Design and Prototype Test of the Homogeneous Crystal EMC for STCF

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Outline

- Introduction to STCF EMC
- Review of the Progress in Concept Design
- Key Technology Research
- Summary

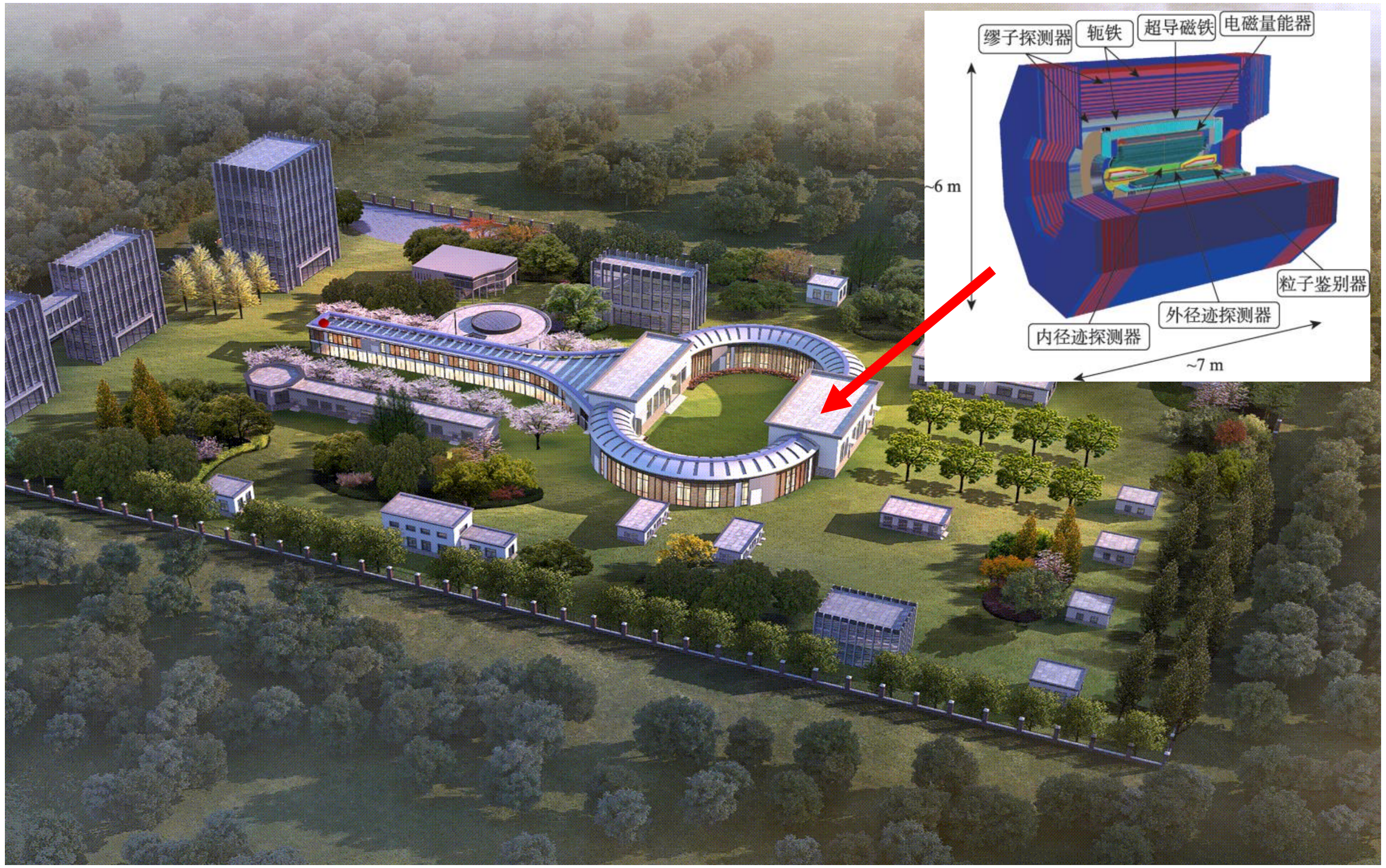
Introduction to STCF EMC

One Slide about STCF

Super Tau-Charm Facility: A post-BEPCII HEP project in China

- High luminosity
- Wider energy range
- Beam polarization
- ....

Accelerator Parameters	Phase 1	Phase 2
Circumference/m	~600	~600
Beam Energy Range/GeV	1-3.5	1-3.5
Collision Angle/mrad	60	60
Luminosity/ $\times 10^{35} cm^{-2}s^{-1}$	>0.5	~1.0
Beam Polarization	No	Yes
Large Piwinski angle Collision +Crab Waist		



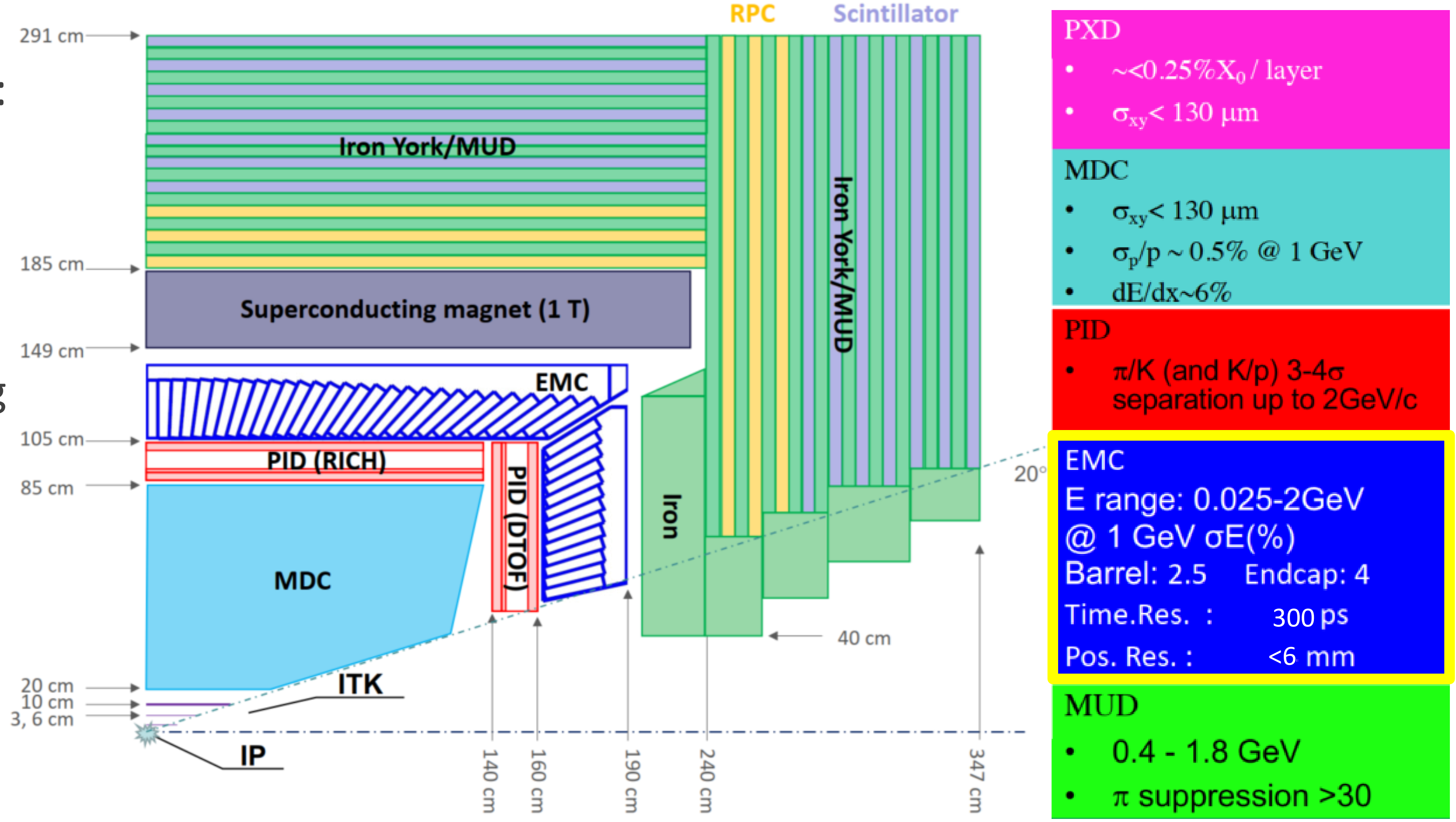
Introduction to STCF EMC

Overview of STCF EMC

Electro **M**agnetic **C**alorimeter: Major detector for probing neutral particles (γ, n, $\bar{n}$, K_L)

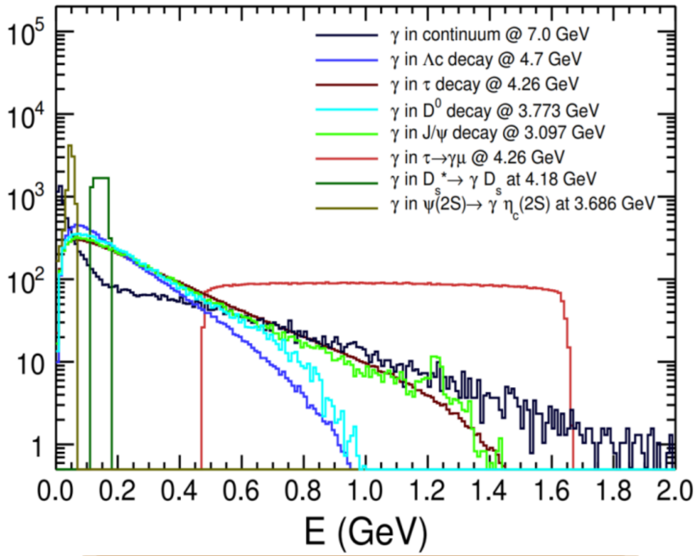
- 4-momentum of photon
- Neutral particle identification
- Neutral trigger & event timing
- ……

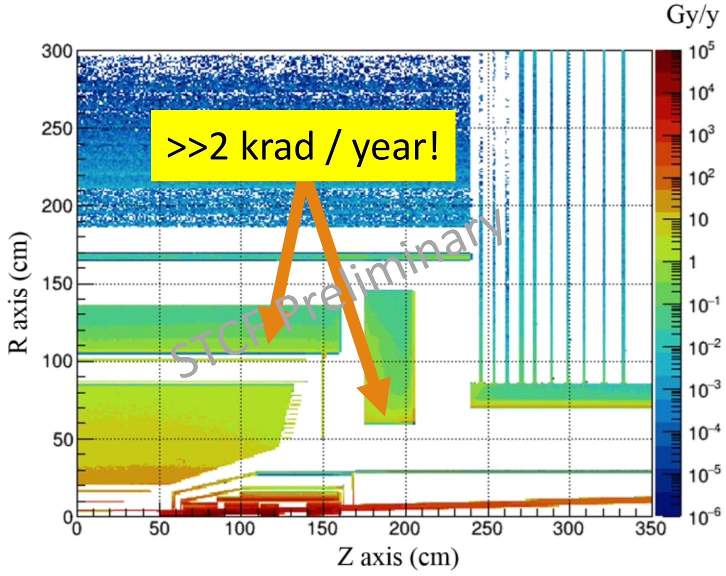
A calorimeter and beyond calorimeter EMC

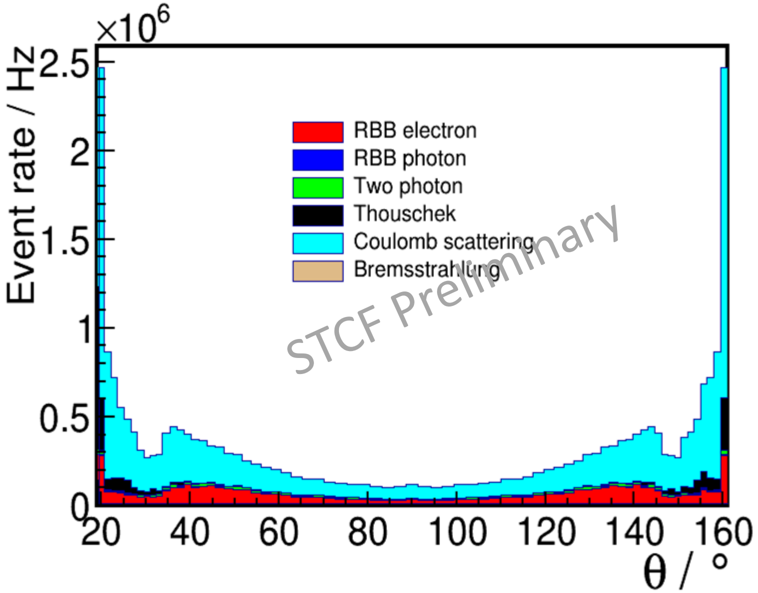


Introduction to STCF EMC

Challenges in EMC Design and Operation







$\mathcal{O}(1)$ MeV – 3 GeV dynamic range

High event rate (>400 kHz)

Low noise & Fast Response

Maximum TID more than 40 krad in 10 years

Radiation Hard Crystal

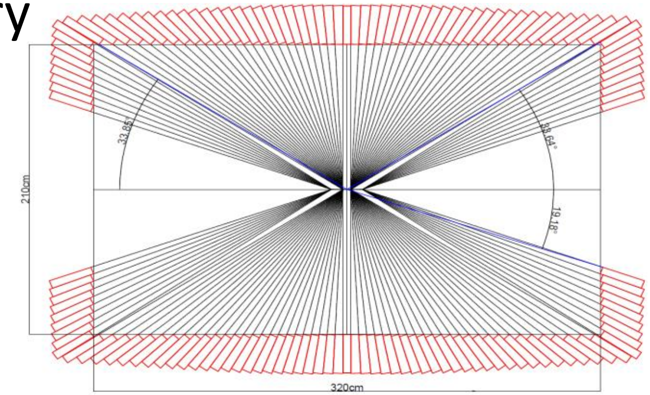
Beam background induced pile up events: more than 2.5 MHz per unit (only over-threshold counted)

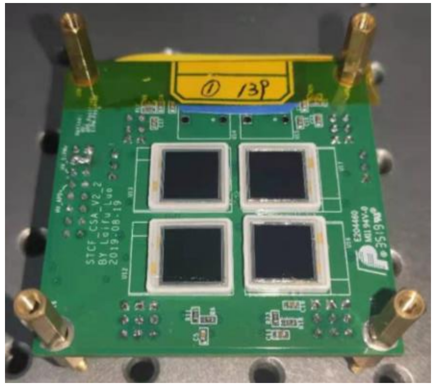
Fast Response & Capable of pile-up

Review of the Progress in Concept Design

EMC Baseline Design & Performance

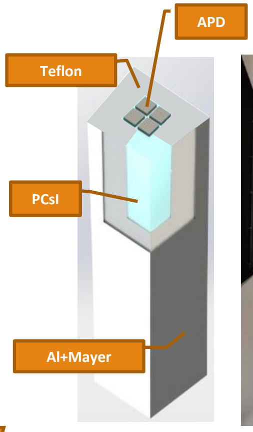
Compact Geometry
- Non-IP oriented design
- Unit size
  - $15X_0$ length
  - ~1 R_M radius





High Q.E. APD & Fast CSA Electronics
- Hamamatsu S8664 APD x4
- Shaping time = 100 ns
- parallel JFET as input stage

Fast and Radiation Hard Crystal (pCsI)
- 30 ns decay time
- Cost-effective
- >10 krad tolerance



Unit Cosmic Ray Test
- High reflectance Teflon
- L.Y. = 155 p.e./MeV
- **E**quivalent **N**oise **E**nergy = 1.2 MeV

Critical Input for Optimization !

Review of the Progress in Concept Design

EMC Optimization in Simulation

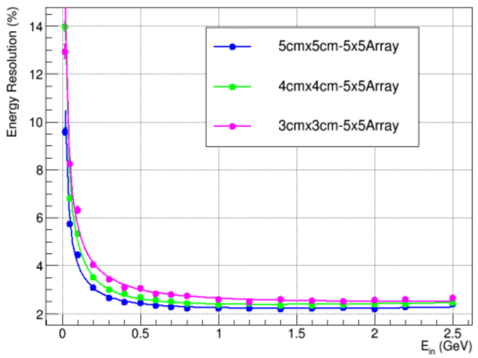
EMC performance study in OSCAR

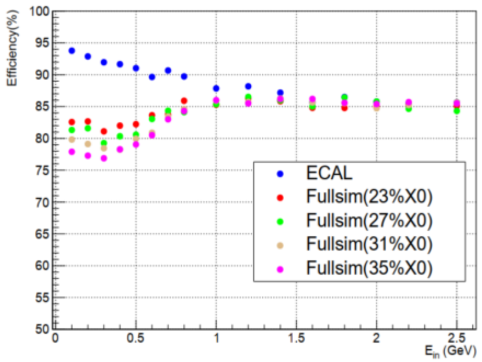
- ✓Geometry construction in DD4hep
- ✓Geant4 simulation
  - ✓Electronics response
  - ✓Light collection uniformity
  - ✓Spike signal on APD
- ✓Energy & position reconstruction
- ✓Energy & position calibration

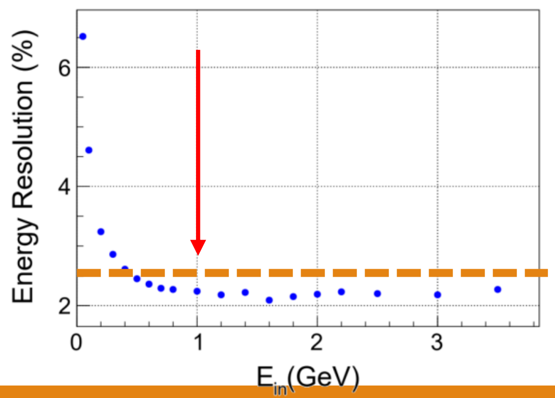
Parameter optimization

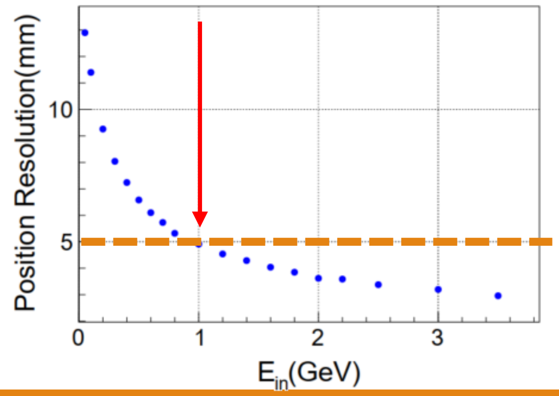
- ✓Package thickness
- ✓Unit radius & length
- ✓Amount of inner substance

Simulation result fulfills energy & position measurement requirements @ 1GeV photon









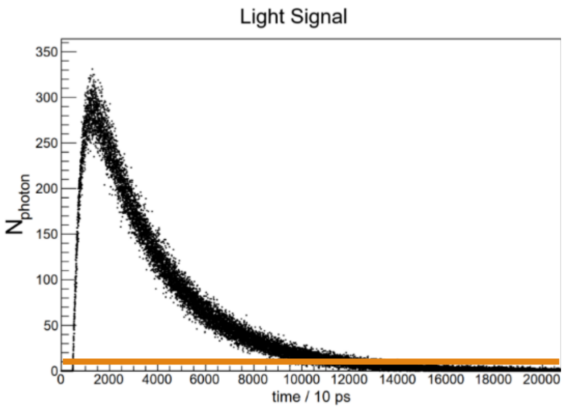
Review of the Progress in Concept Design

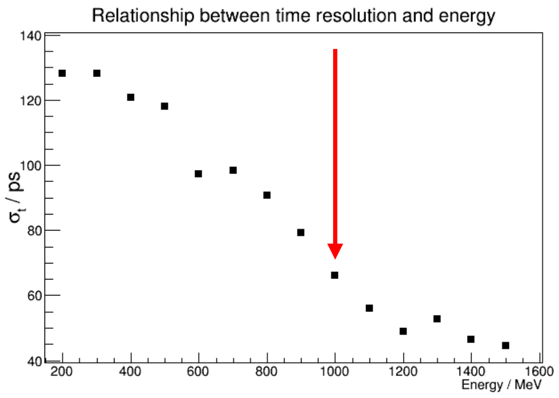
EMC Optimization in Simulation

Time resolution study in simulation

- Shower propagation & light intensity fluctuation
- Geant4 + Optical simulation
- Emulate the Leading Edge Discriminator in C++

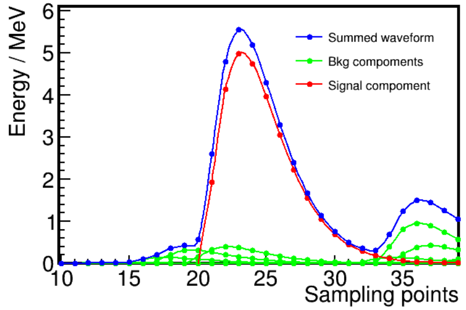
Only contribute 65 ps to time resolution@ 1GeV photon

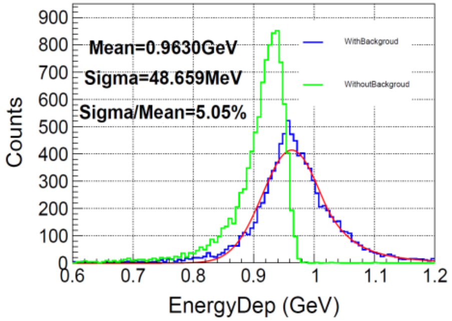


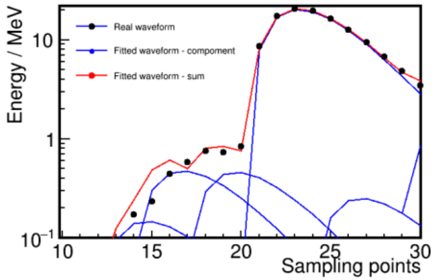


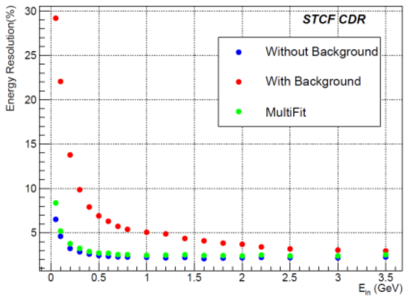
Pile-up validation

- Background sampling & waveform generation implemented into simulation
- Use waveform fit to mitigate the influence of pile-up (One pulse fit & MultiFit)*







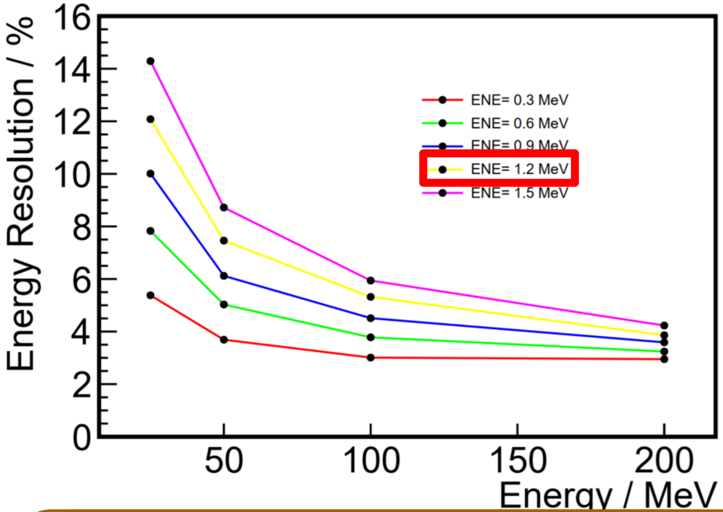


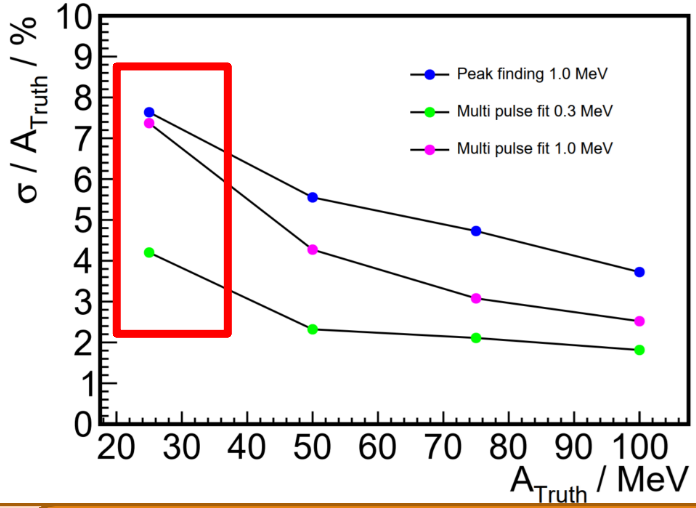
Review of the Progress in Concept Design

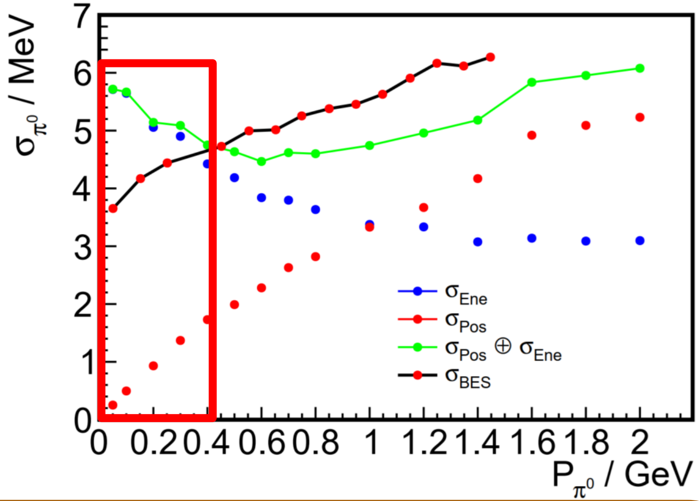
EMC Optimization in Simulation

Things seem great for high energy photon!

However…







Large ENE → Bad energy resolution and detection efficiency at low energy

The pile-up mitigation effect heavily influenced by ENE at low energy

Deteriorated π^0 mass resolution at low energy due to energy resolution (Compared to BESIII)

The reduction of ENE is crucial to EMC performance at low energy!

Review of the Progress in Concept Design

Electronics Parameters Study

Amplitude: $CR-(RC)^{2}$ shaping circuit

3 parallel JFET as input stage

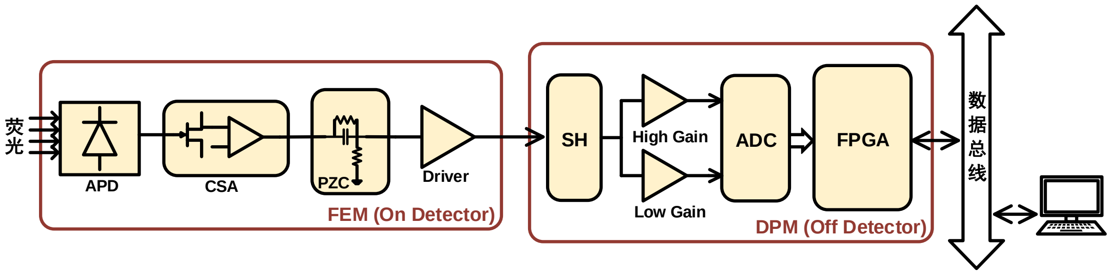
Detailed noise analysis and parameter optimization

- ✓Number of shaping integrators
- ✓Shaping time
- ✓JFET number

JINST 15 C09002

$\sigma_E = 1\ fC$

Very close to the optimal SNR



Time: CSA + FPGA based waveform fit

Comprehensive theory study on time resolution

- Leading edge timing *vs* waveform fit
- Parameter optimization
  - ✓Feedback capacitor
  - ✓Bandwidth of operational amplifier
  - ✓ADC sampling rate

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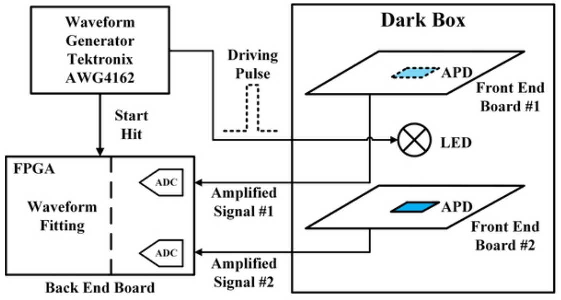
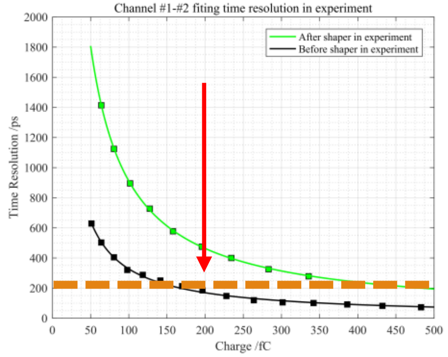
Time resolution better than 200 ps @ 1GeV !





More details in Laifu's talk at the 13th National Conference on Particle Physics

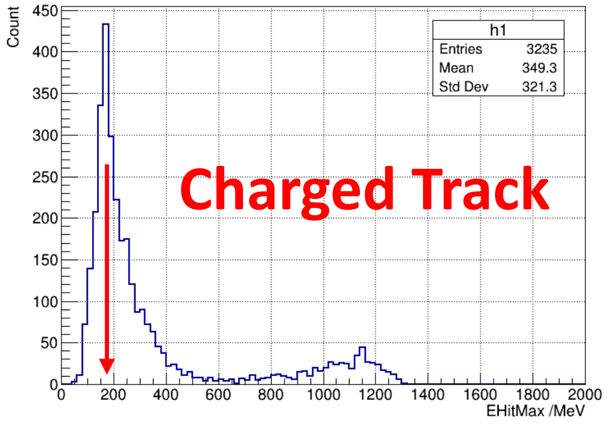
Review of the Progress in Concept Design

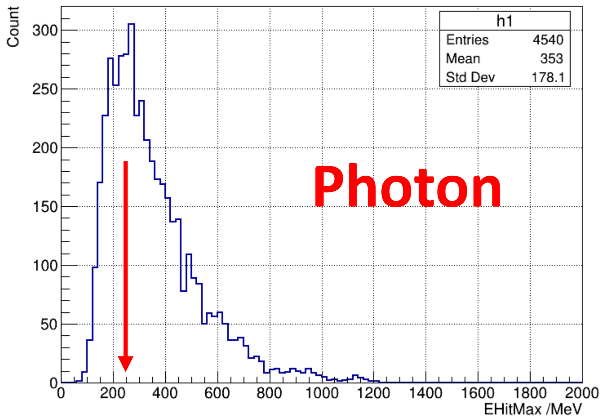
Electronics Parameters Study

The optimal electronics performance is obtained

Remaining issues:

- Improve L.Y. to further reduce ENE
- On the demand of neutral trigger & event timing
  - Take J/ψ decay as example
  - The maximum photon energy deposition is 250 MeV on average
  - Need a fast, accurate trigger system focusing on $\mathcal{O}(100)$ MeV energy region ($\sigma_T > 2ns$ @ $0.1\ GeV$ at present)



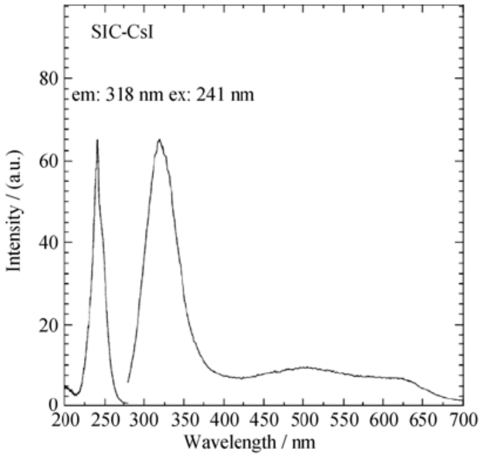


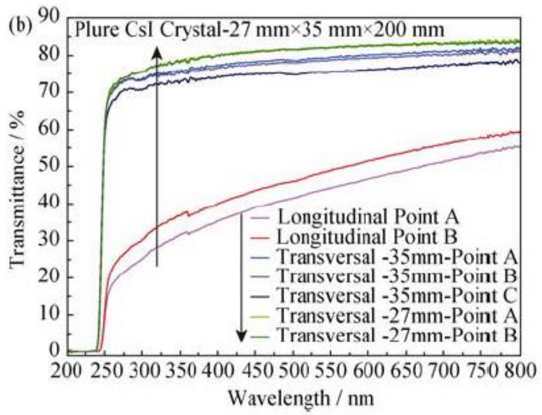
Key Technology Research

Light Yield Improvement

Optical simulation of light propagation

- Emission spectrum
- Absorption length
- Package reflectance
- APD Q.E.





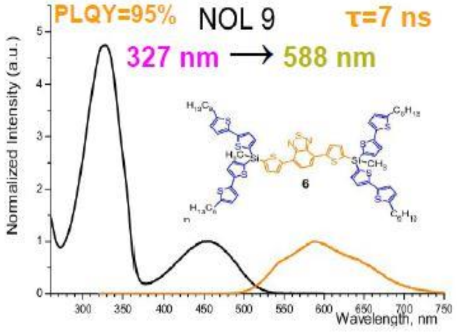
✓ Transmittance of UV component

× APD Q.E. on UV component

Wavelength (nm)	Emission Ratio (%)	Signal Contribution(%)
318	>80	<40
500	<20	>60

Idea: high performance **W**ave**L**ength **S**hifter on crystal surface

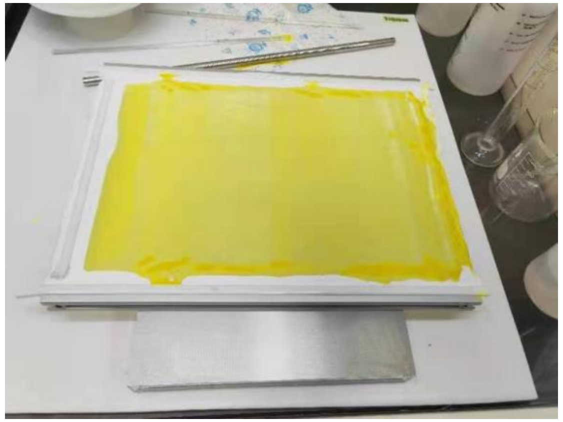
---- Shift UV component into high transmittance wavelength at early stage



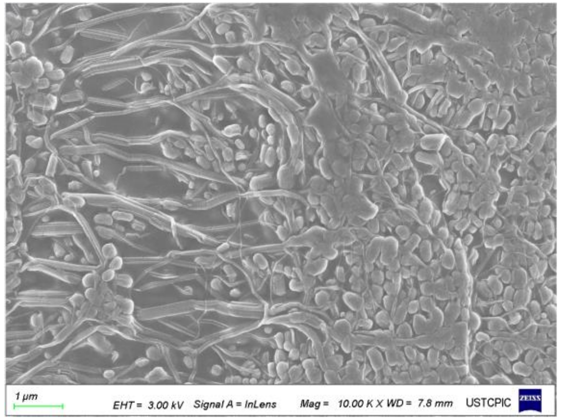
Key Technology Research
Light Yield Improvement

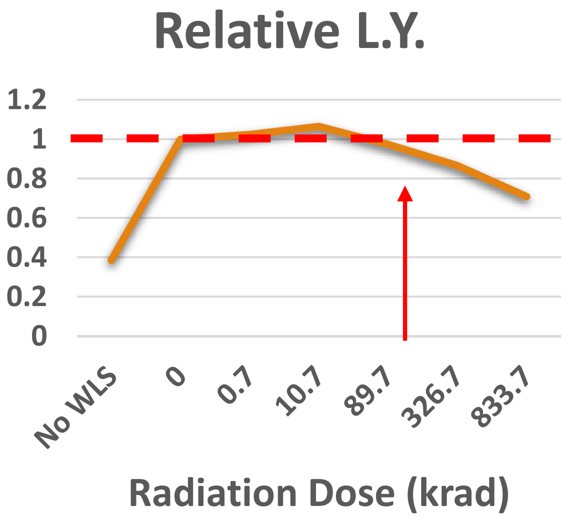
Simulation result is great

Experiment validation
- Coating WLS on Teflon with Mayer Bar
- Effective but not as excellent as simulation
- Need to further improve the WLS occupancy in Teflon (According to SEM)



Set up	LY (photons / MeV)			
	Simulation		Experiment	
W/o WLS	145.6	x 2.2	144	x 1.5
With WLS	322		223	





Radiation hardness test on WLS
- No performance reduction up to 100 krad

Key Technology Research

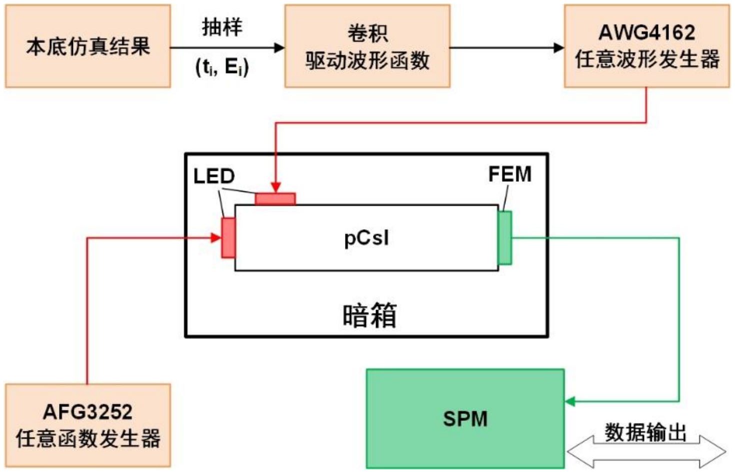
Electronics System for Prototype Array test

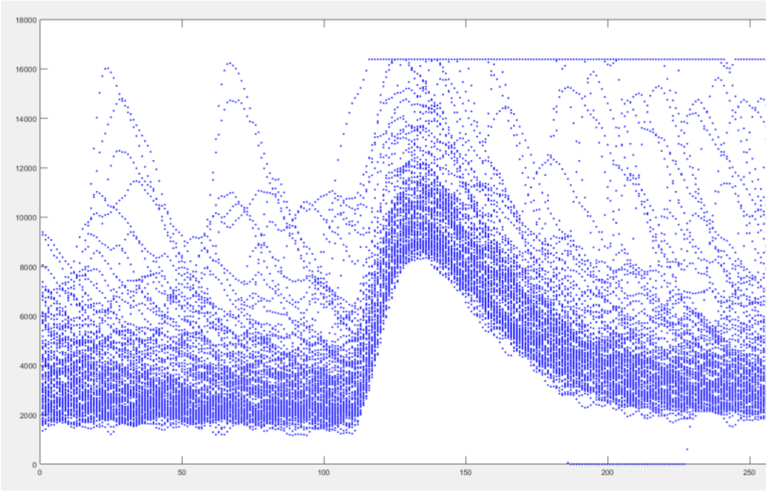
Compact 10-channel BEE

- 125M sampling rate
- Full digital signal processing (Digital filter + waveform fit)
- Optimized resource occupancy in FPGA
- Performance validation finished

LED based pile-up validation system

- To be used for prototype beam test
- Background generator: AWG + LED driver
- Consistent with simulation result





Key Technology Research

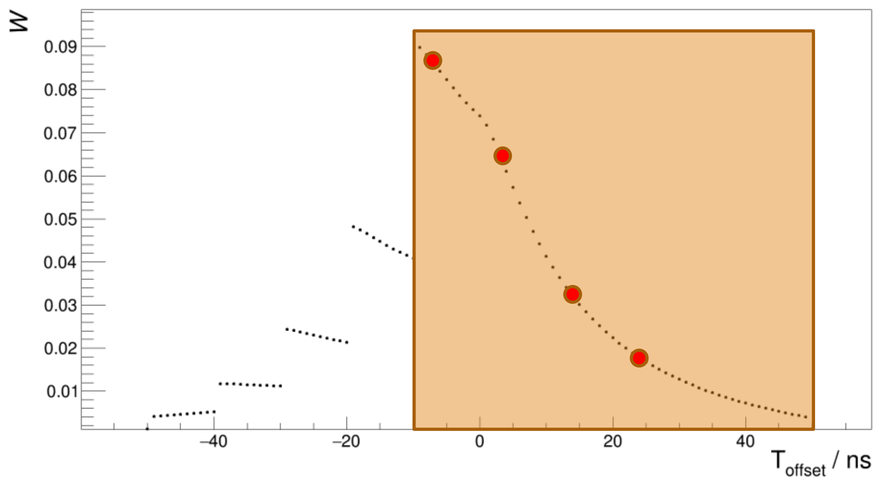
FPGA based on-board Trigger Method

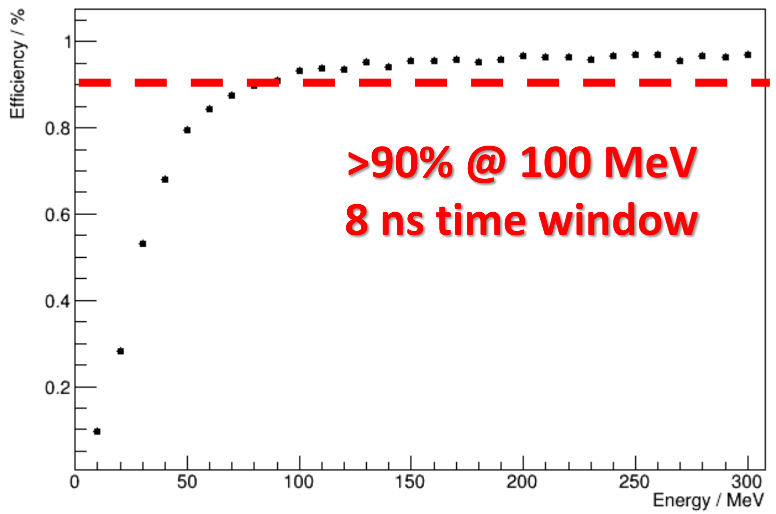
Waveform fit not applicable for trigger

Inspired by **self correlation** method

Propose a **differential** self correlation method for **fast event timing**

- For a template waveform $\boldsymbol{T_i}$ and a signal $\boldsymbol{S_i}$, differential self correlation coefficient is defined as:
- $\mathcal{W} = \sum_i (T_i - T_{i-1})(S_i - S_{i-1})/T_i \cdot S_i$
- $T_{offset,exp} = (100 - \sum_{i=4}^{7} T_{offset}(\mathcal{W}_i))/4$





Advantages:

- Low FPGA resource occupancy
- Low threshold & high accuracy
- No stack & small delay
- Robust to pile-up

Summary

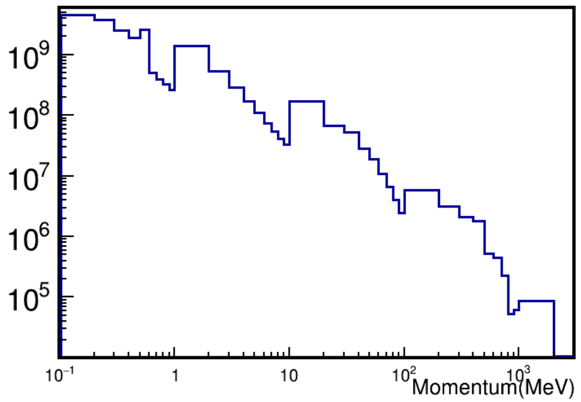
- STCF EMC: a multi purpose calorimeter under challenging operation environment
  - High event rate, high radiation dose, high beam background
  - Energy & position measurement, particle identification, trigger & event timing …
- The baseline design and parameter optimization finished for both detector & electronics

- Recent technical design highlights
  - WLS enhanced unit
    - Significant improvement in light yield
    - Good radiation hardness
  - Electronics System for Prototype Array test
    - Compact BEE design & test
    - LED based pile-up validation system
  - FPGA based on-board Trigger Method
    - Proof of concept finished – feasible for neutral event trigger
    - More efforts on validation needed

BACKUP

Introduction to STCF EMC

Energy distribution of background photons



Review of the Progress in Concept Design

Table of the crystal properties

Scintillator	Density	Radiation Length	Decay time	Emission Peak	Relative Light Yield	Radiation Hardness
	g/cm^3	cm	ns	nm		
BGO	7.13	1.12	300	480	21	Bad
BaF2	4.89	2.03	650(s)	300	36	Good
			0.6(f)	220	4.1	
CsI(pure)	4.51	1.86	30(s)	310	3.6	Good
			6(f)		1.1	
PbWO4	8.3	0.89	30(s)	425	0.3	Bad
			10(f)	420	0.077	
LYSO	7.1	1.14	45	420	75	Very Good
GSO	6.71	1.38	600	430	3	Not too bad
			56	350	30	

Review of the Progress in Concept Design

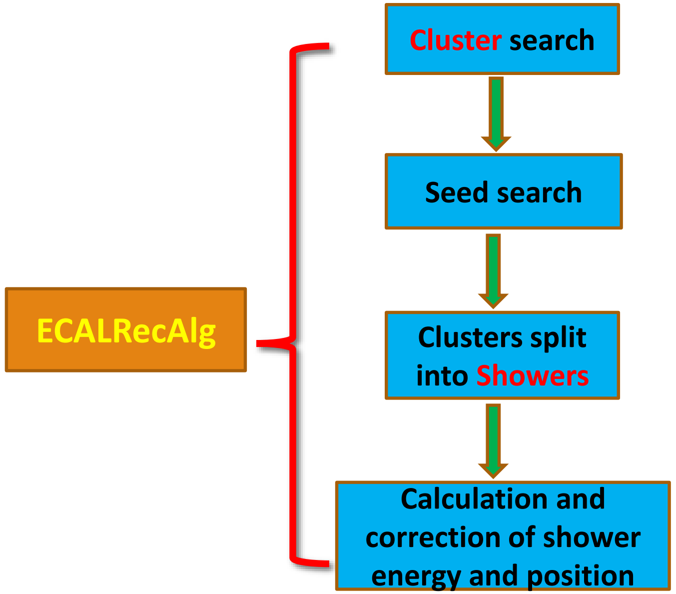
Energy reconstruction procedure:

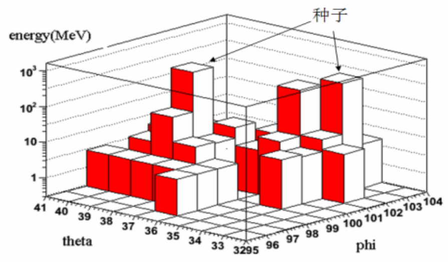
Position reconstruction method:

$$X_c = \sum_j^N W_j(E_j) \cdot X_j / \sum_j^N W_j(E_j)$$

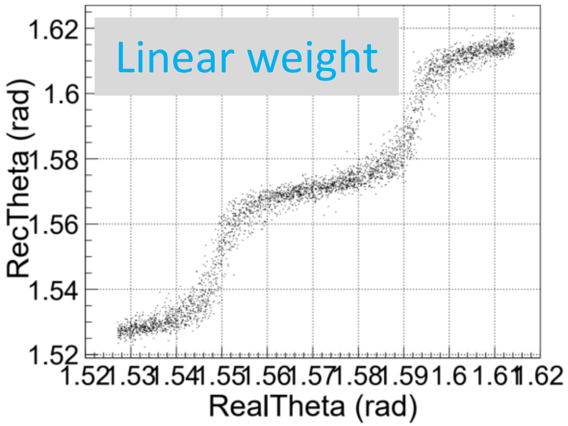
Where:

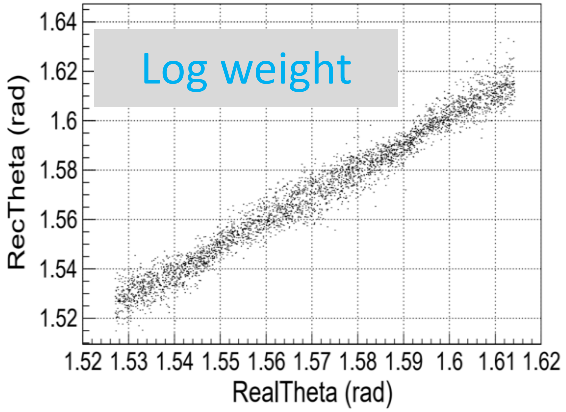
$$W_j(E_j) = \max\{0, a + \ln(E_j / \sum_j^N E_j)\}$$





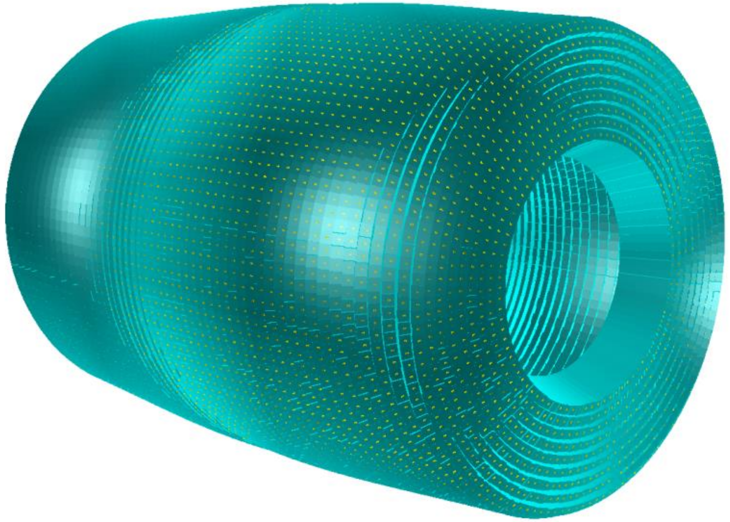
π^0 Cluster (two photons)

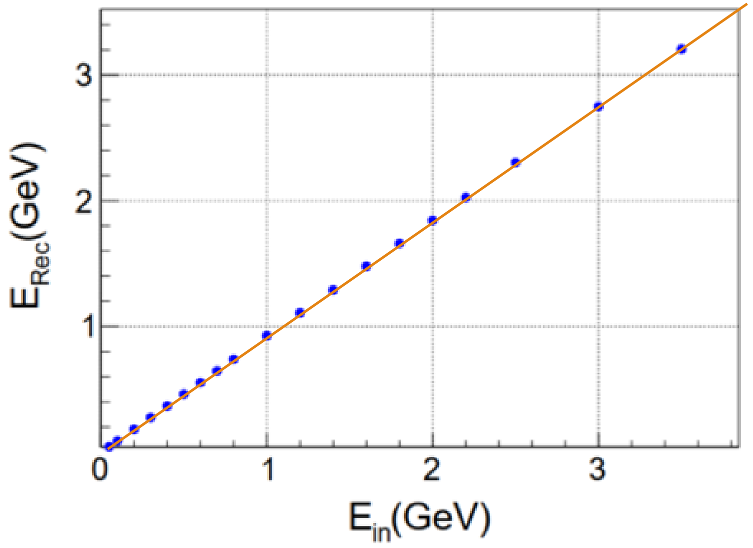




Review of the Progress in Concept Design

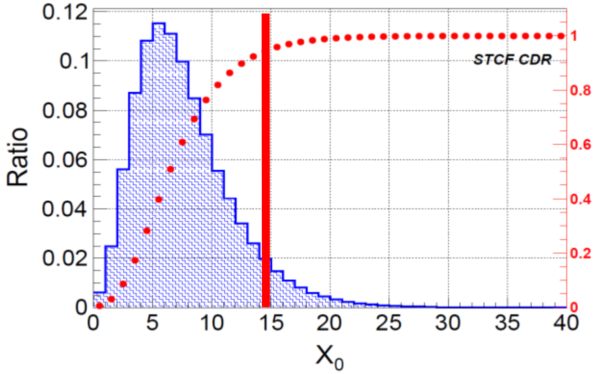
EMC in OSCAR



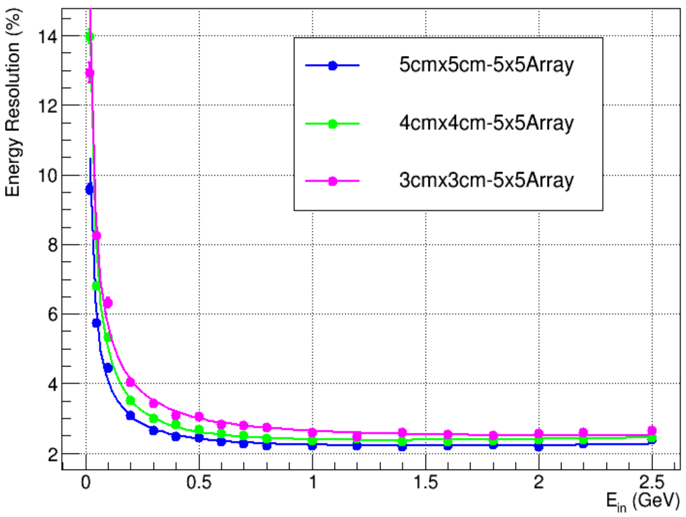


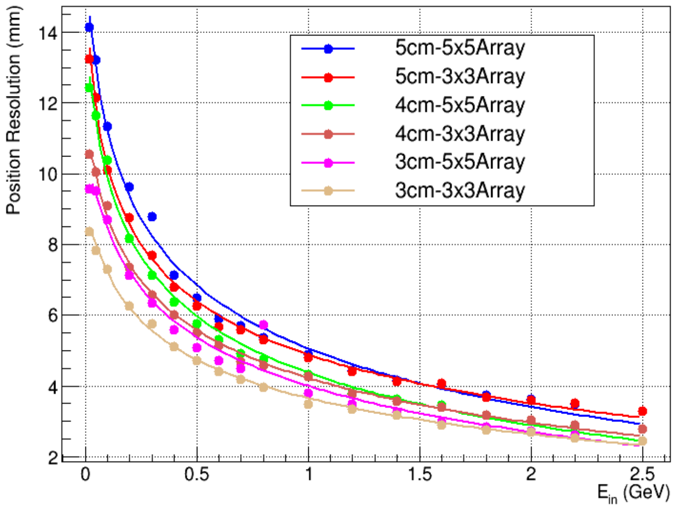
Review of the Progress in Concept Design

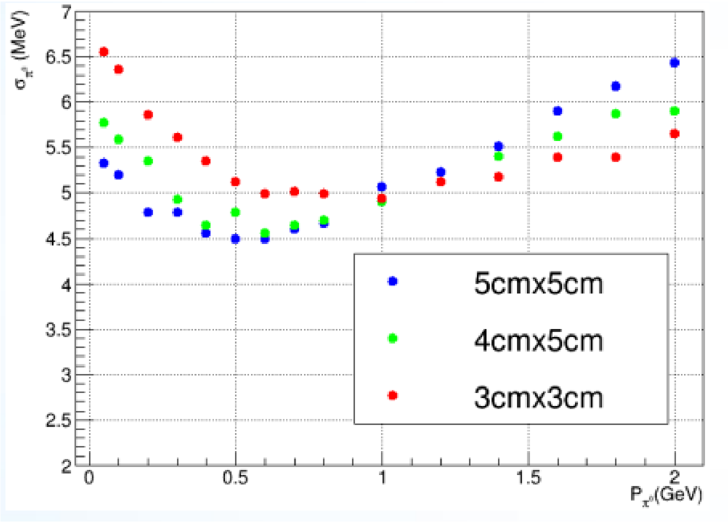
- Unit length
  - 15X_0 enough to guarantee linearity
- End face size
  - **For 1.5GeV π^0, the minimum angle is about 10°, which require the end face size is not greater than $6 \times 6\ cm^2$**



3 GeV γ-ray Shower profile



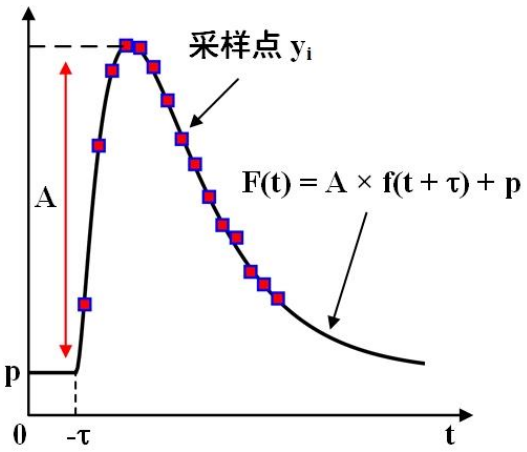




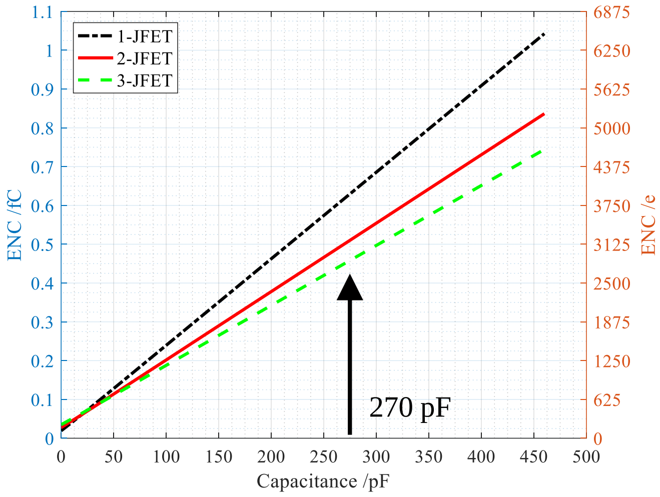
Review of the Progress in Concept Design

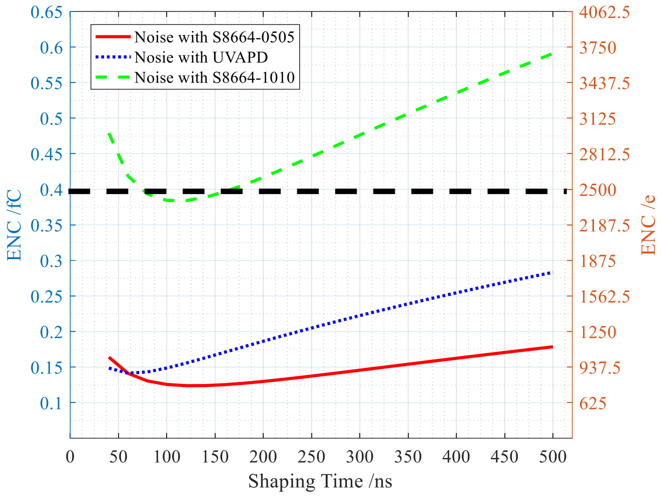
Electronics optimization:

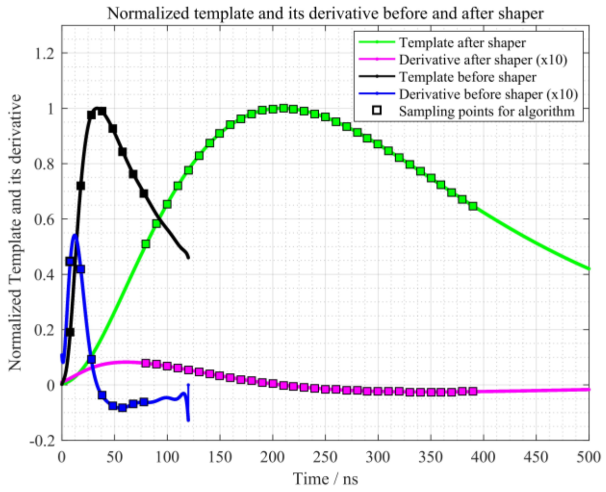
Waveform fit with least square method

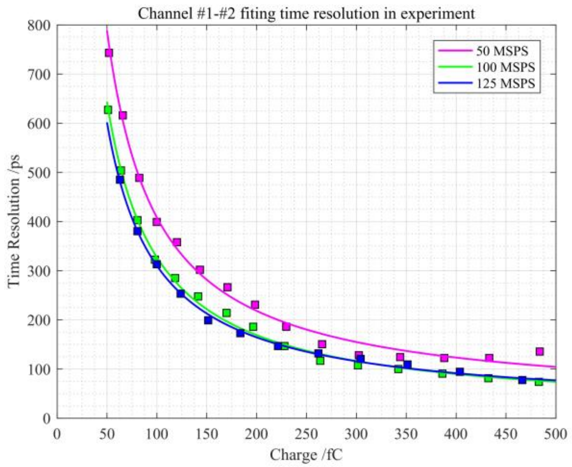


$$\chi^2 = \sum_{i,j} \left(y_i - F(t_i)\right) \cdot S_{ij}^{-1} \cdot \left(y_j - F(t_j)\right)$$



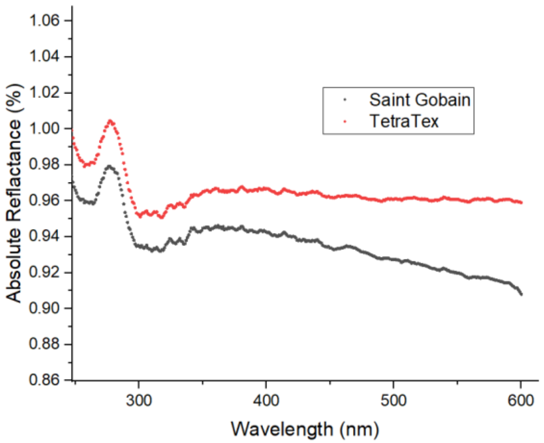


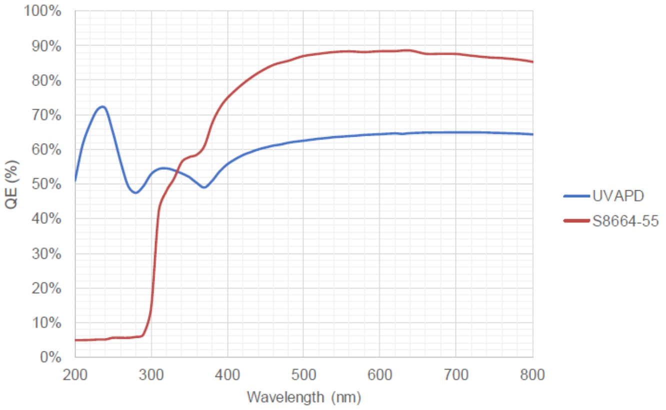


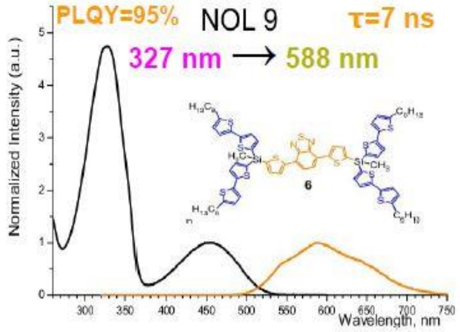


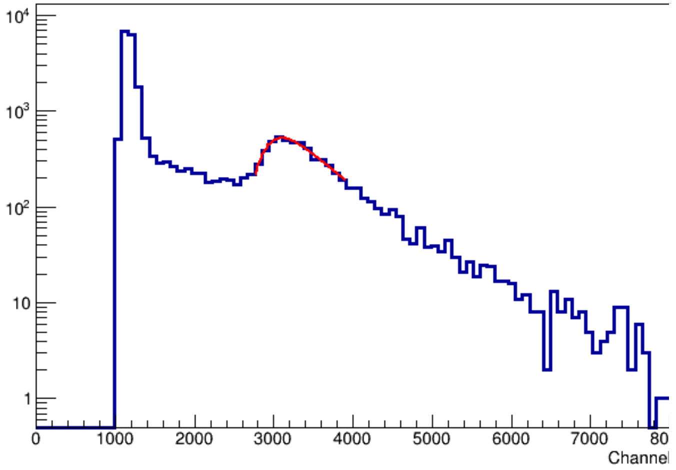
Key Technology Research

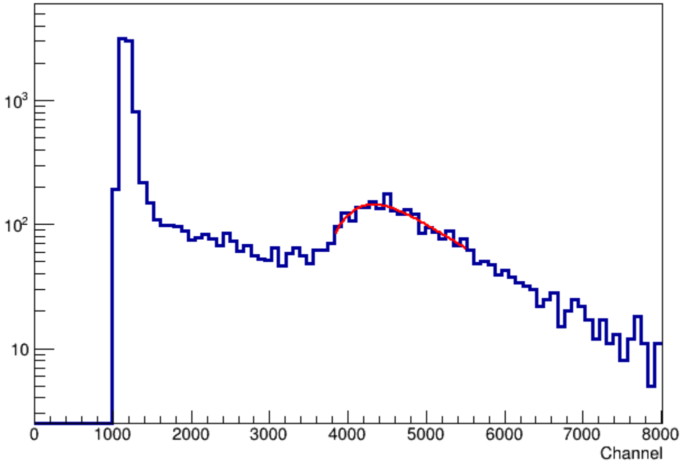
Light Yield Improvement

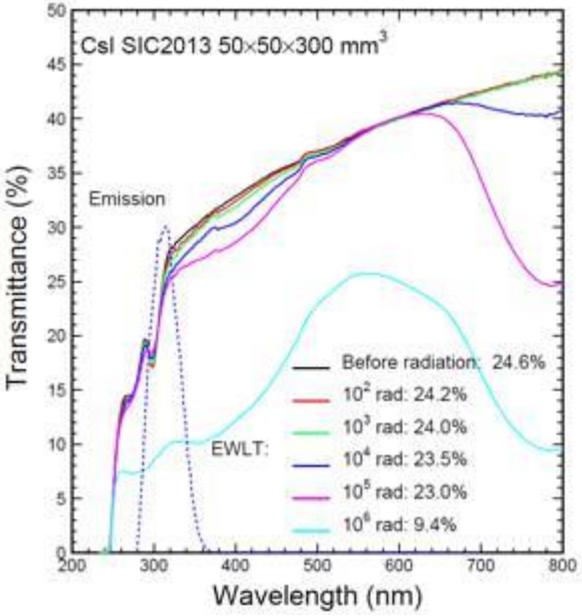








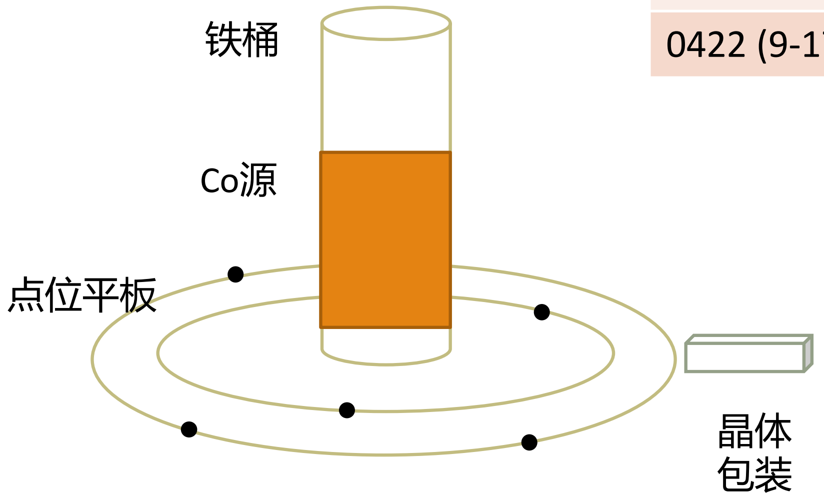




Key Technology Research

Light Yield Improvement

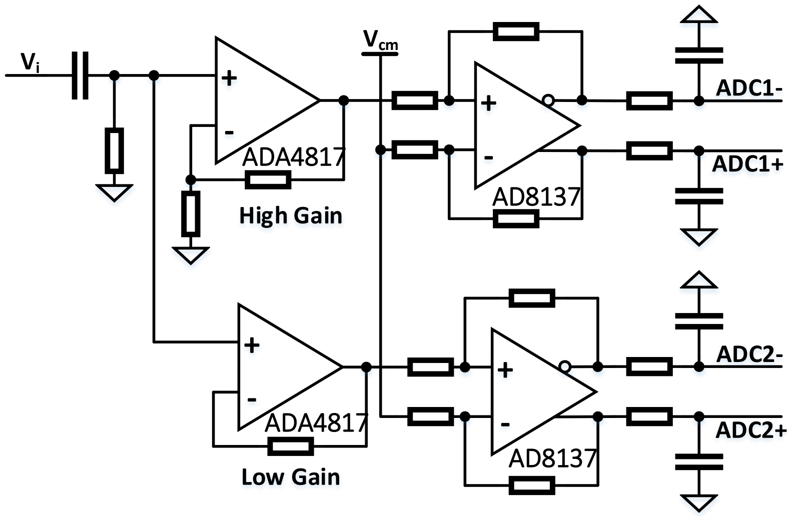
Experiment date	Point Position	Accumulated dose (rad)
0419 (9-11)	362	~700
0420 (9-11)	362	10 700
0420 (15-17)	123	89 700
0421 (9-15)	123	326 700
0422 (9-17)	81	922 700

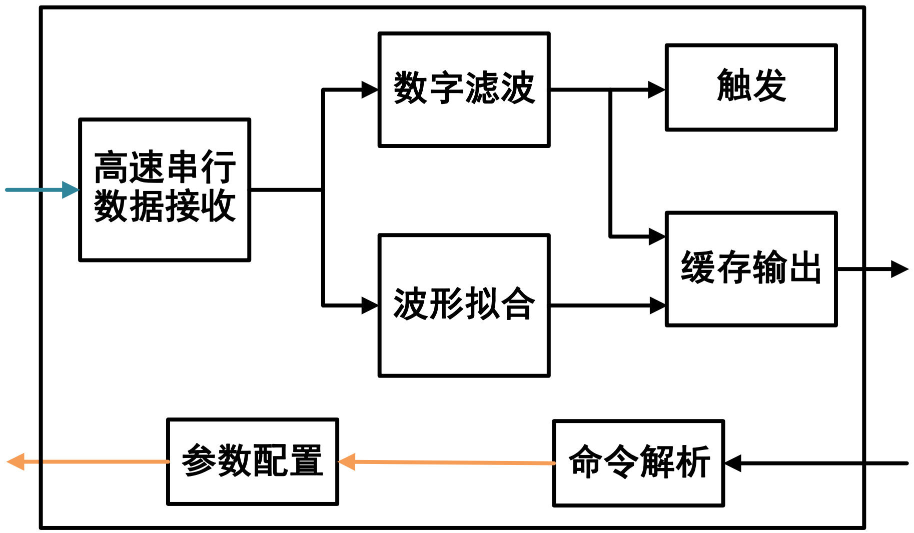


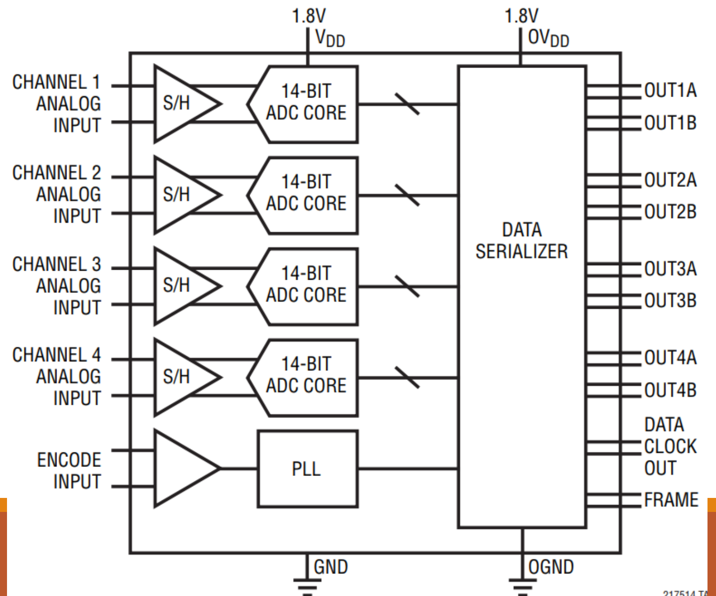
图：辐照装置示意图

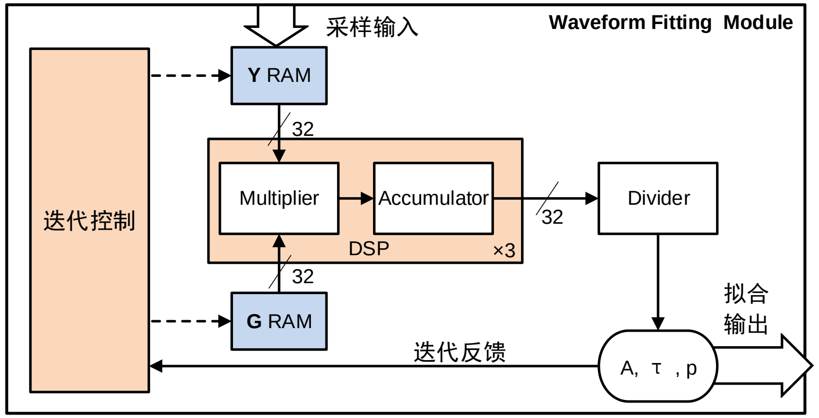
Key Technology Research

Electronics System for Prototype Array test









Resource	Utilization	Available	Utilization...
LUT	9364	101400	9.23
LUTRAM	11	35000	0.03
FF	7651	202800	3.77
BRAM	58	325	17.85
DSP	120	600	20.00
IO	174	285	61.05
BUFG	17	32	53.13
MMCM	1	8	12.50

Key Technology Research
Electronics System for Prototype Array test

Energy spectrum under pile-up obtained from experiment and simulation