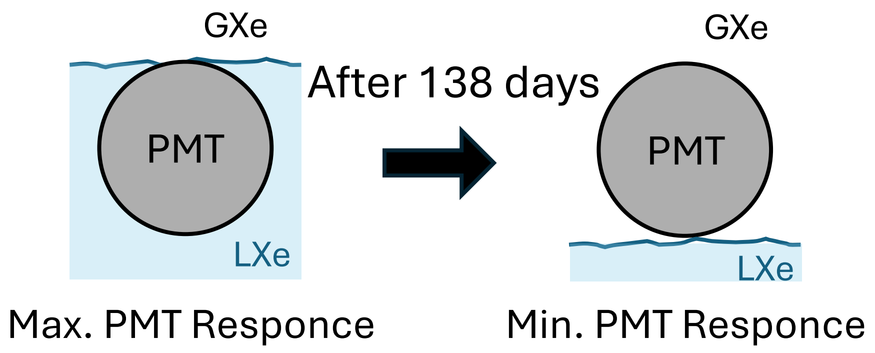
Method to Estimate Liquid Level and Detect Leak

- The number of detected LED photons in the liquid phase is about 2-3 times higher than in the gaseous phase
  - LED located in LXe
  - Due to reflection of LED light at the liquid/gas interface
- This allows us to estimate the liquid level
  - By tracking the charge for PMT
- Leak can be detected by this method

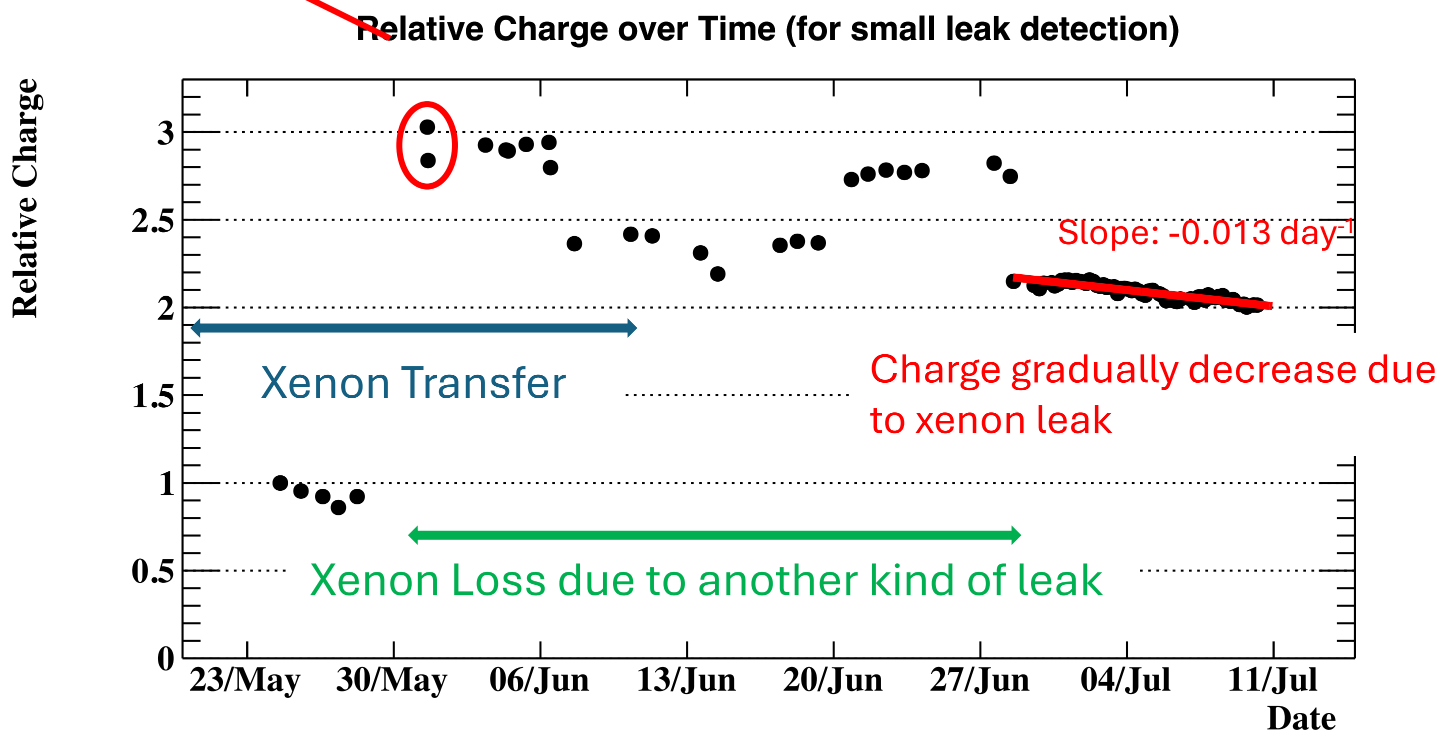




Leak Rate Calculate by PMT Response

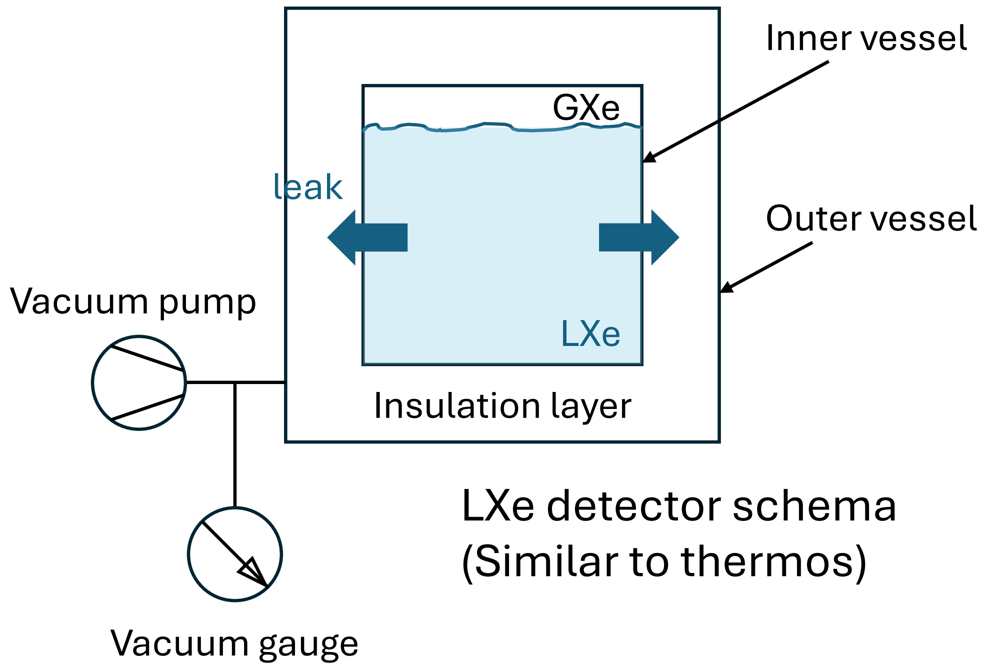


- Maximum PMT response: 2.8 [a.u.]
- Minimum PMT response: 1 [a.u.]
- PMT response decrease slope: -0.013 day^{-1}
- Time t to reach to minimum PMT response: 138 day (from solution of $-0.013t + 2.8 = 1$)
- Estimated lost Xenon mass for a full row of PMTs: 44 kg
- Xenon Leak Rate: 44 kg / 138 d = 0.32 kg/d

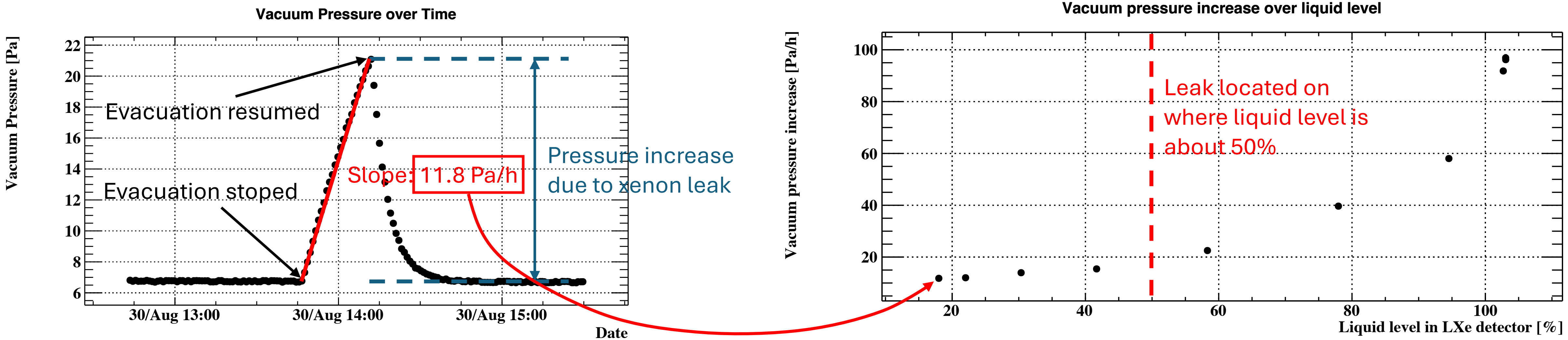


Leak Rate Calculated by Vacuum Pressure Increase

- Pressure of insulation layer increased when evacuation of insulation layer stopped
  - Due to xenon leak from inner vessel
- Calculate the slopes of pressure increase
  - by stopping the evacuation of insulation layer
  - do this measurement while filling LXe
- Track them by liquid level
- Leak rate strongly depends on liquid level

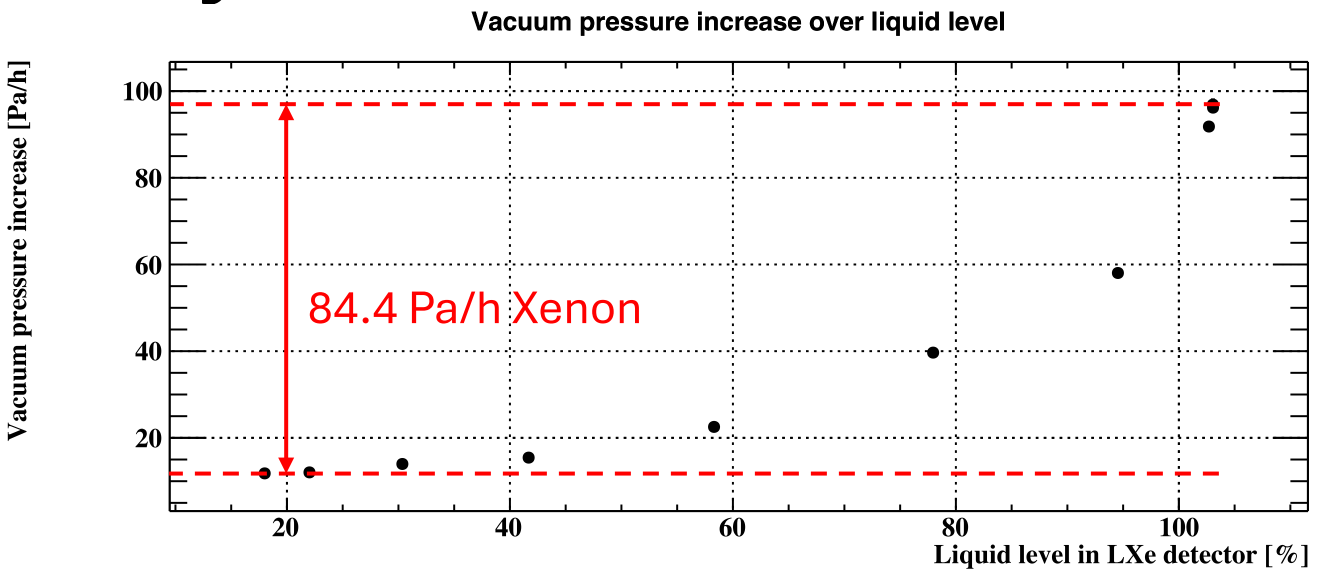


LXe detector schema
(Similar to thermos)



Method to Calculate Leak Rate by Vacuum Pressure Increase

- Mass leak rate: $\dot{M} = \dot{P}\frac{M_{Xe}V}{RT}$
    - $\dot{P}$: Partial pressure increase of insulation layer
    - M_{Xe}: Molar mass of xenon (~131 g/mol)
    - V: Volume of insulation layer(~1000 L)
    - R: Molar gas constant ($8.31\ \mathrm{J\cdot K^{-1}\cdot mol^{-1}}$)
    - T: Temperature of insulation layer (~200 K)



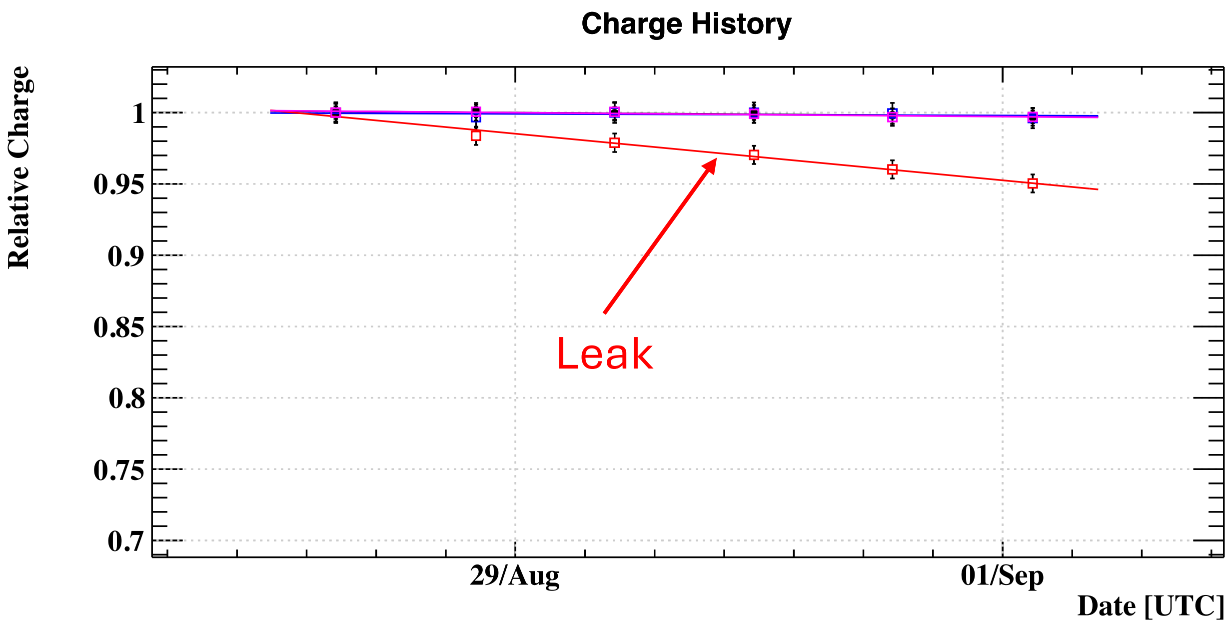
$$\dot{M} = 84.4\ \mathrm{Pa/h}\cdot\frac{M_{Xe}V}{RT} = 0.16\ \mathrm{kg/day}$$

	From PMT charge by PMT Response	From vacuum pressure increase
Small leak rate [kg/day]	0.32	0.16
Cause of uncertainties	Fiducial volume of inner vessel, Maximum PMT response	Volume of insulation layer, Temperature of insulation layer

- The small leaks from PMT charge and vacuum pressure increase are consistent within a factor of 2
- Estimated uncertainties: ~50%

Implement Check of a real-time Leak Detection

- Take PMT response data when LED light blinking (called “LED data”)
- Regularly monitor liquid level using LED data
- Continue run with xenon leak
  - Lose 10-20 kg xenon for 1 month’s run
  - The effects to data will be studied

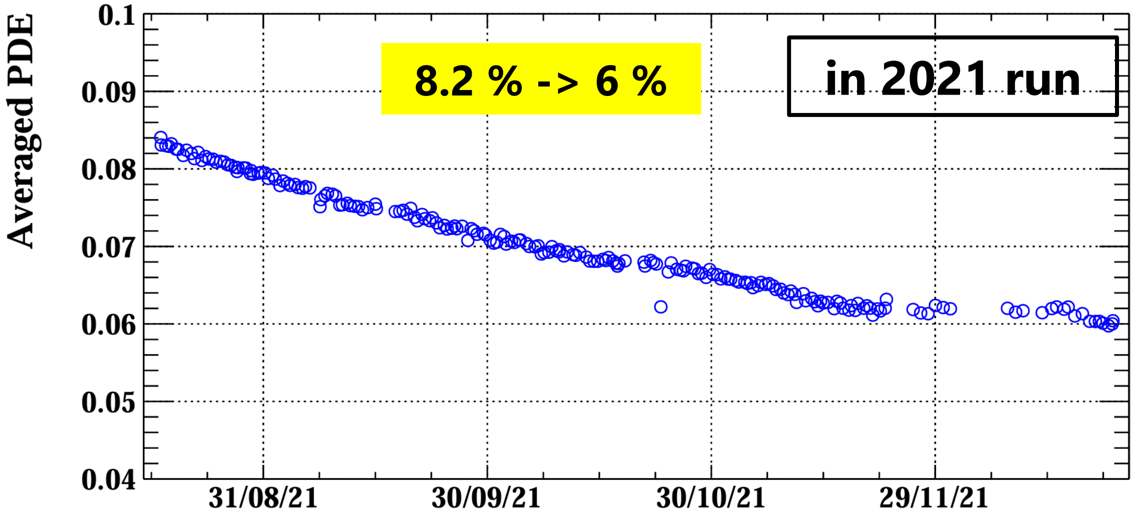


Study on Radiation Damage of SiPM

PDE Degradation of SiPM inside the MEG II Experiment

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

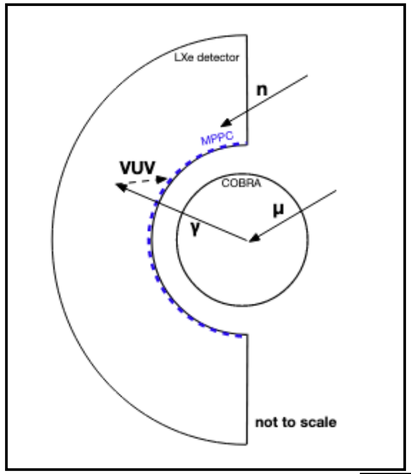
$N_{\text{photon}} = 1.1\times 10^{11}\ \text{photon/mm}^2$

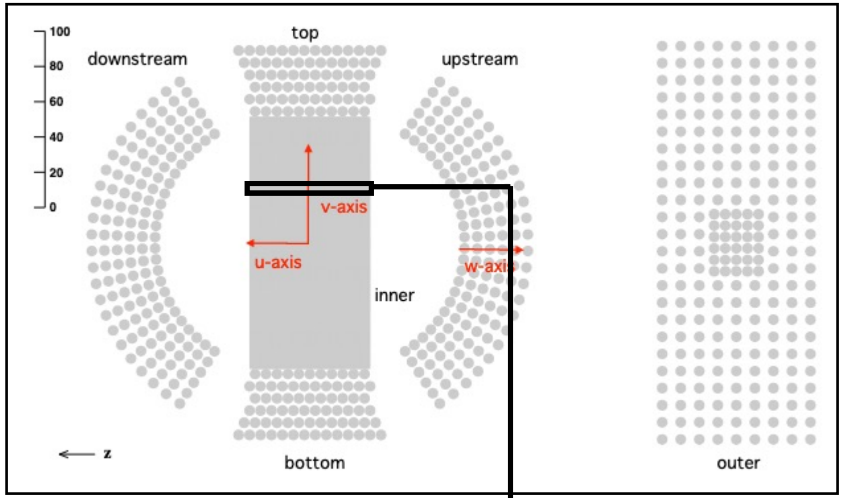


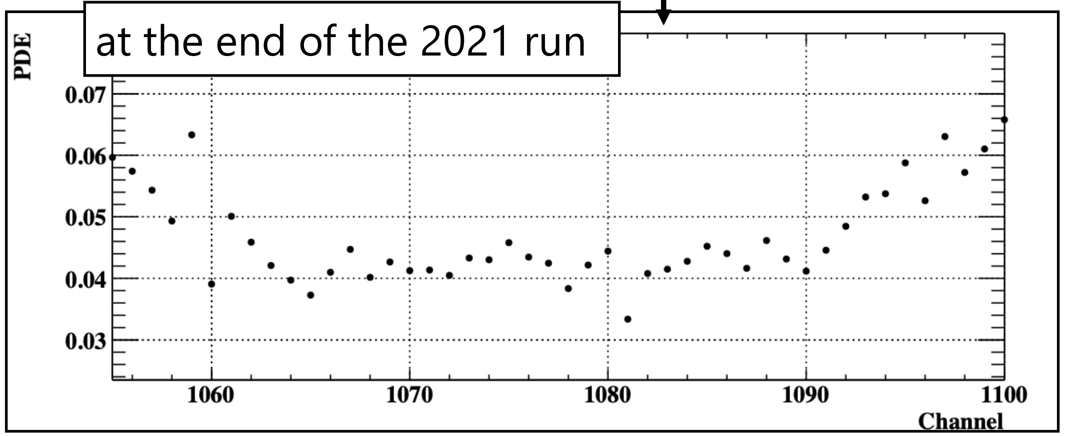
https://arxiv.org/pdf/2310.11902.pdf

Position Dependence of SiPM's PDE Degradation

- Radiation environment
  - Radiation from the muon stopping target
    - Gamma-ray
    - VUV light
  - Radiation from the accelerator
    - Neutron
- PDE decrease at the center is larger
- Muon stopping target is centred with reference to LXe detector







upstream ← center → downstream

→ Most likely to be caused by radiation from muon stopping target

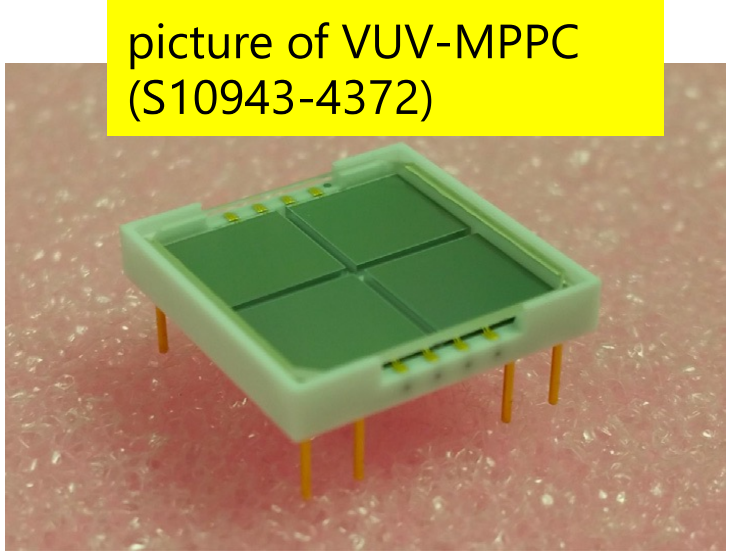
→ Radiation candidates: gamma-rays, ***VUV light***

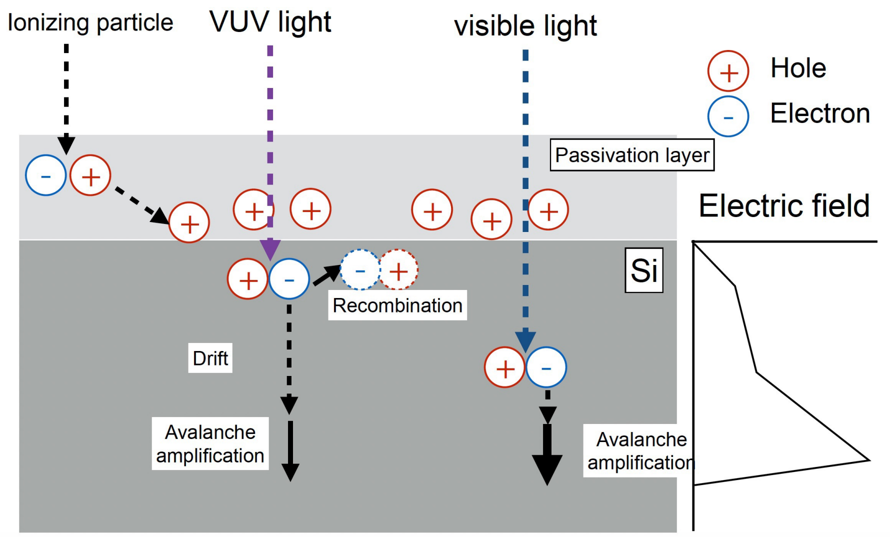
Radiation Damage of VUV-MPPCs

- Candidate for radiation damage:
  Surface damage
  - Caused by ionizing radiation

- Previous lab tests
  - VUV-MPPCs were irradiated with VUV light at room temperature, low temperature (~165 K), in liquid xenon
    - Humidified VUV-MPPC was irradiated with VUV light in room temperature
  - VUV-MPPCs were irradiated with gamma-ray at room temperature, low temperature (~165 K)

- PDE degradation was not reproduced in laboratory





https://www.sciencedirect.com/science/article/pii/S0168900223003558?

Moisture inside SiPM Reduce PDE

1. It's known that water absorbs VUV light
   - VUV-MPPCs have no moisture resistance layer on the surface

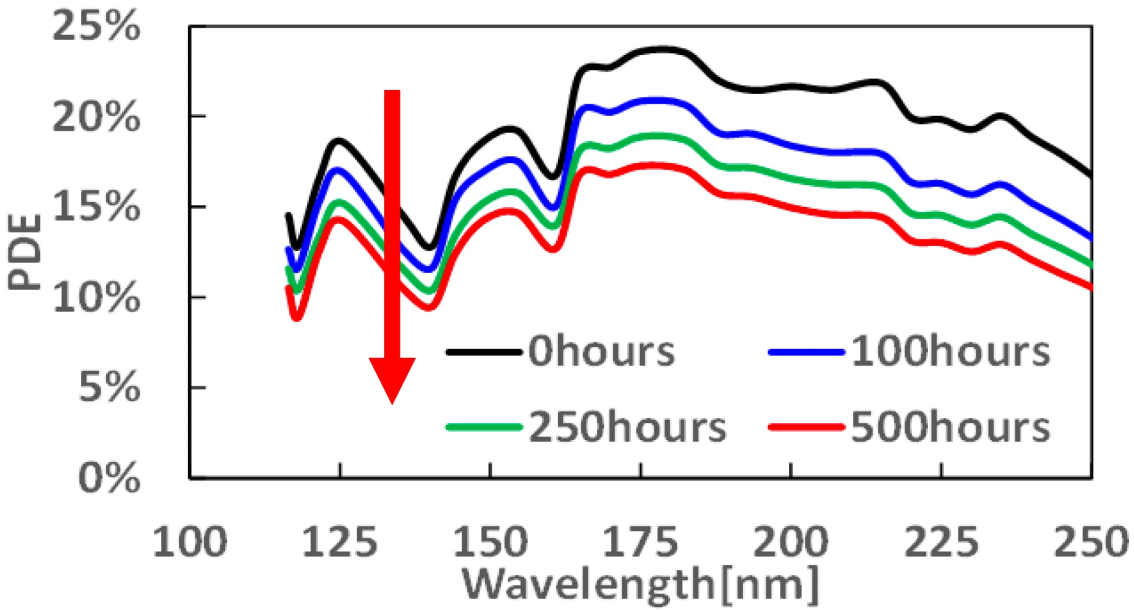
2. VUV-MPPCs in MEG II were exposed to ambient humidity during storage and installation

Combine the above two results

→ Humidity duffused into the MPPCs might accelerate the radiation damage

- Measure PDE of humidified VUV-MPPC during VUV irradiation

Condition: 60°C, 90% r.h.
(89 times faster than 25°C, 60% r.h.)

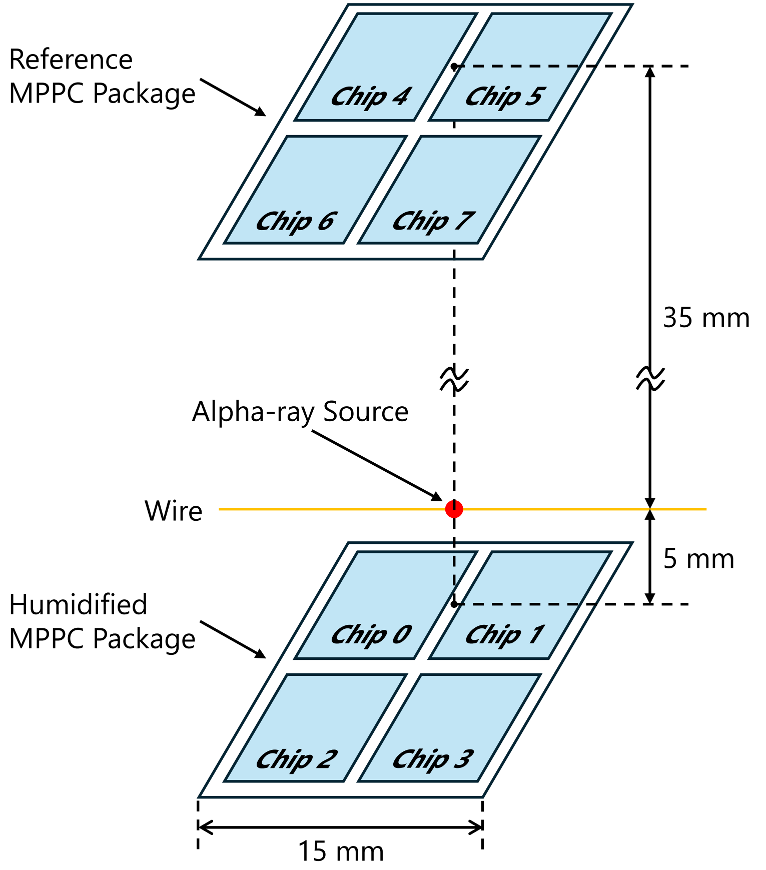


R. Yamada, et al., "Development of MPPC with high sensitivity in NUV or VUV," 2022 IEEE NSS/MIC/RTSD

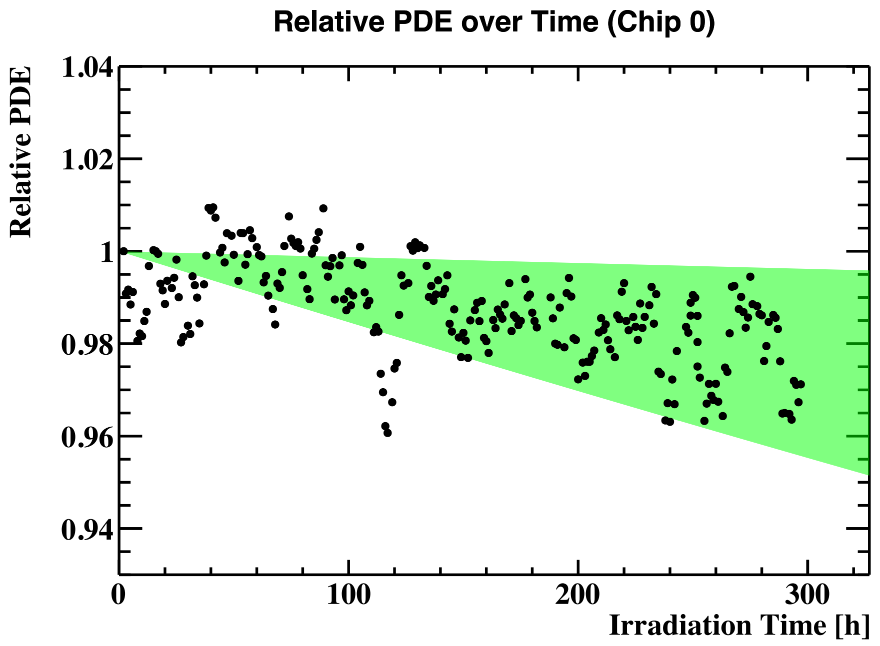
Method

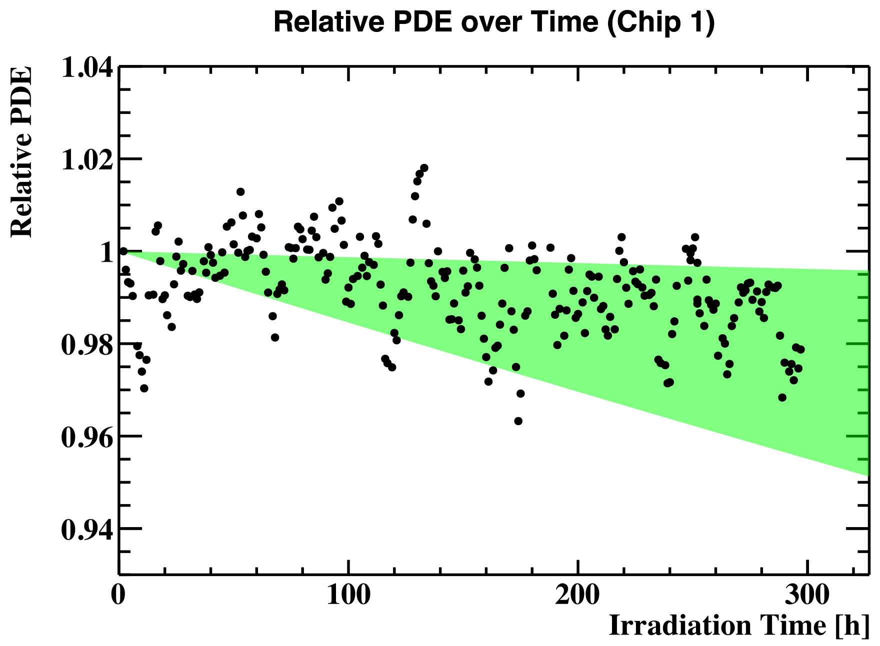
- Irradiate VUV-MPPC with scintillation light in LXe
  - To confirm the humidified VUV-MPPC is damaged by VUV light or not
  - Irradiate enough to reproduce the speed of PDE decrease of the LXe detector
    - Continuous irradiation for 300 hours

- Install the VUV-MPPC, alpha-ray source (Am241) and LED in LXe
  - Alpha-ray is used instead of gamma-ray
  - LED is for the calibration
  - Sustain the temperature in LXe (168 K) during data taking



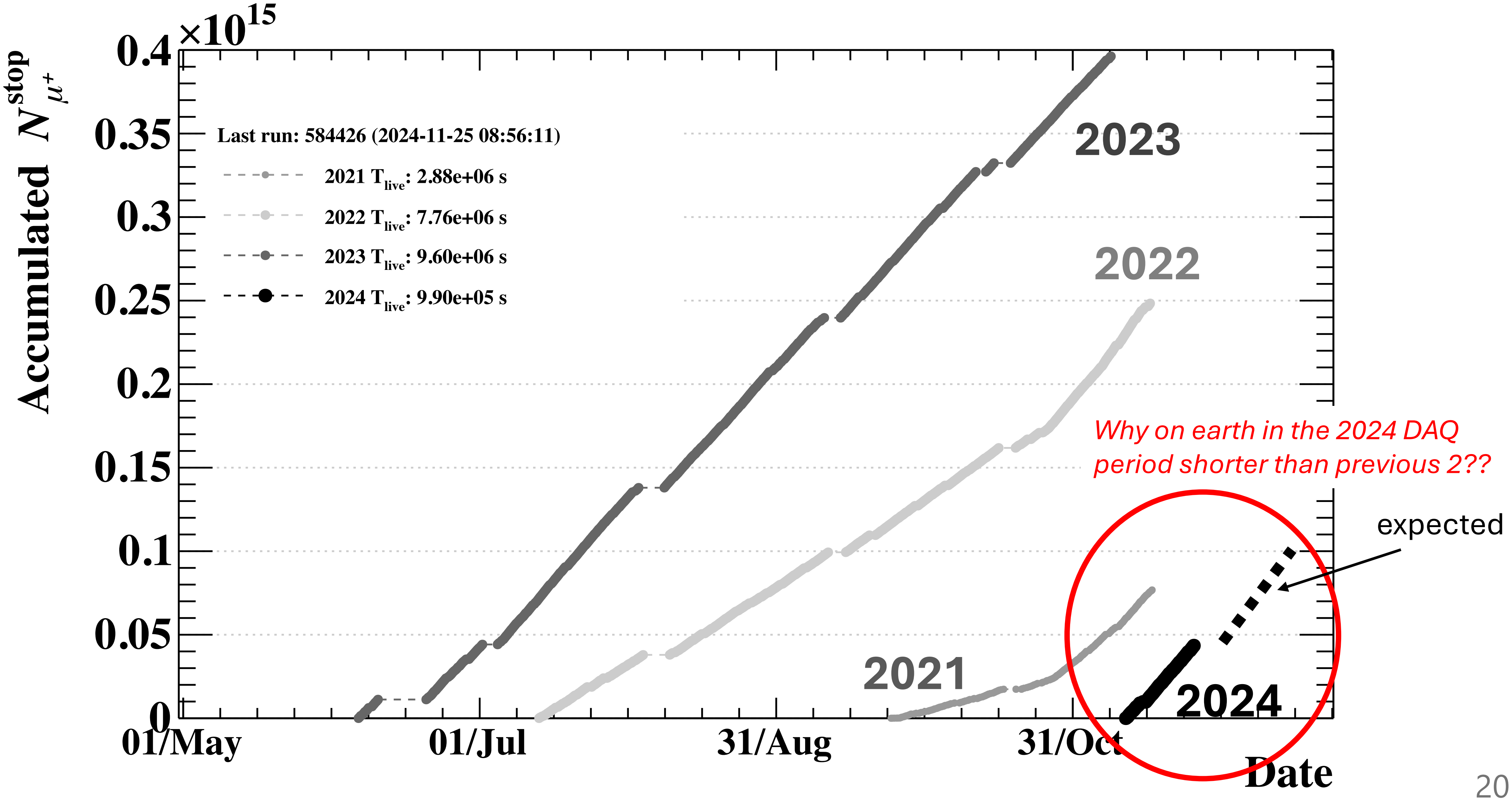
Result – PDE decrease in this study



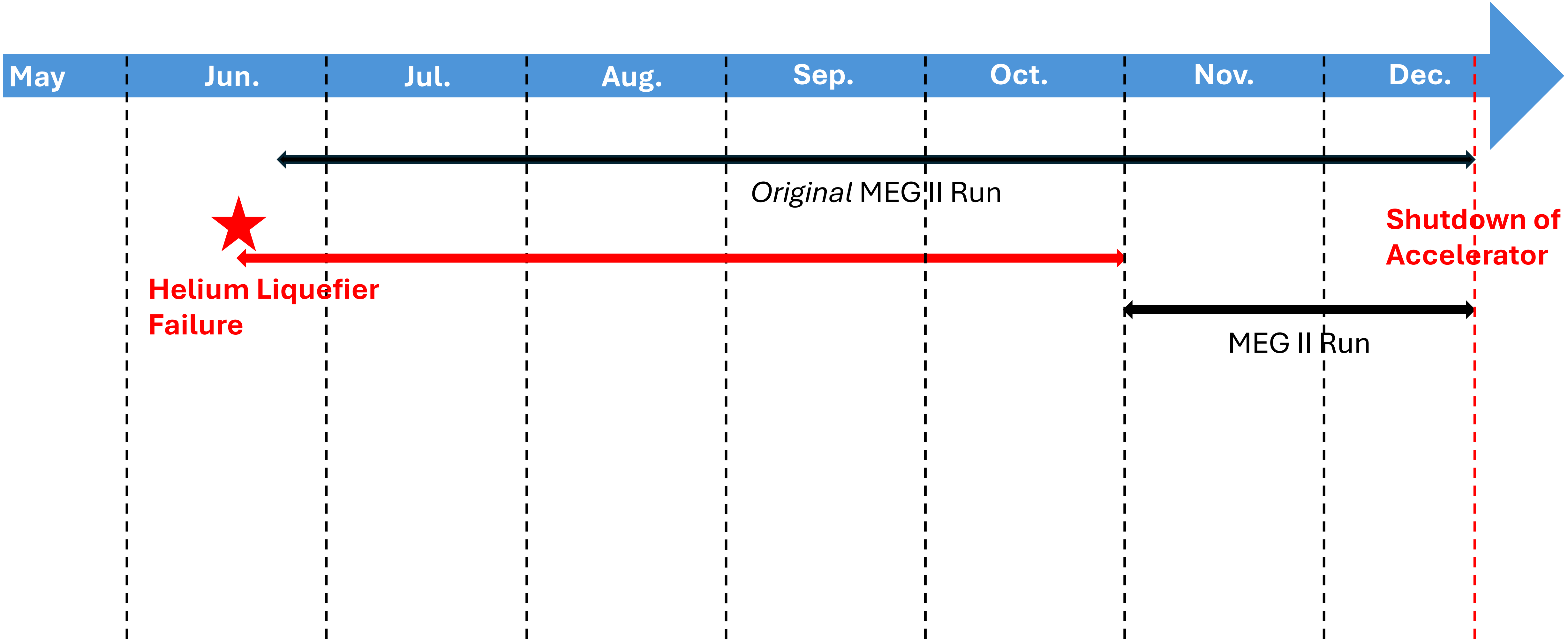


- The PDE decrease expected within the green region
- The relative PDE seems decreased by irradiation as a whole
    - But the fluctuation of each point is too large comparing with the green region
- Statistical errors can be reduced by more precise analysis
- Currently, we cannot determine whether the VUV light is the cause of the PDE decrease or not
- Use PMT as reference photo-sensor instead of MPPC to reduce 3.4 times of systematic error

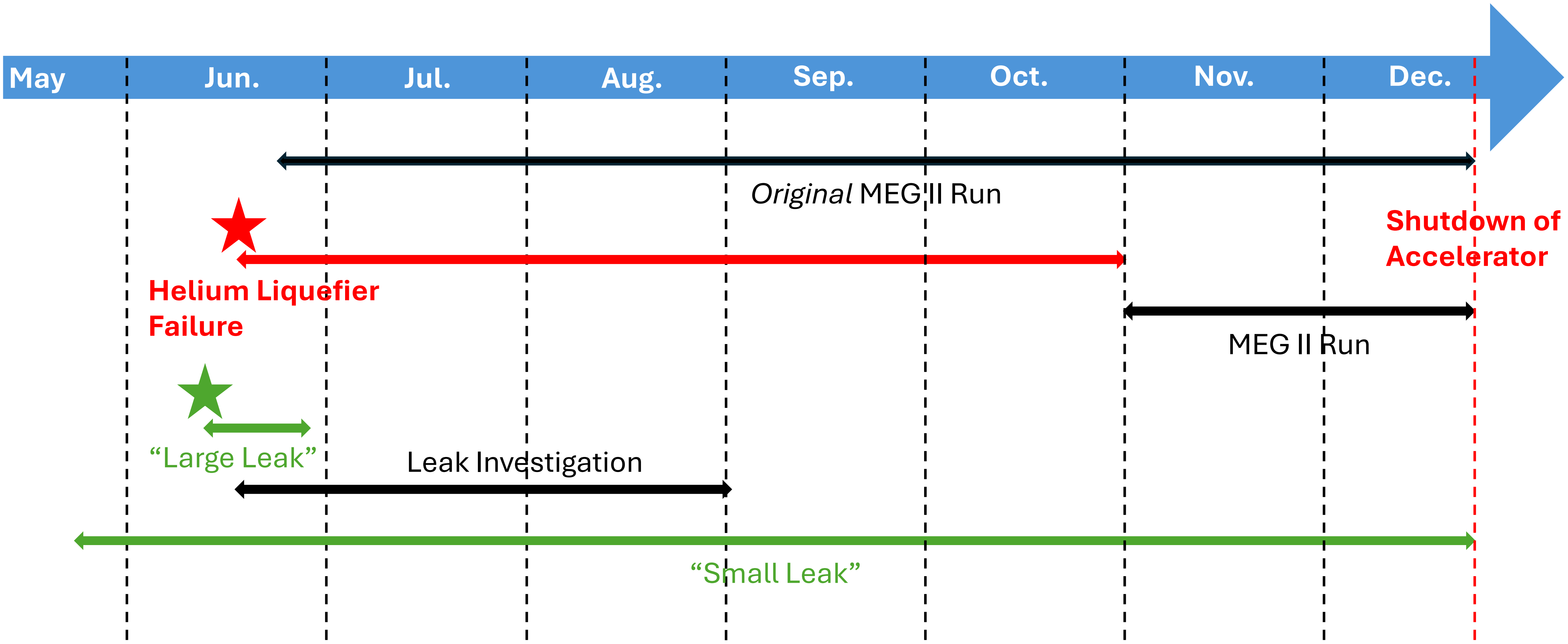
Data Acquisition of MEG II Experiment



Timeline towards 2024 MEG II Run



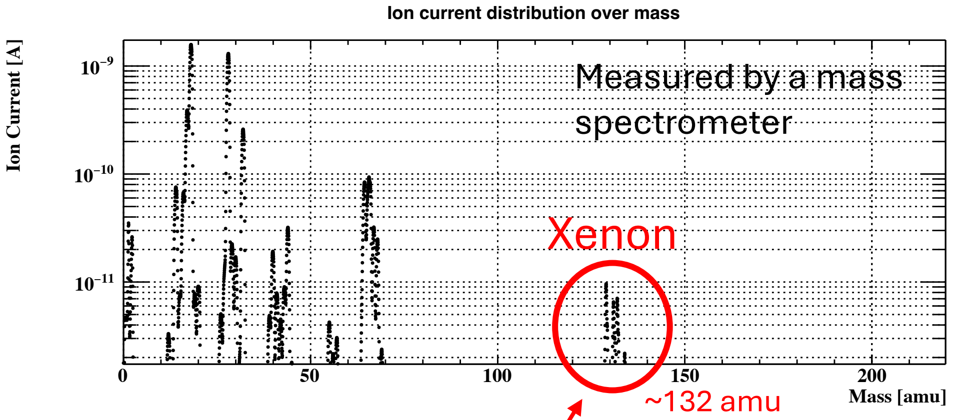
Timeline towards 2024 MEG II Run

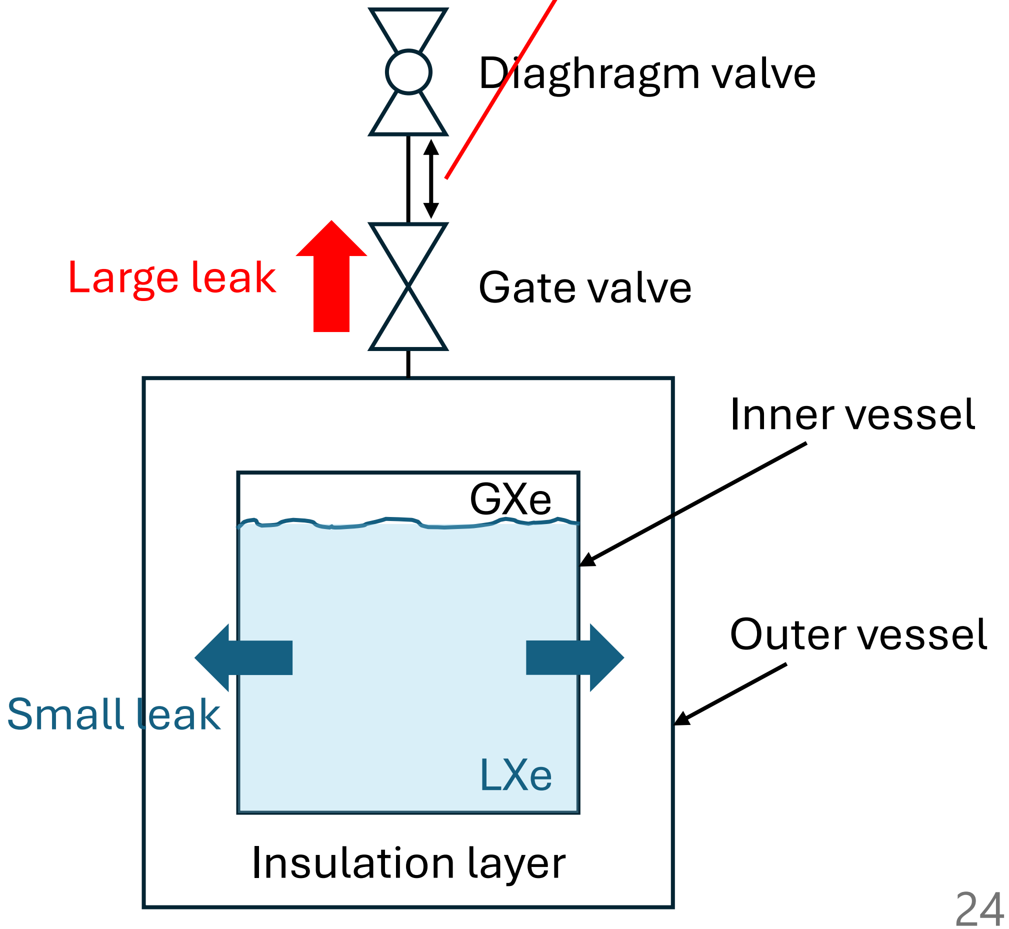


Backup

Two Kinds of Leak: "Large" and "Small Leaks"

- Parts of the LXe detector related to leak
  - Inner vessel: LXe and GXe inside
  - Outer vessel: Evacuated continuously
  - Gate valve: Separate atmosphere and GXe
- **"Large leak"**
  - From inner vessel to atmosphere via gate valve
    - Happened only in 2024
    - Lost 40-80 kg xenon until the middle of September 2024
  - Cause: lack of leak tightness of the gate valve
  - No leak anymore
    - Dealed with temporarily
    - Need exchange of the gate valve
- **"Small leak"**
  - From inner vessel to insulation layer
    - Happened from 2021 MEG II run
    - Lost 10-20 kg xenon until the middle of September 2024
  - Cause: Lack of leak tightness of inner vessel gasket

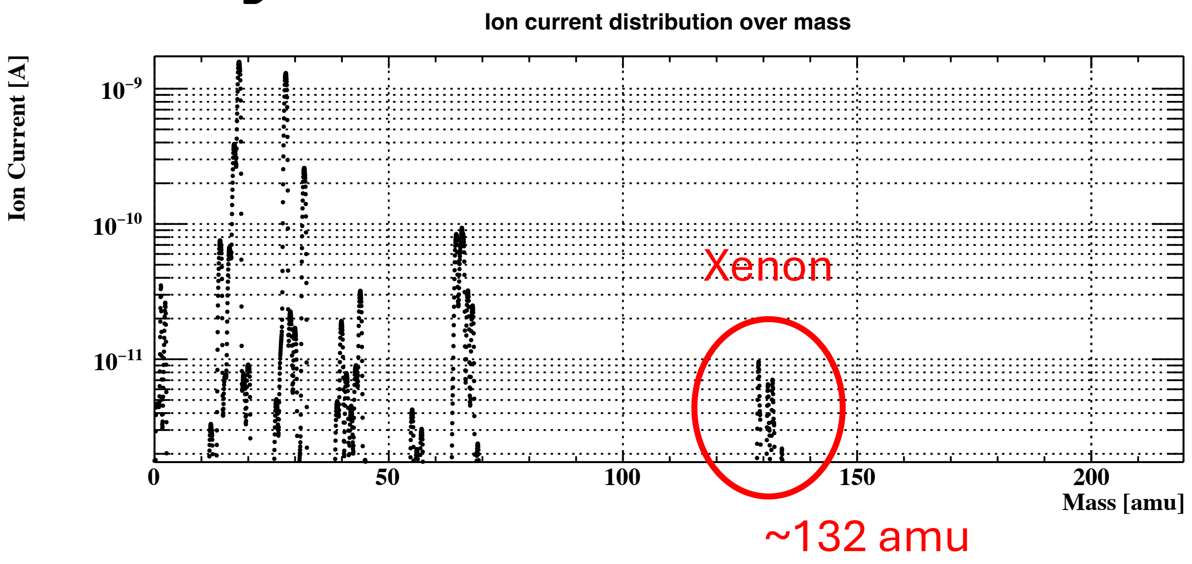


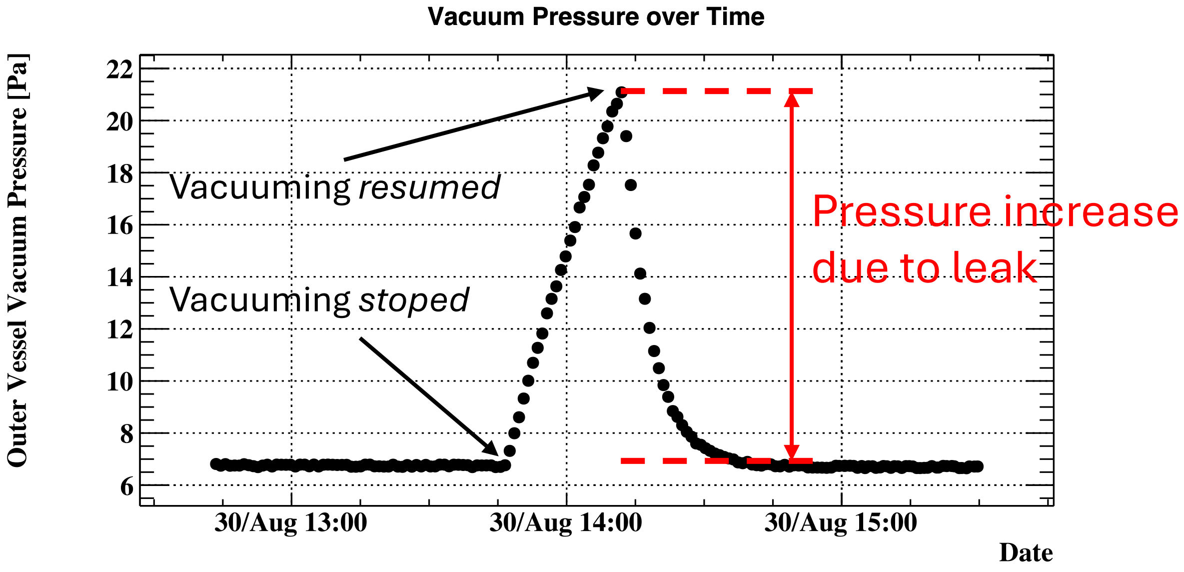


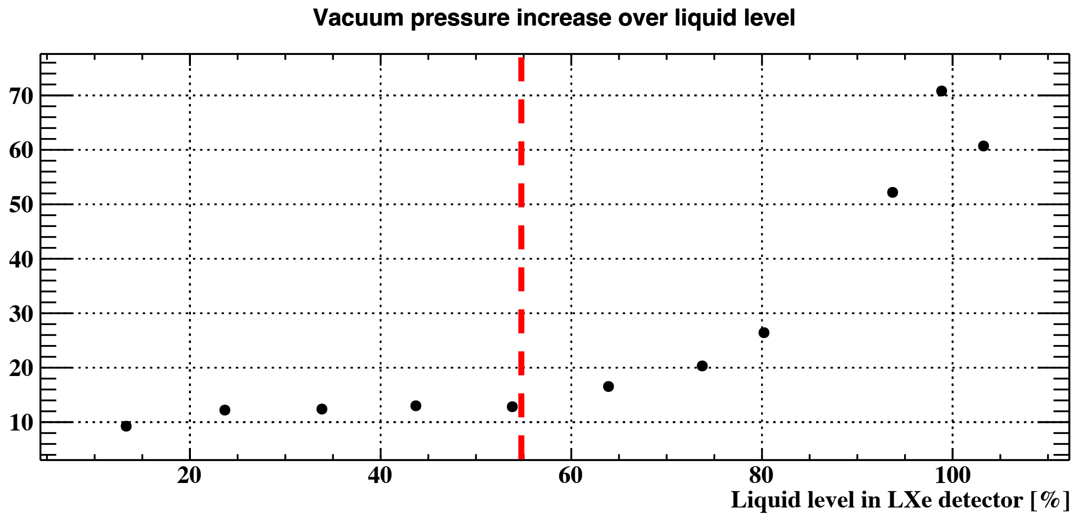
Pressure Increase of Insulation Layer

- Xenon was found in insulation layer

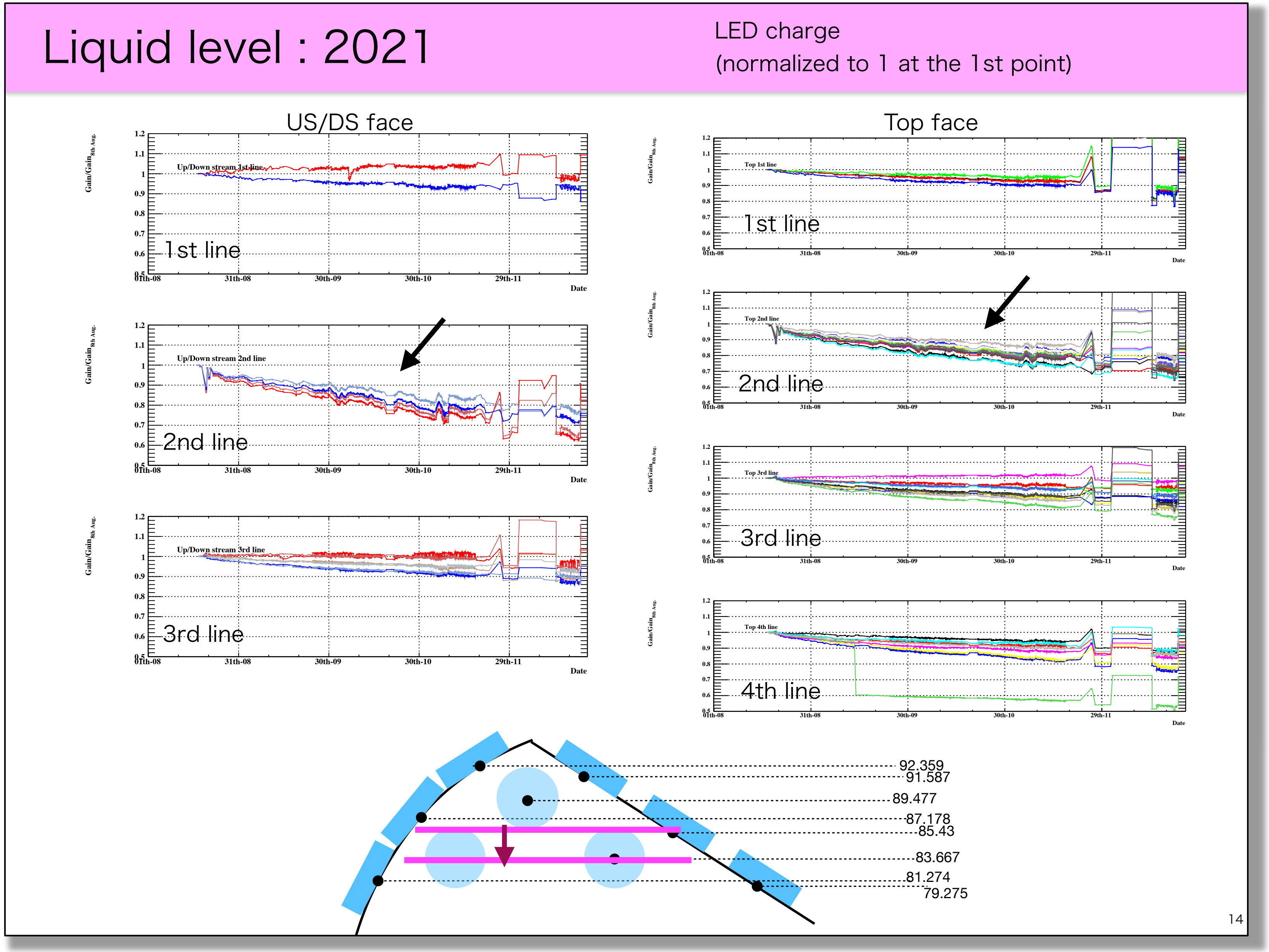
- Vacuum pressure increase rate [Pa/h] increase after 50% liquid level in LXe detector
  - Leak might be located higher than the height of 50% liquid level







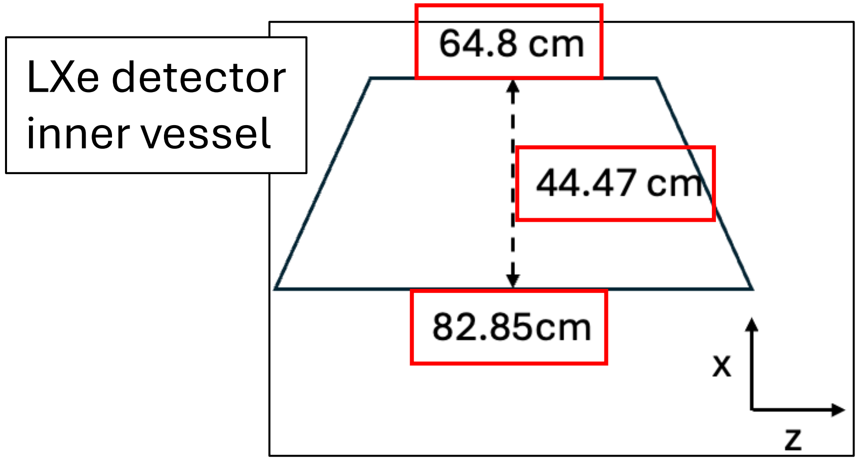
Small Leak in 2021 MEG II Run



Fiducial Volume of Inner Vessel of LXe detector

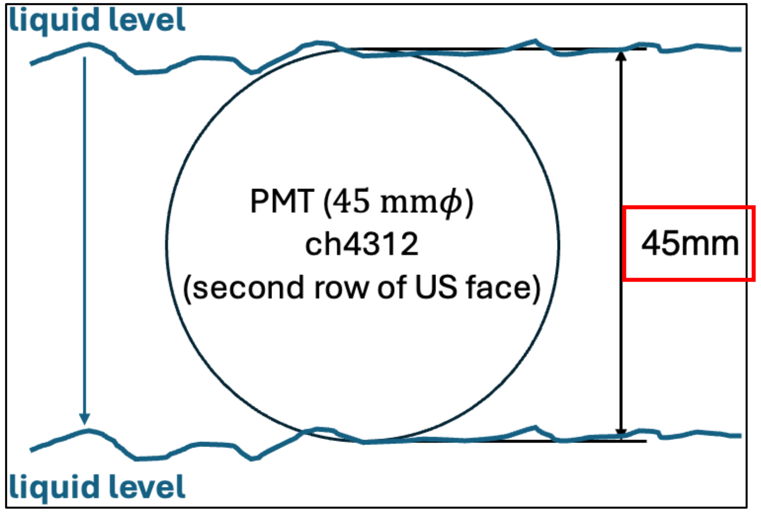
- Fiducial volume (*trapezoid*);

$$\frac{64.8 + 82.85}{2}\ \mathrm{cm} \times 44.47\ \mathrm{cm} \times 45\ \mathrm{mm} \approx 14.8 \times 10^3\ \mathrm{cm}^3 = \mathbf{14.8\ L}$$

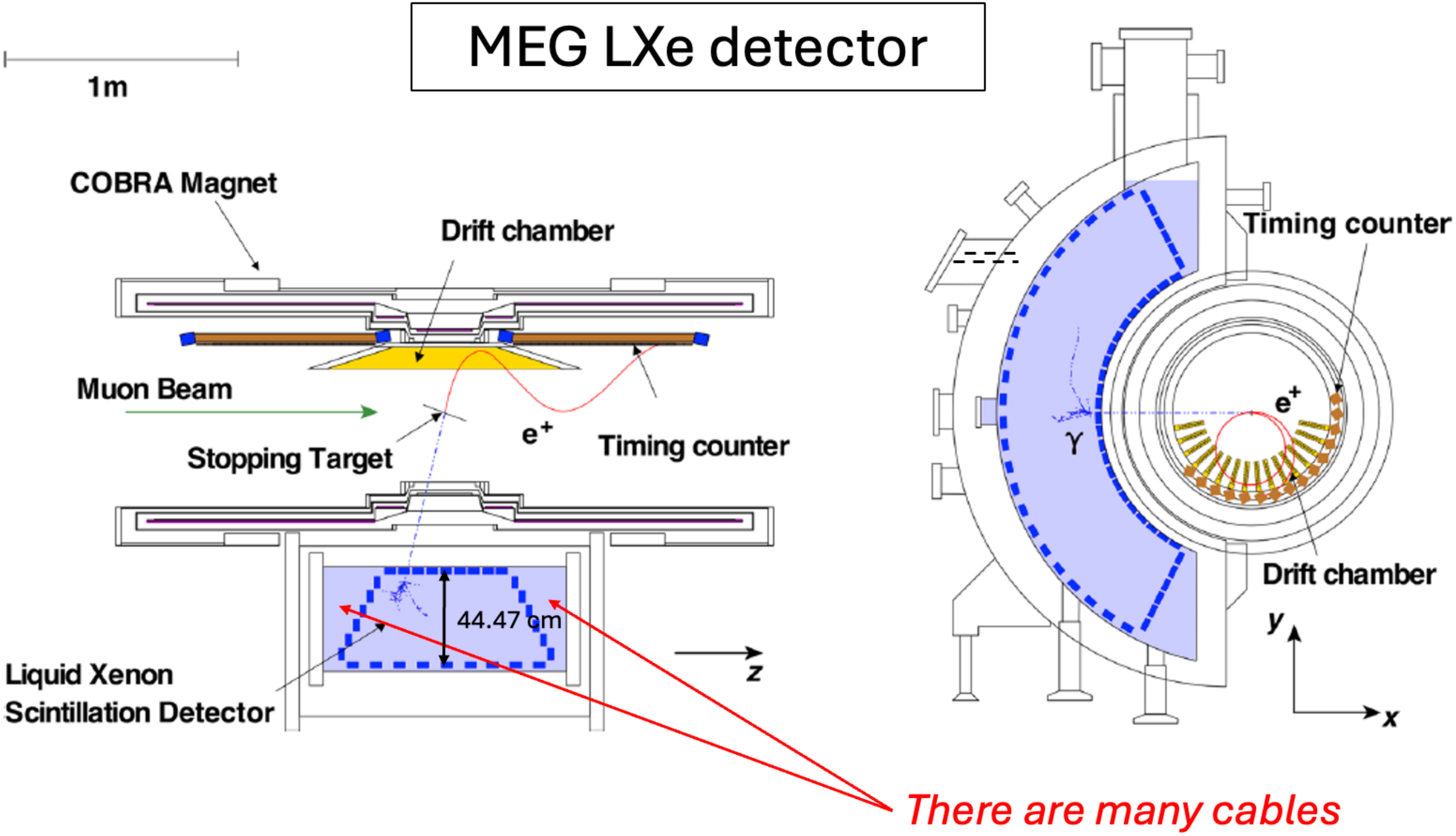


- Assume liquid density is approximately 3 kg/L. If the small leak continue for 139 days, the lost Xe is

$$\mathbf{44.4\ kg}$$



Geometry of LXe detector



Xenon leak during preparing for run

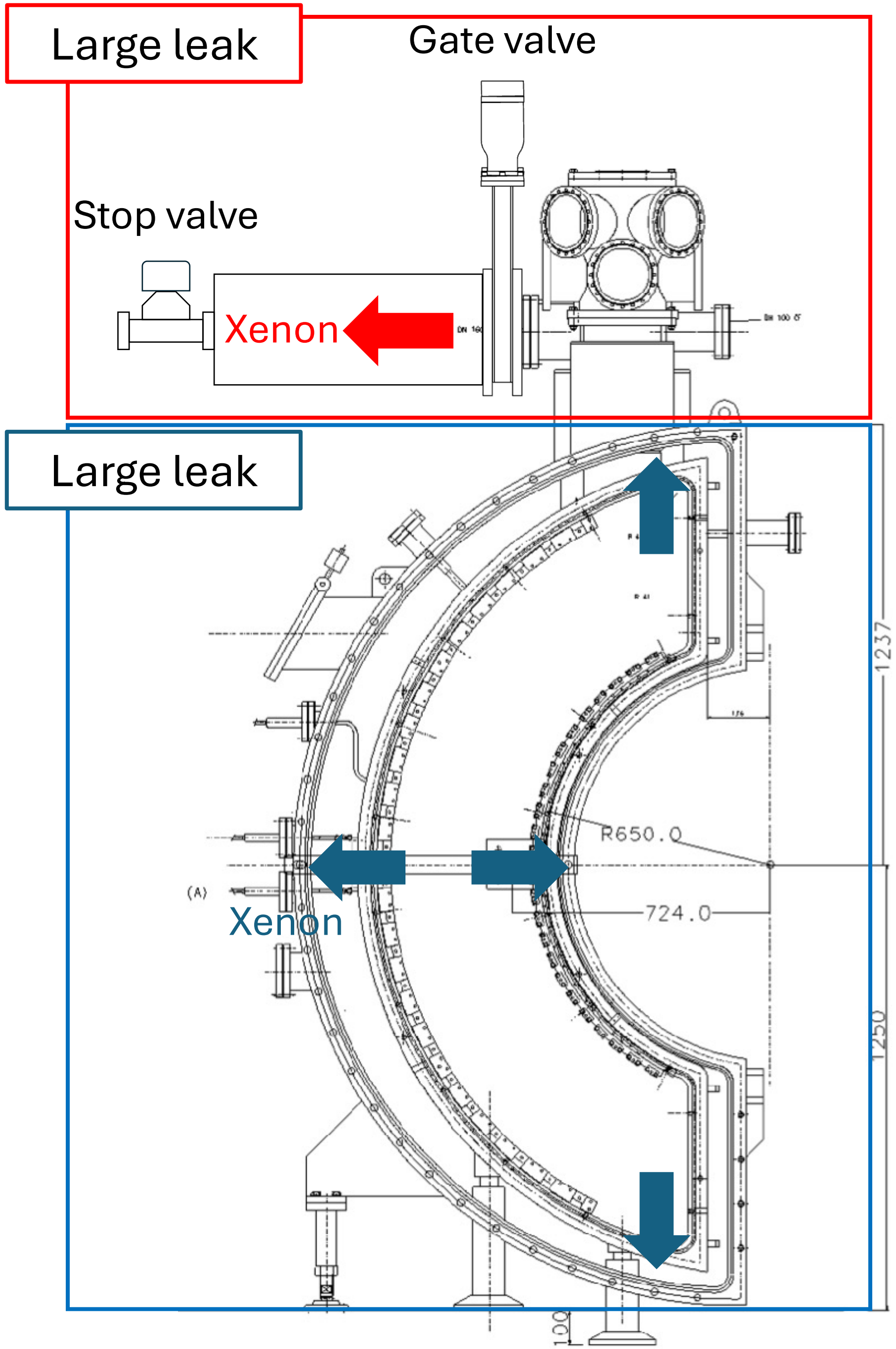
- There are two leak regarding to LXe detector;
  - Large leak
  - Small leak

- Found xenon in insulation layer
  - By mass spectrometer and outer vacuum pressure increase

- Cause of leak
  - There is a leak in inner vessel
  - This leak happened when the detecter is cooling (~165 K)

- Countermeasure
  - Online monitor of small leak detection was implemented
    - Unfortunately, there is no way to stop small leak at least in 2024 run

  - Exchange gasket in inner vessel during shutdown period



<u>Large leak</u>

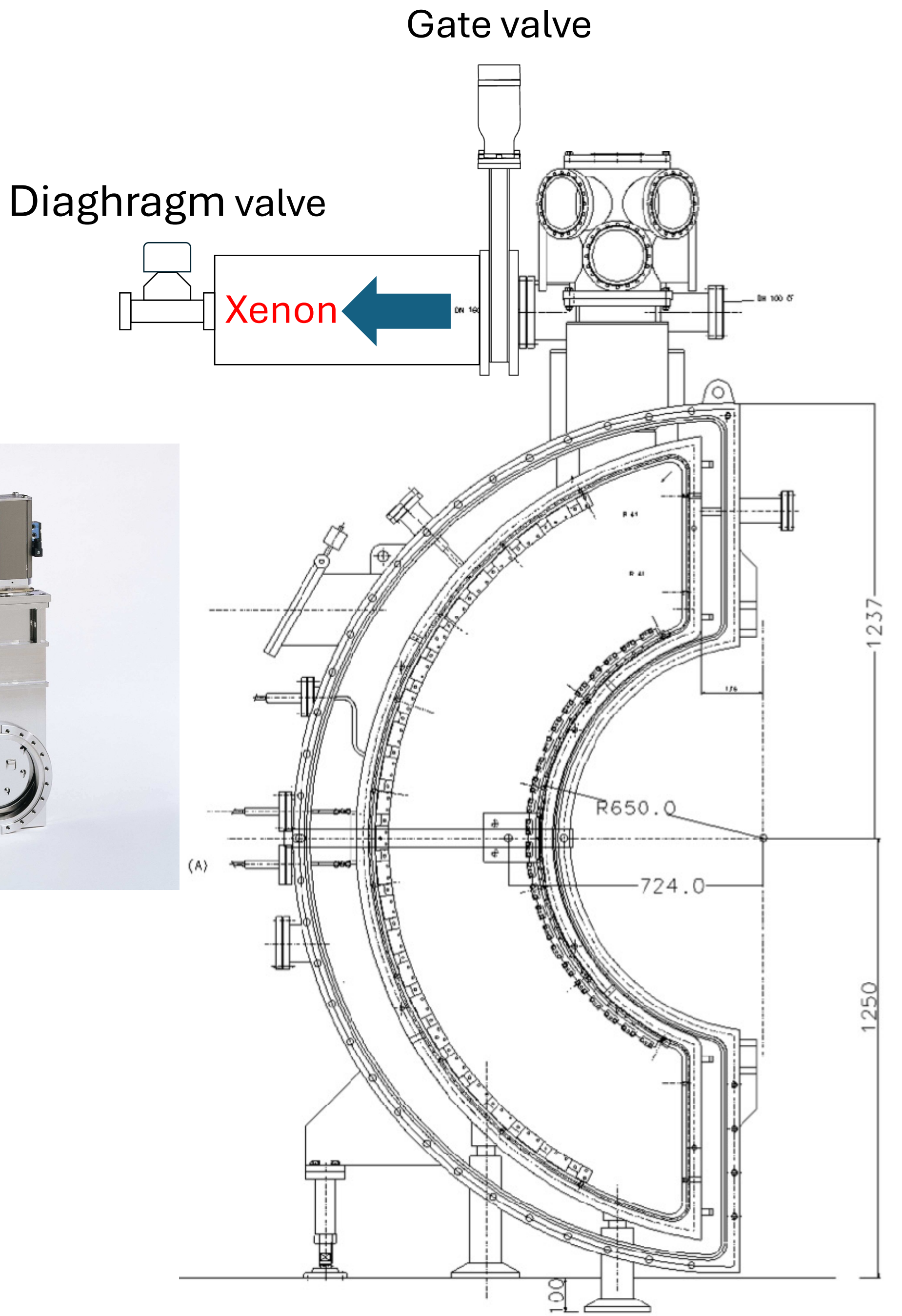
- Found xenon between gate valve and stop valve
  - By mass spectrometer

- Gate valve: 10840-CE14 (CF203), VAT

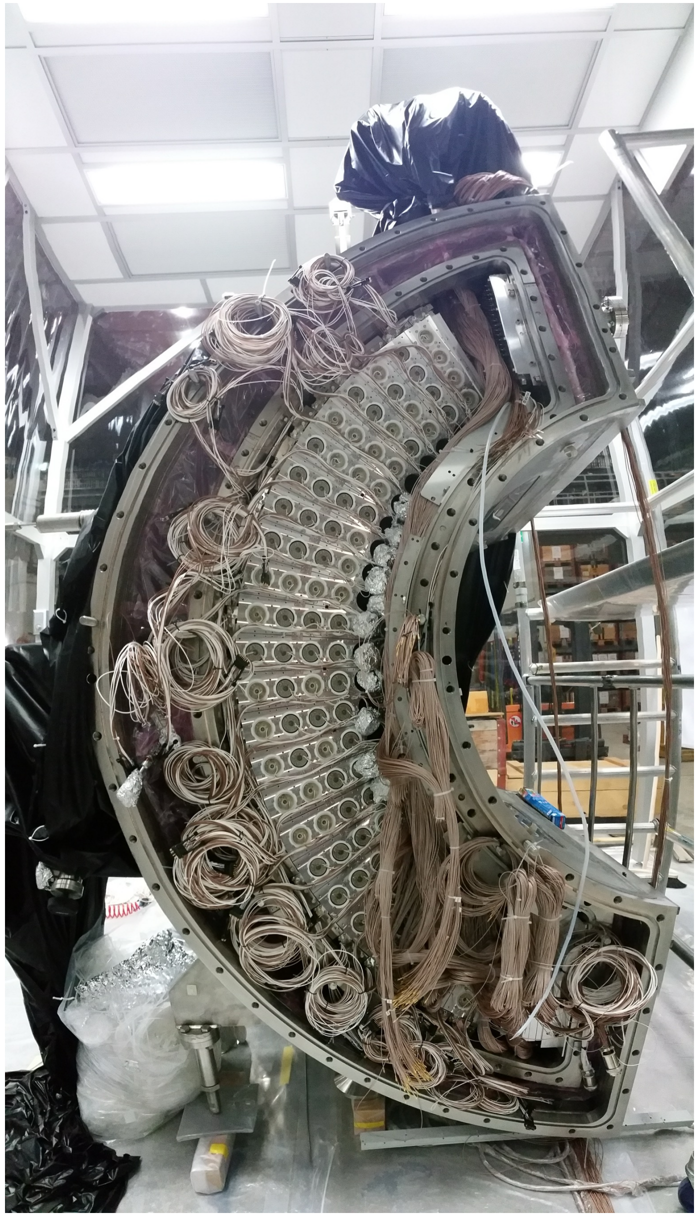
- Leak rate: 5.7 $\pm$ 2.9 kg/day

- Cause of leak
  - Gate valve was not leak tight
    - To open or close gate valve, compressed air should be supplied to pneumatics cylinder
  - Stop valve is not enough leak tight

- Countermeasure
  - For a while, supply compressed air to gate valve continuously
  - Replace diaghragm valve to new
  - Currently, no large leak anymore
  - Online monitor of large leak detection was implemented



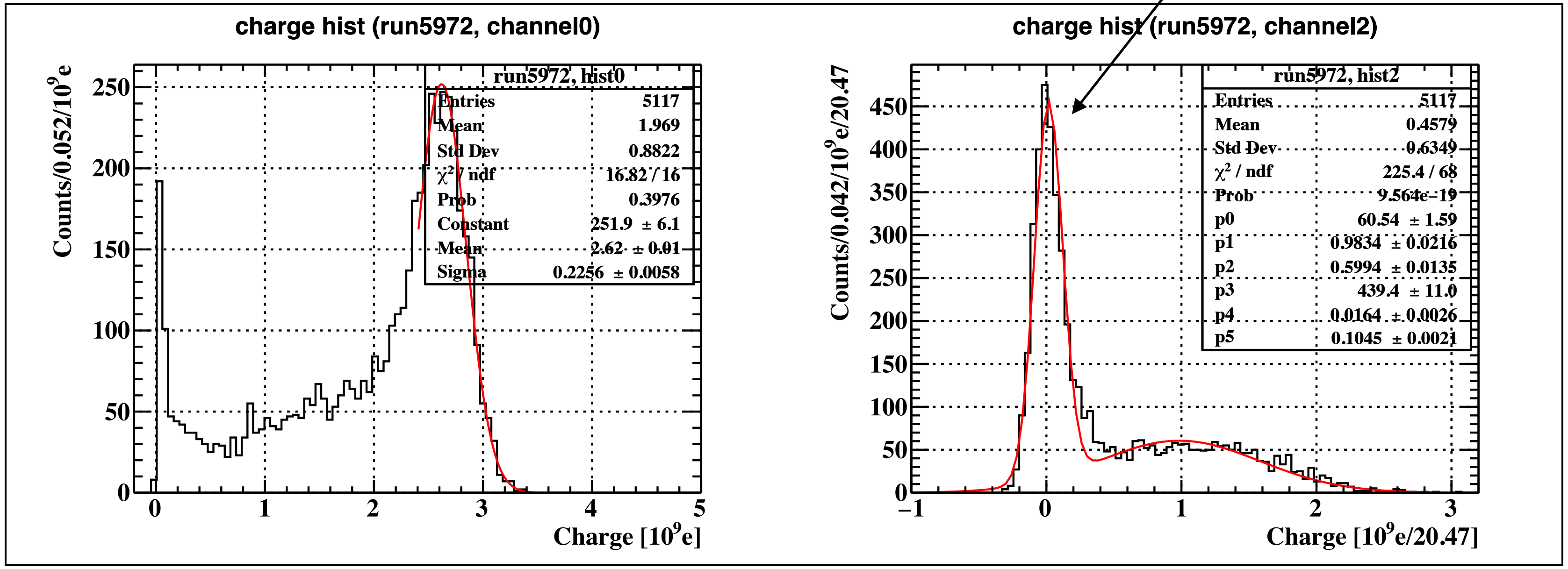
LXe detector inner vessel



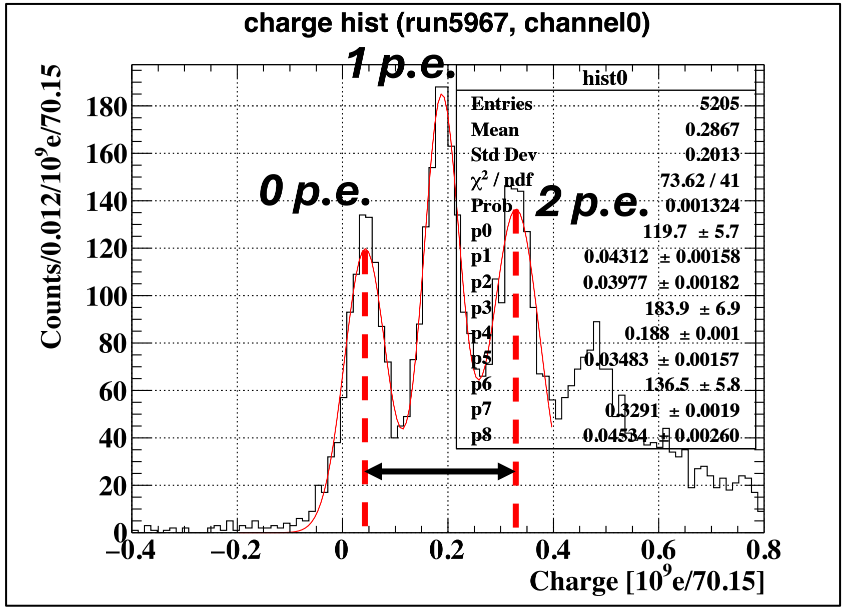
Result – Charge of alpha-ray and MPPC gain

alpha-ray

alpha-ray emitted from the shadow of wire



LED

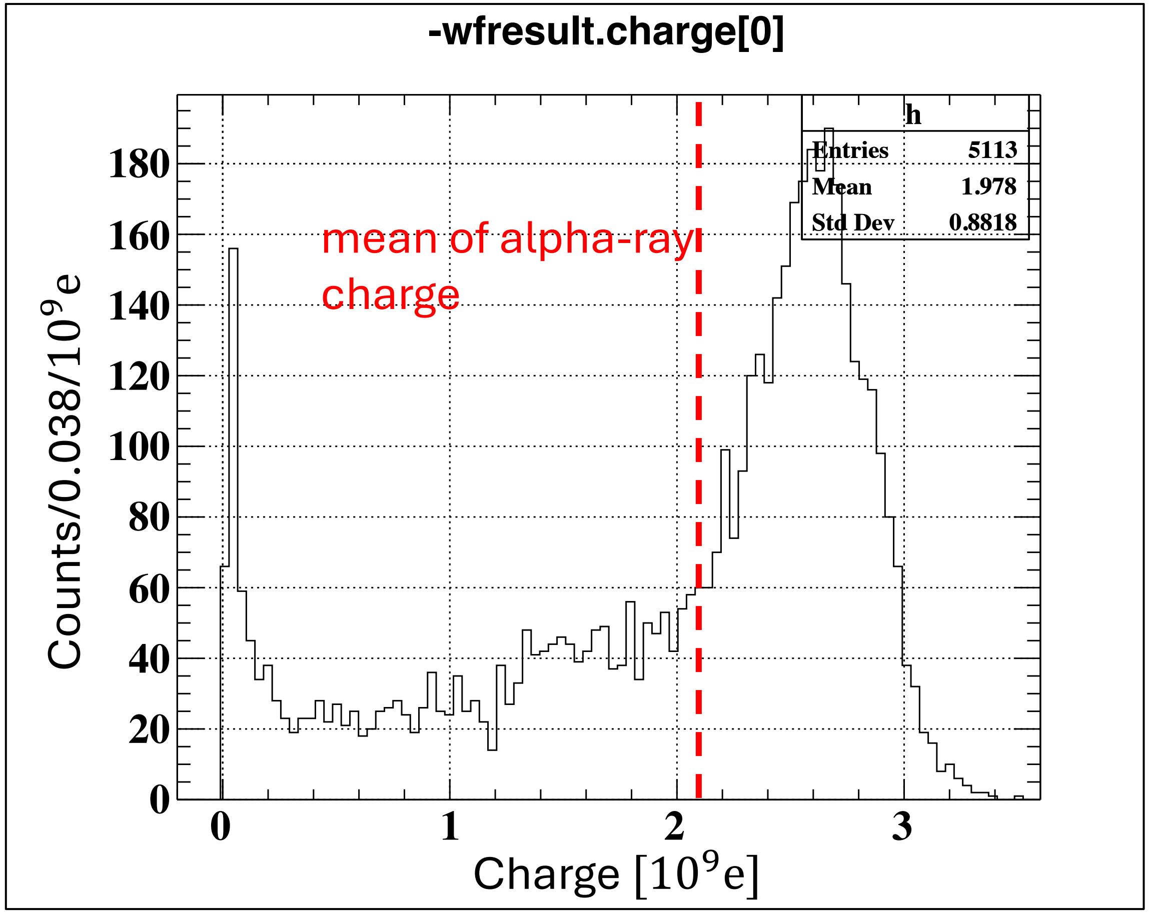


- Charge peak of alpha-ray
  - ch0~7: Calculated by gaussian peak
- MPPC gain
  - ch0~3: Calculated from dividing the difference between 0 p.e. and 2 p.e. peak by 2

Trigger rate and charge of alpha-ray signal

- Trigger rate
  - Calculated by the mean of first 10 runs
    - Because the trigger rate was expected to decrease by VUV photon irradiation
- Average charge of alpha-ray
  - Calculated by the mean of first 10 runs
    - Because the charge of alpha-ray was expected to decrease by VUV photon irradiation

alpha-ray

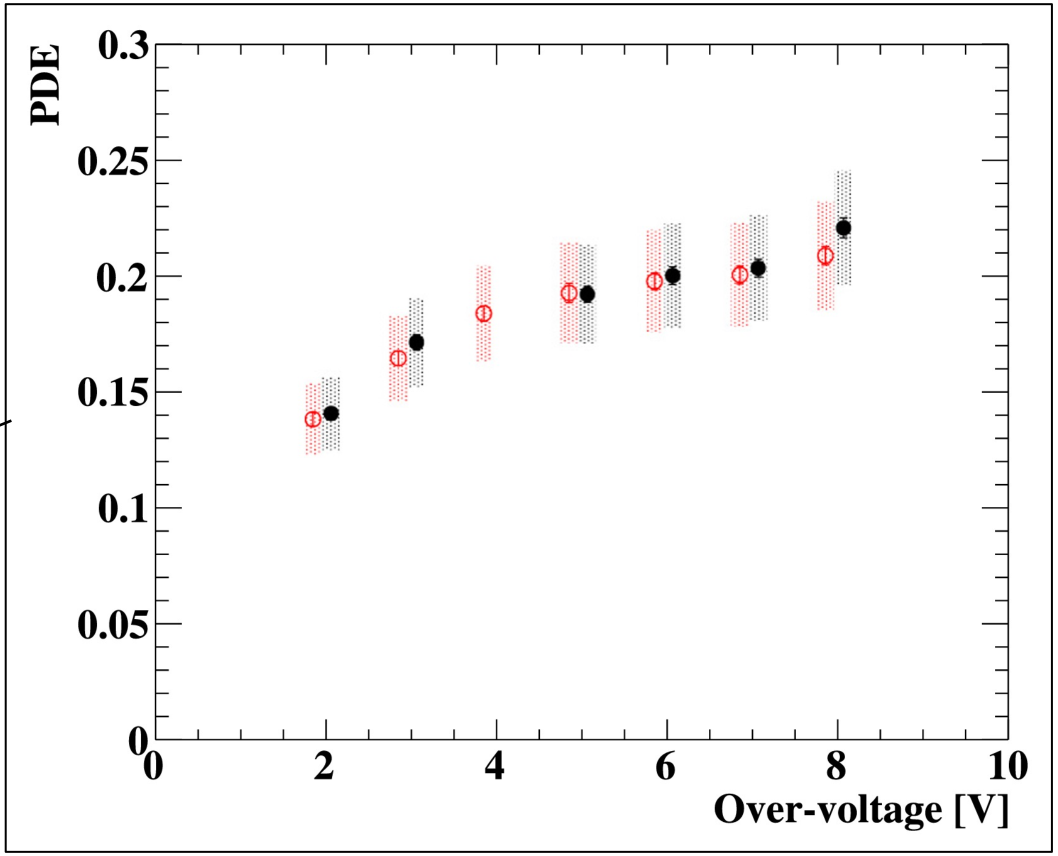


Result – Estimation of initial PDE

	Over voltage [V]
ch0	3.51
ch1	3.53
ch2	3.66
ch3	3.57

- *Expected PDE: ~15 ± 2 %*

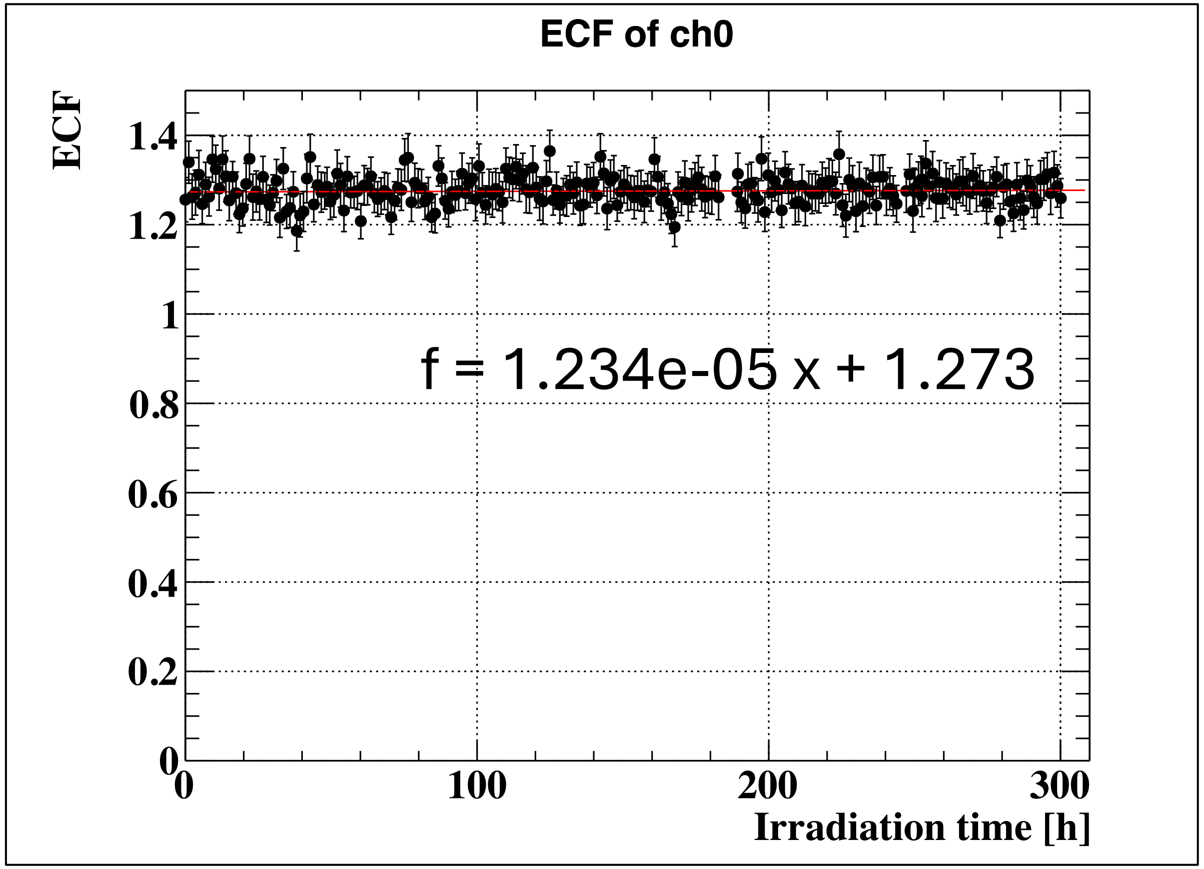
Humidity inside VUV-MPPC decrease PDE



https://arxiv.org/pdf/1809.08701.pdf

Result – ECF Transition

Vover ~ 3.5 V



- Irradiation dose was calibrated by ECF (Excess Charge Factor)

Expected PDE decrease

Stopped muons in 2017-2021: 410×10^{12}

ch	0	1
ratio of radiation dose of this experiment to that of 2017-2021	0.015	0.017
Stopped Muons $\left(N_{\mu}^{\text{stop}}\right)$ corresponding to this experiment	6.2×10^{12}	7.0×10^{12}
Expected Initial PDE	~15 %	~15 %
Expected PDE Decrease	~0.21-0.75 %pt	~0.24-0.85 %pt
Expected PDE Decrease (in relative)	~ 1.4-5.0 %	~ 1.6-5.6 %

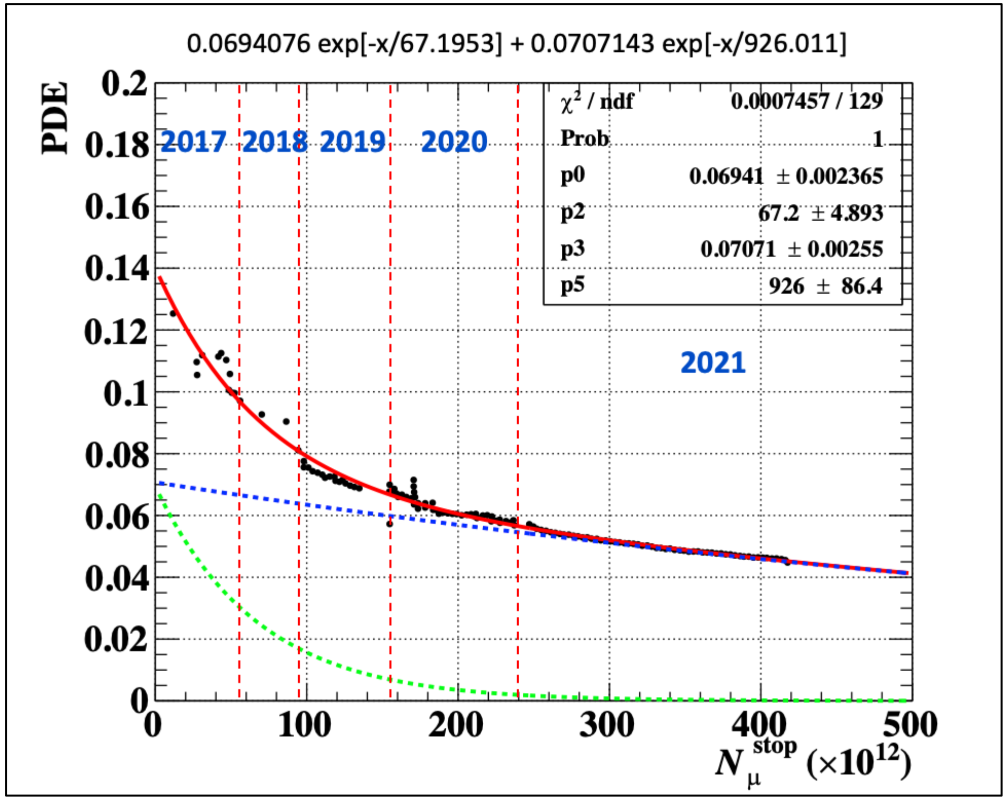
Expected PDE Decrease in relative (Lower Limit)

$$= 1 - \frac{0.074\exp(-N_{\mu}^{\text{stop}}\cdot(15/14)/67) + 0.076\exp(-N_{\mu}^{\text{stop}}\cdot(15/14)/926)}{0.15}$$

Expected PDE Decrease in relative (Upper Limit)

$$= 1 - \exp(-N_{\mu}^{\text{stop}}\cdot(15/7.1)/926.011)$$

The PDEs in 2017-2021 are measured from the VUV-MPPCs at the center of the LXe



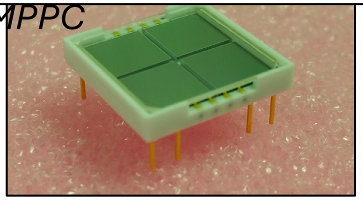
Partially modified from S. Kobayashi, PhD thesis (2022) (https://www.icepp.s.u-tokyo.ac.jp/download/doctor/phD2022_kobayashi.pdf)

Sammary & Outlook

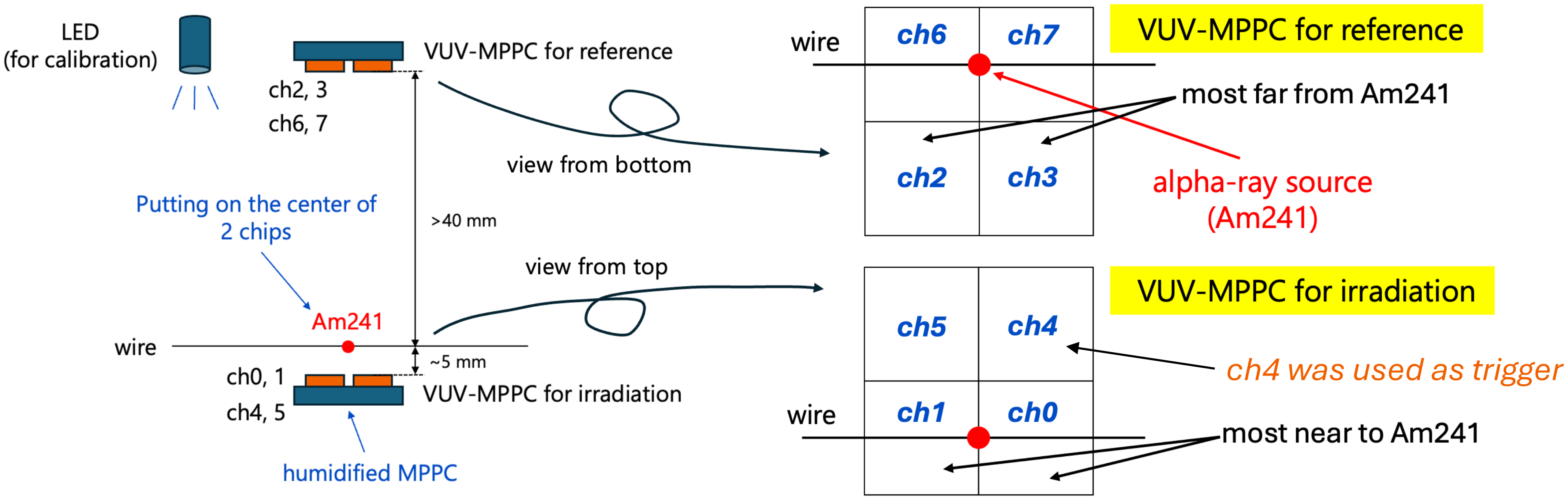
- Summary
  - Rapid PDE decrease for VUV light was observed in the MEG II LXe detector
  - Studied effect of absorption of moisture inside the VUV-MPPC with VUV light irradiation
- Next step
  - Analysis
    - to mitigate the statistical errors of PDE transition
    - to get more precise expected PDE decrease
  - Irradiate VUV-MPPC with gamma-ray
    - in LXe
    - to test the effect of moisture inside the VUV-MPPC

Setup

4 chips in one VUV-MPPC

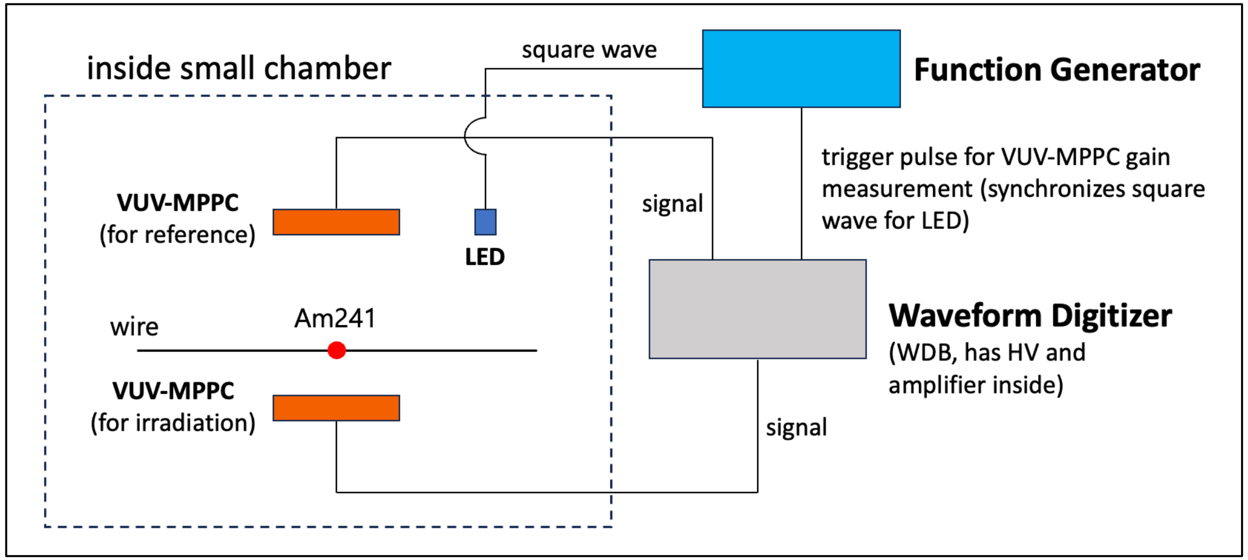


	ch0,1,4,5 (VUV-MPPC's chips for irradiation)	ch2,3,6,7 (VUV-MPPC's chips for reference)
Annealing (done before humidification)	150 ℃ x 16 hours baked before accelerated test (Assume humidity inside VUV-MPPC were removed)	not annealed
Humidity	89 times accelarated (60 ℃ x 250 hours, humidity 90 %)	not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



Control of cooling system and DAQ

- Cooling System
  - SCS2000 was 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
- DAQ
  - Used WaveDREAM Board (WDB) as a waveform digitizer
  - Has HV and amplifier inside
    - Gain for alpha-ray run:
      1 (ch0,1), 5 (ch4,5), 25 (ch2,3,6,7)
    - Gain for LED run: 70.15 (ch0,1,2,3)
  - Took the data of VUV-MPPC signal from alpha-ray and LED light every 1 hour



Result – Calculation of radiation dose

- The number of irradiated VUV light is calculated below

$$\text{VUV light irradiation dose} = \underbrace{\frac{\text{Charge of alpha}-\text{ray}}{\text{Gain}} \cdot \frac{1}{\text{PDE}} \cdot \frac{1}{\text{ECF}}}_{\text{Impinging photon per event}} \cdot \text{trigger rate} \cdot \text{irradiation time} \cdot \frac{1}{\text{Surface area of 1 chip}}$$

Result – Number of photon entering near chips

ch	0	1
trigger rate	37.7 event/sec	37.7 event/sec
mean charge	1.98 10^9e	2.19 10^9e
gain	2.064 10^6e	2.064 10^6e
expected PDE	~15%	~15%
ECF	1.273	1.263
Surface area of 1 chip	$5.95\times5.85\ \mathrm{mm}^2$	$5.95\times5.85\ \mathrm{mm}^2$
Irradiation time	300 hours	300 hours

VUV light irradiation dose in 2017-2021: $4\times10^{11}\ \mathrm{photon}\cdot\mathrm{mm}^{-2}$

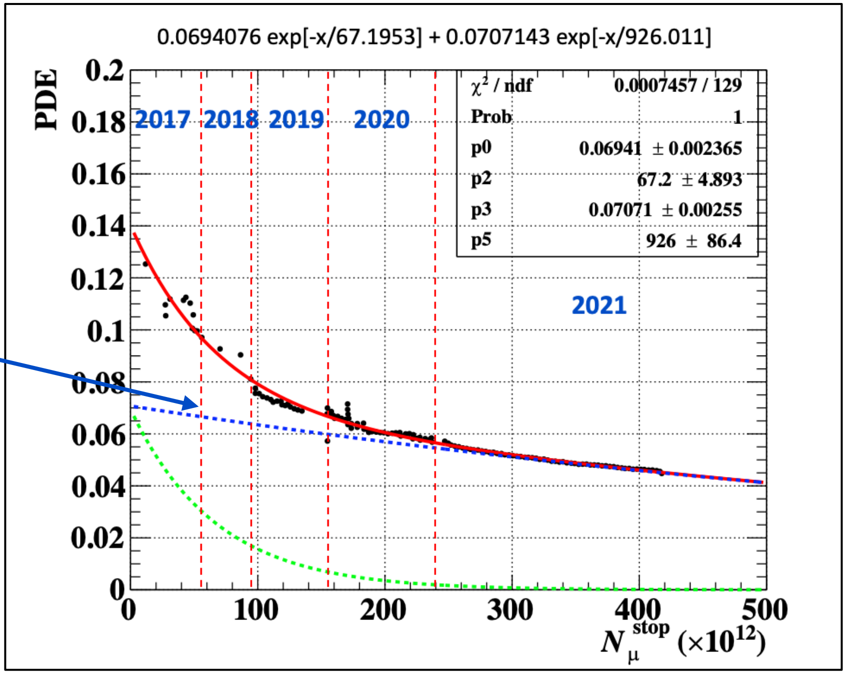
ch	0	1
VUV light irradiation in this experiment	$5.9\times10^9\ \mathrm{photon}\cdot\mathrm{mm}^{-2}$	$6.6\times10^9\ \mathrm{photon}\cdot\mathrm{mm}^{-2}$
ratio of radiation dose of this experiment to that of 2017-2021	$\mathbf{0.015}$	$\mathbf{0.017}$

Normalized Charge Ratio

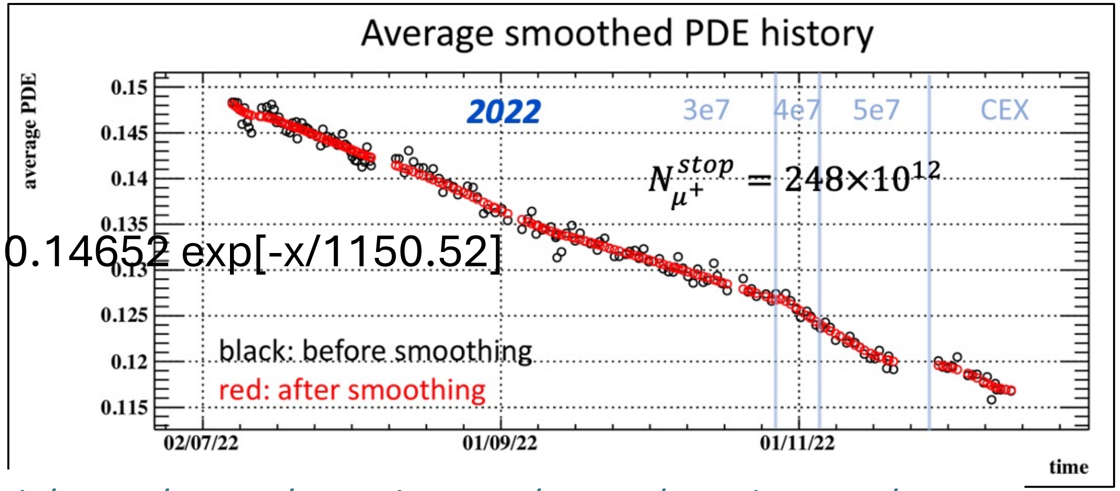
$$\text{Normalized Charge Ratio (at point i for ch m} = 0 \text{ or } 1) = \underbrace{\left(\frac{Q_i^{m=0\text{ or }1}}{\frac{1}{4}\sum_{m=2,3,6,7} Q_i^m}\right)}_{\text{Relative Charge}} \underbrace{\left(\frac{1}{10}\sum_{i=1}^{10} \frac{Q_i^{m=0\text{ or }1}}{\frac{1}{4}\sum_{m=2,3,6,7} Q_i^m}\right)^{-1}}_{\text{Normalization Factor}}$$

Result – Expected PDE decrease

- The one component (blue) of fitting function has similar time constant to that of 2022 physics run
- But the PDE decrease in 2022 physics run is measured from the average PDE of all VUV-MPPCs.
  - The VUV photon irradiation dose has position dependence to each VUV-MPPC (see page 4)



- In 2022 run, the VUV-MPPCs were annealed.
  - This is similar to the VUV-MPPC in this study
- It is better using the PDE history calculated from the VUV-MPPCs at the center of the LXe detector in 2021 physiscs run
  - To compaire with the PDE transition in this study
  - Now analysing. It will be done soon
  - In this presentation, including the effects of annealing and position dependence as expected PDE decrease



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