AXEL: High-pressure xenon gas TPC for neutrinoless double beta decay search

Junya HIKIDA, Kyoto University (Japan)
for the AXEL collaboration

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- Neutrinoless double beta decay
- AXEL experiment
- Performance demonstration of 180L-size prototype
- R&D for 1000L-size detector construction
- Summary

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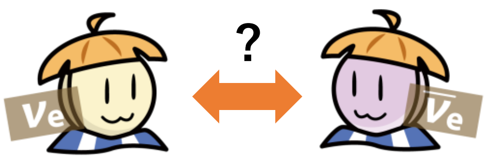
Neutrinoless double beta decay ($0\nu\beta\beta$)

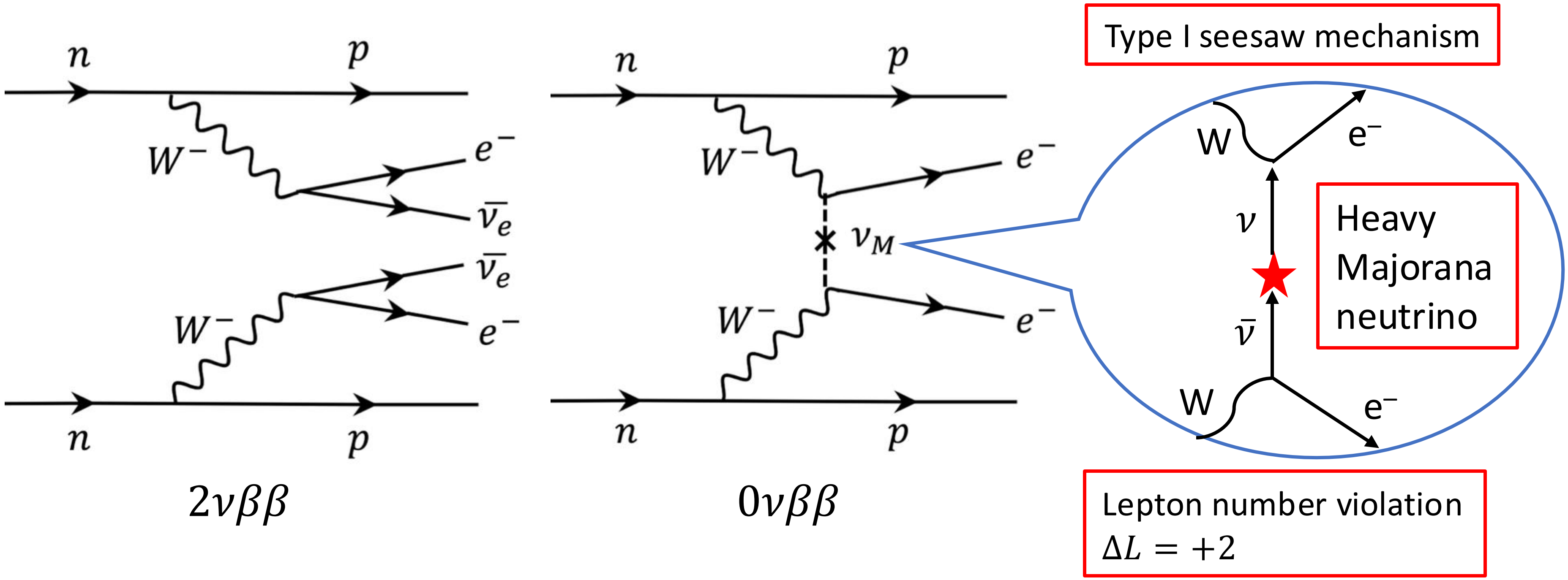
$0\nu\beta\beta$ can occur if neutrino is the same as anti-neutrino

called **Majorana** particle

Majorana nature of neutrino may be the origin of

- Too small mass of neutrino
- Matter-antimatter asymmetry of the universe





Requirements for $0\nu\beta\beta$ search

$0\nu\beta\beta$ is very rare: $T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}$ $years$ (90 % C.L.)[1] for ^{136}Xe

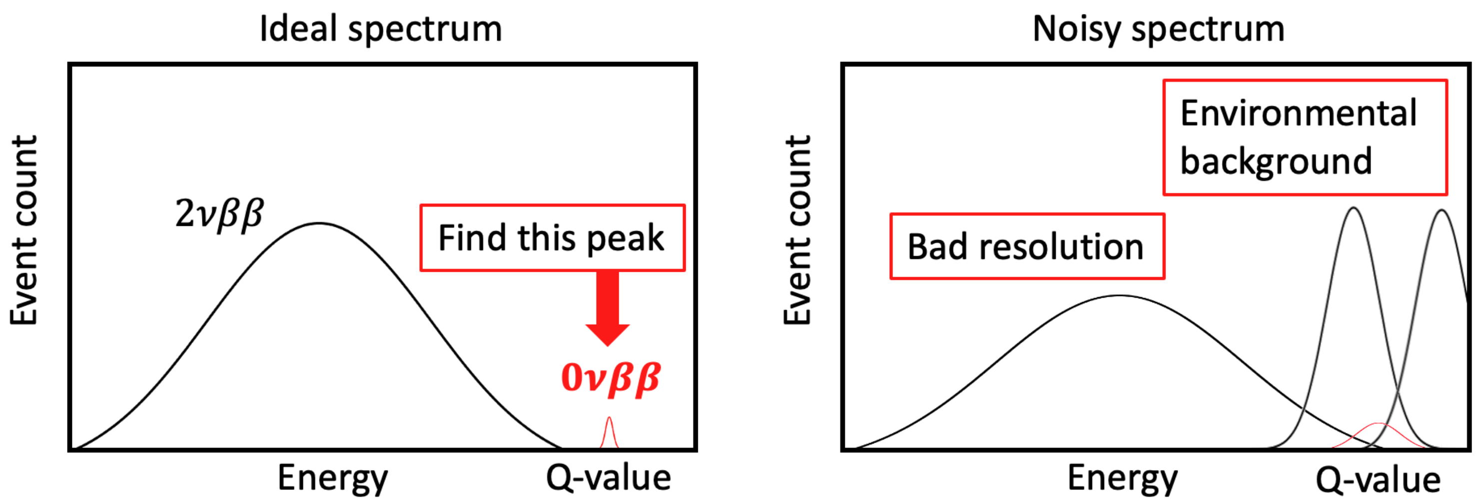
→ **Large mass** and **low background** are required

To realize large mass, **scalable detector** is desirable

To realize low background $0\nu\beta\beta$ search,

- **High energy resolution**
- **Distinction of environmental background**

Xe gas TPC can meet all these requirements!



[1]S.Abe et al., arXiv:2406.11438

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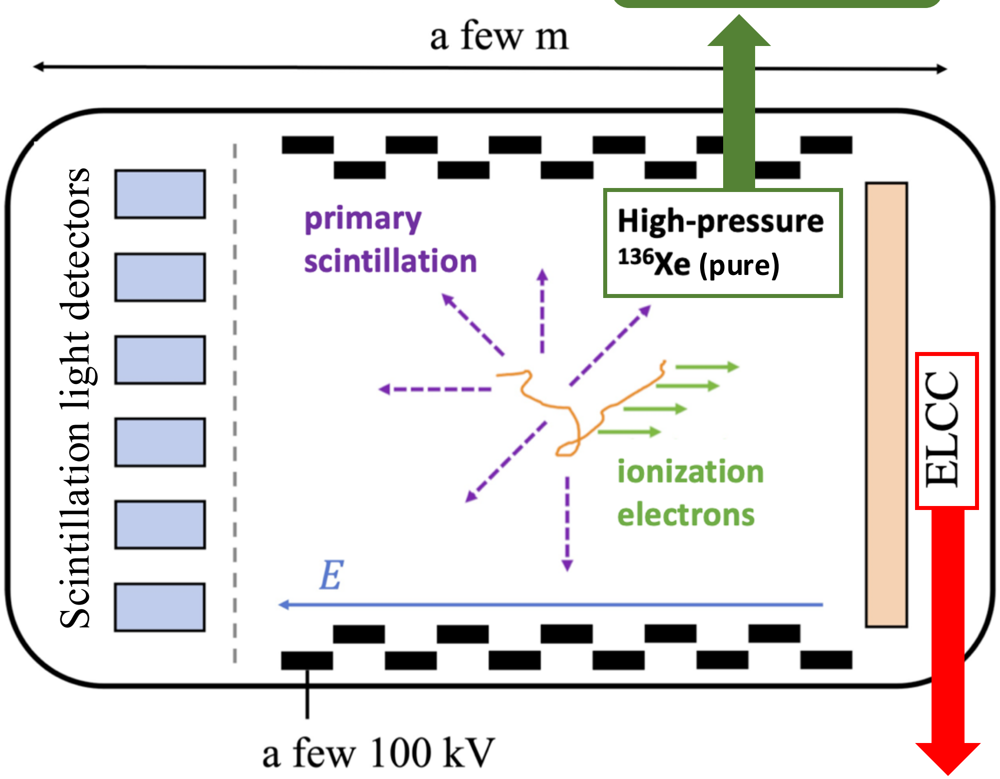
AXEL ~A Xenon ElectroLuminescence

High-pressure Xe gas Time Projection Chamber
for $0\nu\beta\beta$ search

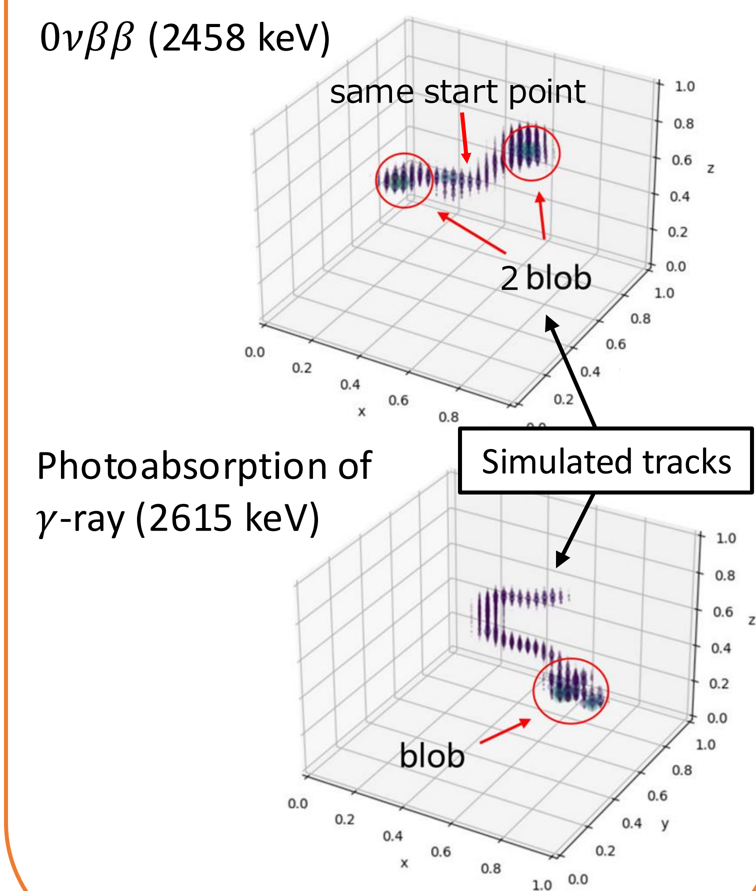
Large mass



High energy resolution

Next page in details

3D tracking for background rejection

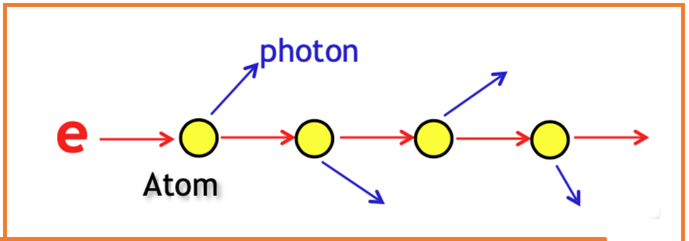


※blob: stopping point of charged particle

ELCC ~Electroluminescence Light Correction Cell

- Using electroluminescence (EL) process to suppress gain fluctuation

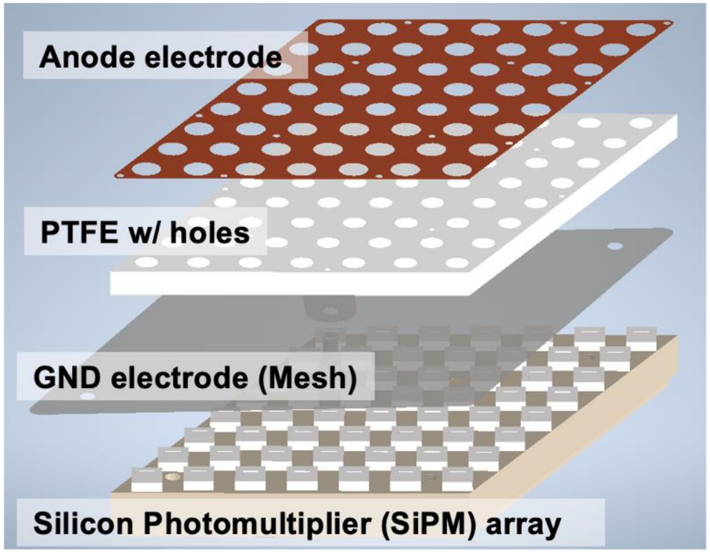
→ **High energy resolution**



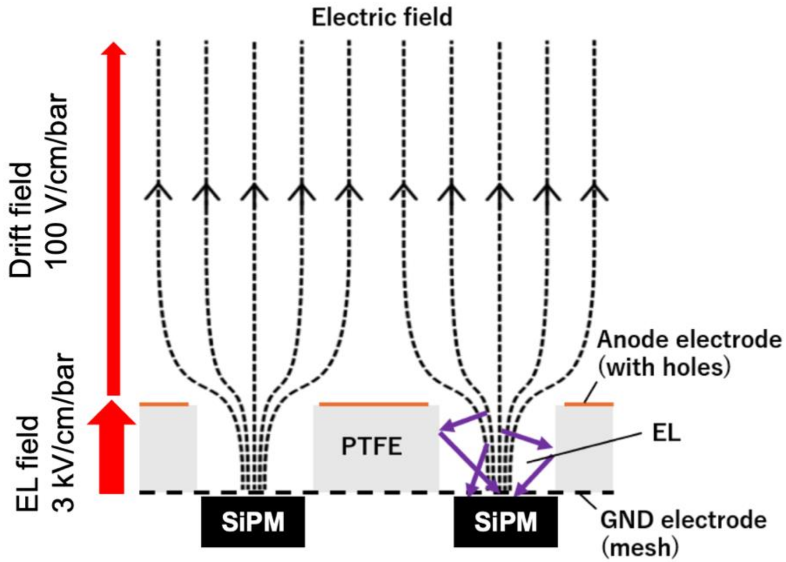
EL process:
# of photons ∝ # of electrons

- Pixelated structure→ **Tracking**
- Modular structure→ **Easy extension**
- HV can be adjusted module by module → **Good for stable operation**

→ Poster presentation by H.Sasaki



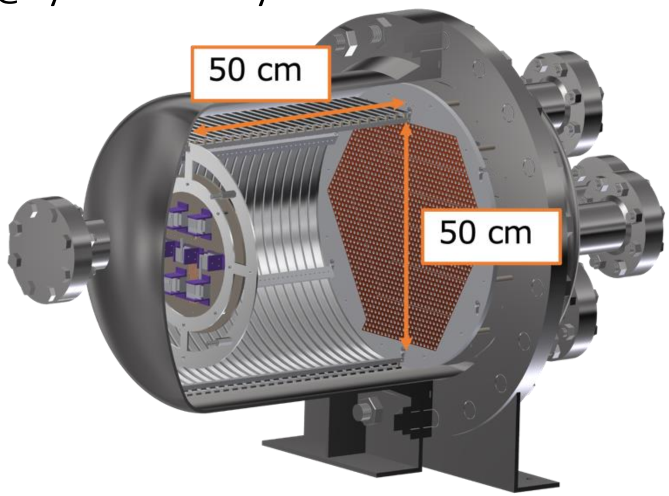
Basic structure of a ELCC module



Detection principle of ELCC

Road map of AXEL experiment

@Kyoto university



Estimated sensitivity (90% C.L.)
$T_{1/2} > 2.18 \times 10^{27}$ *years*
by 10-years operation

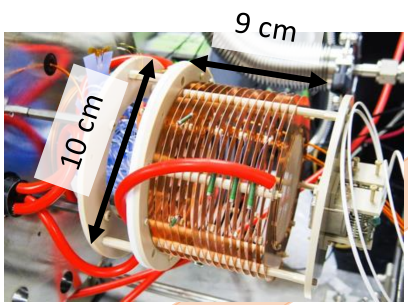
10-ton detector

1-ton detector

140-kg detector

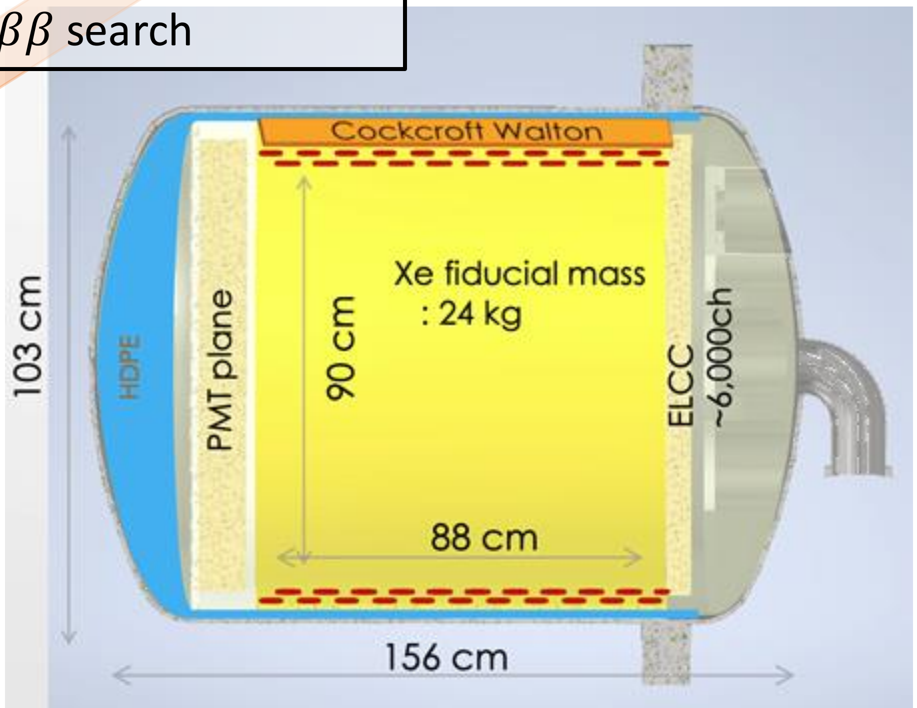
1000L detector (2022-)
- ~20 kg Xe
- $0\nu\beta\beta$ search

180L prototype (2018-)
- ~4.5 kg Xe
- Scalable structure
- R&D of components



10L prototype (2014-2018)
- ~50 g Xe
- ELCC proof of principle

@Kamioka underground



- Neutrinoless double beta decay
- AXEL experiment
- **Performance demonstration of 180L-size prototype**
- R&D for 1000L-size
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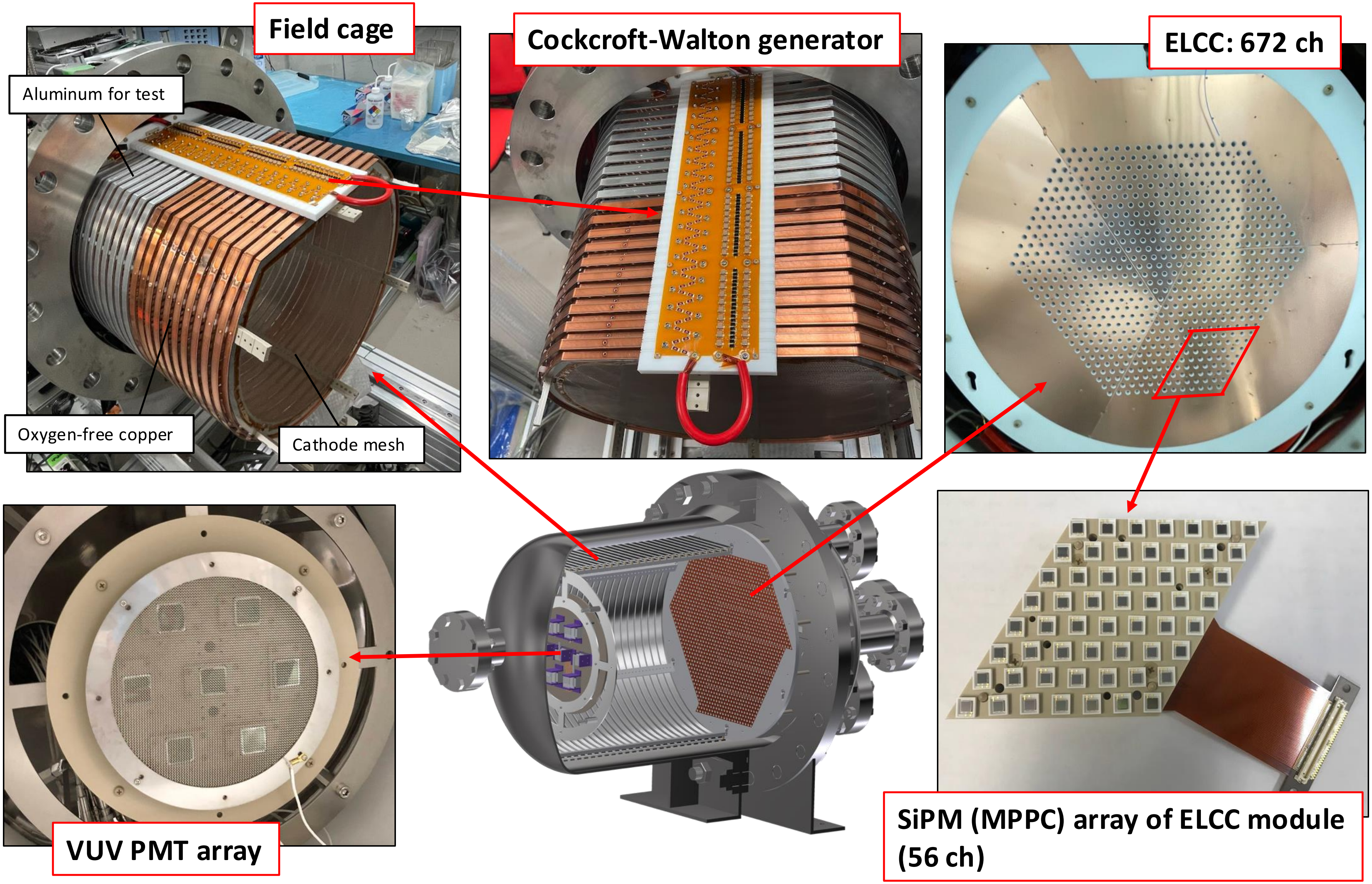
Summary of the latest results (published in May 2025)
https://doi.org/10.1093/ptep/ptaf066

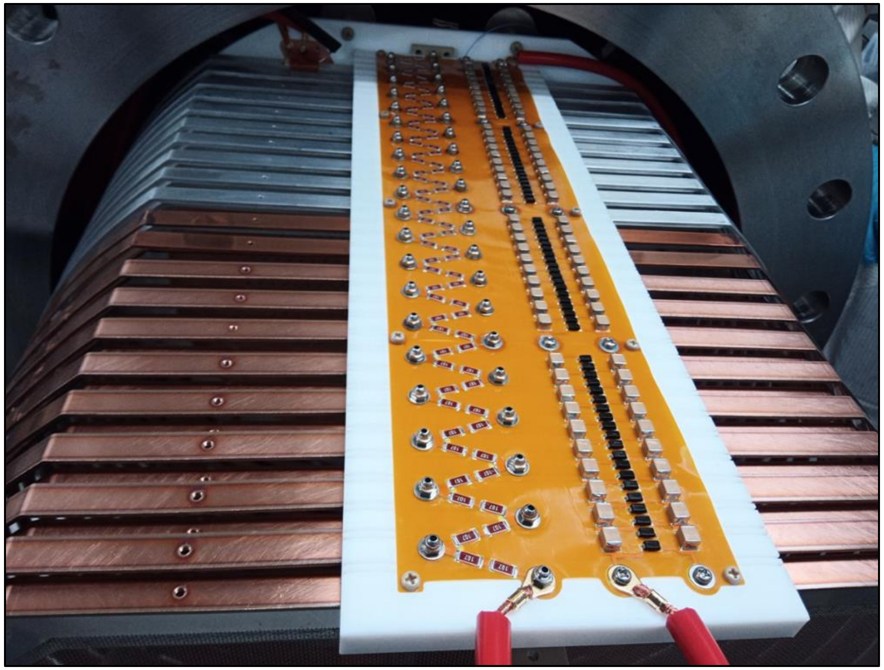
Overview of 180L prototype



Cockcroft-Walton generator

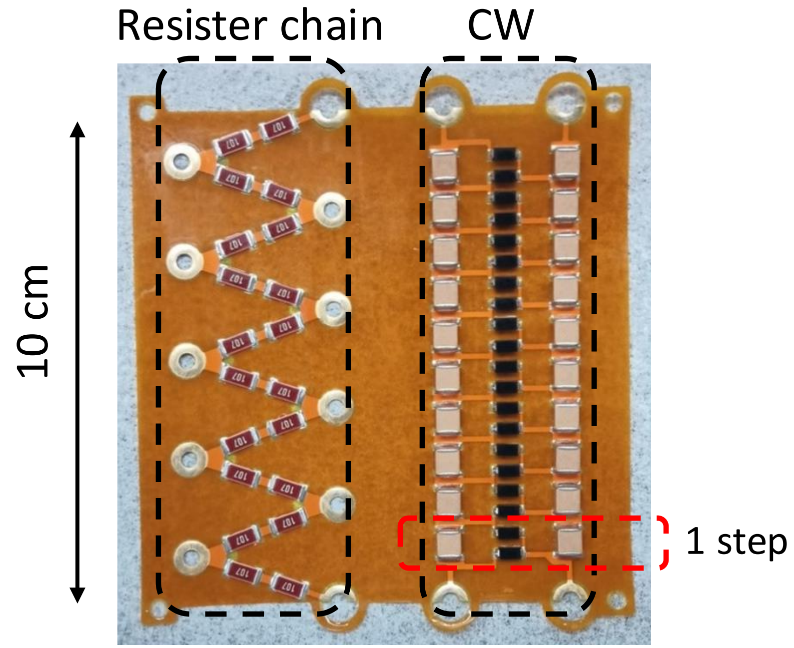
Generate high DC voltage (>30 kV) from low AC input (~1 kV_{pp})
→ No necessity of feedthrough for high pressure and ultra-high voltage

Achievements
- 35.3 kV in Xe gas at 6.0 bar
- Negligible noise effect to MPPC waveform



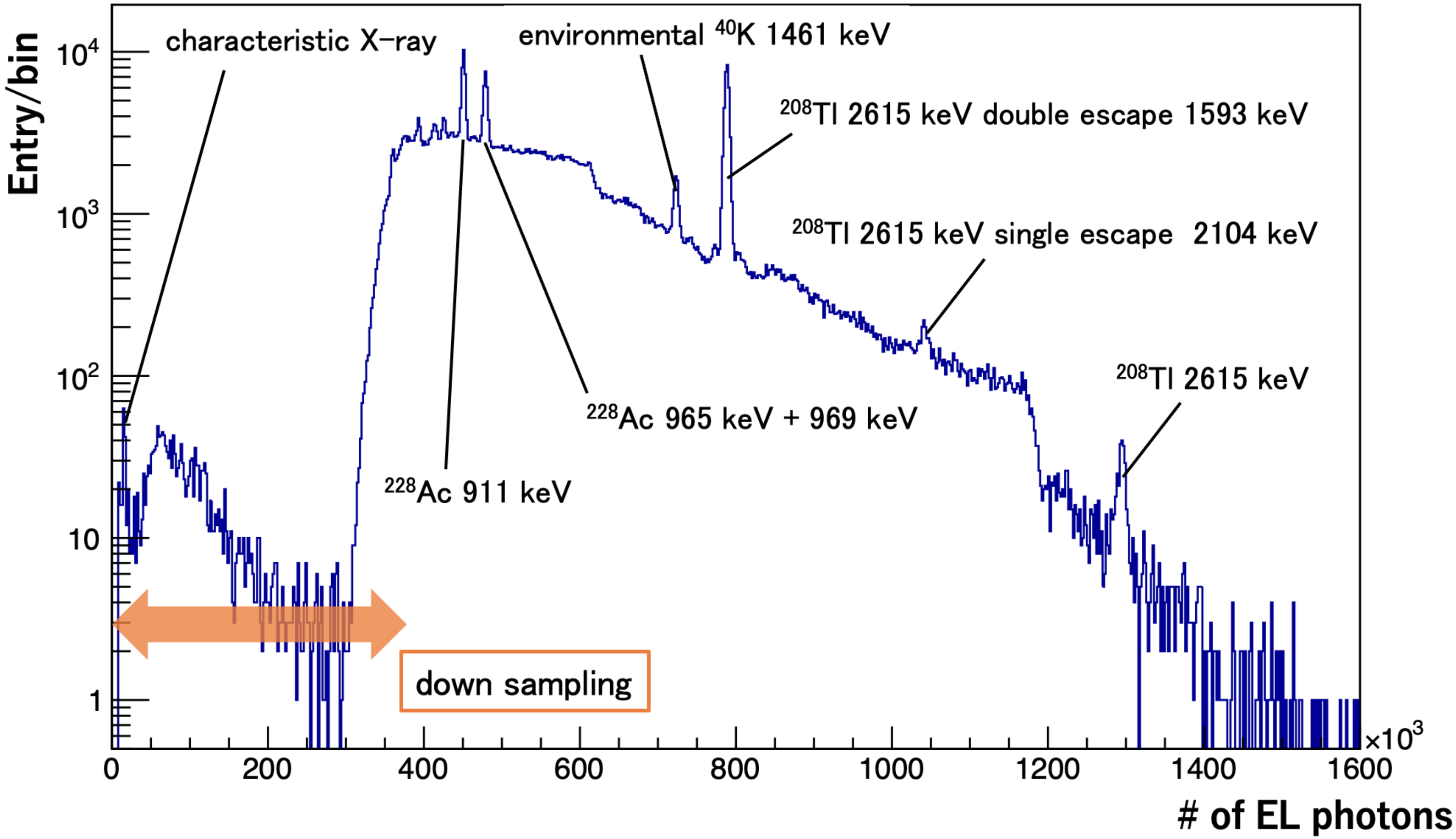
40-step CW generator in 180L prototype

First demonstration for TPC in the World!



Energy spectrum

- RI source: Thorium-doped tungsten rods (γ-ray of Th series)
- EL field = 2.7 kV/cm/bar
- Drift field = 90 V/cm/bar
- 40 days operation

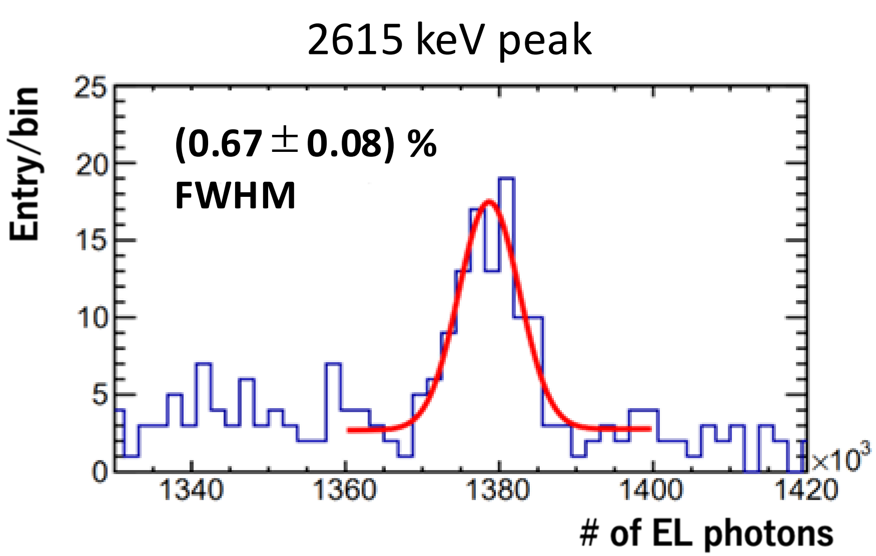


Energy resolution

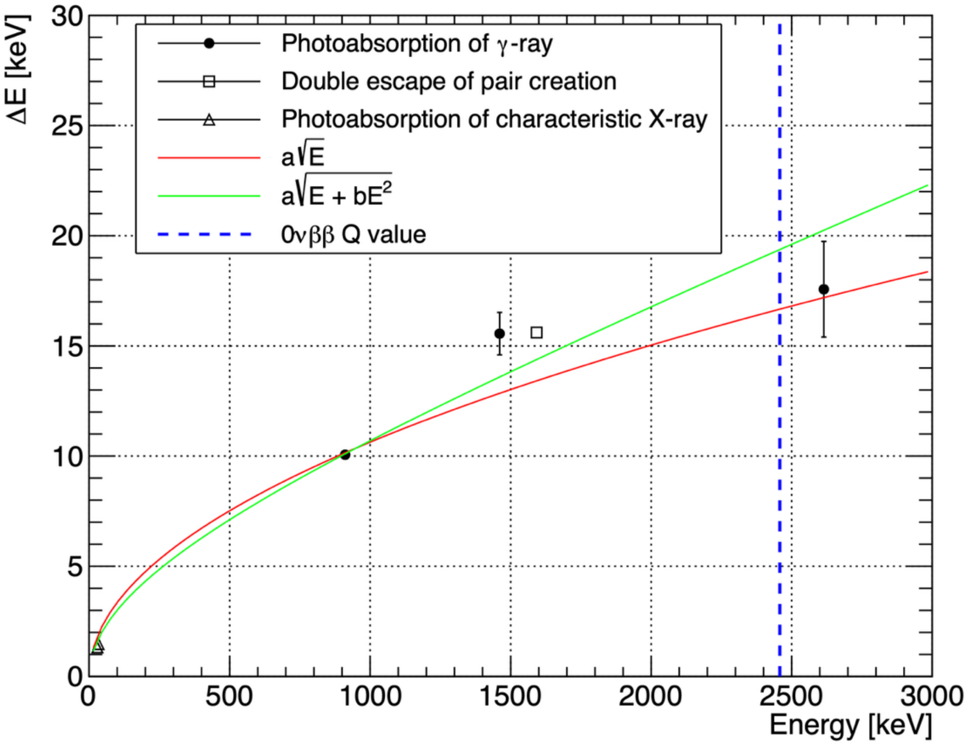
- FWHM resolution @2615 keV: **(0.67 ± 0.08) %**
- Extrapolated FWHM resolution @Q-value (2458 keV)

  $a\sqrt{E}$: **(0.68±0.01) %**, $a\sqrt{E + bE^2}$: **(0.79±0.08) %**

→ **Better than 1 % FWHM resolution around Q-value**



※ the interpolation was performed using only the data points corresponding to photoabsorption events of γ-rays (black dots)



Extrapolation of resolution

Breakdown of resolution @2615 keV

Initial ionization (inevitable)	0.25 %
z mis-reconstruction	0.24 %
Fluctuation of the EL generation and detection	0.20 %
Error in EL gain correction	0.18 %
Error in time variation correction	0.18 %
Recombination	0.17 %
Variation in time bin of time variation correction	0.12 %
Offset of the baseline	≦0.11 %
Error in z dependence correction	≦0.06 %
Accuracy of the MPPC recovery time	≦0.03 %
Fluctuation of the attachment	≦0.02 %
Estimation total	(0.52-0.54) %
Data total	(0.67 ± 0.08) %

Due to low Scinti. det. efficiency
→ Developing new detector

Limited by stat. of EL photon
→ Can be improved with larger area MPPC

Developing new correction methods
→ Expect less than 0.1 %

Can be improved with higher drift field (100 V/cm/bar) by more discharge resistive structure

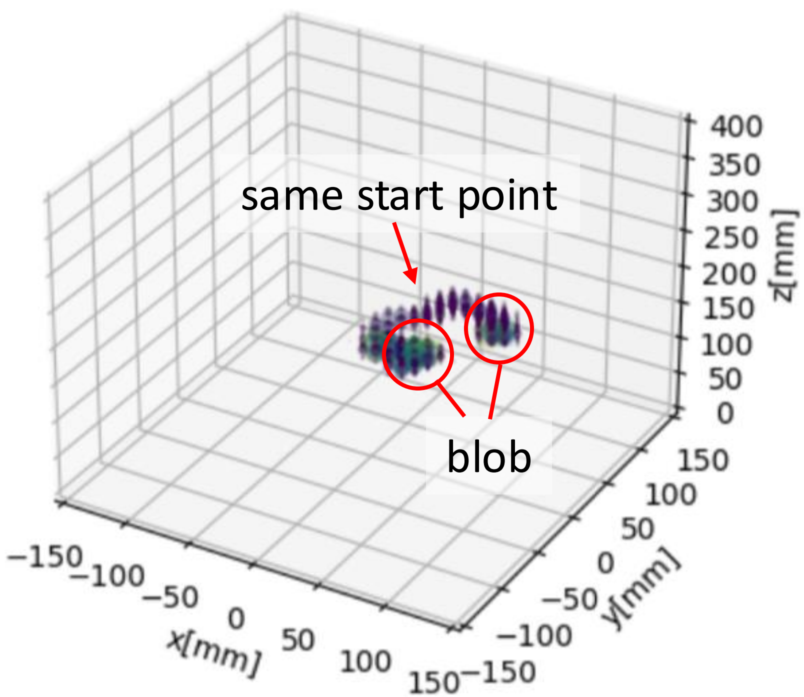
Research on additional contributions is ongoing!

"Fluctuation of the MPPC nonlinearity" (0.18% @1.8 MeV[2]) is being evaluated

[2]M.Yoshida et al., PTEP, 2024(1), 013H01 (2024)

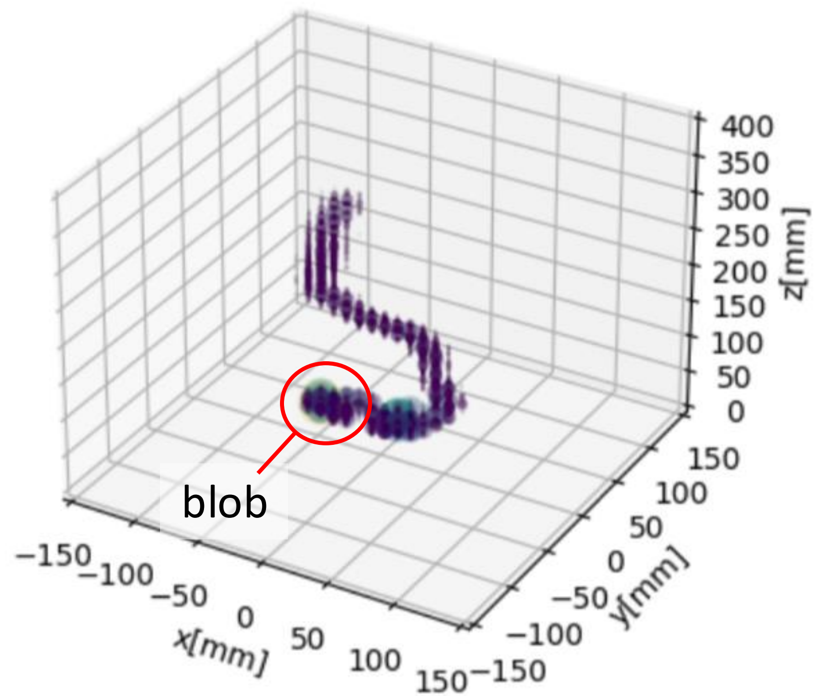
3D track reconstruction (Real data)

Measured track around 1593 keV
(Double escape, i.e. e^+e^- creation)



Same features as double beta decay signal

Measured track around 2615 keV
(Photoabsorption of γ-ray from ^{208}Tl)



Main background tracks in $0\nu\beta\beta$ search window

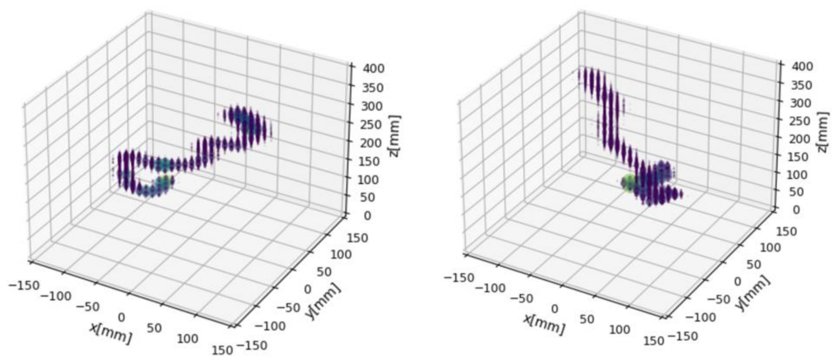
Machine learning (ML)

- Distinguish background tracks by track pattern with ML
- Checked the performance using measured real tracks around 2615 keV

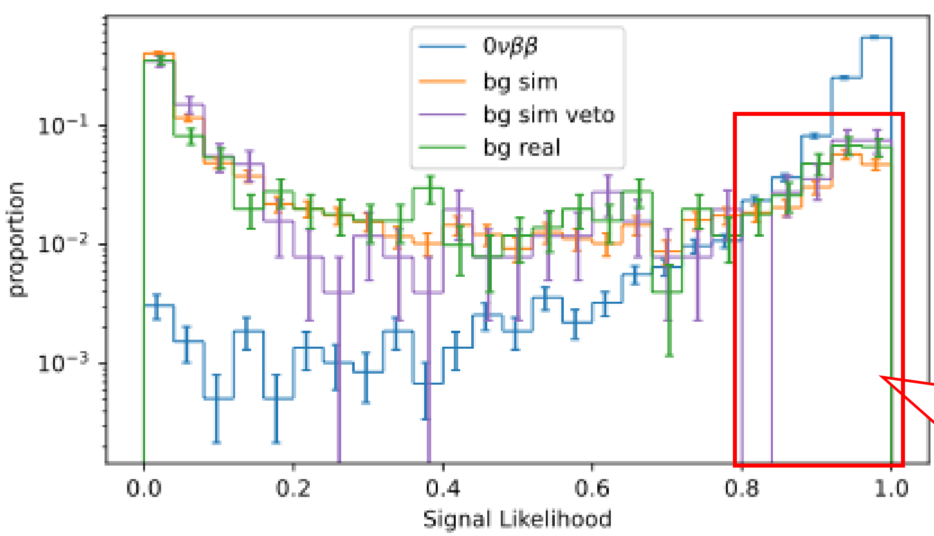
→Signal likelihood of real data matches that of simulated tracks, considering real-data veto channels

→Some background events take high signal likelihood

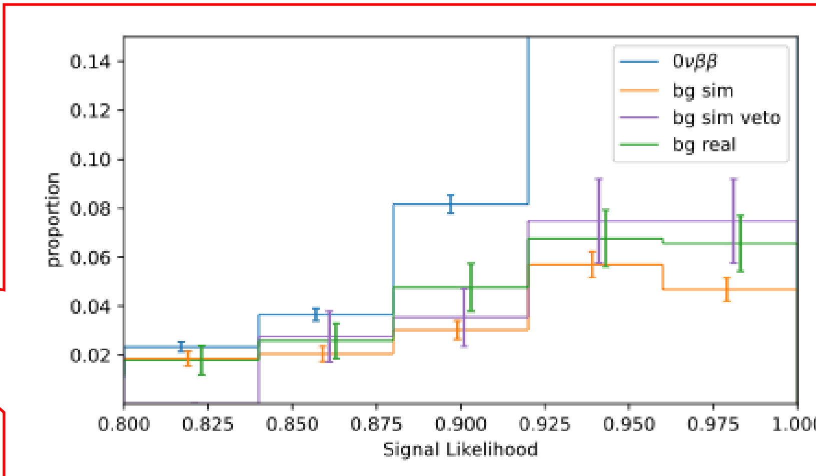
Examples of misclassified events



Signal likelihood distribution



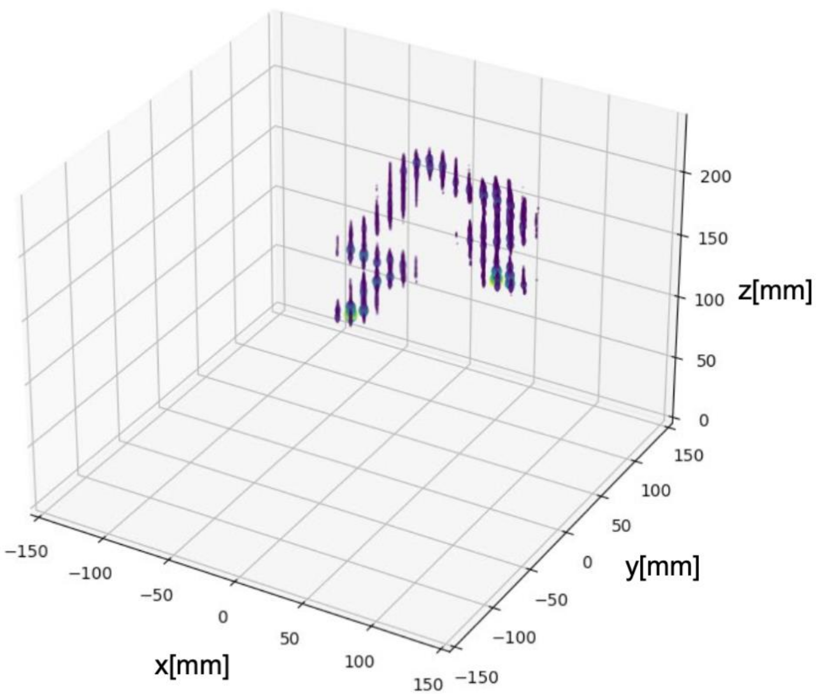
zoom



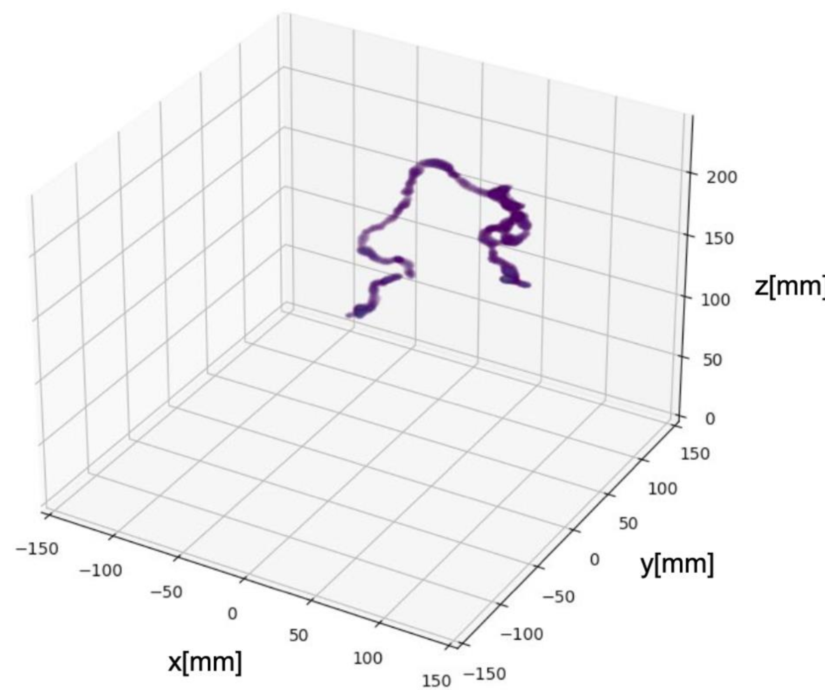
Richardson-Lucy deconvolution

- Applied on Richardson-Lucy deconvolution[3]
  to obtain precise tracks before diffusion
  → Expect to improve ML selection using deconvoluted tracks

Original track



Deconvoluted track



[3]L. B. Lucy, Astronomical Journal, Vol. 79, p. 745 (1974)

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1000L detector project

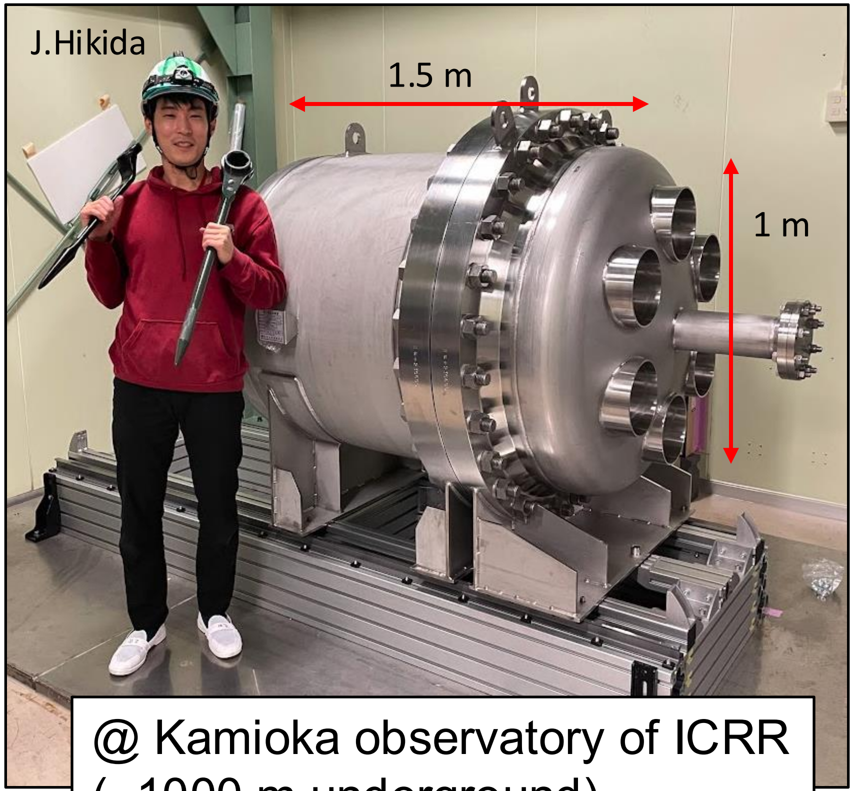
Data taking is planned from 2026

Project objectives

- First $0\nu\beta\beta$ search with AXEL detector
- Demonstration of great background rejection ability

R&D components

- ELCC module with large-area SiPM
- Discharge-resistive ELCC
- Readout electronics
- Cockcroft-Walton generation
- Scintillation detector
  → Poster presentation by S.Urano
- Low-radioactivity field cage
  → Poster presentation by H.Sasaki
- etc



@ Kamioka observatory of ICRR
(~1000 m underground)

ELCC module with large-area SiPM

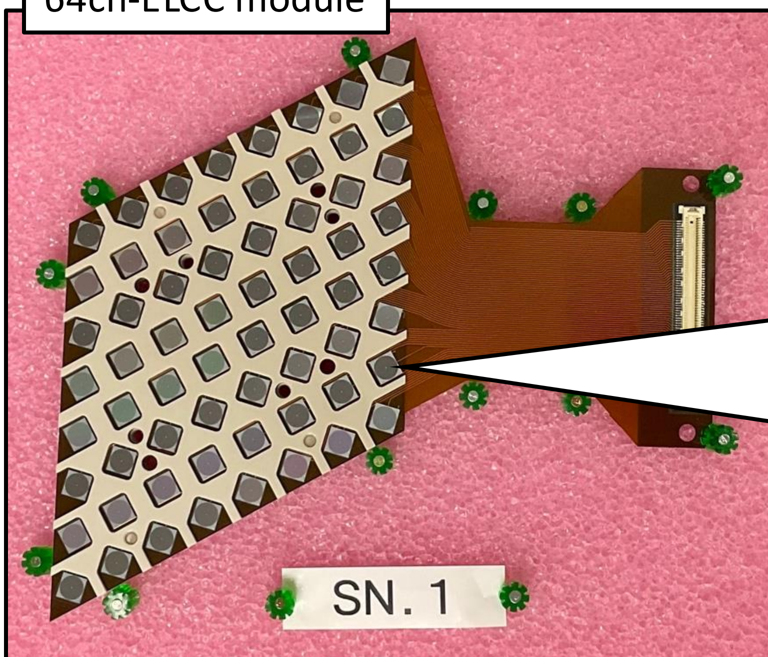
- 64 channels in a module
- Round-shape (ϕ4.7 mm) MPPC with larger detection area

→ Increase statistics of EL photon ※Diameter of ELCC holes: ϕ4.5 mm

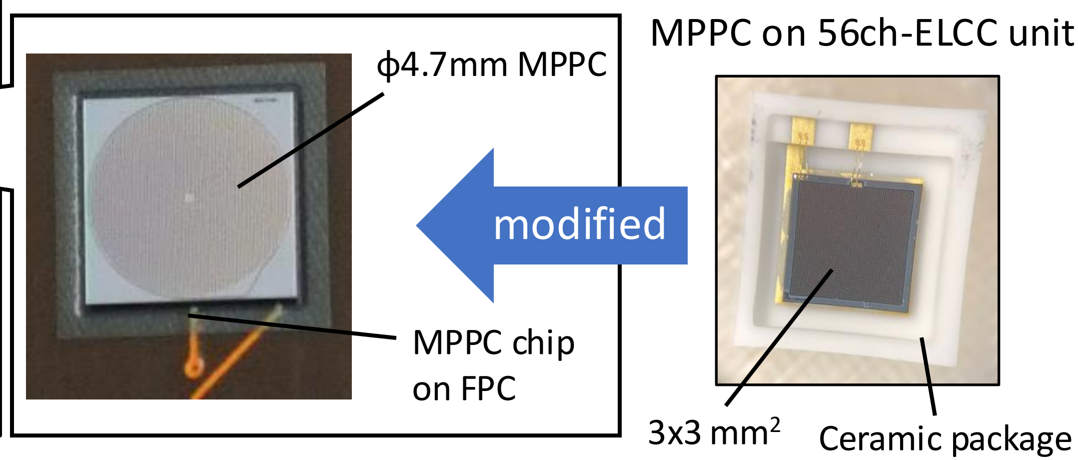
- Mount the MPPC chip directly on flexible printed circuit (FPC)

→ Remove ceramic package containing a lot of RI sources

64ch-ELCC module



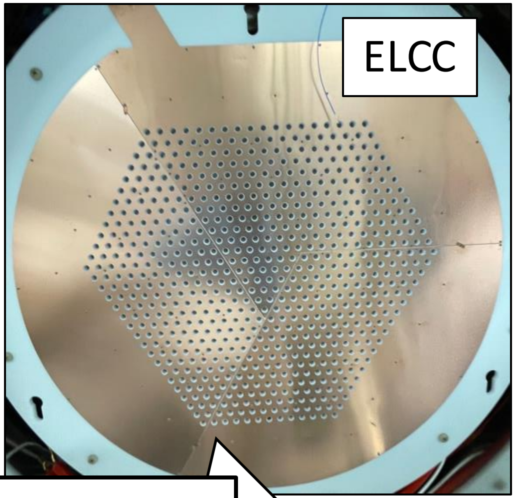
Performance evaluation with 180L prototype is planned for this fall



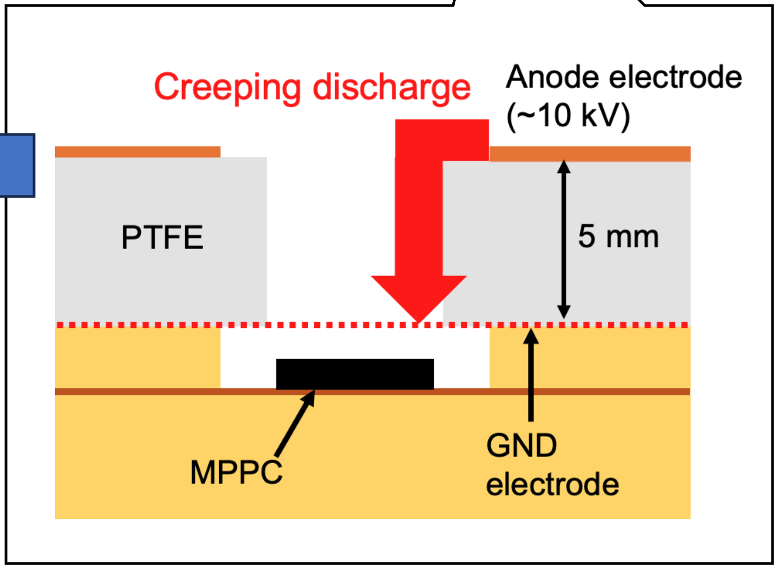
Discharge-resistive ELCC

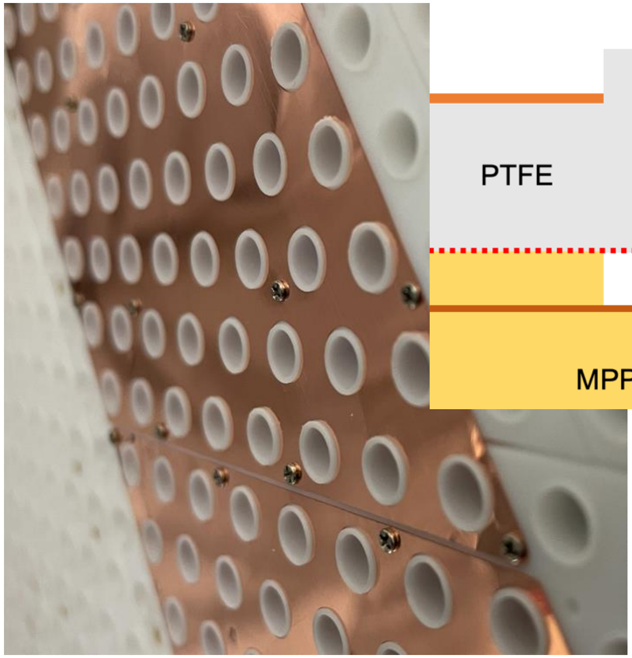
- Creeping discharge on ELCC holes disturbs stable operation at target EL field (3.0 kV/cm/bar)
- To prevent the discharge, develop the structure with a step around each hole

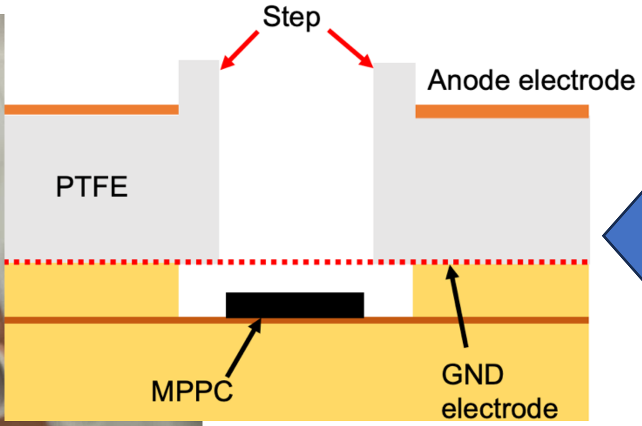
→ Target EL field operation was achieved in Xe gas at 6.1 bar



cross section of the cell





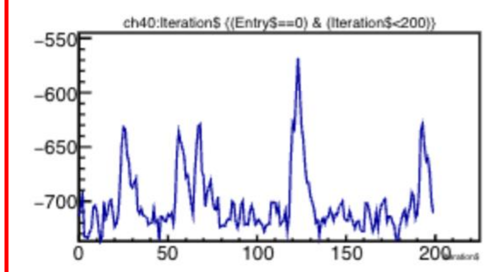


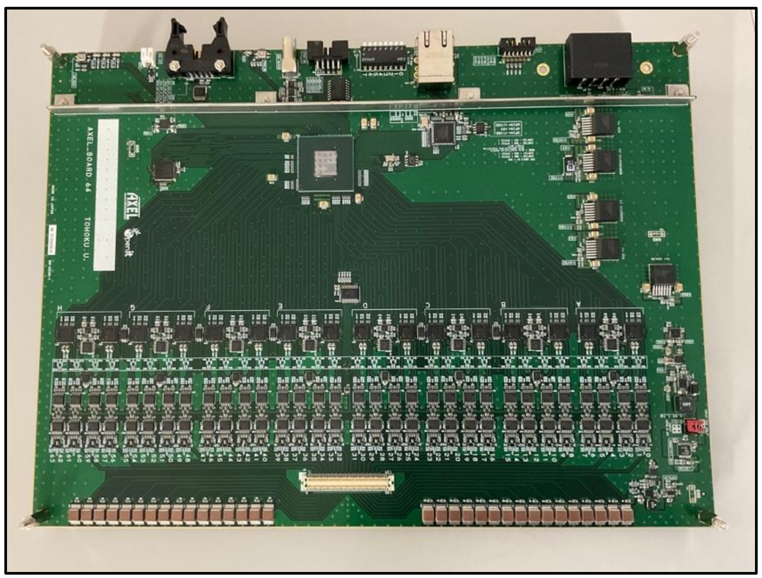
← step height: 0.5 mm

Readout electronics

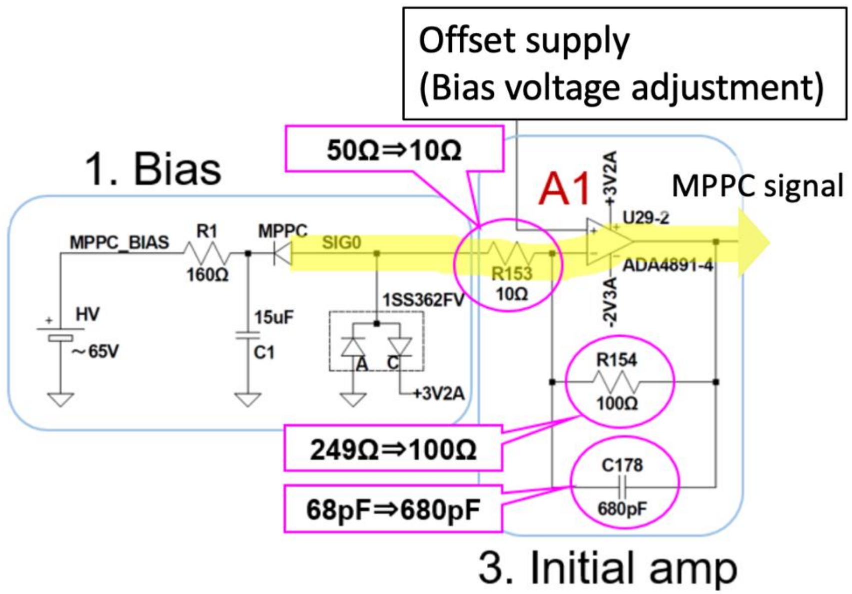
- 64 ch/board, 5 MS/s for EL signal readout, multiplexed 40 MS/s high gain for 1 p.e. calibration
- Adjust bias voltage of each MPPC to align gain
- DC coupling to avoid waveform distortion
- Input impedance is changed from 50 Ω to 10 Ω to suppress MPPC nonlinearity effect

Successfully readout the dark current signal





Readout electronics for 64ch-ELCC unit



Readout circuit

Cockcroft-Walton generation

- Design value: 76.4 kV
- Develop high-power AC power supply to increase efficiency of CW output

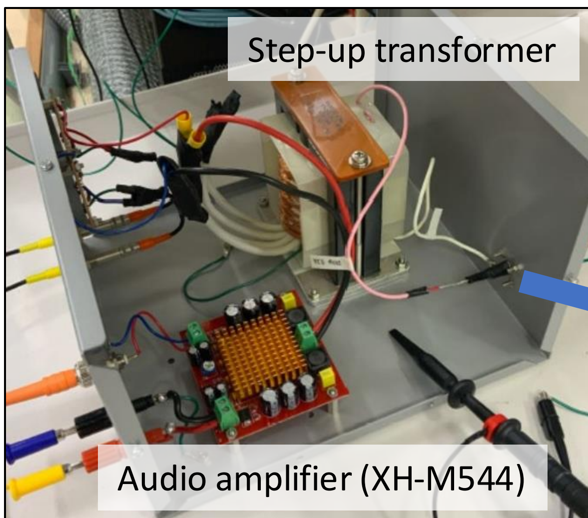
→ **76 kV achieved in atmosphere**
(input: 1.8 kV_{pp}, 13 kHz)

- Need to suppress voltage drop by ripple

→ Symmetrical CW generator[4]

Self-built
AC power supply →

Function generator



[4]M.Ruzbehani, Journal of Electrical and Computer Engineering, 2017, 4805268 (2017)

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Summary

- AXEL aims to search for $0\nu\beta\beta$ using high-pressure Xe gas TPC.
- 180L prototype has demonstrated great ability of AXEL detector.
  - ✓ Scalable structure
  - ✓ High voltage generation with Cockcroft-Walton generator inside vessel
  - ✓ High resolution: (0.67 ± 0.08) % FWHM @2615 keV
  - ✓ Reconstruction of 3D electron tracks
  - ✓ Development of background rejection method by track pattern with ML
- R&D for 1000L detector construction is in progress.
  - ➢ 64ch-ELCC module with new MPPC
  - ➢ Discharge-resistive structure of ELCC
  - ➢ Dedicated readout electronics
  - ➢ High voltage generation with Cockcroft-Walton generator

Related poster presentation by S.Urano and H.Sasaki

For further information, please find documents on our web page
https://www-he.scphys.kyoto-u.ac.jp/research/Neutrino/AXEL/publication.html

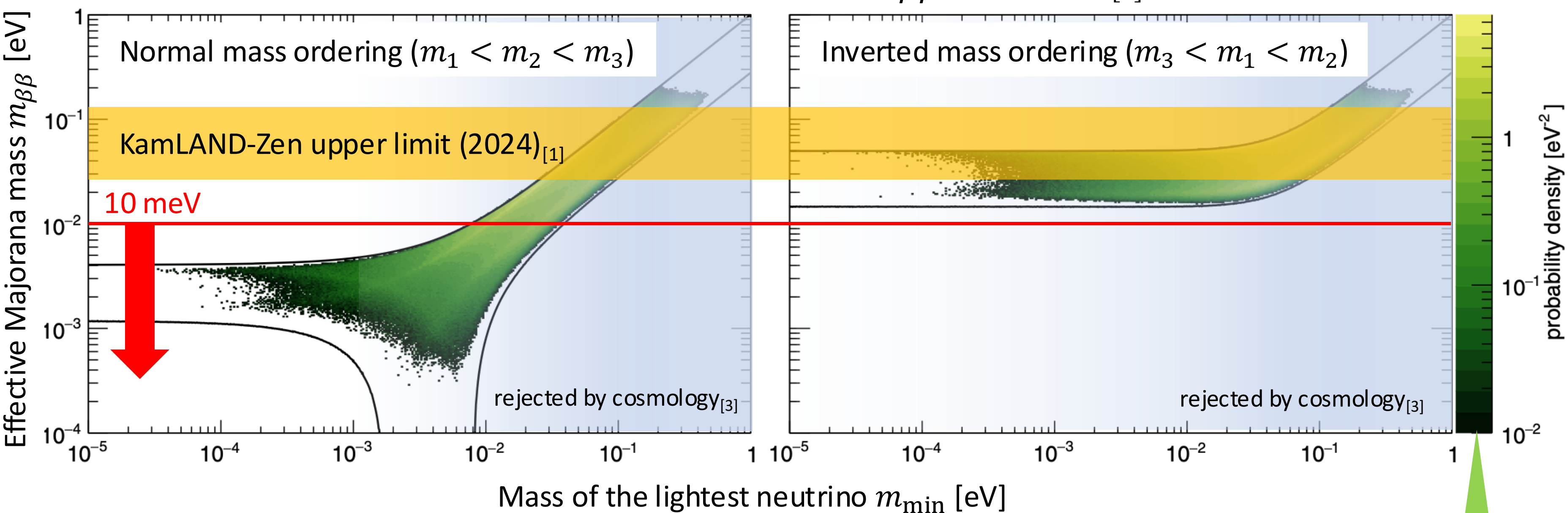
Back up

Status of $0\nu\beta\beta$ search

Relation of half-life time and effective Majorana mass: $T_{1/2}^{0\nu\beta\beta} \propto m_{\beta\beta}^{-2}$
→ Current upper limit of $m_{\beta\beta}$: 36-156 meV (model dependent)[1]

Toward $0\nu\beta\beta$ search in normal mass ordering region ($m_{\beta\beta}$<10 meV), more sensitive detector is necessary

Posterior distributions for $m_{\beta\beta}$ and $m_{\min}$[2]

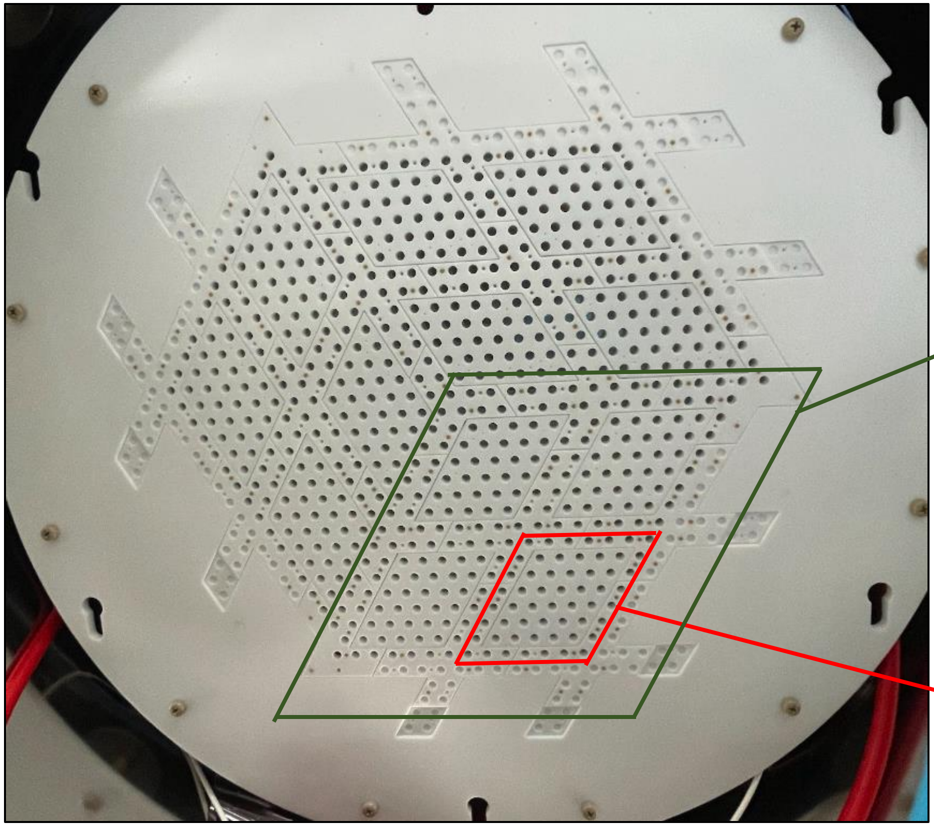


Posterior distribution given the knowledge on neutrino mixing parameters

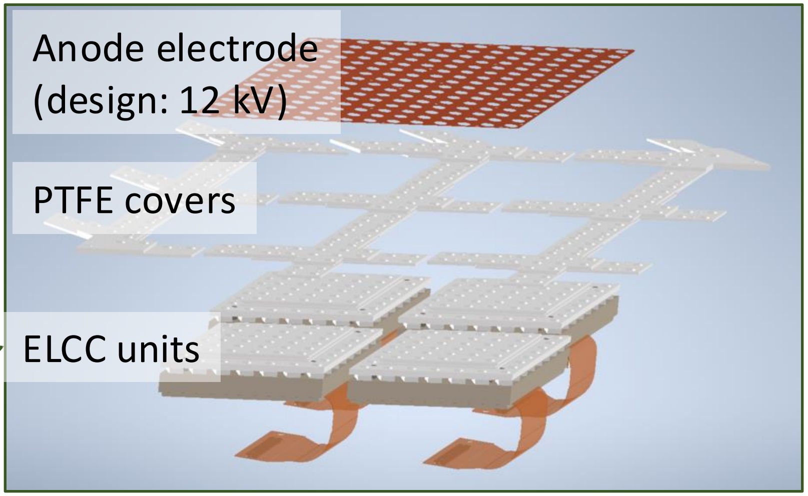
[1]KamLAND-Zen Collaboration, arXiv:2406.11438v1 (2024)
[2]M.Agostini, et. al., PRD 96, 053001 (2017)
[3]Particle Data Group: *Neutrinos in Cosmology, Neutrino masses*

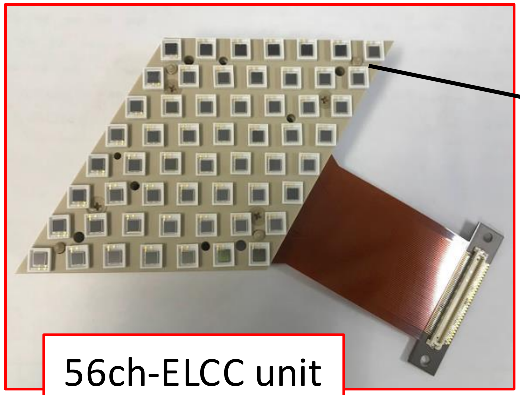
ELCC structure of 180L prototype

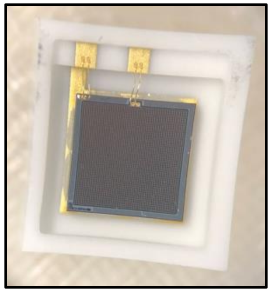
- SiPM: VUV-sensitive Multi-Pixel Photon Counter (VUV-MPPC)
- Unit structure for scalability
- No direct gap b/w units to suppress creeping discharge



12-unit ELCC before attaching anode electrodes







VUV-MPPC
(S13370-3050CN)

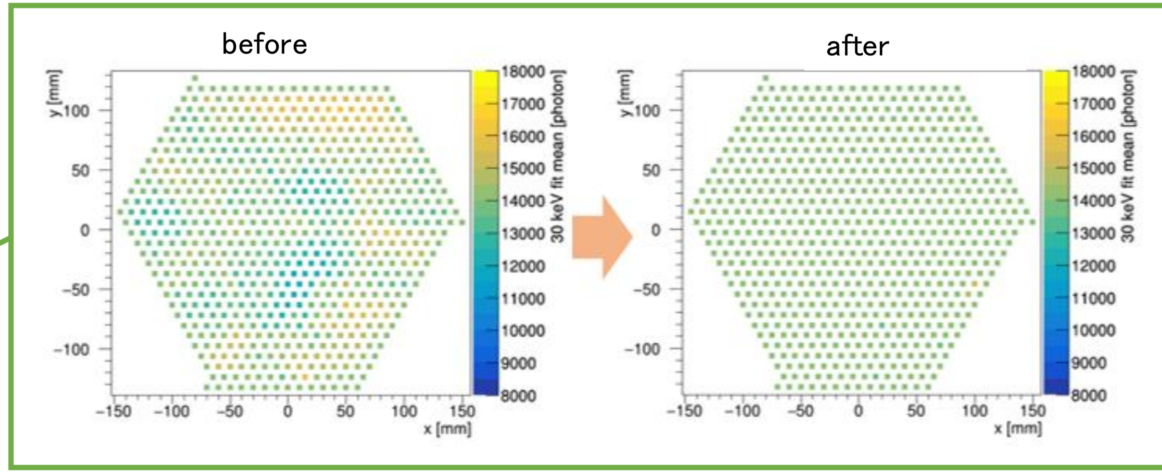
Measurement condition

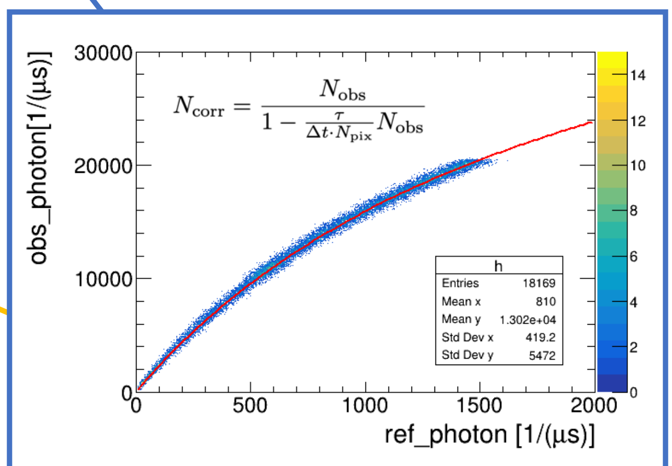
- RI source: Thorium-doped tungsten rods (γ-ray of Th series)
- Xe gas pressure: ~6.8 bar
- Voltage: 90 % of our design (EL: 2.7 kV/cm/bar, Drift: 90 V/cm/bar)
- Measurement period: ~2 months

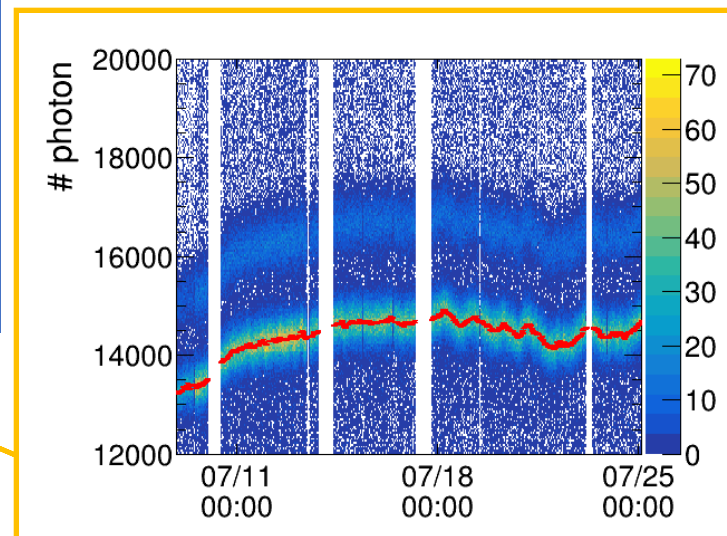
Voltage trend (DAQ in gray-shaded area)

Correction & analysis flow

- MPPC nonlinearity
- EL gain
- Time variation
- z position
- Adjustment of parameter of MPPC nonlinearity

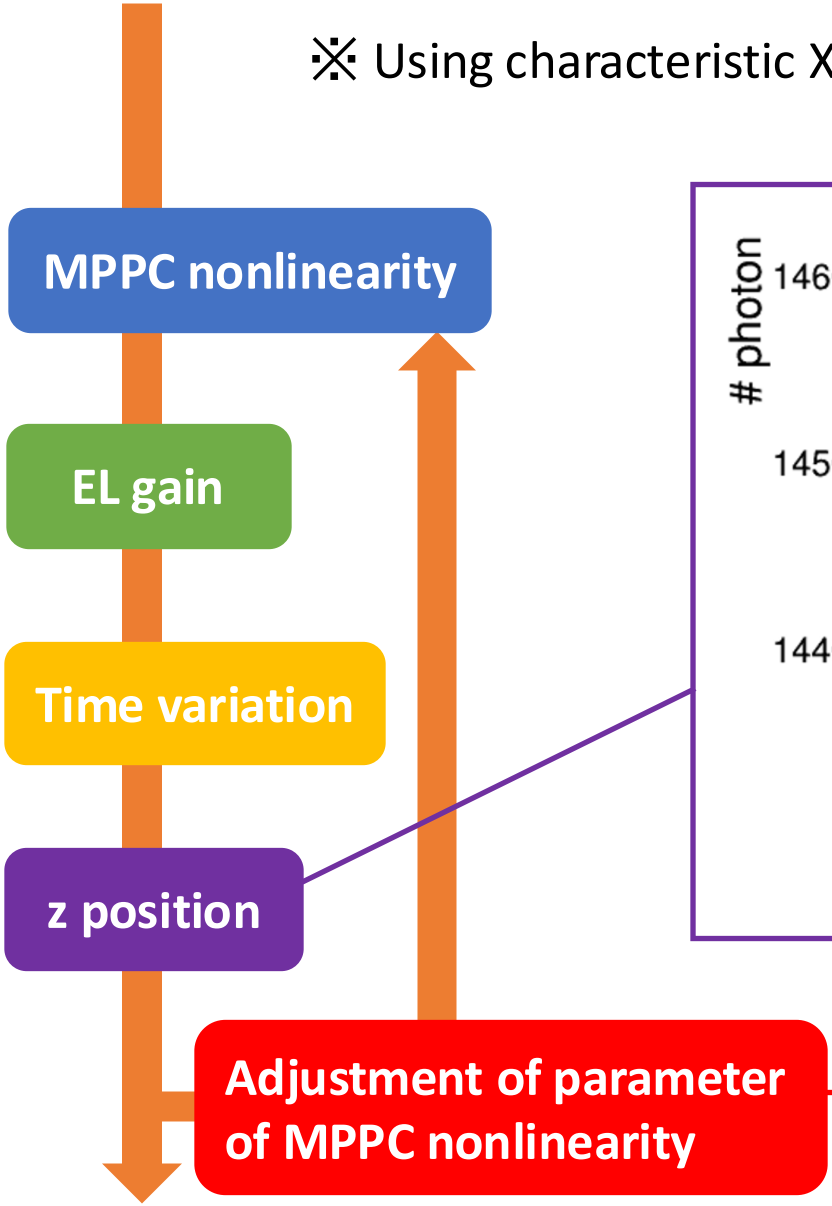


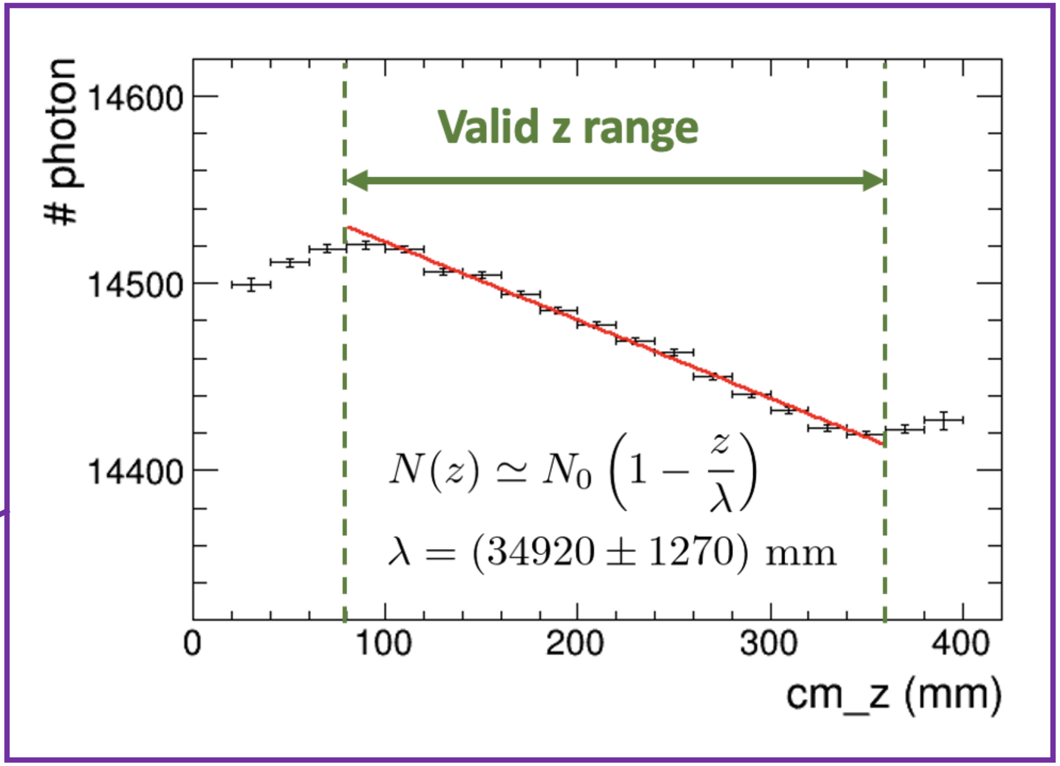




Correction & analysis flow

※ Using characteristic X-ray events (〜30 keV) for each correction

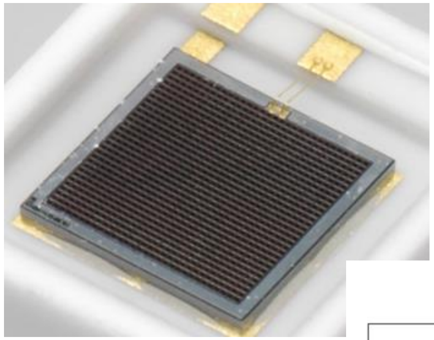


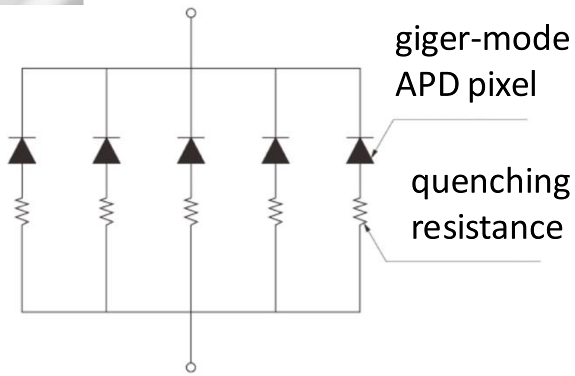


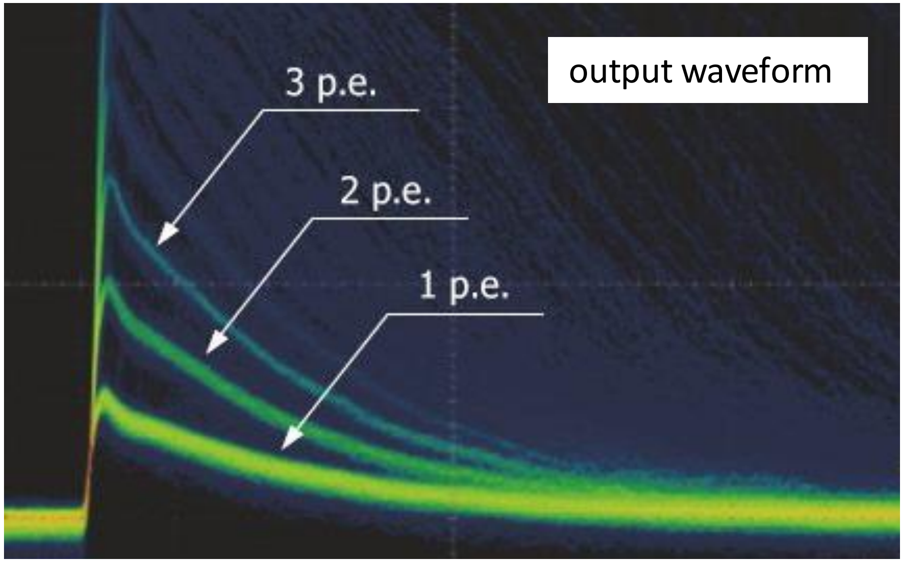
Confirming density of detected EL photon by defining new parameter called CSS (see ref[4])

MPPC ~Multi-Pixel Photon Counter

- Produced by Hamamatsu Photonics
- Arrange a lot of pixels in parallel
- Operated by applying higher voltage than breakdown voltage
→ Output charge is proportional to over voltage
- Constant charge output in 1 pixel detection
→ Count # of detected photon as # of output pixel



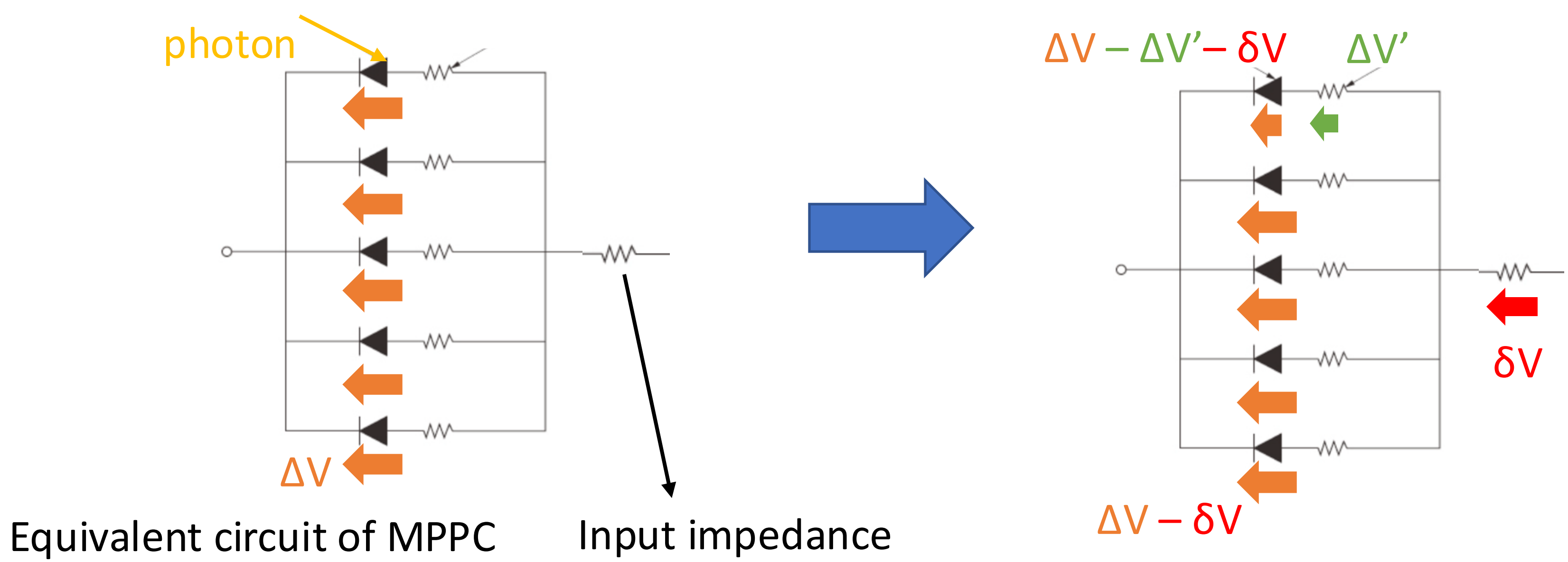




Cause of MPPC nonlinearity

1. When some pixels detect photons successively before they finish recovering (typical recovering time: ~100 ns), the effective gain is decreased

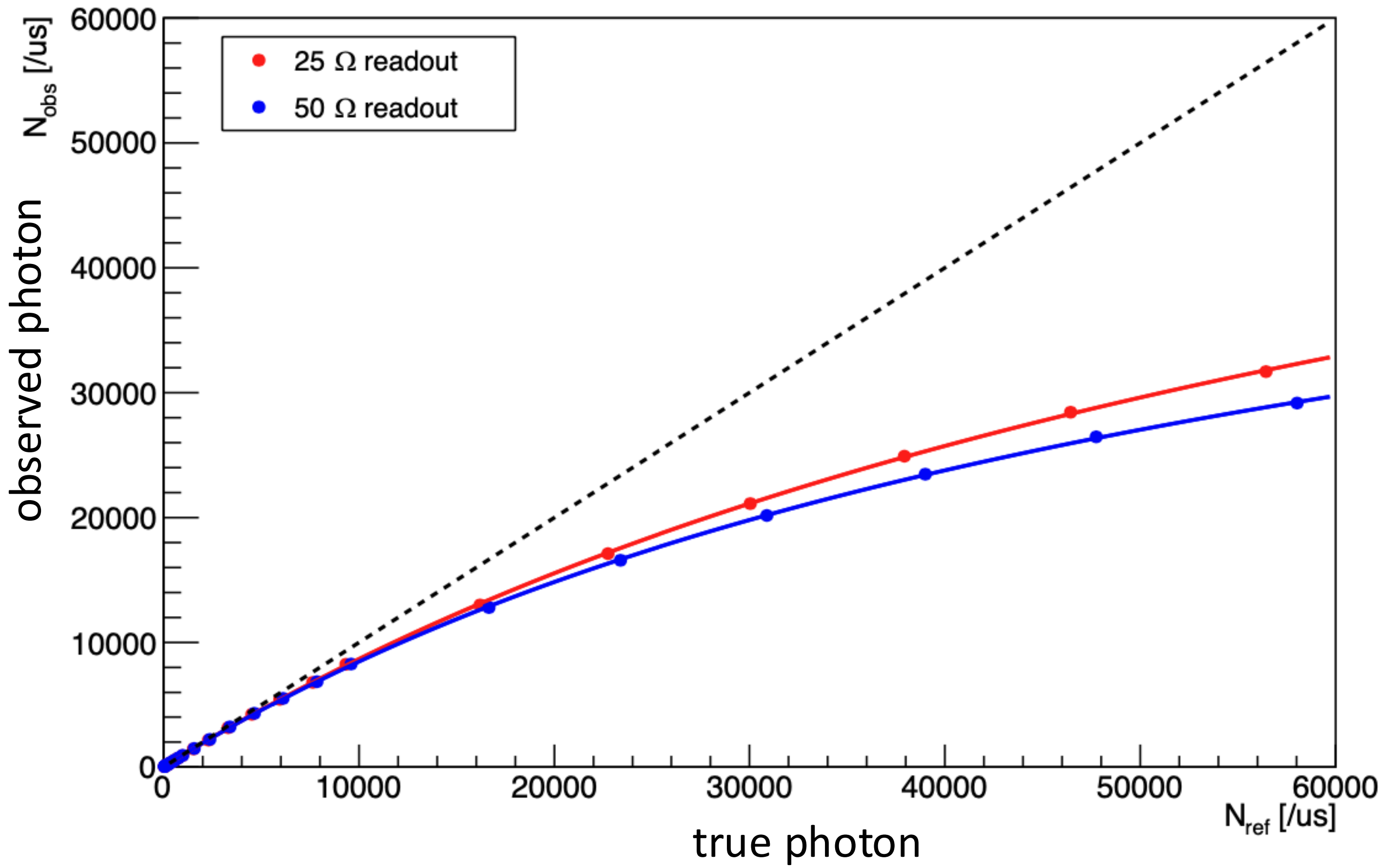
2. When readout voltage is not negligible compared to over voltage applied to MPPC, the effective gain is decreased. (shown in figure below)



Readout resistance & MPPC nonlinearity

- MPPC nonlinearity effect is suppressed with small readout resistance
- Less than 10 Ω readout, overshoot is observed in signal wave

→ 10 Ω readout is adopted for new electronics



Principle of CW generator

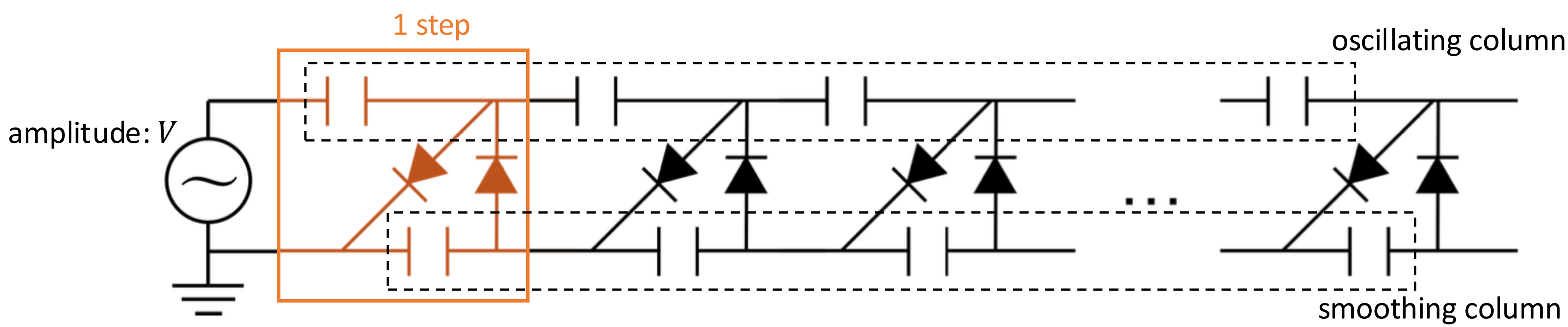
- 1 step composed of 2 capacitors and 2 diodes
- Voltage oscillation of capacitors in oscillating column supply charges to capacitors in smoothing column

→ Ideal output voltage: $2NV$ N: number of steps

- Voltage drop occurs by discharge of capacitors in smoothing column due to ripple effect:

$$\Delta V = \frac{I}{fC}\left(\frac{2}{3}N^3 + \frac{1}{2}N^3 + \frac{1}{3}N\right)$$

I: current in resister chain
f: frequency of input AC
C: capacitance

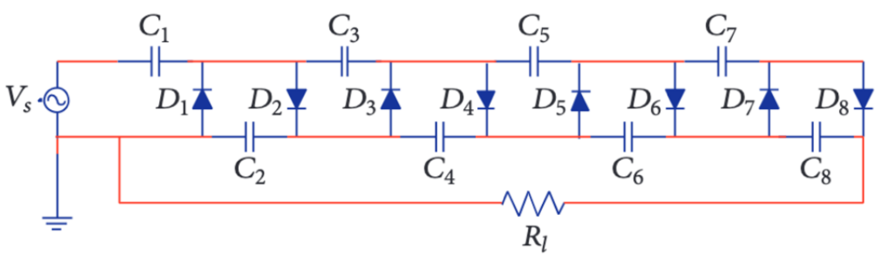


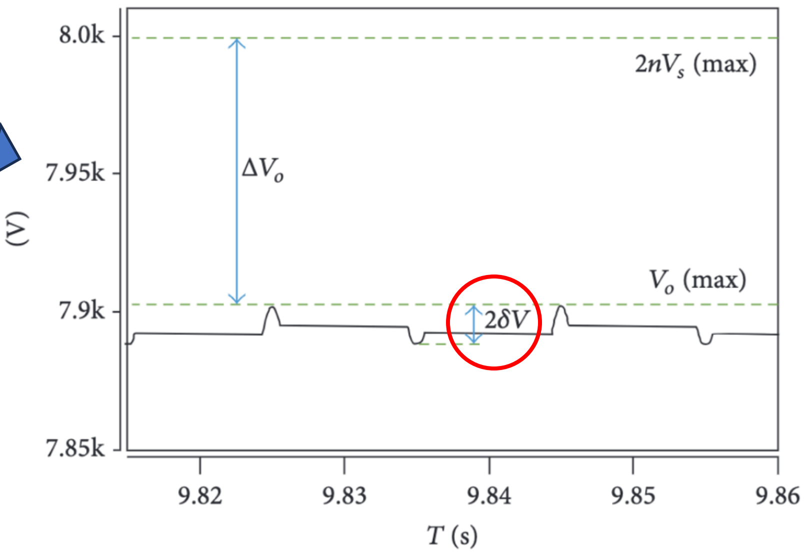
Drawing of Cockcroft-Walton circuit

Symmetrical Cockcroft-Walton[6]

Simulation

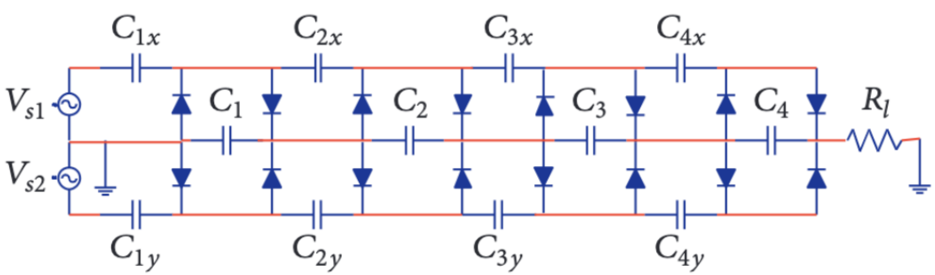
Normal CW generator

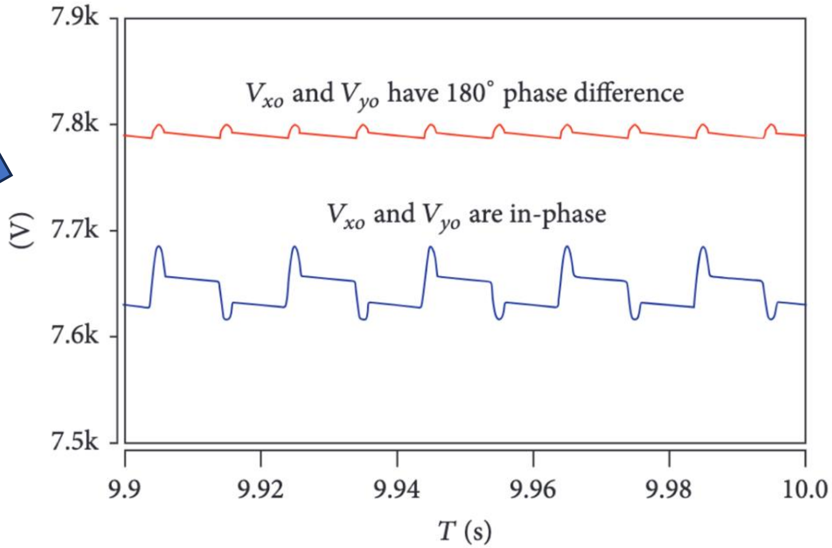




Ripples in all smoothing capacitors affect the output voltage stability

Symmetrical CW generator





Reduce the ripple voltage on 180-deg phase difference operation

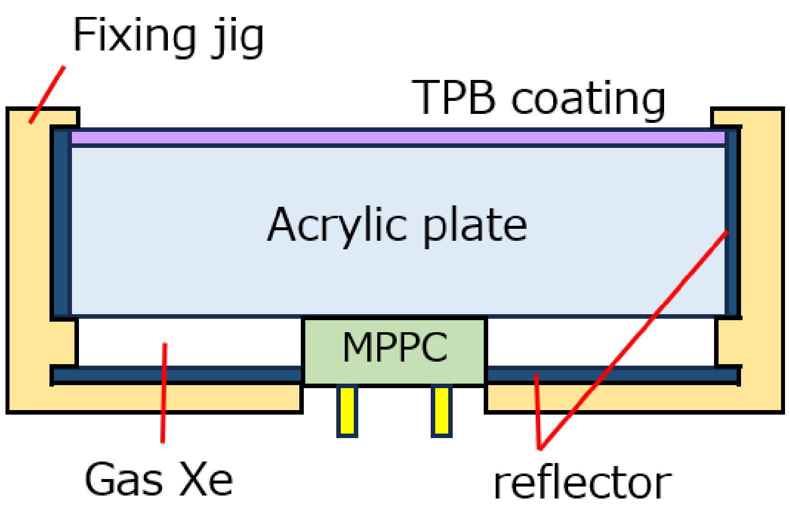
→ Cancel the ripples on each capacitor

Scintillation detection

Low detection efficiency of high-pressure-tolerant VUV-PMT due to small detection area (~0.7 photon/PMT @Q-value) causes mis-reconstruction of *z* position

→ Developing new scintillation light detector

- Wavelength-shifter (TPB)+ Acrylic plate + MPPC (S13360-6075PE)
- Larger detection area: $20.5\times20.5\ mm^2 \rightarrow 50\times50\ mm^2$
- Expect 11 photon/plate @Q-value



Drawing of new scintillation light detector

Evaluate the performance with 180L prototype