Commissioning of liquid Xe detector with VUV-MPPC readout for MEG II experiment

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on behalf of the MEG II Collaboration

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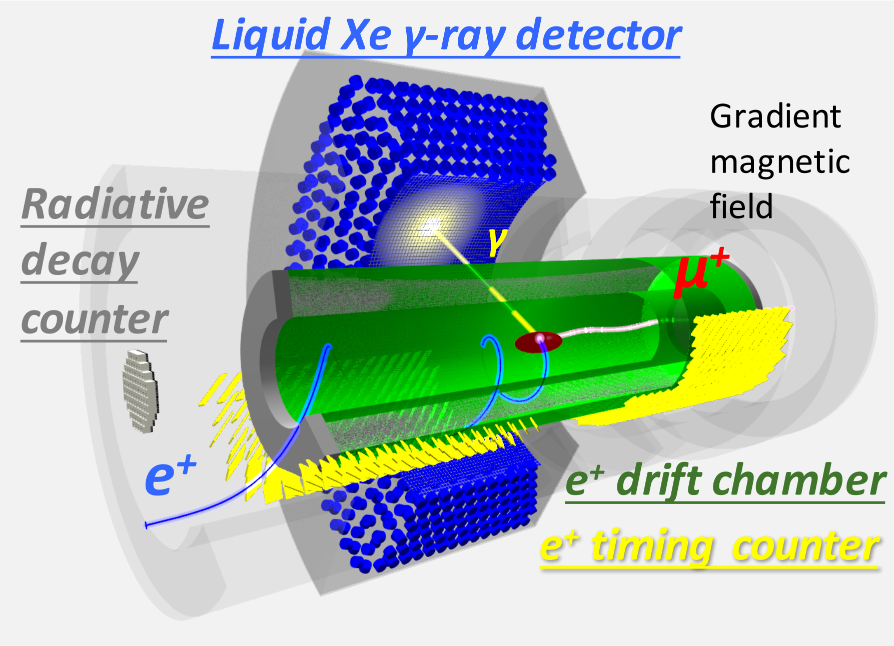
MEG II experiment



Searches for a cLFV decay of muon, $\mu \rightarrow e\gamma$.

- Clear evidence of BSM.
- Detectable branching ratio ($O(10^{-12} \sim 10^{-15})$) is predicted by some BSM models.

Upgrade of MEG experiment

- Doubled μ^+ beam intensity
- Doubled detection efficiency
- Resolutions of all detectors will become half
- Expected sensitivity of MEG II : 6×10^{-14}
  - In MEG. Sensitivity: 5.3×10^{-13}, Upper Limit (90% C.L.): 4.2×10^{-13}

Liquid Xe γ-ray detector

- To detect monochromatic γ-ray from $\mu \rightarrow e\gamma$ ($E\gamma = m_\mu / 2 = 52.8$MeV).
- Measuring the hit position, energy, and timing of γ-ray with good resolution is important to efficiently suppress the accidental background.

LXe γ-ray detector in MEG

LXe γ-ray detector was successfully operated in the MEG experiment.

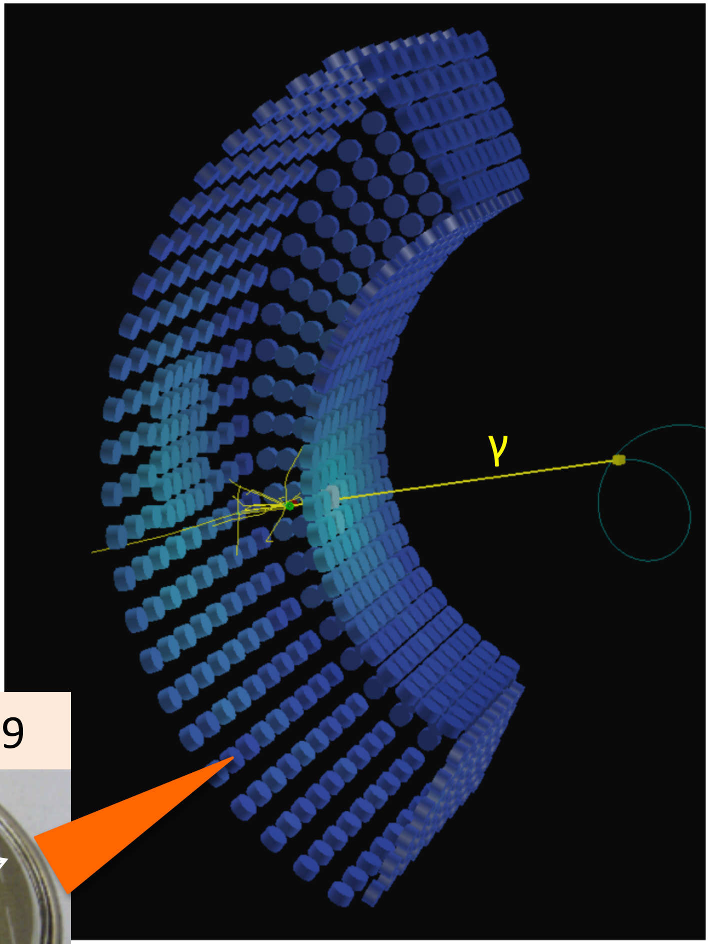
- 900 ℓ LXe.
- Scintillation light readout by 846 PMTs

Advantages of LXe

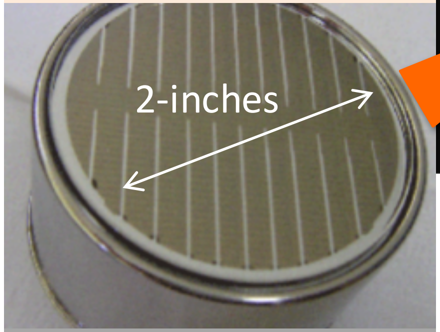
- High light yield (~75% of NaI)
- Fast (τ_{decay} = 45ns for γ-ray)
- High stopping power (X_0=2.8cm)
- Uniform (liquid)

Disadvantages of LXe

- VUV (Vacuum Ultraviolet) scintillation light (λ=175nm)
- High purity is needed
- Low temperature (165K) is required



Hamamatsu R9869



16% QE for λ=175nm

LXe γ-ray detector in MEG II

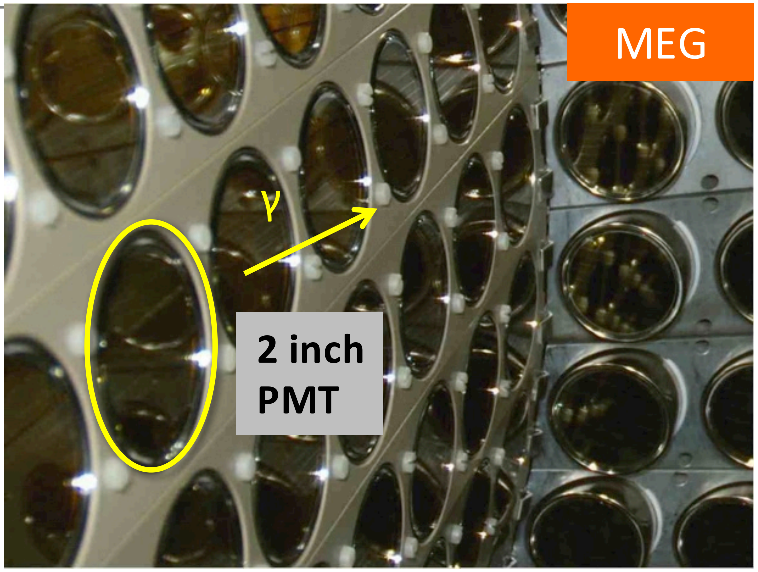
We have **upgraded LXe detector for MEG** II to significantly improve the performance.

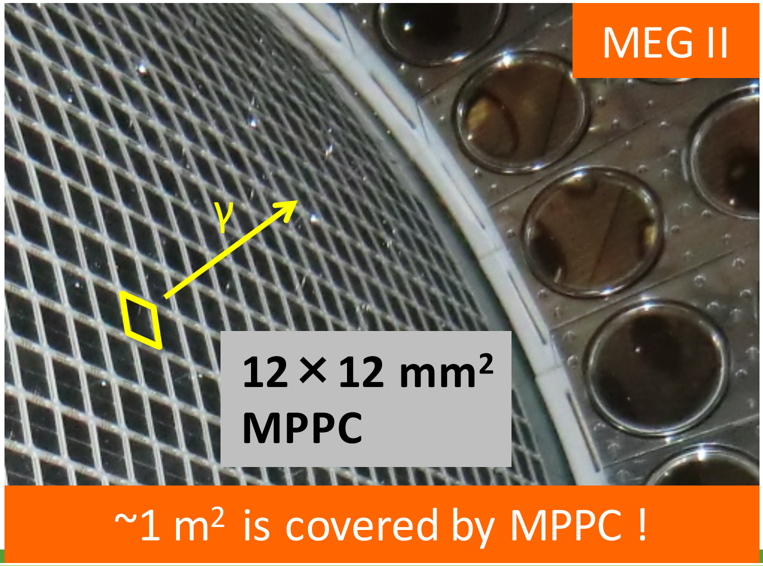
We have **replaced 216 2-inch PMTs** on the γ-entrance face **with 4092 12 × 12 mm^2 MPPCs.**

- **Better position resolution**
  from higher granularity.
- **Improved energy resolution**
  from better uniformity of scintillation readout.
- **Better timing resolution**
  from TOF estimation with better accuracy
  and larger statistics from larger sensitive area.
- **Increased detection efficiency**
  from reduced material of the γ-entrance face.

	MEG (measured)	MEG II (simulated)
σ (position)	~5 mm	~2.5 mm
σ (energy)	~2%	0.7 - 1.5%
σ (timing)	67 ps	50 - 70 ps
Efficiency	63%	69%

improve by a factor of 2!





VUV-sensitive large area MPPC

MPPC for MEG II LXe detector has been developed in collaboration with Hamamatsu Photonics K.K.

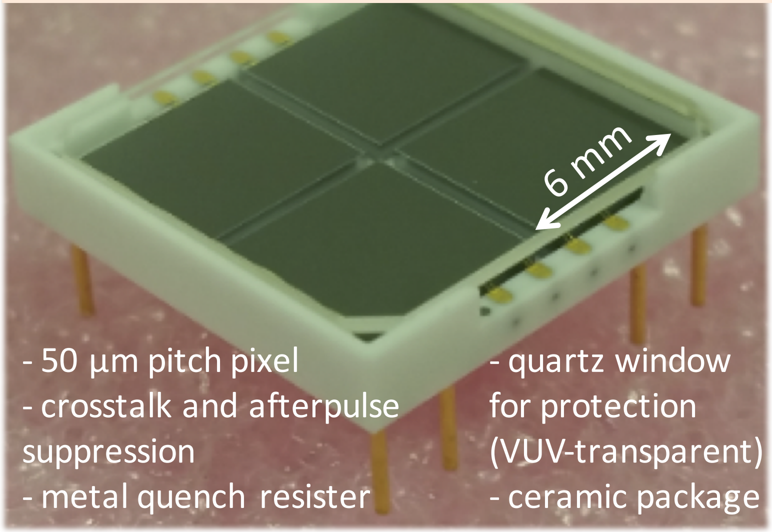
VUV-sensitive (PDE (λ=175nm) > 15%)

- Scintillation light of Xe is in VUV range
- Realized by removing the protection layer of resin, optimizing optical matching b/w LXe and sensor surface, and thinning contact layer.

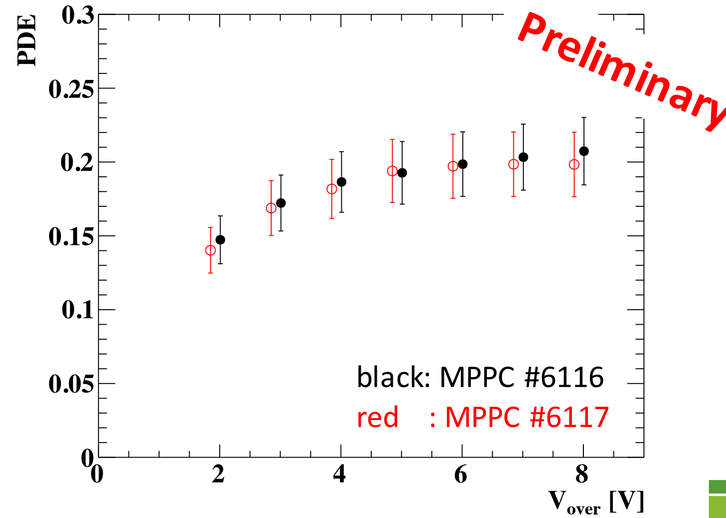
Large sensitive area (12 × 12 mm^2)

- To keep the number of readout channels manageable.
- Discrete array of four 6 × 6 mm^2 chips
- Four chips connected in series at readout PCB to reduce long time constant.

Hamamatsu S10943-4372



PDE vs. Over voltage

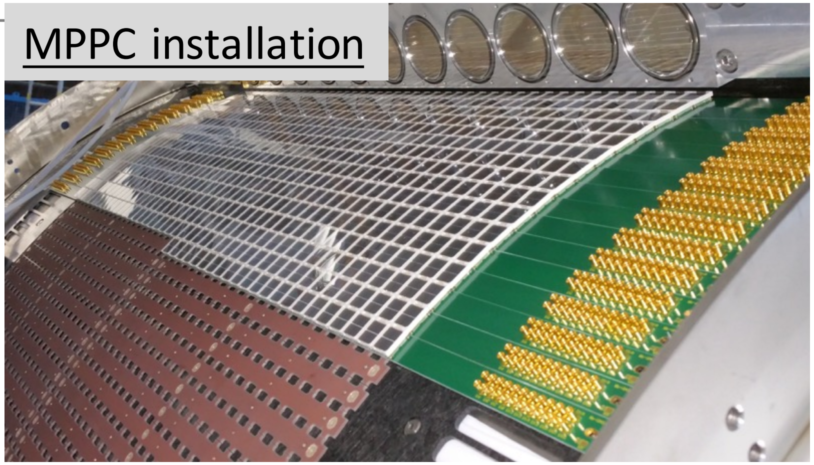


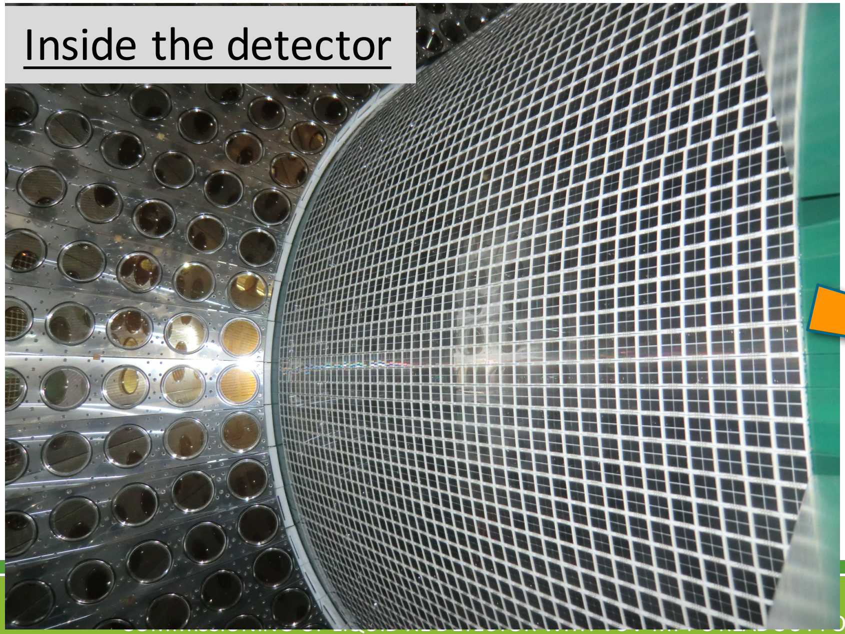
Detector construction

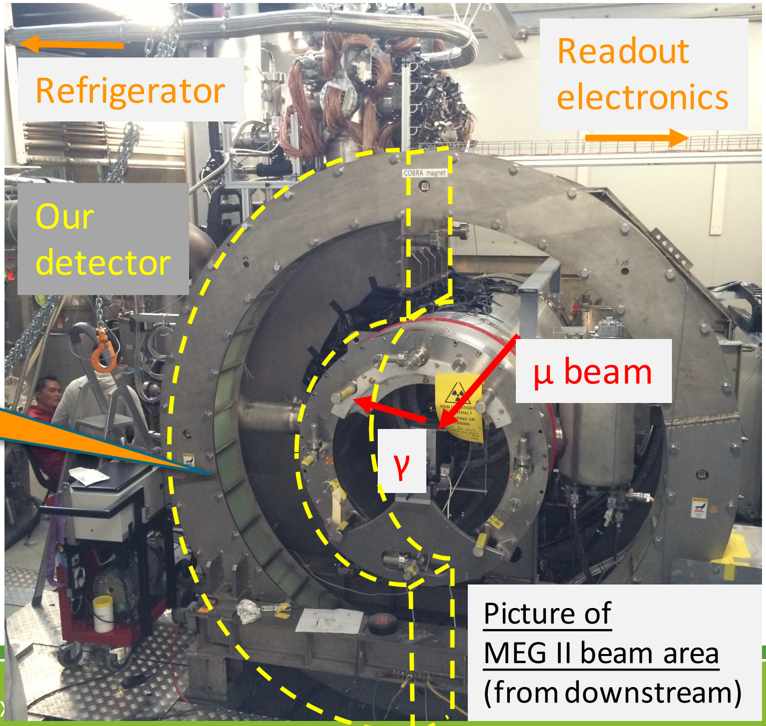
2015
MPPC mass production & mass test

2016
MPPC & PMT installation

2017 Apr.
Construction completed.







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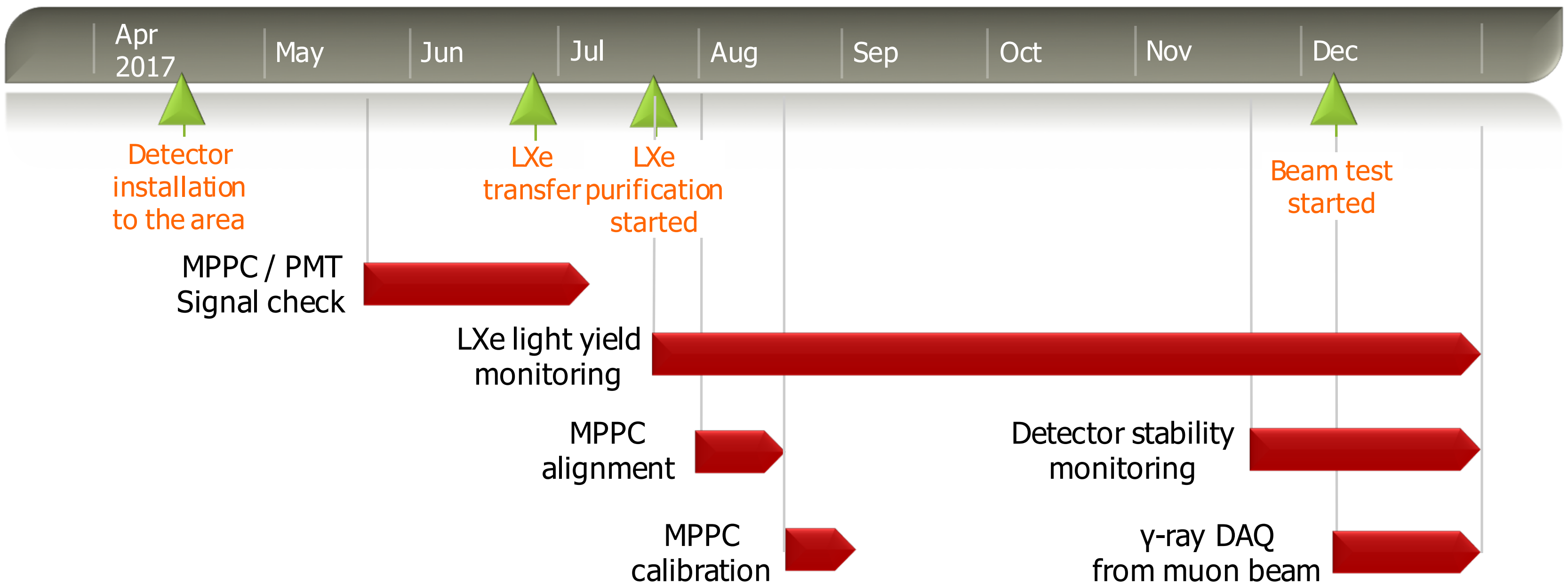
Detector commissioning in 2017

Commissioning of our detector has been started from April in 2017.

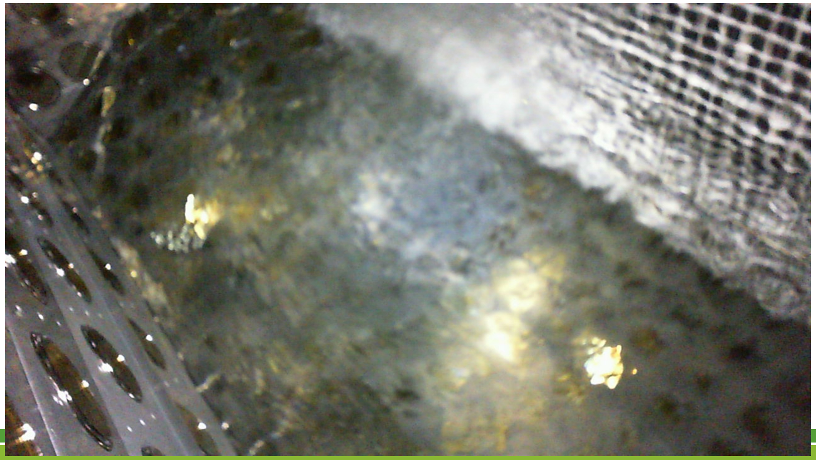
Goal in 2017: Pilot run with muon beam in December.



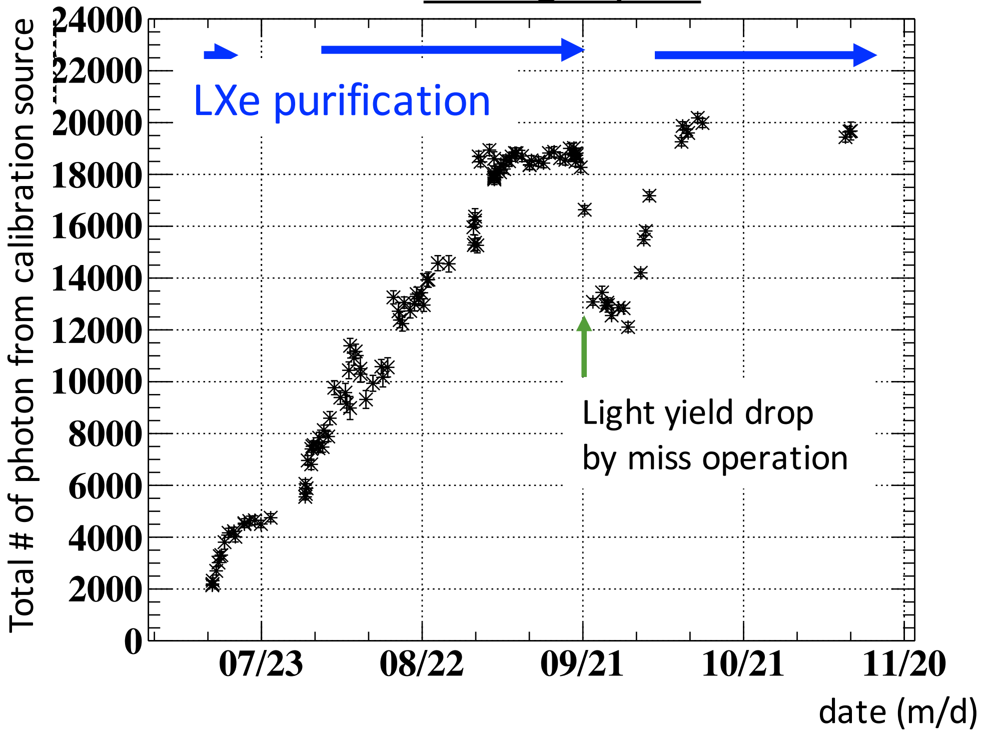
LXe transfer & purification

- LXe has been transferred to the detector.
- After the purification of a few month, sufficient light yield of LXe has been achieved by the purification.
  - Molecular sieves (LXe circulation) + getter (gXe circulation)

Inside the detector during LXe transfer



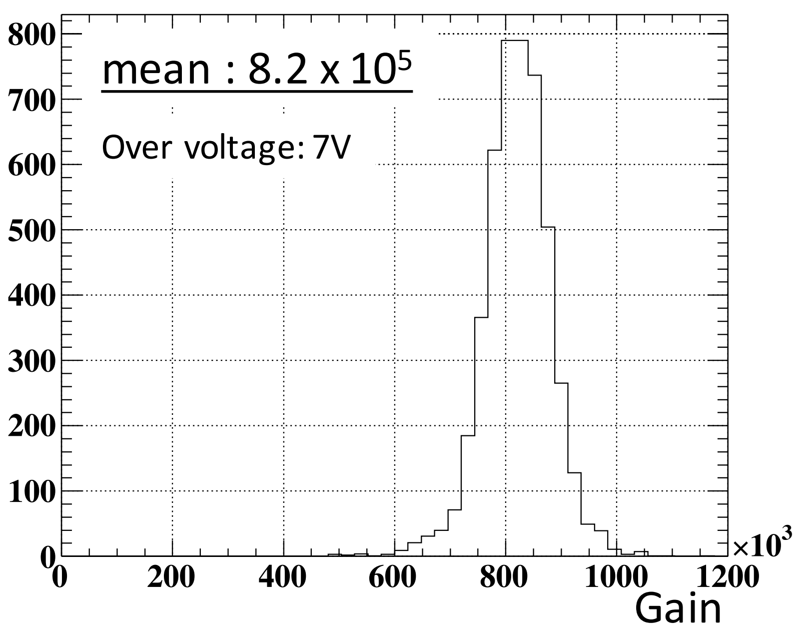
LXe Light yield



MPPC calibration

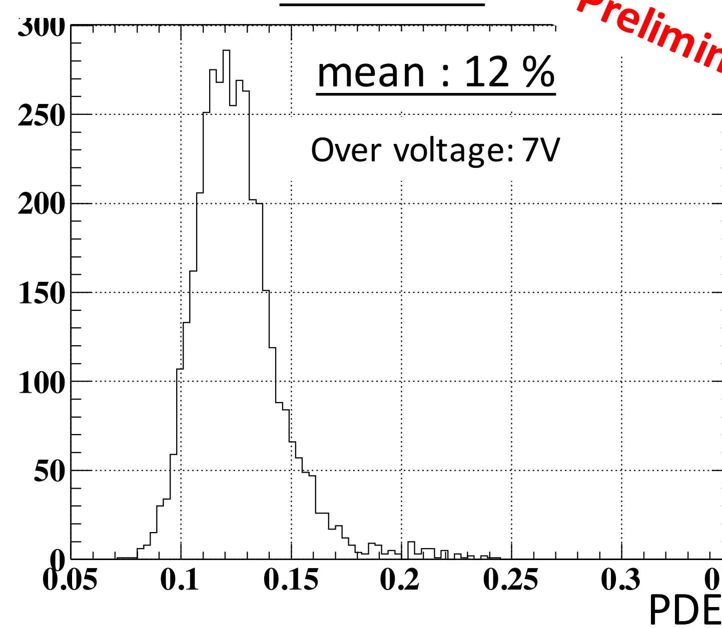
- MPPC gain and PDE has been measured,
  and sufficient performance has been confirmed
  - Gain : Based on 1 p.e. peak from weak LED light
  - PDE : Based on detected number of p.e. from calibration source inside the detector.
    (LXe scintillation light from ^{241}Am)
- Stability of those performance has been confirmed for a month.

MPPC Gain



MPPC PDE

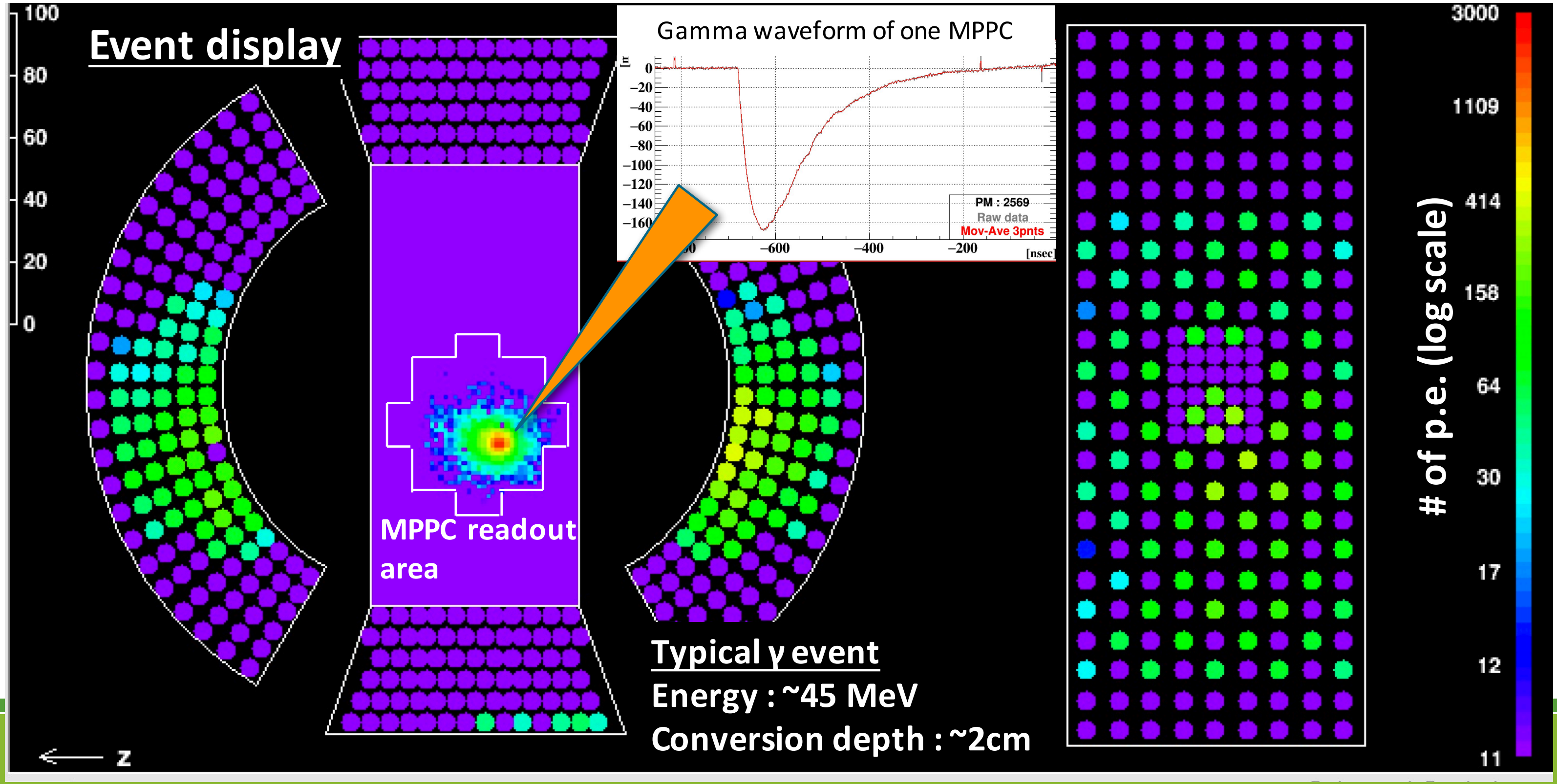
Preliminary



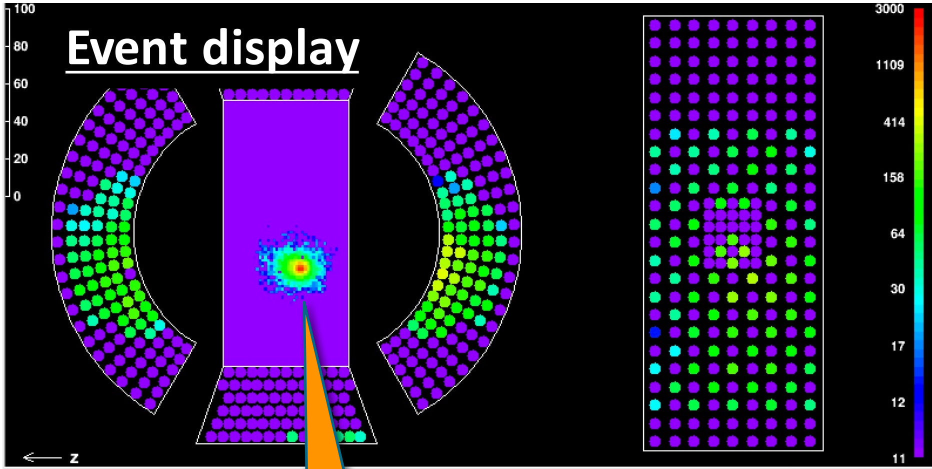
Pilot run with muon beam

Gamma-ray data taking was successfully performed.

- Gamma-rays (~45 MeV) mainly from radiative muon decay is obtained.
- Triggered on sum of MPPC waveform.
- Use WaveDREAM (electronics developed for MEG II) for readout.
  - Due to the limited number of available ch, only 25% of detector was read out. (960 MPPCs + 192 PMTs)

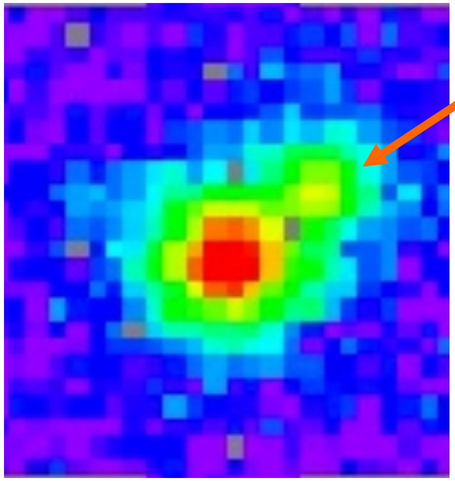


Pilot run with muon beam

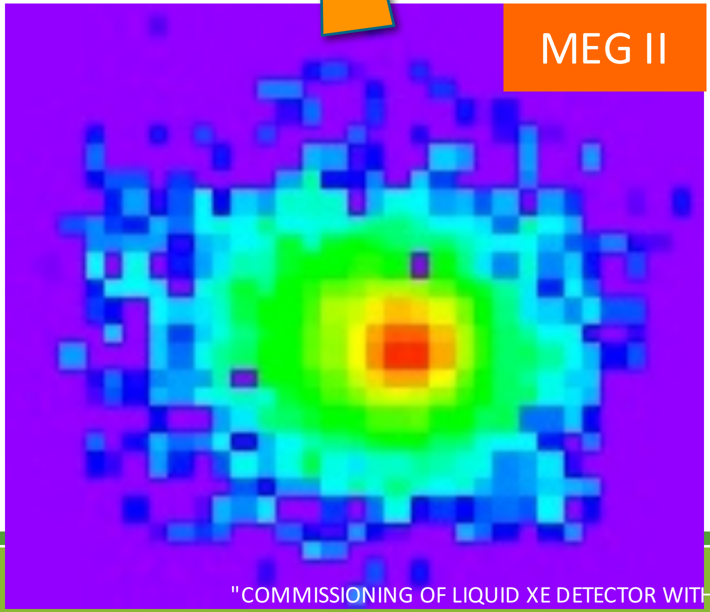


Zoom in

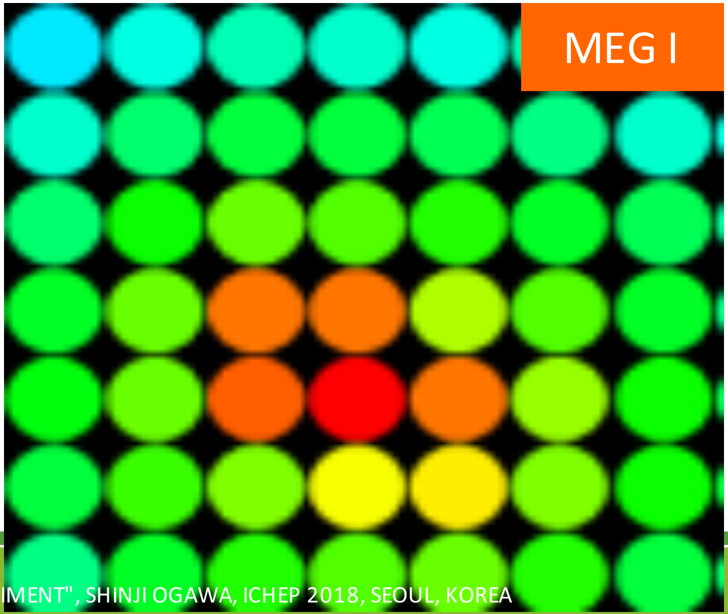
Another event



Pileup γ-ray very close to the main γ can be found.



Granularity improvement by MPPC



Timing resolution

Timing resolution for 50MeV γ-ray has been estimated.

- Gamma hit timing is reconstructed from the timing of waveforms from each photo-sensors.

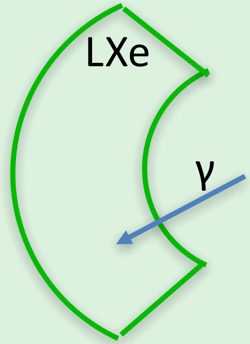
$$\chi^2 = \sum_{MPPC,PMT} \left(\frac{t_{pm} - t_{walk} - t_{prop} - t_{offset} - t_{\gamma}}{\sigma} \right)^2$$

Time info from each MPPC, PMT
Calibration parameters
Gamma hit timing (fitting parameter)

- MPPC waveforms are more sensitive to the noise than PMT.
  - Offline noise reduction has been developed.

- Even-odd resolution is estimated.
- **Obtained 44 ps resolution@ 50MeV γ**
  - Better than MEG II design value. → 15% sensitivity improvement
  - Consistent with MC.

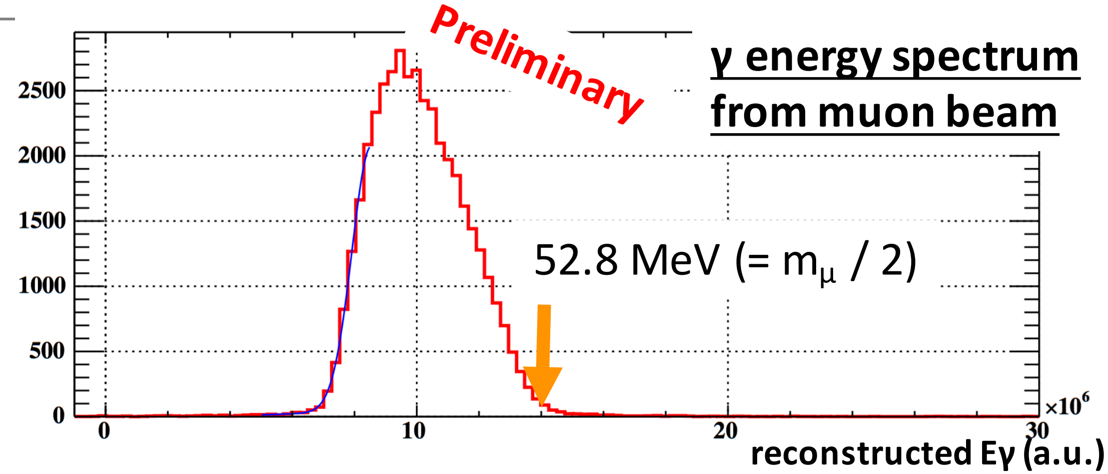
Even-odd resolution



- Reconstruct Tγ from even/odd ch separately.
- $\sigma(T_\gamma) = \sigma(T_{EVEN} - T_{odd})/2$

Energy reconstruction

- Energy spectrum from muon beam was obtained.



- We found it difficult to estimate energy resolution from this data.
  - Limited number of readout channel.
  - Analysis is not yet optimal. (Needs γ-ray calibration source)
  - Low-frequency noise from readout electronics.

- Noise effect is ~ 0.5% of the signal (by reading out 1/4 of whole detector)
  - Looks like due to the coherent noise.

    → Can be **~2%** with whole detector readout.
    Larger than our goal of Eγ resolution (=1%).
- Effort to reduce the noise is ongoing both from hardware and software.

Summary

LXe detector in MEG II

- The MEG II experiment will search for $\mu \rightarrow e\gamma$ decay with the sensitivity of 6×10^{-14}.
- LXe γ-ray detector has been upgraded to significantly improve the resolution by newly developed VUV-MPPCs.

Commissioning of LXe detector

- In 2017, detector commissioning has been started.
- Sufficient performance has been confirmed for most of the MPPCs.
- Gamma-ray near signal energy (50MeV) has been successfully detected.
- Good timing resolution has been achieved by even-odd analysis.

Prospect

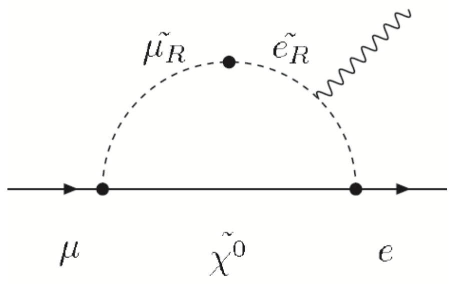
- Position and energy resolution will be measured in 2018, followed by the engineering and physics run of MEG II from 2019.

BACKUP

μ→eγ search

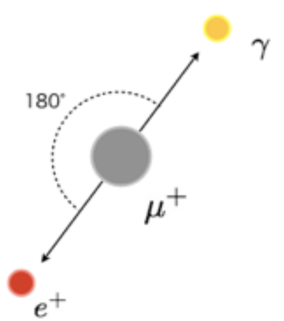
We search for charged lepton flavor violating decay of muon, μ->e+γ.
Prohibited in SM, detectable branching ratio in some BSM model
Main background is the accidental background.

Detector resolutions, **especially energy resolution of γ-ray**, are important to effectively distinguish the signal event from the accidental background



Signal

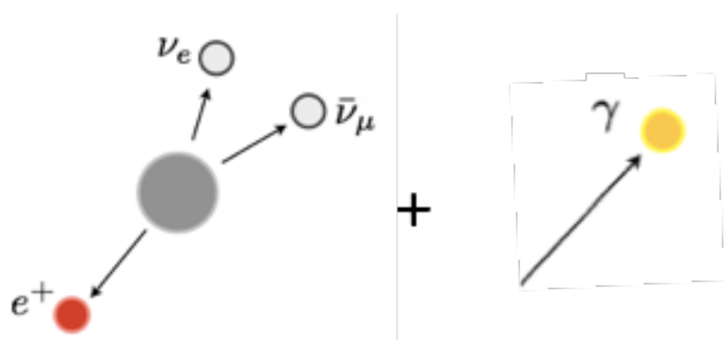
Signal decay



- E=52.8MeV
- back-to-back
- coincident

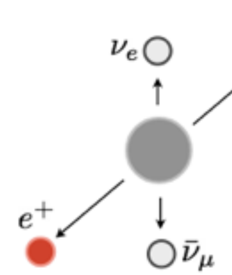
Background

Accidental background



- **Dominant background**
- E < 52.8MeV
- not back-to-back

Radiative muon decay



- E<52.8MeV
- not back-to-back
- coincident

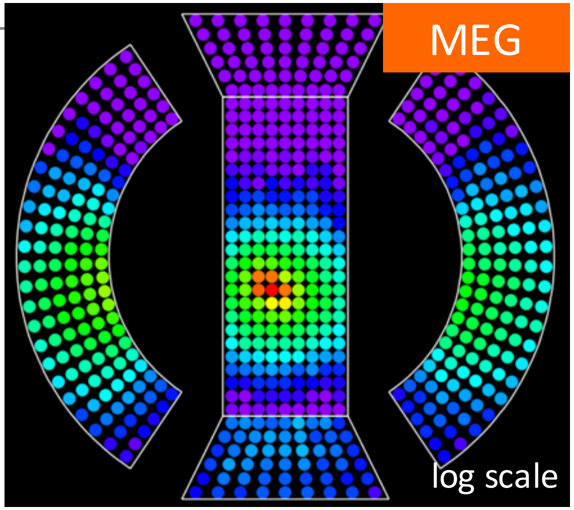
Expected performance

Significant improvement is expected for resolutions and efficiency.

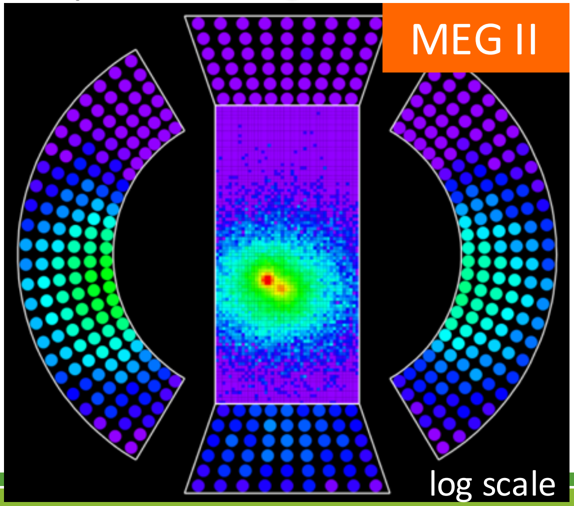
Detector performance for signal γ-ray

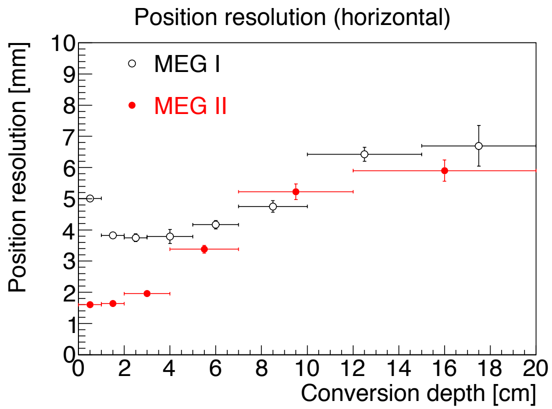
	MEG (measured)	MEG II (simulated)
σ (position)	~5 mm	~2.5 mm
σ (energy)	~2%	0.7 - 1.5%
σ (timing)	67 ps	50 - 70 ps
Efficiency	65%	70%

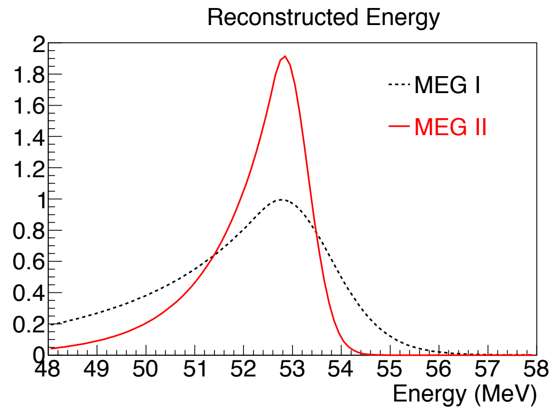
improve by a factor of **2**!



Imaging power improves





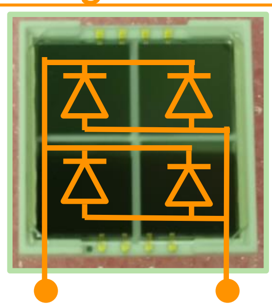


Performance test of our MPPC

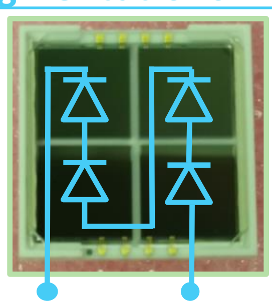
We have tested MPPC in LXe, and **an excellent performance has been confirmed.**

- **Sufficiently short timing constant** has been achieved by series connection.
- **Single p.e. peak is clearly resolved** for large sensitive area.
- Gain: 8.0×10^5 (@ Vover=7V, series connection)
- Low crosstalk & after pulse probability (~15% each @ Vover = 7V)

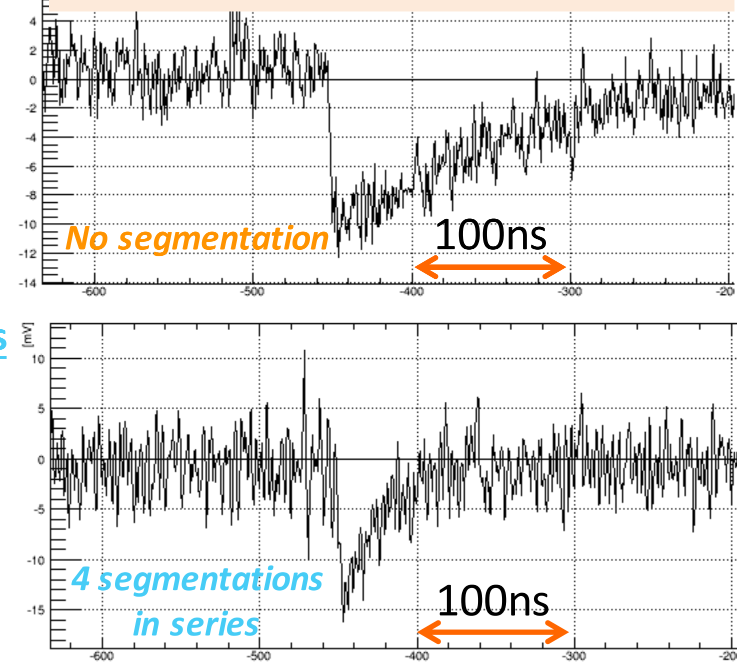
No segmentation



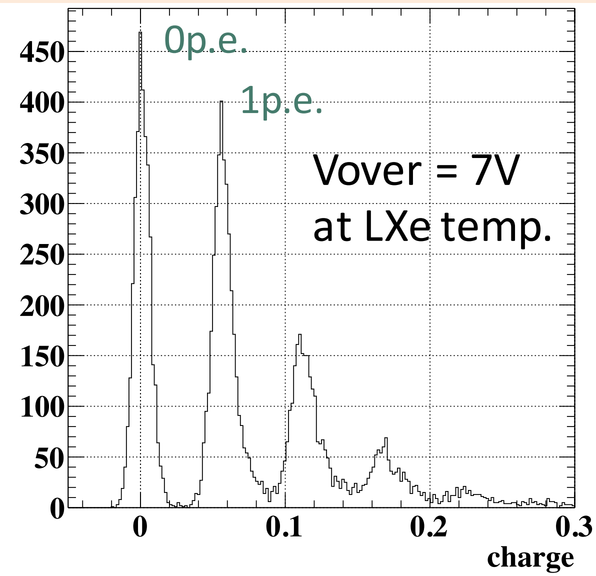
4 segmentations in series



Measured waveform

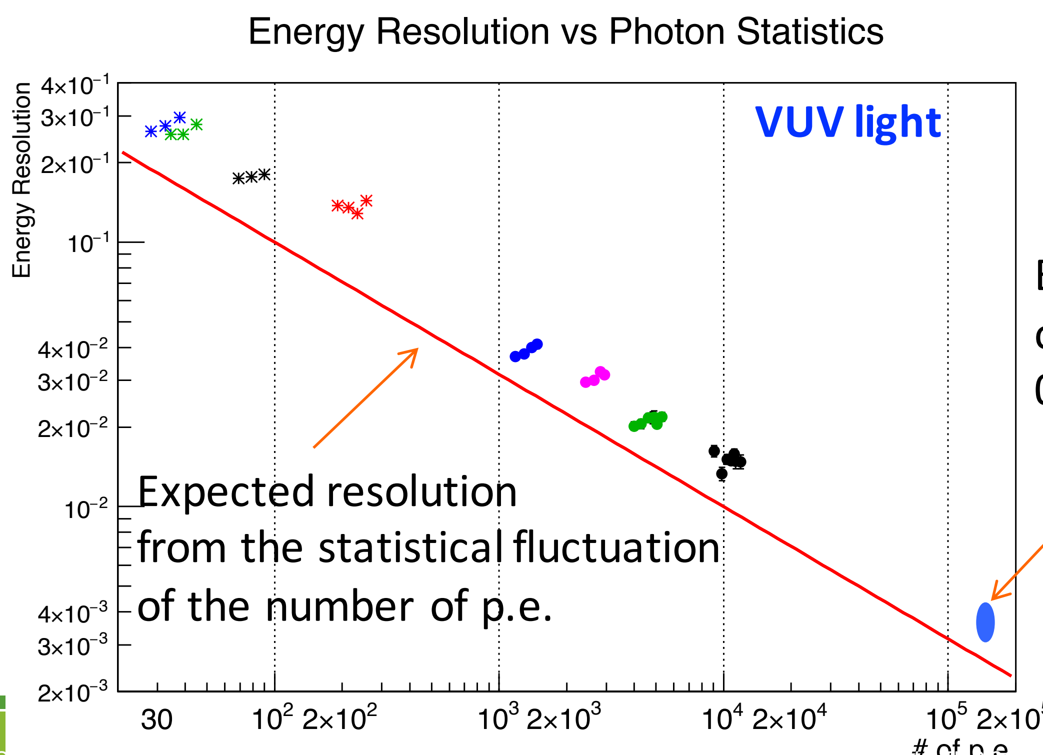


Charge distribution using LED



Energy resolution

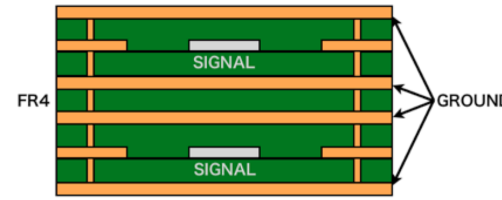
- Energy resolution for VUV light has been measured as a function of # of p.e
  - using a scintillation light from α source.
  - by changing geometrical acceptance with several setups.
- Energy resolution improves as $1/\sqrt{(\#\text{ of p.e.})}$
  - at least down to ~10^4 p.e.
  - excess noise factor: 1.2 - 1.3 (reason has not yet been understood.)



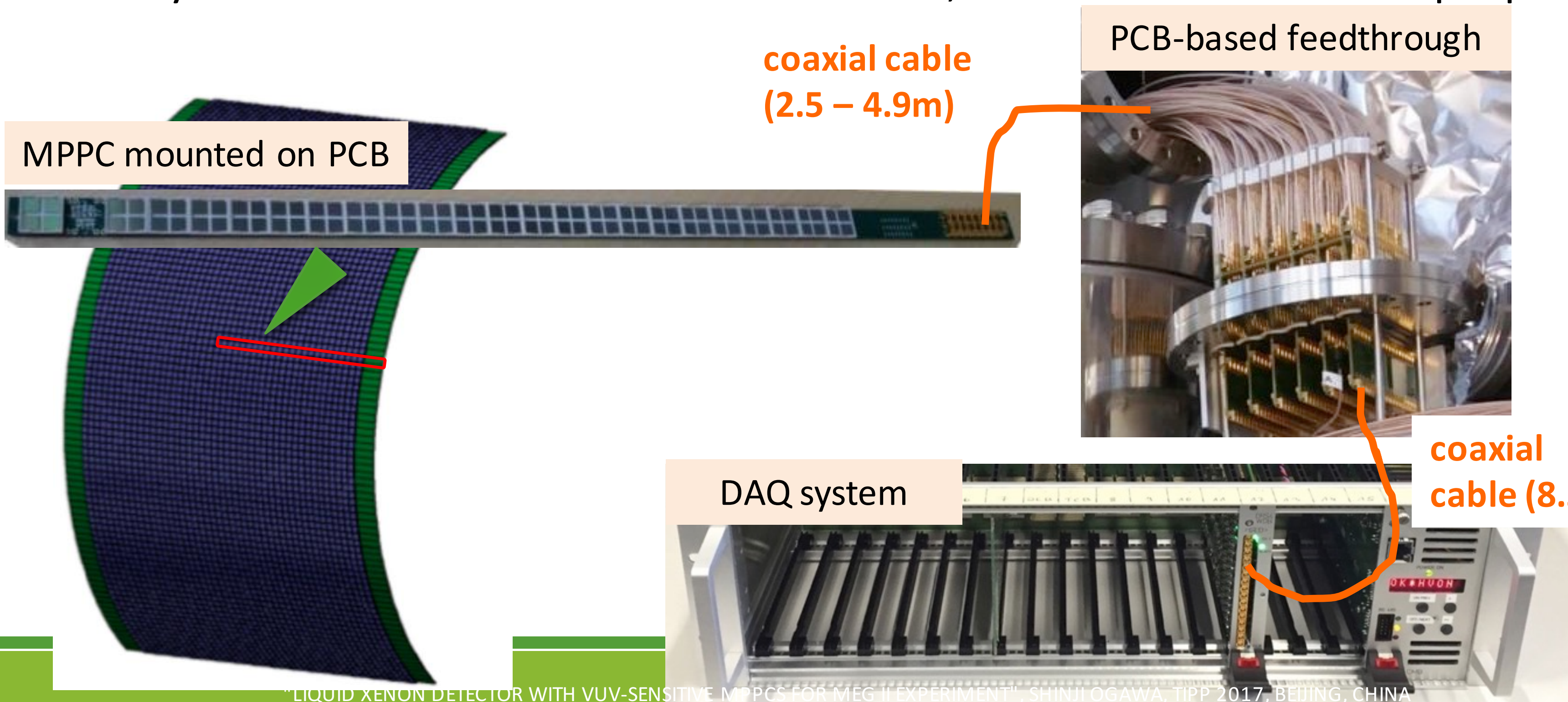
Expected statistical term of our final detector 0.3 - 0.4%

Signal transmission system

“Coaxial-like structure” PCB

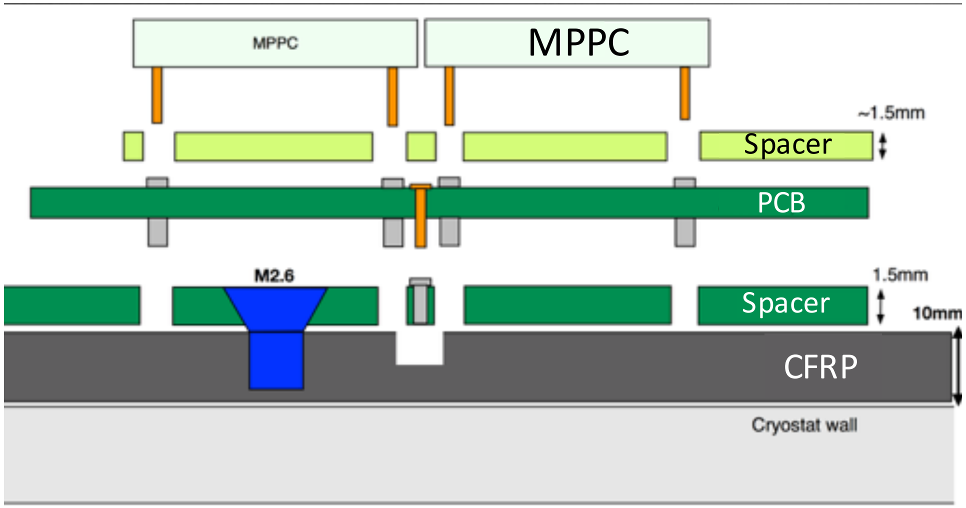


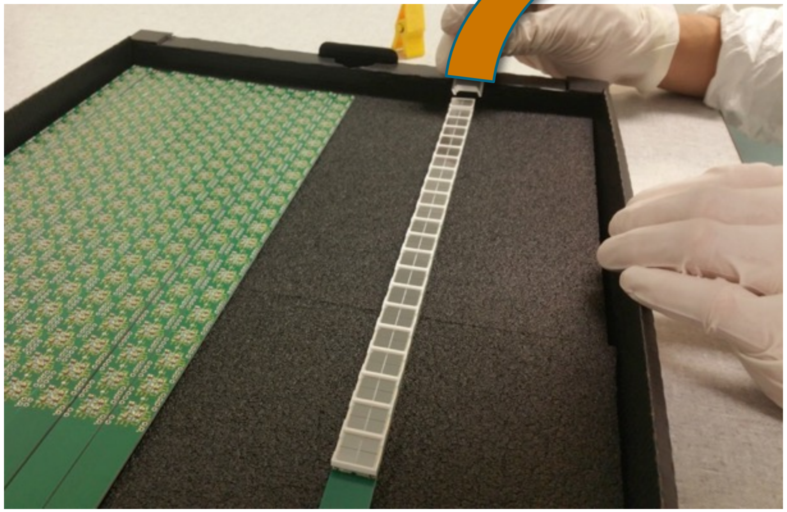
- We have developed signal transmission system.
  - It can transmit ~5000 ch signals.
  - Long cable (~12m) before signal amplification.
  - PCB has coaxial-like structure for impedance matching (50Ω), good shielding from external noise, high bandwidth, and low crosstalk.
  - Feedthrough is based on PCB to realize high density transmission.
- This system has been tested in LXe for 600 ch, and confirmed to work properly.

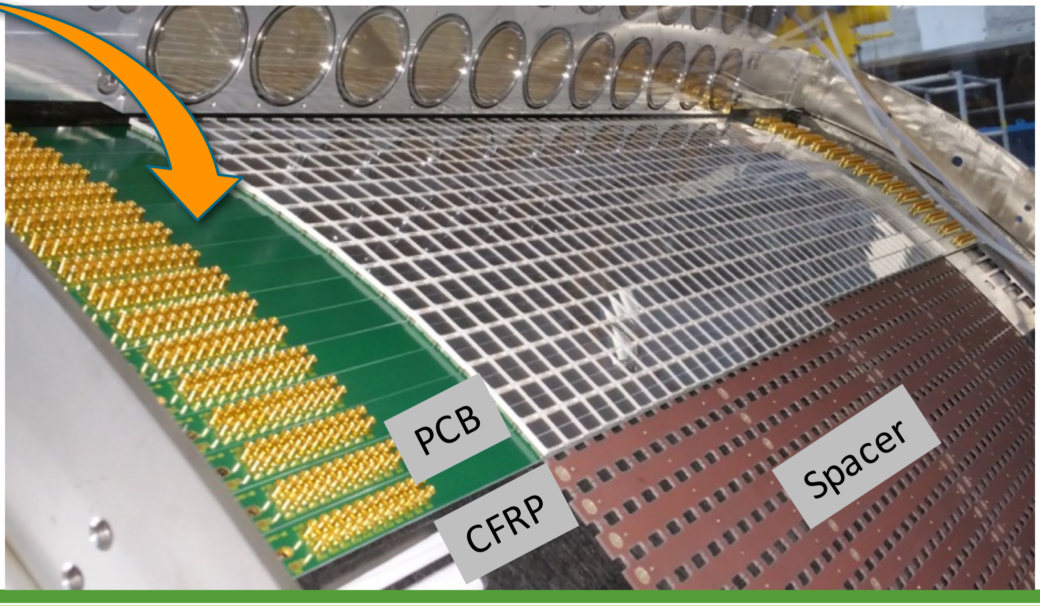


MPPC installation to the cryostat

- MPPCs are mounted on PCBs.
  - for signal readout and alignment.
  - PCBs are fixed on CFRP support structure which is attached on cryostat.
- These support are designed to minimize the material.
  - Thin support structure with low mass material
  - Spacers to reduce LXe.





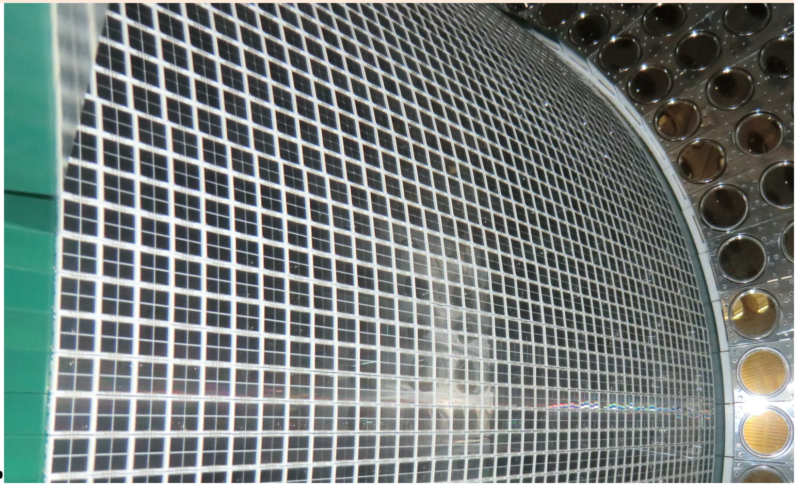


Detector assembly

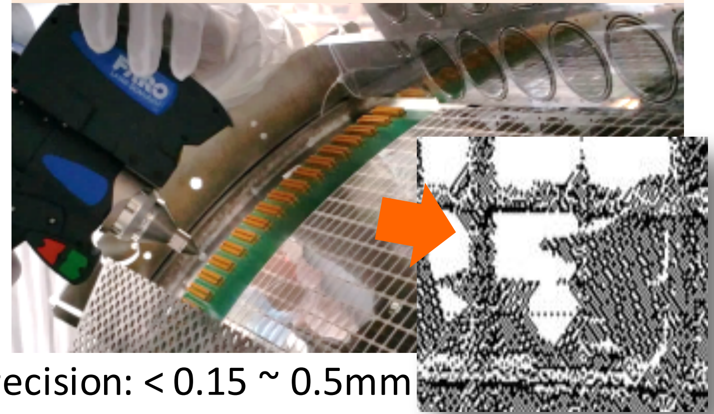
- Detector assembly has been completed.
  - Photo-sensor installation
  - Cabling
  - Connection check for all sensors.
  - Sensor position measurement by 3D Laser scanner (FARO)
  - Calibration source (LED, α source) installation.

→**Detector construction: Finished (Apr.2017).**

Photo-sensor installation

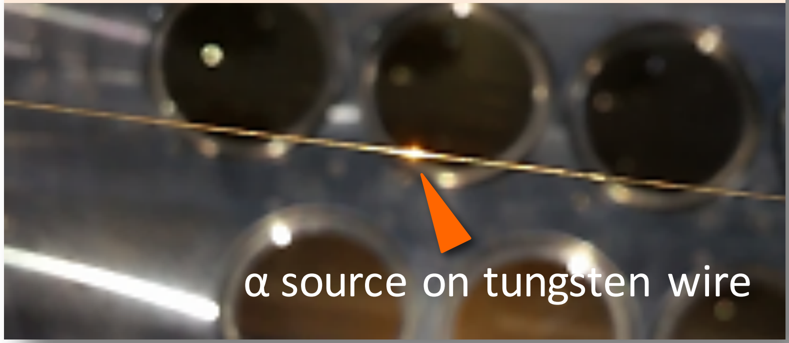


Position measurement by 3D laser scanner



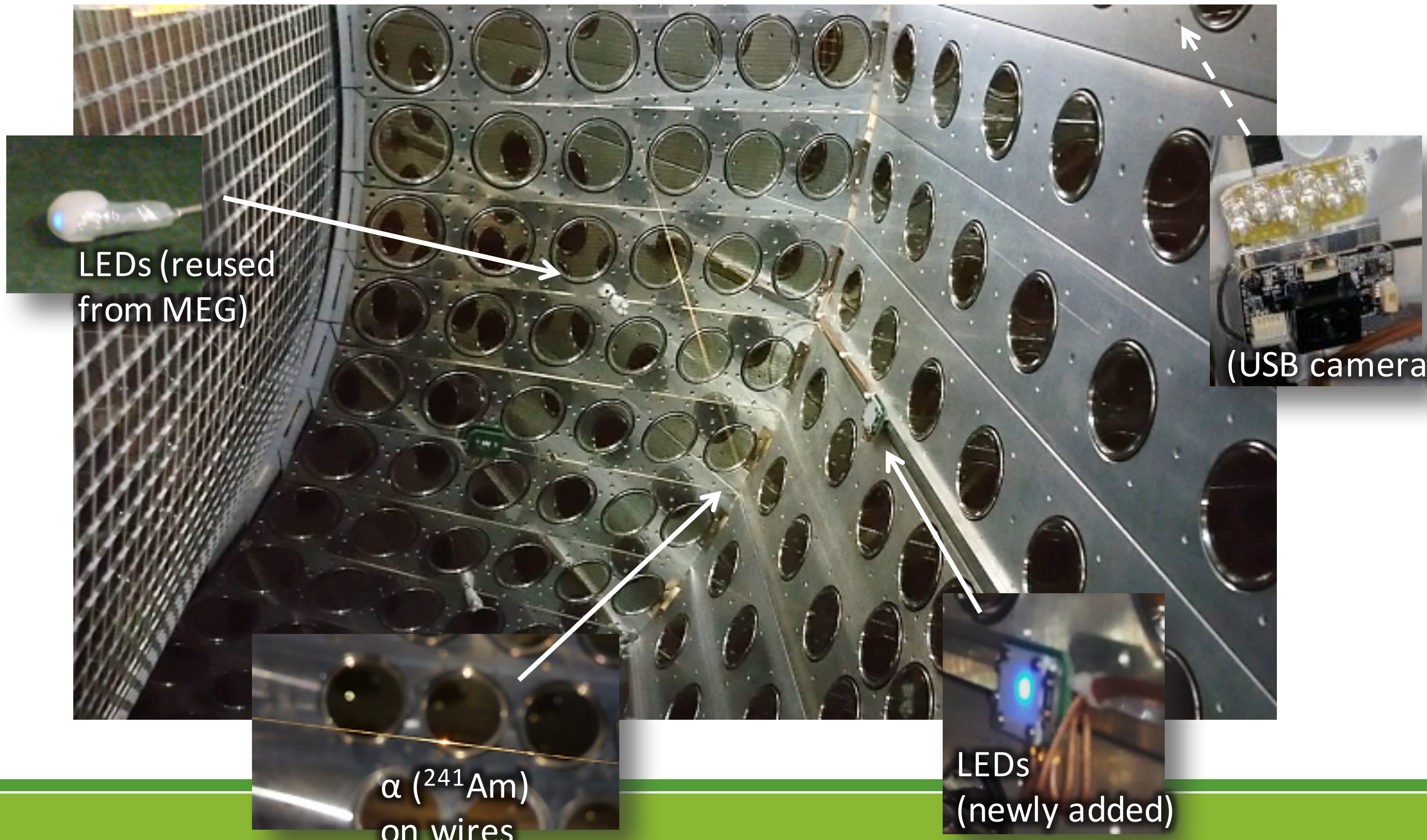
Precision: < 0.15 ~ 0.5mm

Calibration source (α , ^{241}Am)



Calibration & monitoring tools

LEDs and α wires are installed as we did in MEG.
Some LEDs are added for calibration of SiPMs.
(Calibration tools with accelerator are not shown here.)

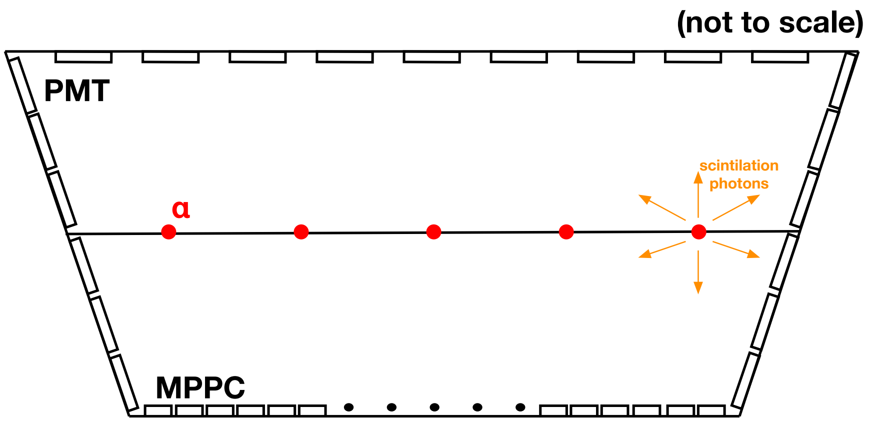


Alpha DAQ

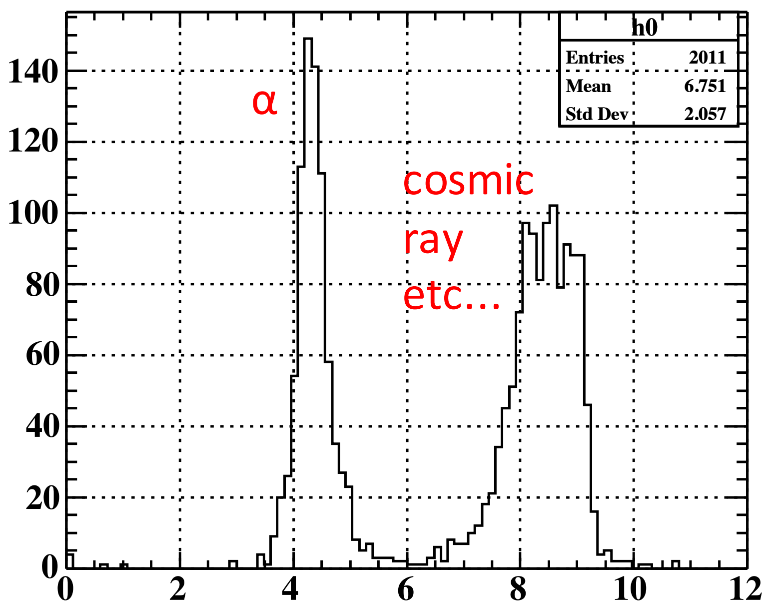
Alpha event trigger by lateral PMT.

Event selection

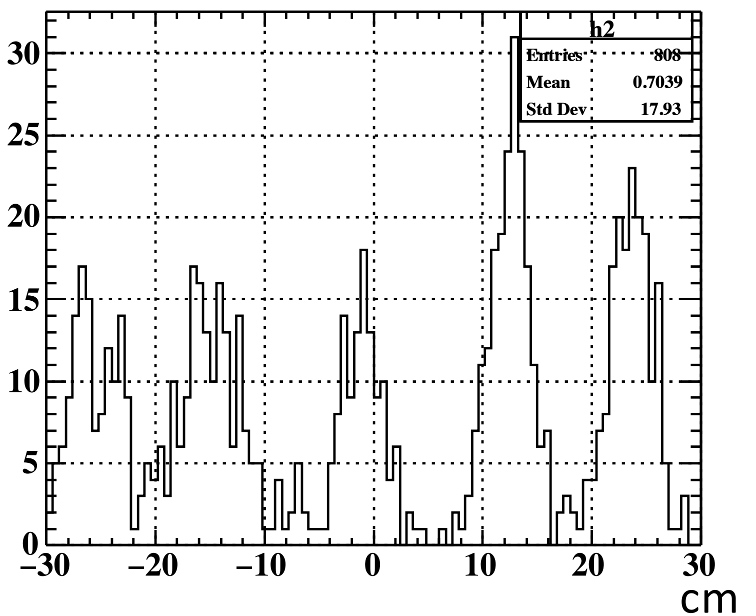
- Separate alpha and others by pulse shape discrimination
- Select events from each alpha source by position reconstruction.



charge / height



Reconstructed position (α event)



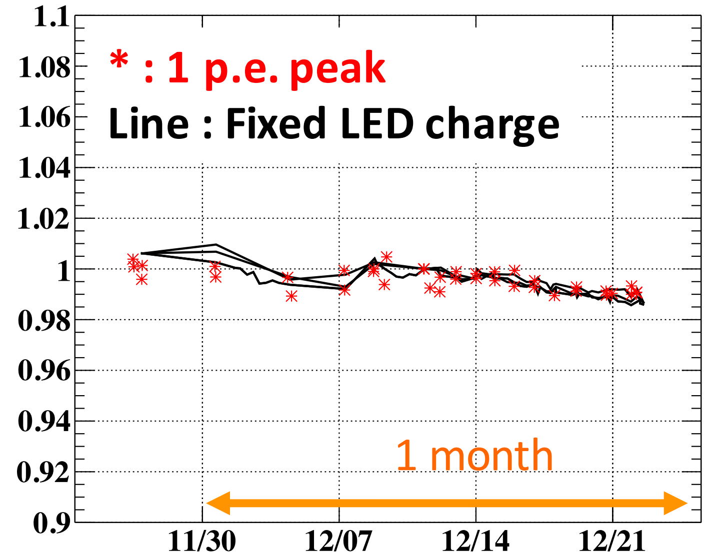
Detector stability

- Detector stability is successfully monitored.
  - MPPC gain, PMT gain, LXe light yield etc...

MPPC Gain

- Monitored by two methods.
  1. By MPPC 1 p.e. charge.
     (Absolute meas. of gain.)
  2. By LED charge at fixed light intensity.
     (Relative meas. of gain change.)
- Gradual change of gain due to LXe temperature, was successfully monitored by both methods.

Gain History (Average of all MPPCs)



PMT Gain

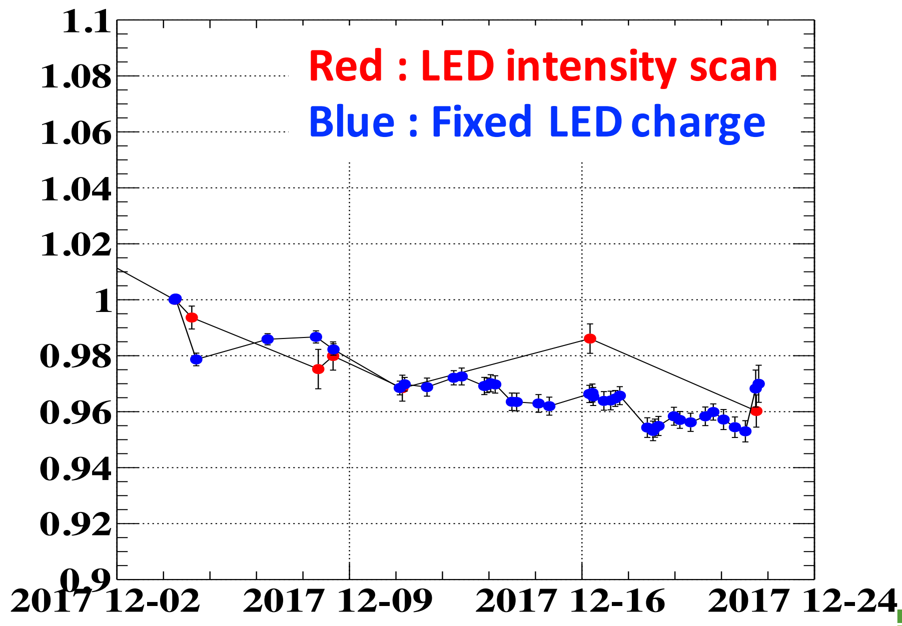
PMT Gain

PMT gain was measured by two independent methods.

1. By LED intensity scan. (Absolute meas. of gain.)
   - Based on Poisson statistics of arrived # of p.e. from LED light.
2. By charge of LED at fixed light intensity. (Relative meas. of gain change.)

Those two methods shows consistent behavior with ~2 % precision.
Gradual decrease of gain is aging of PMT under beam (known from MEG I).

PMT Gain History (All channel average)



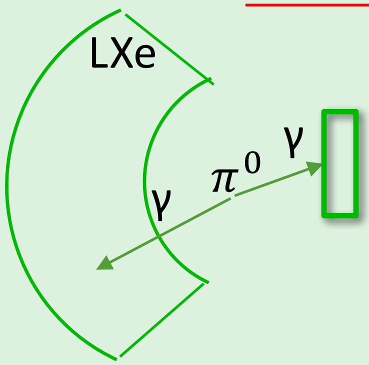
Gamma timing resolution in MEG II

Background

- In the previous MC study,
  MEG II timing resolution can be 40-70 ps depending on the noise level.
- Reference : "Improvement of the event reconstruction method
  for the MEG II liquid xenon detector" at "JPS. 2016年年次大会"

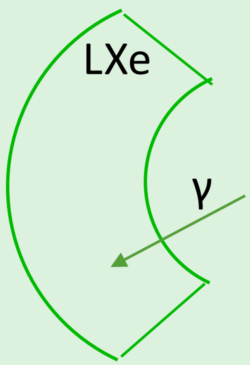
Goal : Check timing resolution in real noise environment.
→Perform even-odd analysis.

Absolute resolution



- Use coincident 2γ & reference counter.
- $\sigma(T_\gamma) = \sigma(T_\gamma - T_{ref}) \ominus \sigma(T_{ref})$

Even-odd resolution



- Reconstruct Tγ from even/odd ch separately.
- $\sigma(T_\gamma) = \sigma(T_{EVEN} - T_{odd})/2$

※"$\sigma_{absolute}(T_\gamma)$" is a part of "$\sigma_{even-odd}(T_\gamma)$".
Difference is "TOF uncertainty of hit position" etc...

How to reconstruct gamma timing

Gamma timing is reconstructed from timing from MPPC & PMT waveforms.

- Timing extraction by waveform analysis
  + χ^2 min fit of time information from all ch.

Waveform Analysis

Noise subtraction

↓

Timing extraction

↓

Timing reconstruction

Apply time calibration

↓

χ^2 minimization fit

Robust analysis to high-frequency noise

- Optimal threshold for timing extraction.
- Subtraction of noise coming from system clocks.
- Application of low-pass filter.

χ^2 minimization fit of all ch time information

$$\chi^2 = \sum_{MPPC,PMT} \left(\frac{t_{pm} - t_{walk} - t_{prop} - t_{offset} - t_{\gamma}}{\sigma} \right)^2$$

Time info from each MPPC, PMT with time calibration

Gamma hit timing (fitting parameter)

Calibration parameters : extracted from data

- Time walk
- Propagation time of scintillation light.
- Time offset of each channel