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

Shinichi Akiyama, Tohoku University

for the AXEL Collaboration

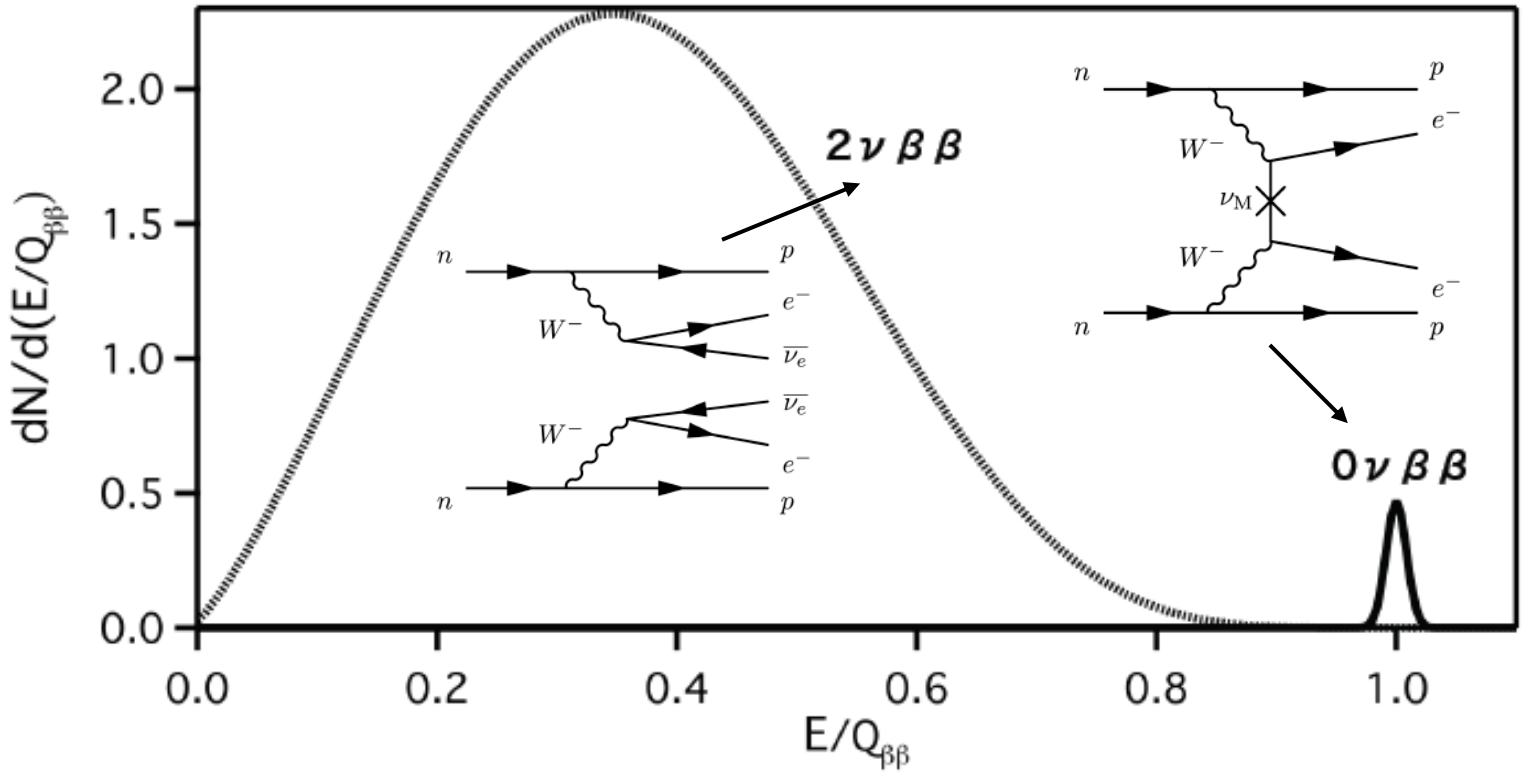
20 July 2022, 18th Rencontres du Vietnam, ICISE Quy Nhon, Vietnam

Table of Contents

Table of Contents

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

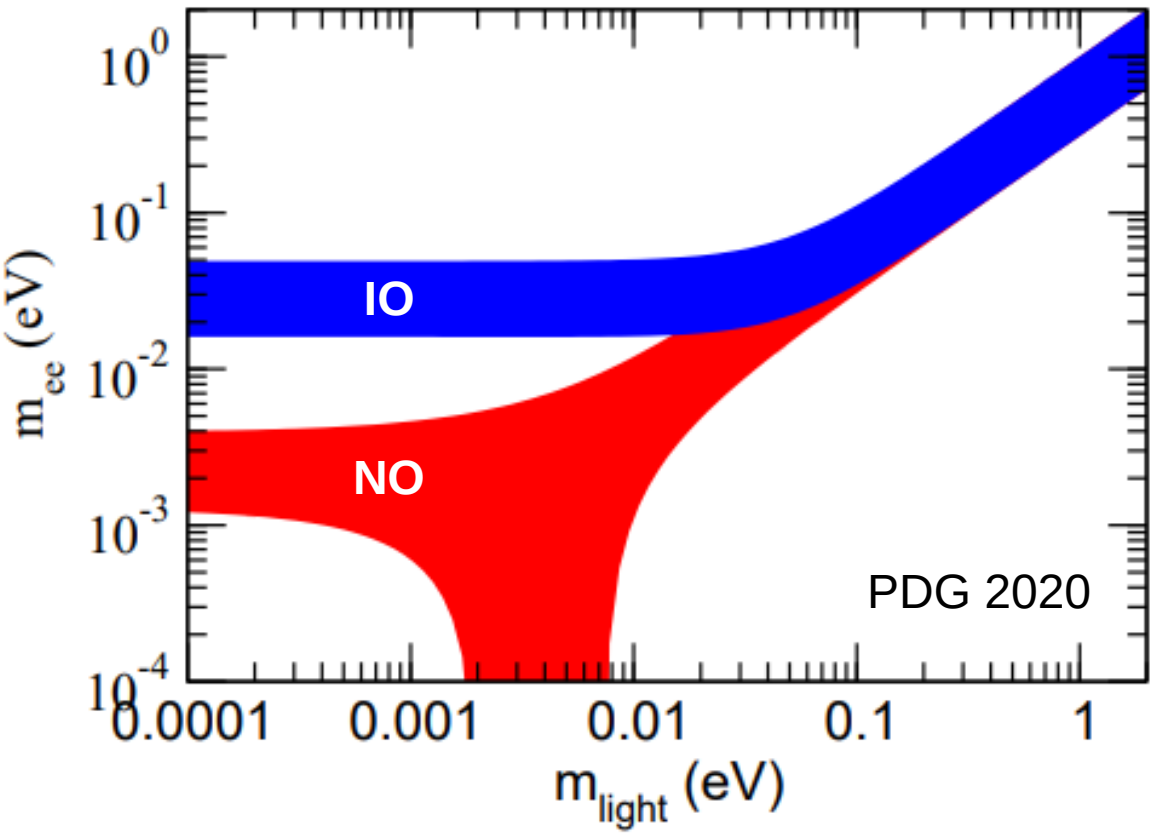


Neutrinoless double beta decay

- 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

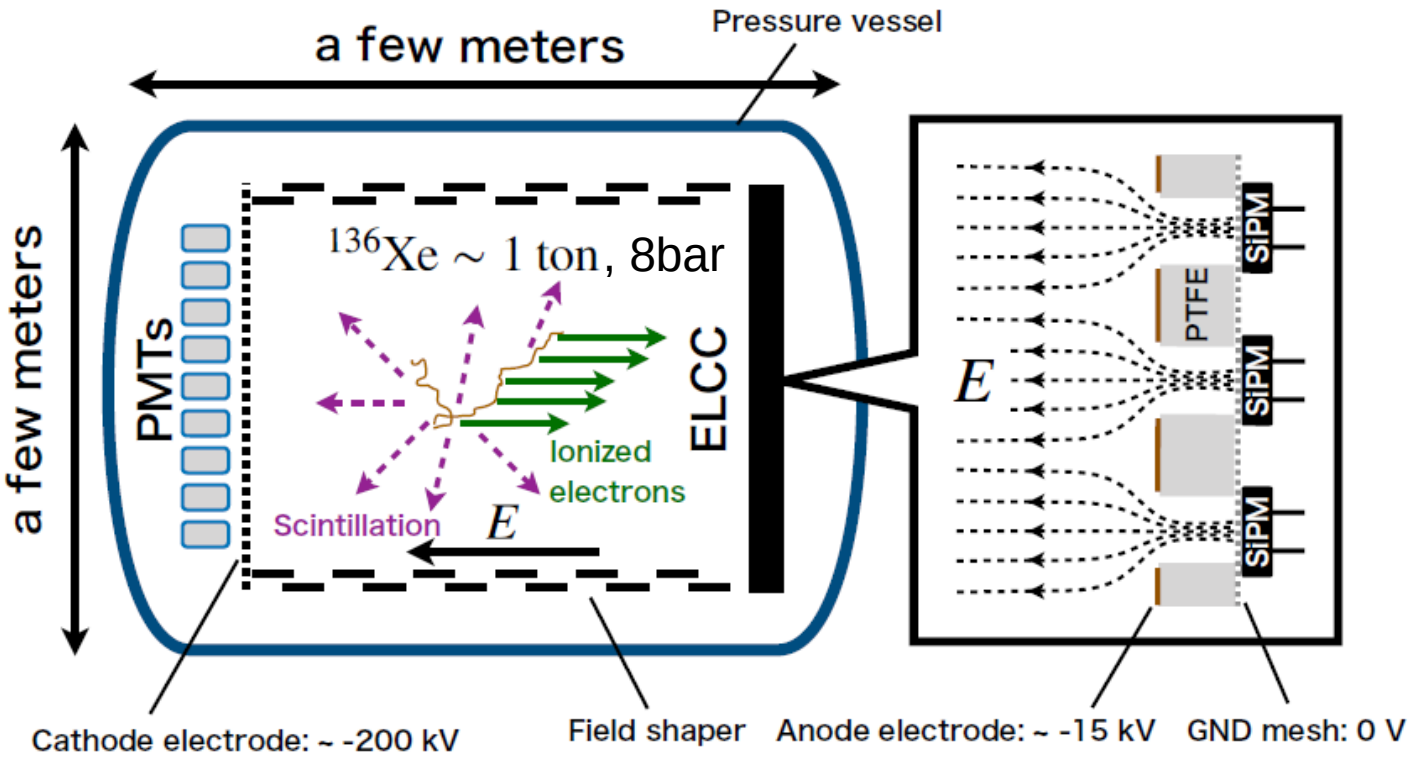
- High pressure gas TPC
  - Large mass
  - Event topology can be obtained

Table of Contents

AXEL experiment

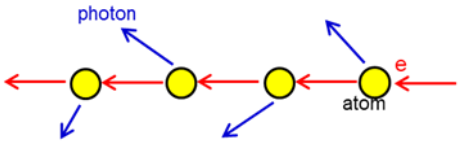
A Xenon ElectroLuminescence detector

- 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



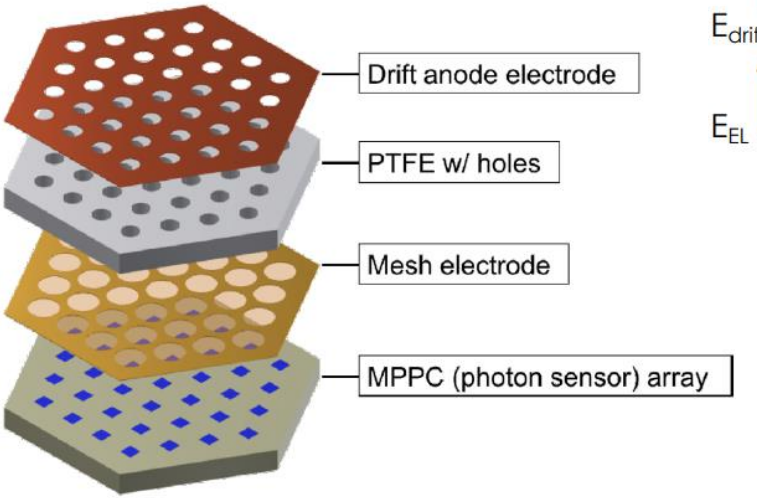
→ High energy resolution

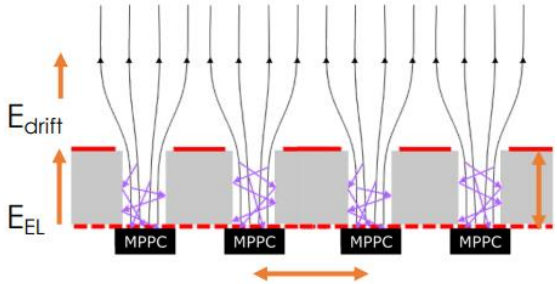
  - Pixelized hit pattern + hit timing for 3D track reconstruction

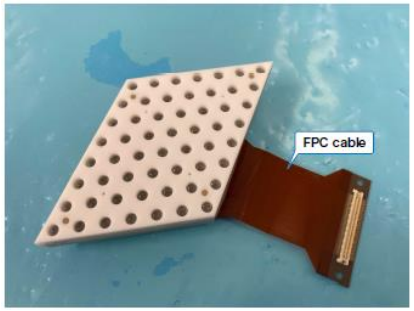
→ BG rejection

  - Extendable to large size thanks to its rigid structures

→ Large mass



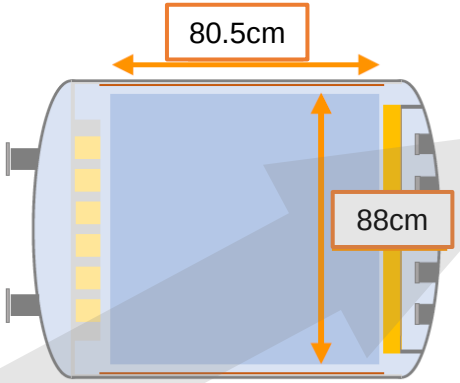




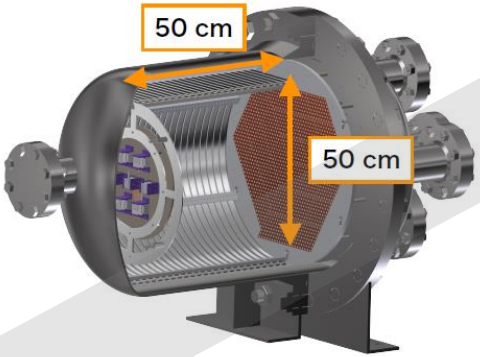
Roadmap

- 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

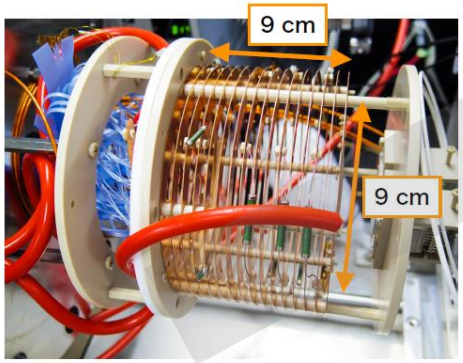
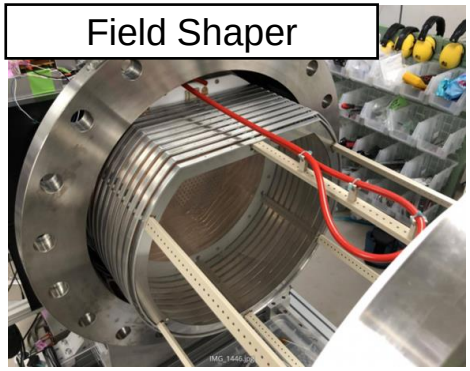


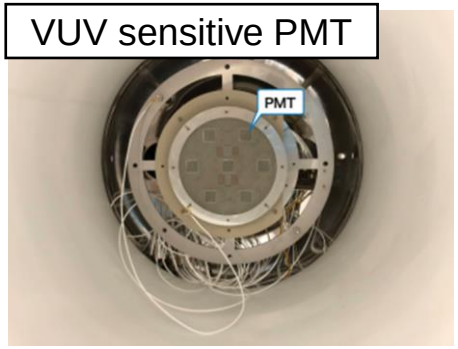
Table of Contents

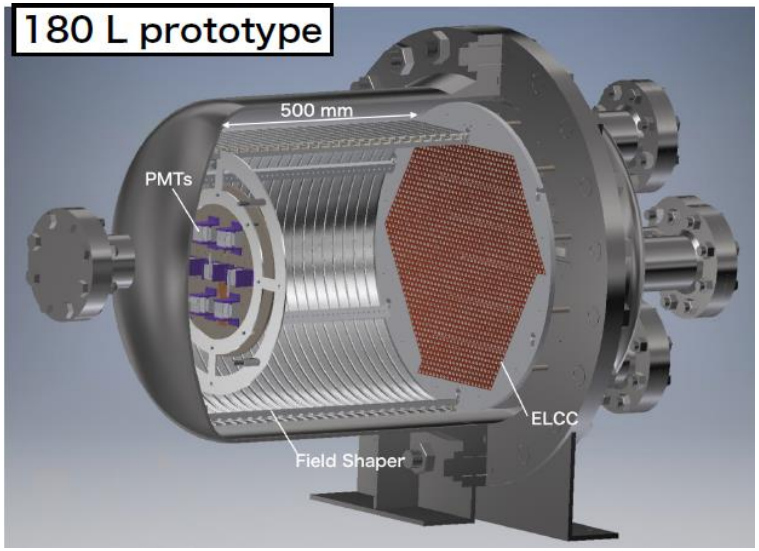
180L prototype detector

Field Shaper

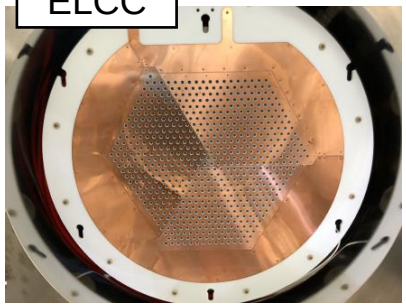


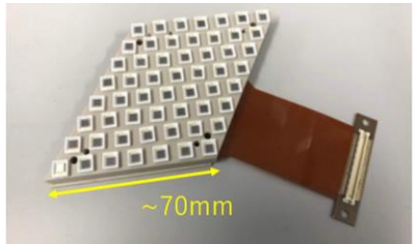
VUV sensitive PMT



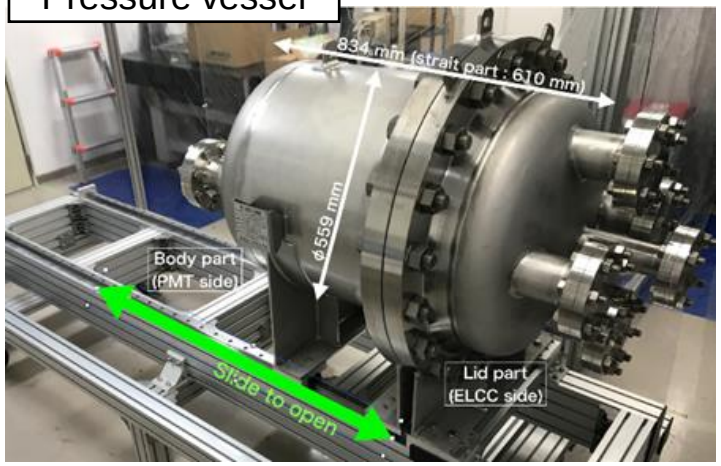


ELCC

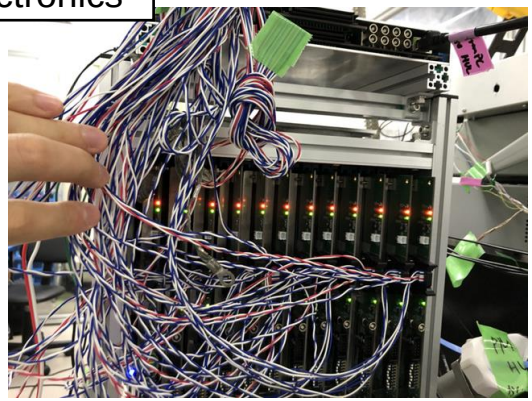




Pressure vessel

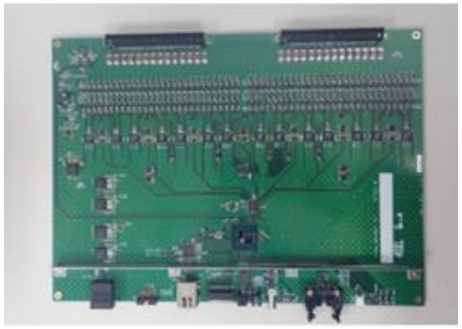


Front end electronics

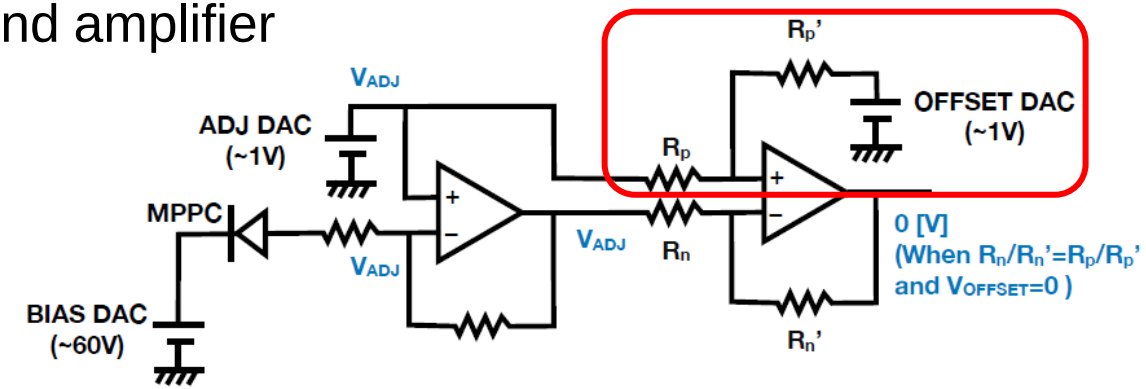


AxFEB

- 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

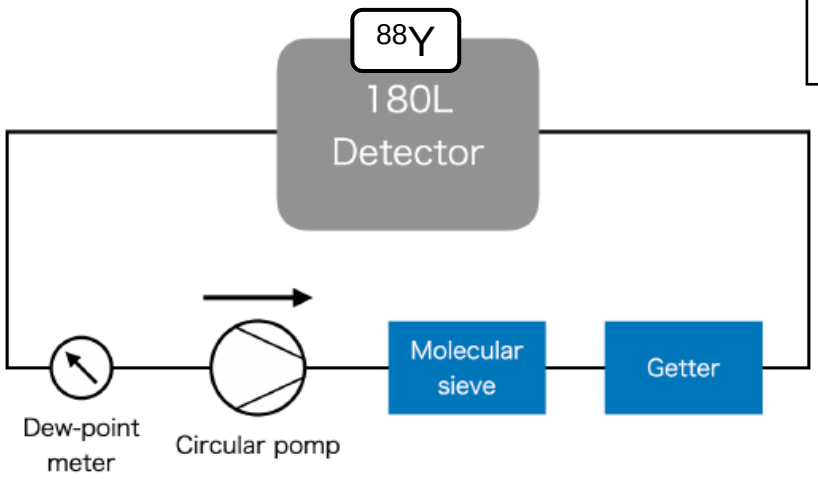


Performance evaluation

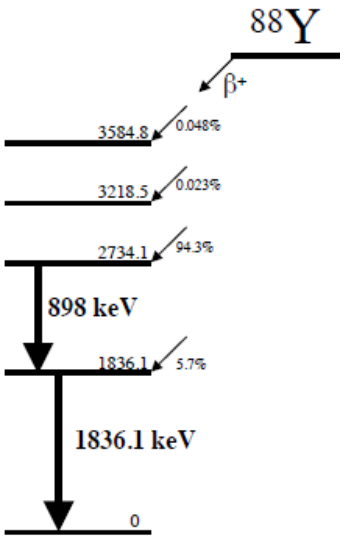
- ^{88}Y gamma ray source is placed on the pressure vessel
  - Measure energy resolution
  - Reconstruct 3D track
- Measurements are conducted in 6 runs, each of which has 200,000 events

condition

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

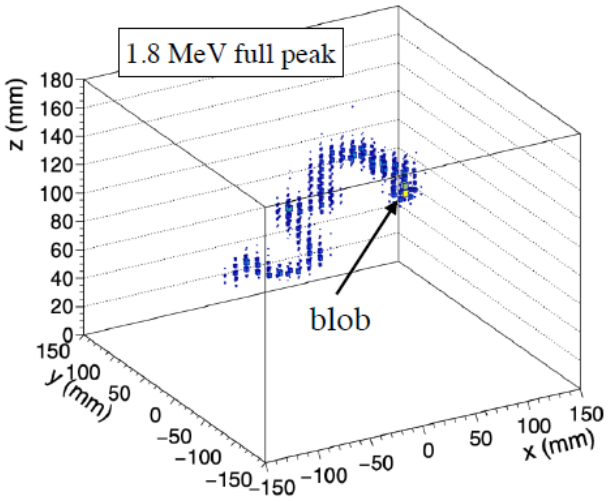


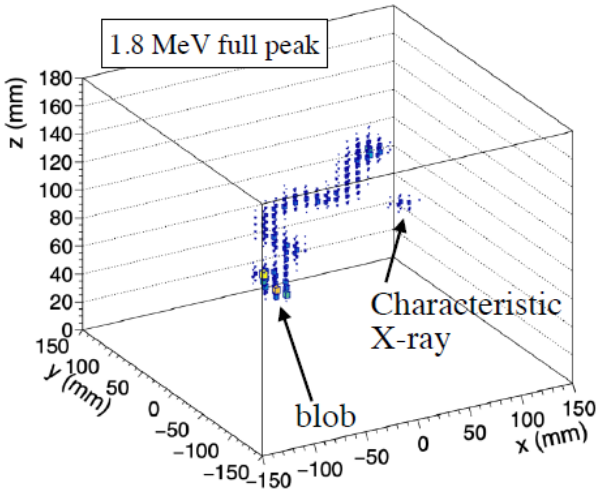
First performance evaluation over 1 MeV

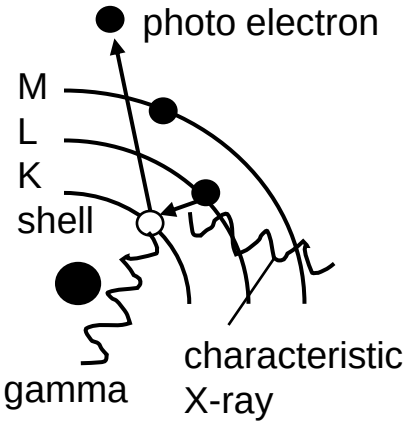


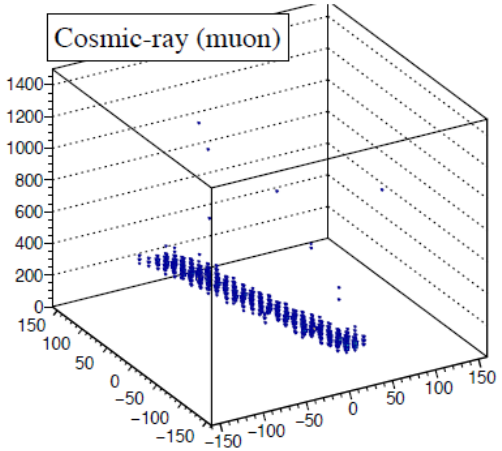
Event topology

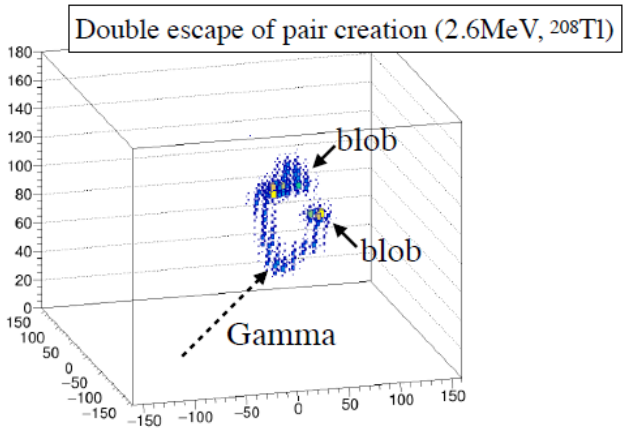
- “Blob” appears in the endpoint of track (Bragg peak)
- Characteristic xray cluster is confirmed near the main cluster in 1.8MeV energy of ^{88}Y gamma event → can be used to reject BG











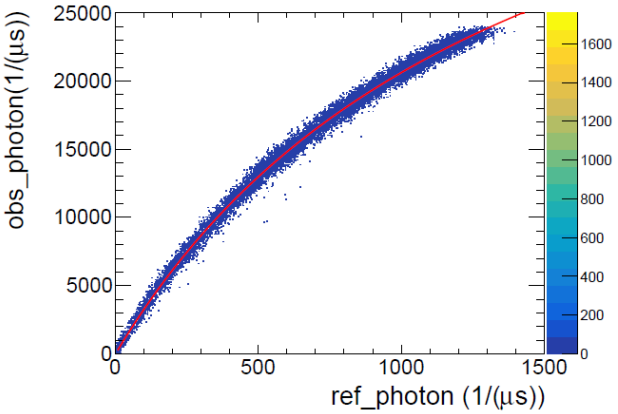
Analysis

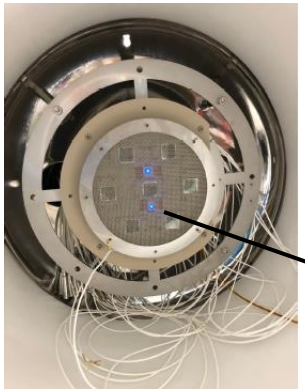
Correction of MPPC non-linearity → EL gain Correction → Time Correction → z Correction

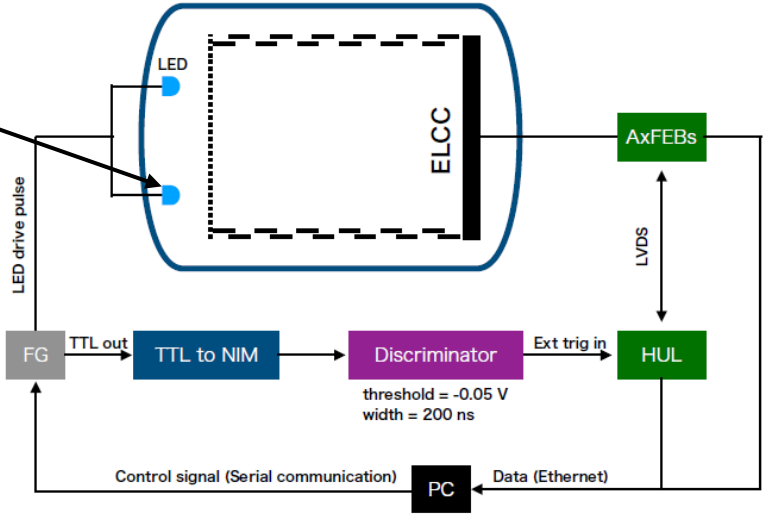
Correction of MPPC non-linearity

- 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

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





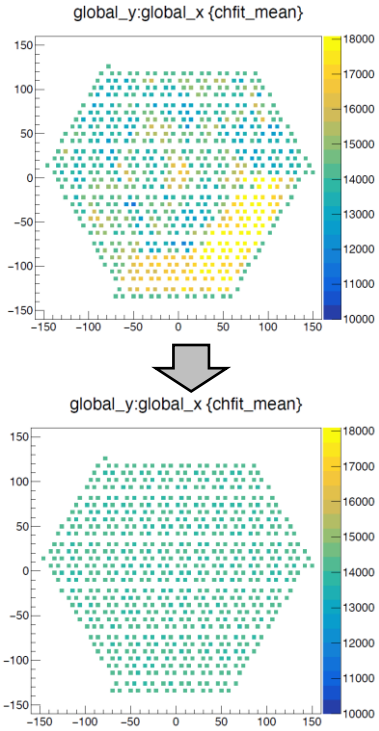


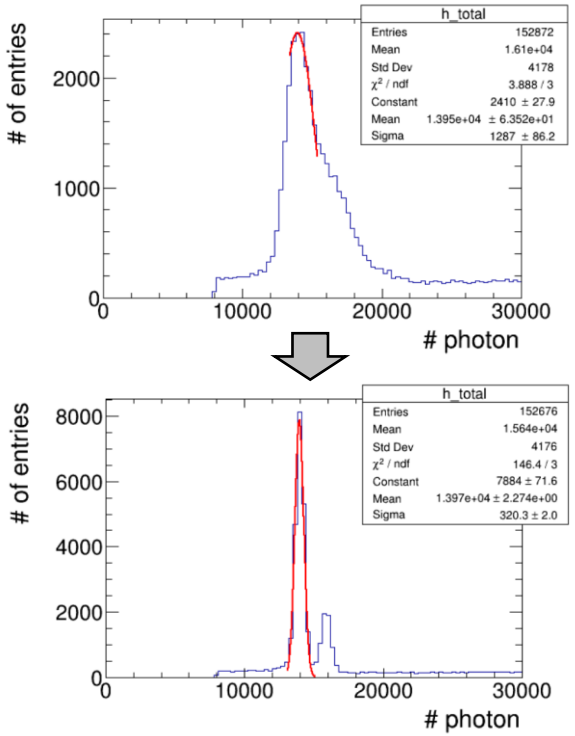
Analysis

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)





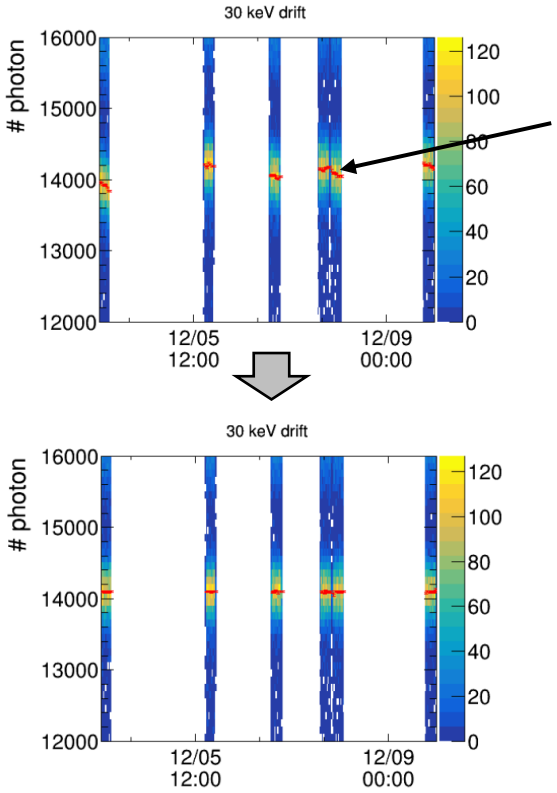
K_α (29.7 keV) and K_β (33.6 keV) peaks are separated

Analysis

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

Time Correction

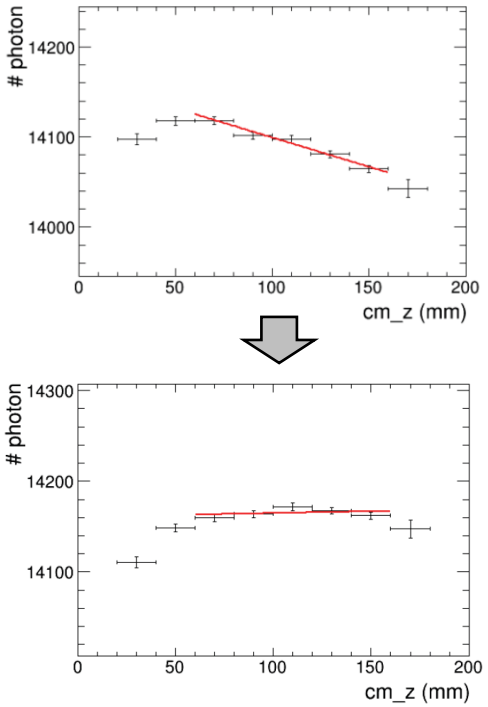
- Correct the time dependence for every 30 min



K_α peak

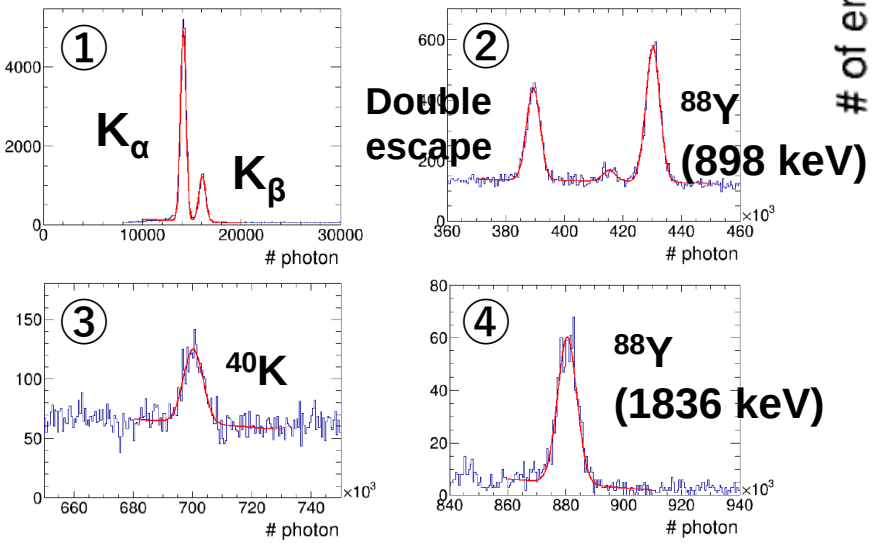
z Correction

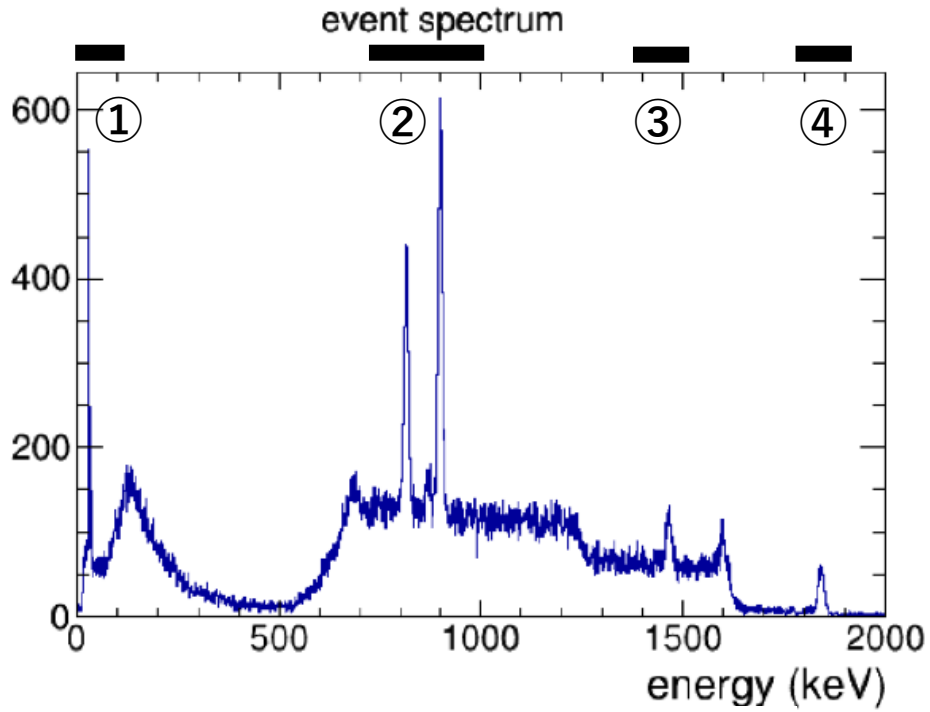
- Correct the z dependence
- Caused by attachment of ionization electrons by impurity



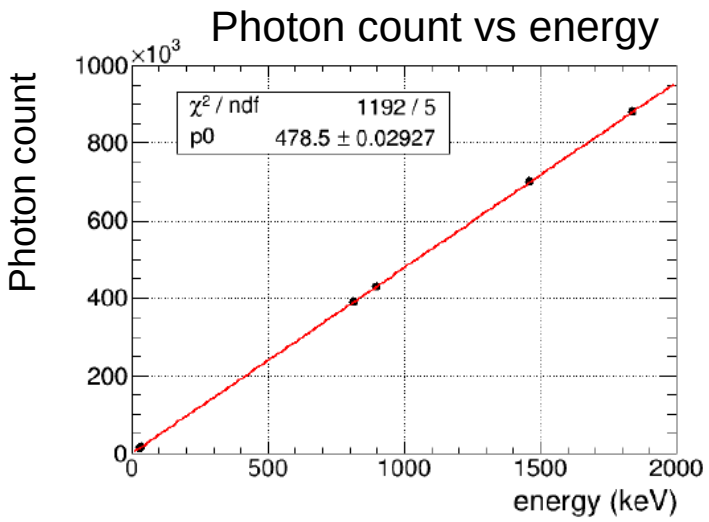
Energy spectrum

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 %



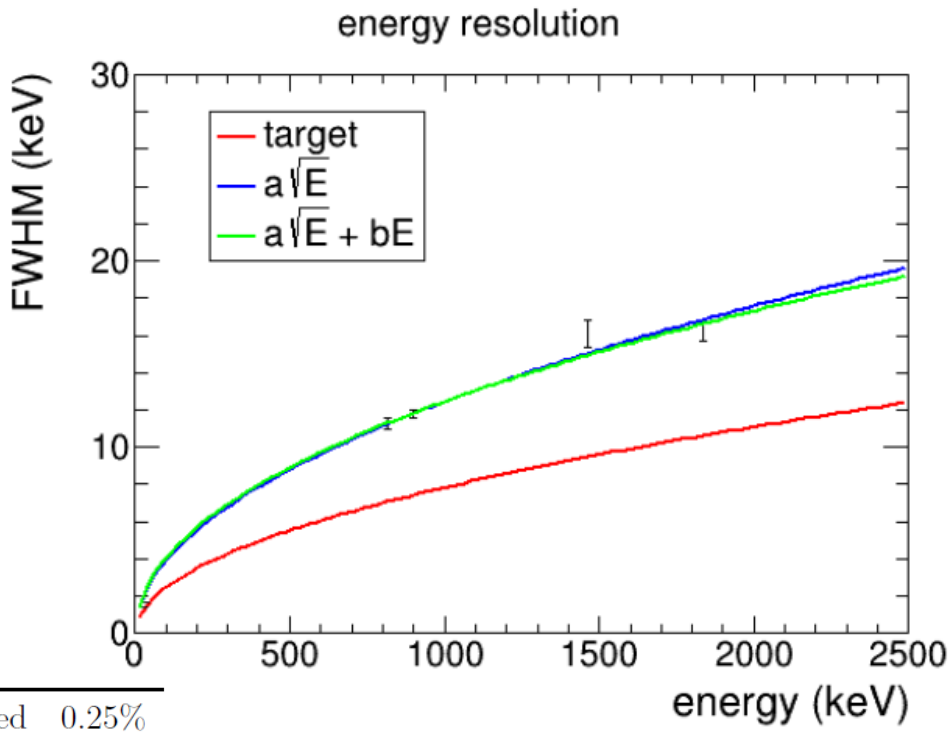
Evaluation of energy resolution

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:

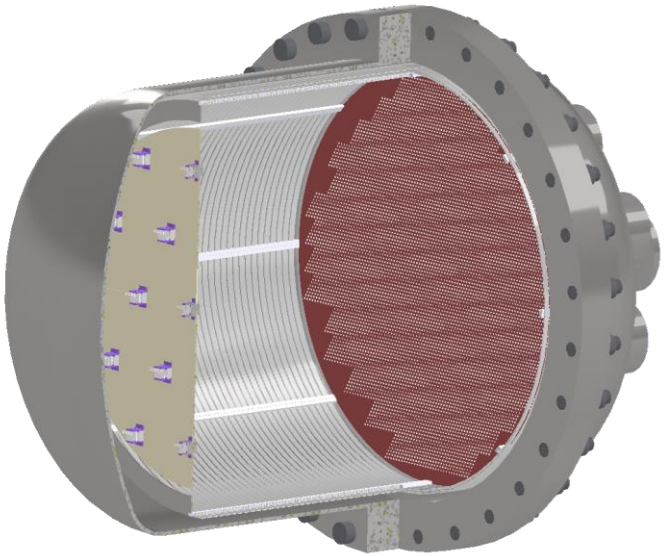
Fluctuation of the number of ionization electrons produced	0.25%
Fluctuation of EL amplification	0.30%
Position dependence of EL amplification factor	0%
Waveform processing in AxFEB	0%
Error in EL gain calibration	0.12%
Accuracy of MPPC recovery time measurement	0%
Error in time correction	0.20%
Error 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%

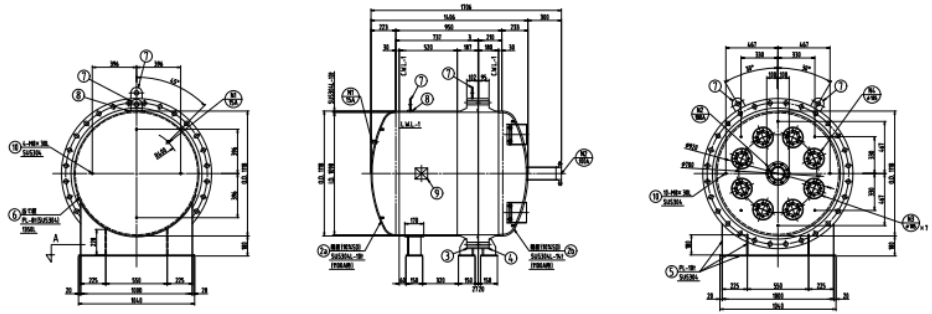
We still have large unknown components
→ further investigation should be done

Table of Contents

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

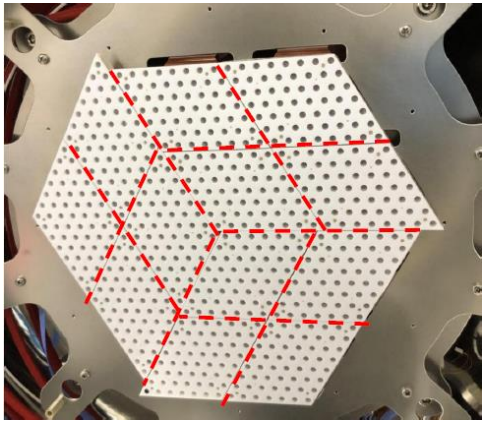




ELCC

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

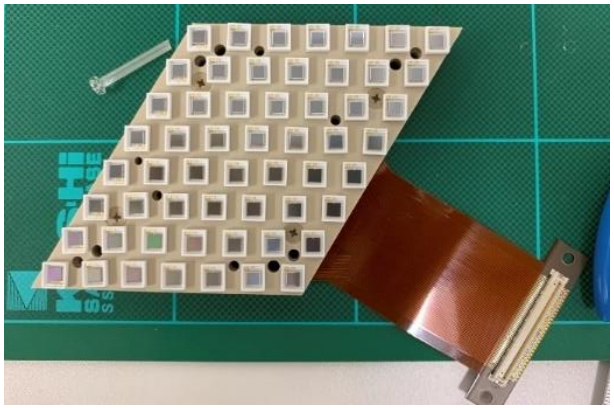
  → Adopt 8x8 ch for 1,000L detector

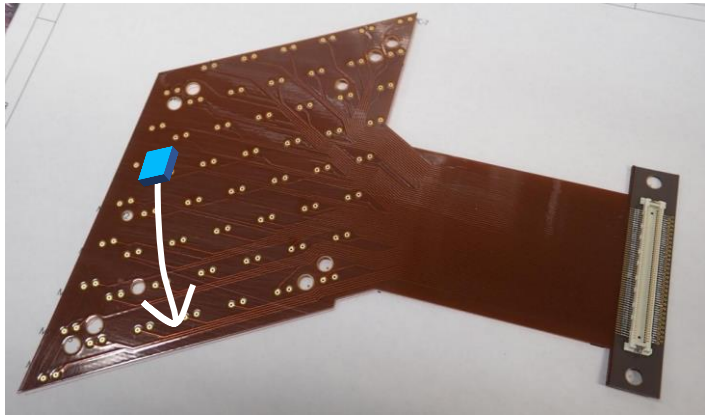


- MPPC
  - High activity found on MPPC ceramic package

  → Planning direct surface-mount on read-out

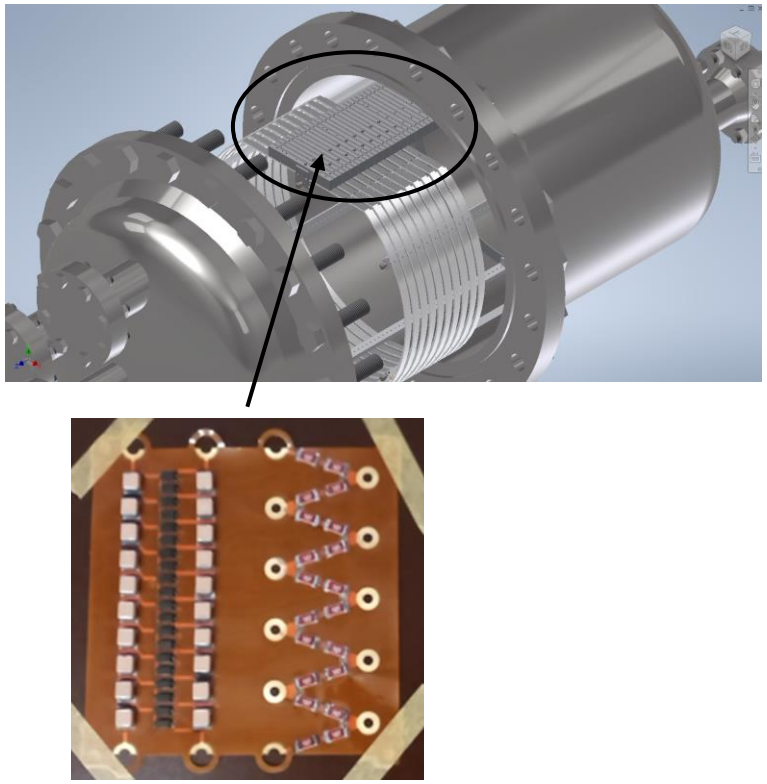
  FPCs without this package
  - Enlarge sensitive area, 3x3mm square → 4.7mmΦ

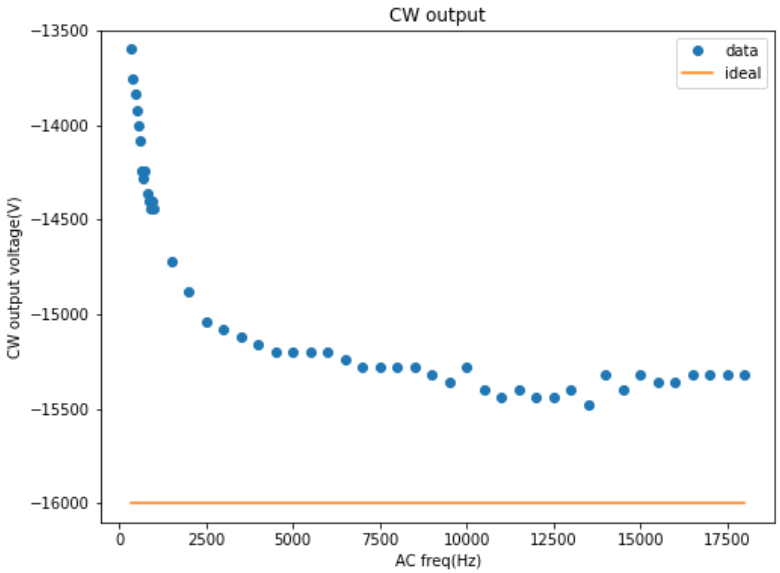




Cockcroft-Walton multiplier

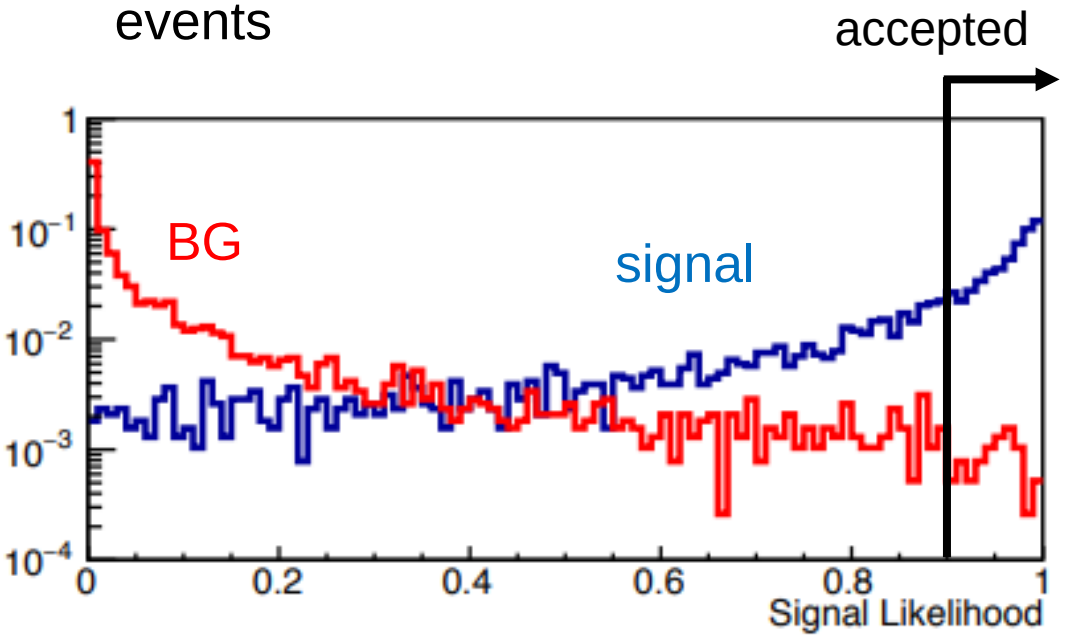
- Apply high voltage (~80kV) to field shaper without using high voltage feedthroughs
- Implemented on FPC
- 15.48kV output is obtained with 800Vpp input and multiplication by 20 steps → Need to increase input (~2kVpp) and steps
- Dedicated jig is designed



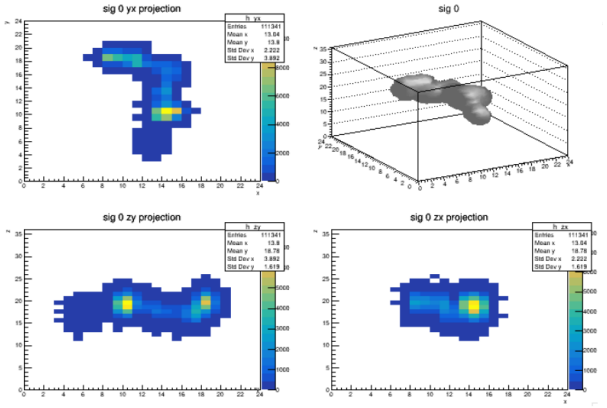


Background rejection with topology using deep learning

- 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

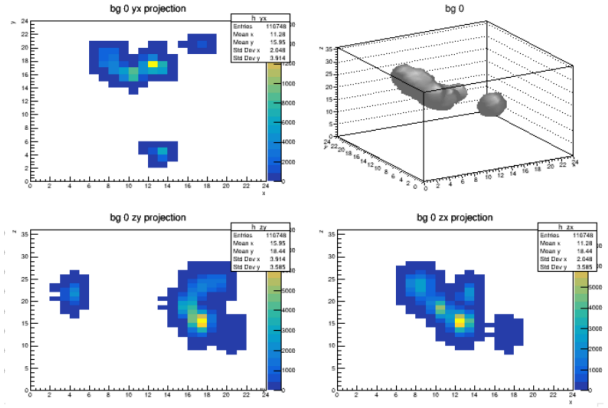
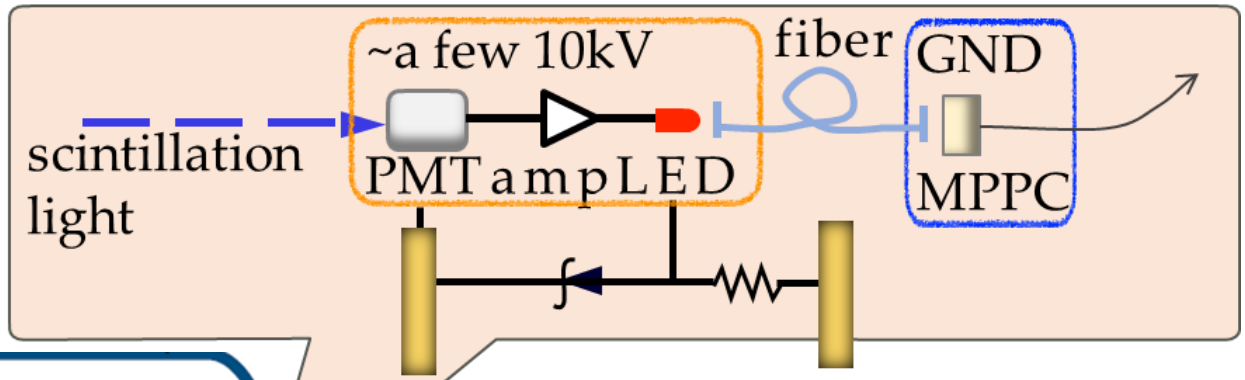
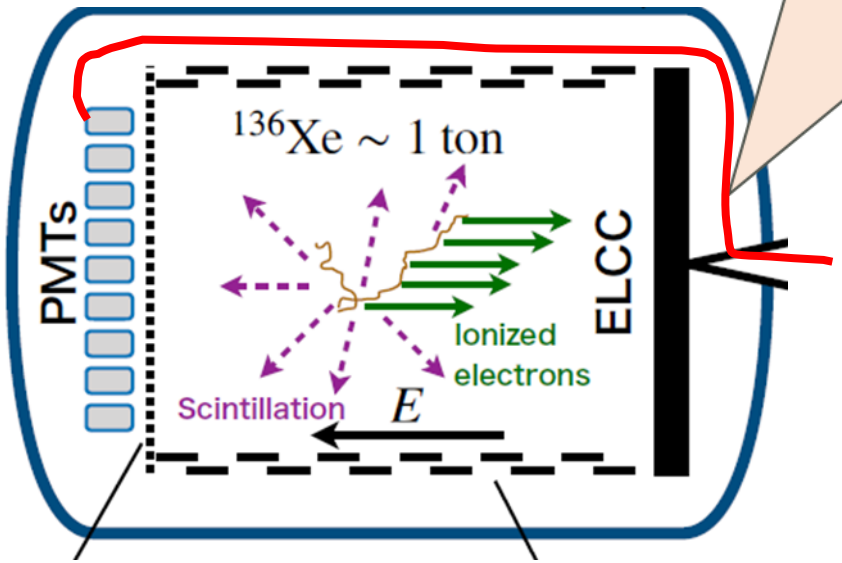


Photo isolation

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





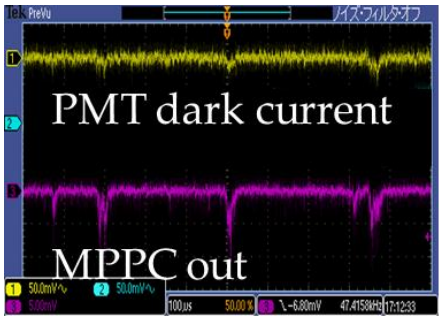
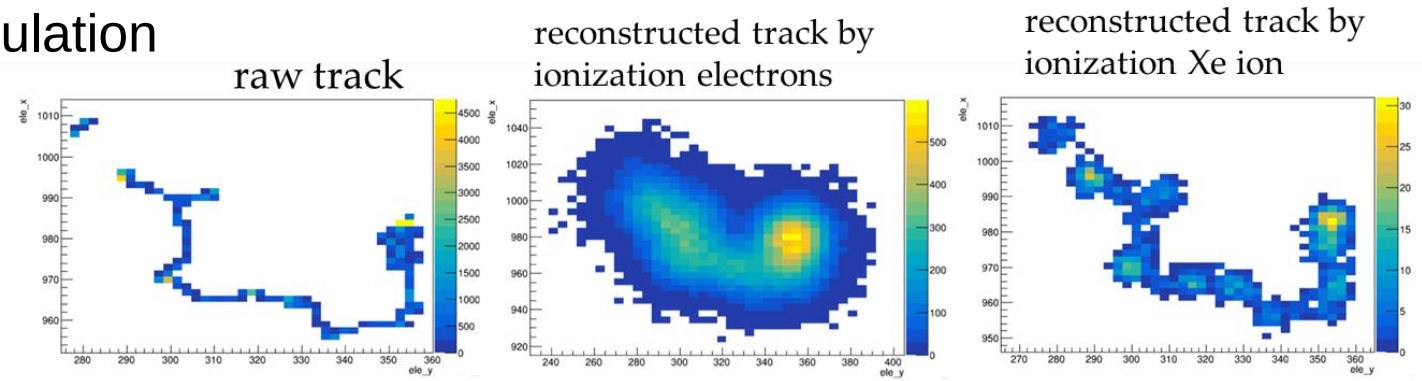


Table of Contents

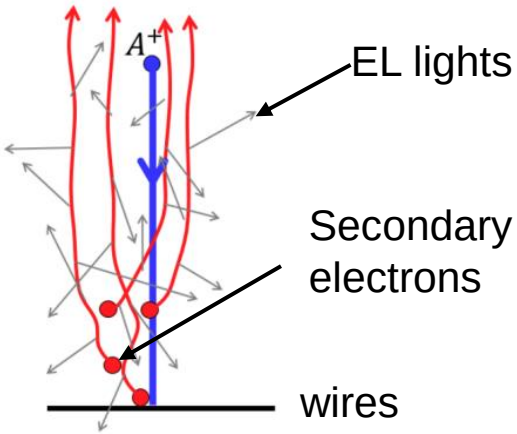
Positive ion detection

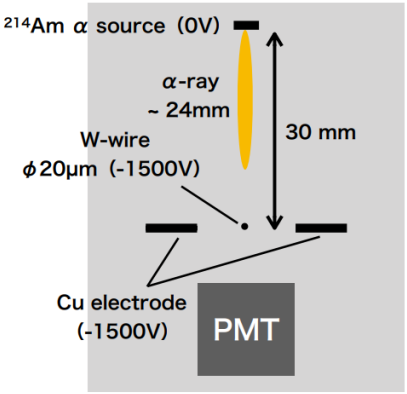
- Diffusion of ion in xenon gas is smaller than electron
  → more precise track reconstruction
  → It may improve the performance of event selection by DL

Simulation



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





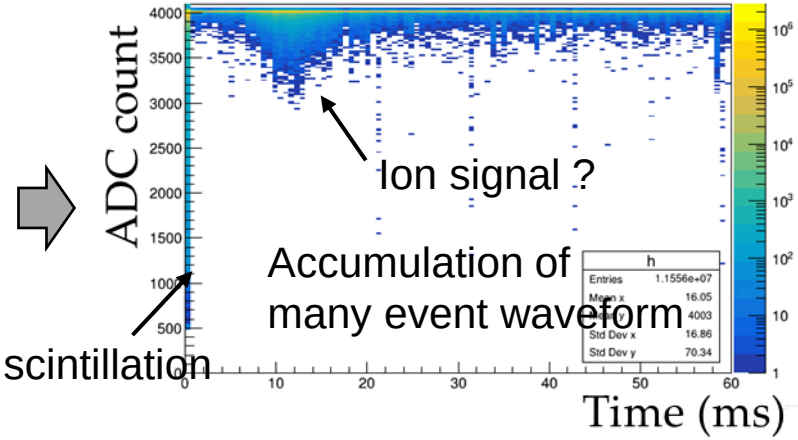


Table of Contents

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

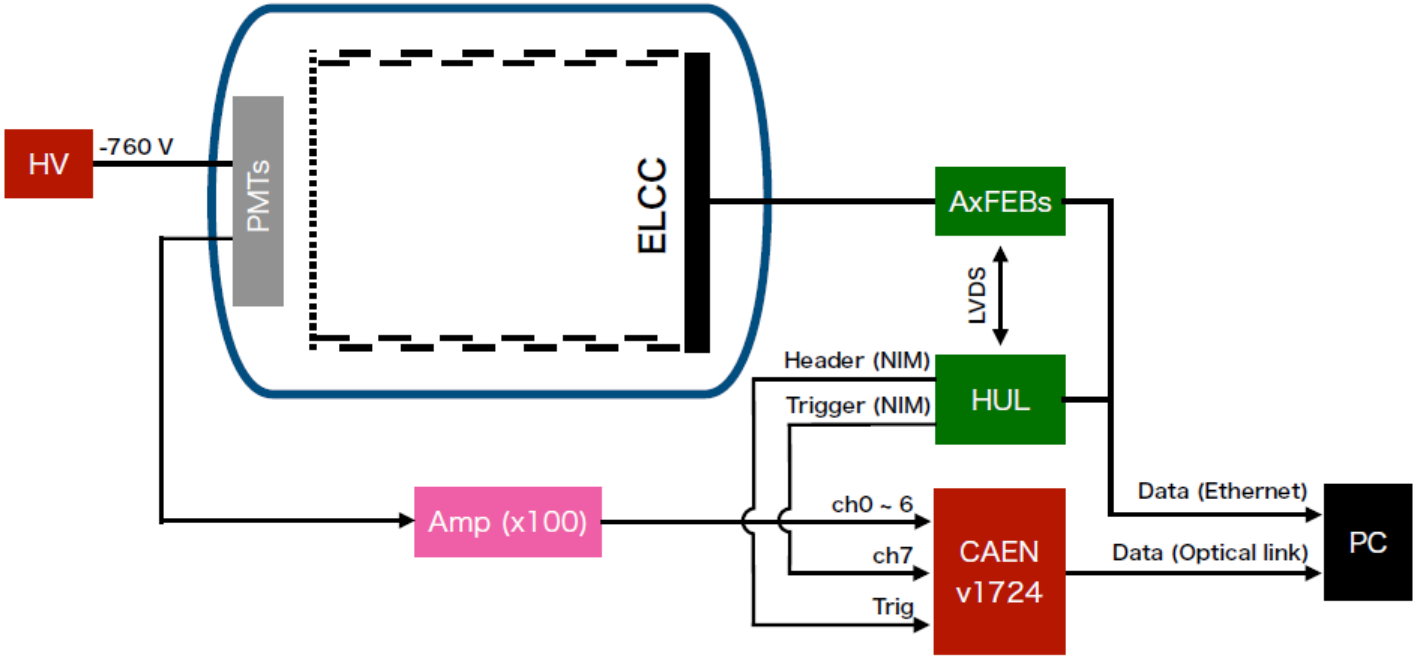
- New 1000L detector is being developed and physics data taking is planned to begin in 2024
  - ELCC upgrade (channel density, surface mount MPPC)
  - Cockcroft-Walton multiplier to apply high voltage to field shaper
  - Background rejection using deep learning
  - Photo isolation (PMT with electrically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

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

backup

Data Acquisition System

- Two types of read-out modules
  - AxFEB : read out the ELCC signal (EL)
  - digitizer (CAEN v1724) : read out PMT signal (scintillation)
- Hadron Universal Logic module (HUL) is used as a trigger card
  - Equipped with Xilinx Kintex7
  - Developed firmware for the 180L detector



DC coupling readout

- By inverting and amplifying twice with an operational amplifier, a DC readout can be performed while adding an adjustment voltage to the MPPC.