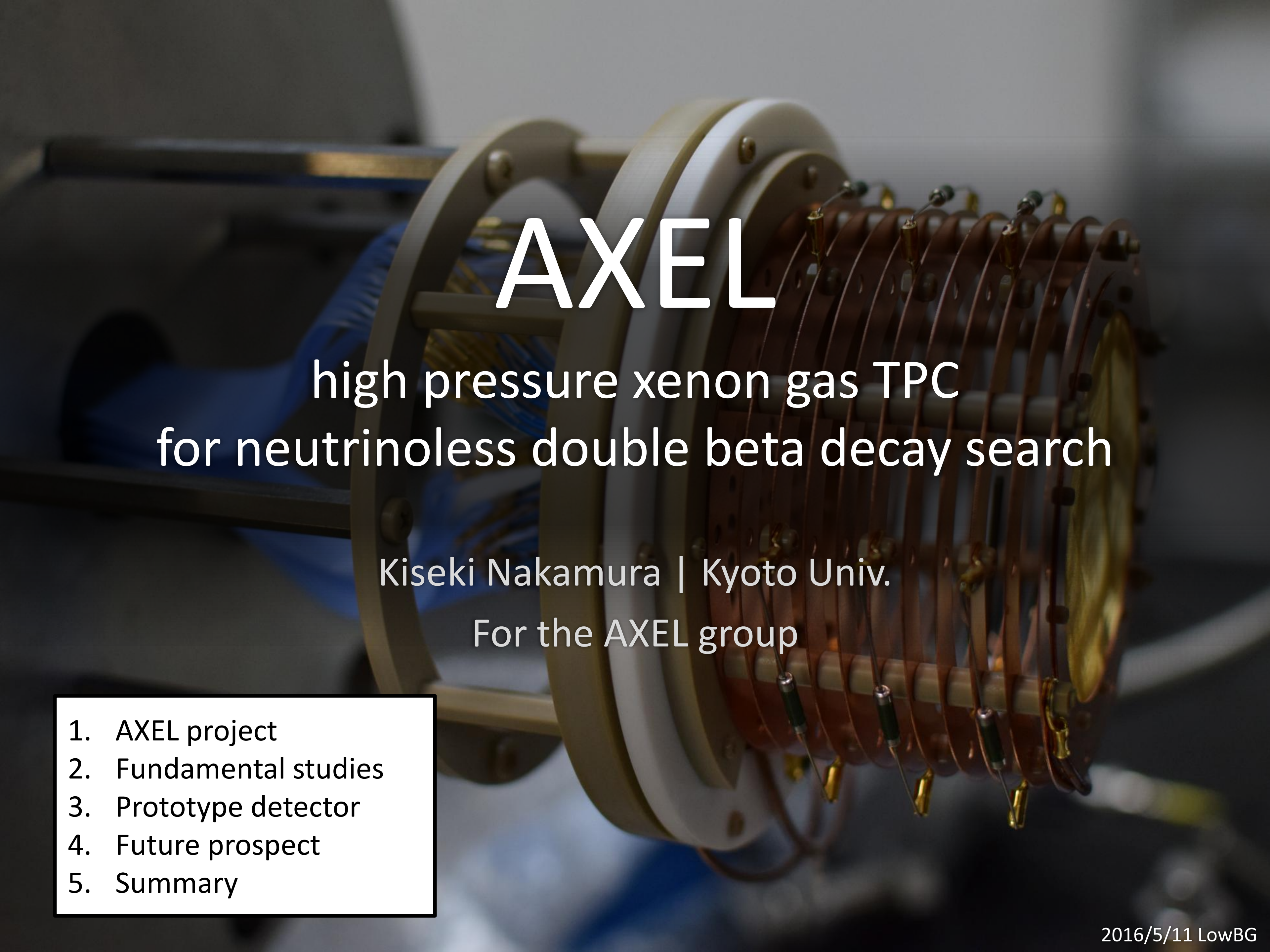


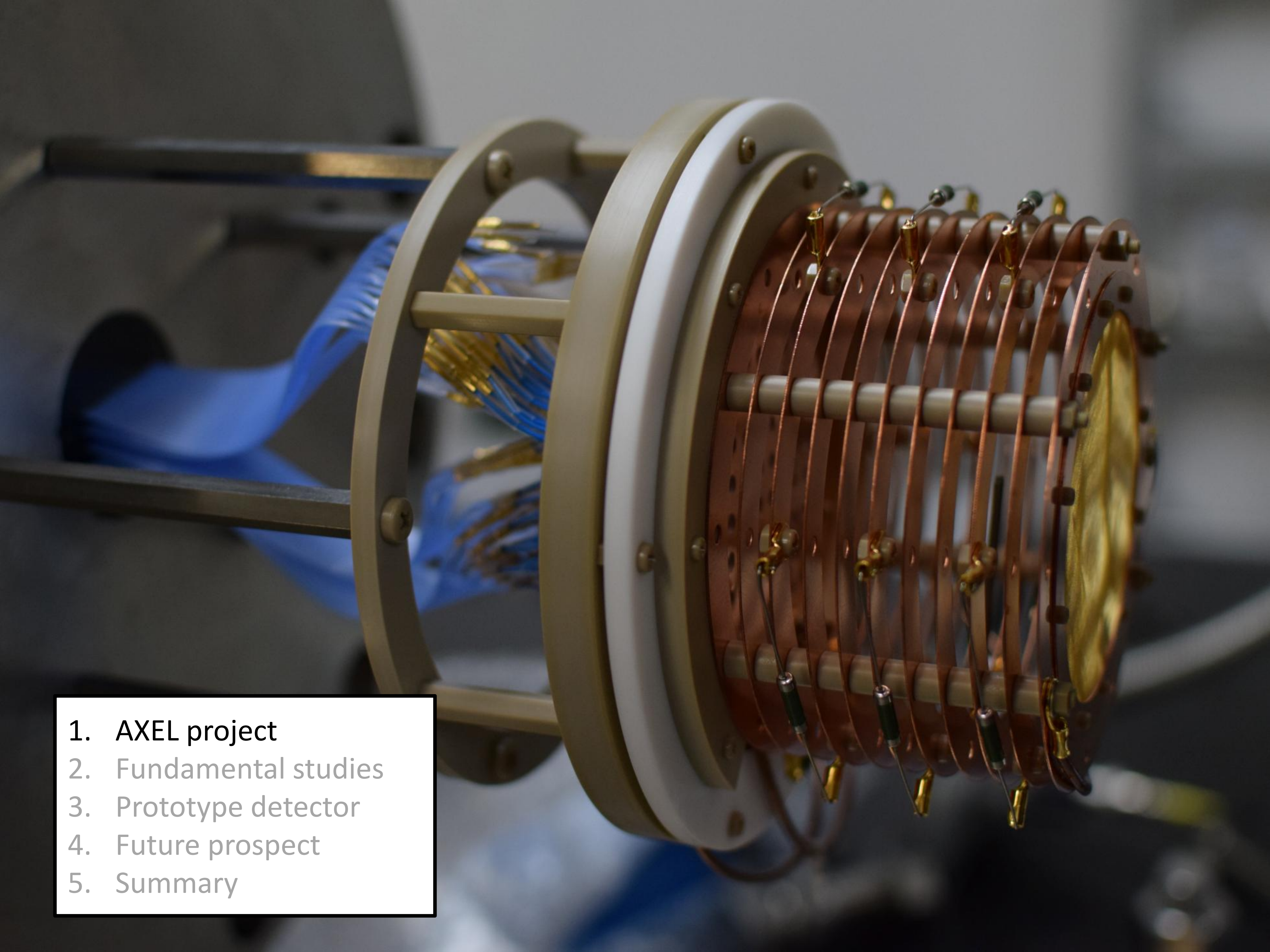
AXEL

high pressure xenon gas TPC for neutrinoless double beta decay search

Kiseki Nakamura | Kyoto Univ.

For the AXEL group

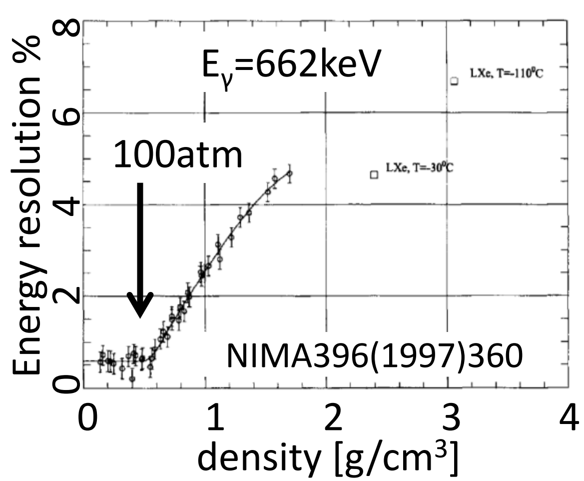
2016/5/11 LowBG

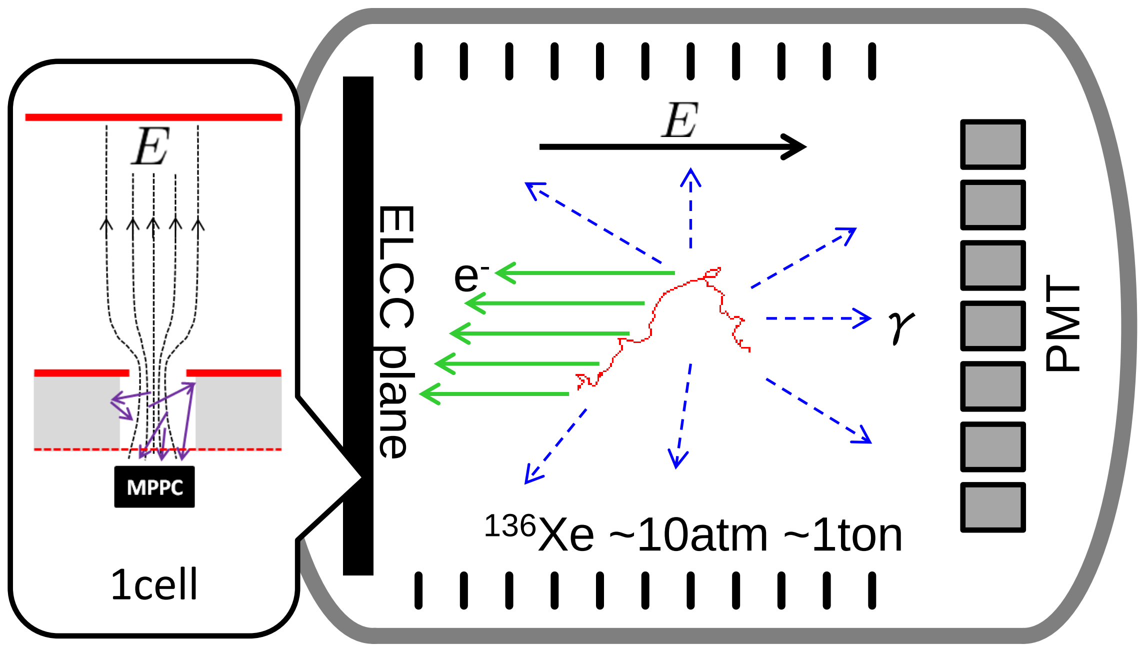


1. AXEL project
2. Fundamental studies
3. Prototype detector
4. Future prospect
5. Summary

AXEL experiment

- <u>High pressure xenon gas TPC for 0νββ search</u>
  - High energy resolution : **0.5%** (FWHM) @2.5MeV
    - gaseous xenon + electroluminescence
  - Large mass : **1ton** (ϕ3×2.5m, 10atm)
  - BG discrimination : **pixel readout** (15mm pitch)

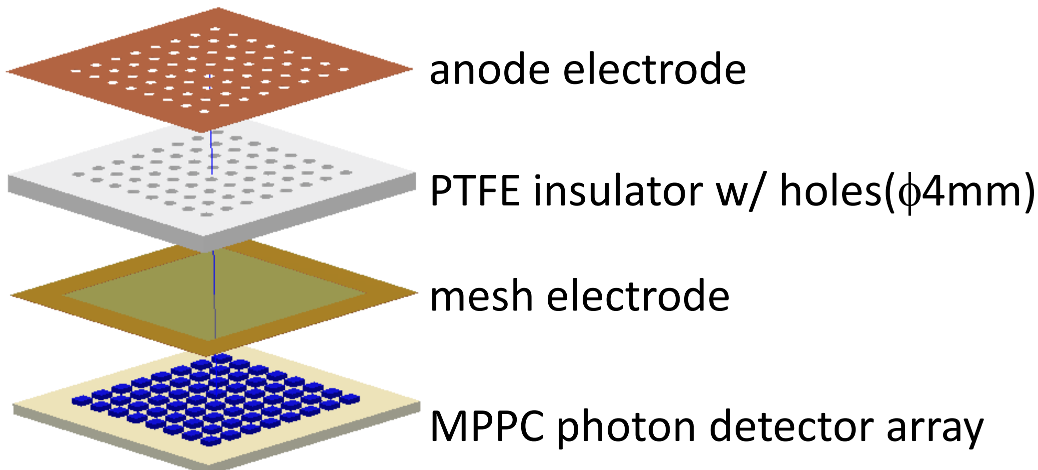


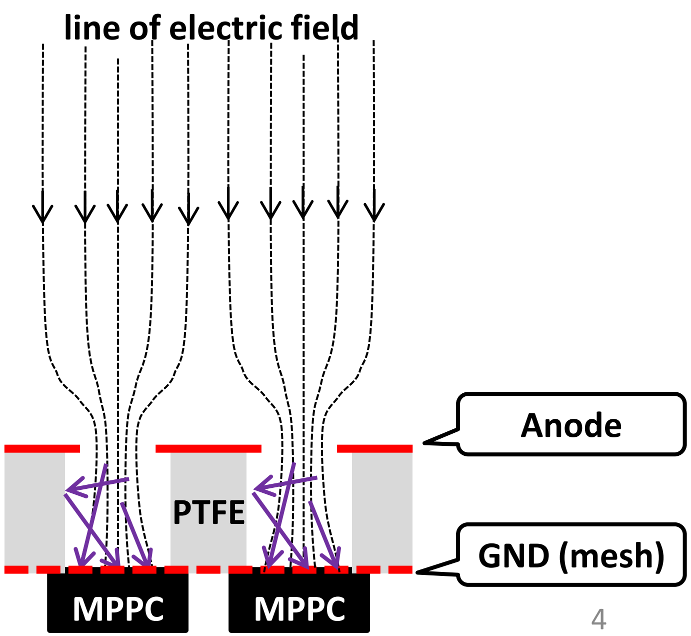


- Similar idea as NEXT experiment
- We introduce a new idea for signal readout (ELCC)

EL readout idea: ELCC
Electro Luminescence Collection Cell

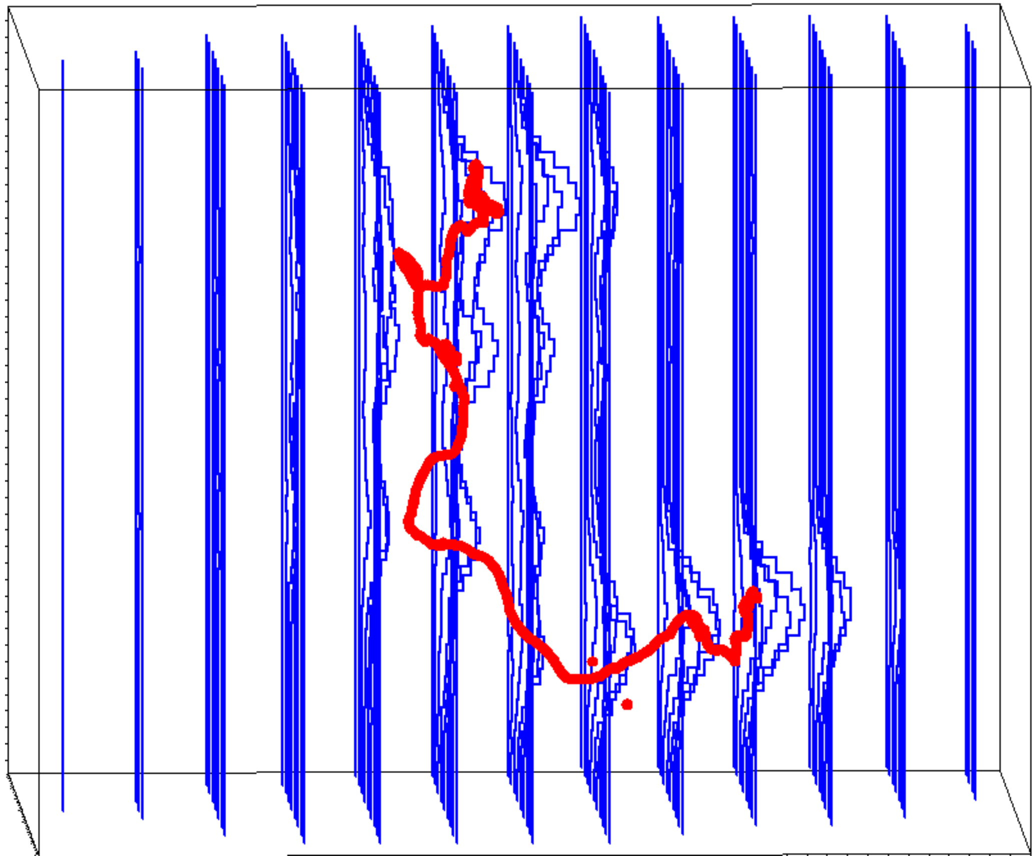
- ELCC
  - in the cell hole, electrons are collected and accelerated, then electroluminescence photons are generated
  - photons are detected by MPPC(SiPM) in each cell
- Merit of ELCC
  - uniform response in wide area
  - rigid structure (--> large size)





What we want to observe

- $0\nu\beta\beta$ signal
  - energy: integrated FADC
  - track: waveforms (pixel readout TPC)

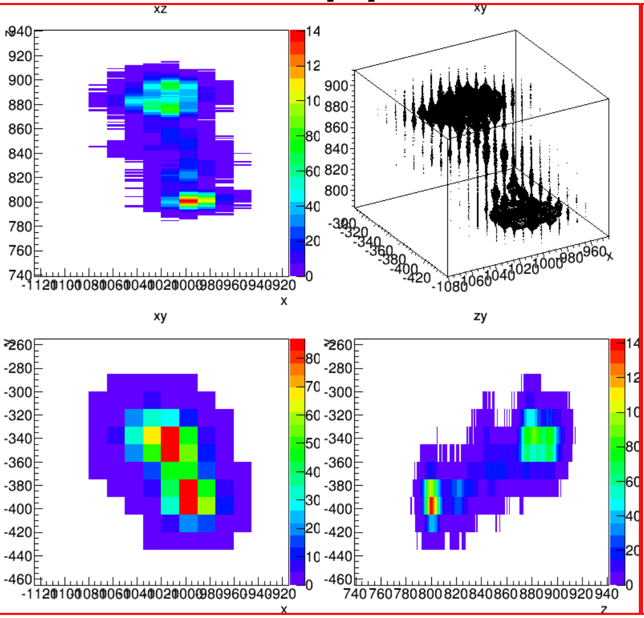


10atm
Xe100%
15mm pitch
1μs sampling (~1mm)

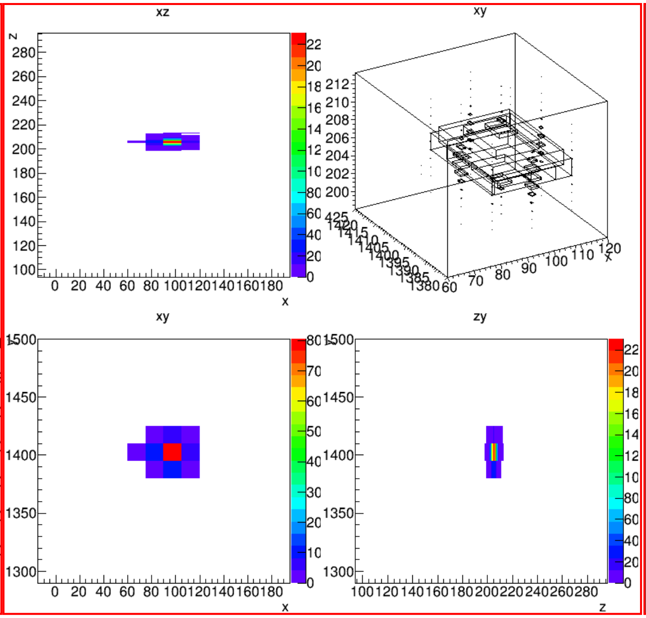
Tracking strategy

- energy resolution 0.5% --> reject non-2.5MeV
- tracking --> reject α, γ (98%: compton)

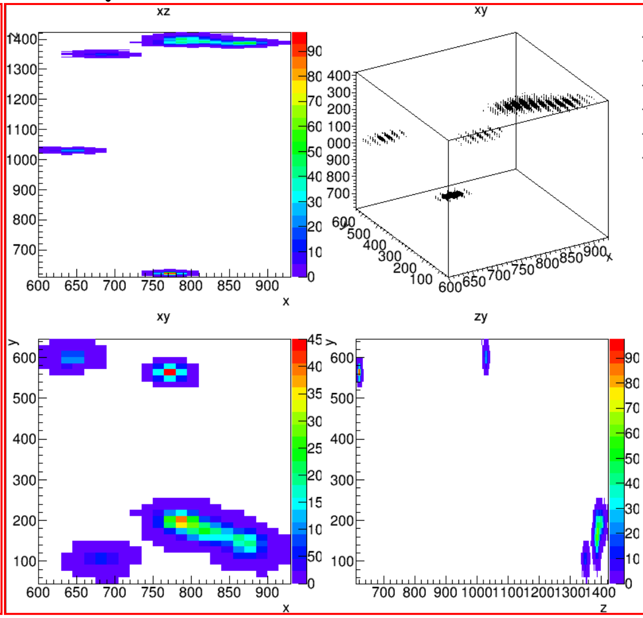
$0\nu\beta\beta$



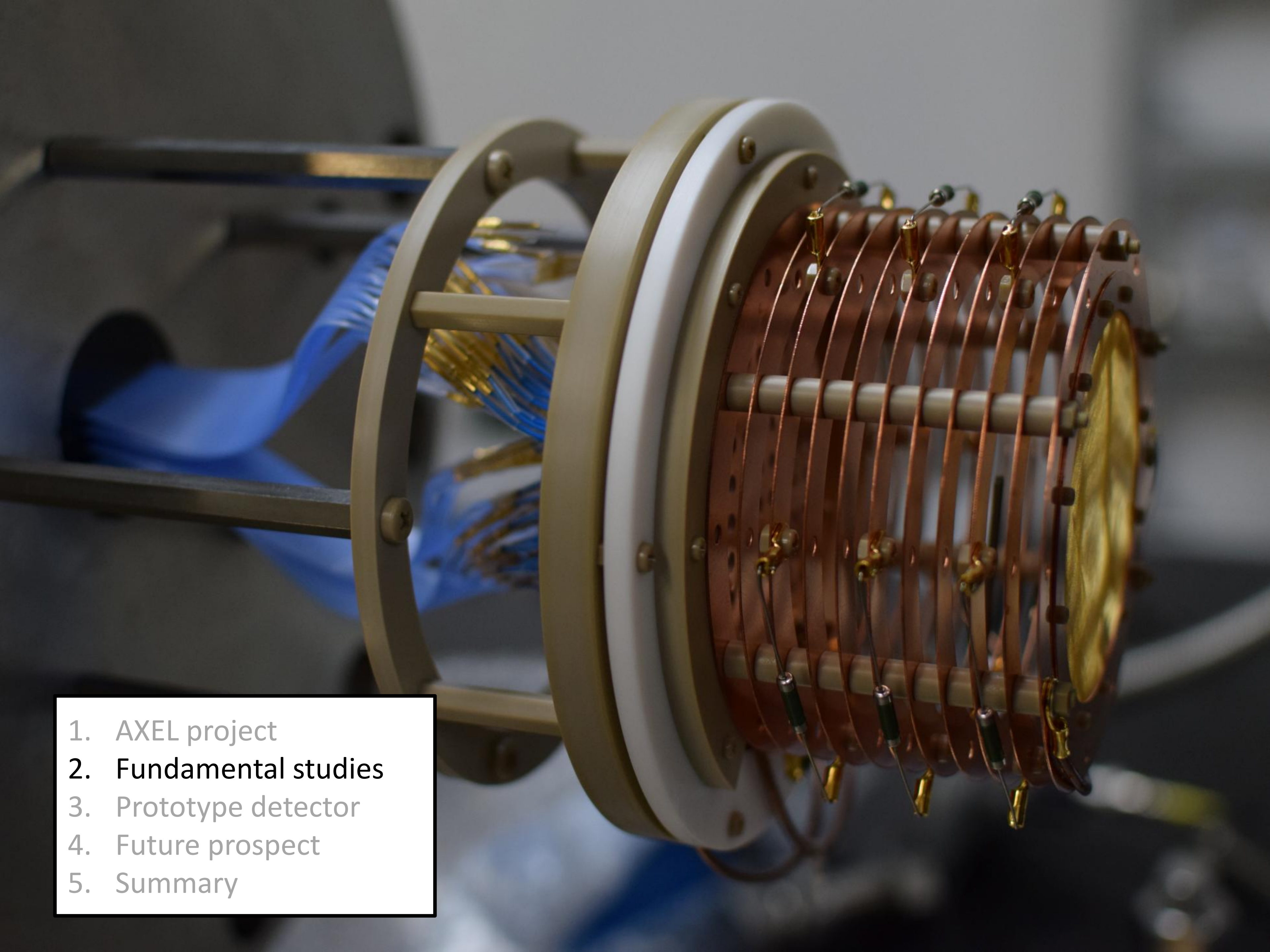
α-ray (2.5MeV)



γ-ray (2.5MeV)



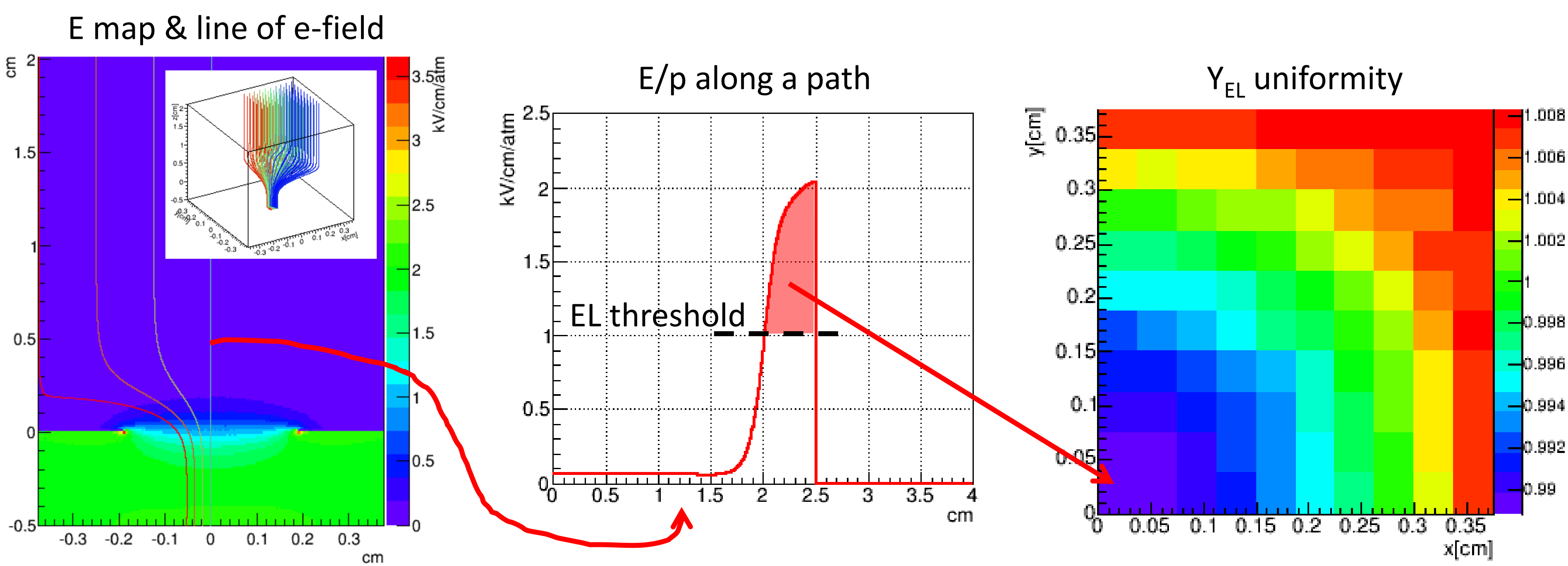
10atm, Xe100%, 15mm pitch, 1μs sampling (~1mm)



Electric field simulation (FEMM)

- Line of electric field are collected
- Uniformity of EL yield is 0.47% (sigma)

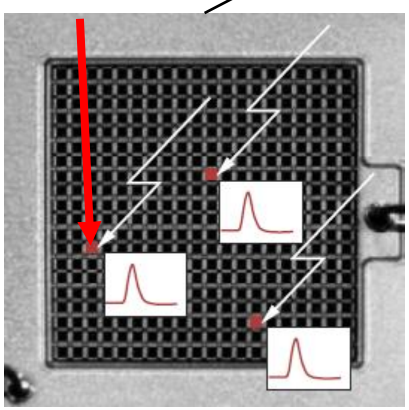
$$dN_{ph}/dx = 70(E/p - 1.0)p$$

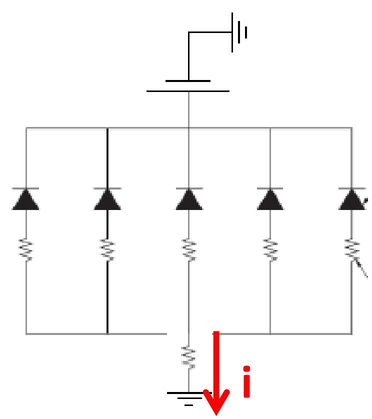


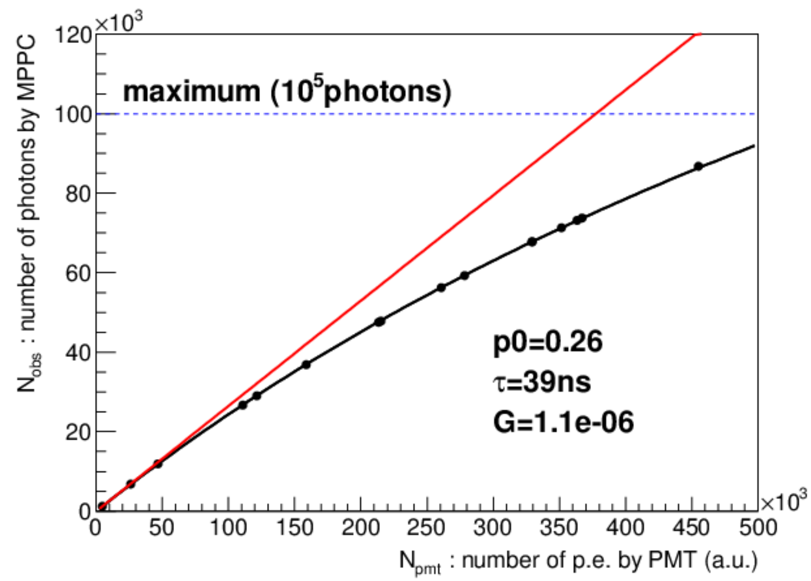
MPPC linearity

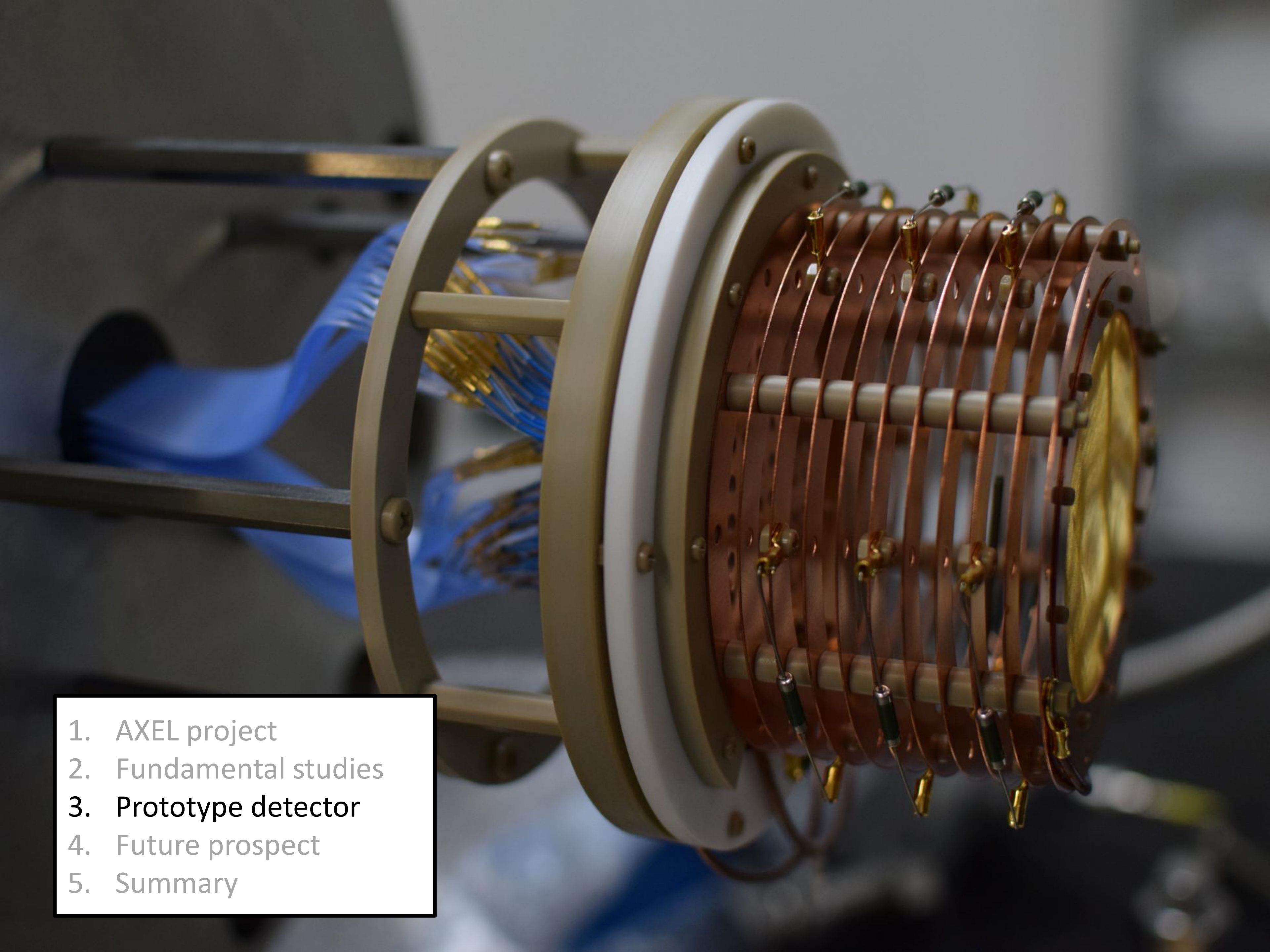
- Check large and long pulse photon response (~10^5/5μs)
- Saturation was observed
  - "simultaneous hit" and "decrease of bias voltage"
- After correction, expected residual fluctuation is 0.11%

$$N_{obs} = \frac{p_0 N_{pmt}}{1 + \boxed{k\tau} + \boxed{G p_0 N_{pmt}}}$$









1. AXEL project
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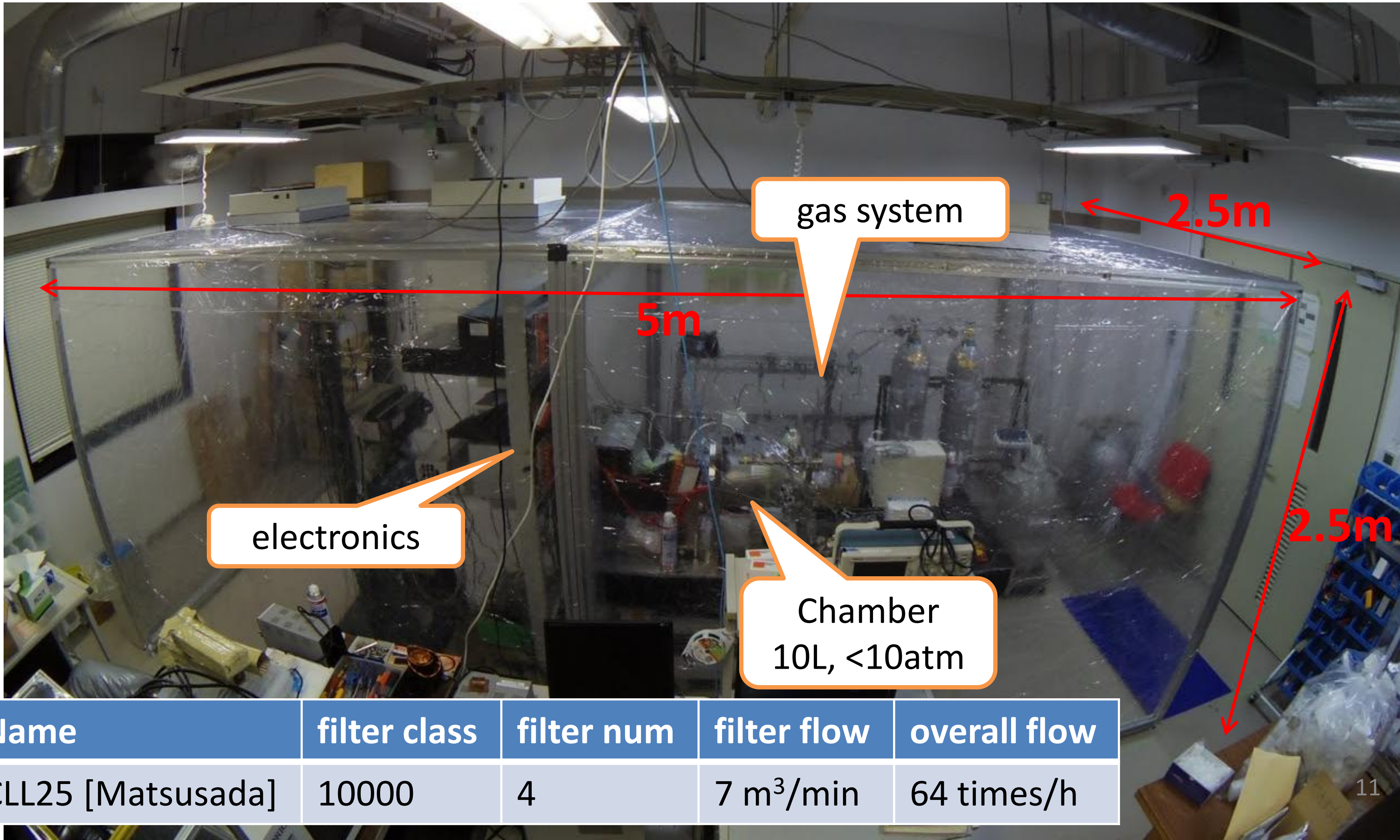
Overall view

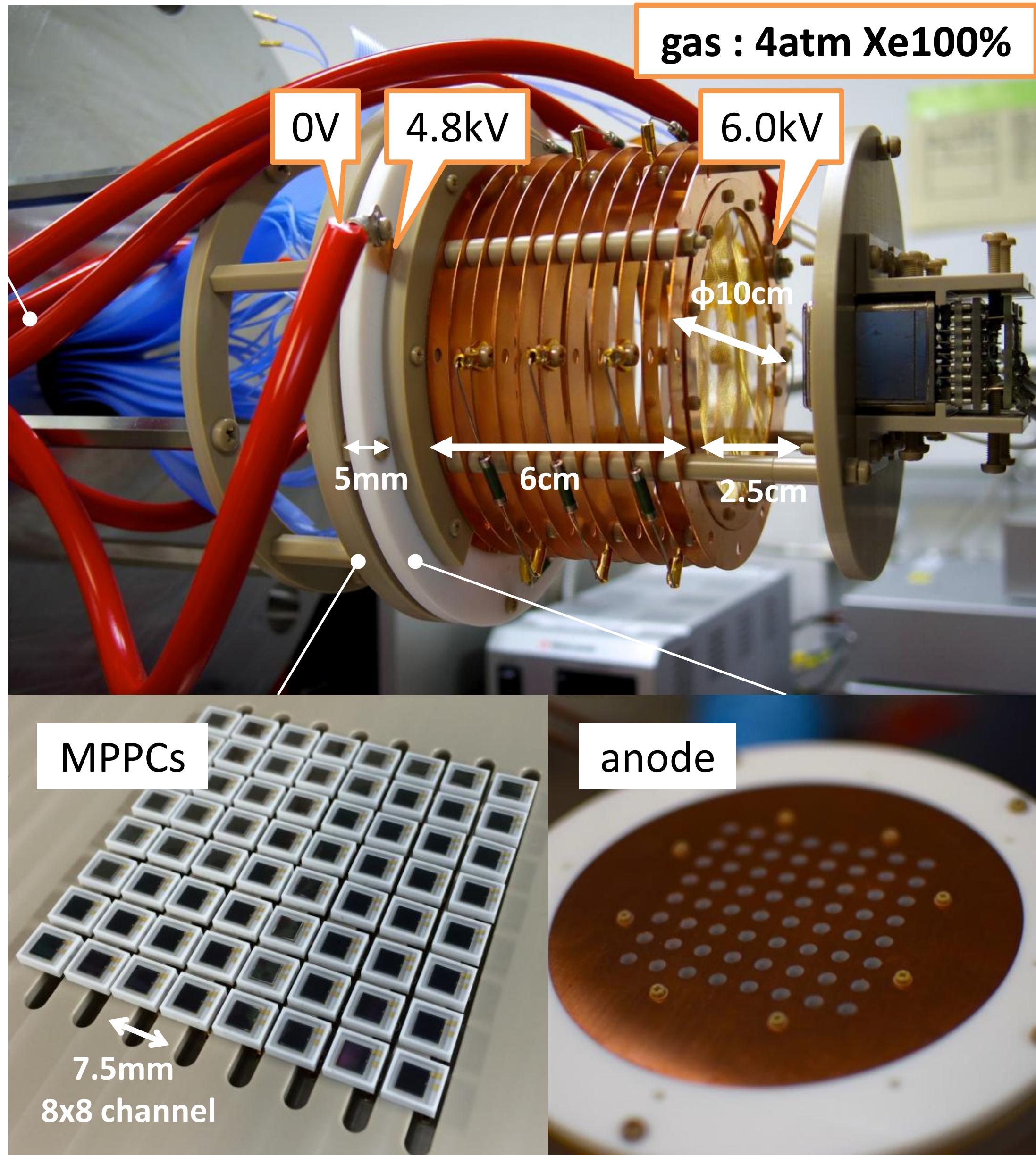
- Kyoto Univ. 3F (welcome!)



Name	filter class	filter num	filter flow	overall flow
CLL25 [Matsusada]	10000	4	7 m^3/min	64 times/h

Prototype detector

- Detection volume
  - $6*6*6\text{cm}^3$
  - 5.7g (4atm Xe)
- Sensor
  - WLS coated MPPC x64
  - VUV-PMT x2
- Electric field
  - EL: 2.4kV/cm/atm
  - drift: 50V/cm/atm

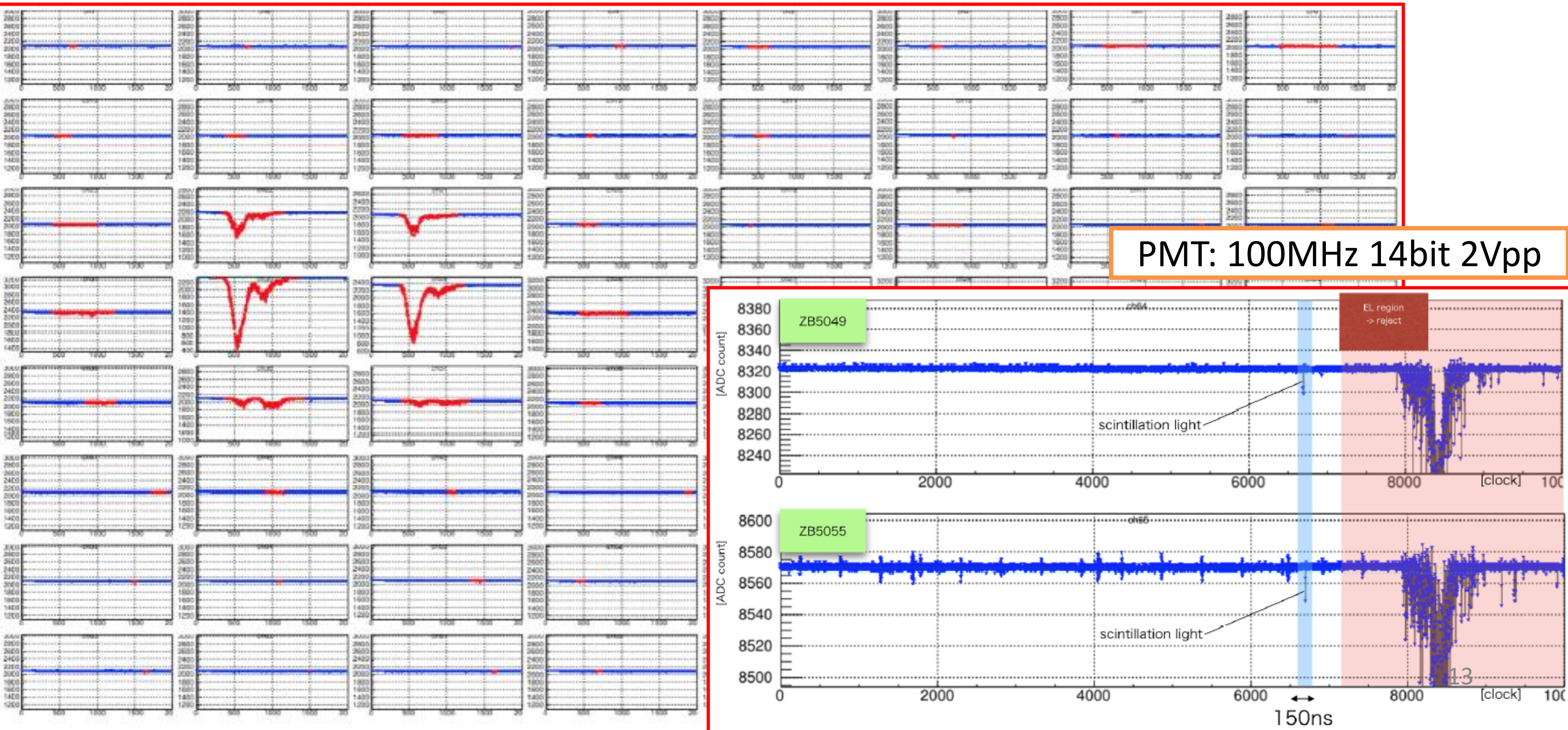


Event sample

- waveforms of MPPC and PMT
  - EL light & scintillation light are observed

MPPC: 65MHz 12bit 2Vpp

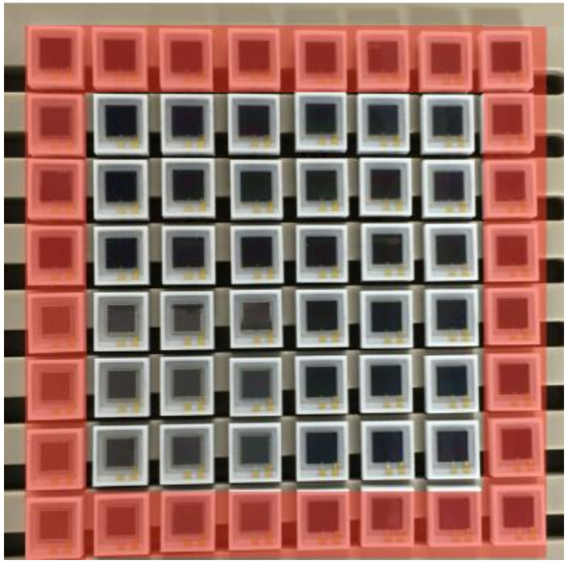
PMT: 100MHz 14bit 2Vpp

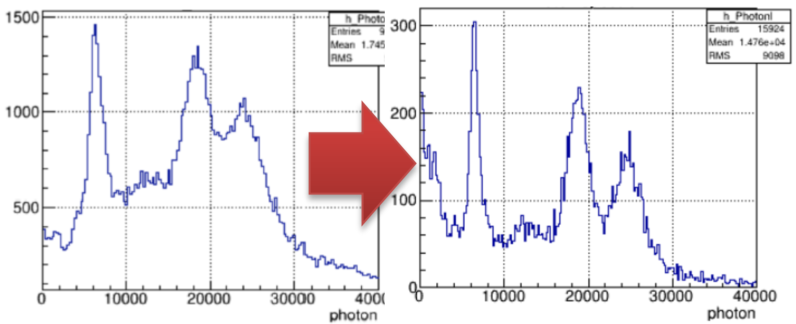


γ-ray measurement (^{57}Co 122keV)

- Fiducial cut
  - veto region: outer 28 MPPCs

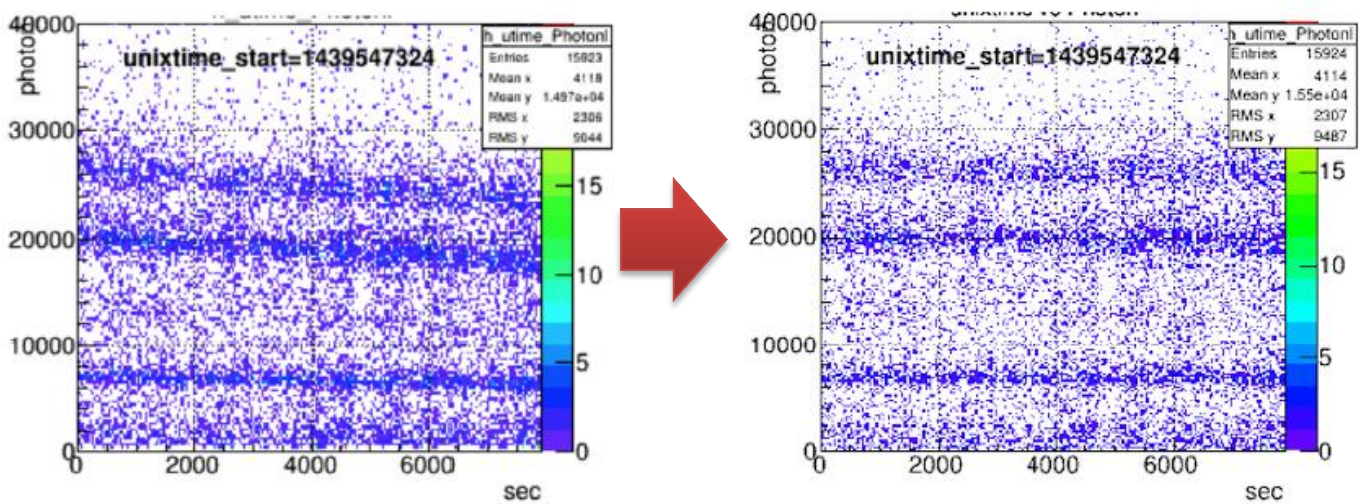
red: veto

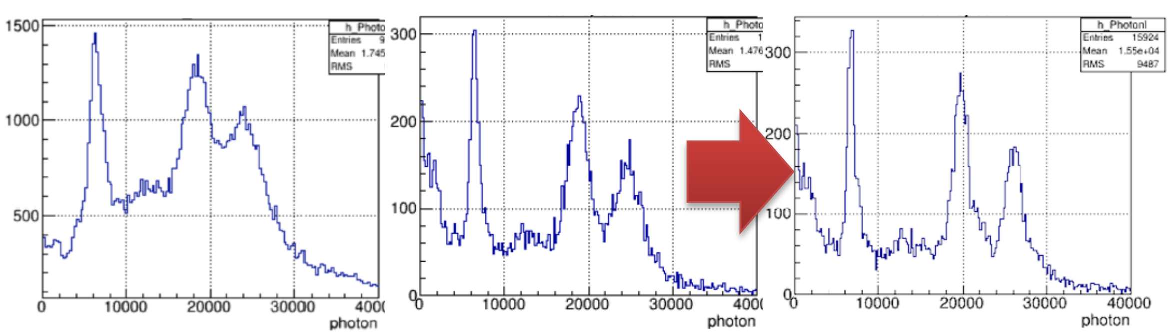




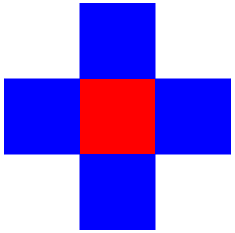
γ-ray measurement (^{57}Co 122keV)

- Time dependence correction
  - Impurities decrease EL gain
  - Gas circulation system is now under construction

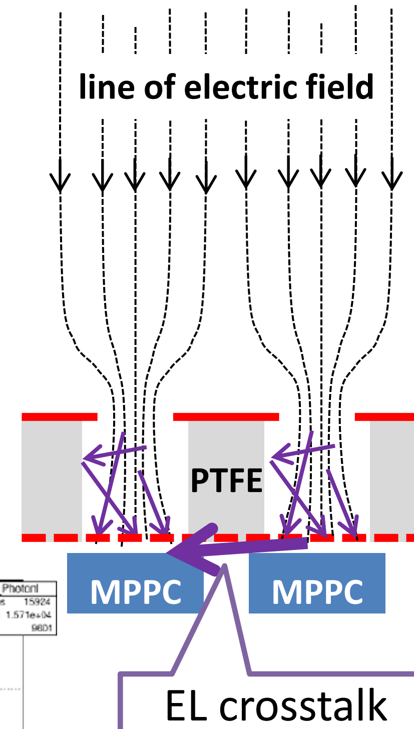




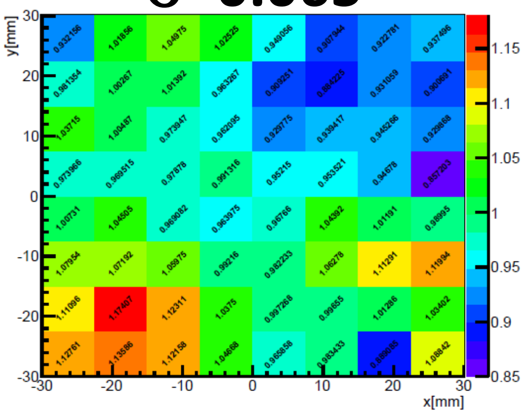
γ-ray measurement (^{57}Co 122keV)



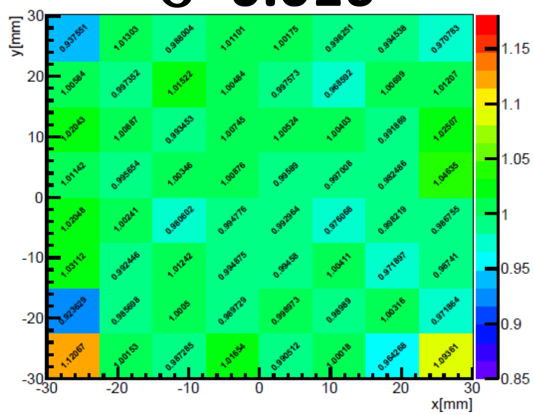
- EL-gain correction
  - photon num of 30keV γ-ray for "each cell"
    - One MPPC(red) selection is too strict, so blue MPPCs are allowed
    - EL crosstalk suppression structure is under designing

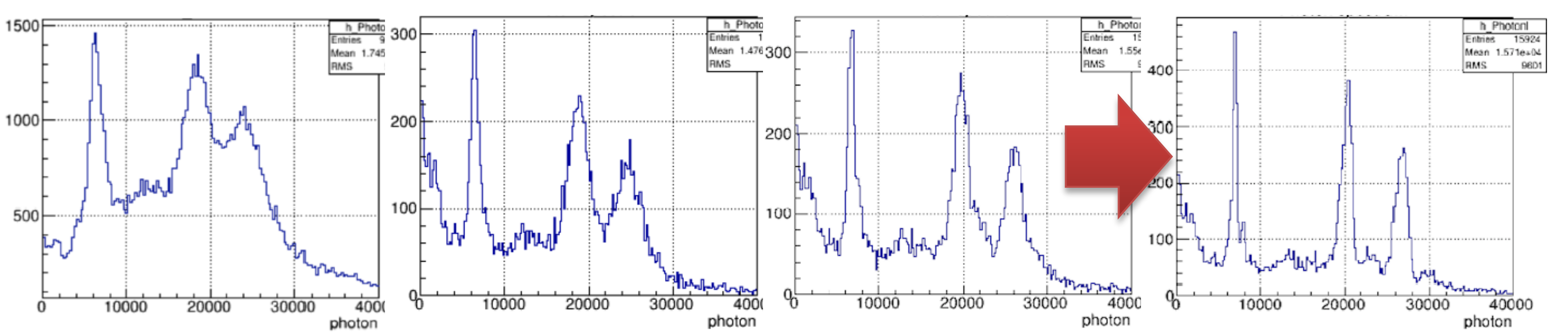


σ=0.065



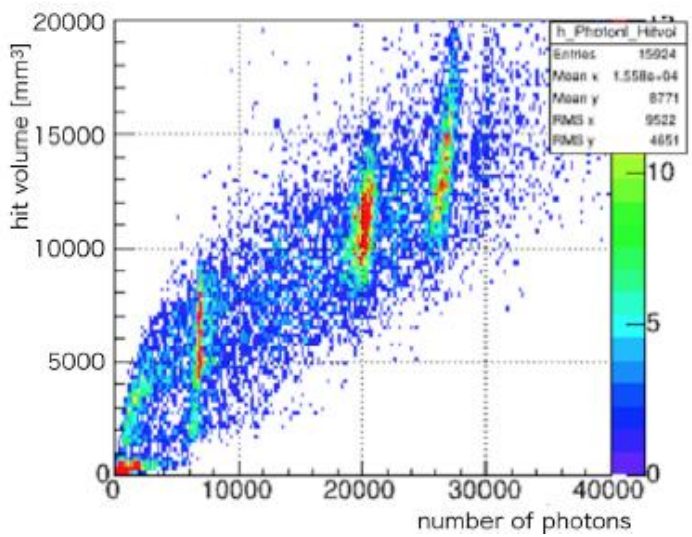
σ=0.016

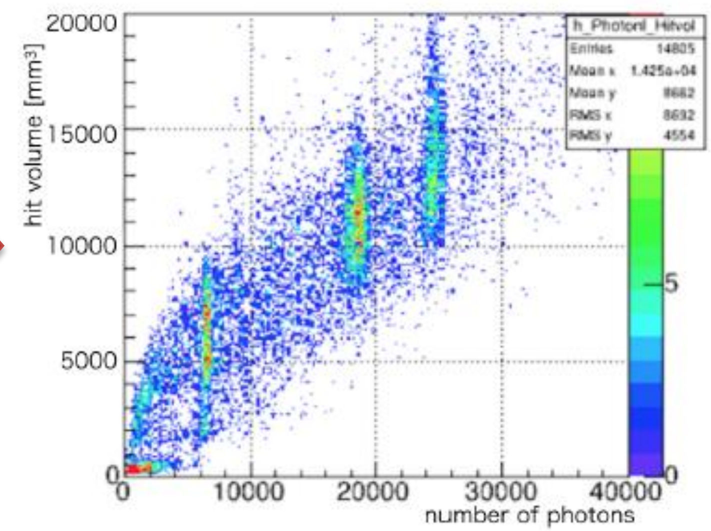


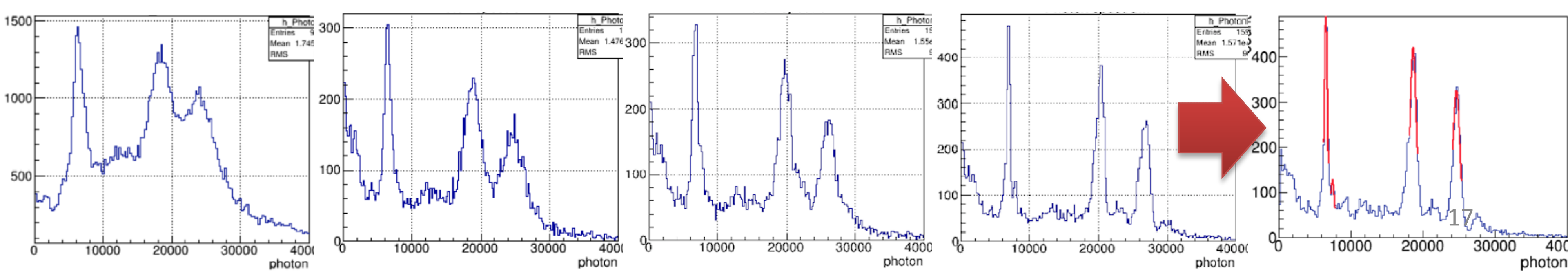


γ-ray measurement (^{57}Co 122keV)

- Hit volume correction
  - strong correlation was obtained
  - (recombination is seen ?)

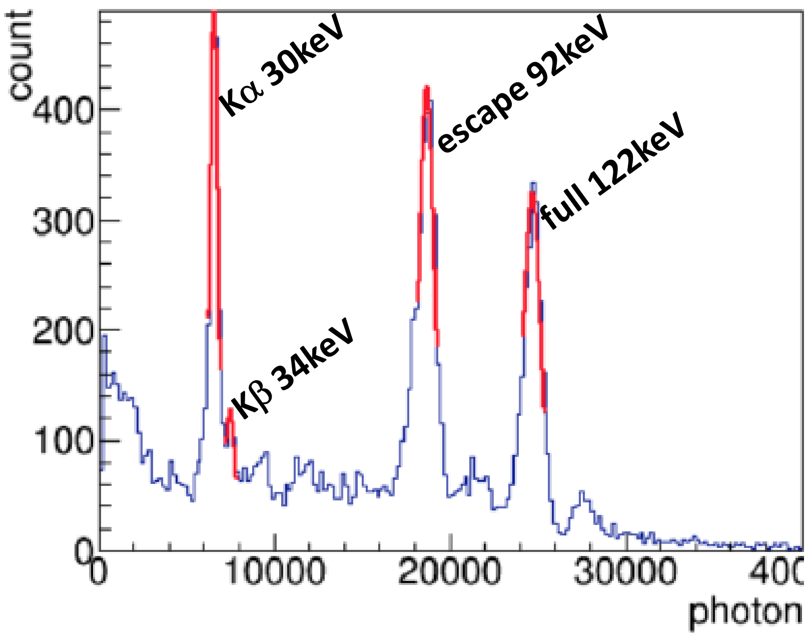






Energy resolution

- Four peaks are observed
- FWHMs are evaluated by Gaussian fitting



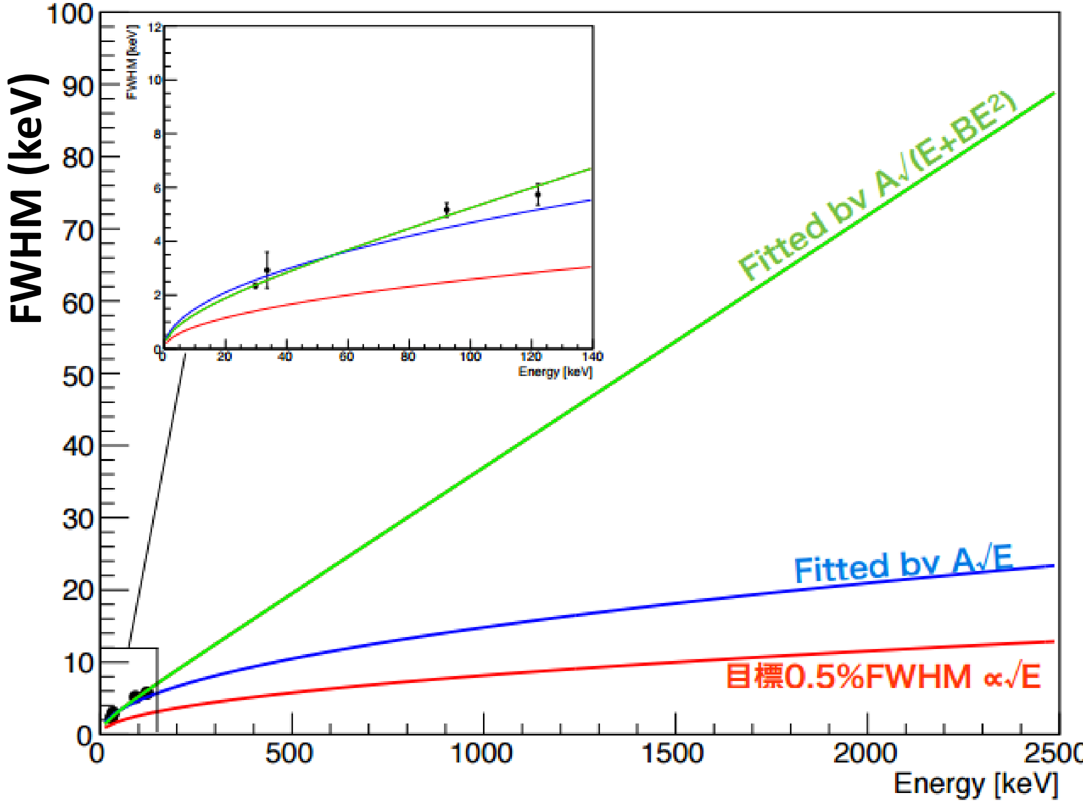
	Kα	Kβ	escape	full
energy	29.8keV	33.6keV	92.3keV	122keV
photon #	6605	7516	18711	24710
FWHM	7.9%	8.7%	5.6%	4.7%

Energy resolution estimation at Q

- Estimated resolution is 1~3.6%(FWHM) @2.5MeV
  - Several factor for the target

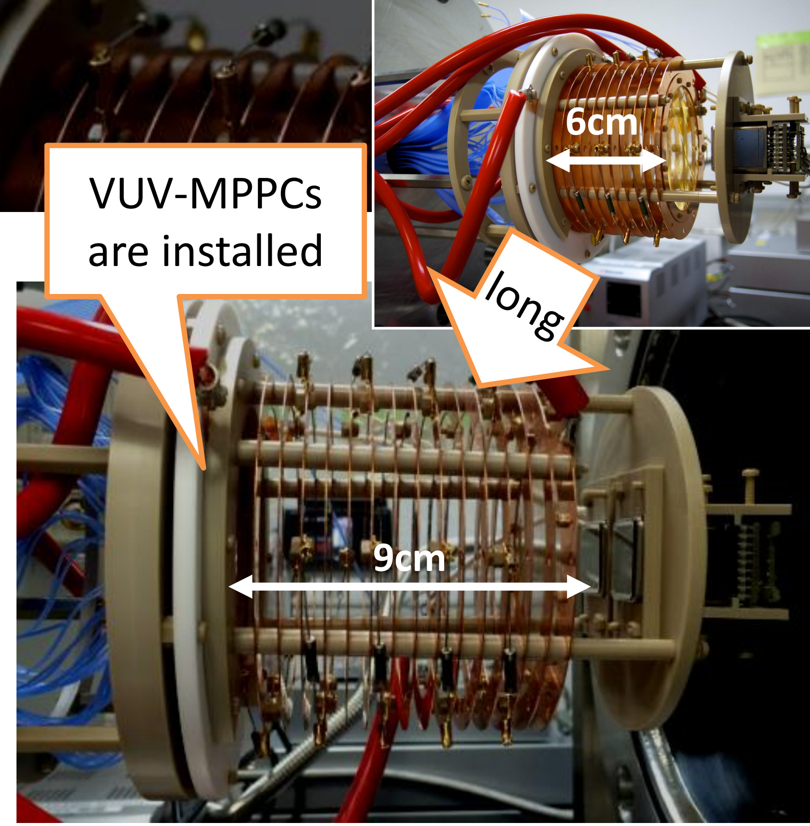
- We plan to improve energy resolution by
  - VUV-MPPC
  - gas circulation
  - crosstalk suppress
  - etc...

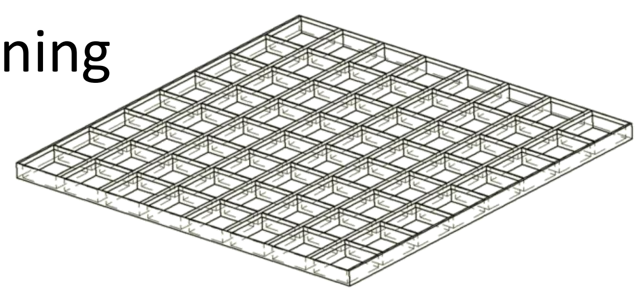
- We also plan to make larger detector



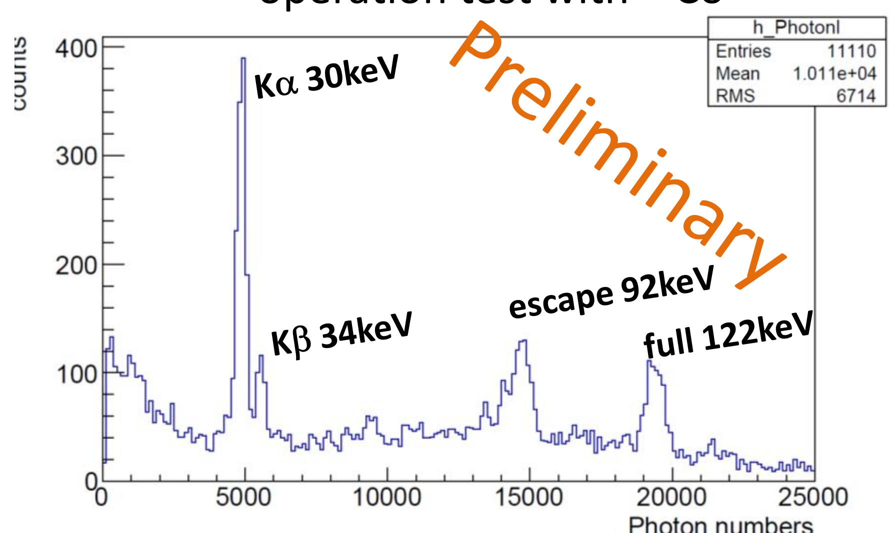
Upgrades

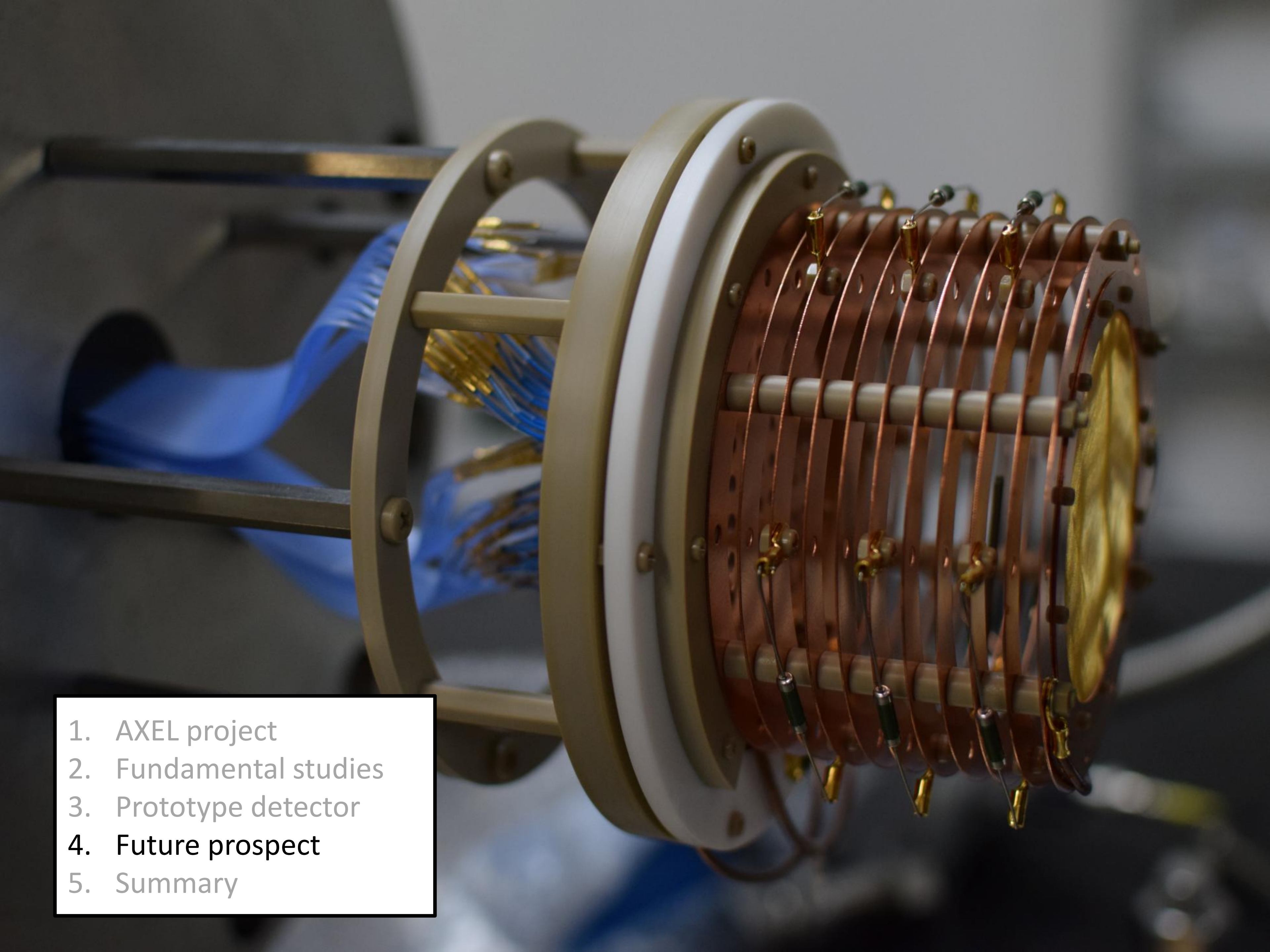
- Long field cage
  - For 511keV γ-ray
- New VUV-sensitive MPPCs
  - instead of WLS-painted MPPC
  - operation test with ^{57}Co seems OK
- Gas circulation
  - pump (last component) is now vacuum test
- EL crosstalk suppression
  - designing





operation test with ^{57}Co

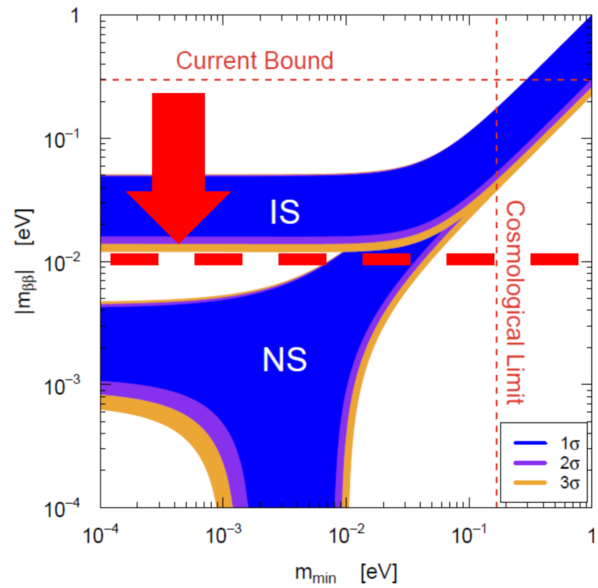




1. AXEL project
2. Fundamental studies
3. Prototype detector
4. **Future prospect**
5. Summary

Our goal is ....

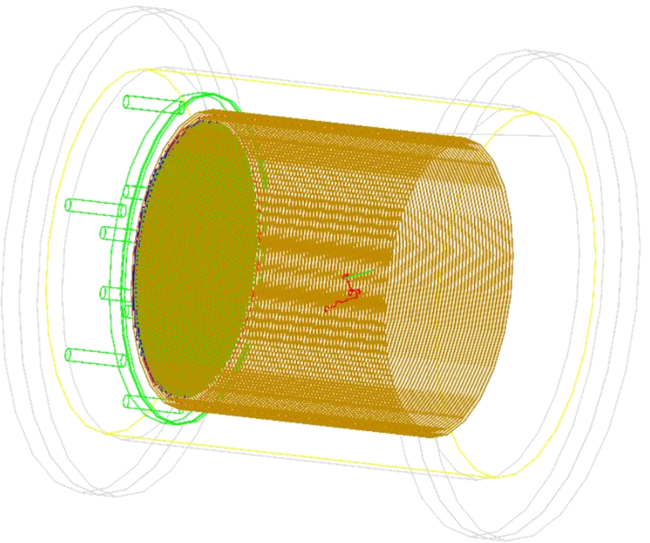
- $0\nu\beta\beta$ discovery !!!
  - or exclude inverted hierarchy
- Expected event rate
  - 0.5 count/year/ton ($m_{\beta\beta}$=10meV)
  - We need ton scale detector
  - BG rate requirement in ROI < ~1 count/year



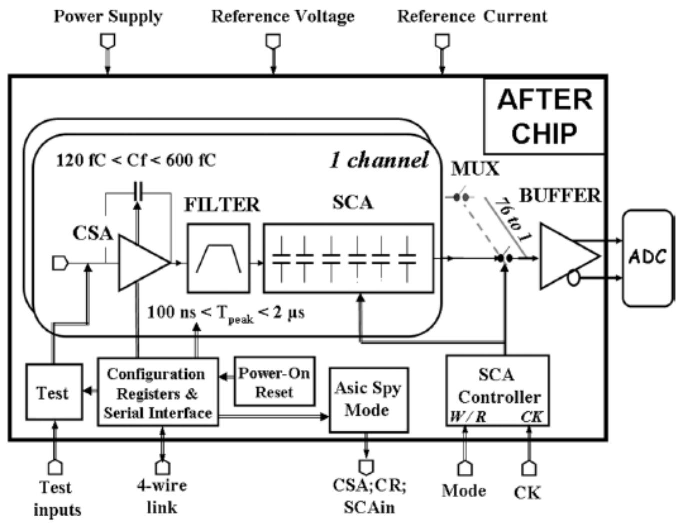
	volume	mass	MPPC #	purpose
current	0.216L	~10g	64	ELCC test (122keV, 511keV)
next (2016~2017) next2 (2018~)	~200L	~10kg	~2000	2.5MeV demonstration enriched ^{136}Xe
future (202X~)	~18000L	~1ton	~31000	$0\nu\beta\beta$ search

Next prototype detector

- Purpose
  - energy resolution @ 2.5MeV(Q value)
  - establish large size technique
  - tracking ability
  - BG observation



- Status
  - readout board --> Tanaka's poster
  - structure : designing with Geant4
  - clean room : constructed large size
  - gas system : considering safety devices
  - etc...

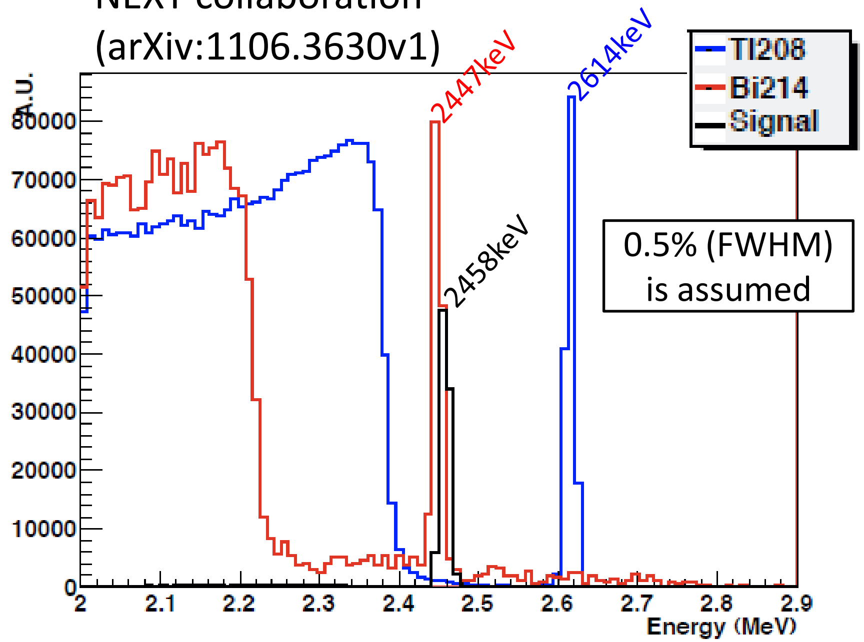


Most serious BG for AXEL

- γ-ray from ^{214}Bi is our enemy

- chamber mass : 25 ton
- expected BG is 1000 cts/year

NEXT collaboration
(arXiv:1106.3630v1)



Mass ~25*10^{6} g

Contamination 2.9*10^{-12} g/g

Avogadro # 6.02*10^{23}

solid angle ~0.1

branching ratio 0.0157

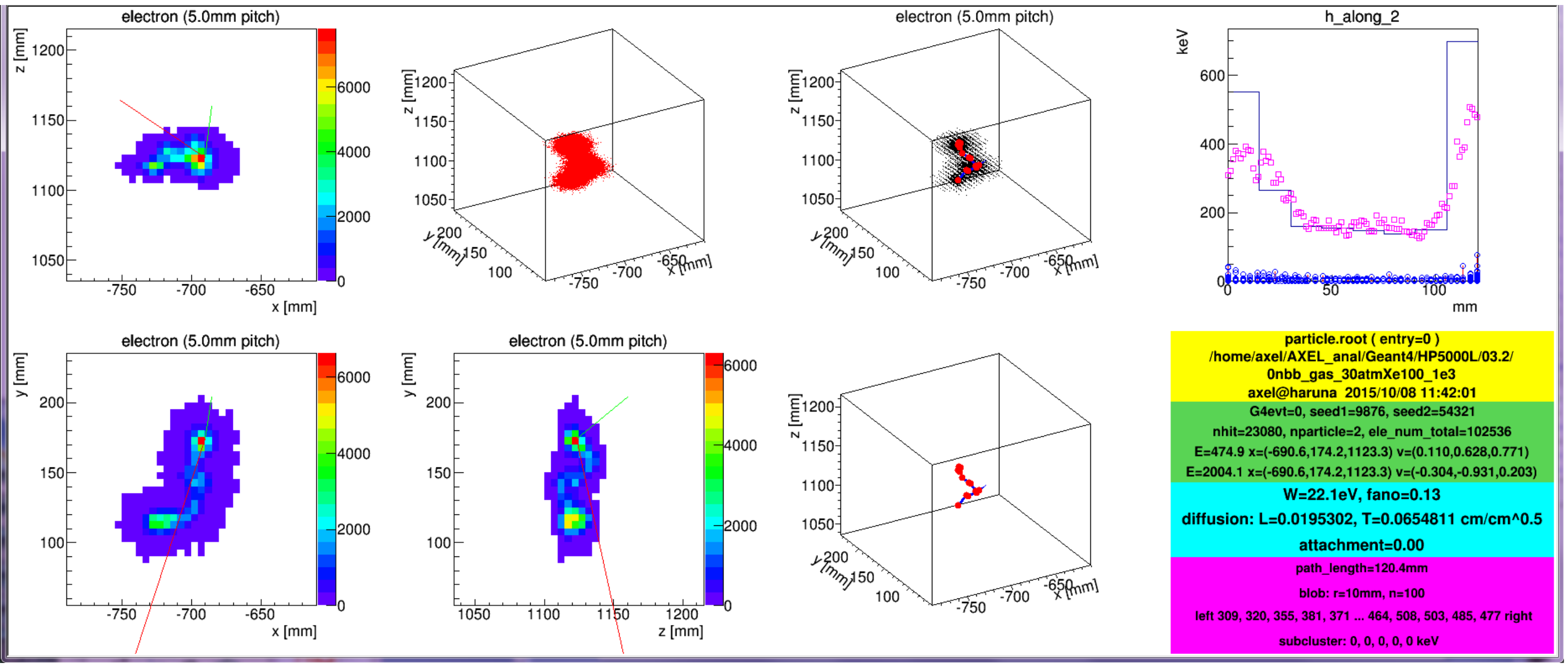
photoab. ratio 0.02

$$R_{BG} = M \times C \times \frac{N_A}{M_{^{238}\mathrm{U}}} \times \frac{\ln 2}{T_{1/2}^{^{238}\mathrm{U}}} \times \Omega \times B \times R =$$ **~1000 counts/year**

atomic weight 228

half life 4.468*10^{9}

Tracking simulation



- Geant4 + diffusion
- Two blobs detected
- 1/10 reduction will be expected
  - (still remain 100 cts)

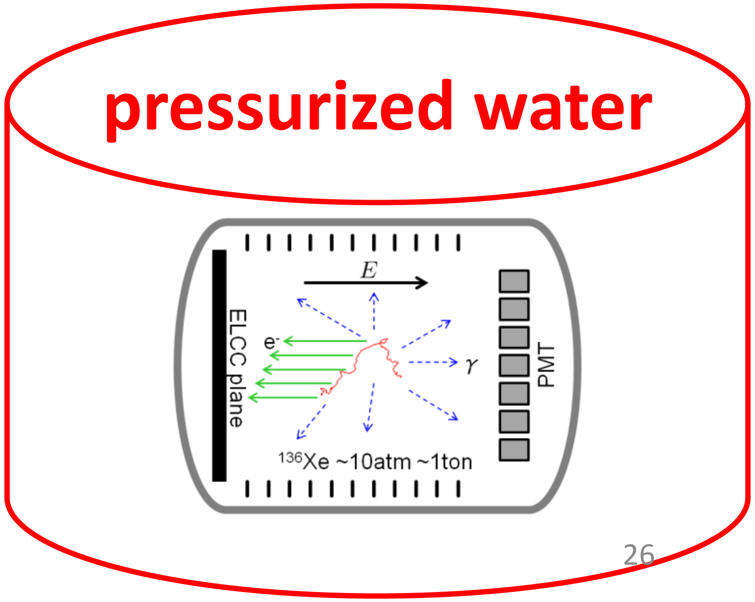
signal efficiency [%] (with BG 10%)

	2.5	5	7.5	10 [mm]
30atm Xe25%+He75%	84.6	75.8	73.0	71.0
30atm Xe50%+He50%	80.5	77.4	73.9	67.1
30atm Xe75%+He25%	77.6	73.2	69.2	59.5
30atm Xe100%	64.7	60.5	51.4	36.7

Pressurized water shield

- Concept
  - Similar structure to KamLAND-Zen
  - Thickness : 37.3mm --> 3mm (ex. EXO achieved 1.37mm)
    - or thinner thickness like balloon
  - BG will be 10 counts/year

- Plan
  - pressure test for various materials
  - construct small system

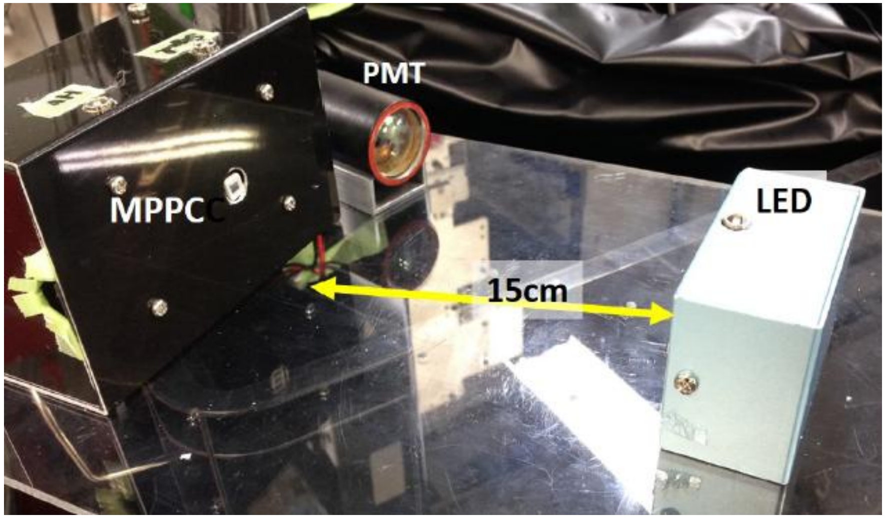


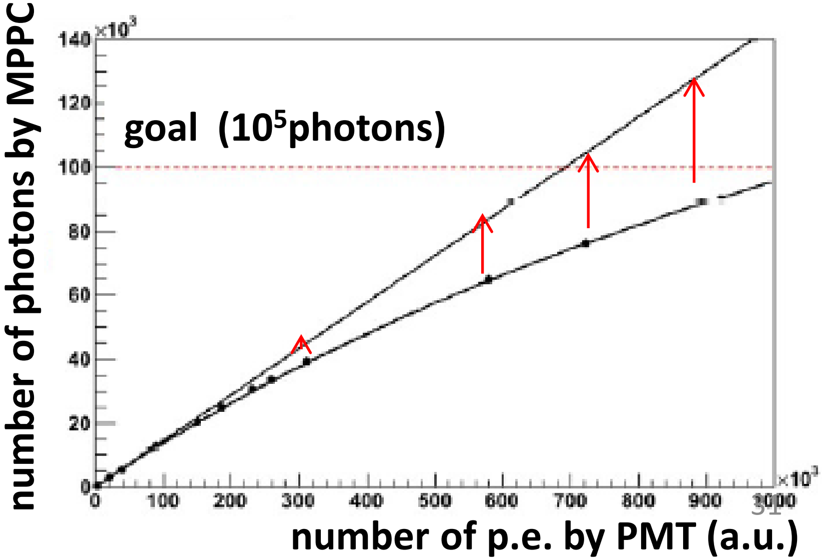
Summary

- AXEL project
  - $0\nu\beta\beta$ search using high pressure xenon gas TPC with high energy resolution, large mass and tracking ability
  - New readout idea : ELCC (electric field simulation is OK)
  - Linearity for 1e5/5μs : correction fluctuation is 0.12% (OK)
- Prototype detector
  - Energy resolution : 1~3.6%(FWHM) at Q (many improvements are ongoing)
  - Long size + VUV-MPPC result will come soon (511keV)
- Future prospects
  - We started making large size detector --> Tanaka's poster
  - γ-ray BG from ^{214}Bi in the chamber (heaviest component) will be reduced by tracking and water shield: 1000->100->10

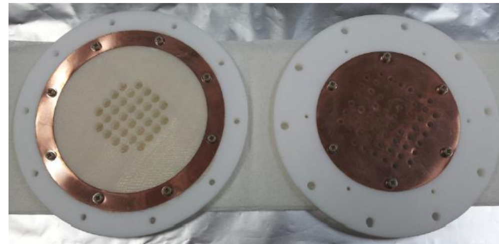
Linearity measurement

- We measured MPPC's linearity by using PMT as a reference
  - Irradiated LED light up to ~10^5/5μs
  - Observed saturation is slightly larger than expected from the number of pixels and recovery time. Under investigation
  - After correction, expected residual fluctuation is 0.12% (< 0.5% : target energy resolution)



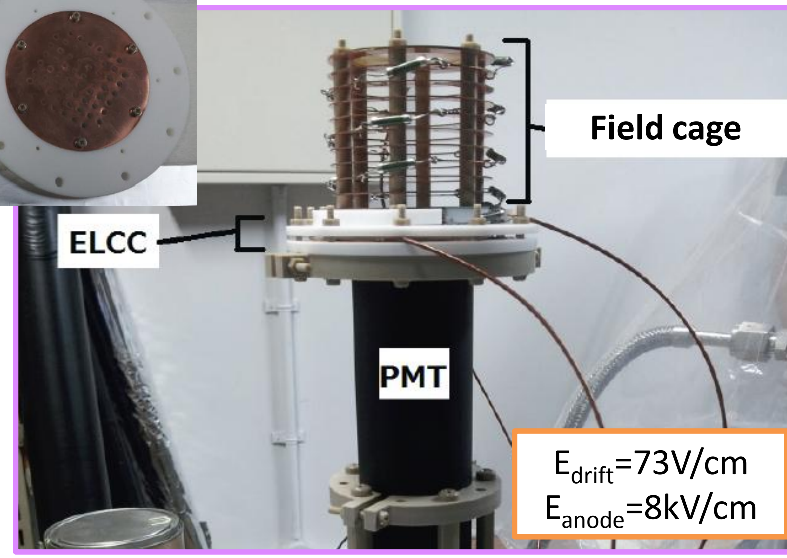


ELCC demonstration by UV-PMT



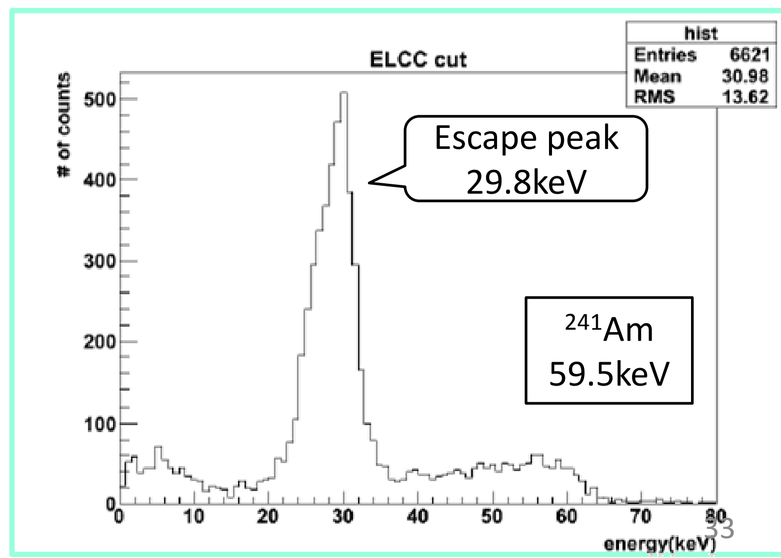
Setup

- 1atm Xe
- UV-PMT (H3178-51Q)
- all cells are merged
- detection size: 28x28x55mm



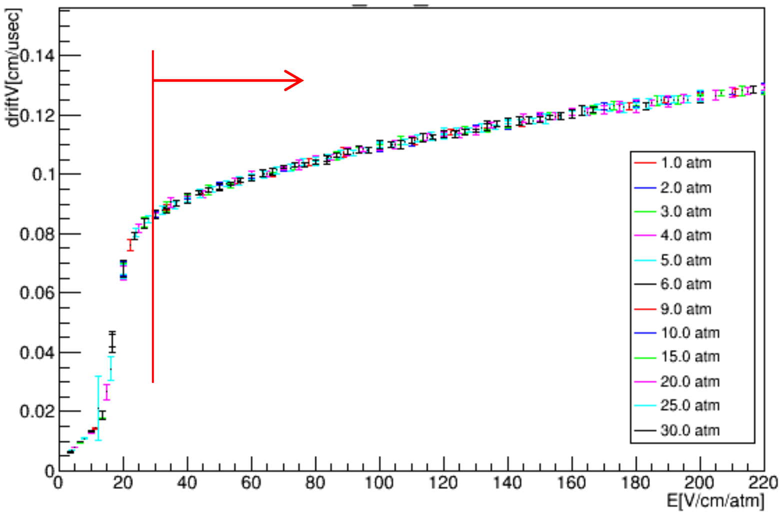
energy resolution (FWHM)

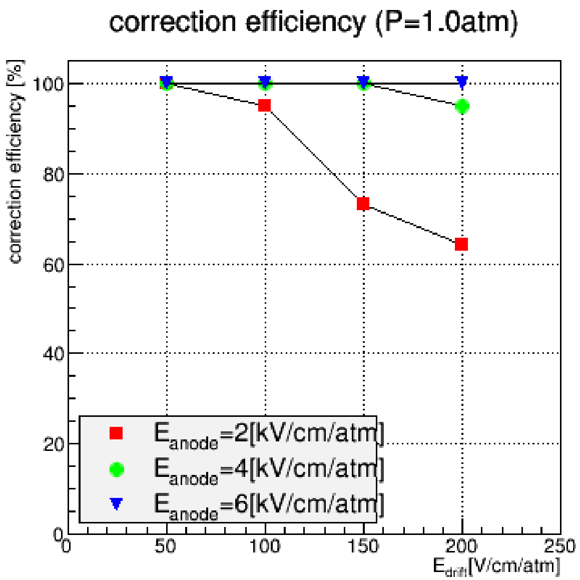
- 13.8% @30keV (fit right edge)
- 1.5% @2.5MeV (converted)

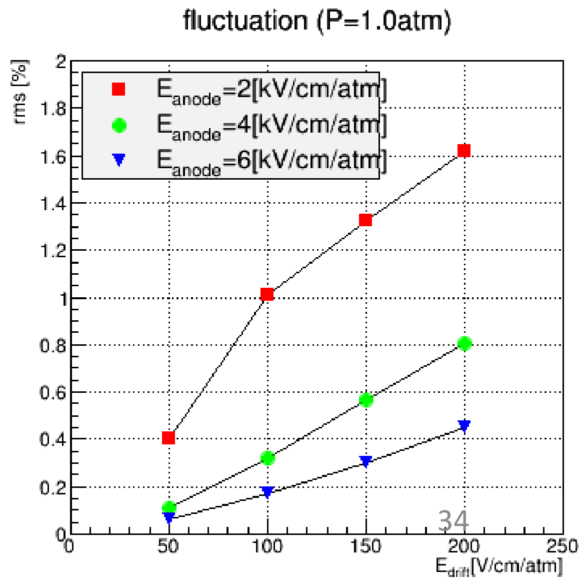


Voltage for 1atm

- Drift
  - driftV change small at >30 V/cm
- Anode
  - 8kV is enough



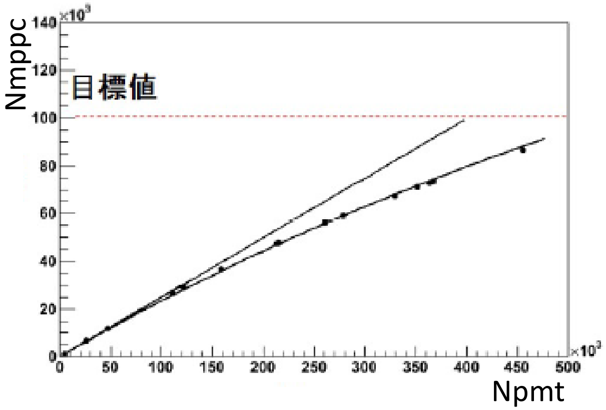


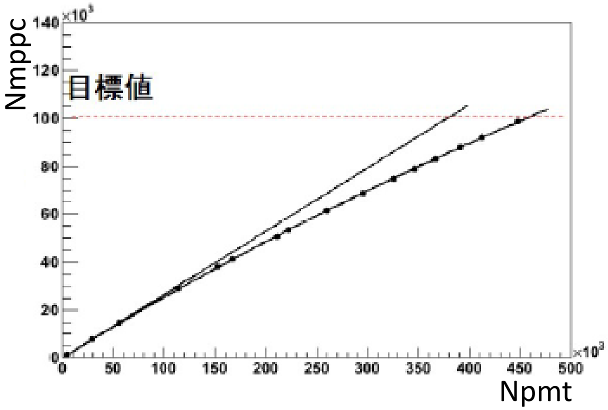


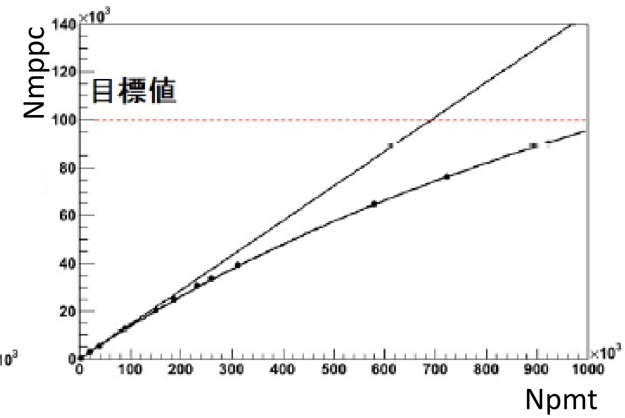
Linearity measurement

Result

- Slowly saturated (25mm pitch is better)







MPPC pixel pitch	50μm	25μm	VUV 50μm
photon# to keep linearity	1.5×10^4	2.5×10^4	1.5×10^4
N_{pixel}	3600	14400	3600

- After correction, fluctuation is 0.12% (< 0.5% : aim of Eres)

Linearity measurement

- photon rate per pixel : $k[1/(\mathrm{pixel}\cdot \mathrm{s})] = \dfrac{N_{\mathrm{true}}}{N_{\mathrm{pixel}} \cdot \Delta t}$

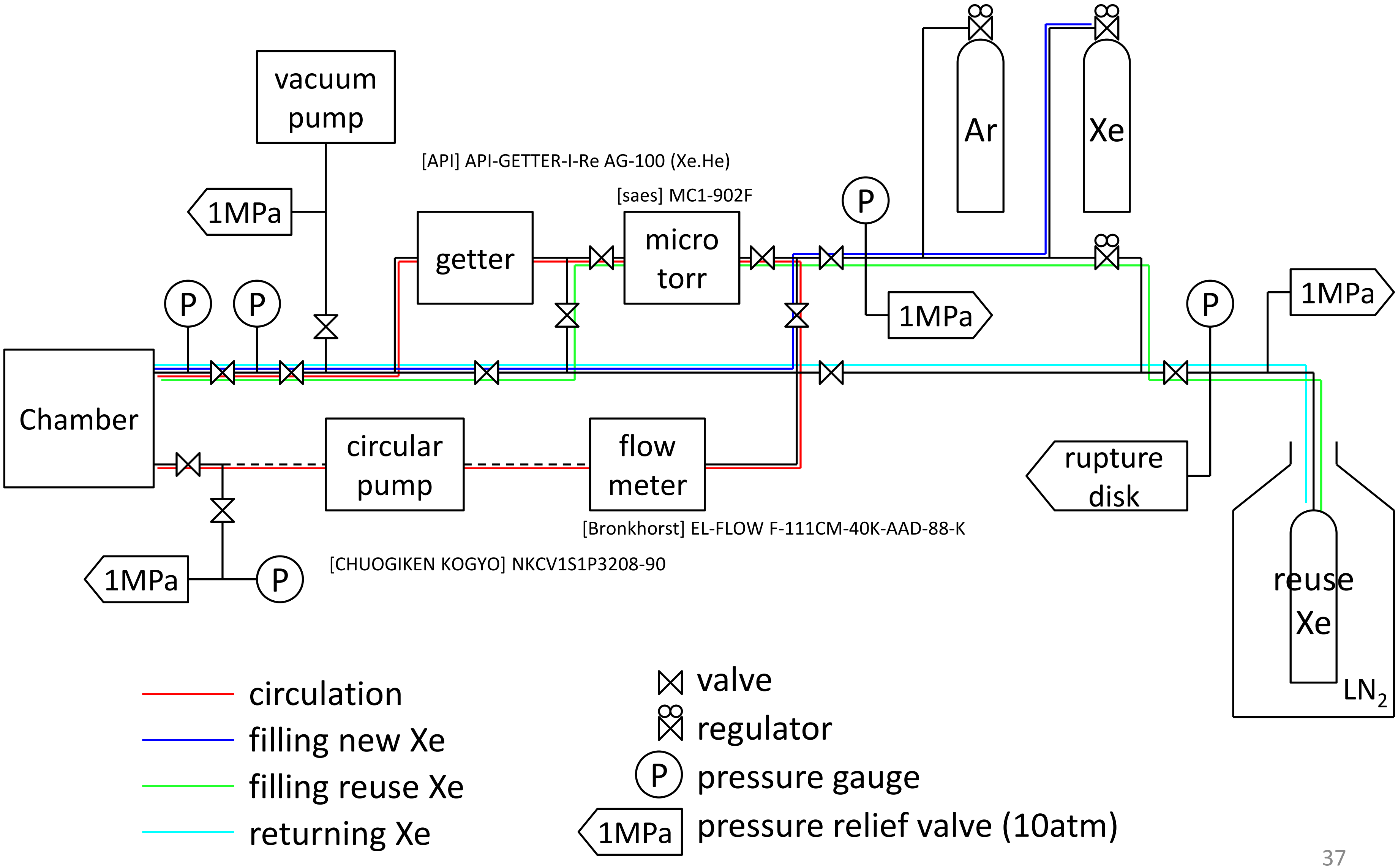
- average gain : $g = \displaystyle\int_0^\infty \underbrace{ke^{kt}}_{\text{probability to hit after t sec}} \underbrace{g_0(1-e^{-t/\tau})}_{\text{gain after t sec, } \tau \text{ : recovery time}} dt = \frac{g_0}{1+k\tau}$

- Observed photon# : $N_{\mathrm{obs}} = \dfrac{N_{\mathrm{true}}}{1+k\tau}$

- Fluctuation of correction

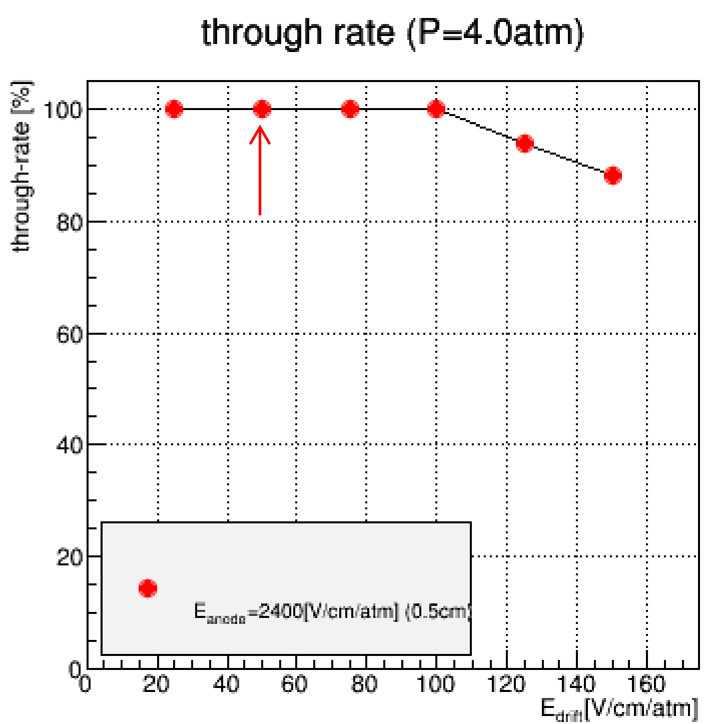
$$\frac{\Delta N}{N} = \frac{N_{\mathrm{true}} - N_{\mathrm{obs}}}{N_{\mathrm{true}}} = \sqrt{\frac{\tau}{N_{\mathrm{pixel}} \cdot \Delta t}} = \sqrt{\frac{25\mathrm{ns}}{3600 \cdot 5\mu\mathrm{s}}} = 0.0012$$

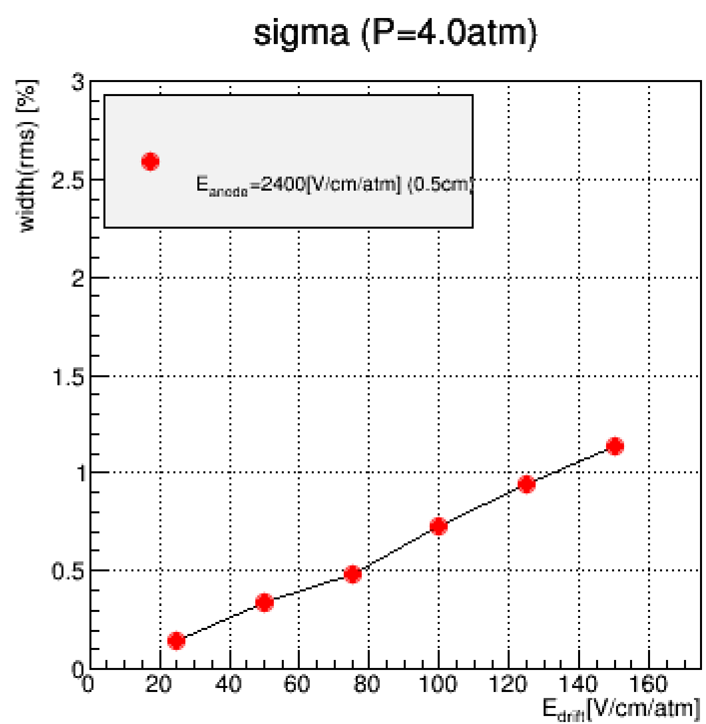
Prototype detector : gas system



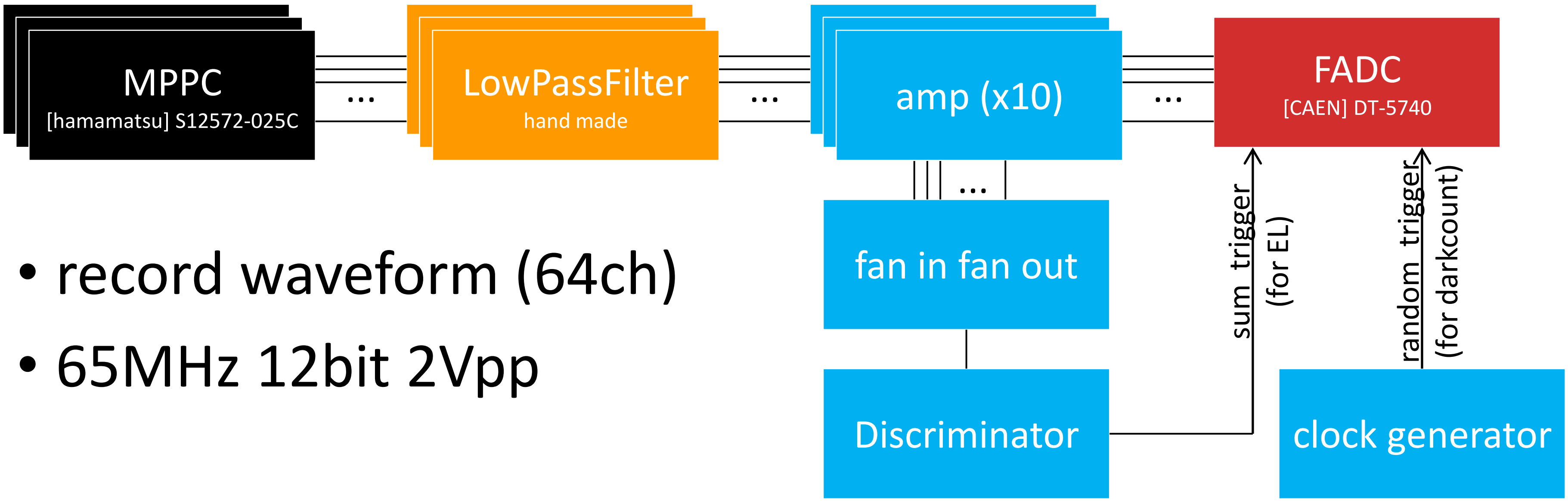
High voltage optimization

- Electric field
  - E_{anode} = 2.4kV/cm/atm
  - E_{drift} = 50V/cm/atm
- correction efficiency (by FEMM) is 100%

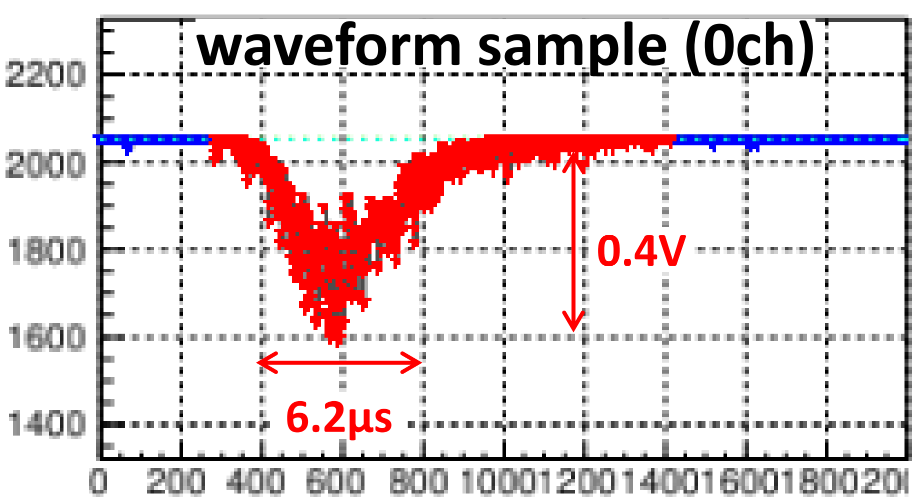


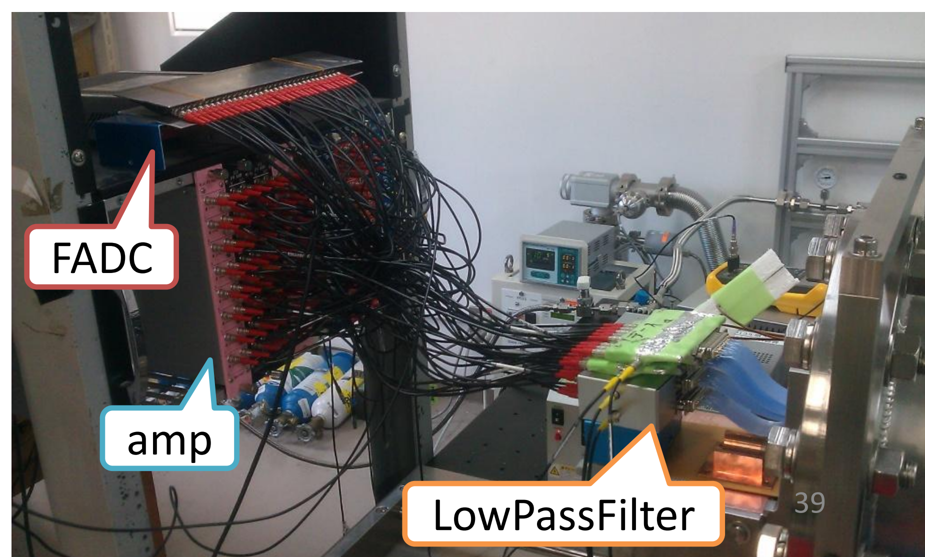


Data acquisition



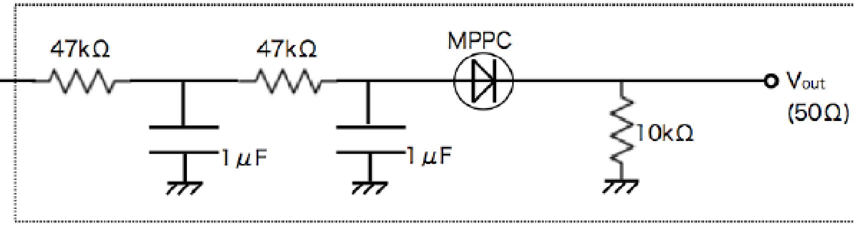
- record waveform (64ch)
- 65MHz 12bit 2Vpp

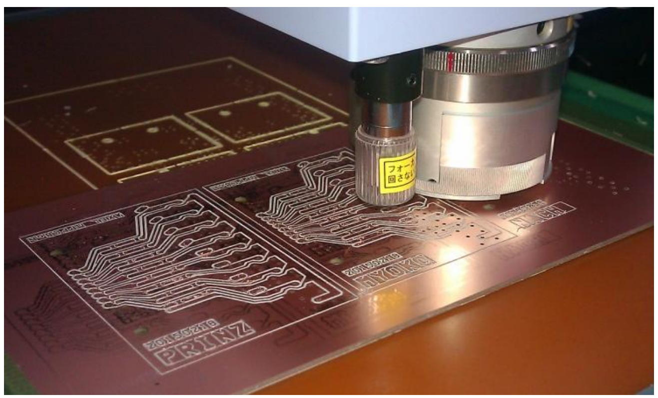


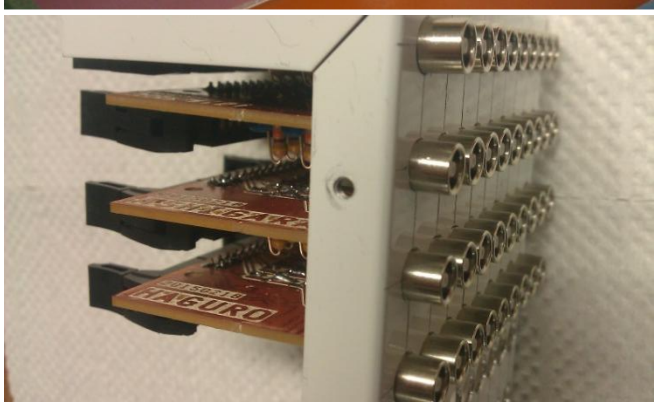


electronics

- low pass filter (64ch)
    - large time constant : 50msec
    - large capacitance : 1uF
    - for large and long pulse

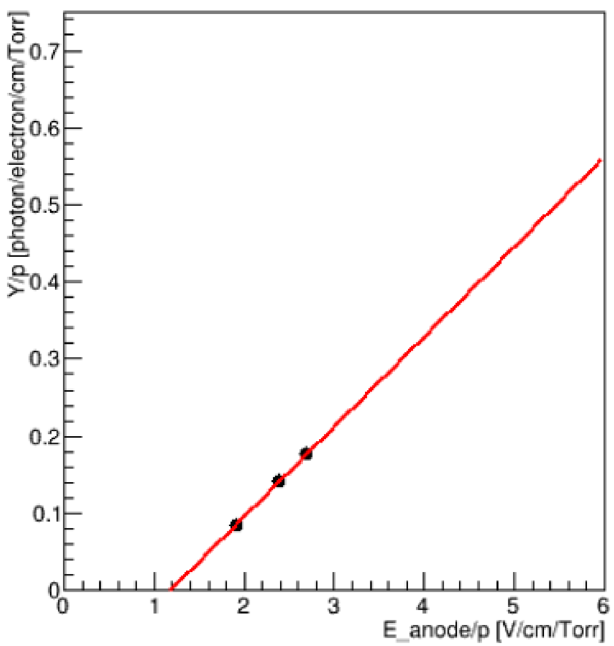


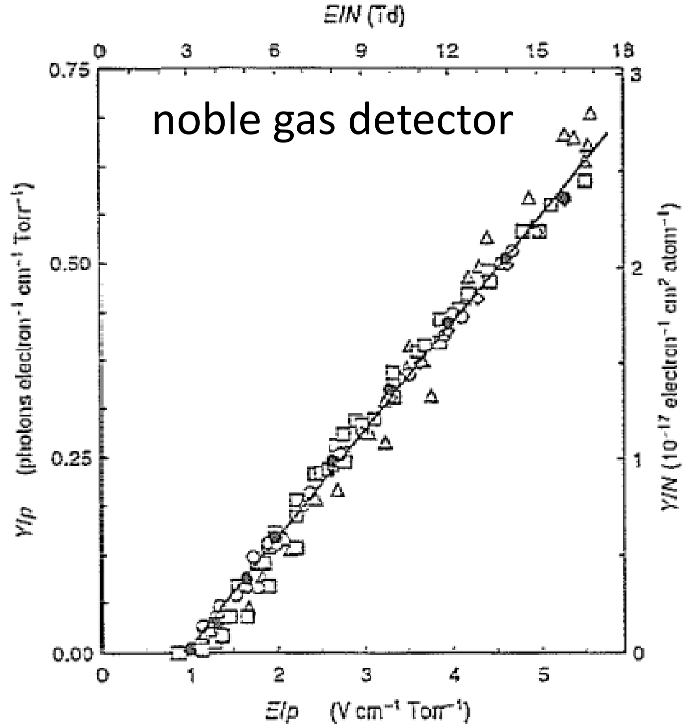




E_{anode} dependence

- Linear dependence --> OK
- We can supply higher E_{anode}





Yield calculation

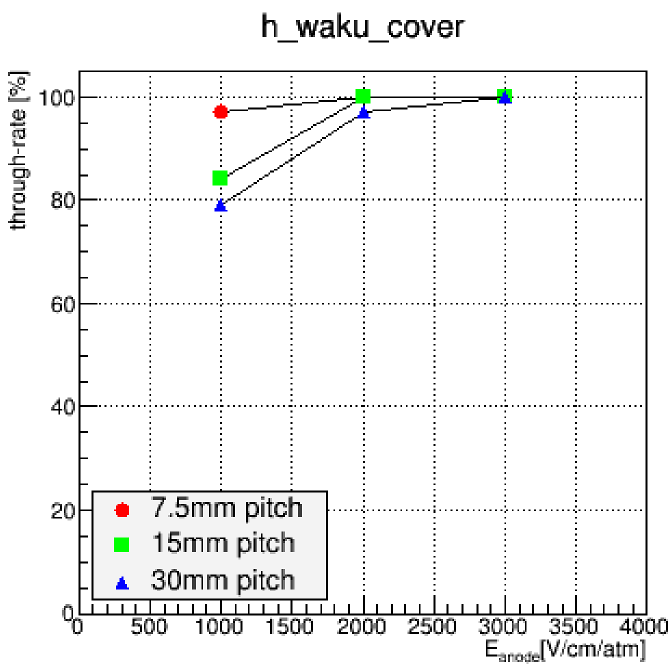
$$\underbrace{\alpha}_{\text{measured}} = P_{\text{coll}} \times \underbrace{Y}_{\text{calculated}} \times \Omega \times P_{\text{trans}} \times \frac{1}{2} \times \text{PDE}$$

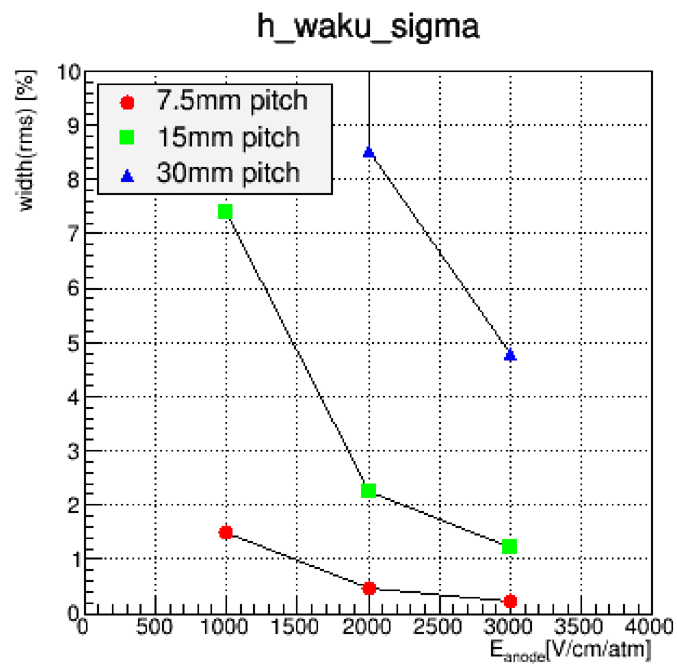
- α : detected EL photon# per electron (measured)
- P_{coll} : collection efficiency of electric field line (100%)
- Y : Yield of EL (calcutated)
- Ω : solid angle of EL photon to MPPC (12.9%)
- P_{trans} : WLS translation efficiency 50%
- 1/2 : translated photon direction (up/down)
- PDE : PDE of MPPC (35%)

cell pitch

Garfield++

- finer pitch is better (but ch# increase)

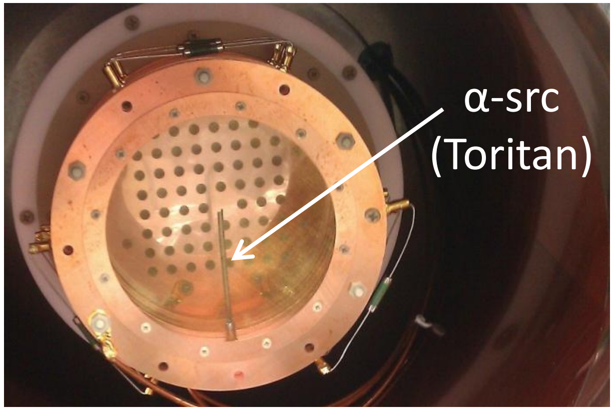


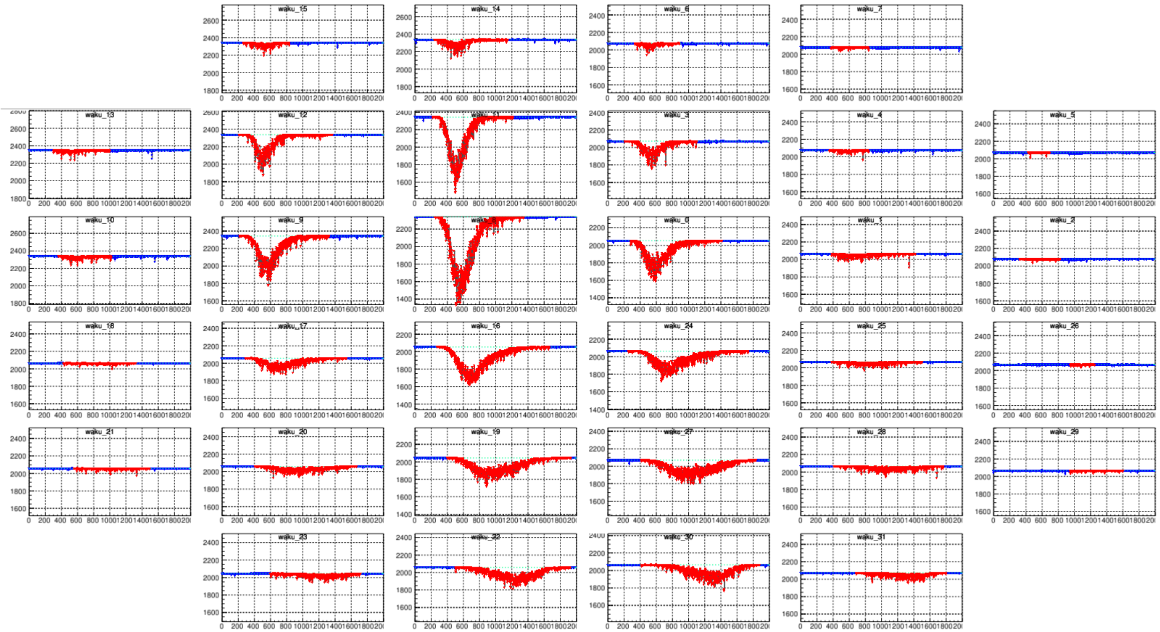


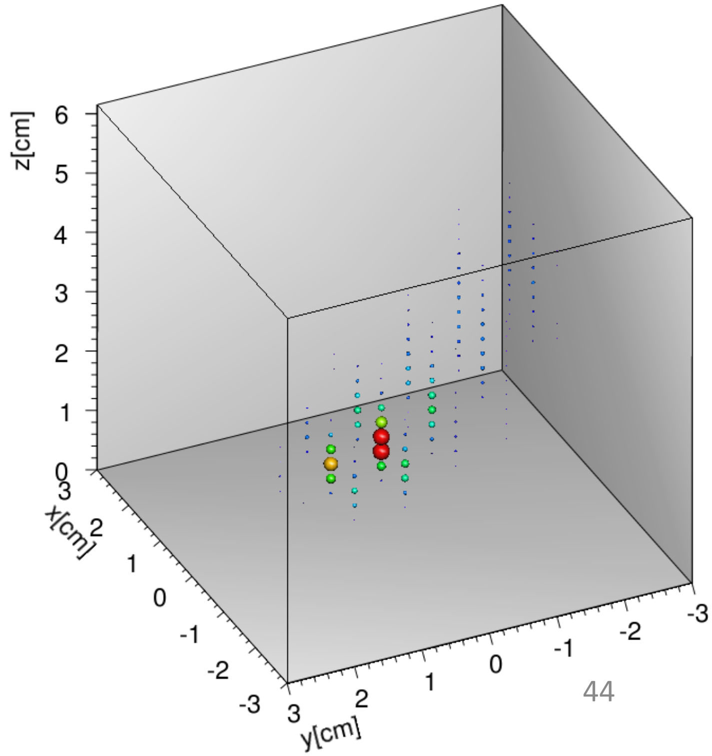
Tracking demonstration (α-ray)

- Detect EL light
  - OK !
- Track width is too large ?
  - large Diff_{tra} --> High Pressure
  - blurred at WLS --> UV-MPPC

gas : Xe 1atm
E_{anode}=1.6kV/0.5cm
E_{drift}=0.4kV/6cm
Diff_{tra}=0.34cm/√cm

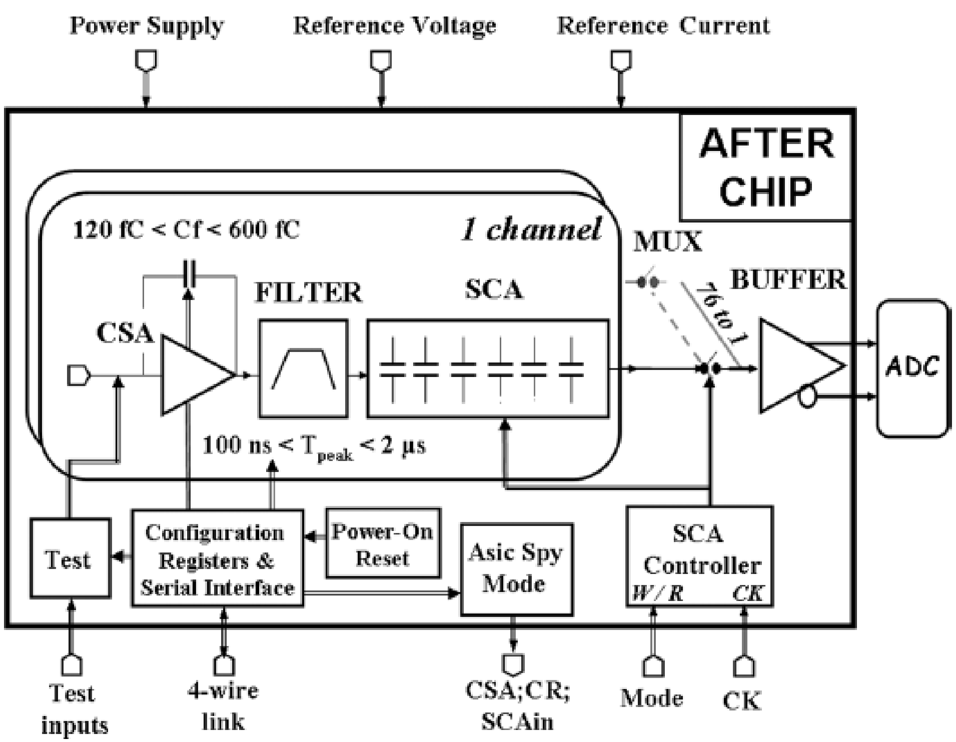






Readout electronics

- For 1ton detector, MPPC # will be 50000
- AFTER chip (ASIC) 72ch 511sampling
- developing board for AFTER



Parameter	Value
Number of channels	72
Samples per channel	511
Dynamic Range	2 V / 10 MIPs on 12 bits
MIP charge	12 fC to 60 fC
MIP/Noise ratio	100
Gain	4 values from 4 mV / fC to 18 mV / fC
"Detector" capacitor range	20 pF -30 pF
Peaking Time	100 ns to 2 µs (16 values)
INL	1% 0-3 MIPs ; 5% 3-10MIPs
Sampling frequency	1 MHz to 50 MHz
Readout frequency	20 MHz to 25 MHz
Polarity of detector signal	Negative (T2K) or Positive
Test	1 among 72 channels or all

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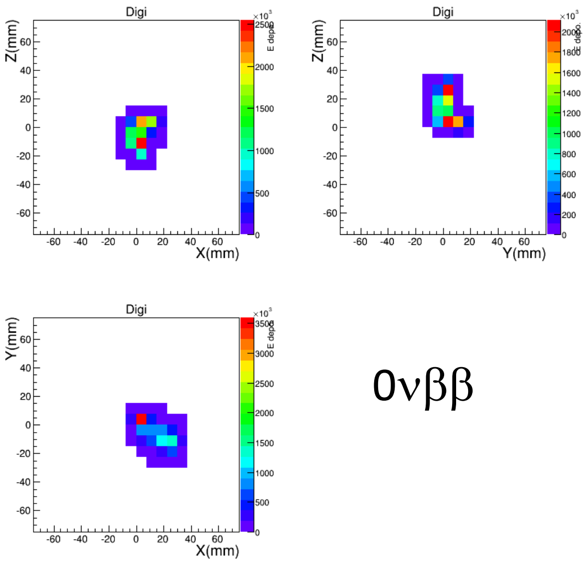
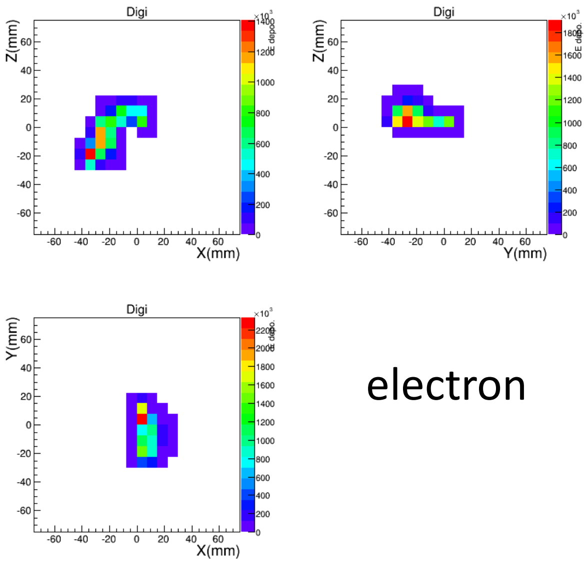
Comparison of 0νββ, e and α

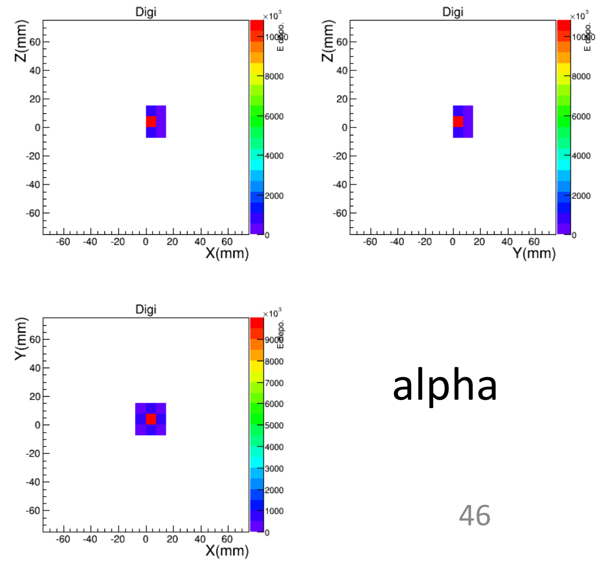
- Event topology by tracking
  - α BG is well rejected
  - γ BG with 2.5MeV photoelectric absorption is difficult to reject perfectly.
  - (multi site events such as Compton scattering can be rejected)



0νββ



electron



alpha

Comparison of 0νββ, e and α

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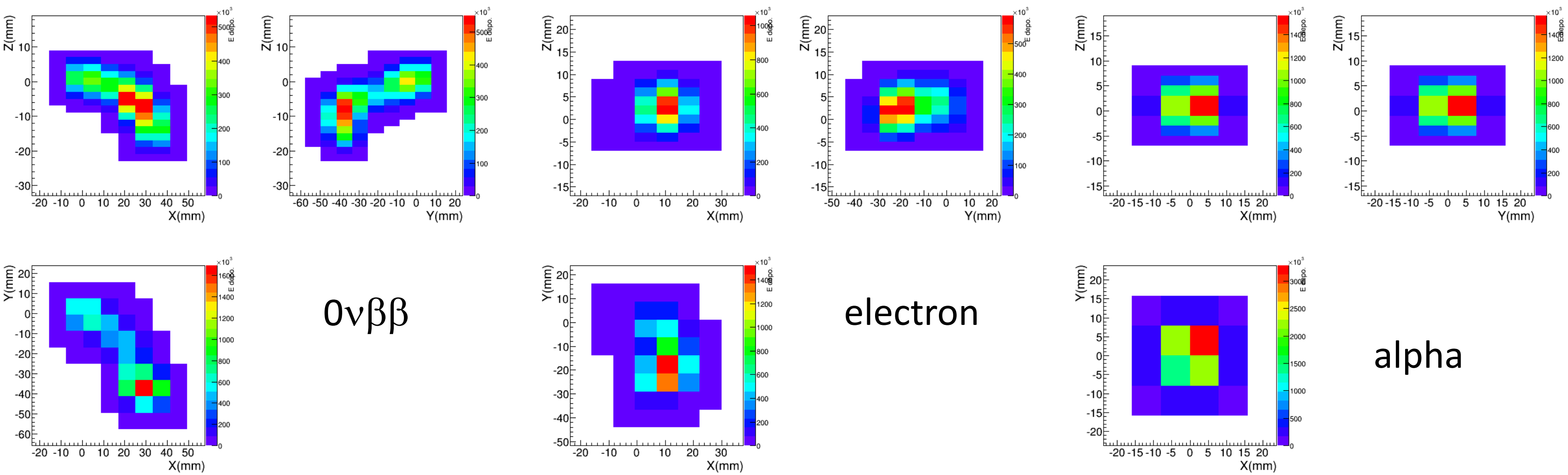


View scales are different. Cell size is same.

Rate of ^{214}Bi γ-ray

- Attenuation length of 2.5MeV γ-ray
  - 140cm in 30atm Xe -> self shielding is not effective
  - 20cm in water -> external BG stop by water shield
- Materials of detector must be checked
  - Vessel is the most heavy component (10ton : copper)
  - EXO uses clean copper for vessel : U < 5ppt 95% U.L.

Mass ~$10*10^6$ g

Contamination $5*10^{-12}$ g/g

Avogadro # $6.02*10^{23}$

solid angle ~0.1

branching ratio 0.0157

photoab. ratio 0.02

$$R_{BG} = M \times C \times \frac{N_A}{M_{^{238}\mathrm{U}}} \times \frac{\ln 2}{T_{1/2}^{^{238}\mathrm{U}}} \times \Omega \times B \times R = 643$$

counts/year

atomic weight 228

half life $4.468*10^9$

How to deal with ^{214}Bi ?

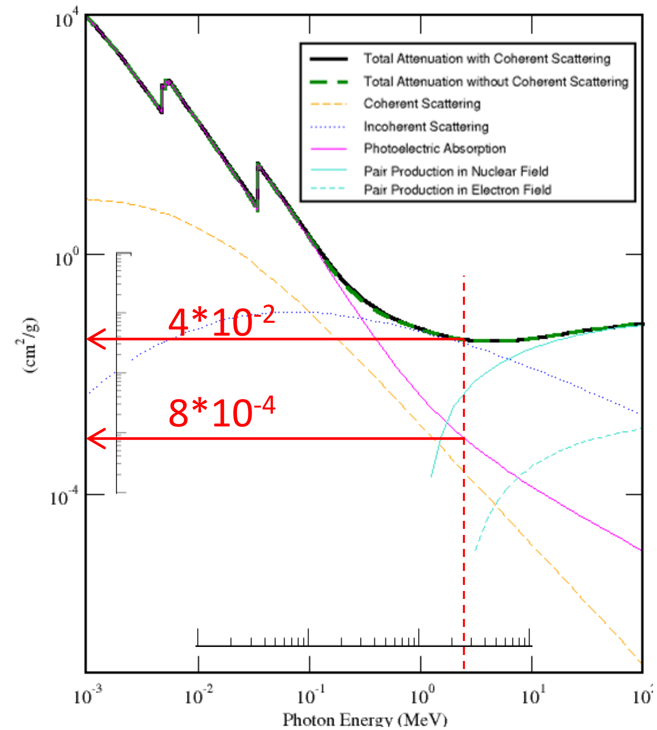
- Improve energy resolution
  - Energy difference between 0νββ and γ from ^{214}Bi is 0.44%
  - Intrinsic energy resolution is 0.25%
- Put some shield “in” the vessel
  - pressure vessel become huge
- Make clean vessel
  - purifying copper
- Make light vessel
  - titanium is strong and light (NEXT group’s approach)
  - need 2 ton --> still need purification

- --> we noticed rejection of high energy γ is not so easy

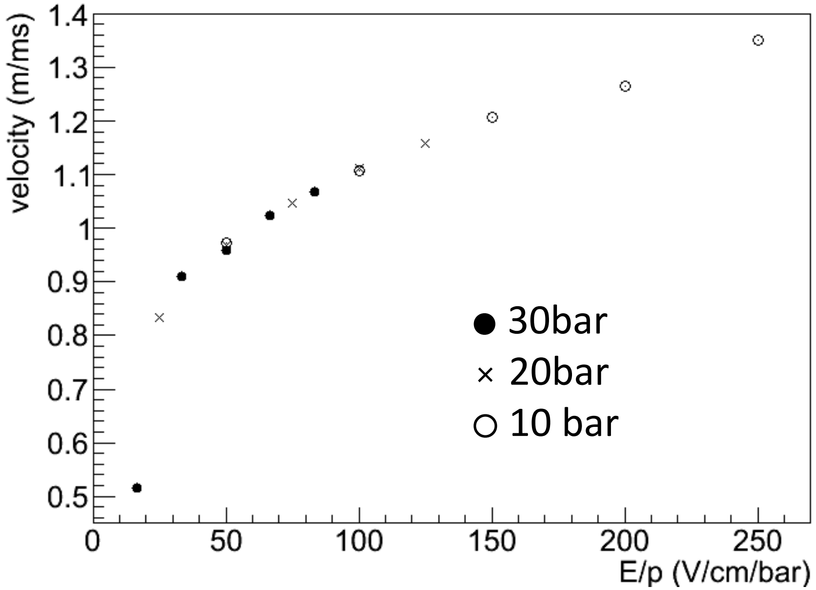
Stopping power

- Attenuation length of 2.5MeV γ-ray
  - 140cm in 30atm Xe
  - 20cm in water

- Shielding
  - Xe self shielding is not effective



Electric Field and electron drift



@ E=1.5kV/cm, p=30 bar

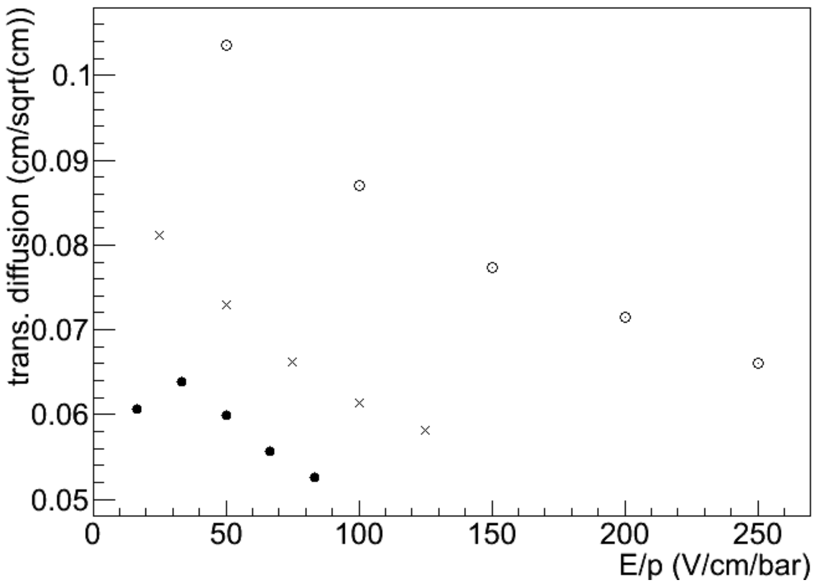
Drift velocity 0.96m/ms

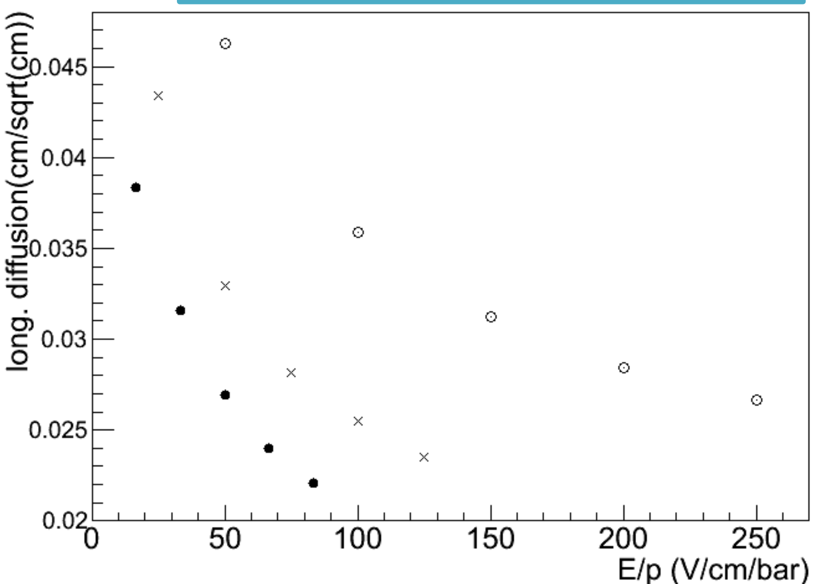
- Possibly add H_2, N_2 or He to increase the drift velocity.
  - It will also reduce diffusion.
  - It will also reduce light yield

diffusion after 1m drift

- transverse : 6mm
- longitudinal : 2.7mm

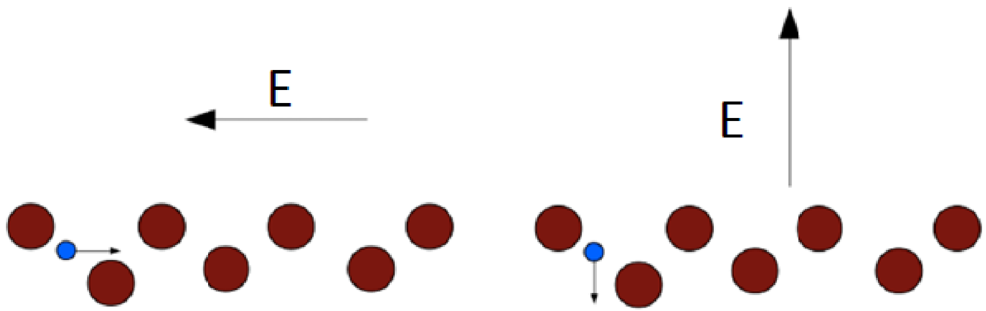
MAGBOLTZ calculation





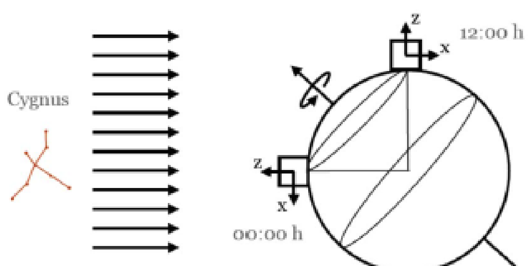
Directional dark matter Search

Approaches to directionality detection (3):
Columnar recombination and
Inferring direction without track image



Case 1:
More Recombination

Case 2:
Less Recombination

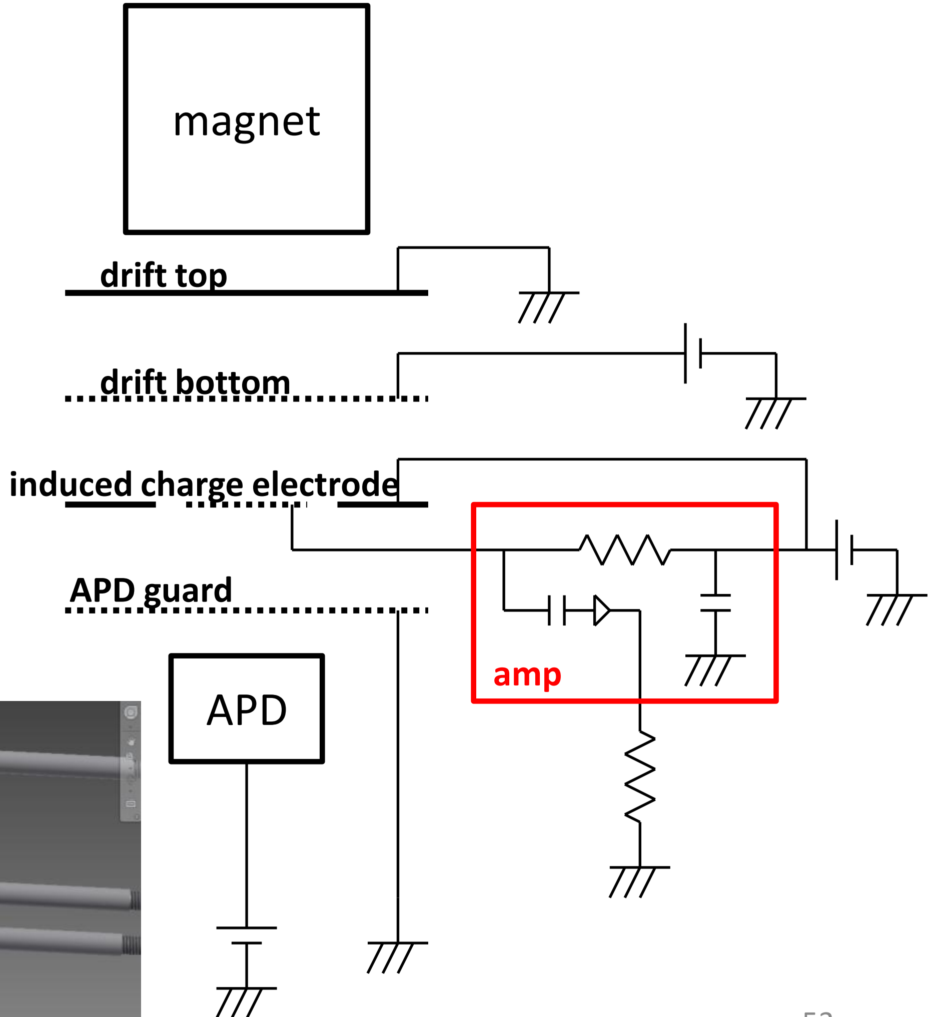


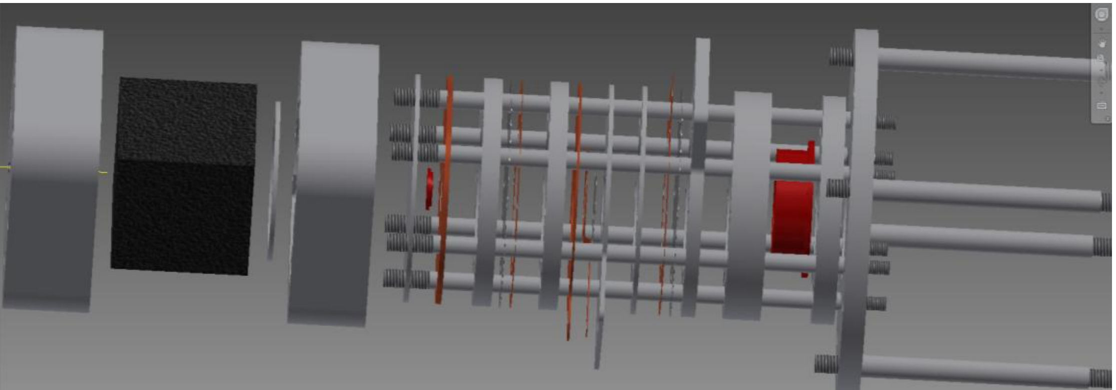
Concept by Dave Nygren, LBNL

- Measure recombination rate from scintillation yield and ionization yield
- We are planning to apply magnetic field to enhance the recombination yield for one direction

Recombination measurement

- Purpose
  - measure recombination and ionized signal (5.4MeV α)
  - test putting magnetic field





Recombination measurement

- Status
  - construction just started