Status of ZDC ECal Prototyes EIC-Asia@20250313

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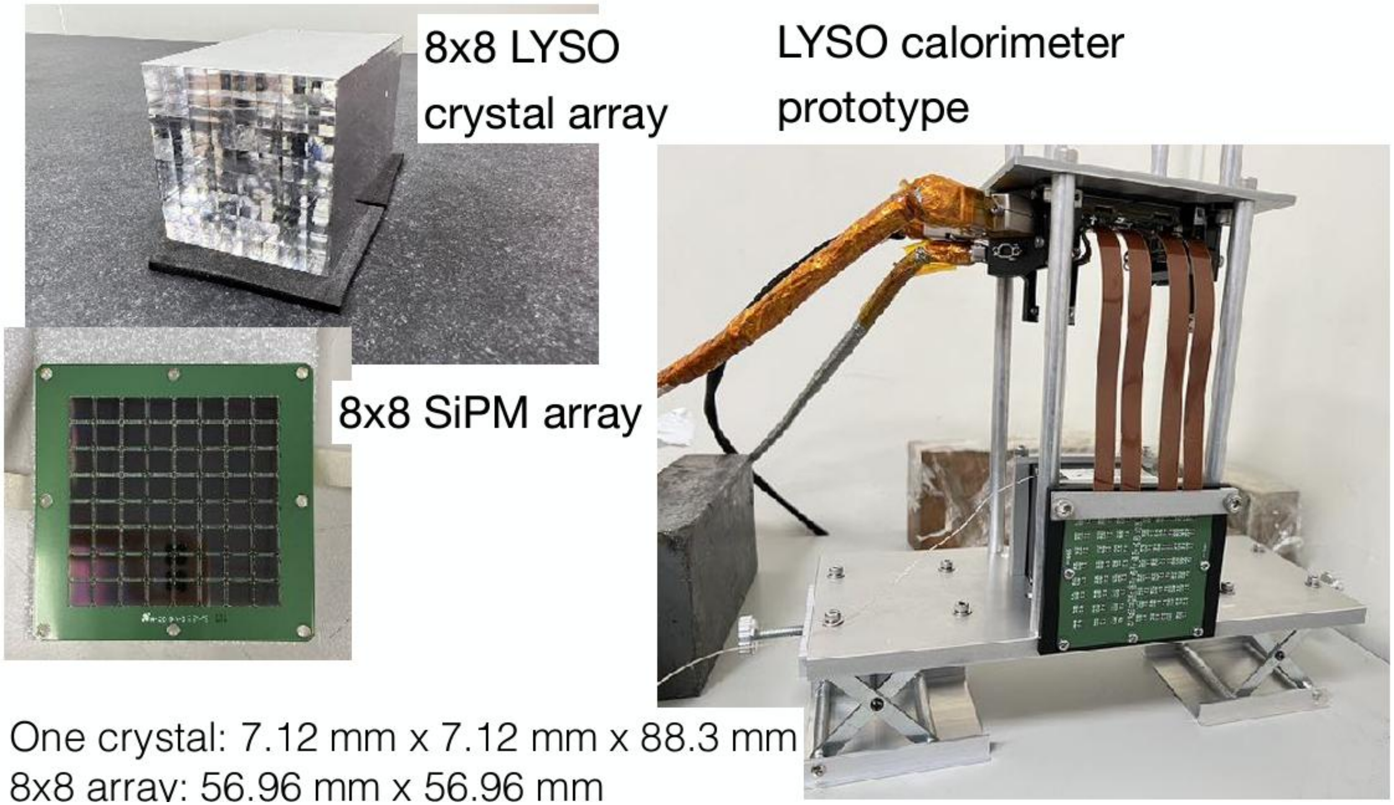
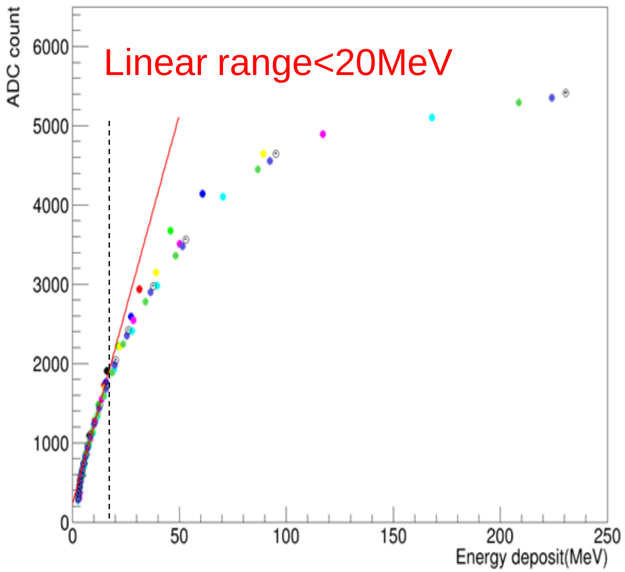
Review (1) : 1st Prototype of ZDC ECal



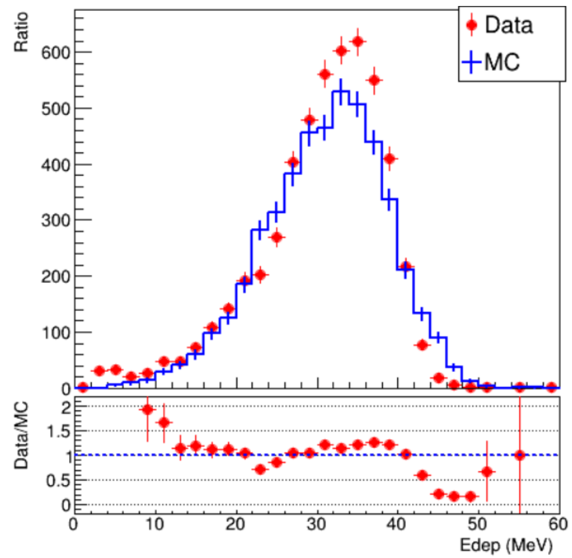
- LYSO + SiPM
- One crystal : 7.12mm * 7.12mm * 88.3mm (8X0)
- 8x8 array with 56.96mm* 56.06mm active area

Review (2) : 1st Prototype of ZDC ECal

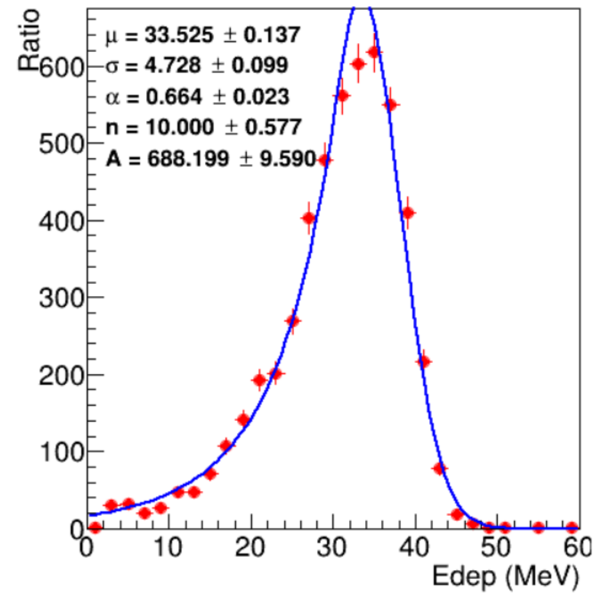
SiPM Saturation



47MeV 5x5 cluster



47MeV 5x5 cluster



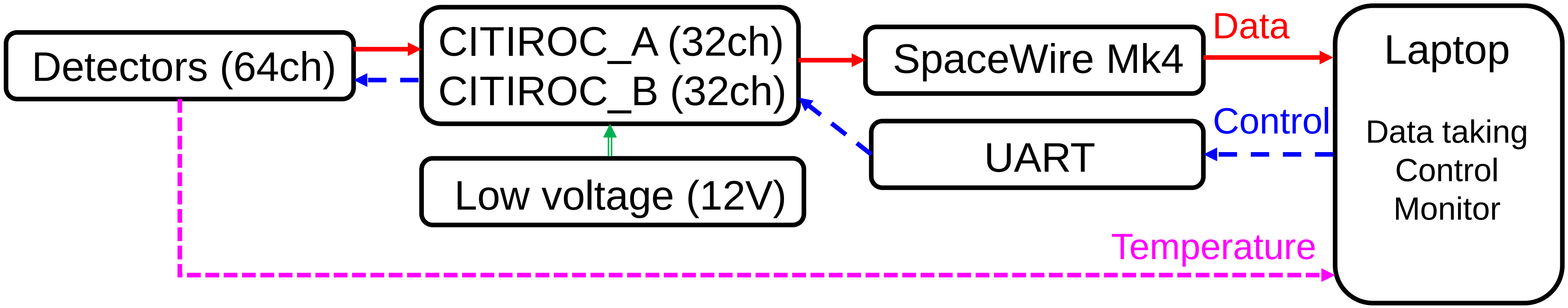
- ELPH test beam @ Feb. 2024
- 50MeV – 800 MeV positron beam
- Most of the data fall within the saturated range, except for the 47 MeV data, which is approximately 60% within the linear range.
- The energy resolution without energy regression is 14% for the 47 MeV beam. After accounting for the beam momentum resolution provided by ELPH, the energy resolution improves to approximately 11%.

2^{nd} Prototypes : Choice of Crystal and PM

Detector	Crystal	Sensor	One crystal	Length	Array	Note
ZDC ECal 1^{nd} **LYSO + SiPM**	**LYSO** Taiwan	**SiPM** MICROFC-60035	0.7cm*0.7cm	8.83cm (8X0)	8x8	Gain to high
ZDC ECal 2^{nd} **LYSO + APD**	**LYSO** Taiwan	**APD** C30739ECERH	1cm*1cm	6.6cm (6X0)	8x8	Crystal size is half Moliere radius
ZDC ECal 2^{nd} **PbWO4 + SiPM**	**PbWO4** Czech	**SiPM** MICROFC-60035	2cm*2cm	5.3cm (6X0)	6x6	Two sensors for one crystal
Beam Monitor	**Plastic** Scintillator	**SiPM** MICROFC-10010	2mm*2mm	8cm	32ch in X 32ch in Y	Two sets 4 planes : 2X & 2Y

- We observed strong saturation effect with 1^{st} prototype which is the combination of LYSO and SiPM.
- Goal of the 2^{nd} prototypes is to reduce gain, therefore there are two options.
  - LYSO + APD : gain of APD is around 1/1000 times of SiPM (rough estimation from datasheet).
  - PbWO4 + SiPM : gain of PbWO4 is around 1/100 times of LYSO (rough estimation from datasheet).
- Beam monitor is reconstructed to better identify the position of beam tracks to perform better gain calibration and possibly remove pile up events. The position resolution of beam monitor is 2mm.

Electronics

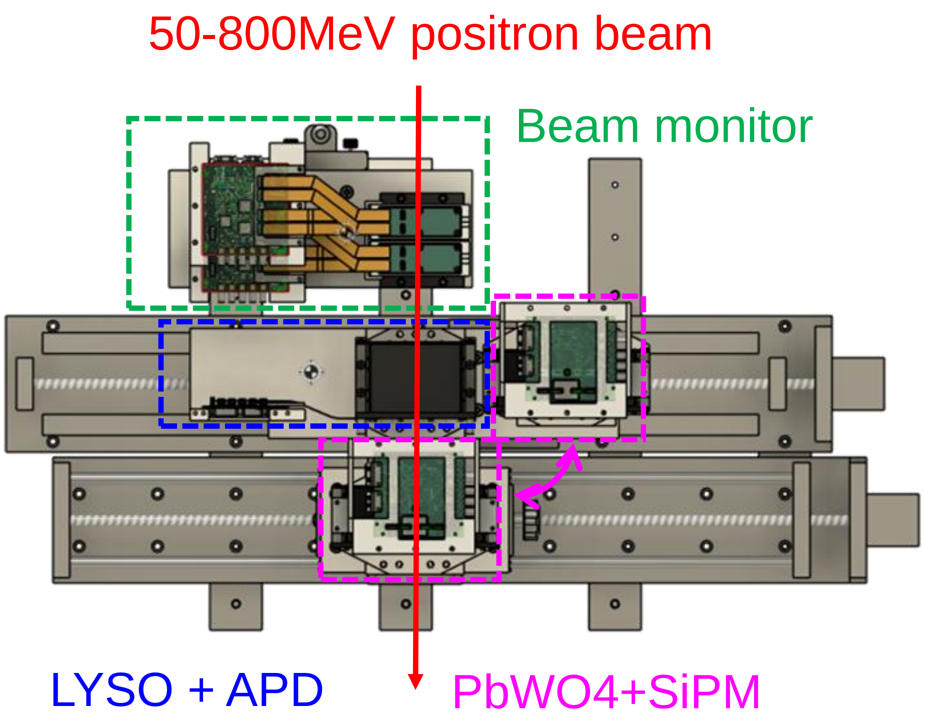


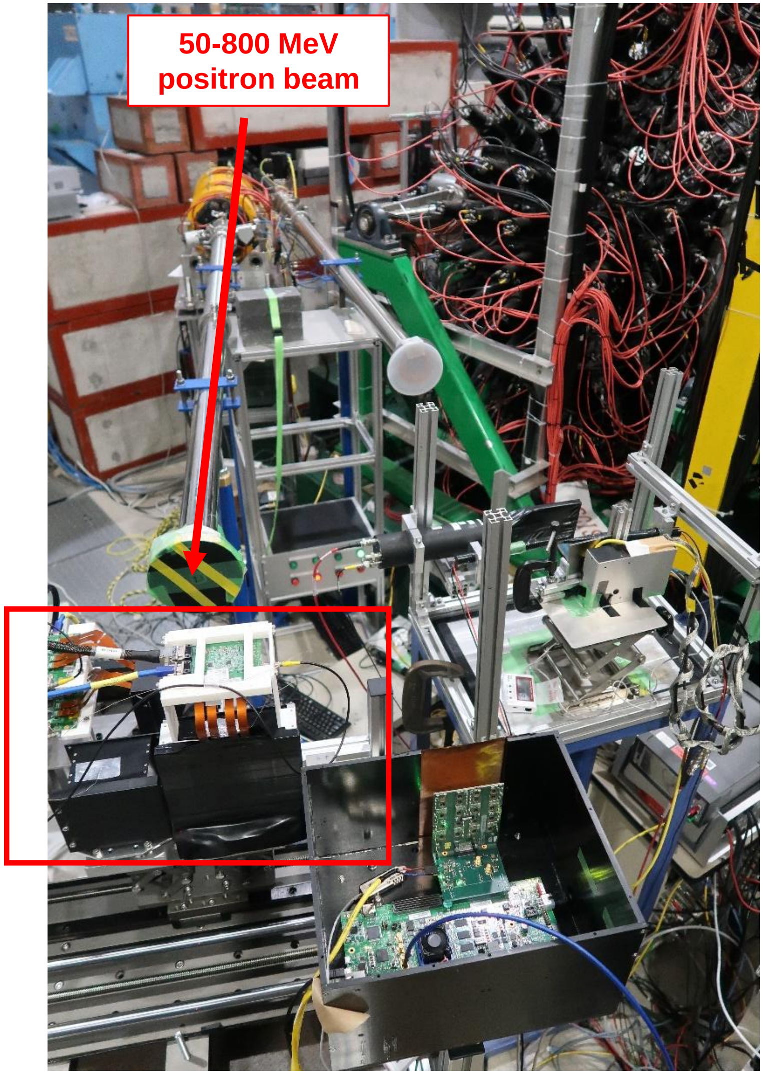
- Same as 1st prototype. We use CITIROC. CITIROC is is a 32-channel front-end ASIC designed to readout silicon photo-multipliers.
- All the detectors use CITIROC including **LYSO+APD, PbWO4+SiPM, and beam monitor.**

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

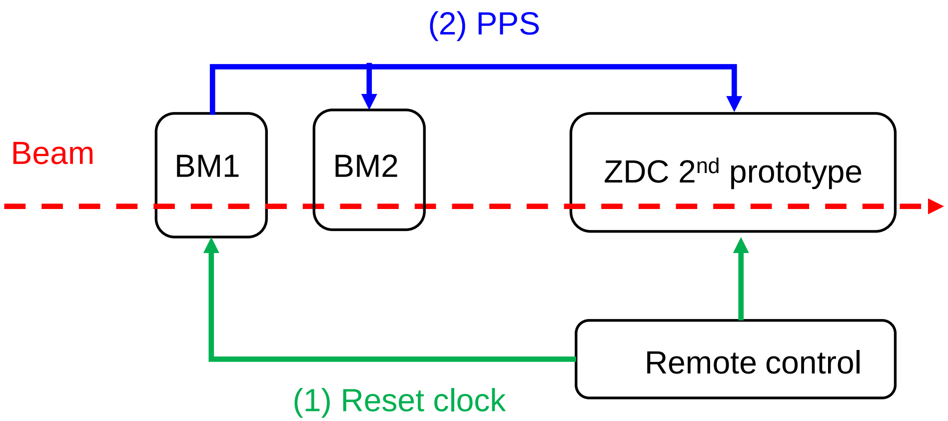
Experimental Setup





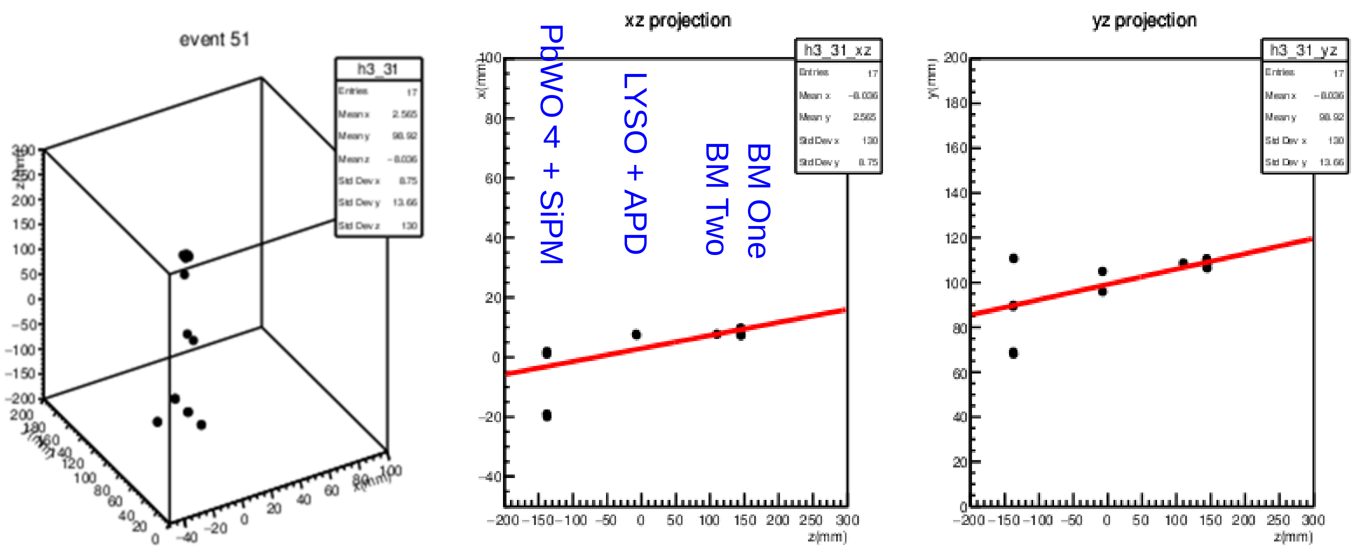
We had test beam at ELPH (now called RARIS) on 2025 Feb with 2nd prototype system.

Tracking



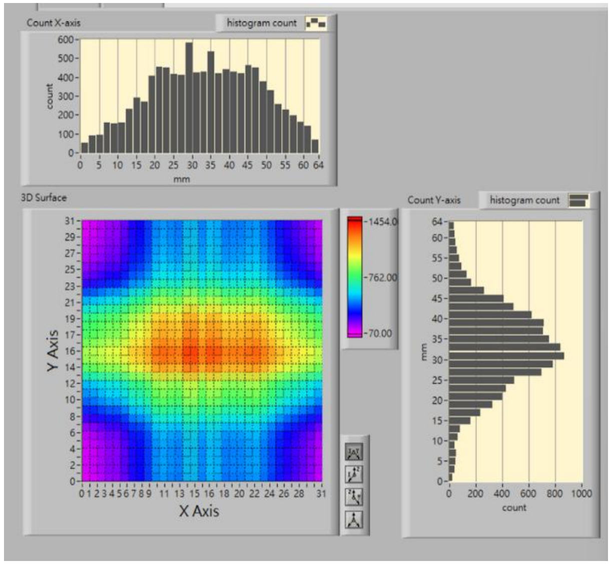
- All detectors, including beam monitors and the ZDC ECal prototype, operate in **self-triggered mode**.
- **Trigger and event matching** are performed offline using **PPS signals**.

1) Remote control set commands to reset the clocks : course time (count PPS signals, 20Hz) and fine time (0.24us).
2) The **PPS signal** is distributed from **beam monitor #1** to all other detectors.
3) **Timing matching**: Events are synchronized by ensuring the **same coarse time** and a **fine time difference within 0.24 μs**, accounting for cable delays.
4) **Position matching :** Not yet implemented, but verified through plots, confirming that tracking appears correct.

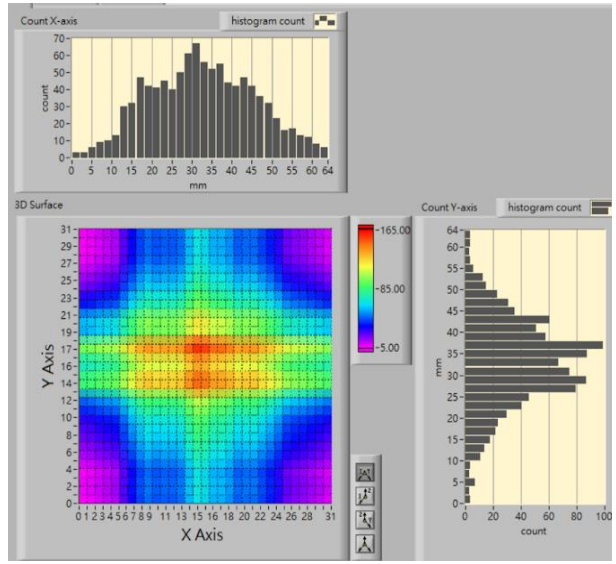


Online Monitoring

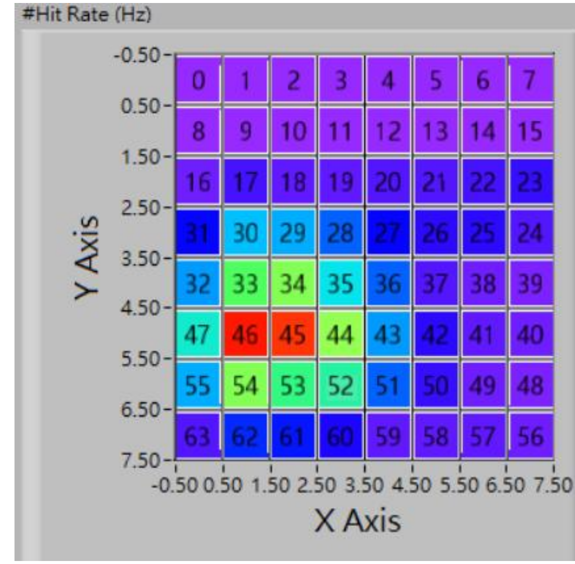
BM1 (downstream)



BM2 (upstream)

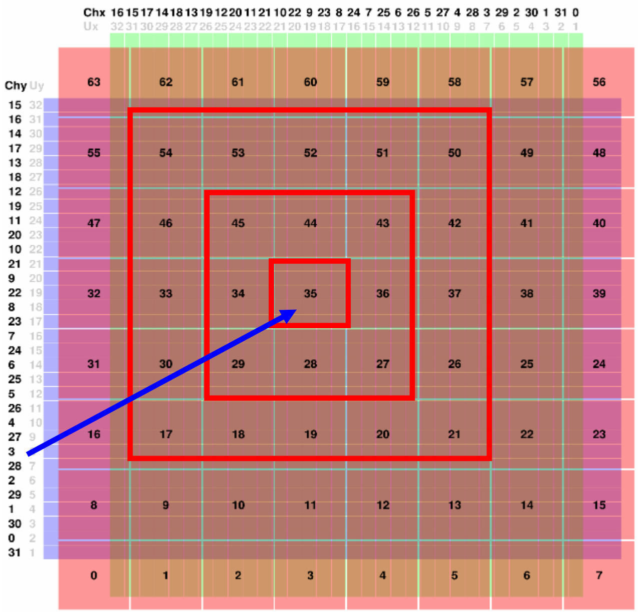


LYSO + ADP : beam shoot ch45

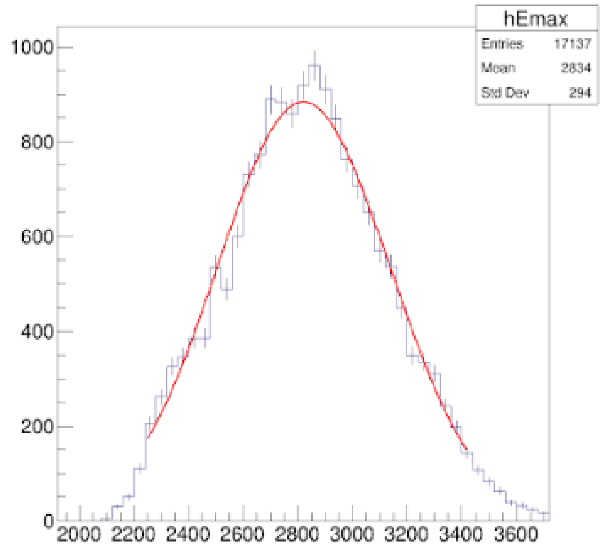


- Energy: 395 MeV positron beam
- Beam spread: ~2 cm radius in the x-direction, ~1 cm in the y-direction
- Beam monitor calibration: Gain calibration was not performed due to time constraints before the test beam. We will improve next time.

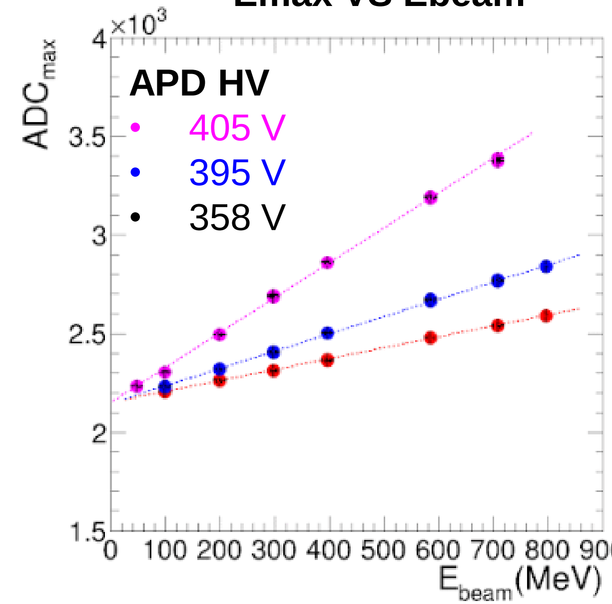
HV Scan and Position Scan



Emax of “LYSO + ADP”



Emax VS Ebeam

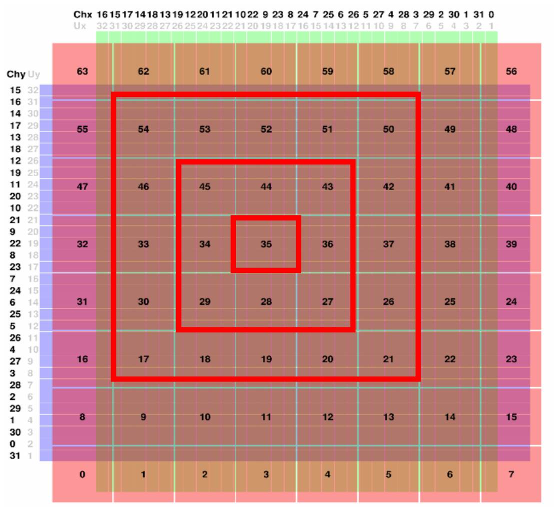


- **Optimizing Settings**: Initially, we focused on the central cell, performing HV and beam energy scans. The threshold was set to the lowest level at which no signal was detected in the absence of a beam.

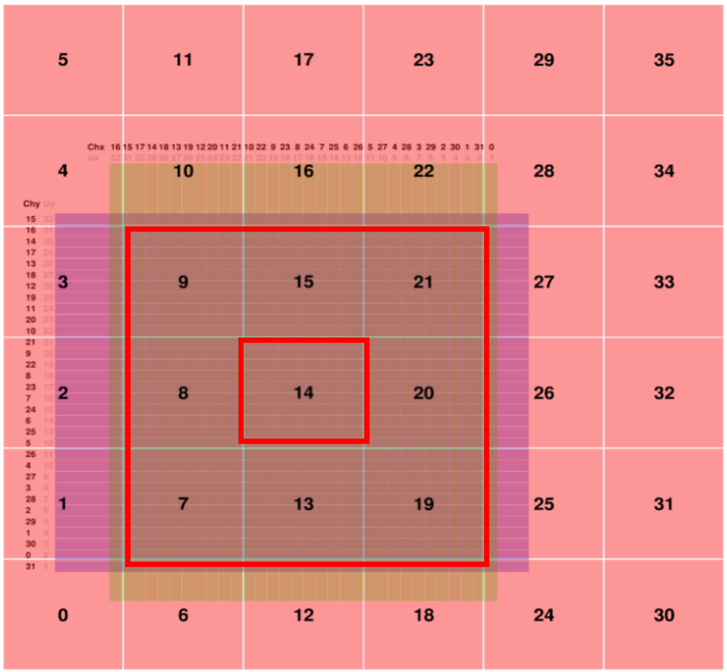
- **Position Scans**: After determining the optimal settings, we conducted a beam energy scan at the center of different crystals:

Position Scan/Clustering

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



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

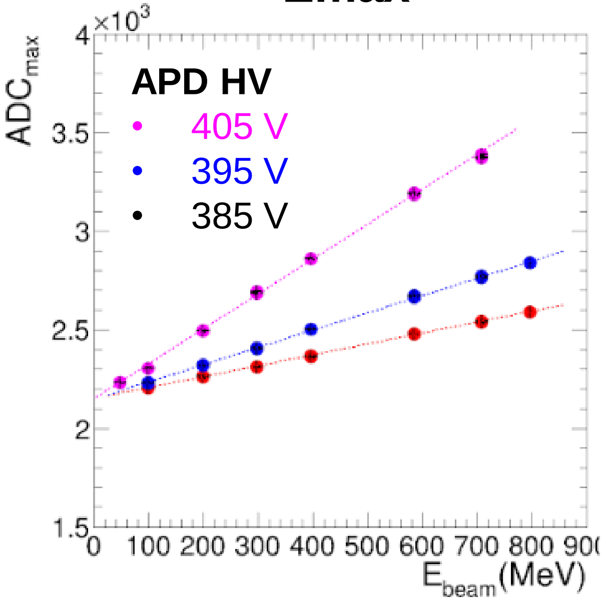


- **Molière radius : the radius of a cylinder containing on average 90% of the shower's energy deposition**. Two Molière radii contain 95% of the shower's energy deposition.

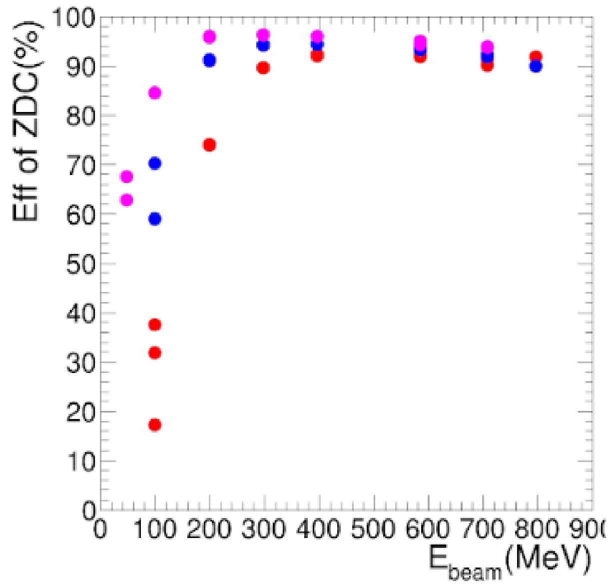
- **Both LYSO and $PbWO_4$ have a Molière radius of approximately 2 cm.** 4cm*4cm clustering size covers around 90% energy; 8cm*8cm clustering size covers around 95% energy. **Our systems covers 90%-95% energy deposition.**

LYSO + APD : General Behavior

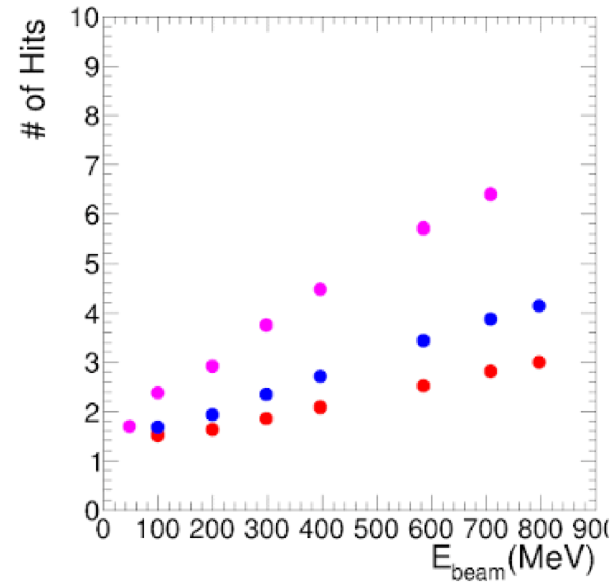
Emax



Efficiency



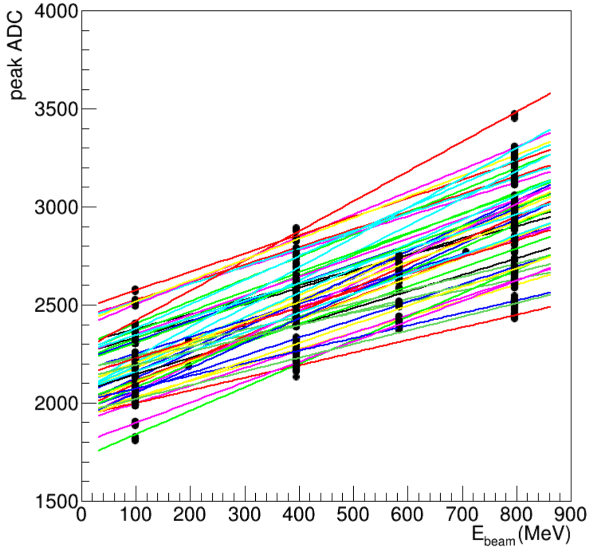
Num. of Hits



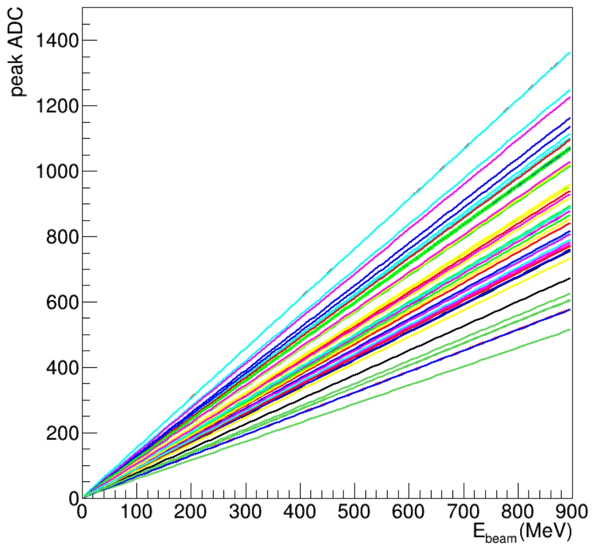
- Initial tests were conducted using the **central channel** to determine optimal settings.
- **Linearity:** It exhibited reasonable linearity with an electron beam in the 50 MeV to 800 MeV range.
- **Efficiency** : It is defined as :
- Eff= (LYSO && BM/BM) **with only timing matching verified**.
- Efficiency decreases with increasing beam energy.
- Higher HV improves efficiency, reaching ~98% at 405V for 200–400 MeV beams.
- **Best Performance: Achieved at 405V for the APD.**

LYSO + APD : Gain Calibration

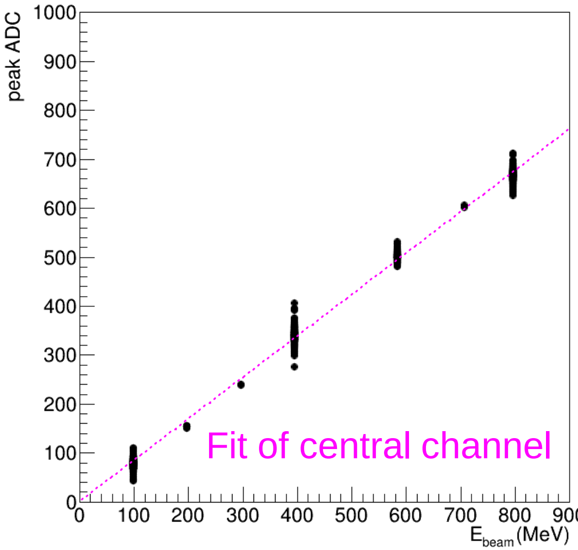
Linear fit of Emax



Gain calibration by fit



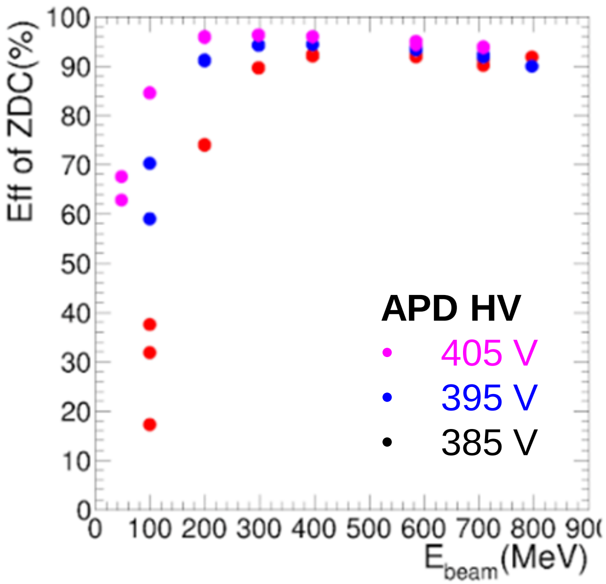
Emax after calibration



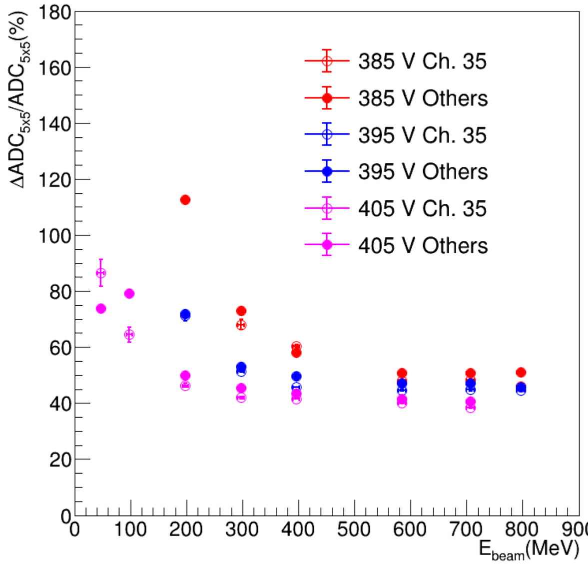
- **Setup** : A 5 × 5 crystal array was used for the LYSO + APD position scan. Data was collected at 100 MeV, 400 MeV, and 800 MeV.
- **APD Gain Behavior** : The gain of each APD follows a linear function, but the linearity varies across positions due to differences in individual APD gains.
- **Gain Calibration** : All channels were shifted to zero to align sector offsets. The slopes were adjusted to match the central channel, which served as the reference. After calibration, the data points showed better alignment across different positions.

LYSO + APD : Energy Resolution of Emax (Preliminary)

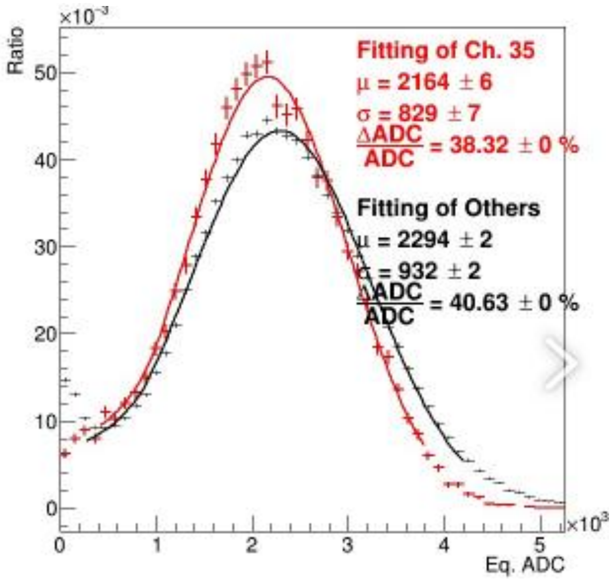
Efficiency



Energy resolution (E5x5)



E5x5 : 405V, 706MeV

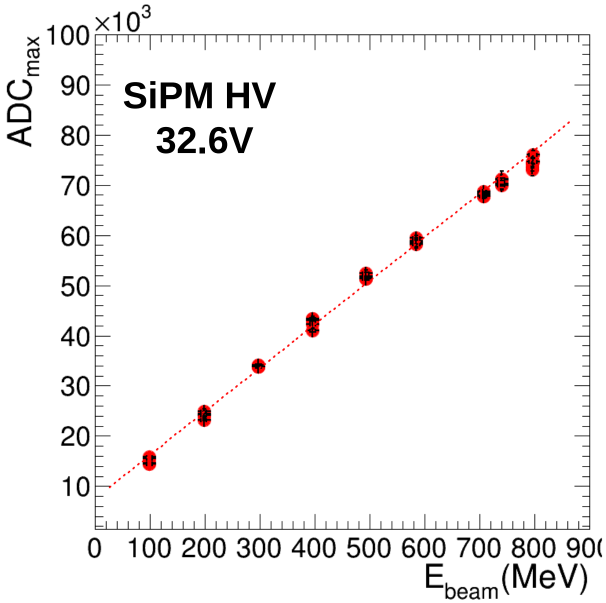


- **"LYSO + APD" system ~40% energy resolution** falls short of the desired performance. In contrast, the **LYSO + SiPM system achieved ~15%** resolution. Suspected **errors in APD operation.** Or the gain of LYSO + APD is simply too low. **Energy resolution declines** when **efficiency drops below 95%.**

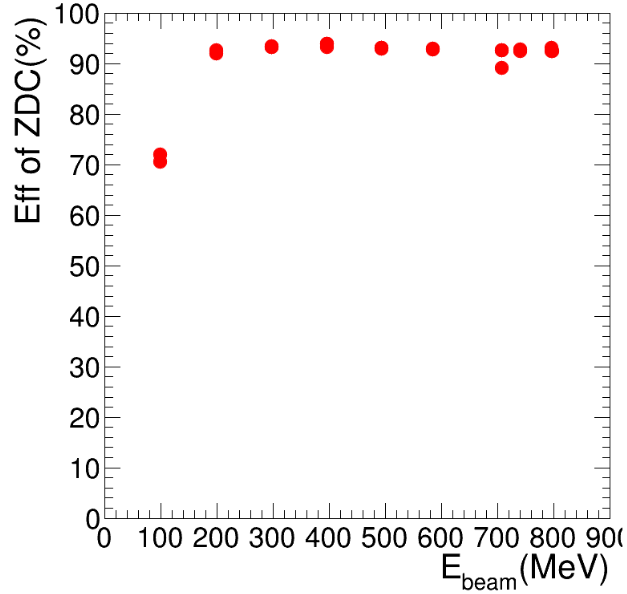
- **Timing matching** is the only applied track-matching criterion. **Expected improvements through position matching and energy regression**, but results are unlikely to improve beyond 10% resolution.

PbWO4 + SiPM : General Behavior

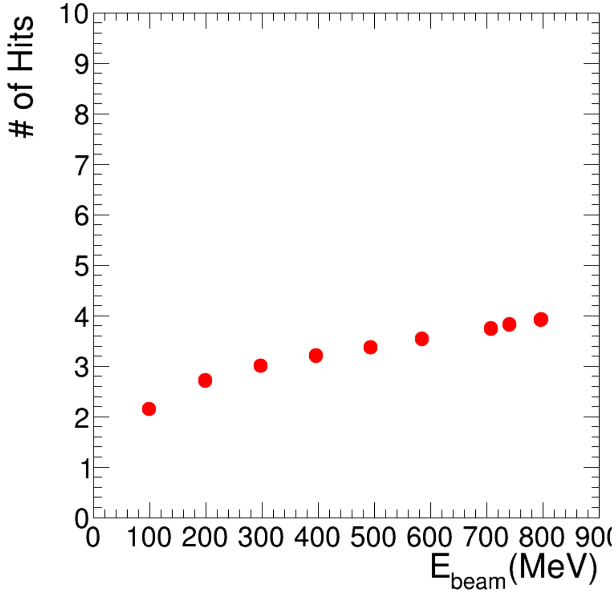
Emax



Efficiency



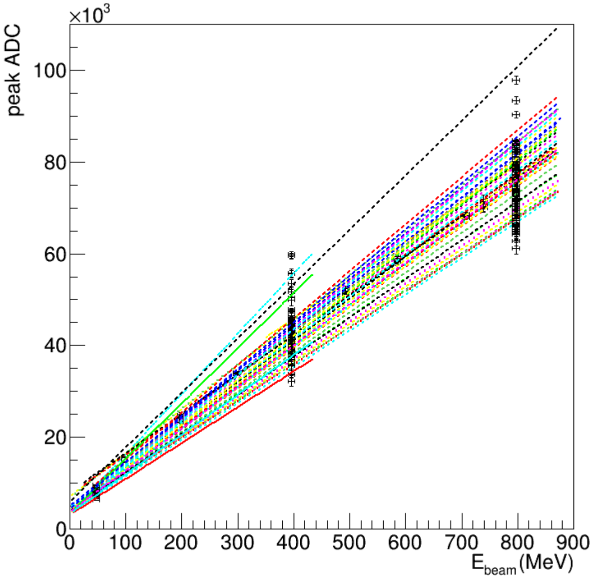
Num. of Hits



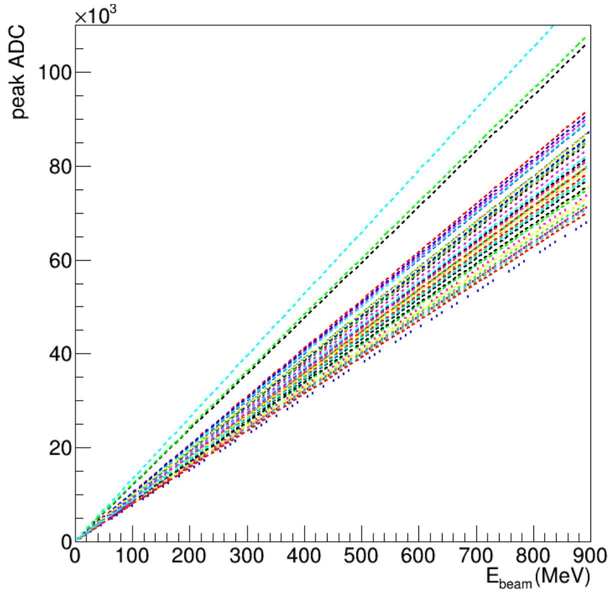
- Due to the time limitation, only one HV of SiPM was tested.
- Linearity looks fine. However, **nonlinearity starts to show up around 700MeV.** Efficiency is approximately **95%** for beam energies above **200 MeV**.

PbWO4 + SiPM : Gain Calibration

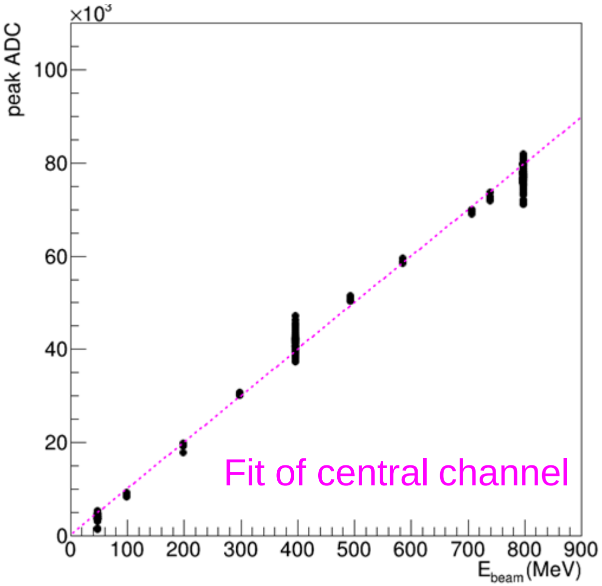
Linear fit of Emax



Gain calibration by fit

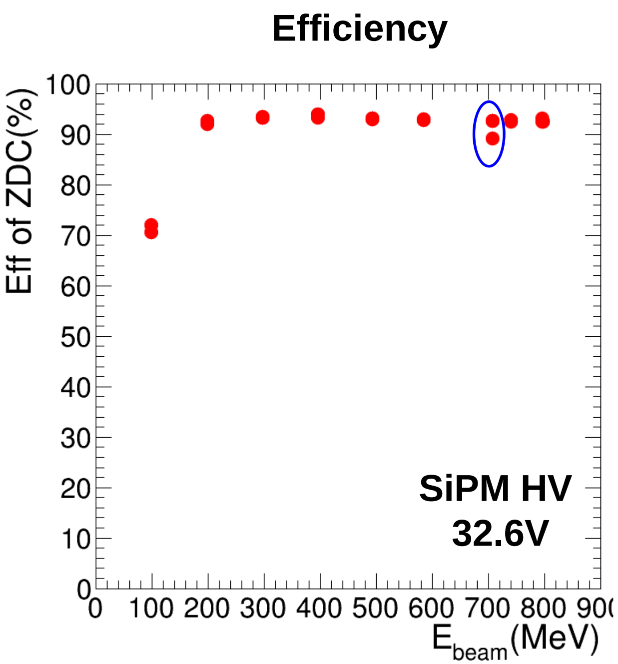


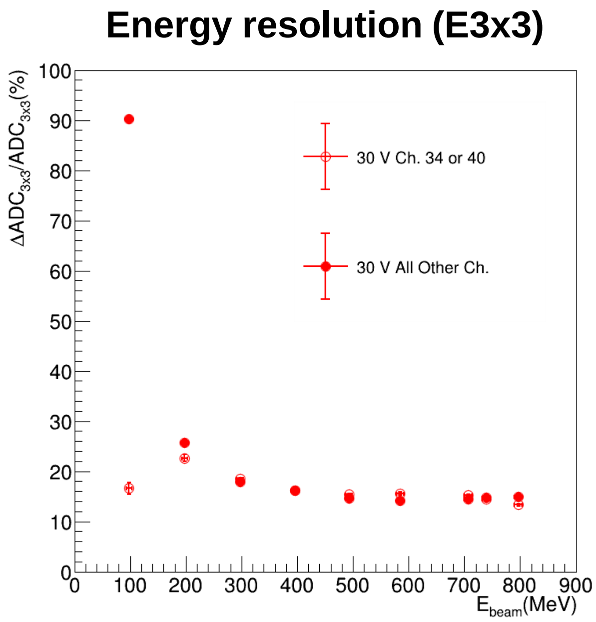
Emax after calibration

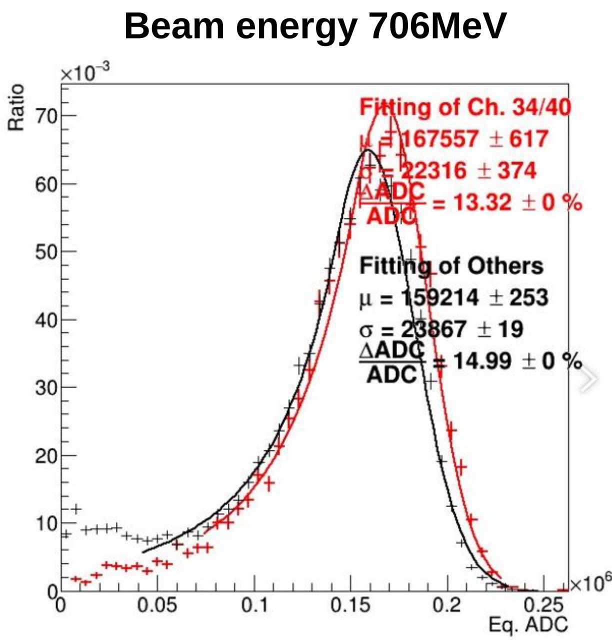


- **3 × 3 crystal** array was calibrated.
- Reference calibrated line is from central channel.

PbWO4 + SiPM : Energy Resolution (Preliminary)



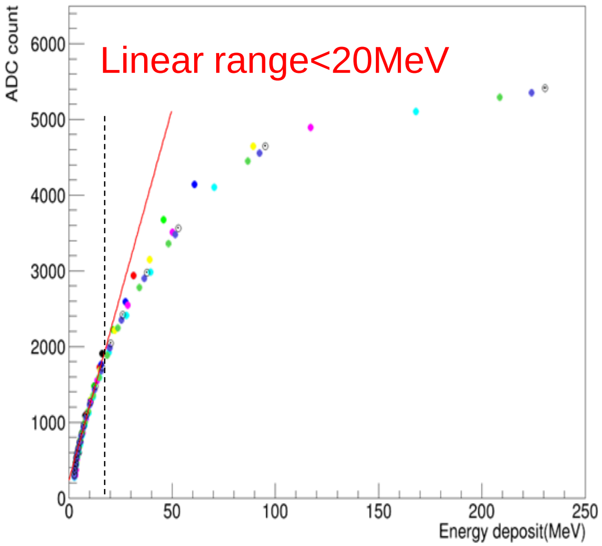




- Timing matching is the only applied track-matching criterion.
- **Energy resolution ~ 14% @ 706MeV.**
- Expected improvements through position matching and energy regression.

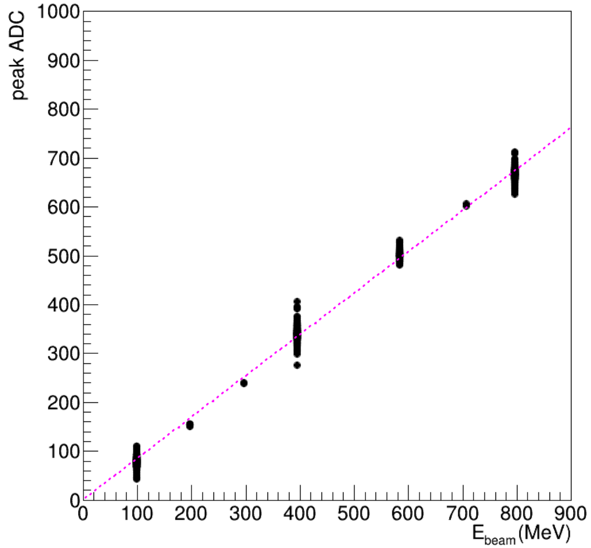
Gain Comparison

LYSO + SiPM



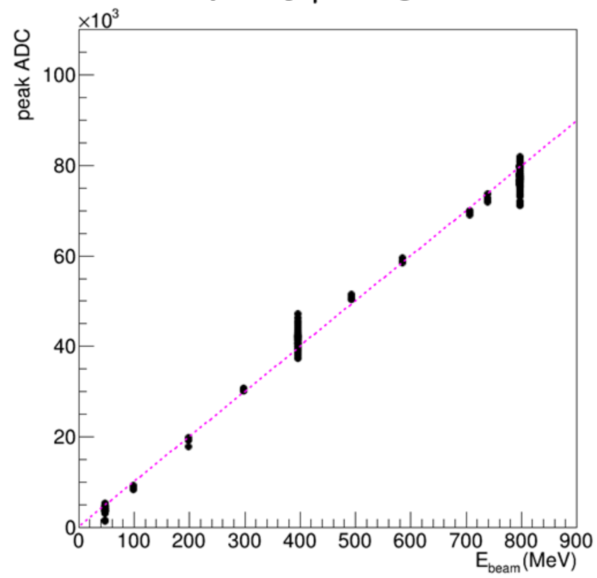
2000 ADC/ 20MeV
➔ 100 ADC / MeV

LYSO + APD



150 ADC/ 200MeV
➔ 0.75 ADC / MeV

PbWO4 + SiPM



20000 ADC / 200MeV
➔ 100 ADC / MeV

- All the systems were using same electronics with CITIROC chip.
- Gain of “LYSO + SiPM” system and “PbWO4+SiPM” system are similar.
- Gain of “LYSO + APD” system are 1/100 times smaller than the other two.

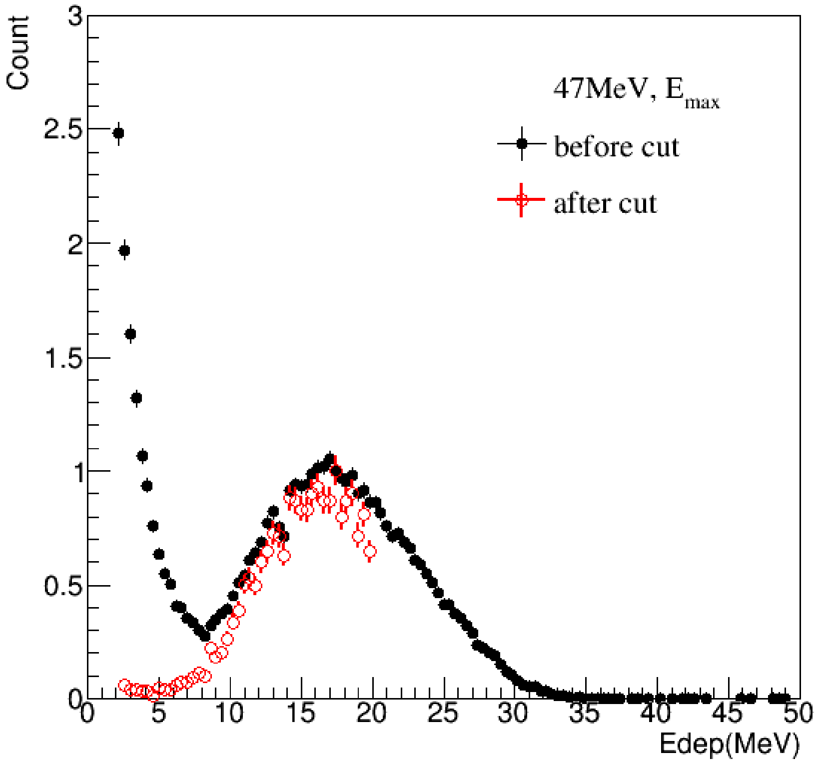
Summary

- **2nd Prototypes :**
  - Based on the results from the first beam test with the **LYSO + SiPM** system, **nonlinearity** was observed due to the system's high gain.
  - For the second prototype, two systems were designed :
  1) **LYSO + APD**
  2) **$PbWO_4$ + SiPM**

  The primary objective of these designs is to **reduce the system gain** and improve performance.
  - Additionally, a **beam monitor system** was implemented to enable better **beam selection**, enhancing the overall analysis quality.
- **Test beam**
  - The test beam was conducted at **RARIS (ELPH), Sendai, Japan, in February 2025**, using a **50–800 MeV positron beam**.
  - During the test, initial runs were performed to **optimize system settings**, including **HV and threshold adjustments**. Once the optimal settings were identified, a **position scan** was conducted to enable **offline gain calibration**.
  - **Preliminary Results:**
  1) **LYSO + APD: 40% energy resolution** at **800 MeV beam energy**.
  2) **$PbWO_4$ + SiPM: 15% energy resolution** at **800 MeV beam energy**.
  - Currently, **track matching is based only on timing synchronization**. Improved results are expected with **more detailed analysis**, such as **position matching of tracks and energy regression**.
  - The **poor performance of the LYSO + APD system** is still under investigation.

Back up

Selection Criteria



- **Two cut criteria**

(1) 2.5MeV<Emax<20 MeV

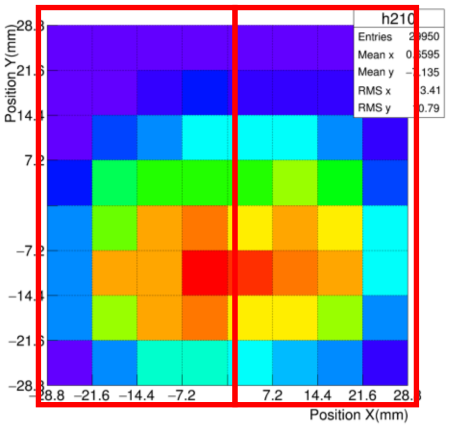
To focus data only in linear range and remove the low momentum photons coming from beam.

(2)Fire both left and right crystals

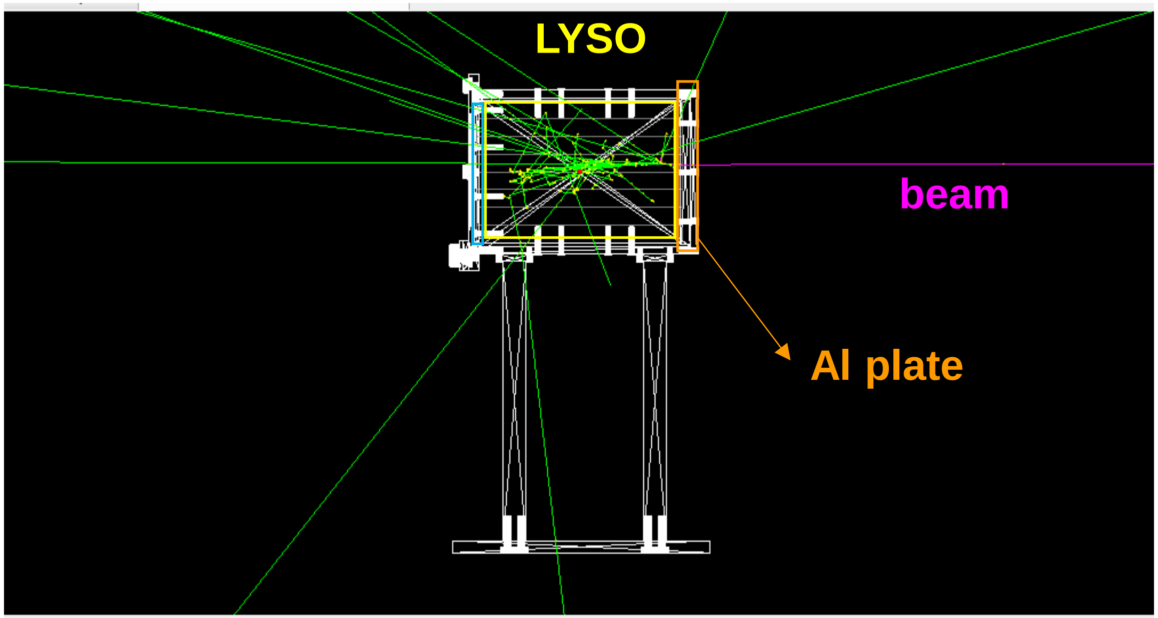
Ask hits from both FEE left and FEE right to remove events only contains noise.

We chose the 47MeV data only in linear range and remove the possible low energy photon and noise contributions.

- **Beam profile @ 47MeV**



MC Simulation



- **MC implementation**

① Detector geometry / material
② Beam momentum w/ resolution
③ Beam profile
④ Beam angle 90 degree

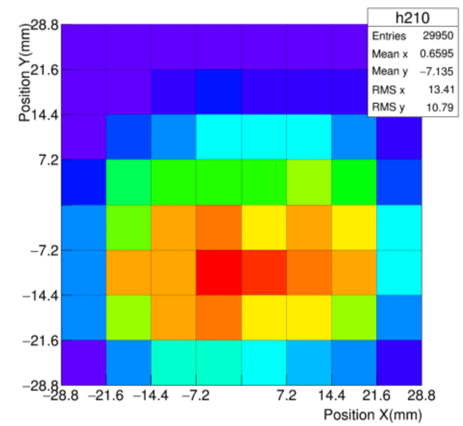
- **SiPM MC is not implement.**
  It should be fine for linear range data.

- **Beam Mom. w/ Res.**

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)

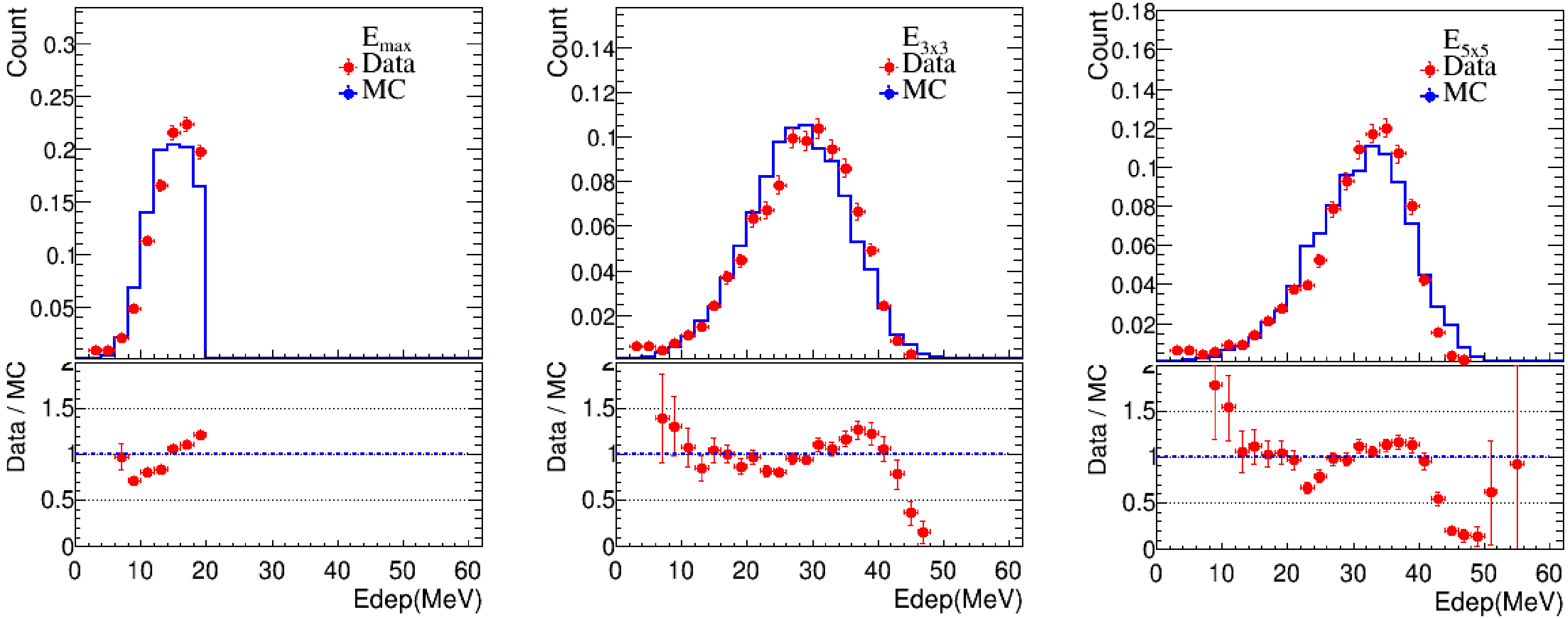
Energy resolution of 47MeV positron beam ~ 11.6%

- **Beam profile @ 47MeV**

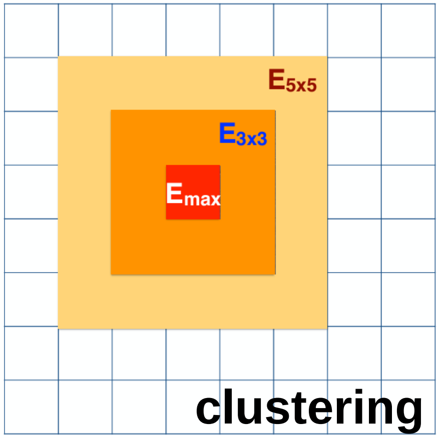


Beam is ellipse shape and not well centered.

Data and MC Comparison



Reasonable agreement between data and MC for 47MeV positron beam data.



Estimation of ADC Value

//============== **Gain values** ===================

- LYSO + SiPM : 2580/0.29 (digits/MeV)
- **SiPM gain = 1e6 ~ 5e6 (here use 1e6)**
- **APD gain = 1 ~ 100   (here use 100)**
- **LYSO PDE = 25e3-35e3 photons/MeV (here use 3.0e4 photons/MeV)**
- **PbO4 PDE = 1e2-2e2 photons/MeV   (here use 1.5e2 photons/MeV)**
- Note : Polystyrene 1e4

//============== **6X0 LYSO + APD** ===================

- ADC digits = [(2580/0.29)/1e6*1e2]*Emax = 0.89*Emax
- ADC dynamic range = 11, 000
- 50MeV electron , Emax = 21.5 , ADC = 19.18   => might be too low, close to noise level
- 800MeV electron, Emax = 240.1, ADC = 213.689
- 1GeV gamma   , Emax = 248.6, ADC = 221.254
- 40GeV gamma   , Emax = 3190, ADC= 2839.1

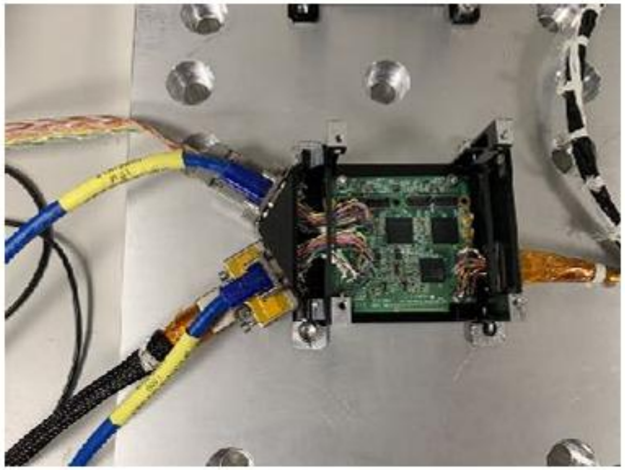
//============== **6X0 PbWO4 + SiPM** ===================

- ADC digits = [(2580/0.29)/3e4*1.5e2]*Emax = 44.48*Emax
- ADC dynamic range = 11, 000
- Saturation of SiPM ~ 3000 ADC
- 50MeV electron , Emax = 22.43, ADC =997.8
- 800MeV electron, Emax = 266.7, ADC = 11862.8   => out of linear range of SiPM
- 1GeV gamma   , Emax = 284.0, ADC = 12632.32 => out of linear range of SiPM also ADC dynamic range
- 40GeV gamma   , Emax = 4198 , ADC = 186727   => out of linear range of SiPM also ADC dynamic range

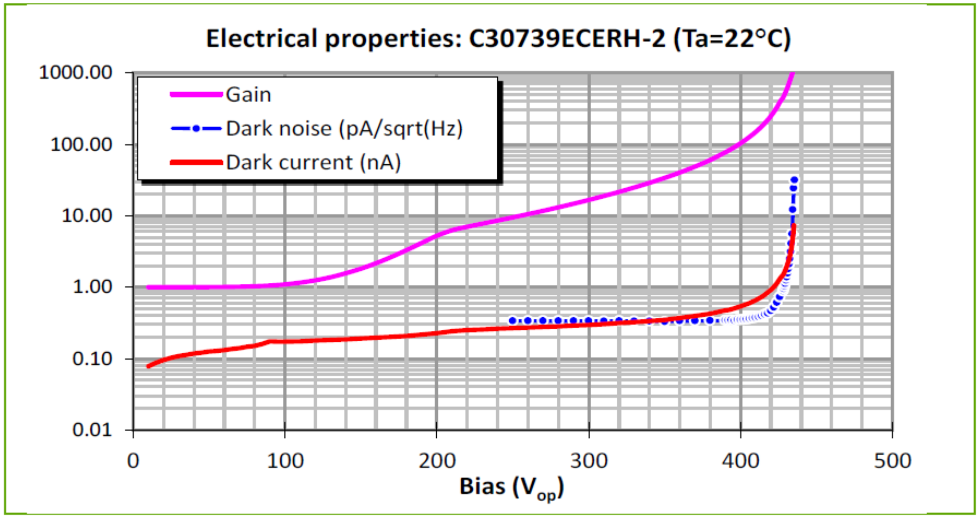
Readout of 1st Prototype

Readout for the ZDC ECAL Prototype with LYSO Crystals

- Designed by Chih-Hsun Lin of Academia Sinica
- 64 channels
- Trigger:
    - Self-triggered
    - Can accept external timing signal → needs to be studied
    - May accept external trigger → needs to be studied



APD : C30739ECERH, Standard



Symbol	Parameter	C30739ECERH (standard version)		
		Min	**Typ**	**Max**
V_{op}	Operating Voltage	-	400	420
dV	$dV = V_{br} - V_{op}$	-	15	-
M	Gain at V_{op}	80	100	-
Q.E.	Quantum Efficiency	65	80	-
R	Responsivity	-	26	-
T_{coeff}	Temp. Coefficient for constant gain		1.2	
C_J	Capacitance	-	60	-
t_R	Rise Time	-	2	-
I_D	Dark Current	-	1.5	-
I_N	Noise Current	-	0.3	-