ePIC ZDC ECAL Prototype Hardware and AC-LGAD

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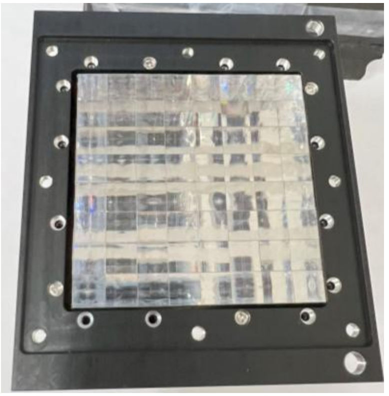
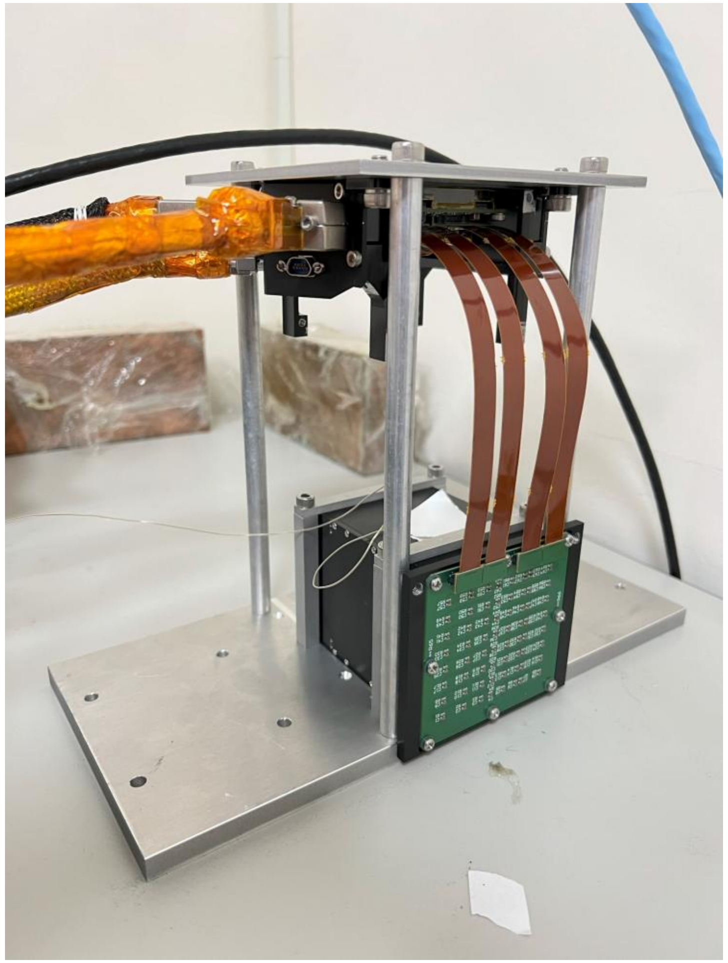
1^{st} Prototype LYSO ECAL

- **LYSO**
  - 8x8 array
  - Each crystal : 7.1mm*7.1mm*88.3mm ($8X_0$)
- **SiPM**
  - MICROFC-60035
  - 6x6 mm^2 sensitive area
- **Gamma-ray Transients Monitor (GTM) Readout board**
  - 2 Citiroc1A (2 x 32 channels)
  - Peak sensing mode

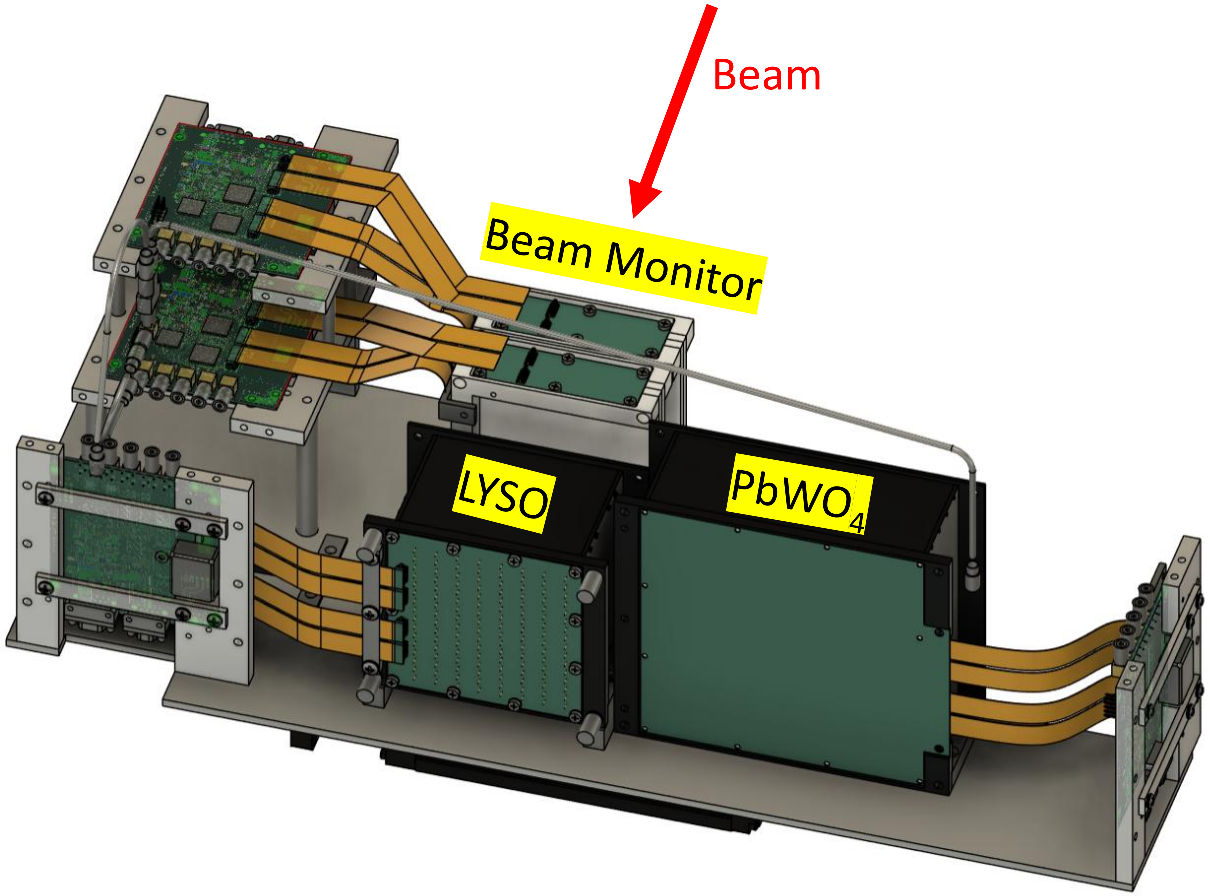
- ~12% energy resolution at 50MeV
- Obviously non-linear relation when energy lager than 50MeV
- (Show in Chia-Yu report)





2^{nd} Prototype LYSO ECAL

- **LYSO crystal:**
  - 8x8 array
  - APD readout
- **$PbWO_4$ crystal:**
  - 6x6 array
  - SiPM readout
- **Beam monitor x 2:**
  - 32 scintillator strip x 4
  - 2 X-Y monitor

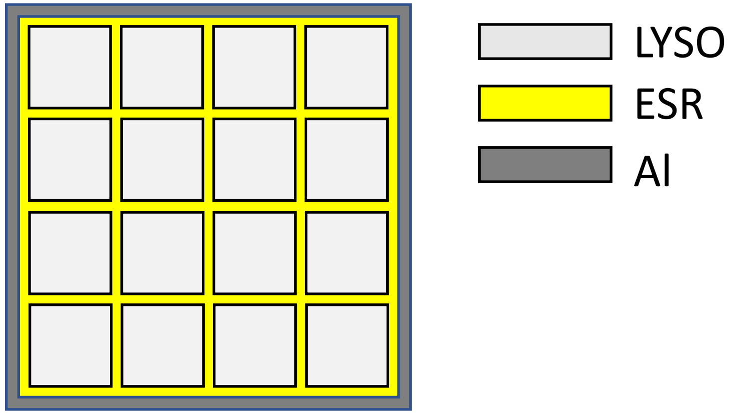


- Each of the four detectors acquires data independently and synchronizes timing using a 20 Hz clock.
- LYSO + APD energy resolution ~35%
- PbWO4 + SiPM energy resolution ~15%

LYSO Calorimeter

8 × 8 Crystal Array

- Crystal size: 1 cm × 1 cm × 6.6 cm (6 X_0)
- Light yield: ≈ 33k photons/MeV (≈100 × $PbWO_4$)
- Each crystal is wrapped with ESR on five sides
- A 4 × 4 crystal array forms one tower, wrapped with aluminum foil
- Four towers in total



APD (C30739ECERH)

- Activate area : 5.6 x 5.6 mm^2
- Operating Voltage : 400V
- Gain : x 100 (≈ 1/10000 x SiPM)
- Quantum efficiency : 80% at 430nm

APD operating voltage

394.5	391.4	390.3	389.4	382.5	381.6	390.8	392.3
390.3	384.1	384.8	383.8	387.5	384.2	382.3	379.4
382.8	385.3	386.7	386.5	386.7	385.2	382.8	379.9
389	385.3	386.3	385.9	386.1	385.3	389.2	392.4
389.2	387.1	386.6	385.6	385.3	385.1	389.5	379.4
382.3	388.9	384.7	386.6	384.3	388.7	389.6	380.8
381	394.7	381.3	382.7	381.8	381.6	391.2	392.2
394.5	393.9	393.6	392.6	393.4	393.7	394	393.9

APD Bias Difference

8.5	5.4	4.3	3.4	-3.5	-4.4	4.8	6.3
4.3	-1.9	-1.2	-2.2	1.5	-1.8	-3.7	-6.6
-3.2	-0.7	0.7	0.5	0.7	-0.8	-3.2	-6.1
3	-0.7	0.3	-0.1	0.1	-0.7	3.2	6.4
3.2	1.1	0.6	-0.4	-0.7	-0.9	3.5	-6.6
-3.7	2.9	-1.3	0.6	-1.7	2.7	3.6	-5.2
-5	8.7	-4.7	-3.3	-4.2	-4.4	5.2	6.2
8.5	7.9	7.6	6.6	7.4	7.7	8	7.9

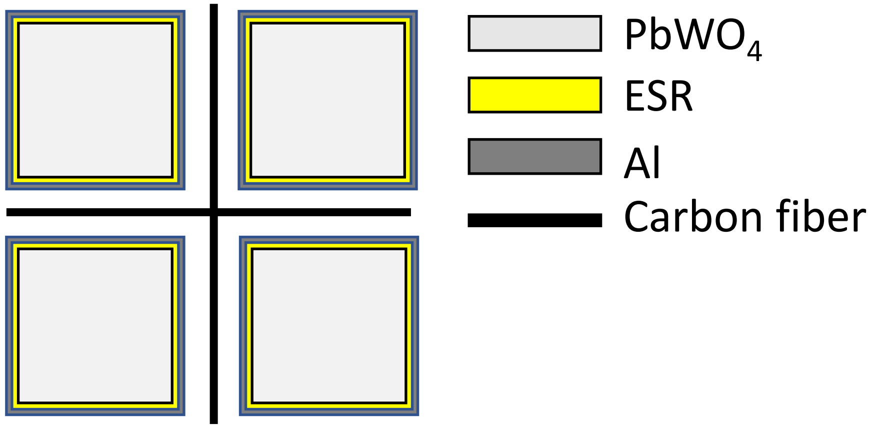
$PbWO_4$ Calorimeter

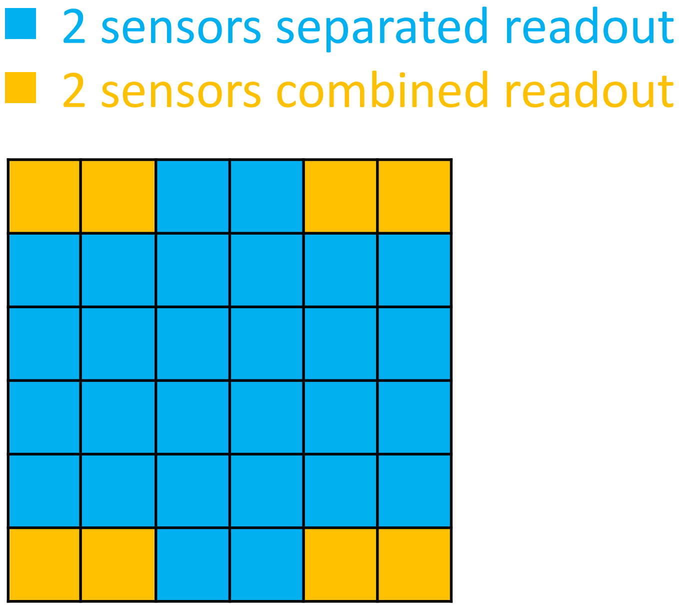
6x6 $PbWO_4$ Crystals

- Bar Size : 2cm*2cm*5.3cm(6X0)
- Light yield : 300
- Each crystal is wrapped with ESR and aluminum foil on five sides.
- Each Crystal bar has two SiPM sensor
- The two SiPMs on the central crystal are read out separately
- The corner crystals use combined readout.

SiPM (ONSEMI MICROC-60035)

- Activate area : 6 x 6 mm^2
- Breakdown Voltage : 24V
- Gain : > 10^6
- Photon detection efficiency (PDE) : 41% at 430nm





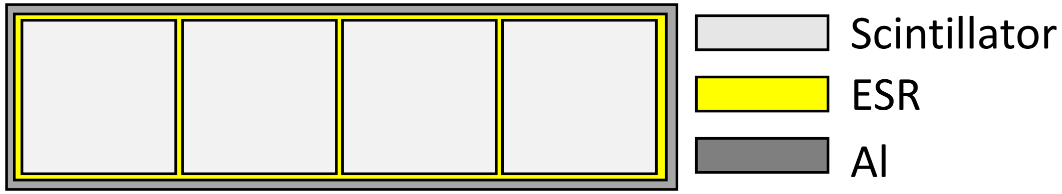
Beam Monitor

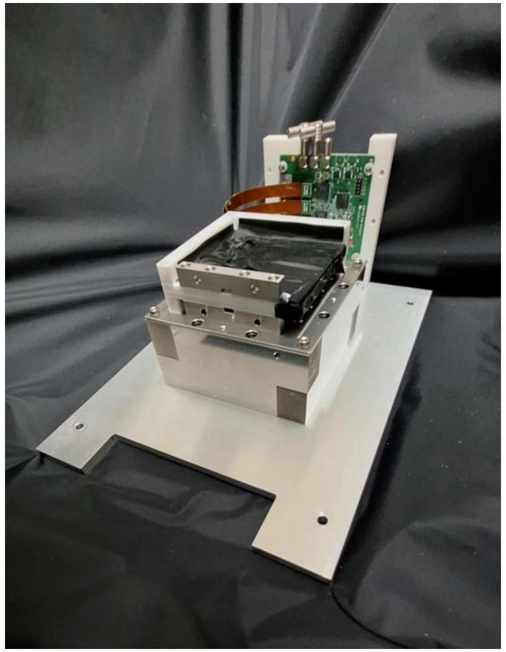
X-axis: 32 scintillator bars
Y-axis: 32 scintillator bars

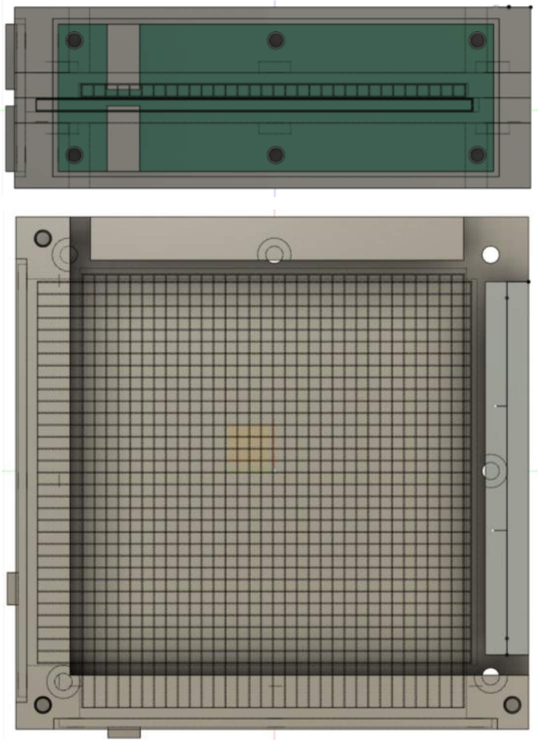
- Bar size: 2 mm × 2 mm × 75 mm
- The monitors cover a 5 × 5 region in the LYSO array and a 3 × 3 region in the $PbWO_4$ array.
- Each bar is wrapped with ESR
- A 1 × 32 scintillator bar array is wrapped with aluminum foil
- Two X–Y position monitors are installed

SiPM (ONSEMI MICROC-10020)

- Activate area : 1 x 1 mm^2
- Breakdown Voltage : 24V
- Gain : > 10^6
- Photon detection efficiency (PDE) : 41% at 430nm





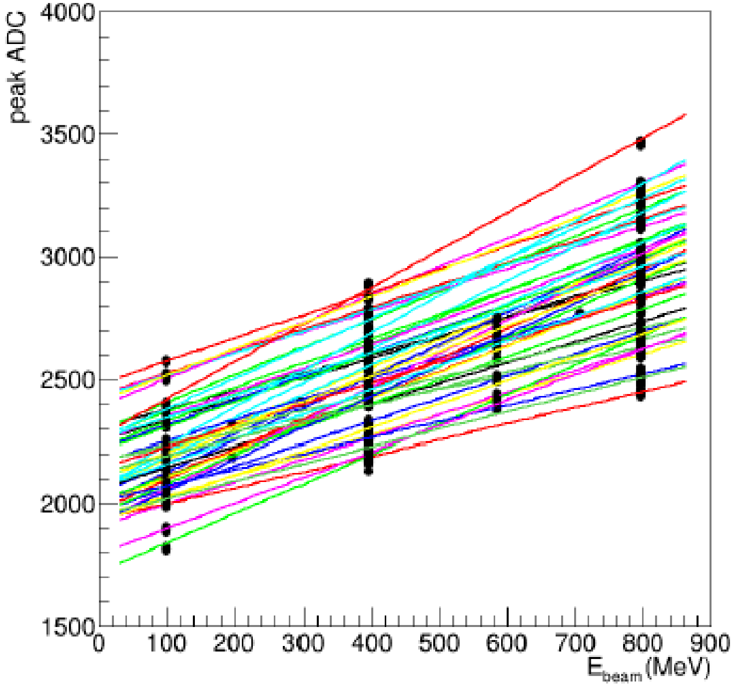


LYSO + APD Gain Calibration

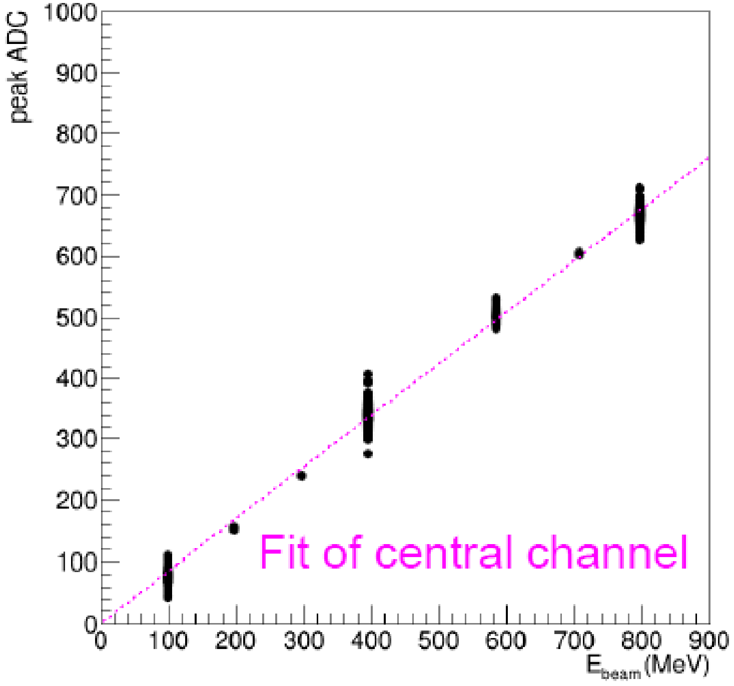
Calibration procedure:

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.

Before Gain Calibration



After Gain Calibration

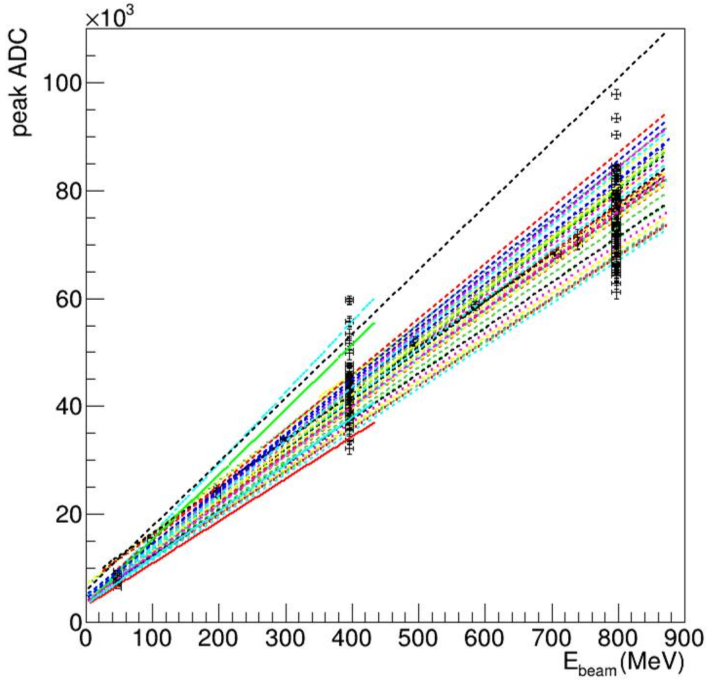


$PbWO_4$ + SiPM Gain Calibration

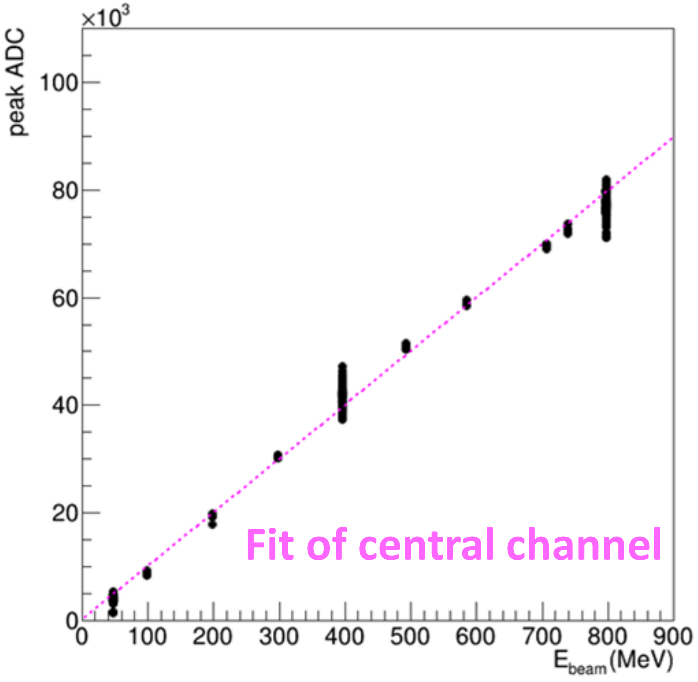
Calibration procedure:

The beam energy was varied to scan all channels in the 3×3 crystal array. The gain of each channel was then adjusted (scaled and shifted) so that its response aligned with that of the central channel.

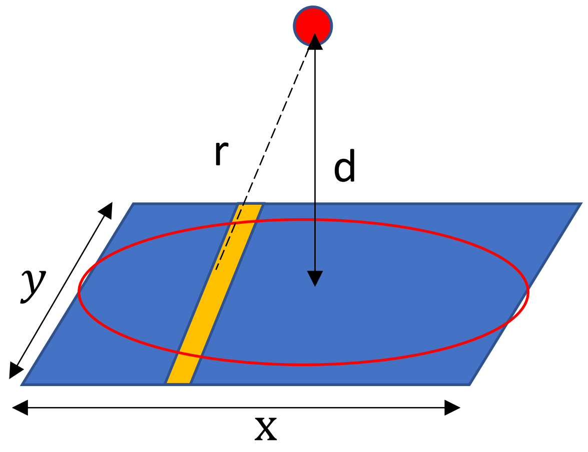
Before Gain Calibration



After Gain Calibration

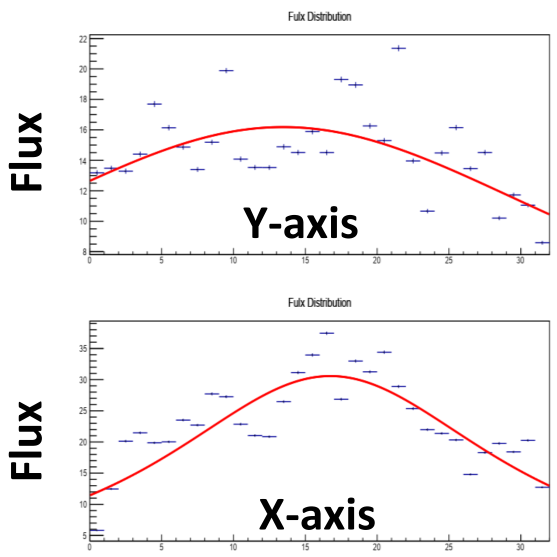


Beam Monitor Gain Calibration

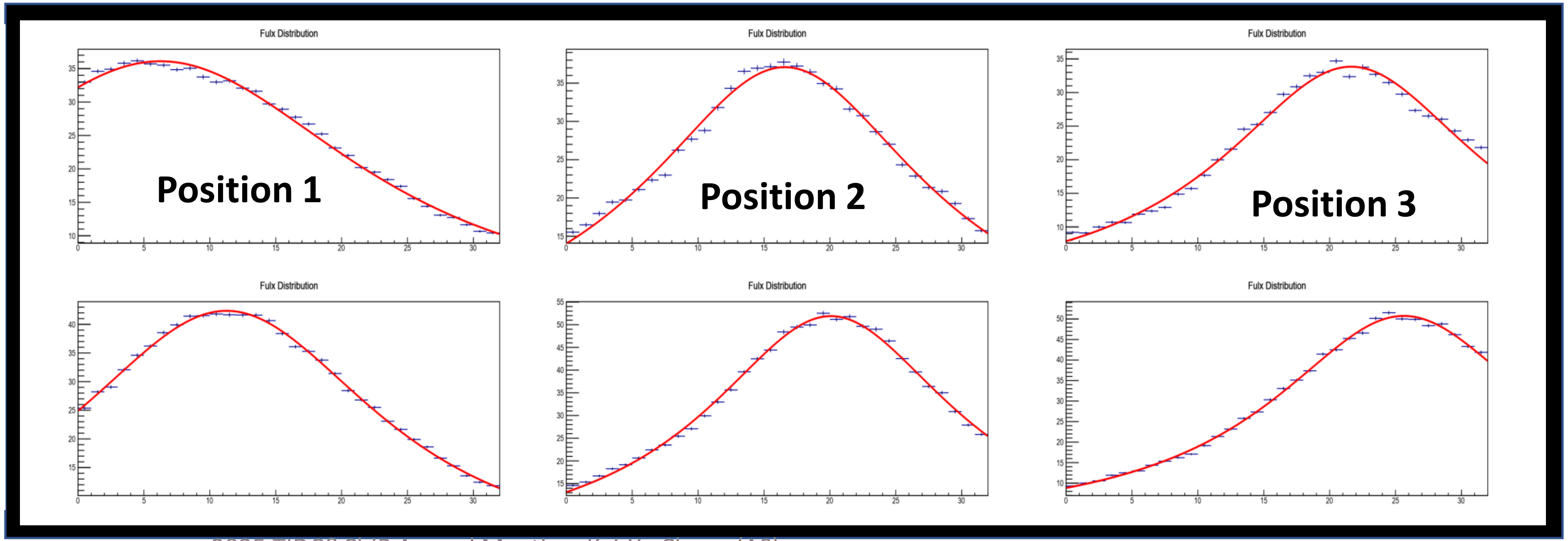


- Using flux of ^{22}Na source to do the beam monitor calibration.
- Channel flux $\propto \Omega \propto \iint \frac{d}{((x-x_0)^2+(y-y_0)^2+d^2)^{3/2}} dxdy$
- Flux distribution results with source placed at different positions after calibration

Before Calibration



After Calibration

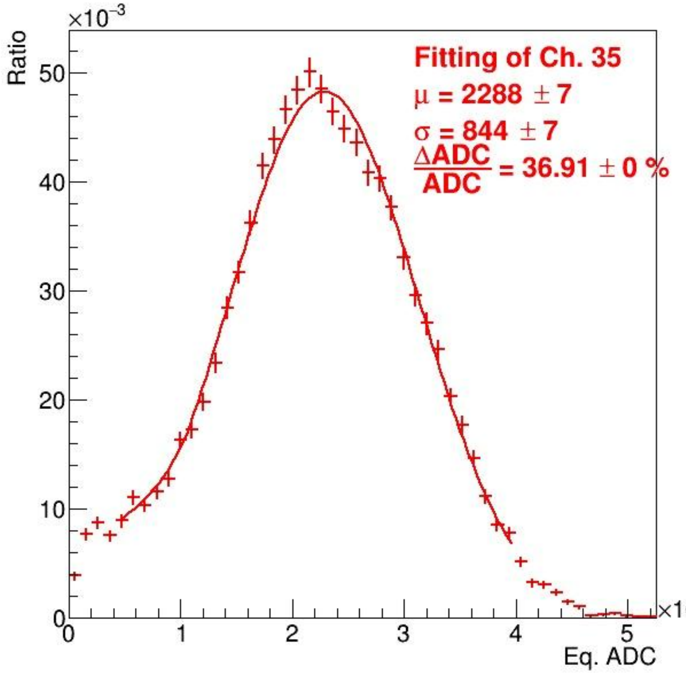


Clustering Spectrum After Gain Calibration

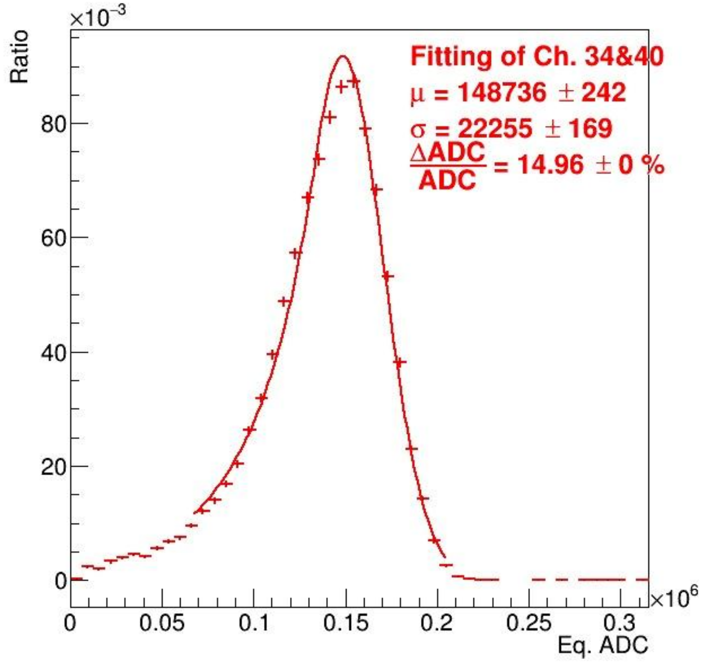
Energy spectrum from summed ADC values using 5 × 5 (LYSO) and 3 × 3 ($PbWO_4$) clustering after gain calibration.

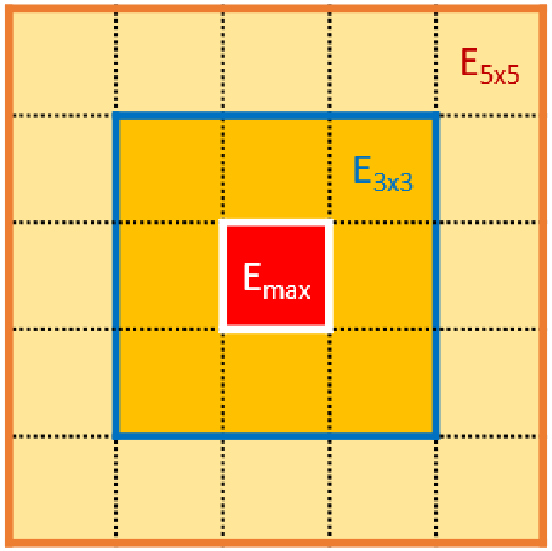
※No energy regression applied.

LYSO 706MeV



$PbWO_4$ 706MeV





Plan List

2nd Prototype ZDC ECal

- Cosmic Ray Study
- Noise Study

3rd Prototype ZDC ECal

- Using H2GCROC DAQ.
- Change to Hamamatsu S141603010 SiPM for LYSO Crystal
  Higher micro pixels density => higher dynamic range
- Change to Hamamatsu S141603015 SiPM for PbWO4 Crystal
  Number of pixels are lower than S141603010, but has higher PDE => better choice for PbWO4

Maximum Energy Estimate for 3rd Prototype :

$$3010PS: E_{max} = \frac{89984\ pixels * 0.7(Linear\ range)}{18\%\ (PDE) * collected\ ratio} * \frac{10 * 10mm^2}{3 * 3mm^2} * \frac{1}{33\text{k}\ (Photons/MeV)} \geq 117.8\ MeV \quad \Rightarrow E_{beam} = \frac{117.8\ MeV}{39\%} \geq \mathbf{302MeV}$$

$$3015PS: E_{max} = \frac{39984\ pixels * 0.7(Linear\ range)}{32\%\ (PDE) * collected\ ratio} * \frac{20 * 20mm^2}{3 * 3mm^2} * \frac{1}{300\ (Photons/MeV)} \geq 13.0\ GeV \quad \Rightarrow E_{beam} = \frac{1.30\ GeV}{45\%} \geq \mathbf{28.9GeV}$$

ePIC ZDC ECAL Prototype Hardware
and
AC-LGAD

Cheng Kai-Yu

AC-LGAD Production in Taiwan

Project Objectives

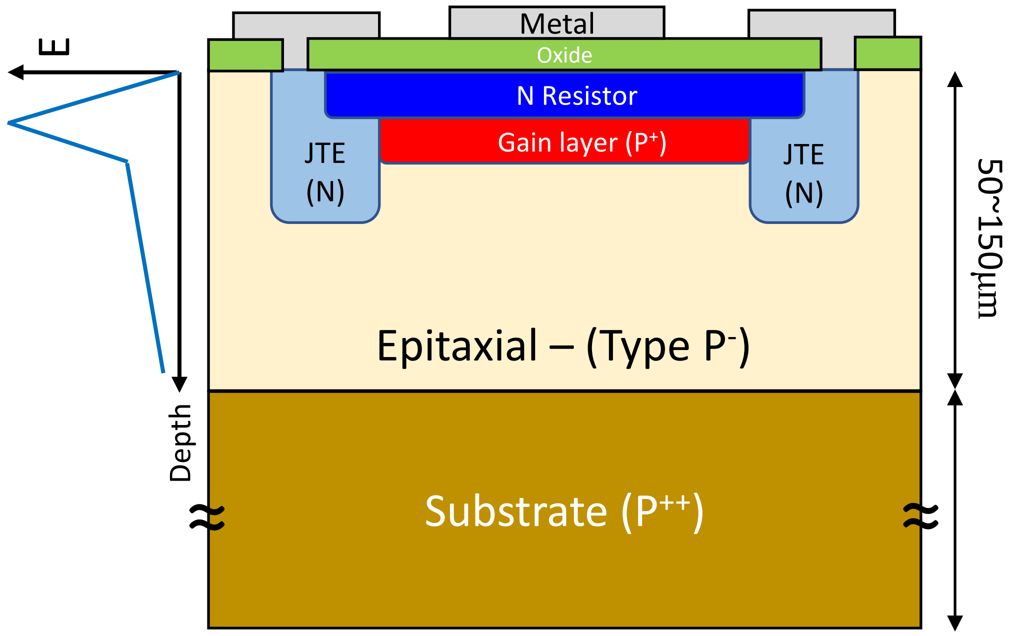
- Partner with Brookhaven National Laboratory (BNL) to establish AC-LGAD production capability in Taiwan for the Electron-Ion Collider (EIC).
- Develop a localized particle sensor production line and learn fabrication expertise.

Project Progress

- Identified two foundries with process capabilities aligning with BNL requirements.
  - 鼎元光電 (Tyntek)
  - 茂矽電子 (MOSEL)
- Completed initial process parameter verification at Tyntek.
  - Validated manufacturing capabilities for BNL technical review.
  - Provided baseline data for TCAD simulation calibration.

Rapid Process Validation in 鼎元光電

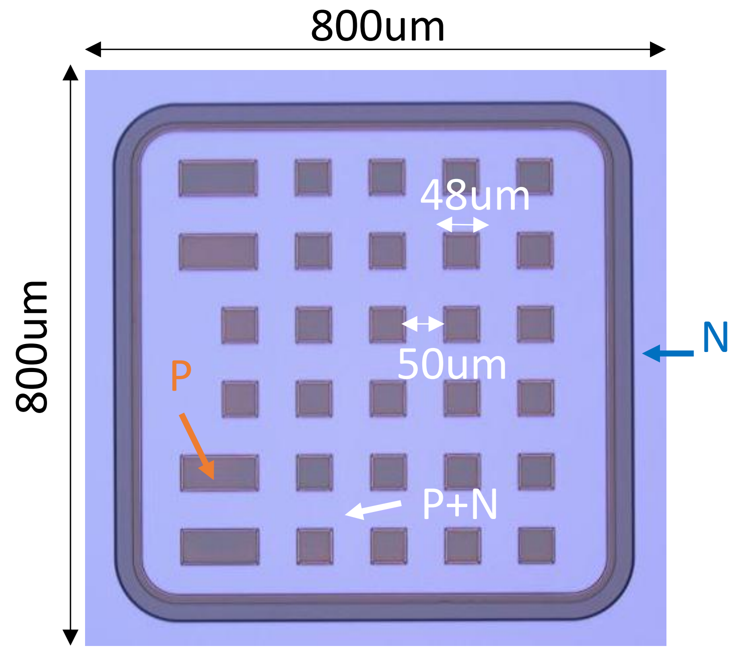
- **SIMS-based verification** of **gain-layer** formation and **n-type sheet resistance** process reliability
- Serves as a **simulation calibration reference**
- **Process Split:** One p-type and two n-type implant groups.
- **Four wafers per split**
- No electrode structures were included.

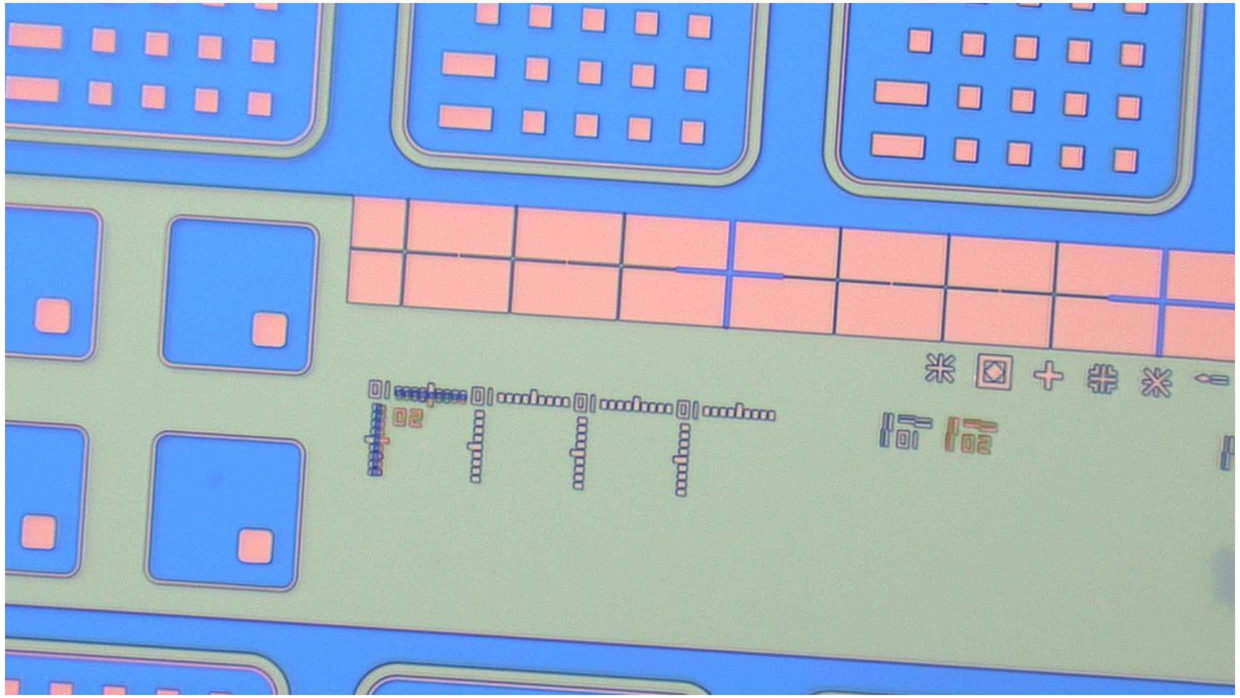


	Implant 1			Diffusion 1		Implant 2			Diffusion 2	
	impurities	Dose(cm^{-2})	Energy	^{o}C	min	impurities	Dose(cm^{-2})	Energy	^{o}C	min
#03-06	B	1.00E+12	380keV	800	20	As	1.00E+14	90keV	800	20
#07-10						P		80keV		

Pattern Resolution

- For rapid process validation (non–full process), an in-house MOS test mask was adopted.
- Among the eight test wafers fabricated, the photomask patterns exhibited good clarity and uniformity.
- However, further optimization of the photoresist baking process is required to prevent minor localized exposure defects.

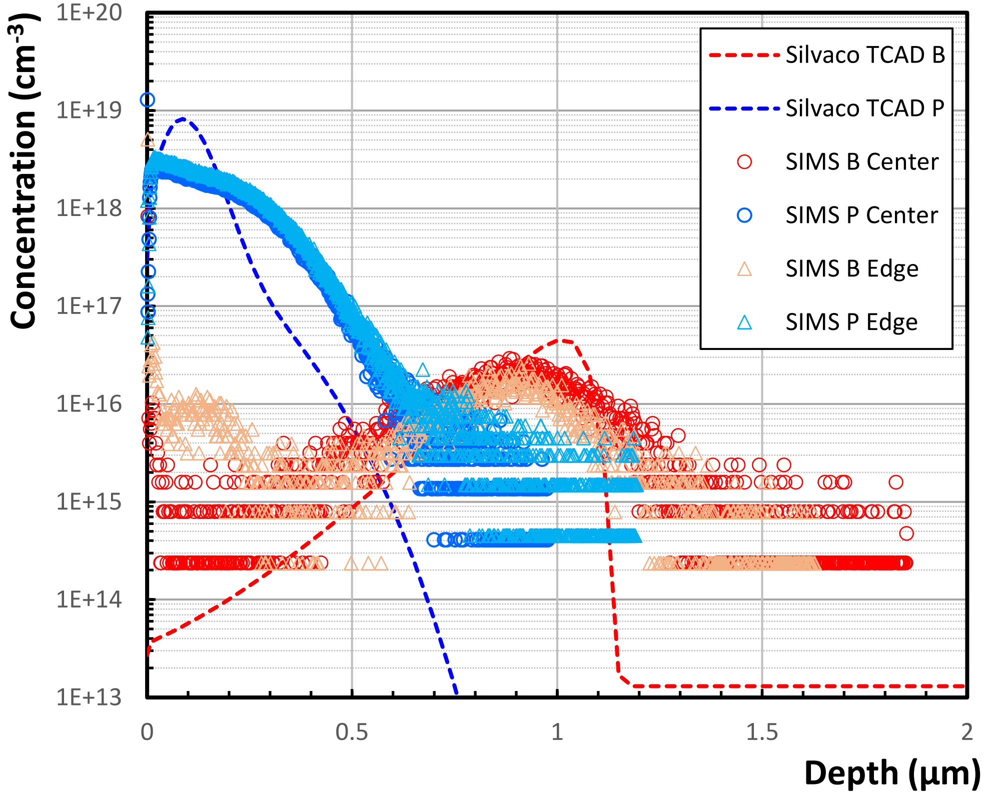




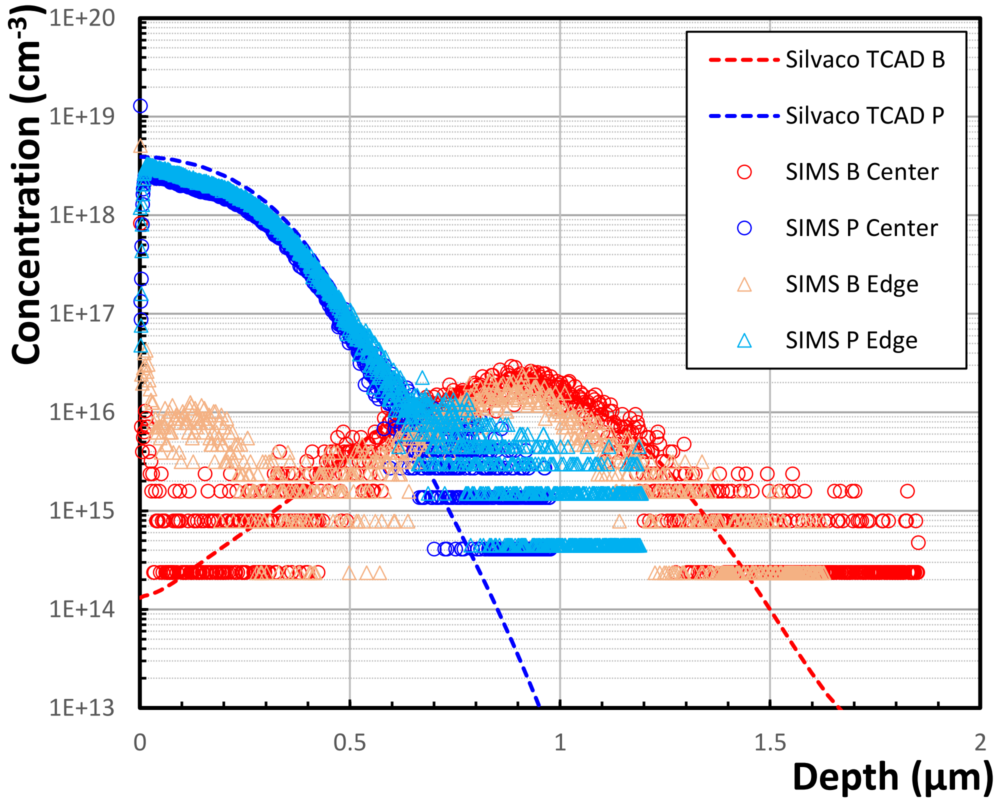
TCAD Process Simulation Calibration

- Including implantation-induced damage in the simulation significantly improved agreement with the SIMS measurements.

Simulation before fabrication



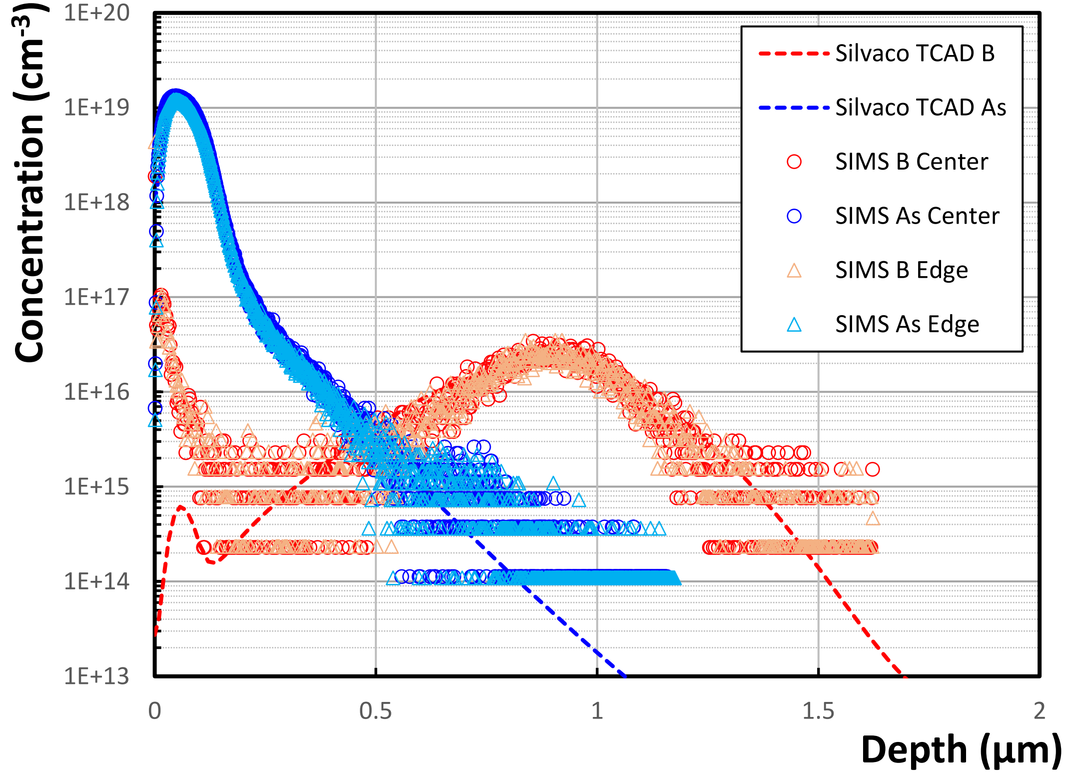
Simulation after fabrication



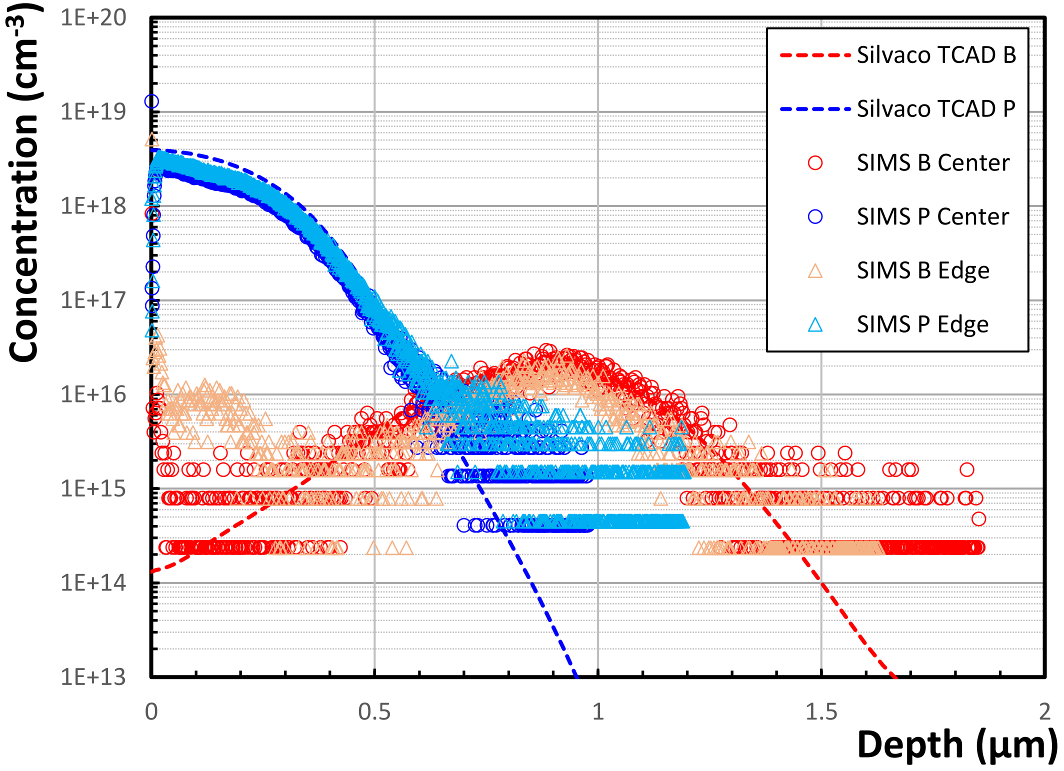
SIMS & TCAD with Calibration

	Implant 1			Diffusion 1		Implant 2			Diffusion 2	
	impurities	Dose(cm^{-2})	Energy	°C	min	impurities	Dose(cm^{-2})	Energy	°C	min
#04	B	1.00E+12	380keV	800	20	As	1.00E+14	90keV	800	20
#10						P	1.00E+14	80keV		

Wafer #04 As + B



Wafer #10 P + B



Full Process

- After the test run, we received detailed full process technical documentation from BNL.
- We are currently discussing the full-process AC-LGAD fabrication with 鼎元光電 (Tyntek) and 茂矽電子 (MOSEL).
  - 6-inch EPI wafer processed using stepper masks
  - Process splits: AC coupling capacitor process and implant dose
- The first fabrication run is expected to begin in late January.
- The first run aims to direct compare with BNL sensors to benchmark the process status in Taiwan.
- Measurement Plan :
  - I–V and C–V characterization
  - LGAD gain measurement
  - n-type sheet resistance
  - RC coupling performance
  - SIMS analysis

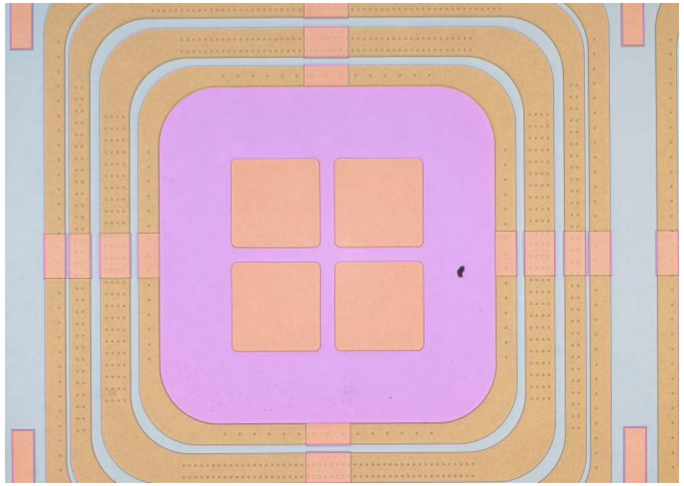
- In later tests, different process and other options will be studied.

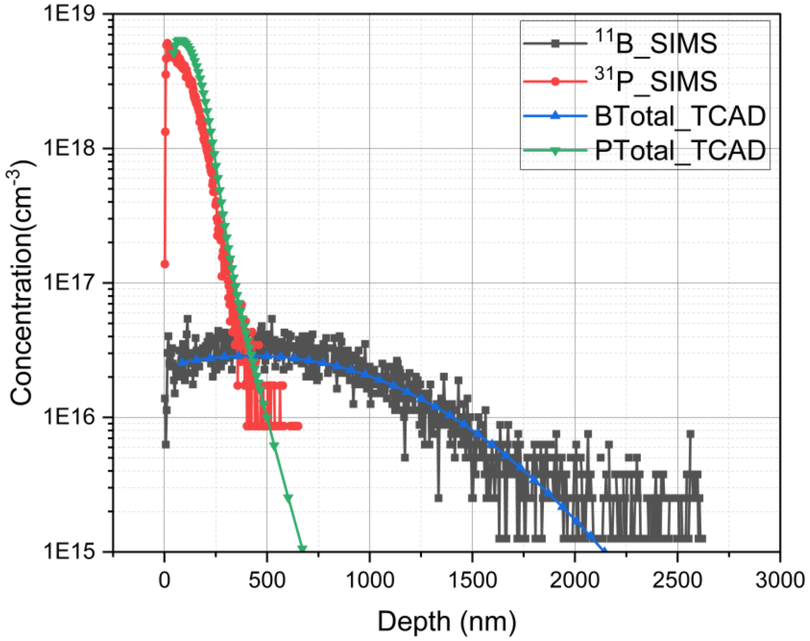
Process Study at TSRI

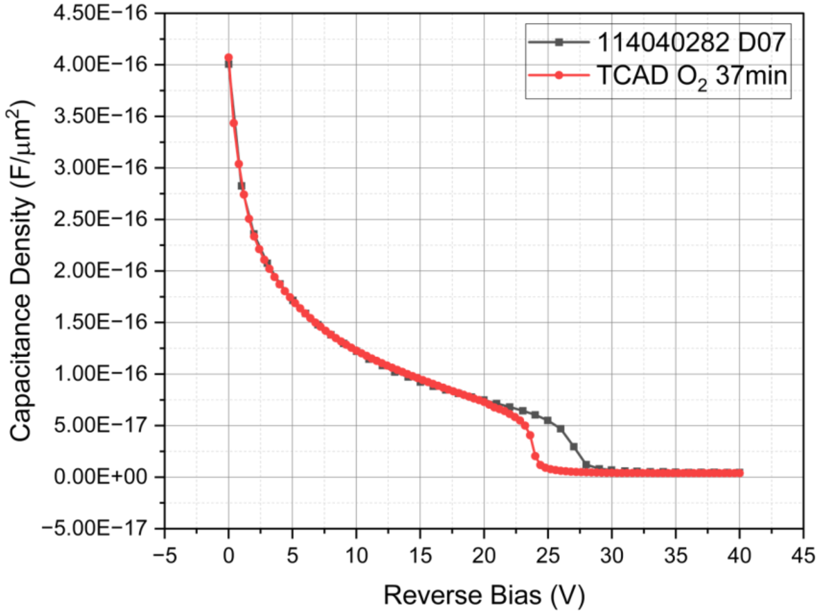
Collaborator: Prof. I-Shan Lee (NTHU), Yu-Hsuan, Lee

Objective: To obtain process know-how through hands-on AC-LGAD fabrication by students at TSRI. This experience will help us better understand how to adjust the process based on LGAD measurement results.

- Across three test runs, the students successfully resolved multiple process-related technical issues encountered at TSRI.
- The SIMS measurements and C–V curves show good agreement with TCAD simulation expectations.



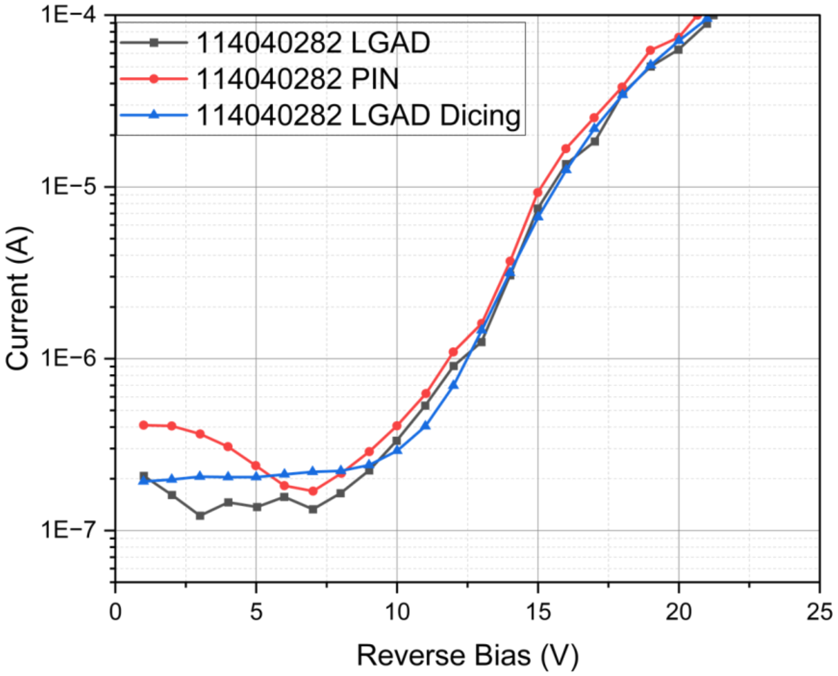




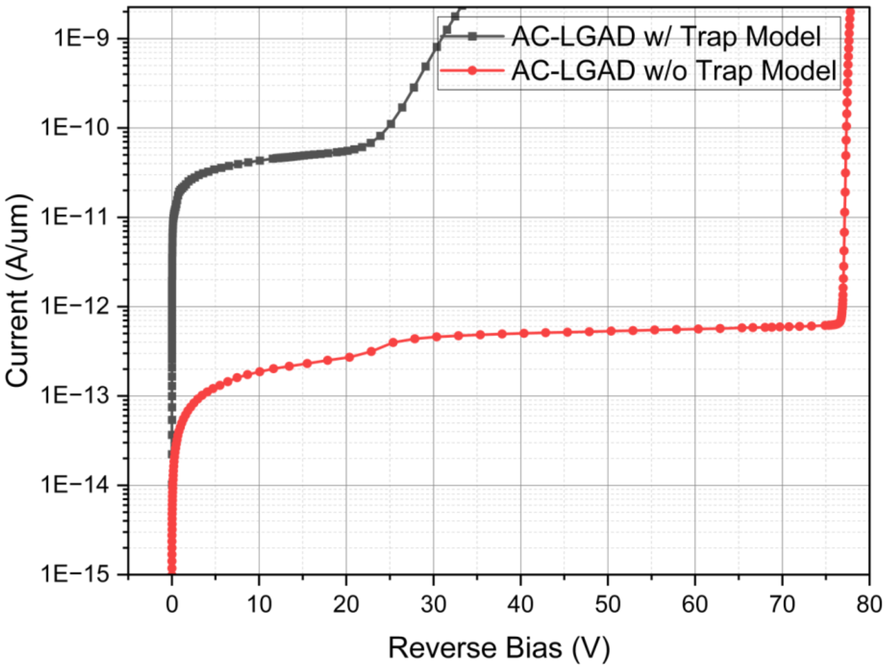
I-V Analysis and Simulation Study

- Severe leakage current was observed in the TSRI samples during electrical testing, indicating the need for further process optimization.
- The leakage current issue may be related to Dit, defined as the trap density at the Si/oxide interface.
- Potential process adjustments are currently being investigated through TCAD simulations.

Sample Measurement



TCAD Simulation (w & w/o Trap Model)



Summary

ZDC Crystal ECal

- **In the second prototype, the detector system consisted of LYSO + APD, $PbWO_4$ + SiPM, and two position monitors.**
    - After gain calibration, the **energy resolution** was measured to be **35% for LYSO** and **15% for $PbWO_4$**, **without applying energy regression.**
- **A linear response was achieved for LYSO read out by APDs; however, the energy resolution degraded significantly.**
    - This issue is still under study and may be related to the APD operating conditions and readout configuration.
- **We're currently focusing on improving electronic noise performance.**
    - During the second beam test, the poor S/N ratio led to a loss of energy details.
    - The threshold level has been reduced to ~17 MeV, and stability tests are ongoing.
- **In the next version, the H2GCROC DAQ will be used together with high-density SiPMs from Hamamatsu.**
    - The expected dynamic range is up to ~28 GeV for $PbWO_4$ and ~300 MeV for LYSO.

Summary

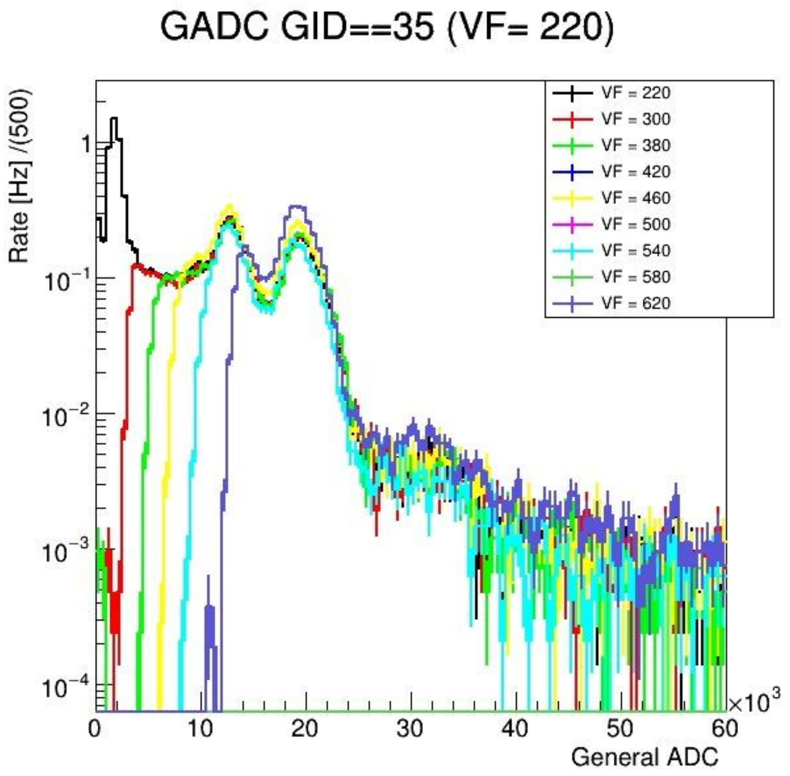
AC-LGAD

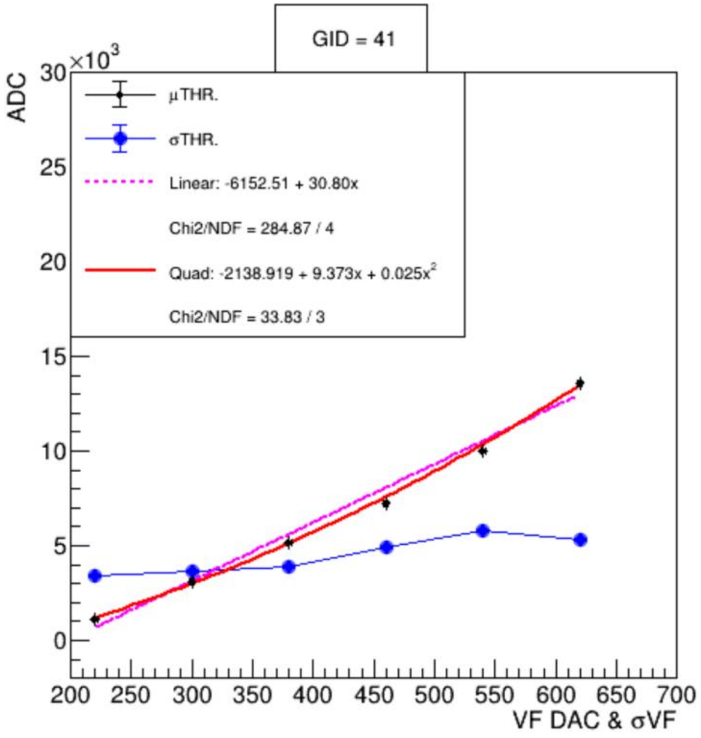
- **In collaboration with BNL, and based on BNL's experience in AC-LGAD development, we aim to establish an LGAD production line at 鼎元光電 (Tyntek) and 茂矽電子 (MOSEL).**
  - The goal is to produce a portion of the AC-LGAD sensors for the EIC.
- **Rapid process validation at Tyntek shows that implantation-induced damage must be included in simulations to achieve good agreement with experimental data.**
  - The damage behavior may be partly caused from the AC coupling oxide capacitor process, which will be included in test.
- **The full-process fabrication is in progress, aiming for a direct comparison with BNL AC-LGAD samples under identical process conditions.**
  - AC-LGAD samples from BNL have been received.
  - Next step : Establish the measurement system and characterization workflow based on BNL's recommendations.
- **Process studies are also ongoing at TSRI to support future LGAD analysis.**
  - Good agreement has been achieved in the doping profiles.
  - Large leakage current due to process-related issues is still under investigation through simulation tuning.

Back up

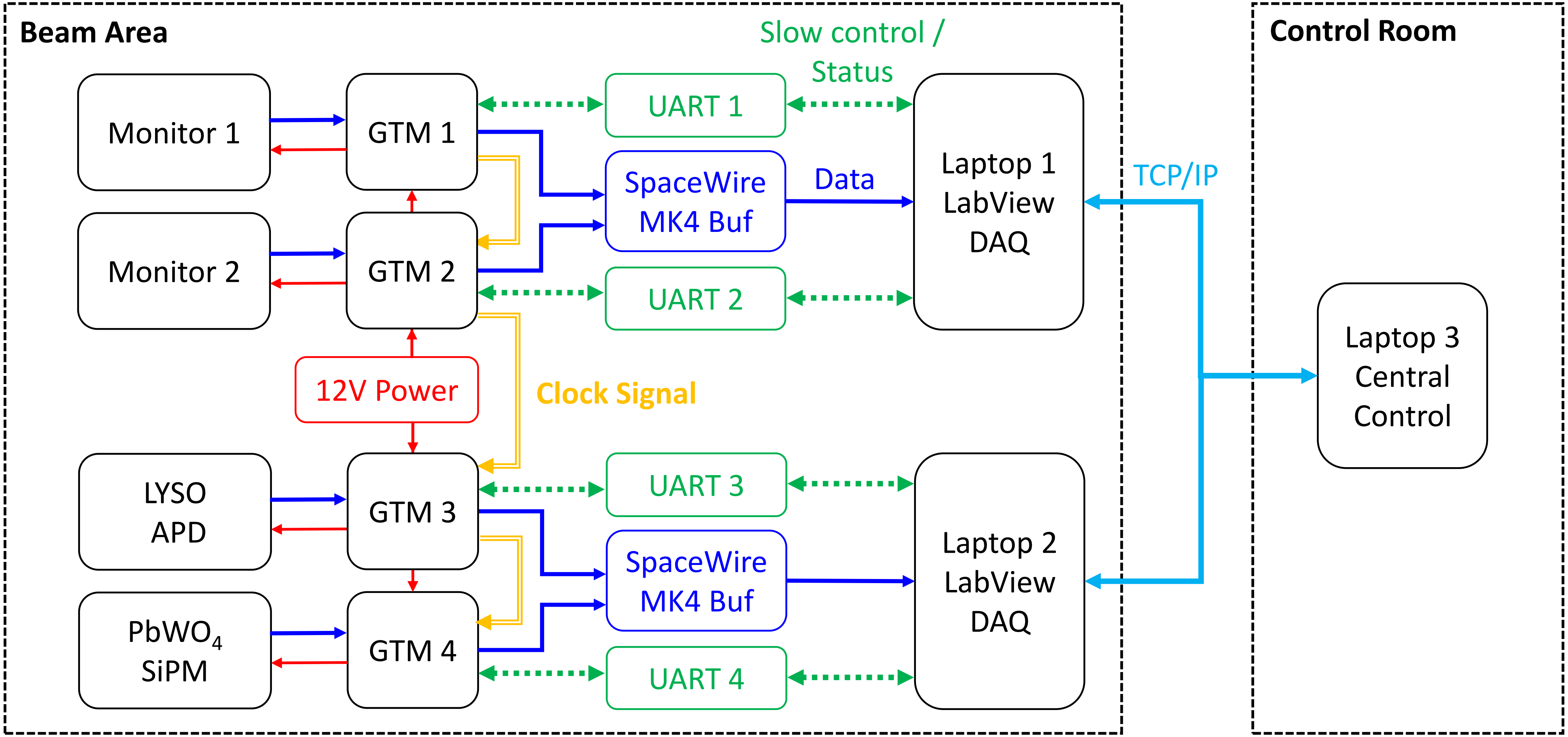
Threshold Study (DAC to ADC Mapping)

- Due to excessive system noise in the second experiment, a more stable GAGG+SiPM module was used to help study the relationship between threshold and voltage.
- The discriminator threshold setting of CITIROC is independent of the input signal and the module.
- Once the ADC cut corresponding to a given threshold DAC value is identified, the corresponding energy cut used in the beam test can be determined.





Setup of 2nd ZDC ECAL Prototype

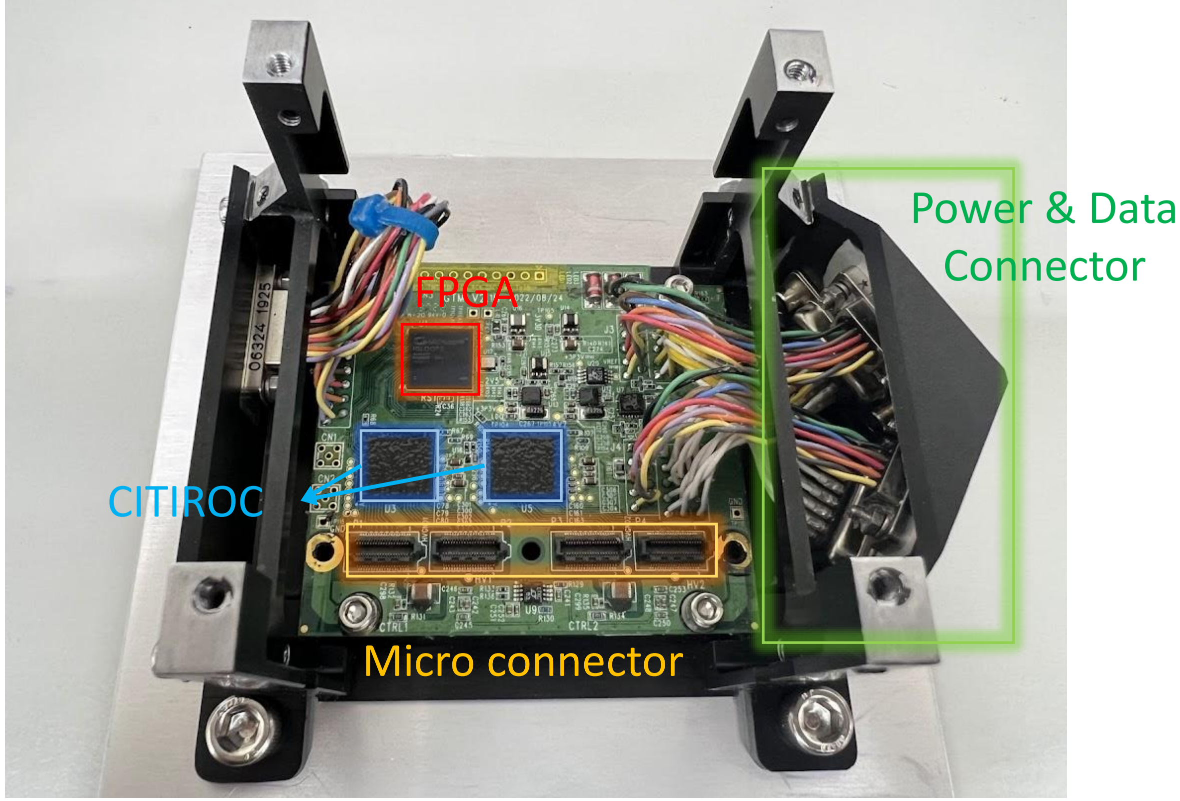


GTM Readout Board

Gamma-ray Transients Monitor (GTM)

The SiPM array readout system for gamma-ray detector in other space experiment. It includes :

- FPGA chip
- 2 x CITIROC 1A ASIC = 2 x 32 channels
- 2 x High-voltage convertor for bias of SiPM
- Samtec Micro Blade & Beam connectors for SiPM interface (16 channels + HV + GND)
- SpaceWire data interface
- Self-Trigger mode
- Maximum taking rate : 40k Hz



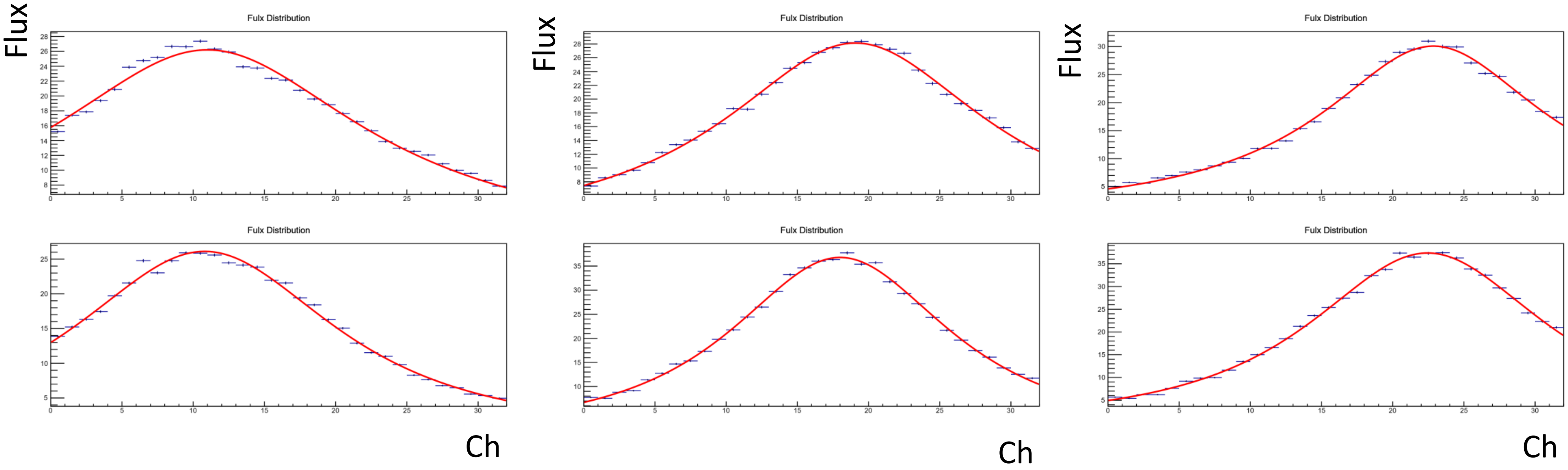
BM2 Flux Distributions after Ch Adjustment

- Flux distribution results with the ^{22}Na source placed at different positions under the same voltage setting.

Position 1 **Position 2** **Position 3**

Y-axis (ROCA)

X-axis (ROCB)



TCAD Device Simulation

- Electrical simulations were performed based on the corrected doping profiles.
- $Gain = {}^{Q_{gernerated}}/_{Q_{Injected}}$
- Due to variations in boron concentration, the **As + B** condition did not achieve sufficient gain.
- In contrast, the **P + B** case still showed adequate gain in the simulation.
- The n-type sheet resistance was ~600 Ω/□.