R&D Progress of STCF pCsI ECAL

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On behalf of the STCF calorimeter working group

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Outline

- STCF pCsI ECAL
- Development of Prototype
- Beam Test Results
- Summary

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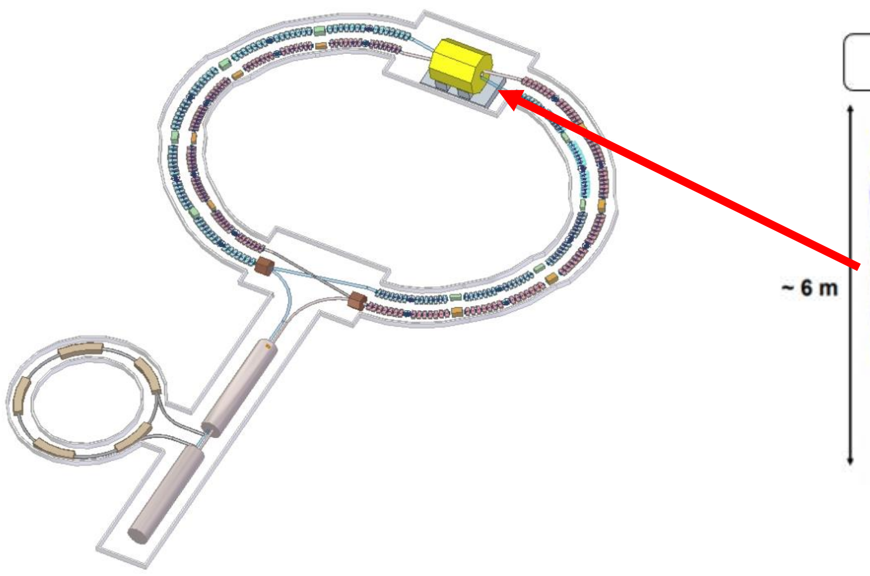
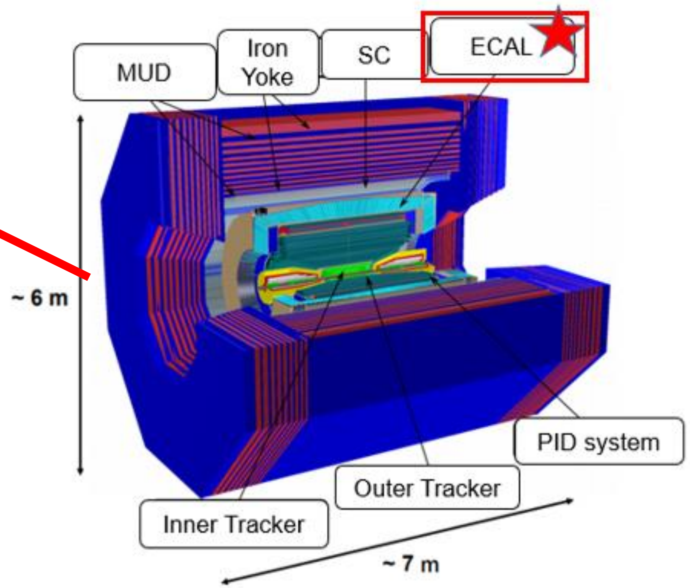
Super Tau-Charm Facility (STCF)

- **Next-generation high luminosity e^+e^- collision experiment in China**
  - luminosity: $\geq 0.5 \times 10^{35}\ cm^{-2} \cdot s^{-1}$@ 4 GeV
  - center-of-mass : 2-7 GeV



Accelerator layout



Detector layout

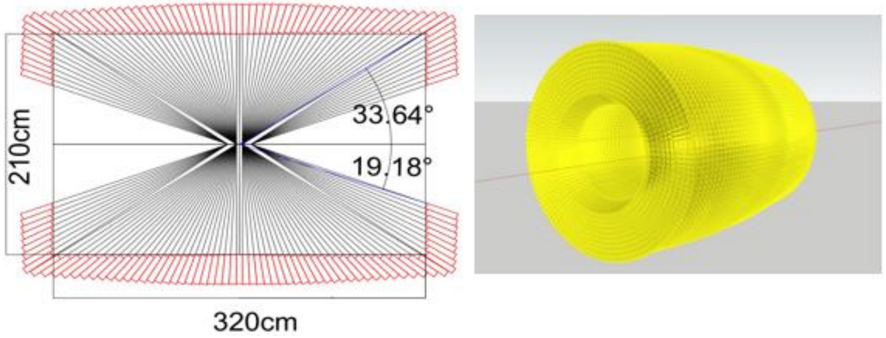
- **Challenges and requirements of electromagnetic calorimeter (ECAL)**
  - High event rate (400 kHz)
  - High background level (~MHz)
  - Response energy range: 25 MeV ~ 3.5 GeV
  - Precise energy resolution : < 2.5% @ 1 GeV
  - Good position resolution : ~5 mm @ 1 GeV
  - Good time resolution: ~300 ps @ 1 GeV

Design of pCsI ECAL

- **Design of Sensitive Units**
  - ◆ Pure CsI (pCsI) crystal ($\sim 5 \times 5 \times 28\ (15X_0)\ cm^3$)
    - ➢ Fast decay time (~30 ns)
    - ➢ Good radiation hardness
    - ➢ Low light yield
  - ◆ Avalanche photodiode (APD)
    - ➢ Large area array ($1 \times 1\ cm^2 \times 4$)
- **Design of Electronics**
  - ◆ Based on CSA
  - ◆ Waveform sampling readout
- **Design of Geometry**
  - ◆ Barrel: 6732 crystals
  - ◆ Endcap: 969 × 2 crystals


pCsI crystal & APD (S8864-1010)


Front end board & Back end board



Geometry model

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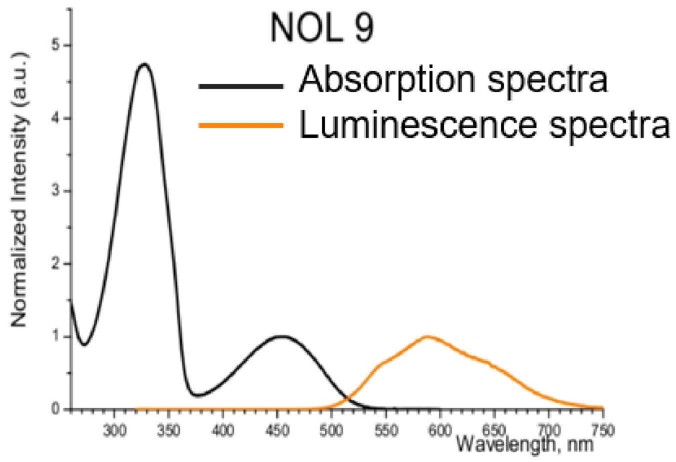
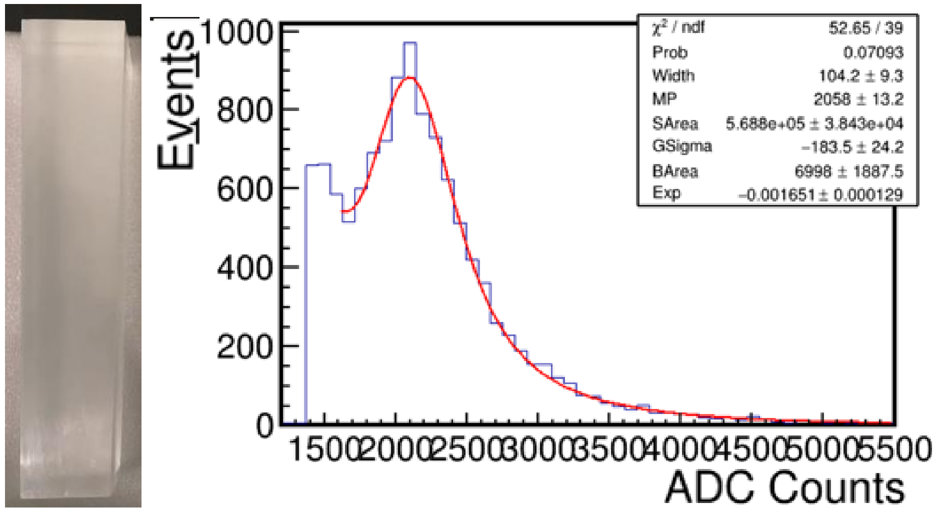
Light yield of the pCsI

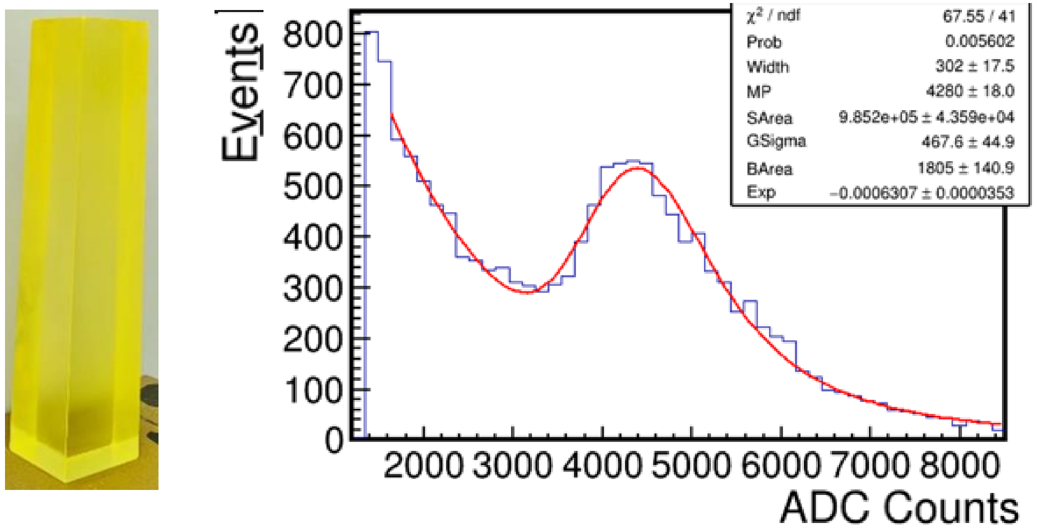
- **Use the WLS material (NOL-9) to increase the L.Y.**
  - Emission peak of pCsI is about 320 nm
  - Reduce self-absorption
    - Transmittance of pCsI: ~30% @ 320nm, ~50% @ 600nm
  - "Increase" the Q.E. of APD
    - Q.E. of APD: ~40% @ 320 nm, ~80% @ 600nm



- **Coat the NOL-9 on crystal**
  - L.Y. increased from 99 p.e./MeV to 265 p.e./MeV, ~170% increase.



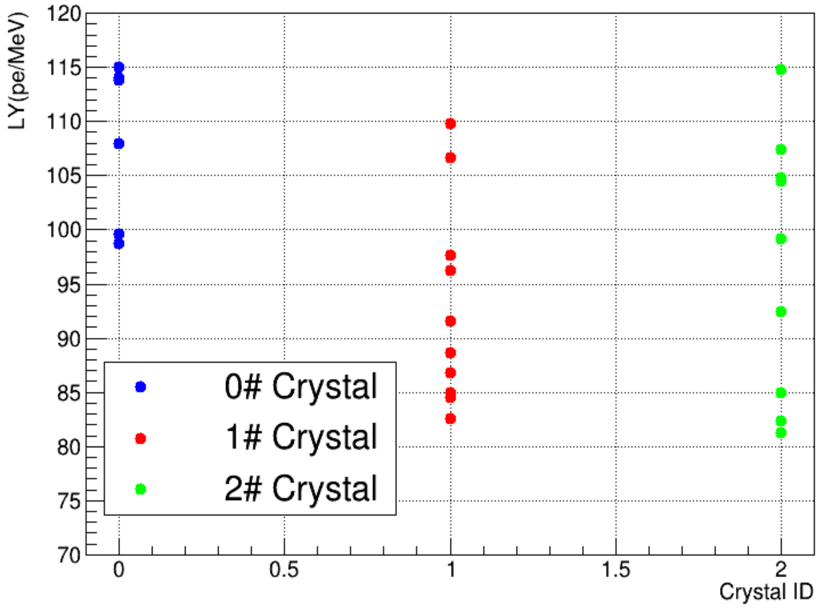
Cosmic ray energy spectrum before coating the NOL-9



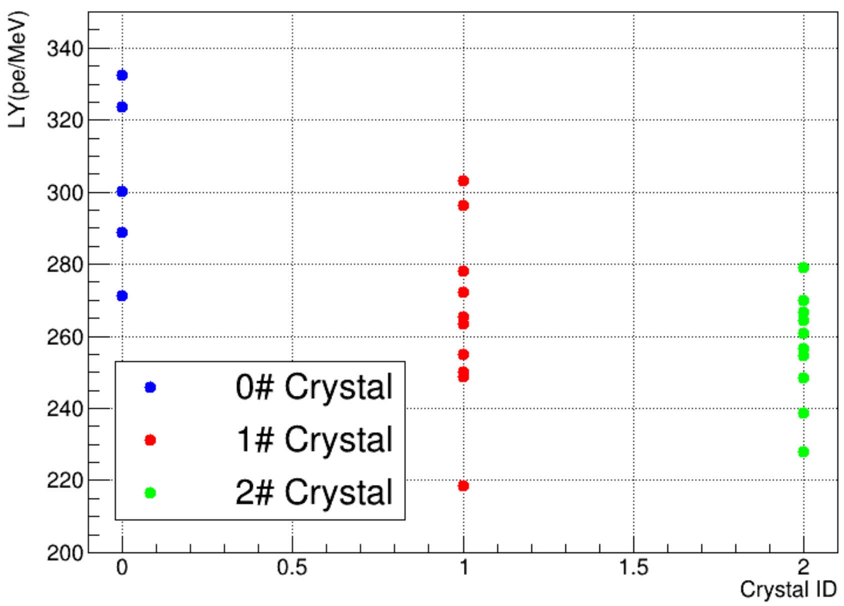
Cosmic ray energy spectrum after coating the NOL-9

Light yield of the pCsI

- **Coat the NOL on crystals used in the prototype**
- **Test the L.Y. before & after coating the NOL**
  - Average L.Y. increased from 102 p.e./MeV to 281 p.e./MeV, increase of ~175%



Average L.Y. before coating the NOL: 102 p.e./MeV

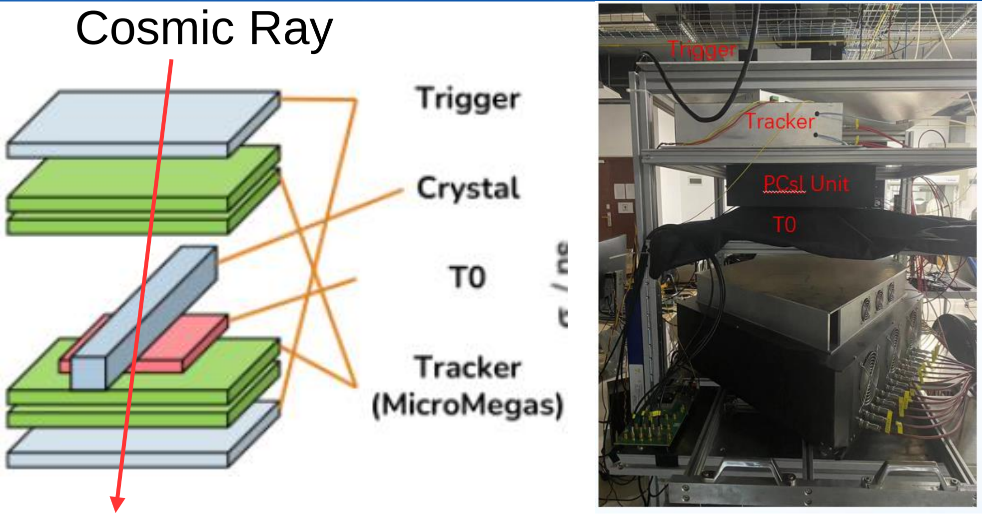


Average L.Y. after coating the NOL: 281 p.e./MeV

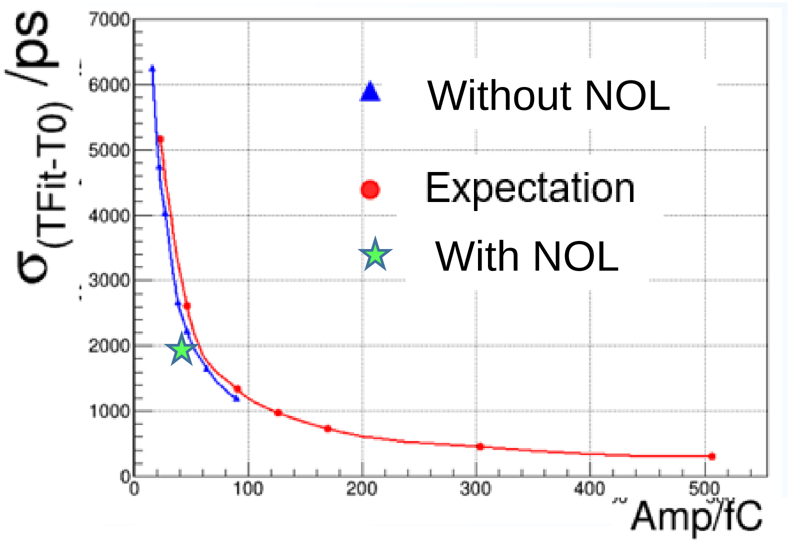
Timing Performance

- **Test timing performance using cosmic rays**
  - Use waveform fitting method for timing
  - $\sigma_t@30\ MeV$: $\sim 5\ ns$(w/o NOL)→ $\sim 2\ ns$(with NOL)
  - Relationship between time and incident position:

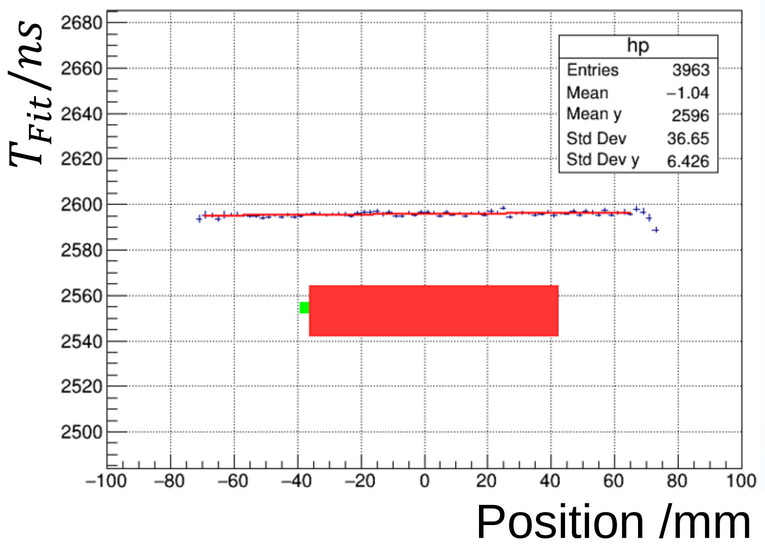
$T_{Fit} \sim 0.01(ns/mm) \times l\ (mm)$, l is the distance from the APD



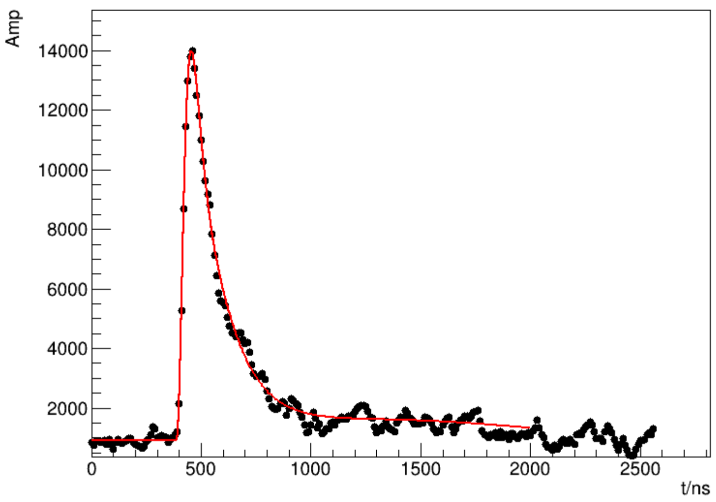
Cosmic ray test system



Cosmic ray timing test result



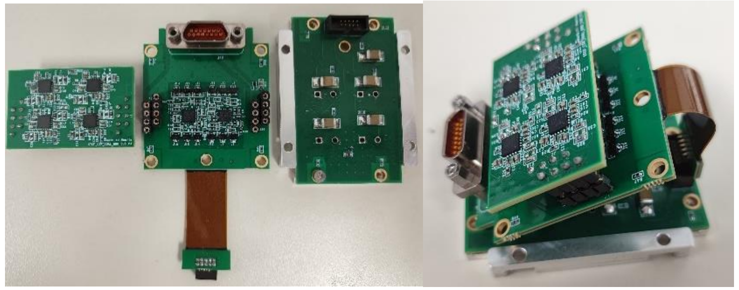
Time vs. Incident position

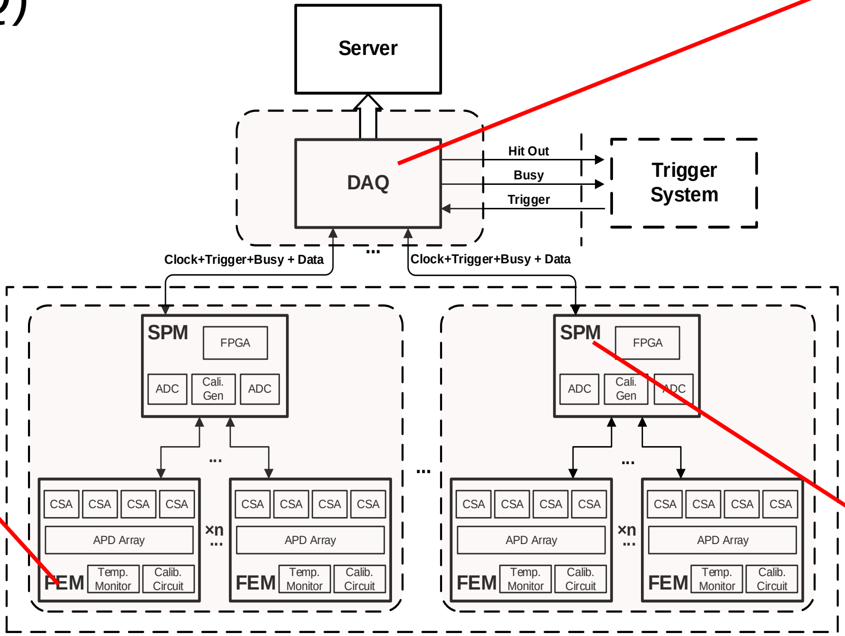


A fit result of signal waveform

Electronics for ECAL prototype

- **Electronics system**
  - ➢ Front-End Module (FEM)
  - ➢ Signal Processing Module (SPM)
  - ➢ Data Acquisition System (DAQ)





- **DAQ**
  - ➢ Data Acquisition
  - ➢ Clock Distribution

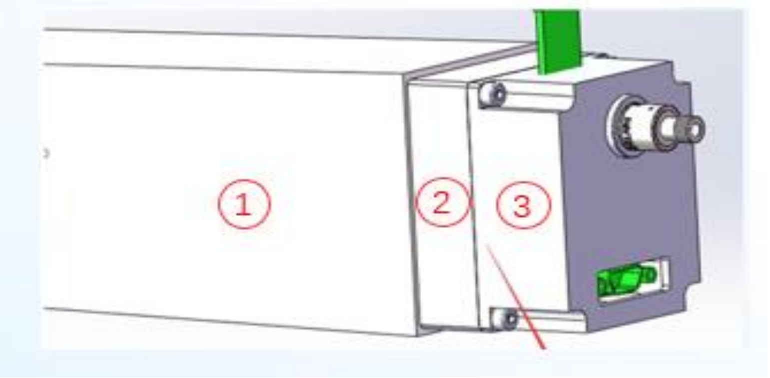
- **FEM**
  - ➢ Multi-layer structure
  - ➢ 4 APD-CSA Channel
  - ➢ High-Low Gain

- **SPM**
  - ➢ A-D Converter
  - ➢ Data packaging

Mechanical Design of Sensitive Unit

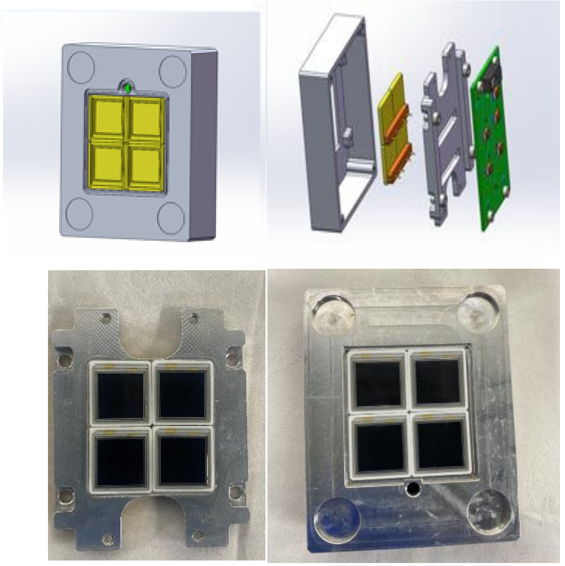
- **Sensitive Unit consists of three parts**
  ① pCsI crystal with package materials
  - 3-layer Teflon (300 um)
  - Mylar-Al film (50 um)

  ② APD Box
  ③ Electronics Box

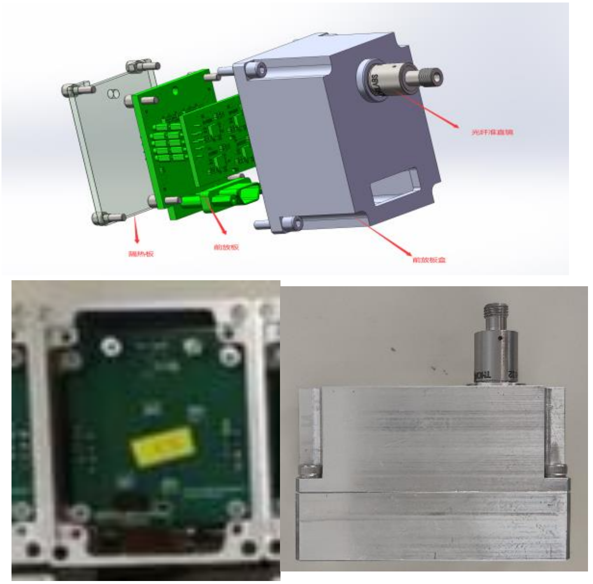


Sensitive Unit

pCsI wrapped by Teflon & Mylar-Al film

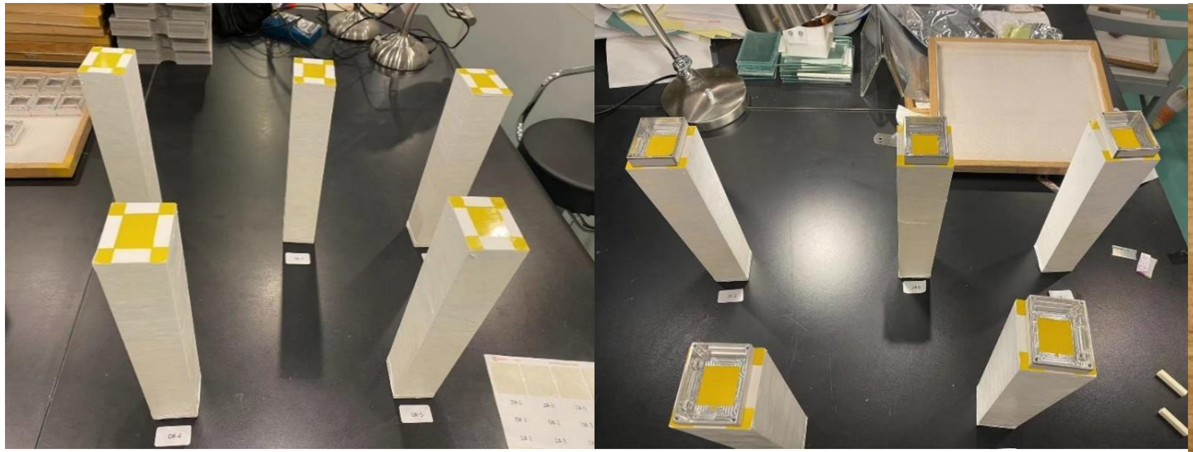


APD Box

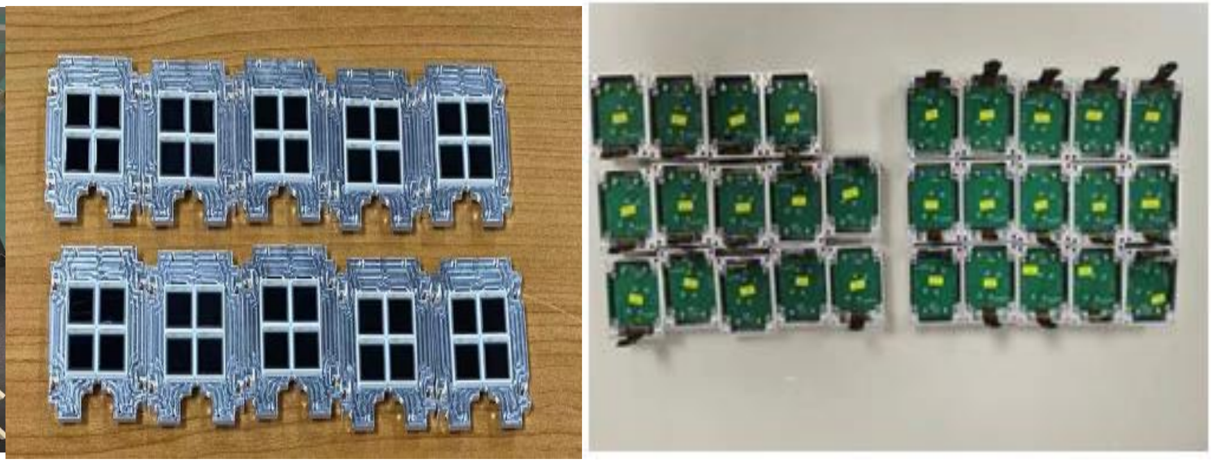


Electronics Box

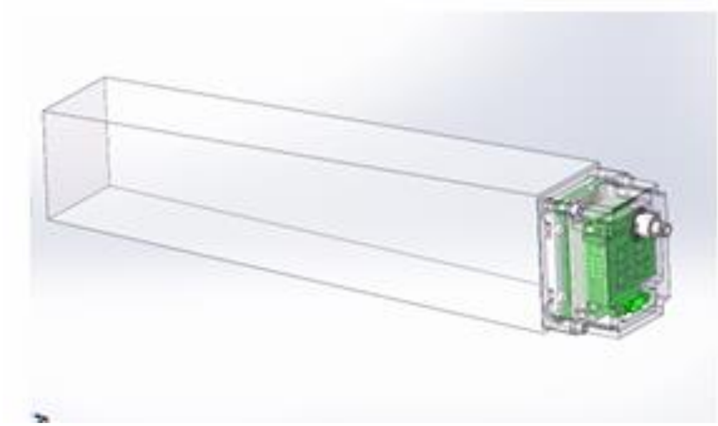
Batch assembly of sensitive units



Use glue to fix the APD box and the crystal together

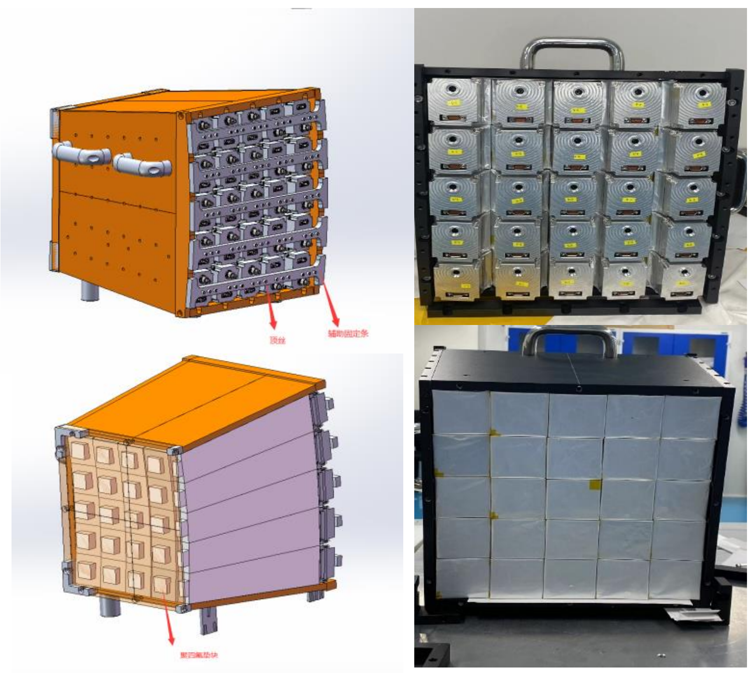


APD boxes and the Electronics boxes



ECAL Prototype

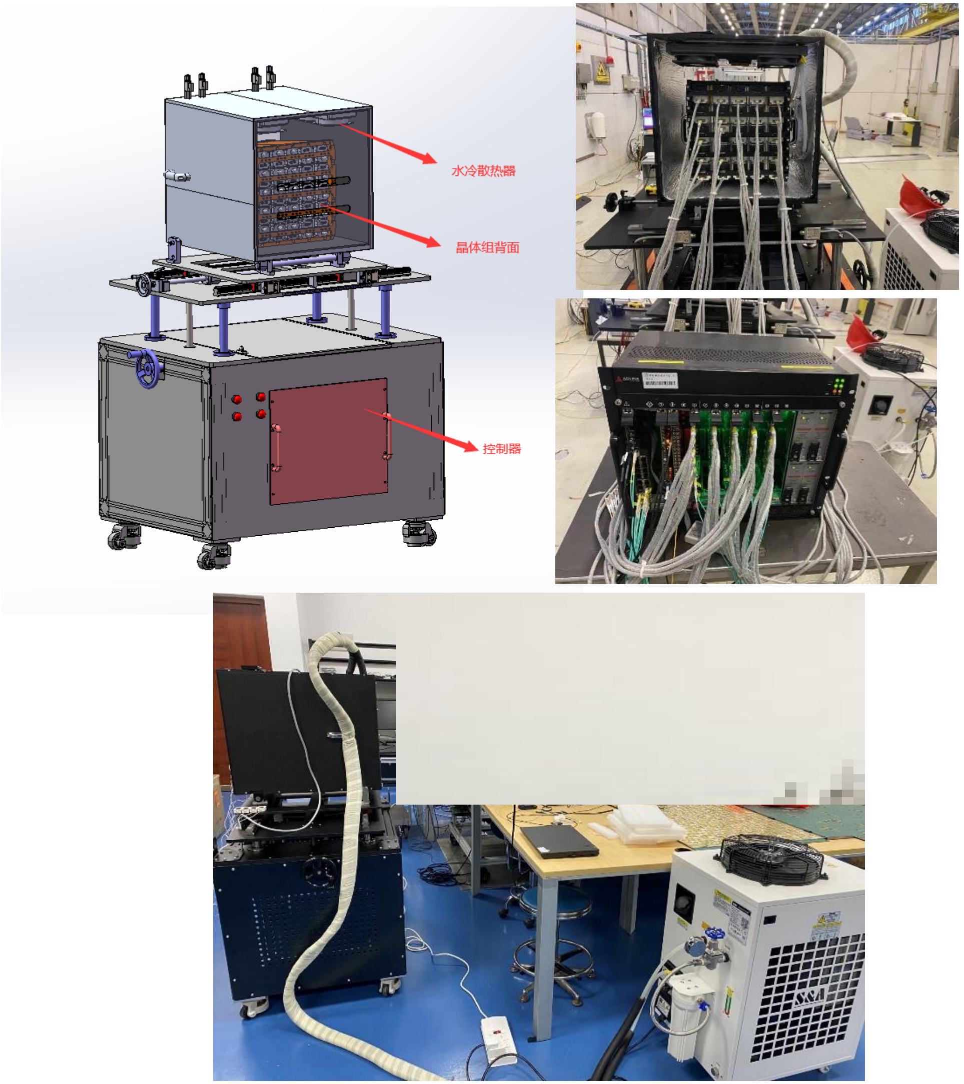
- **ECAL prototype consists of three parts**
  - 5 × 5 sensitive unit array
  - PXI chassis, carrying SPM & DAQ
  - Temperature controller



5 × 5 sensitive unit array

PXI chassis

water chiller



ECAL Prototype

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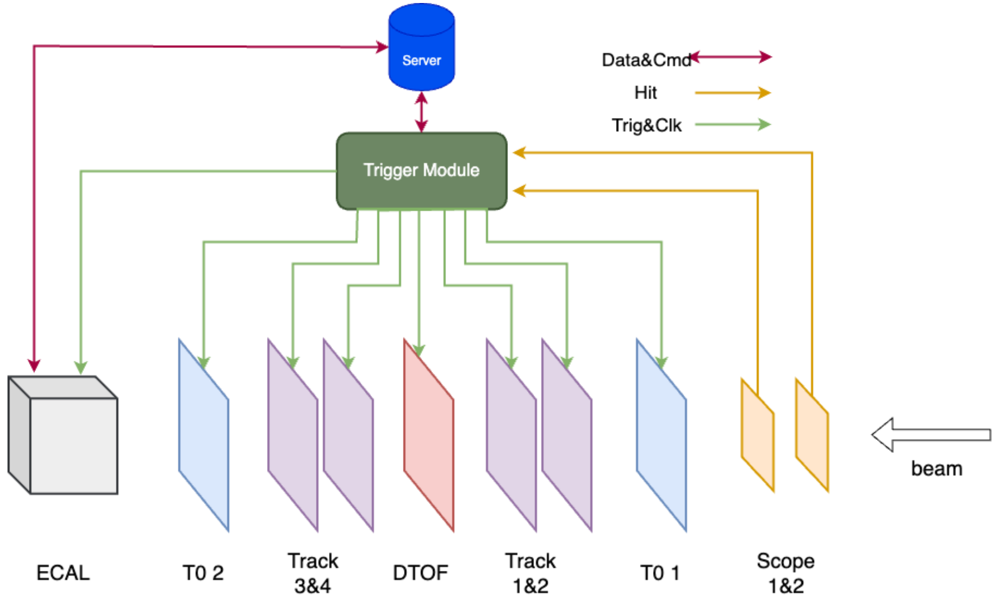
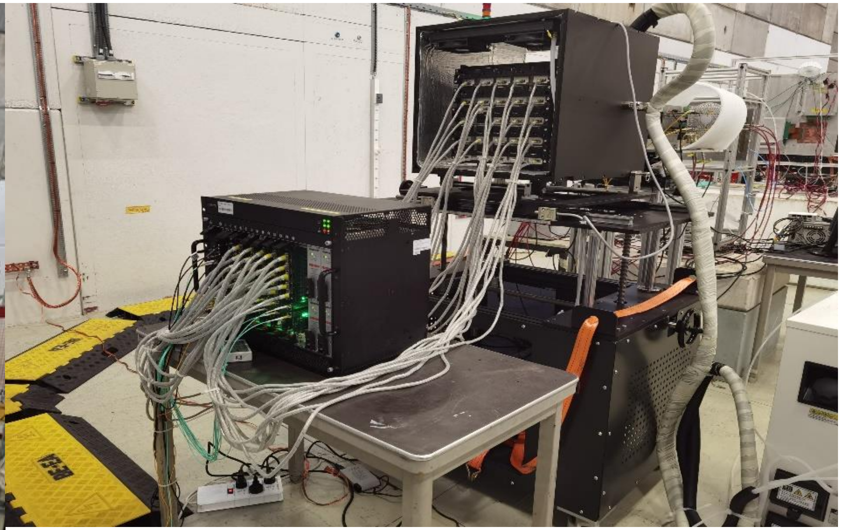
Beam Test

- **Beam test on the ECAL prototype**
  - PS T09 beam line at CERN
  - Multi-system beam test
    - T0 Detector
    - Track Detector
    - PID Detector——DTOF
    - ECAL
  - Beam particle and momentum

Particle	Momentum
μ^+	~ 5 GeV/c
e^+	0.5-5 GeV/c
$hardon^+$	1-5 GeV/c

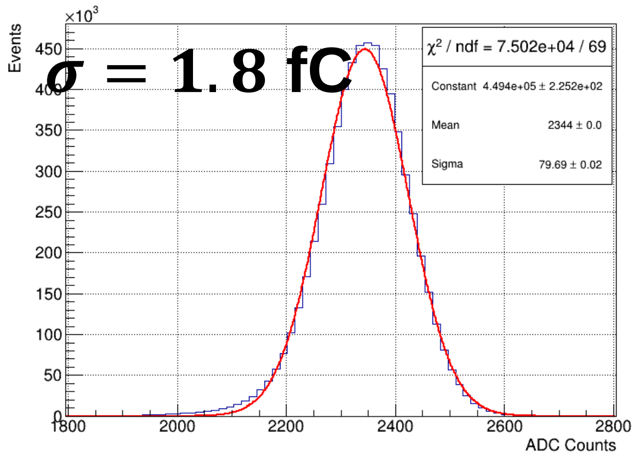


Beam Test

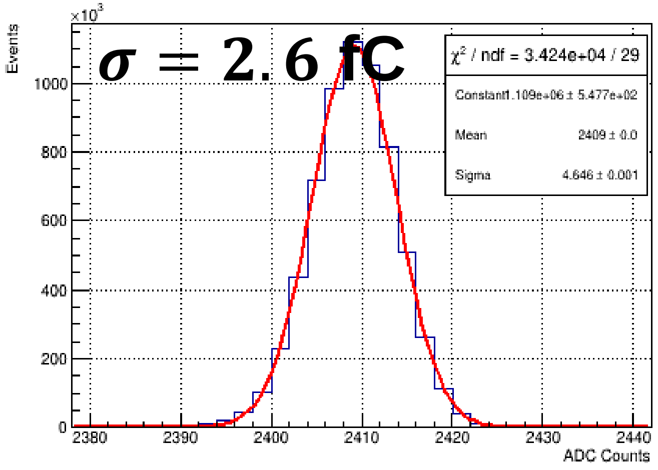


Working State of Prototype

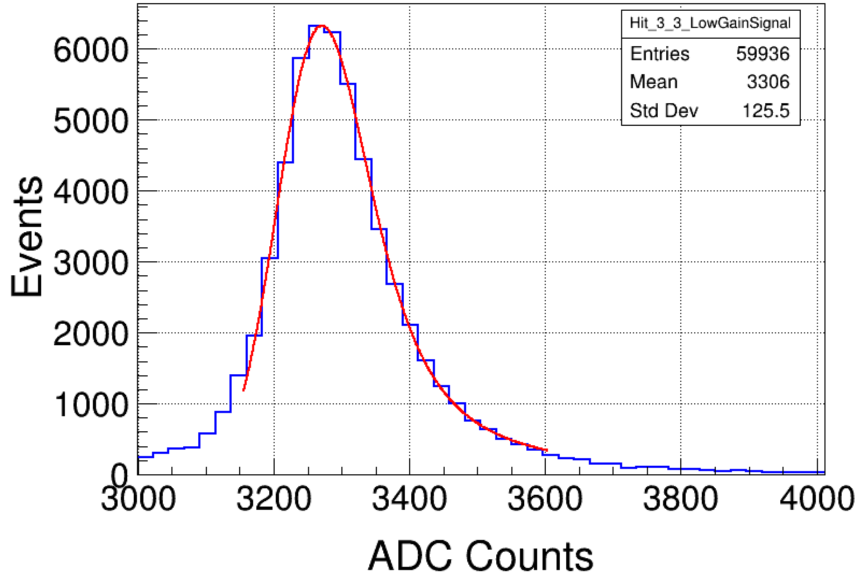
- **Noise level**
  - ➢ Low Gain : ~1.8 fC (ENE: ~ 0.8 MeV)
  - ➢ High Gain: ~2.6 fC (ENE: ~1.2 MeV)
- **High-Low gain ratio : ~ 25**
- **Calibration with Muon Beam**
  - ➢ MIPs : ~ 180 MeV



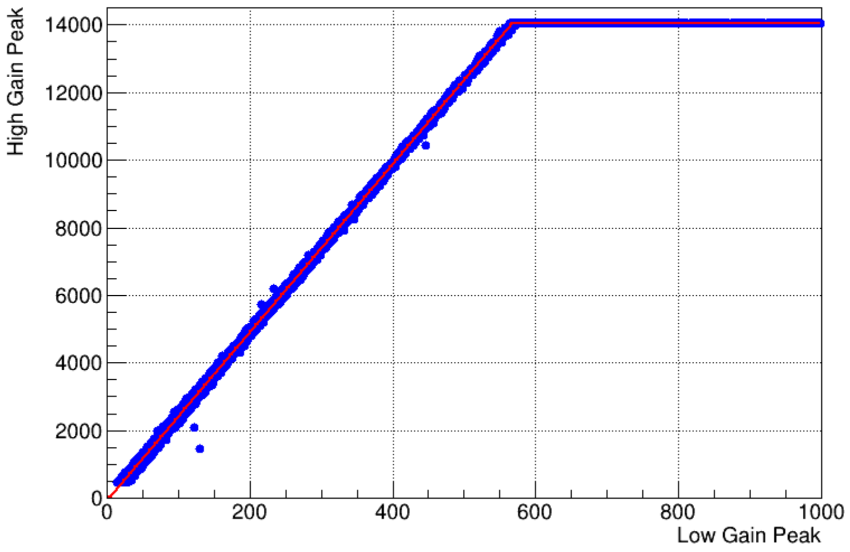
High gain Noise



Low gain Noise



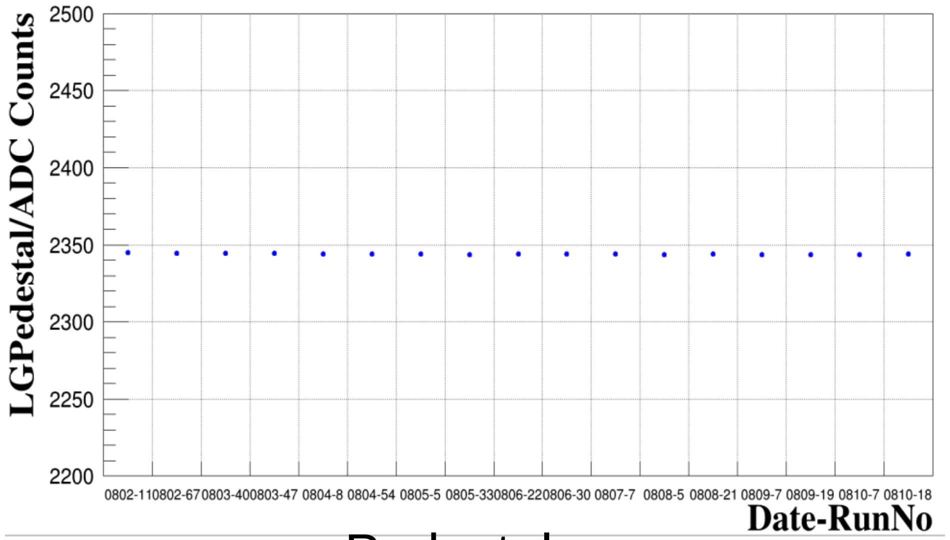
MIPs energy spectrum



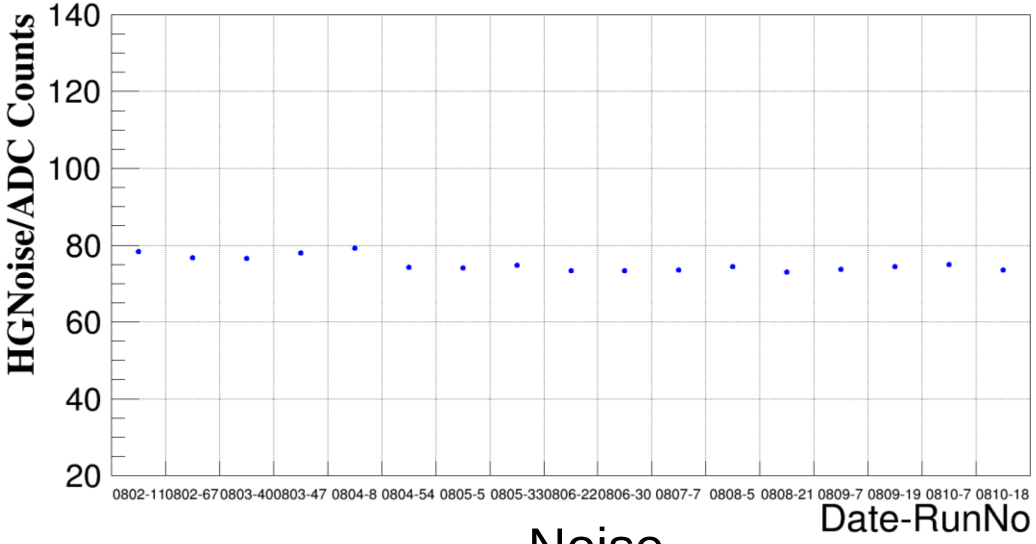
High-Low gain ratio

Stability of the Prototype’s Working State

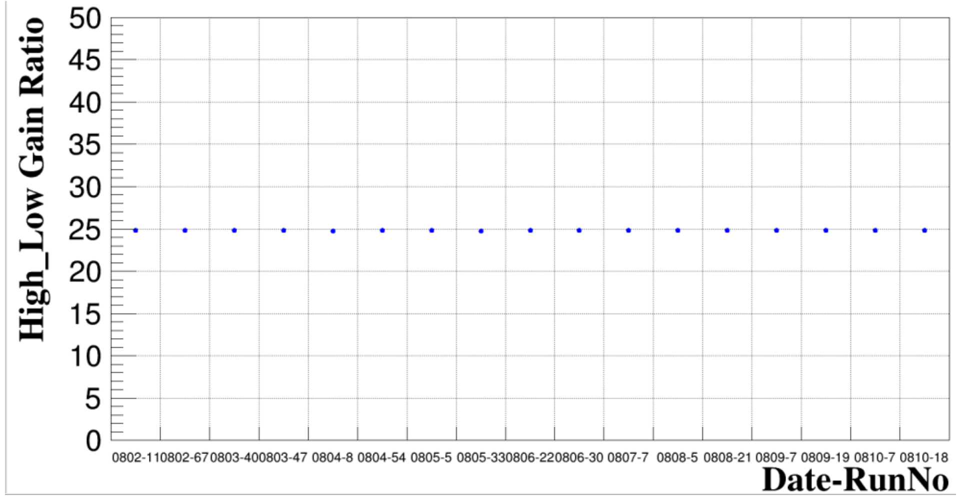
- **Working state is stable during testing**



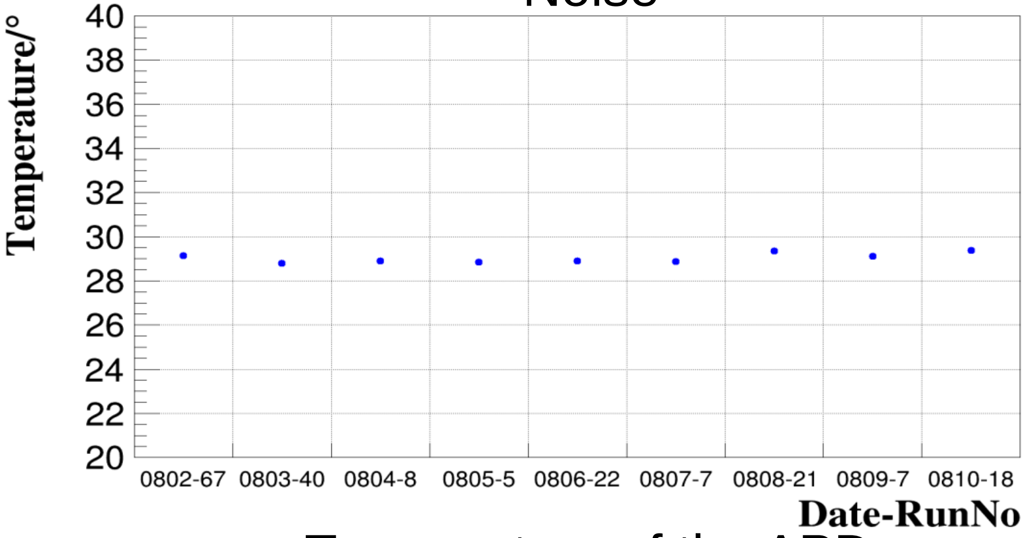
Pedestal



Noise



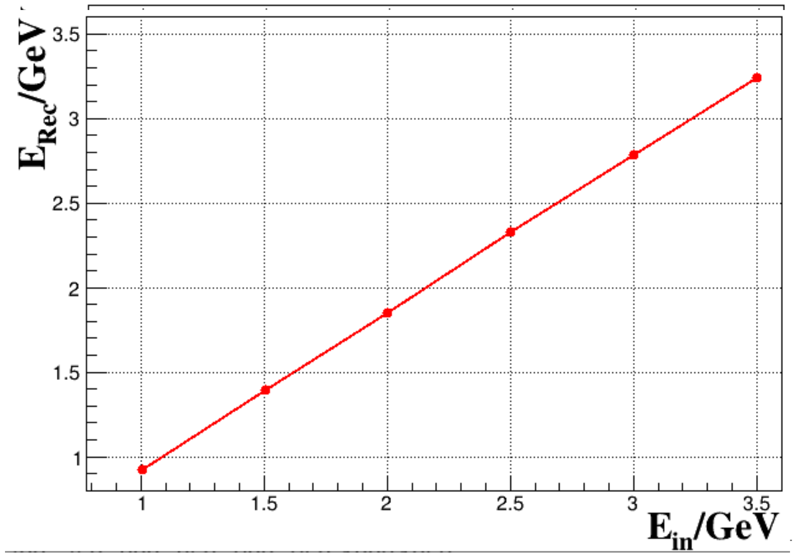
High-Low gain ratio



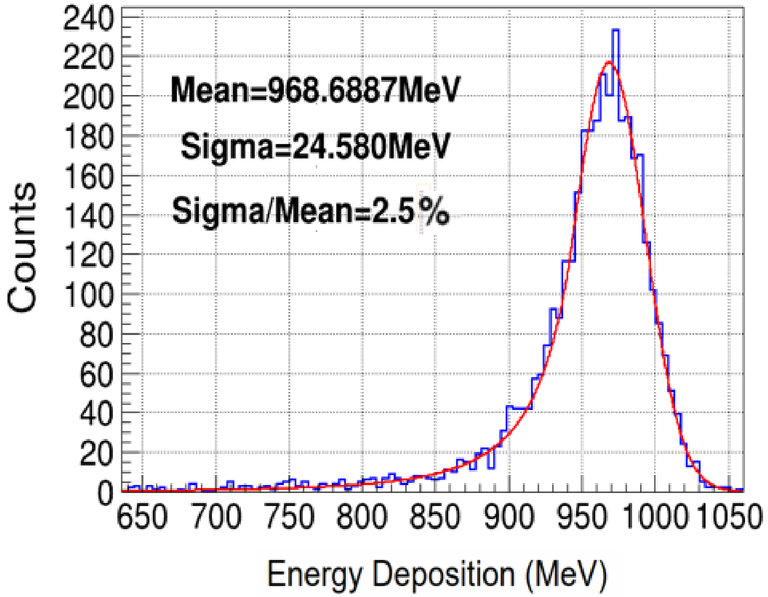
Temperature of the APD

Energy Reconstruction Performance

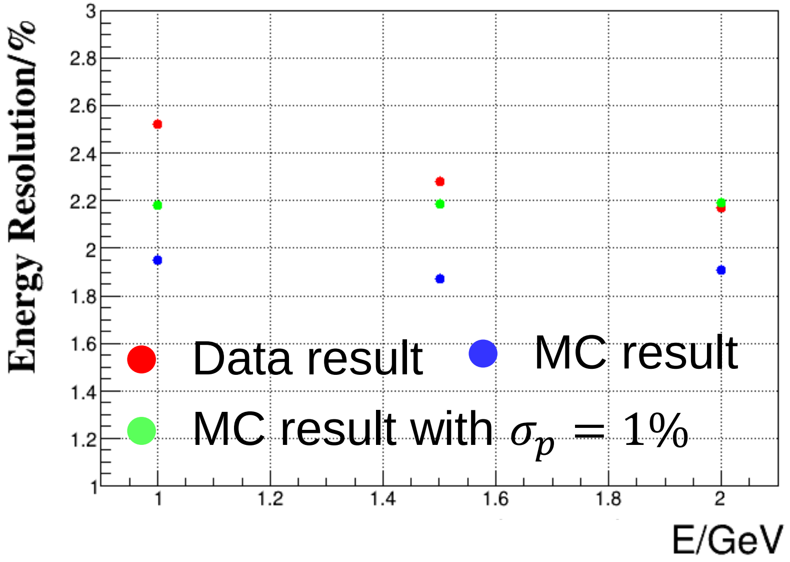
- **Good Energy linearity**
- **Energy resolution of 1 GeV e is ~2.5%**
- **Test results are worse than the simulation results**
  - Material in front of ECAL
  - Beam momentum dispersion (>1% @ 1 GeV)



Energy linearity



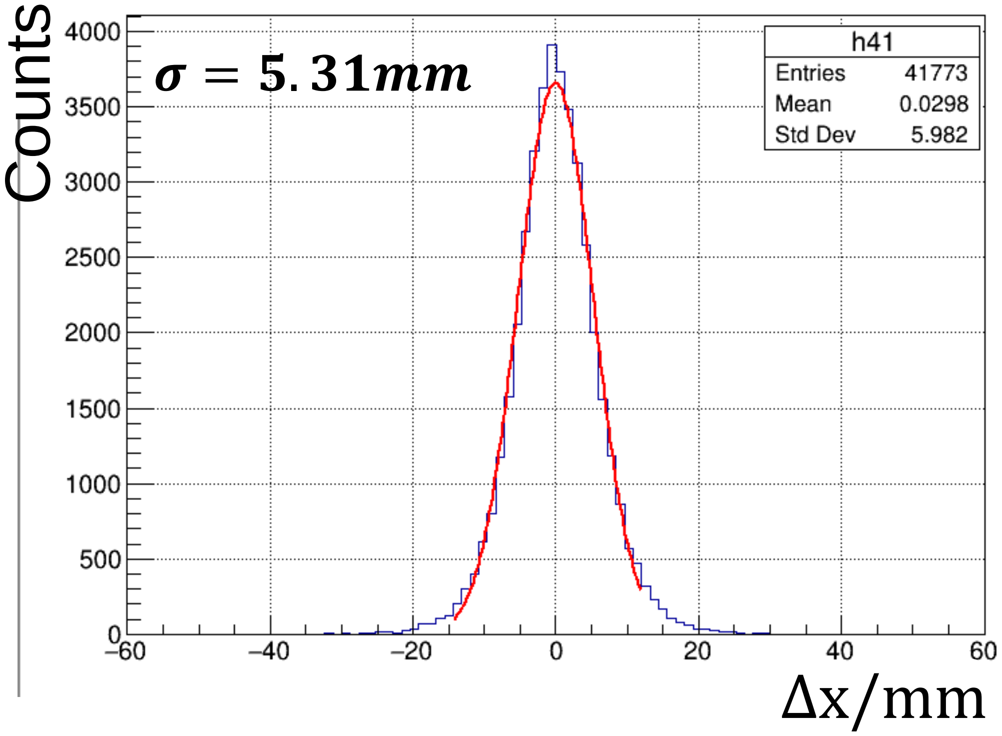
Energy spectrum of 1 GeV e^+



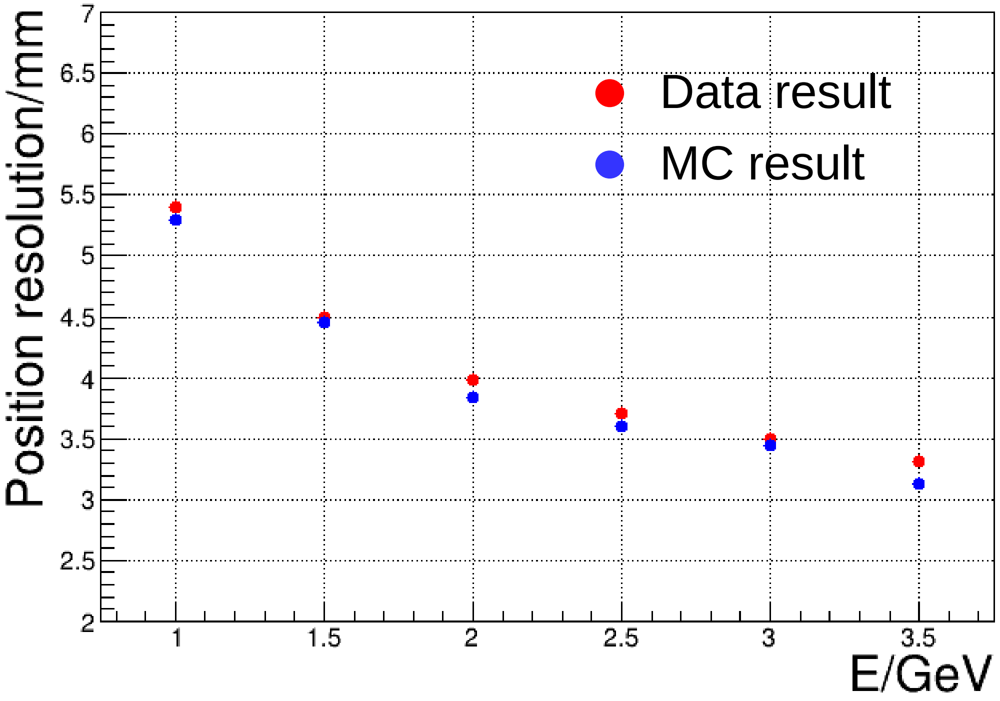
Energy resolution vs. Energy

Position Reconstruction Performance

- **Position resolution of 1 GeV e is ~5.3mm ($\Delta_x = x_{ECAL\_rec} - x_{incident}$)**
- **Test results are consistent with the simulation results**



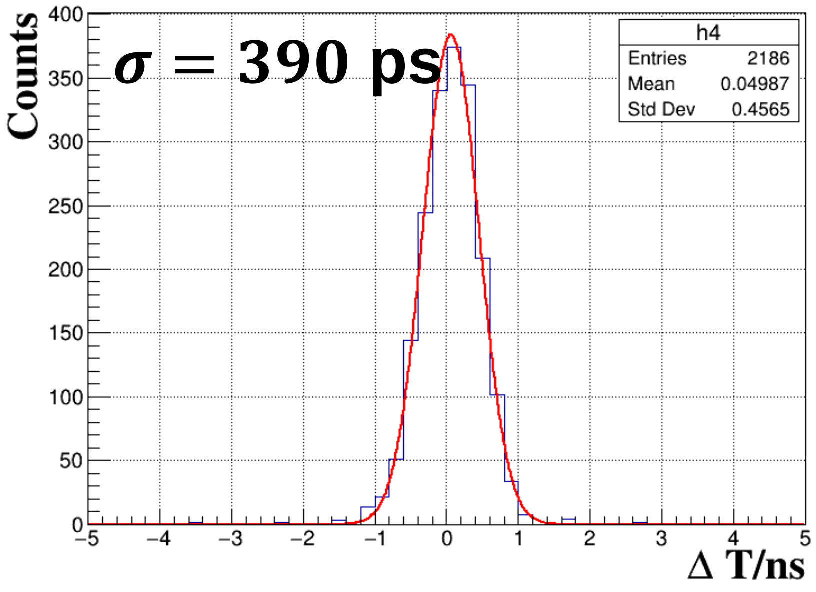
Position reconstruction results of 1 GeV e^+



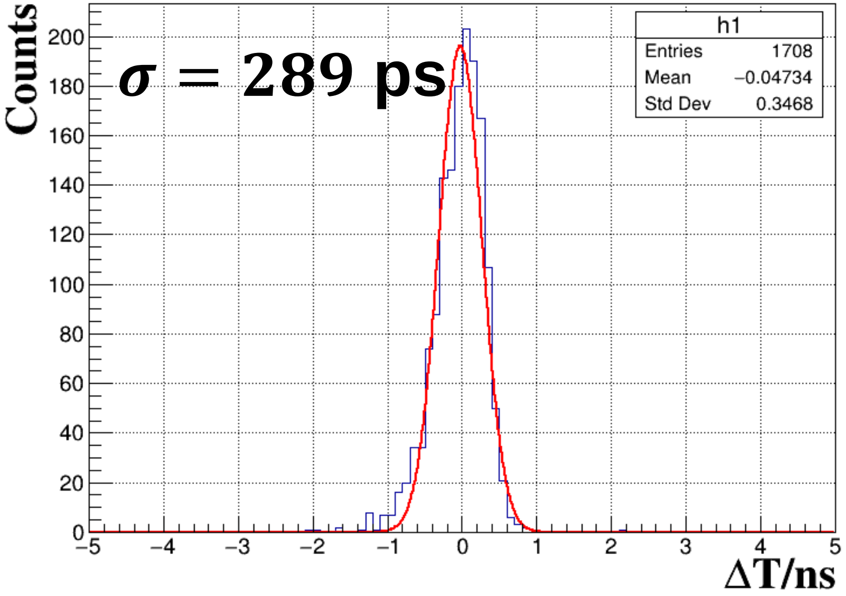
Position resolution vs. Energy

Time Reconstruction Performance

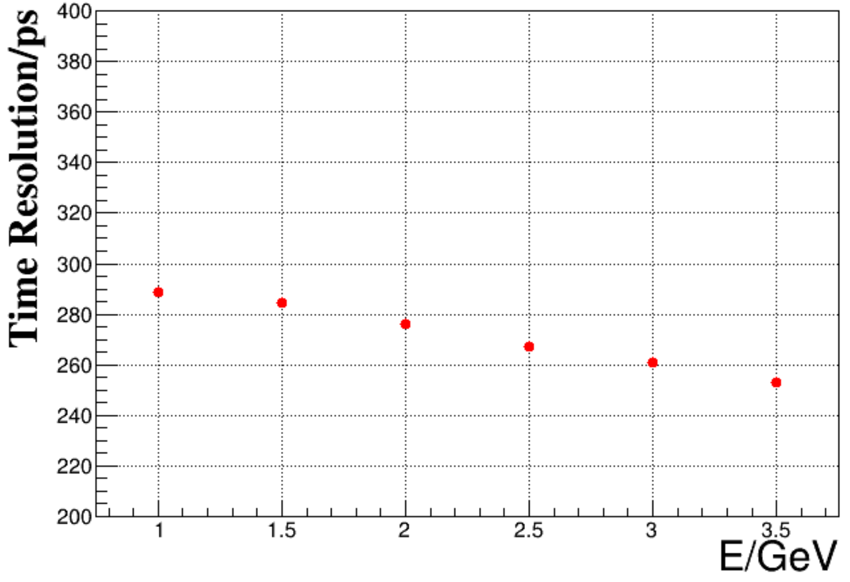
- **For MIPs (~180 MeV), σ_t~390 ps ($\Delta_T = T_{ECAL\_Rec} - \mathrm{T_0}$)**
- **For Shower (~1 GeV), σ_t~290 ps**
  - The fluctuations in the development of the shower have an impact on the timing and further correction is needed.
  - Need optical simulations to verify and understand the test results, which is in progress



Time reconstruction results of MIPs



Time reconstruction results of 1 GeV e^+



Time resolution vs. Energy

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- **Completed the development of ECAL prototype**
  - The average L.Y. reached 280 p.e./MeV
  - Under the current design, timing performance could meet the requirements
- **Successful beam test at CERN**
  - The working state of the prototype is stable
  - The beam test results show that the performance of ECAL could meet the requirements of STCF
  - More data analysis work is underway, such as the analysis of hadron data

Summary

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  - The working state of the prototype is stable
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Thanks!

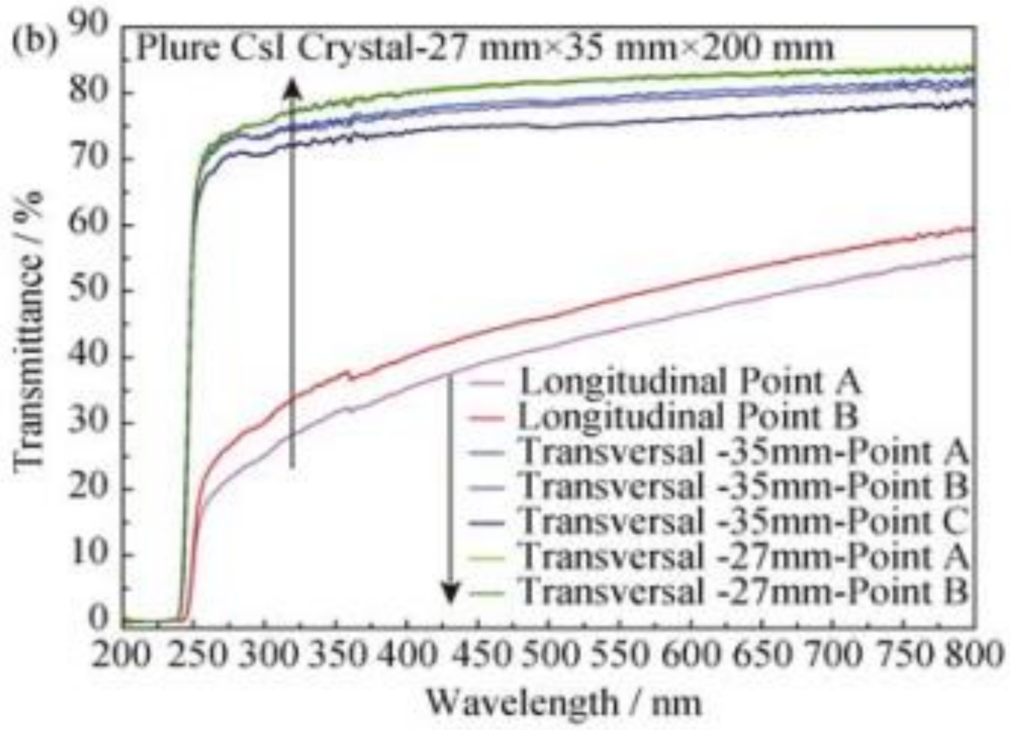
Back Up

ECAL Design —— Crystal Selection

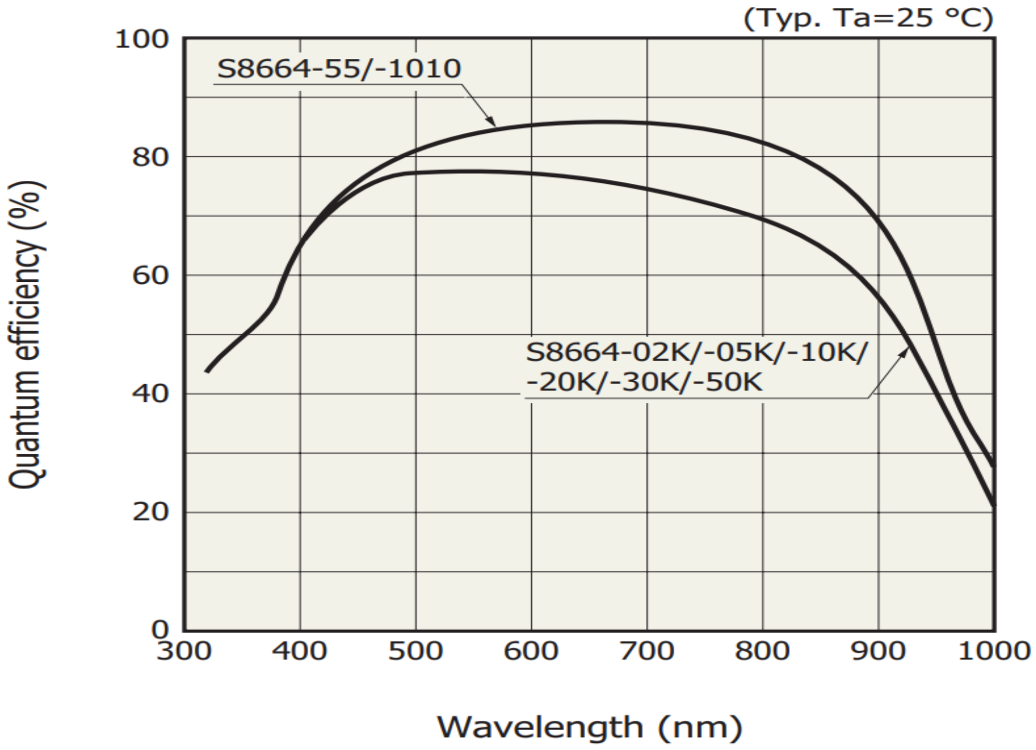
- Total absorption calorimeter
  - pCsI crystal + APD photo-device

Crystal	Pure CsI	LYSO	GSO	YAP	PWO	BaF:Y
Density (g/cm^3)	4.51	7.40	6.71	5.37	8.30	4.89
Melting Point (°C)	621	2050	1950	1872	1123	1280
Radiation Length (cm)	1.86	1.14	1.38	2.70	0.89	2.03
Moliere Radius (cm)	3.57	2.07	2.23	4.50	2.00	3.10
Refractive index	1.95	1.82	1.85	1.95	2.20	1.50
Hygroscopicity	Slight	No	No	No	No	No
Luminescence (nm)	310	402	430	370	425 420	300 220
Decay time (ns)	30 6	40	60	30	30 10	600 1.2
Light yield (%)	3.6 1.1	85	20	65	0.3 0.1	1.7 4.8
Dose rate dependent	No	No	TBA	TBA	Yes	No
D(LY)/dT (%/°C)	-1.4	-0.2	-0.4	TBA	-2.5	TBA
Experiment	KTeV Mu2e				CMS ALICE PANDA	

Increase the light yield of pCsI

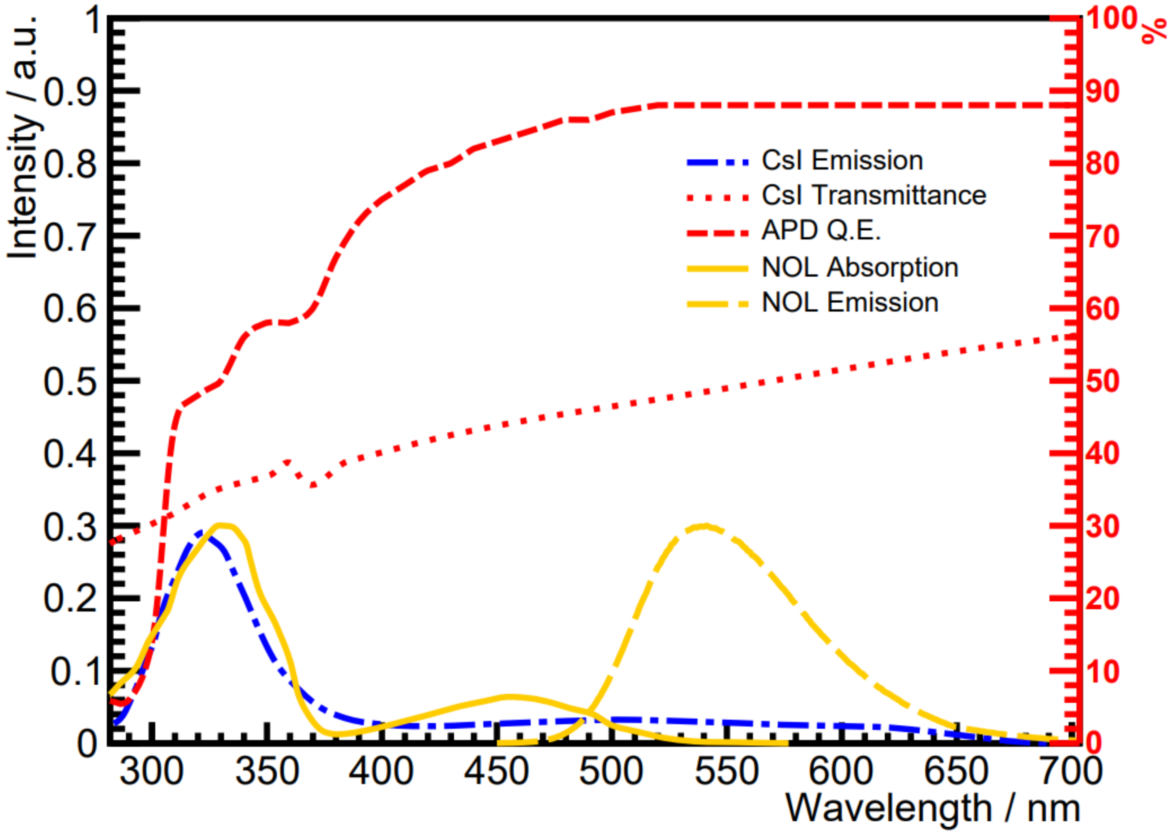


Transmittance of pCsI



APD Q.E.

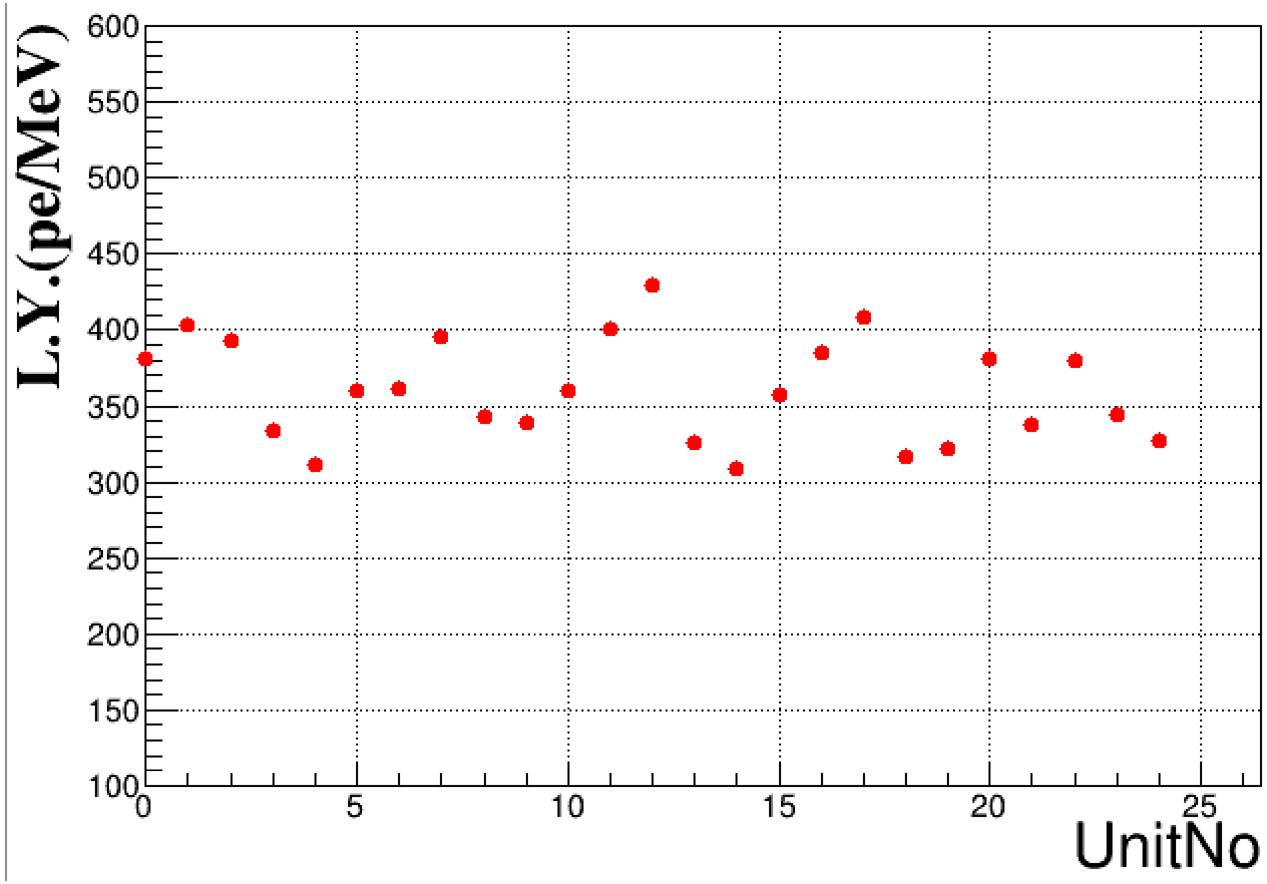
WLS



quantum yield of 95 %

luminescence decay time of 7.17 ns

L.Y. in Beam Test



1-Template Fitting

- Template shape function： $f(t) = A \times f(t-\tau) + p$
- $\chi^2 = \sum_{i,j}(y_i - A \cdot f(t_i - \tau) - p) \cdot S_{ij}^{-1} \cdot \left(y_j - A \cdot f\left(t_j - \tau\right) - p\right)$
- Apply $\frac{\partial \chi^2}{\partial A} = 0, \frac{\partial \chi^2}{\partial \tau} = 0, \frac{\partial \chi^2}{\partial p} = 0$:

$$\begin{cases} \sum_{i,j} f_{ki} \cdot S_{ij}^{-1} \cdot \left(y_j - Af_{kj} - Bf'_{kj} - p\right) = 0 \\ \sum_{i,j} f'_{ki} \cdot S_{ij}^{-1} \cdot \left(y_j - Af_{kj} - Bf'_{kj} - p\right) = 0 \\ \sum_{i,j} 1 \cdot S_{ij}^{-1} \cdot \left(y_j - Af_{kj} - Bf'_{kj} - p\right) = 0 \end{cases}$$

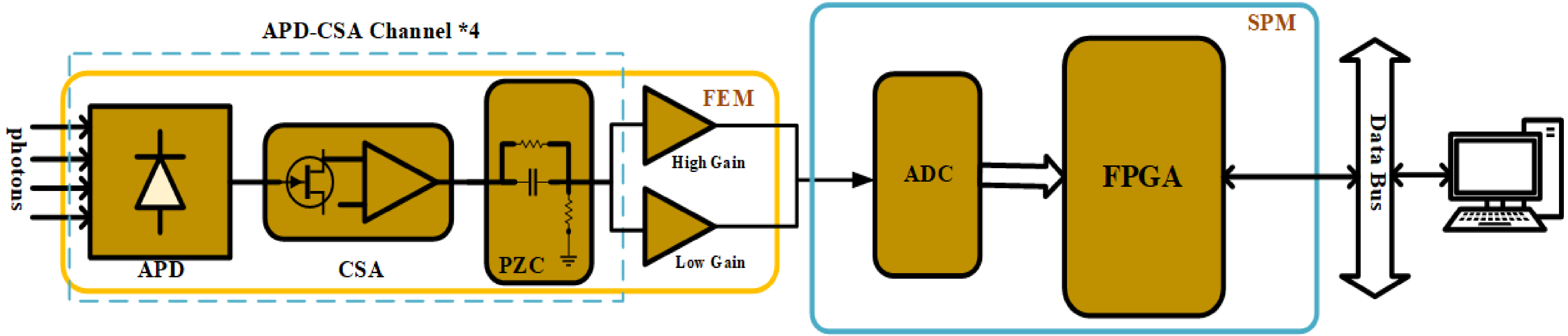
$$\begin{pmatrix} \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k^T & \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k'^T & \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{I} \\ \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k^T & \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k'^T & \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{I} \\ \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k^T & \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k'^T & \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{I} \end{pmatrix} \cdot \begin{pmatrix} A \\ B \\ p \end{pmatrix} = \begin{pmatrix} \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{Y} \\ \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{Y} \\ \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{Y} \end{pmatrix}$$

$$\begin{pmatrix} A \\ B \\ p \end{pmatrix} = \begin{pmatrix} \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k^T & \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k'^T & \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{I} \\ \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k^T & \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k'^T & \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{I} \\ \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k^T & \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{F}_k'^T & \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{I} \end{pmatrix}^{-1} \cdot \begin{pmatrix} \boldsymbol{F}_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{Y} \\ \boldsymbol{F}'_k \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{Y} \\ \boldsymbol{I} \cdot \boldsymbol{S}^{-1} \cdot \boldsymbol{Y} \end{pmatrix}$$

Electronics

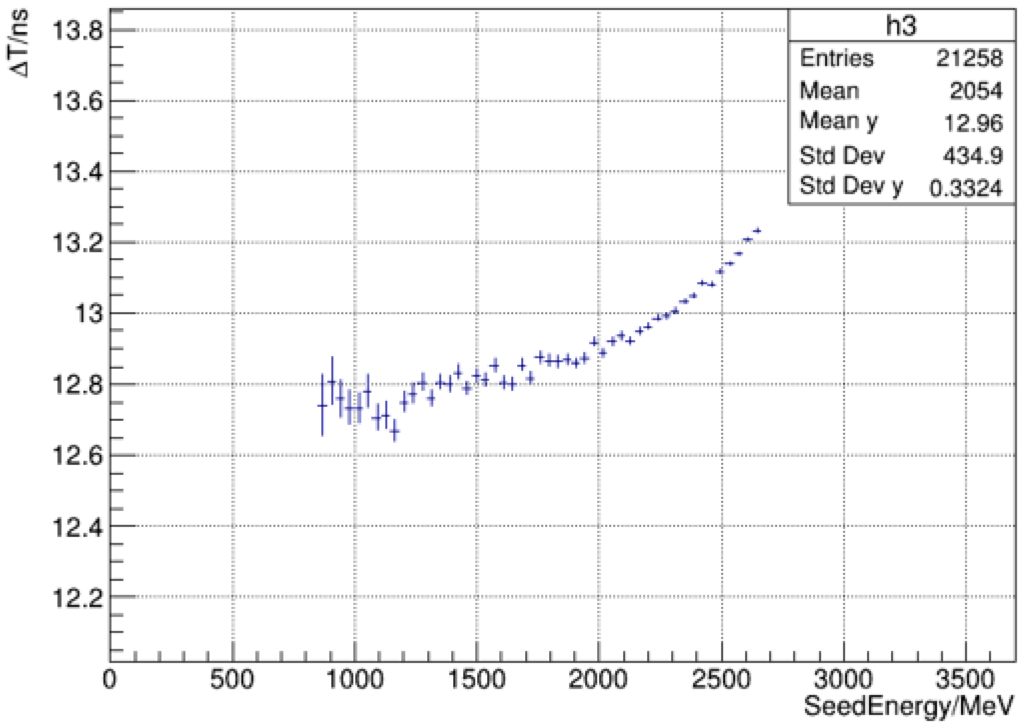
➢ Readout electronics design based on CSA

- Architecture Description:

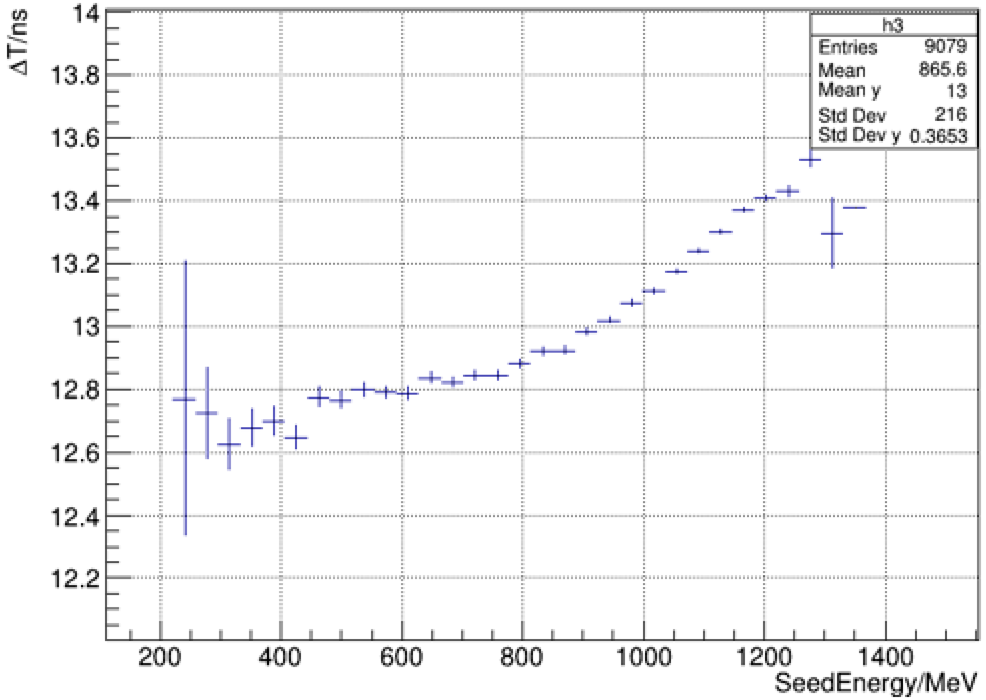


- APD: Large Junction capacitance (270pF) , Large leakage current(20nA) —— JFET & CSA
- Dynamic Range : Up to 7.2pC —— High & Low Gain Channel

Energy Deposition vs. Δ_T



3.5 GeV

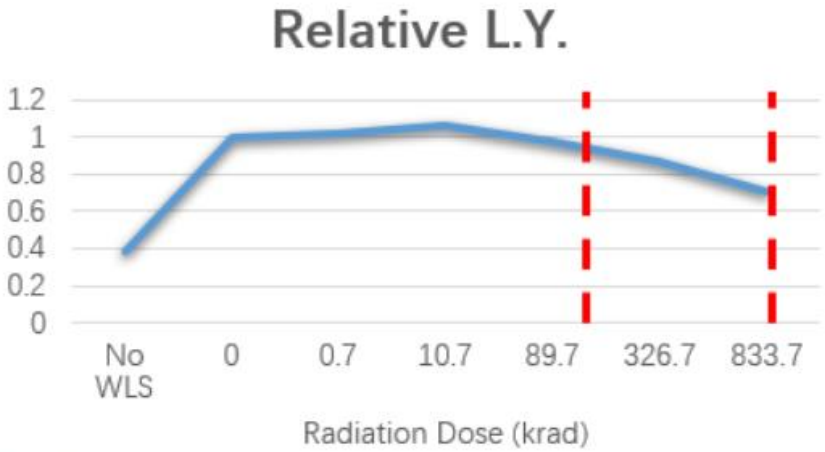


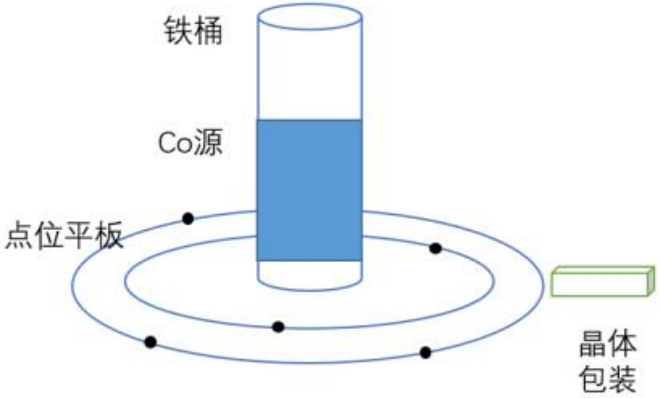
1.5 GeV

Wavelength shifter material study

- Radiation resistance test of WLS film using ^{60}Co
- The irradiated WLS film coated crystals were tested by cosmic rays：
  - 100 krad: No significant change
  - 1000 krad: close to 40% degradation

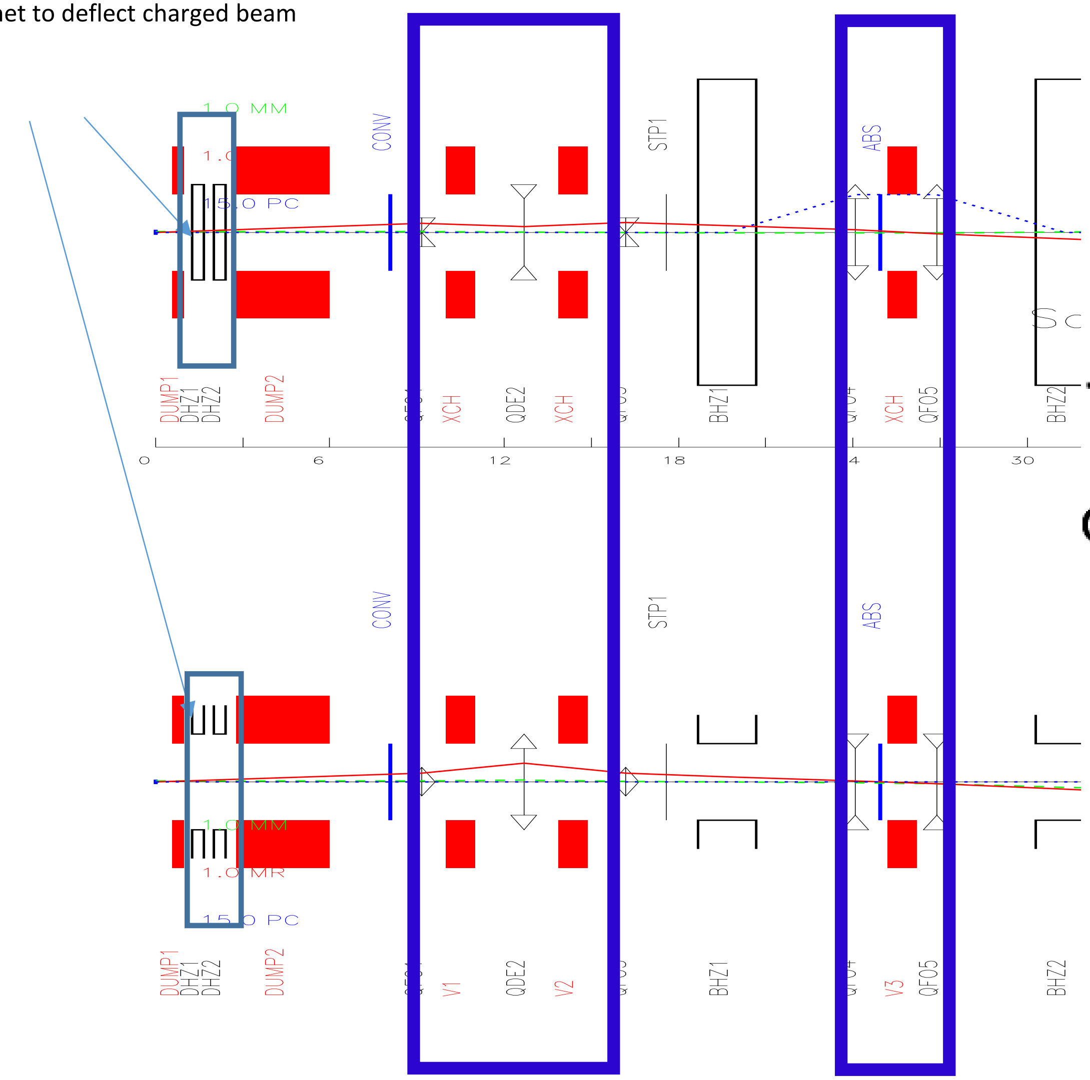
Radiation test

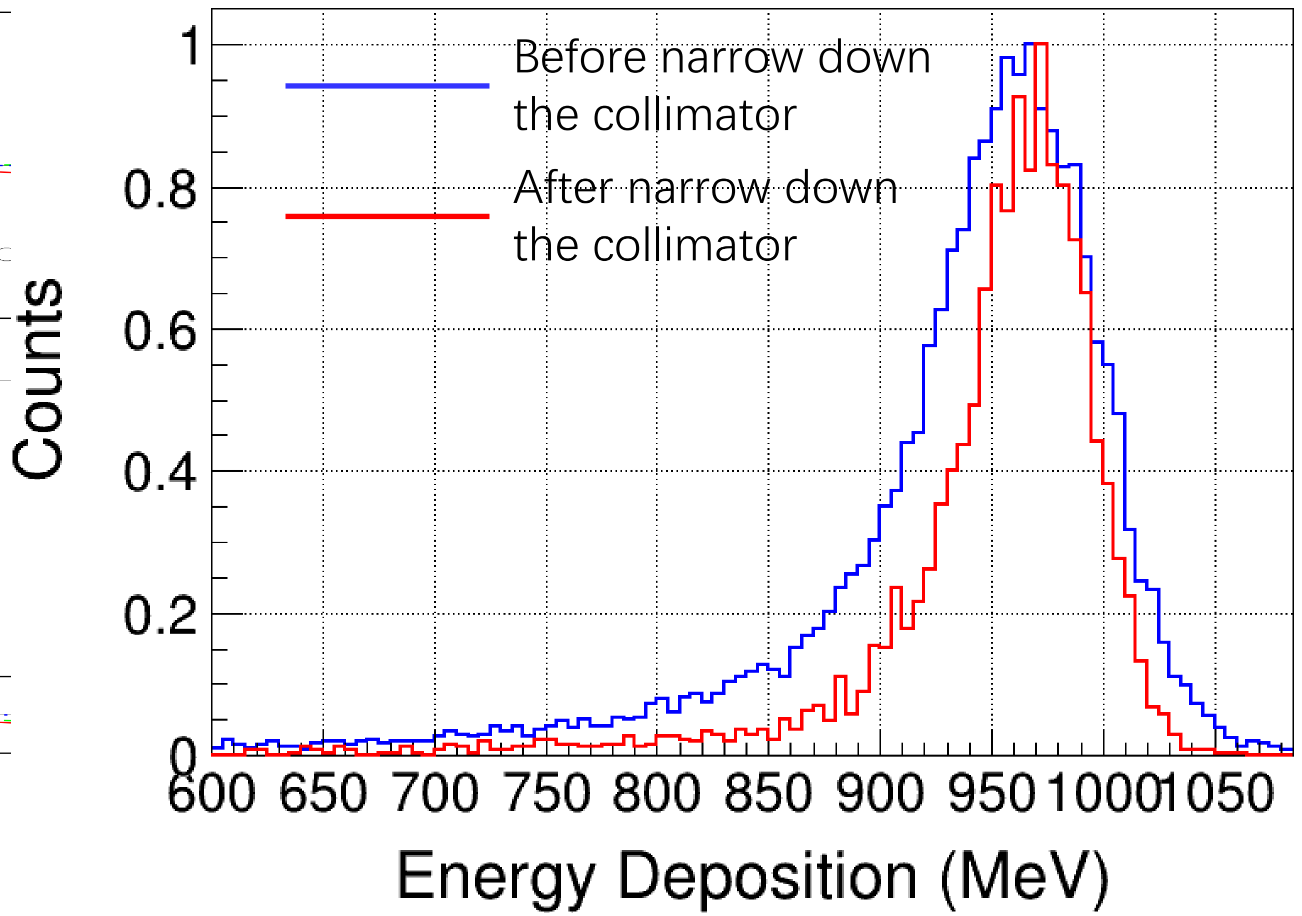




Influence of Beam momentum dispersion

Magnet to deflect charged beam





Influence of Beam momentum dispersion