Status and planning of ECAL R&D

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On behalf of CEPC Calorimeter working group

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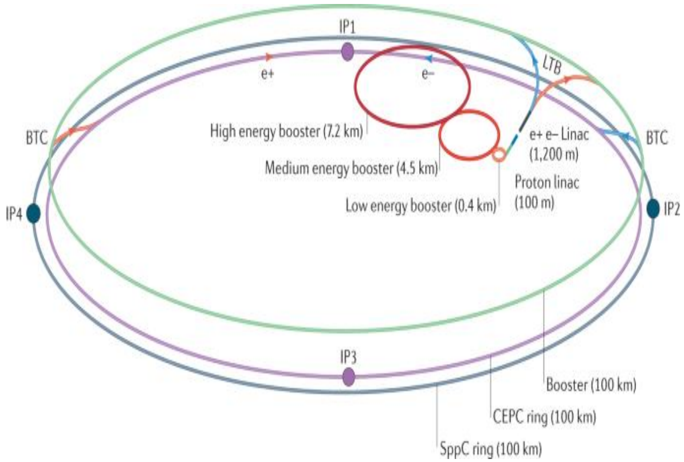
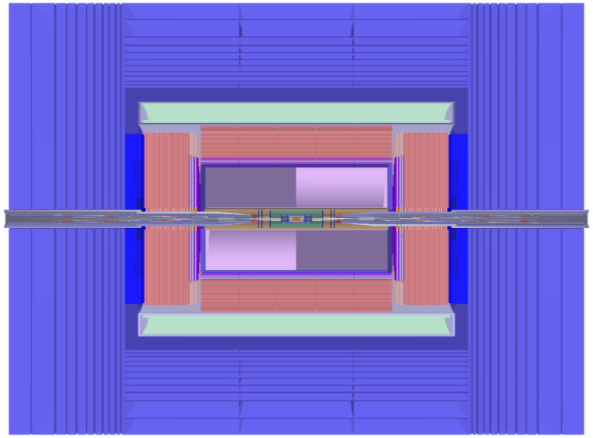
Outline

- Motivation
- CEPC PFA ECAL
  - Sci-W calorimeter
  - Full crystal calorimeter
- Summary

Motivation

- Circular Electron Positron Collider (CEPC)
  - Ecm≈240GeV, luminosity ~2×10^{34} $cm^{-2}s^{-1}$ can also rum at the Z-pole
  - Precision measurement of the Higgs boson (and the Z boson)



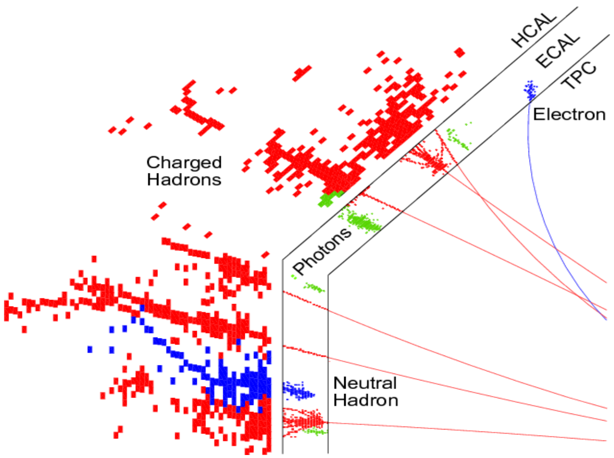


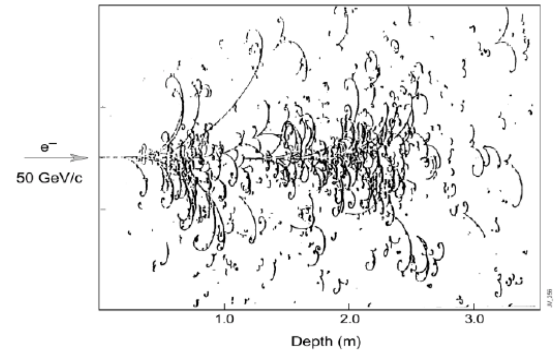
Detector Challenges:

- **Momentum:** $\sigma_{1/p} < 5\times10^{-5}\ \mathrm{GeV}^{-1}$
- **Impact parameter:** $\sigma_{r\phi} = 5 \oplus 10/(p\cdot\sin^{\frac{3}{2}}\theta)\ \mu m$
- **Jet energy:** $\frac{\sigma_E}{E} \approx 3-4\%$

What kind of calorimeter do we need

- Good separation of particles
- Compact showers to minimize overlap
  - Small moliere radius
- Minimum amount dead material
  - inside the magnet coil
- Detailed information of showers
  - High granularity





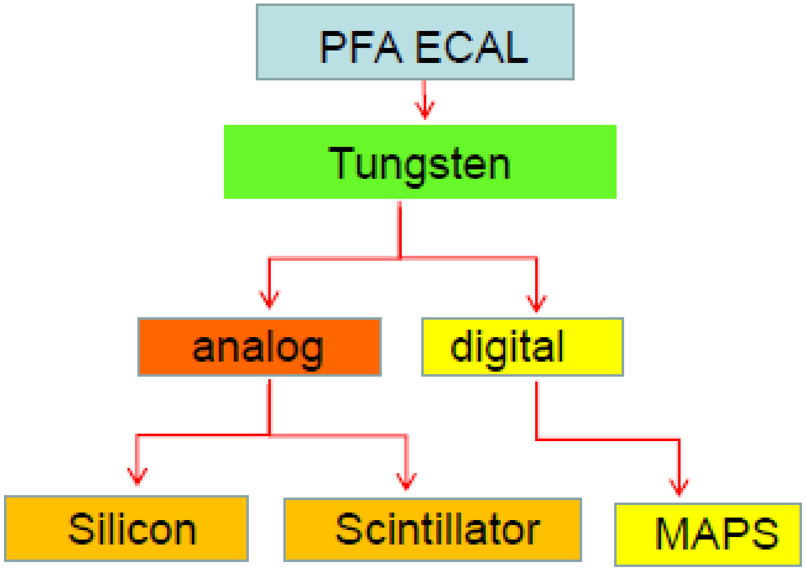
Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, $X_0 \approx$34 cm, 50 GeV incident electron

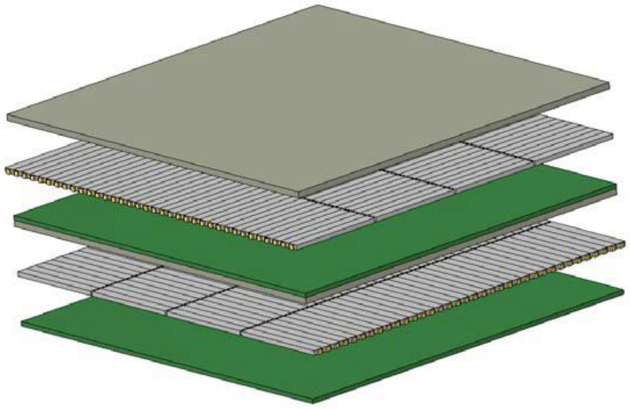
An imaging calorimeter could meet our requirement

A PFA calorimeter based on sampling method

Sci-W PFA ECAL of CEPC

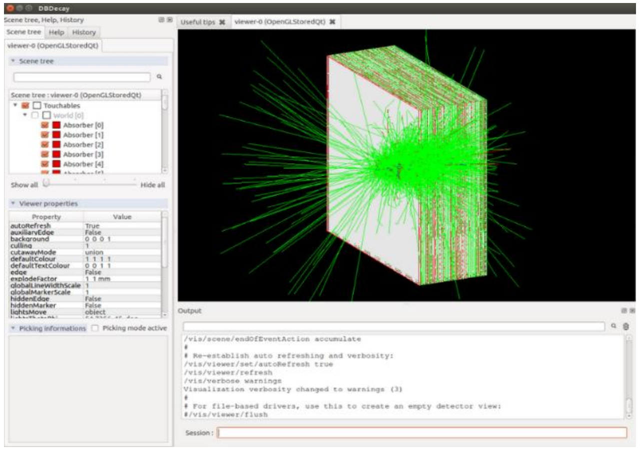
- Sampling Calorimeter
  - Sandwich structure
  - Absorber + SD + Electronics
- Absorber
  - Tungsten
- Sensitive Detector
  - Plastic Scintillator + SiPM
- Electronics
  - SPIROC2E ASIC Chip



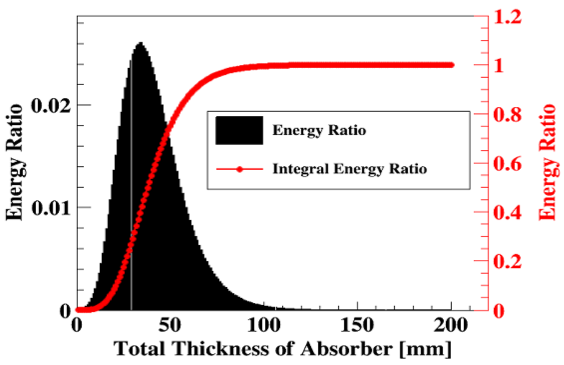


ECAL Optimization

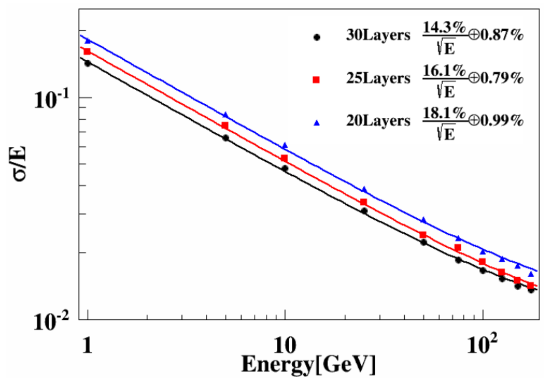
- Total thickness: 24 X_0
- Sampling number: 30 layers
- Granularity: <10 mm × 10 mm



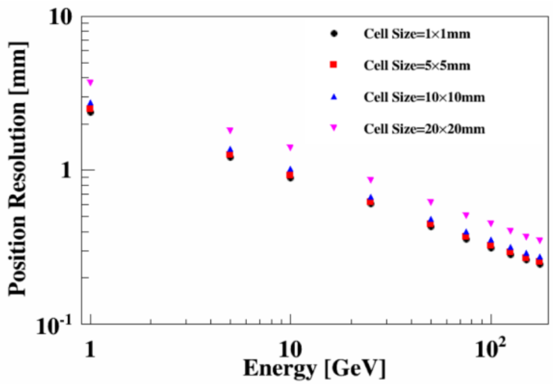
Total radiation length



Sampling number

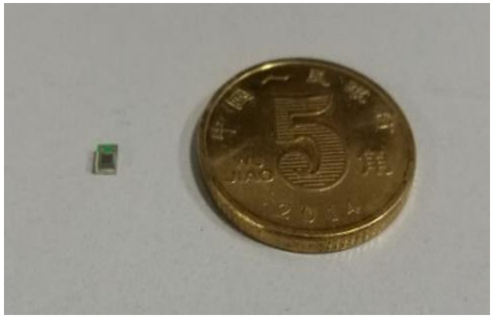


Cell size



Detector elements

Scintillator
（5mm*45mm*2mm）



SiPM

SPIROC chip

- Three additional functions were designed in the ECAL EBUs
  - DAC calibration
  - LED calibration
  - Temperature monitor and compensation

EBU

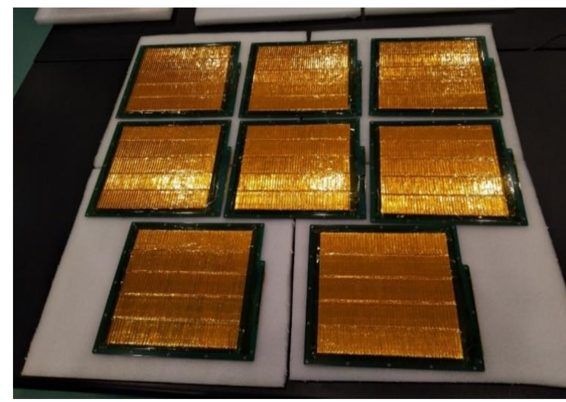
Single Layer assembly

Cutting
↓
Grooving
↓
Polishing
↓
Annealing
↓
Cleaning
↓
Packing

Visual inspection

cleaning

assembling

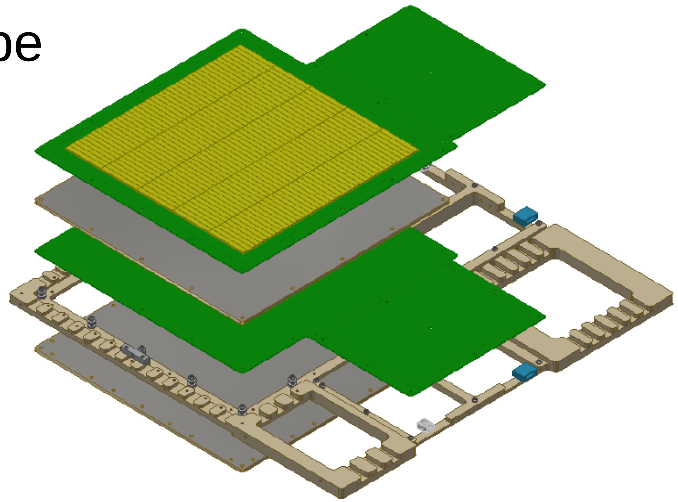


EBU

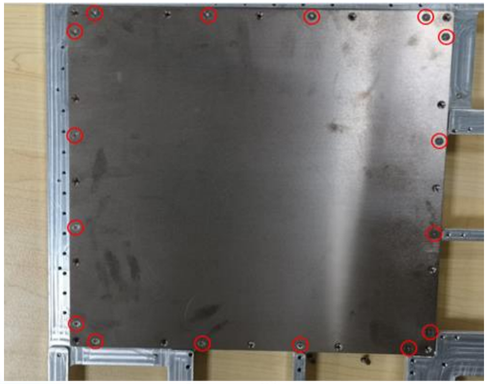
The single layers were assembled in Shanghai Institute of Ceramic (SIC)

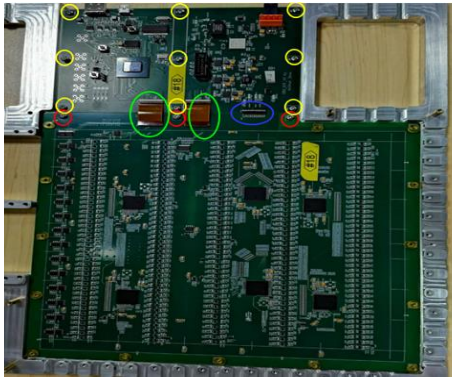
super-layers assembly

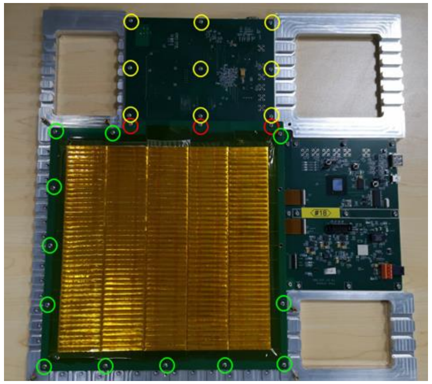
- There are 16 super-layers in ECAL prototype
- Each super-layer has 2 Ecal Board Units (EBU) and 2 Data InterFace boards (DIF)
- Also has 2 W-Cu alloy plates, W:Cu 85%:15%, thickness is 3.2 mm ~ 0.73 X_0
- The aluminum frame is used to support the super-layer



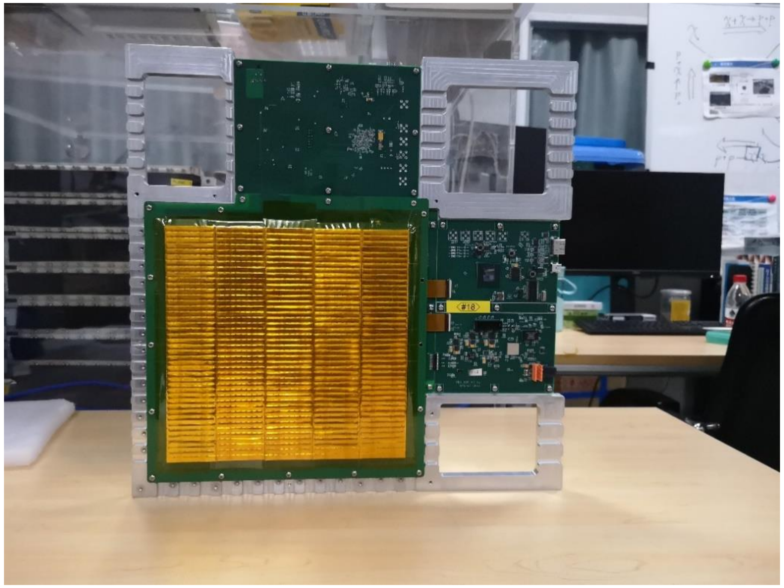
The structure of super-layer

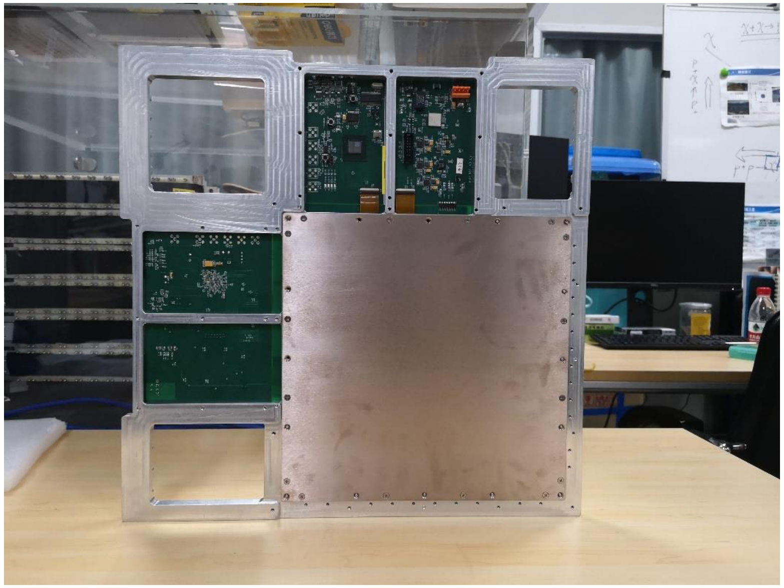


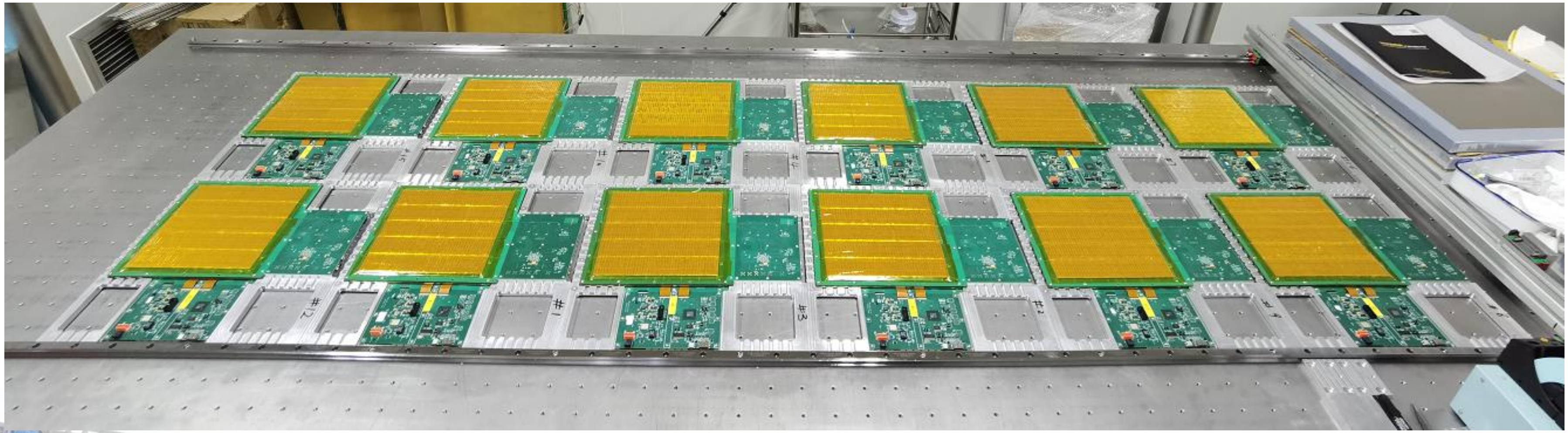




Super-layer

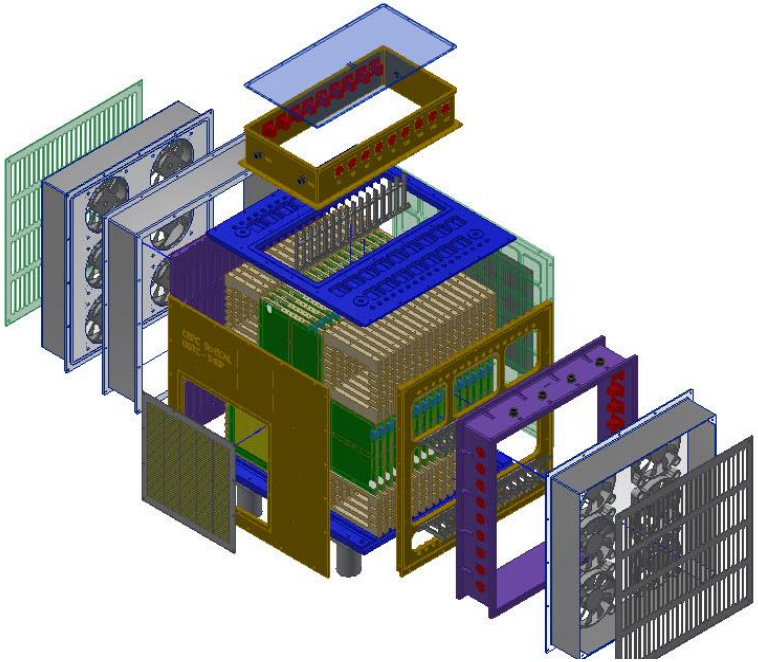


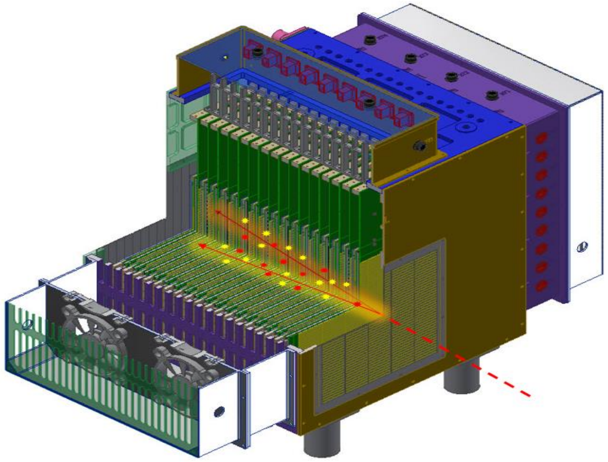




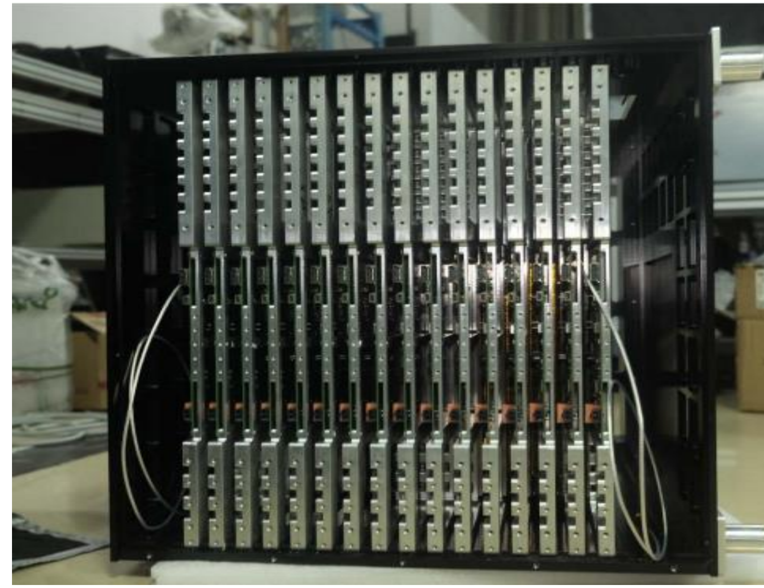
Calorimeter assembly

- The calorimeter prototype has 16 super-layers
- The total radiation length is about 23.4 X_0
- The adjacent layers are arranged in orthogonal order to ensure the 5 mm granularity
- The gap between two super-layers is smaller than 1 mm
- There are 12 fans on two sides to dissipate heat



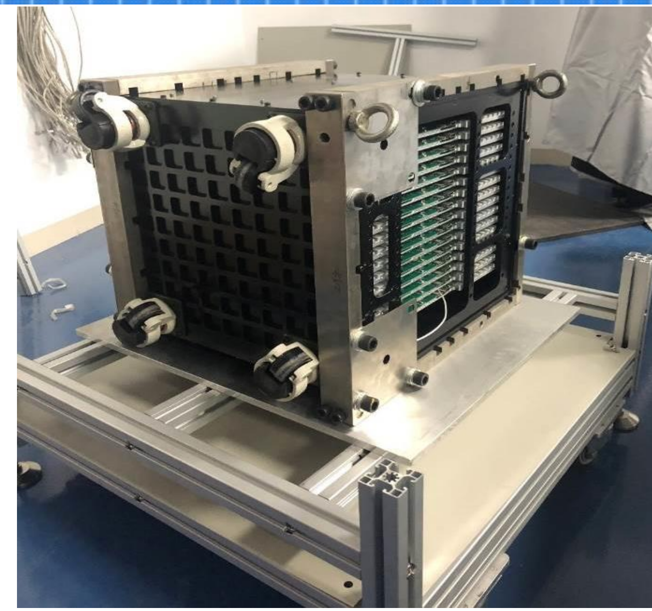


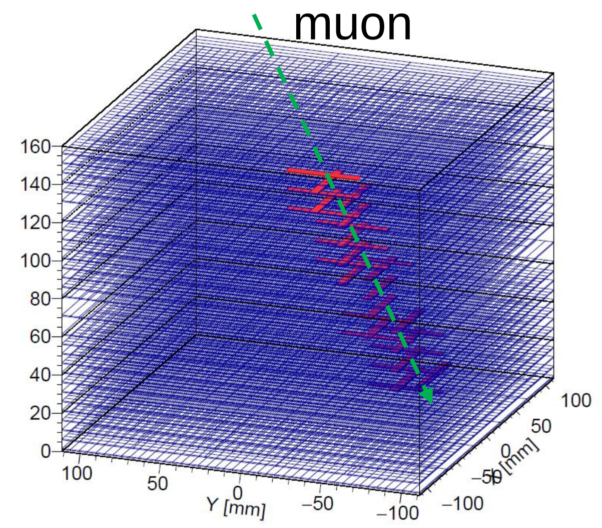
Calorimeter assembly

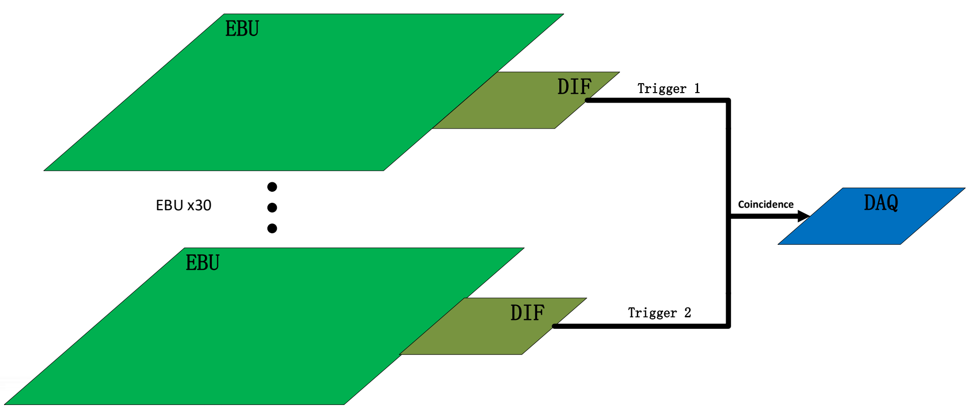


Cosmic Ray test

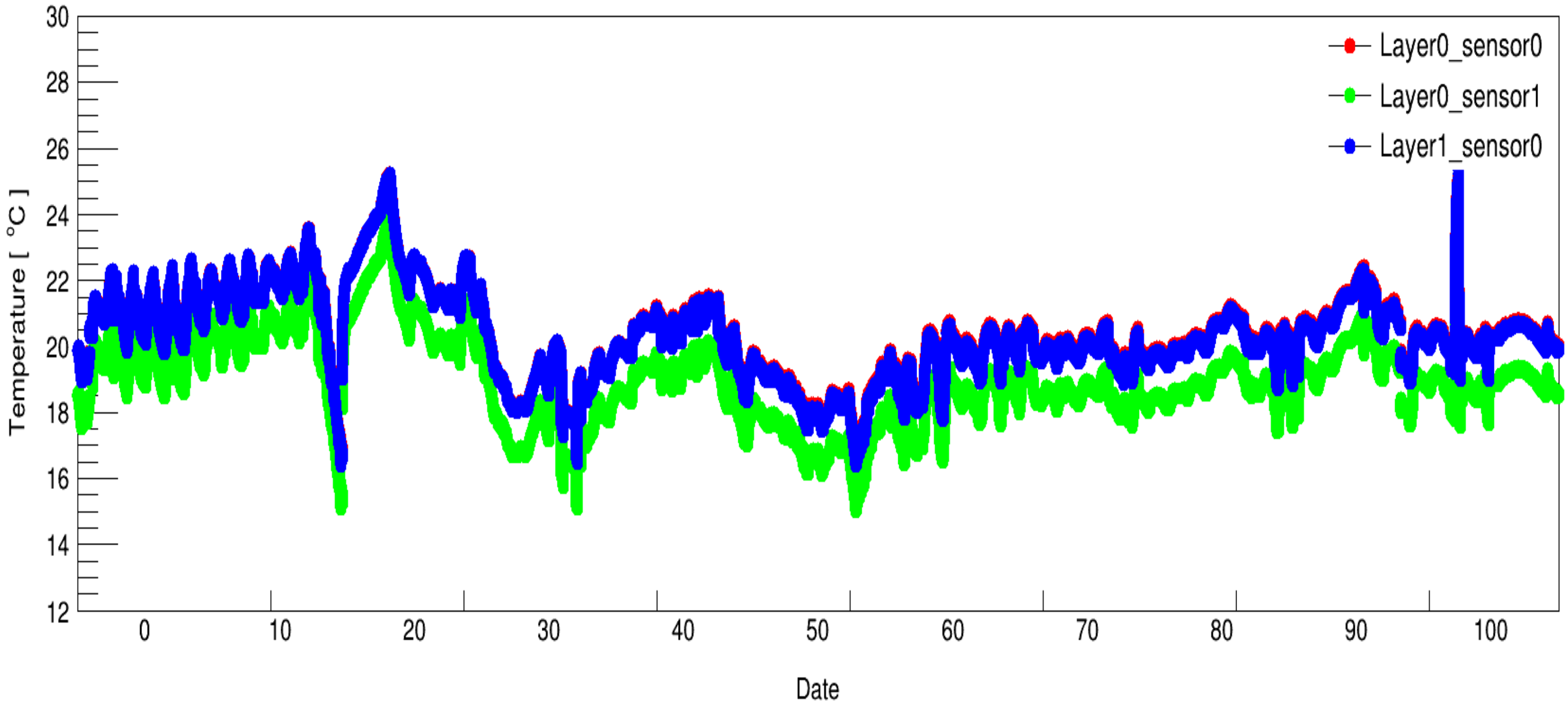
- Long term cosmic ray test: 90 DAYs
  - ScECAL has been rotated by 90 degree
  - Coincidence trigger of Layer1 & Layer29
  - Event rate : ~ 16 per minute
  - ~1.5 million cosmic ray events collected
- Purpose
  - Function verification (stability, temperature correction, etc)
  - EBU efficiency and Position resolution
  - Cell-to-cell MIP calibration







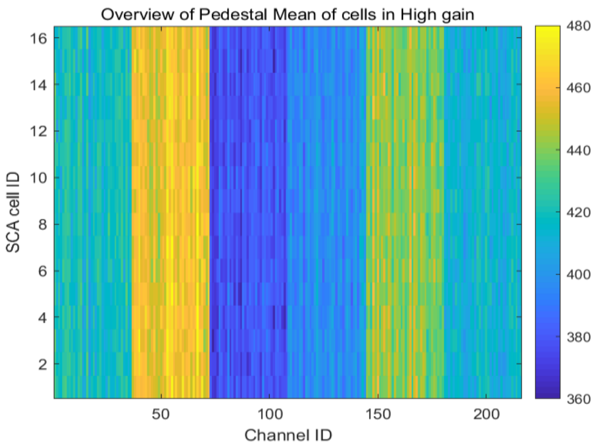
Temperature



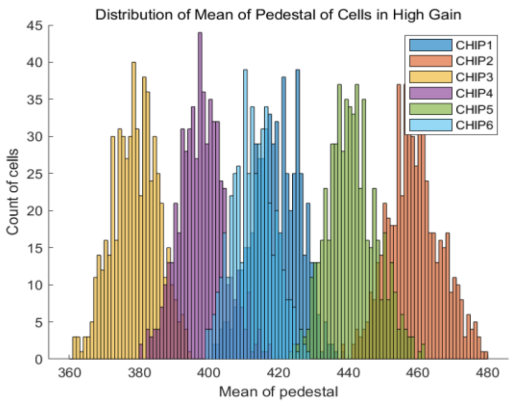
- The temperature is between 14 and 26 degrees, with an average of 20 degrees
- At first the test room with relatively good temperature control conditions
- Most of the time, the temperature control condition of the room is not good

pedestal

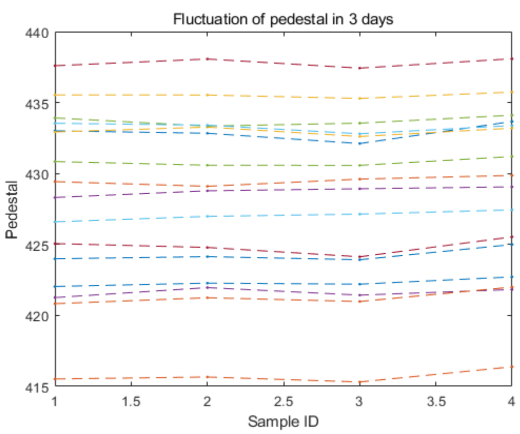
- The noise of each cell in each channel tested by random trigger from DIF boards
  - The pedestal position of the same chip is more uniform
  - The pedestal position of different chips is a little different
  - The pedestal position is very stable with the change of time



Pedestal position of each cell in each channel



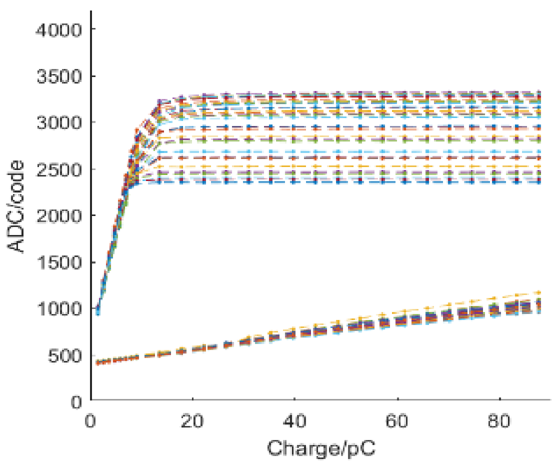
Pedestal position distribution of each channel



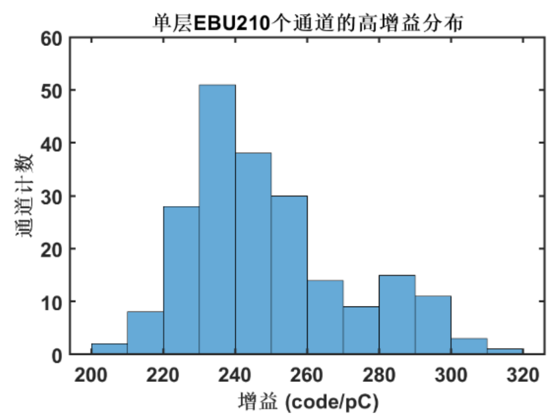
Pedestal position stability (3 days)

DAC calibration

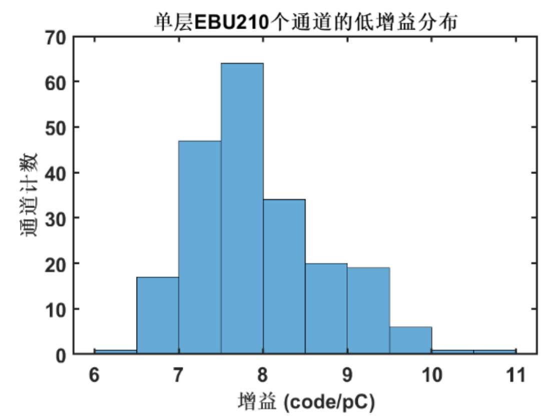
- The readout linearity
  - The high and low gain channels could achieve the upper limit of 10 pC and 100 pC respectively
  - The gain coefficients of high and low gain are about 240 and 8 code/pC respectively, and the ratio of high and low gain is about 30.



Linearity of the high/low gain channel



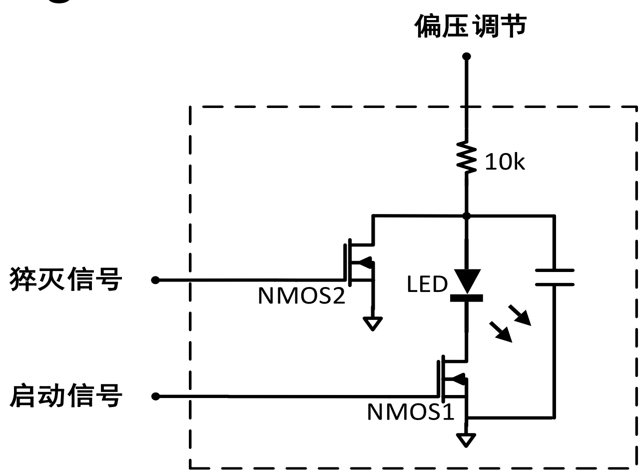
The high gain channel factor

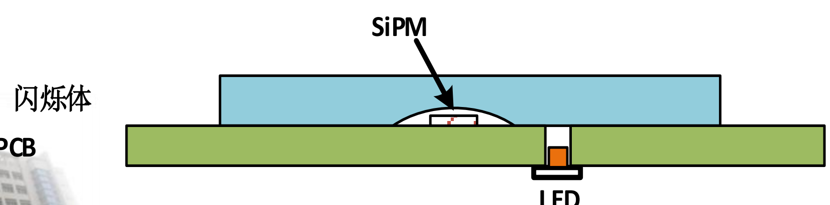


The low gain channel factor

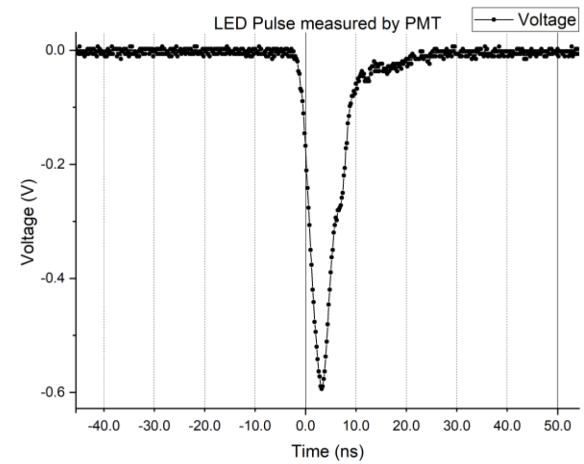
LED calibration

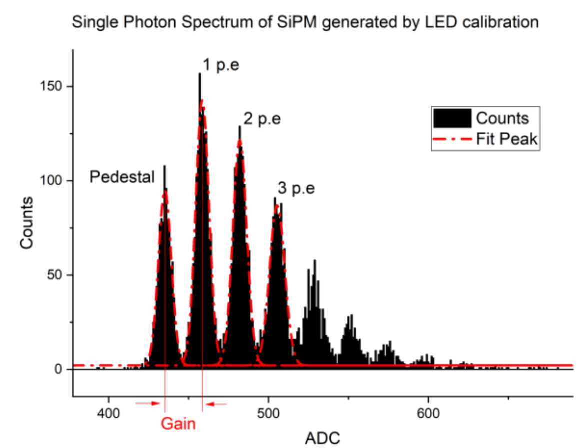
- The LED was put near the SiPM
- A circuit was designed to drive LED to calibrate SiPM, like the photo-electron peaks, the ratio of low gain and high channels





LED light spectrum

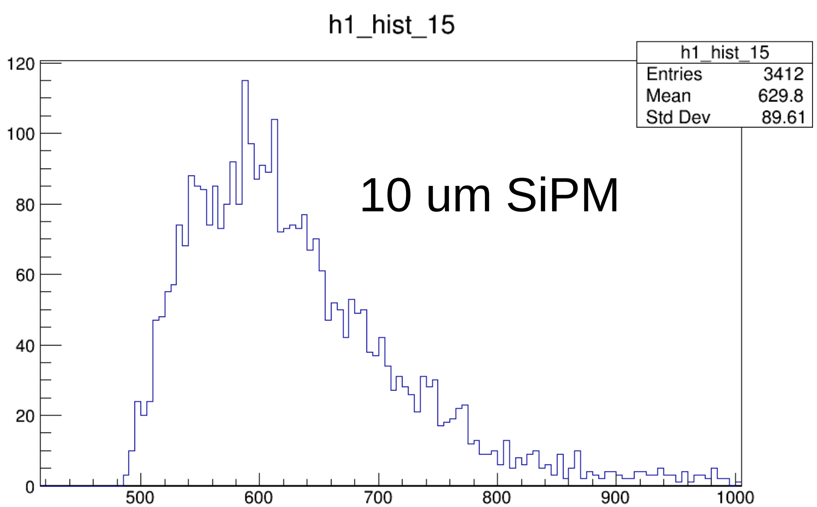


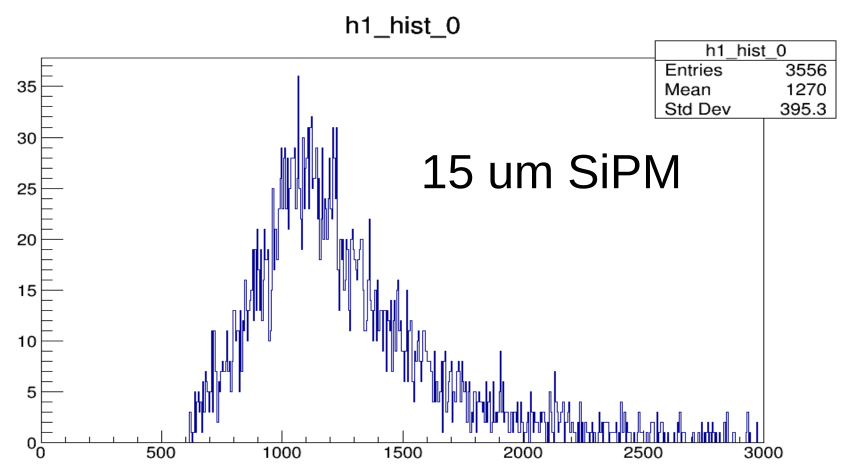


SiPM photon electron peak

MIPs Spectrum

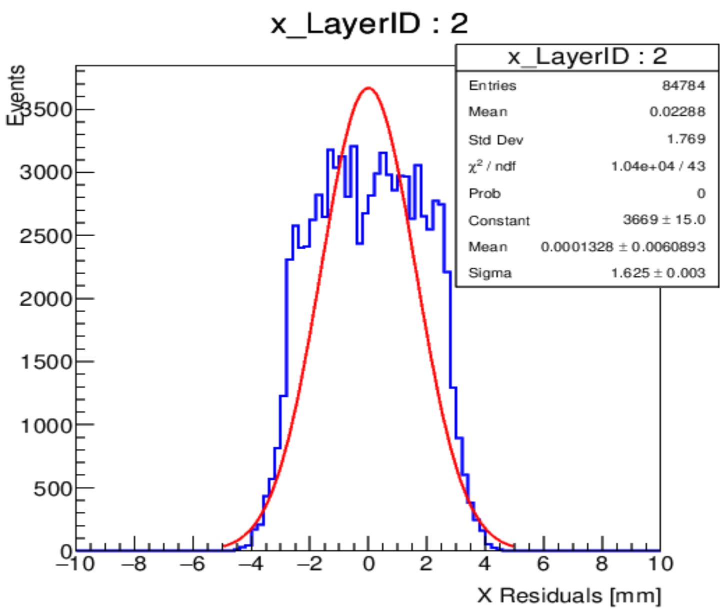
- MIPs spectra measured by 10 um and 15 um SiPM can be seen clearly
  - The amplitude of 10 um is about 200 ADC counts, and 500 ADC counts for 15 um SiPM (After subtracting the pedestal)
  - Considering the gain and PDE of the two SiPMs, the results are reasonable

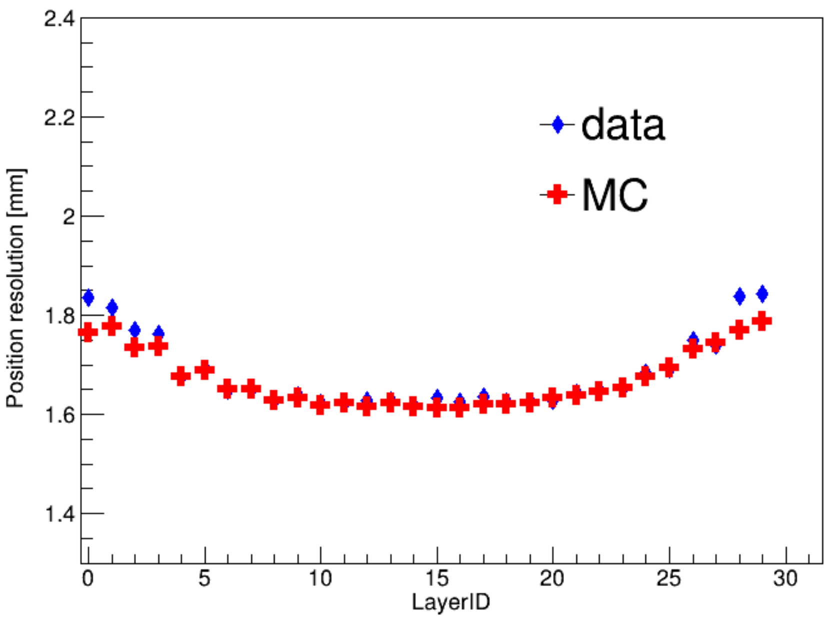




Position resolution

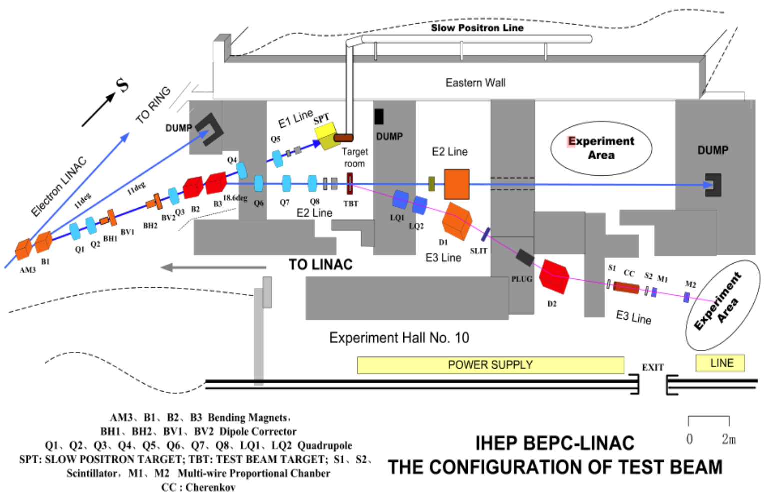
- Position resolution is better than 2 mm
  - The RMS of residual distribution is referred as the position resolution
  - The settings of simulation should fine tuning

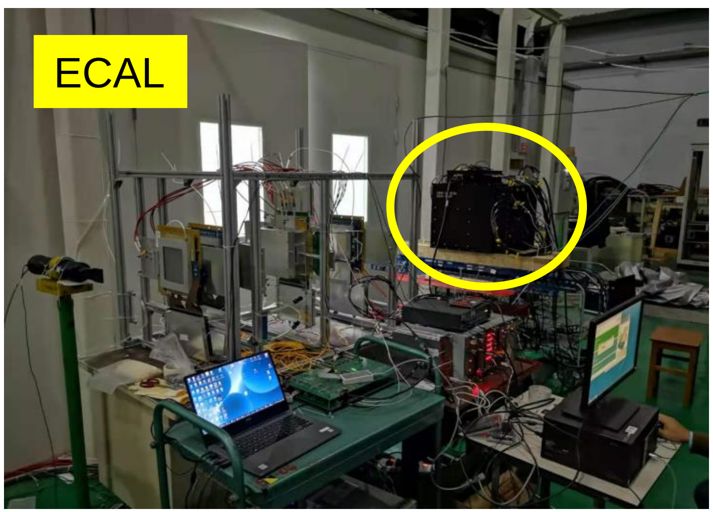


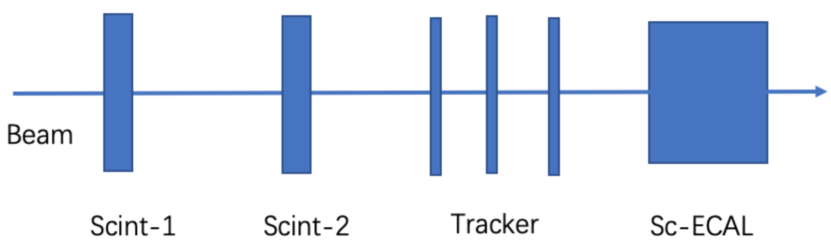


Beam Test in IHEP

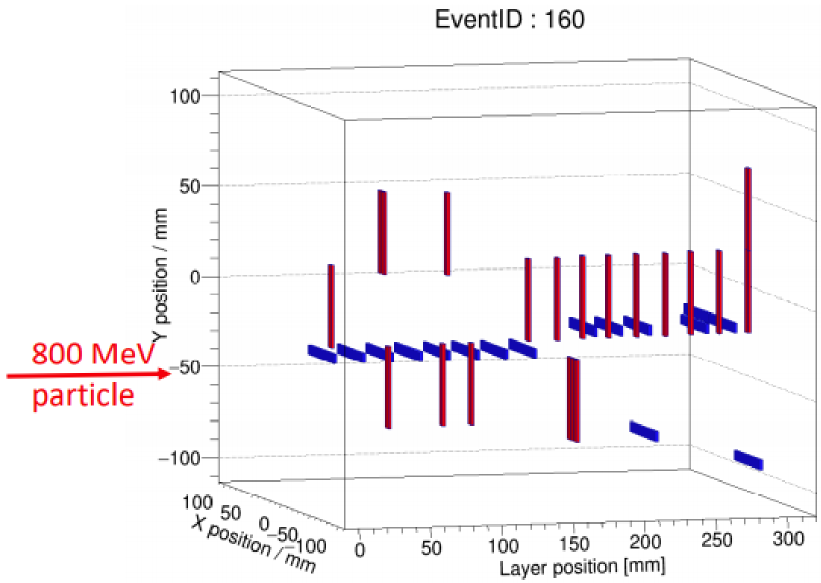
- E3 beam line
- 2.5 GeV e- interacted with Be target
- Three momentums were selected in the beam
  - 500 MeV/c, 800 MeV/c, 1000MeV/c

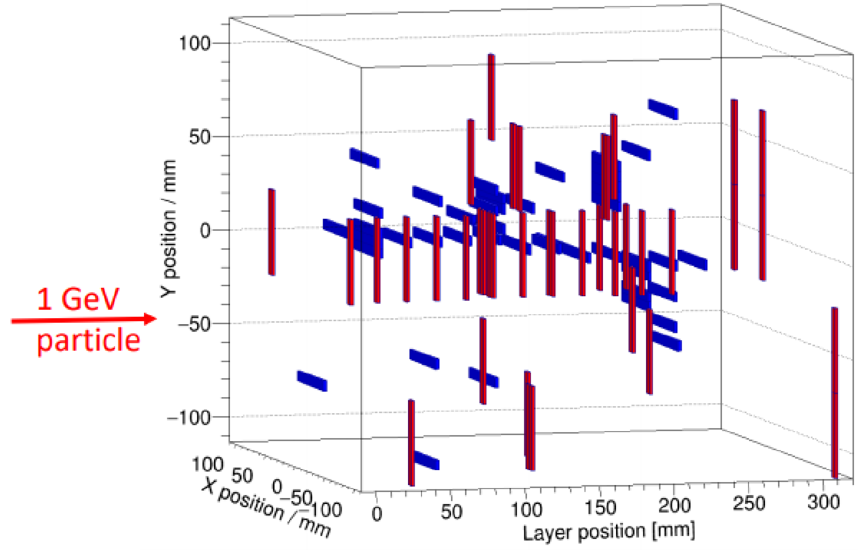


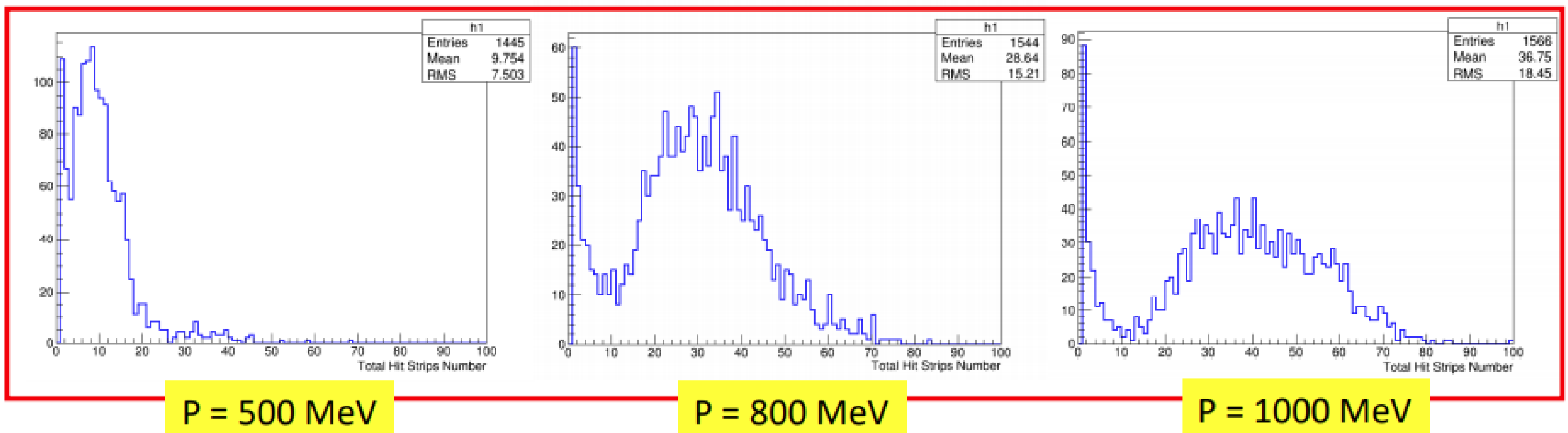




Beam Test in IHEP



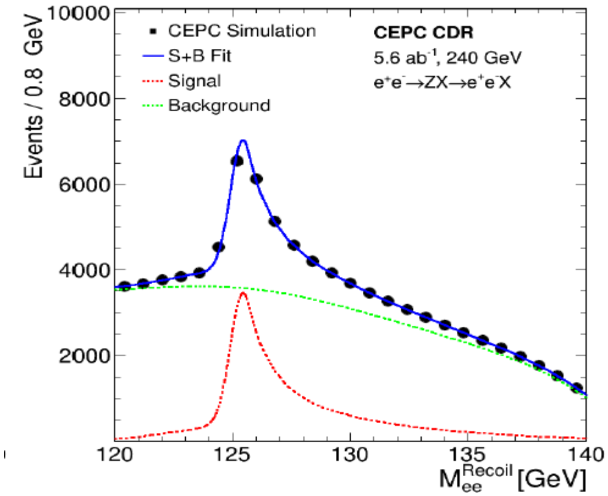




Total hits Number in ECAL

A PFA ECAL based on total absorption method

- The imaging sampling calorimeter
  - Achieve high granularity
  - The energy resolution is not good

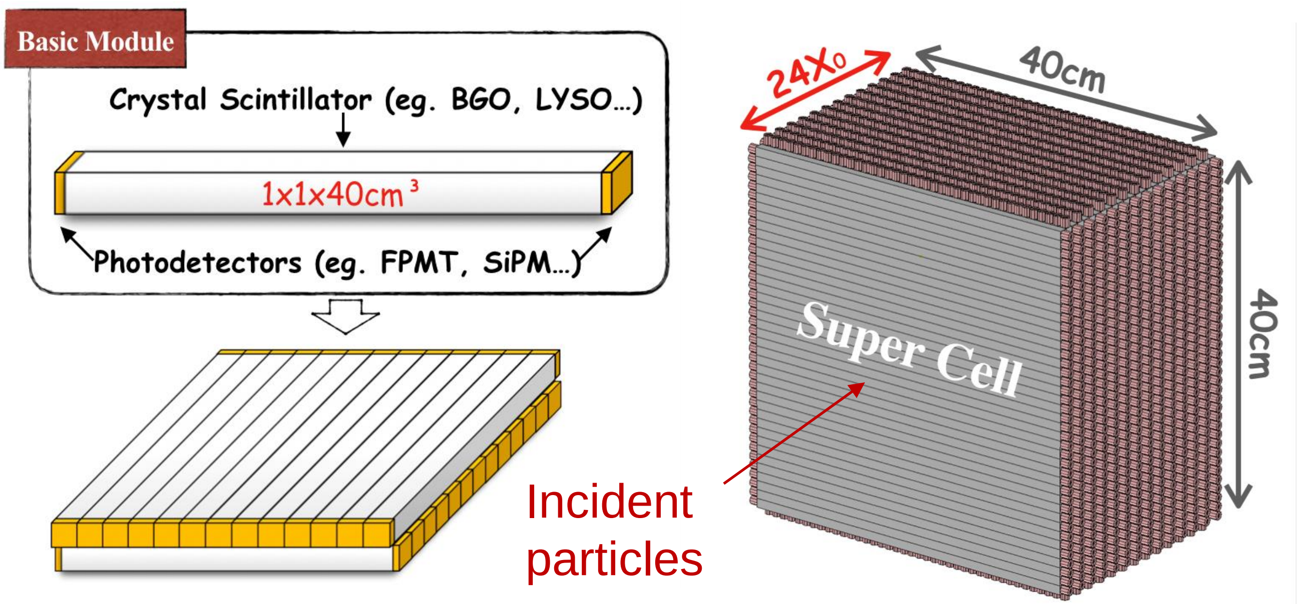


Could we balance the energy resolution and imaging ability ?

- Full crystal calorimeter with fine segmentation
  - Homogeneous structure to achieve good energy resolution
    - Energy recovery of electrons: to improve Higgs recoil mass
  - Finely segmented crystals
    - PFA capability for precision measurements of jets

Full crystal PFA ECAL

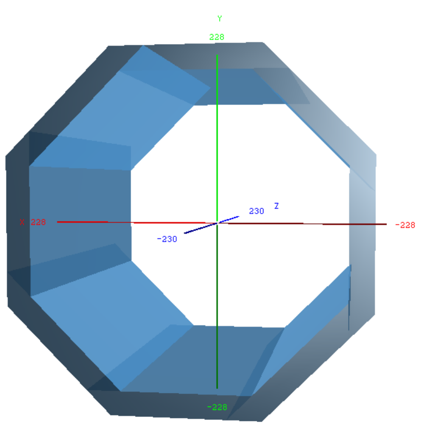
- Super cell size: 40 cm × 40 cm
  - Total thickness: 24 X_0
  - BGO crystal bar size: 1 cm × 1 cm × 40 cm
- Crossed arrangement in adjacent layers
- Timing (double sides readout): positioning along bar

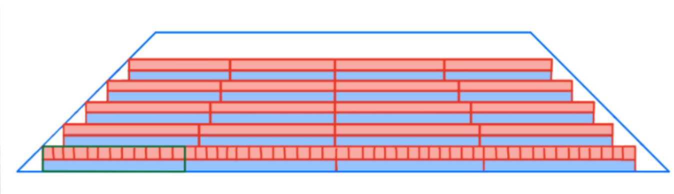


The details could be seen in Yong's talk

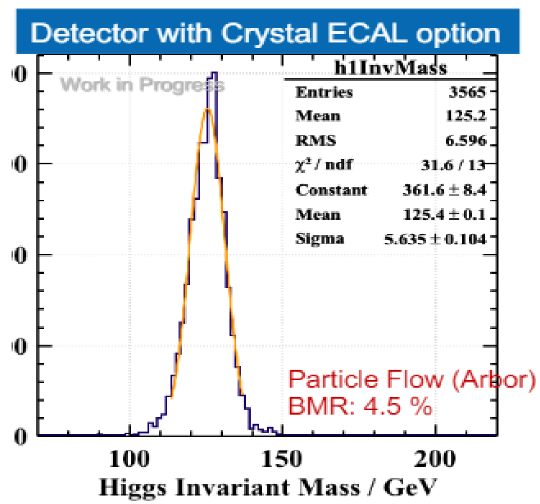
performance studies and optimization

- Software development in the new framework CEPCSW
  - Geometry construction in DD4HEP
  - Simulation and digitization
- PFA performance with jets with ArborPFA
  - benchmark: 2-jets in $ZH(Z \to \nu\nu, H \to gg)$ and $ZH(Z \to \nu\nu, H \to \gamma\gamma)$

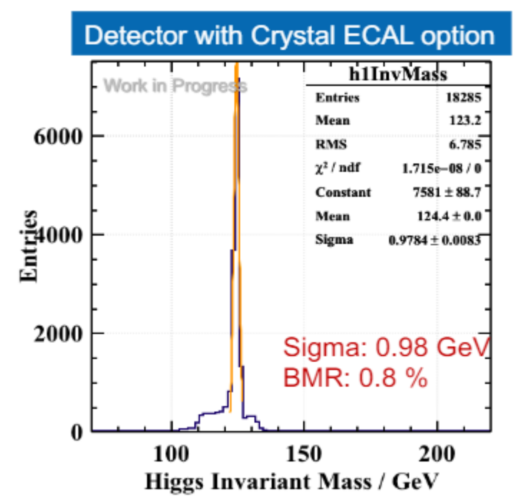




$ZH(Z \to \nu\nu, H \to gg)$

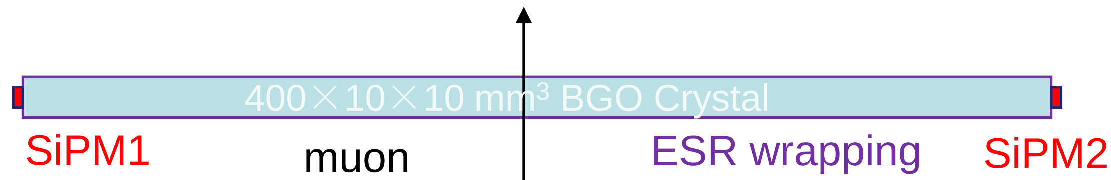


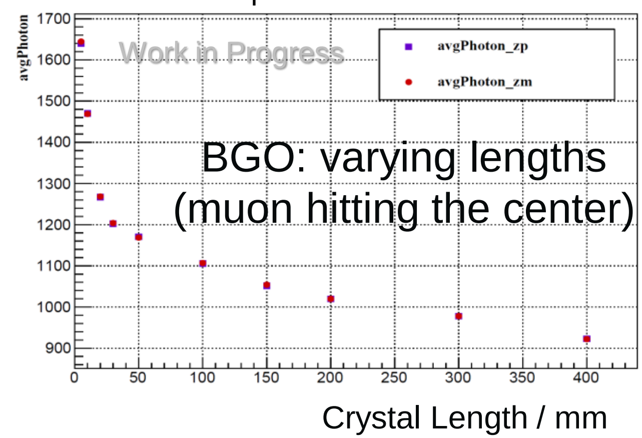
$ZH(Z \to \nu\nu, H \to \gamma\gamma)$

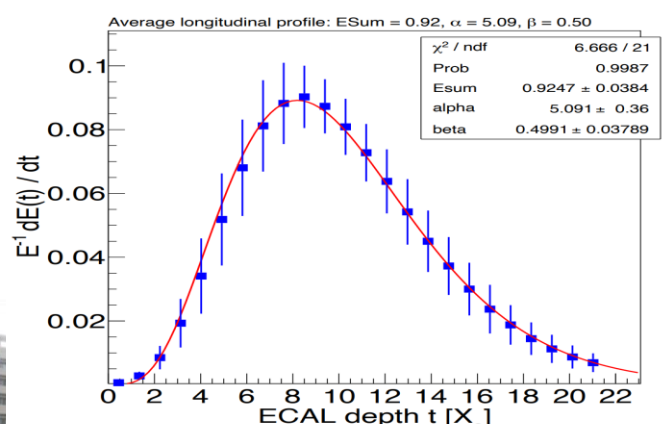


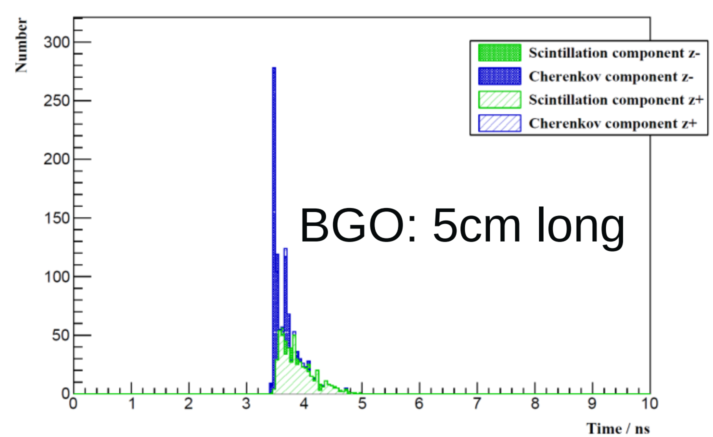
Critical technical I: Detector Unit

- BGO crystal + SiPM
  - MIPs response
    - LY: stochastic term (≤3%)
  - High dynamic range
    - From 1 MeV to 30 GeV
  - Fast time measurement
    - Better than 100 ps



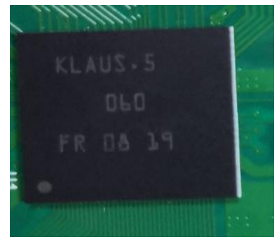


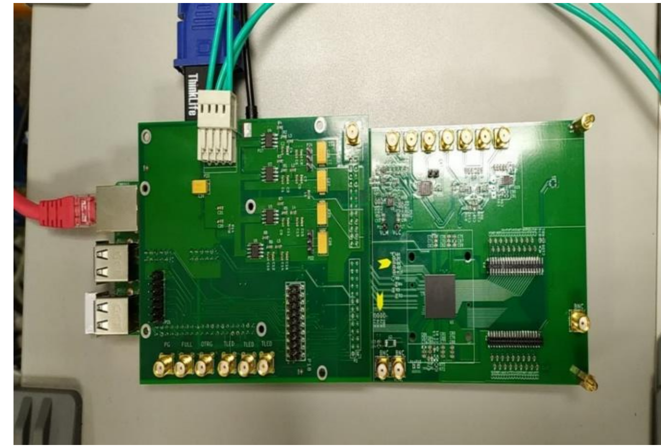


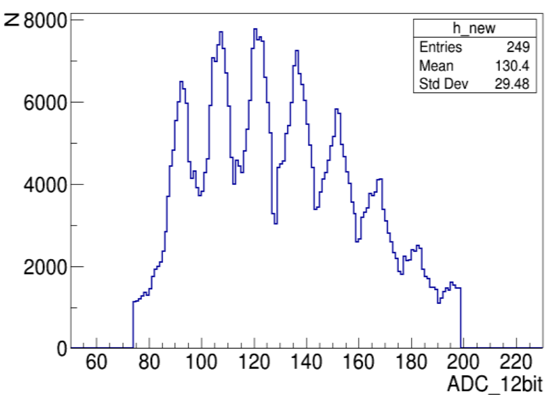


Critical technical II: electronics

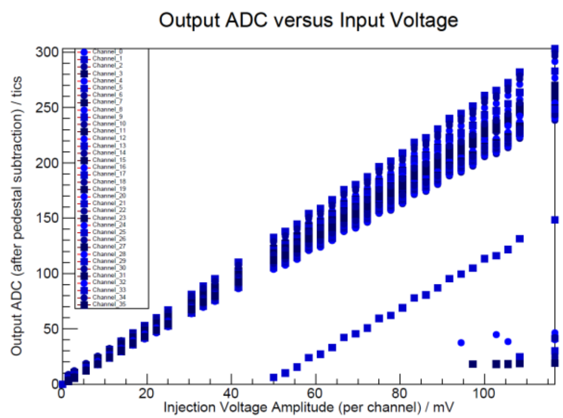
- The electronics was designed by KIP based on Klaus chip
- The SiPM was designed by NDL of Beijing Normal University



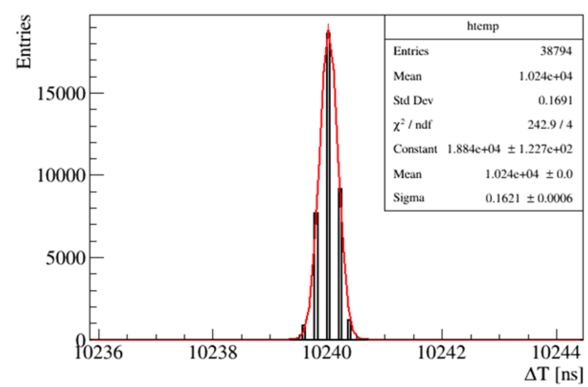




NDL-SiPM: nominal gain 2×10^5 with 10μm pixels



Linearity of Klaus5 chip (after pedestal subtraction)



Time resolution of Klaus6: 160ps

Summary and outlook

- CEPC is the next generation accelerator physics experiment aiming to study Higgs, and the design of calorimeter has many challenges
- The PFA calorimeter is a very competitive choice, two different methods were studied in laboratory
  - Sci-W calorimeter prototype which with 30 layers was designed and tested using cosmic rays and test beam.
  - Full crystal calorimeter which also with fine segmentation was studied based on CEPCSW. Its advantage is that it ensures good energy resolution while ensuring good enough imaging capability

Summary and outlook

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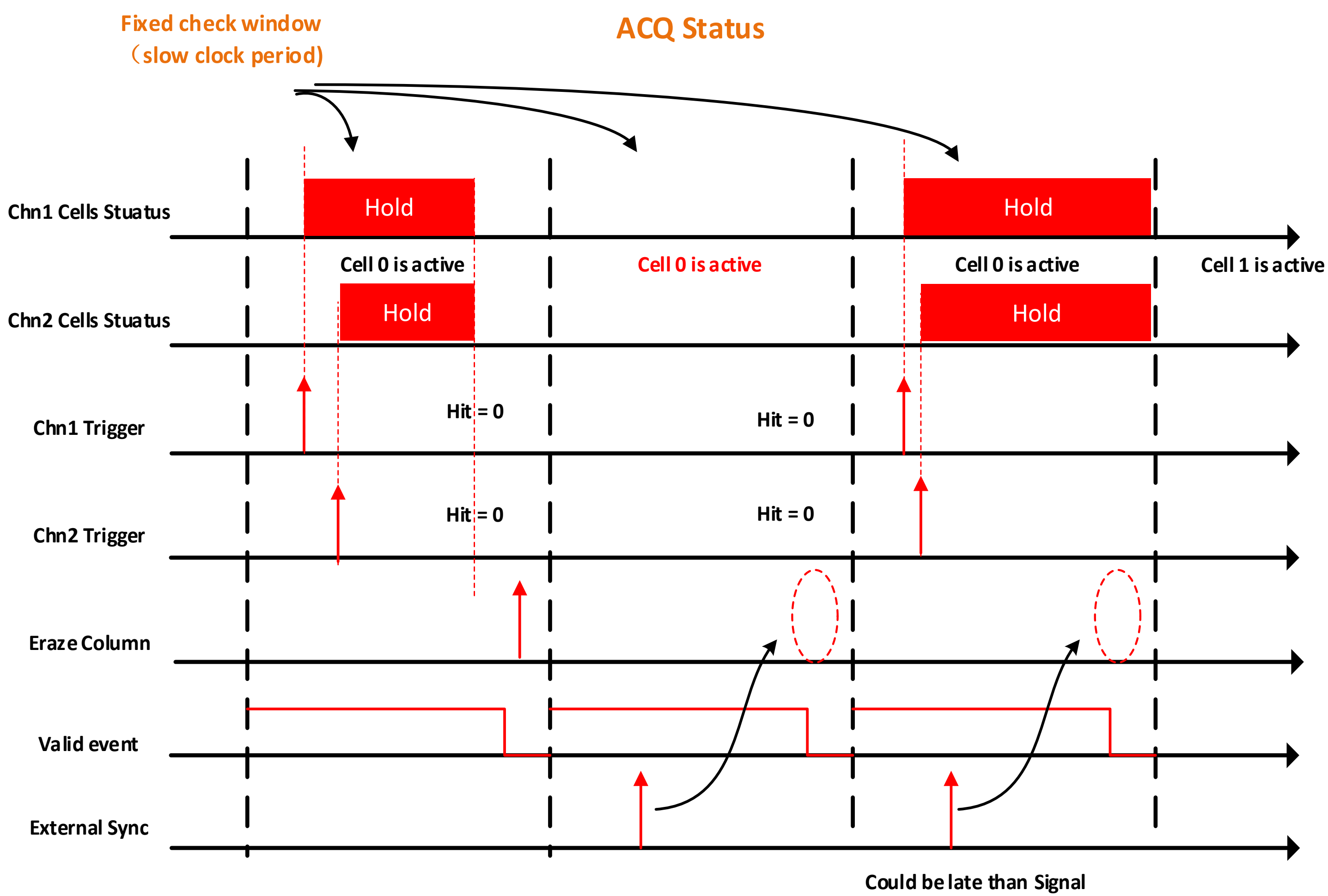
THANKS

backup

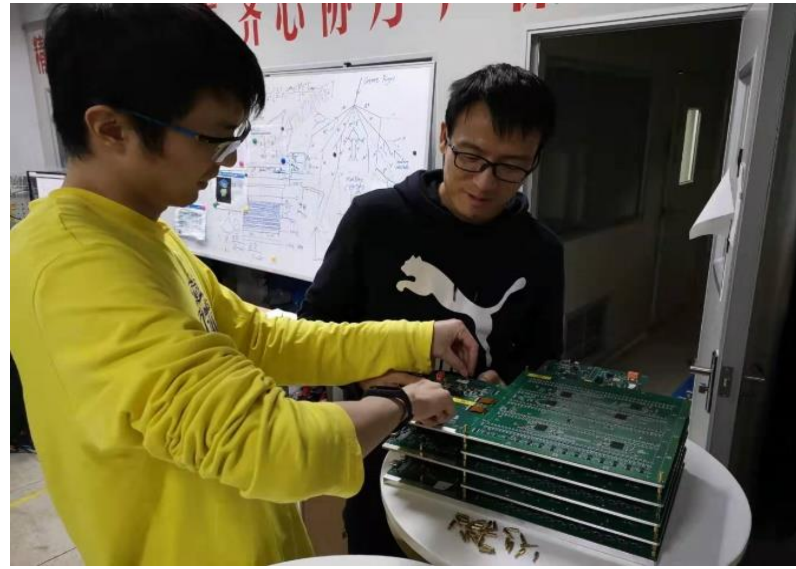
ECAL trigger



Validation Mode

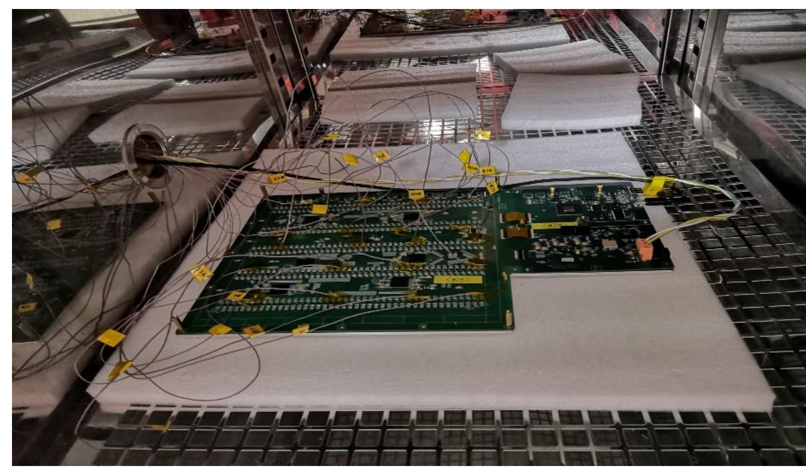
EBU Test

- Aging Test
  - 50+/-2 degree
  - 48 hours



Temperature correction

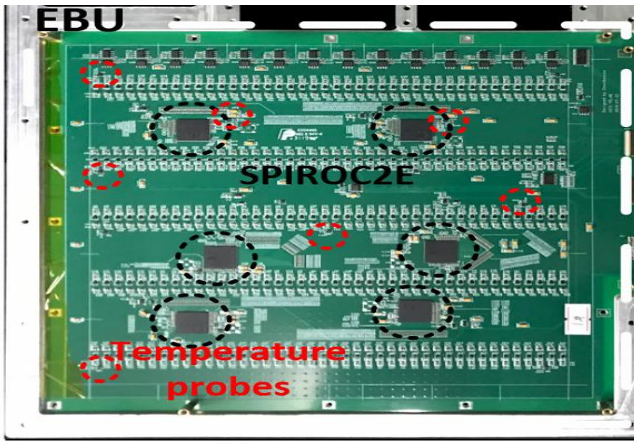
- In order to check this interpolation method, 20 thermocouples are pasted on the EBU to monitor the temperature change on the EBU in different position.
- Put the EBU into a high and low temperature box, and change the temperature from 20 - 45 degree.
- Both the temperature sensors of EBU and the pasted thermocouples could measure the temperature in real time



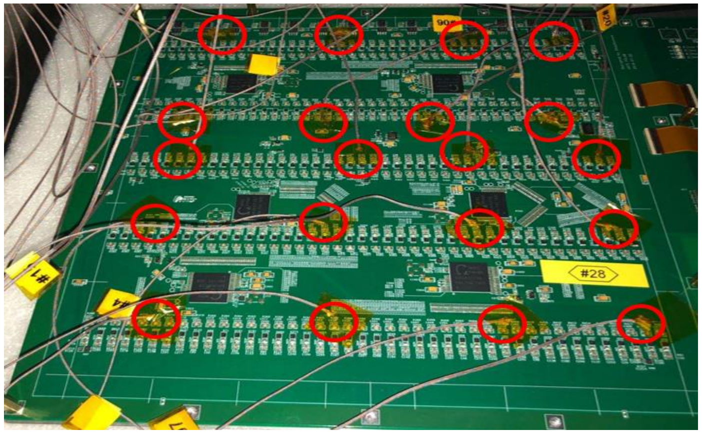
EBU in the high-low temperature box

Temperature correction

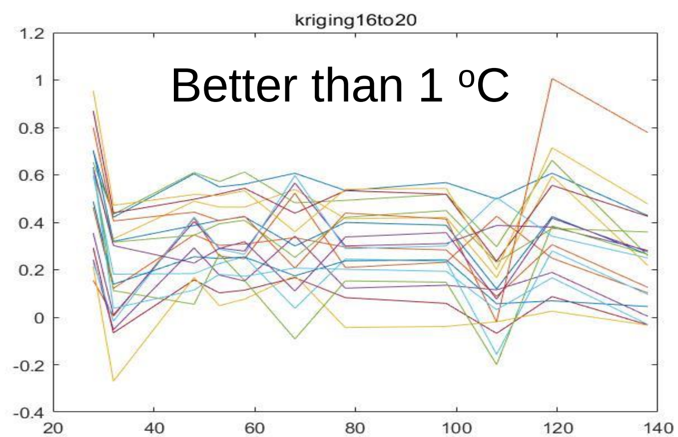
Position of temperature sensor of EBU



Position of the pasted thermocouples



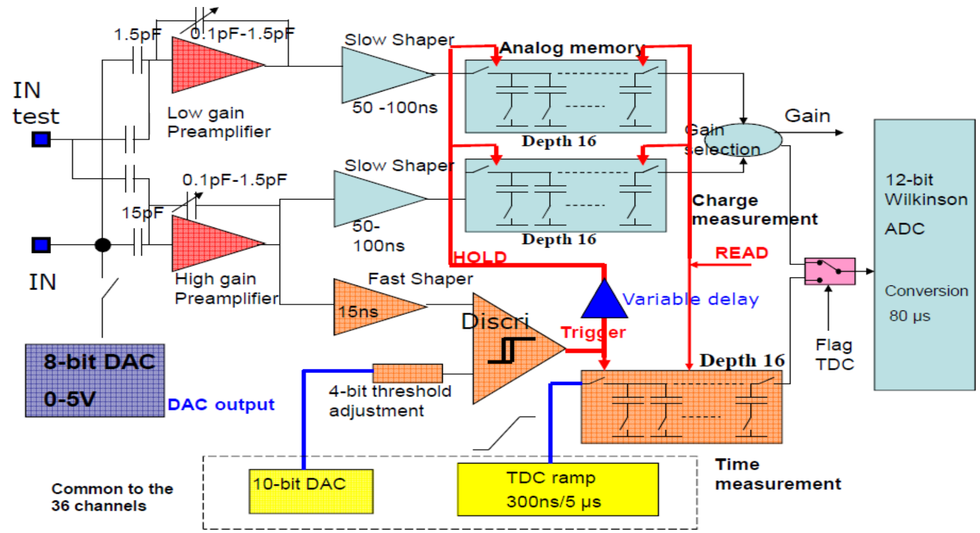
- According to the temperature measured by the sensors on the EBU, the temperature of the thermocouple position is calculated by interpolation method using the values of these sensors and compared with it measured by thermocouple itself.

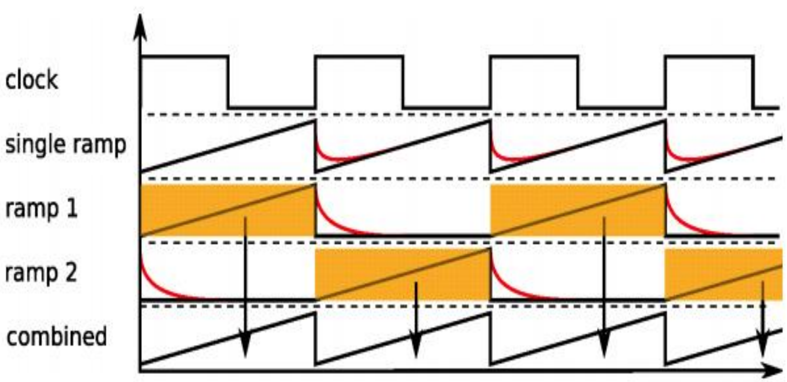


ΔT between calculated and measured

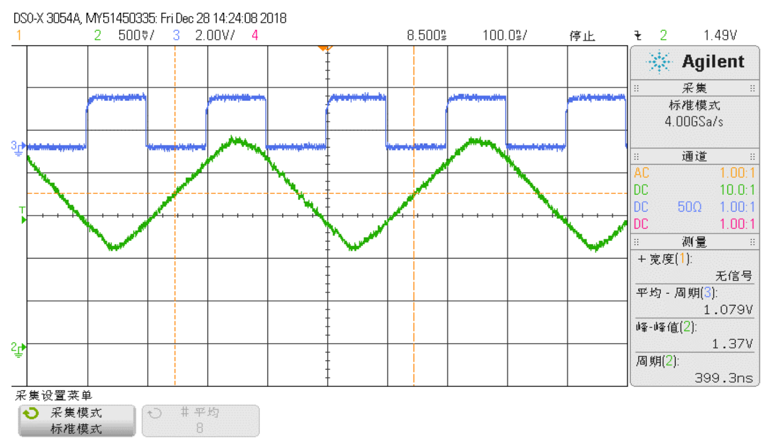
Time measurement

- Channel schematic of SPIROC2E chip
  - High gain
  - Low gain
  - Time measurement





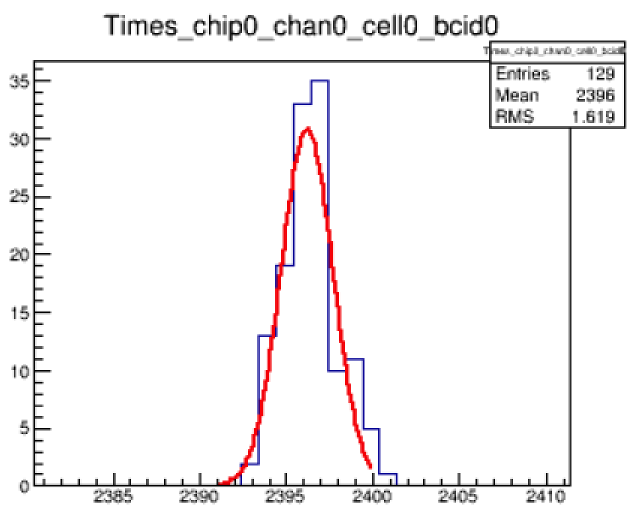
SPIROC2B chip



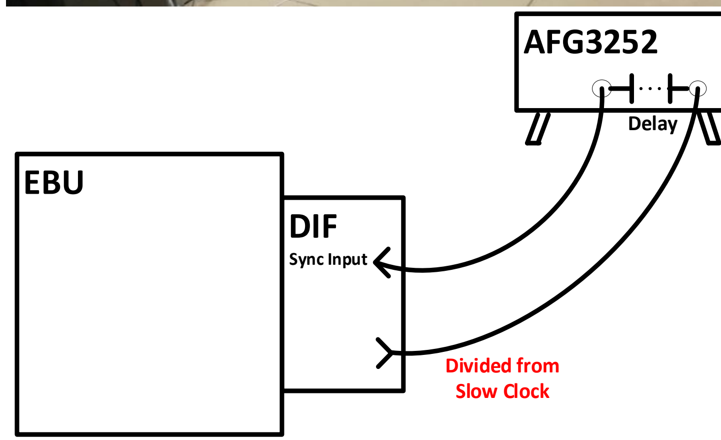
SPIROC2E chip

Time Calibration

- Fan-out signal synchronized with slow clock to AFG3252
- Delay *t* ns then give it to DIF
- Trigger charge injection (Ecalib) and valid it as external trigger



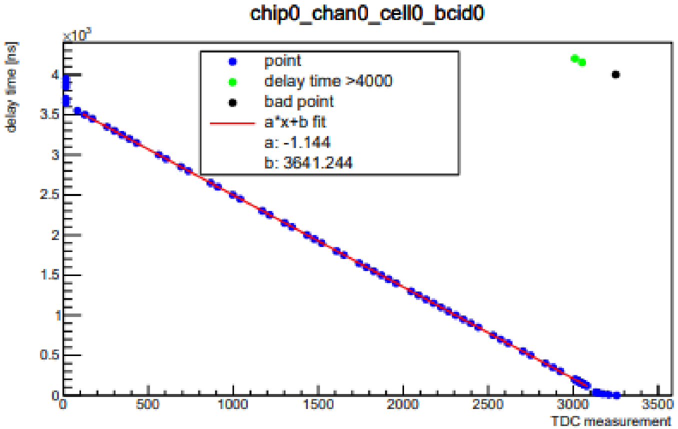
TDC response for a fix delay time

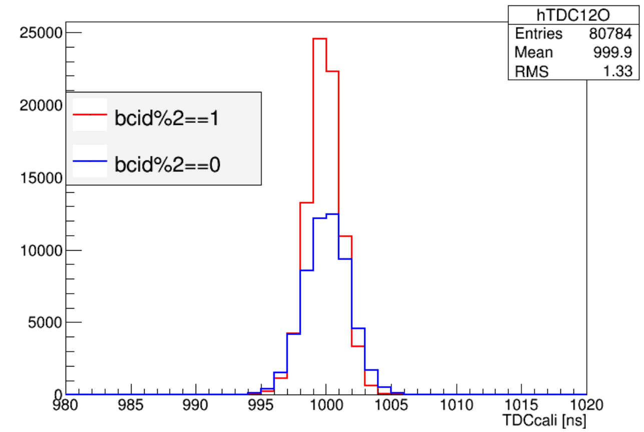


TDC Calibration

Time calibration

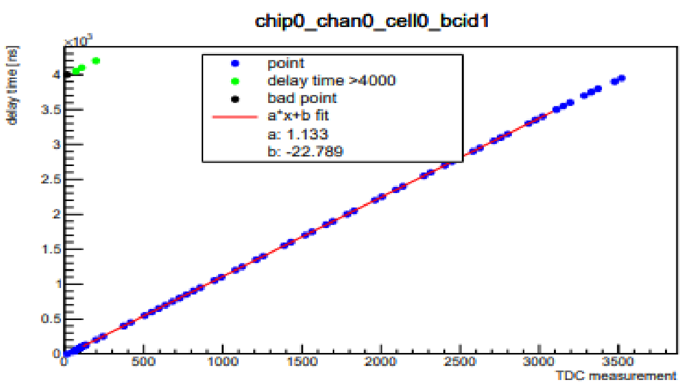
Negative slope ramp



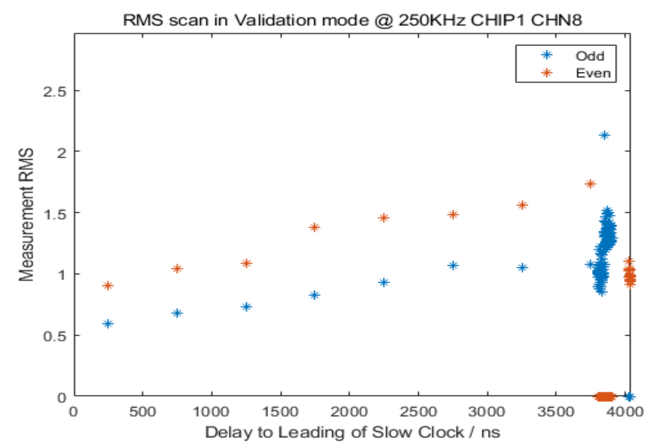


Time resolution at 1000 ns

Positive slope ramp



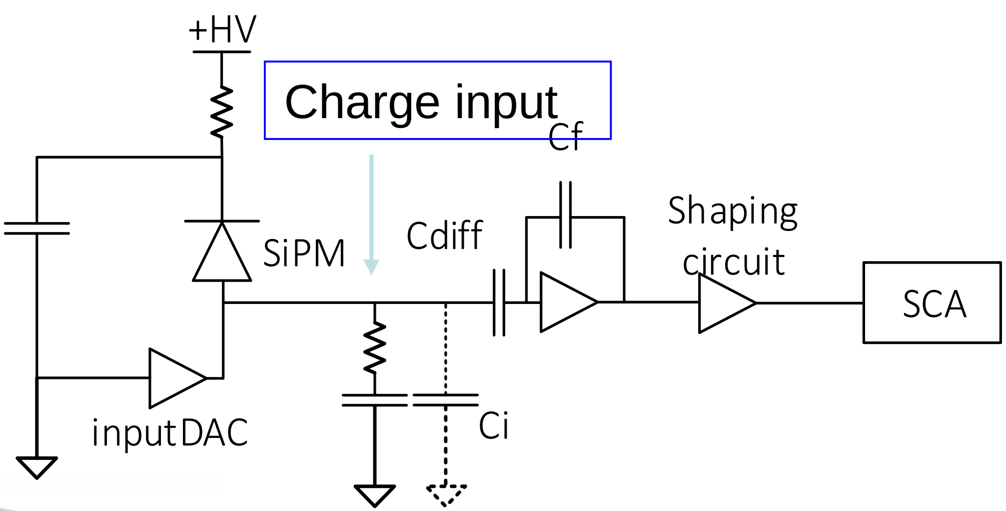
TDC Channel vs. delay time



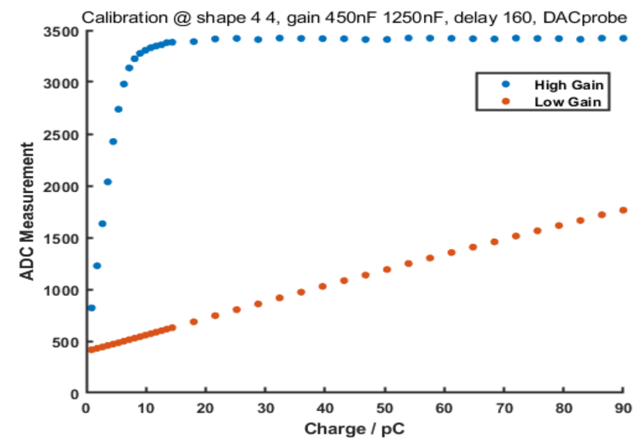
Time resolution of TDC

Electronics I

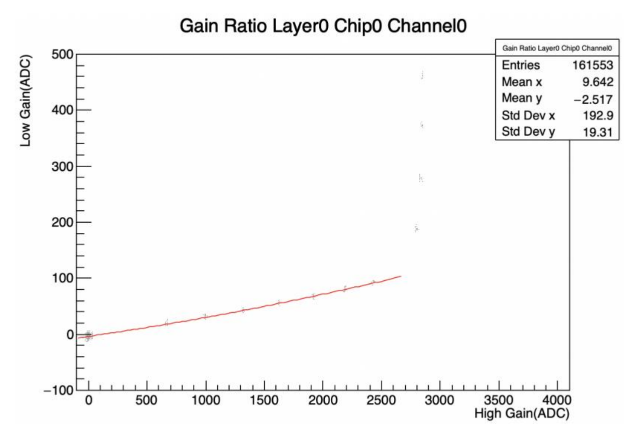
- DAC calibration
  - to calibrate the linearity of readout channels, both the high gain and low gain channels
  - Also could be used to calibrate the ratio of low gain and high gain channels



Linearity of readout channels

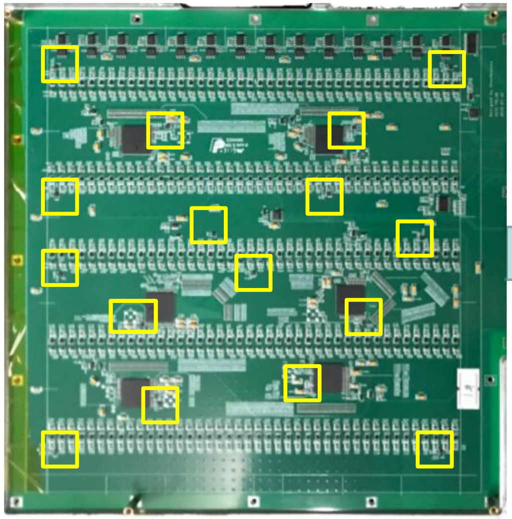


Low gain high gain ratio

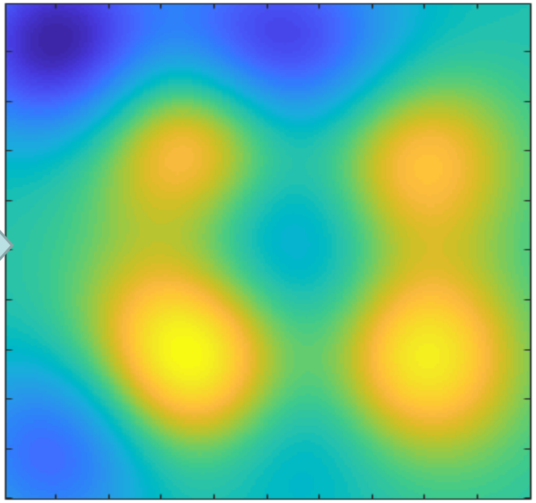


Electronics III

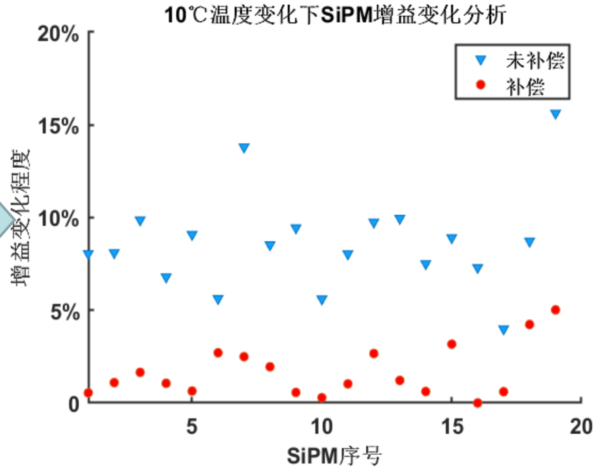
- Temperature monitor
  - Each EBU has 16 sensors to monitor the temperature
  - reconstruct the temperature field using these data
  - and to adjust the gain of SiPMs on the board (operation voltage)



Temperature sensors



Temperature field



Gain stability after compensation