Status of the high pressure Xe gas TPC 0νββ experiment AXEL

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for the AXEL Collaboration

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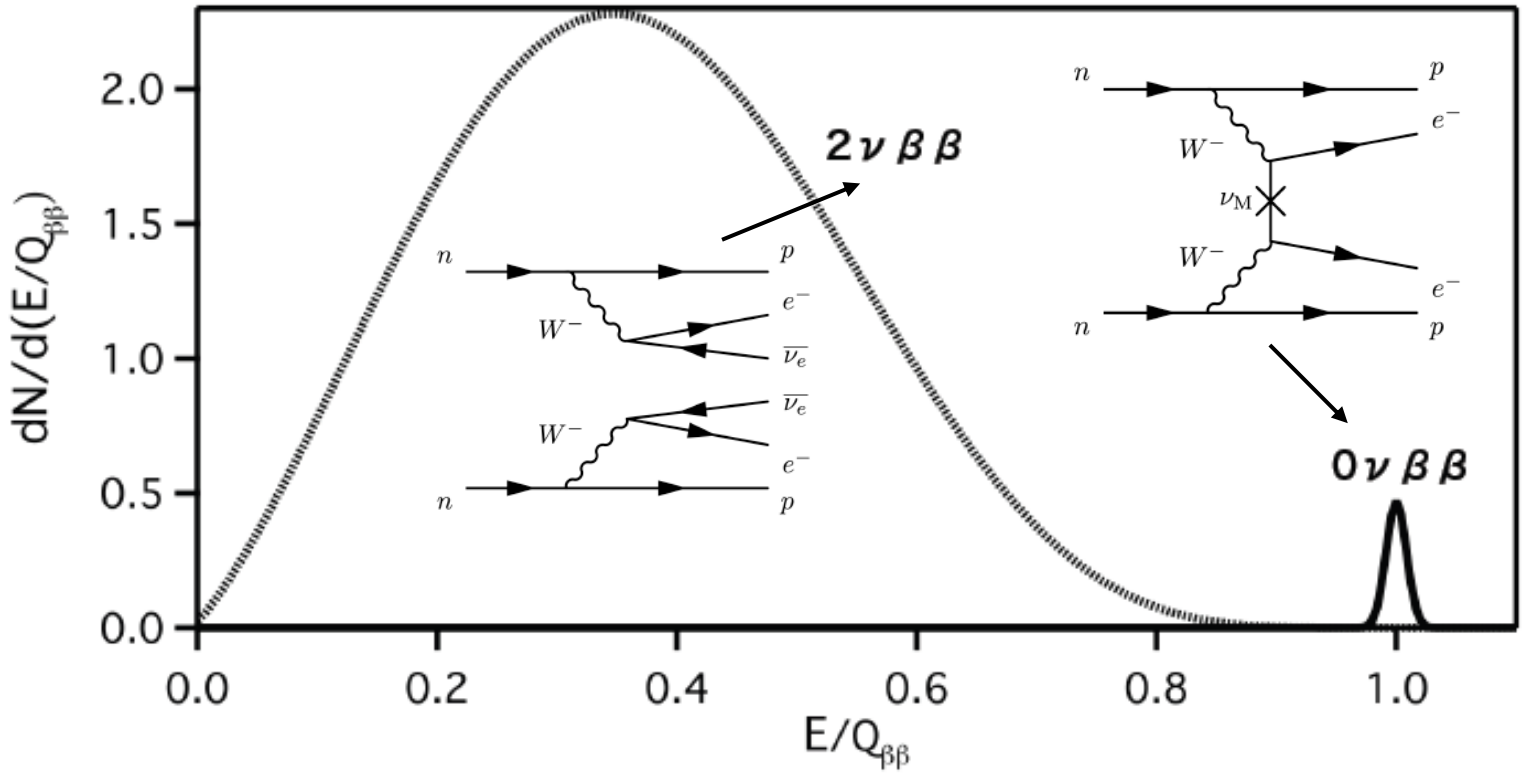
Neutrinoless double beta decay

- It occurs only if neutrinos have Majorana-mass
- Key to understand
  - Origin of the light neutrino mass: See-Saw mechanism
  - Matter-antimatter asymmetry in the universe: Leptogenesis

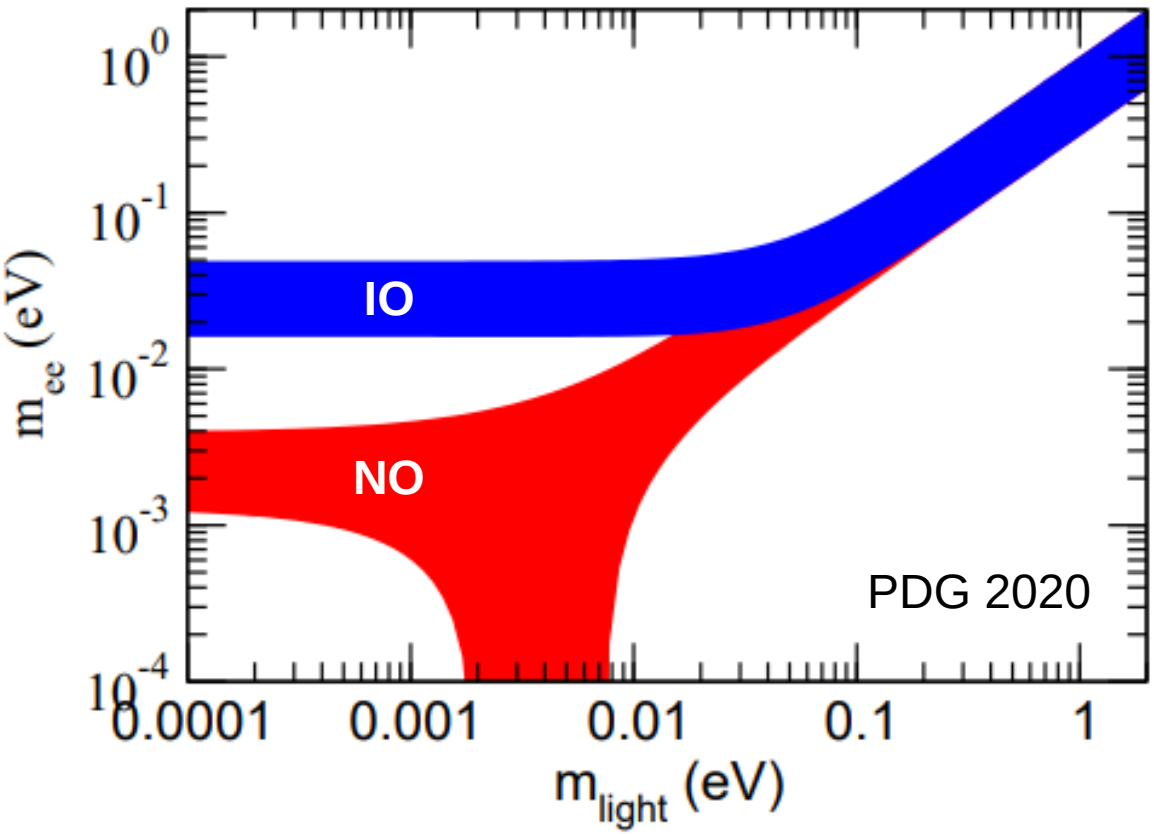


Neutrinoless double beta decay

- To reach Normal hierarchy, BG free & ton-scale is required
  → High pressure Xenon gas TPC is a good solution

BG free $\propto \frac{1}{\sqrt{MT}}$

BG limited $\propto \left(\frac{b\Delta E}{MT}\right)^{1/4}$



1ton x 10 yr

1ton x 10 yr

100ton x 10 yr

High Pressure Xenon gas TPC

High pressure xenon gas TPC has advantages for 0νββ search

- ^{136}Xe
  - Source & detection media
  - Natural abundance is 8.9% and can concentrate by centrifugation
  - Long $T^{2\nu}_{1/2}$ (2.1×10^{21} year) → Low background

- High pressure gas TPC
  - Large mass
  - Event topology can be obtained

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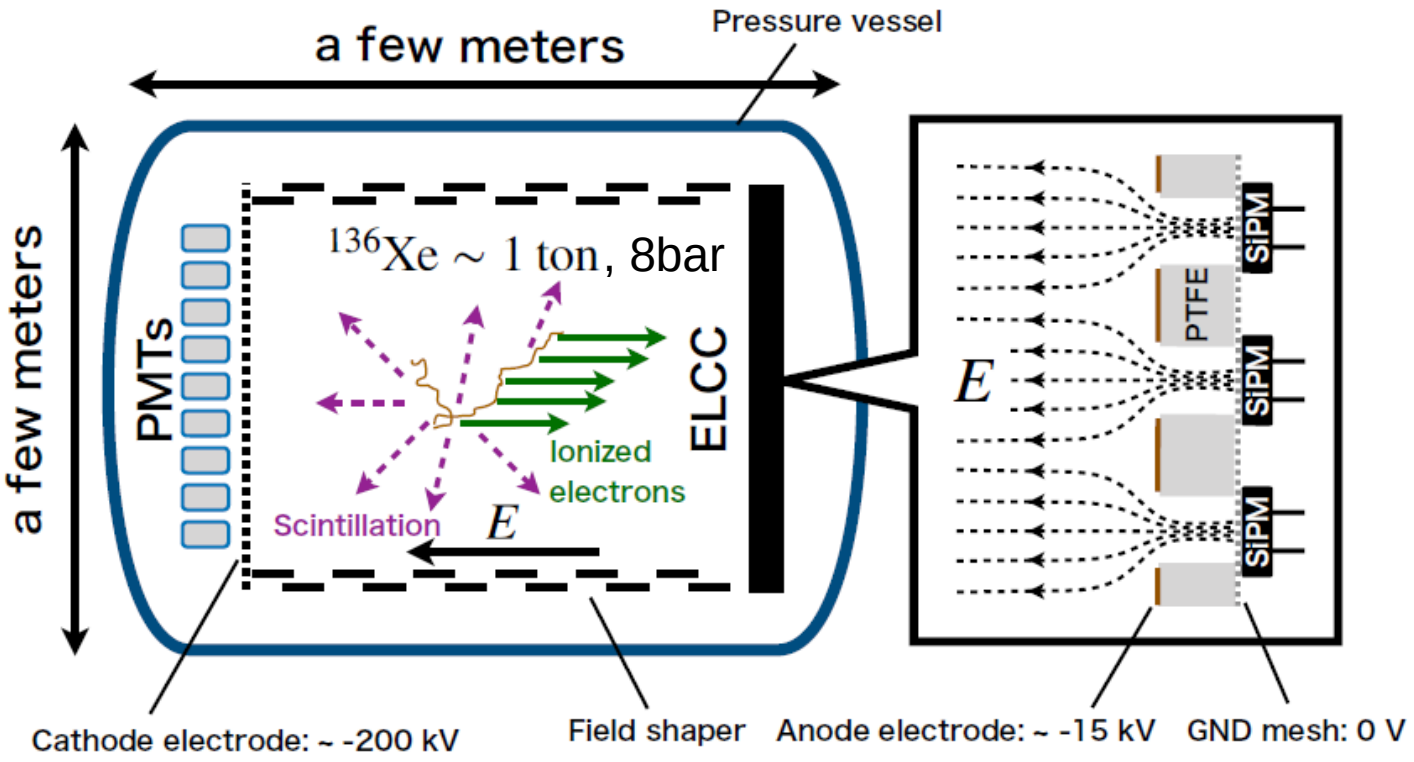
AXEL experiment

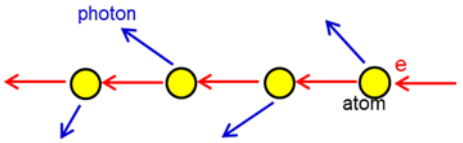
A Xenon ElectroLuminescence detector

- High pressure xenon gas TPC
- 0νββ nuclei : ^{136}Xe
- Unique cell readout structure (ELCC)



ELCC : Electroluminescence Light Collection Cell

- Drawing ionization electrons into cells
- EL process in cells and photon counting by MPPC
  - EL is a linear gain process
  - Position dependence is suppressed



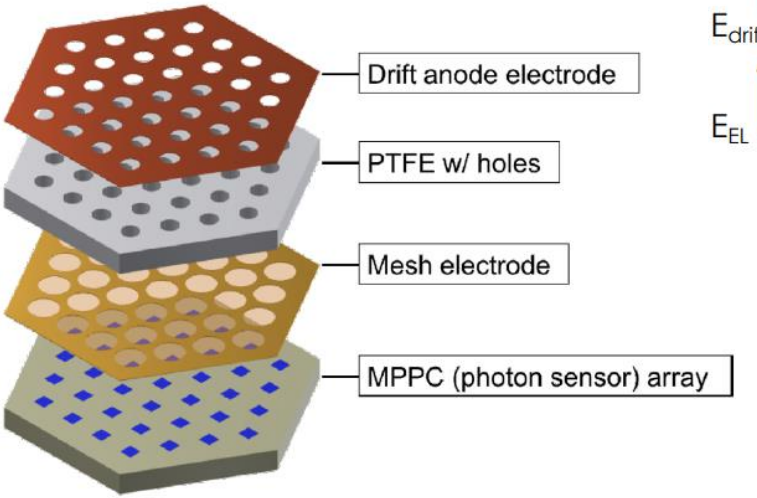
→ High energy resolution

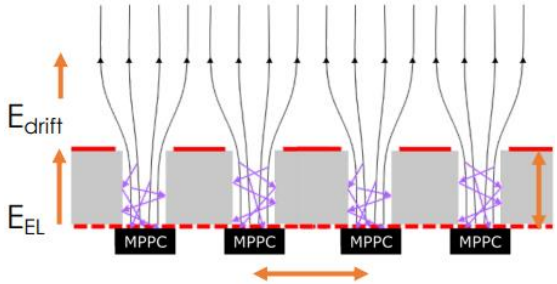
  - Pixelized hit pattern + hit timing for 3D track reconstruction

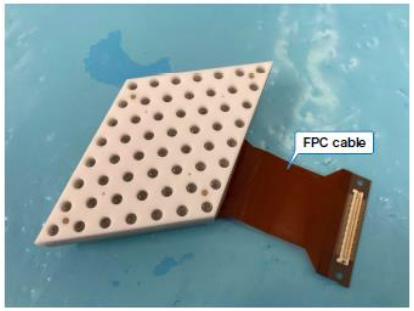
→ BG rejection

  - Extendable to large size thanks to its rigid structures

→ Large mass



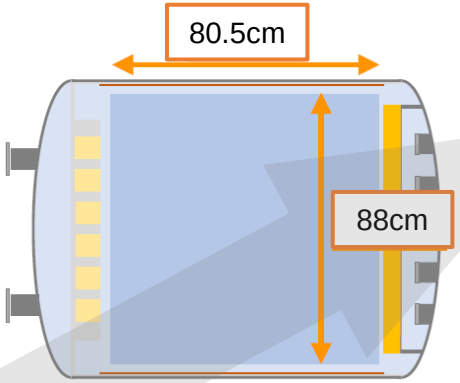




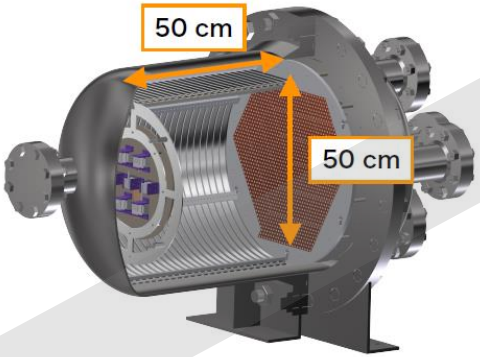
Roadmap

- Aiming to achieve our target sensitivity $<m_{\beta\beta}>$ = 10meV with a ton scale detector
- Constructed 10-L, 180-L prototype
- New 1000L detector is being developed

ton scale

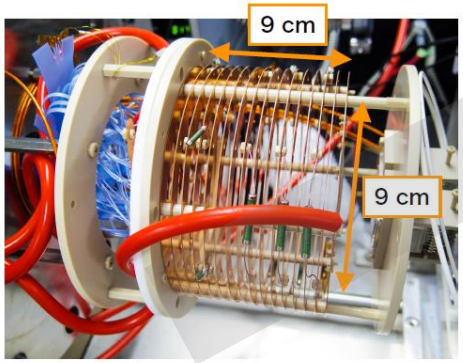


1,000-L detector
・2024 –
・Physics run
・Underground
・6kch



180-L prototype
・2018 -
・～4.5kg @ 8bar
・phase-1 : 168ch
・phase-2 : 672ch

10-L prototype
・2014 - 2018
・0.05kg @ 8bar
・ELCC proof of concept



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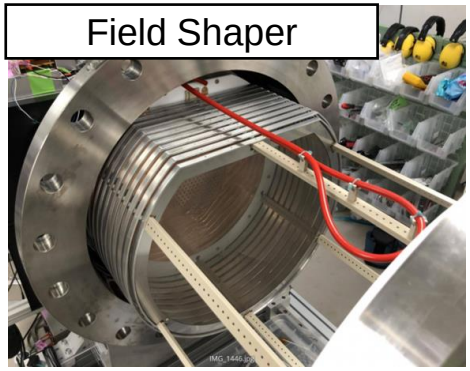
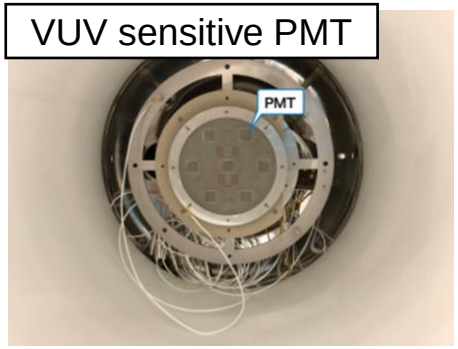
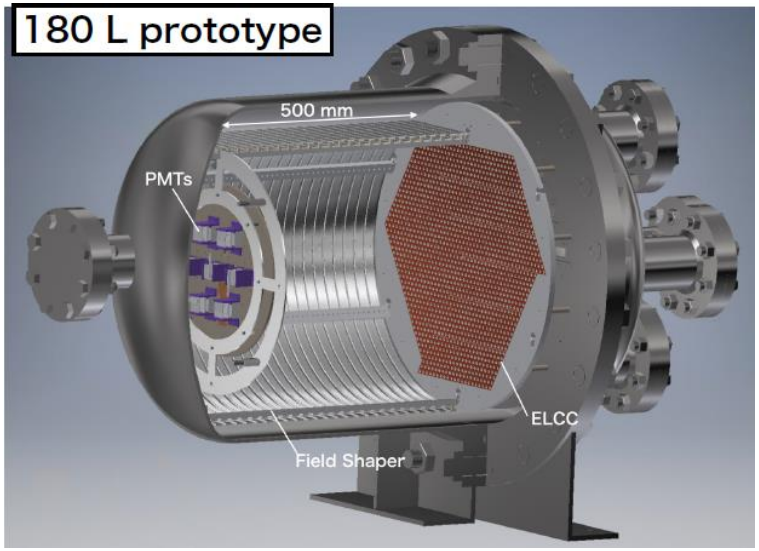
180L prototype detector

Field Shaper

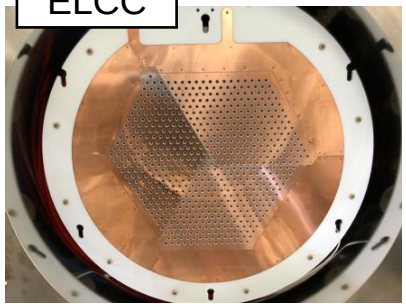


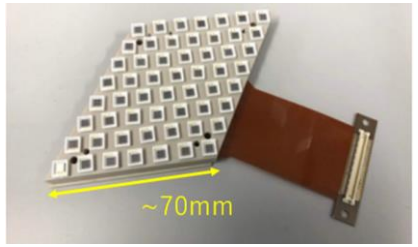
VUV sensitive PMT



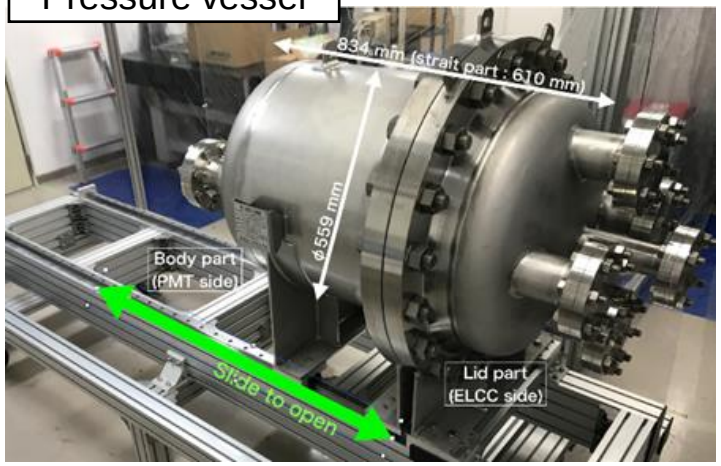


ELCC

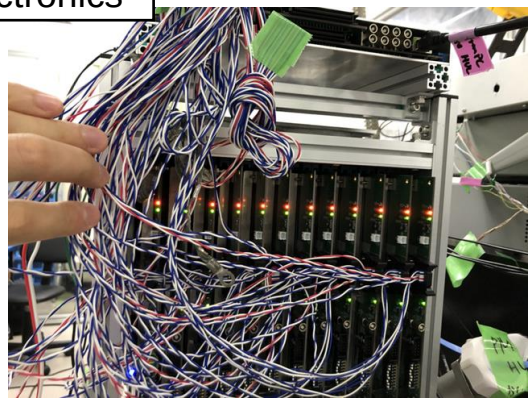




Pressure vessel

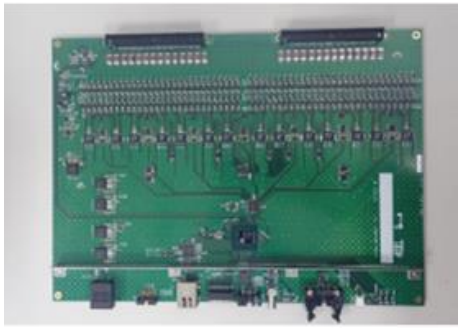


Front end electronics

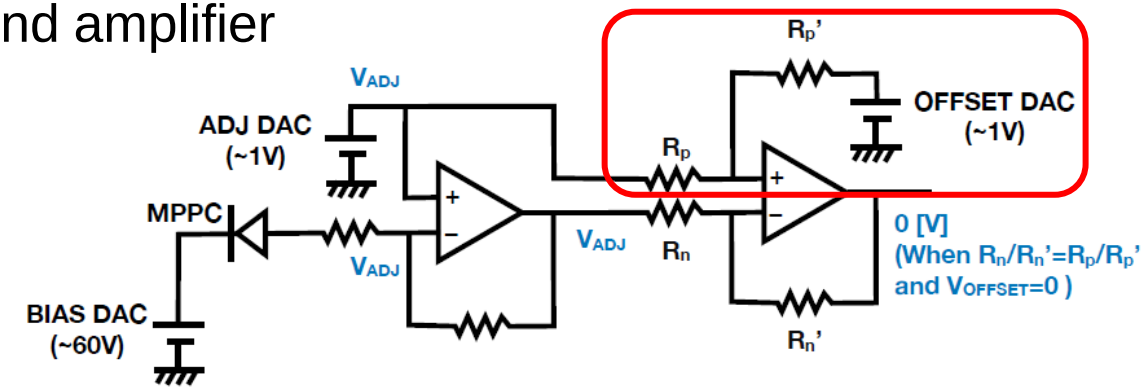


AxFEB

- Front end electronics for 180L prototype to read out MPPC signal
  - Low gain ADC (ADCL) for the EL light waveform acquisition
  - High gain ADC (ADCH) for the dark pulse acquisition
- ADCL 5MS/s x 56 ch readout
- ADCH
  - 40MS/s x 7 ch readout
  - Acquiring channels can be changed by a multiplexer



- Provide the bias voltage adjustment by applying V_{ADJ} to each MPPC
  - Individual bias voltages can be adjusted with 10mV units
  - DC coupling to avoid pulse shape distortion
  - Cancel V_{ADJ} at the second amplifier

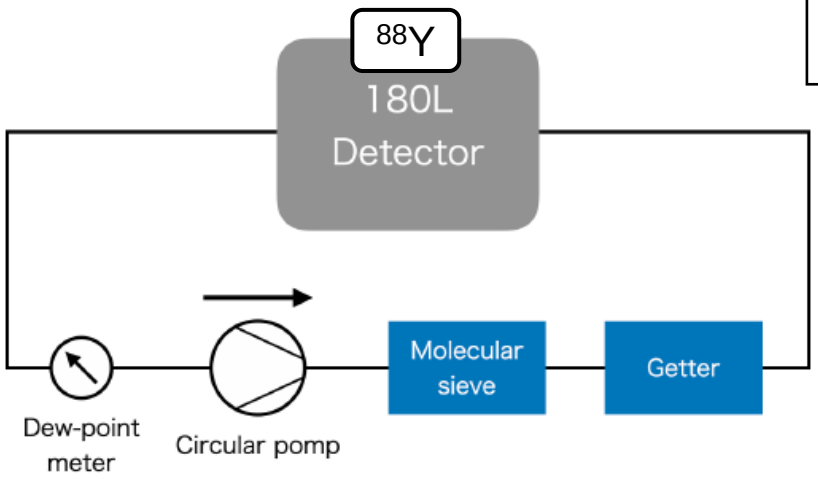


Performance evaluation

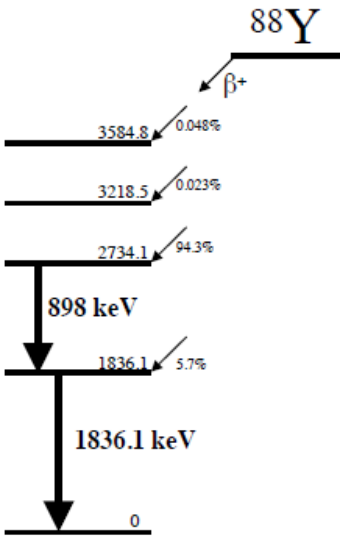
- ^{88}Y gamma ray source is placed on the pressure vessel
  - Measure energy resolution
  - Reconstruct 3D track
- Measurements are conducted in 6 runs, each of which has 200,000 events

condition

Gas pressure	8 bar
EL field	2.25 kV/cm/bar
Drift field	75 V/cm/bar
Source	^{88}Y

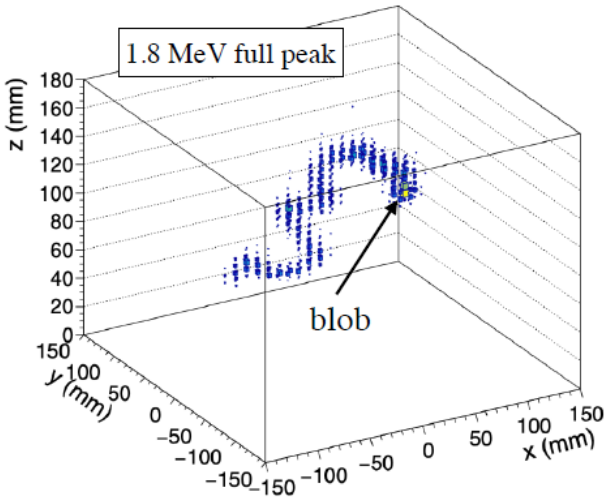


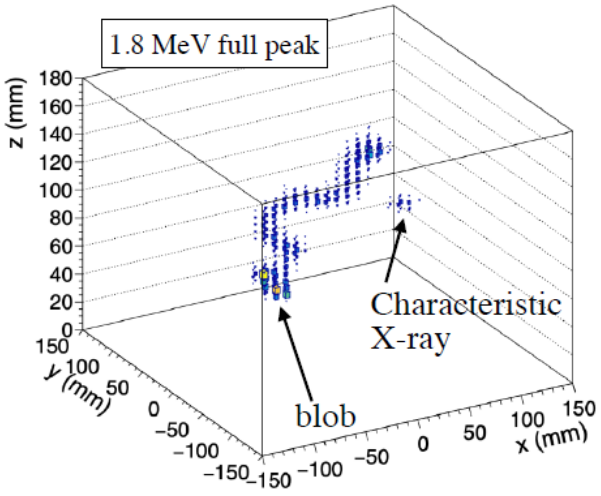
First performance evaluation over 1 MeV

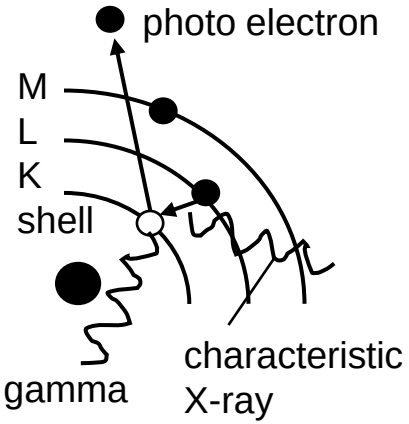


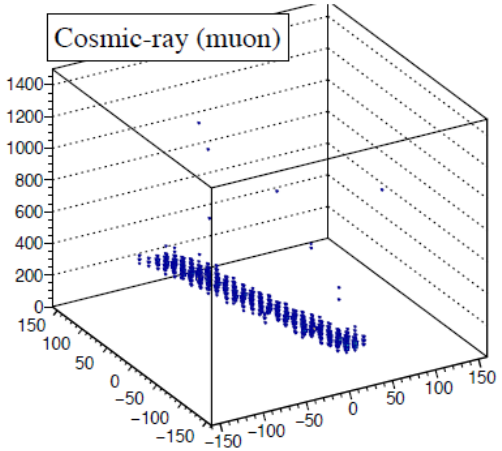
Event topology

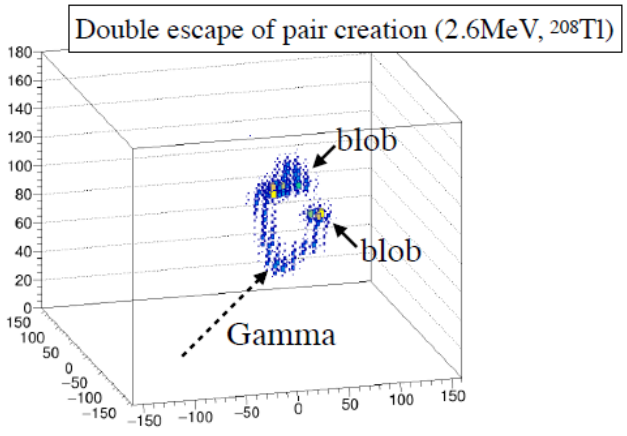
- “Blob” appears in the endpoint of track (Bragg peak)
- Characteristic xray cluster is confirmed near the main cluster in 1.8MeV energy of ^{88}Y gamma event → can be used to reject BG











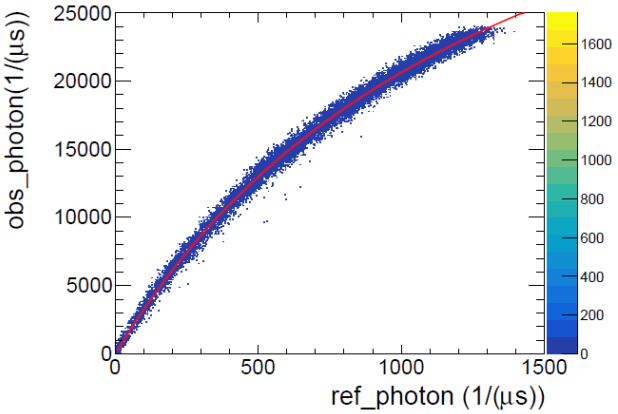
Analysis

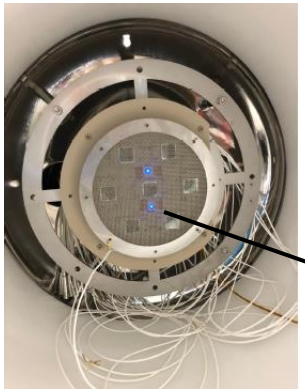
Correction of MPPC non-linearity → EL gain Correction → Time Correction → z Correction

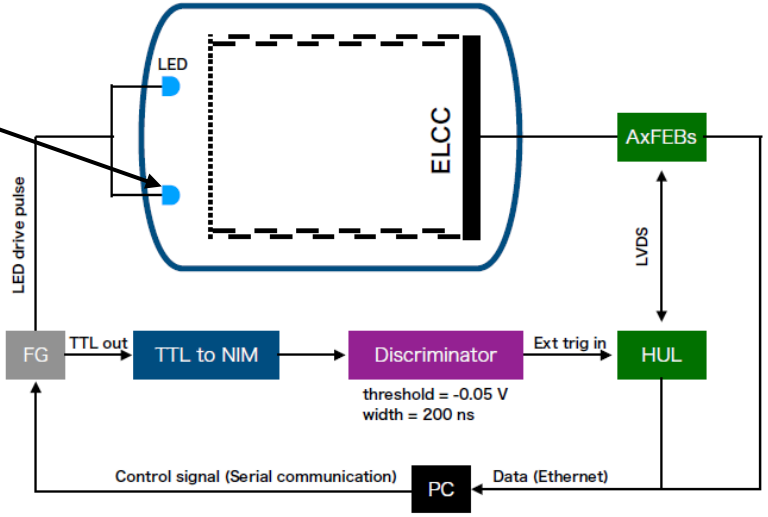
Correction of MPPC non-linearity

- MPPCs have a significant nonlinearity under high light intensity
- The nonlinearity can be characterized by recovery time τ
- τ's of each MPPC are measured with LED light in advance

$$N_{\mathrm{obs}} = \frac{N_{\mathrm{true}}}{1 + \tau \dfrac{N_{\mathrm{true}}}{\Delta t \cdot N_{\mathrm{pix}}}}$$





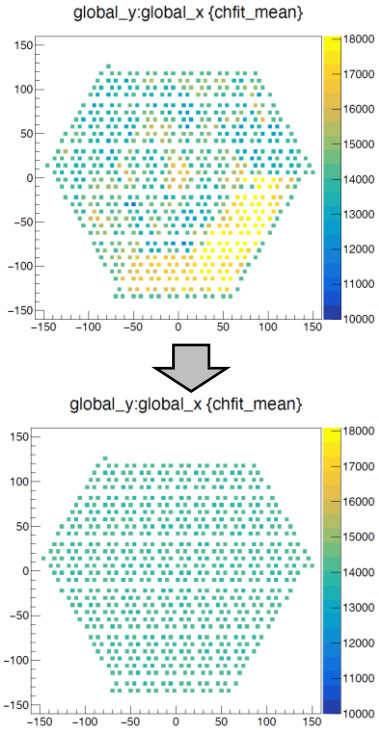


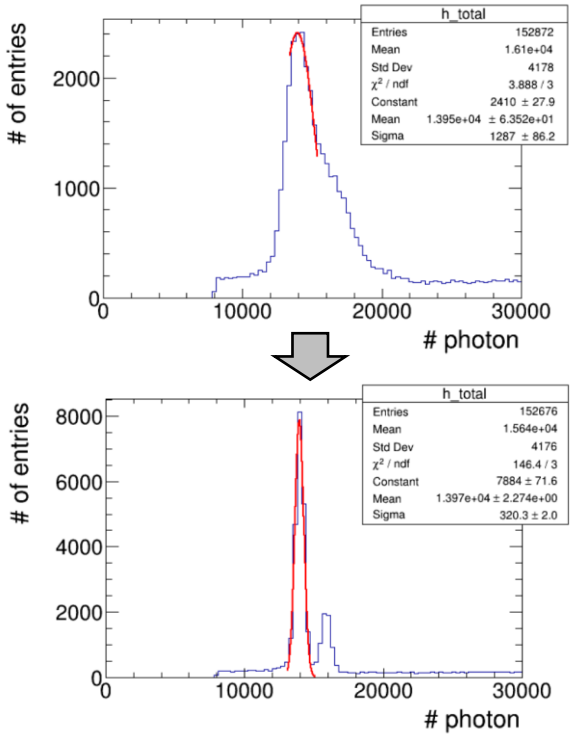
Analysis

Correction of MPPC non-linearity → **EL gain Correction** → Time Correction → z Correction

EL gain Collection

- Conversion factors of EL process are different for each ELCC cell
- Correct non-uniformity by using xenon K_α X-ray (29.7keV)





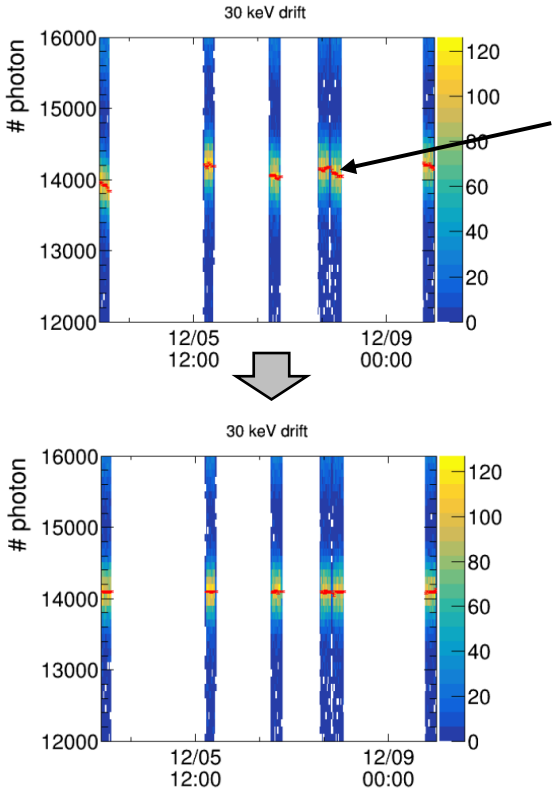
K_α (29.7 keV) and K_β (33.6 keV) peaks are separated

Analysis

Correction of MPPC non-linearity → EL gain Correction → Time Correction → z Correction

Time Correction

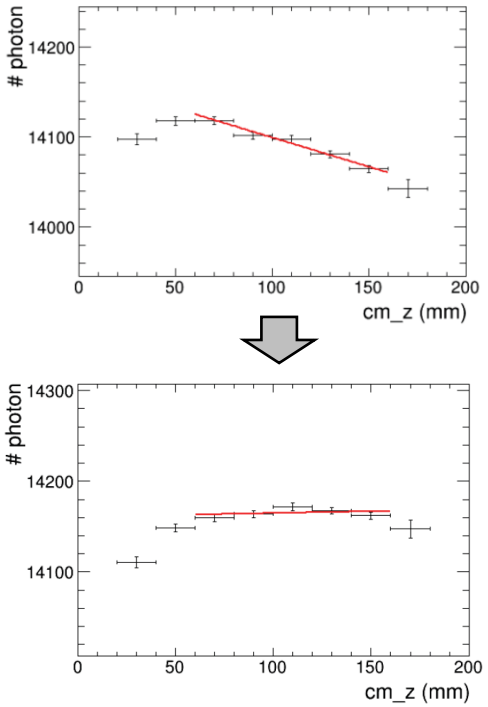
- Correct the time dependence for every 30 min



K_α peak

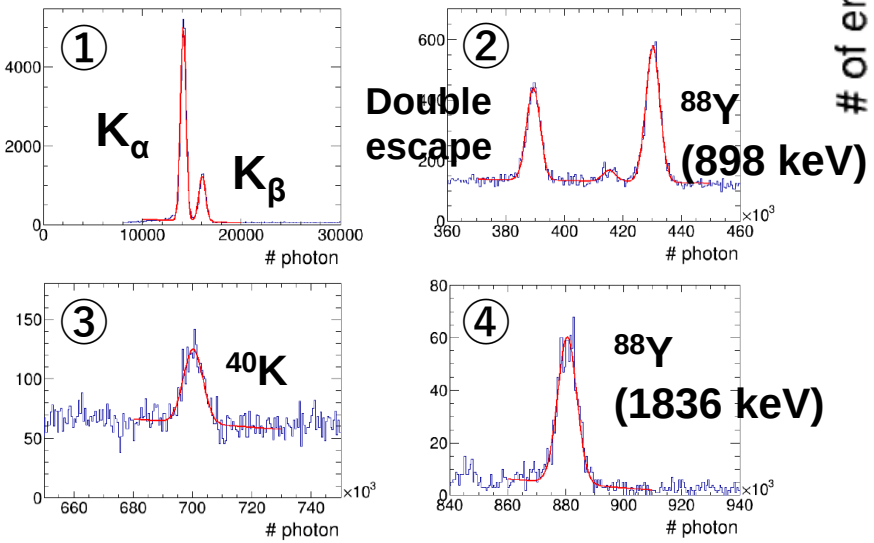
z Correction

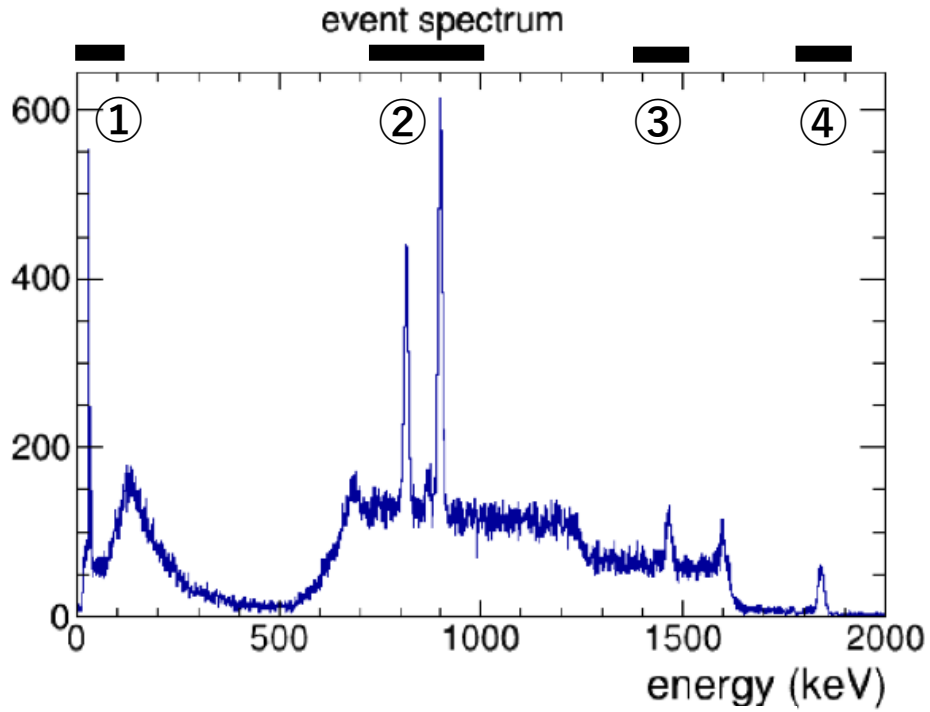
- Correct the z dependence
- Caused by attachment of ionization electrons by impurity



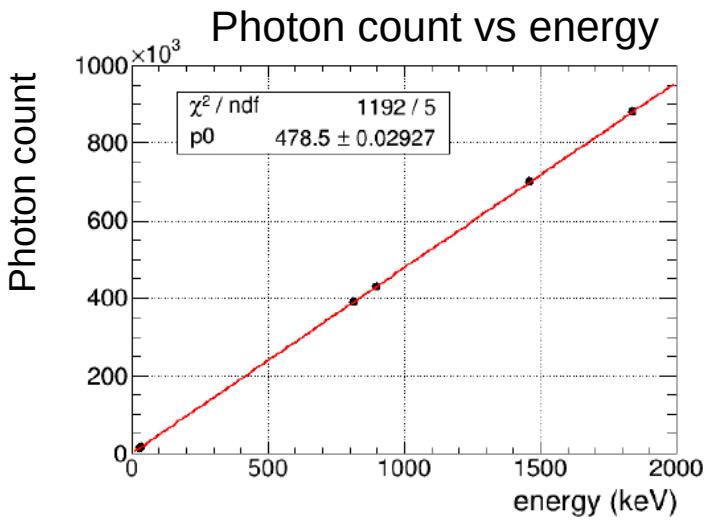
Energy spectrum

Each peak is fitted by Gaussian and linear function





target	ΔE/E(FWHM)
K_α : 29.68 keV	4.67 ± 0.02 %
K_β : 33.62 keV	4.98 ± 0.05 %
double escape : 814 keV	1.38 ± 0.04 %
^{88}Y : 898 keV	1.31 ± 0.03 %
^{40}K : 1461 keV	1.10 ± 0.07 %
^{88}Y : 1836 keV	0.89 ± 0.03 %



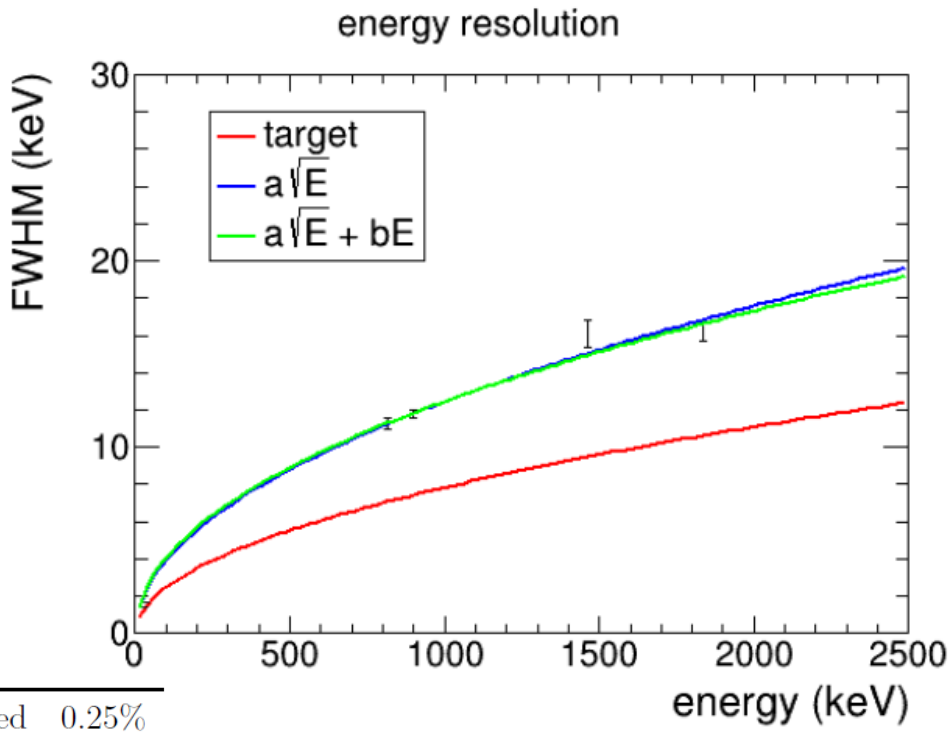
Evaluation of energy resolution

Extrapolation of the energy resolution to the 2,458keV by a√E

ΔE/E = 0.79% (FWHM)

No significant linear components

(Target ΔE/E = 0.5% (FWHM))



Breakdown of energy resolution at 1.8MeV is estimated as below:

Fluctuation of the number of ionization electrons produced	0.25%
Fluctuation of EL amplification	0.30%
Position dependence of EL amplification factor	0%
Waveform processing in AxFEB	0%
Error in EL gain calibration	0.12%
Accuracy of MPPC recovery time measurement	0%
Error in time correction	0.20%
Error in z correction	0.31%
Dependence of the drift electric field	0.27%
Unknown	0.62%
Total	0.89%
Target which corresponds to 0.5% FWHM at Q-value	0.58%

We still have large unknown components
→ further investigation should be done

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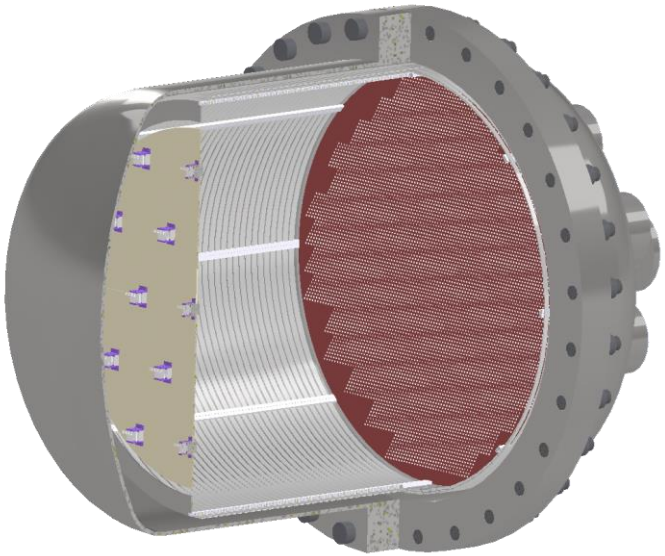
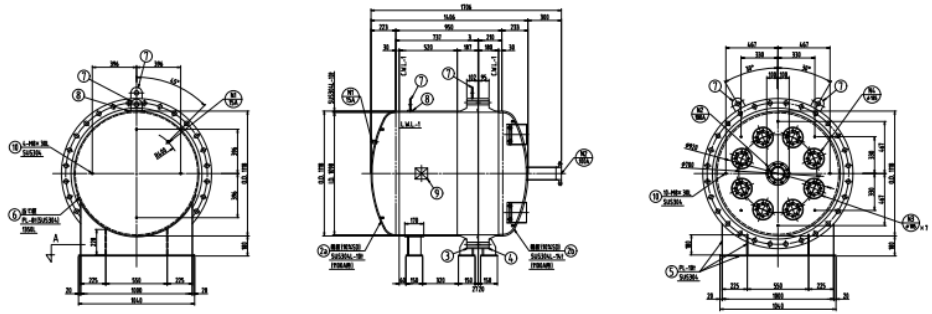
1000L detector

- Physics data taking is planned to begin in 2024 (Taking data with partial detector in 2023)
- The gas system has arrived in June
- New Pressure vessel will be created in this fiscal year

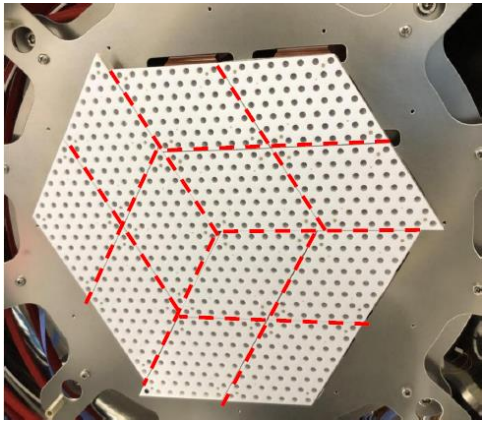




ELCC

- For 180L prototype, 7x8 channels was adopted as a unit
  - FEB channel density needs to be increased to fit the ELCC size

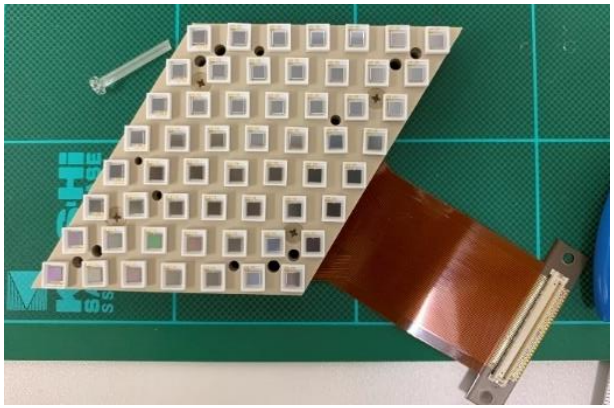
  → Adopt 8x8 ch for 1,000L detector

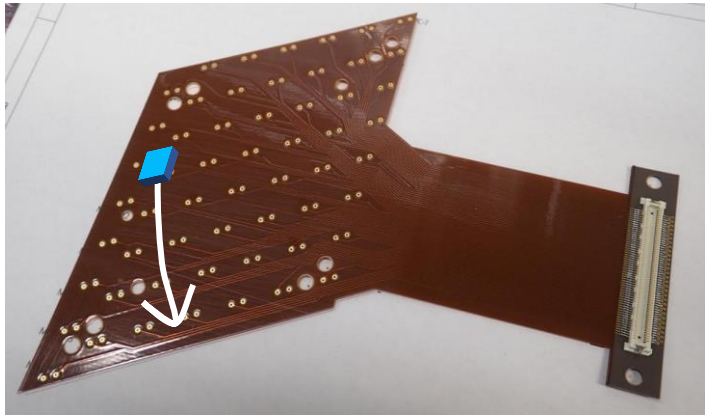


- MPPC
  - High activity found on MPPC ceramic package

  → Planning direct surface-mount on read-out

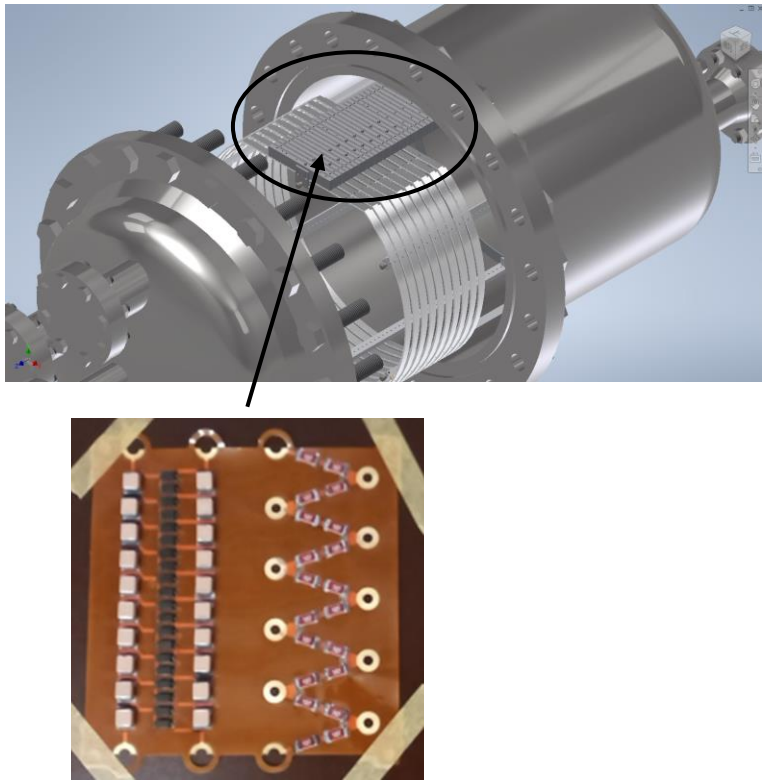
  FPCs without this package
  - Enlarge sensitive area, 3x3mm square → 4.7mmΦ

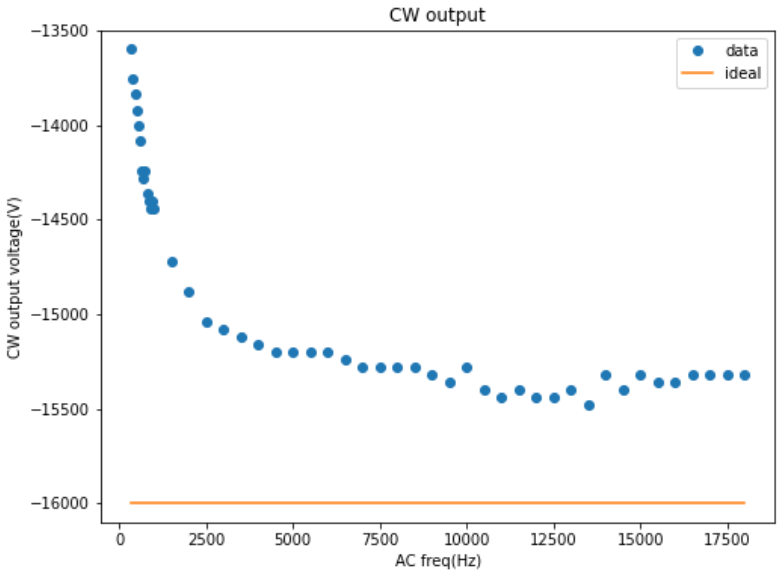




Cockcroft-Walton multiplier

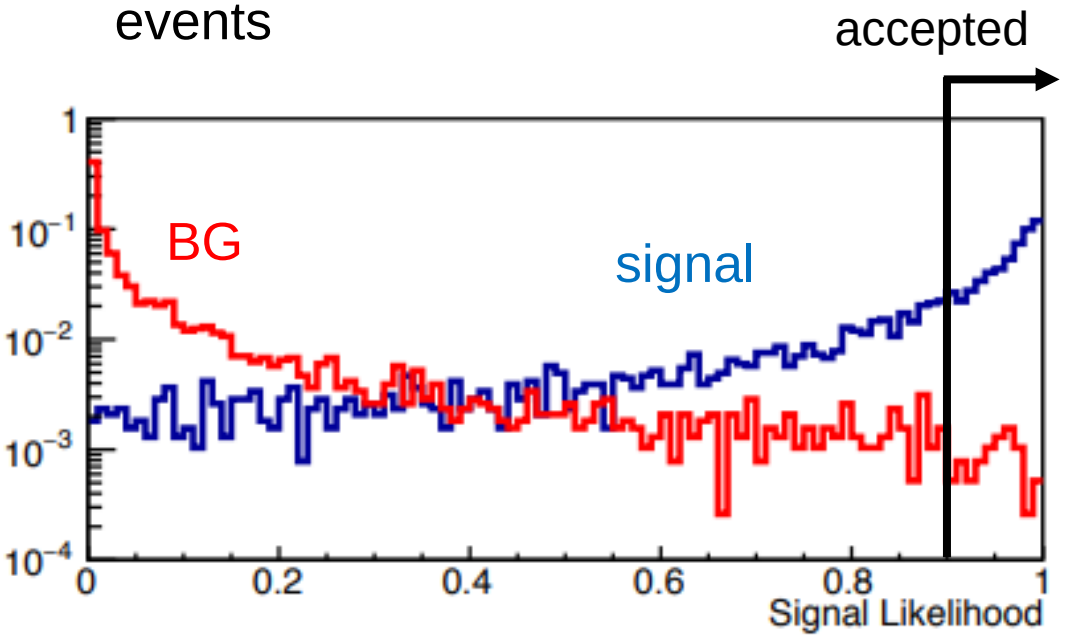
- Apply high voltage (~80kV) to field shaper without using high voltage feedthroughs
- Implemented on FPC
- 15.48kV output is obtained with 800Vpp input and multiplication by 20 steps → Need to increase input (~2kVpp) and steps
- Dedicated jig is designed



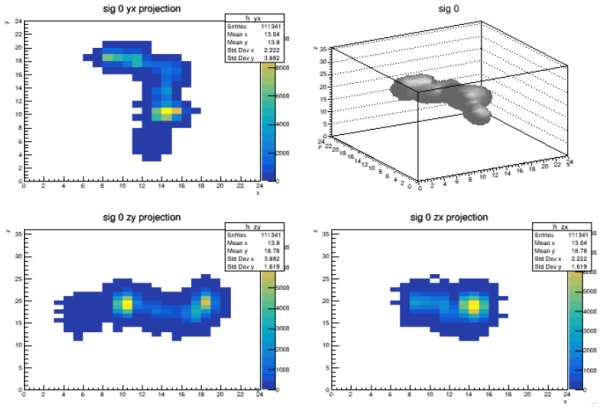


Background rejection with topology using deep learning

- Classify 0νββ and BG using deep learning (3D-CNN, Densenet)
- Using simulated 0νββ and gamma-ray (^{214}Bi 2,448 keV) event topologies
- Achieved signal acceptance 27%, BG rejection: 99.9996% @ threshold 0.9008
- Will confirm using actual data of pair-creation



signal



BG

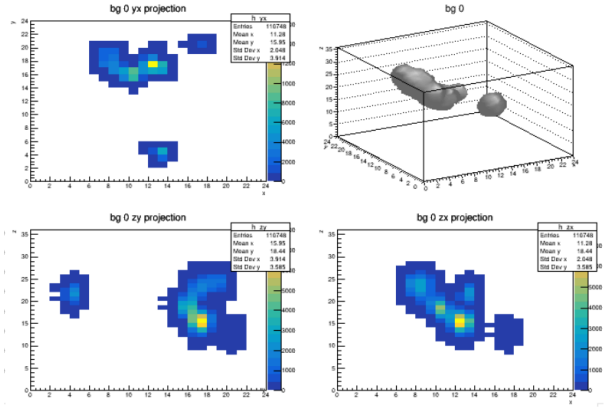
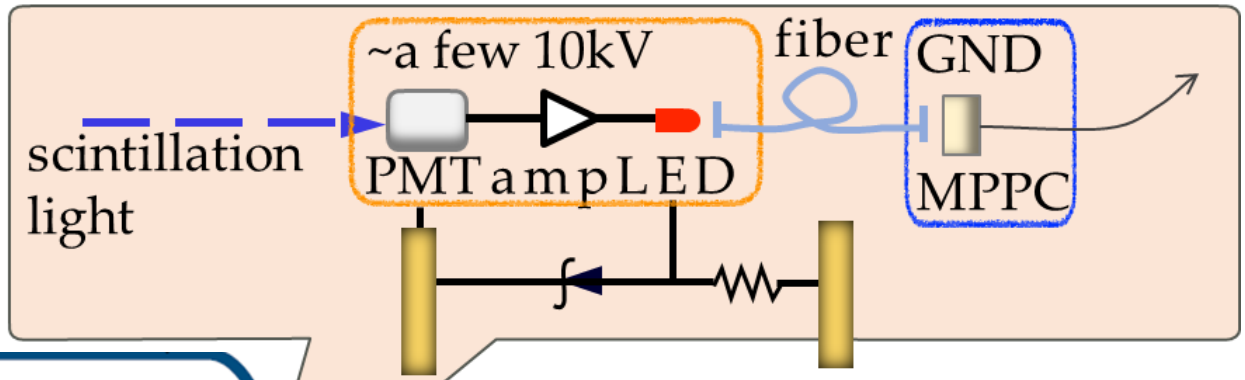
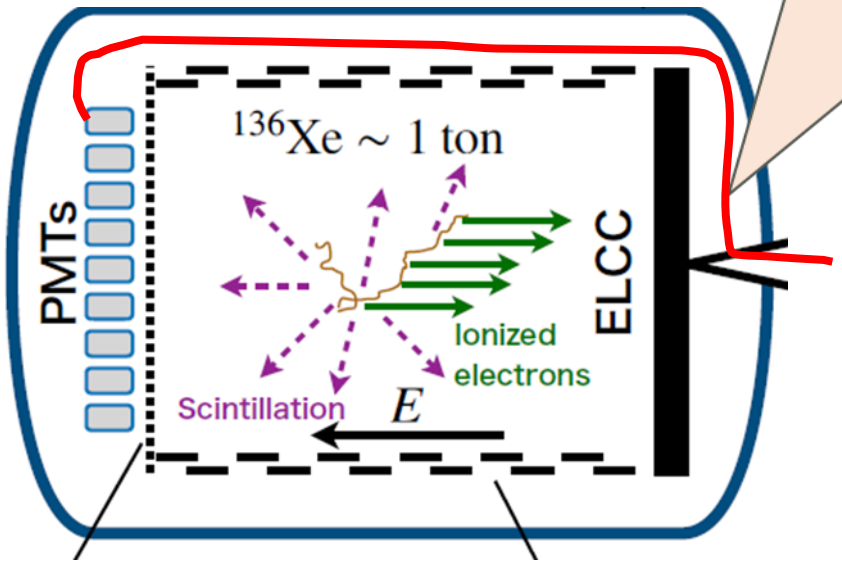
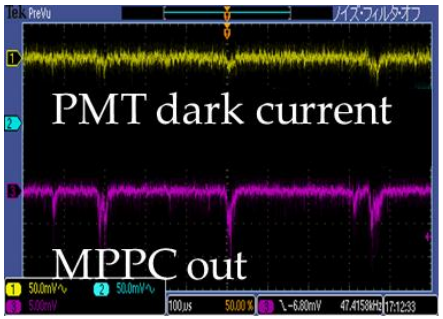


Photo isolation

- Operate PMTs at high electric potential
  - To put PMTs close to the cathode mesh
  - Drive LED with amplified PMT signal and readout with MPPC







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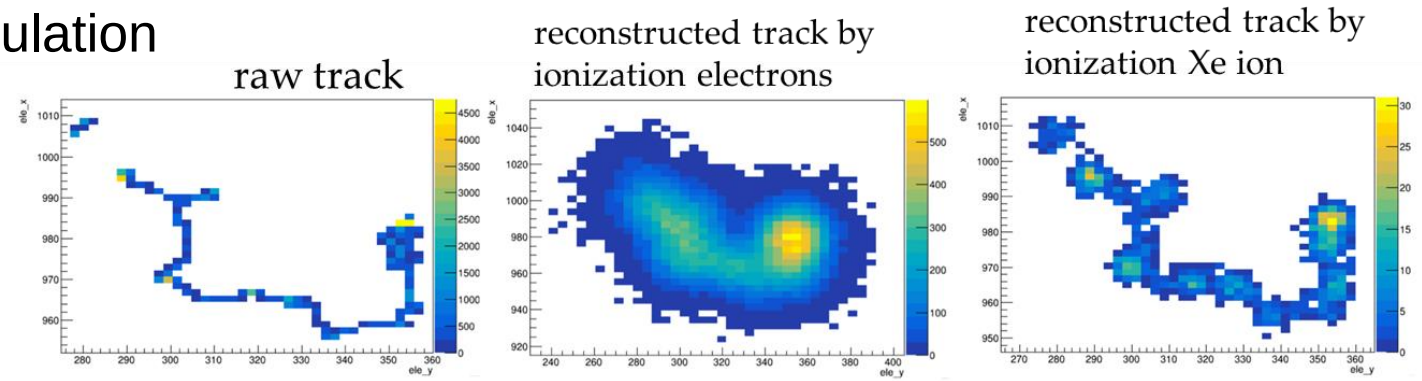
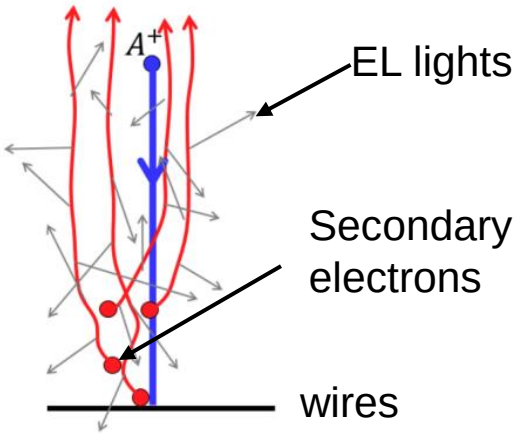
Positive ion detection

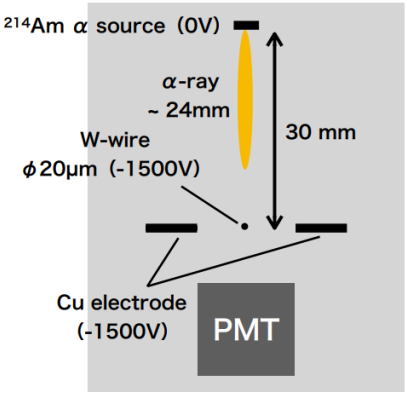
- Diffusion of ion in xenon gas is smaller than electron
  → more precise track reconstruction
  → It may improve the performance of event selection by DL

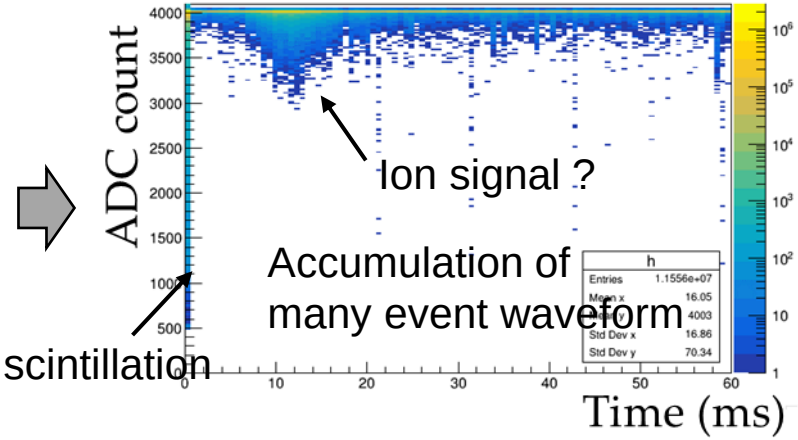
Simulation



- Detect the EL lights from secondary electrons generated by ions hit at anode wires







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Summary

- AXEL : High pressure xenon gas TPC for 0νββ search
  - High energy resolution, large mass, low background
  - Unique readout structure ELCC

- 180L prototype detector demonstration
  - ΔE/E = 0.89 % FWHM @ 1.8MeV gamma (^{88}Y)
    → extrapolate to the Q value (2,458keV) : 0.79 % FWHM (great resolution)
    → Further improvement is needed to achieve the target energy resolution
    0.5% FWHM @ Q-value

- New 1000L detector is being developed and physics data taking is planned to begin in 2024
  - ELCC upgrade (channel density, surface mount MPPC)
  - Cockcroft-Walton multiplier to apply high voltage to field shaper
  - Background rejection using deep learning
  - Photo isolation (PMT with electrically floating to put them near the high voltage)

- R&D
  - Positive ion detection for more clear track