



*Institute of High Energy Physics
Chinese Academy of Sciences*



X-Ray Detector Development and Future Plans for the High Energy Photon Source

Wei Wei

**Institute of High Energy Physics, CAS
High Energy Photon Source (HEPS)**

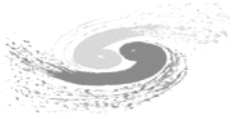
On behalf of the Detector R&D Team of HEPS

2026-10-14



- **Detector Development Progress in HEPS Phase I**
 - **X-ray Pixel Detector**
 - **Other Detectors**
 - **XBPM Diamond Detector**
 - **SDD Spectroscopic Detector**
 - **APD Detector**
 - **Other Related Research (Silicon Microstrip Detector, LGAD Detector, etc.)**
- **Future Detector Research Plans**
- **Detector R&D Platform PAPS**

Detectors in Advanced Light Sources



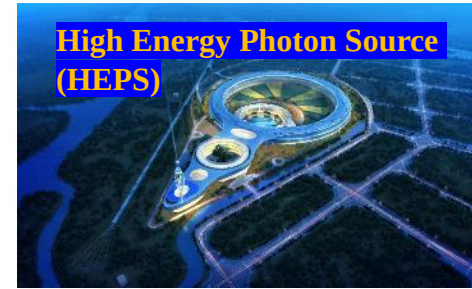
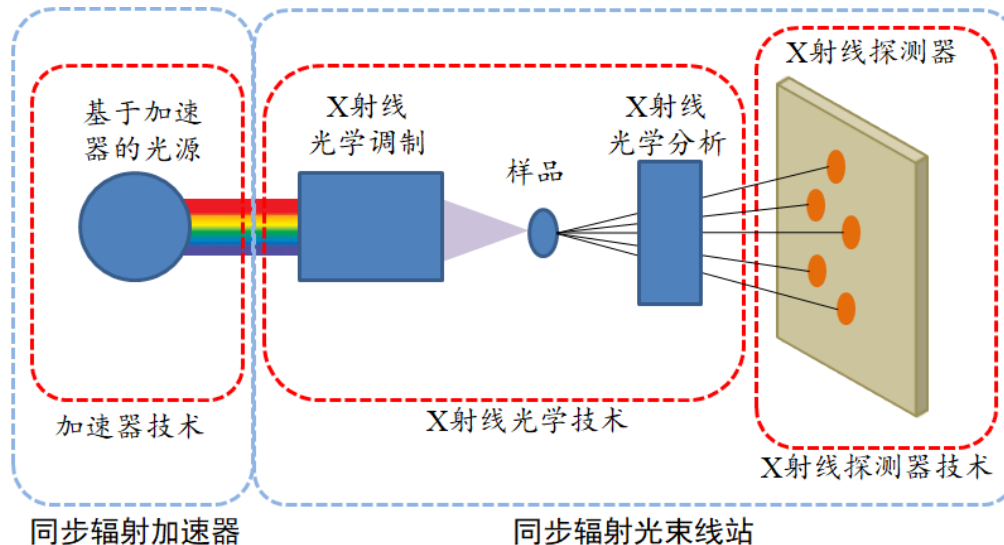
Accelerator
Light Source

Bottleneck 1
Optics
Technology

Bottleneck 2
Detection
Technology

Bottleneck 3
Data Analysis

User
Achievements



北京科创中心——怀柔科学城



上海科创中心——张江实验室



合肥综合研究中心



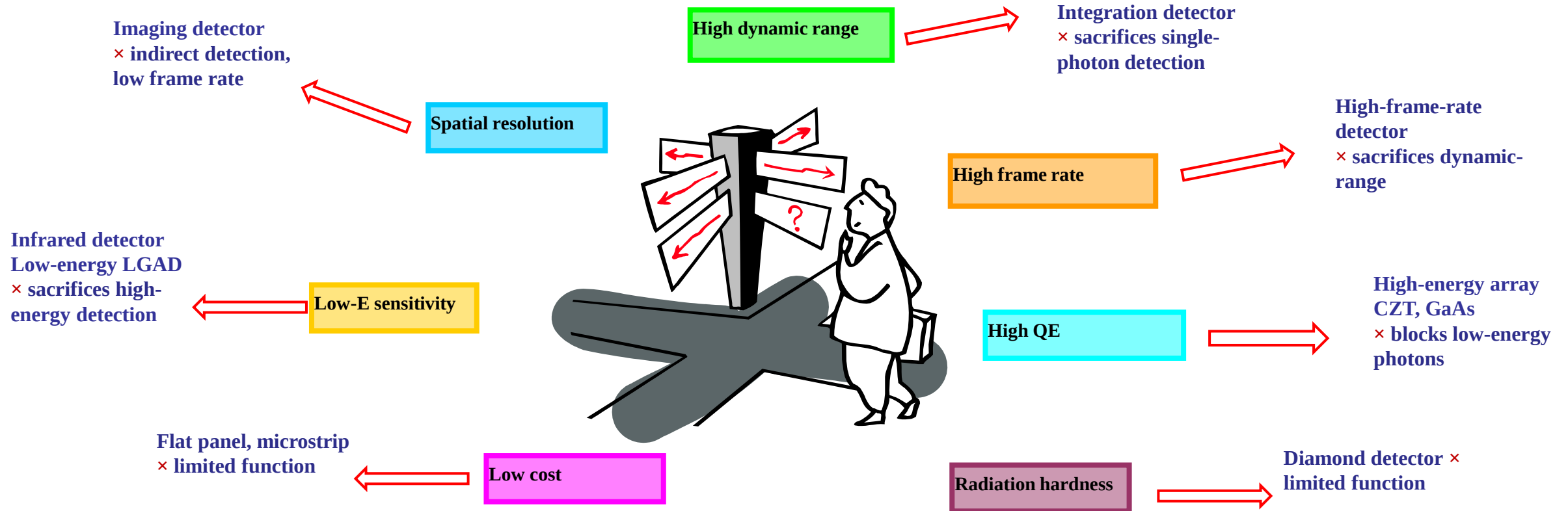
粤港澳大湾区



武汉综合性国家科学中心

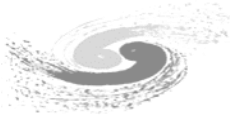
Detectors have become one of the main factors limiting the performance of light sources

Detector Customization for Light Sources

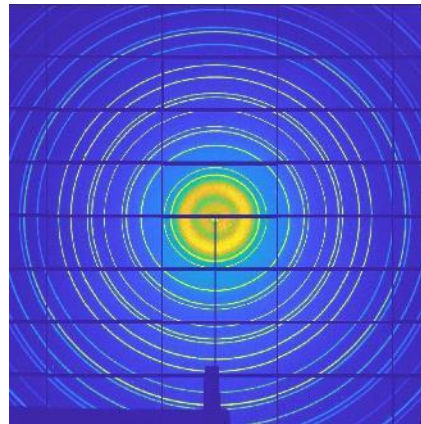


- Detector needs at light sources stem from each beamline's specific scientific goals
- A detector's performance dimensions constrain each other - no device excels in all
- General-purpose detectors cannot reach extreme demands on sensitivity, efficiency or speed
 - Optimizing one dimension usually costs others: e.g., spatial resolution vs frame rate
- **Customized detectors matched to beamline goals are intrinsic to advanced light sources**

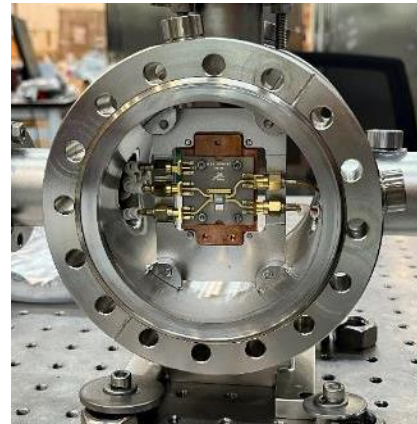
HEPS Beamlines and In-House Developed Detectors



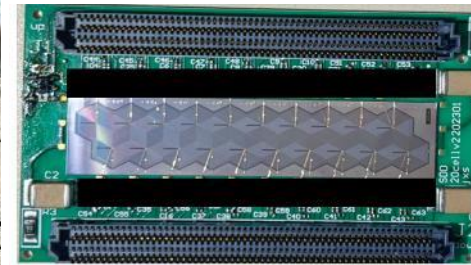
Main parameters of HEPS	
Beam energy [GeV]	6
Circumference [m]	~1360
Emittance [nm.rad]	0.06
Beam current [mA]	200
Cell units	48
Injection	Top-up
Brightness [phs/s/mm ² /mrad ² / 0.1%BW]	>10 ²²



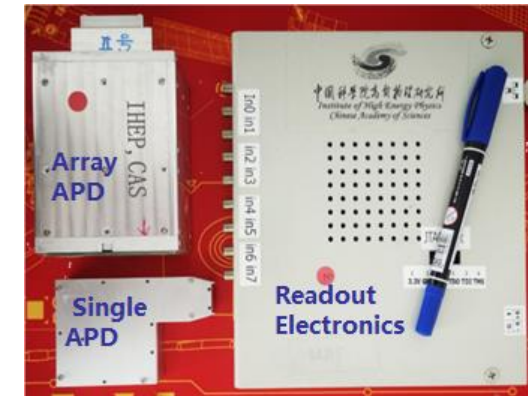
Silicon Pixel Detector



Diamond Detector XBPM



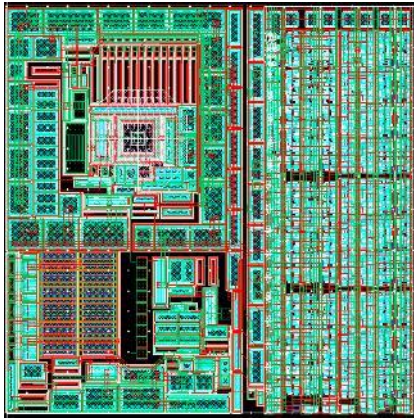
Silicon Drift Detector (SDD)
Spectroscopic Detector



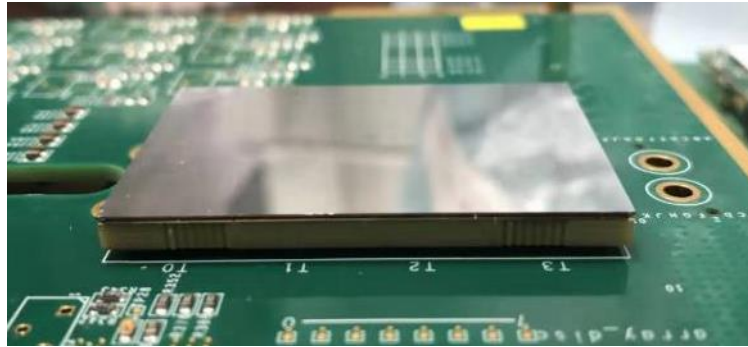
APD Detector

- HEPS beamlines passed performance and process acceptance testing in Oct. 2025
- **Four in-house detectors — pixel, diamond, SDD and APD — are deployed at the beamlines**

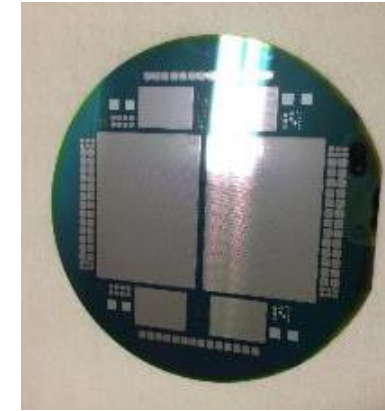
Development of Silicon Pixel Detector for HEPS — Key Technologies



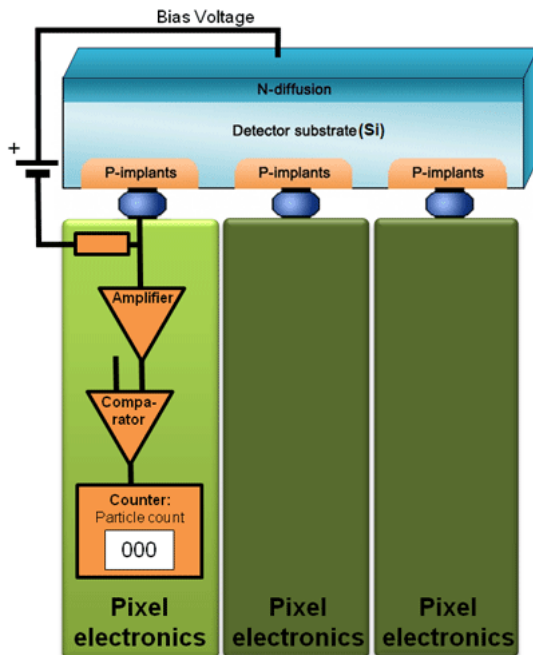
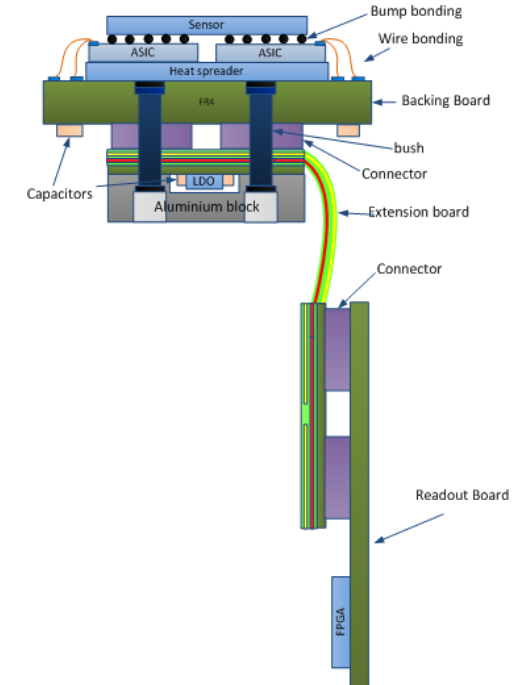
Pixel Readout Chip (ASIC)



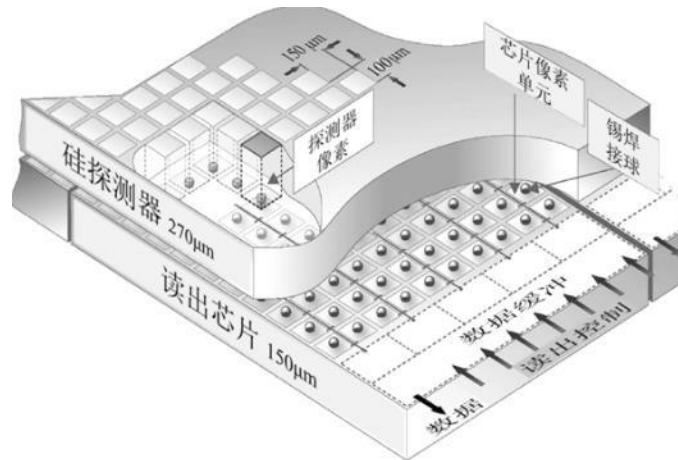
Front-end module
sensor + ASIC + flip-chip bonding



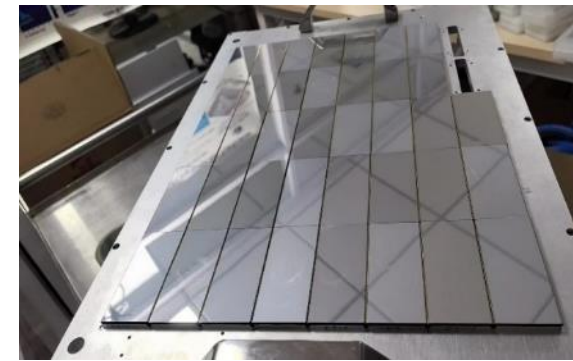
Sensor Array



Single-Photon Counting

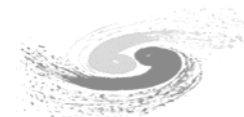


Hybrid Pixel Detector



System Integration

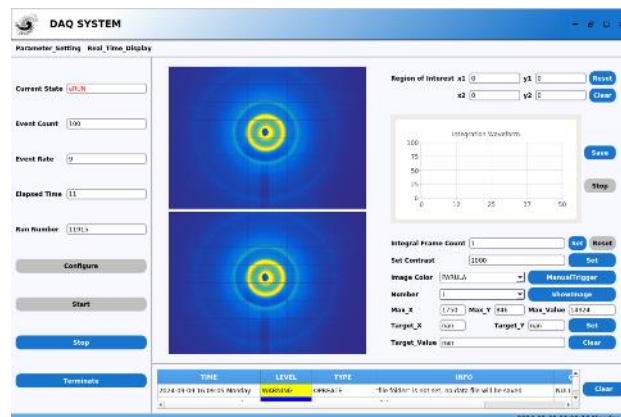
HEPS-BPIX 6M System



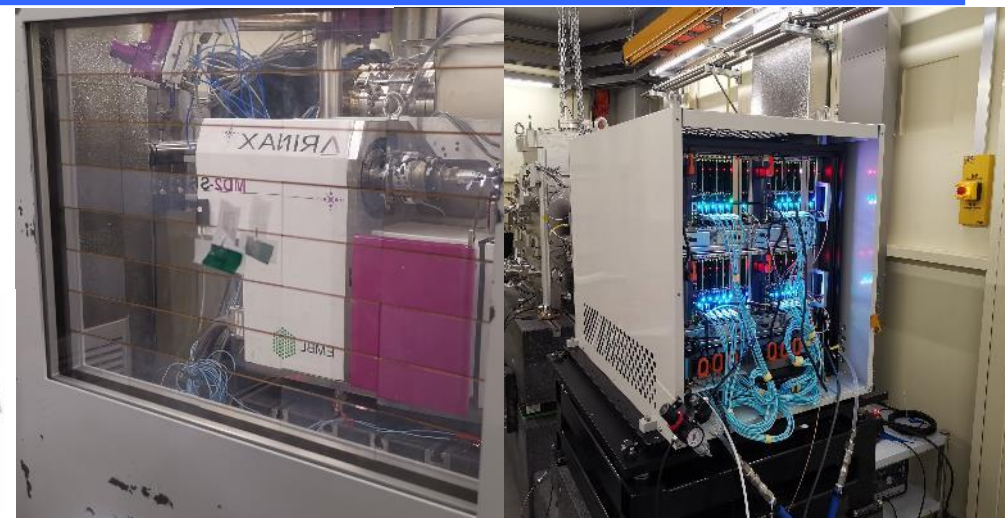
Specs	BPIX-40-6M
Pixel size	140 μm X 140 μm
Sensor	Silicon 450 μm
Pixels per module	256 X 576
Modules per system	5 X 8
Total pixels	5.898M
Number of thresholds	2
Gain settings	2 bits tunable
Count rate	> 1 Mcps/pixel
Frame rate	100 Hz (1 kHz)
Counter depth	14 bit
Image depth	16 bit / 32 bit
Module dead area	2.7 mm by WB
Defective pixel rate	< 0.5%



Detector module and readout electronics

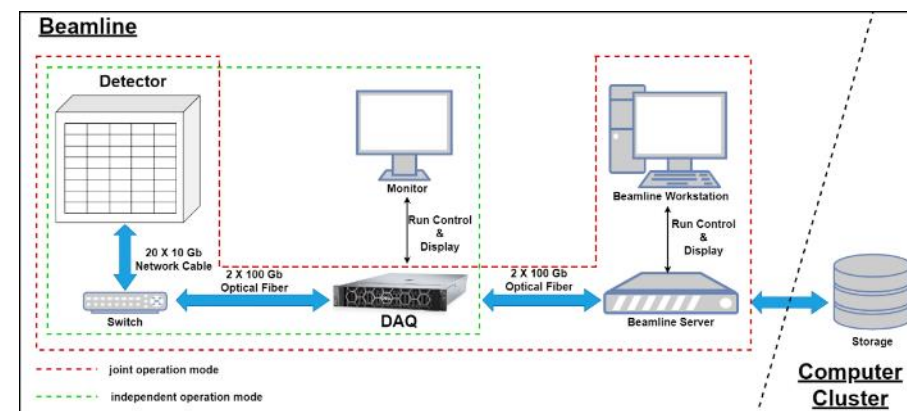


User interface



Detector front panel

System and readout

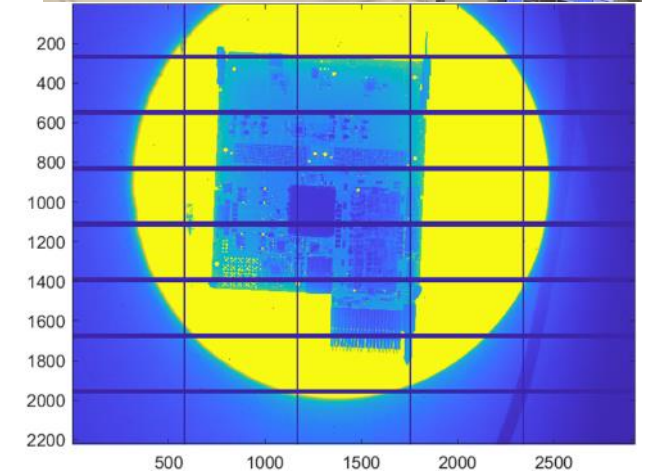
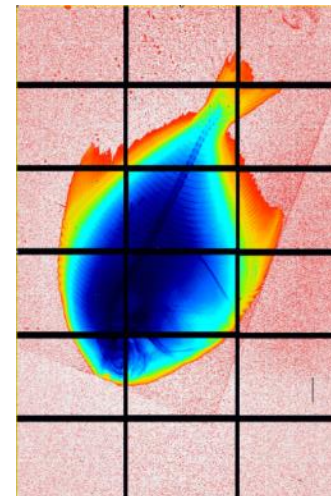
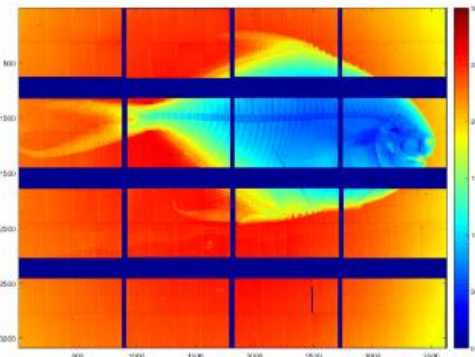
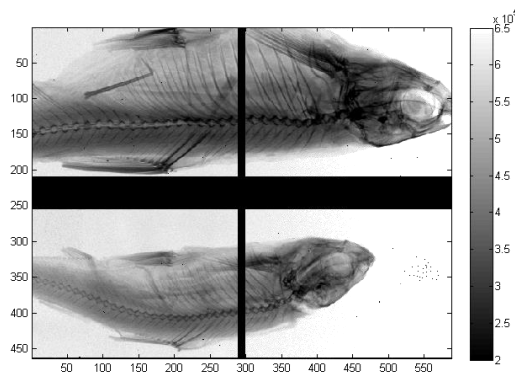
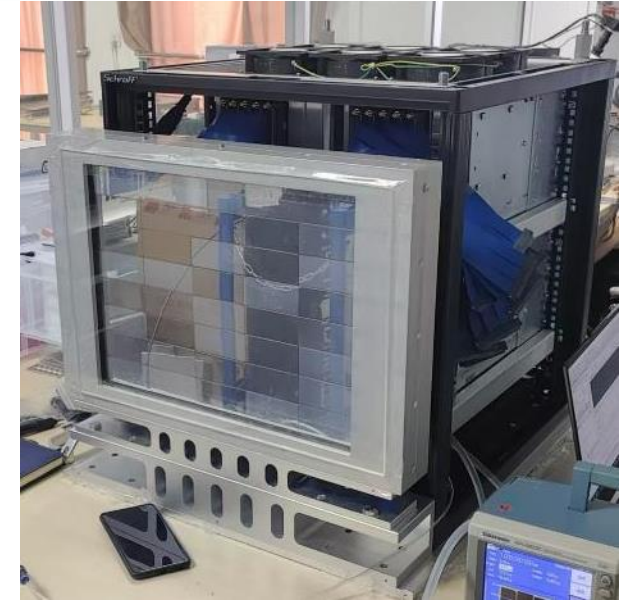


Beamline system

- Fully in-house design: ASIC, sensor, packaging, electronics, mechanics, DAQ, software

From Proof-of-Principle Prototype to Beamline Equipment

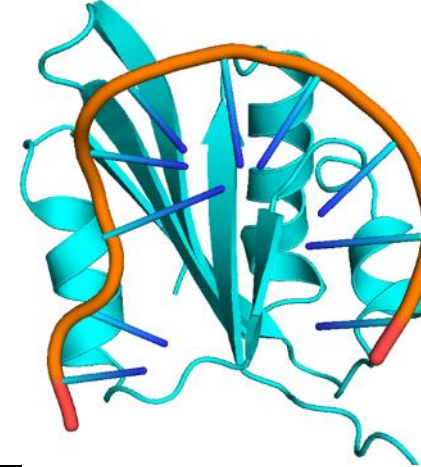
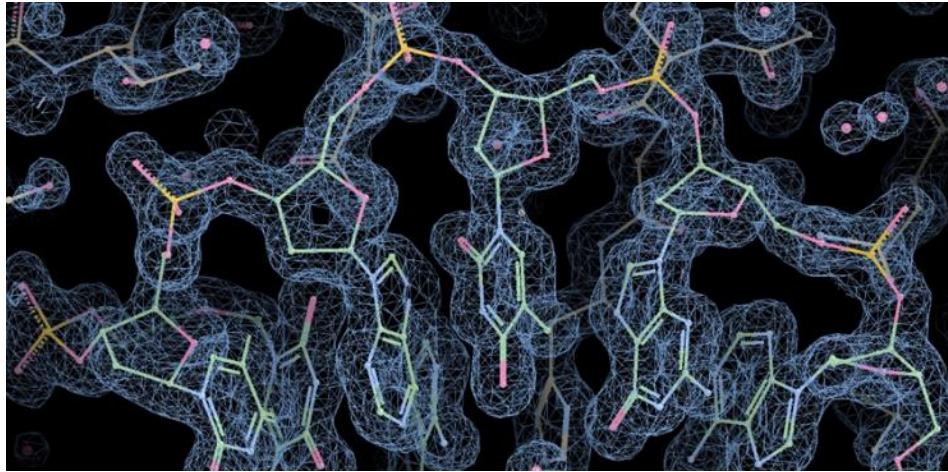
	1st BPIX (2015-2016)	2nd BPIX (2017-2018)	3rd BPIX (2019-2021)	4th BPIX (2022-2025)
Modules	6	16	24	40
Total pixels	360K	~1M	1.4M	6M



Beamline Commissioning — User Experiments



Data1:
Protein-DNA
complex



Virus replication enzyme-DNA complex

Resolution: 1.5Å

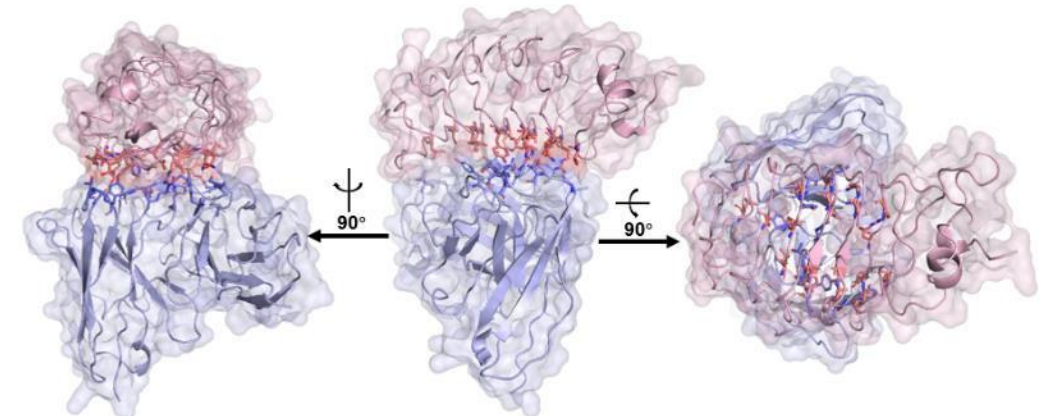
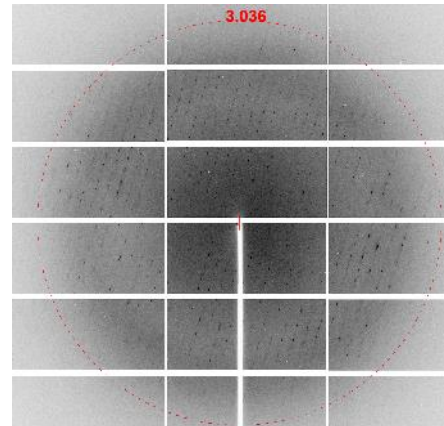
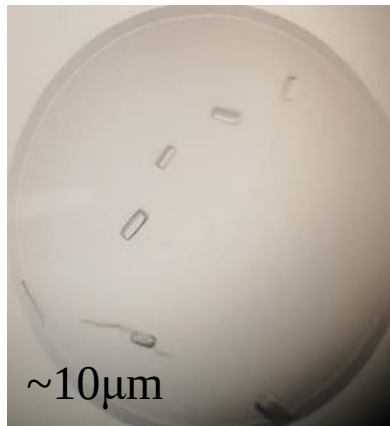
Rmerge:

Total: 9.1%;

inner/outer shell: 5.1%/68.2%

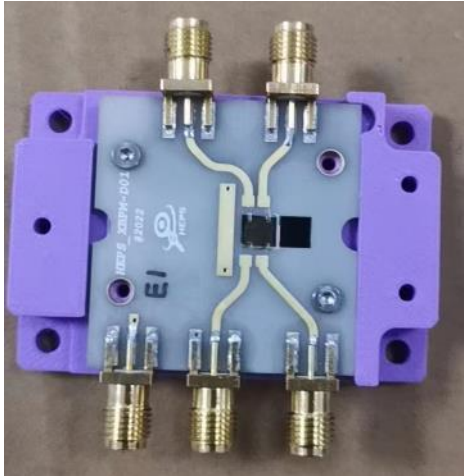
Rwork/Rfree: 19.8%/22.1%

Data2:
Protein-protein
complex

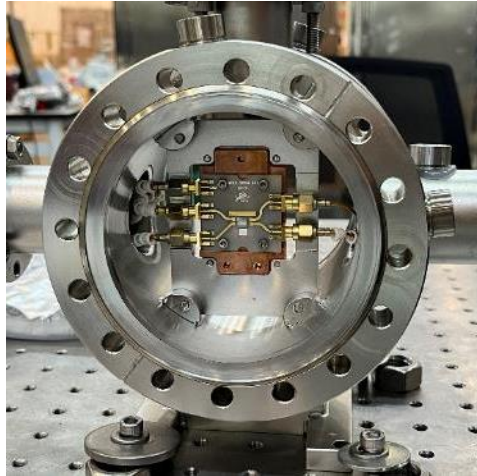


- During commissioning of the BA macromolecule beamline, 47 user proposals were submitted, 40 approved and 31 completed. Cumulative fault-free operation time > 2000 hours
- **As the main detector of the BA beamline, the BPIX detector enabled stable operation of user experiments**

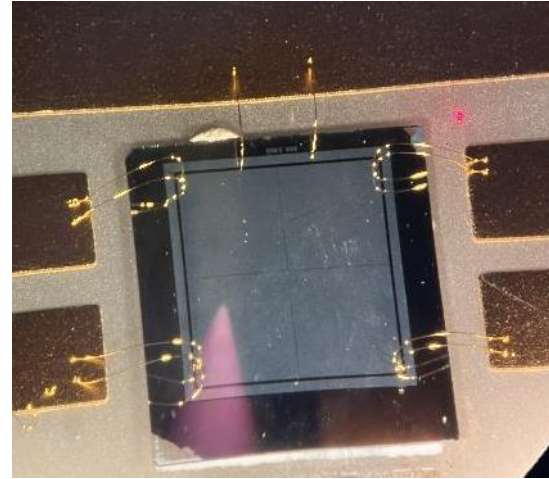
Diamond XBPM Detector



XBPM Detector

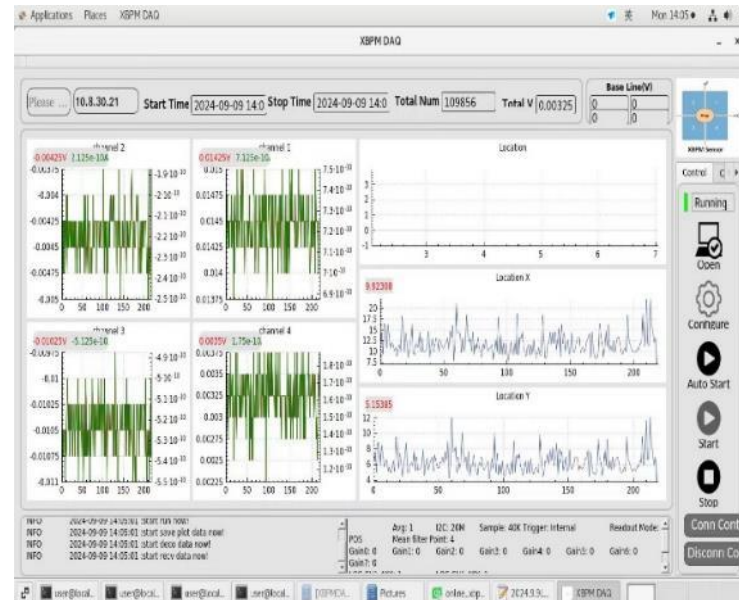


Beamline installation



Diamond Detector:

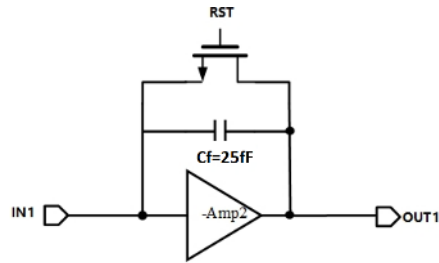
- ❑ 4-quadrant structure, 4 μm pitch
- ❑ Thickness 50 μm , transmission 95% @ 10 keV
- ❑ Ceramic packaging, usable in vacuum
- ❑ Leakage current < 10 pA
- Fabrication and testing of all XBPMs completed;
- **XBPM performance meets engineering requirements;**
- **All detectors installed and commissioned, about 30 sets in total;**
- Electronics and detector systems fully installed and commissioned;
- During beam commissioning, an important means of determining the beam spot position;
- During operation, real-time monitoring of the beam spot;



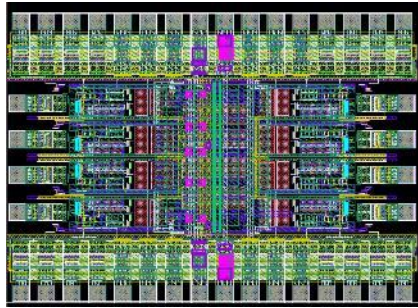
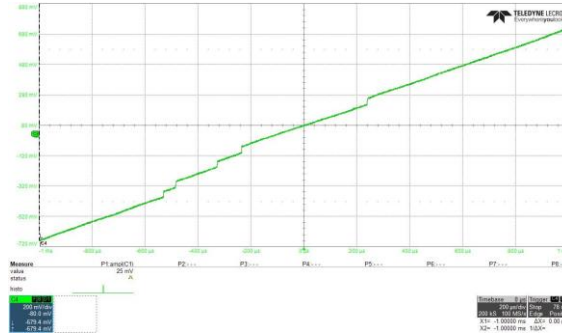
SDD Spectroscopic Detector: Readout ASIC and Detector Design



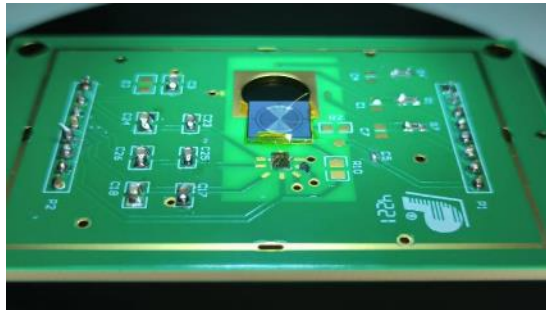
Switch-reset charge-sensitive preamplifier ASIC



Switch-reset CSA ($C_f = 25 \text{ fF}$)



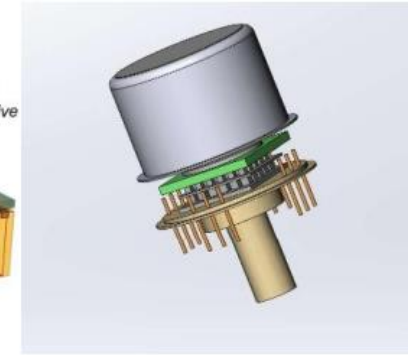
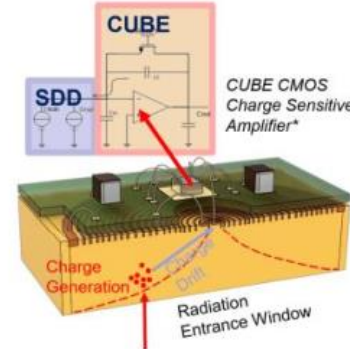
ASIC layout



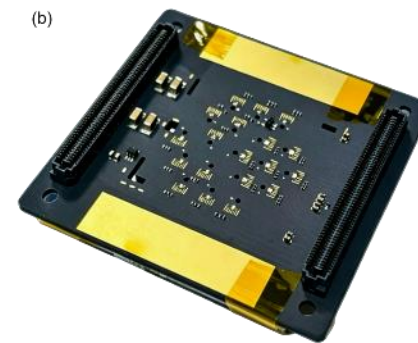
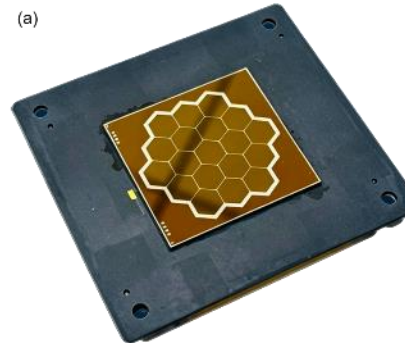
Detector + readout board

- Power: 20 mW/ch • Gain: 40 mV/fC
- ENC: $\sim 5 \text{ e}^- + 6 \text{ e}^-/\text{pF}$ @ -20° C — ultra-low noise
- Ultra-fast recovery (switch reset)
- Radiation qualified:
 - TID 20 krad
 - SEL threshold $\geq 30 \text{ MeV}\cdot\text{cm}^2/\text{mg}$ (Proton test)

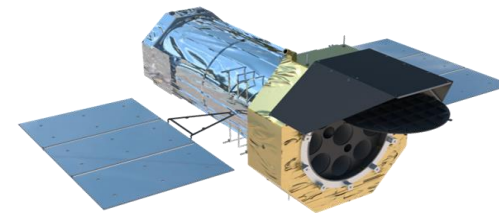
SDD detector design



Unit SDD: SDD in commercial-style package



Array SDD



19 pixel SDD for eXTP

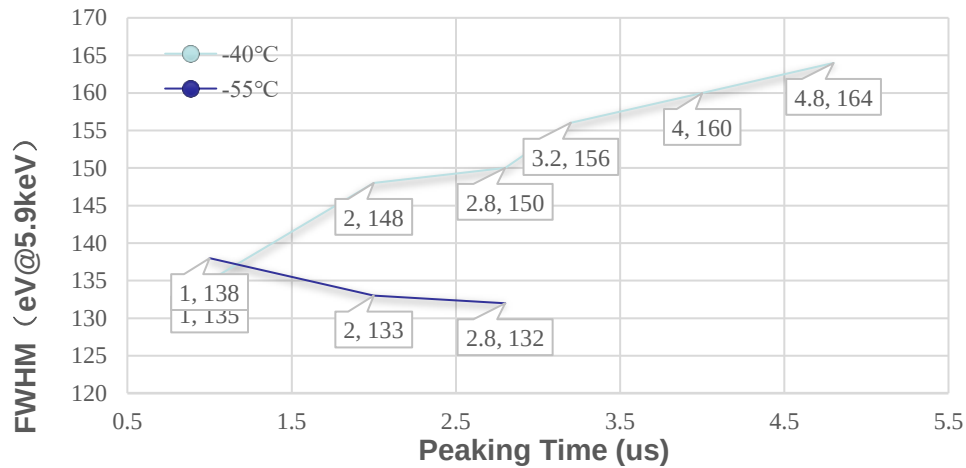
Fully analog, parallel readout — one ASIC + one ADC per channel

SDD Spectroscopic Detector: Test Results and Applications

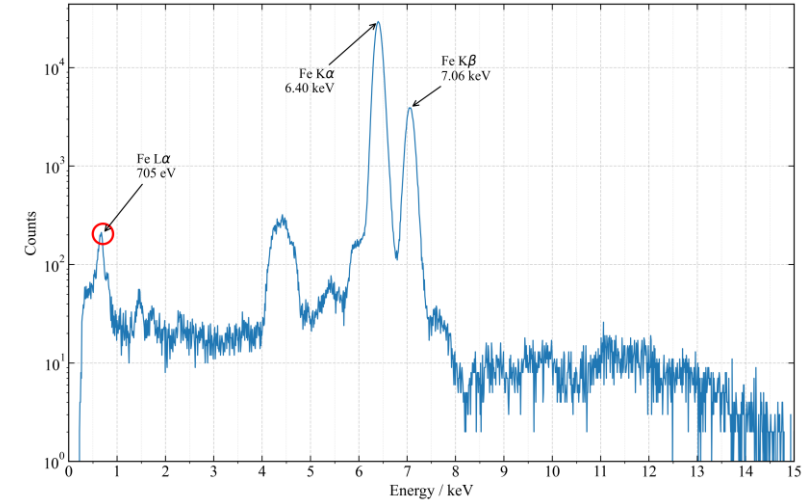
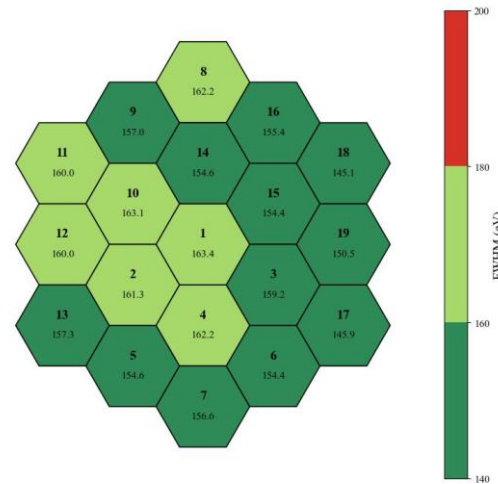


Unit SDD: 135 eV FWHM @ 5.9 keV (-45°C) • 19-pixel detector: ≤ 180 eV @ 5.9 keV (-45°C)

FWHM VS Peaking Time (30mm²)

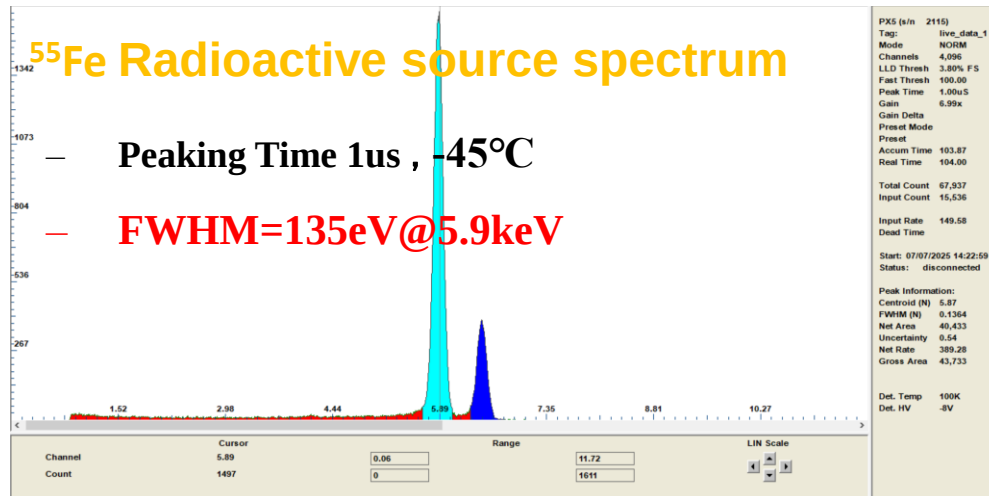


FWHM Map at 6.4keV @ -45°C



⁵⁵Fe Radioactive source spectrum

— Peaking Time 1us, -45°C
— FWHM=135eV@5.9keV



- X-rays detected down to 705 eV — good low-energy response
- Energy resolution and low-energy response meet the CXBe requirements
- Final configuration to be selected based on overall system integration

Nanosecond-resolution Detector



- Achieves nanosecond time-resolved photon measurements to meet special experimental needs;

- **No commercial product available; fully in-house design;**

Development of multiple single-element APD detectors

- Time resolution better than 500 ps
- Maximum count rate 8 Mcps
- Low noise - 6.4 keV single-photon counting capability

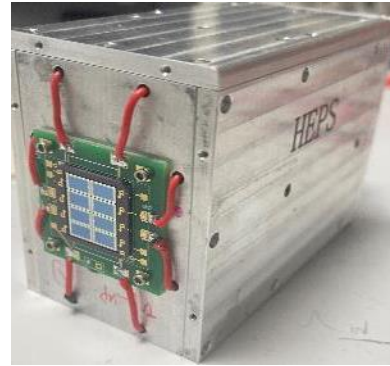
Single-element APD detector

Multi-element APD detector

Array APD detection system



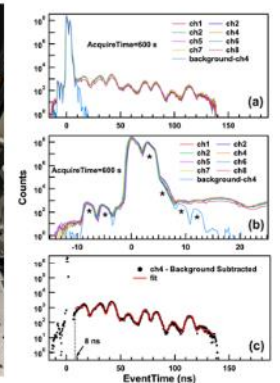
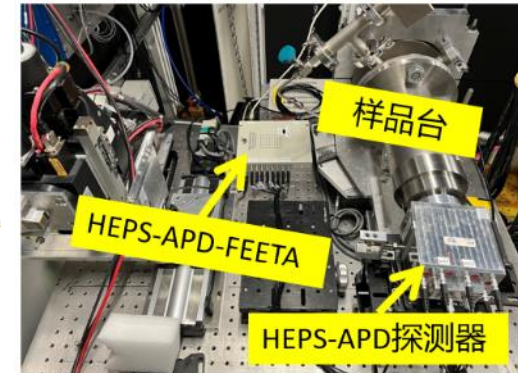
Single-element APD



Multi-element APD



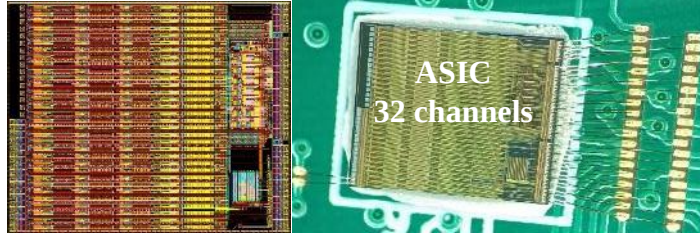
Electronics



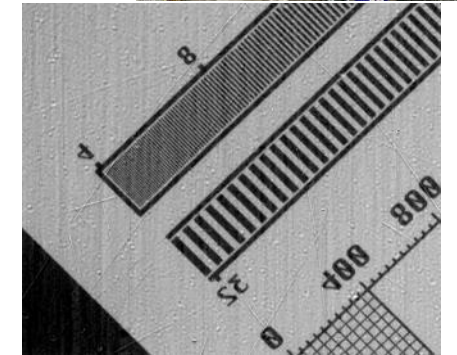
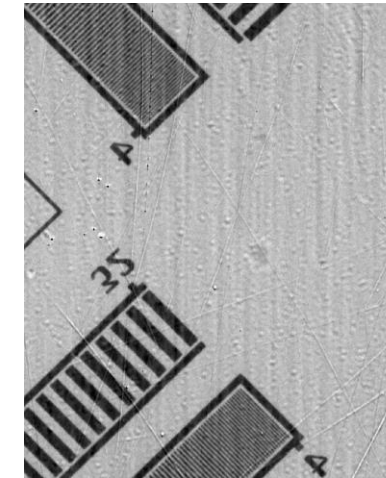
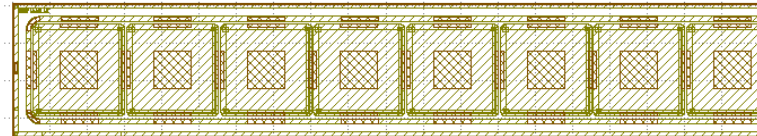
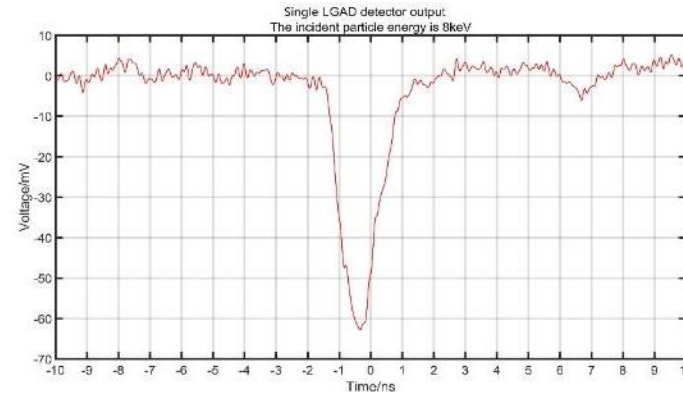
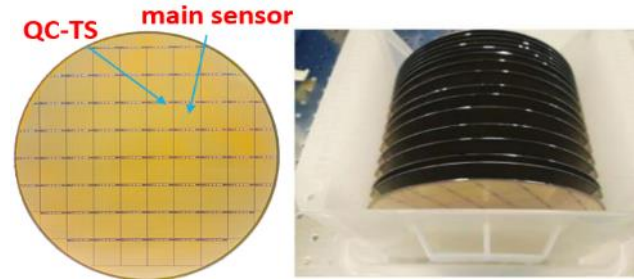
Testing

- **Nanosecond-resolution detectors have been delivered to the B5 high-resolution spectroscopy beamline, and detector collaboration with an overseas light source (APS) has been initiated**

Other Related Detector Development



Prototype silicon microstrip detector
320 channels



- A prototype silicon microstrip detector with all key technologies validated
- strip width 100 μm , strip length 10 mm, thickness 320 μm
- LGAD detectors supplied in batches to the CERN ATLAS experiment (particle physics)
- In-house development of LGAD sensor devices adapted for synchrotron radiation, to be matched with electronics and chips
- In-house High-Performance SRX Imaging Detector
- Large field of view, high spatial resolution, fully domestic
- Based on the indirect detection principle, achieving sub-micron spatial resolution
 - Proposed a novel electron-coupled SRX with spatial resolution down to 50 nm

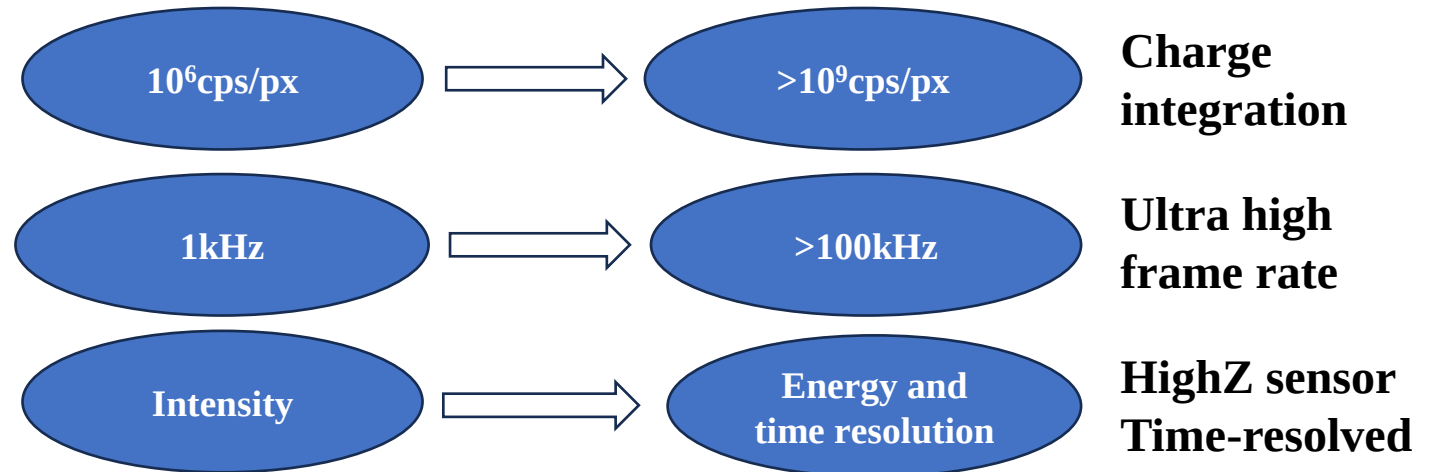
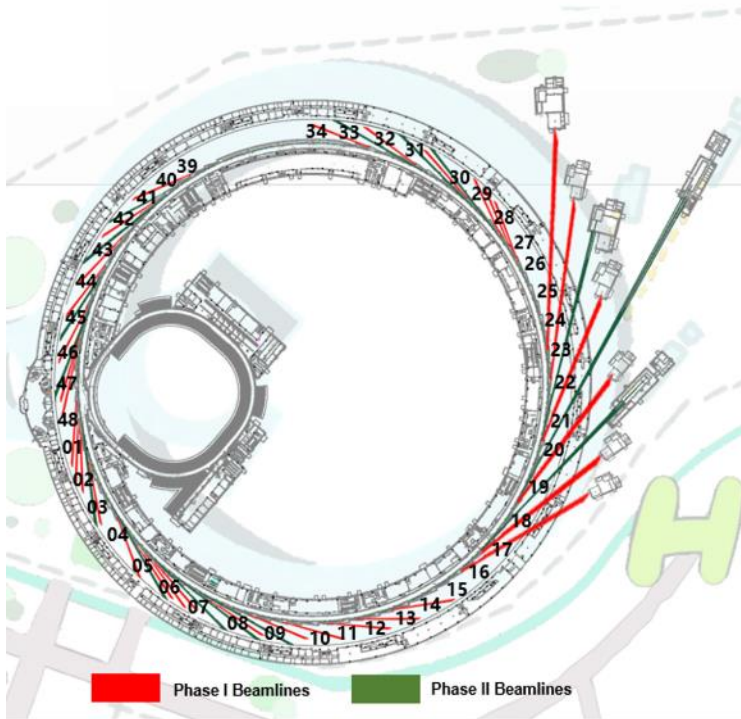


- **Detector Development Progress in HEPS Phase I**
 - X-ray Pixel Detector
 - Other Detectors
 - XBPM Diamond Detector
 - SDD Spectroscopic Detector
 - APD Detector
 - Other Related Research (Silicon Microstrip Detector, LGAD Detector, etc.)
- **Future Detector Research Plans**
- **Detector R&D Platform PAPS**

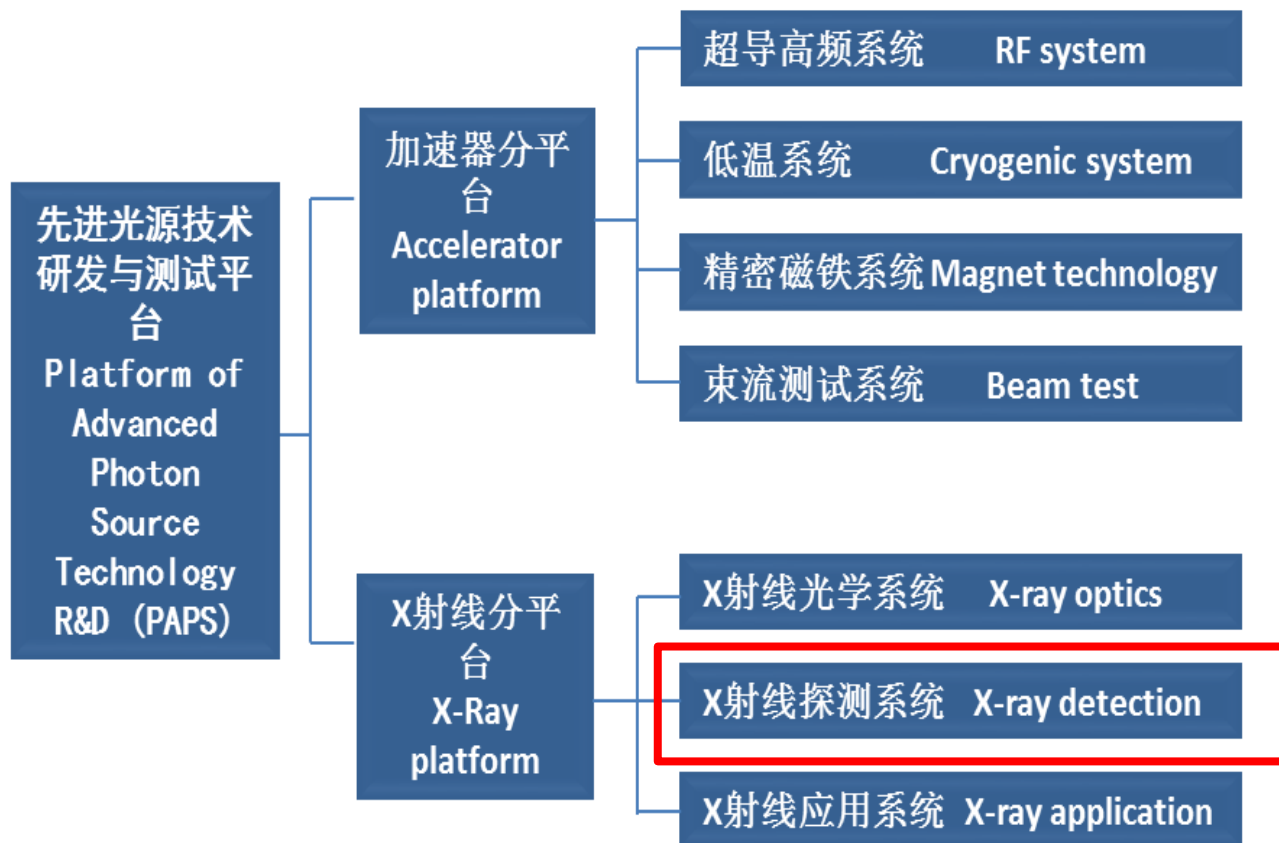
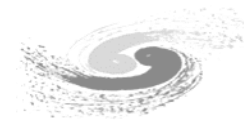
Future Plans and Considerations for Advanced Detectors

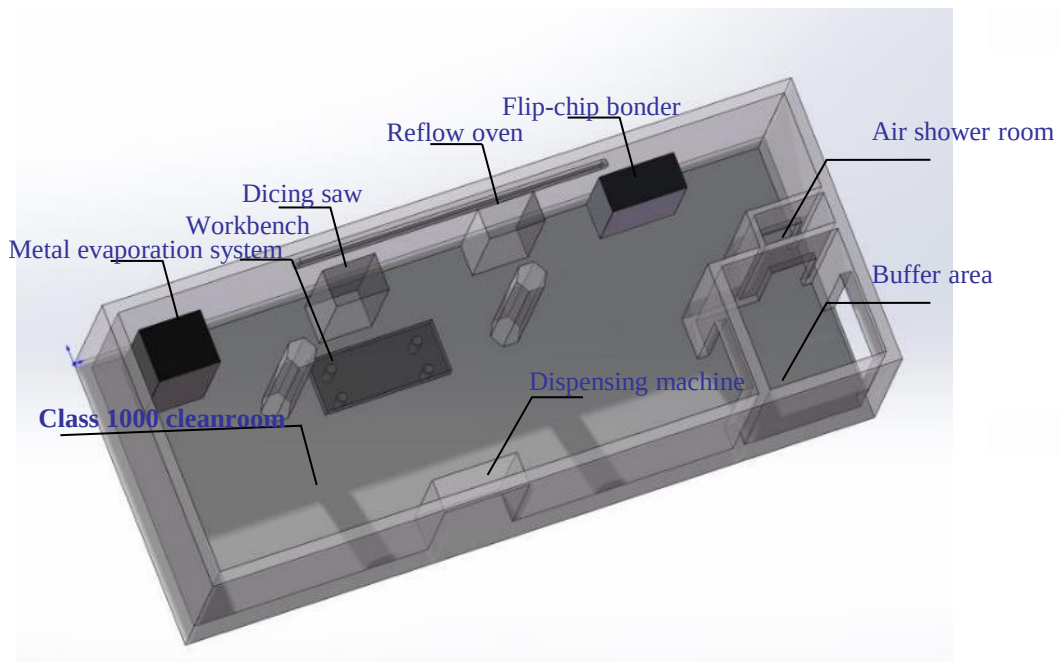
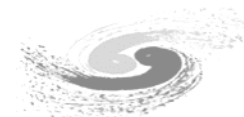


- **HEPS Phase I with 14 beamlines vs Phase II plans 24 beamlines**
- **Current detector performance at home and abroad is still far from fully realizing the potential of light sources**
 - **From counting-type to integrating-type with large dynamic range — brightness**
 - **Ultra-high frame rate detectors enable time-resolved measurements — dynamics and coherence**
 - **New Detectors — innovative experimental methods**



Platform of Advanced Photon Source Technology R&D





- Sensor Process and Testing Laboratory
- ASIC Testing Laboratory
- Electronics Laboratory
- Semiconductor Packaging Laboratory
- Detector Integration Laboratory



Metal indium evaporation system
Indium bump flip-chip process



Automatic dicing saw



Wire bonder



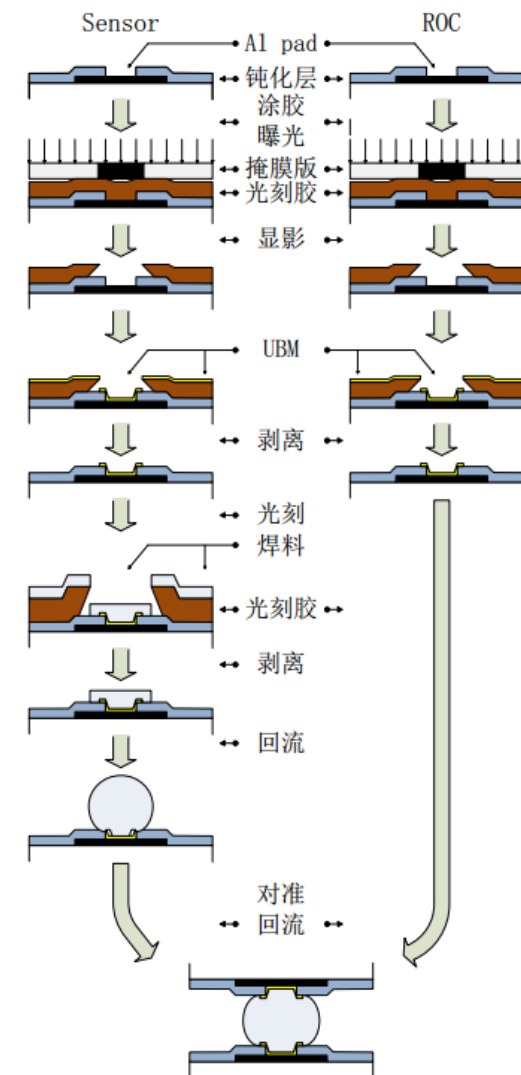
Flip-chip bonder



Electron microscope



Reflow oven



Conclusion



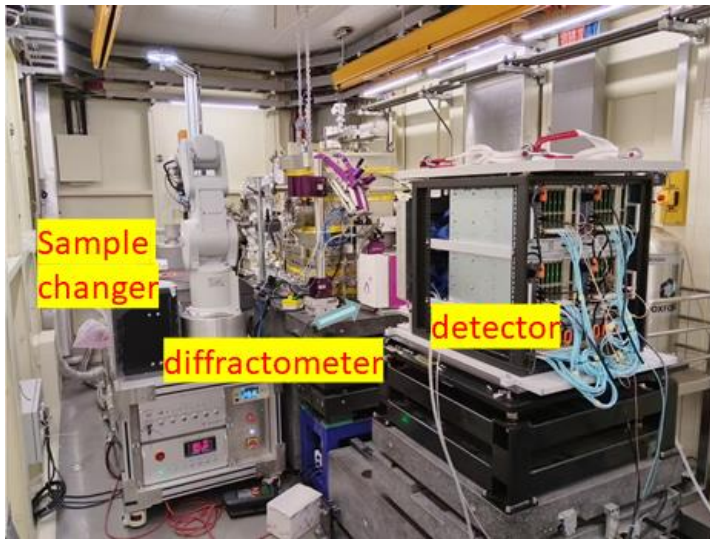
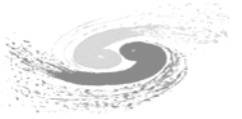
- **Four in-house detectors (pixel, diamond XBPM, SDD, APD) deployed at the HEPS Phase I beamlines; beamline acceptance testing passed in Oct. 2025**
- **More advanced detectors will be developed during the HEPS Phase II, aiming at a more powerful support for the beamline science.**
- **Collaborations on detector development and applications are warmly welcome.**

Thank You!

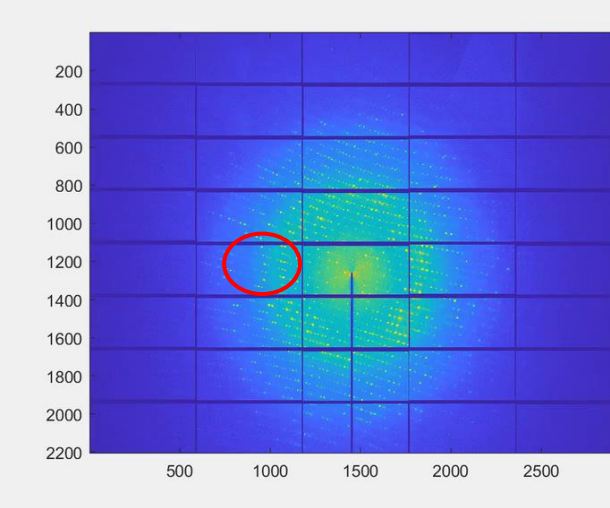


Backup Slides

HEPS-BA Beamline and Biological Macromolecular Crystallography (MX)

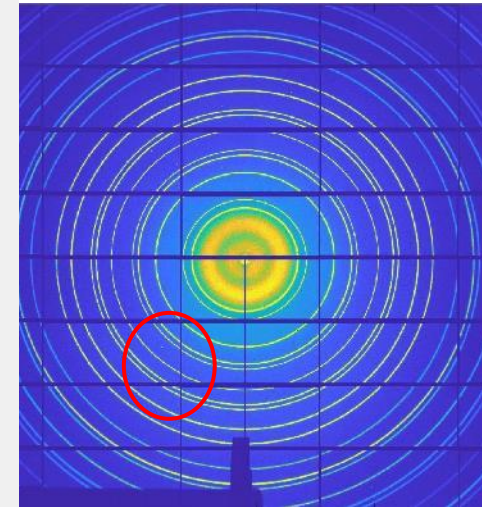


**HEPS-BA Biological
Macromolecule Beamline**



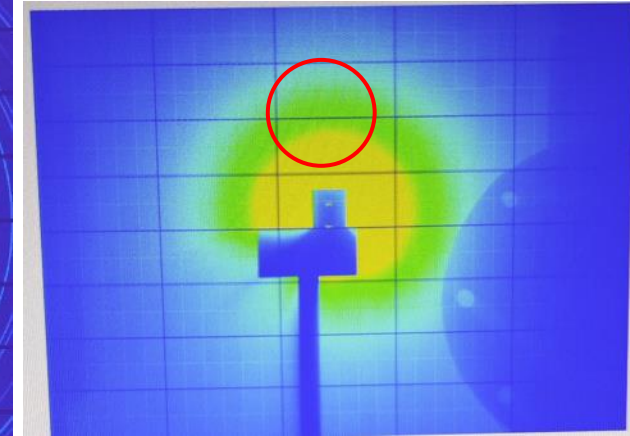
Structural crystallography (MX)
Diffraction spots

Weak, single-point diffraction signals;
high frame rate, large panel and high
dynamic range required



Powder diffraction (XRD)
Diffraction rings

High signal intensity, ring data
averaged; low frame rate, small
panel and moderate dynamic
range required



Small-angle scattering (SAXS)
Central diffuse scattering

Low resolution requirement;
high frame rate for dynamics
experiments, high sensitivity and
small panel required

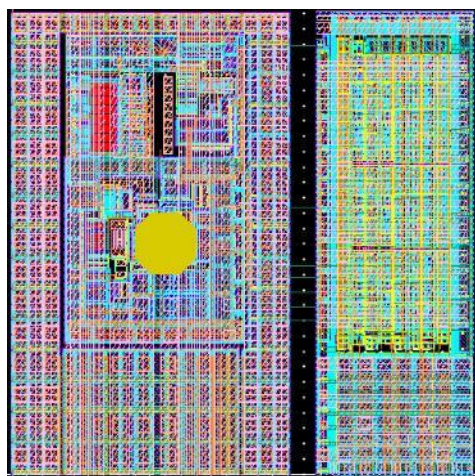
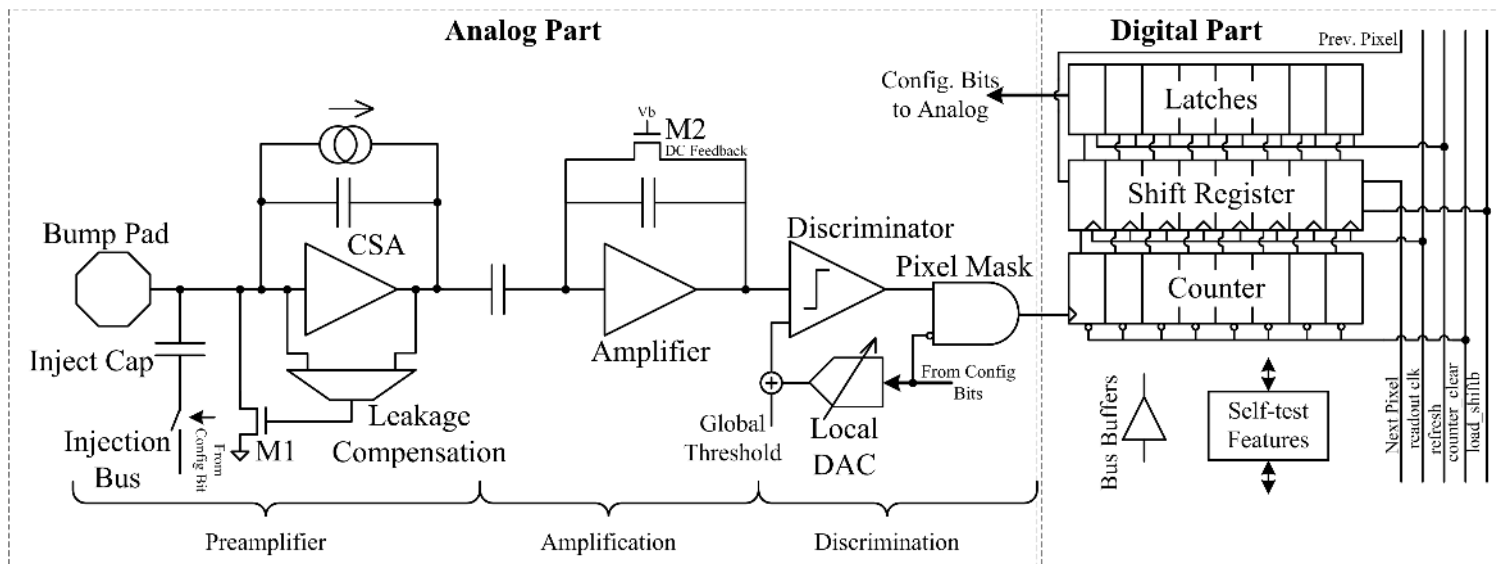
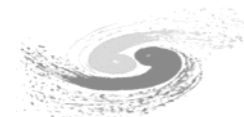
- Compared with other pixel detector applications such as powder diffraction and small-angle scattering, biological macromolecular structure determination imposes the most demanding requirements on detector performance
 - Diffraction spots vs. diffraction rings (powder): weak signal, sensitivity limit
 - Simultaneous measurement of very strong low-angle and very weak high-angle diffraction spots: dynamic range limit (intensity dynamic range & sensitive-area dynamic range)
 - "Rotation collection" of 3D sample information: frame rate speed limit

Main Hardware Parameters and Upgrades

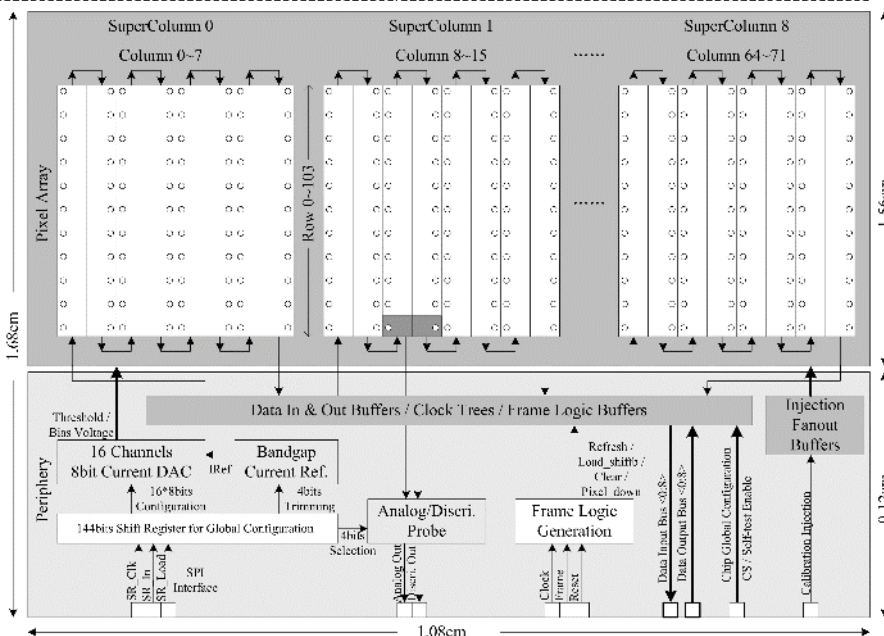


	1st BPIX (2015-2016)	2 nd BPIX (2017-2018)	3 rd BPIX (2019-2024)	4 th BPIX (2024-2026)
Pixel size	150 μm X 150 μm	150 μm X 150 μm	150 μm X 150 μm	140 μm X 140 μm
Modules	6	16	24	40
Chips per module	104*72*2*4	104*72*2*4	104*72*2*4	128*96*2*6
Total pixels	360K	1M	1.4M	6M
Energy range	10~20 keV	8~20 keV	8~20 keV	6~20 keV
Bump bonding	Indium	CuSn	CuSn	CuSn
Interconnection	Wire bonding	Wire bonding	Through Silicon Via (TSV)	Wire bonding
PCB scheme	Rigid-flex PCB	Rigid-flex PCB	Rigid-flex PCB with low CTE	HTCC
Dead area	26.3%	26.3%	11.8%	9.3%
Back-end electronics	Spartan6 + SFP	Kintex7 + DDR3 + Molex Nano-Pitch I/O™ Cable	Kintex7 + DDR3 + Molex Nano-Pitch I/O™ Cable	UltraScale Kintex Plus + DDR4 + MicroTCA.4
Data interface	1G Ethernet x12	1/10 G Ethernet x4	40G Ethernet	100G Ethernet
Cooling	Air cooling	Air cooling	Water cooling + air cooling	Water cooling + air cooling
Power consumption	100W	370W	500W	<2500W

HEPS Photon Counting Detector



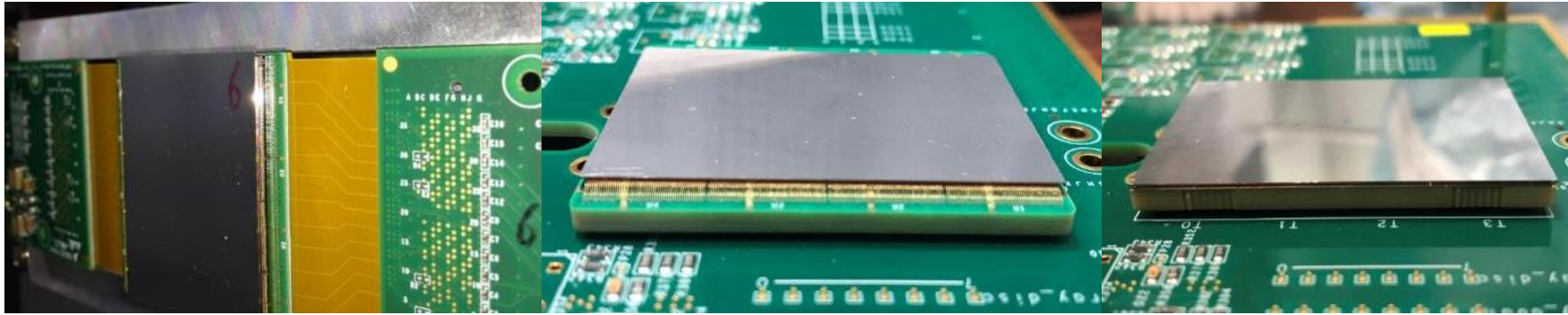
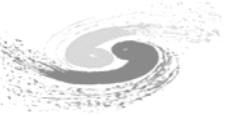
Pixel layout $150\ \mu\text{m} \times 150\ \mu\text{m}$



Specification	Parameter
Sensor	320um silicon PIN
Pixel size	150umX150um
Number of pixels	104X72
Count rate	>2Mcps/pixel
Counter depth	20bit
Frame rate	1.2kHz continuous
Energy range	8-20keV
Threshold	Single threshold
Detector module	24 chips (208,288 pixels)
Power consumption	38μW/Pixel

- **HEPS BPIX-20 photon counting chip**
- **CMOS 0.13μm, 1P8M**
- **3 MPW tape-outs + 1 full-mask tape-out**
– May 2012 ~ Aug. 2014
- **Full chip size 1.7 cm × 1.1 cm**

Module Packaging Research

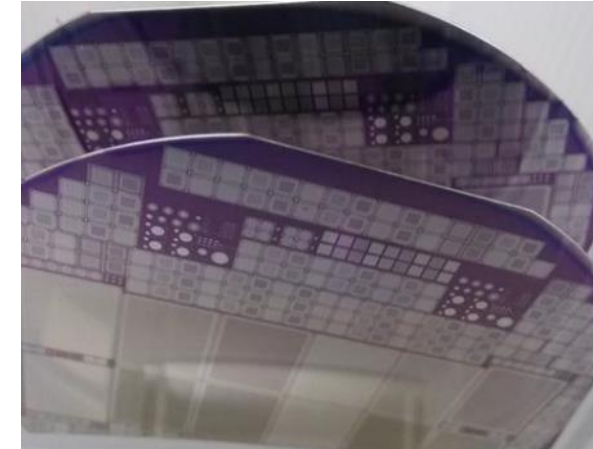
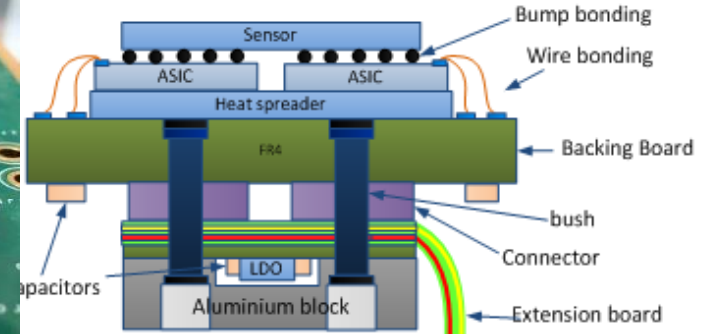


1st-generation prototype: indium bump bonding module

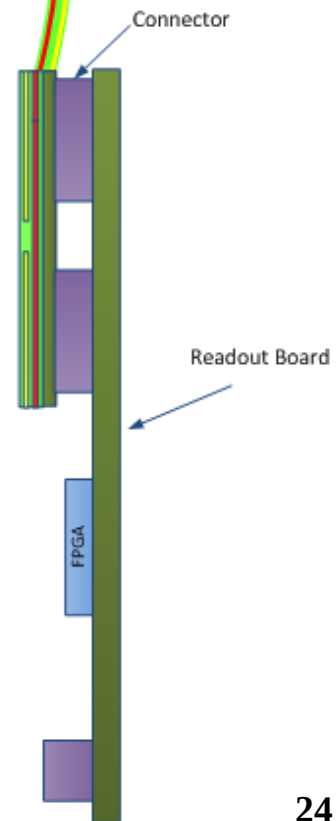
2nd-generation prototype: CuSn bump bonding module

3rd-generation prototype: bump bonding + TSV module

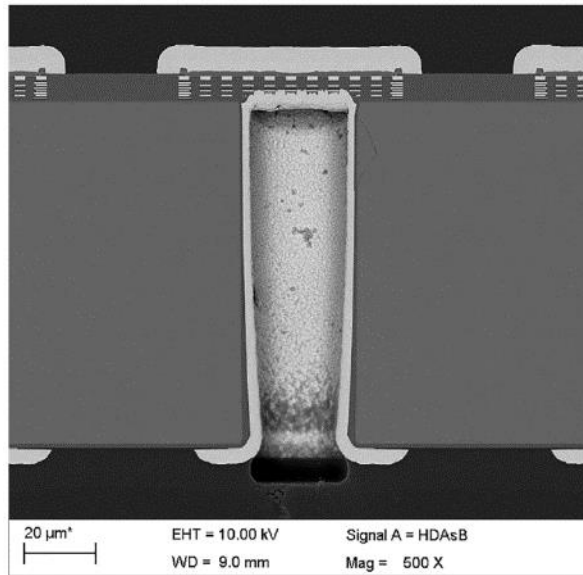
- Sensor, packaging, system electronics and cooling are all in-house developed
- Module packaging has gone through three generations of prototype systems:
 - The first generation used indium bumps: good yield but low throughput
 - The low-temperature requirement throughout the process was a challenge
 - The second generation used CuSn bumps: suitable for mass production, high throughput and compatible with high-temperature processes
 - The third generation introduced TSV technology, eliminating wire bonding and achieving smaller module assembly gaps



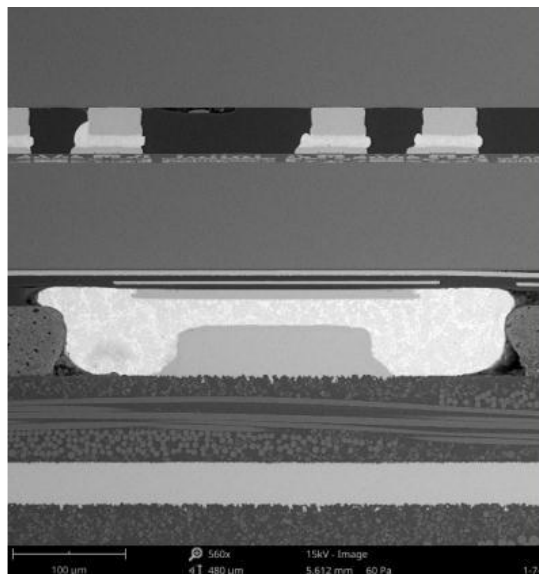
In-house developed silicon sensor



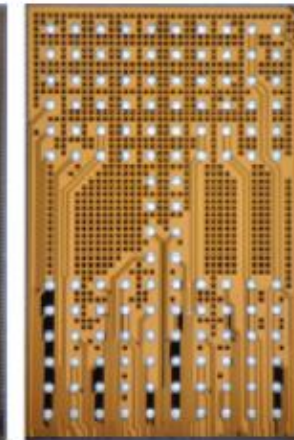
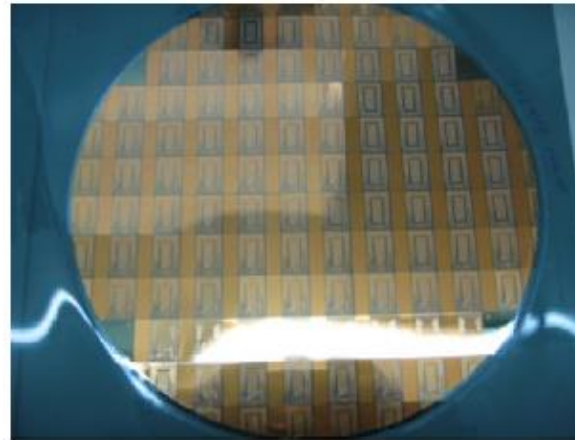
Bump Bonding and TSV Technology



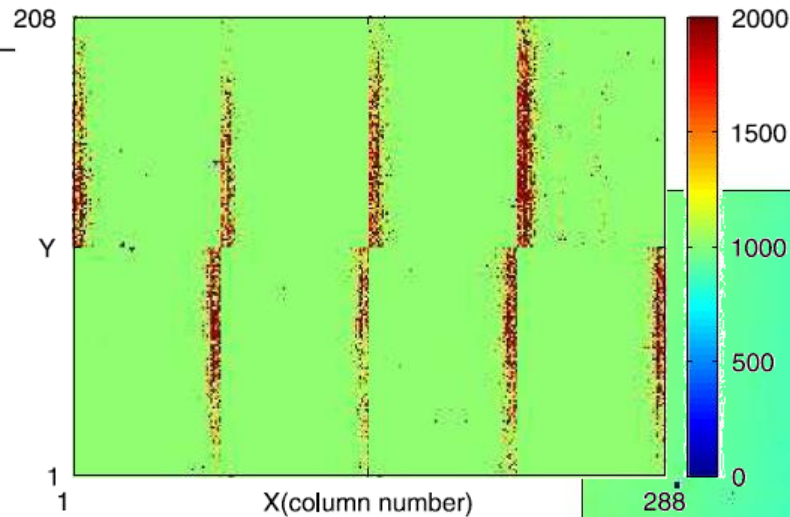
Cross-section of TSV connection



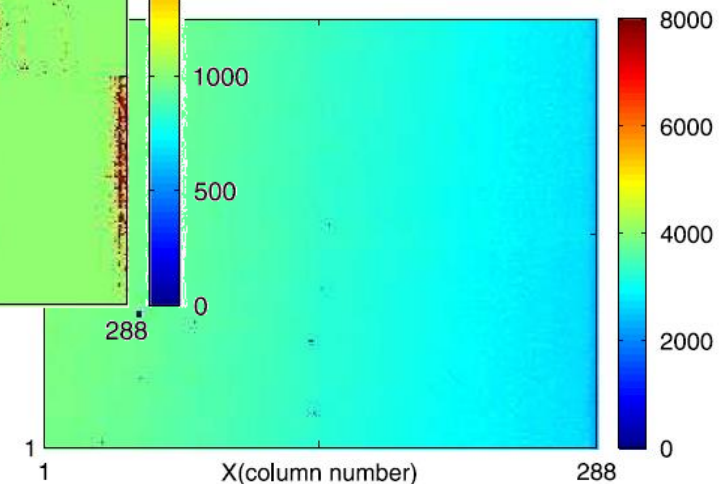
Cross-section of bump bonding + TSV 3D stacking



Wafer after TSV processing: front-side bump view, back-side RDL view



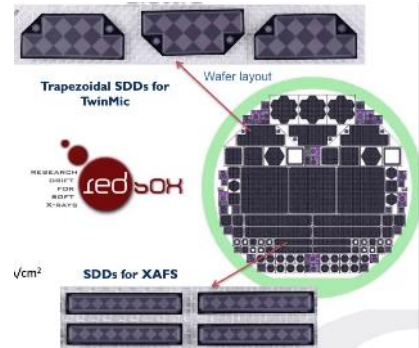
Single-layer RDL TSV



Double-layer RDL TSV



SDD Silicon Drift Spectroscopic Detector



Semiconductor device development

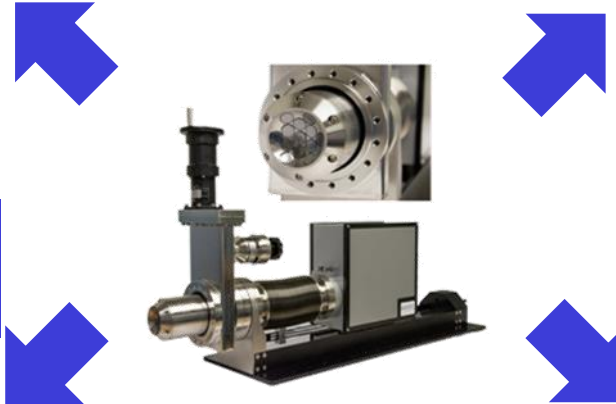
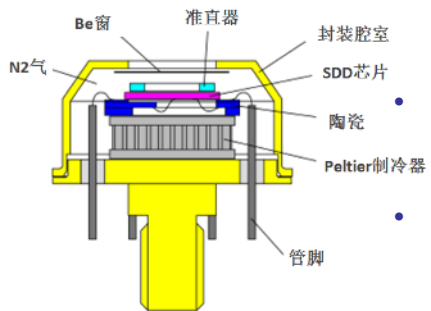
- SDD sensor design
- Process optimization

Low leakage, high photoresponse

Semiconductor packaging technology

- Semiconductor intelligent temperature-controlled cooling
- Vacuum packaging process

High-density wire bonding, vacuum soldering



Detectors for beamline research

Low-noise front-end electronics

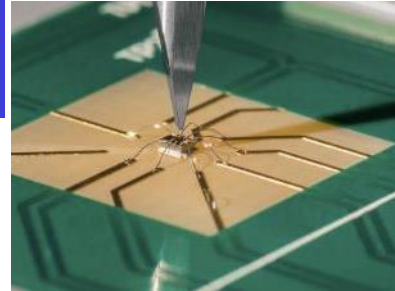
- Charge-sensitive preamplifier
- Application-specific integrated circuit (ASIC)

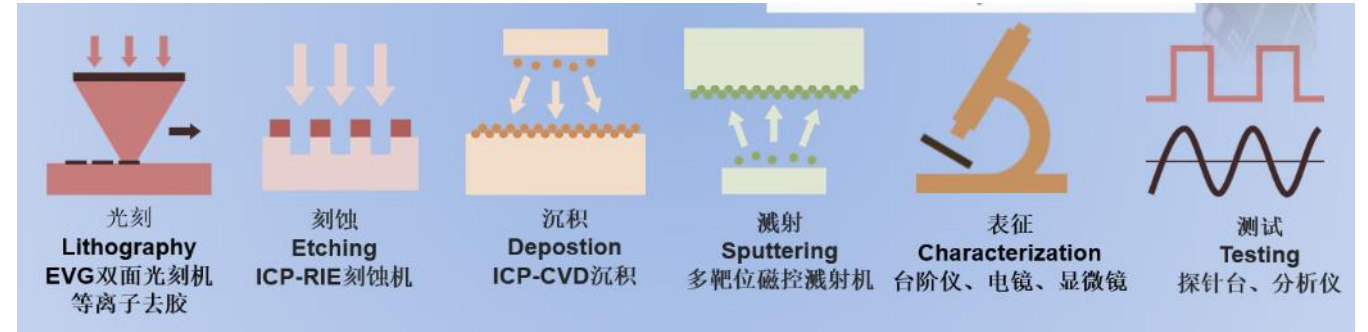
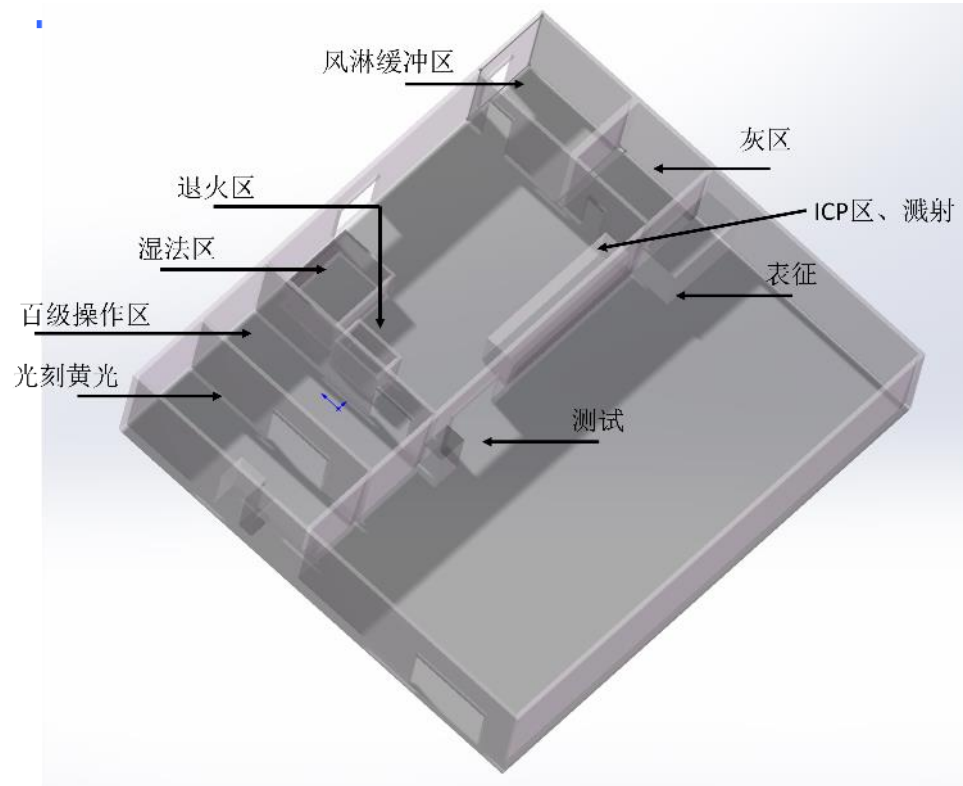
High integration, ultra-low noise

Efficient signal processing electronics

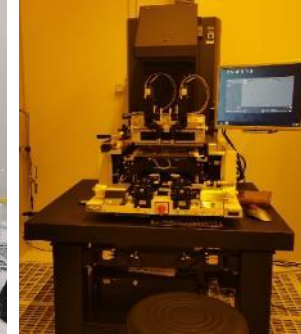
- High-speed data acquisition and transmission
- Efficient signal processing algorithms

Digital shaping, pile-up signal processing





ICPCVD
Oxide growth
Surface passivation process



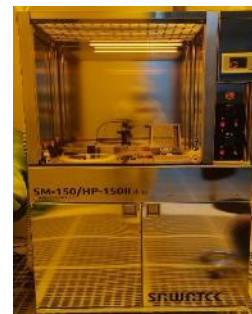
Lithography exposure
0.8 μm resolution



ICPRIE
Dielectric etching



Magnetron sputtering
deposition
Metal deposition



Spin coater
Coating thickness ≥ 1 μm



High-magnification optical
microscope
Lithography process inspection



Profilometer
Step height accuracy 2 nm

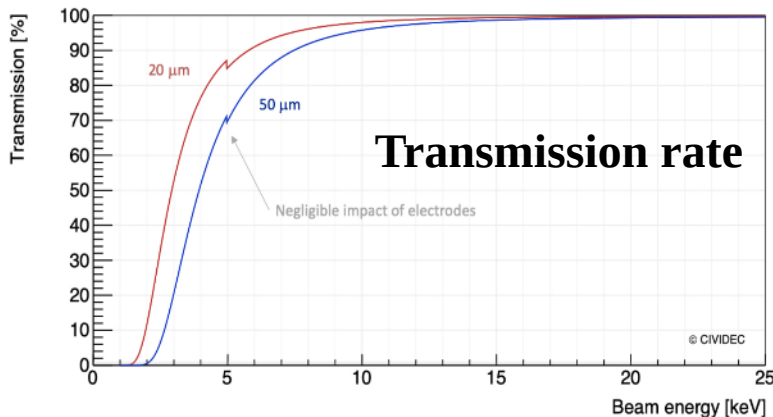
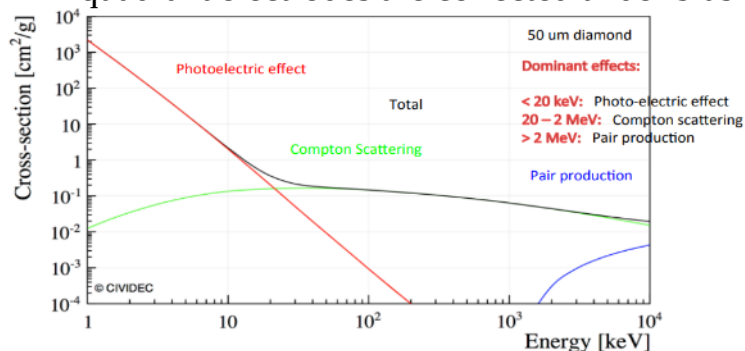


Rapid thermal annealing furnace
1300°C 20°C/s

- Sensor Process and Testing Laboratory
- ASIC Testing Laboratory

➤ High-Flux Synchrotron Diamond Detector

- Advantages of diamond detectors: radiation hard, X-ray transparent, low dark current, low noise, fast response, uniform sensitive region
- XBPM principle: X-rays interact with diamond, and electron-hole pairs generated at the four-quadrant electrodes are collected under bias

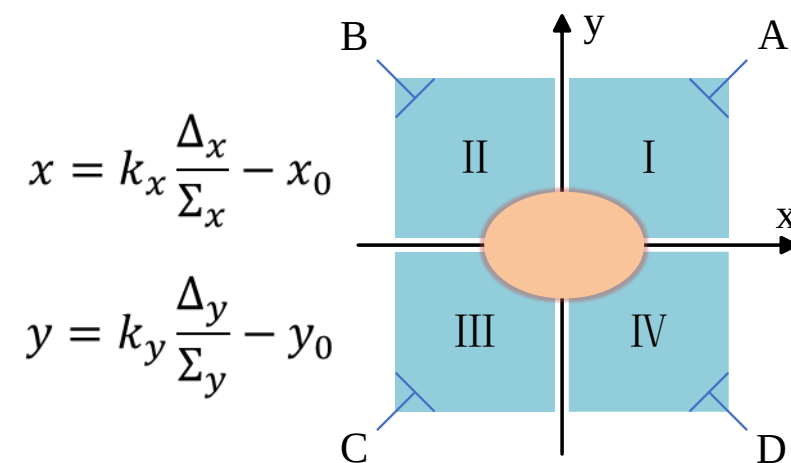
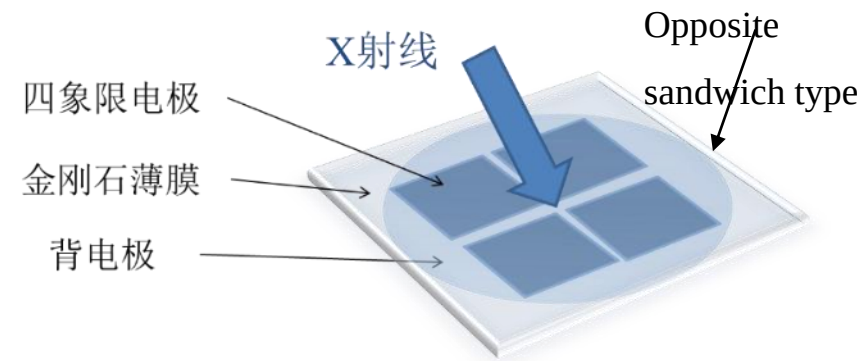


Material: single-crystal CVD diamond

Thickness: 50 μm, 500 μm

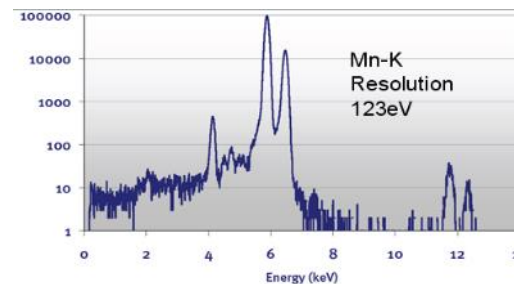
Size: 2 mm × 2 mm, 4 mm × 4 mm

- Solid-state detector**
- Semiconductor: electrons and holes**
- Insensitive to visible light**
- Temperature insensitive**
- Low dark current (pA)**
- Intrinsically low noise**
- Fast response ($v_{\text{sat}} = 1\text{e}5 \text{ m/s}$)**
- Very robust**
- Used for fast beam loss monitors**

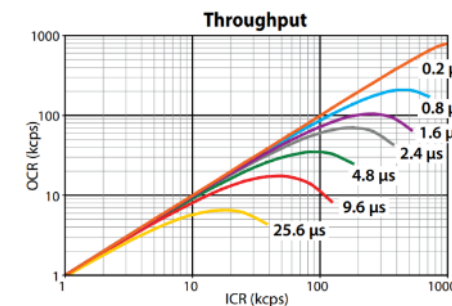


■ Advantages of fluorescence spectrometers based on SDD detectors

SDD		Performance comparison
Active area	7 mm ² to 150 mm ²	Much larger than Si-PIN diodes
Cooling method	Thermoelectric cooling	Better than Si(Li) and pure Ge detectors
Resolution	Minimum 123 eV	Much higher than CCD
Count rate	Typically 1 Mcps	
Stability	+ 80 °C normal operation	Stability higher than APD



Typical Fe-55 spectrum (10mm²) with excellent P/B ratio (~16k)



Best 123 eV

❑ **Very high energy resolution;**

❑ **The single-element SDD has a high count rate, up to 10⁶ cps;**

❑ **No liquid nitrogen cooling required; compact and low cost.**

Challenges

There are no domestic SDD detector products; all are imported and costly;

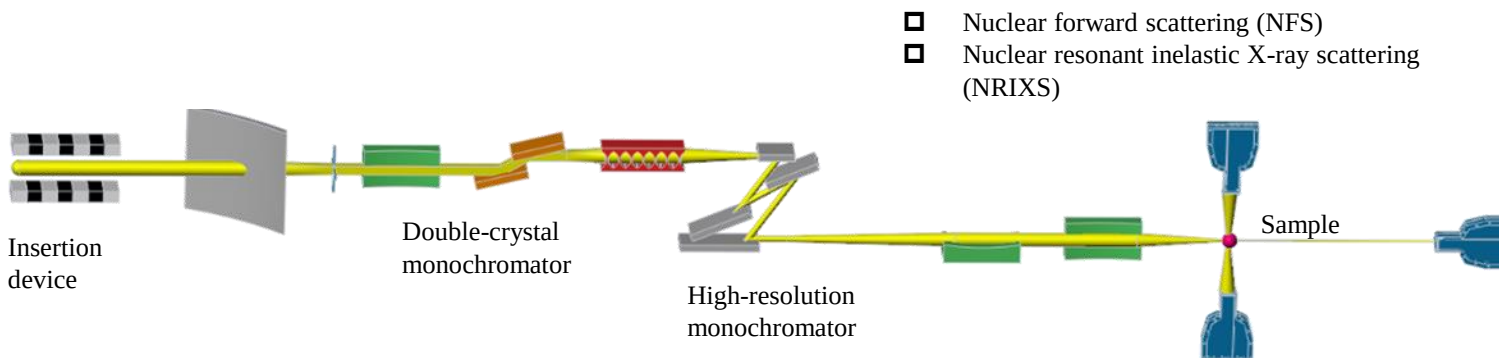
As HEPS brightness increases, existing commercial products cannot meet the detection efficiency requirements and cannot exploit the brightness advantage of the advanced light source.

Major light sources and research institutions worldwide are racing to develop array-type SDD detectors in-house.

- **Conducting full-chain in-house development in semiconductor devices, ultra-low-noise front-end chips, semiconductor vacuum packaging and readout electronics**

➤ HEPS-B5 engineering requirement: single-element and array APD detectors

- **High time resolution** — better than 1 ns
- Low noise — 6.4 keV single-photon counting capability
- **High saturation count rate** — 10^8 cps
- System stability — long-term stable operation



➤ Design of high-speed readout electronics for single-element and array detectors



Prototype functions

Signal threshold discrimination

1

- Supports user-defined thresholds
- Independent threshold discrimination per channel

Packed data transmission

2

- Real-time data feedback
- Supports Gigabit Ethernet UDP transmission

Prototype performance

TDC time measurement

3

- **Delay-line TDC algorithm**
- **Time bin improved from 1 ns to 74 ps**

Prototype testing

Continuous stable system operation

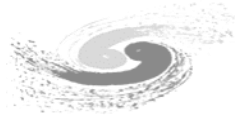
4

- Prototype burn-in > 200 hours
- Overall system integration test (low noise)

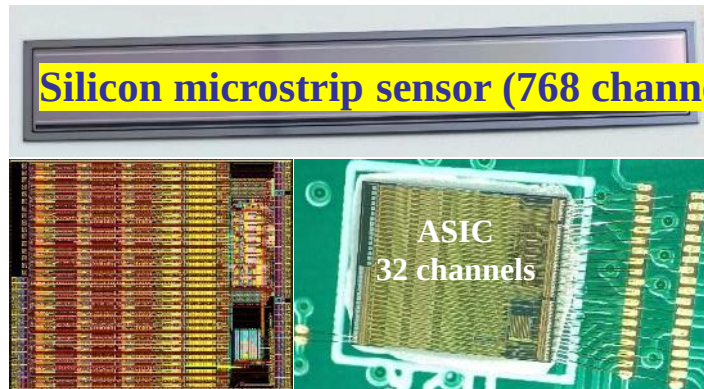


Meets engineering requirements

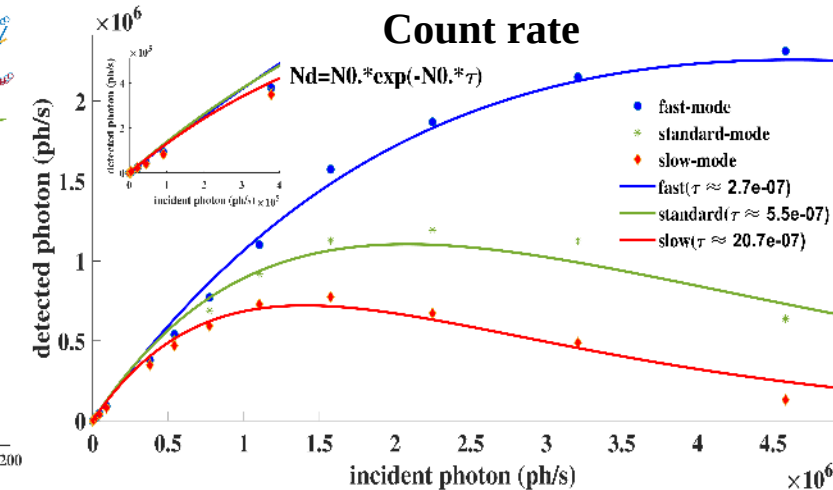
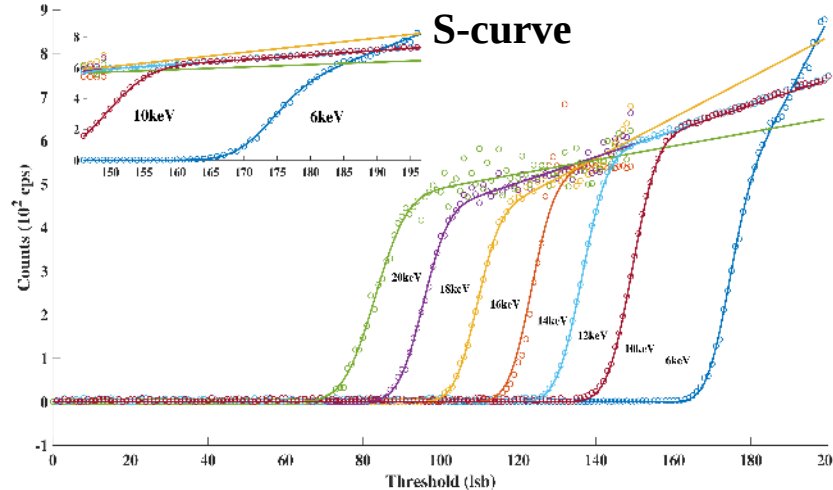
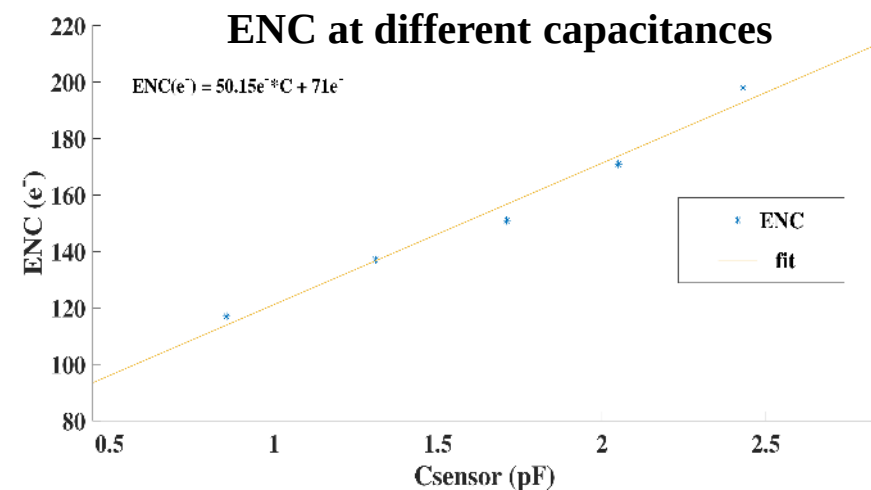
Research Progress on the Silicon Strip Detector (SSD)



Silicon microstrip sensor (768 channels)



Prototype silicon microstrip detector
320 channels



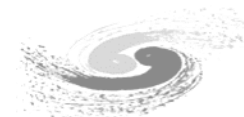
Main performance specifications of the prototype detector

Parameter	Value	Parameter	Value
Strip width [μm]	100	Frame rate	16 kHz
Strip height [mm]	10	Count rate	≤ 2.3 MHz/strip
Minimum threshold [keV]	3.4	Counter depth [bit]	24
ENC	187 e ⁻	Channels	320

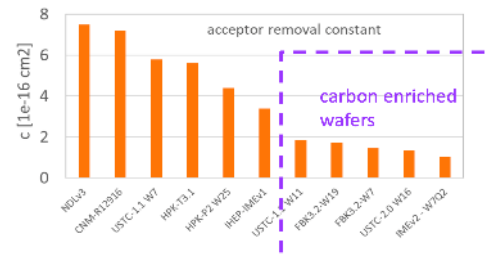
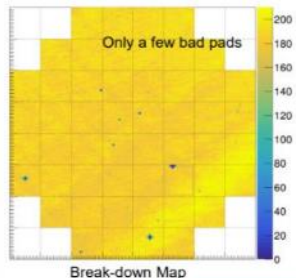
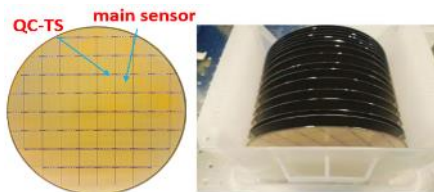
- Silicon strip sensor: strip width 100 μm, strip length 10 mm, thickness 320 μm
- All key technologies of the silicon strip detector have been



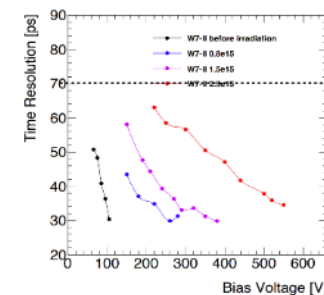
X-ray LGAD Detector



Future research will focus on integrating low-gain avalanche detectors (LGAD) for X-ray detection to improve sensitivity and time resolution



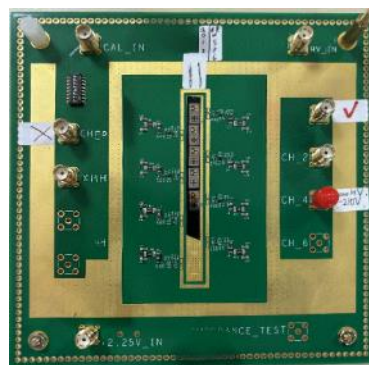
Lowest acceptor removal constant



- With its excellent radiation hardness, the IHEP-designed LGAD will supply 90% of the sensors for ATLAS HGTD
- Pre-production of IHEP LGAD sensors for HGTD has been completed (90 wafers manufactured in 2024)
- IHEP LGAD sensors achieve time resolution better than 40 ps both before and after irradiation

- Test results: LGAD sample pixel area 2.6 mm × 2.6 mm, active thickness ~80 μm, capacitance ~10 pF

- New design:
Pixel area: 2.5 mm × 2.5 mm, array: 1 × 16
Active thickness: 50 μm, 80 μm
Capacitance: ~15 pF (50 μm), 9.5 pF (80 μm)



Testing board

