AXEL: high-pressure Xe gas TPC for neutrinoless double beta decay search

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On behalf of the AXEL collaboration

21th September. 2026

International School of Nuclear Physics, 47th Course @Erice

Outline

- AXEL experiment
- Performance evaluation of 180L-size prototype
- R&D for 1000L-size detector
- Summary

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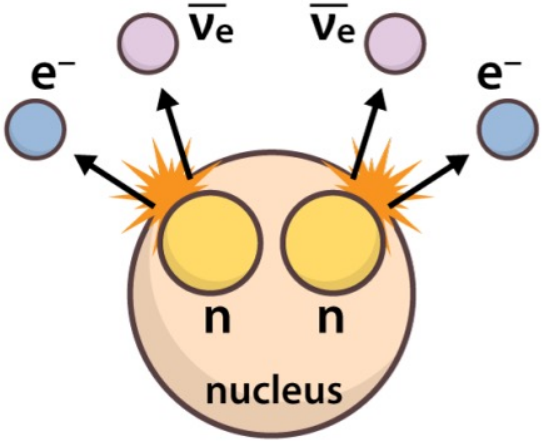
Neutrinoless double beta decay ($0\nu\beta\beta$)

- Neutrino can be identical to its anti-particle: **Majorana** nature

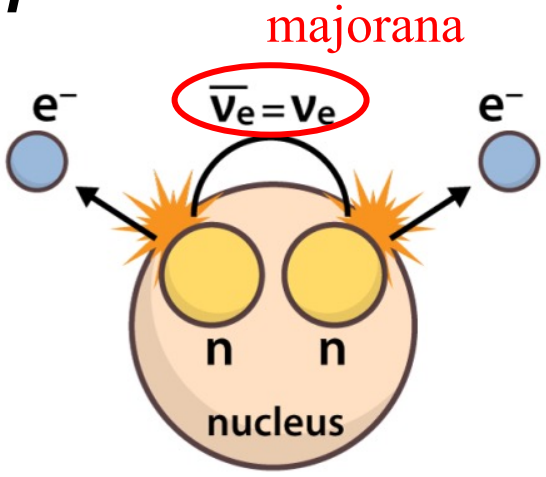
- It may explain
  - ➢Too small mass of neutrino (seesaw mechanism)
  - ➢Matter-antimatter asymmetry of the universe (leptogenesis)

Ettore Majorana

- Almost the only probe: detection of $\boldsymbol{0\nu\beta\beta}$



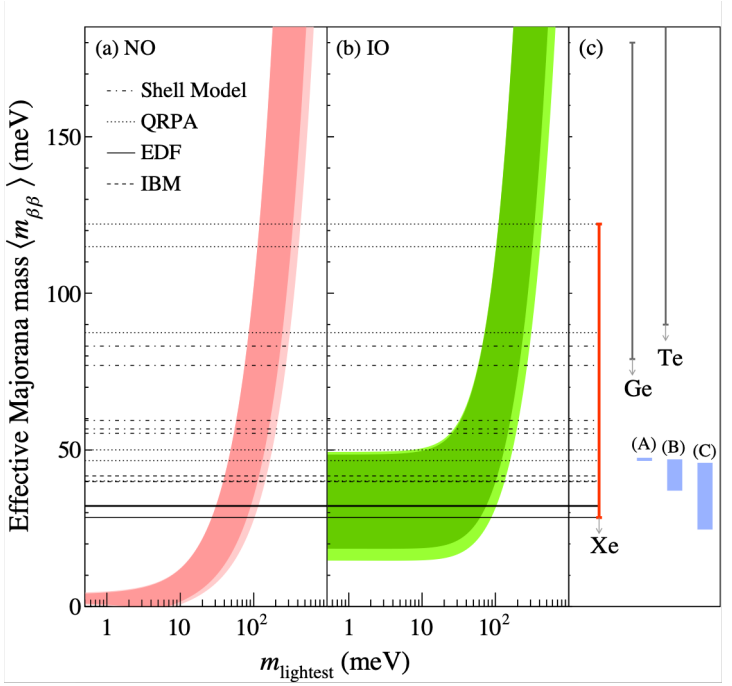
$2\nu\beta\beta$



$\boldsymbol{0\nu\beta\beta}$

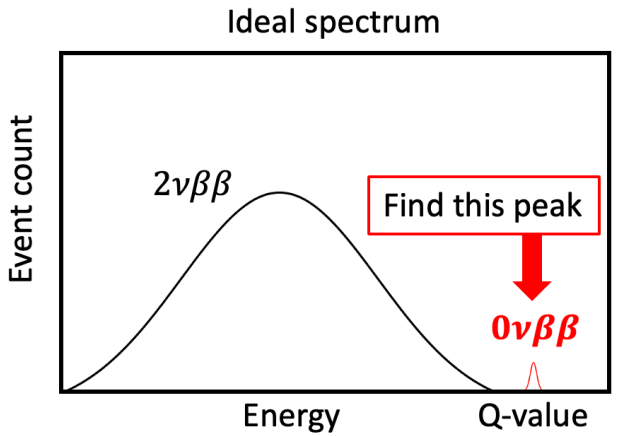
Result and requirements of $0\nu\beta\beta$ search

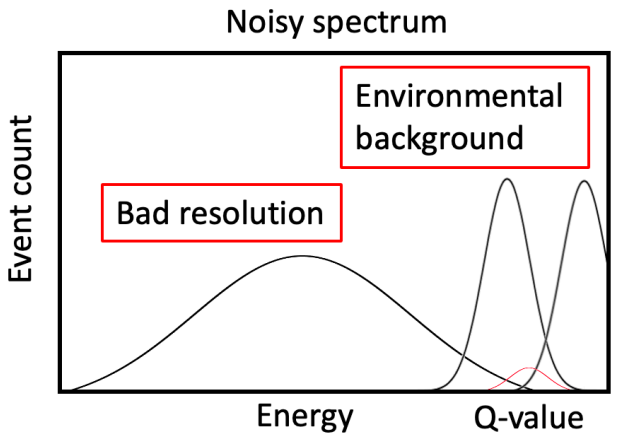
- $0\nu\beta\beta$ is very rare (even if it can occur)
  - $T_{1/2} > 3.8\times10^{26}\ years$ (90 % C.L.) for ^{136}Xe by KamLAND-Zen
  - If neutrino mass ordering is normal, $\langle m_{\beta\beta}\rangle < 10$ meV



S.Abe et al., Phys. Rev. Lett. **135**, 262501

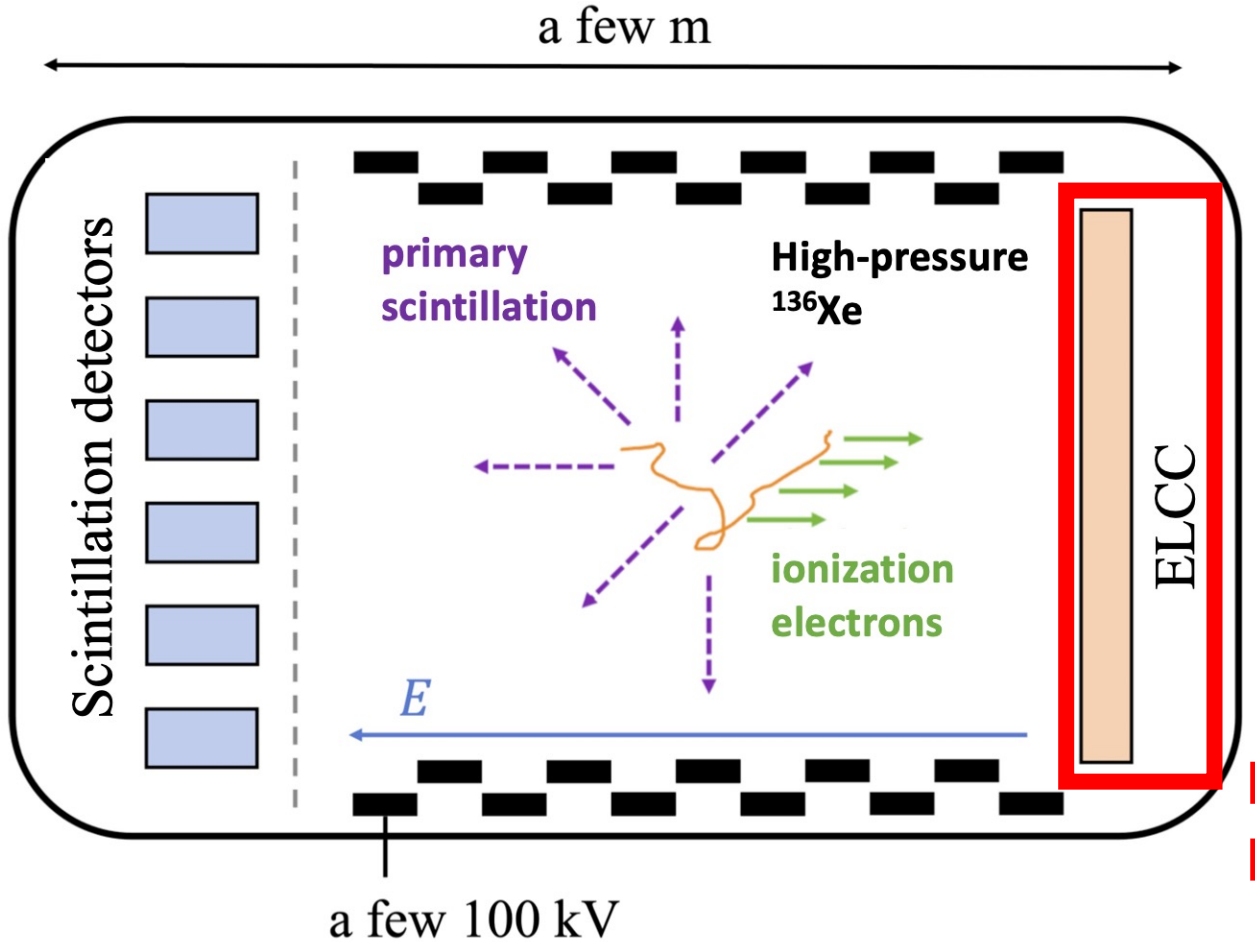
- Requirements for more sensitive search:
  - **High energy resolution**
  - **Environmental radiation discrimination**
  - **Mass scalability**





AXEL: A Xenon ElectroLuminescence

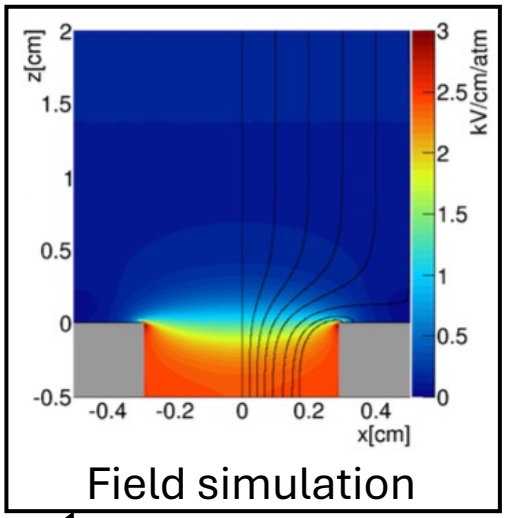
- AXEL: High pressure Xe gas Time Projection Chamber (TPC)
  - ➢Detection system **ELCC**: High energy resolution + Scalability (p7)
  - ➢**Tracking ability**: Background rejection by topology (p15-16)



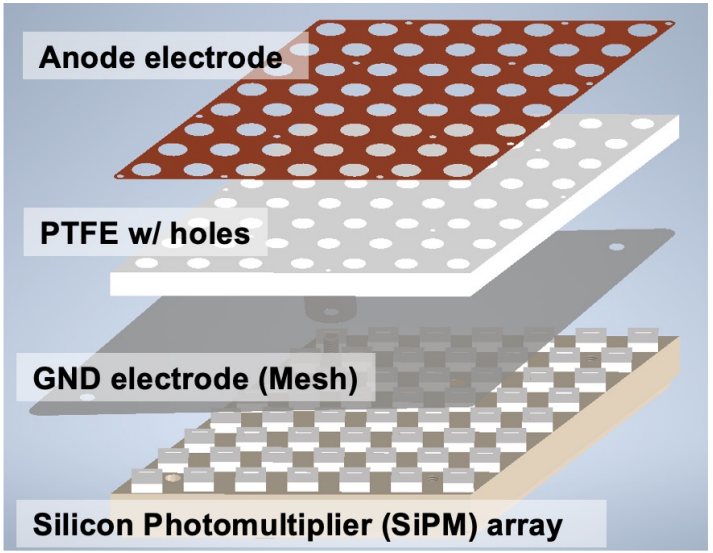
Details in Next slide!

ELCC: Electroluminescence Light Collection Cell

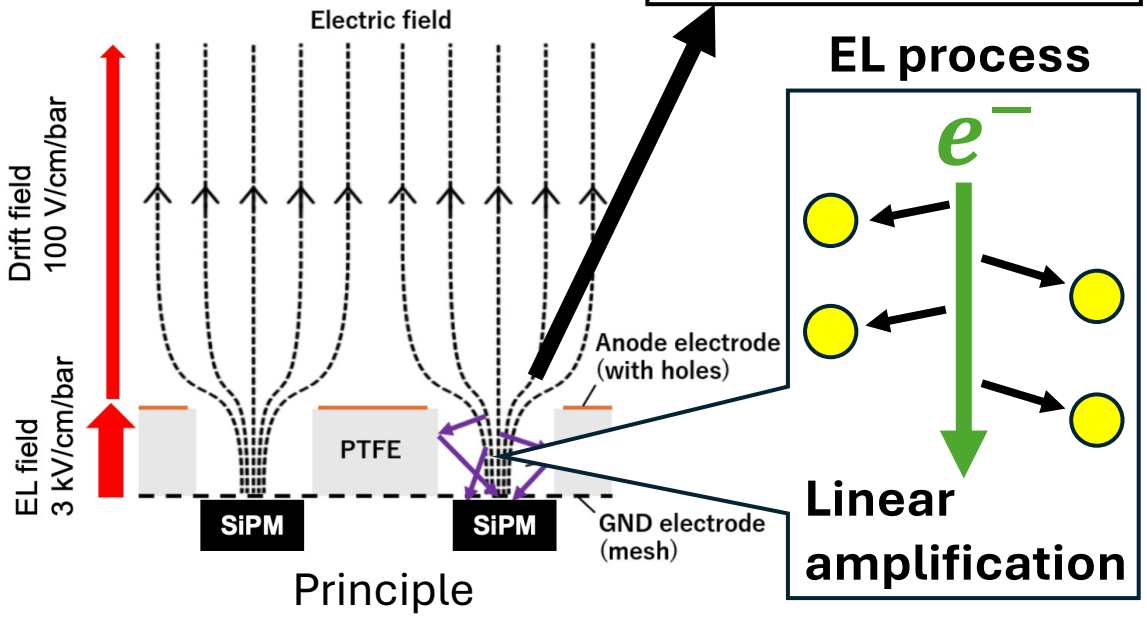
- Pulling ionization electrons into cells and detect through <u>electroluminescence (EL)</u>
- Low fluctuation process due to linear amplification → **High energy resolution**
- Rigid structure and modular extension → **Good Scalability**



Field simulation

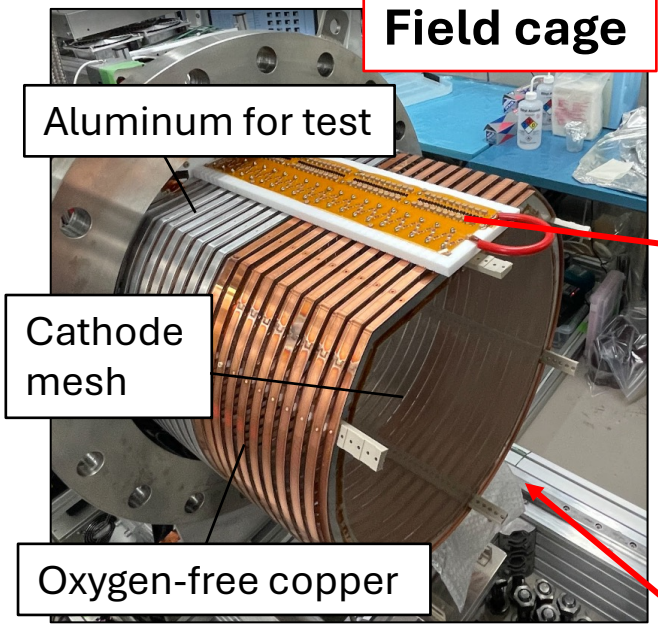


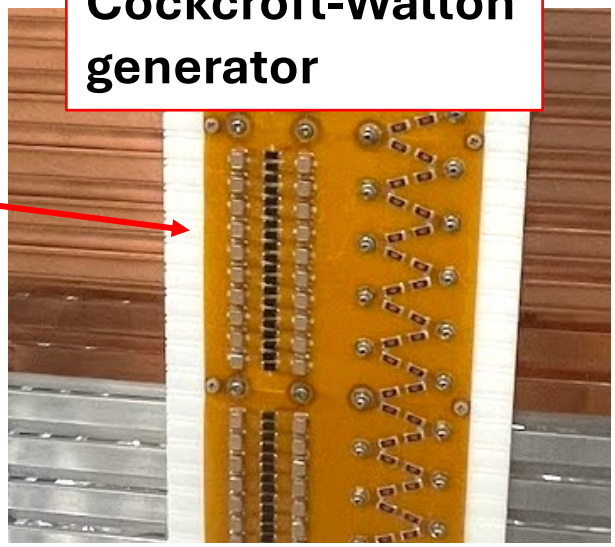
Structure

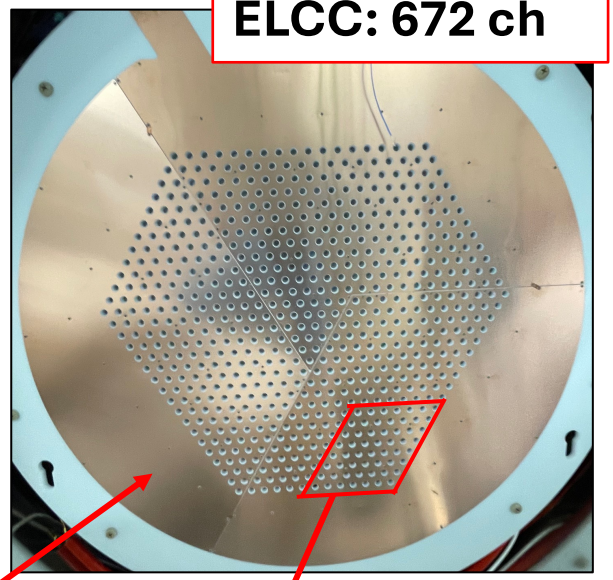


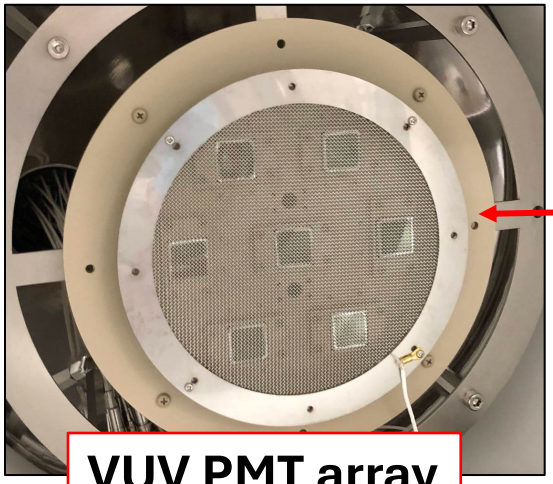
Principle

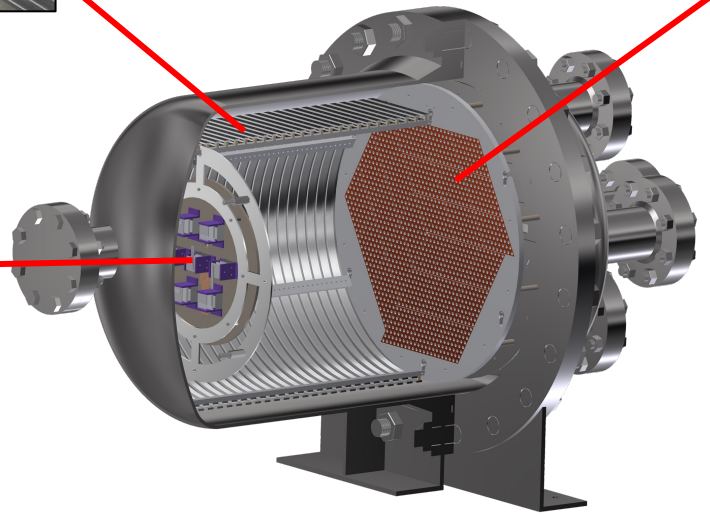
Overview of AXEL detector (180L-size prototype)



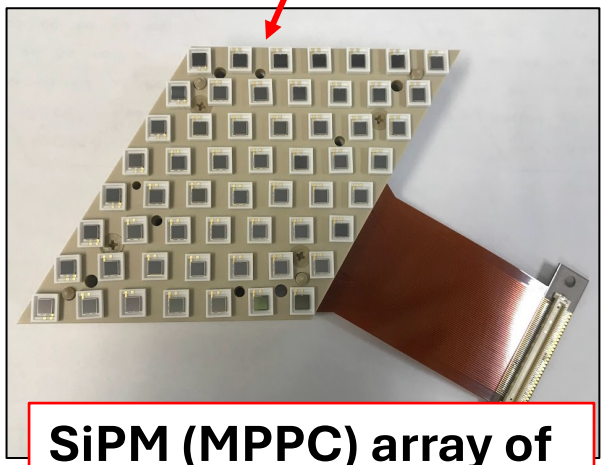








Cad model of 180L prototype



Road map of AXEL experiment

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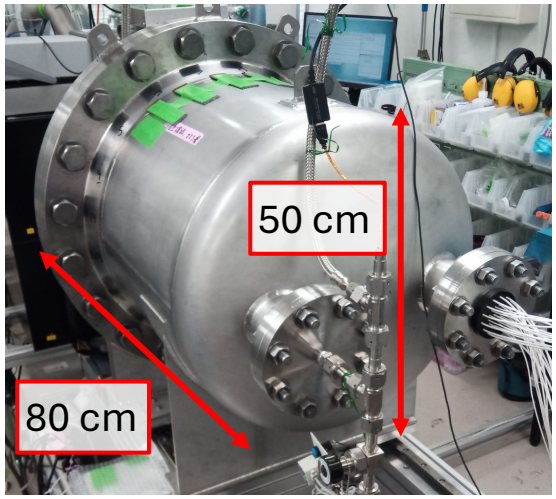


Estimated sensitivity (90% C.L.)
Up to $T_{1/2} > 4.1\times10^{27}$ *years*
by 10-years operation

10-ton detector

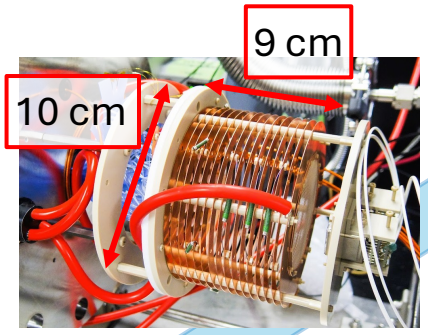
1-ton detector

100-kg detector (2028-)

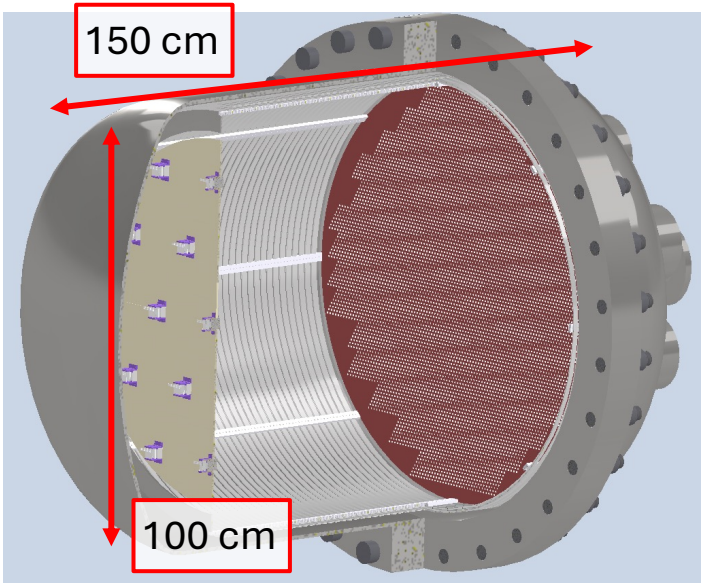
Collaboration with NEXT experiment is undergoing

1000L detector (2026-)
- ~20 kg ^{136}Xe
- $0\nu\beta\beta$ search

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



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



@Kamioka underground

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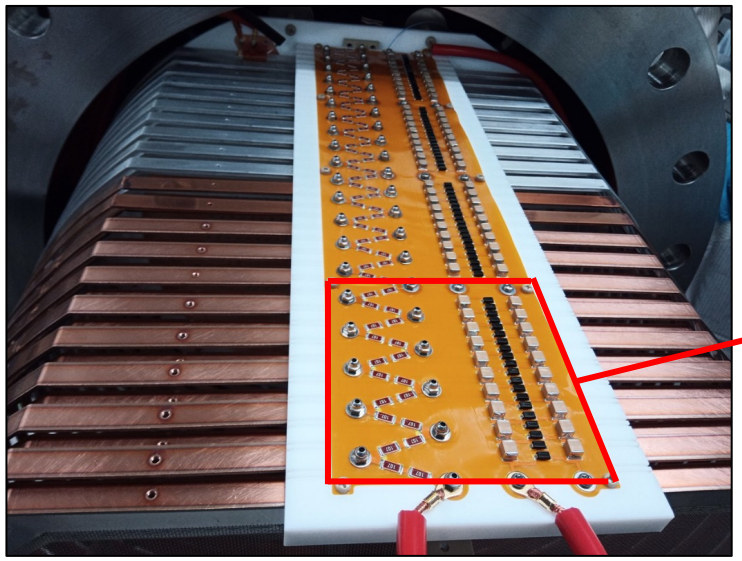
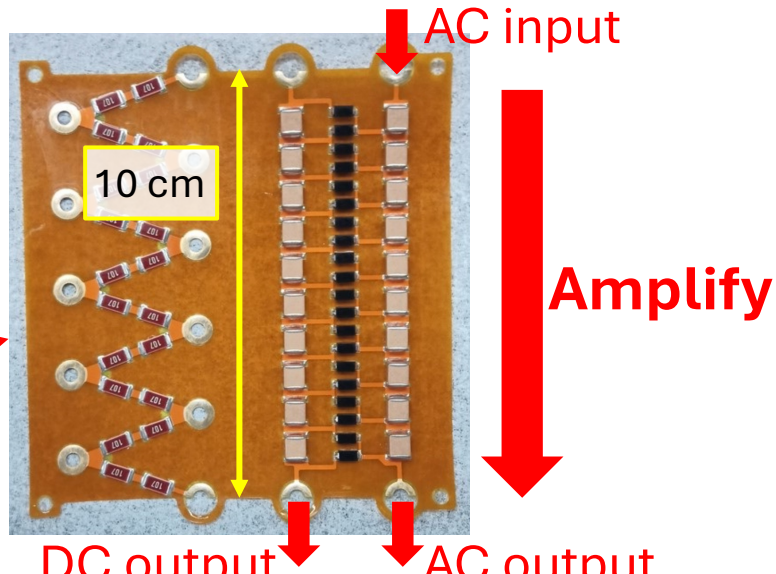
Cockcroft-Walton generator

- High DC voltage generation from low AC input
  - ➢No need to develop special feedthrough for high pressure and HV
- -35.3 kV was achieved in 6.0 bar Xe with 1.2 kV_{pp} input
  - ➢<u>First operation demonstration for TPC in the world!</u>



40-step generator in 180L prototype



10-step generator

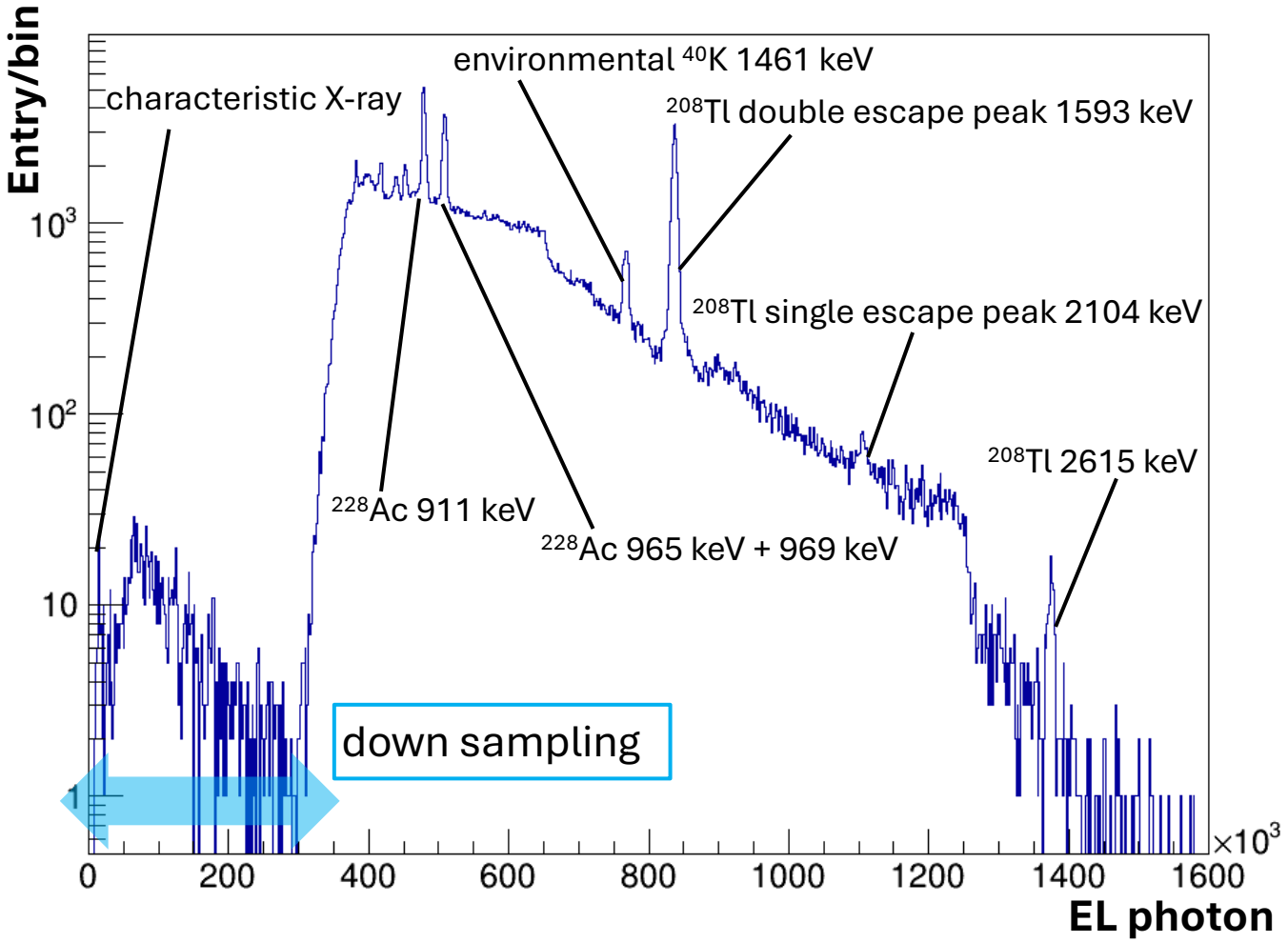
@Tohoku univ.

- Also, -76.4 kV was achieved with 80-step generator in atmosphere for the 1000L-size upgrade (p18).

Energy Spectrum

Measurement Conditions

- ^{208}Tl source
- Xe gas pressure: 6.8 bar
- Anode Voltage: -9.2 kV
- Cathode Voltage (CW output): -34.1 kV
- EL field: 2.7 kV/cm/bar
- Drift field: 90 V/cm/bar
- 40 days operation



Detail: S.Akiyama et al., PTEP 2025(2025) 053H03

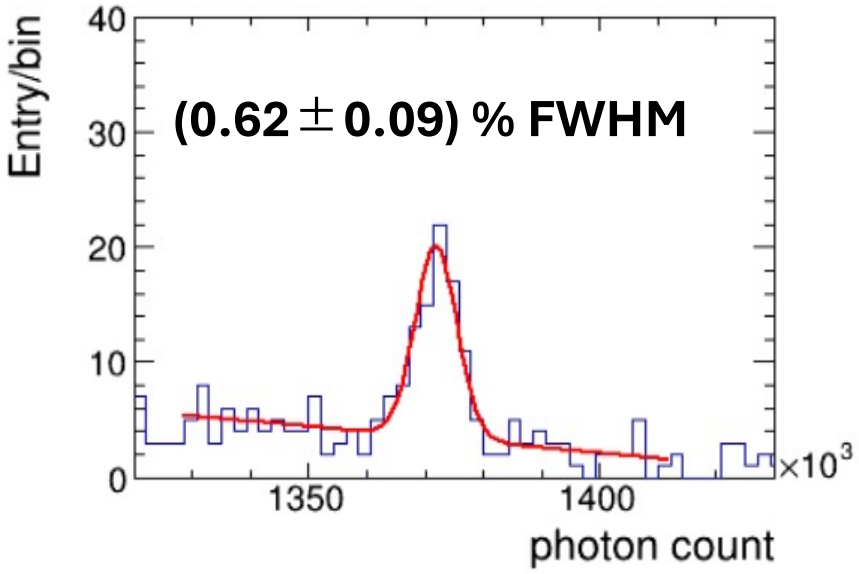
Energy resolution

- FWHM resolution @2615 keV: **(0.62 ± 0.09) %**
- Extrapolated FWHM resolution @Q-value (2458 keV)

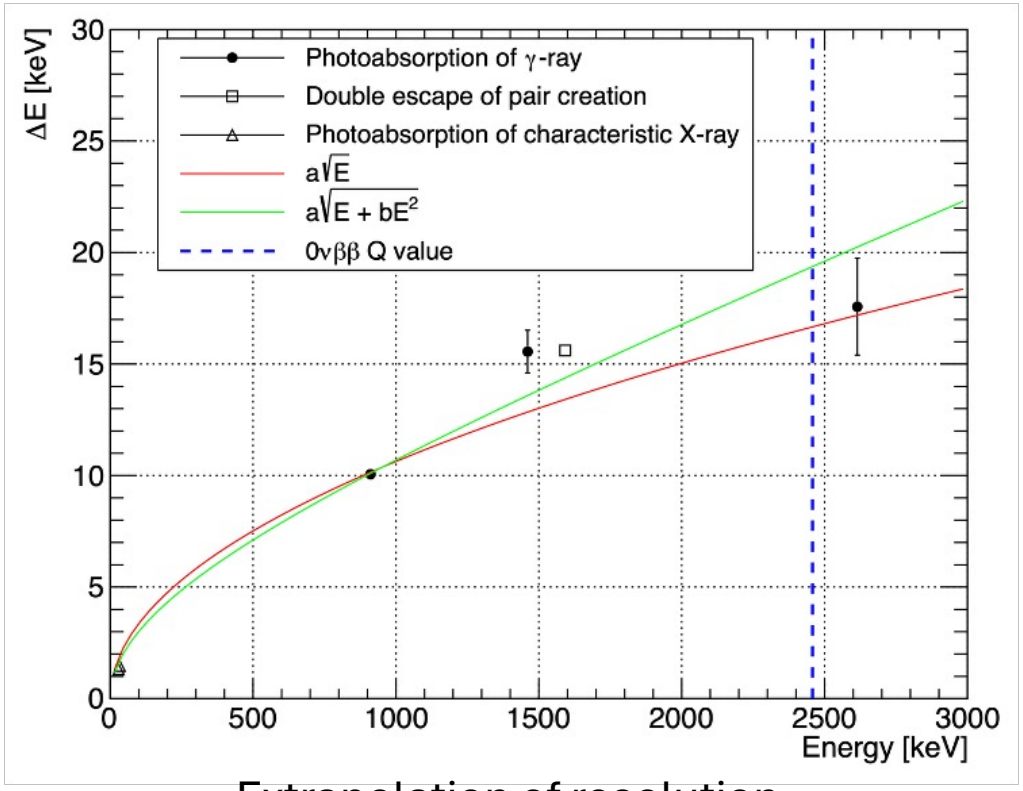
  $a\sqrt{E}$: **(0.66±0.01) %**, $a\sqrt{E + bE^2}$: **(0.85±0.11) %**

→ **World highest resolution for gas TPC in the world!**

2615 keV peak



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



Extrapolation of resolution

Breakdown of energy resolution

@ 2615 keV	
Fluctuation of the number of initial ionization electrons	0.25 %
Mis-reconstruction of z-position	0.24 %
Fluctuation of the EL generation and detection	0.20 %
Recombination	0.17 %
MPPC non-linearirty correction	0.16 %
Variation in time bin of time dependence correction	0.12 %
Offset of the baseline	$\leq$ 0.11 %
Error in time dependence correction	0.10 %
Error in z dependence correction	$\leq$ 0.06 %
Fluctuation of MPPC non-linearity	$\sim$ 0.04 %
Accuracy of the MPPC recovery time	$\leq$ 0.03 %
Fluctuation of the attachment	$\leq$ 0.02 %
Estimation total	0.50 % to 0.52 %
Data total	0.62 ± 0.09 %

Prospect for further improvement

Enhancing scintillation detection efficiency (p23)

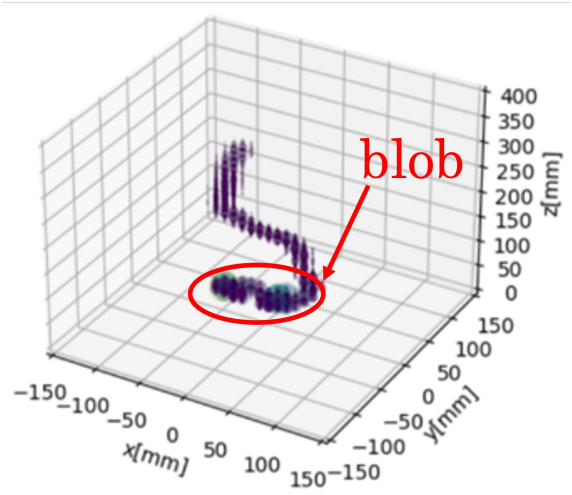
More statistics of EL photons detected by MPPC (p20)

Higher drift field (100 V/cm/bar) by more discharge resistive structure (p19)

Precise correction with deconvoluted waveform (p24)

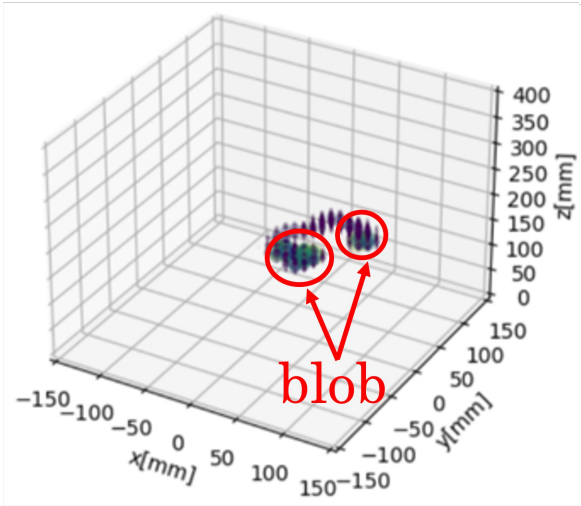
Track pattern recognition

Background feature: 1 track

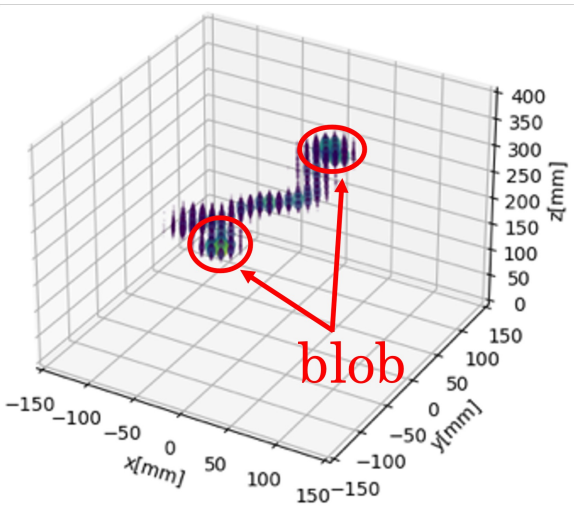


γ-ray photoabsorption 2615 keV

Signal feature: 2 tracks



Pair creation 1593 keV



$0\nu\beta\beta$ 2458 keV (simulated)

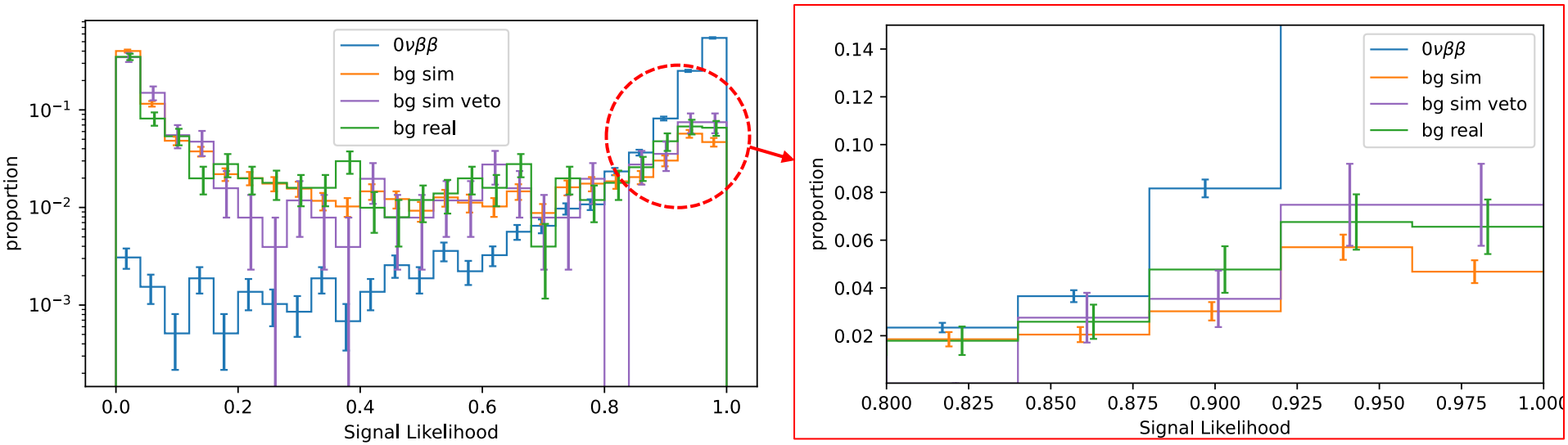
- Discrimination ability for $0\nu\beta\beta$ and background
  - ➢Numbers of blob structure
  - ➢2 tracks tend to drop more energy in the same volume than 1 track

BG rejection with machine learning

- CNN-based ML was constructed using tracks calculated by GEANT4
  - ➢Input: Photon counts in each voxel ($10 \times 10 \times 2.5$ mm^3)
  - ➢**95 % BG rejection with 60 % signal efficiency**

- Real BG data tends to be more signal-like than simulated data
  - ➢Due to dead channels on measurement

→ Simulated data with the same dead channels shows similar tendency



Signal likelihood distribution

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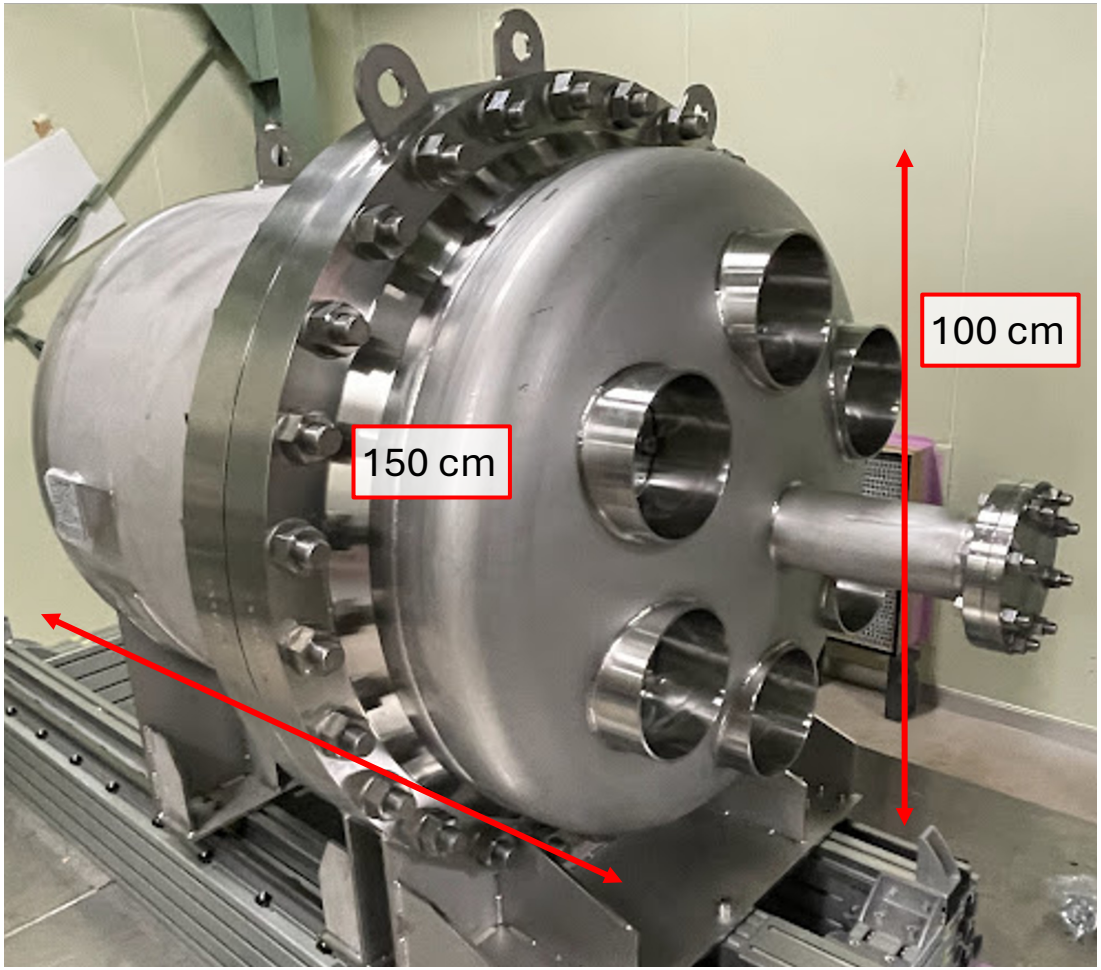
1000L-size detector project

- Planning first $0\nu\beta\beta$ search on AXEL
  - ➢Demonstration of BG rejection ability
- R & D components
  - ➢Discharge-resistive ELCC
  - ➢MPPC upgrade in ELCC
  - ➢FPC-made field cage
  - ➢Scintillation detection
  - ➢MPPC non-linearity correction by RL deconvolution



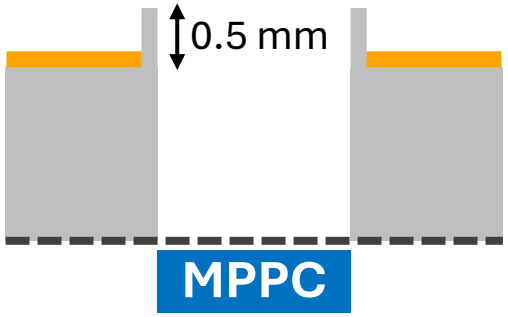
@Kamioka underground

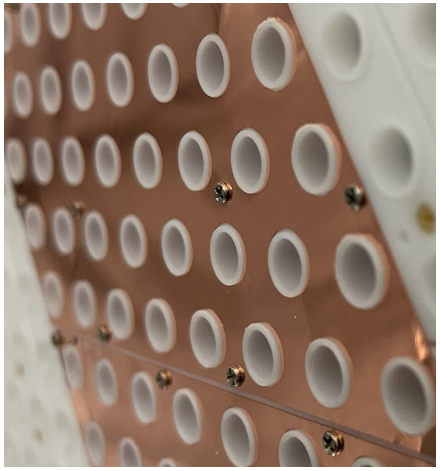
Discharge-resistive ELCC

- Creeping discharge along the cell prevent achieving the target electric field (EL field: 3 kV/cm/bar, Drift field: 100 V/cm/bar)

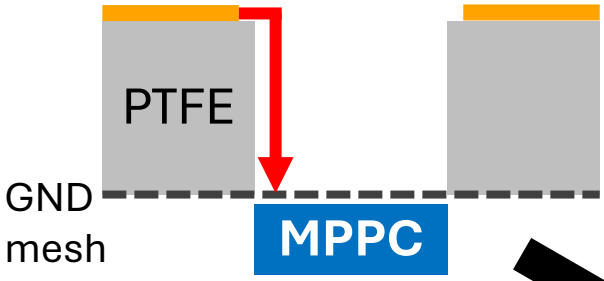
→ More resistive structure is being developed.

1.Step around the cell

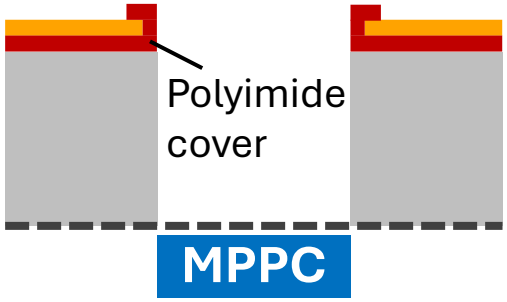


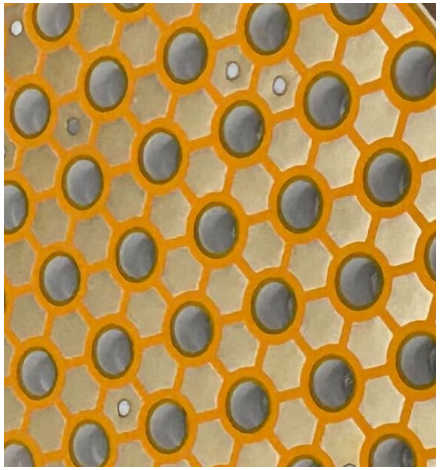


- Achieved target voltage in 6 bar Xe
- Enough EL yield was confirmed



2.Flexible printed circuit (FPC) anode



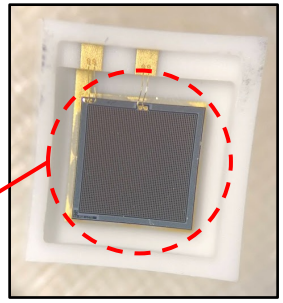


- Achieved target voltage in 7 bar Xe
- EL yield is now under evaluation

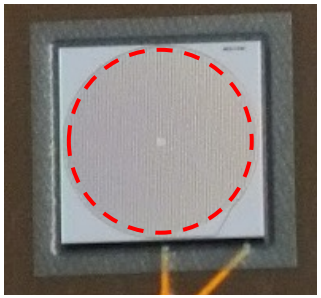
MPPC upgrade in ELCC

- Conventional MPPC: non-sensitive area for the cell (ϕ 4.5 mm)

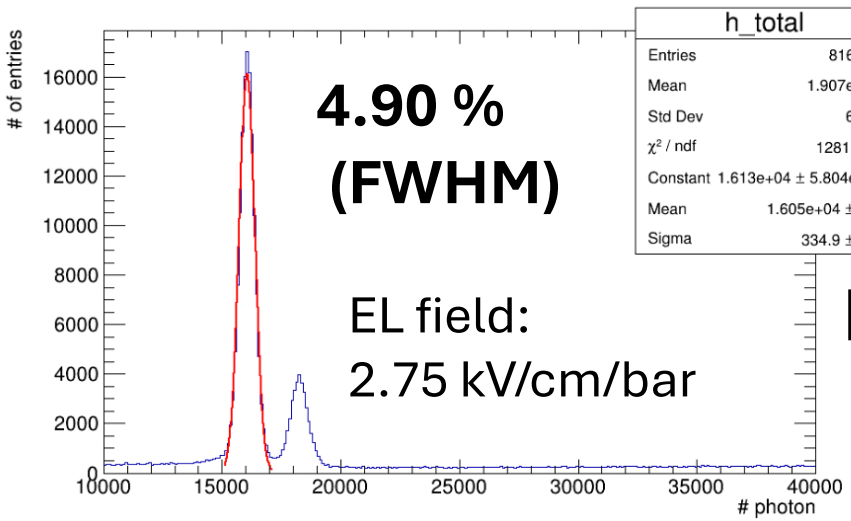
→ Replaced by MPPC with larger sensitive area

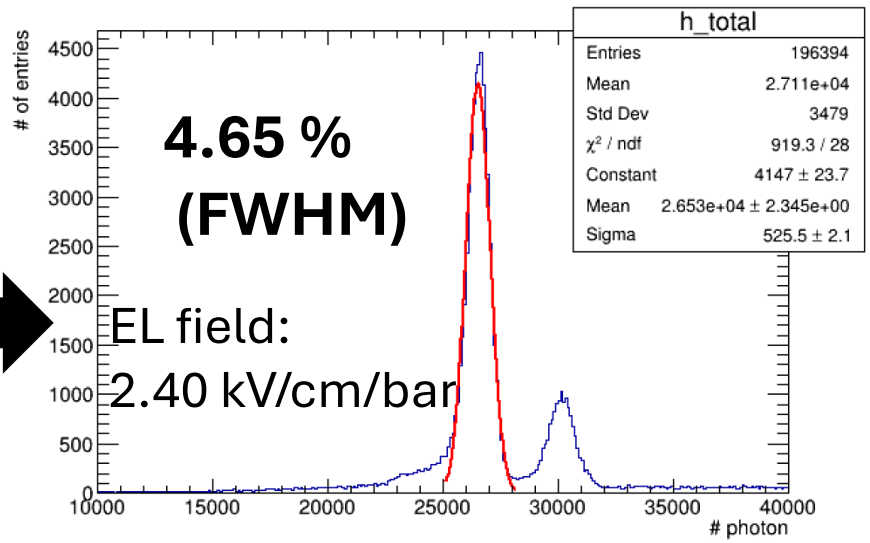


3x3 mm^2



ϕ4.7 mm

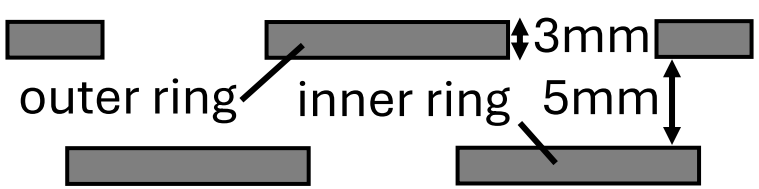


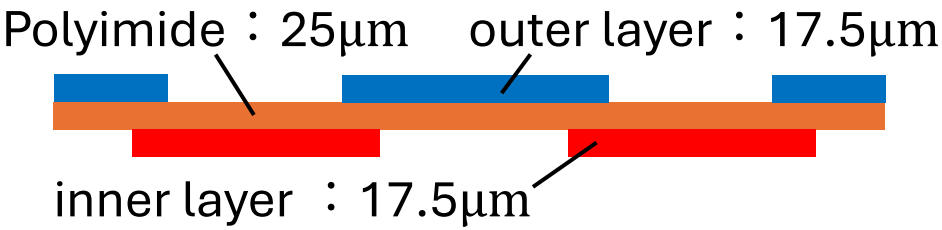


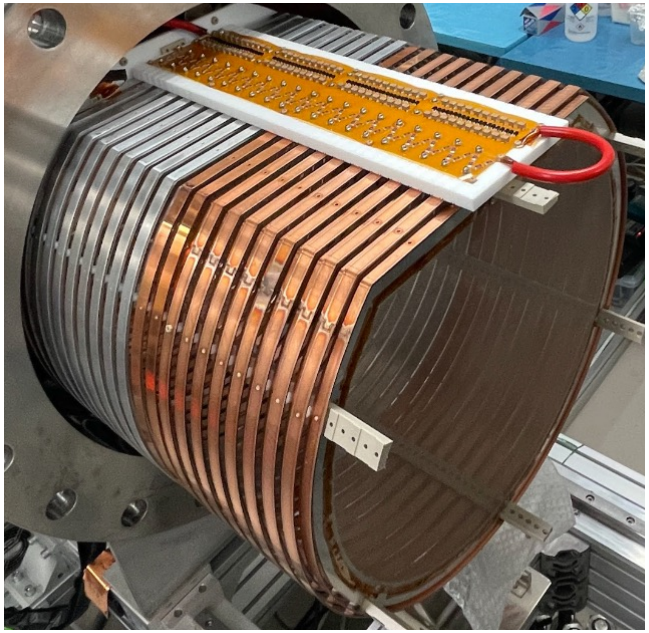
EL photon counts increased greatly, even with lower EL field!

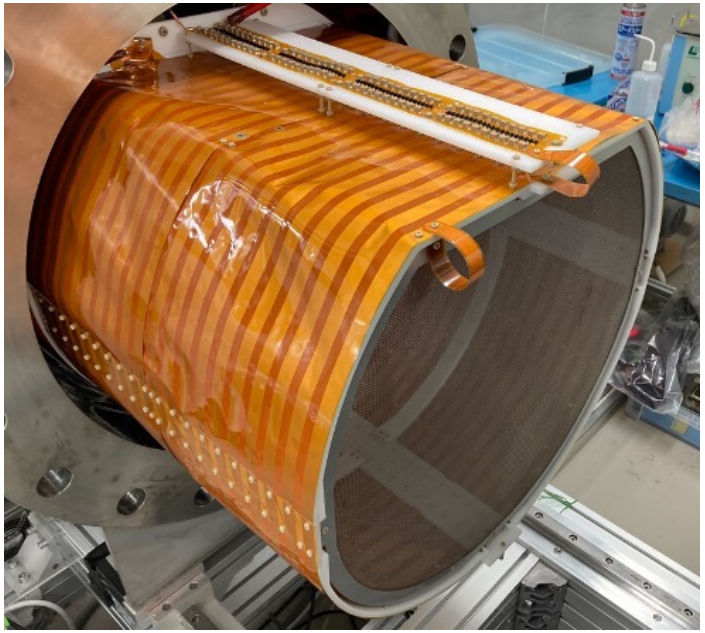
FPC-made field cage

- Replacing copper and aluminum rings to FPC
  - ➢Low material budget, less dead space, production cost reduction







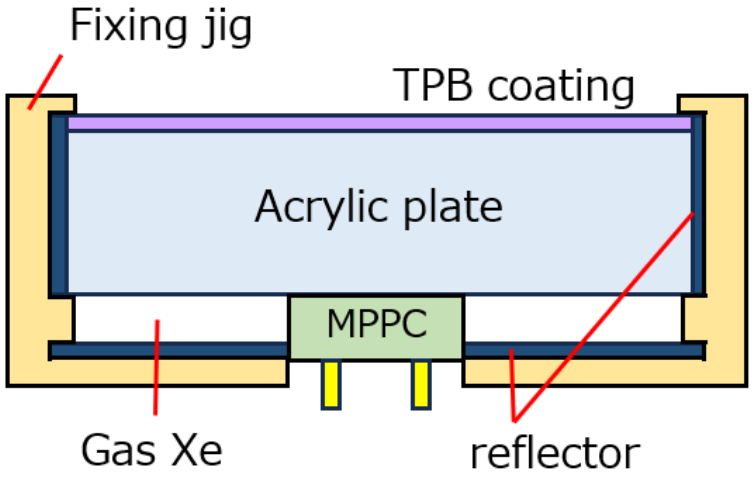


- HV endurance: **98.1 %** of target drift field was achieved.

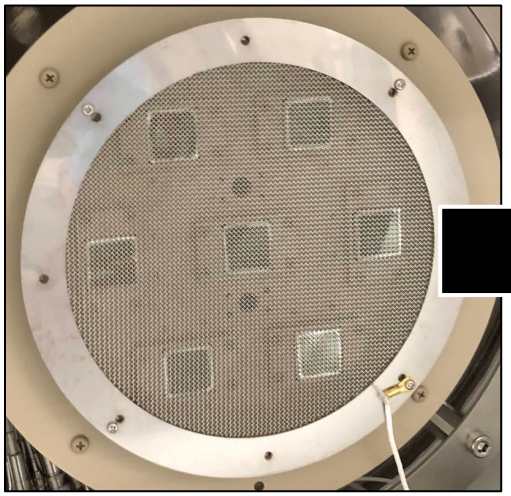
Scintillation detection

- Low scintillation detection efficiency on PMTs leads to frequent the Z (location along the drift direction) mis-reconstruction

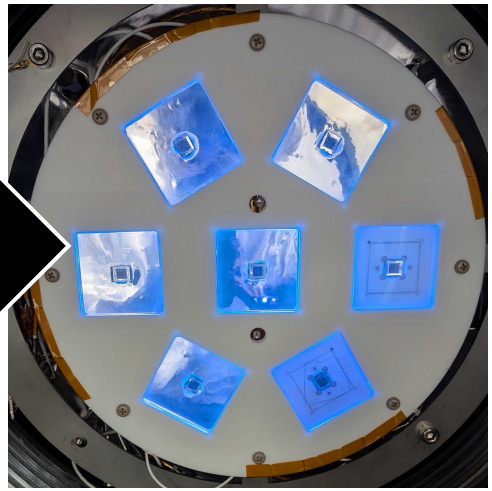
- New scintillation detector
  - ➢Large detection area
  - ➢Trapping photon by reflectors
  - ➢Estimated photon detection: **7.6 times more than that of PMTs**



Structure



PMTs



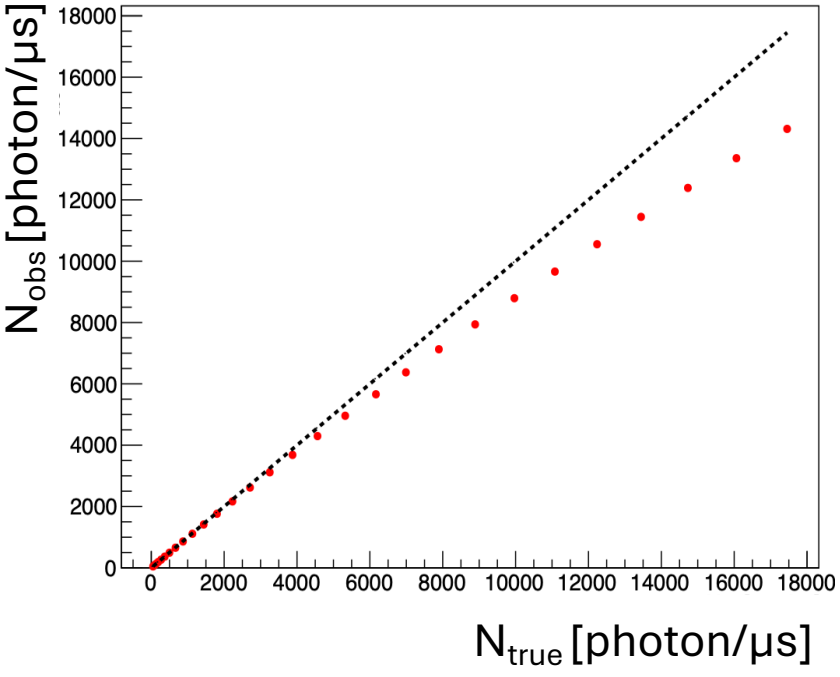
New scintillation detectors

MPPC non-linearity correction by RL deconvolution

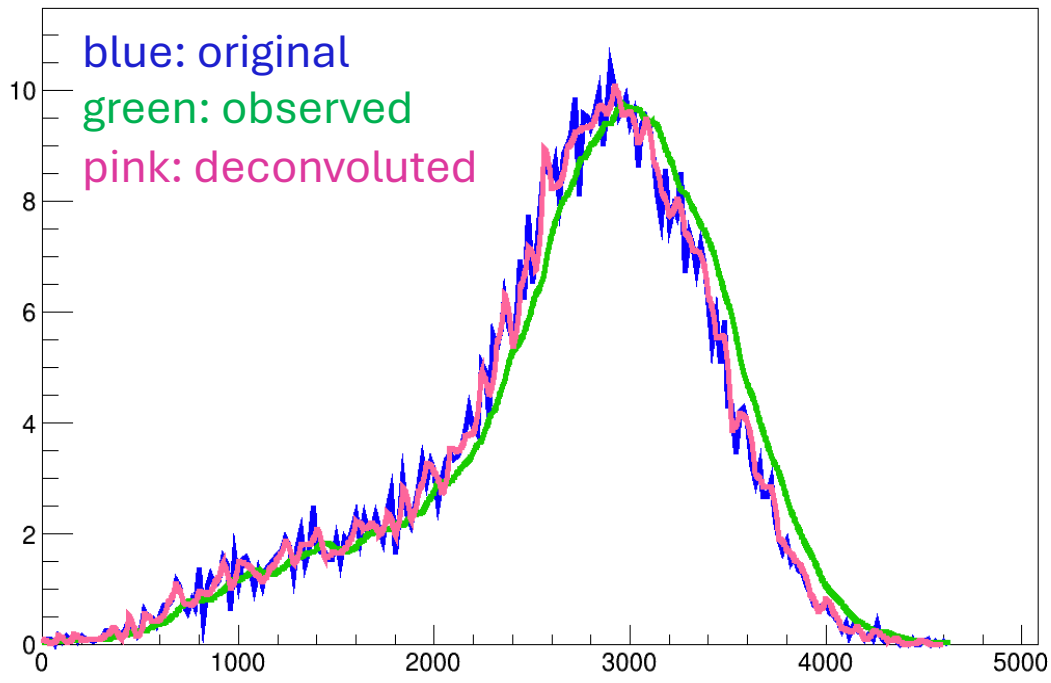
- MPPC shows non-linear response → Corrected on each sampling clock
- Sampling is 5 MHz, after low-pass filter (~ 200 MHz in original wave)
  - ➢LPF worsens non-linearity correction accuracy
- RL deconvolution was applied to waveform for more precise correction

→ **Energy resolution contribution reduced from 0.16 % to 0.042 %!**

MPPC non-linearity



Waveform before and after RL deconvolution



Outline

- AXEL experiment
- Performance evaluation of 180L-size prototype
- R&D for 1000L-size detector
- Summary

Summary

- AXEL experiment is developing high-pressure Xe gas TPC to do $0\nu\beta\beta$ search under ideal conditions.

- Performance was evaluated with 180L-size prototype.
  - Energy resolution: 0.62 % @2615 keV (FWHM)
  - BG rejection with ML: 95 % rejection with 60 % signal efficiency

- First $0\nu\beta\beta$ search is planned with 1000L-size detector and many R & D are ongoing for it.

- ELCC installation for NEXT-100 is under active discussion between AXEL and NEXT.

Backup

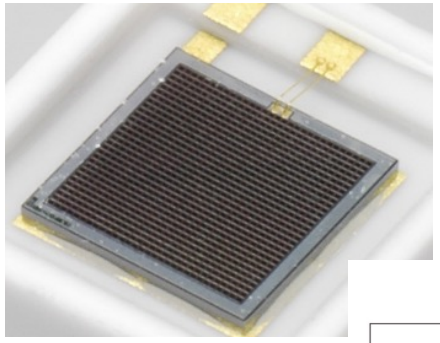
MPPC ~Multi-Pixel Photon Counter

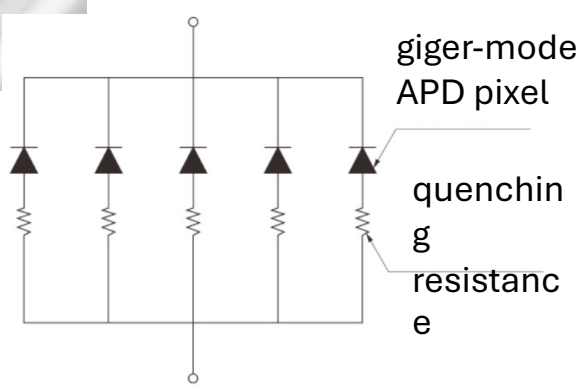
- Produced by Hamamatsu Photonics
- Arrange a lot of pixels in parallel
- Operated by applying higher voltage than breakdown voltage

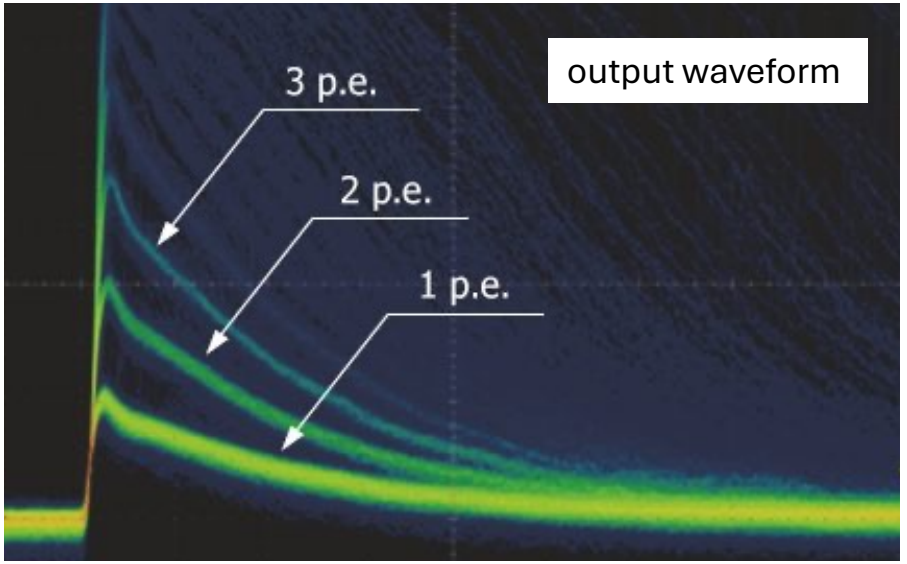
→ Output charge is proportional to over voltage

- Constant charge output in 1 pixel detection

→ Count # of detected photon as # of output pixel



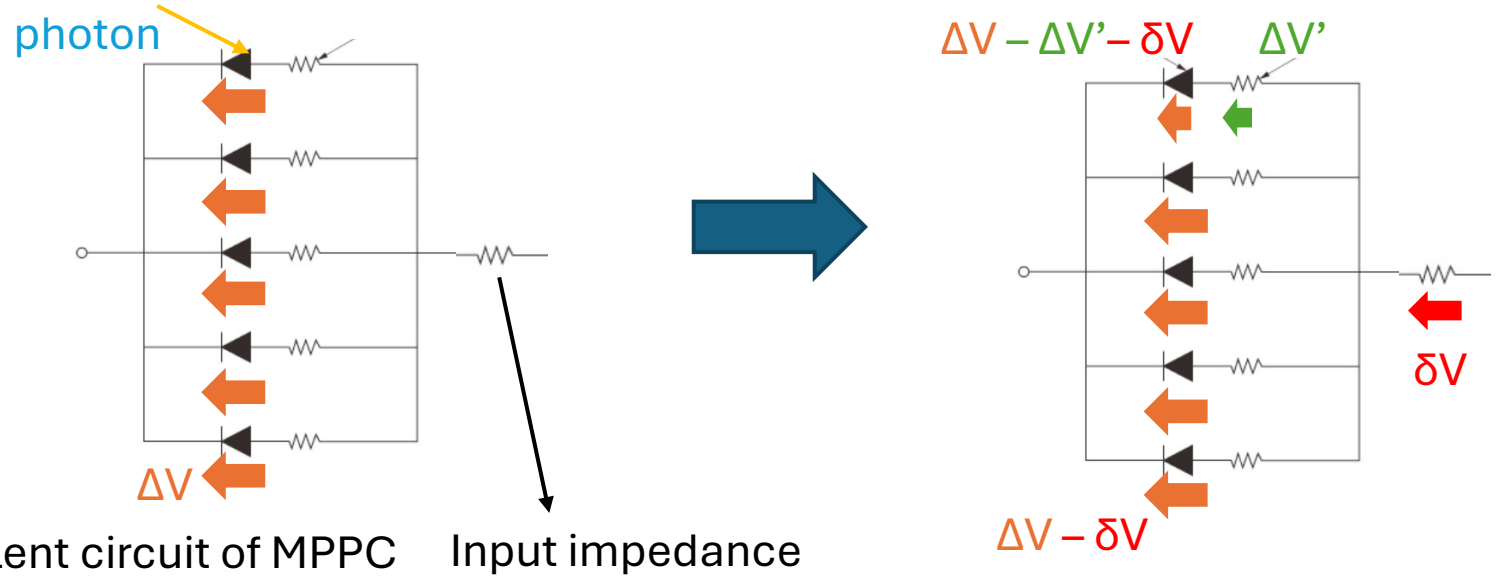




Cause of MPPC nonlinearity

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)



Principle of CW generator

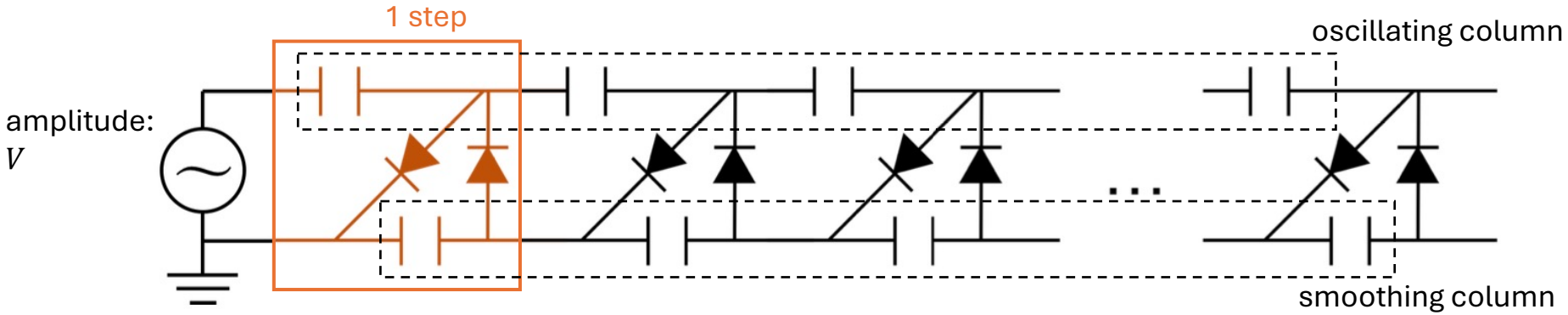
- 1 step composed of 2 capacitors and 2 diodes
- Voltage oscillation of capacitors in oscillating column supply charges to capacitors in smoothing column

→ 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

Field cage RI contamination

		^{214}Bi	^{208}Tl
Material	Aluminum	$< 3400\,\mathrm{mBq/kg}$	$361\,\mathrm{mBq/kg}$
	Oxygen-free copper	$< 0.012\,\mathrm{mBq/kg}$	$< 0.004\,\mathrm{mBq/kg}$
	FPC	$< 1.86\,\mathrm{mBq/kg}$	$< 0.898\,\mathrm{mBq/kg}$
Field cage	Aluminum $6.17\,\mathrm{kg}$	$< 2.10 \times 10^{4}\,\mathrm{mBq}$	$2.23 \times 10^{3}\,\mathrm{mBq}$
	Oxygen-free copper $20.5\,\mathrm{kg}$	$< 0.246\,\mathrm{mBq}$	$< 8.18 \times 10^{-2}\,\mathrm{mBq}$
	FPC $152.8 \times 10^{-3}\,\mathrm{kg}$	$0.284\,\mathrm{mBq}$	$0.137\,\mathrm{mBq}$