ZDC ECAL for ePIC Experiment

TIDC 2026 @ 台中, 台灣

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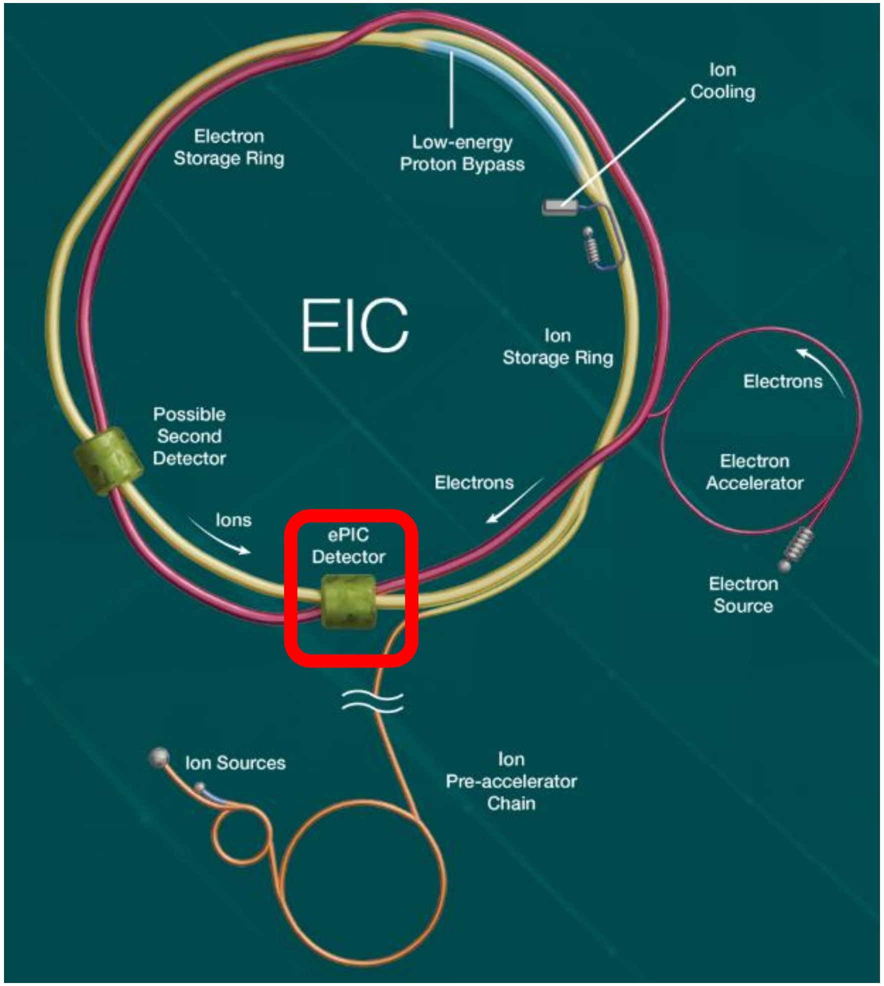
on behalf of the ZDC ECal Taiwan Group

ePIC Experiment @ BNL



Electron-Ion Collider (EIC)
@ Brookhaven National Laboratory (BNL)

- **Collaboration**

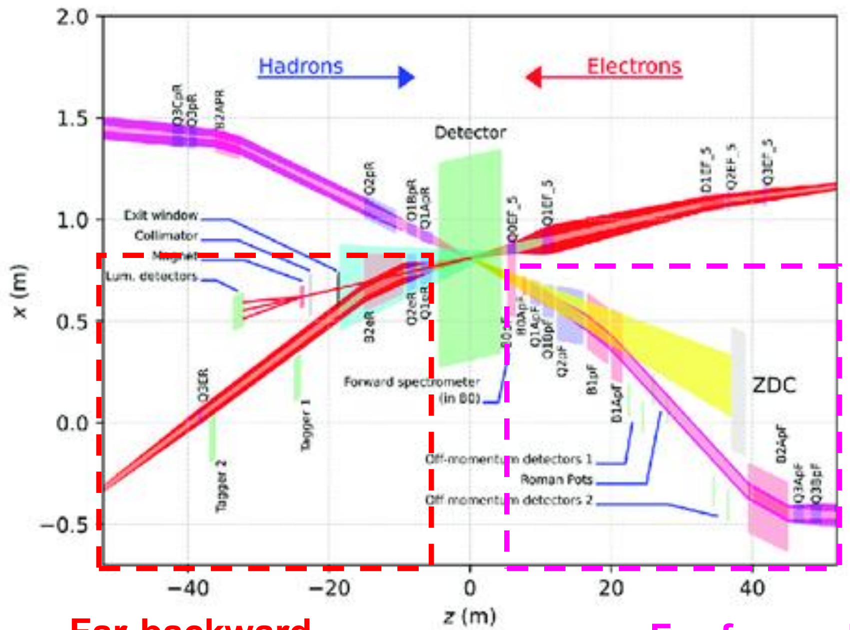
~500 scientists, 171 institutions, 26 countries

- **Physics Goals**
- **3D structure of protons and nuclei.**
- **proton spin puzzle (polarized beam)**
- **nuclear interaction in nuclei**

- **Beam**
- **Electrons**: 5 – 18 GeV,
  Luminosity ~ $10^{33-34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (polarized)
- **Protons**: up to 275 GeV,
  Luminosity ~ $10^{33-34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (polarized)
- **Heavy ions (e.g. Au, Pb)** : up to 100 GeV

- **Timeline**
- **current : detector R&D**
- 2028-2030 : detector commission
- **Early 2030s : 1st physics run**

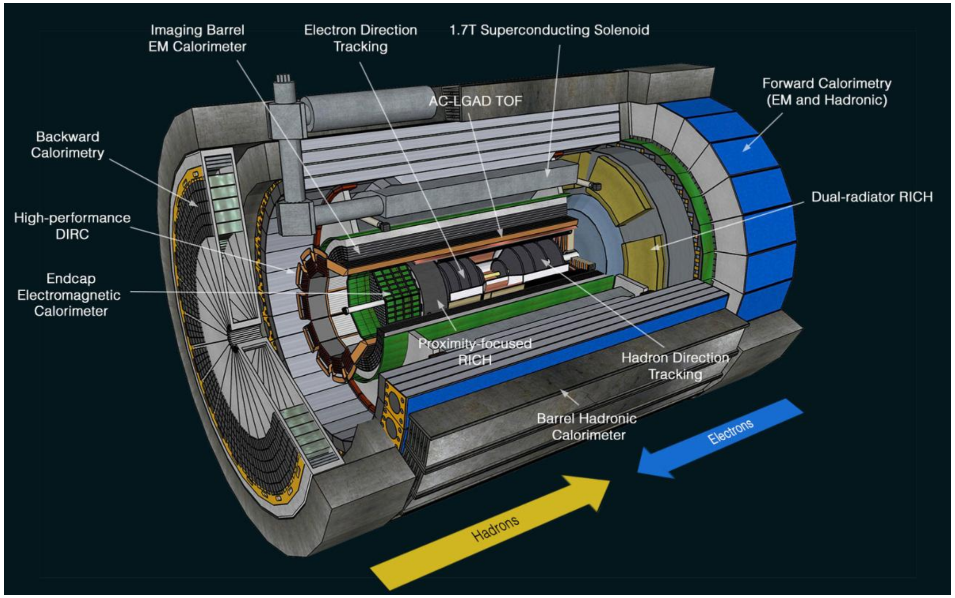
ePIC Detectors



Far-backward detector

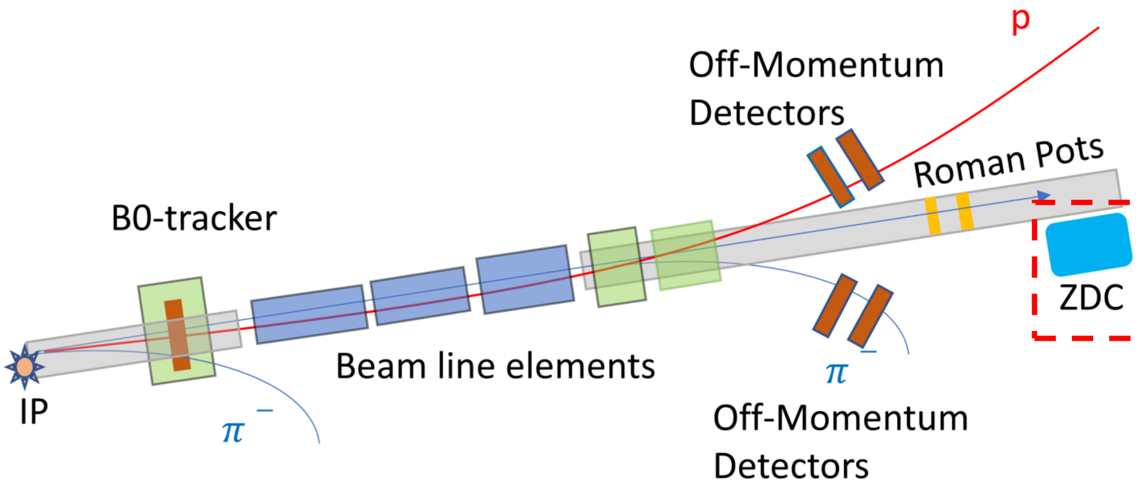
Main detector

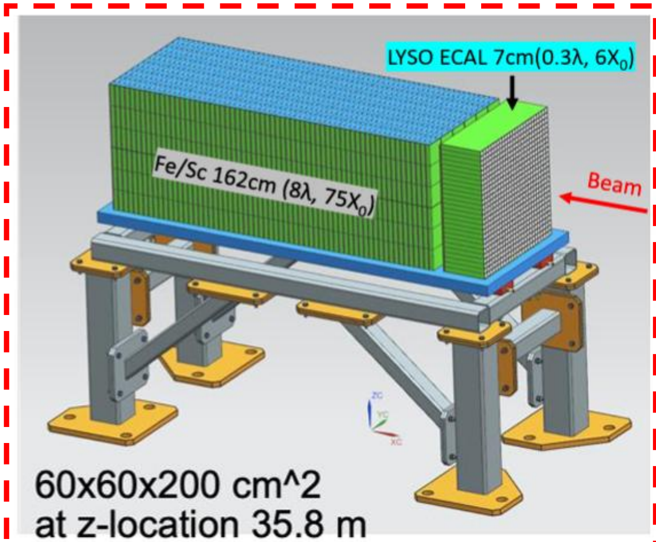
Far-forward detector



- **EIC Detector System**
  - **Main detectors :** Tracks electrons and hadrons, PID, vertexing.
  - **Far-forward**: Detects protons, neutrons, fragments.
  - **Far-backward:** Detects low-angle scattered electrons. Monitoring luminosity.

Zero Degree Calorimeter (ZDC) in Far-forward Detectors



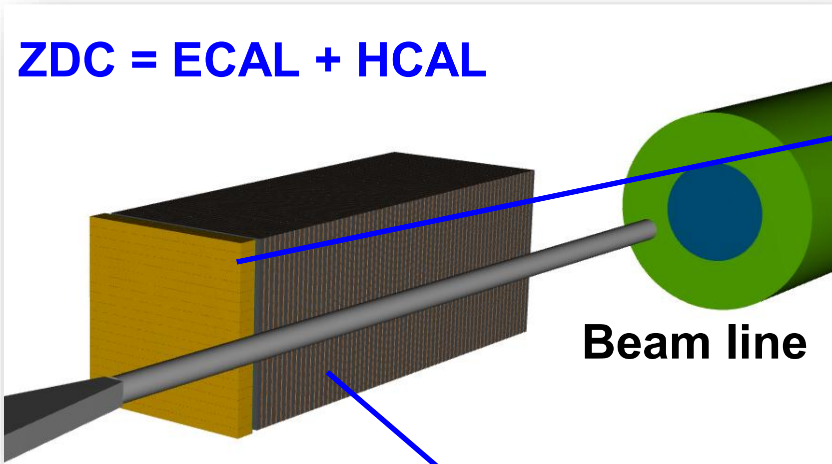


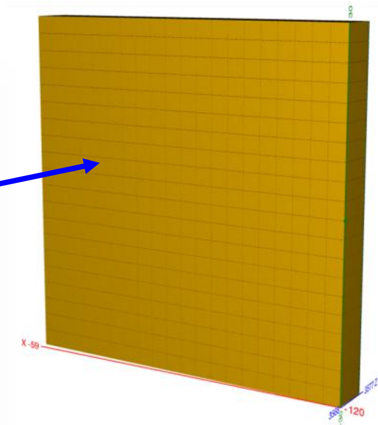
- **Physics for Far-forward detectors**
- **Sullivan process for pion structure** : $e+p \rightarrow e'+X+\boldsymbol{n}$
- **Sullivan process for kaon structure** : $e+p \rightarrow e'+X+\Lambda$ and $\boldsymbol{\Lambda} \rightarrow \boldsymbol{n}+\boldsymbol{\pi}^{\mathbf{0}} \rightarrow \boldsymbol{n}+\mathbf{2}\boldsymbol{\gamma}$
- **Spectator-neutron tagging for nuclear physics** : $(1) e+d \rightarrow e'+X+n$ $(2)\, e+A \rightarrow e'+X+(A-1)+n$
- **Background**, secondary photons showers : $\pi^0 \rightarrow \gamma\gamma$

⇒ **Neutron and gamma detection.**

- **Far-forward detectors**
- **B0 tacker** – Detects small-angle charged particles for exclusive reactions.
- **Off-Momentum Detectors** – Tag decay products and spectator fragments.
- **Roman Pots** – Measure forward protons to study exclusive processes.
- **ZDC – tagging photon and neutron with good energy and angular/position resolution.**

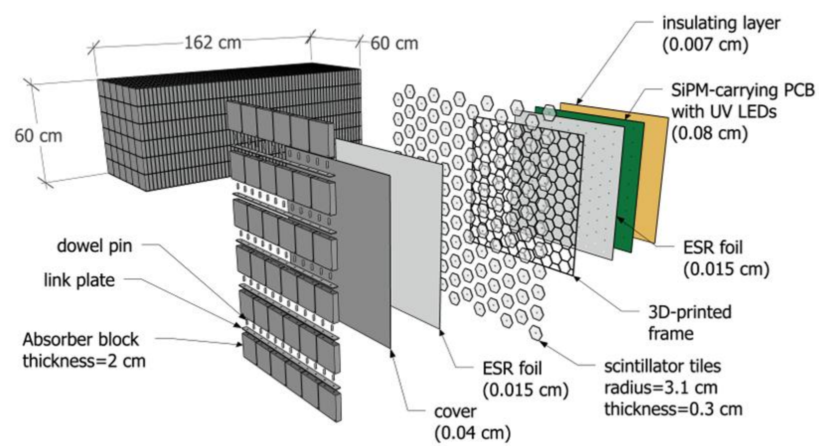
ZDC Design





ECAL

1. **LYSO Crystal**
2. 20*20 cells
3. 3cm*3cm*7cm / cell
4. 60cm*60cm
5. **7cm ~ 6.5X0 in Z**



- **ECAL**
  - crystal calorimeter
  - provide **good energy resolution**
  - Development is leaded by **Taiwan group**

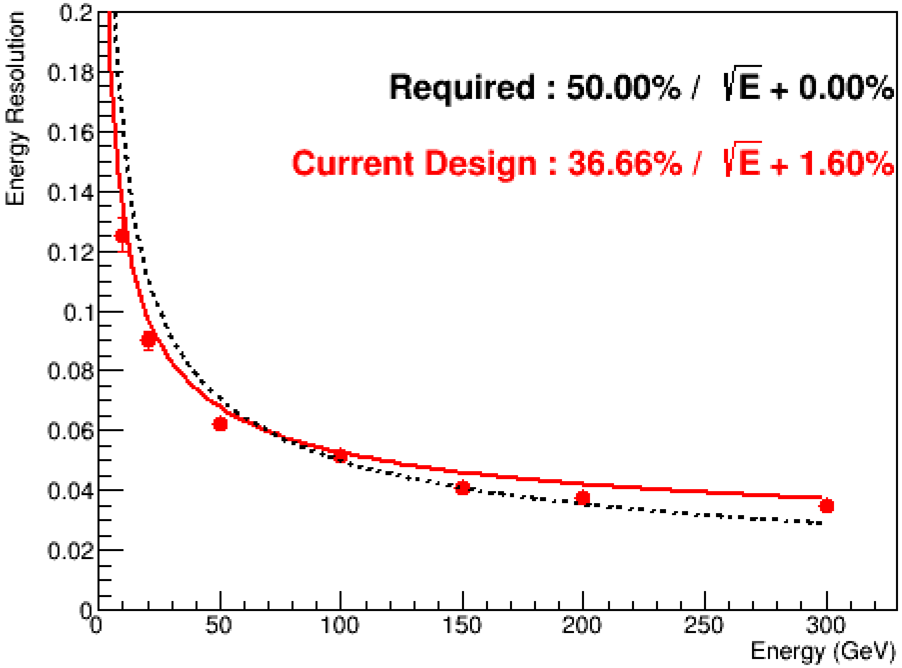
- **HCAL**
  - Sampling calorimeter
  - provide **good position resolution**
  - Developed by **UC riverside**

HCAL : sampling calorimeter

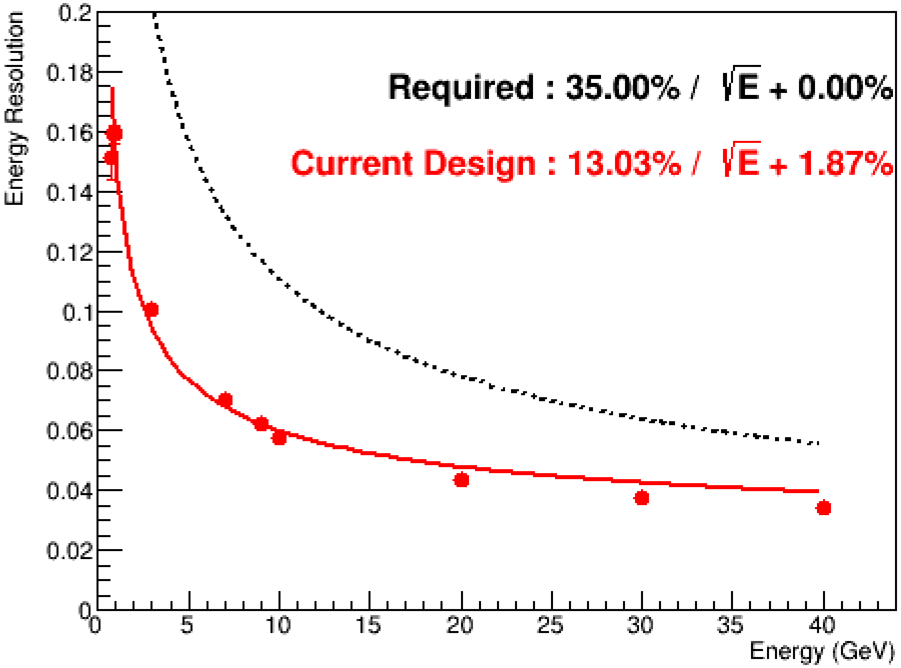
1. **1 layer = steel + scintillator tile + SiPM**
2. 64 layers, 8 slice/layer
3. 65cm in X, 60cm in Y, 163cm in Z

ZDC Performance from MC Simulation

Energy resolution : 10-300GeV neutron



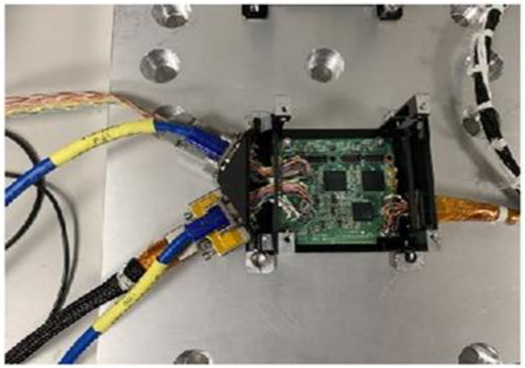
Energy resolution : 10-40GeV gamma

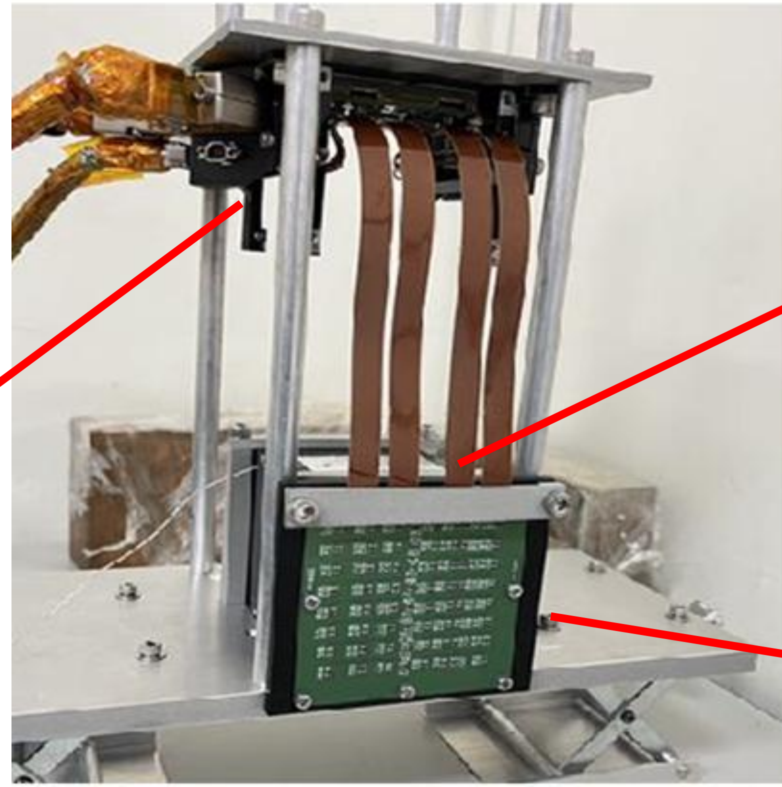


The design in MC fit the requirement given on yellow report published on 2021.

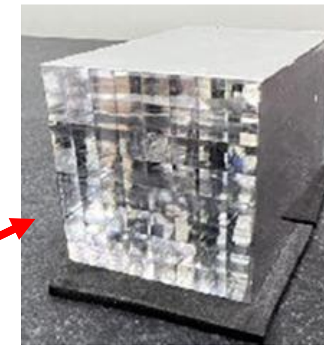
1st Prototype of ZDC ECAL

CITIROC (160-400pC)

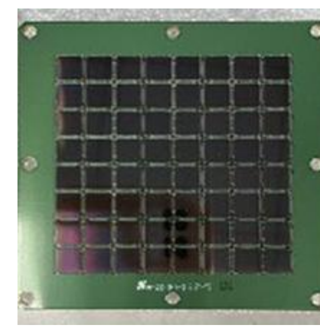




LYSO crystal (8x8 , 8X0, ESR)

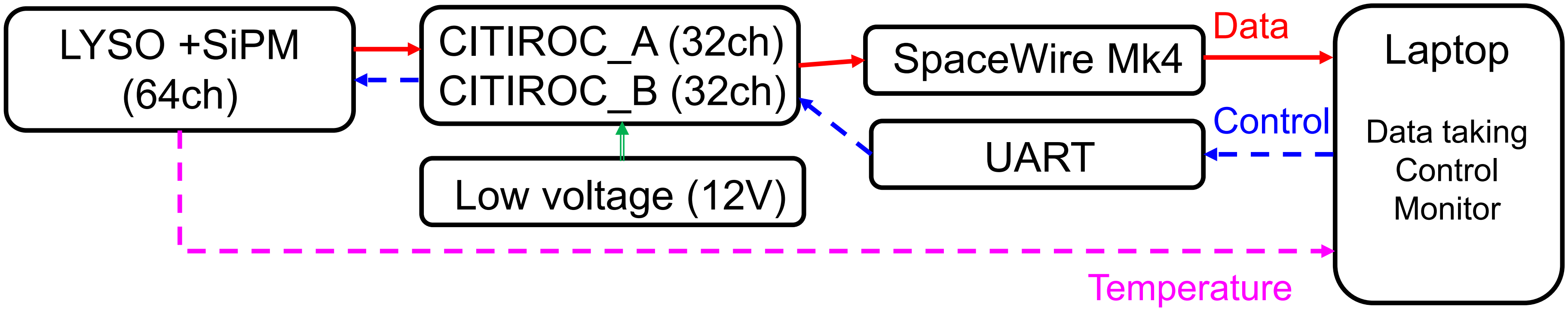


Onsemi SiPM



	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	Sensor /crystal	
1st prototype 2023-2024	**LYSO + SiPM**	LYSO	0.7cm*0.7cm	**8cm (8X0)**	8x8	SiPM Onsemi MICROFC-60035	1	CITIROC

CITIROC DAQ



- **CITIROC** is a 32-channel front-end ASIC designed to readout silicon photo-multipliers.
- **Dynamic range up to 400pC**
- **Shaper**
- **Peak Sensenig ADC**

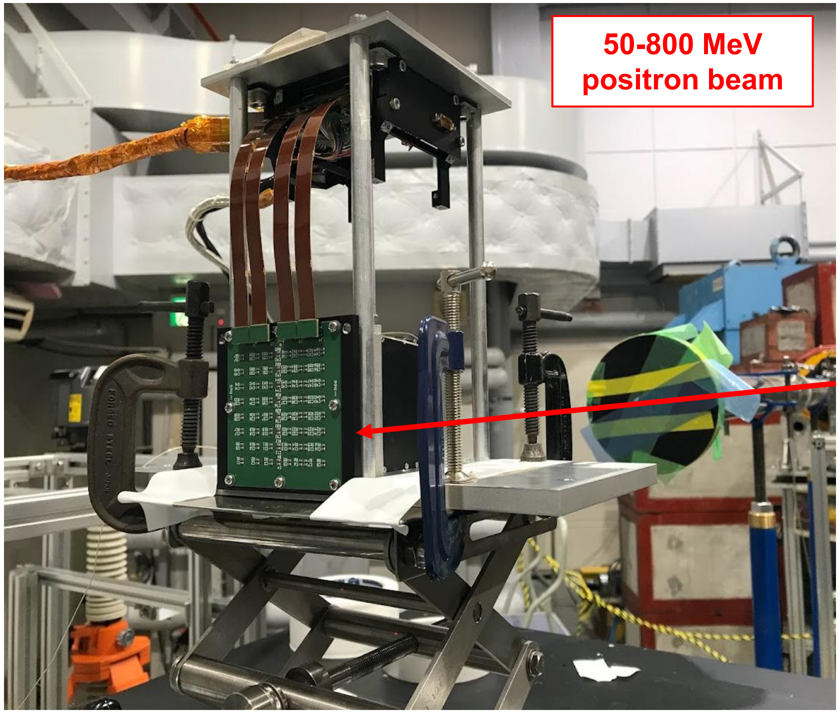
- **Data, slow control** (threshold, gain, etc setup), **online monitoring (**DAQ deadtime, temperature) are all through laptop interface.

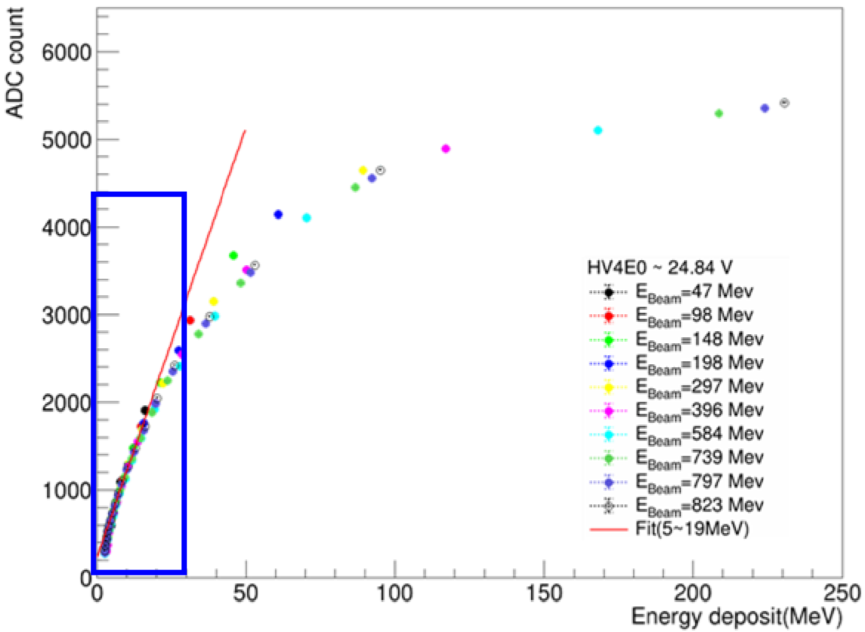
- More details concerning **DAQ will be introduced by the talk given by Kai-Yu later.**

CITIROC spec.

- **TRL Technology Readiness Level**: 8 – Full system using ASIC running – learn more
- **Detector Read-Out**: SiPM, SiPM array
- **Number of Channel**: 32
- **Signal Polarity**: Positive
- **Self-Triggers**: Programmable 10-bit DAC with min threshold = 1/3 p.e.
- **OR trigger**: for timestamping and start of conversion
- **Dynamic Range**: 0-400 pC i.e. 2500 photoelectrons @ 10^6 SiPM gain
- **High and low gain branches,** with 1:10 ratio for a total 0.95-600 amplification range
- 8-bit input DAC for channel-by-channel **fine bias adjustment**
- **Slow shaper** with adjustable shaping time from 12.5 to 87.5 ns
- Energy measurements by Track&Hold or Peak Detector
- 1% linearity energy measurements up to 2500 p.e.
- **Power consumption**: 7 mW/channel

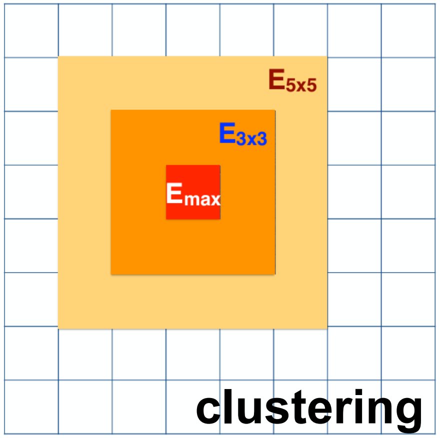
1st Prototype : SiPM Saturation



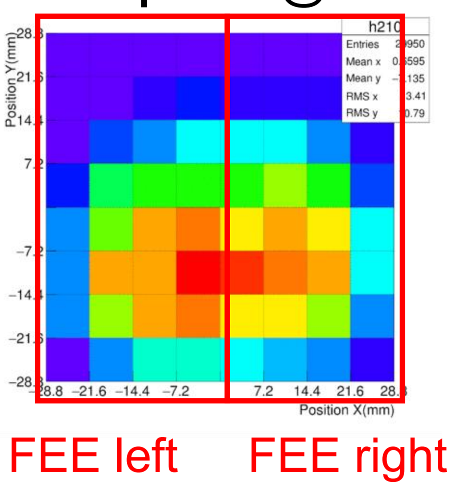


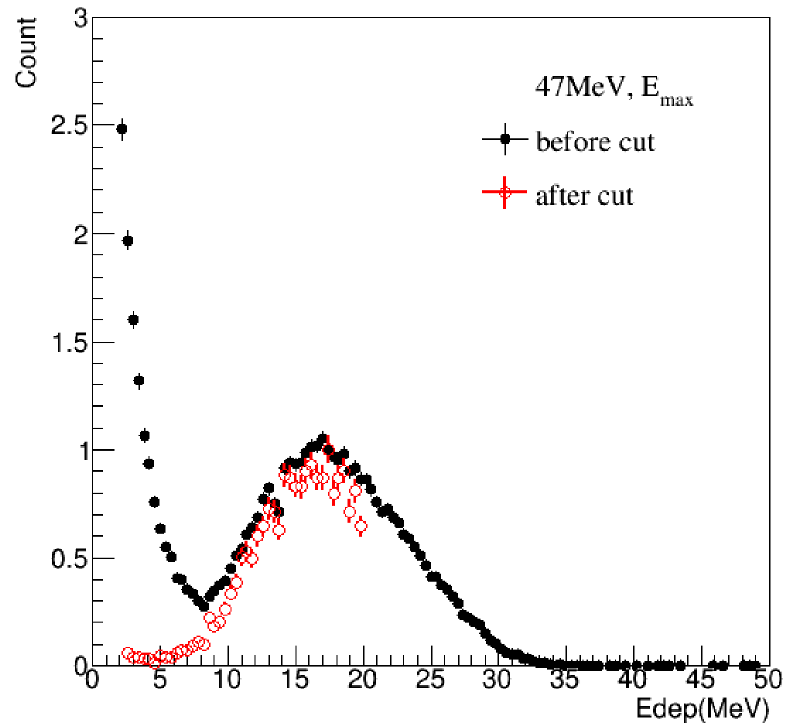
- We had test beam at RARiS on 2024 Feb with 2nd prototype system, using **50MeV - 800MeV positron beam.**
- **Non-linearity** becomes apparent above 20 MeV, with most data points lying in the non-linear region, and **only the 47 MeV data set retaining about 60% of events within the linear range.**

1st Prototype : Selection Criteria



Beam profile @ 47MeV

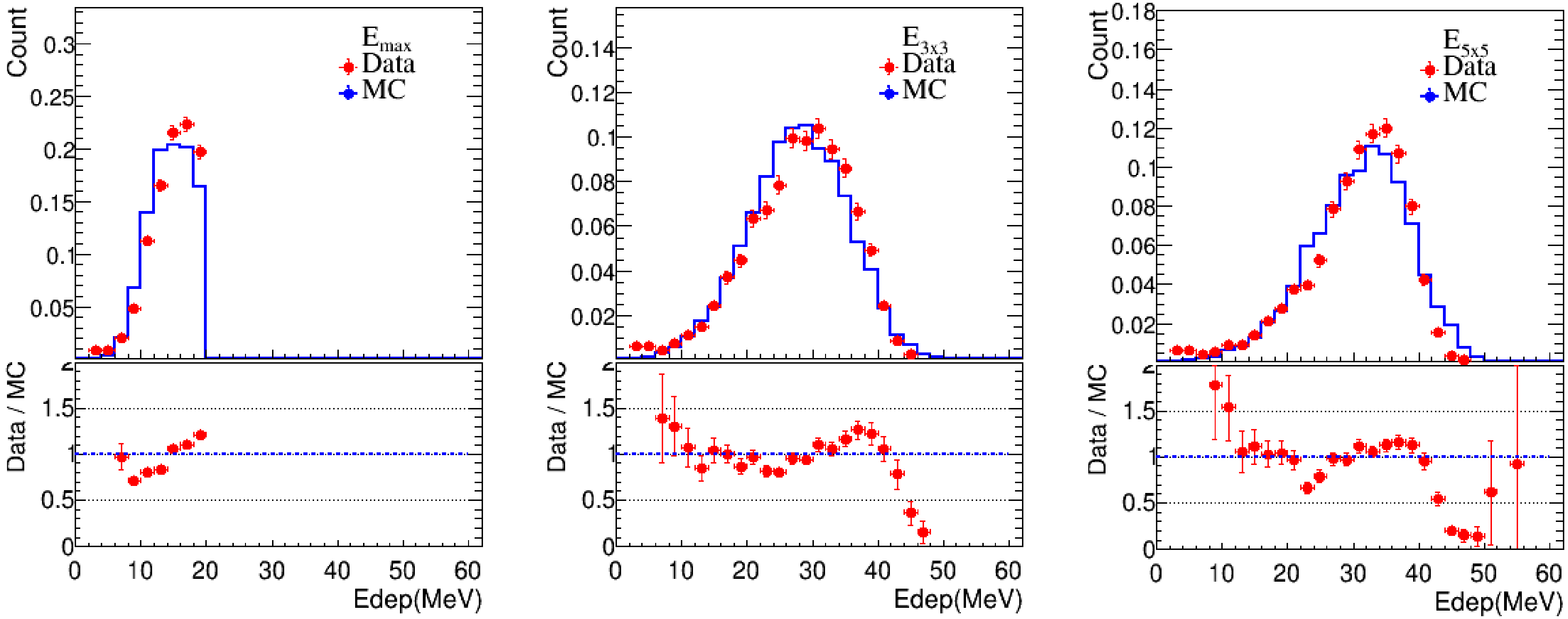




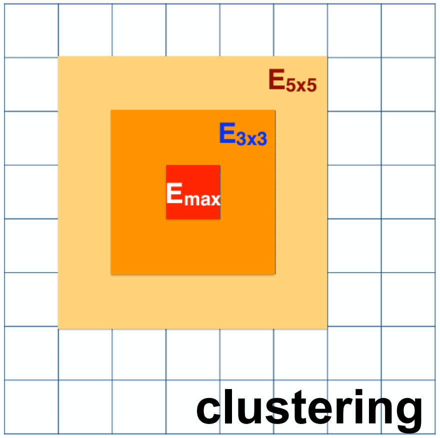
Cut Criteria

1. **2.5 MeV < E_{max} < 20 MeV**
   - Selects data within the linear response range.
   - Removes low-momentum photons originating from the beam.
2. **Both Left and Right Crystals Fired**
   - Requires hits in both FEE-left and FEE-right channels.
   - Eliminates events containing only noise.

1st Prototype : Data and MC Comparison

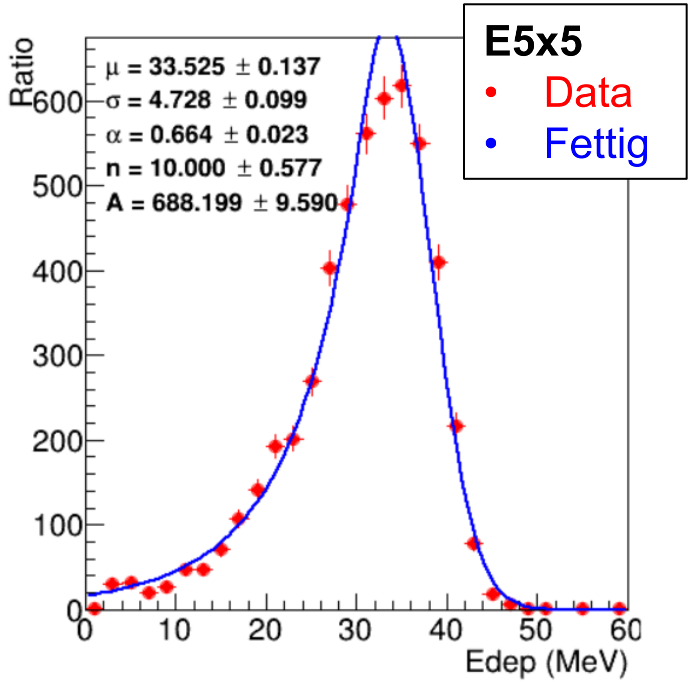


The comparison between data and Monte Carlo (MC) for the 47 MeV positron beam shows **good overall consistency**.



1st Prototype : Energy Resolution w/o Energy Regression

47MeV positron



I (A)	x_{PS} 制限なし		
	μ_P (MeV/c)	σ_P (MeV/c)	σ_P/μ_P (%)
025	47.18(2)	5.48(1)	11.63(3)
050	98.19(4)	4.92(3)	5.01(3)
075	148.22(4)	4.77(2)	3.22(2)
100	197.94(3)	4.91(2)	2.48(1)
125	247.79(3)	5.00(2)	2.02(0)
150	297.30(2)	5.29(2)	1.78(0)
175	346.81(2)	5.31(1)	1.53(0)

Energy resolution of 47MeV momentum resolution = 11.6%

Energy resolution without energy regression is **14% for the 47 MeV beam**. After accounting for the beam momentum resolution provided, **the energy resolution improves to approximately 11%.**

Design of 2^{nd} Prototype

Choice of crystal

Material	Light yield (photons/MeV)	Relative to LYSO
LYSO	~32,000 – 38,000	1.0
$PbWO_4$	~200 – 400	**≈ 1/100 of LYSO**

Choice of sensor

Sensor	Typical Gain	Relative
SiPM	$\sim 10^5 - 10^6$	1.0
APD	$\sim 10^2 - 10^3$	**≈ 1/1000 – 1/10,000 of SiPM**

- **1^{st} prototype @ 2023-2024 : LYSO + SIPM, <u>saturation</u>**
- **2nd prototype @ 2024-2025 : <u>reduce the gain.</u>**

- **LYSO + APD**

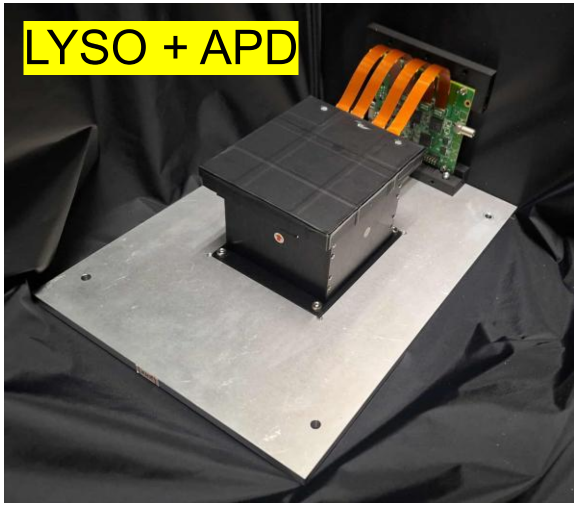
The gain of an APD is about **1000 times lower** than that of a SiPM.

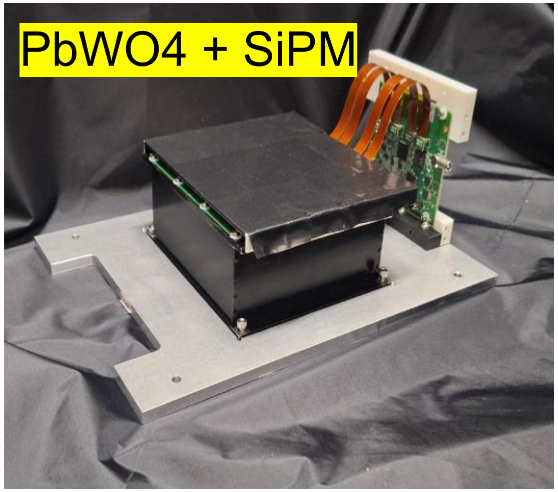
- **$PbWO_4$ + SiPM**

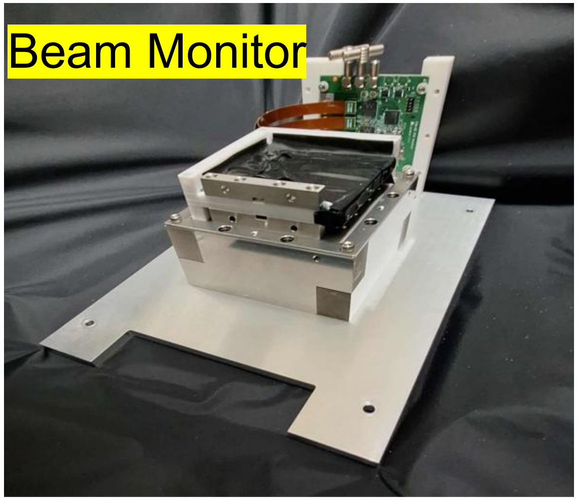
The light yield of $PbWO_4$ is about **100 times lower** than that of LYSO.

- **We continue using CITIROC as DAQ system.**

2^{nd} ZDC ECAL Prototype

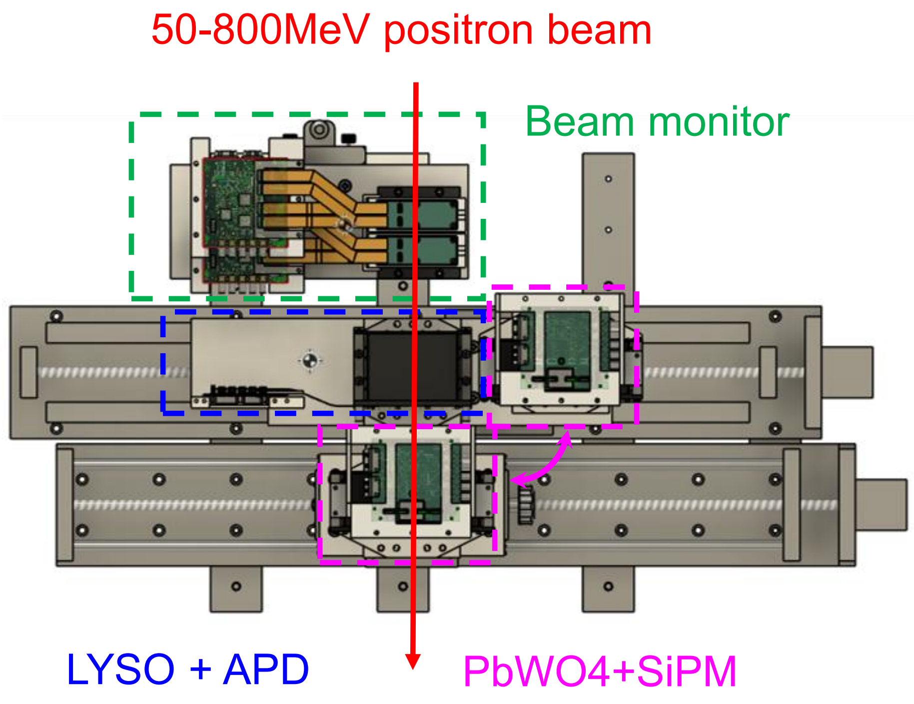


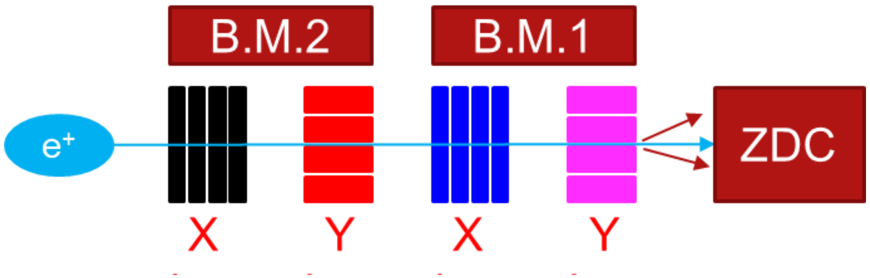


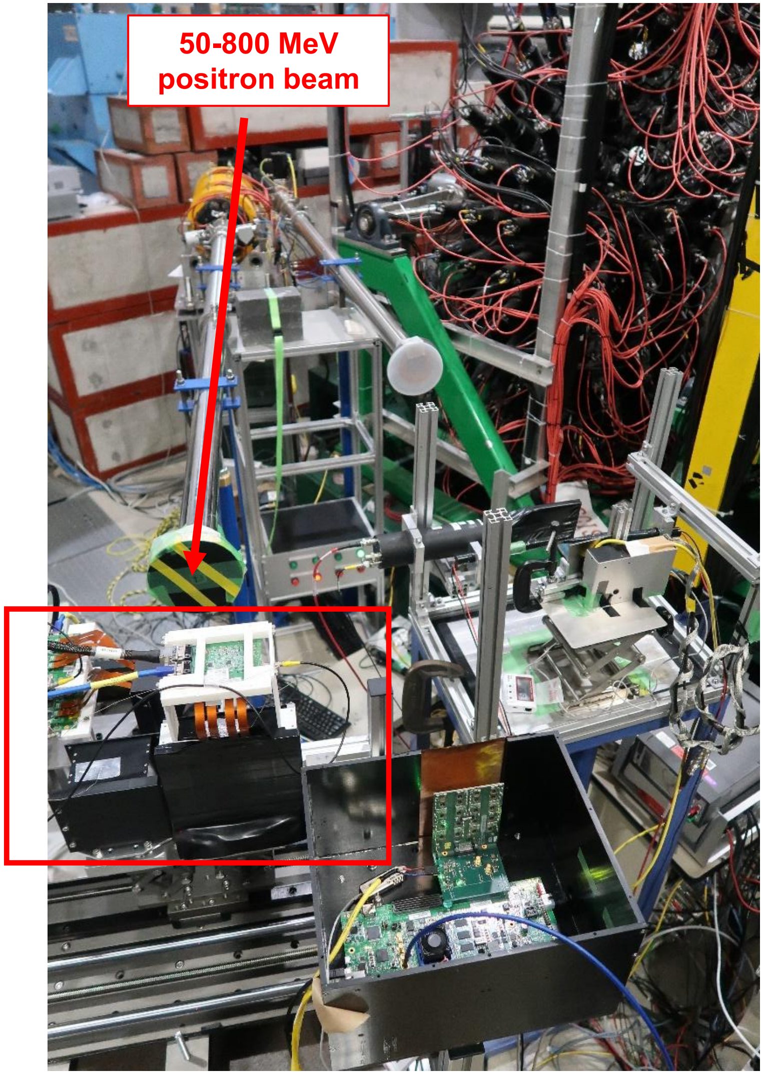


	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
2^{nd} prototype 2024-2025	**LYSO + APD**	LYSO	1cm*1cm	**6.6cm (6X0)**	8x8 8cm*8cm	APD C30739ECERH	1	**CITIROC**
	PbWO4 + SiPM	PbWO4	2cm*2cm	**5.3cm (6X0)**	6x6 12cm*12cm	SiPM Onsemi MICROFC-60035	2	**CITIROC**

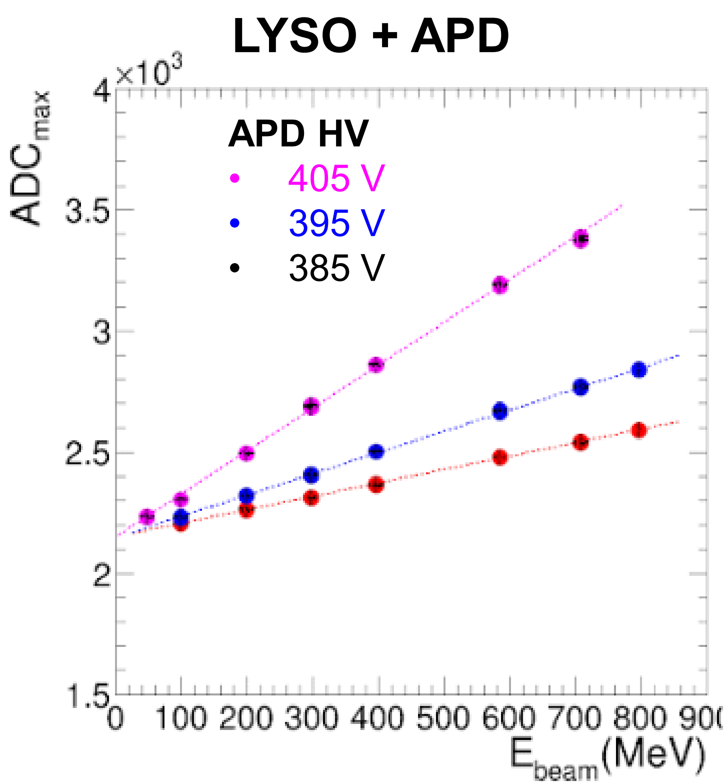
2^{nd} Prototype : Test Beam

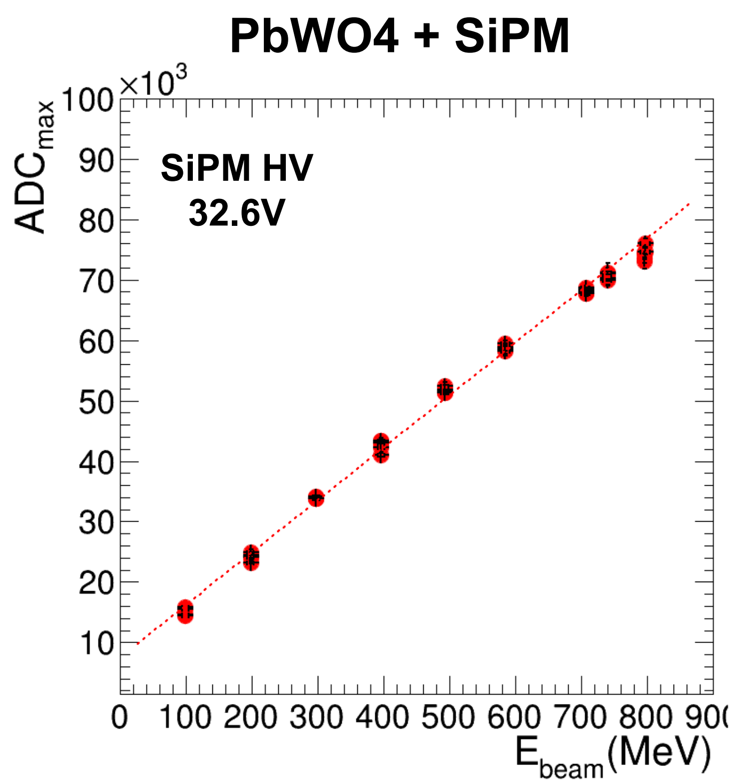






2nd Prototype : **Linearity**

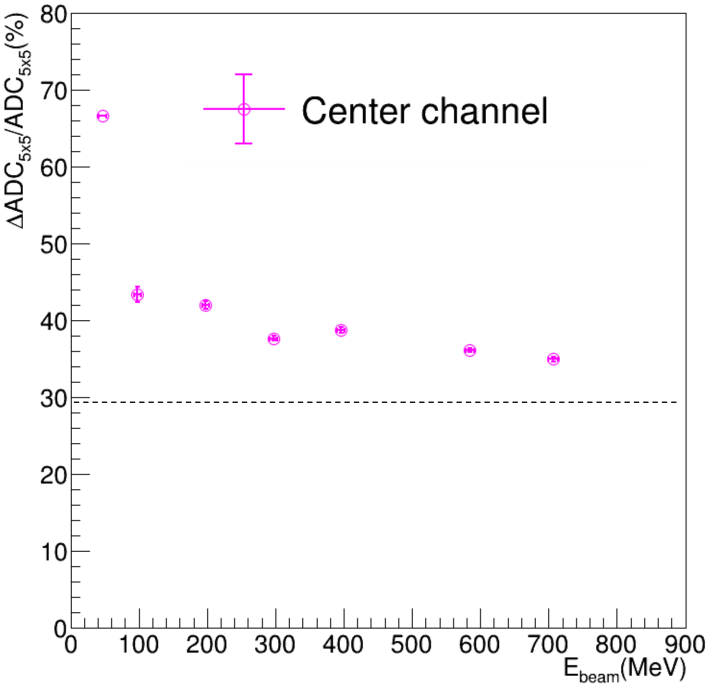




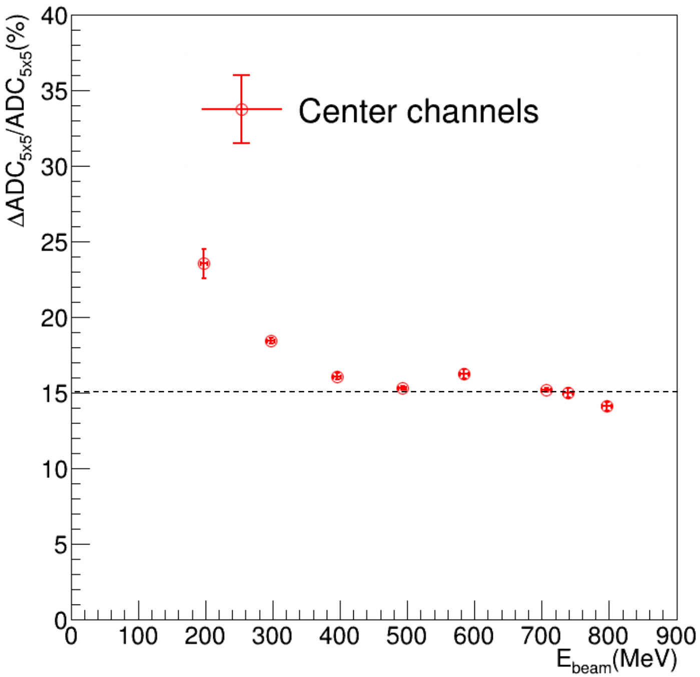
Linearity: The detectors showed **good linearity** when tested with an electron beam from 50 MeV to 800 MeV.

2^{nd} Prototype : **Energy Resolution (w/o Energy Regression)**

LYSO + APD (APD=405V)



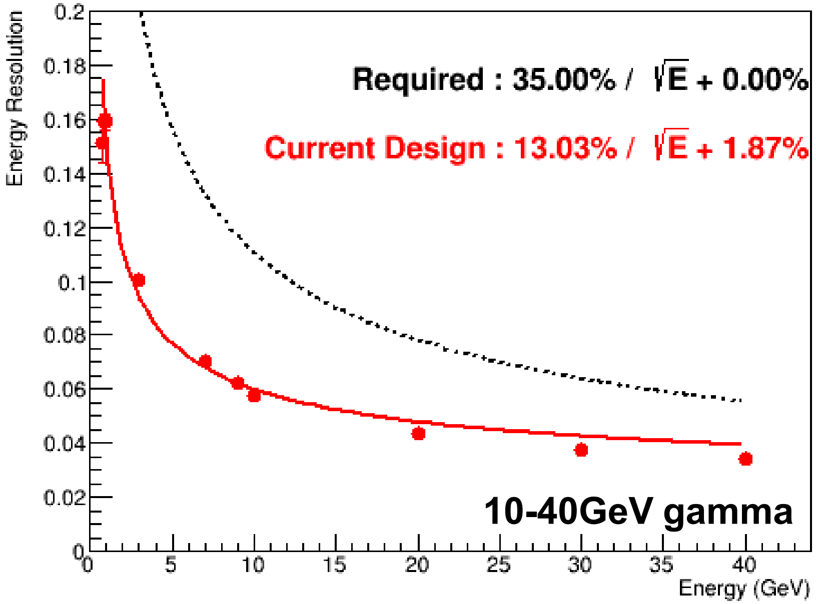
PbWO4 + SiPM (SiPM=32.6V)



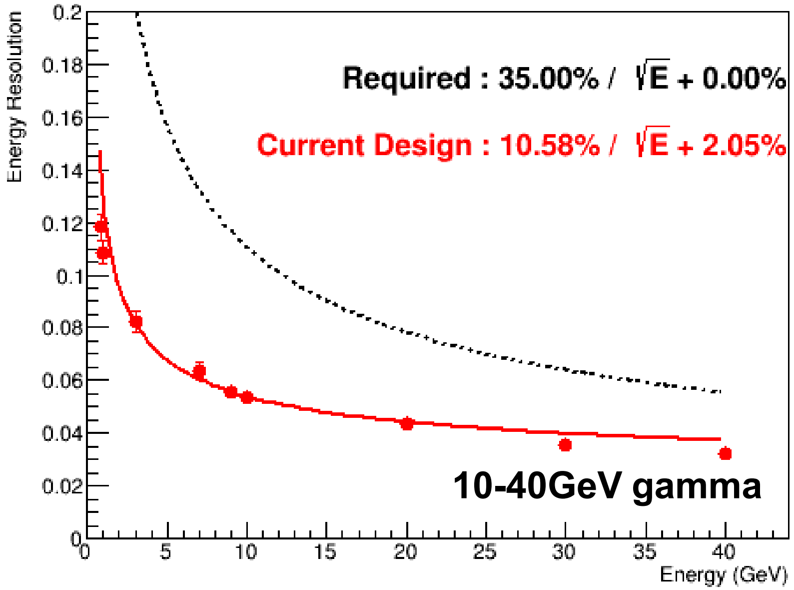
- **LYSO + APD :** Poor performance **~ 35% energy resolution** with 700MeV positron beam.
- **PbWO4 + SiPM :** Reasonable performance **~ 15% energy resolution** with 700MeV positron beam.
- The energy regression is not performed.

Possible Cause of **LYSO + APD system**

LYSO crystal



PbWO4 crystal

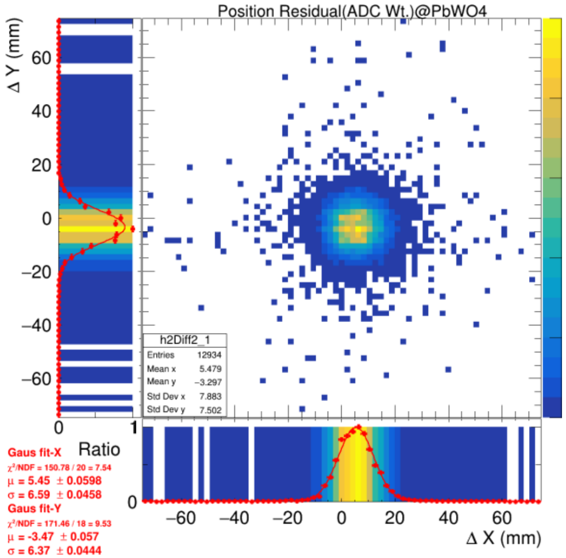


- LYSO and PbWO4 crystal give similar performance in MC simulation (sensors are not simulated). ➔ not the problem of crystal.
- We suspect the APD operation is the problem. Exact reason is still unknown.

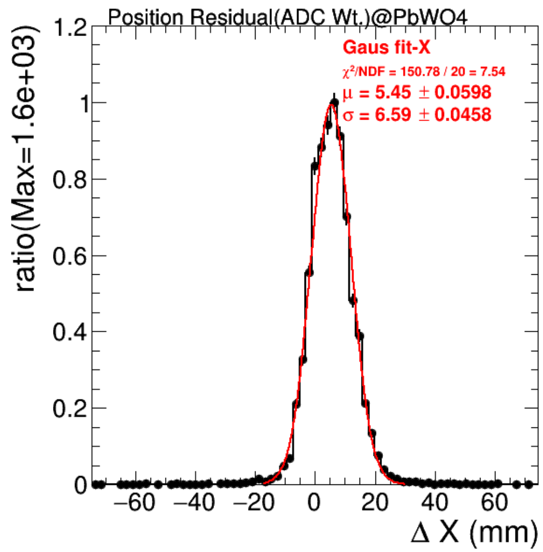
Position Resolution of **PbWO4 + SiPM** System

PbWO4 system @ 739 MeV

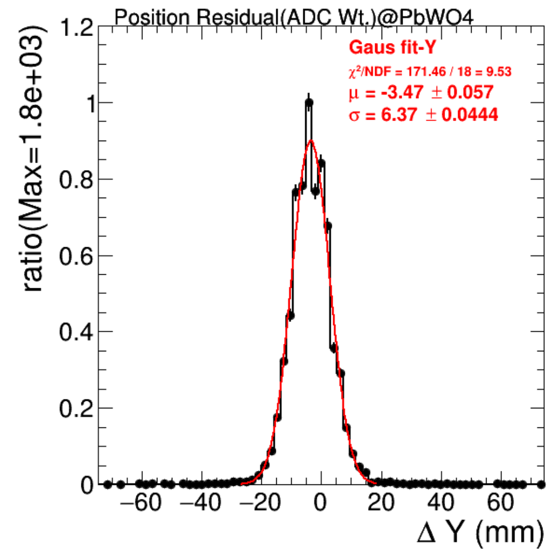
Residual

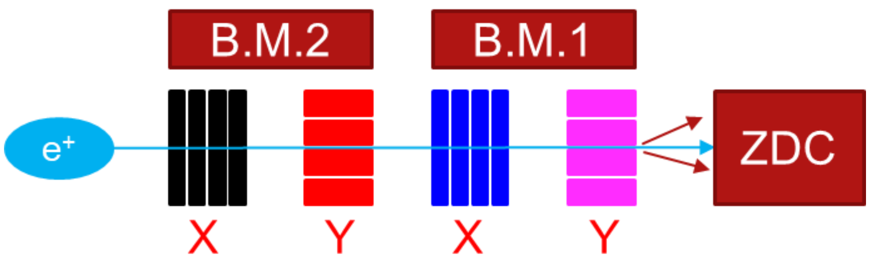


Residual in X



Residual in Y





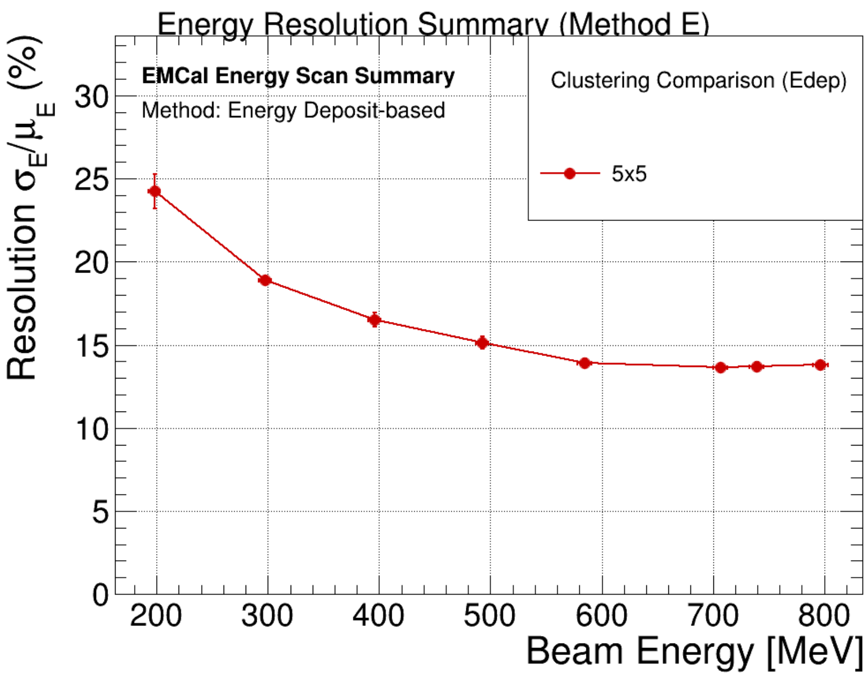
Position resolution

$$\Delta^2 = \sigma_{BM}^2 + \sigma_{PbWO4}^2$$

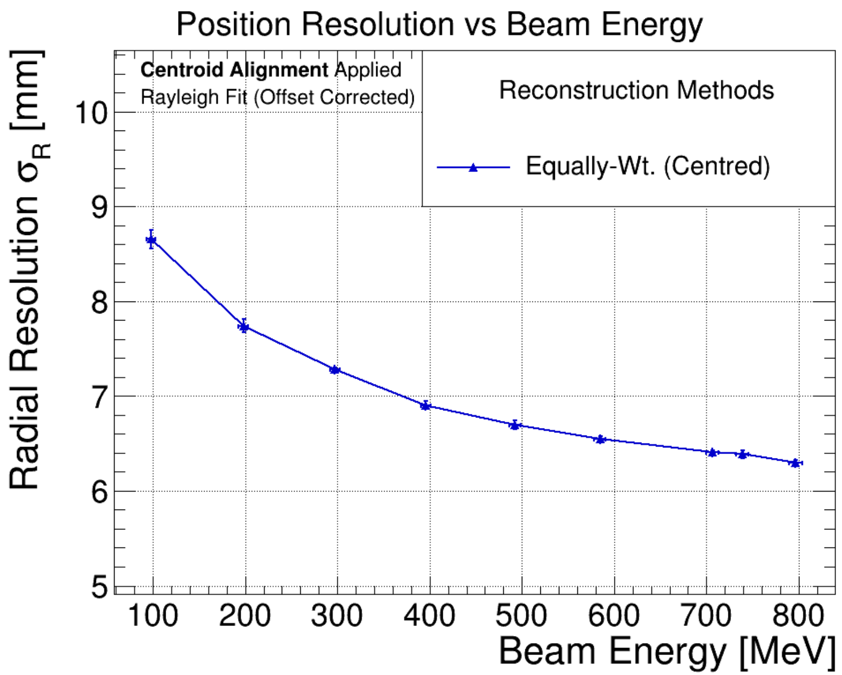
Since the resolution of BMs (2mm pitch) are very small compared PbWO4 crystal (2cm pitch). **The position resolution ~6.5mm is mostly from PbWO4 crystal itself.**

Performance of PbWO4 System

Energy resolution



Position resolution



- Energy resolution : ~15% @ 800MeV positron beam
- Position resolution : ~ 6.5mm @ 800MeV positron beam

Planning for 3rd Prototype

	Detector	Crystal				Sensor		DAQ
		name	Size of one cell	Length	Array	Type	sensor/crystal	
1st prototype 2023-2024	LYSO + SiPM	LYSO	0.7cm*0.7cm	8.8cm (8X0)	8x8	SiPM Onsemi MICROFC-60035	1/crystal	CITIROC
2nd prototype 2024-2025	LYSO + APD	LYSO	1cm*1cm	6.6cm (6X0)	8x8	APD C30739ECERH	1/crystal	CITIROC
	PbWO4 + SiPM	PbWO4	2cm*2cm	5.3cm (6X0)	6x6	SiPM Onsemi MICROFC-60035	2/crystal	CITIROC
3rd prototype 2025-2026 (developing)	PbWO4 + SiPM	PbWO4	2cm*2cm	5.3cm (6X0)	6x6	**SiPM Hamamatsu S14160-3015PS**	16/crystal	**HGCROC**
	LYSO + SiPM	LYSO	1cm*1cm	6.6cm (6X0)	8x8	**SiPM Hamamatsu S14160-3015PS**	4/crystal	**HGCROC**

- Currently preparing the 3rd prototype.
- The 3rd prototype will use the same crystals
  - **SiPM** will be changed from **Onsemi** → **Hamamatsu**
  - **DAQ** will be upgraded from **CITIROC** → **H2GCROC**
- Possible test beam opportunities:
  - **RARiS in Japan @ April : 50MeV - 1 GeV electron/positron beam**
  - **DESY in Germany @ June : 1GeV - 6GeV electron/positron beam**
  - Australian Synchrotron in Melbourne : 1GeV-3GeV electron/positron beam

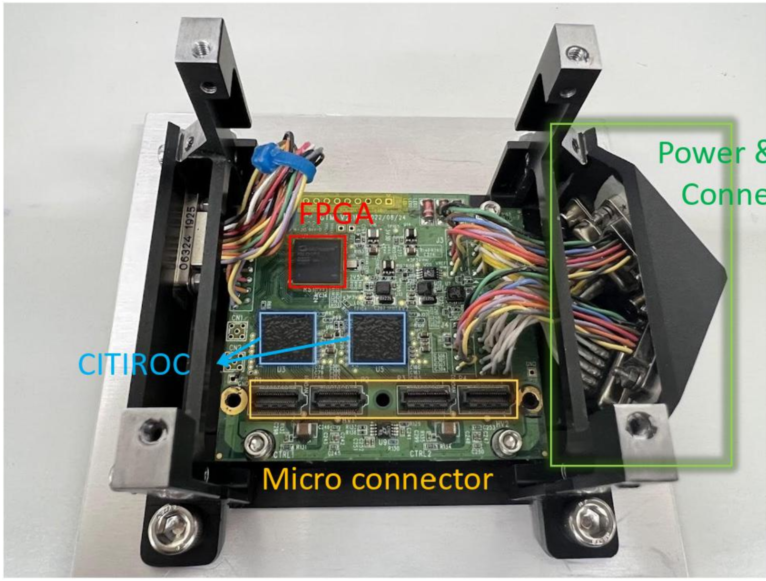
Photon Sensors

- **Excelitas Si-APD :** https://www.excelitas.com/product/c30739ecerh-2-si-apd-ceramic-carrier-high-gain
- **Onsemi SiPM (MICROFC-60035)** : https://www.onsemi.com/pdf/datasheet/microc-series-d.pdf
- **Hamamatsu SiPM (S14160-3015PS)** : https://www.hamamatsu.com/us/en/product/optical-sensors/mppc/mppc_mppc-array/S14160-3015PS.html

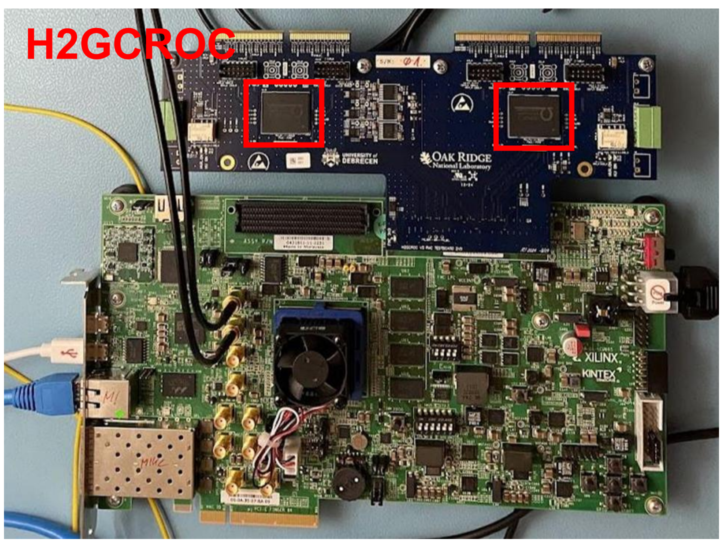
Feature	**Excelitas Si-APD (C30739ECERH-2)**	**onsemi SiPM (MICROFC-60035)**	**Hamamatsu SiPM (S14160-3015PS)**
Sensor type	APD **(linear mode)**	SiPM **(Geiger mode)**	SiPM **(Geiger mode)**
Active area	~Ø3 mm	6×6 mm²	3×3 mm²
Gain	~50–200	$\sim 10^6$	$\sim 10^6$
Bias voltage	~100–400 V	~24–30 V	~38–55 V
PDE (peak)	~70% @ ~800 nm	~40–50%	~45–55%
Dynamic range (p.e.)	$\sim 10^4 – 10^8$ p.e.	**1 – ~1.5 × 10⁴ p.e./cell 527 cells/mm²**	**1 – ~3 × 10⁴ p.e./cell 4,443 cells/mm²**
Limiting factor	Readout electronics	Microcell saturation	Microcell saturation

Smaller area (more microcells per unit area) and larger dynamic range gives the Hamamatsu SiPM better linearity than the onsemi device.

CITIROC VS H2GCROC



CITIROC
- **Dynamic Range: 160 fC – 400 pC**
- **Per-Channel Bias Control:**
  0–4 V, 8-bit DAC for SiPM gain equalization
- **Dual-Gain Preamplifier:**
  - Low Gain: ×1–×60
  - High Gain: ×10–×600
  (higher resolution, smaller range)
- **Signal Shaping**
- **Self trigger**
- **Automatic Gain Selection:**
  Auto HG/LG switching or LG-only mode



H2GCROC
- **Dynamic Range: 160 fC – 320 pC**
- **Digitization:**
  - 10-bit ADC @ 40 MHz (integrated charge)
  - 12-bit TOA (TDC 24 ps)
  - 12-bit TOT (TDC 50 ps)
  - If ADC is saturated, then automatically switch to TOA and TOT mode.
- **Trigger & Data Flow:**
  - FPGA **supports self-trigger or external-trigger mode**

Updated Requirements in 2025

Physics process	Final State particles	ZDC HCAL		ZDC ECAL	
		Energy resolution	Angular resolution	Energy resolution	Spatial resolution
Spectator tagged e+d	Neutrons	$\frac{\sigma_E}{E} \leq \frac{50\%}{\sqrt{E}} \oplus 5\%$	$\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}$	N/A	N/A
Incoherent vetoing of e+A	Neutrons photons	$\frac{\sigma_E}{E} \leq \frac{100\%}{\sqrt{E}}$	N/A	**100 MeV photon sensitivity**	N/A
u-channel backward DVCS	Photons	N/A	N/A	$\frac{\sigma_E}{E} \leq \frac{20\%}{\sqrt{E}} \oplus 3\%$	< 1–2 cm
Pion/Kaon structure	Neutrons Photons	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{35-50\%}{\sqrt{E}} \oplus 3-5\%}$ $(\boldsymbol{before: 50\%})$	$\boldsymbol{\frac{\sigma_\theta}{\theta} \leq \frac{2\,mrad}{\sqrt{E}}}$	$\boldsymbol{\frac{\sigma_E}{E} \leq \frac{2-5\%}{\sqrt{E}} \oplus 1-3\%}$ **for 10GeV-20GeV photon** (**before : 35%**)	**?** **(before < 1–2 cm)**

- The crystal ECAL cannot fulfill the updated requirements for kaon structure studies, which demand **high spatial resolution** to **accurately detect two photons and reconstruct the Λ decay vertex.** Consequently, the development and evaluation of a **WSi ECAL** are currently underway to address these needs.

Sullivan process for kaon structure : $e + p \rightarrow e' + X + \Lambda$ and $\boldsymbol{\Lambda} \rightarrow \boldsymbol{n + \pi^0} \rightarrow \boldsymbol{n + 2\gamma}$

Physics program	ECAL technology	Key requirement
Kaon / Λ structure	WSi ECAL	**High spatial resolution for lambda decay to two photons**
e+A nuclear effects	Crystal ECAL	Low-energy (~100 MeV) photon detection

Summary

- **Purpose of ZDC ECAL**
  Detect 0-300GeV neutron and 0-40GeV photons for several physics programs.

- **1st Prototype (LYSO + SiPM + CITIROC)**
  Test-beam results revealed **strong SiPM saturation and non-linearity** at low energies, limiting usable data and motivating a **systematic gain-reduction redesign**.

- **2nd Prototype (Gain-reduced designs)**
  Two approaches were tested: **LYSO + APD**, which showed good linearity but poor energy resolution, and **$PbWO_4$ + SiPM**, which achieved **stable linearity, ~15% energy resolution, and ~6.5 mm position resolution**, making it the most promising configuration so far.

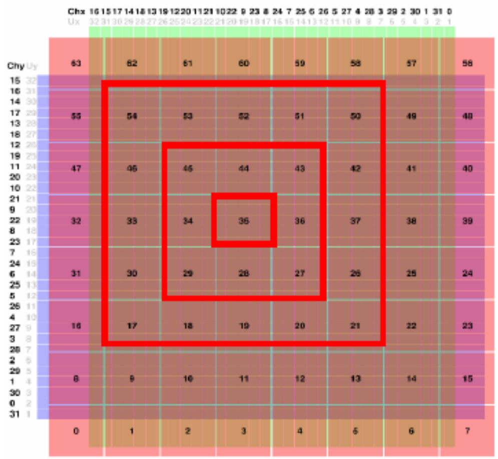
- **3rd Prototype Plans**
  The next prototype will retain the **$PbWO_4$ crystal design**, upgrade the **SiPM (Onsemi → Hamamatsu)** and **DAQ (CITIROC → H2GCROC)**, and be validated in upcoming test beams in RARiS and DESY.

- **Updated ZDC ECAL Requirements**
  While the crystal ECAL remains suitable for **~100 MeV photon detection** in *e+A* physics, the **updated meson/kaon structure requirements** demand **~improved spatial/pointing resolution**, which crystal ECAL can't meet the requirement.

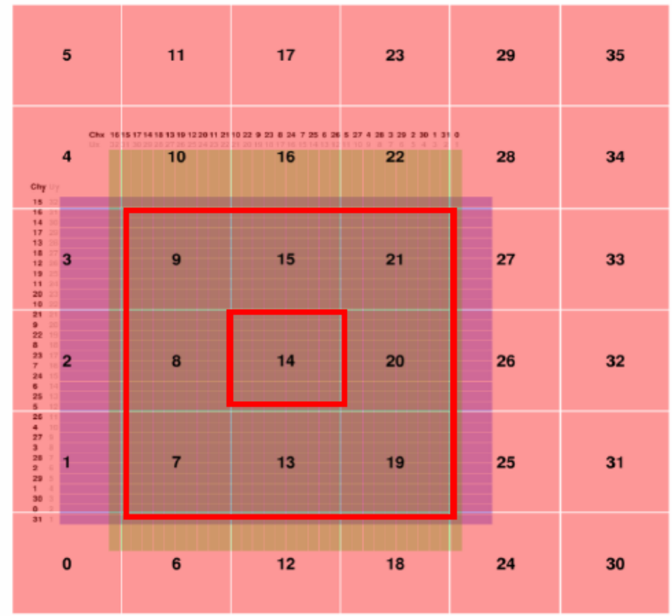
Backup

Crystal Clustering

LYSO + APD
5x5 clustering (~5cm*5cm)



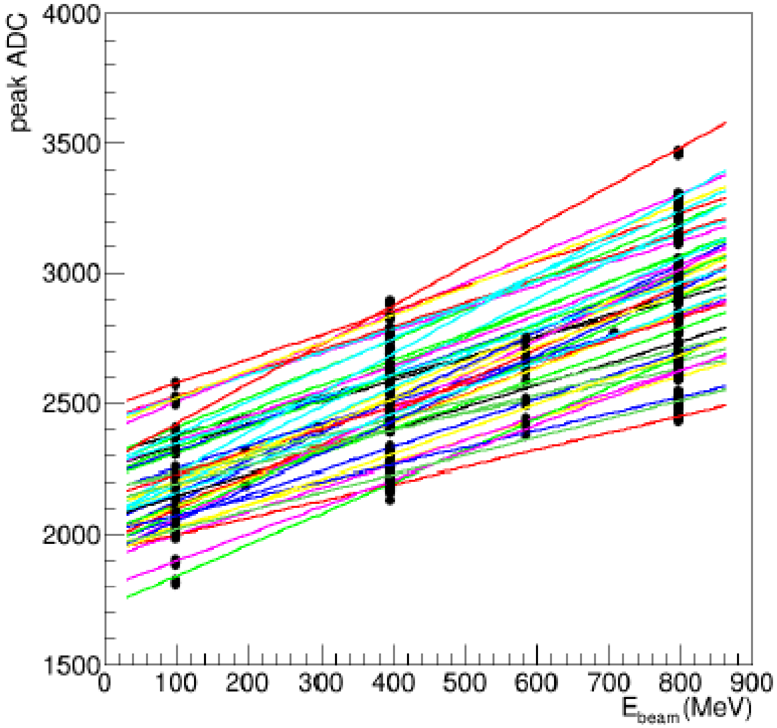
PbWO4 + SiPM :
3x3 clustering (~6cm*6cm)



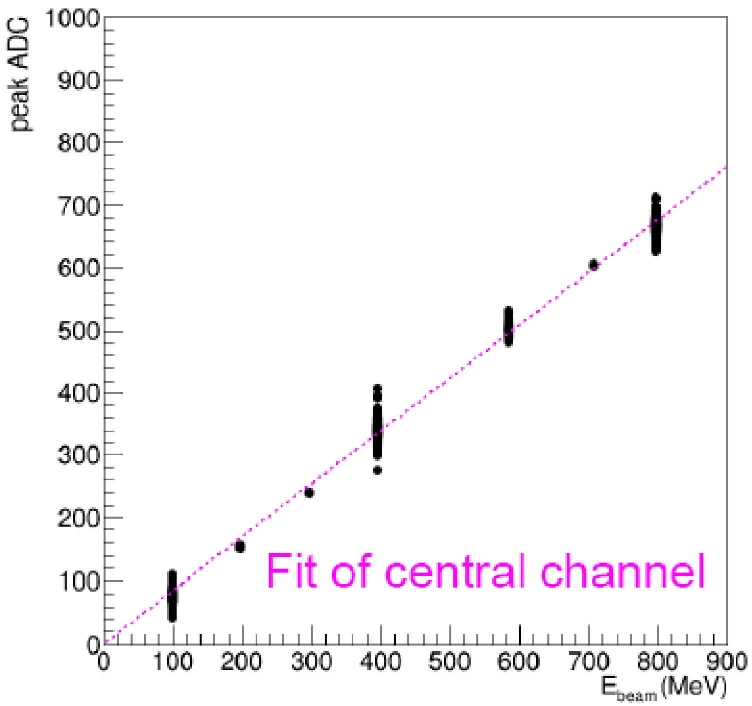
- Both **LYSO** and **PbWO$_4$** crystals have an approximate Molière radius of 2 cm. (A 4 cm × 4 cm cluster captures about 90% of the total energy deposition, while an 8 cm × 8 cm cluster captures around 95%.) Hence, **the two systems collectively achieve 90%–95% energy containment with 5*5 array clustering for LYSO+PAD and 3*3 array for PbWO4+SiPM.**
- During the beam test, we performed **high-voltage** and **beam-energy scans** to study its response under varying operating conditions.

2nd Prototype **LYSO + APD** : Gain Calibration

Gain before Calibration



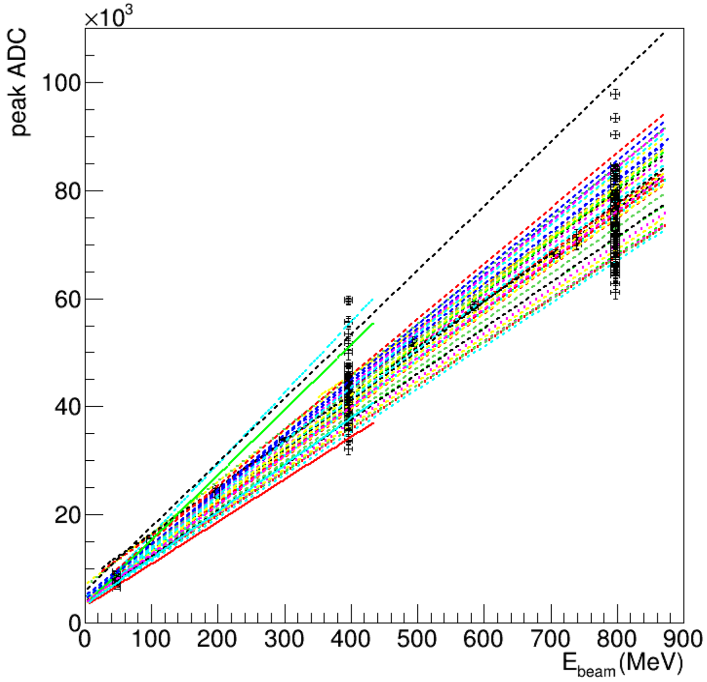
Gain after Calibration



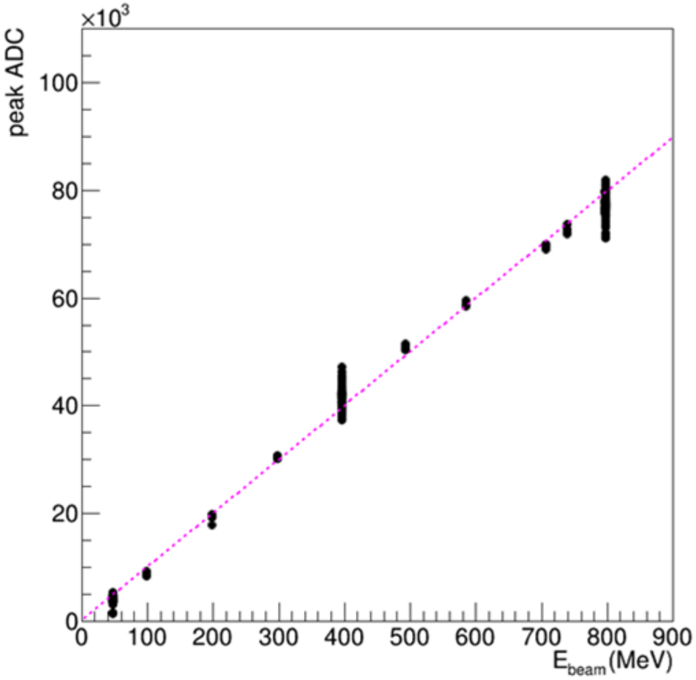
Calibration procedure:
The beam energy was varied to scan all channels in the 5×5 crystal array. The gain of each channel was then adjusted (scaled and shifted) so that its response aligned with that of the central channel.

2^{nd} Prototype **PbWO4 + SiPM:** Gain Calibration

Gain before Calibration



Gain after Calibration



Fitting : Resolution VS Energy

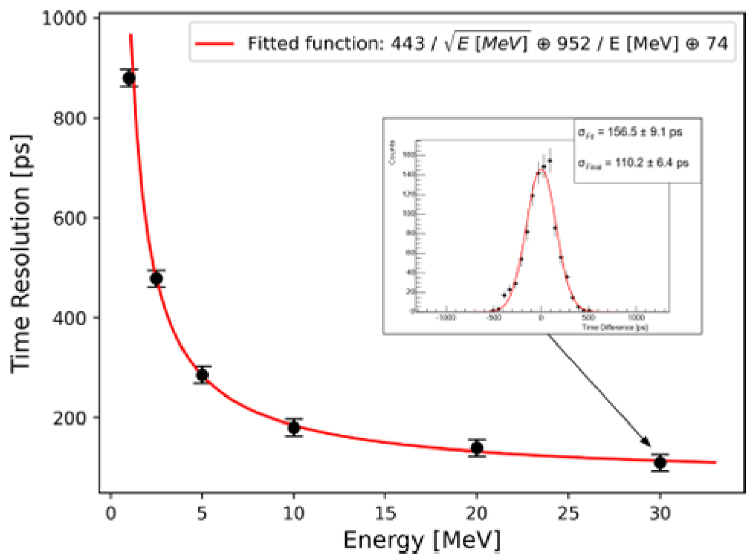


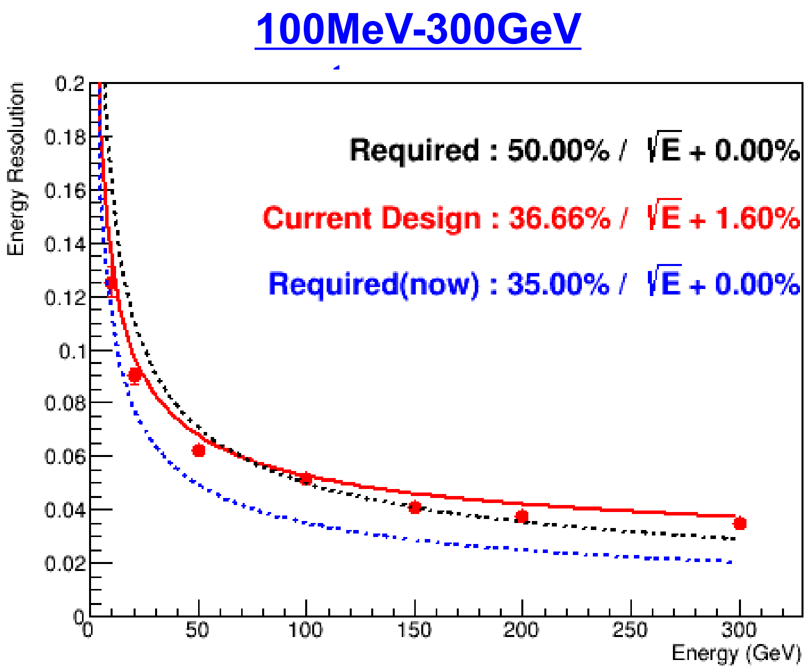
Fig. 13. Dependence of time resolution of a LYSO crystal in the array on the energy deposition in the LYSO crystal for energy deposition between 1–30 MeV. A 110 ps time resolution is measured for 30 MeV energy deposits after the resolution of the reference time is removed via quadrature from σ_{Fit}.

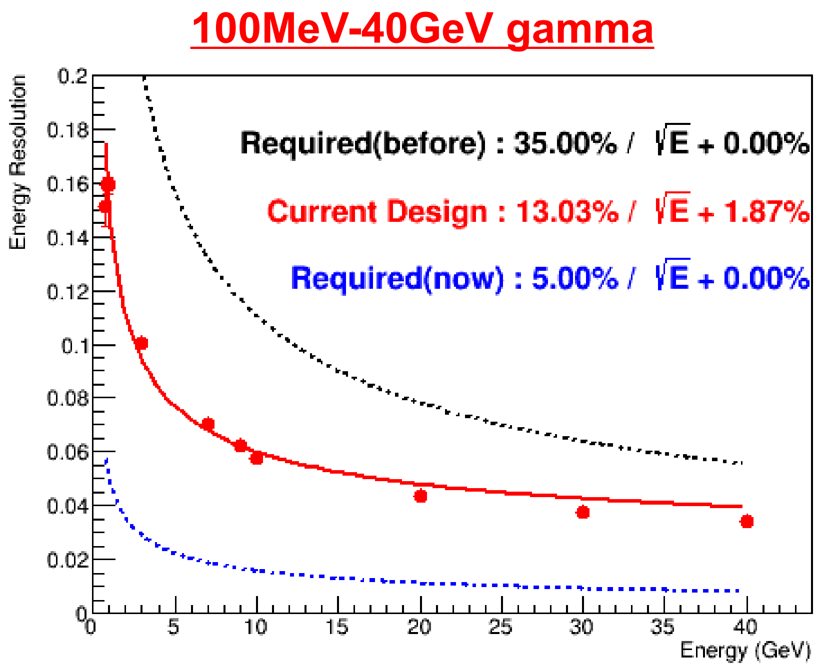
Energy resolution measurements were performed using all three radioactive sources, which provided nine different energies in total. The resulting energy resolution of a LYSO crystal as a function of γ-ray energy is shown in Fig. 5. An electromagnetic calorimeter energy resolution is typically represented with the following functional dependence:

$$\frac{\sigma_{E_\mu}}{E_\mu}(\%) = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2)$$

where a, b, c are constants and E_μ is the incident particle energy in MeV. Here, $a/\sqrt{E}$ is a statistical term used to express the contribution from Poisson processes, such as photostatistics, to energy resolution. The b/E term parameterizes noise contributions to energy resolution from electronics and PMTs, and the constant c parameterizes contributions from shower leakage, crystal non-uniformity, and intra-crystal miscalibrations to energy resolution. In single crystal testing, the photosensor used to read out the crystal is operated at a high voltage where noise is minimized, thereby resulting in $b \rightarrow 0$ in the fit to Eq. (2). The constant term c is also assumed to be dominated by crystal non-uniformity for single crystal tests. We find $a = (3.84 \pm 0.19)\ \sqrt{\text{MeV}}$ and $c = (0.64 \pm 0.57)$. Because the PIONEER experiment operates at a higher energy range than radioactive sources ($\mathcal{O}(10) - \mathcal{O}(100)$ MeV), the stochastic term will be greatly suppressed in the PIONEER energy regime.

Updated Requirements in 2025





The updated ECAL requirement demands a significantly improved energy resolution, from 35% to 5%, which the current setup cannot achieve, making a redesign of the ECAL necessary for meson structure studies.