



MicroPattern Gaseous Detectors (GMCP & THGEM) for Particle Detection in Space

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On behalf of CXPB, POLAR-2/LPD and HERD/TRD Calibration

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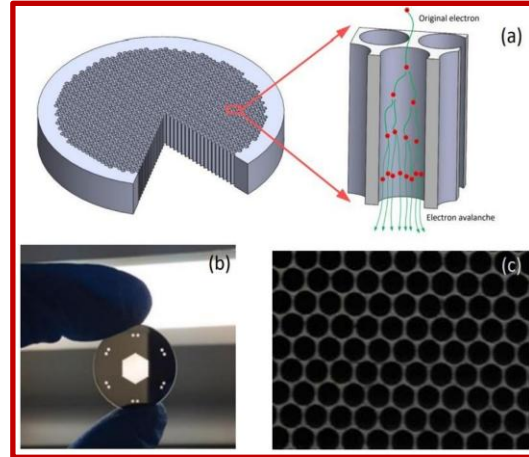
2. POLAR-2/LPD

3. HERD/TRD

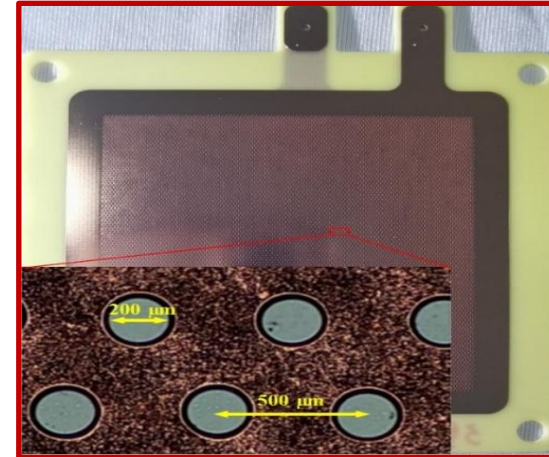
4. Conclusion



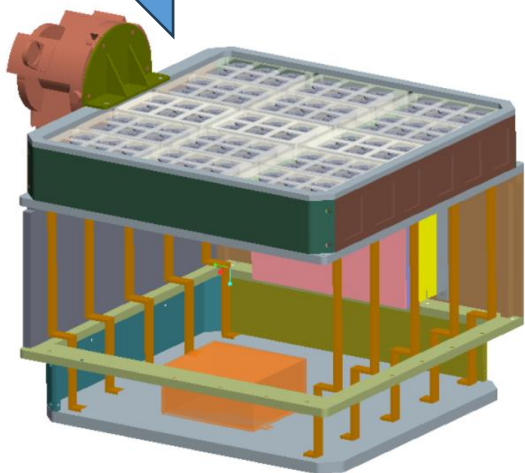
Introduction



Gaseous Microchannel Plate (GMCP)



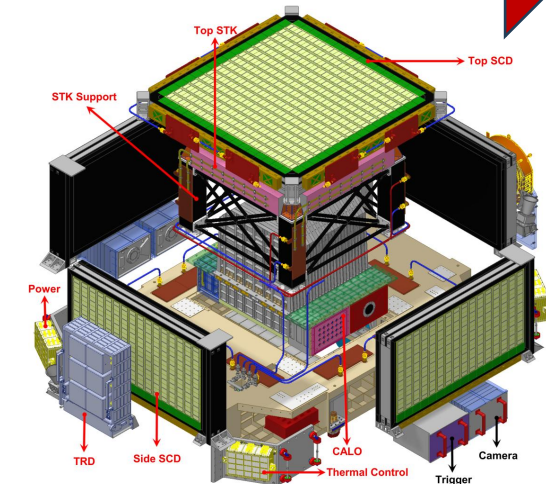
THick Gaseous Electron Multiplier (THGEM)



POLAR-2/LPD

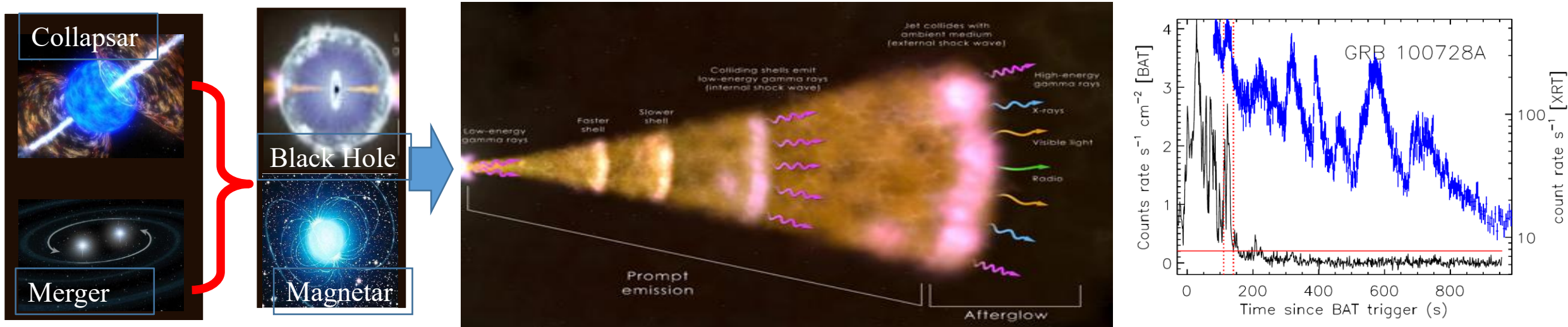


China Space Station



HERD/TRD

Scientific goals of POLAR-2/LPD

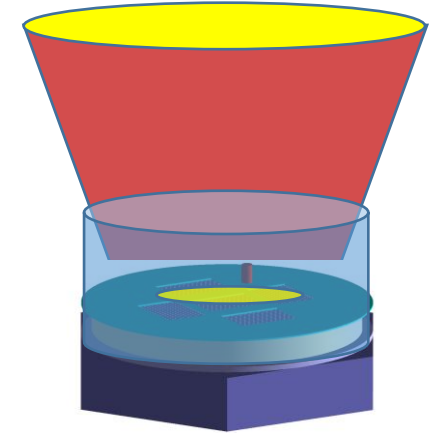
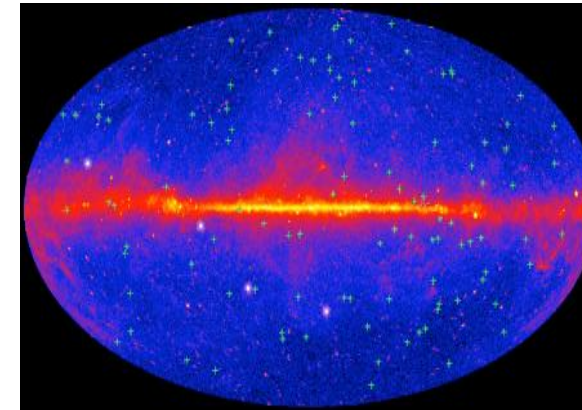
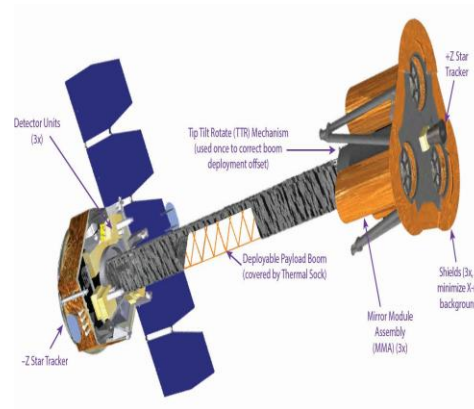
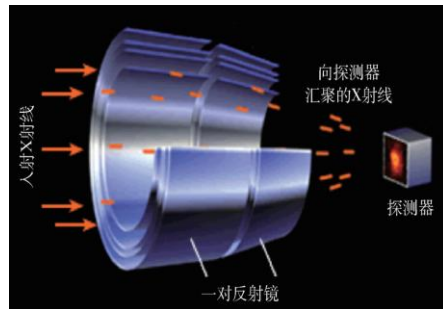


Gamma-ray bursts

- massive stars explosions
- neutron stars or black holes mergers

Are gamma-ray bursts and X-ray flares of the same origin?
What is the GRB radiation mechanism?

Scientific requirement

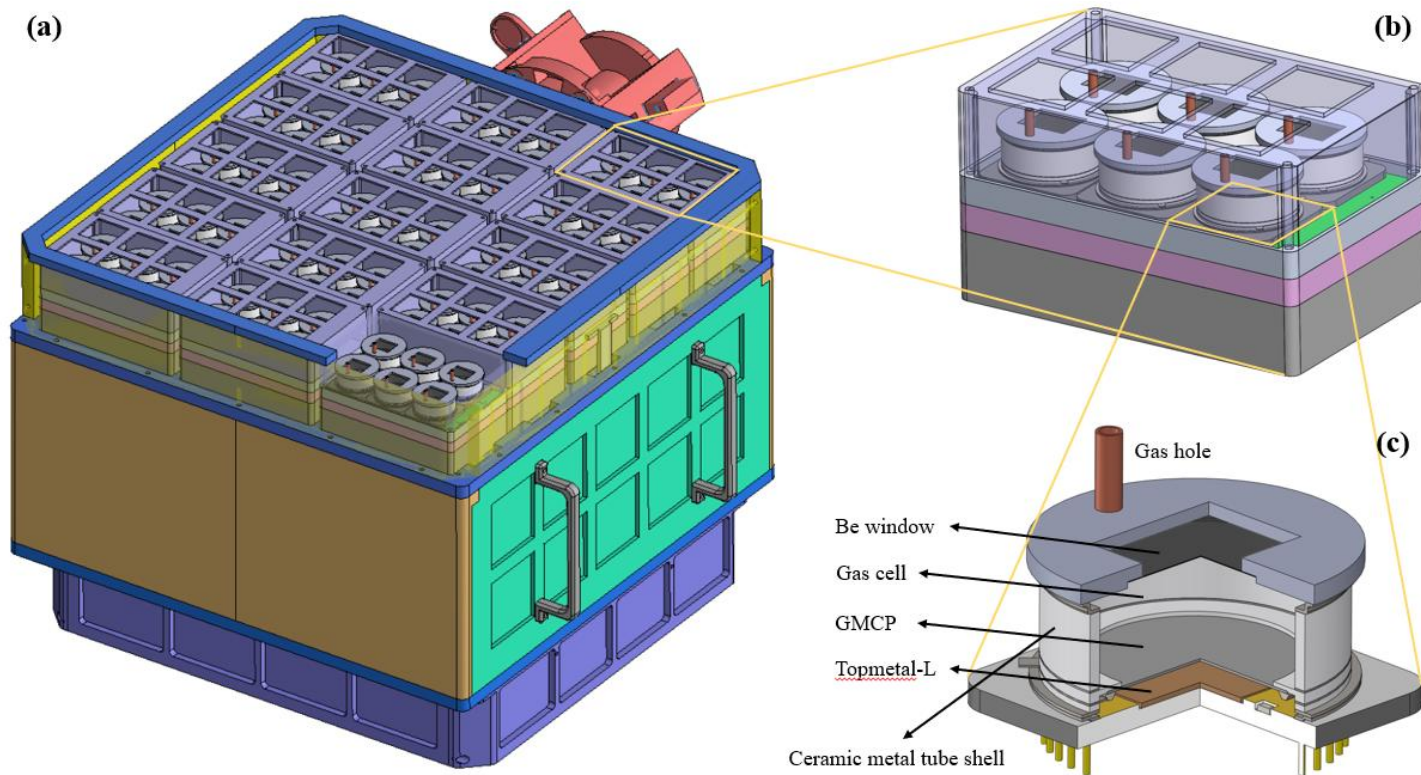


- IXPE: grazing incidence telescope, narrow field of view
- Objects: Bright X-ray sources, such as Crab, Vela, pulsars, etc.

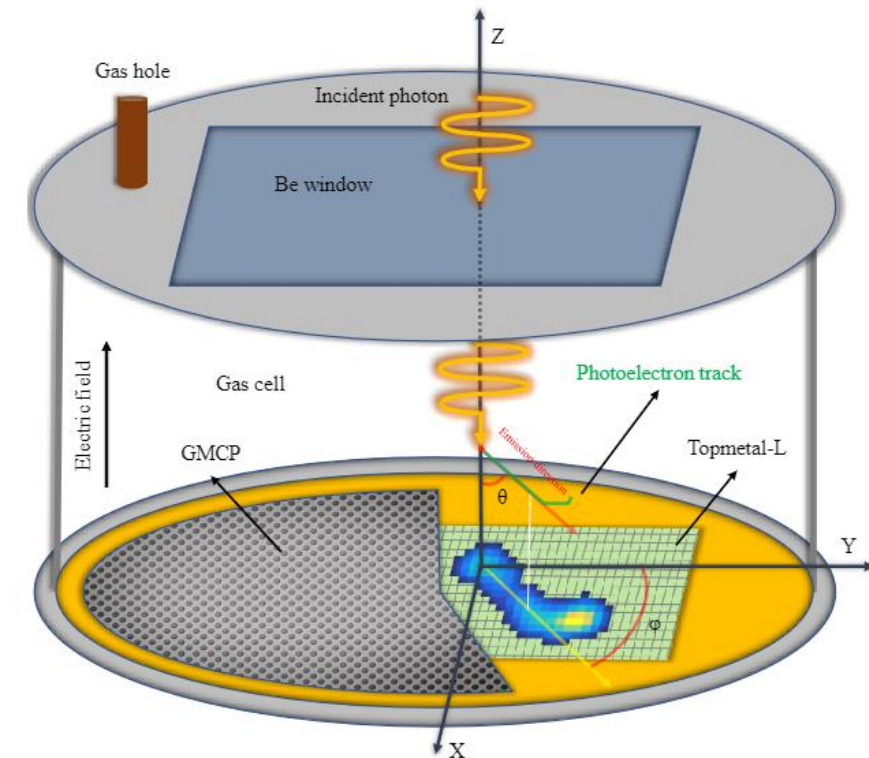
- ❑ GRBs are transient sources that appear unpredictably, without prior knowledge of when or where they will occur.
- ❑ Requires LPD with large area and wide field of view

Polar2/LPD payload and detection principle

➤ Polar-2/LPD payload

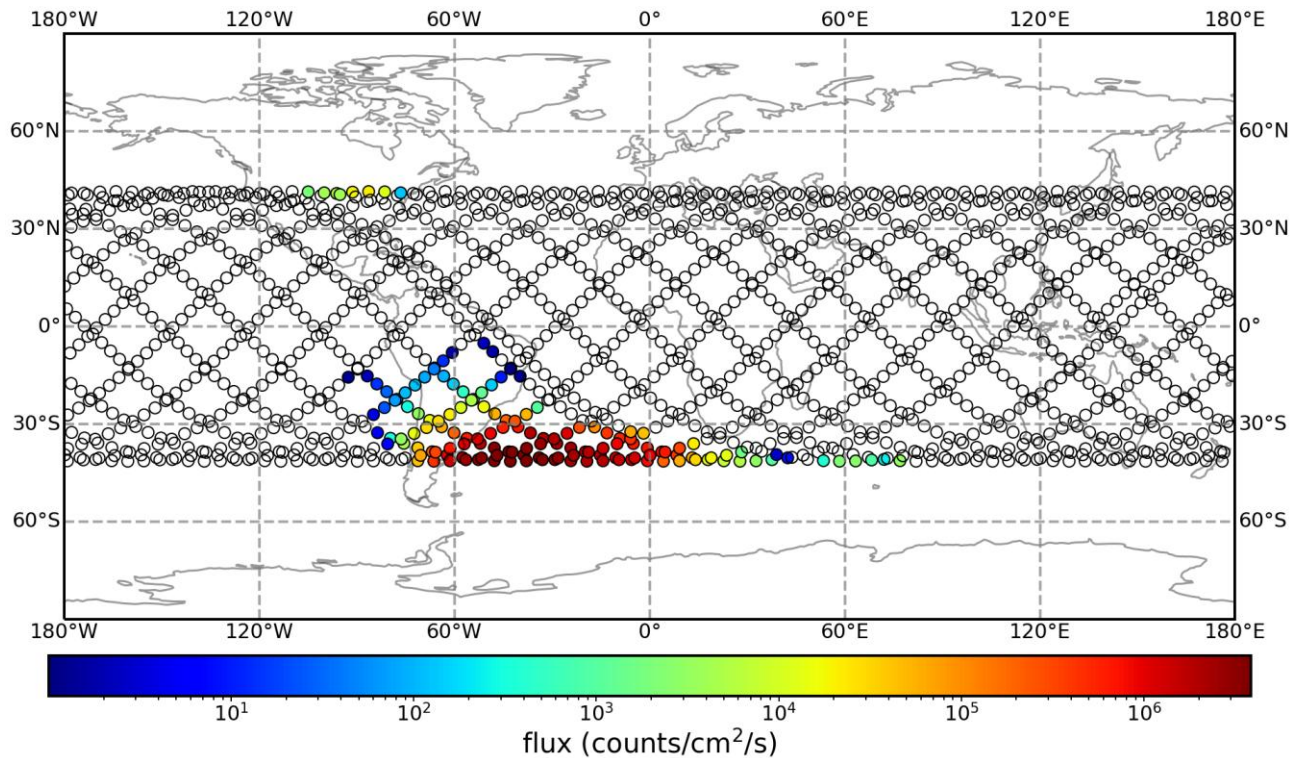


➤ Principle of polarization detection

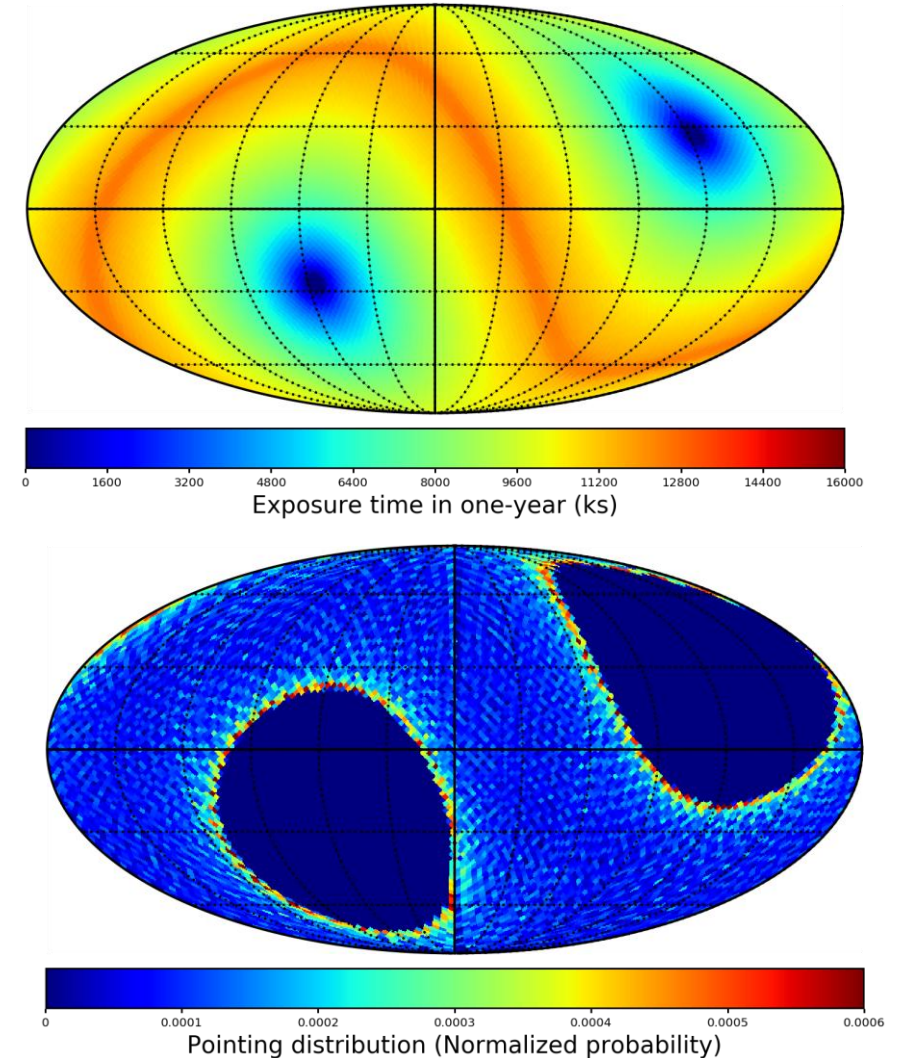


LPD in orbit simulation

➤ Chinese space station orbit

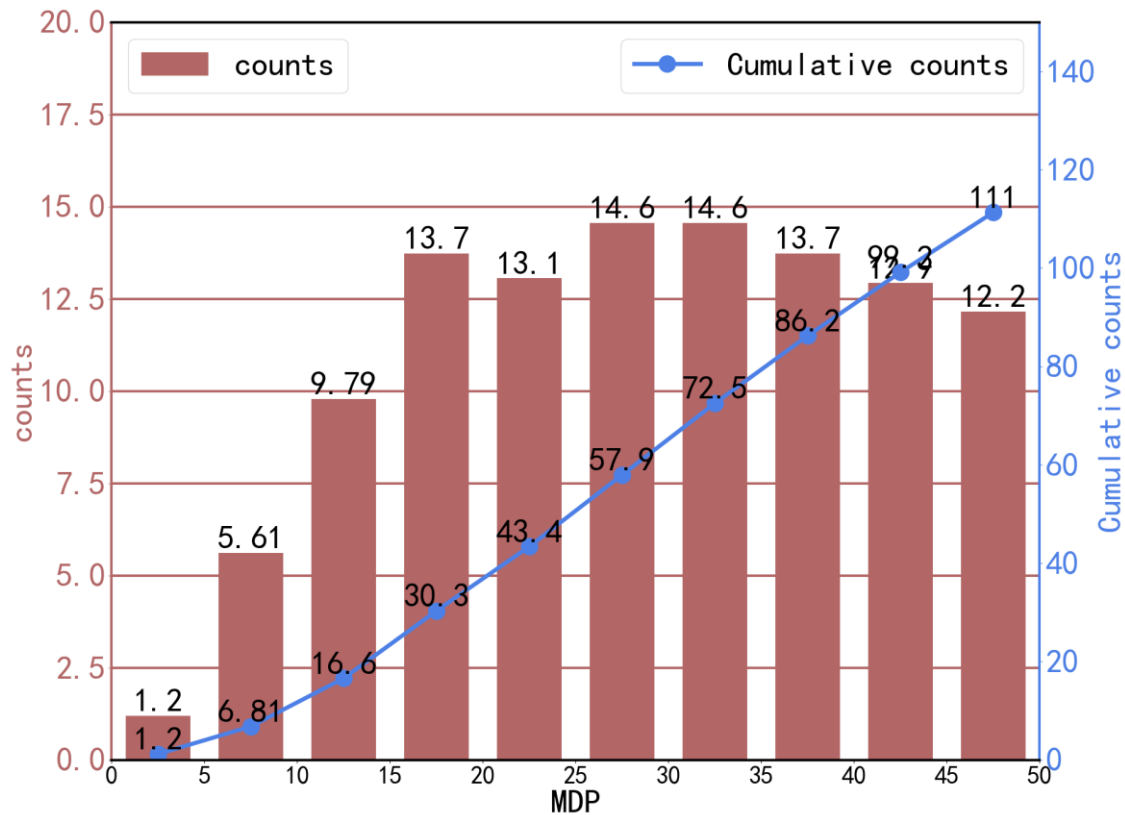


The projection of LPD orbit on Earth in 1 day



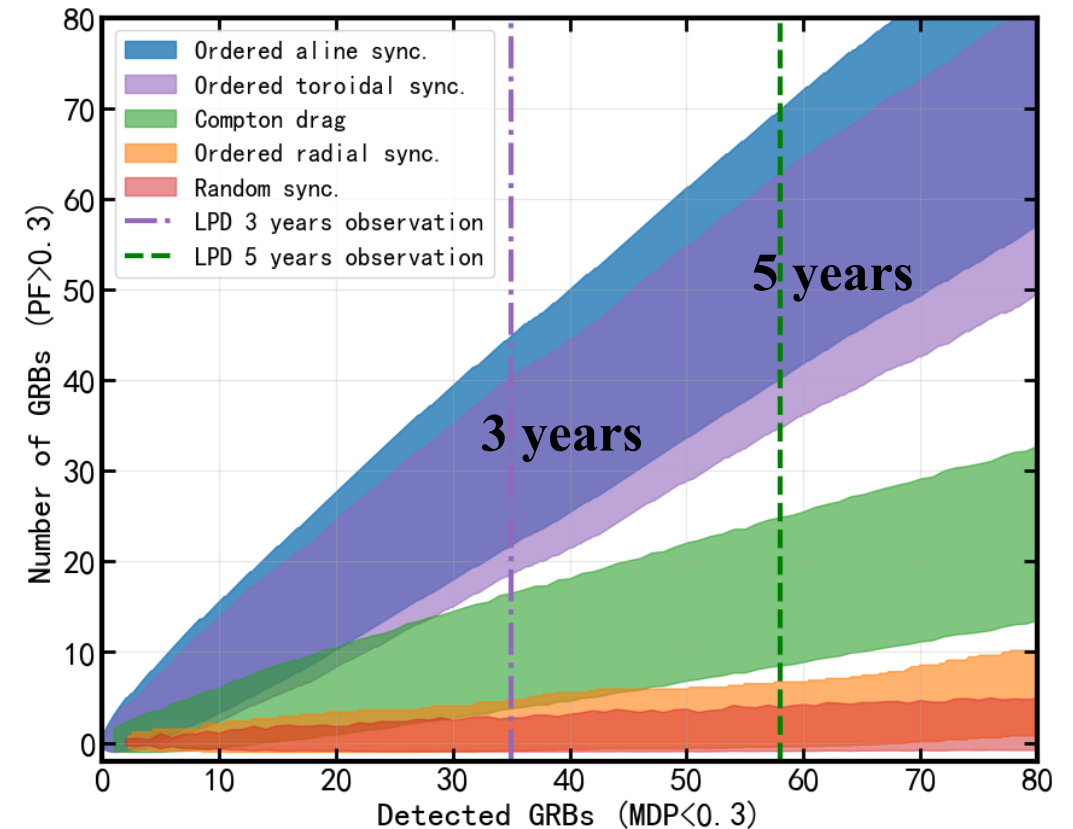
Polarization Statistics

➤ Statistical distribution of MDP of LPD in 5 years



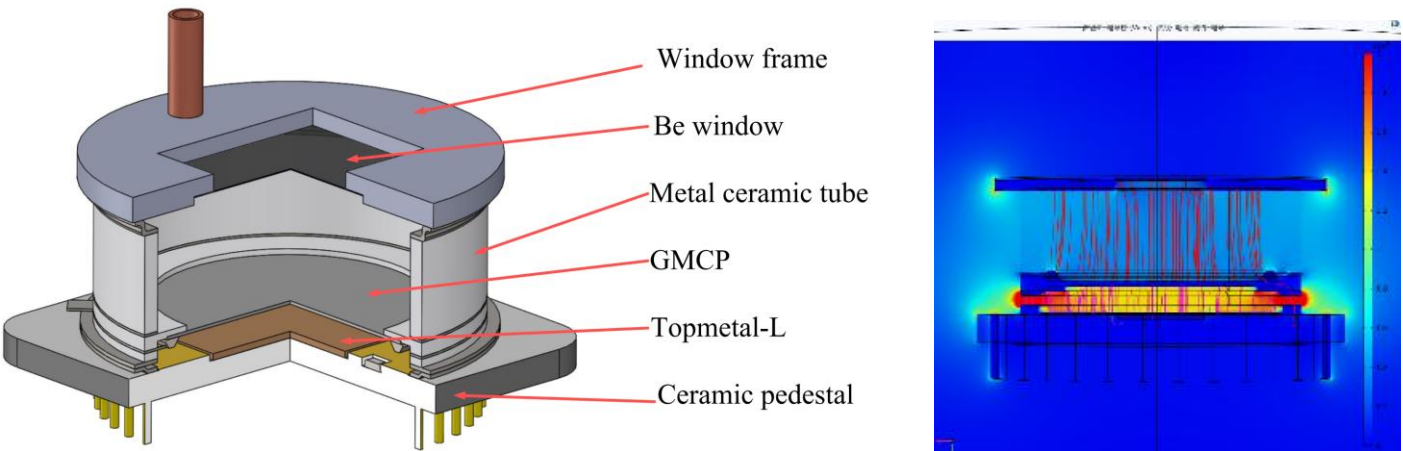
Zuke Feng et al., APJ, 2023

➤ Statistical distribution of PD (Toma et al. 2009, Lan et al. 2021)

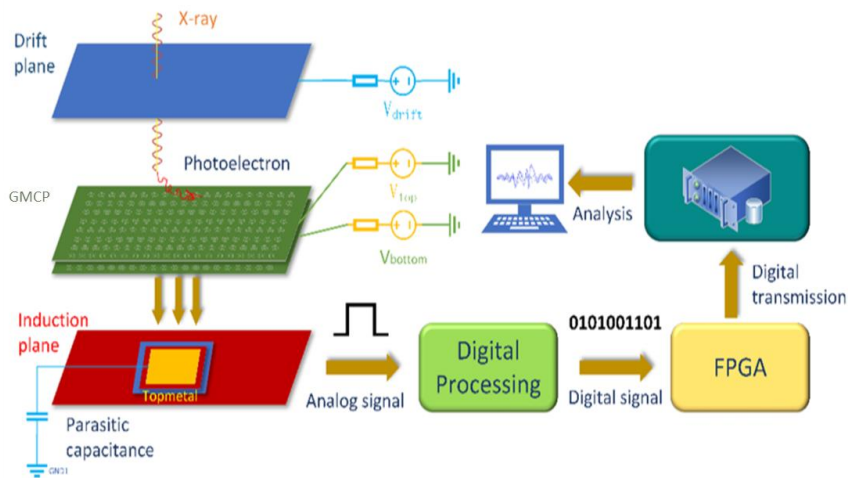


The radiation mechanism of GRBs could be determined after 5 years of observations.

X-ray polarization detector



3D drawing and electric field map of the Detector.

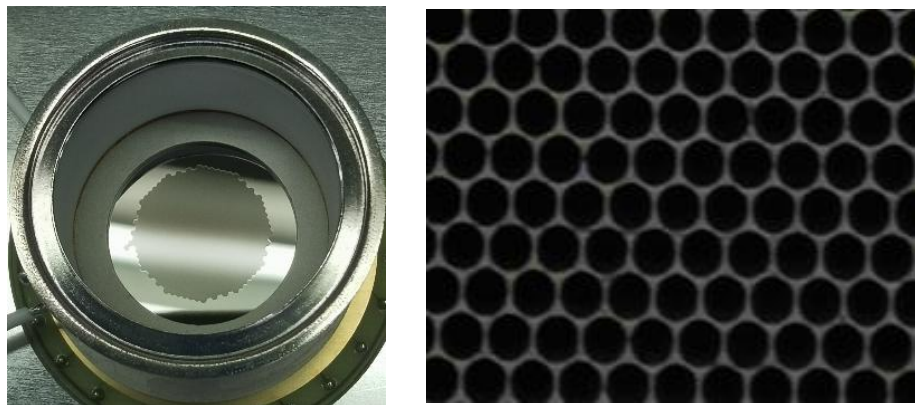


Schematic diagram of the Detector.

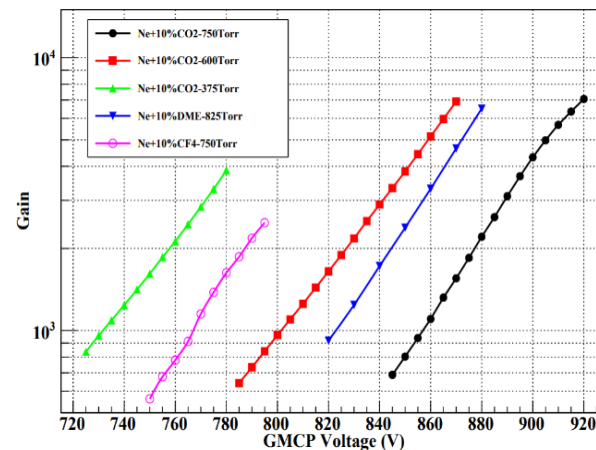
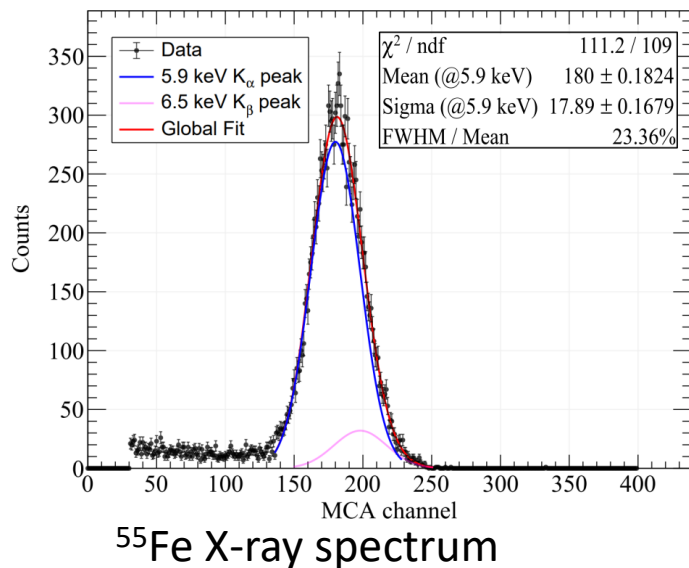
Performance indicators	value
Area	>3.6 cm ²
Window	100 μm, beryllium
Mixture	He and DME
gas thickness	14 mm
GMCP pitch	≤60 μm
Pixels pitch	≤45 μm
Electronic noise	<40 electrons ENC
GMCP gain	>3000
Energy resolution	<20% @ 5.9 keV
Time resolution	100 μs
Modulation factor	>40% @ 4.5keV
Residual modulation factor	<1%

Huan-Bo Feng et al., Nucl. Sci. Tech, 2024
Zili Li et al., Nucl. Instrum. Meth. A, 2021
Hui Wang et al., Nucl. Sci. Tech, 2023

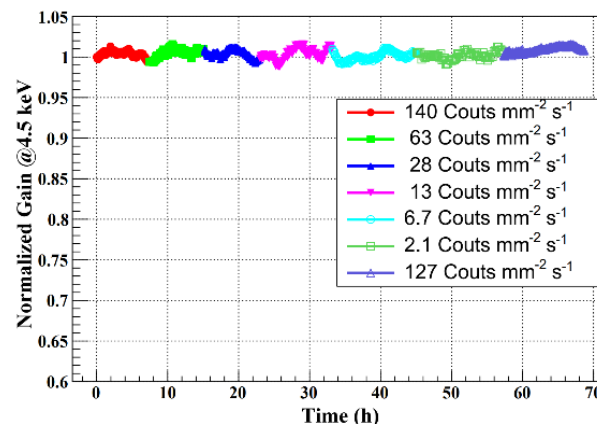
Gaseous Microchannel Plate (GMCP)



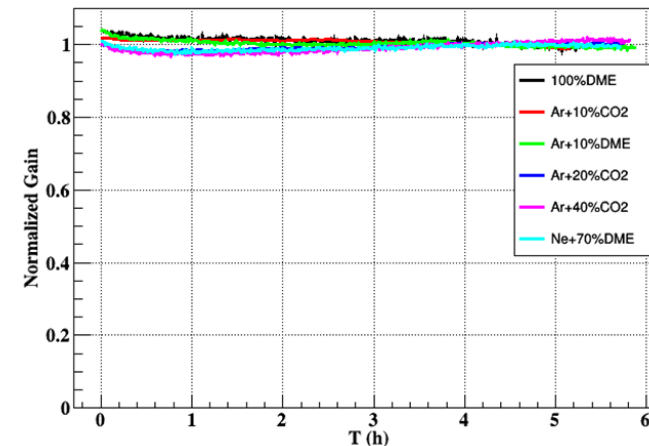
Hole diameter : 50 μm ; Hole pitch : 60 μm ;
 Bias angle: 0° ; Thickness : 400 μm ;
 Bulk resistance : 5 G Ω
 A total of 85 units of GMCP with 15 different
 parameter configurations were developed.



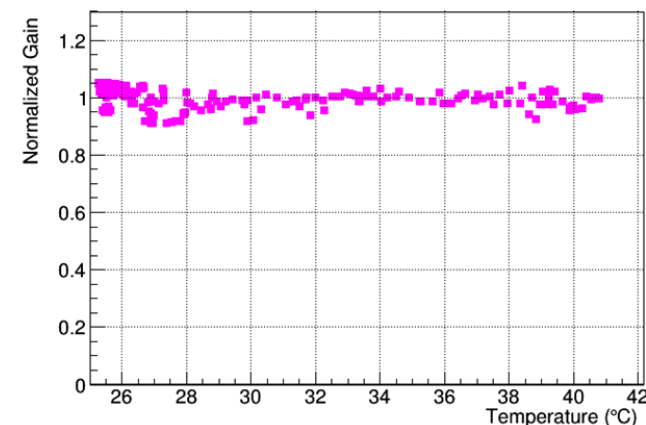
Gain curves for the GMCP under
 different gas conditions.



At different counting rates, the relative
 gain of the GMCP varies with time.



Gain stability of the GMCP
 in different working gases.

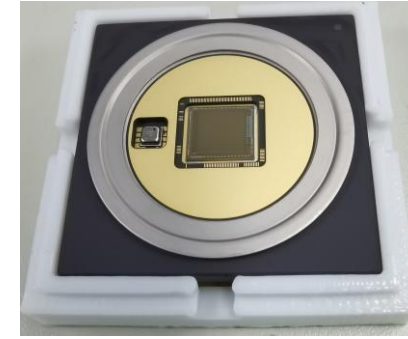


Response curve of the detector
 gain to temperature.

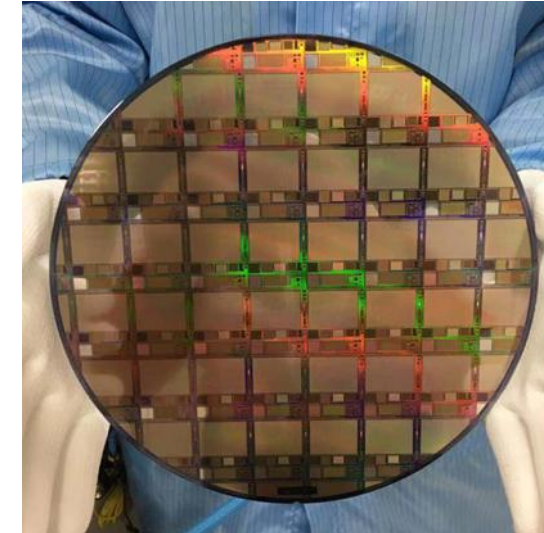
Topmetal Chip

	Topmetal-II ⁺	Topmetal-M1/M2	Topmetal-L
Chip Size /mm ²	6 × 6	18 × 23	17 × 24
Pixel Array	72 × 72	400 × 512	356 × 512
Pixel Size /um ²	83 × 83	45 × 45	45 × 45
Pixel Electrode / um ²	15 × 15	10 × 20	26 × 26
ENC	~ 13.4e-	~ 15.4e-	~ 20.0e-
Power Consumption	~ 1W @3.3V	~ 4.3W @3.3V	~ 0.8W @3.3V
Clock	40MHz	5MHz	20MHz
Frame Rate	2.5ms	2.4ms	0.37ms @Sentinel Readout
Readout Mode	Rolling Shutter	Rolling Shutter	Rolling Shutter /Sentinel Readout
Readout Channel	1	16	1

The fabrication and testing of the **Topmetal-II**, **Topmetal-M1**, **Topmetal-M2** and **Topmetal-L** chips have been completed.

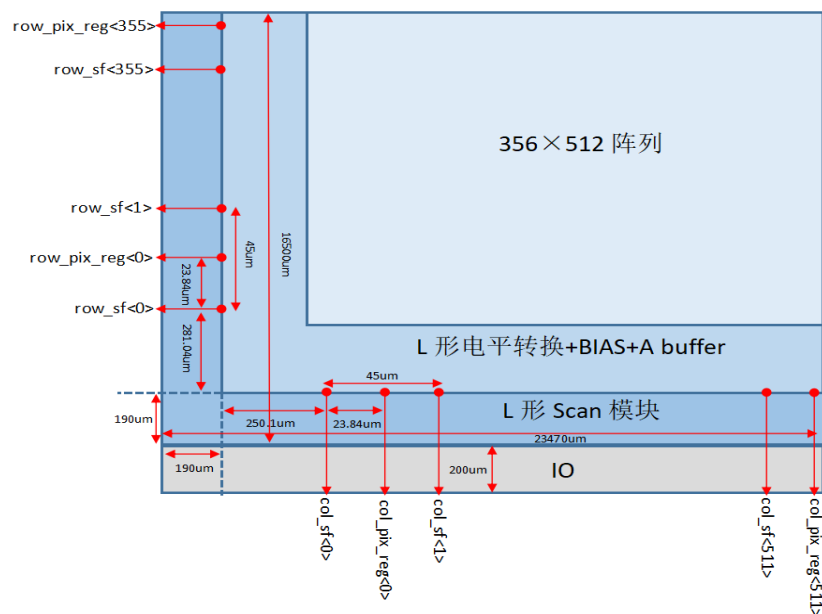
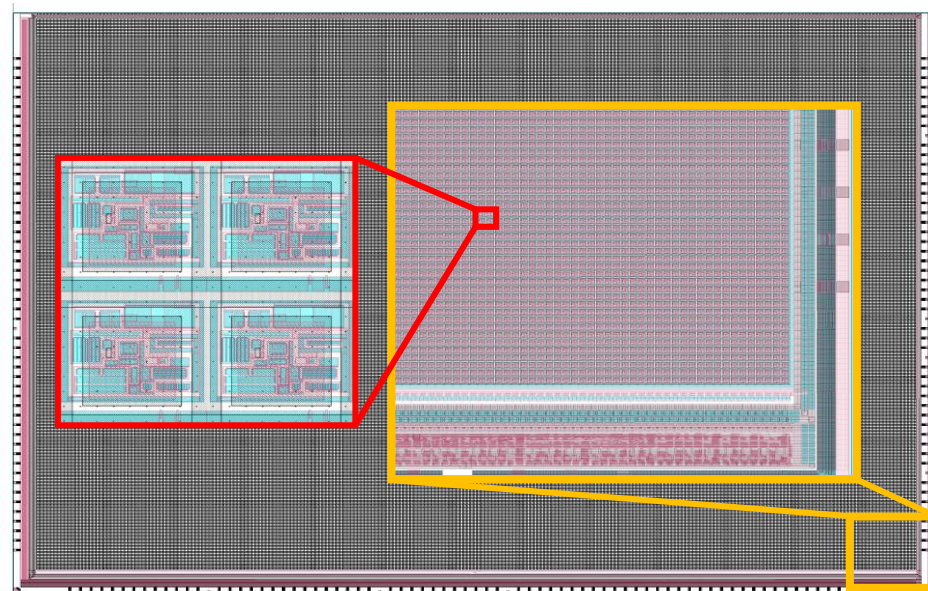


Topmetal-II⁺

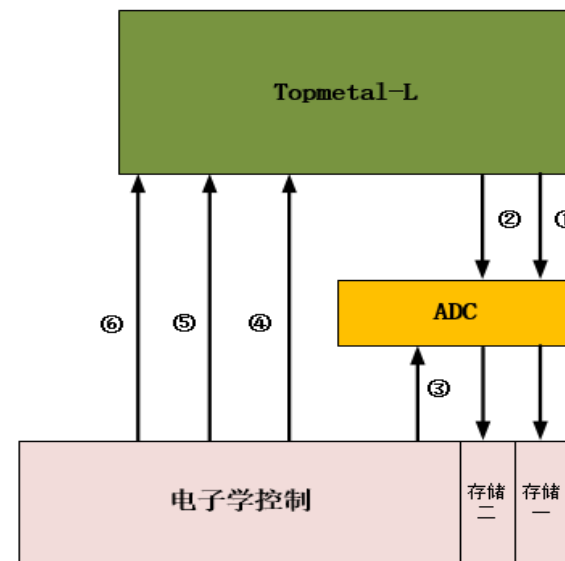


Topmetal-M1/M2

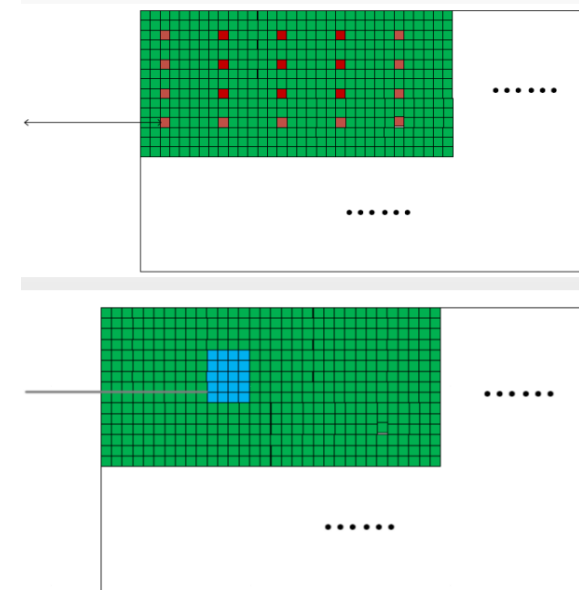
Topmetal-L and Readout



Topmetal-L layout structure.



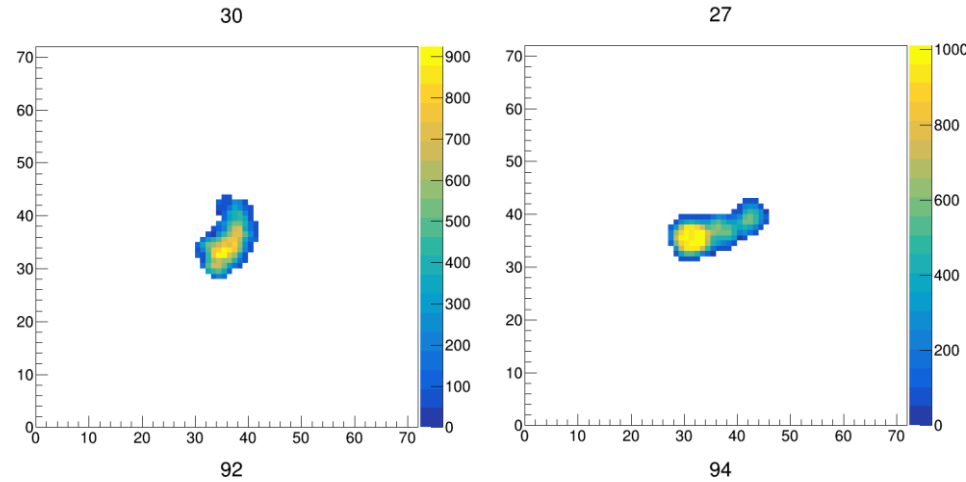
Data communication instructions.



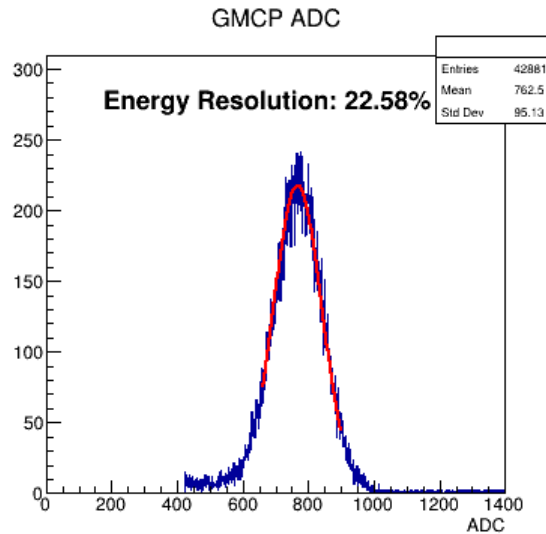
Sentry scanning and area scanning.

In the readout section of the Topmetal-L chip, a novel readout scheme called the **Sentinel readout scheme** is adopted.

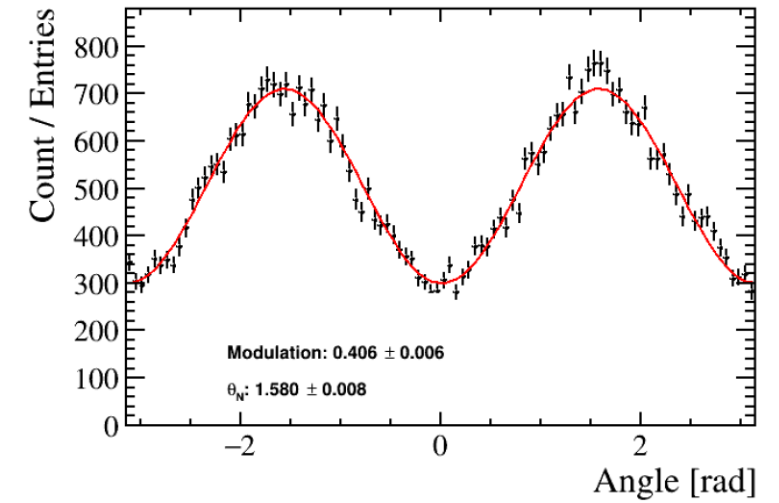
GMCP & Topmetal-L Commissioning



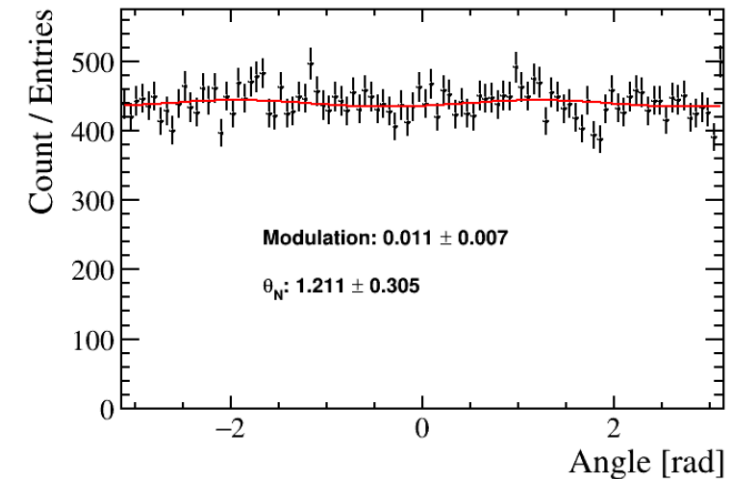
Example electron tracks
produced by 5.9 keV X-rays.



4.5 keV X-ray spectrum

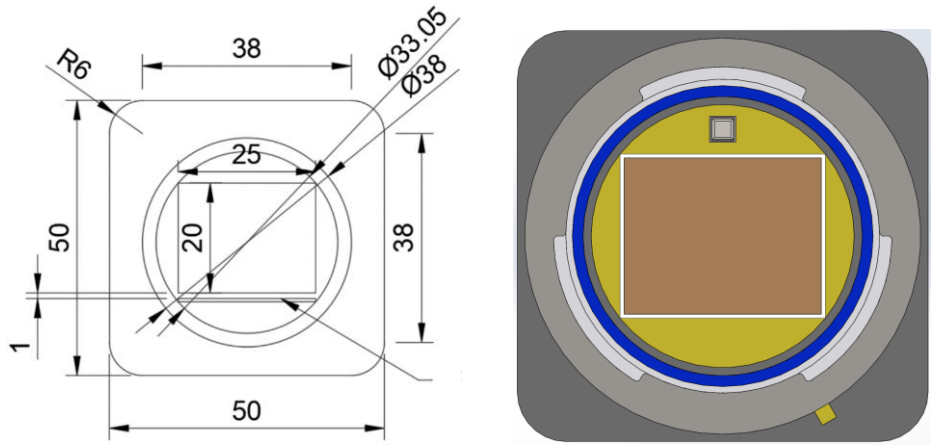


Modulation curve obtained from a 4.5
keV polarized X-ray measurements.

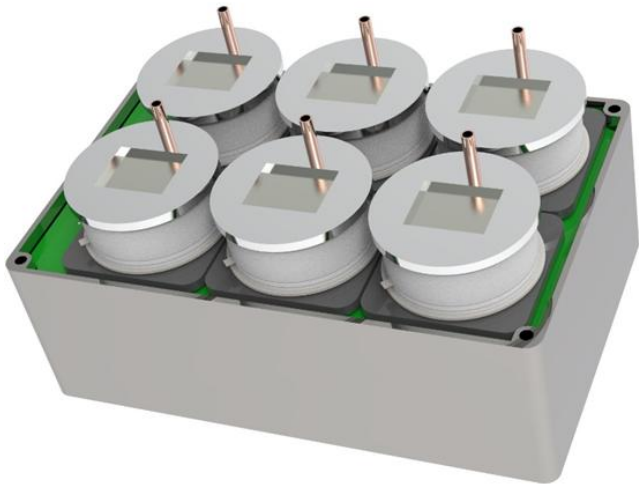


Modulation curve obtained from a 5.9
keV unpolarized X-ray measurements.

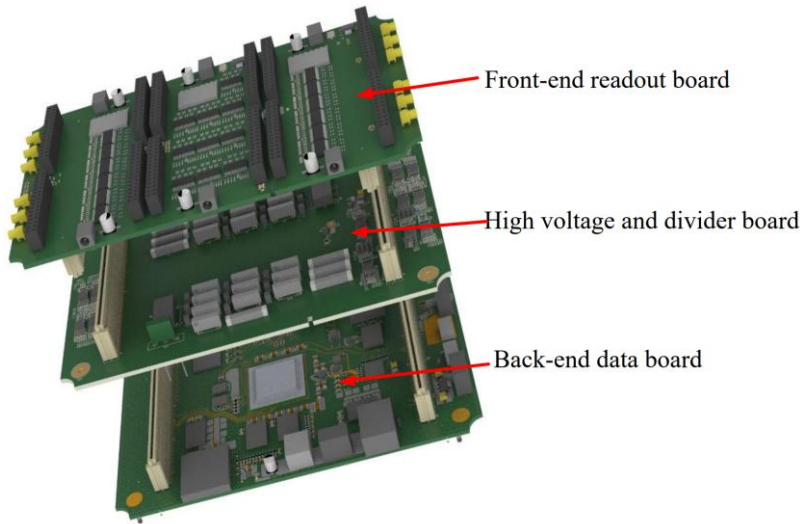
LPD Detector Unit & Electronics



Schematic diagram of the Topmetal-L chip bonding design.



Overall diagram of the detection unit (Includes 6 Topmetal-L chips).



Schematic diagram of the electronics. The three boards are connected board-to-board and have the same planar structure.

	Data volume (Day)
Particle background	1GB
Diffuse photon background	65.29 GB
Normal GRB	0.80 GB
Ultra-intense GRB	39.83 GB
Total data volume	81.81GB

The estimation of data volume for the LPD detector.

Flight validation of LPD prototype

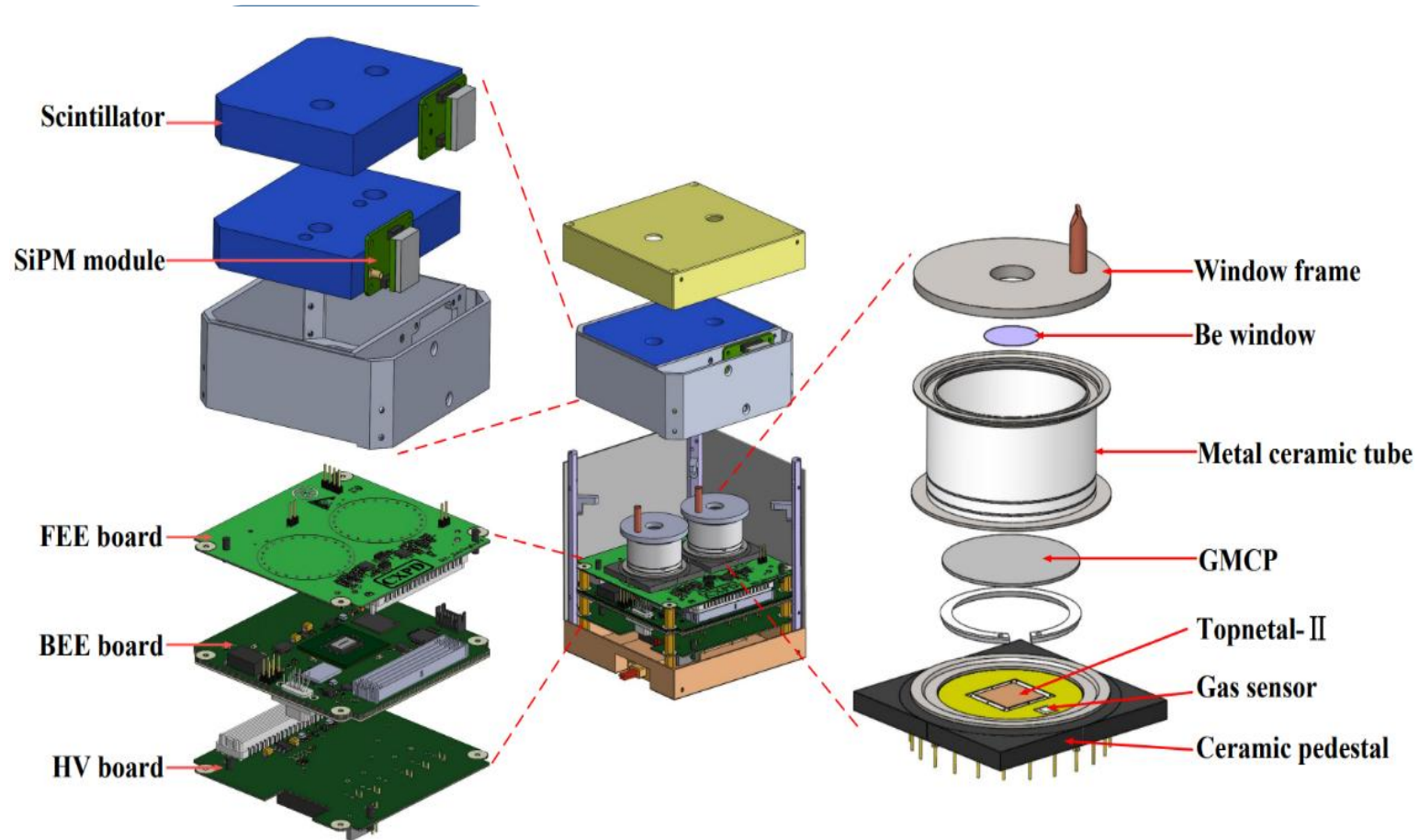
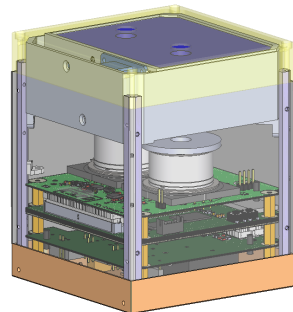
Cosmic X-ray Polarimeter Detection (CXPDP) CubeSat

- * Validation of soft X-ray polarization detection technology
- * Spatial background measurement
- * Standard X-ray source polarization measurement

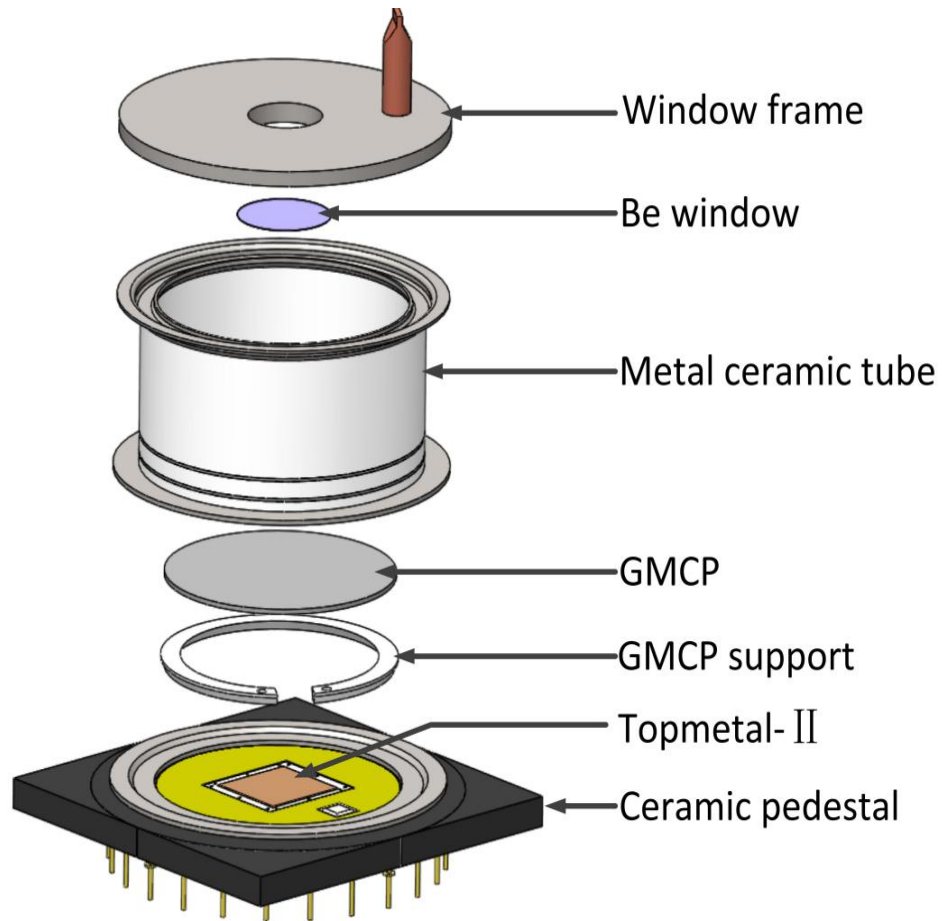
Size : $96 * 96 * 108 \text{ mm}^3$

Mass: $\sim 900 \text{ g}$

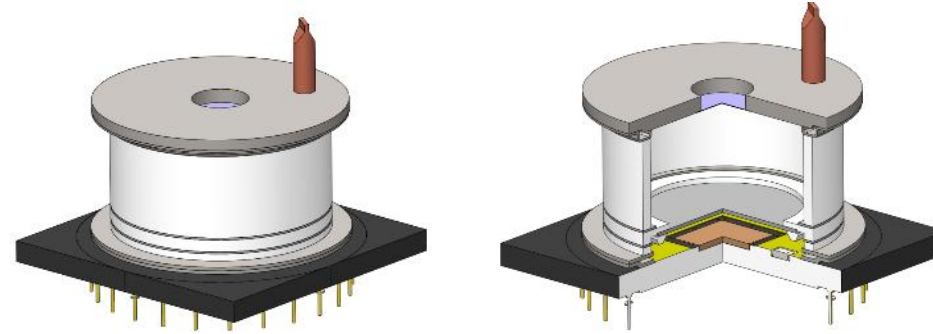
Power consumption : $< 5 \text{ W}$



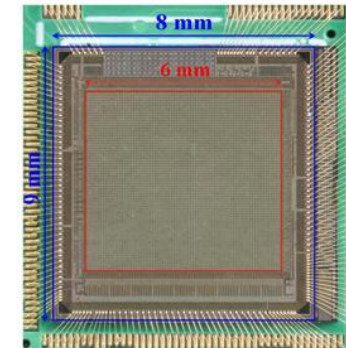
LPD prototype



A schematic drawing of the GMPD

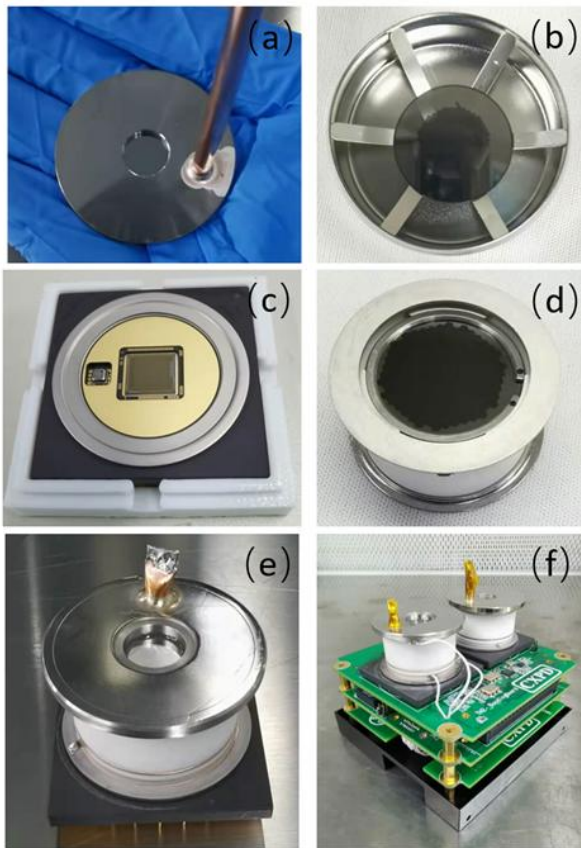


Gas Microchannel Plate (GMCP):
Hole pitch : $60\ \mu\text{m}$
Hole diameter : $50\ \mu\text{m}$
Effective diameter : $12\ \text{mm}$



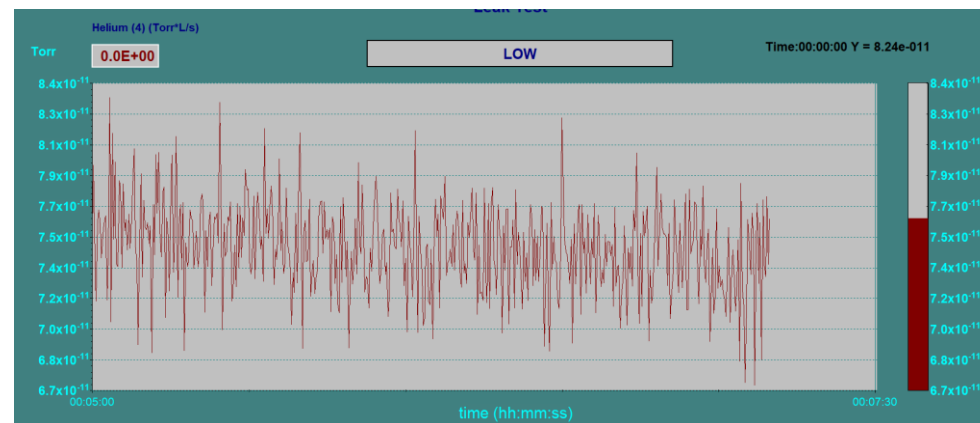
Topmetal-II:
Pixel pitch : $83\ \mu\text{m}$
Pixel arrays : 72×72
Effective area : $6 \times 6\ \text{mm}^2$

Assembling of gas detectors

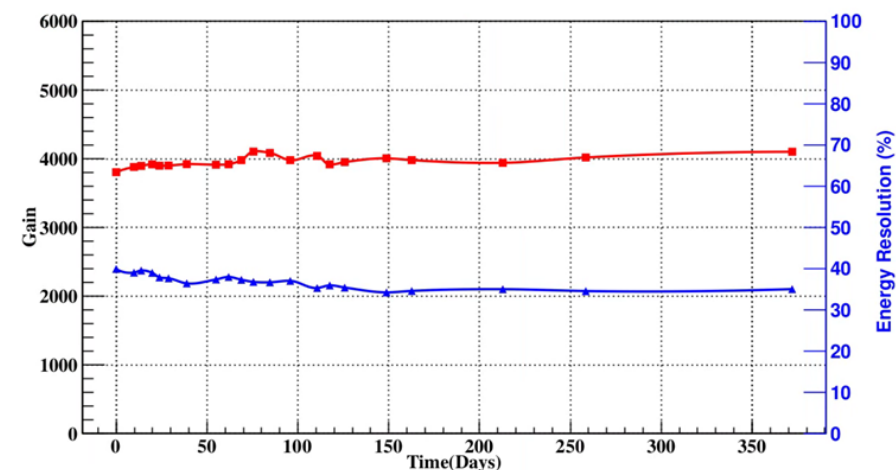


Materials with low outgassing rates: ceramics, alloys, beryllium, glass, etc.

Welding technology: brazing, laser welding, ultrasonic welding.

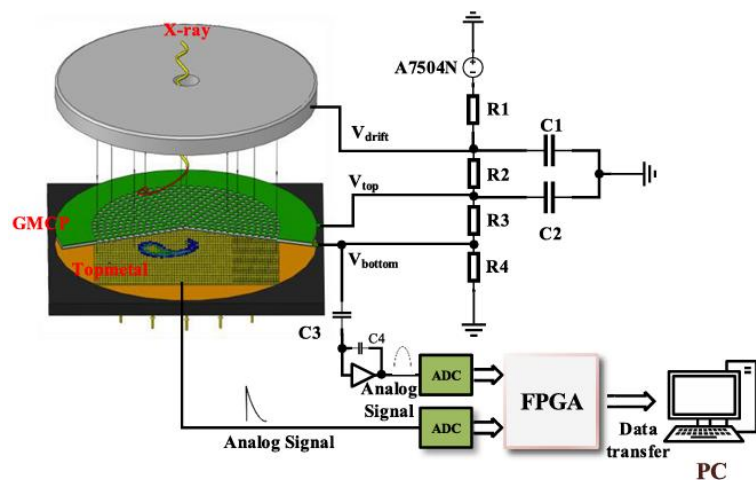


Leakage rate : 7.6^{-11} Torr*L/s

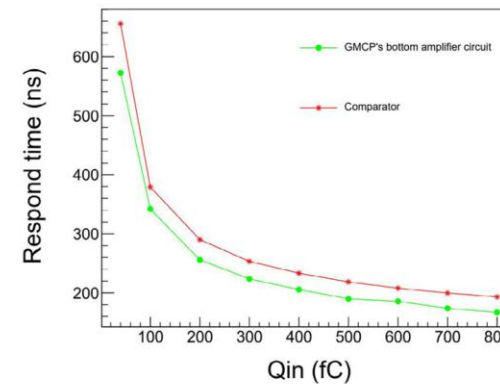


Long-term monitoring of the detector's normalized gain (Red) and energy resolution (Blue).

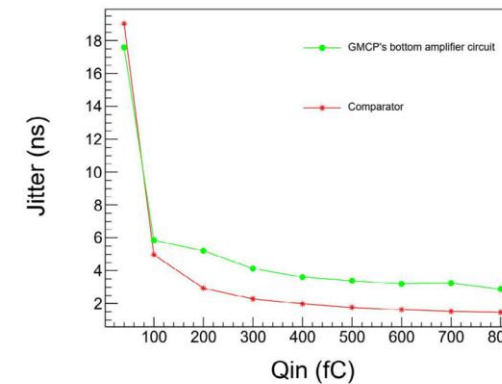
GMCP bottom amplifier circuit



Schematic of the GMCP experimental system.

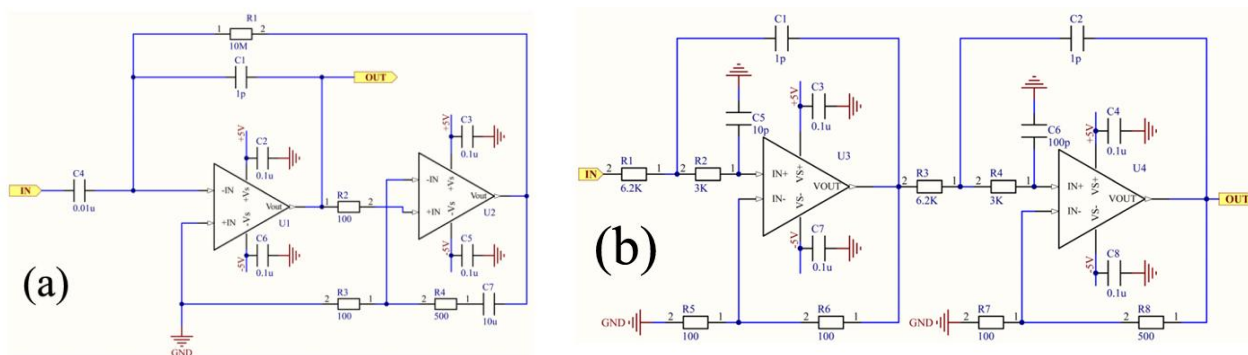


(a)



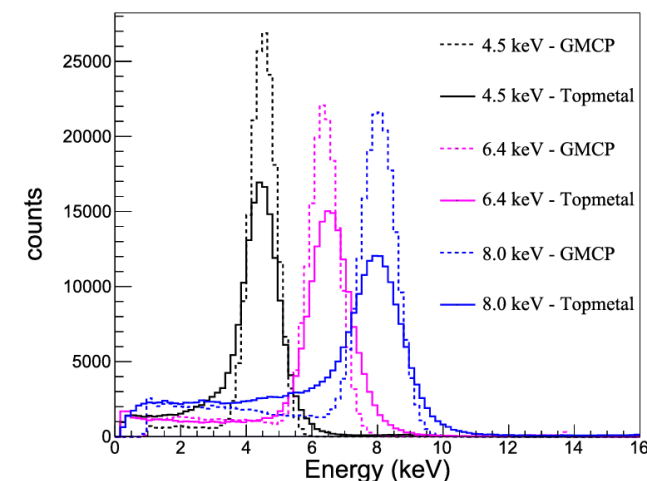
(b)

Time performance of the GMCP's bottom amplifier circuit. (a) Time walk. (b) Time accuracy.



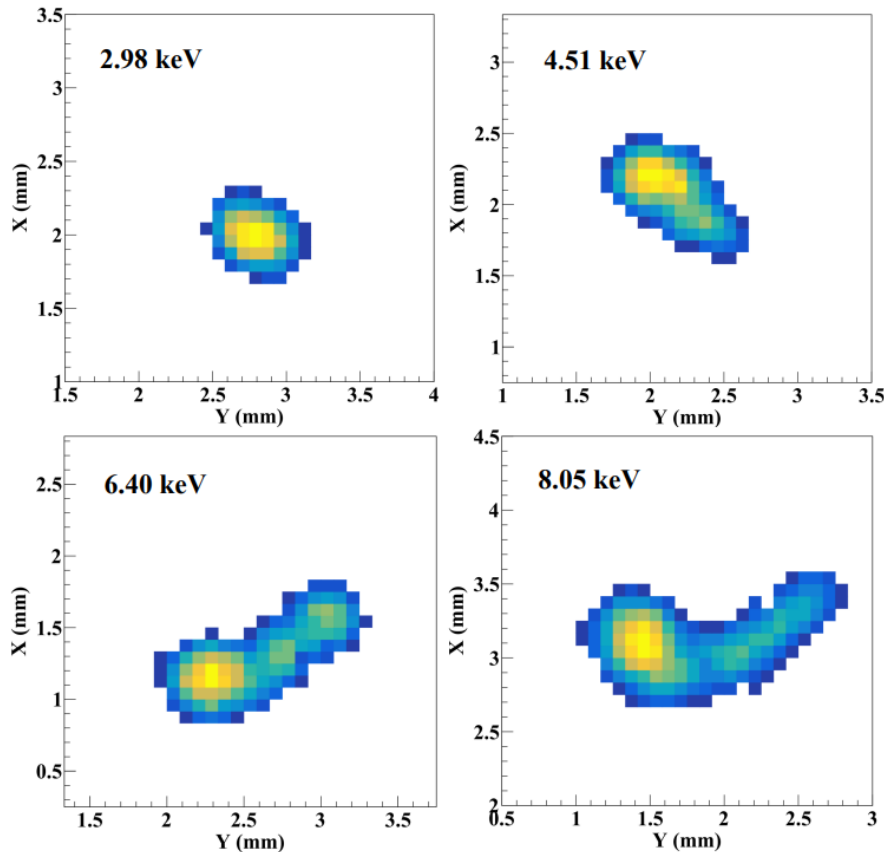
GMCP's bottom amplifier circuit. (a) CSA. (b) Filter shaper.

➤ Improve the time resolution and energy resolution.

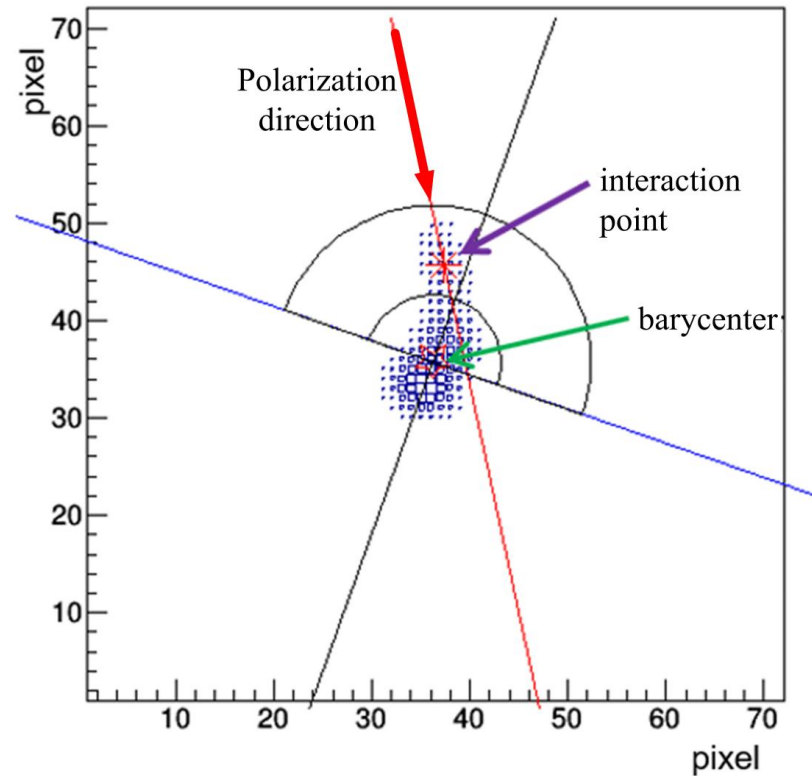


Energy spectrum of GMCP and Topmetal-II after events matching.

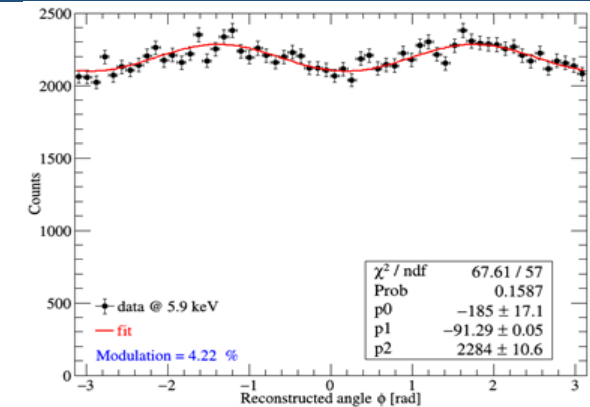
Polarized X-ray measurements



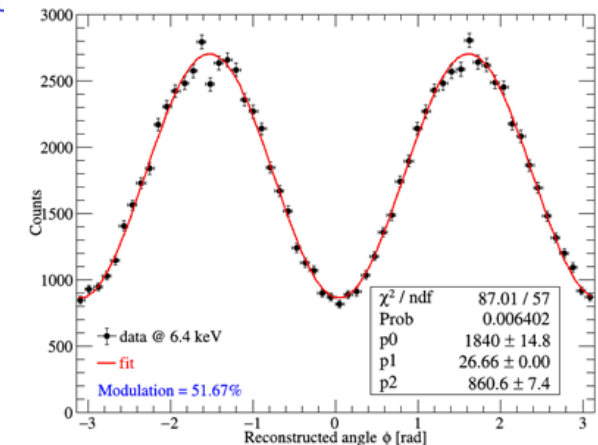
Example electron tracks produced by X-rays of different energies.



Schematic diagram of photoelectron track reconstruction.

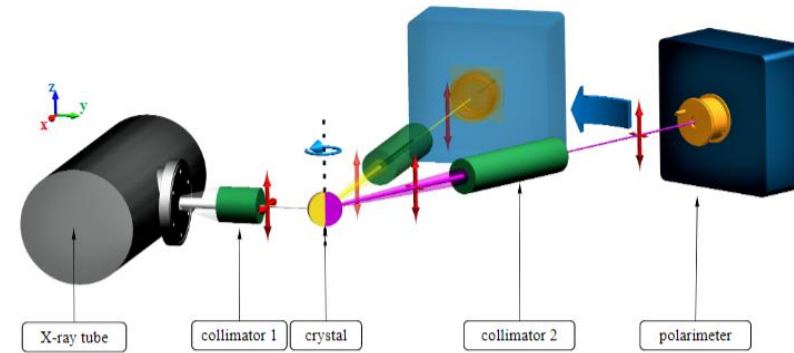
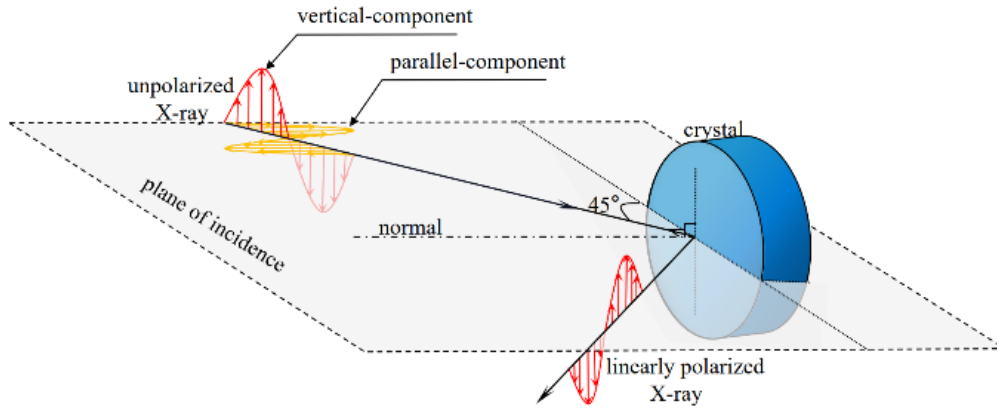


Modulation curve obtained from a 5.9 keV unpolarized X-ray measurements.

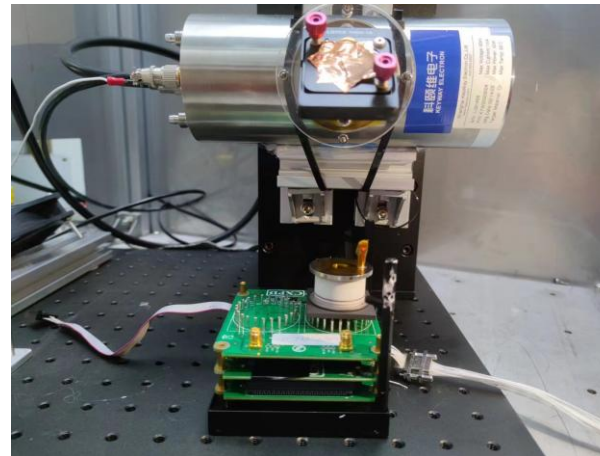
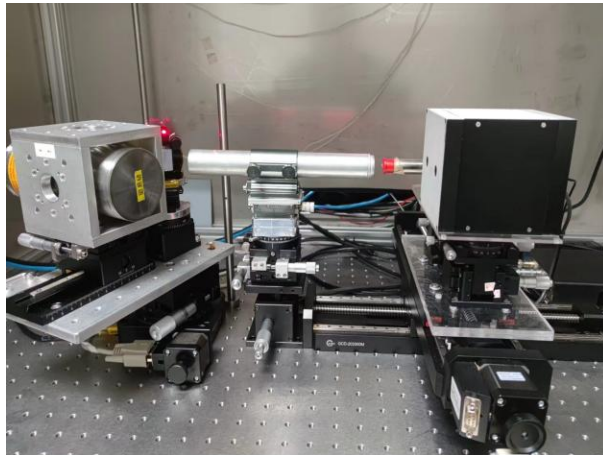


Modulation curve obtained from a 6.4 keV polarized X-ray measurements.

X-ray polarized calibration platform



Schematic diagram of the principle of polarized X-ray source based on Bragg diffraction.



X-ray polarization calibration platform set up in the laboratory.

X-ray polarized calibration platform

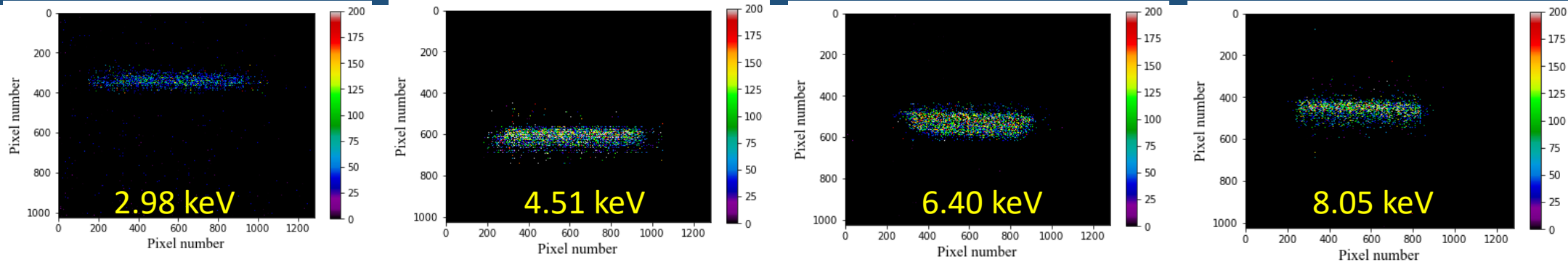
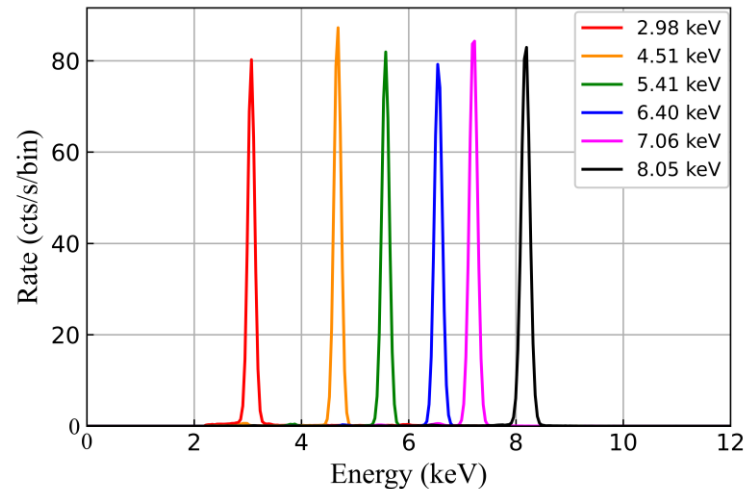


Image with the CCD imager of the photons generated with the polarized source.



Spectrum of the polarized source.

TABLE II. Configurations and performance list of 8.05 keV linear polarized sources. The polarization degree is calculated using Eq. (3).

Energy(keV)	2.98	4.51	5.40	6.40	7.06	8.05
Crystal	Si(111)	Si(220)	Si(311)	Si(400)	Si(331)	Si(224)
Incident radiation	Ag L_{α}	Ti K_{α}	Cr K_{α}	Fe K_{α}	Fe K_{β}	Cu K_{α}
Diffraction angle(deg)	41.6	45.8	44.5	45.5	44.9	44.1
Rate(cts/s)	207.52	375.49	370.49	375.8	426.77	439.25
Proportion of monochromatic light ^a (%)	93.04	97.91	98.31	98.64	97.40	97.32
FWHM(eV)	139.38	146.69	149.39	142.42	158.62	159.73
X-ray tube settings	8.0 kV, 0.49 mA	6.5 kV, 0.19 mA	7.0 kV, 0.19 mA	8.0 kV, 0.31 mA	9.8 kV, 0.44 mA	9.5 kV, 0.58 mA
Polarization(%)	97.4	99.8	99.9	99.8	99.9	99.8

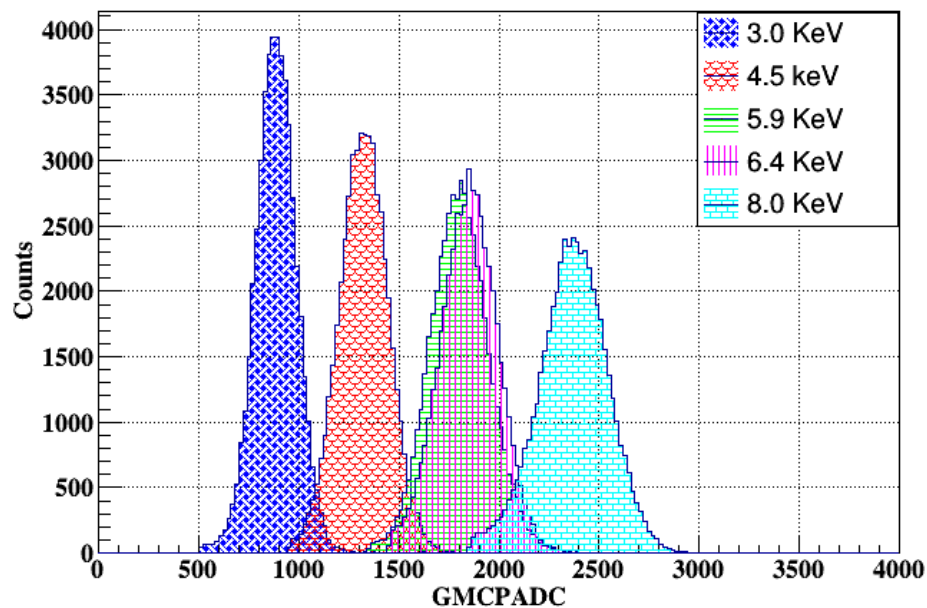
^a The proportion of monochromatic light is defined as the ratio of the number of photons falling within three times the sigma of the target peak centre value to the total photons.

TABLE III. Configurations and performance list of 8.05 keV partially polarized sources. The copper K_{α} characteristic line diffracted by silicon crystal to generate beams with different degrees of polarization. The polarization degree is calculated using Eq. (3).

Energy(keV)	8.05	8.05	8.05	8.05	8.05	8.05
Crystal	Si(111)	Si(220)	Si(311)	Si(400)	Si(331)	Si(224)
Incident radiation	Cu K_{α}	Cu K_{α}	Cu K_{α}	Cu K_{α}	Cu K_{α}	Cu K_{α}
Diffraction angle(deg)	14.2	23.7	28.1	34.6	38.2	44.1
Rate(cts/s)	277.75	166.66	224.14	657.92	146.97	555.92
Proportion of monochromatic light ^a (%)	92.82	96.84	98.32	98.40	98.36	98.37
FWHM(eV)	193.05	162.63	159.61	159.24	159.11	159.73
X-ray tube settings	9.3 kV, 0.19 mA	9.4 kV, 0.39 mA	10.3 kV, 0.19 mA	11.5 kV, 0.29 mA	10.0 kV, 0.29 mA	10.5 kV, 0.29 mA
Polarization(%)	12.8	37.0	52.6	77.5	89.5	99.8

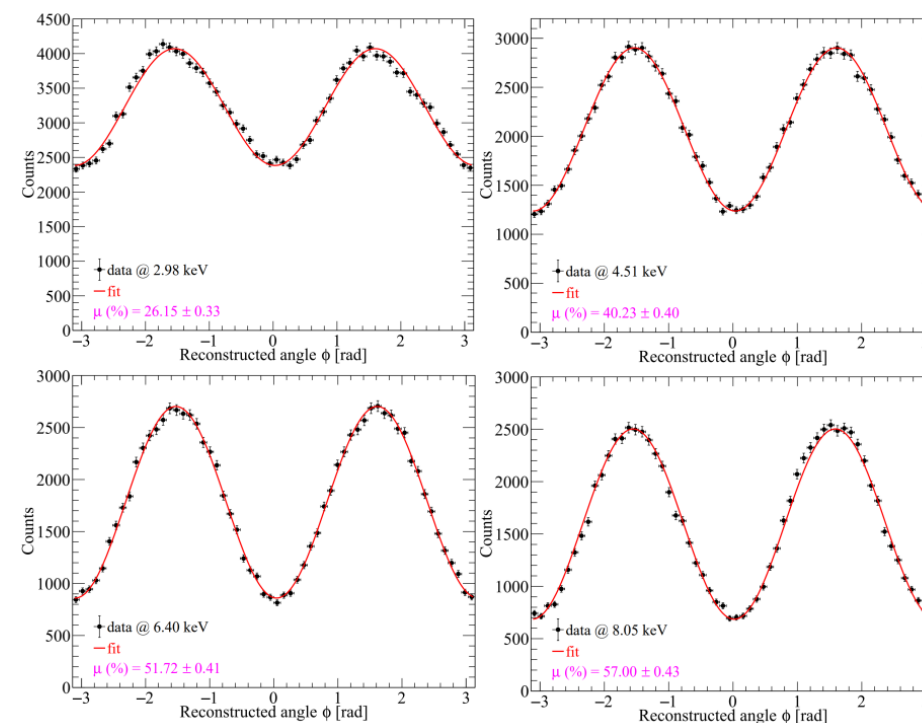
^a The proportion of monochromatic light is defined as the ratio of the number of photons falling within three times the sigma of the target peak centre value to the total photons.

Spectral and polarimetric characterization



Energy spectra measured with Bragg diffractions.

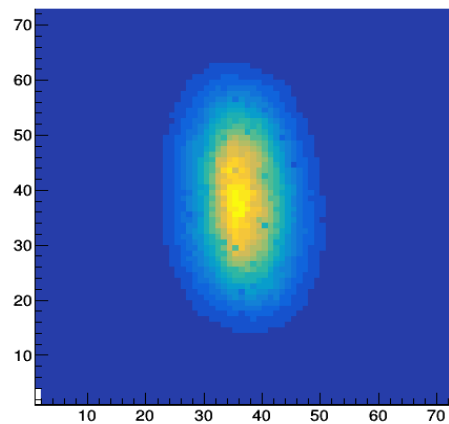
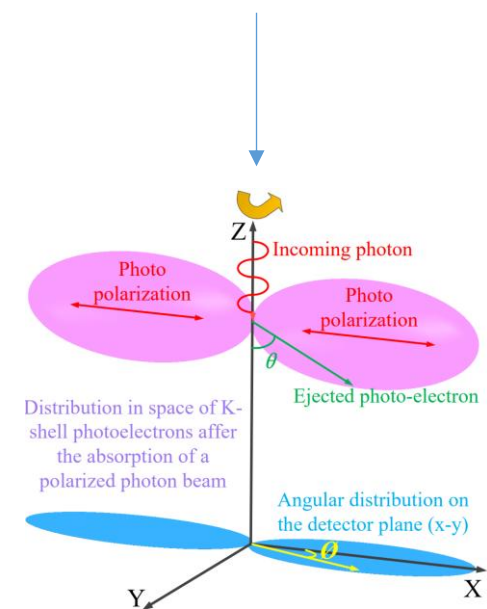
Energy (keV)	E_{peak} (ADC)	FWHM (ADC)	FWHM/ E_{peak}
2.98	885.5 ± 0.5	230.3 ± 0.9	0.260 ± 0.002
4.51	1323.1 ± 0.6	285.0 ± 1.1	0.215 ± 0.001
6.40	1880.1 ± 0.7	338.9 ± 1.4	0.180 ± 0.001
8.05	2369.6 ± 0.9	190.1 ± 1.7	0.165 ± 0.001



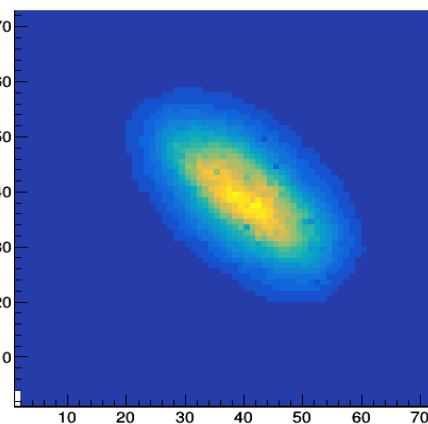
Modulation curves measured with Bragg diffraction.

GMPD, 40%He+60%DME, 0.8 atm		
Energy (keV)	μ	$\mu\sqrt{\varepsilon}$
2.98	0.2615 ± 0.0033	0.0753
4.51	0.4023 ± 0.0040	0.0749
6.40	0.5172 ± 0.0041	0.0608
8.05	0.5700 ± 0.0043	0.0486

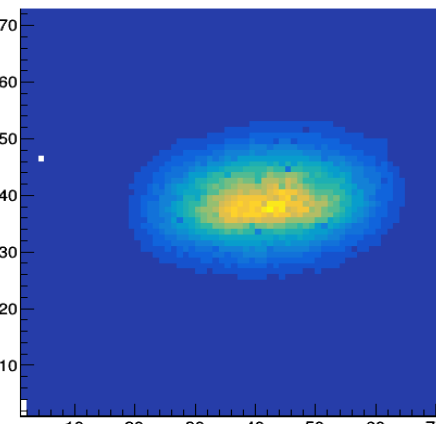
Calibration for different Polarimetry directions



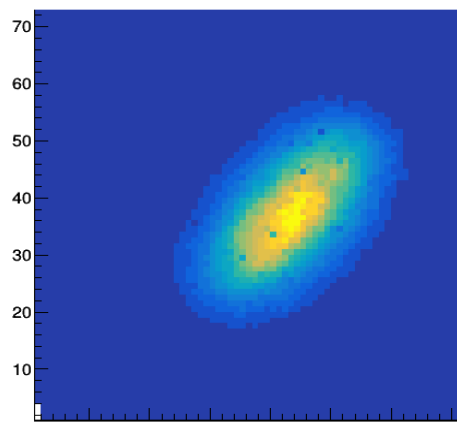
Rotation angle: 0°



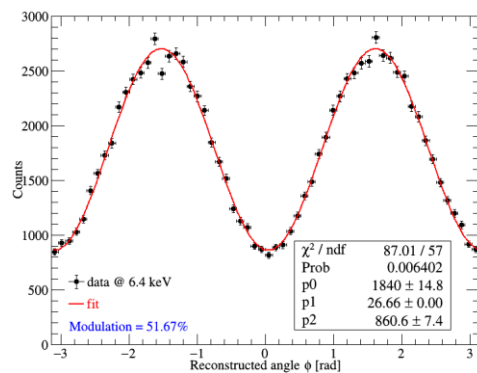
Rotation angle: 45°



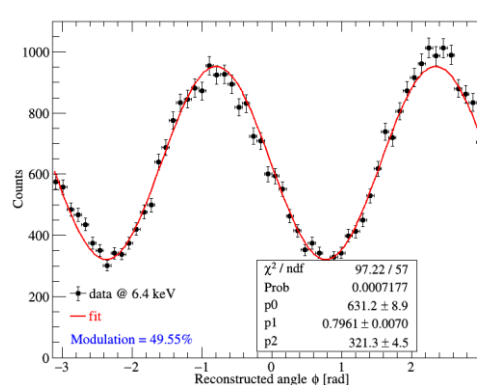
Rotation angle: 90°



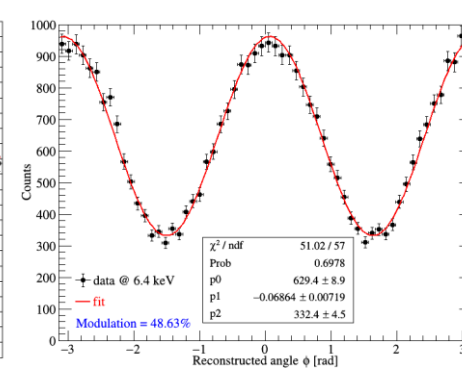
Rotation angle: 135°



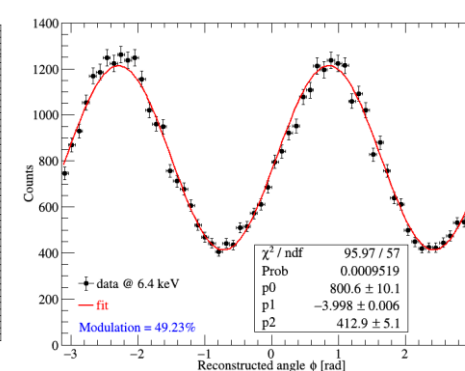
modulation
factor: 51.67%



modulation
factor: 49.55%

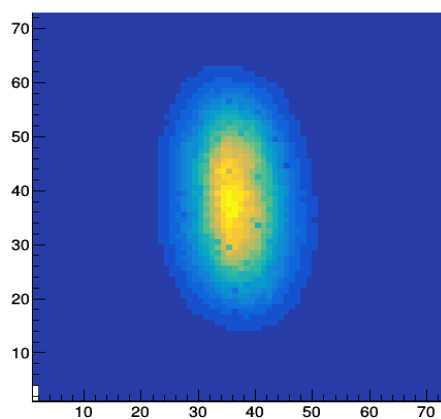
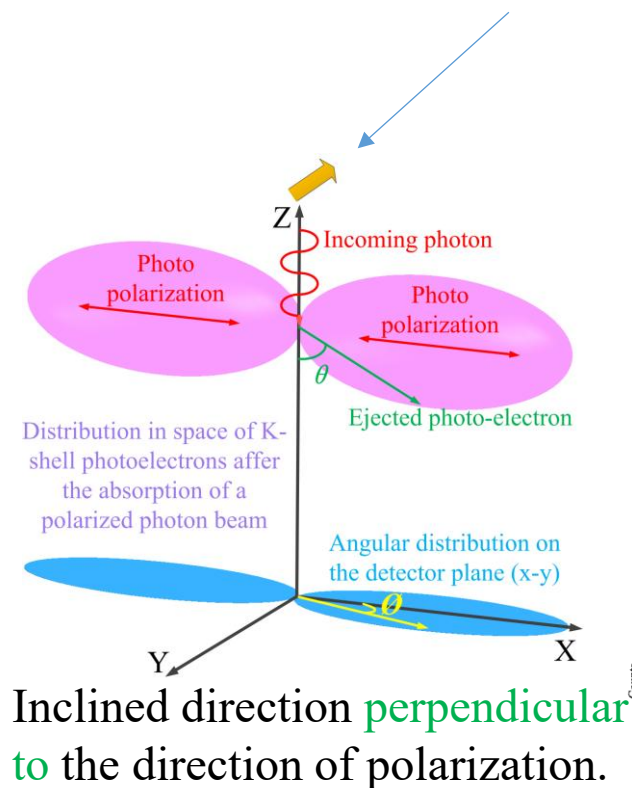


modulation
factor: 48.63%

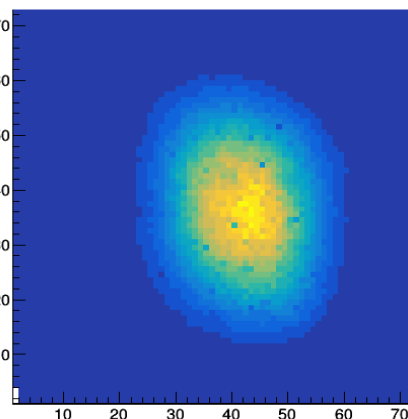


modulation
factor: 49.23%

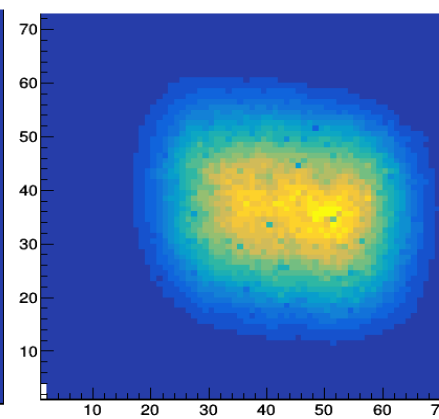
Calibration of the oblique incidence



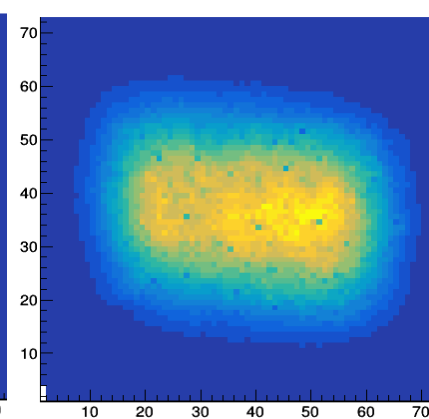
Inclined angle : 0°



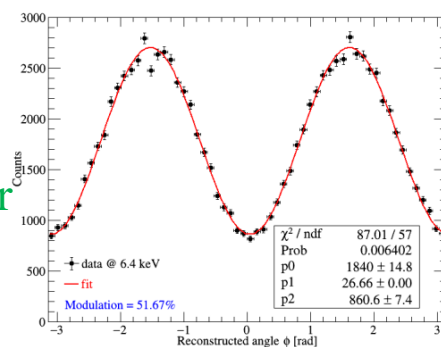
Inclined angle : 5°



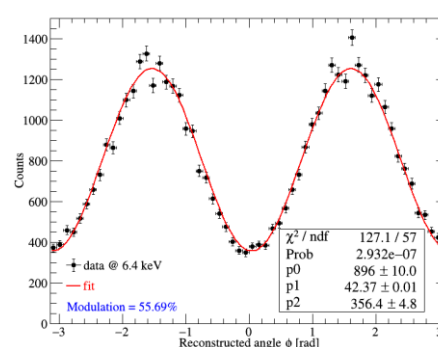
Inclined angle : 10°



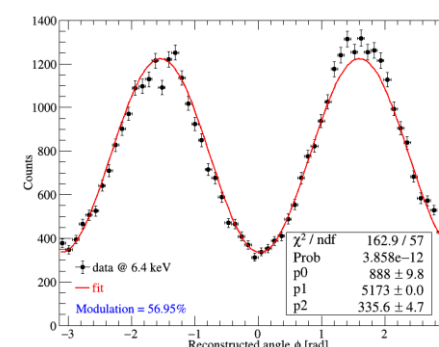
Inclined angle : 13°



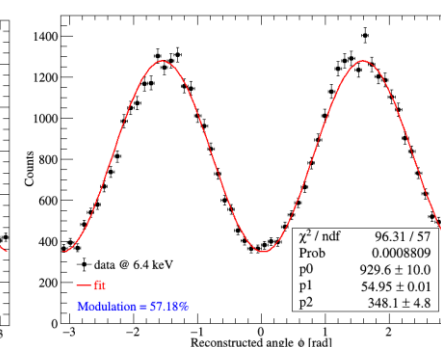
modulation
factor : 51.67%



modulation
factor : 55.69%

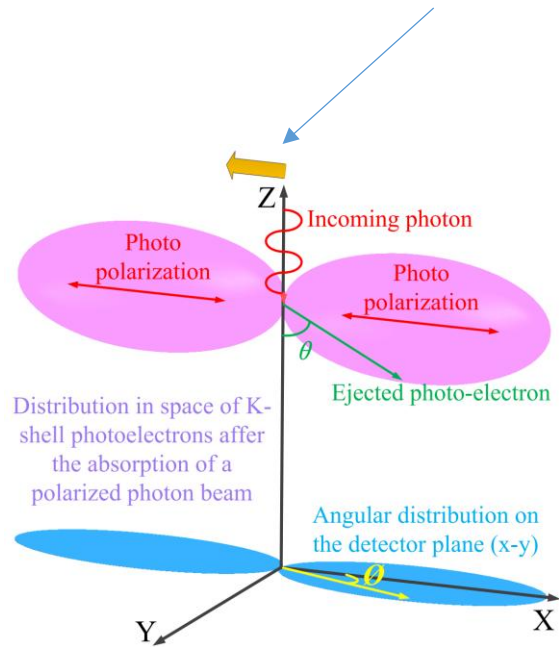


modulation
factor : 56.95%

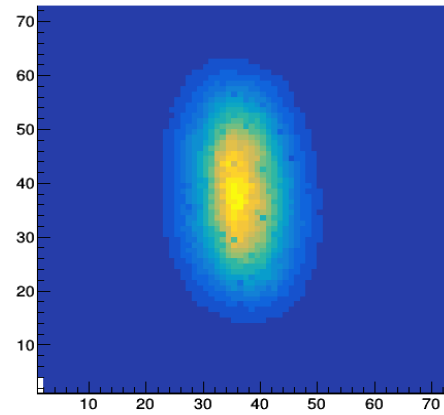


modulation
factor : 57.18%

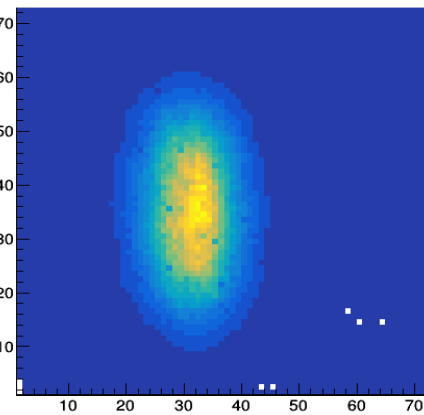
Calibration of the oblique incidence



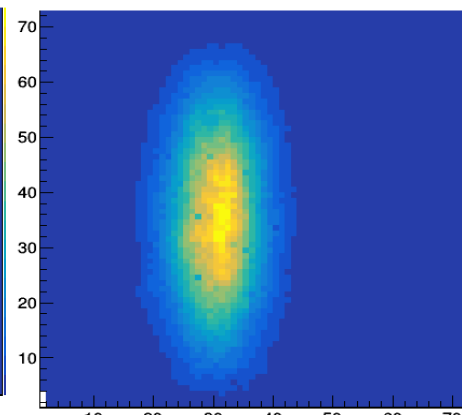
Inclined direction **parallel to** the direction of polarization.



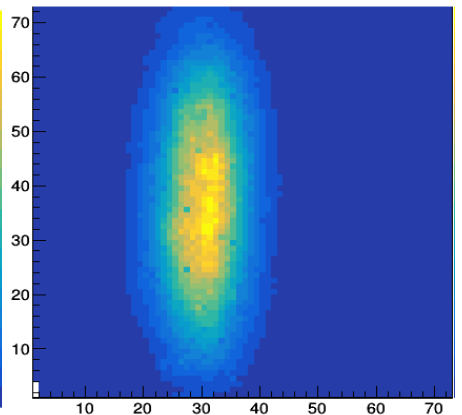
Inclined angle : 0°



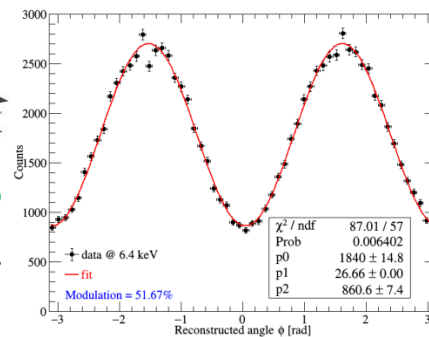
Inclined angle : 5°



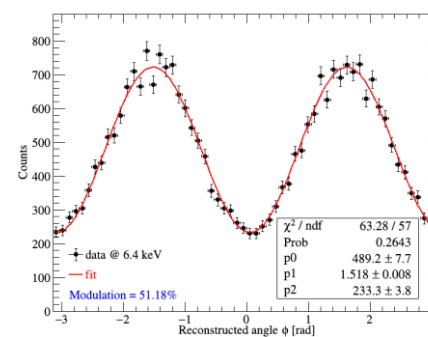
Inclined angle : 10°



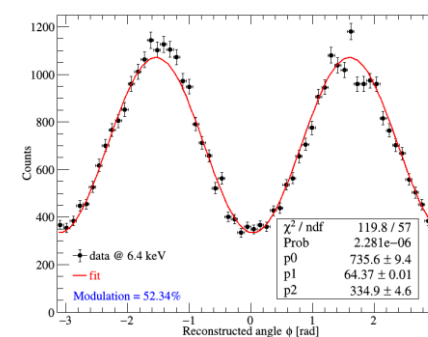
Inclined angle : 13°



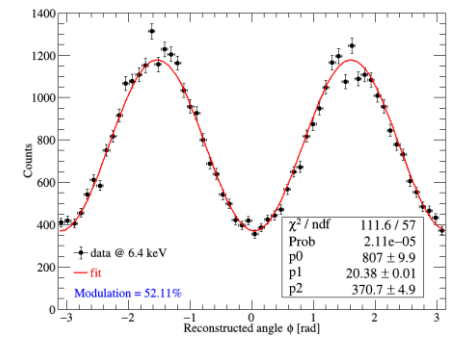
modulation
factor : 51.67%



modulation
factor : 51.18%

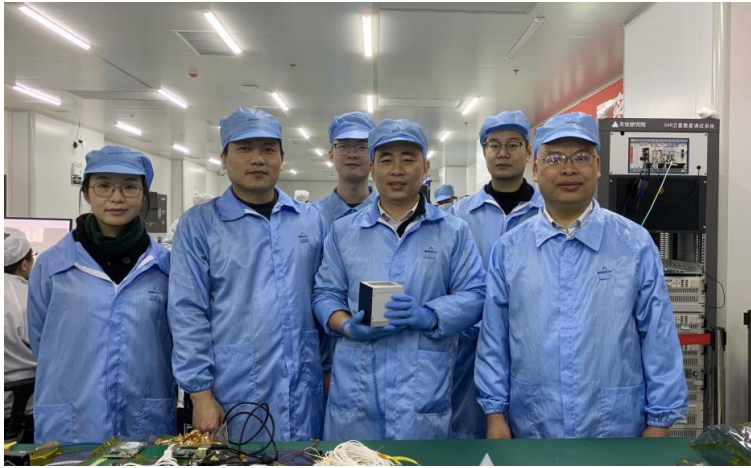


modulation
factor : 52.34%



modulation
factor : 52.11%

Status of CXPD payload



The CXPD payload was delivered in February 2023.

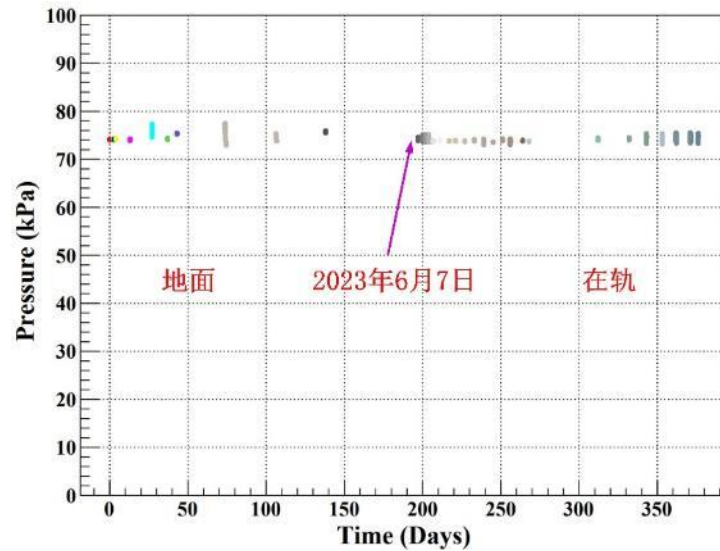
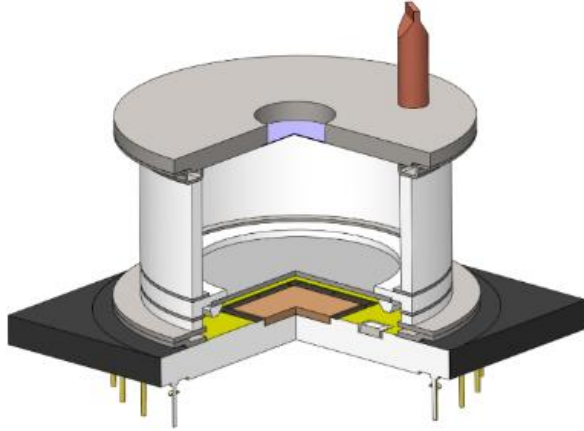


On May 10th, the installation and testing of the CXPD payload with the CubeSat were completed.

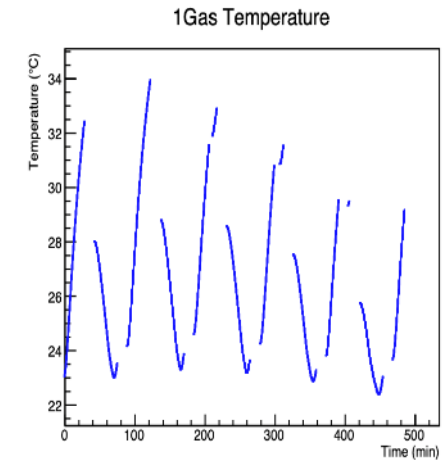
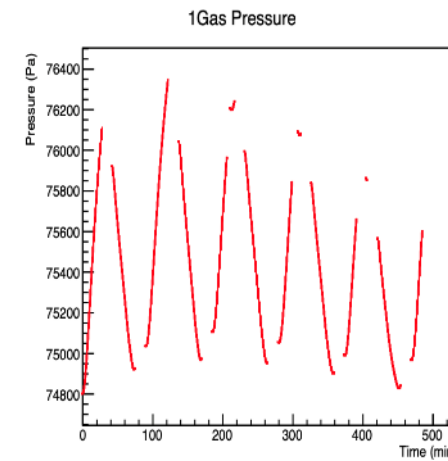
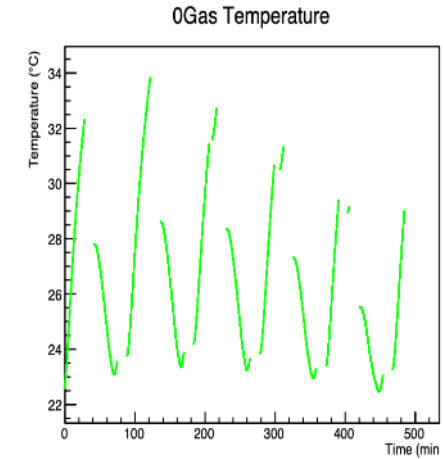
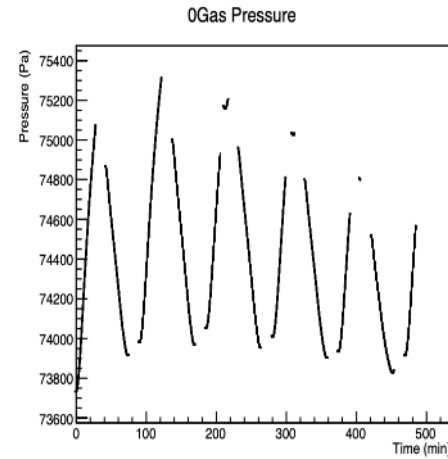


On June 7th, the CXPD payload was successfully launched along with the CubeSat.

Status of CXPD payload

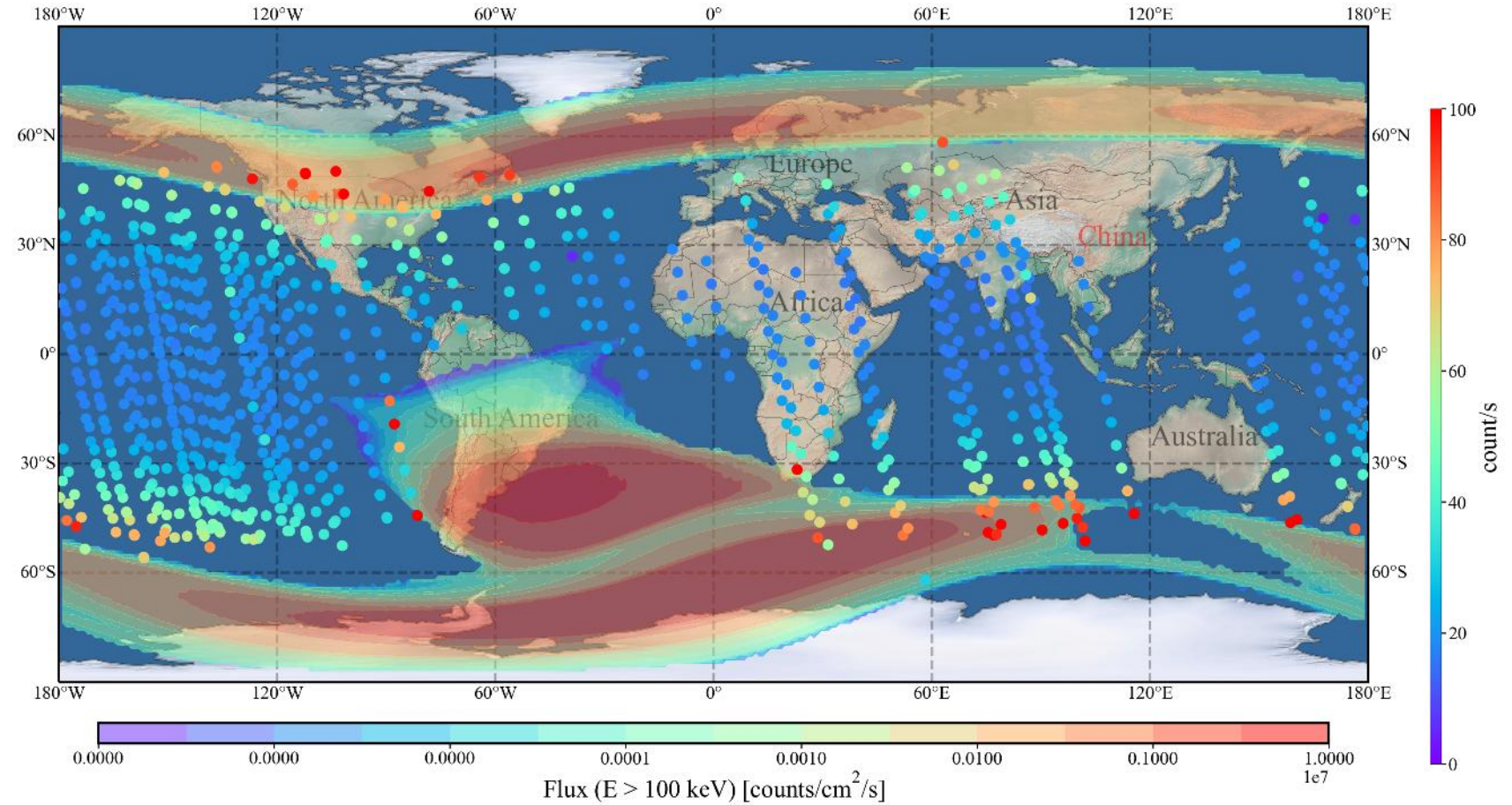
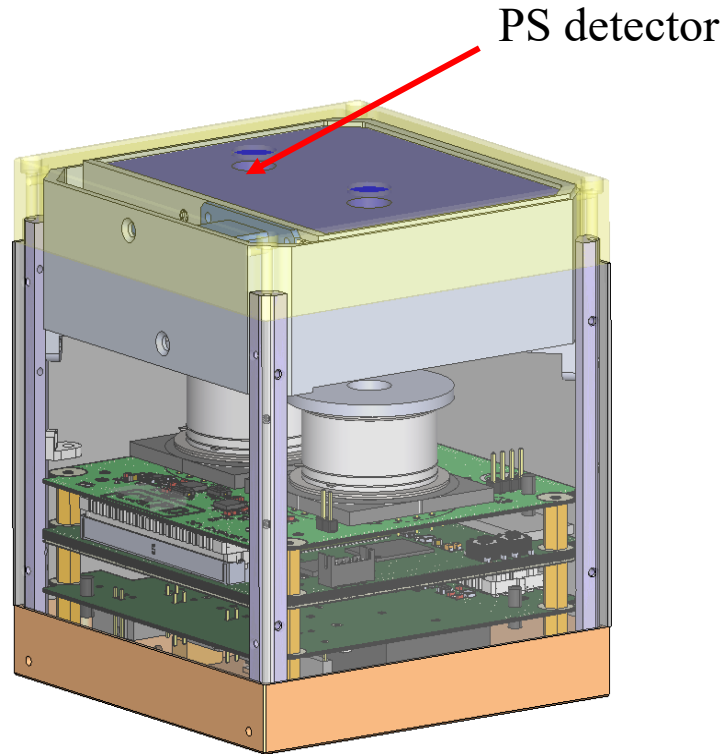


Gas pressure monitoring



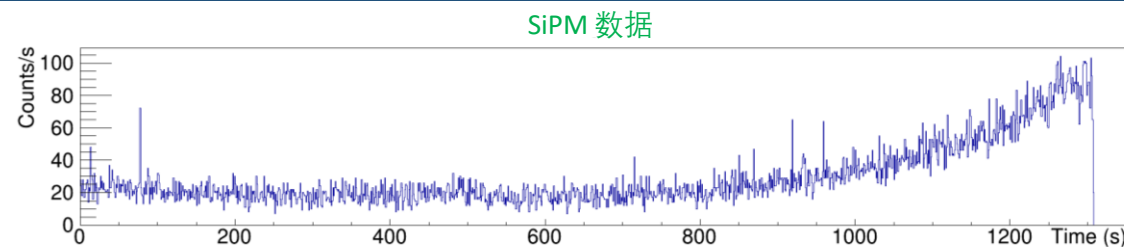
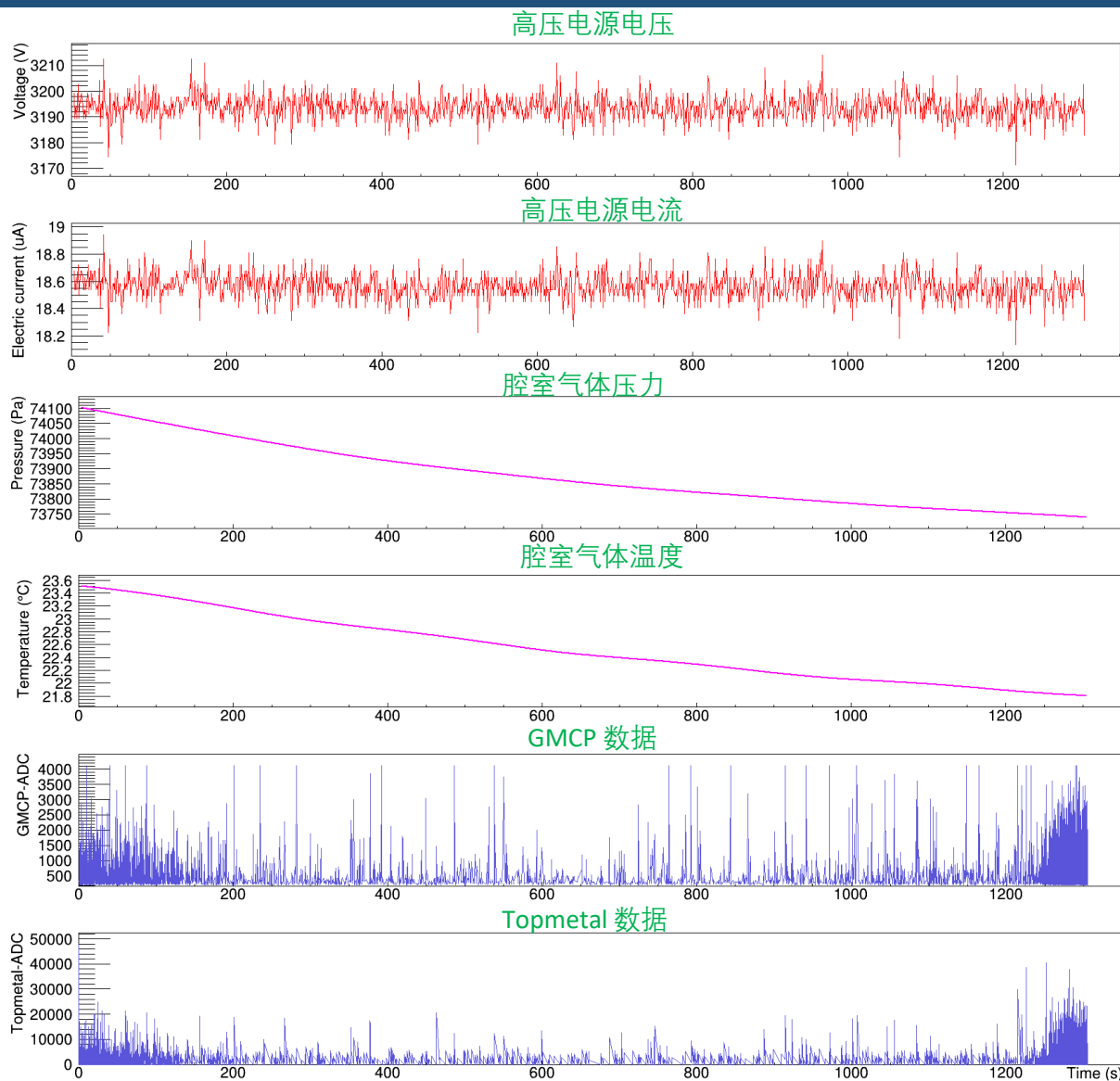
Gas pressure and temperature vary with the orbit

Status of CXPD payload

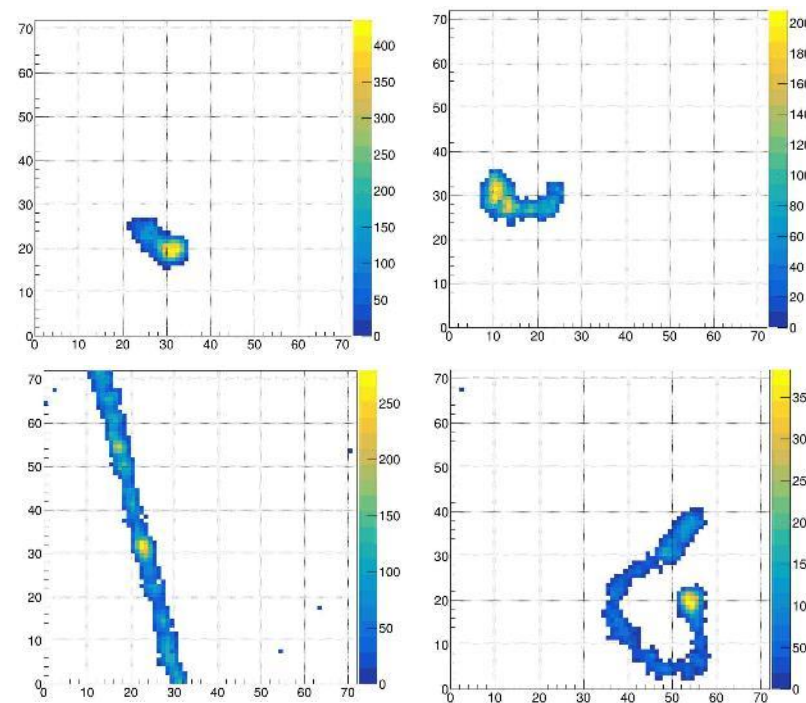


Particle background detect by PS detector

Status of CXPD payload



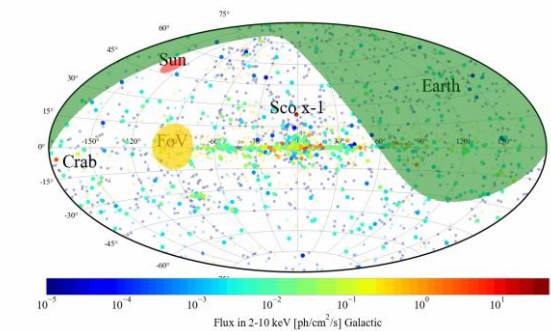
偏振探测器测量的径迹



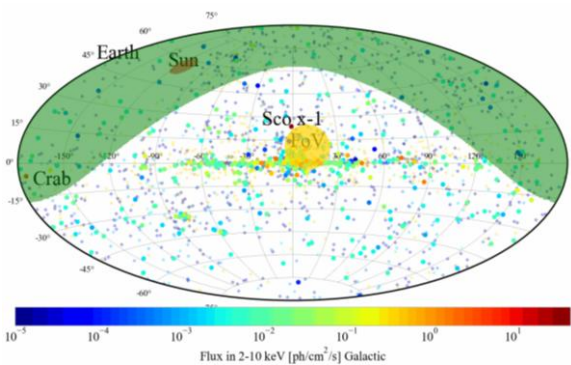
CXPD载荷的所有数据正常，工作良好，完成了空间X射线偏振测量的技术验证。

Status of CXPD payload

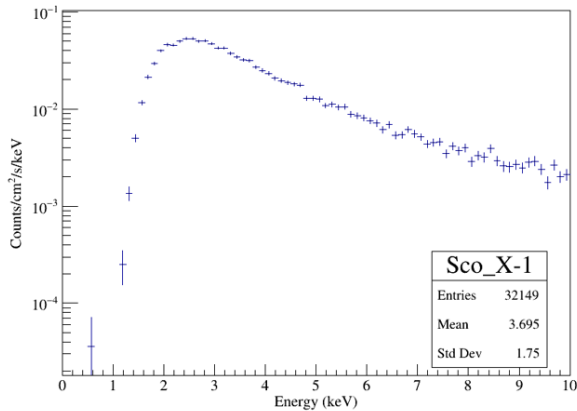
Observation of X-ray sources



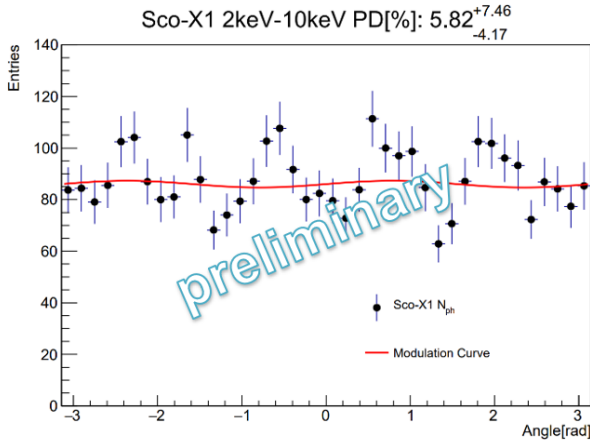
Sco X-1



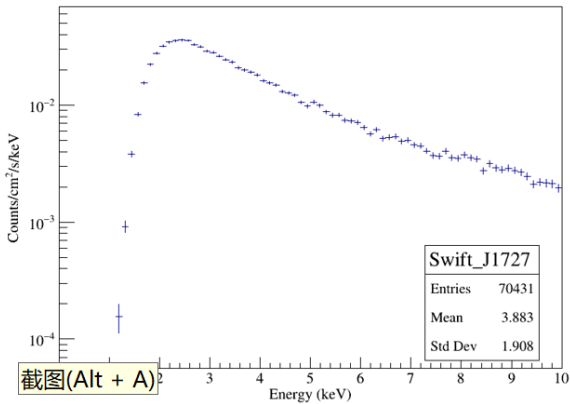
swift J1727 X-ray binary



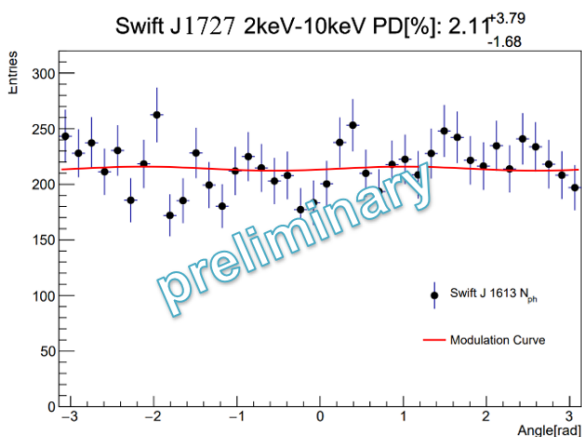
Sco X-1 能谱响应



Sco X-1 X射线偏振响应



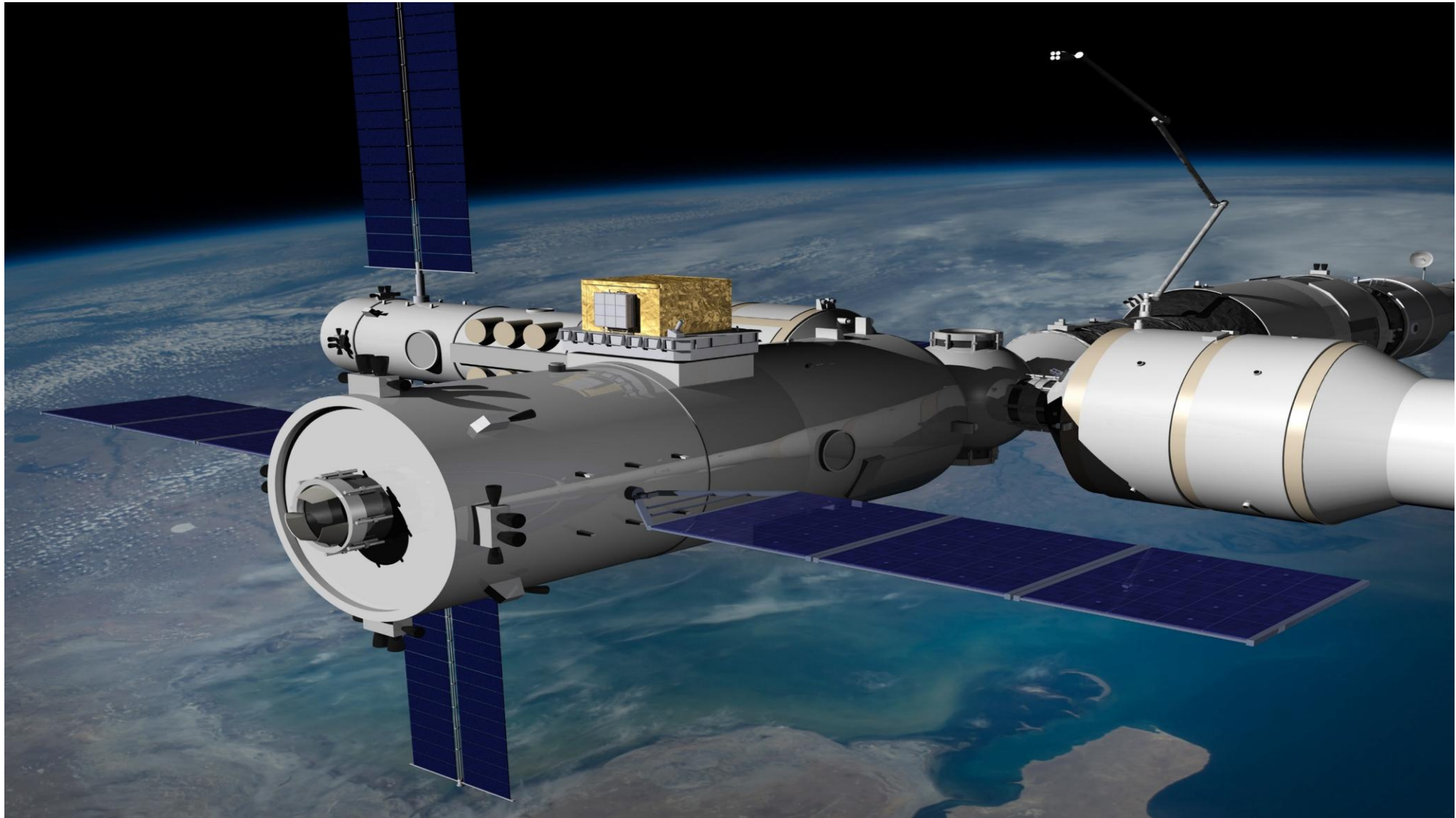
swift J1727 能谱响应



swift J1727 X射线偏振响应

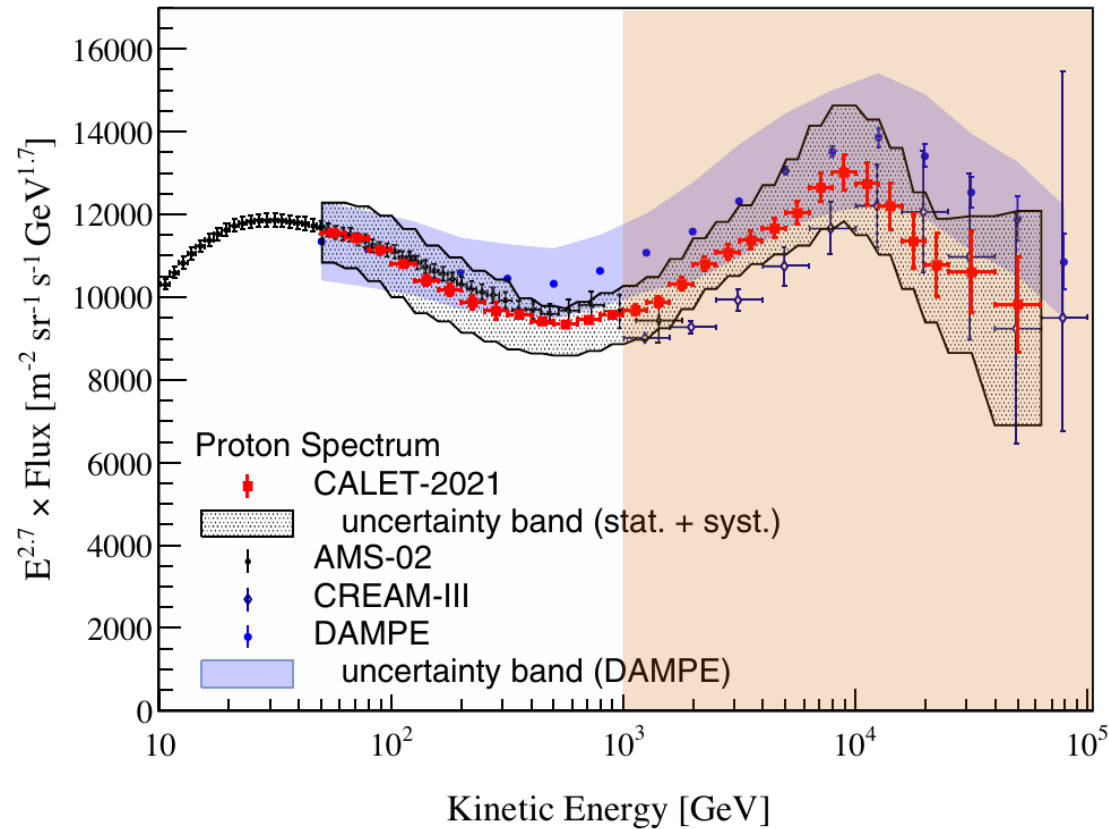


High Energy Cosmic Radiation Detection (HERD)

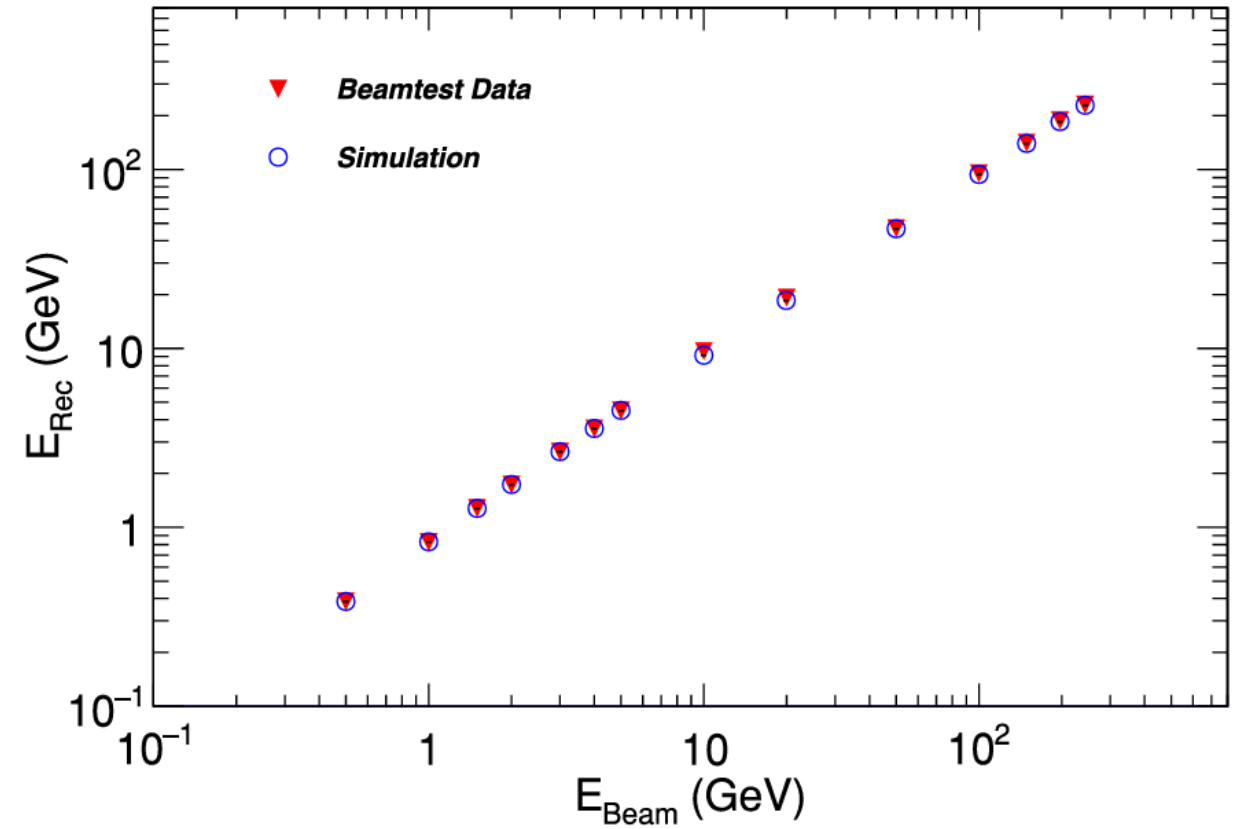


Energy Calibration for High-Energy Particles

- ❑ Current accelerator-based energy calibration techniques are limited to energies up to 400 GeV
- ❑ What alternative methods are available for energy calibration in the high-energy region (>TeV)?



[O. Adriani et al., Phys. Rev. Lett. 2022](#)



[J. Chang et al., Astropart. Phys. 2017](#)

Transition Radiation (TR) and Energy Calibration

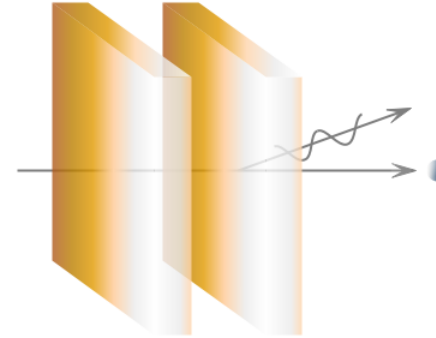
- TR is generated when extremely relativistic charged particles pass through the interface between media with different dielectric constants

$$\left(\frac{d^2W_{TR}}{d\omega d\theta}\right)_{\text{stack}} = \frac{2\alpha\theta^3 Z^2}{\pi} \left(\frac{1}{\gamma^{-2} + \theta^2 + \xi_1^2} - \frac{1}{\gamma^{-2} + \theta^2 + \xi_2^2}\right)^2 \times 4 \sin^2\left(\frac{l_1}{z_1}\right) \times \frac{\sin^2[N(l_1/z_1 + l_2/z_2)]}{\sin^2[l_1/z_1 + l_2/z_2]}$$

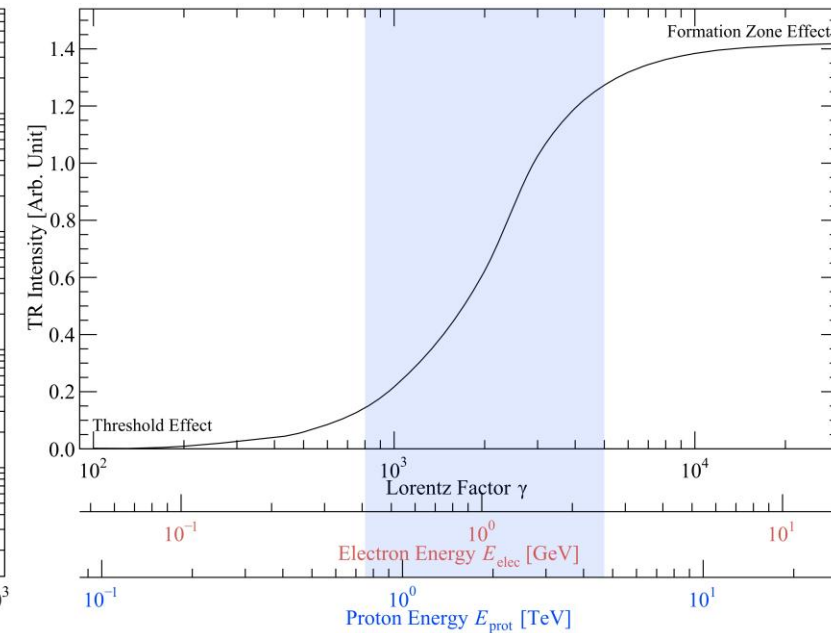
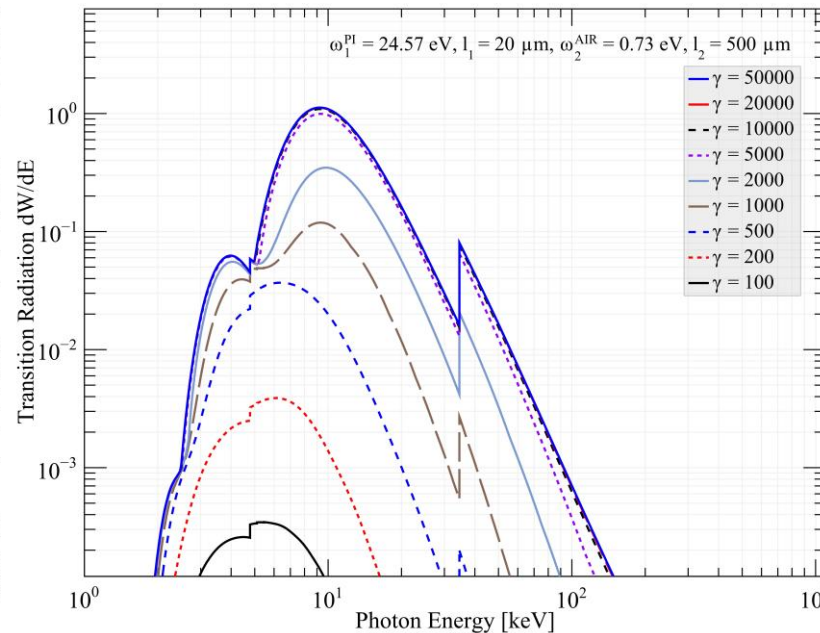
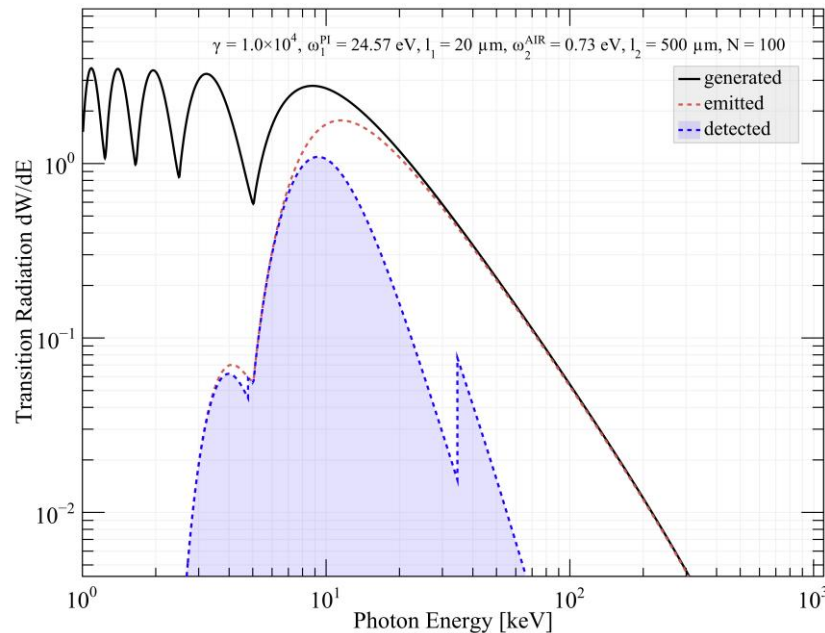
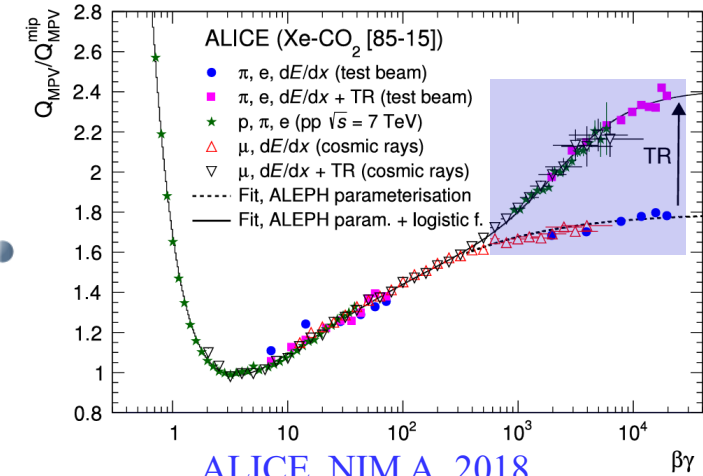
- The TR intensity is proportional to γ :

$$W_{TR} = \frac{\alpha Z^2 (\omega_1 - \omega_2)^2}{3 (\omega_1 + \omega_2)} \gamma$$

- Different particles exhibit the same TR intensity



TR generation

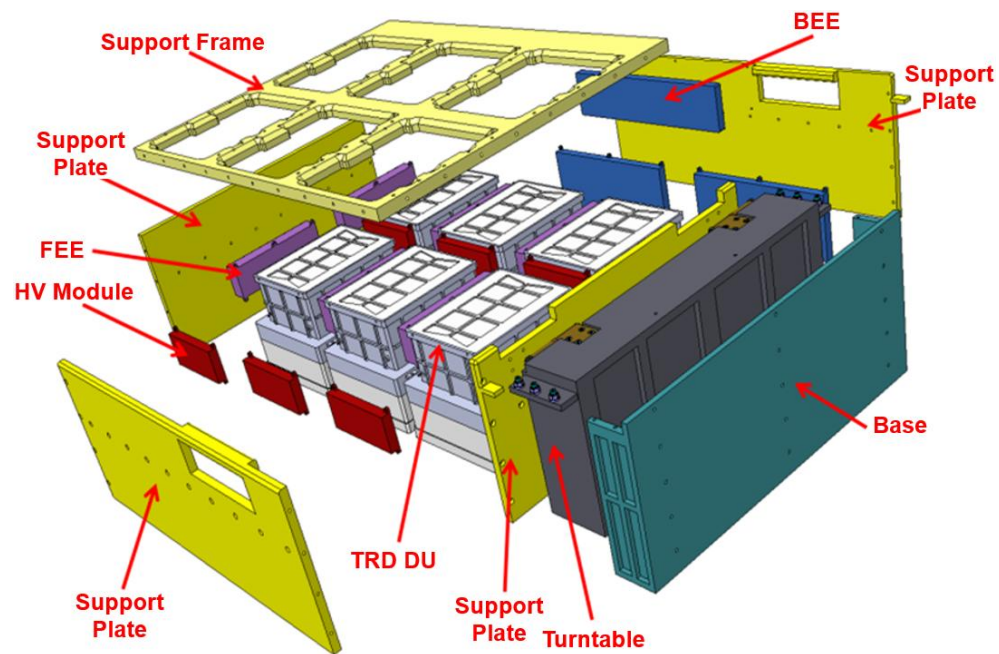




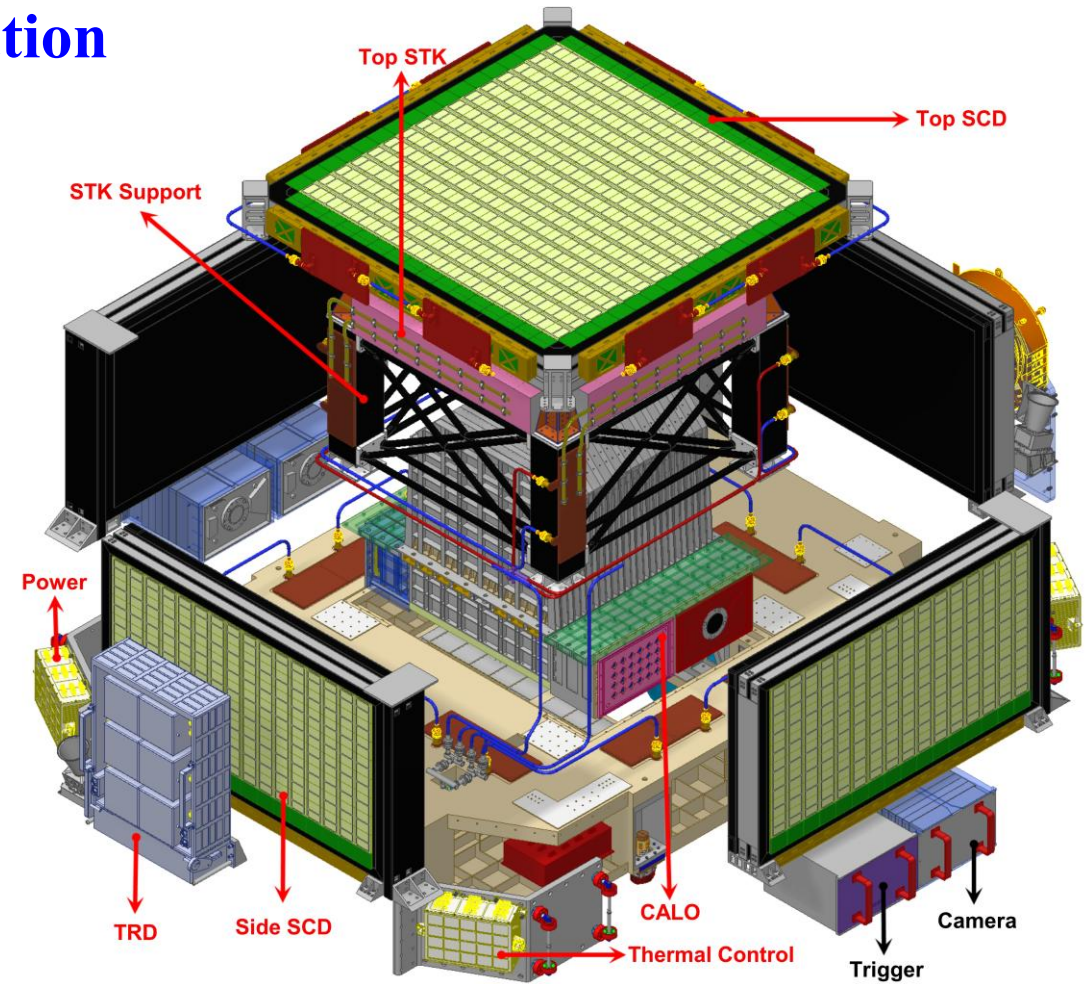
Overview of HERD/TRD Structure

❑ The TRD provides in-orbit TeV energy calibration

- ❑ The statistical TR response measured by TRD
- ❑ Calibrated energy above 1TeV
- ❑ Expected performance: better than 10% @ 2 TeV



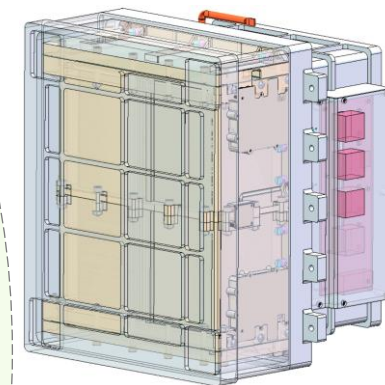
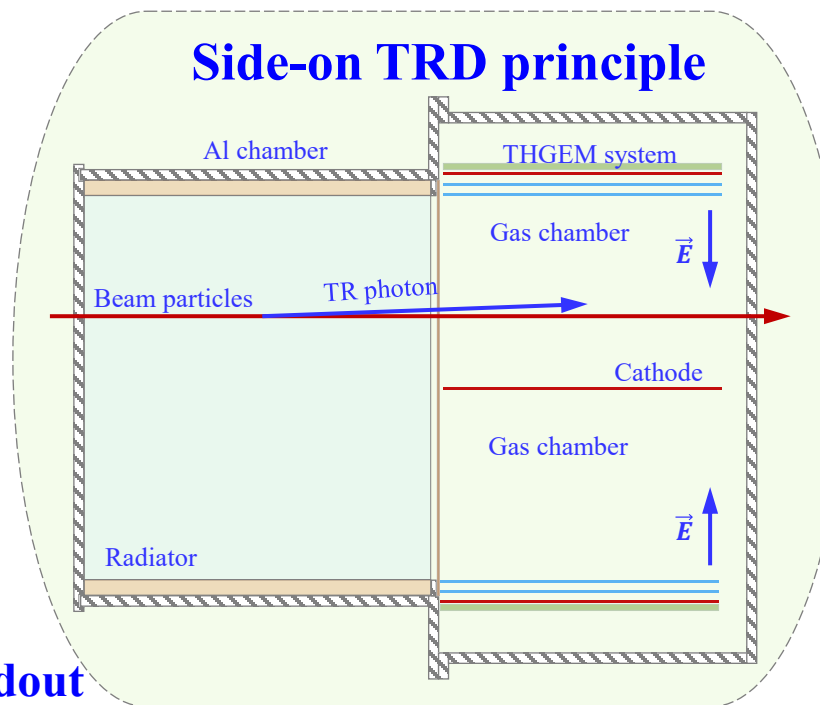
Schematic of HERD/TRD



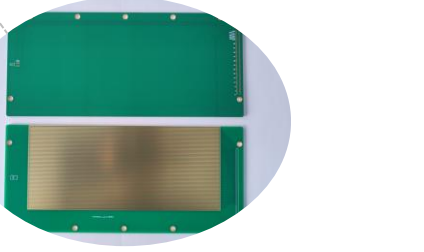
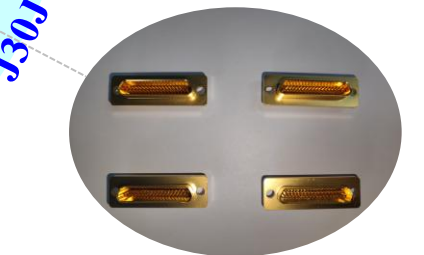
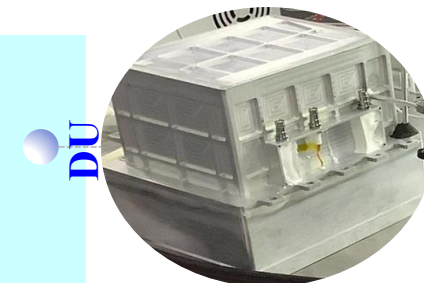
Schematic of HERD Payload

Side-on TRD detector unit

- ❑ Radiator: TR-photon generation
- ❑ Membrane: separated gas
- ❑ Frame: installation and fixation
- ❑ Cage: drift region electric field
- ❑ Cathode: negative high voltage
- ❑ THGEM: electron multiplication
- ❑ Anode: electron collection
- ❑ J30J: signal extraction
- ❑ HV Module: provides high voltage
- ❑ Electronics (FEE + BEE): data readout



detector unit



Radiator

Membrane

Frame

Field Cage

Cathode

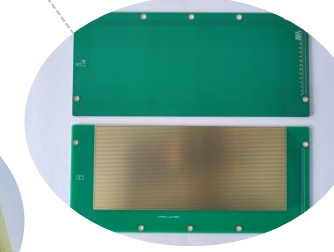
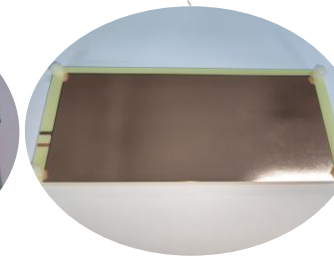
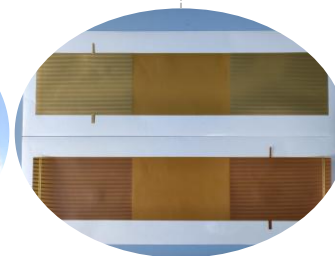
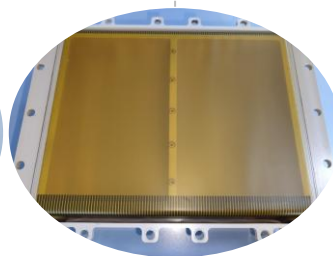
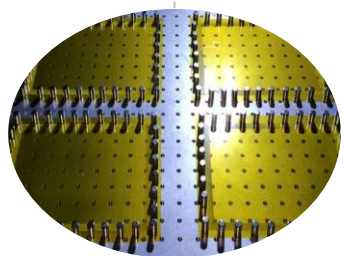
THGEM

Anode

J30J

FEE

DU



TRD Prototype Development

— 2018

BT2018@CERN

BT2019@IHEP

BT2019@DESY

BT2022@CERN

2023.02

BT2023@CERN

Proposed

Principle
Prototype

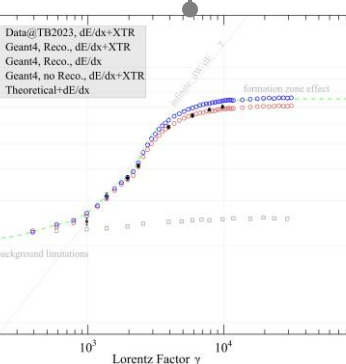
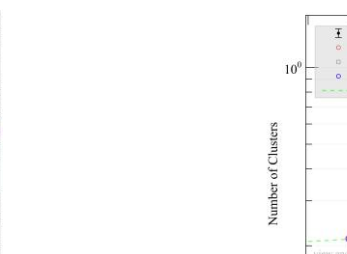
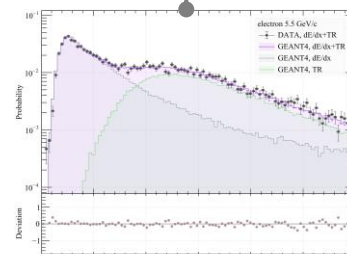
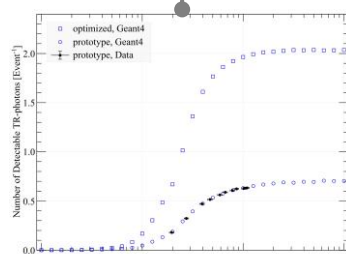
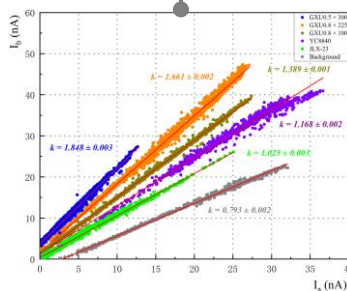
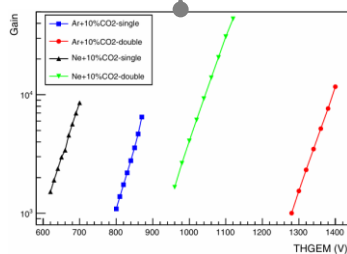
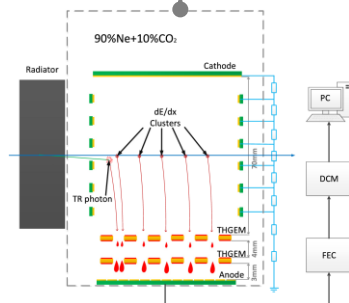
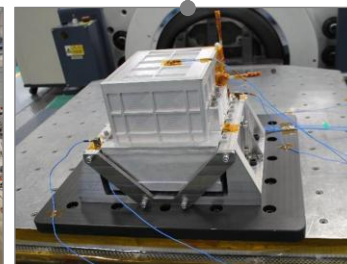
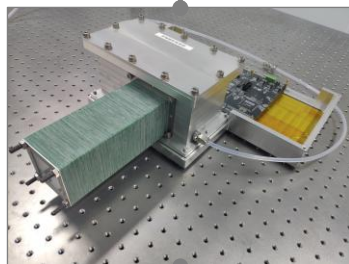
TR-photon yield

Response curve

Fully Sealed
Prototype

Mechanical
Testing

Final prototype



□ [B. Huang et al., NIM A 2020](#)

□ [X. Liu et al., RDTM 2020](#)

□ [J. Gu et al., JINST 2022](#)

□ [C. Dai et al., JINST 2023](#)

□ [C. Dai et al., ICRC 2023](#)

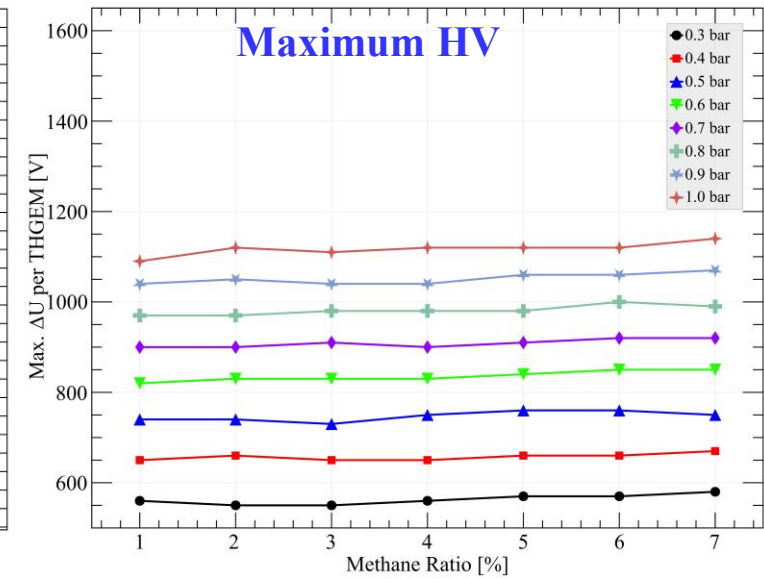
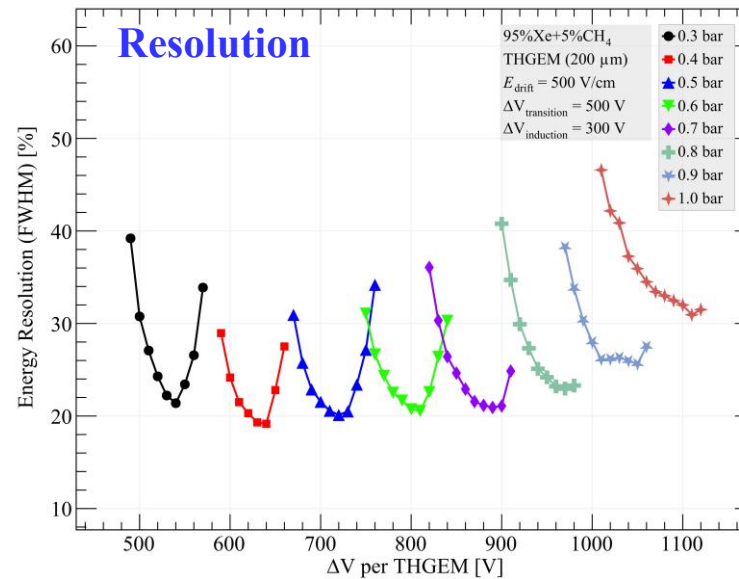
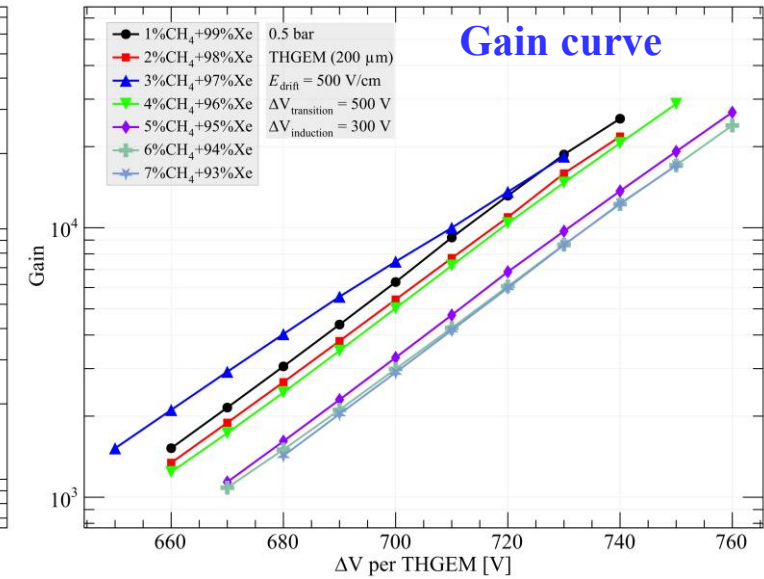
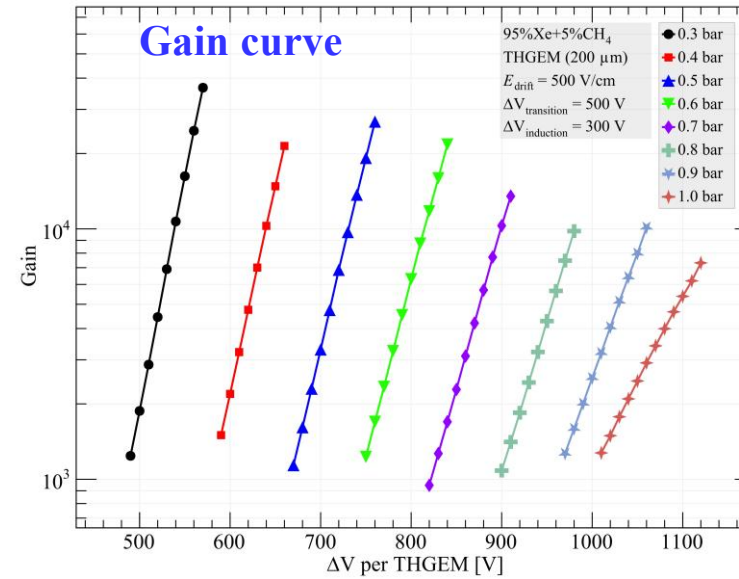
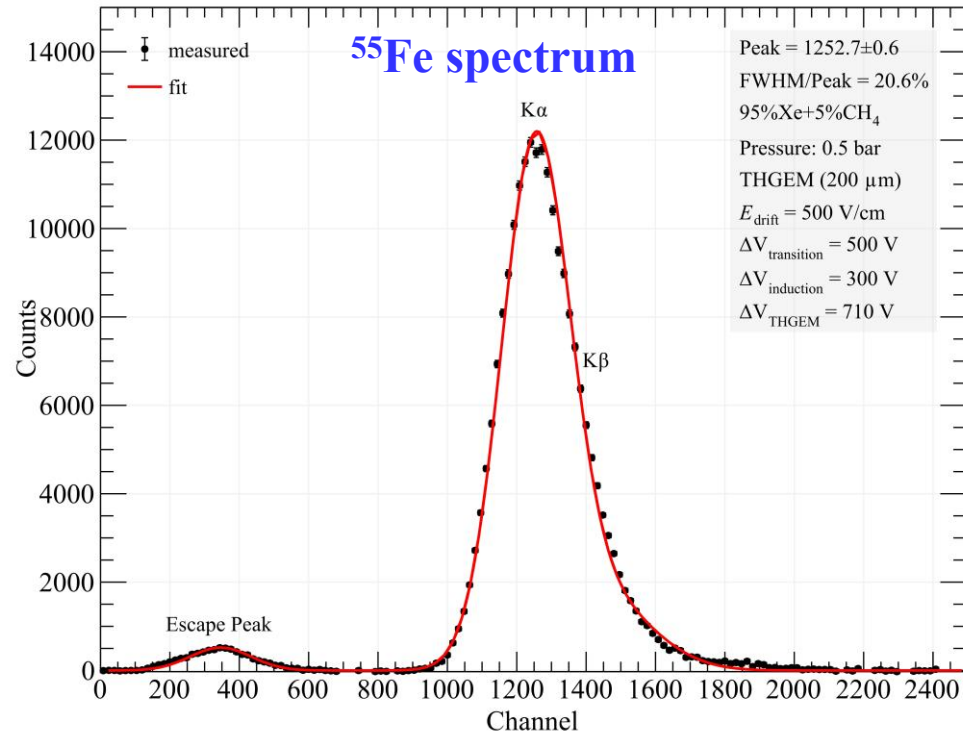
The experiment is consistent with theory and simulation.



TRD Performance (Xe/CH₄)

□ Gas gain > 10⁴

□ Energy resolution 20%

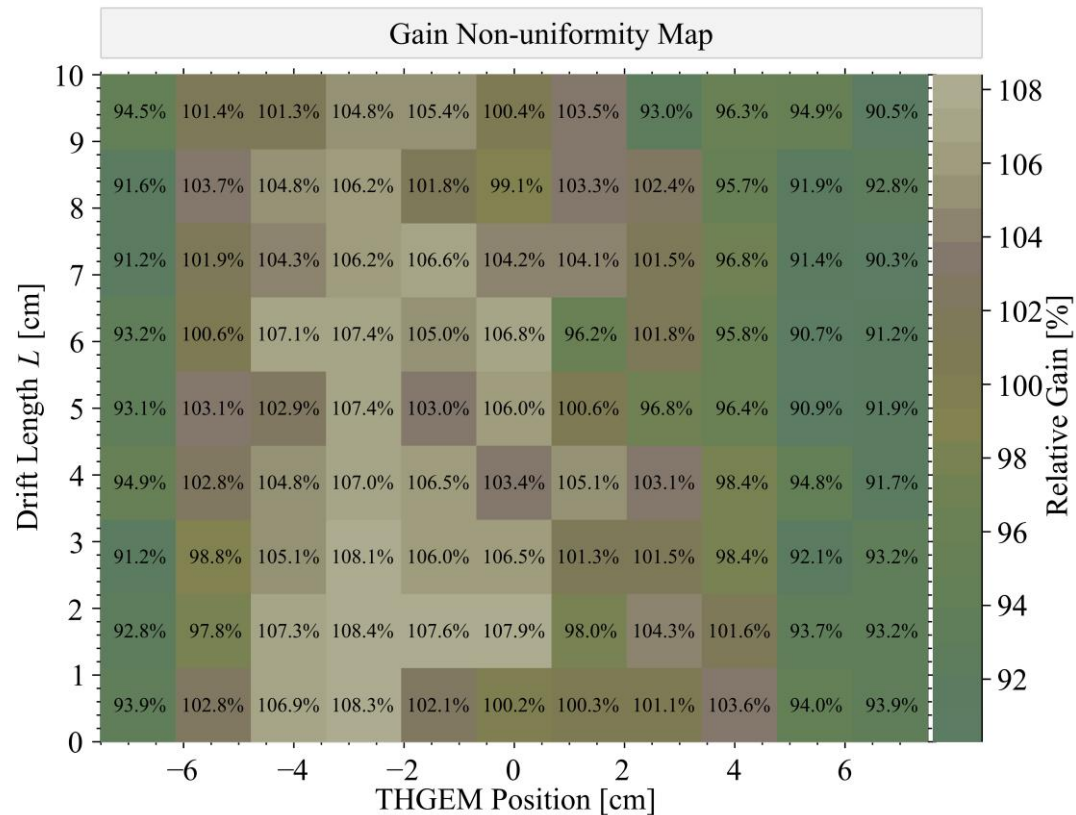




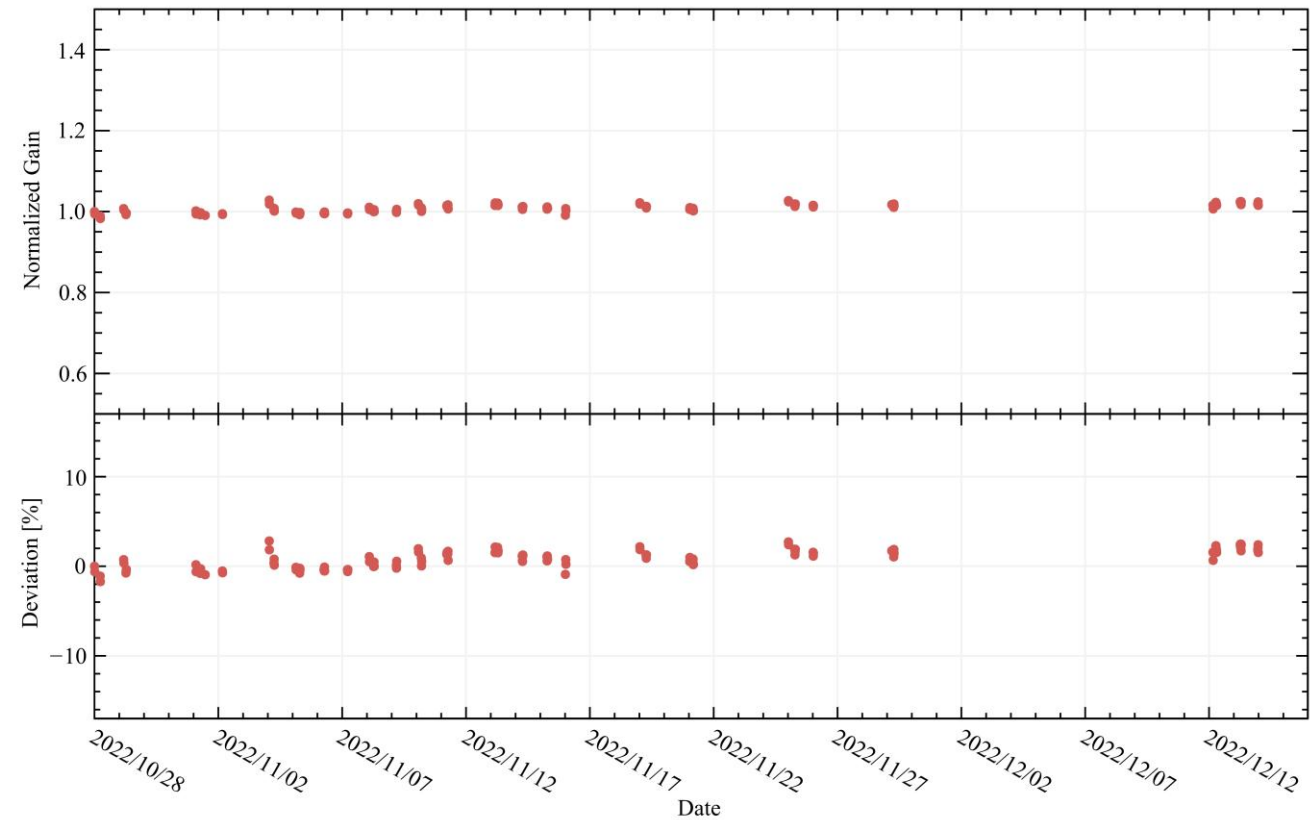
TRD Performance (non-uniformity and stability)

- ❑ Gain non-uniformity: $< 10\%$
- ❑ Gain stability: $< 4\%$

non-uniformity

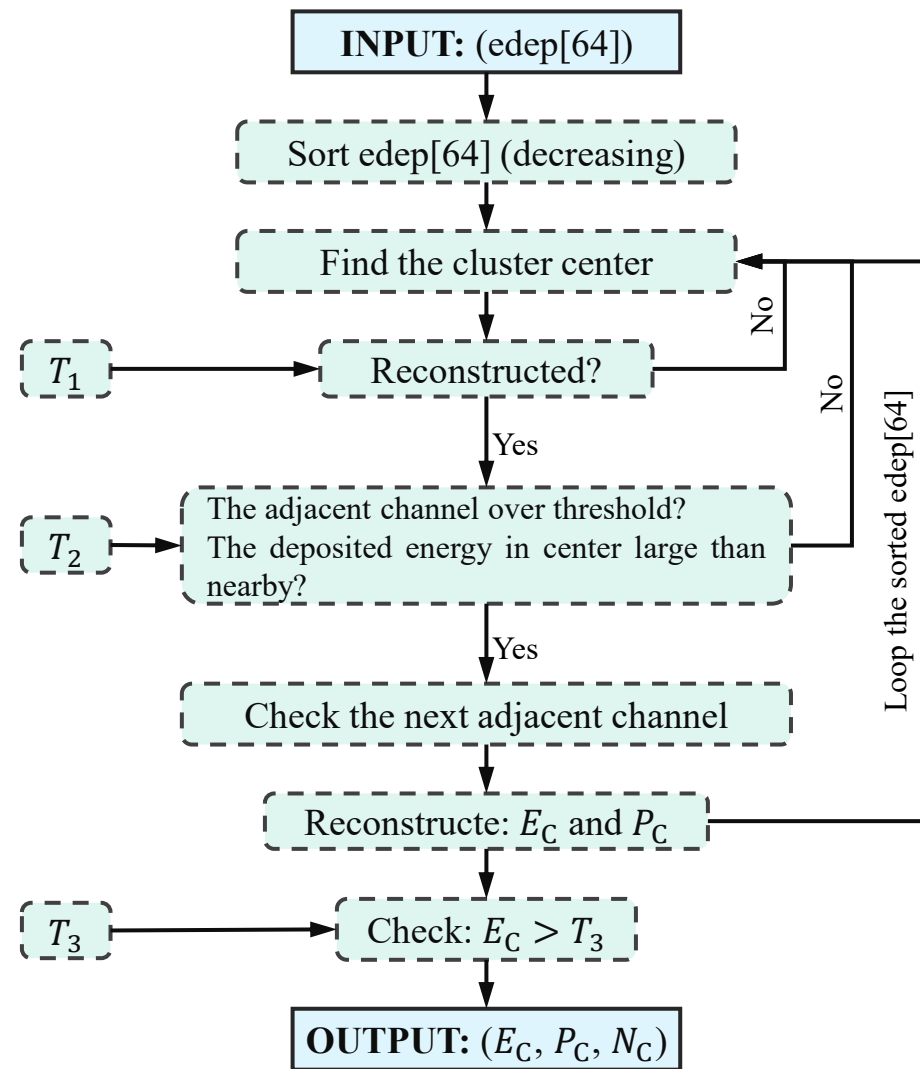
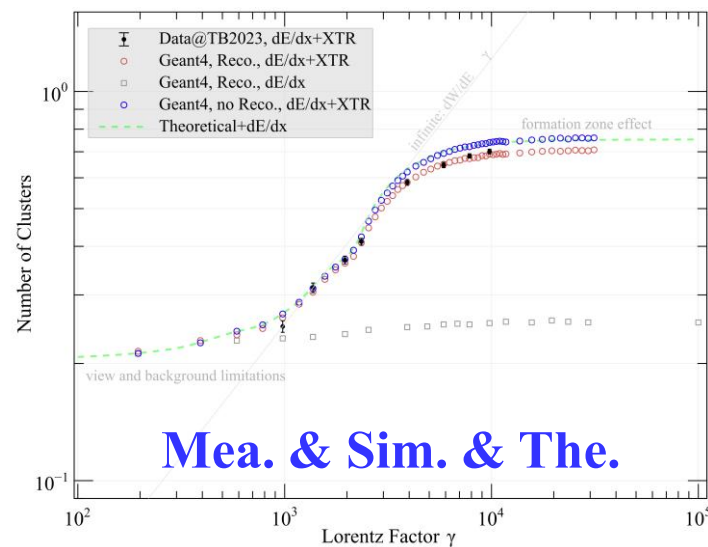
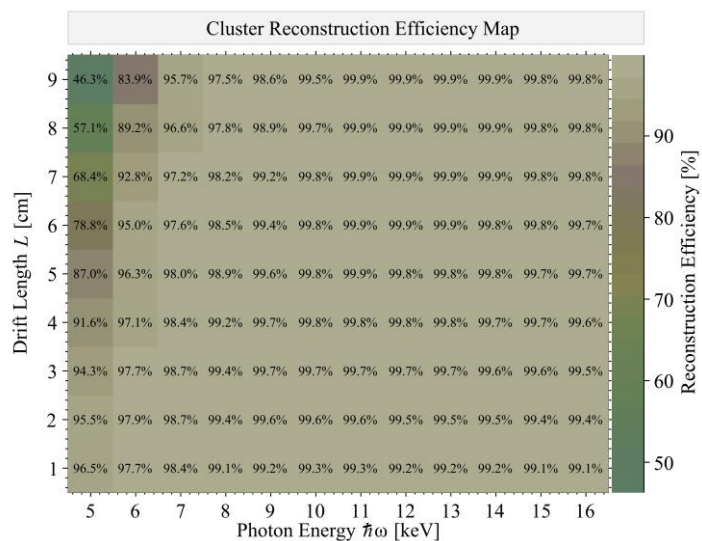
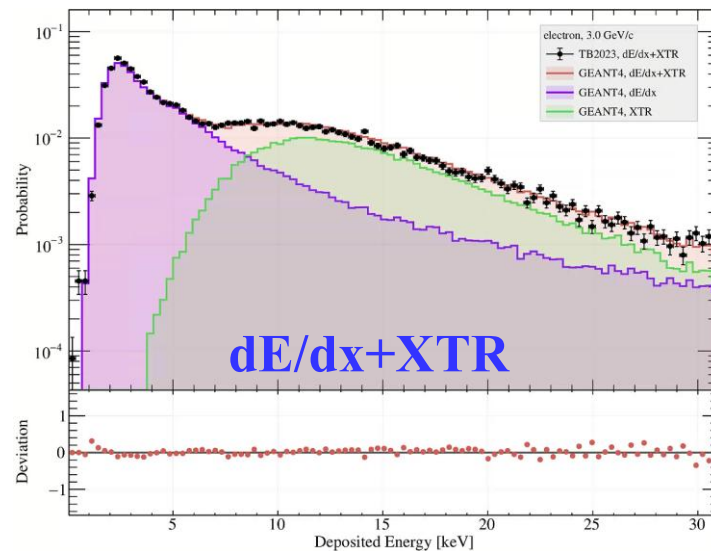
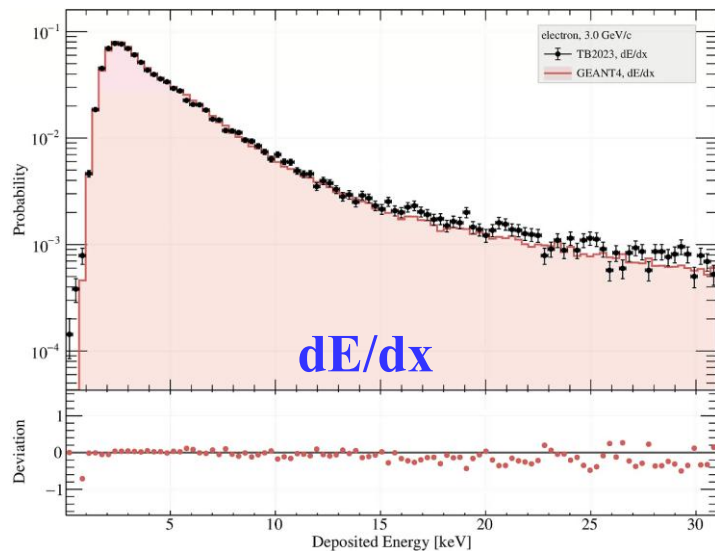


stability





Performance (2023 Beam Test and Result)



Logic Flowchart of TRD Cluster Reconstruction



TeV Energy-Calibration Precision

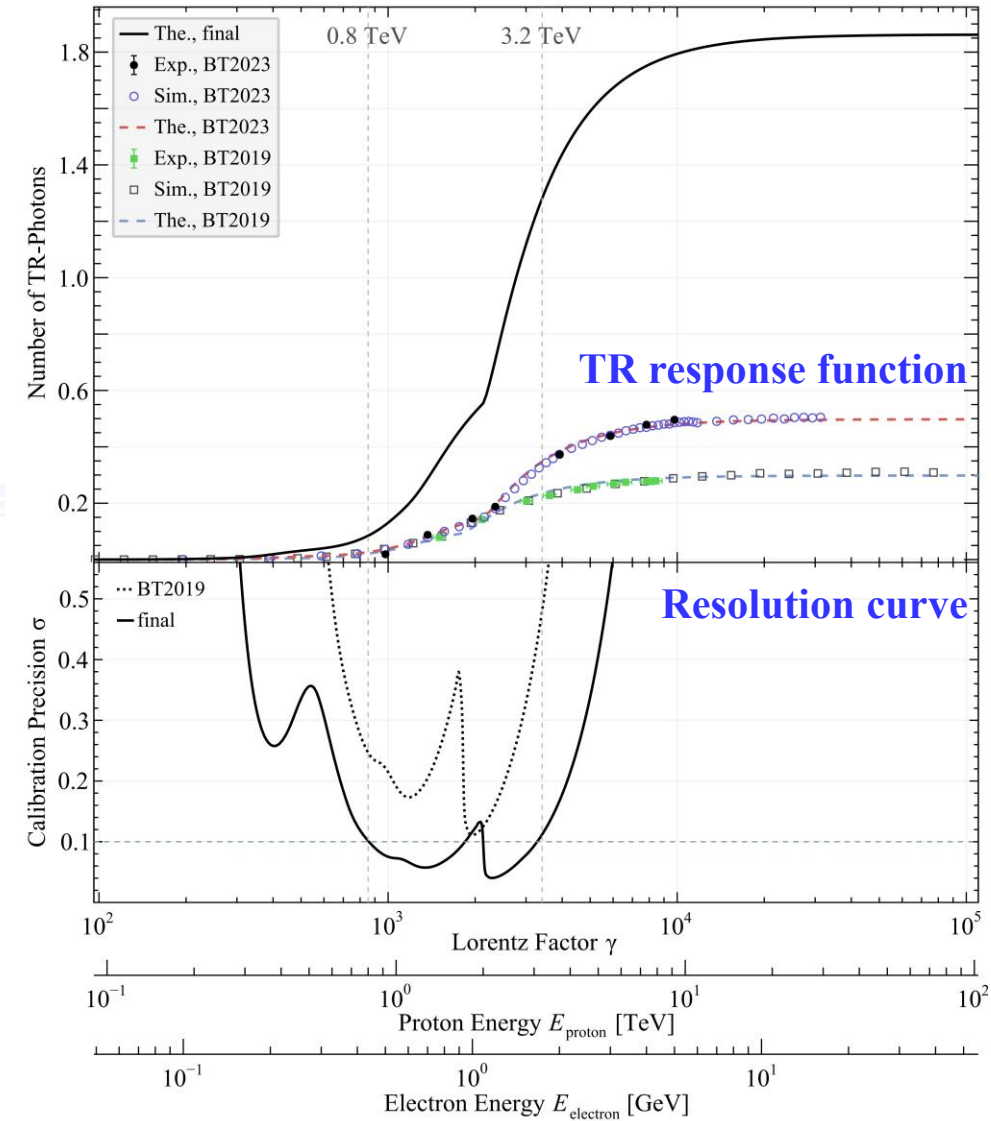
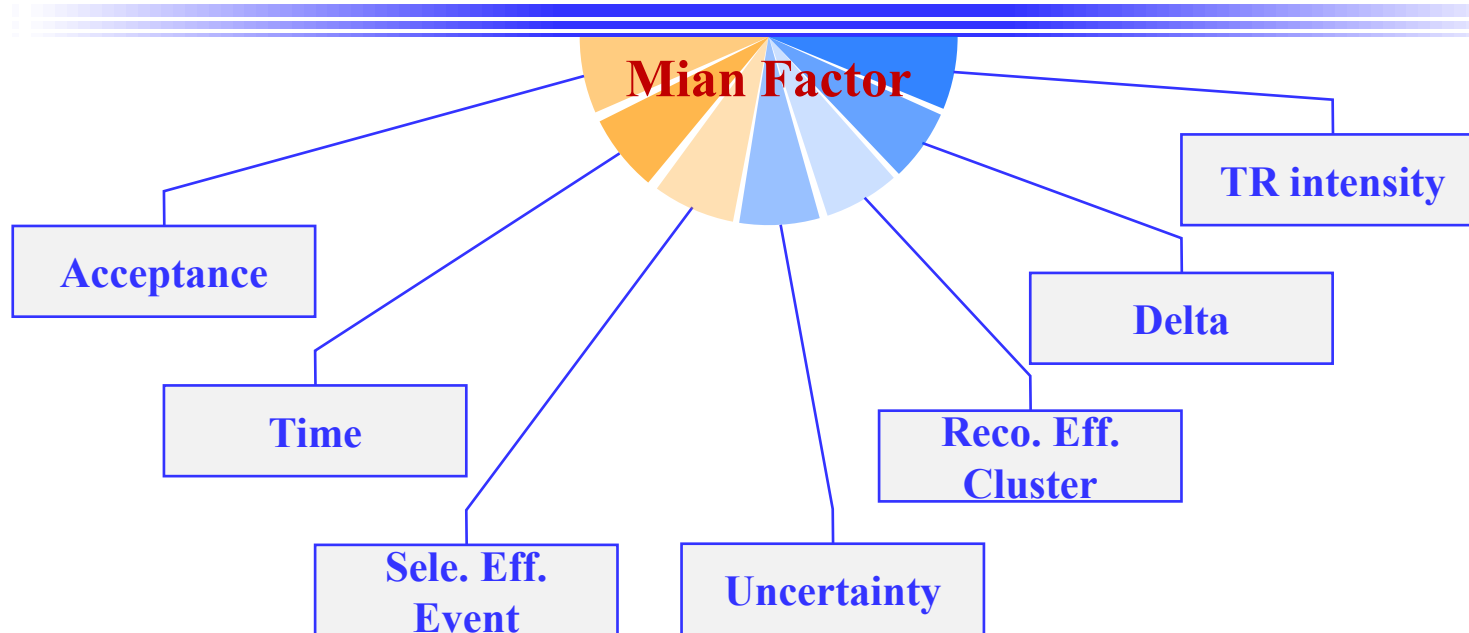
TRD energy resolution:

$$\Delta E/E = \Delta \mathcal{R}(E)/[E \mathcal{R}'(E)], \text{ (S. Wakely, Astropart. Phys. 2002)}$$

TRD resolution depend on the TR intensity

Energy range: 0.8 to 3.2 TeV

Precision: 10% @ 3 months



Thanks!