Development of a high energy resolution xenon gas TPC for 0νββ decay search :

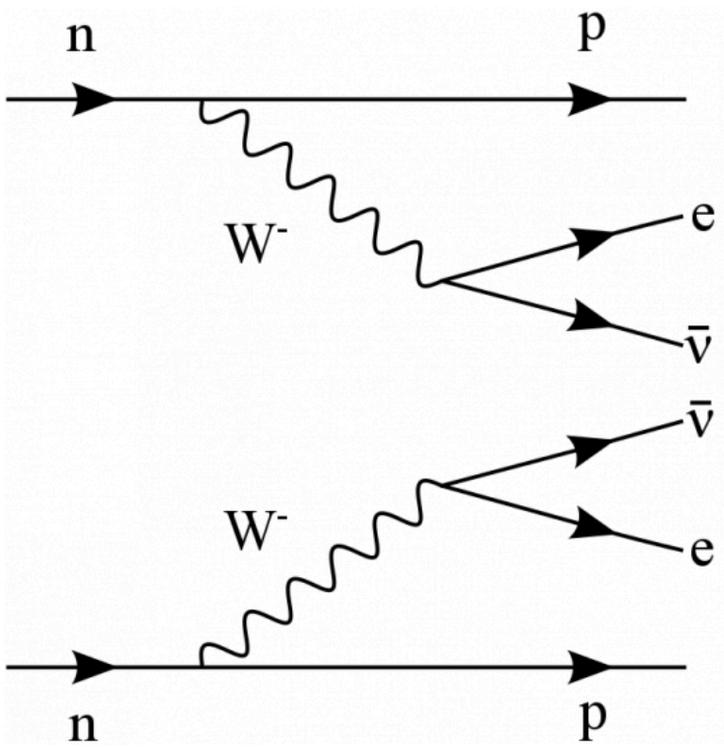
Sei Ban

Kyoto University

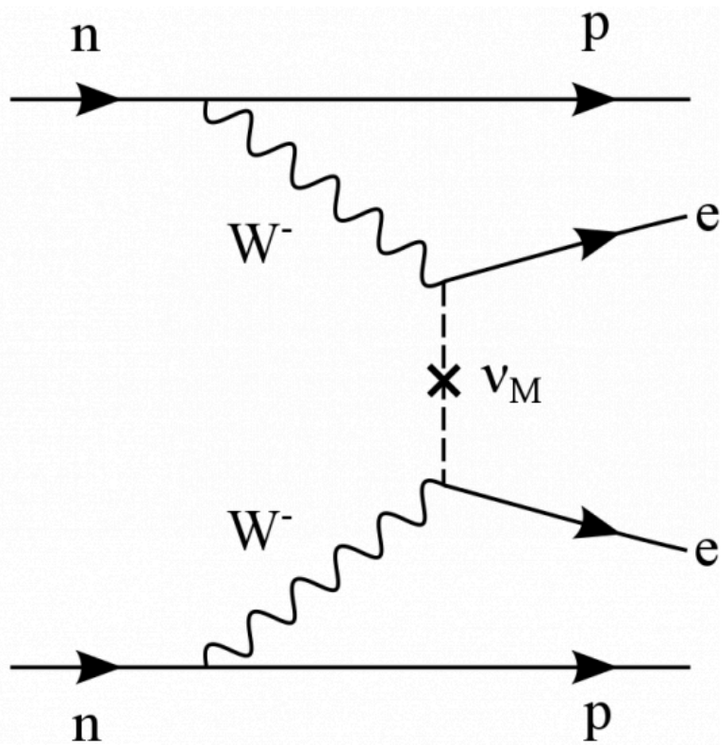
For the AXEL collaboration

Introduction : Neutrinoless Double Beta Decay (0νββ decay)

It occurs only if the neutrino has Majorana mass term



2νββ decay



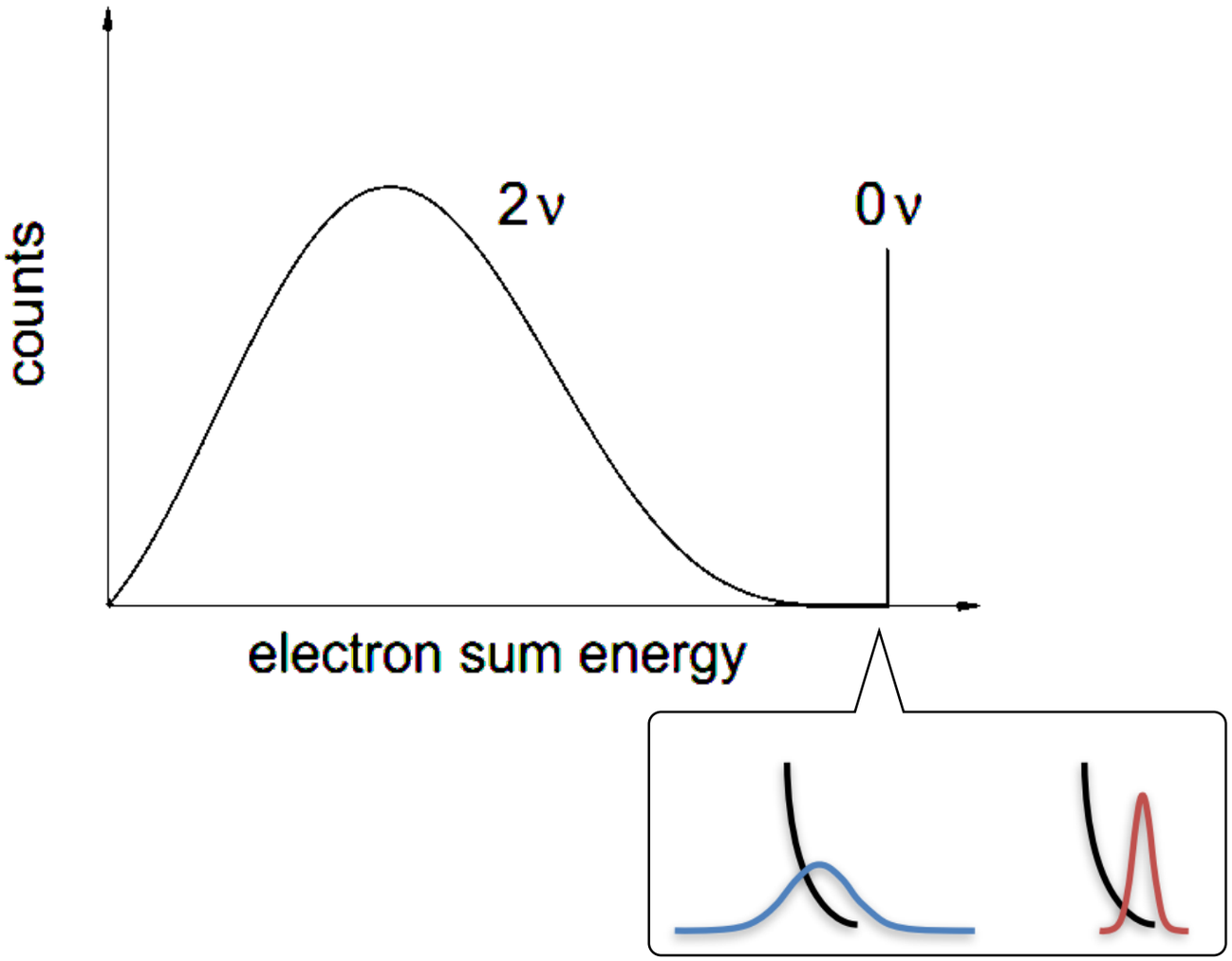
0νββ decay

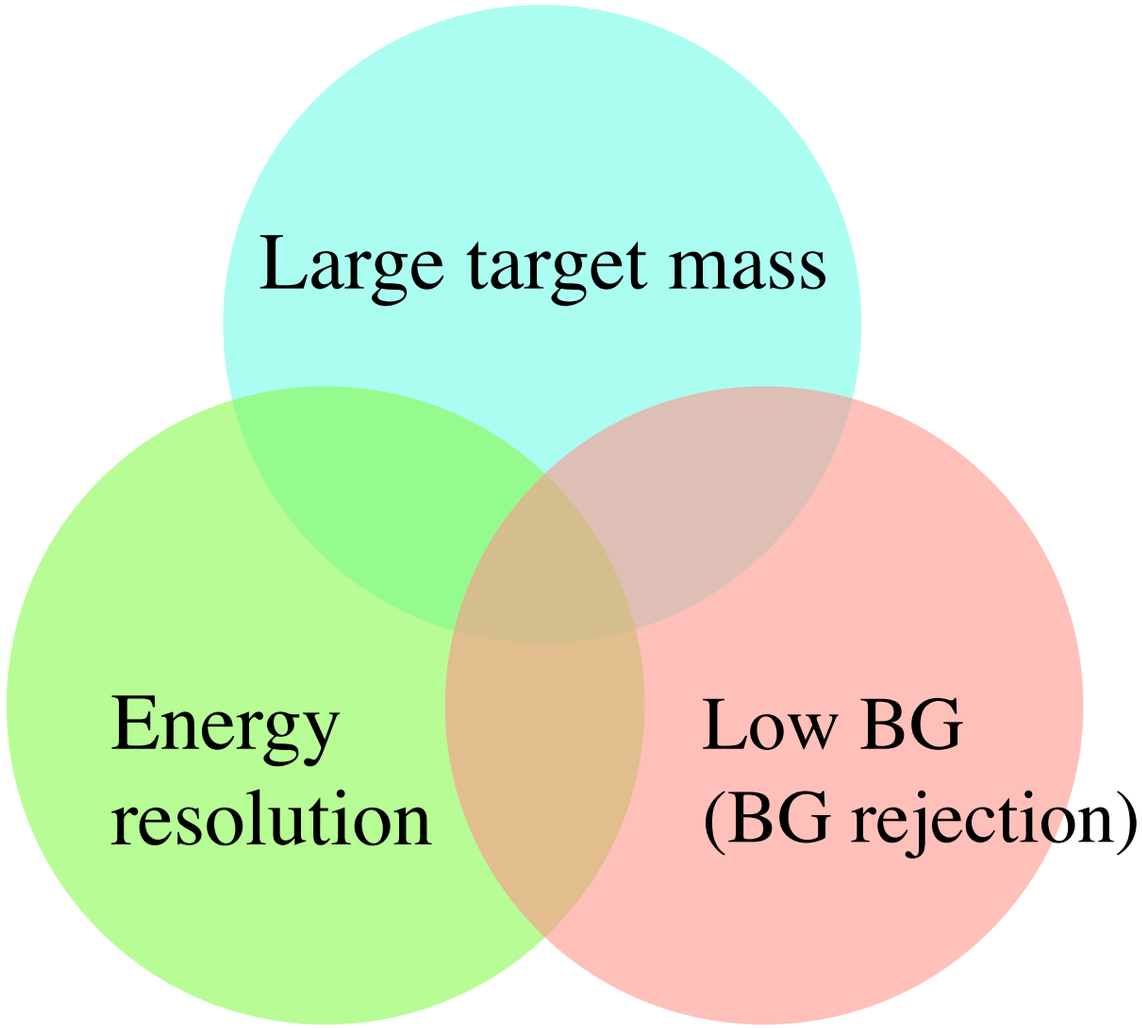
If the neutrino is Majorana ……

- naturally explains the smallness of the neutrino mass
- One of the conditions of Leptogenesis story

Introduction : Neutrinoless Double Beta Decay (0νββ decay)

To discovery 0νββ decay ……





Pioneering work by the NEXT experiment group demonstrated usability of high pressure xenon gas time projection chamber (TPC) for 0νββ decay search

Contents

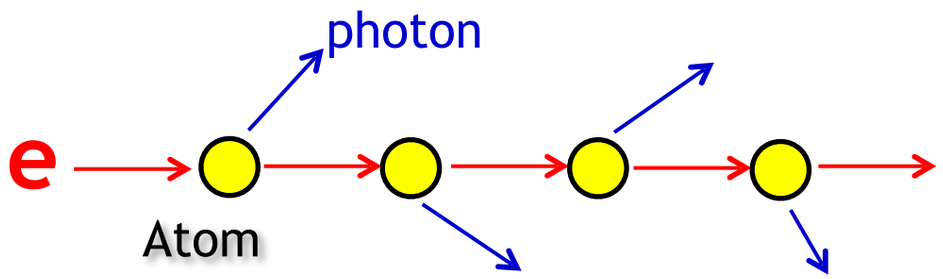
Contents

A Xe ElectroLuminescence : AXEL experiment

High pressure Xe gas TPC with unique cell readout structure for 0νββ decay search

Readout Ionization signals

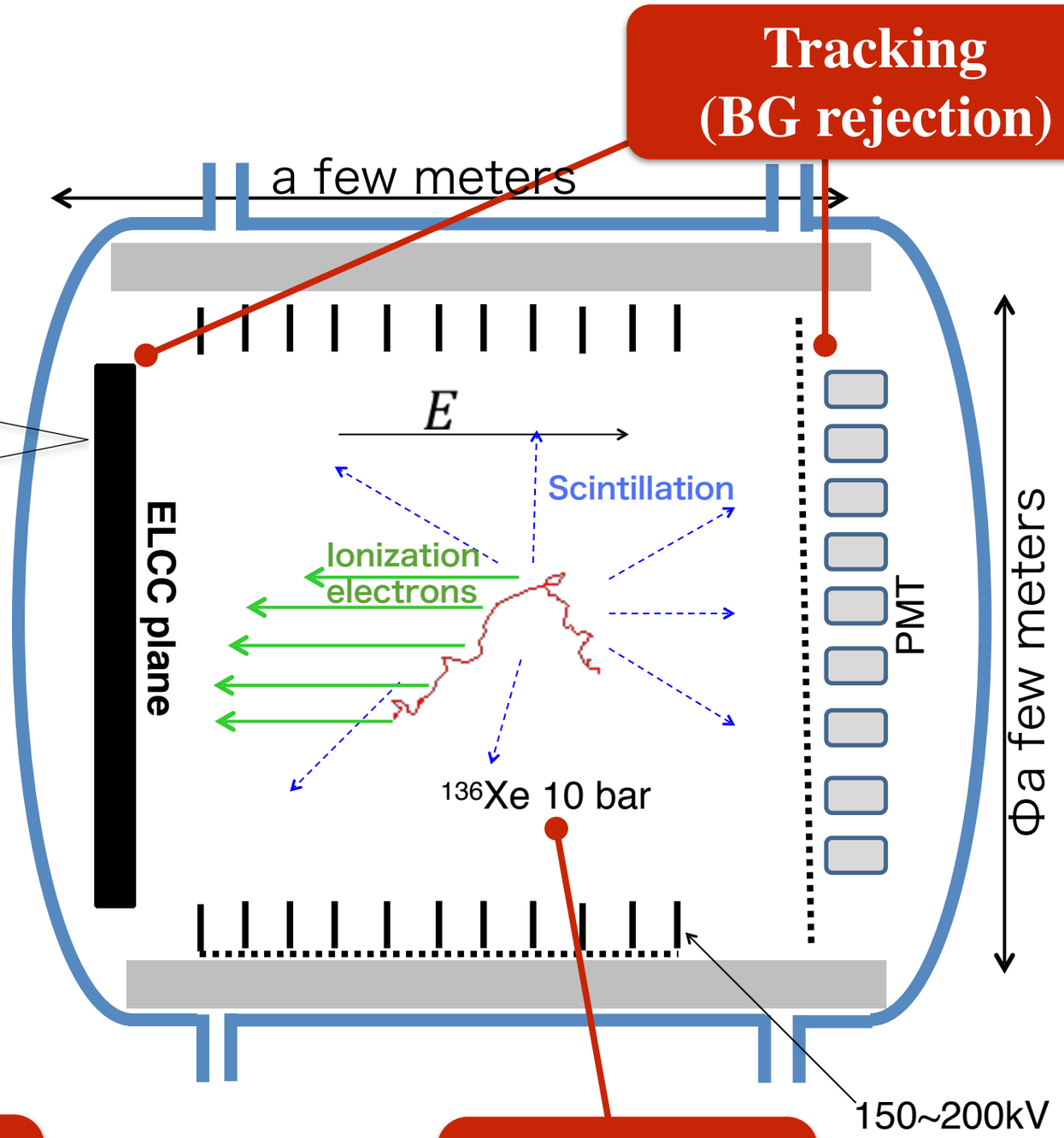
- Electroluminescence (EL) process



Linear response to applied electric field

Without avalanche process
→ less fluctuation of multiplication

Details are in the next page



Good energy resolution

→ goal : 0.5%FWHM @ Q-value

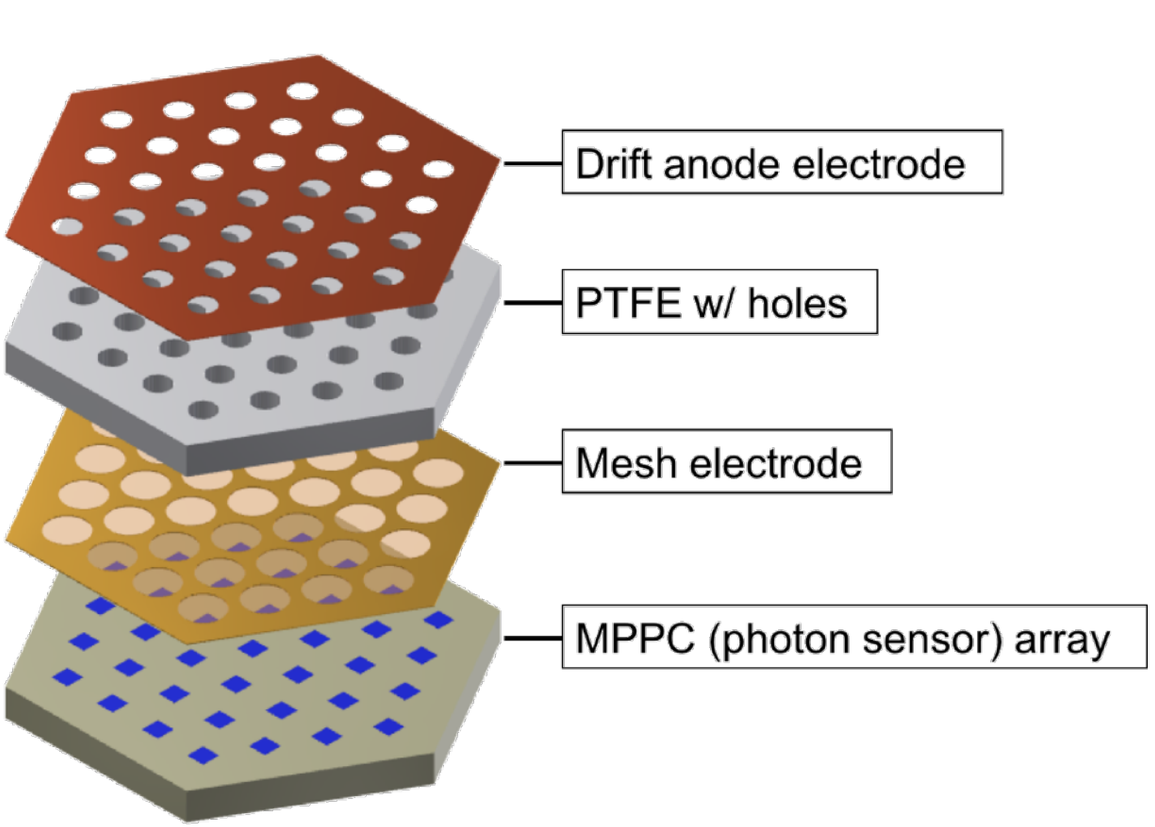
Large mass

→ ton scale ^{136}Xe gas

A Xe ElectroLuminescence : AXEL experiment

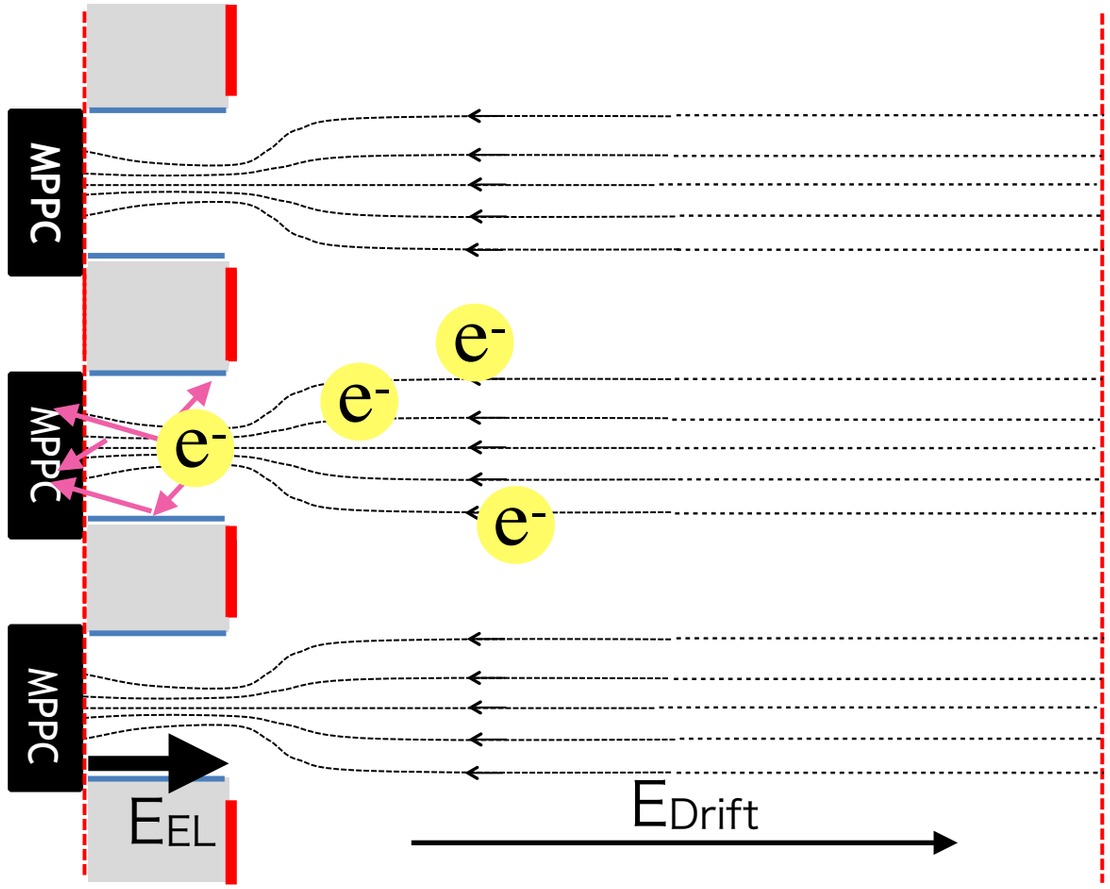
Electroluminescence Light Collection Cell : ELCC

- Energy measurement and Tracking in each cells
- Uniform response to event position
- Extendable to large size because of its rigid structures



Simulation study of ELCC was done and presented in XeSAT2017

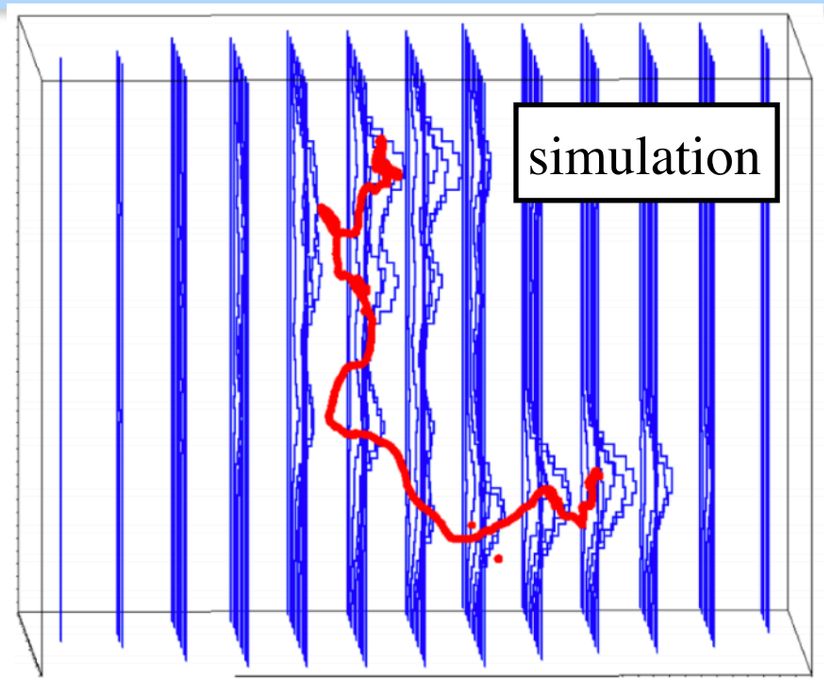
(https://indico.cern.ch/event/573069/sessions/230066/attachments/1440275/2217034/kisekinakamura_20170405_XeSAT.pdf)



Ionization electrons are collected into cells if $E_{EL} > E_{Drift}$, And converted into EL light

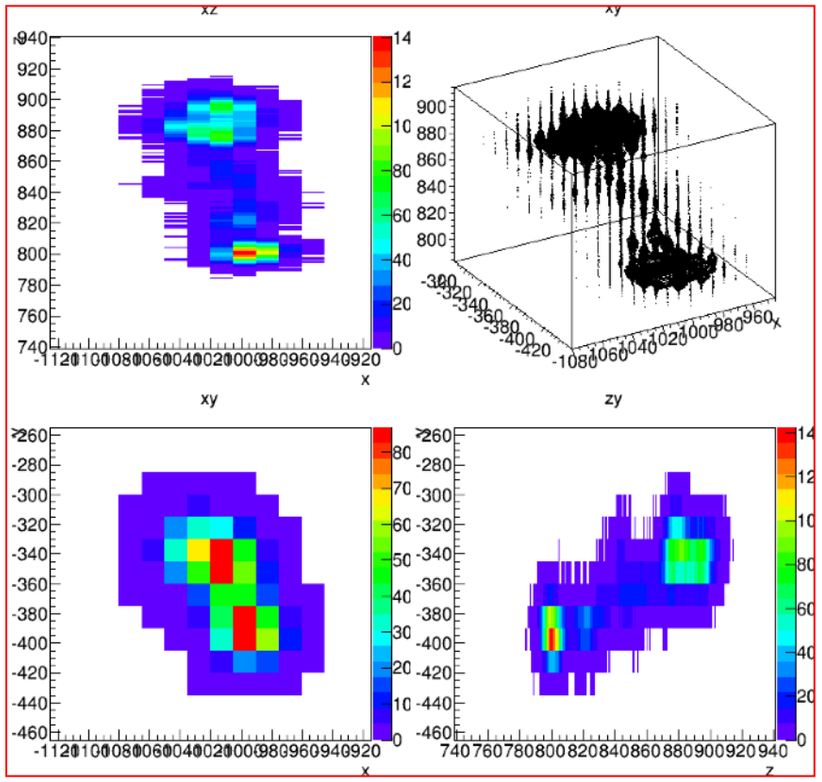
A Xe ElectroLuminescence : AXEL experiment

Reconstruct the event topologies from
hit pattern and wave form
 - α and multi-site events are easily removed

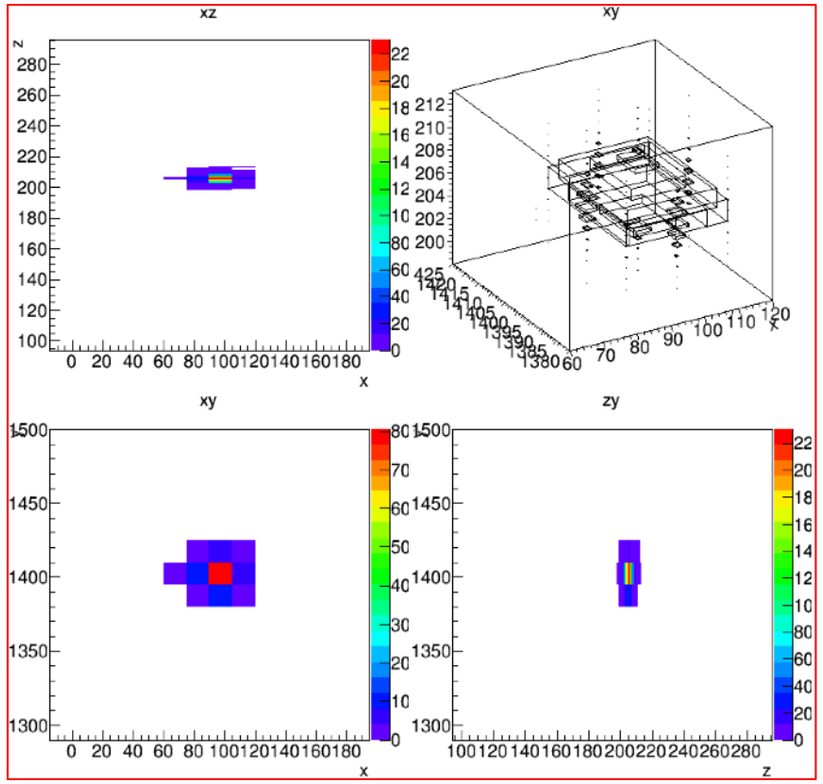


expected event displays
(simulation : 10 atm Xe, 15mm-pitch, 1MHz sampling)

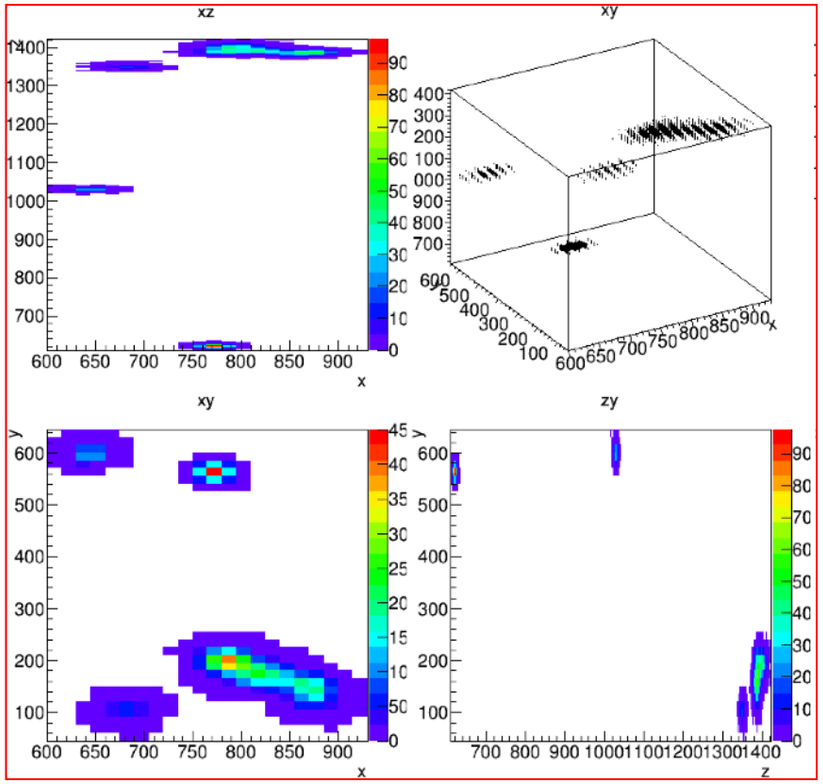
0νββ



α-ray (2.5MeV)



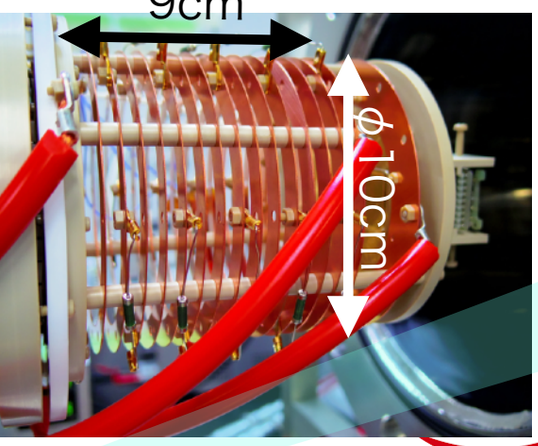
Compton γ-ray (2.5MeV)



A Xe ElectroLuminescence : AXEL experiment

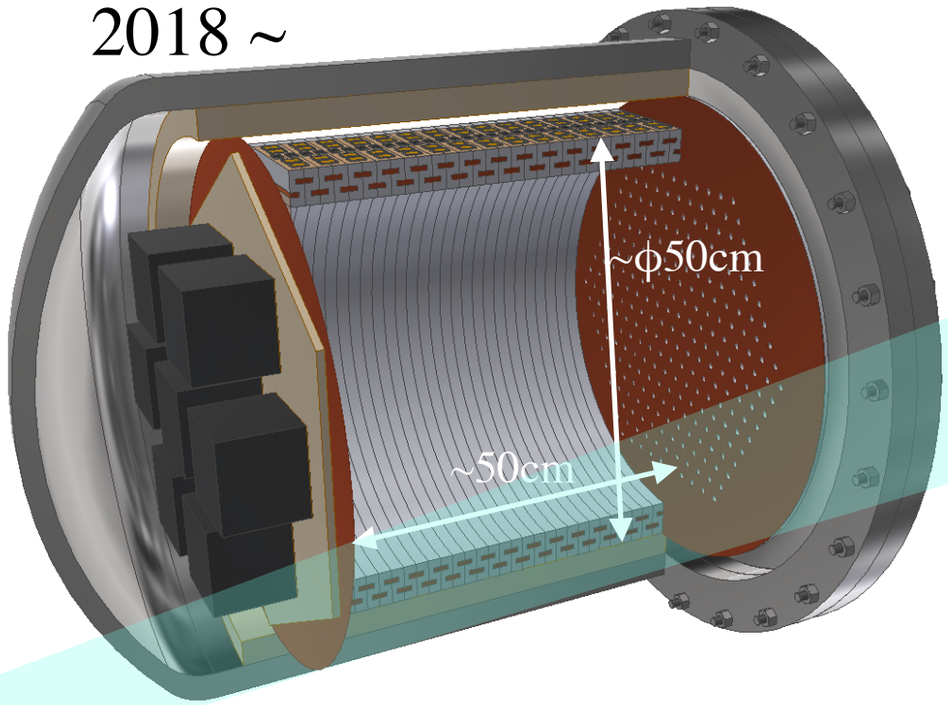
Road map of the AXEL experiment
- Finish evaluation of the prototype detectors until 2020
- aiming to start physics run from 2021

2014~2018



- ~0.08kg Xe
- Demonstrate the ELCC concept
- Energy resolution study
  (122keV, 356keV, 511keV)

2018 ~



- ~5.6kg Xe
- Know-how of enlargement
- Energy resolution study
  (near the Q-value)
- Background study
- now, constructing

2021 ~

~100kg scale

- Physics run
- World record

202X ~

ton scale

- Discovery(?)
- sweep out IH

Contents

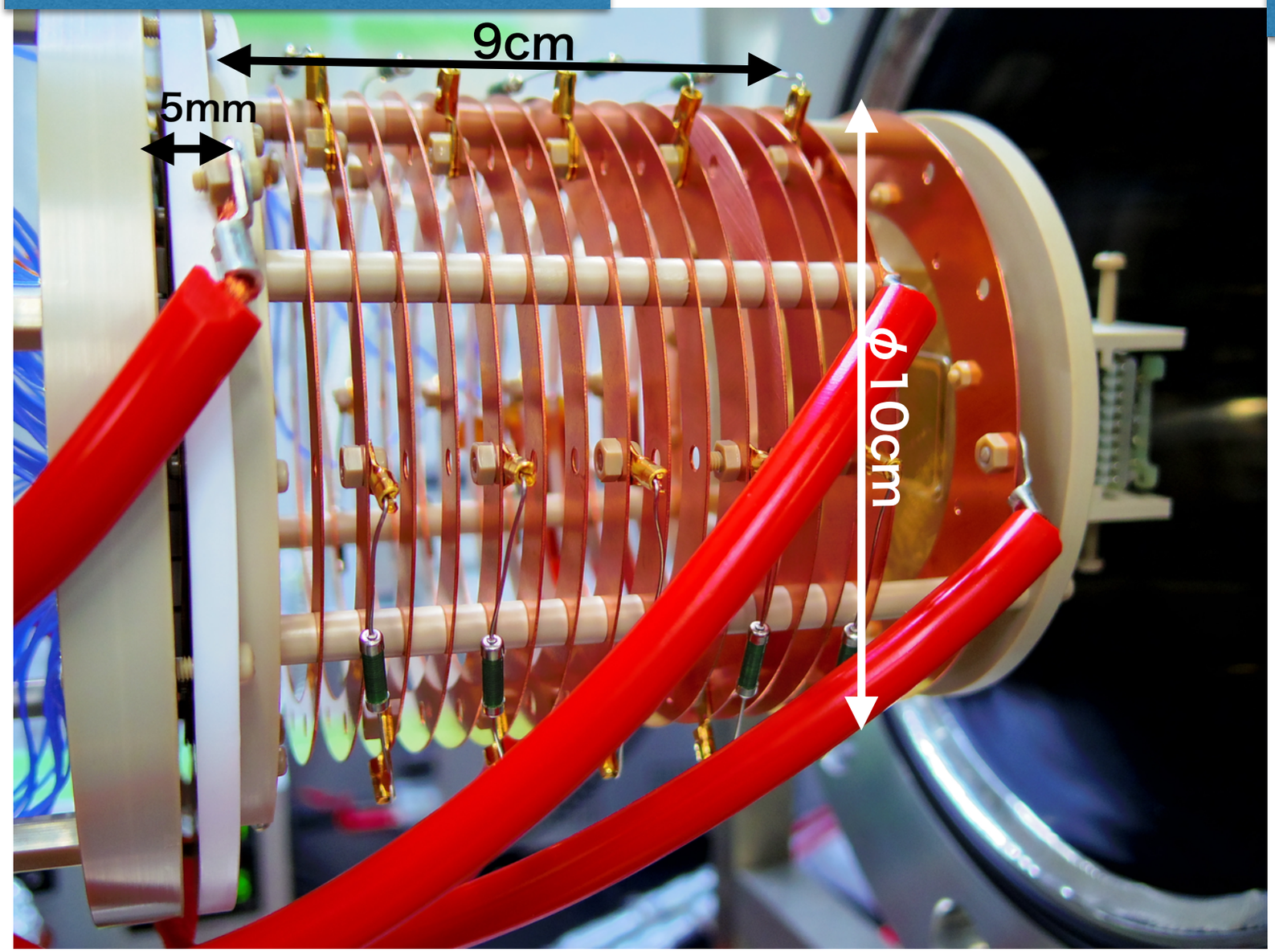
Prototype detector (1) : 10L prototype

Sensitive region : ϕ10cm × 9cm

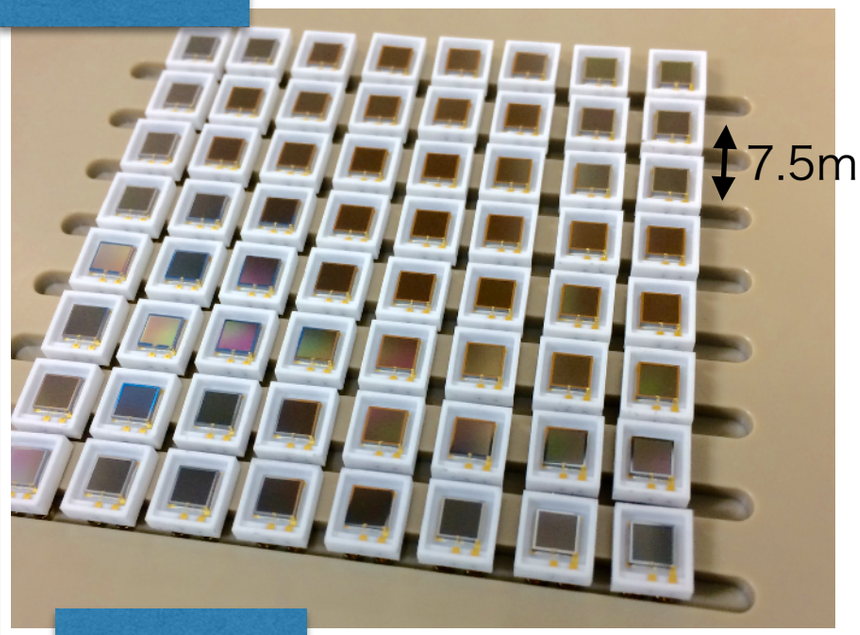
# of channel : 64

Purpose : Demonstrate the performance of ELCC

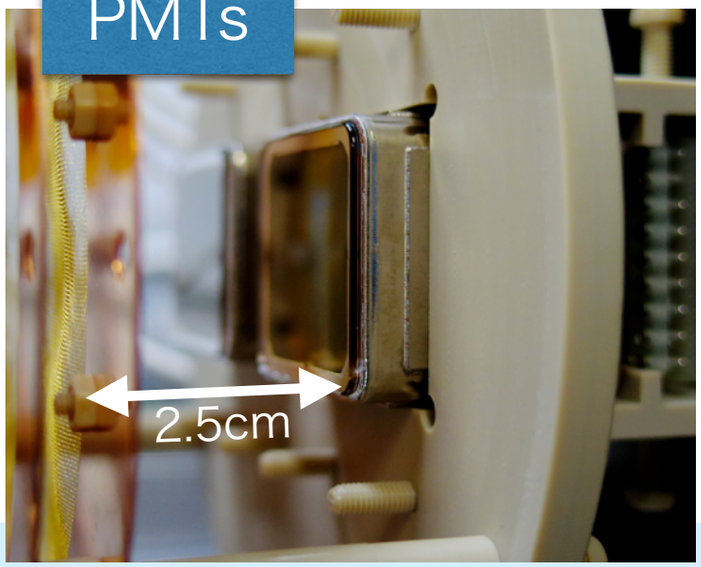
Prototype detector



MPPCs Sensitive to VUV light



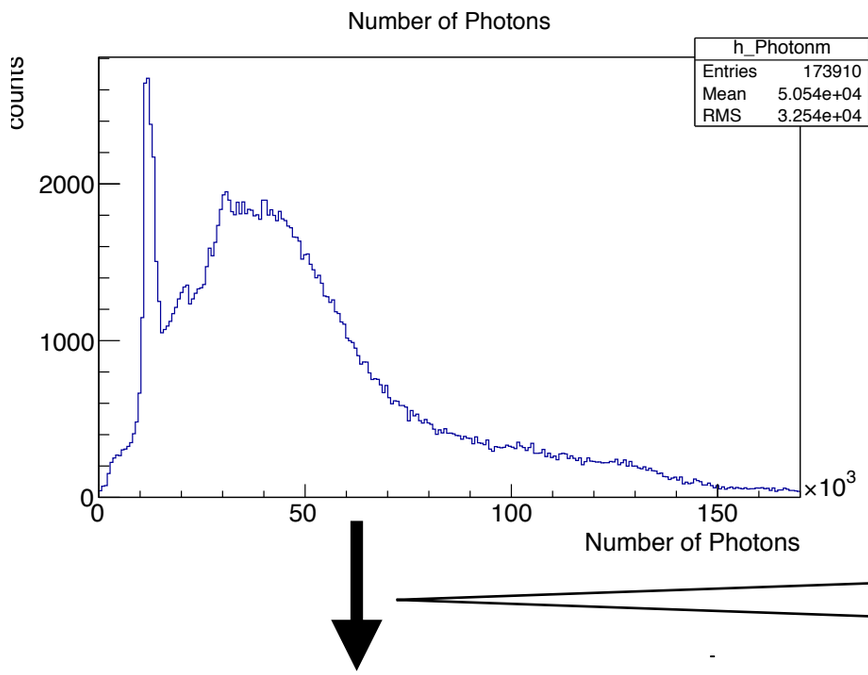
PMTs



Prototype detector (1) : 10L prototype

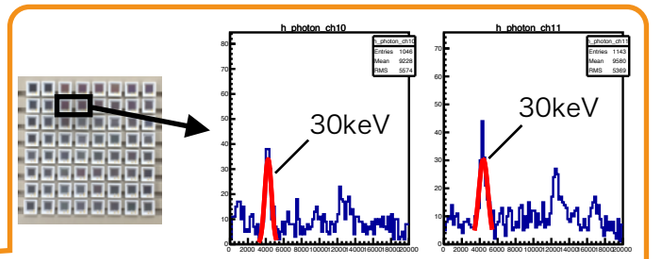
Data and Analysis

- Gas : Xe 8 bar
- E_{drift} : 83 V/cm/bar
- E_{EL} : 2.375 kV/cm/bar
- source : ^{133}Ba

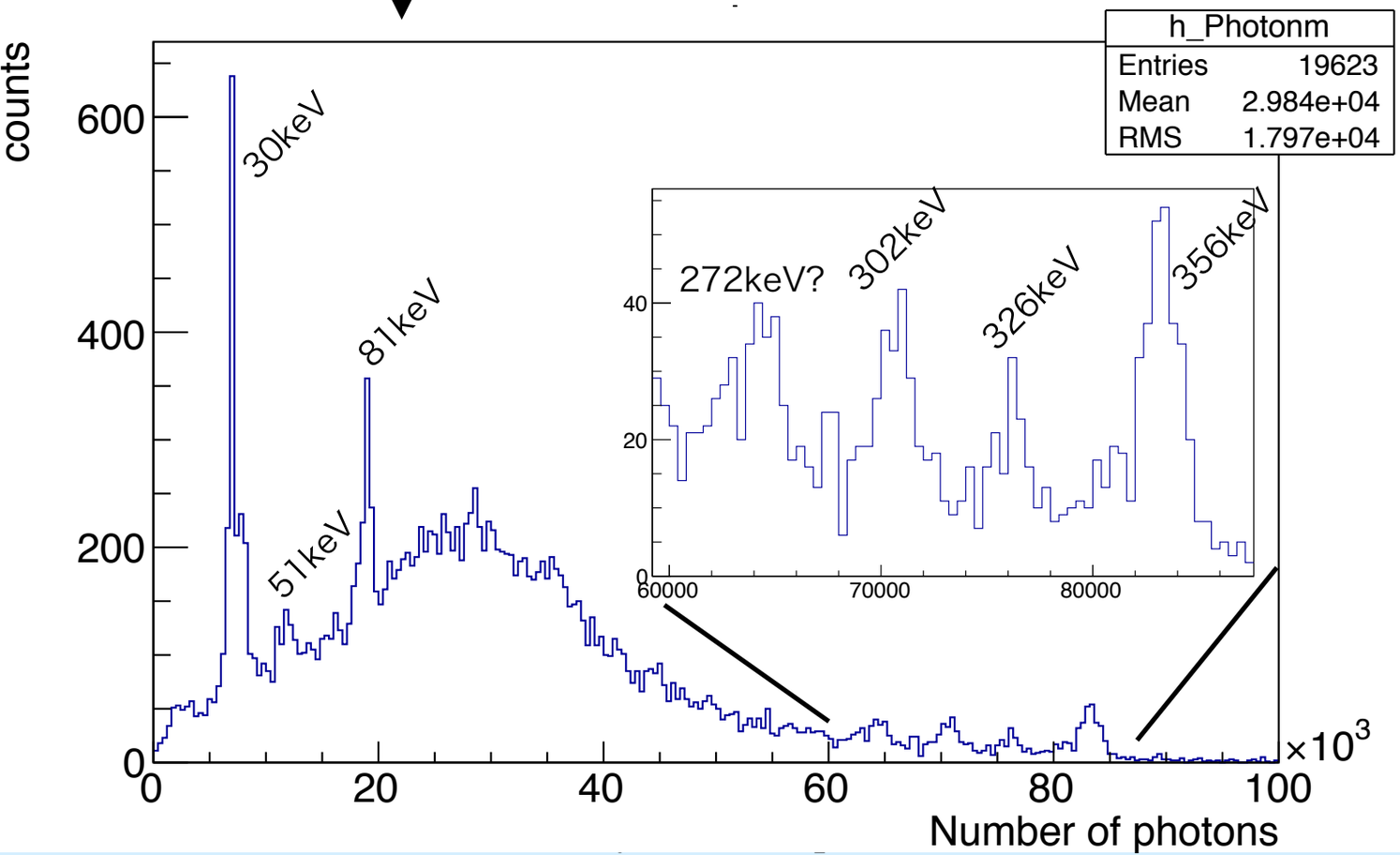


- Fiducial cut
- Saturated events → cut
- Cell gain calibration
- MPPC saturation correction

etc……



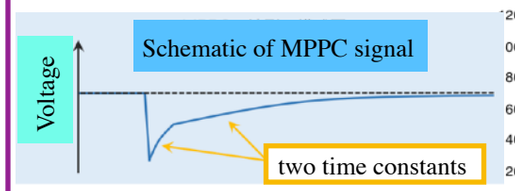
Correction using 30 keV X-ray peak position

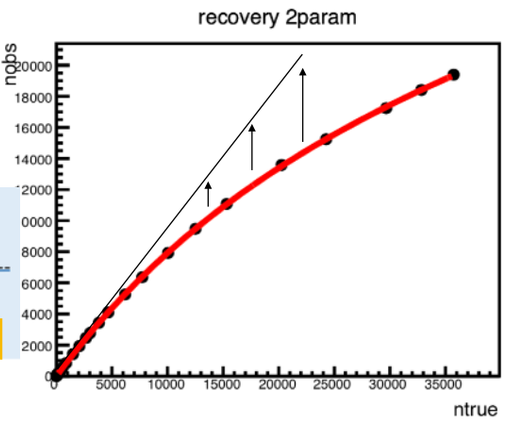


MPPC signal saturate as # of incident photons increases

- saturation curve is characterized by MPPC recovery time
- measured recovery time one by one

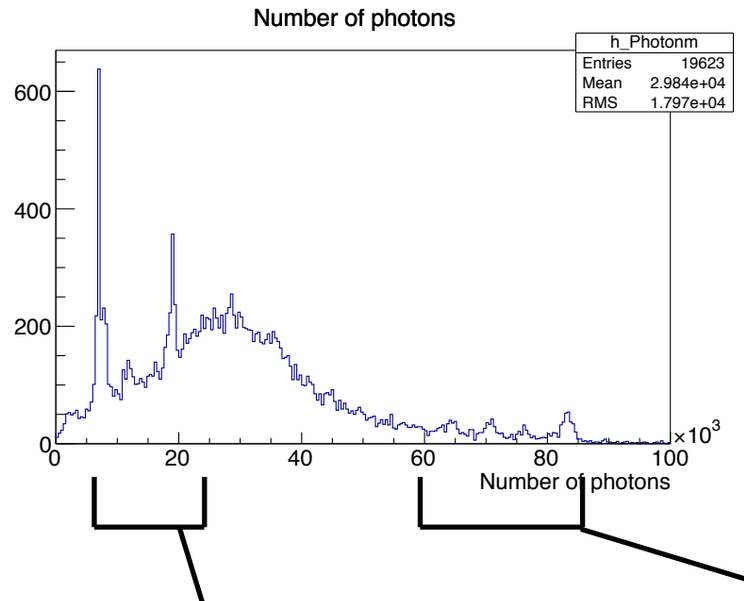
→ apply to correction





Prototype detector (1) : 10L prototype

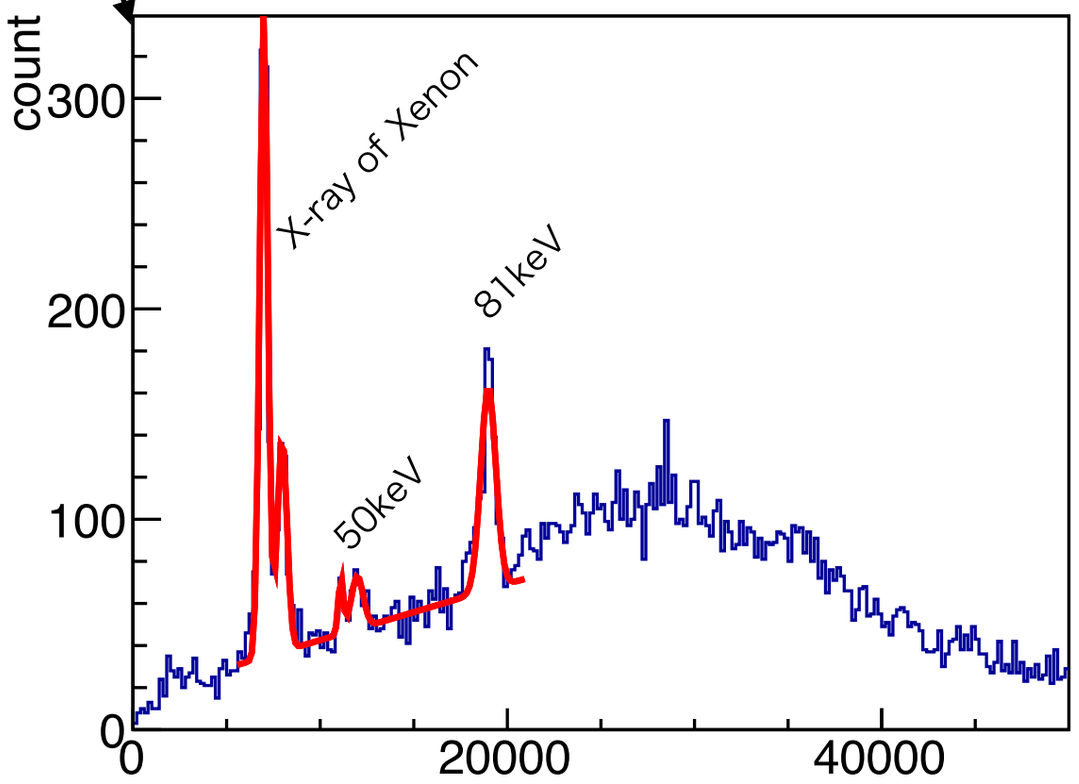
Fitting of the histogram

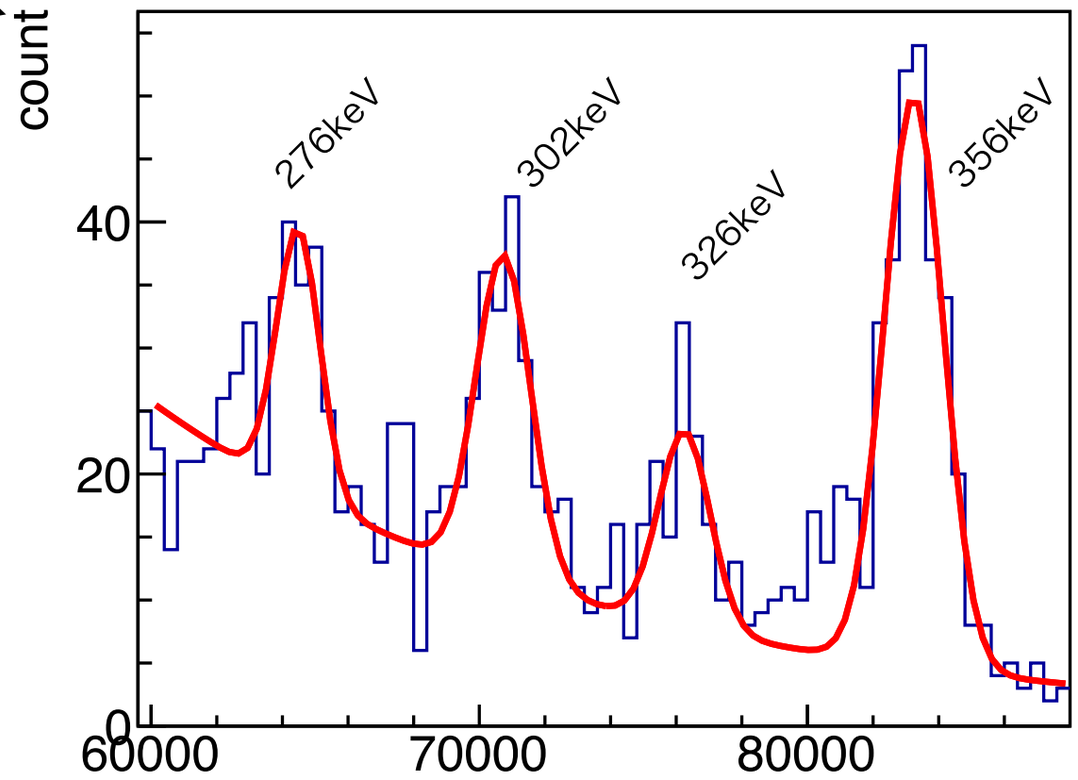


- Fitting by “ Σgaussian + ax+b” in low E region
- Fitting by “ Σgaussian + exp” in high E region

→ ⊿E : 2.54% FWHM at 356 keV

→ 0.97% FWHM at Q-value, extrapolated by √E

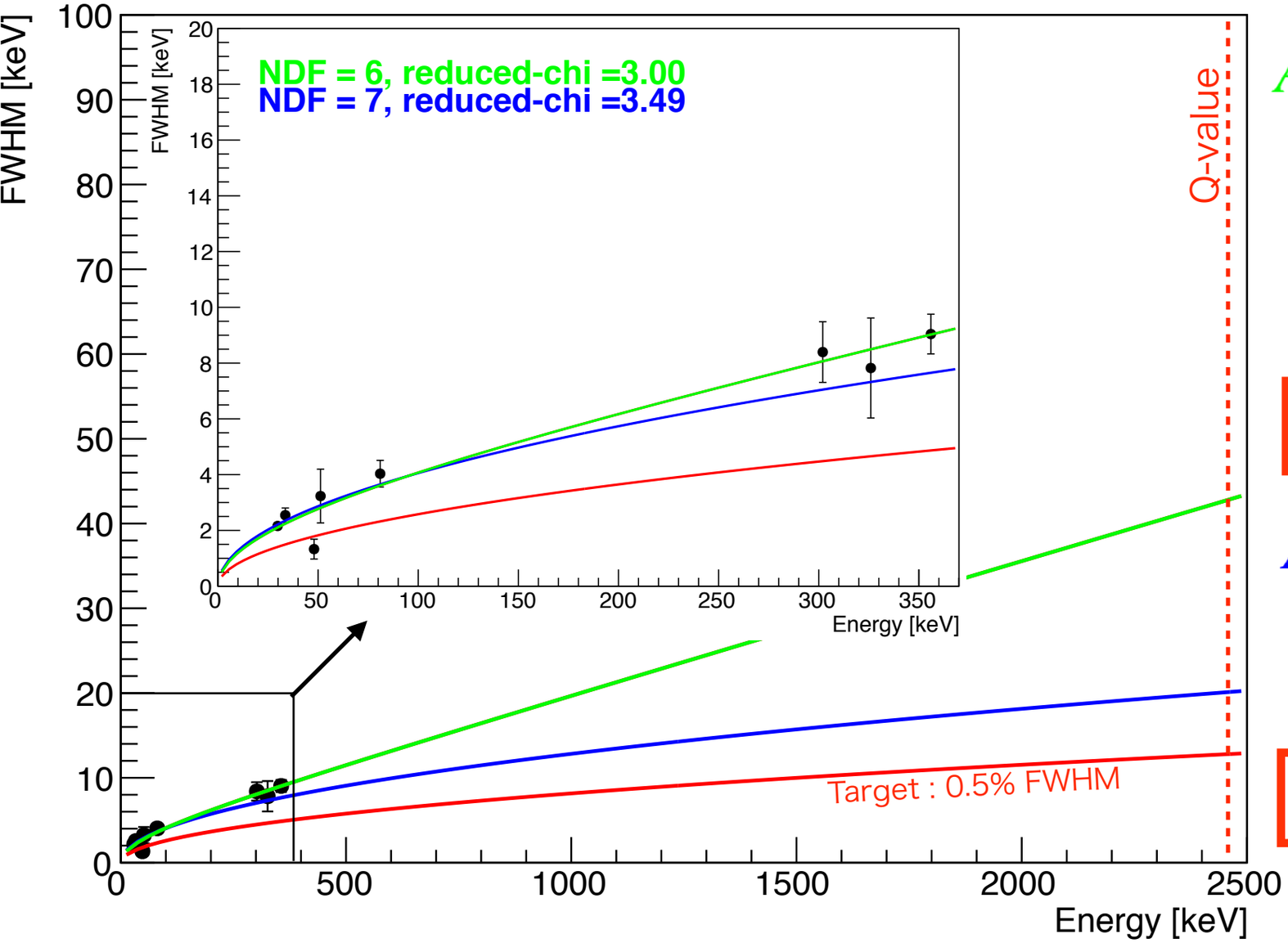




Prototype detector (1) : 10L prototype

Energy resolution at Q-value

- Estimated to 0.82 ~ 1.74 % FWHM at Q-value (2458keV)
- Simulation (Geant4) is also on-going to understand this result



$A\sqrt{E+BE^2}$

A = 0.376 +/- 0.0186

B = 0.002 +/- 0.0008

-> Extrapolate to Q-value

FWHM 1.74% (@2458keV)

$A\sqrt{E}$

A = 0.406 +/- 0.0140

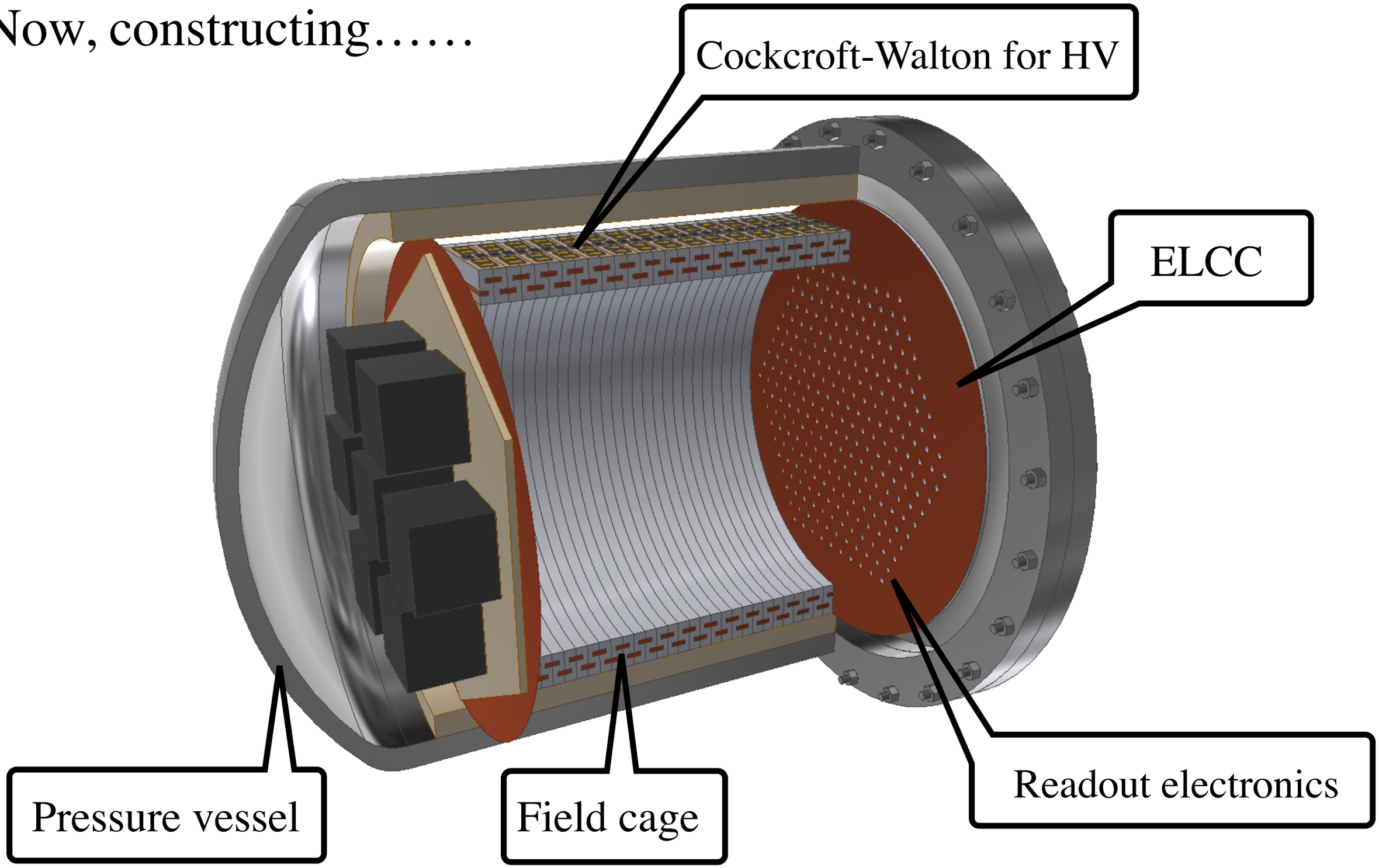
-> Extrapolate to Q-value

FWHM 0.82% (@2458keV)

Contents

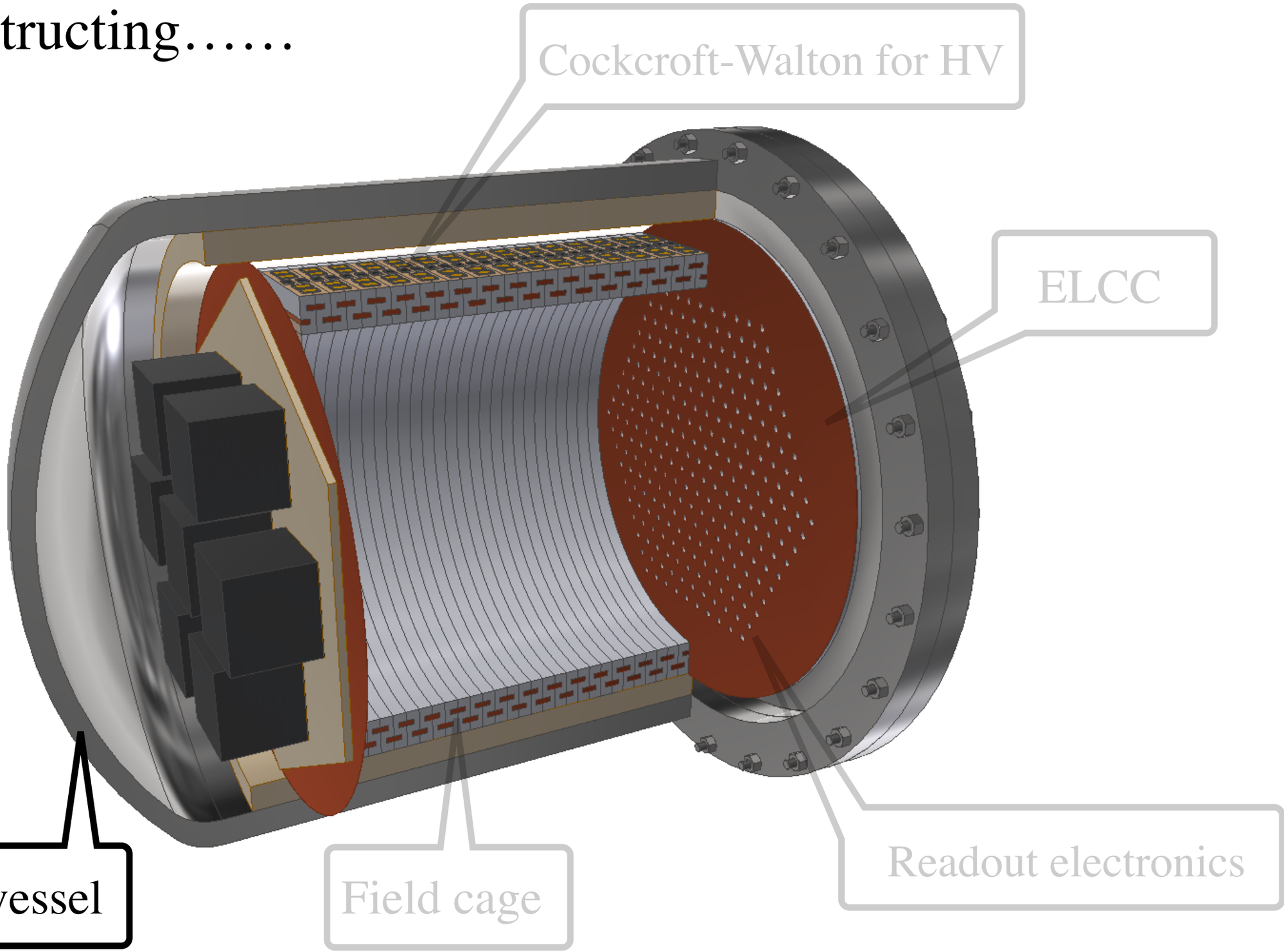
Prototype detector (2) : 180L prototype

- Evaluation of energy resolution near the Q-value
- Now, constructing……



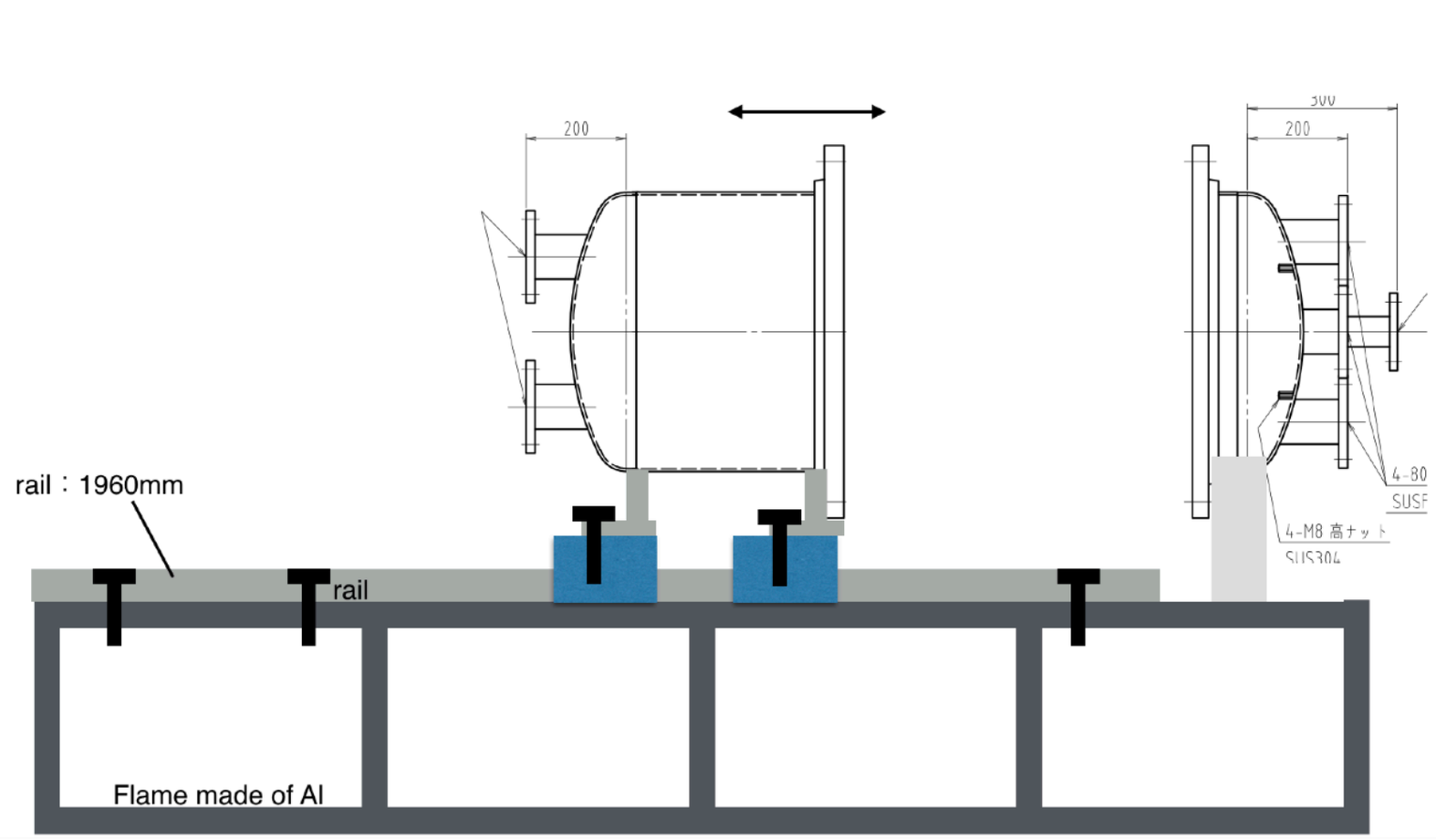
Prototype detector (2) : 180L prototype

- Evaluation of energy resolution near the Q-value
- Now, constructing……



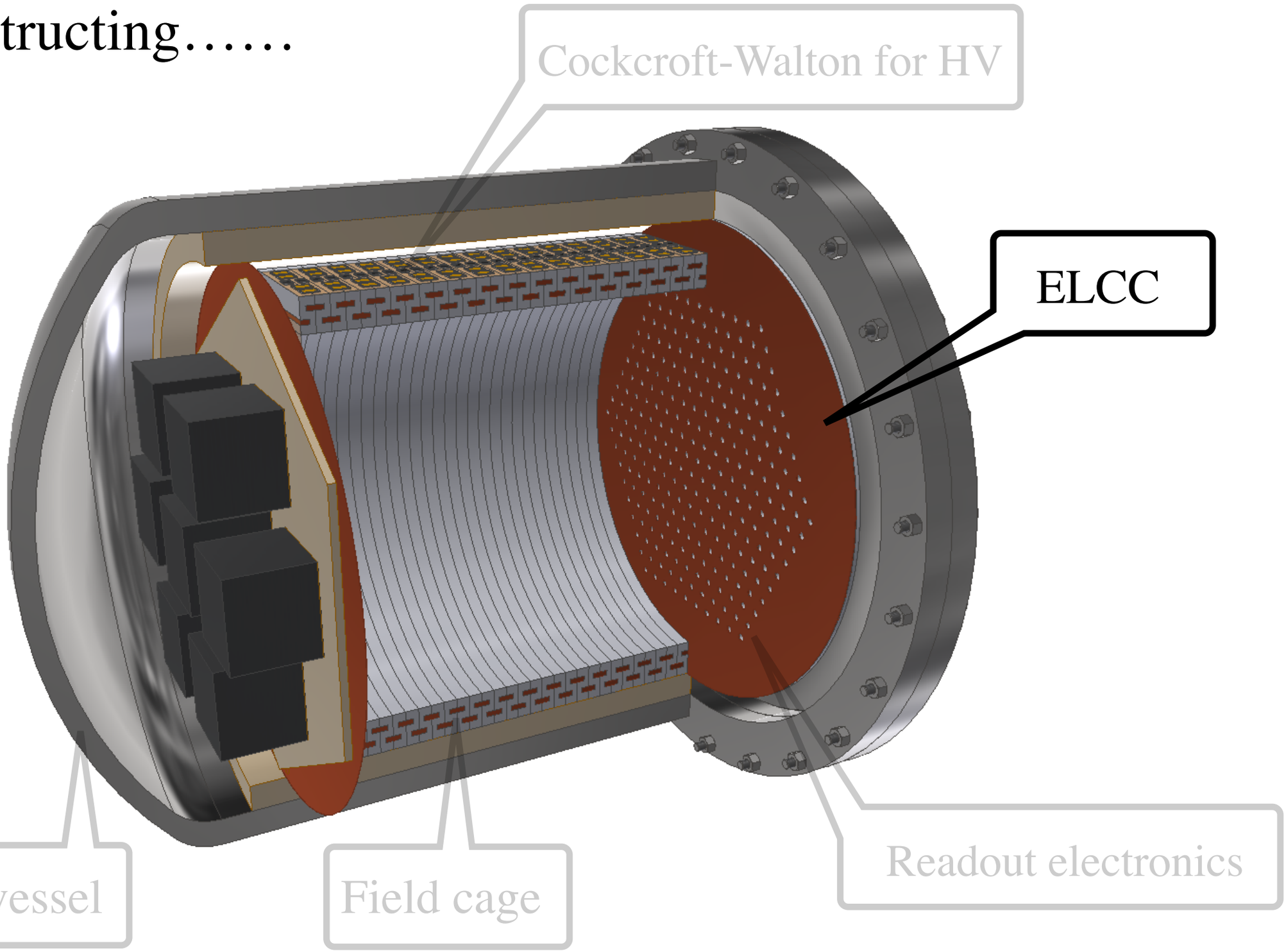
Prototype detector (2) : 180L prototype

Pressure vessel
- SUS304L
- Volume : ~180L (Sensitive Volume : ~100L)
- Now, ready !



Prototype detector (2) : 180L prototype

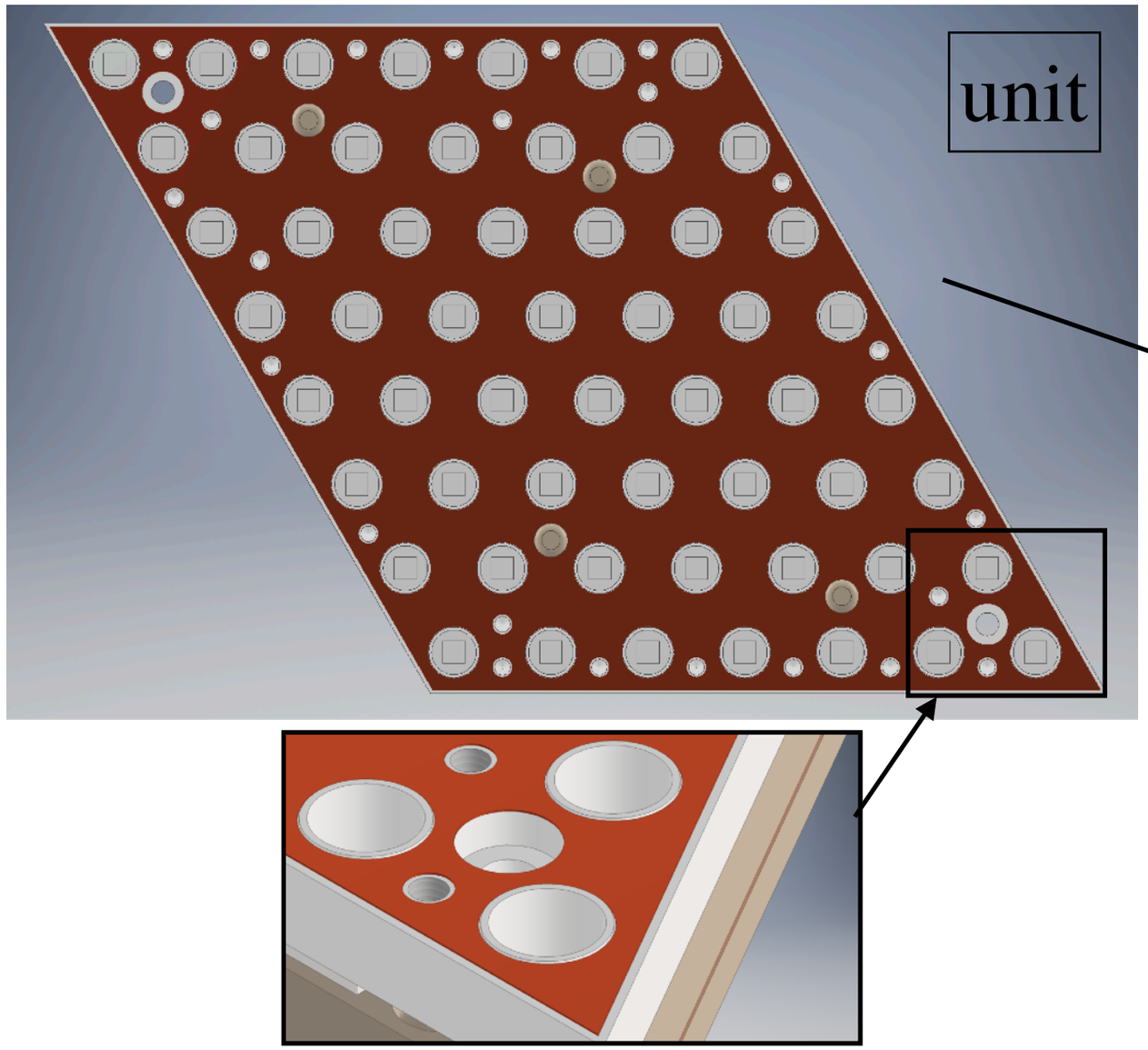
- Evaluation of energy resolution near the Q-value
- Now, constructing……

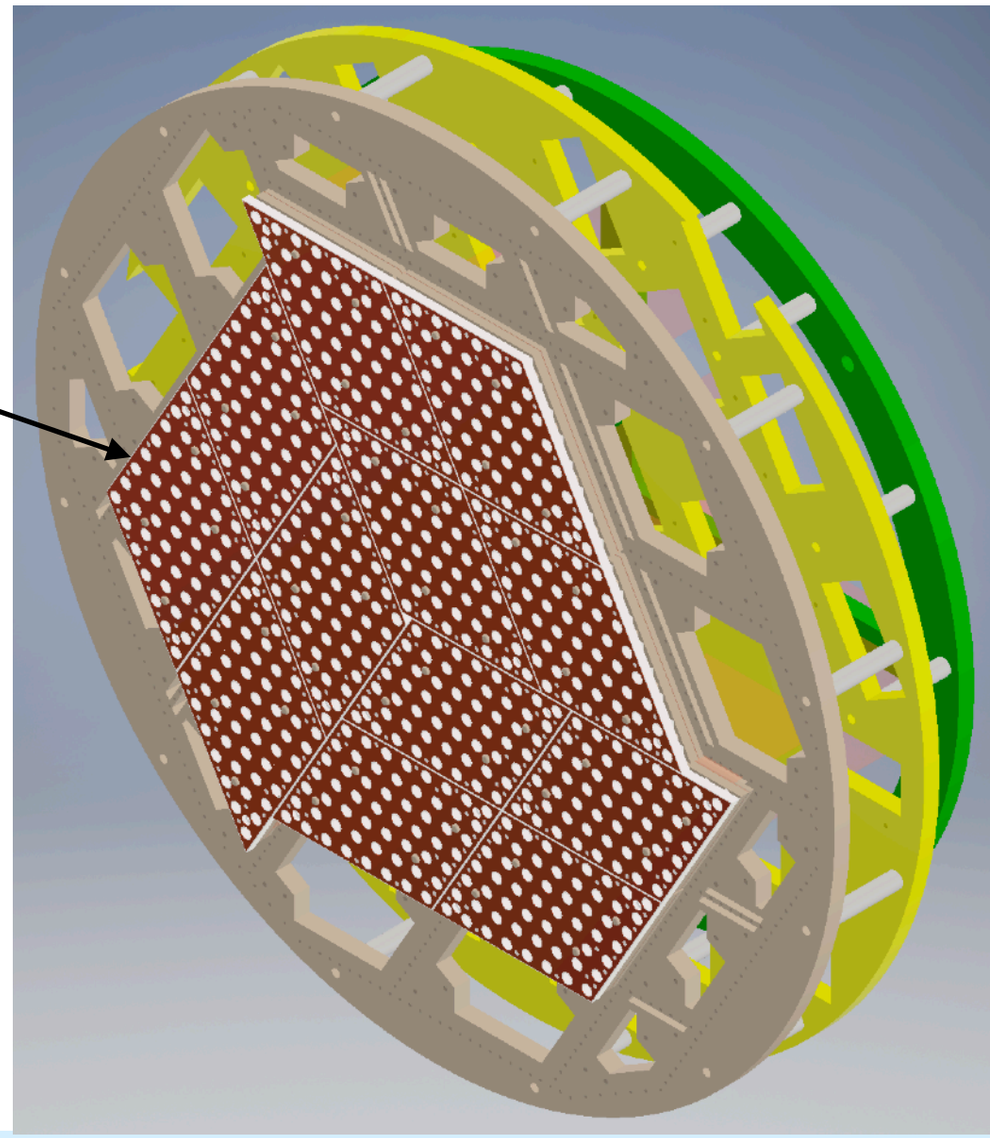


Prototype detector (2) : 180L prototype

ELCC

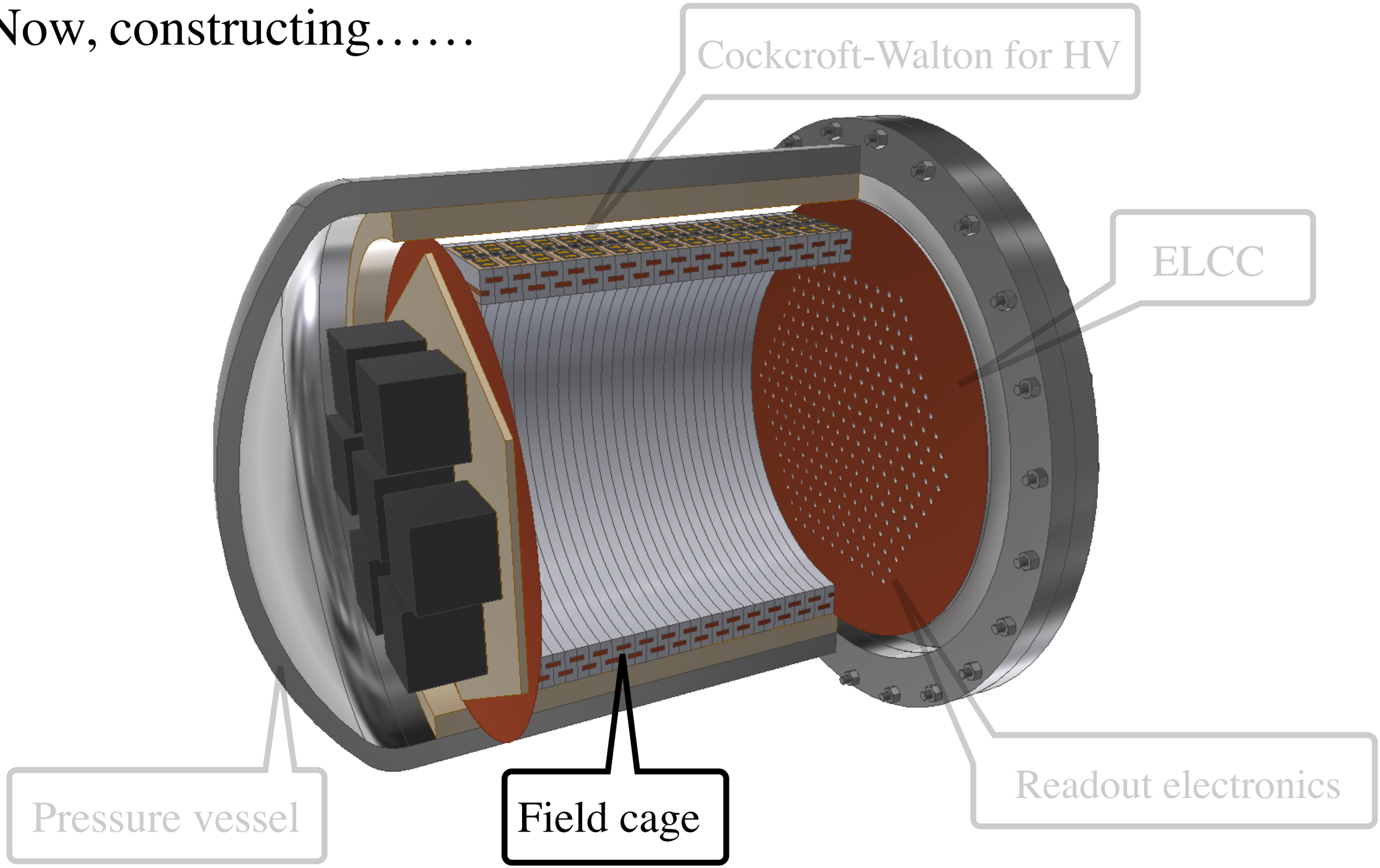
- Prefabricated style → easily to extend
- Number of channels : ~1000 ch
- Design is almost fixed





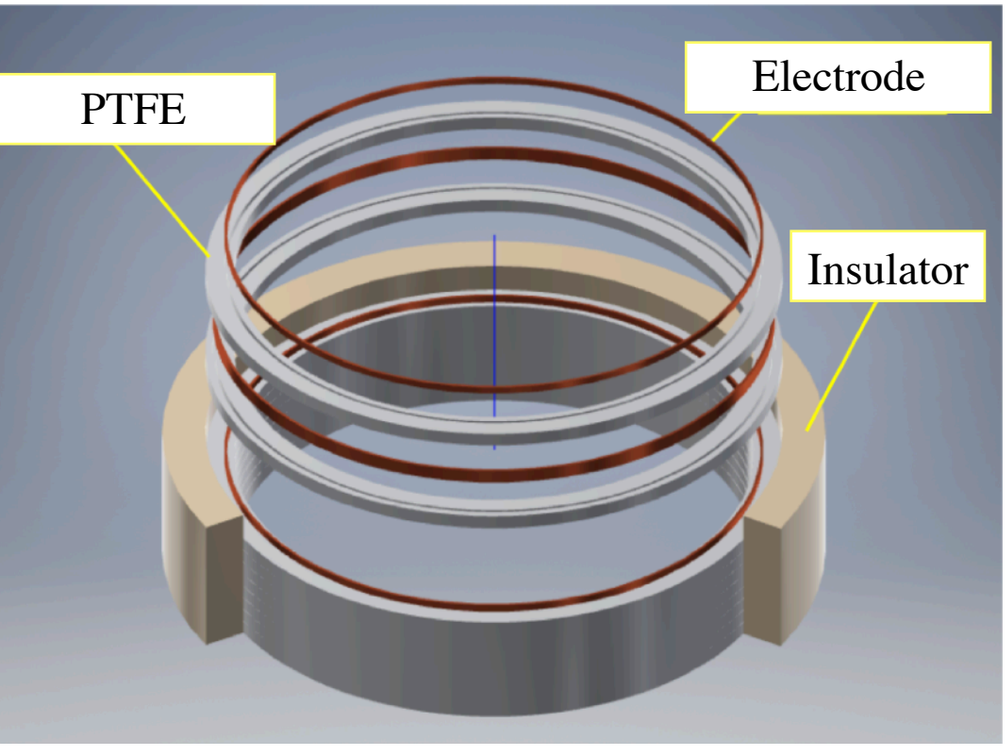
Prototype detector (2) : 180L prototype

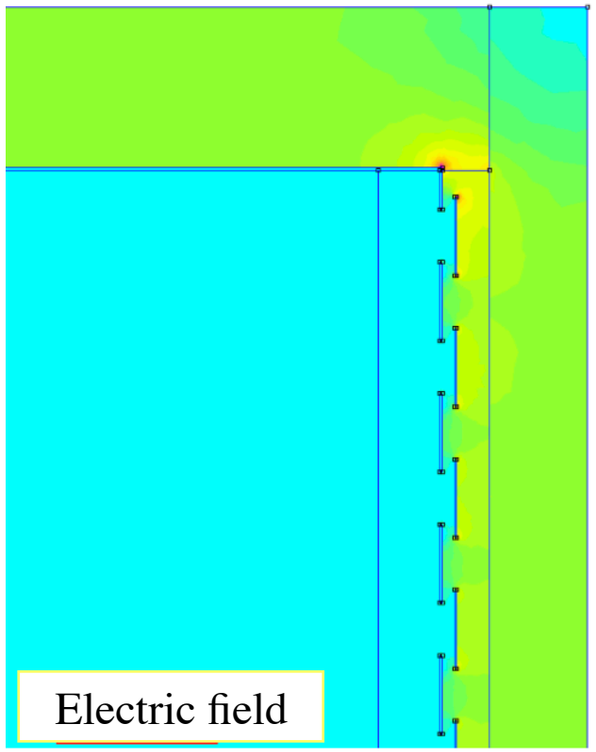
- Evaluation of energy resolution near the Q-value
- Now, constructing……



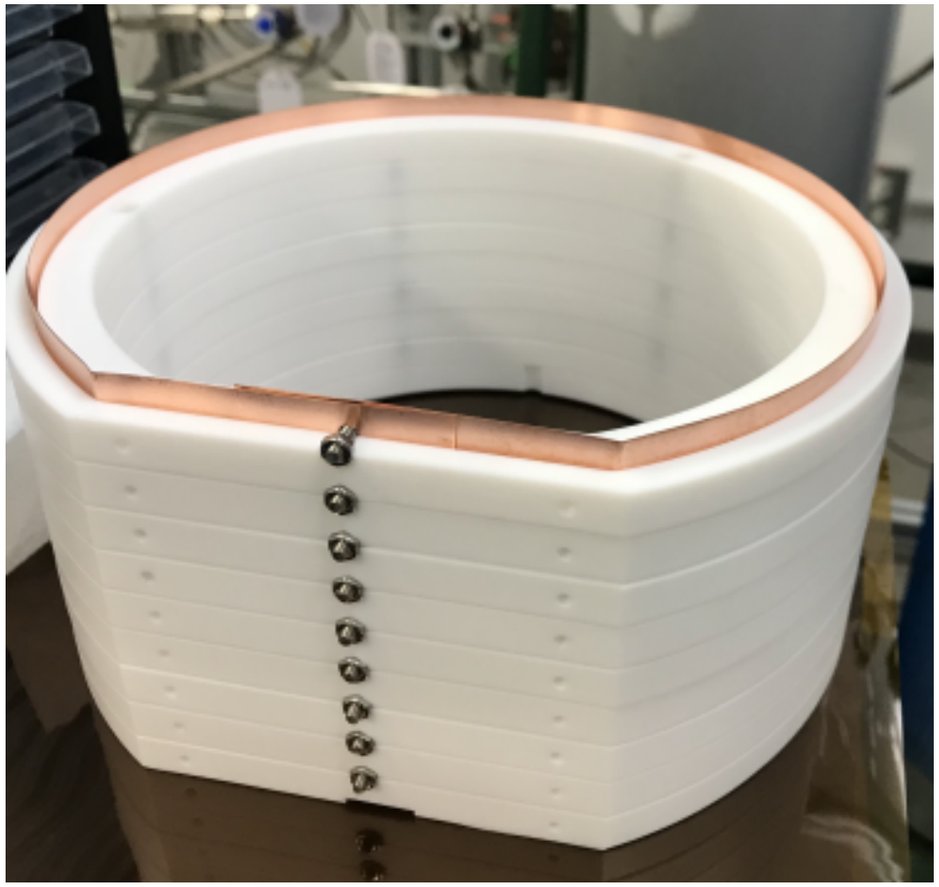
Prototype detector (2) : 180L prototype

Field cage
- Alignment drift field by strip electrodes
- Reflecting scintillation photons by PTFE
- Withstand discharge structure
- Uniformity of Field strength is checked by FEM simulation
- Now, testing with 10L prototype detector



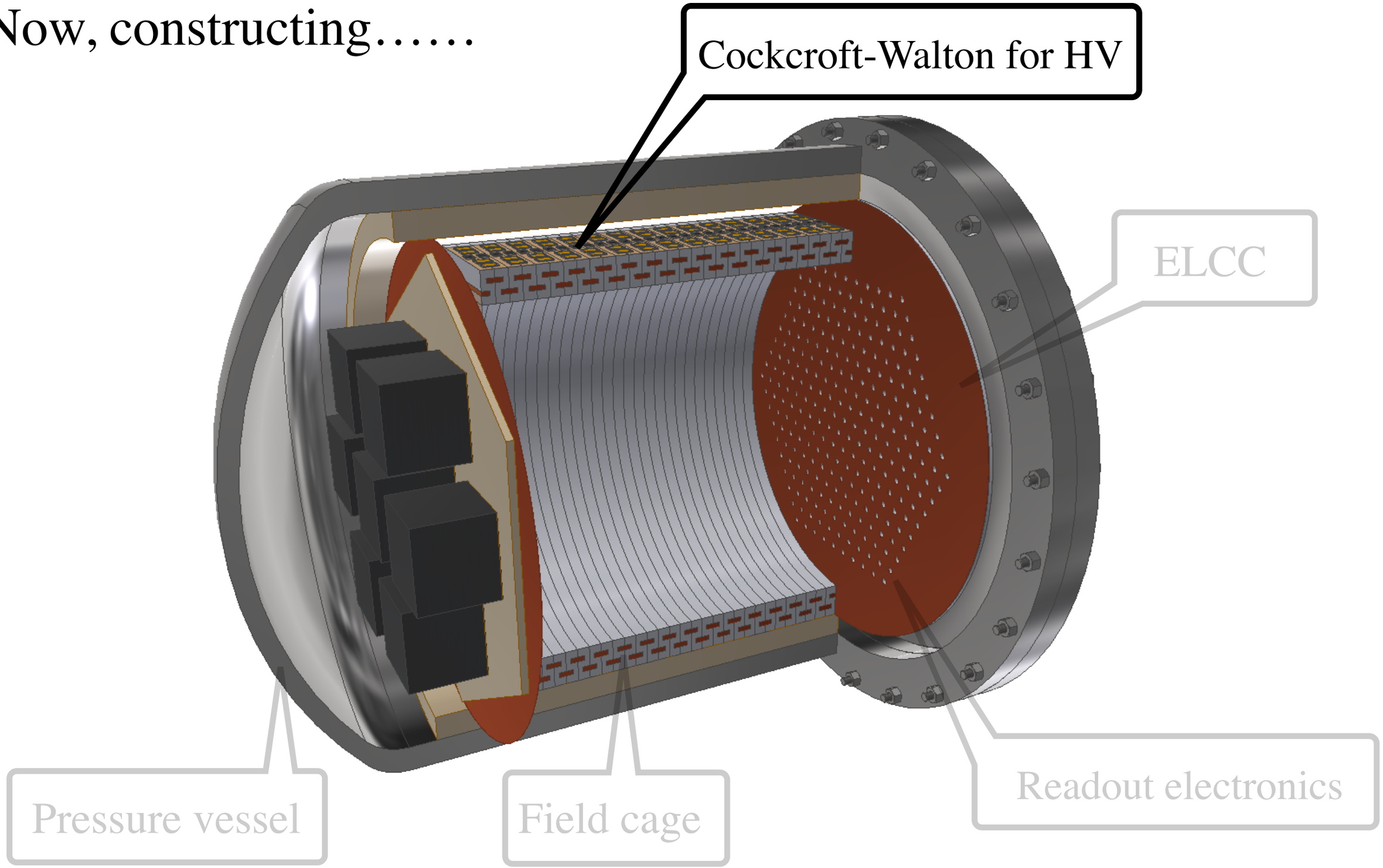


Electric field simulation by FEM



Prototype detector (2) : 180L prototype

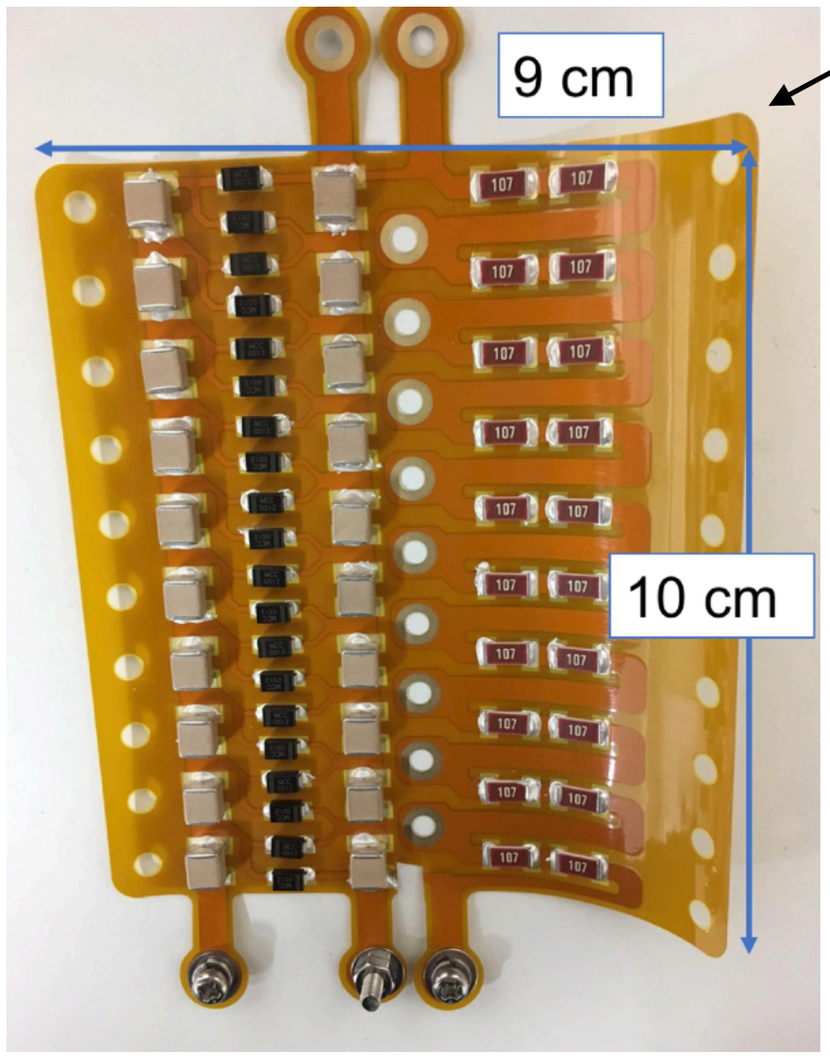
- Evaluation of energy resolution near the Q-value
- Now, constructing……

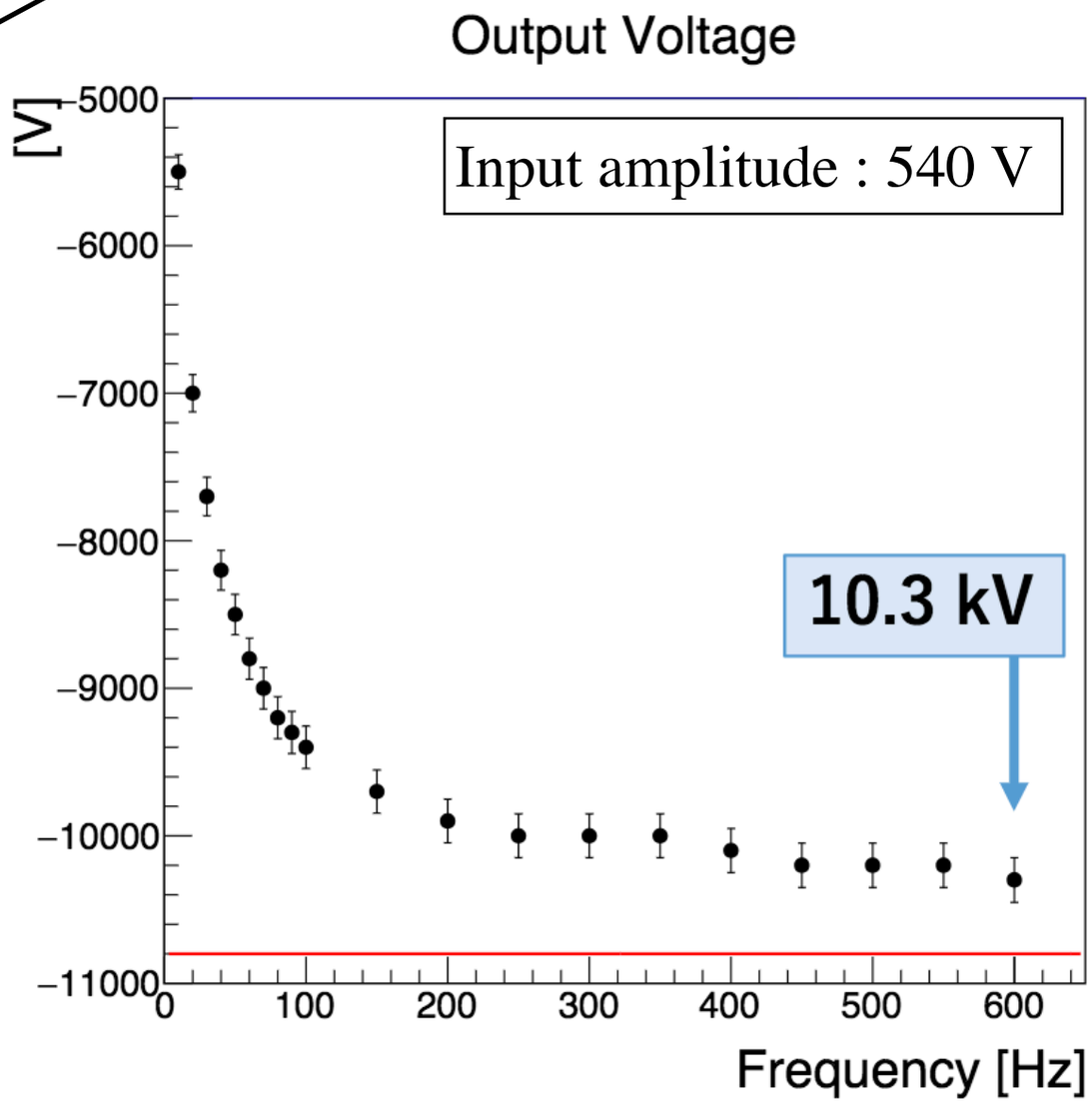


Prototype detector (2) : 180L prototype

Introduce low voltage into chamber and boost by Cockcroft-Wakton inside the chamber to avoid discharge at feedthrough

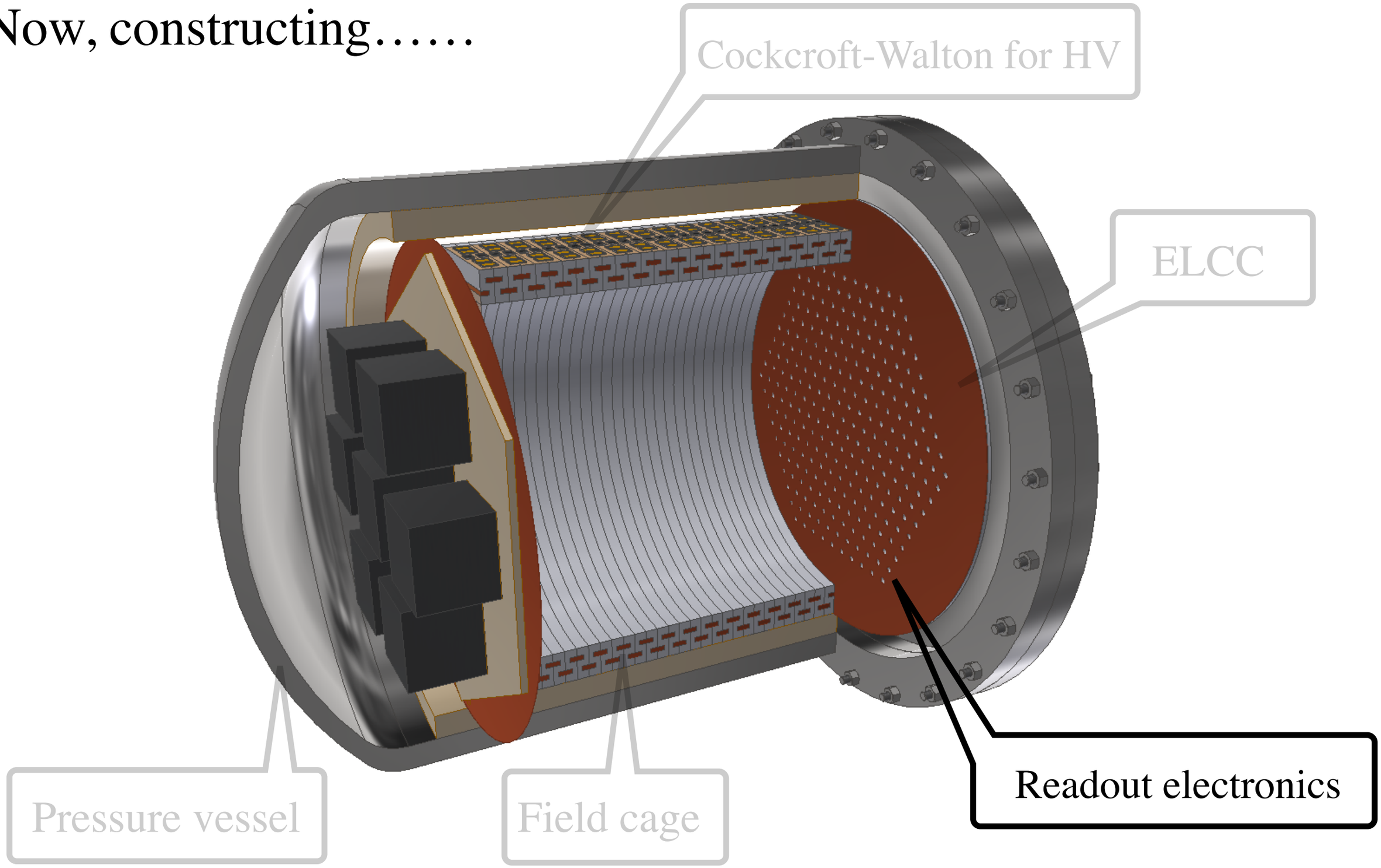
- Low outgas due to Polyimide
- succeed to generate 10kV with a prototype





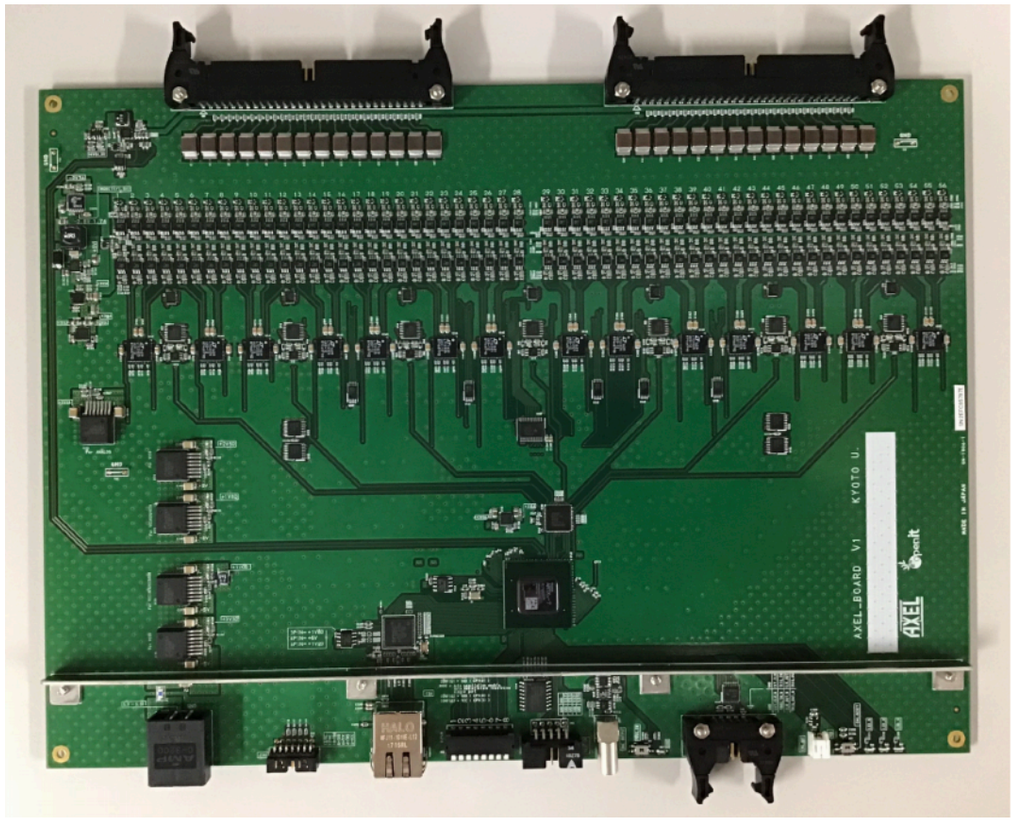
Prototype detector (2) : 180L prototype

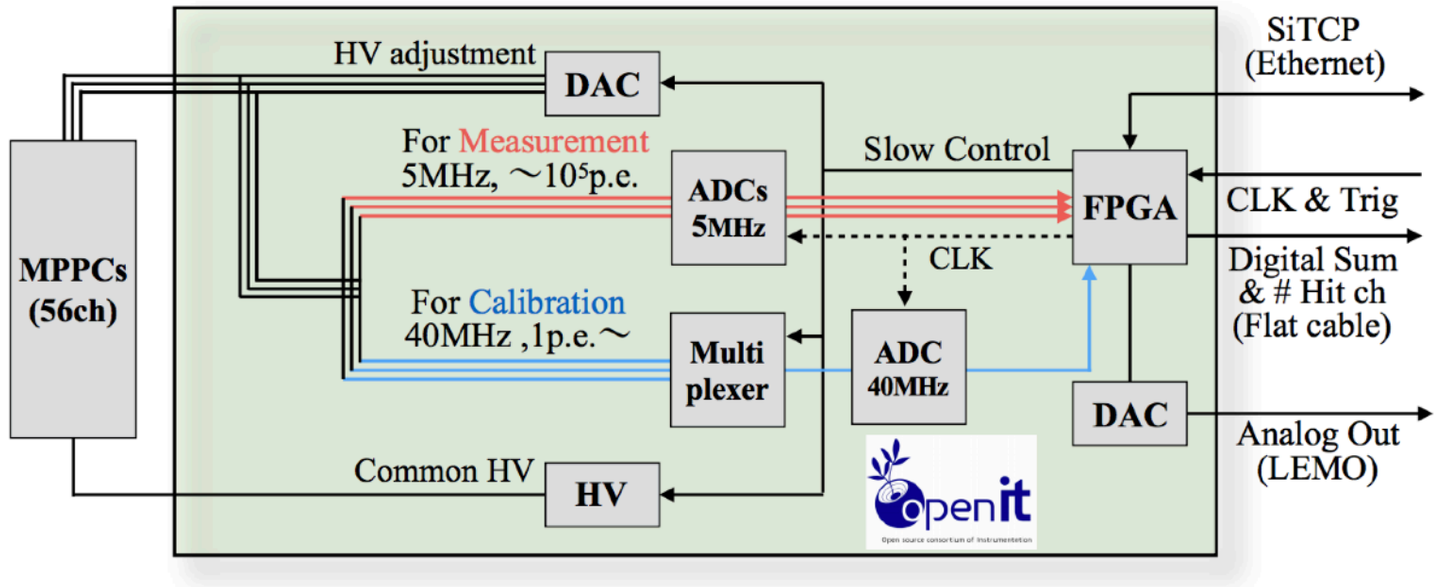
- Evaluation of energy resolution near the Q-value
- Now, constructing……



Prototype detector (2) : 180L prototype

Readout Electronics
- Readout waveforms of MPPC : 56 ch/board
- Two Flash ADCs to achieve wide dynamic range : 1 p.e ~ 10^4p.e
- High Voltage supply to MPPCs (in the 0.2mV)
- Monitor MPPC gain constantly
  → adjust (feedback) gain in 0.25% accuracy
- Low cost





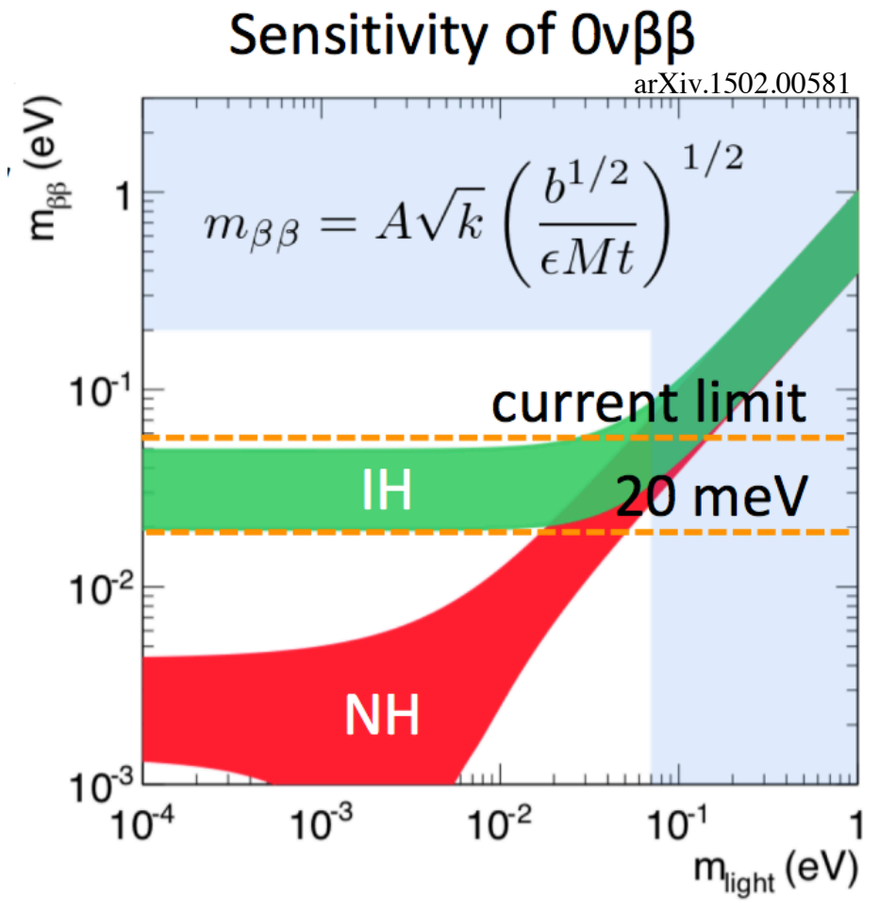
Contents

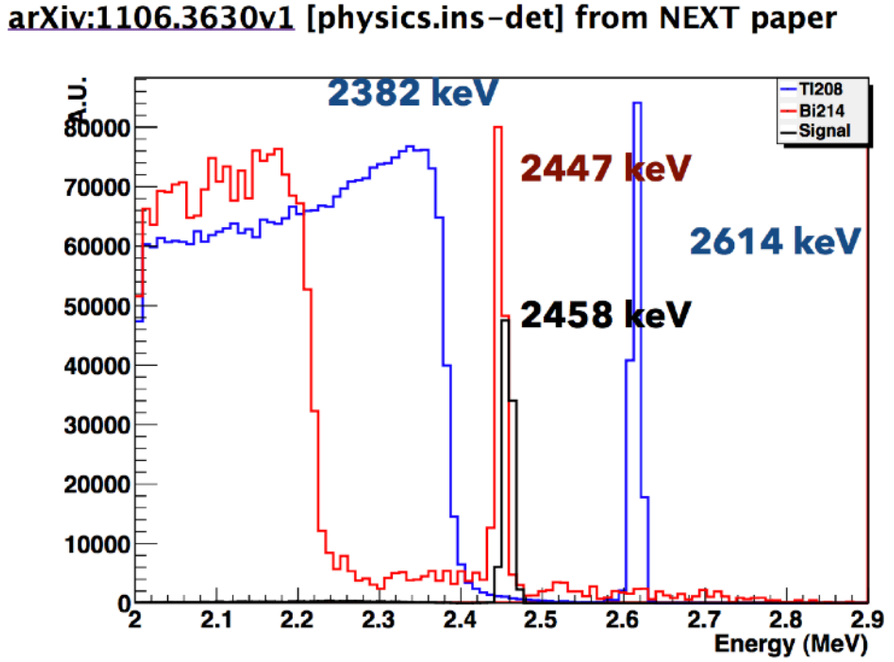
Future prospect

Sensitivity estimation for 1 ton detector
- Need to reach $m_{\beta\beta}$ = 20 meV
- Background free is required

- ^{214}Bi (2447 keV) is serious BG source
- Main source : Pressure vessel (~10 ton)

- Even if we use oxygen-free copper
  2.9 ppt ^{214}Bi (cf. EXO-200)
  → 75 event/year for 1 ton detector



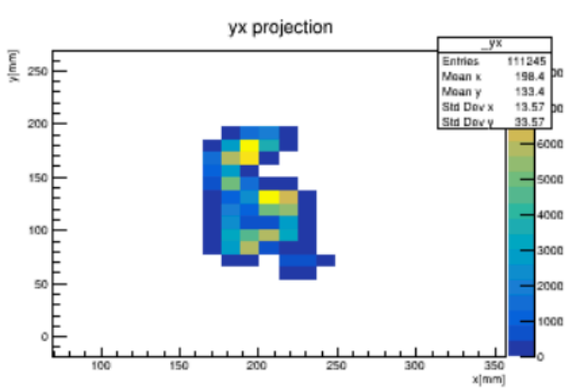


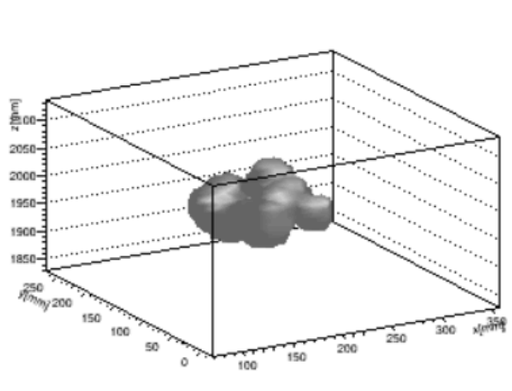
Future prospect

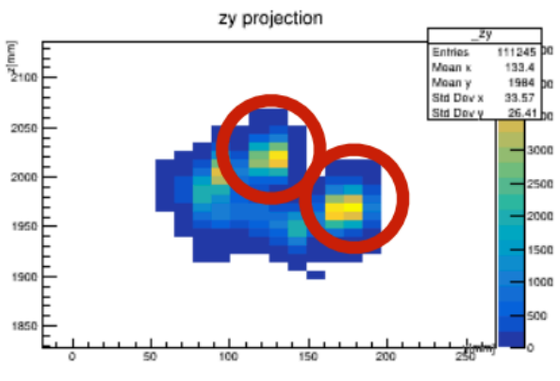
Topological information
- 0νββ decay has two blobs
- Photoelectric absorption of gamma event only has one blob

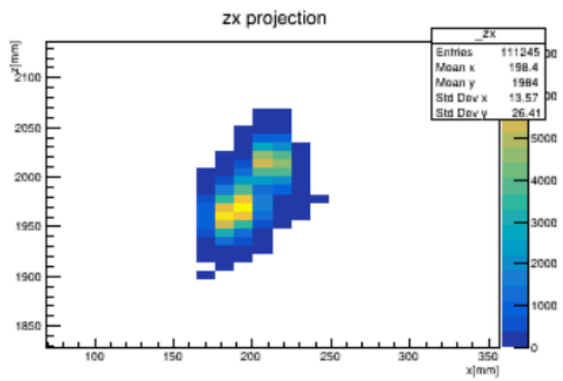
→ To Identify two blobs is very powerful strategy

0νββ

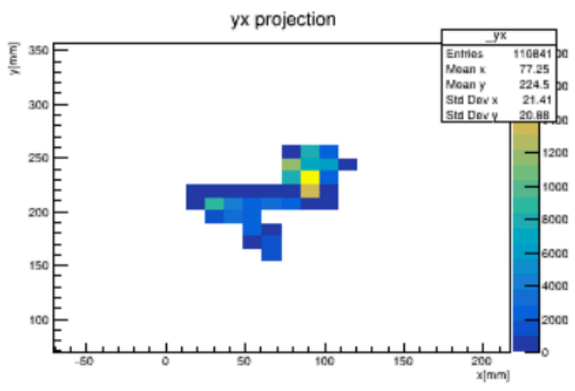


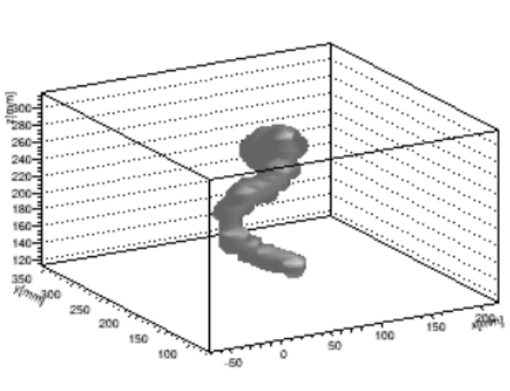


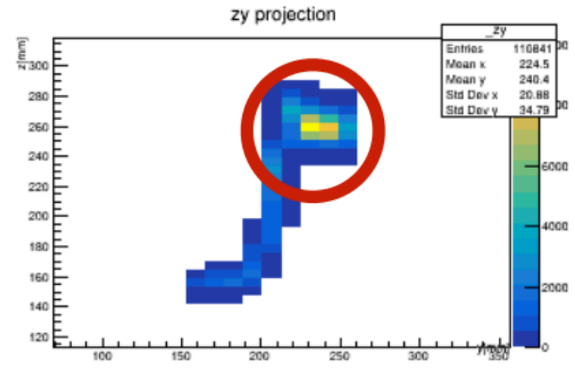


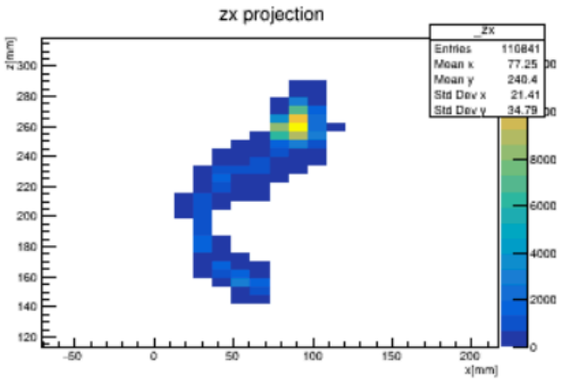


Gamma-ray



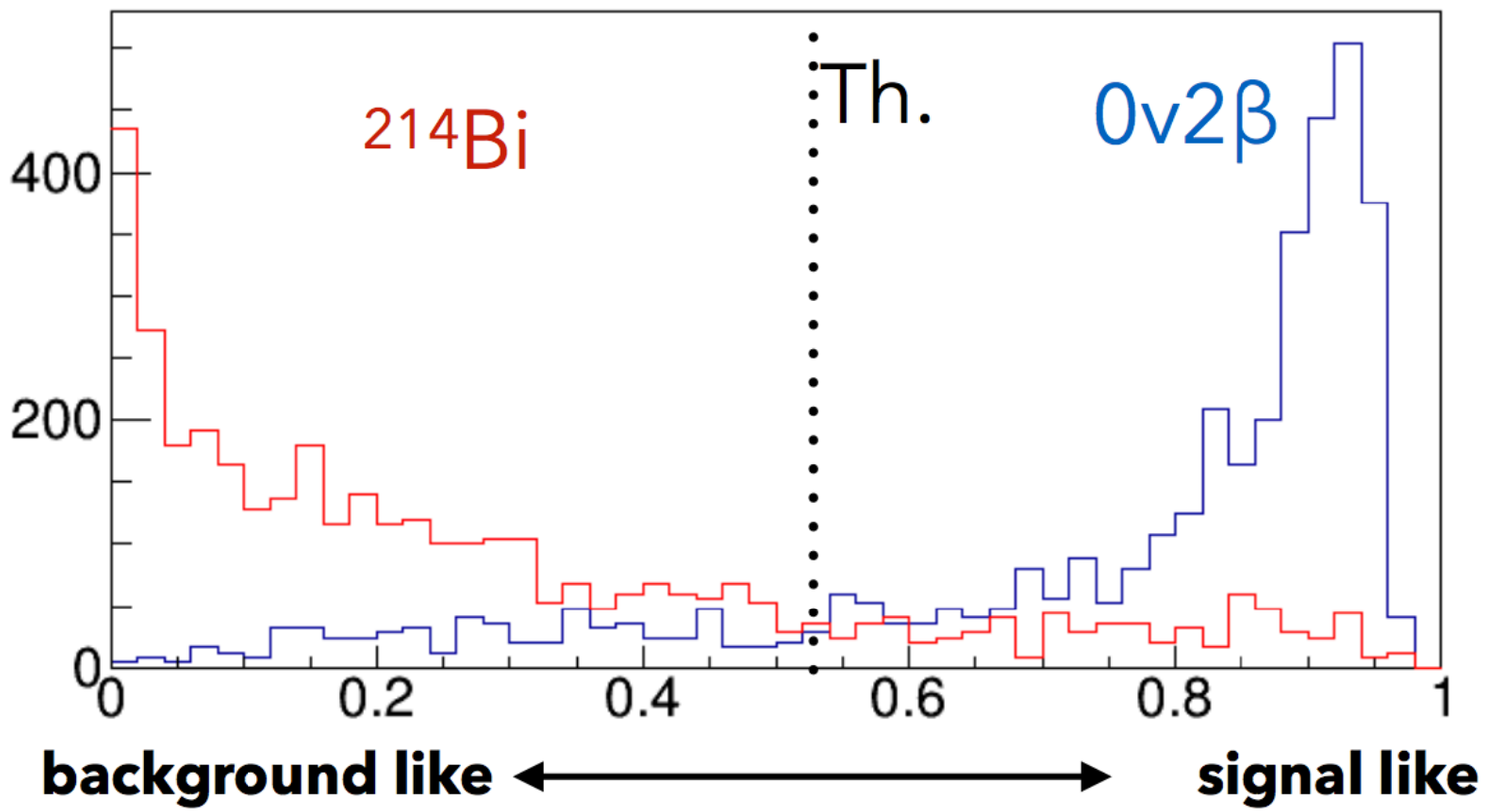






Future prospect

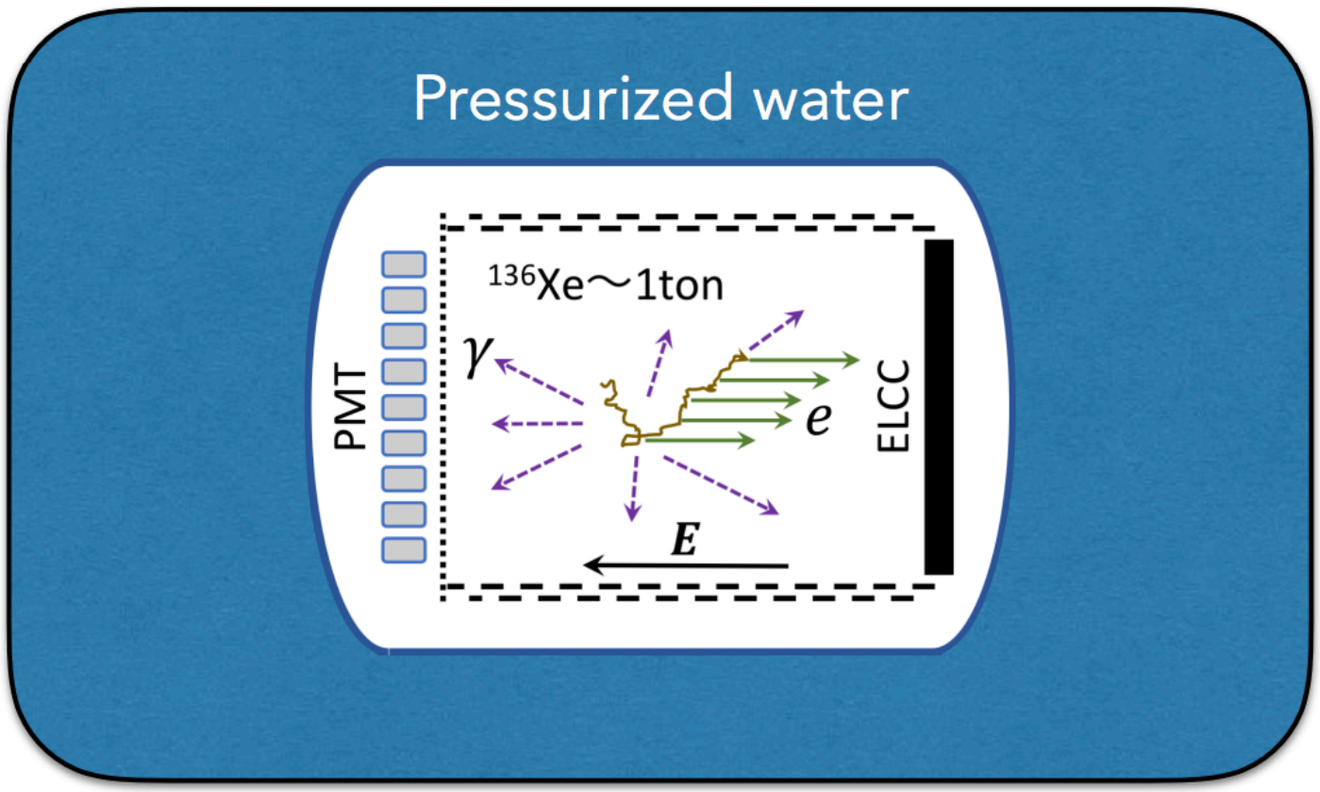
Topological information
- Deep Learning is one of the options
- Learning with simulation of 0νββ and gamma-ray
- Signal efficiency : 48.8% : BG : 75 evt/ye → 7.9 evt/yr (1 ton Xe)
  (assuming 10 tons of pressure vessel made of Oxygen-free Cu)
- Estimated sensitivity : $m_{\beta\beta}$ = 37 meV (1 ton yr Xe)



Future prospect

Further more…

- Pressurized water shield
  - water Cherenkov can be used for muon veto
  - thin pressure vessel to reduce mass → reduce ^{214}Bi BG
- Active shield vessel
  - detects alpha and beta ray event of ^{214}Bi in the materials of vessel



Polyethylene Naphthalate

Contents

Summary

AXEL is high pressure gas Xe TPC for 0νββ decay search
- Cellular readout structure (ELCC) is characteristic of AXEL

Small (10L) prototype detector has constructed
- Demonstrate the performance of ELCC
- ⊿E : 0.82 ~ 1.74 %(FWHM, extrapolated to Q-value) is estimated

Large (180L) prototype detector is now constructing
- Pressure vessel : Done
- ELCC : Design is done
- Field cage : Now, testing…
- Cockcroft-Wakton : Now, testing…
- Readout electronics : Prototype is done

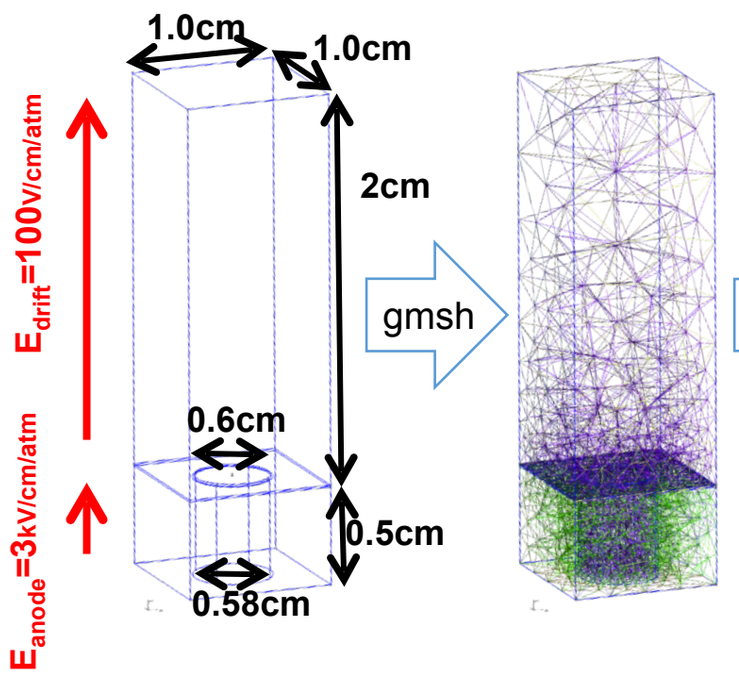
Aiming to $m_{\beta\beta}$ = 20 meV with some ideas (e.g. Deep leaning)

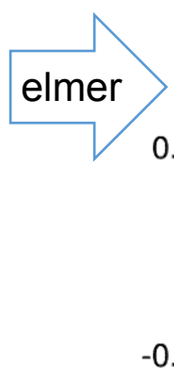
Backup

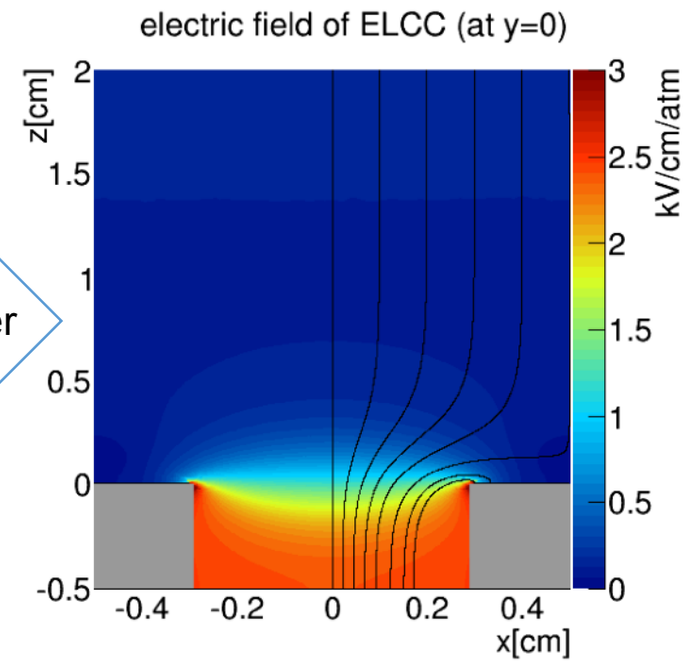
Contents

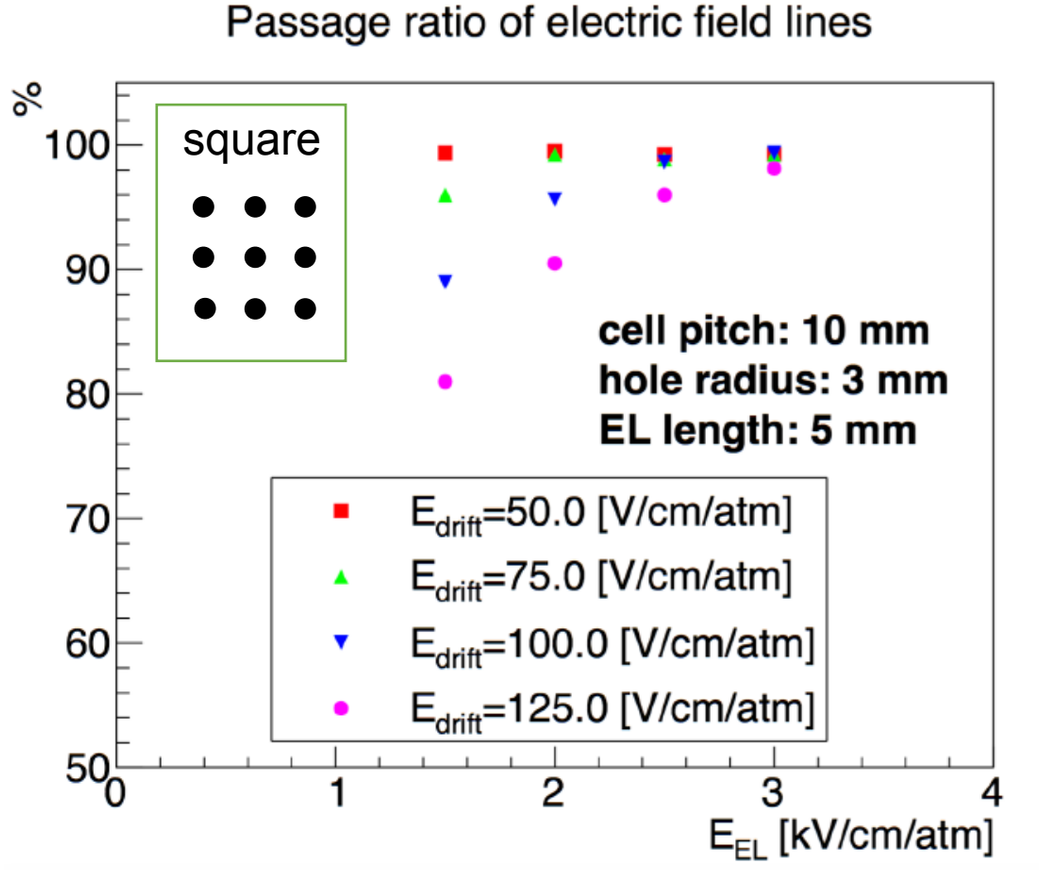
Simulation study

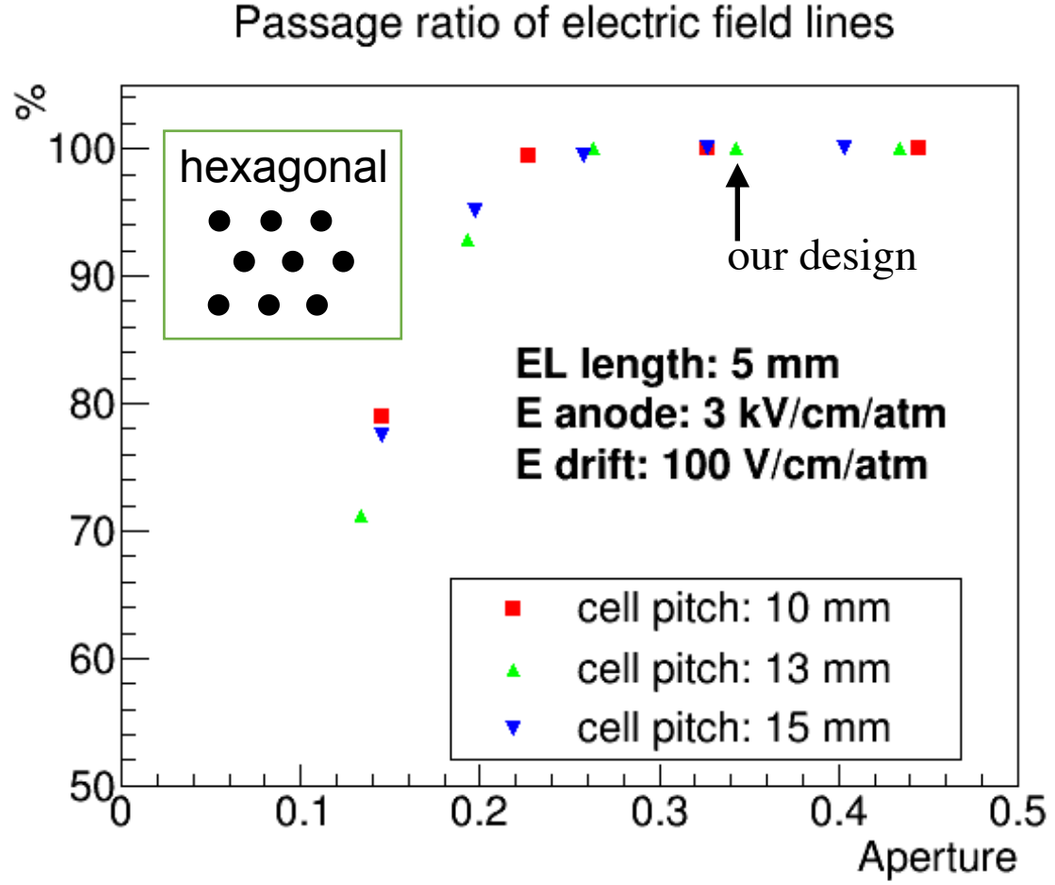
Collection efficiency
of electric field line
is checked by simulation
(gmsh + Elmer)



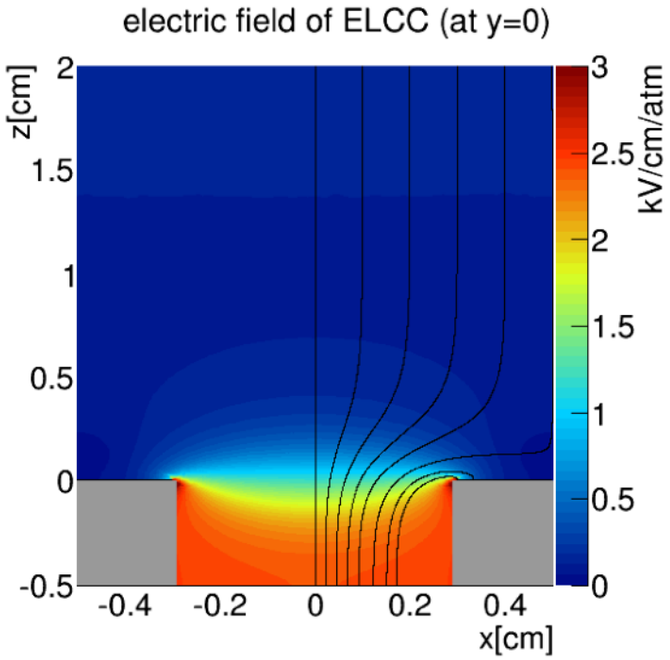




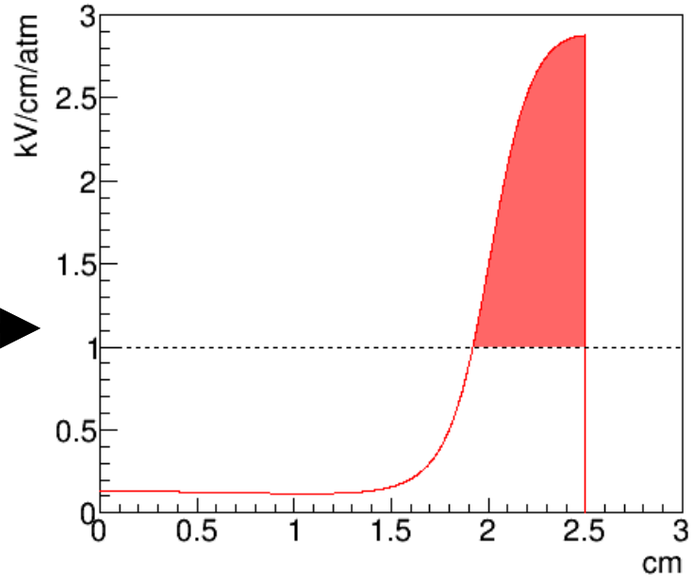




Simulation study

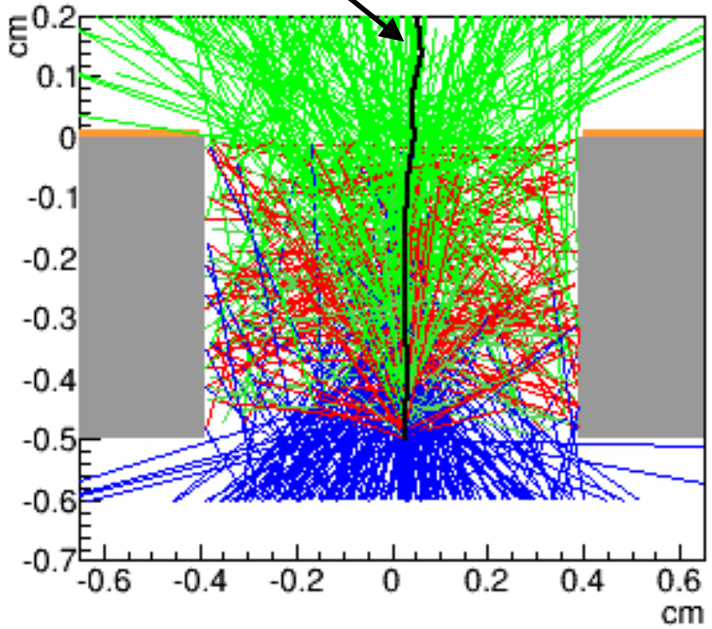


Line of electric field

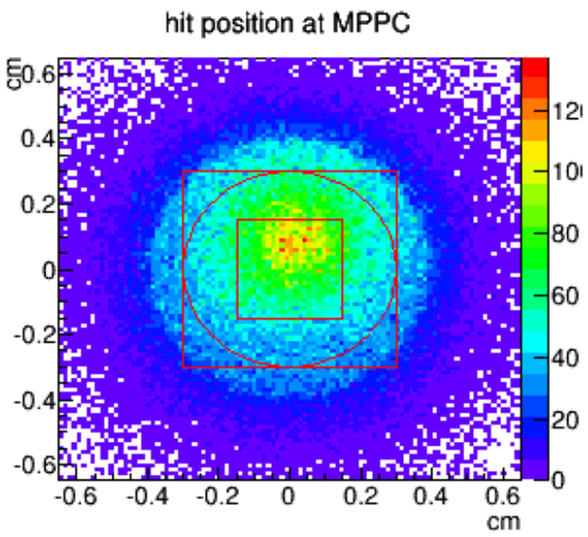


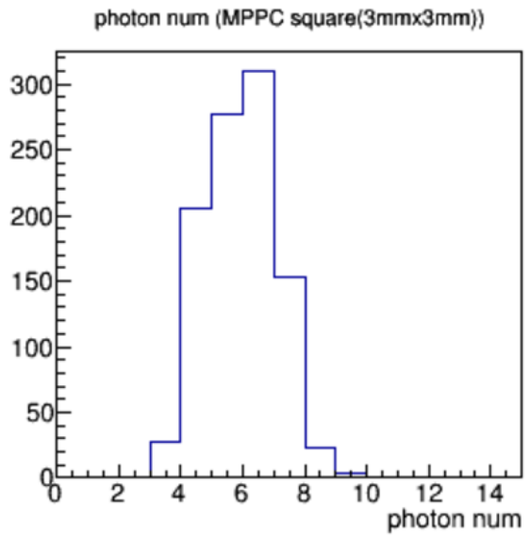
Electric field strength along the line
(red : EL region)

Electron track by Garfield++



Generate EL lights by MC method
(reflect coefficient of PTFE : 60%)





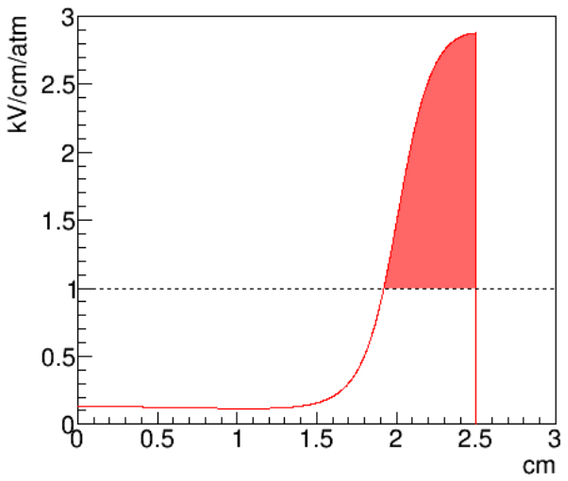
Uniformity of EL generation

- EL Yield is proportional to [electric field strength] x [path length]

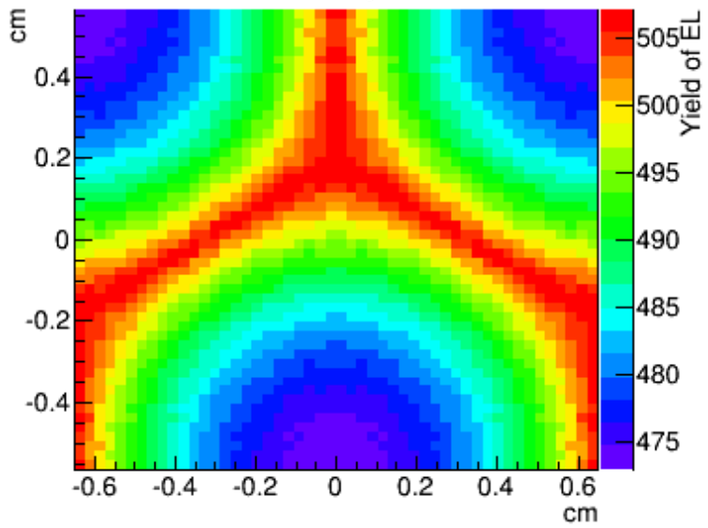
$$dN_{ph}/dx = 70(E/p - 1.0)p$$

- Uniformity : 1.4%
- Since initial electron number is 1e5, effect on energy resolution will be 1.4%/√1e5 = 0.005%

Electric field along the path



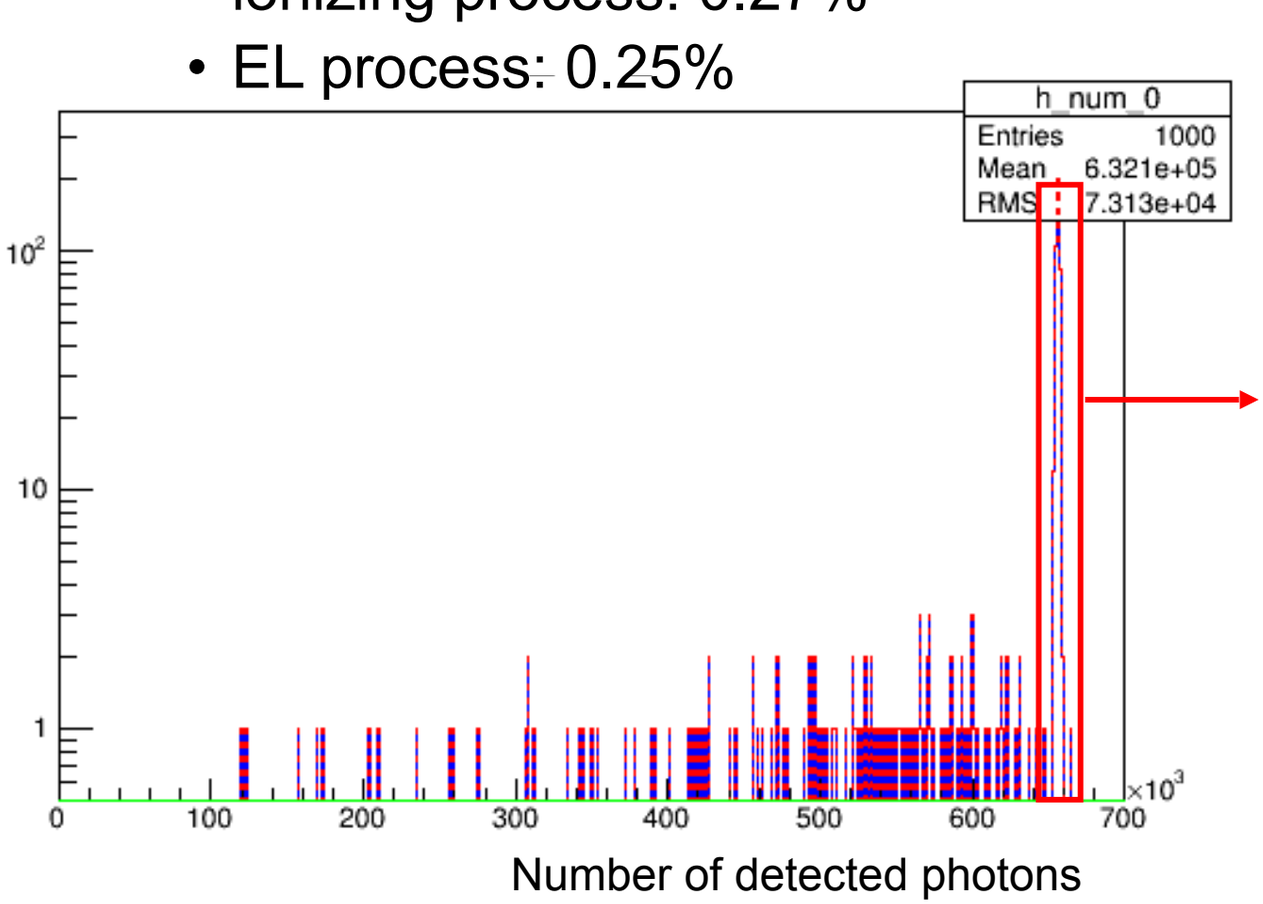
Initial position dependence of EL yield

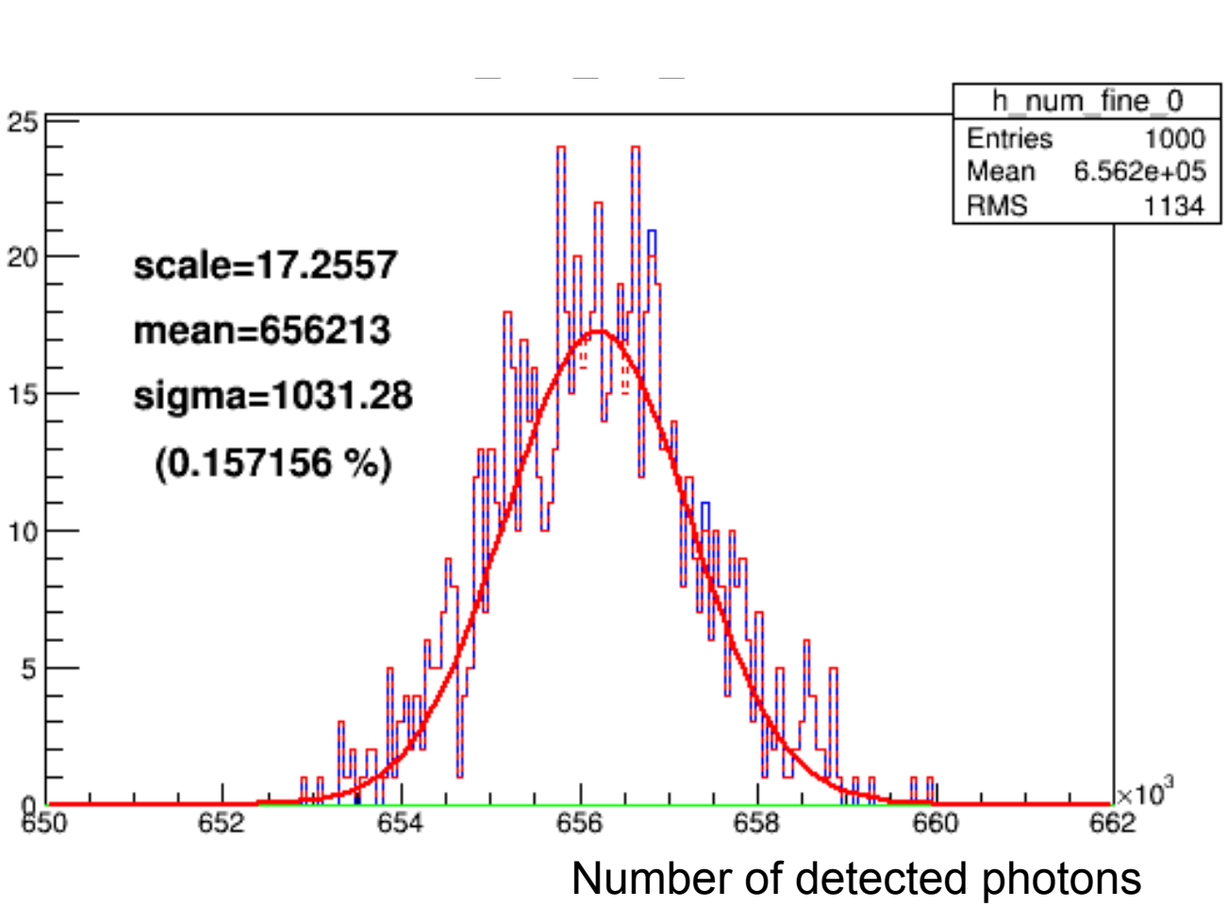


Simulation study

Estimated energy resolution

- Simulation process
  - $0\nu\beta\beta$ event by Geant4
  - statistical fluctuation with fano factor
  - drift to the ELCC plane with diffusion
  - EL generation (6photon/e^-)
- Simulated energy resolution: 0.37%(FWHM)
  - ionizing process: 0.27%
  - EL process: 0.25%



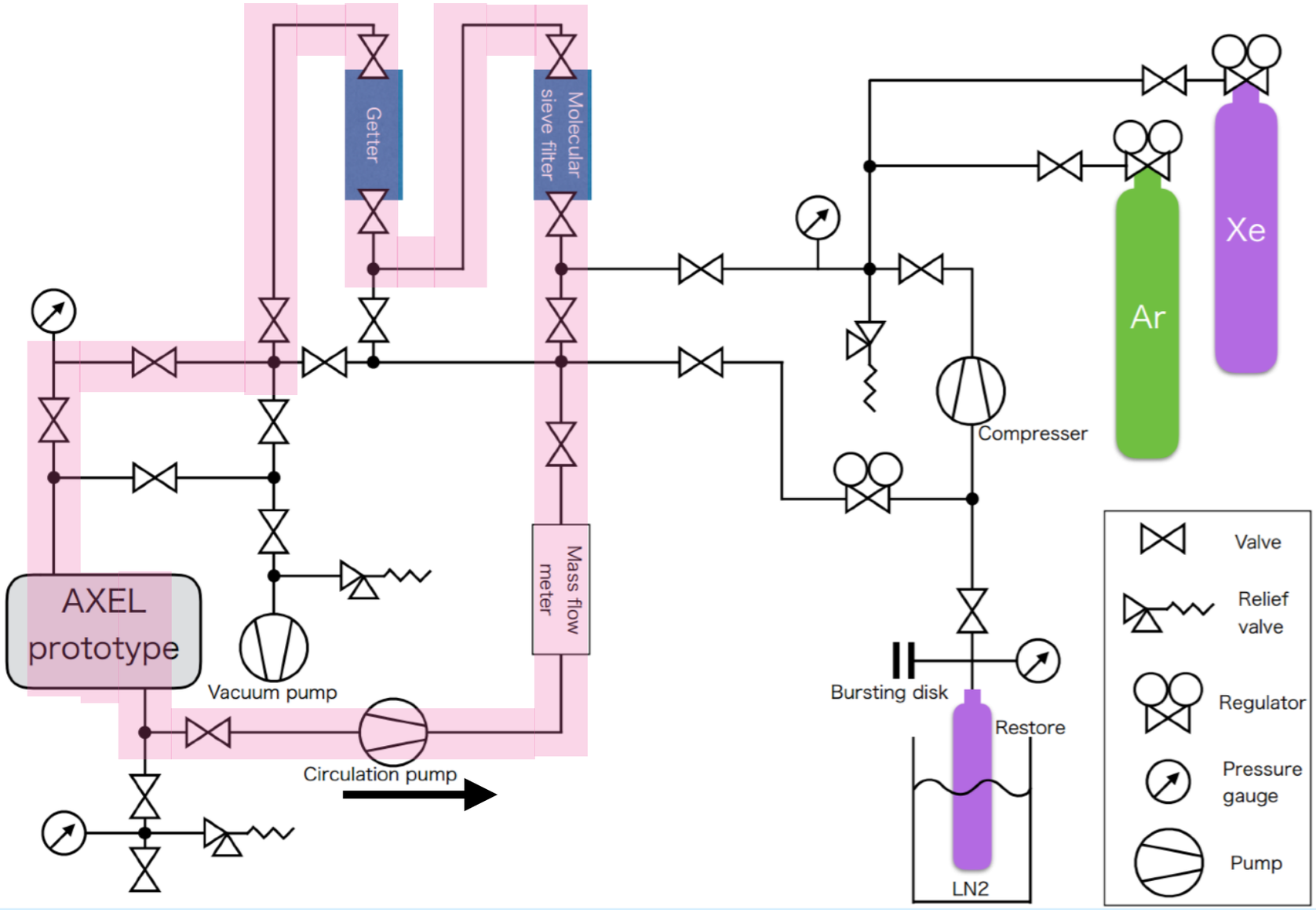


Contents

Prototype detector (1) : 10L prototype

Gas system

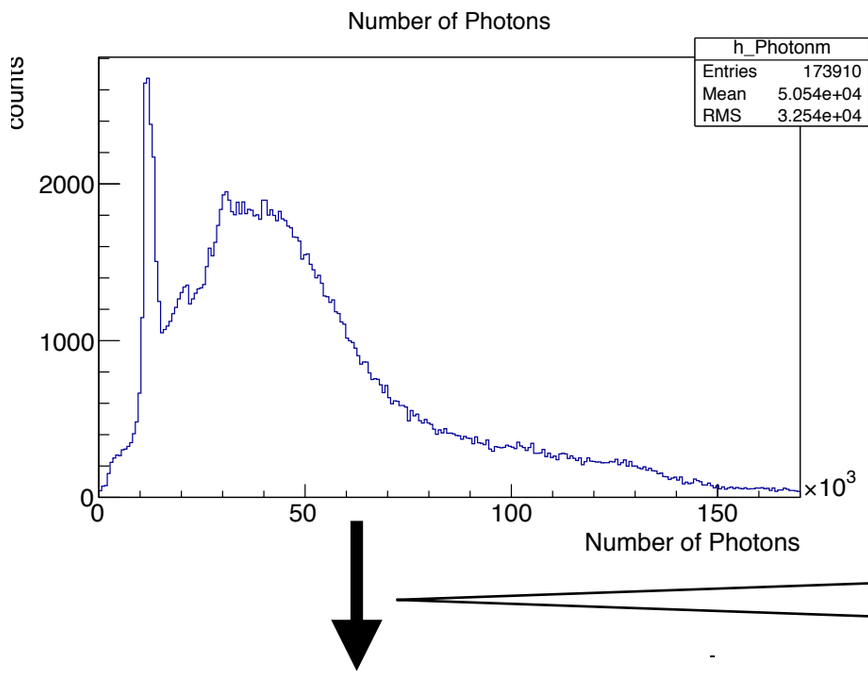
- circulation pump : PumpWorks PW2070
- SEAS micro torr MC1-902FV
- API GETTER-I Re



Prototype detector (1) : 10L prototype

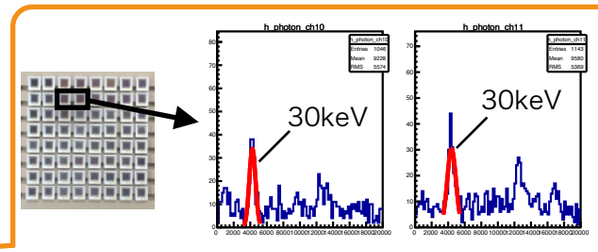
Data and Analysis

- Gas : Xe 8 bar
- E_{drift} : 83 V/cm/bar
- E_{EL} : 2.375 kV/cm/bar
- source : ^{133}Ba



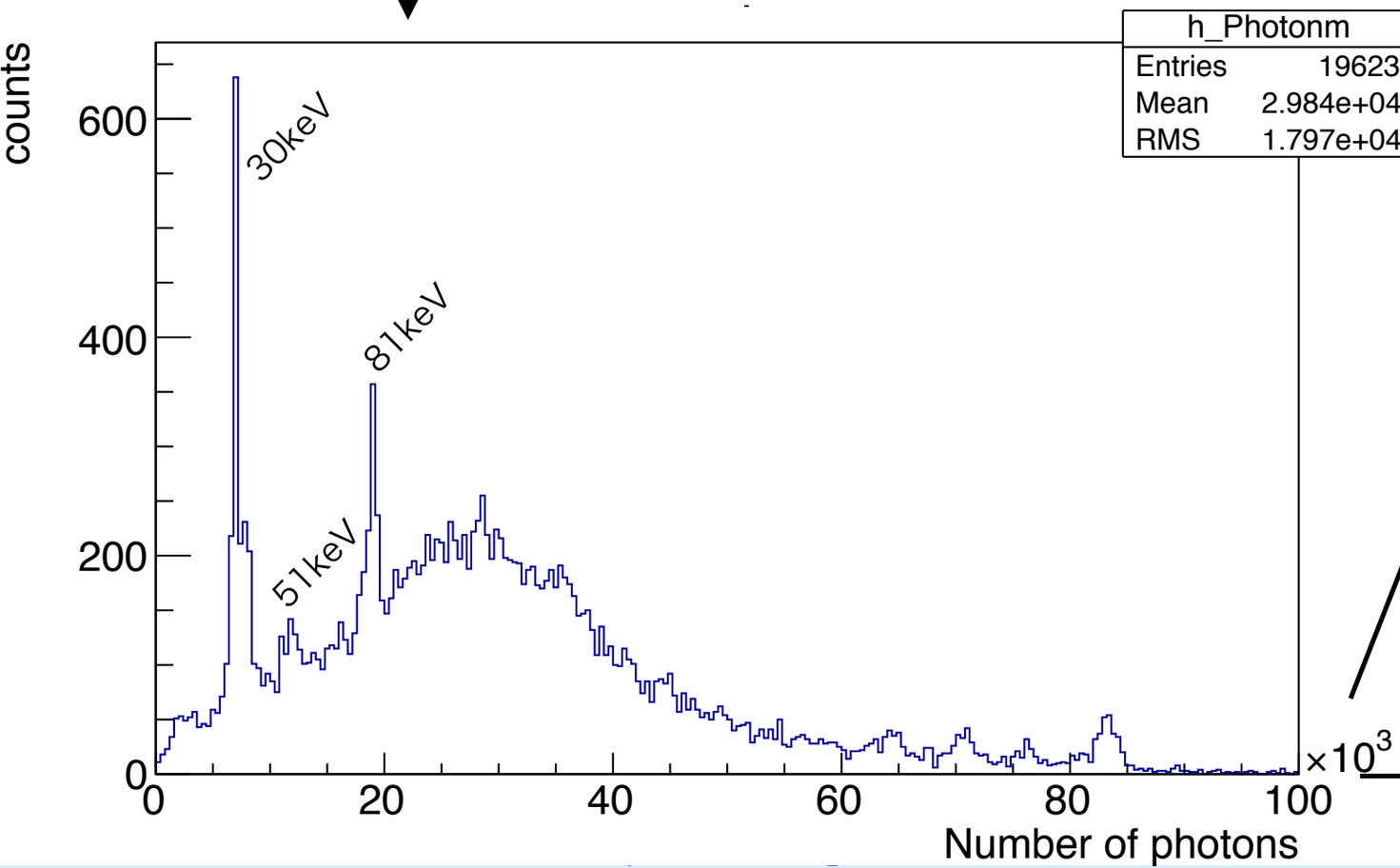
- Fiducial cut
- Saturated event → cut
- Cell gain calibration
- MPPC saturation correction

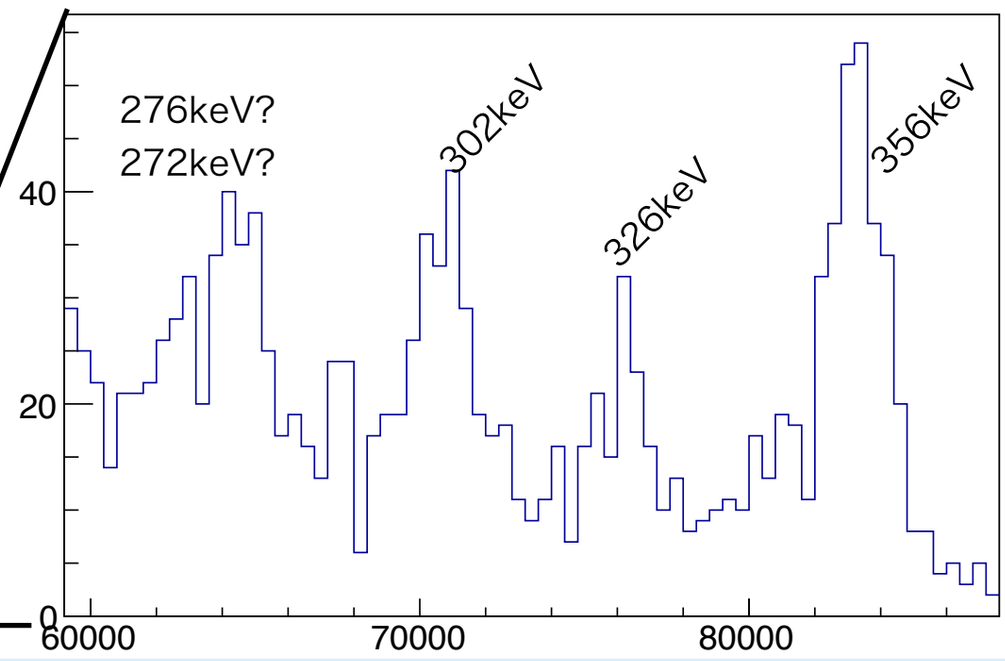
etc……



Correction using 30 keV X-ray peak position

Details in the next page

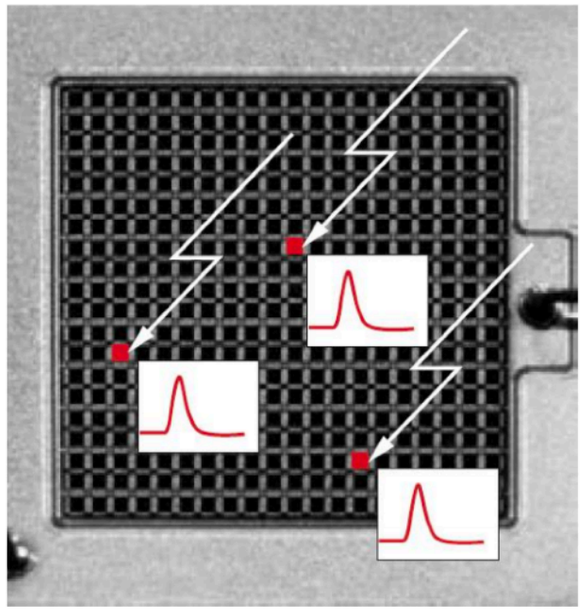


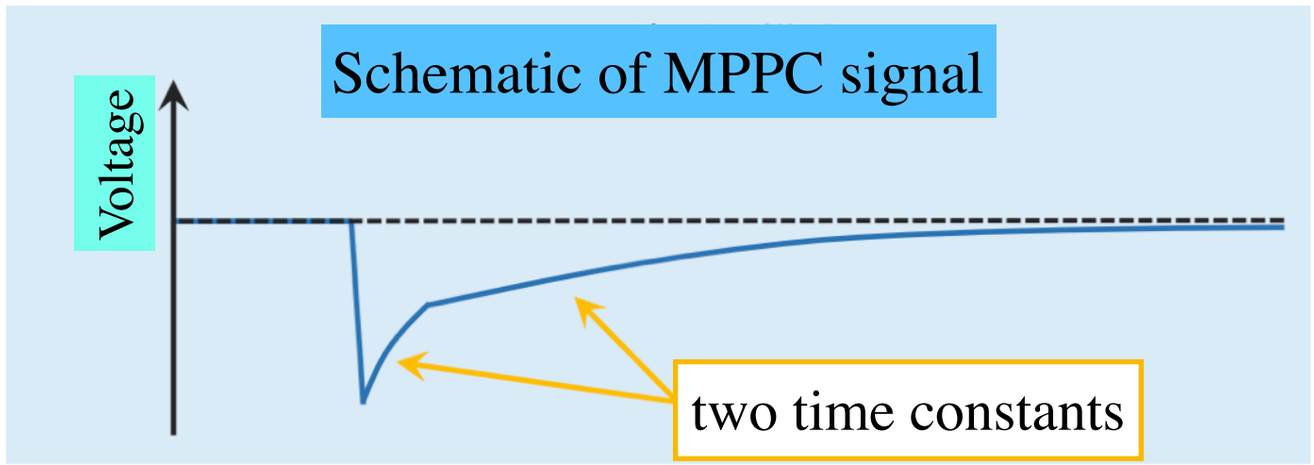


Prototype detector (1) : 10L prototype

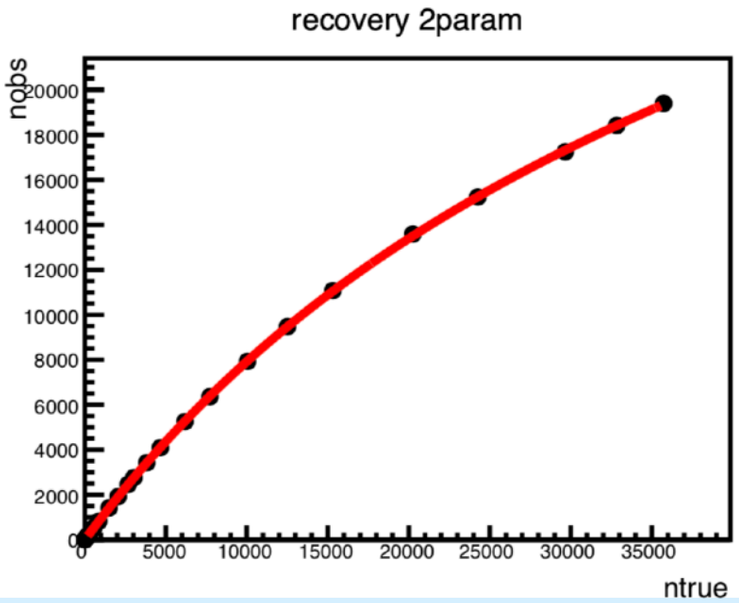
MPPC saturation correction

- Signal is saturated as # of incident photons approaches the total number of pixel of MPPC





$$N_{\mathrm{obs}} = \frac{\alpha N_{\mathrm{ref}}}{1+\tau_1/(N_{\mathrm{pix}}\cdot\Delta t)N_{\mathrm{ref}}} + \frac{\beta N_{\mathrm{ref}}}{1+\tau_2/(N_{\mathrm{pix}}\cdot\Delta t)N_{\mathrm{ref}}}$$



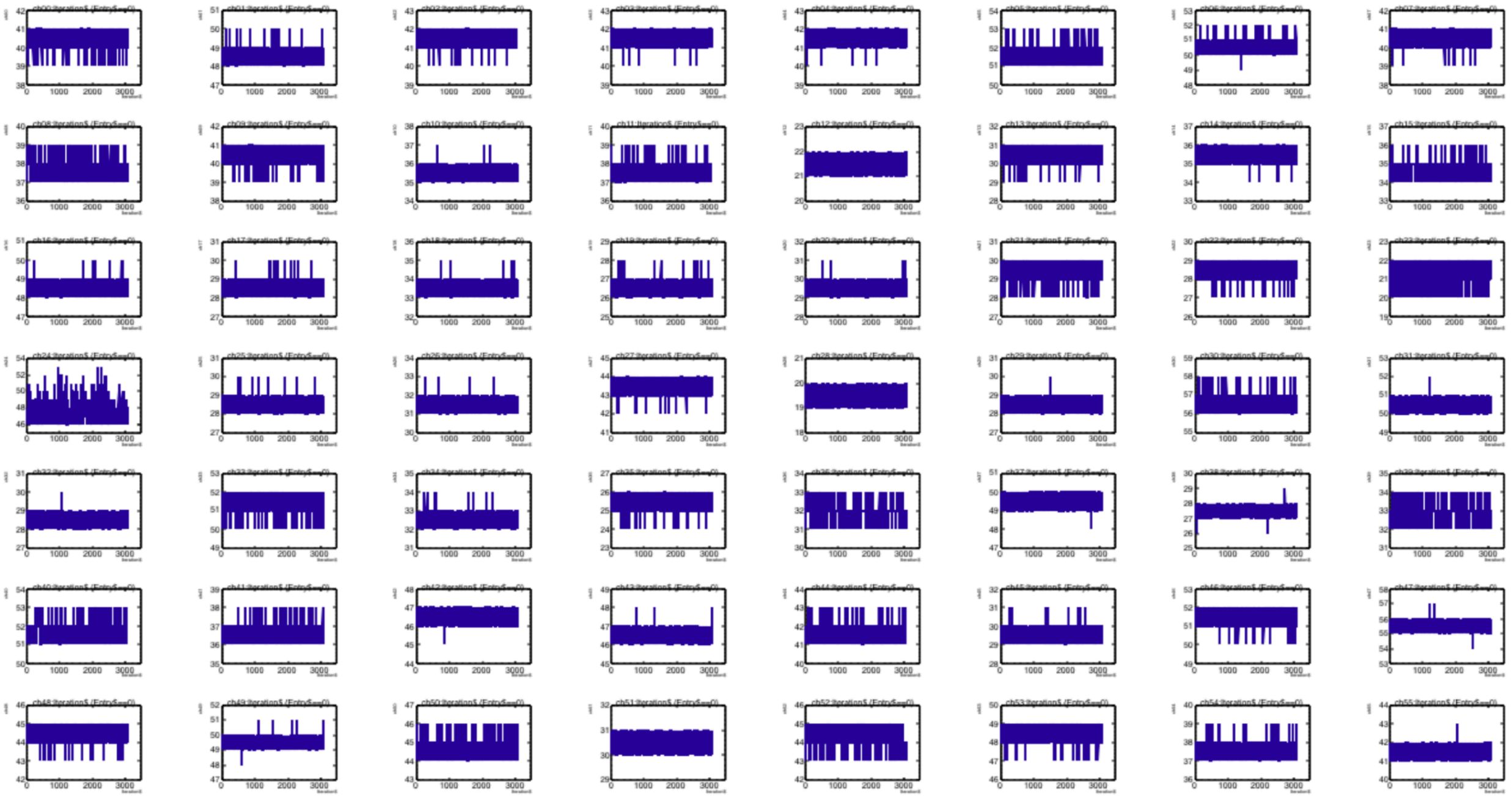
- saturation curve is determined by recovery time of MPPC
- Measured recovery time of MPPC one by one, and apply to analysis

Contents

Prototype detector (2) : 180L prototype

Readout Electronics

- Succeed to readout waveform signals with both of ADCs



Contents

Future prospect