The 8th International Conference on Micro-Pattern Gaseous Detectors

China spallation neutron source and neutron detectors

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I China spallation neutron source

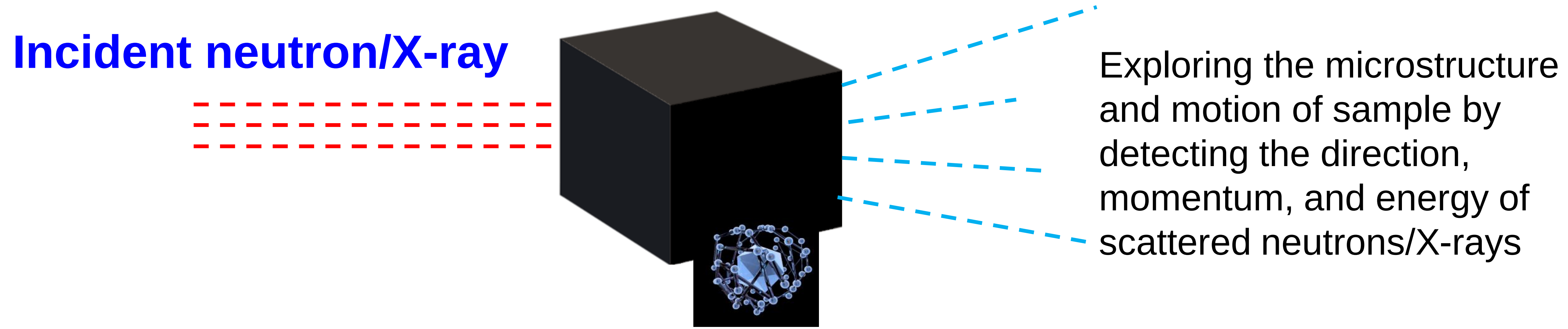
II Status of the detectors development

III R&D for CSNS Phase II

IV Summary

Neutron source and synchrotron radiation light source: A multidisciplinary frontier research platform

A complementary research platform for studying the structure and dynamics of matter



Neutron: interact with nuclei
X-ray: interact with extranuclear electrons

Spallation neutron source technology:

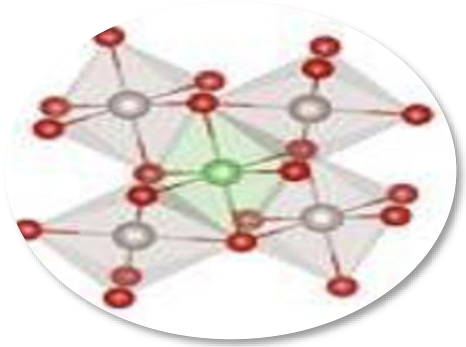
More complex technique, higher cost (compared to synchrotron radiation); low neutron intensity; difficult experiment; only 4 spallation neutron sources in the world (more than 60 synchrotron radiation light sources).

Widely-applied neutron technology

Neutron technology plays an irreplaceable and important role in research fields such as **new materials, new energy, aerospace and industry**

Fatigue & Residual stress of aircraft engine

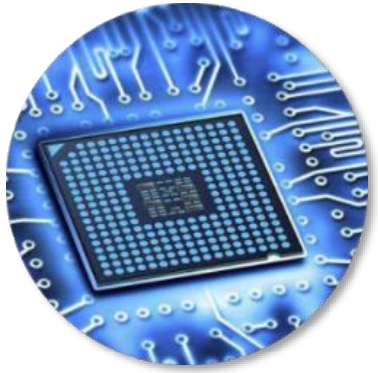
Residual stress of high-speed train wheel



Chemistry

Detection of battery charge and discharge

Research on combustible ice

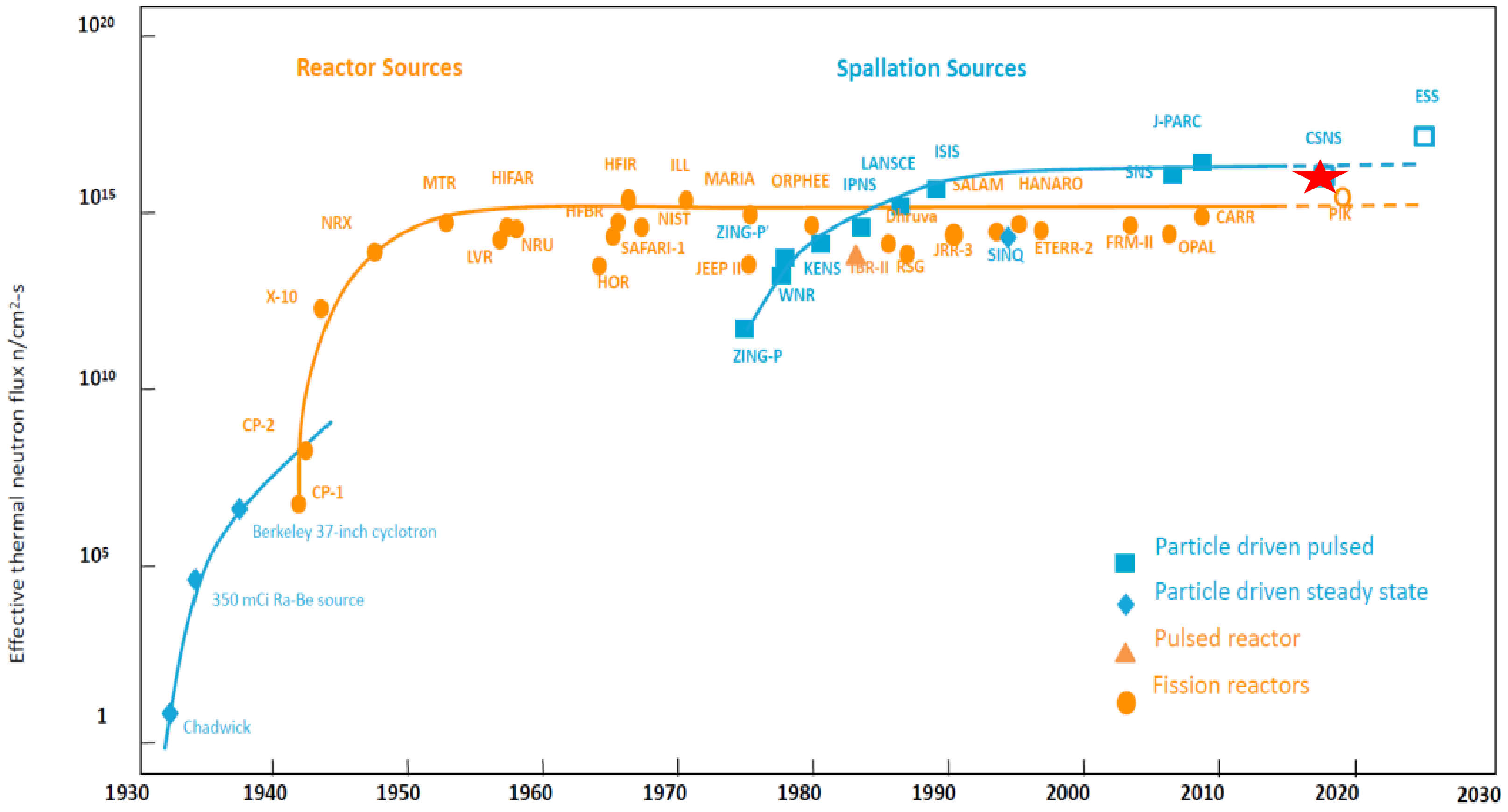


Single event effect on chip

Development trend of neutron sources in the World

Neutron sources are developing towards high-flux, pulsed neutron sources based on large accelerators:

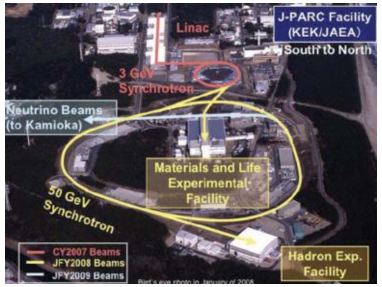
- Four Spallation neutron sources: ISIS, SNS, J-parc and CSNS.
- ESS under the construction.



ISIS (UK)

SNS (US)

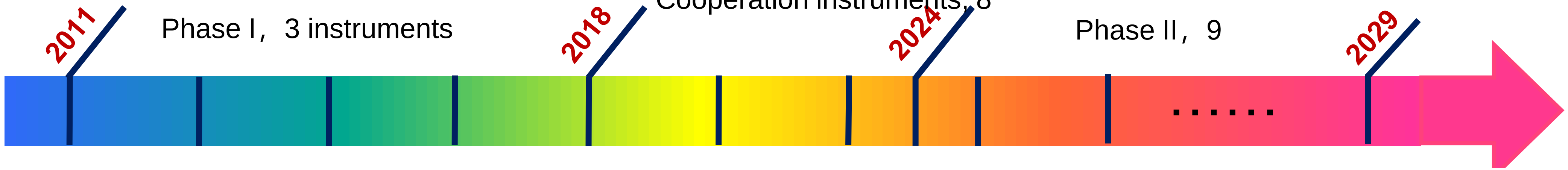
J-Parc (JP)

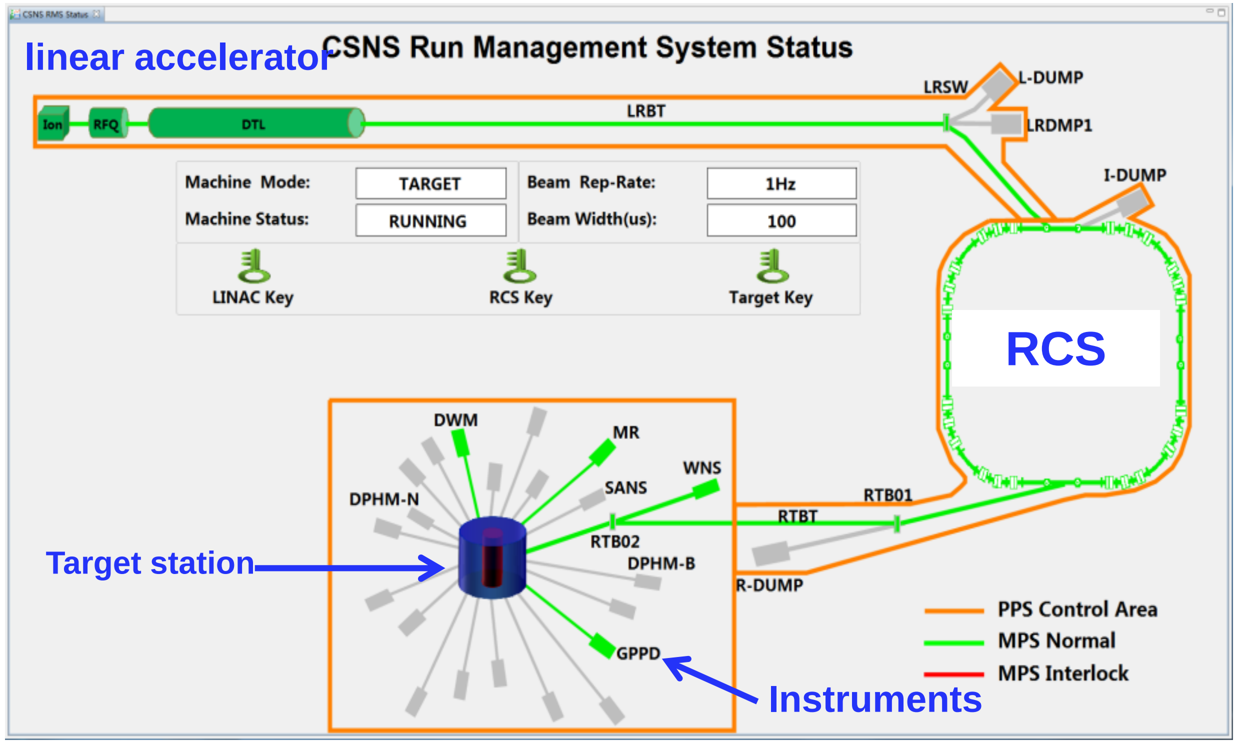


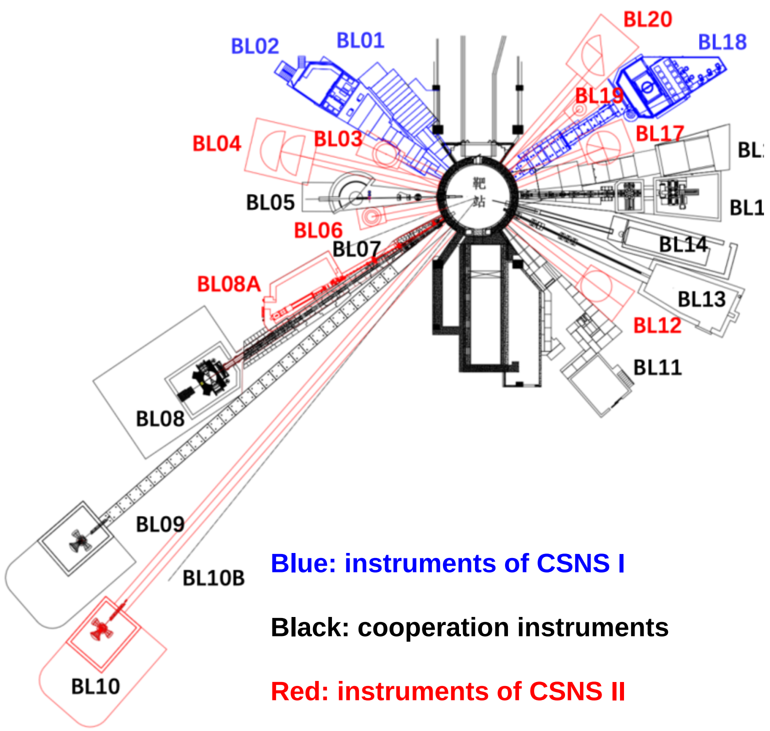
CSNS (CN)

China Spallation Neutron Source (CSNS)

- **Legal Entity: Institute of High Energy Physics, Chinese Academy of Sciences. Co-construction Department: Guangdong Provincial Government, Construction Location: Dalang, Dongguan, Guangdong. Cost of CSNS-I: 1.86 Billion RMB and the budget for phase II: 2.89 Billion RMB.**







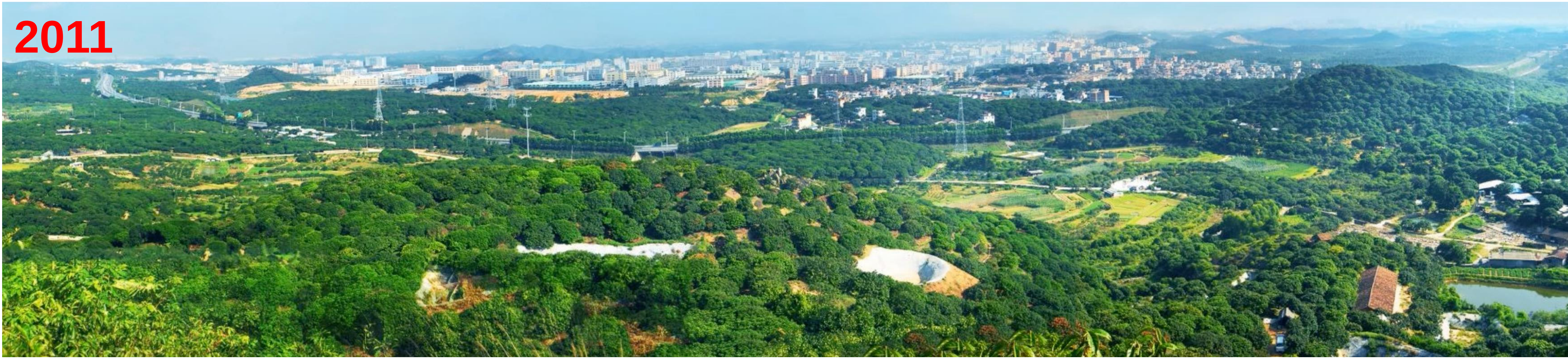
Blue: instruments of CSNS I

Black: cooperation instruments

Red: instruments of CSNS II

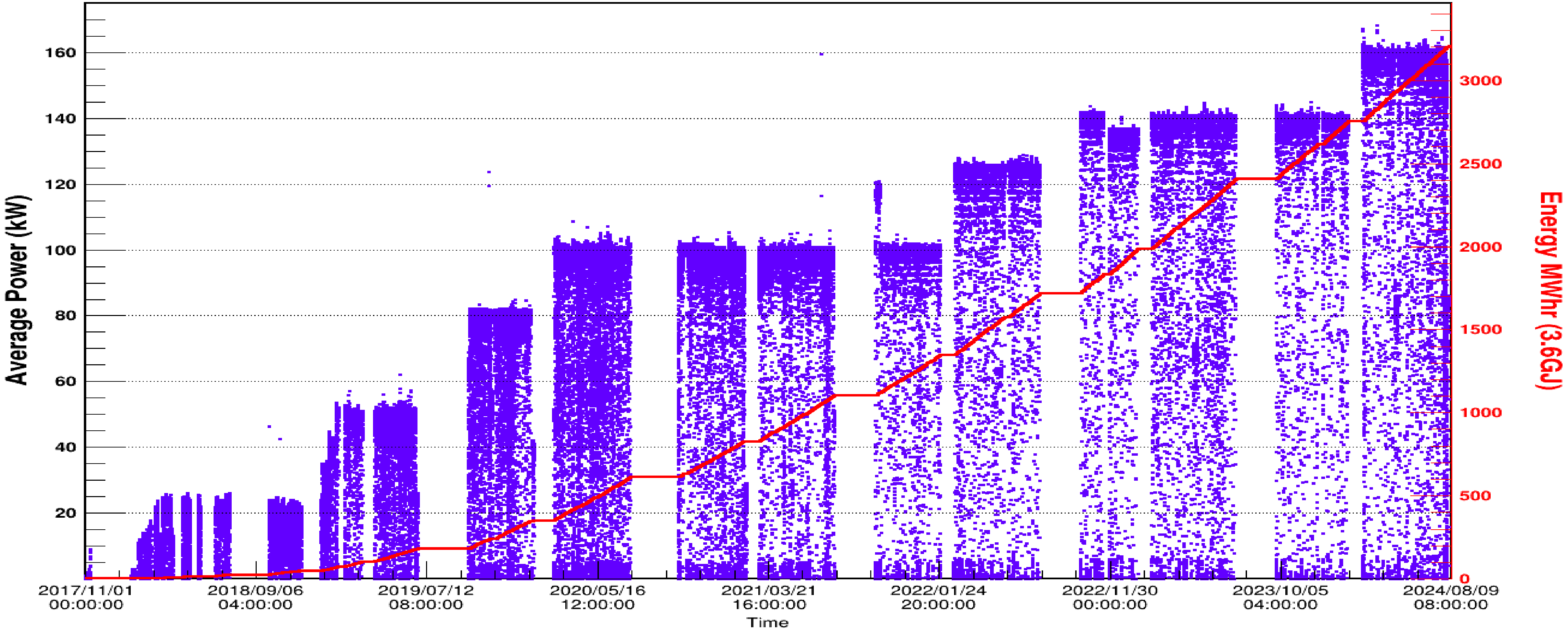
BL1. Small Angle Neutron Scattering Instrument
BL2. Multi-functional Reflectometer
BL3. Liquid Neutron Reflectometer
BL4 Cold Neutron Direct Geometry Inelastic SpectrometerBL5. High-Energy Inelastic Spectrometer
BL5. High-Energy Inelastic Spectrometer
BL6. Inverse Geometry Molecular Vibrational Spectrometer
BL7. (Reserved)
BL8A. Neutron Technology Development Beamline
BL8. Engineering Materials Neutron Diffractometer
BL9. High-Resolution Neutron Diffractometer
BL10. Neutron Backscattering Spectrometer
BL10B. (Reserved)
BL11. Atmospheric Neutron Irradiation Spectrometer
BL12. Neutron Physics and Applications Spectrometer
BL13. Energy-Resolved Imaging Spectrometer
BL14. Very Small Angle Neutron Scattering Instrument
BL15. High-Pressure Neutron Diffractometer
BL16. Multi-Physics Spectrometer
BL17. Elastic Neutron Scattering Spectrometer
BL18. General Purpose Powder Diffractometer
BL19. Single Crystal Neutron Diffractometer
BL20. Direct Geometry Polarized Inelastic Spectrometer

Bird's eye views of CSNS from 2011 to 2024



Operation Status

- **Through continuous commissioning and optimization, the accelerator beam power is increased constantly**
  - **In Feb. 2020, the beam power reached the expected value of 100kW (1.5 years ahead of schedule)**
  - **In Mar. 2024, the beam power reached 160kW and the beam availability is higher than 97%.**

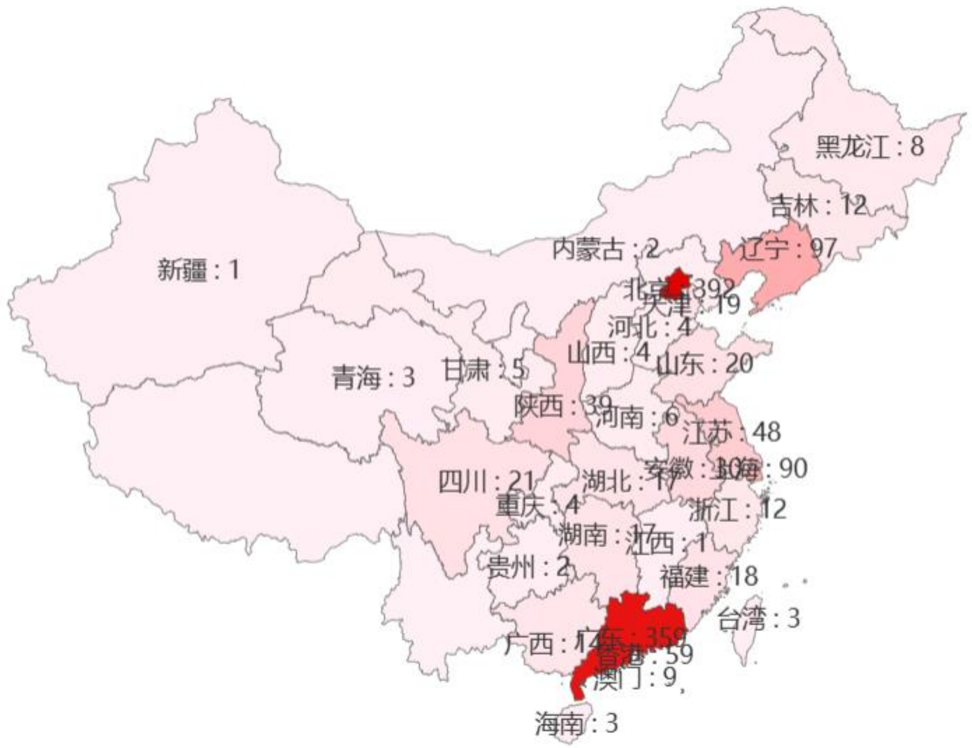


User proposals

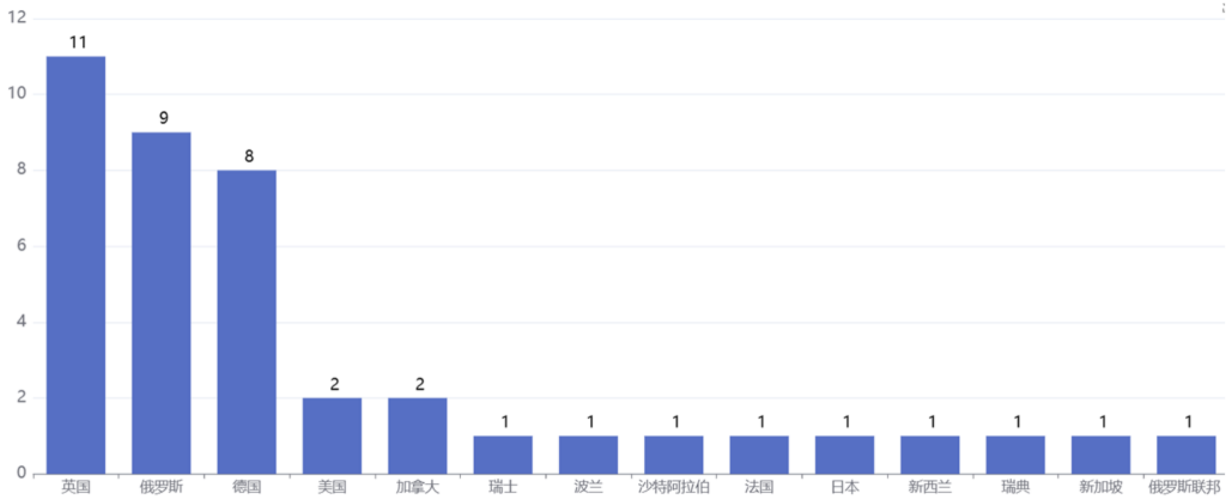
Demand on neutron scattering experiments grows fast

- Over 7,100 registered users, more than 1,700 proposals completed after 12 cycles of open operation
- Pass rate of the proposals is ~30% due to limited beam time, less instruments and increased users

Distribution of CSNS users in China



CSNS global users



Britain ： 11	Russia ： 10	Germany : 8	America: : 2	Canada : 2	Switzerland : 1
Poland : 1	France : 1	Saudi Arabia : 1	France : 1	NewZealand:1	Japan : 1
Sweden : 1	Singapore : 1				

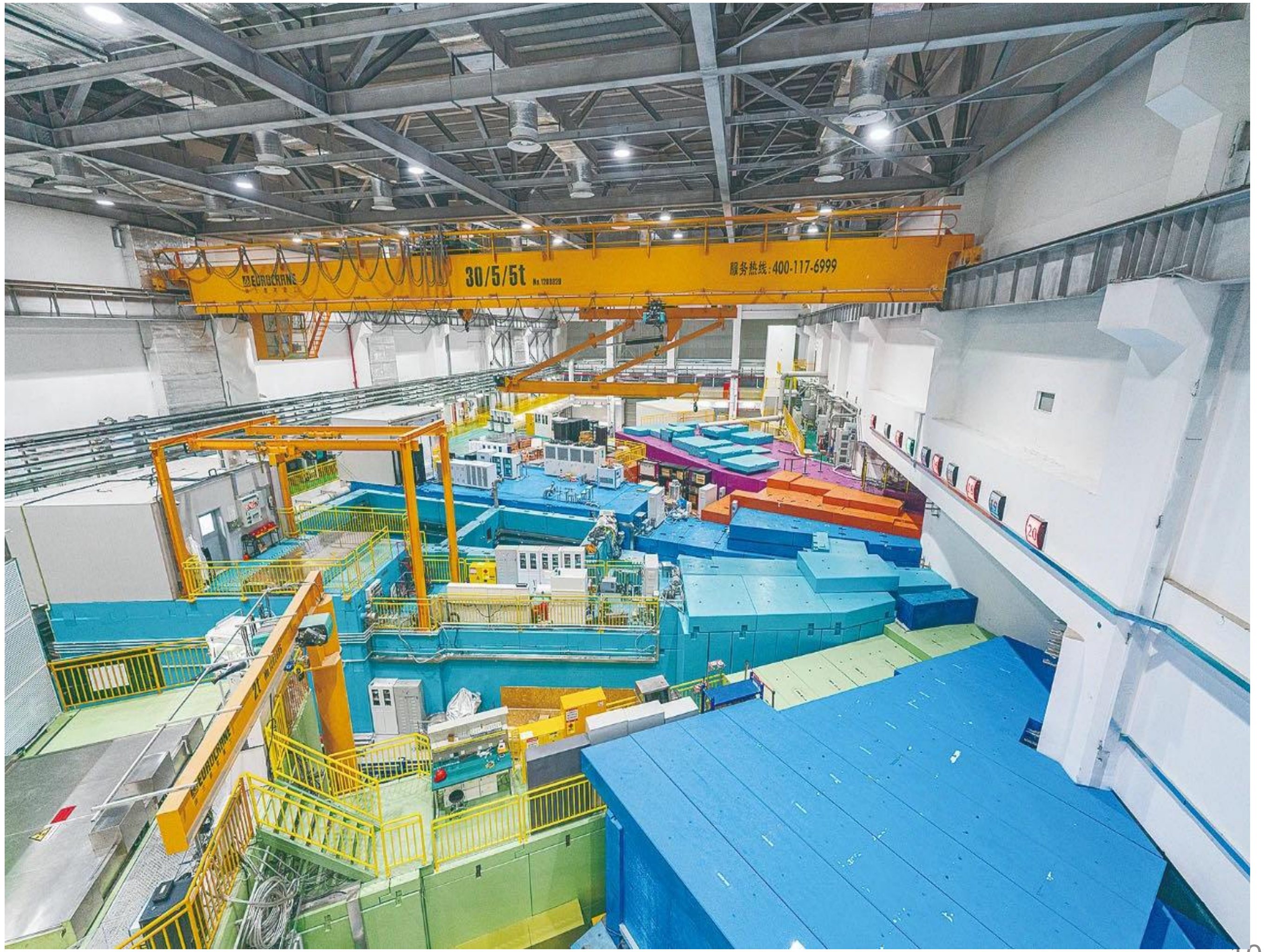
Multi-scale and multi-dimensional neutron characterization technologies

CAS CHINESE ACADEMY OF SCIENCES

8 instruments completed, 3 instruments under commissioning, 11 instruments and terminals planned in CSNS II

- **Microstructure characterization**
  - Powder Diffraction (Crystal Structure)
  - Monocrystalline Diffraction (Single Crystal Structure)
  - Small Angle Scattering (Nanostructure)
  - Reflection (Interface Structure)
- **Dynamics Characterization**
  - Time-of-Flight Spectrometer (Lattice Vibrations)
  - Inverse Geometry Inelastic Scattering (Vibrational Spectra)
  - Backscattering (Diffusion Relaxation)
- **Non-destructive detection of residual stress**
  - Powder Diffraction
  - Bragg-edge imaging
- **Non-destructive microscopic detection**
  - Neutron imaging
- **Measurement of trace element**
  - Neutron activation
- **Radiation effect**
  - neutron radiation
  - proton radiation
  - gamma radiation

In-situ sample environment:
Temperature range: ~mK to +1600°C
Magnetic field: 14 T
Pressure: 30 GPa
Tensile force: 100 kN
Dimensions: 2 tons, 2 meters
Electric field, gas filling, etc.



Single-Event Effect (SEE) in Integrated Circuit Chips

ANIS was to provide an advanced atmospheric neutron acceleration test and scientific research platform for communication, aerospace, nuclear power, medical treatment, transportation, high-performance computers and other fields.

- On June 2022, ANIS passed the acceptance. The energy spectrum is very closer to that of the actual atmospheric environment.

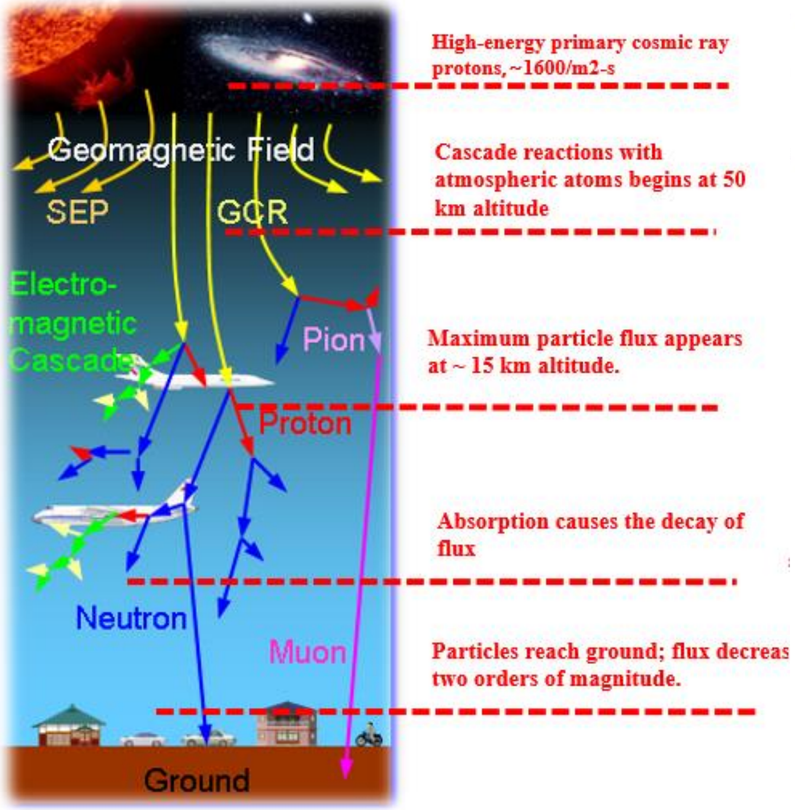
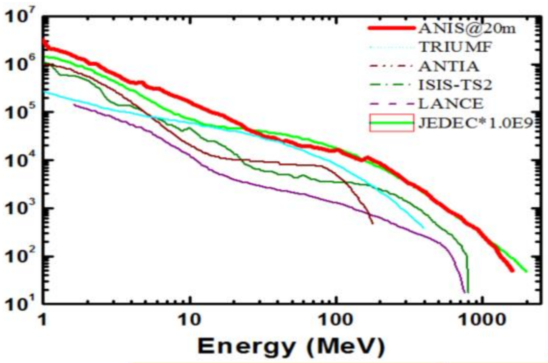
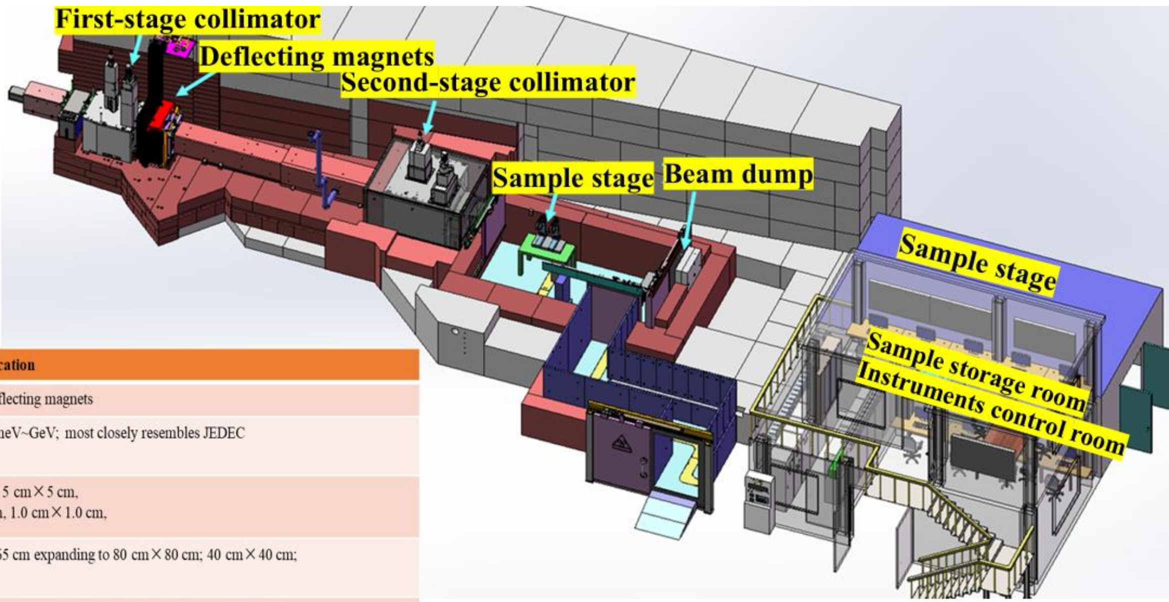


Diagram of secondary radiation produced by cosmic rays in the atmosphere

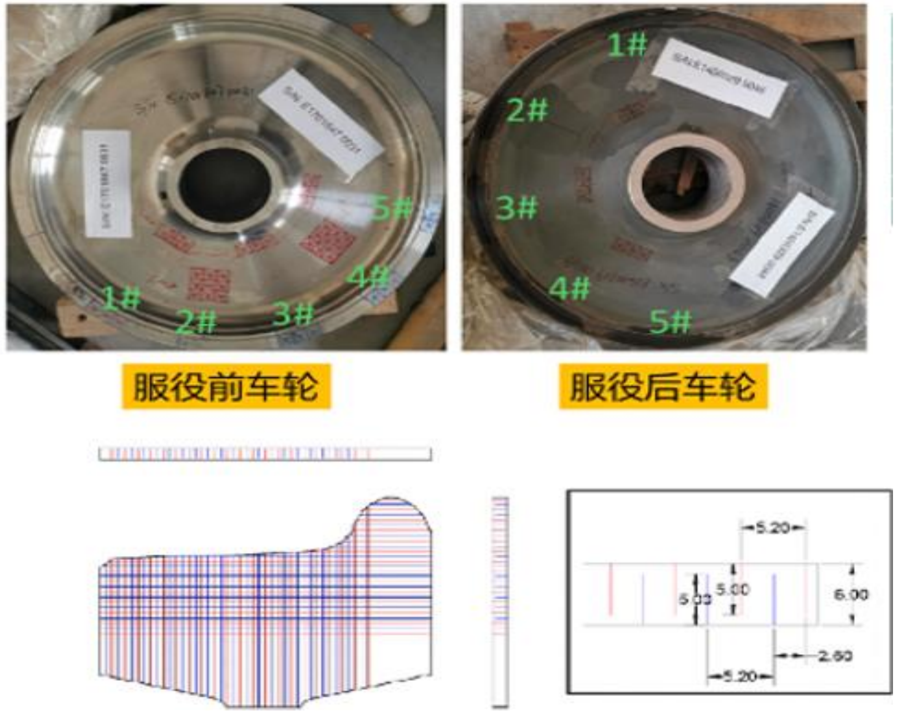




Contents	Design Specification
Charged particles	Removal by deflecting magnets
Neutron energy spectra	Ranging from meV~GeV; most closely resembles JEDEC
Spot size of the collimated beam	10 cm×10 cm, 5 cm×5 cm, 2.5 cm×2.5 cm, 1.0 cm×1.0 cm,
Spot size after beam expansion	From 65 cm×65 cm expanding to 80 cm×80 cm; 40 cm×40 cm;
Neutron flux	collimated spot:10^4~10^7 n/cm²/s, increasing in steps of 5 times expanding spot:10^3~107 n/cm²/s, increasing in steps of 5 times
Uniformity	>90%
Sample stage	20m/25m, High accuracy sample XYZ stage
Measurement environment of sample	-55℃ ~ 150℃

Research on the wheel of high-speed train

This preliminary research on residual stress in wheels used for 350 km/h high-speed trains obtained stress data of the wheels, which is the first time in China. Experimental research on the performances of wheels before and after use was conducted at the engineering material Diffractometer, helping to improve the processing technology and lifetime of wheels. At present, we plan to advance the research on 400 km/h high-speed wheels.



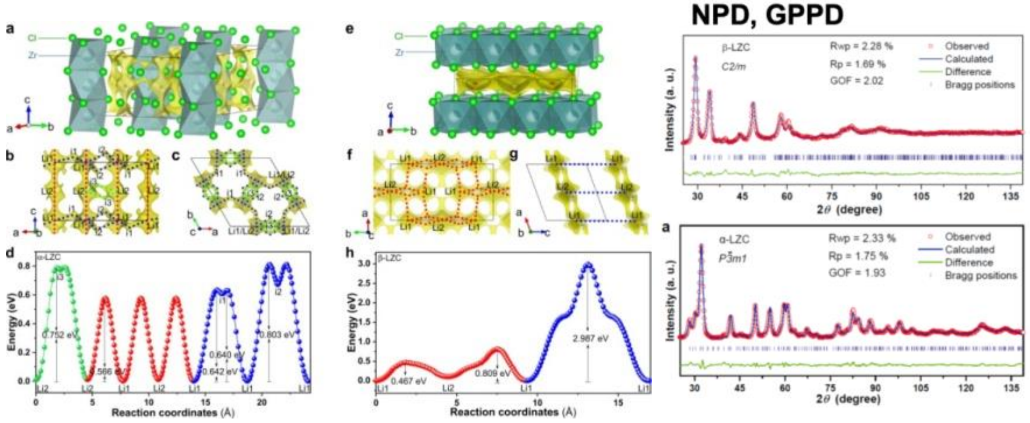
Academician Wang Haizhou's group
(Central Iron & Steel Research Institute)

New energy materials

Structural characterization on new energy storage materials such as lithium batteries, sodium batteries, hydrogen storage, and organic solar cells.

- Using neutron diffraction technology, Ma Cheng et al from USTC determined the lithium distribution of Li_2ZrCl_6, which is

1) overcoming the cost bottleneck of solid-state electrolytes;
2) advancing the commercialization of all-solid-state batteries;
3) good for environmental protection (Nat. Comm. 2021，12, 4410)

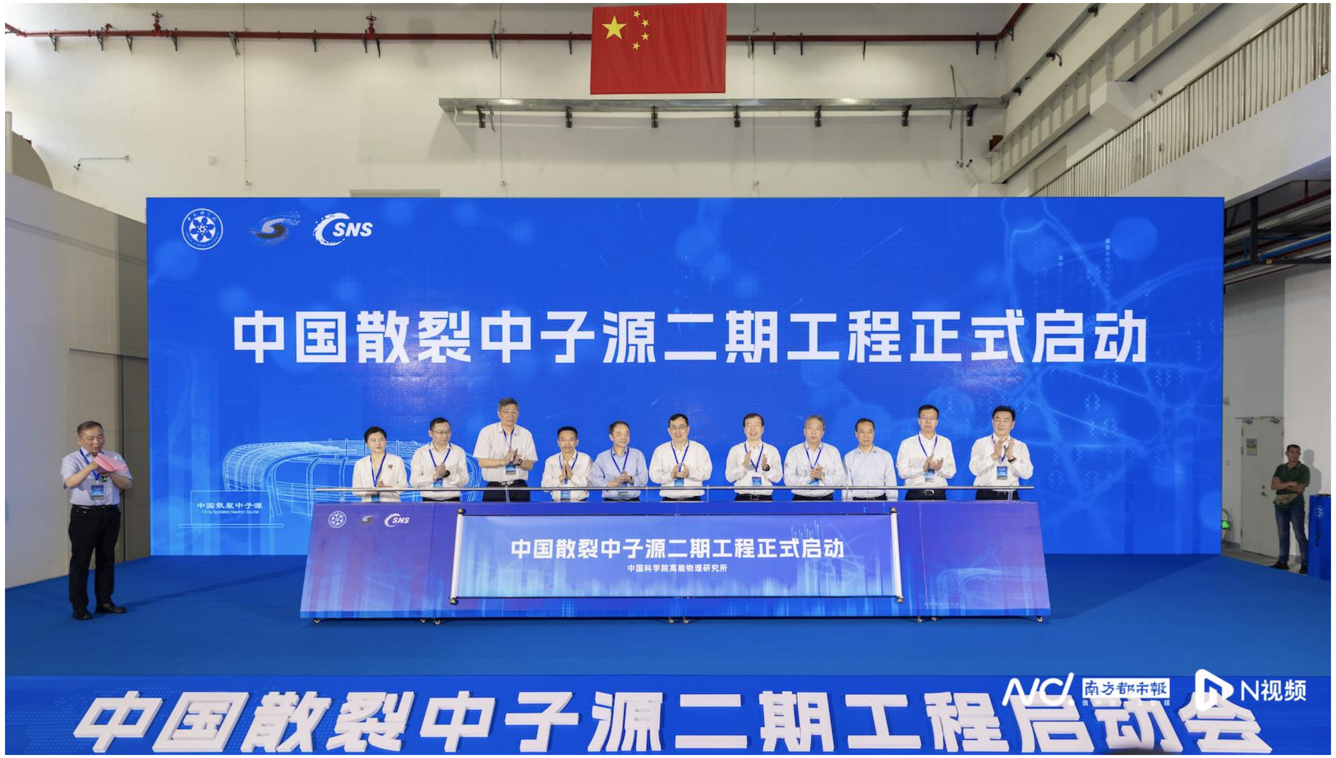


Other progresses

University/Institute	Researcher	Progress
BUAA	Shui Jianglan. et al	Hydrogen storage in incompletely etched multilayer Ti2CTx at room temperature (Nature Nanotechnology 2021, 16, 331)
PKU-SZI	Xiao Yinguo	Unveiling the migration behavior of lithium ions in NCM/Graphite full cell via in operando neutron diffraction (Energy Storage Materials, 2022, 44)
IOP	Gu Lin	Topologically protected oxygen redox in a layered manganese oxide cathode for sustainable batteries (Nat. Sustainability, 2021, 5, 214)
SCNU	Liu Shengjian & Li Qingduan	Superior layer-by-layer deposition realizing P–i–N all-polymer solar cells with efficiency over 16% and fill factor over 77% (J. Mater. Chem. A 2022, 10, 10880)
CUP & NEPU	Hu Qinhong & Sun Mengdi	Research on shale oil and gas (China Energies 2022, 15, 913; Scientific Reports, 2021, 11, 1)

CSNS phase II

On Mar. 30, 2024, **CSNS II project construction began**, with a construction period of 5 years and 9 months. After completion, the research capabilities of the facility will be significantly enhanced and basically cover all application fields of neutron scattering. The experimental precision and efficiency will be improved, providing a more solid foundation for exploring scientific frontiers, and resolving key issues in industrial development.



What to construct:

- **Improving the accelerator power to 500kW**
- **9 neutron instruments and 2 experimental terminals**
- **The first muon experimental terminal in China**
- **High-energy proton experimental terminal in China**

Future plan

- **Spallation Neutron Source and the Synchrotron Radiation Light Source complement each other, forming complementary research methods**
  - **Constantly improve the performance of CSNS**
  - **Construct Southern Advanced Photon Source (SAPS)**

Contents

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I China spallation neutron source

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III R&D for CSNS Phase II

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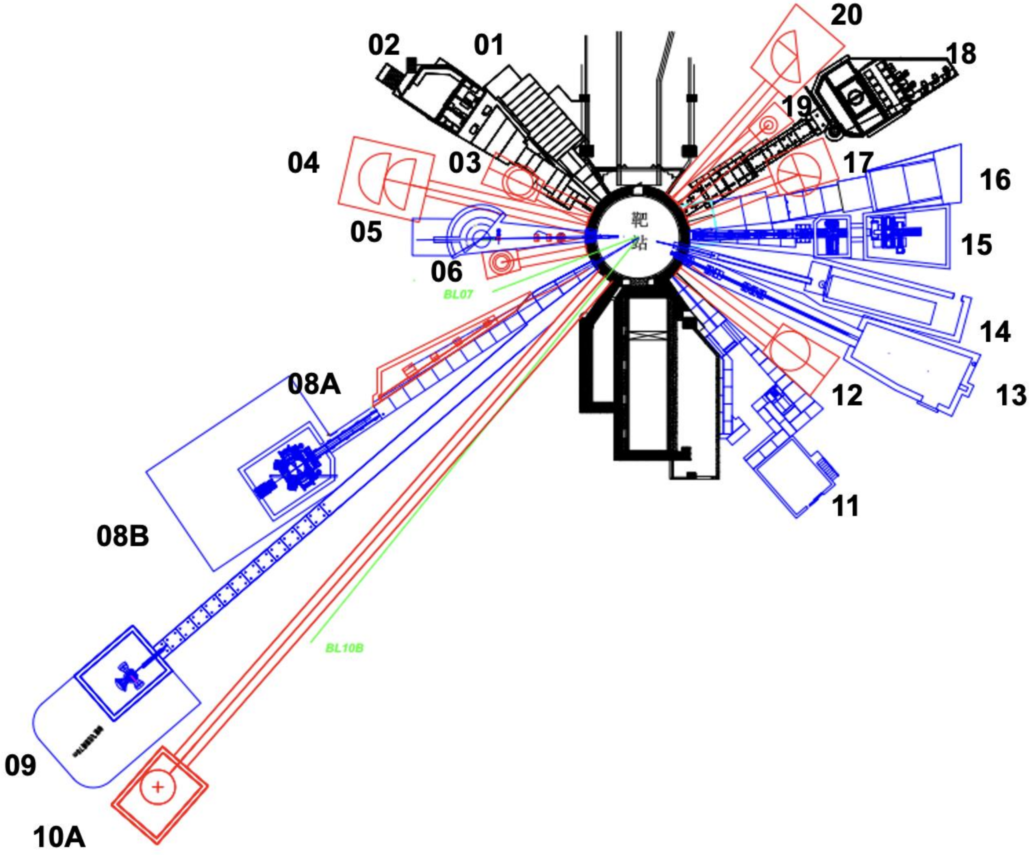
The detector and electronics team

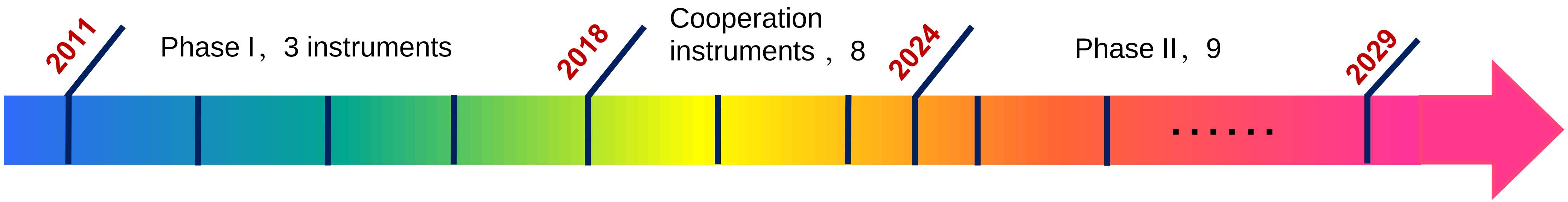
- **Team Mission:**
  - **Focusing on the requirements of the CSNS neutron Instruments**
  - **Developing advanced neutron detection system**



- **Team composition:**
  - **Professors: 3, Senior Researchers: 11**
  - **Total Number of Members: 50+**
  - **Expertise: Detection Physics , Electronics, Data Acquisition, Mechanics, and Engineering Processes**
  - **Average Age: ~36 years old**

Roadmap

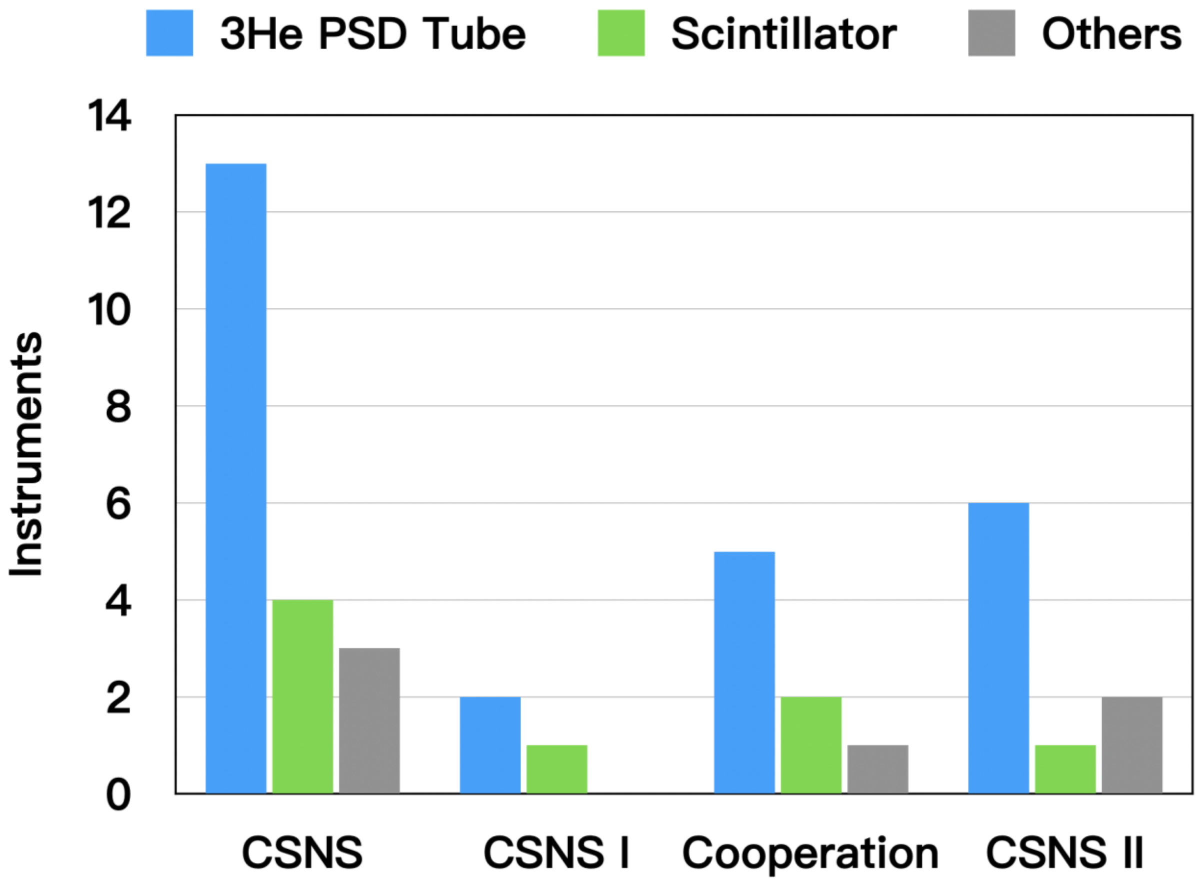
Develop detectors **“family”** for neutron instruments at CSNS

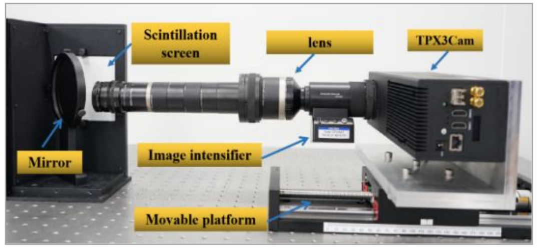


Detector

- **Neutron Scattering experiments**
  - **Diffraction, Inelastic**
Large area coverage
(>1m², Res ~cm) → **³He tube array detector**
Scintillation detector
  - **SANS, Reflection**
High spatial resolution
(<1m², Res ~ mm) → **GEM neutron detector**
Beam monitor
- **Neutron imaging experiments**
  - **Large FOV or**
High spatial resolution
(20cm*20cm, Res ~ μm) → **Scintillator coupled with CCD camera**
  - **Timing resolution**
for energy resolution
(Timing Res ~1μs, Res ~10 μm) → **nMCP detector**
Scintillator coupled with TPXCamera

Detector requirements for instruments at CSNS





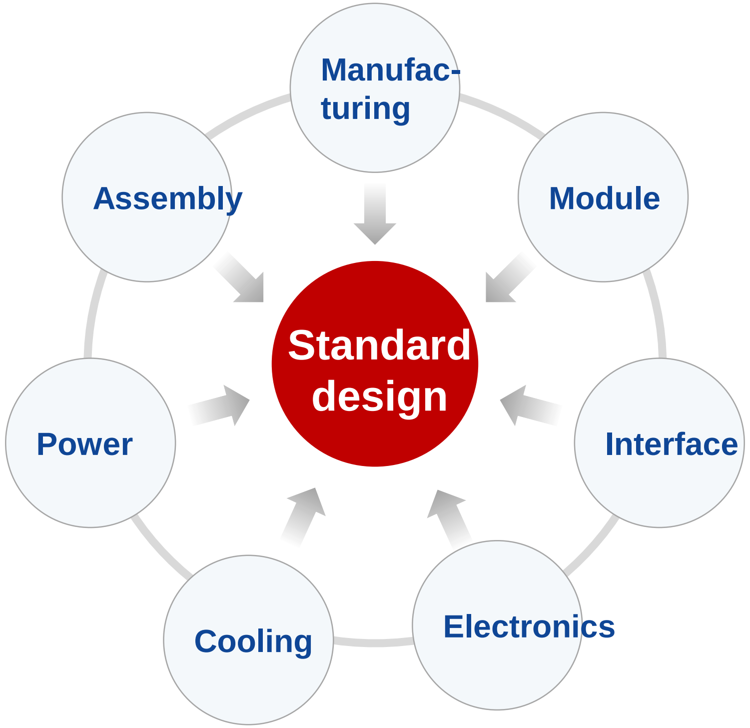
- The present engineering approach is based on the technology developed over the past 5-10 years.
- The ongoing research aims to provide the solution for the neutron instruments in the future.

Large-Area ^{3}He Tube Array Detector - Standardization

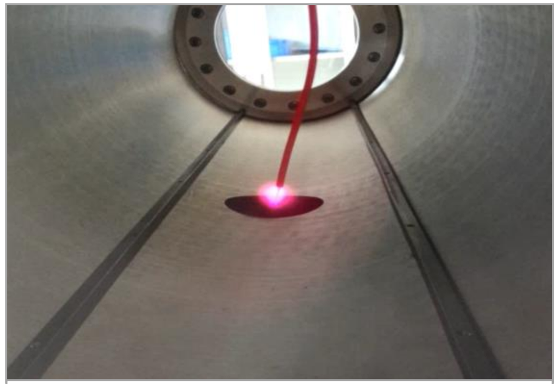
A continuously optimized and Standardized Engineering Design

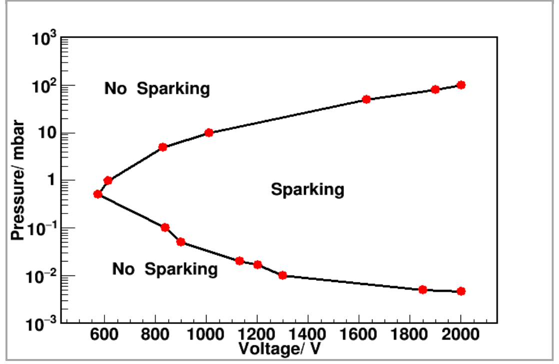
- Three technical solutions for atmosphere, high vacuum and low vacuum
- Solve vacuum discharge, electronics cooling, space limitation, system noise and channel consistency.

Standardized Engineering Design



HV Discharge in vacuum





Continuously upgrade solutions

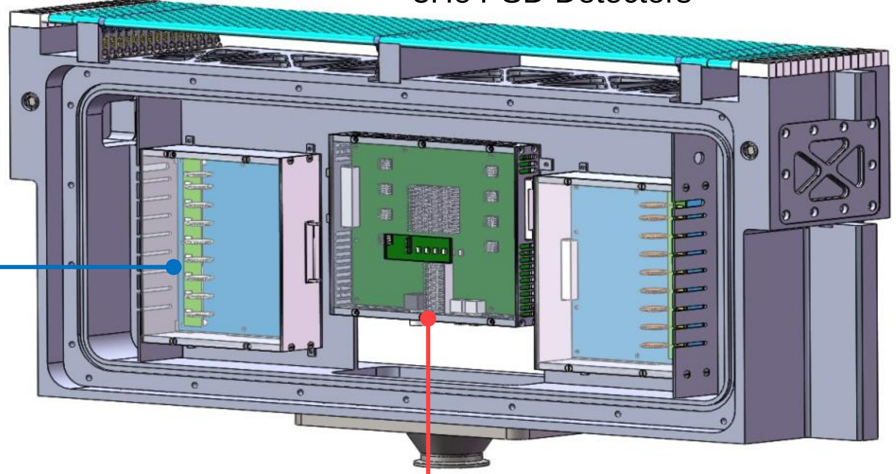
- Module design with 8 or 16 tubes
- Key component from multiple supply, avoiding single source dependency.
- FEE close to detector to reduce noise
- Optical fiber connections between devices to prevent electromagnetic interference.
- Improve stability and real-time monitoring

Large-Area ^{3}He Tube Array Detector Readout Electronics

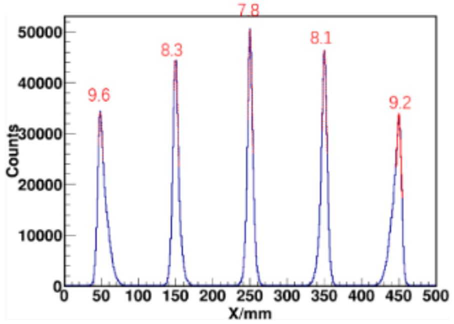
Based on customized high-density pre-amplifier ASIC, with induvial DAC for threshold tuning

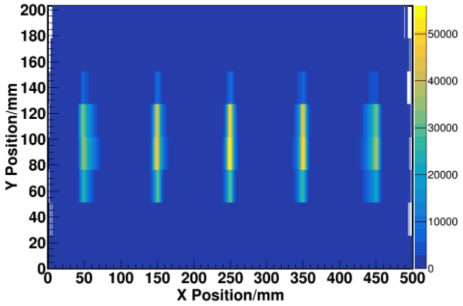
Pre-Amplifier Board x 2
- 8 channels
- CSA + CRRC + Single-ended to differential
- Shaping time: ~ 2 us
- High-Voltage distribution
- Power consumption: ~ 4 Watt

3He PSD Detectors



Digitization Board
- 16 input channels
- FPGA: Virtex5-LX85T
- Waveform sampling of 65 Msps @ 14bit
- Peak finding and hit-position calculation by charge division method
- Optical SiTCP for DAQ
- Power consumption: ~ 5 Watt
- T0/ID receiver for timing and tagging





Specs	Requirement	Results
Dynamic Range	100 - 800 fC	100 - 830 fC
Charge Resolution	< 15 fC	< 5 fC
INL	< 1%	< 0.5%
Counting Rate (Channel, peak)	> 100KHz	> 100KHz
Timing Resolution	< 1us	< 20 ns
Position Resolution	< 10 mm with 1m tube	< 8 mm

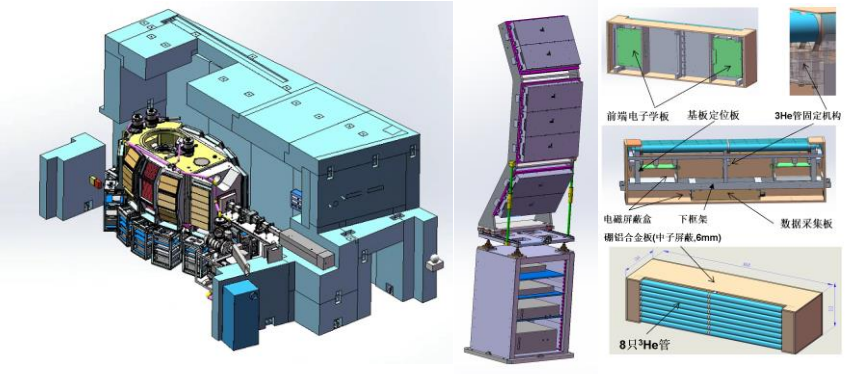
Large-Area ^{3}He Tube Array Detector - Atmosphere

Multi-Physics Instrument (MPI) detector system

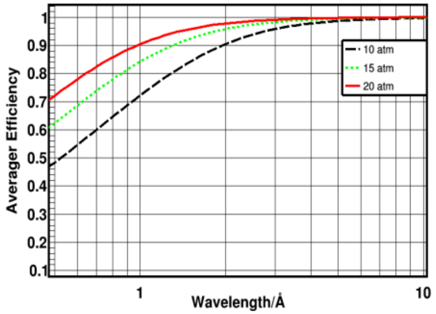
RDTM 2021, 5: 200-206. Nuclear Science and Techniques, 2022, accepted

- Large-area coverage: 6.6m^2 (544 1-inch diameter ^{3}He tube)
- Start operation in July 2021 and run stably for 3 years

Detector system design



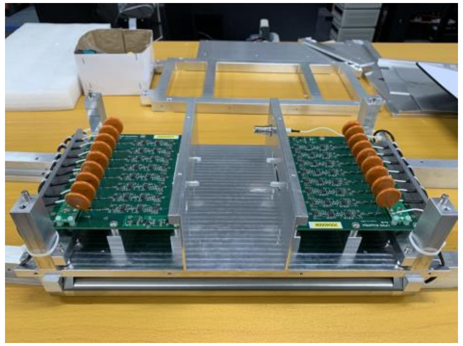
M.C. simulation



Technical review

Beam test

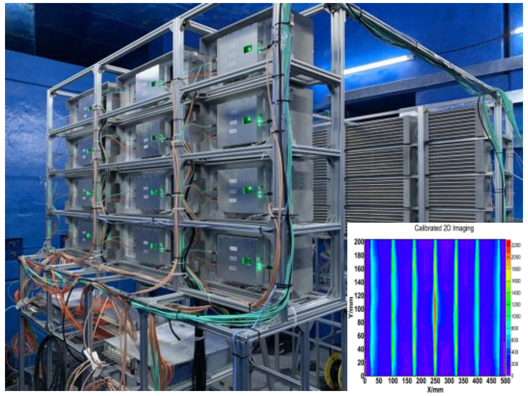
Key technology



Mass production

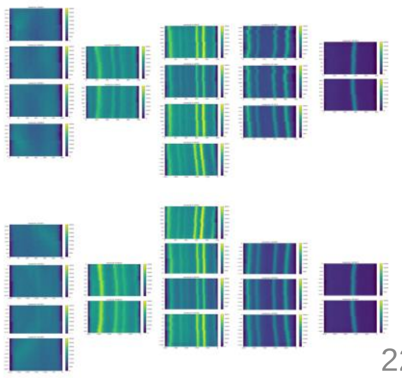
Assembly & testing

System calibration



On-site installation

Sample experiment

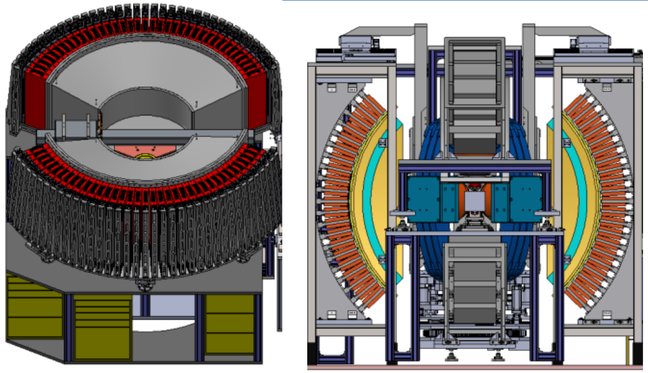


Large-Area ^{3}He Tube Array Detector - High Density

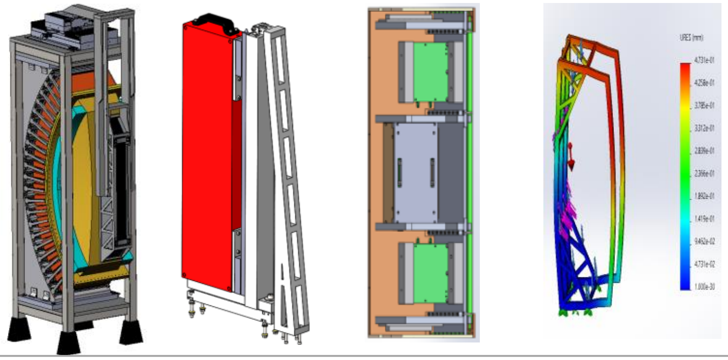
High Pressure Neutron Diffractometer (HPND) & High Resolution Diffractometer(HRD)

HPND: 928 8mm/half-inch ^{3}He tube, one module with 16 tubes, finished in next 3 months.

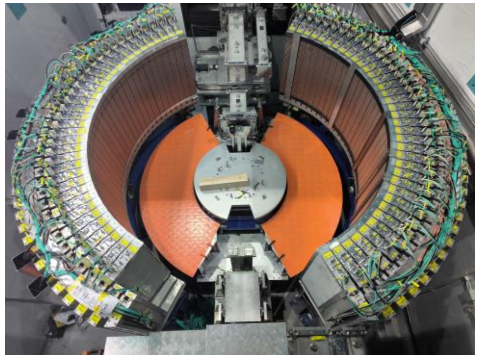
Engineering Design of HPND

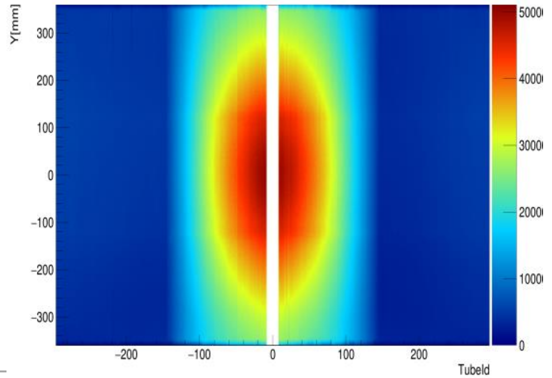


Detector Module Design



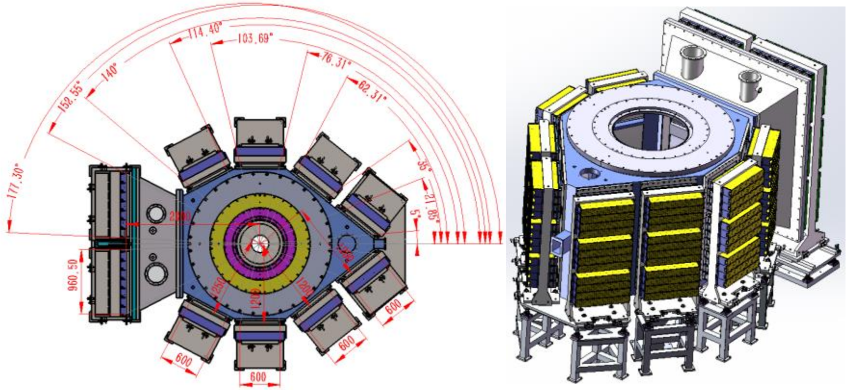
Installation & commissioning



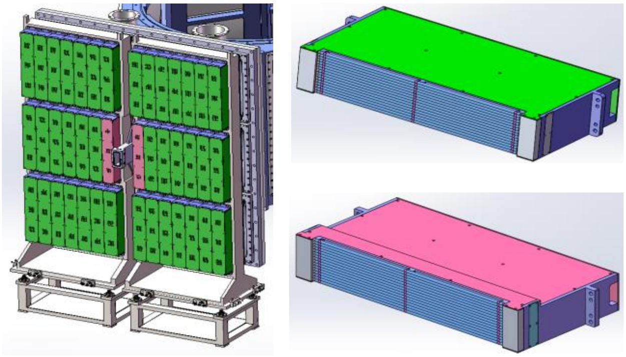


HRD: 1376 8mm/half-inch ^{3}He tube, one module with 16 tubes, finished in next 3 months.

Engineering Design of HRD



Detector Module Design



Installation & commissioning

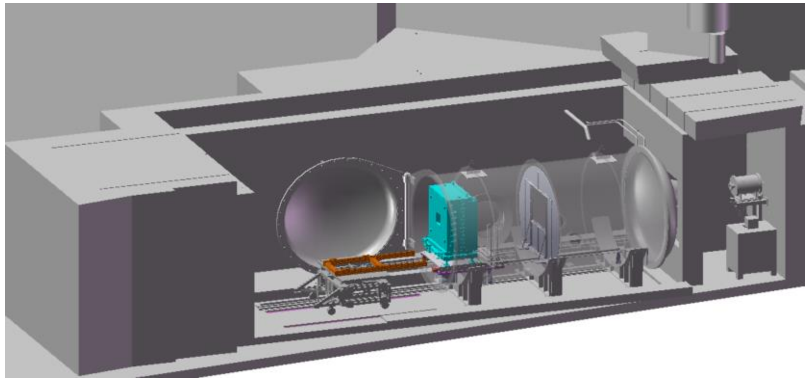
Large-Area ^{3}He Tube Array Detector - Low Vacuum

Nuclear Science and Techniques, 2022, 33: 89

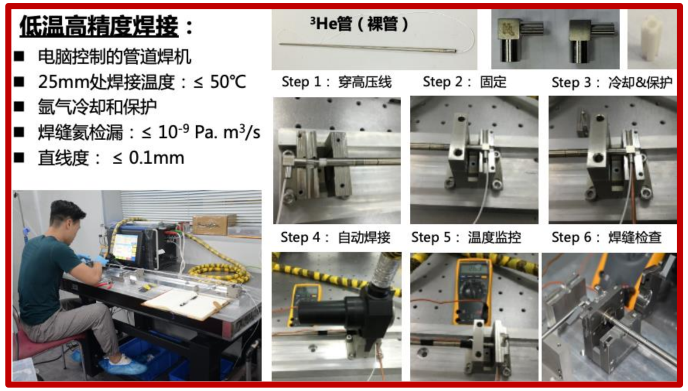
Small-Angle Neutron Scattering (SANS) detector system

- 120 8mm diameter ^{3}He tubes, small space, low vacuum environment (10Pa), movable base.
- All-metal connections and low-temperature welding. Operating stably for 6 years.

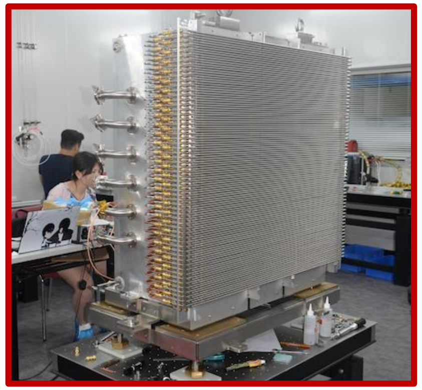
Detector system design



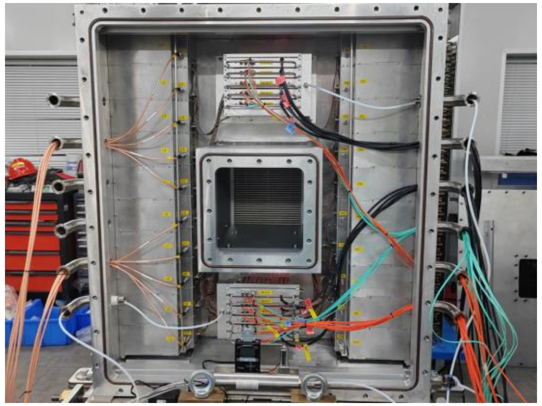
Low temperature and high precision welding on ^{3}He tube



All metal pipeline connection



Readout Electronics

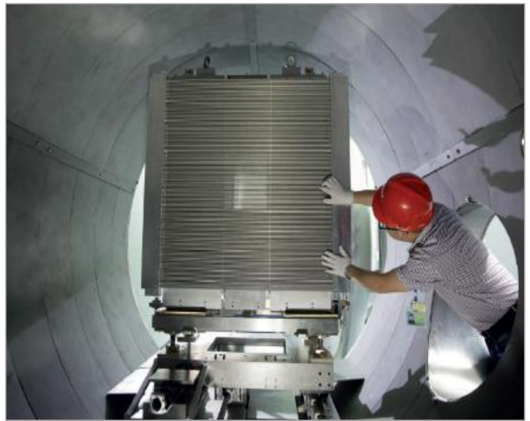


Beam test

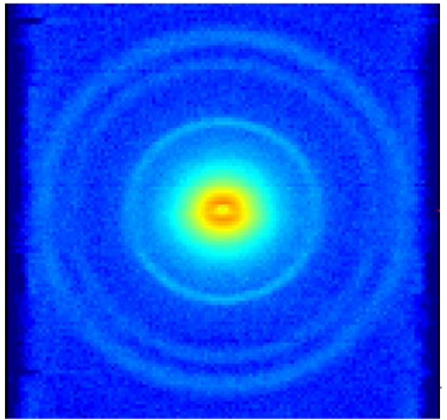
Assembly and testing

On-site installation

Nature News @2017.11.1



Sample experiment

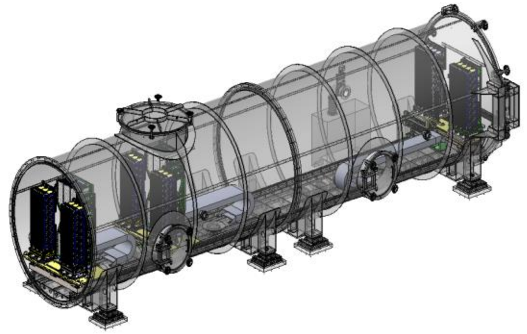


Large-Area ^3He Tube Array Detector - Low Vacuum

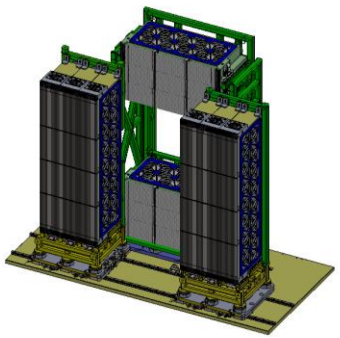
Very Small Angle Neutron Scattering (VSANS) detector system

- 512 8mm diameter ^3He tubes, low vacuum environment (10Pa), movable base.
- One module with 16 tubes. **Operating stably for 1 year.**

Detector system design



Module design

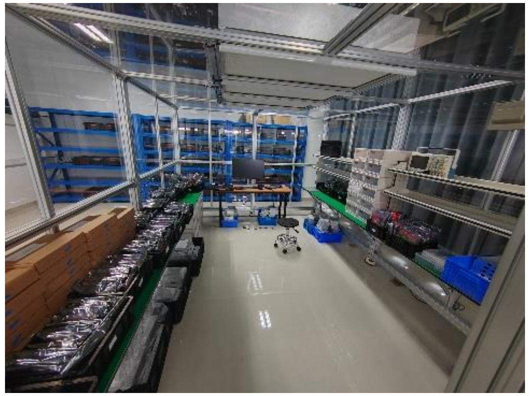


Prototype development

key technology

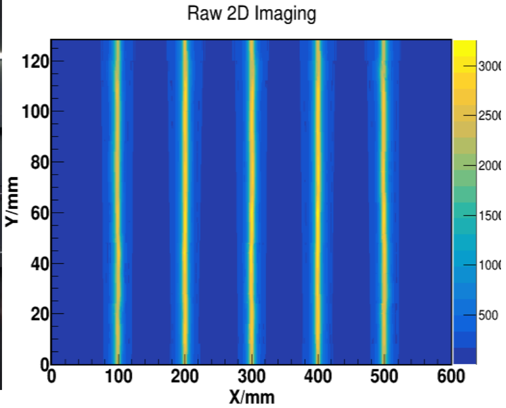
Batch manufacturing

Assembly and testing

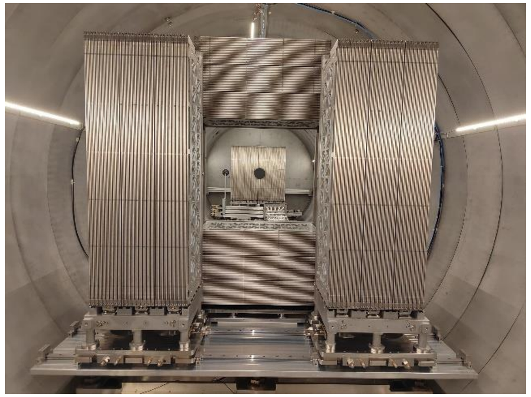


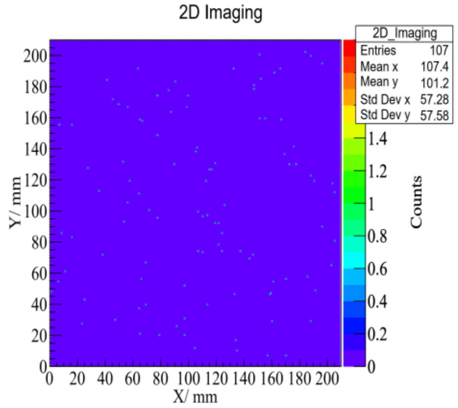
Beam test

Calibration



On-site installation



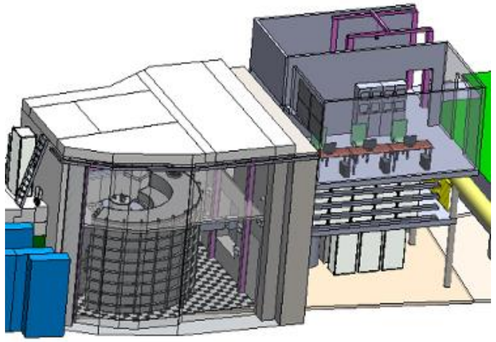


Large-Area ^{3}He Tube Array Detector - High Vacuum

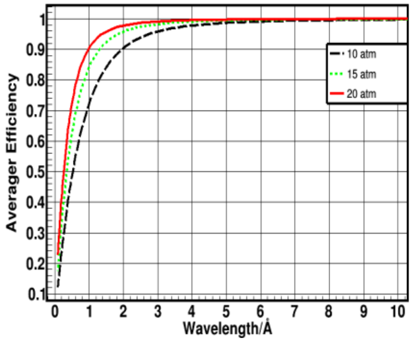
High energy Direct geometry inelastic neutron scattering instrument

- 264 1-inch, 3 meters long ^{3}He tube, high vacuum environment (10^{-4}Pa).
- The detector installation has been completed and **commissioning is underway**.

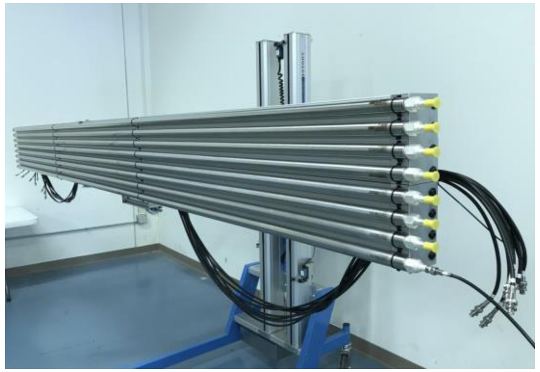
Detector system design



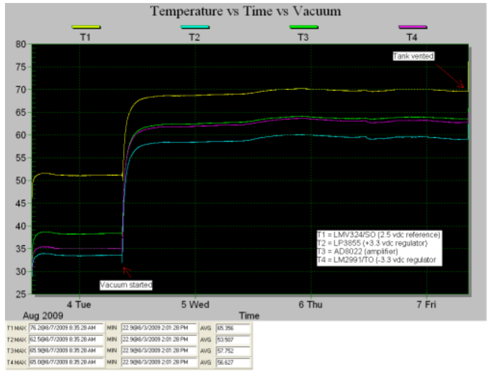
M.C. simulation



Prototype development



key technology research

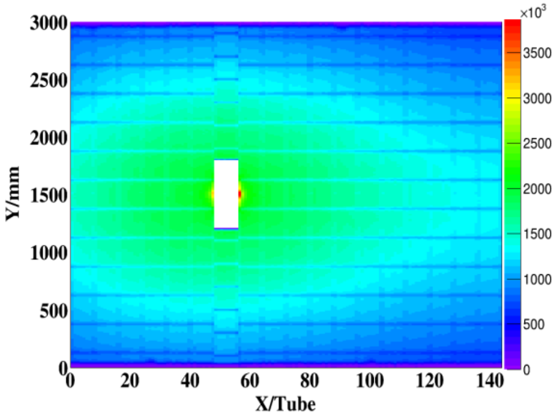


Mass production

Assembly and testing

On-site installation and commissioning

Position Calibration



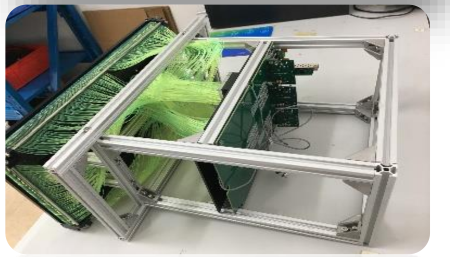
Large-Area Scintillator Detector

Module design: front-end digital for fast readout, highly integration and easy assembly

2010~2018

First-generation

- **0-> 1 Breakthrough**
- **laboratory-level to engineering-level products**

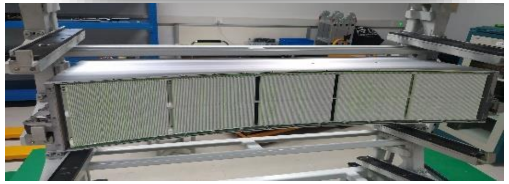


- **Engineering application: GPPD spectrometer 6m^2 space coverage**

2018~2023

Second -generation

- **Performance further improved**
- **implementation of batch production**



- **High integration, low power consumption**
- **Engineering application: EMD, ERNI and other spectrometers 8m^2 area coverage**

2023~2029

Third -generation

- **More compact**

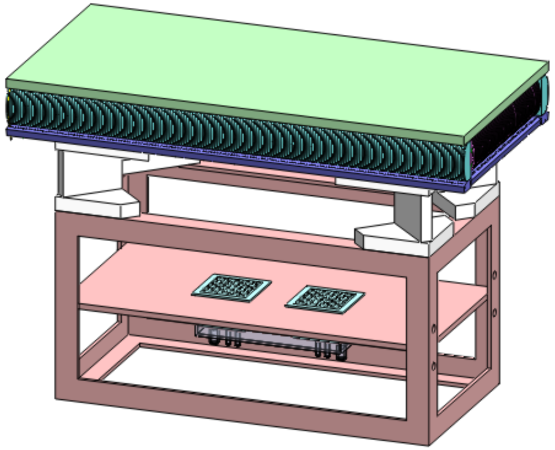
- **High spatial resolution: <1mm**
- **Can work in vacuum environment**
- **Domestic Key Components**
- **Engineering application: CSNS II**

Large-Area Scintillator Detector – 1st generation

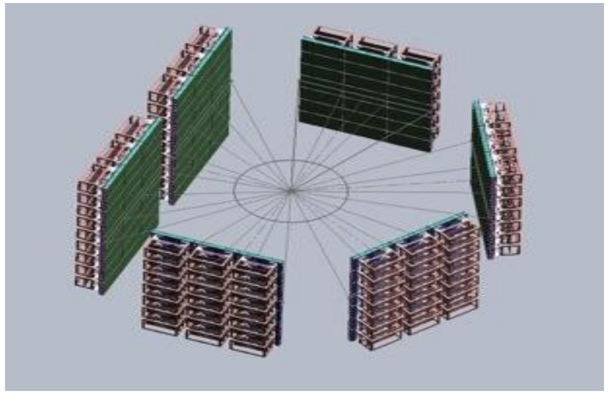
Flat Panel Scintillation Neutron Detector for GPPD

- Detection area 6m^2, ^{6}LiF/ZnS(Ag)+WLSF+MA-PMT
- Start operation from August 2018 and run stably for 6 years.

Detector module design

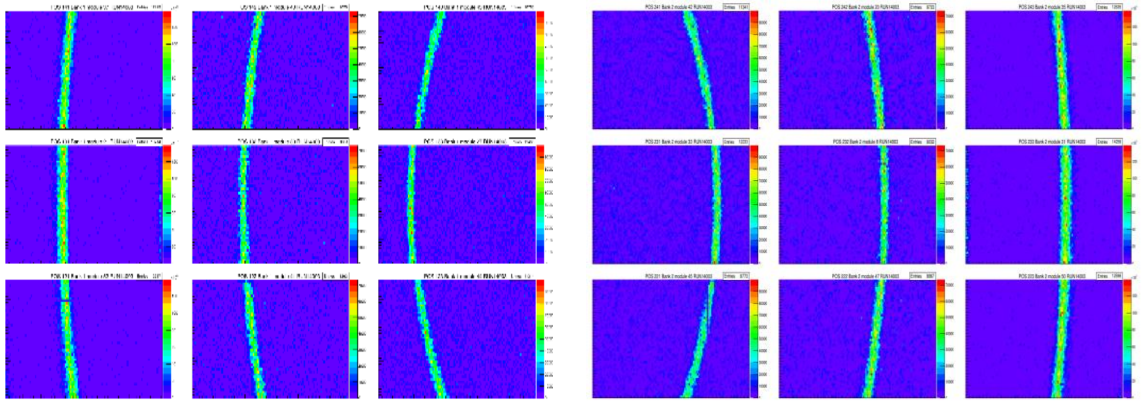


Detector array design

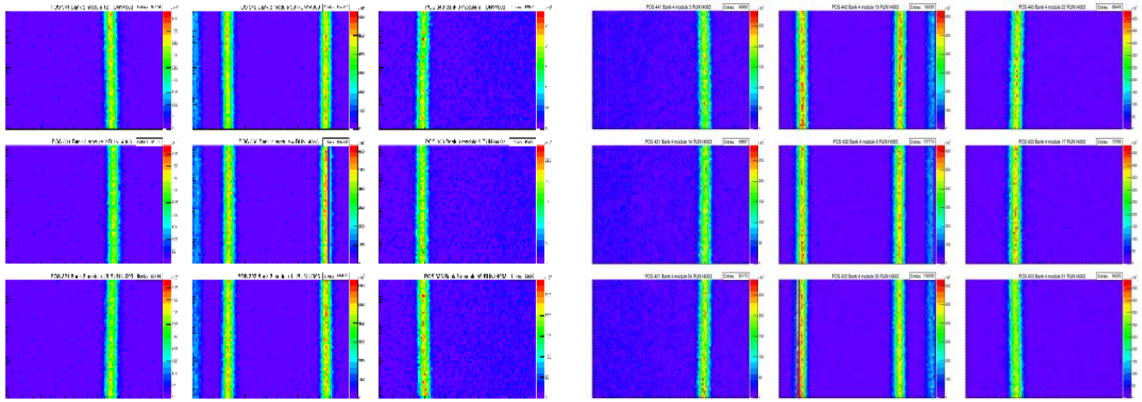


Sample experiments

Bank1 and Bank2



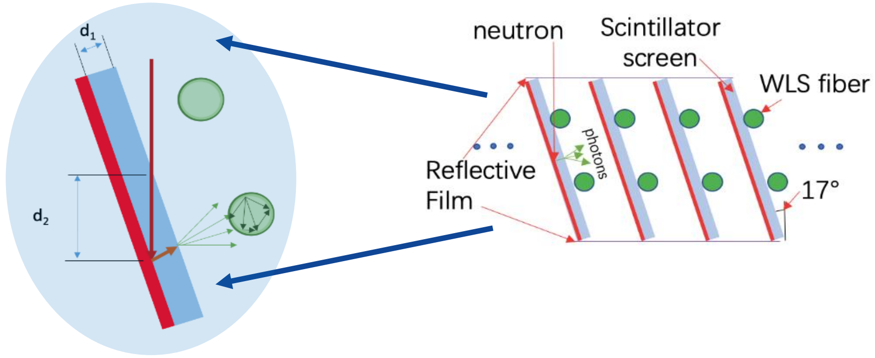
Bank3 and Bank4



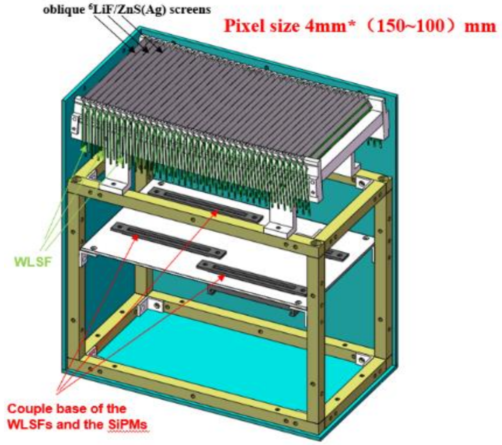
Large-Area Scintillator Detector – 2nd generation

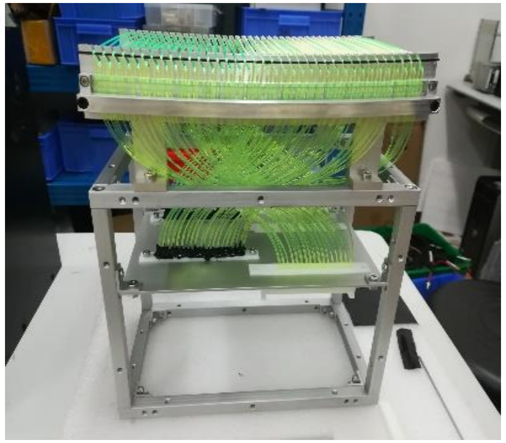
Oblique Incidence Scintillation Detector Based on SiPM

- **Including scintillator, WLSF, electronics, SoC, power supply, temperature monitoring, temperature compensation modules.**



$$n + {}^{6}Li \rightarrow \alpha(2.05MeV) + {}^{3}H(2.72MeV)$$

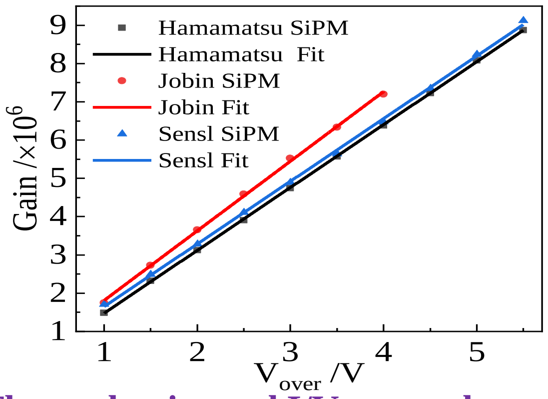


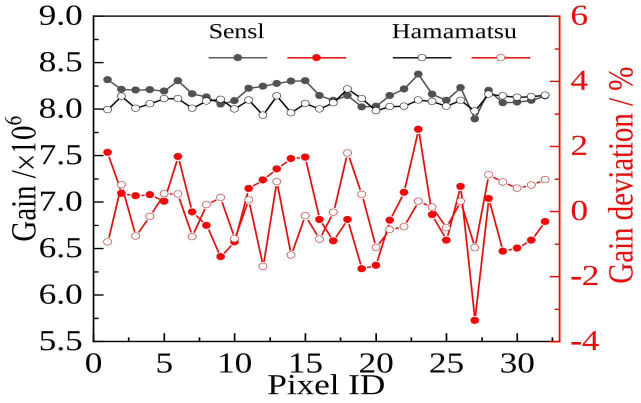


Detector module design

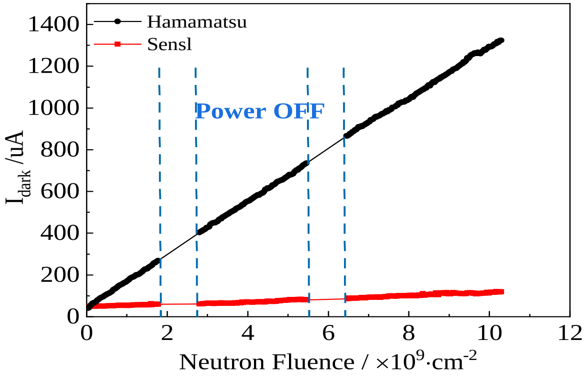
Solve problems of SIPM for large -scale engineering application

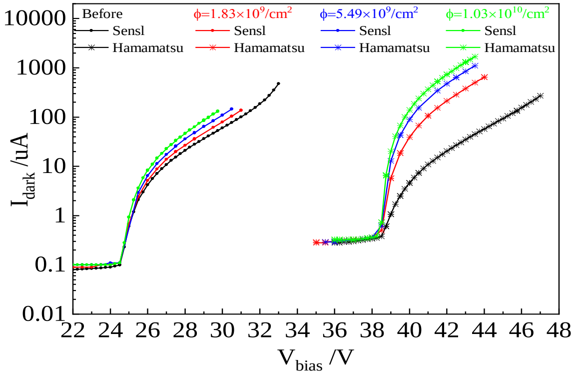
SiPM gain and gain uniformity comparison test





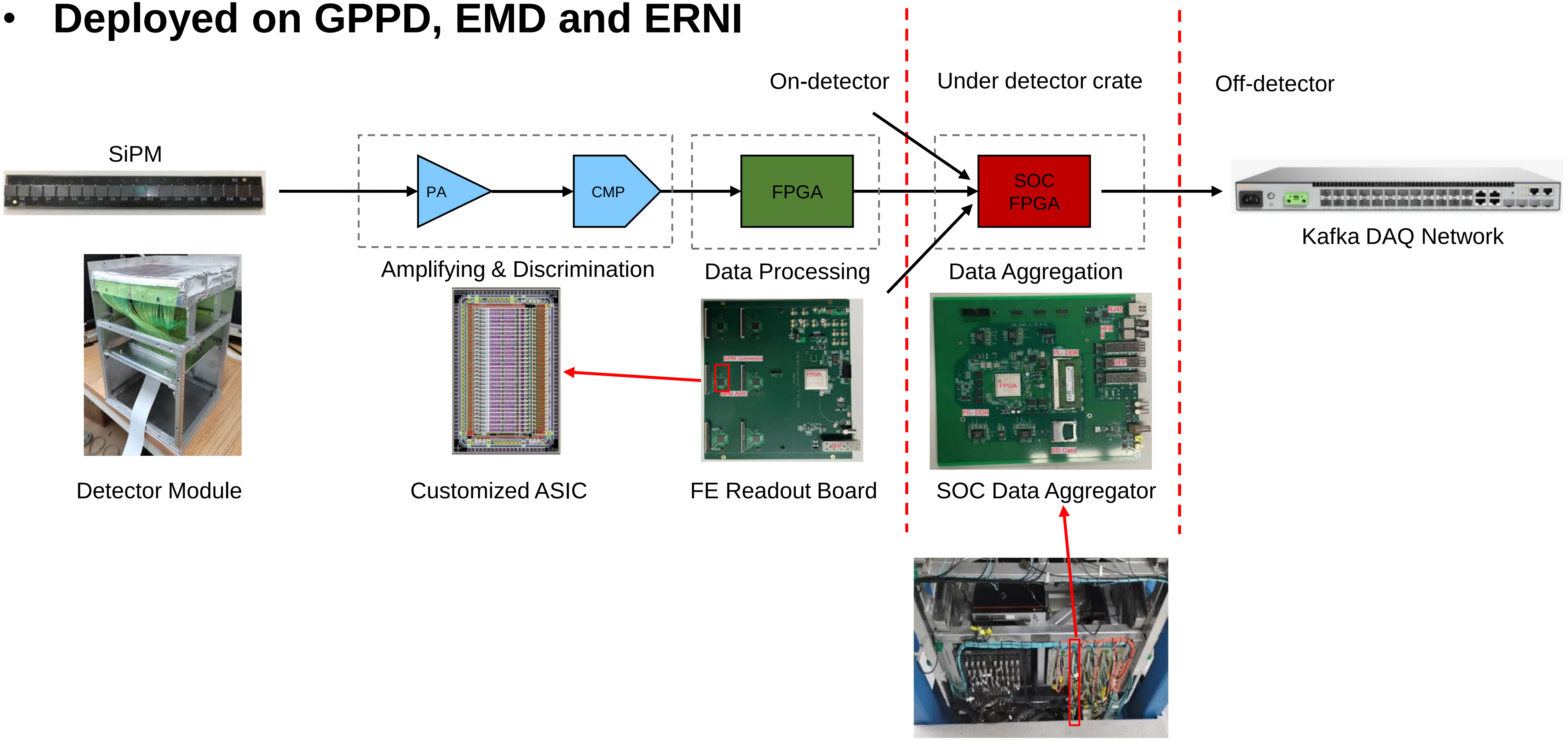
Thermal noise and I/V curve change before and after thermal neutron radiation





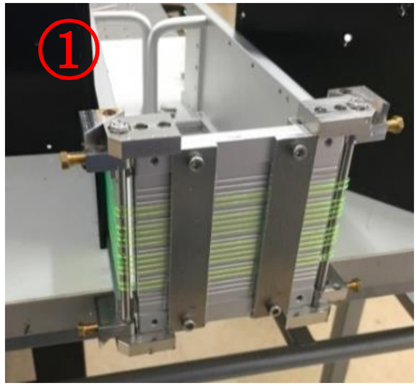
Large-Area Scintillator Detector Readout Electronics

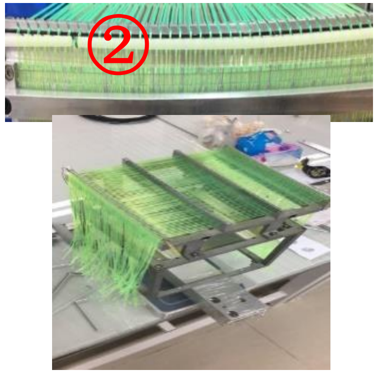
- **Based on customized high-density pre-amplifier ASIC, with induvial DAC for threshold tuning**
  - **Deployed on GPPD, EMD and ERNI**

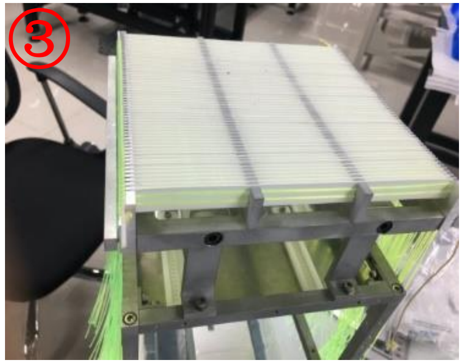


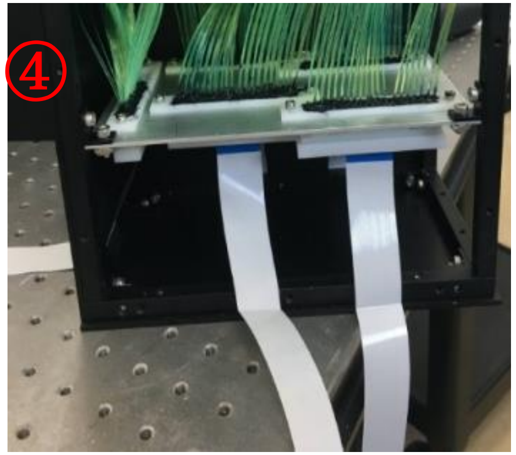
Large-Area Scintillator Detector - Mass Production

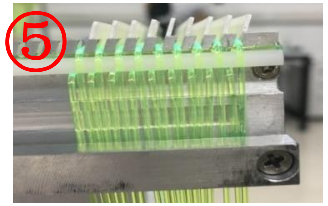
Mass production based on assembly line to reduce the impact of human factors in the process, improve the uniformity of the detector and control the quality

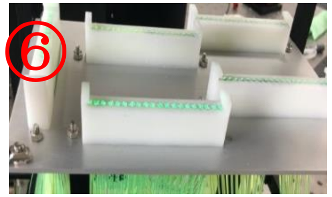










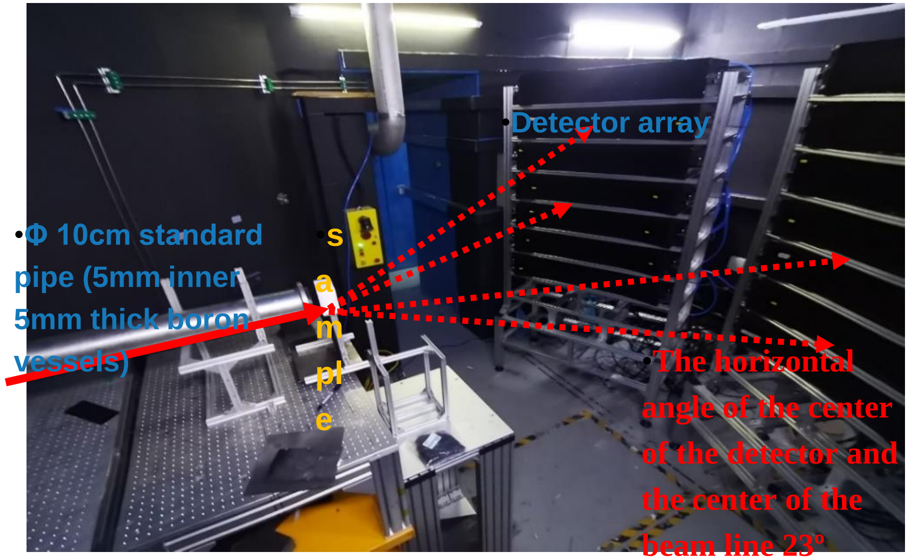


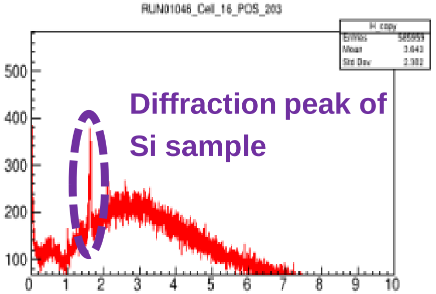
Large-Area Scintillator Detector

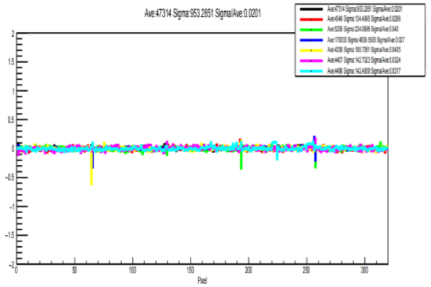
Applicated to Engineering Material Diffractometer (EMD) (100 units)

Batch calibration and optimization of the detector with neutron beam

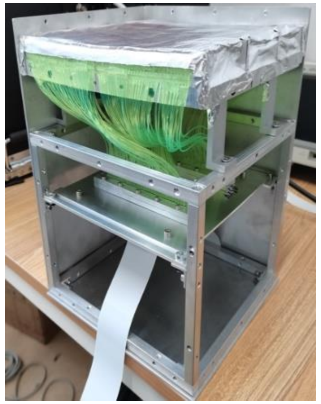
Beam Test

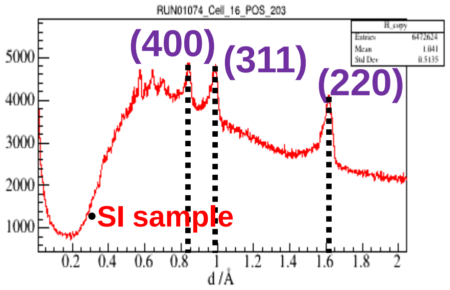


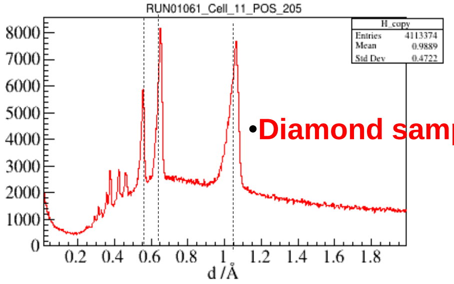




Uniformity of detection efficiency is better than 95%







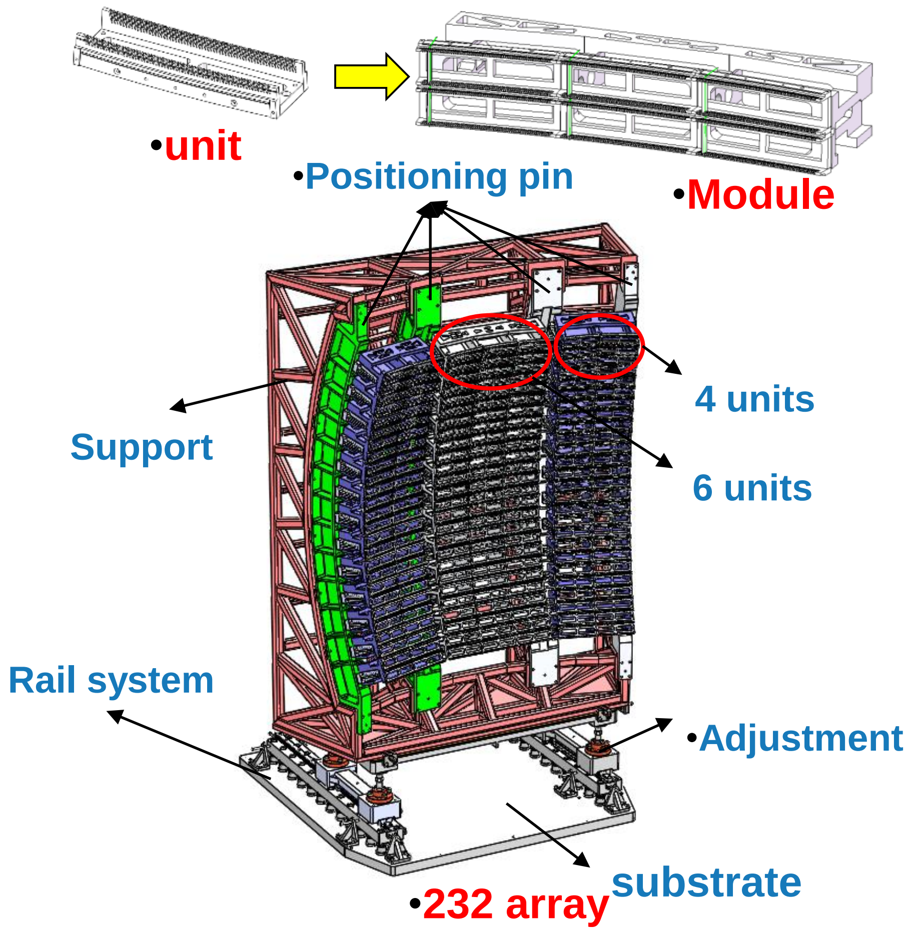
Characteristic diffraction peak of standard sample

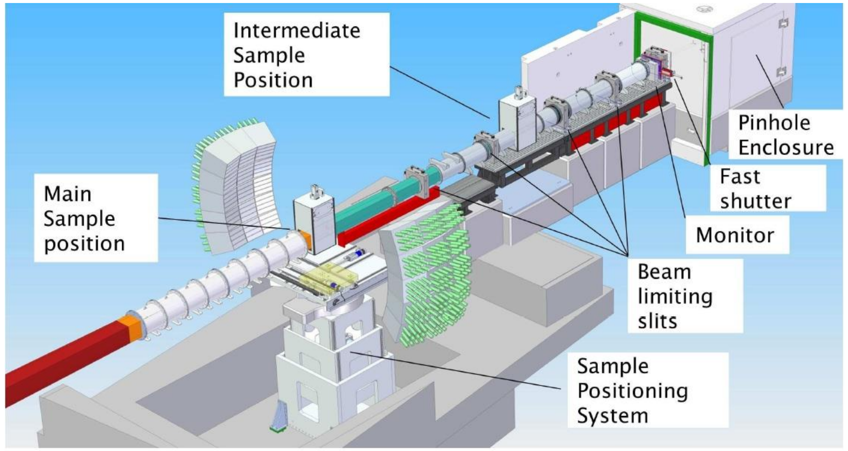
Start operation in the coming cycle

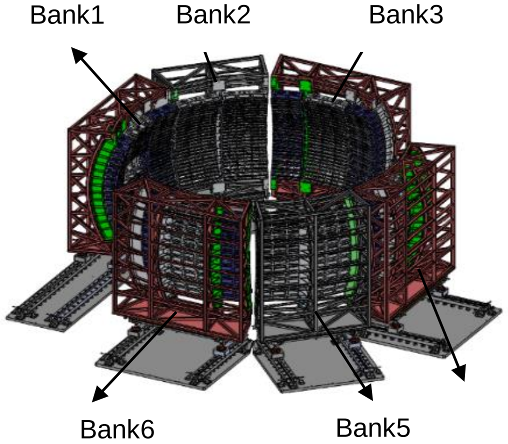
Large-Area Scintillator Detector

Applicated to Energy-Resolved Neutron Imaging instrument (ERNI) (400 units)

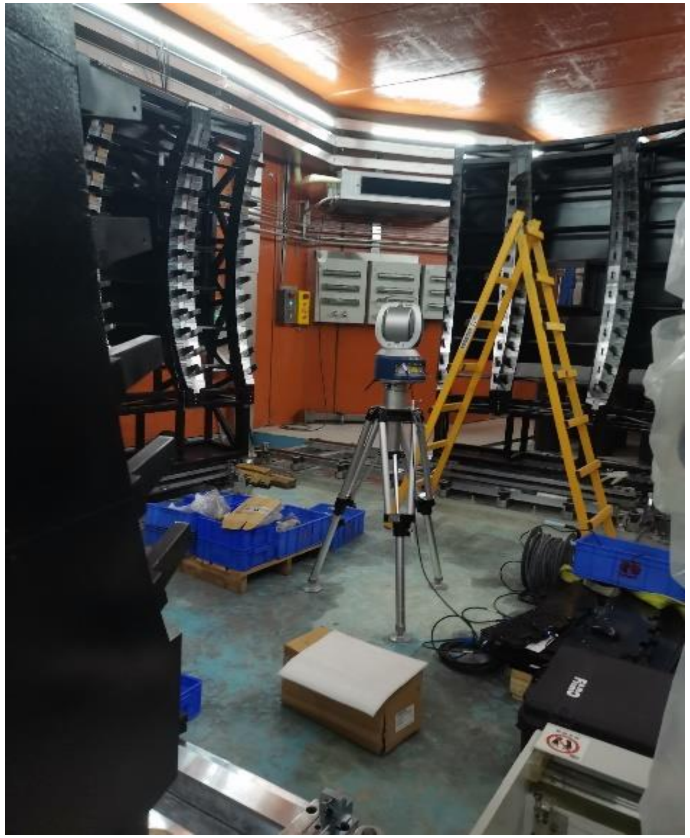
- Detection area: ~ 3m^2, 25,000 channels of electronics, solved the problem of power consumption and heat dissipation. Operating stably for 1 year.







Detector engineering design



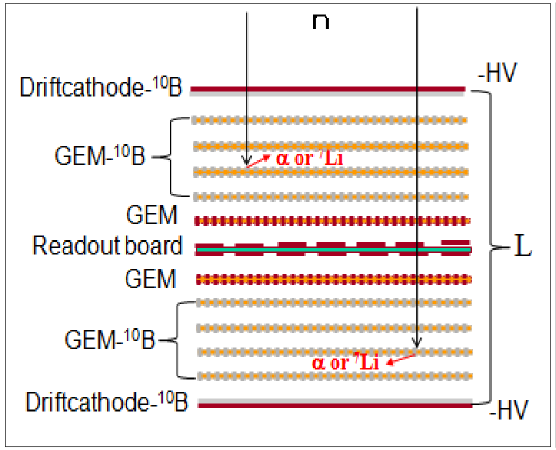
on-site installation and commissioning

Ceramic GEM Neutron Detector

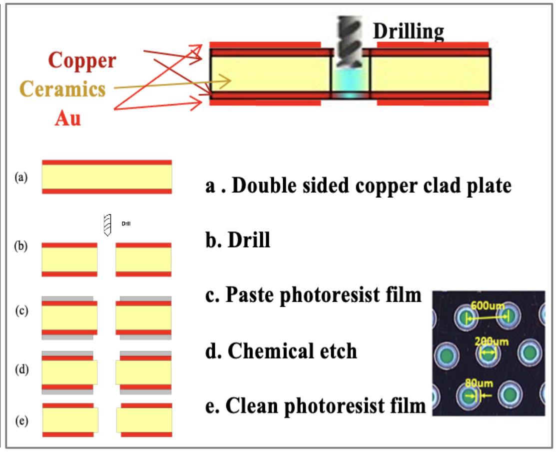
In 2013 the ceramic GEM was invented to reduce hydrogen containing materials with low neutron scattering, high radiation resistance and high temperature resistance

Aiming at engineering applications，ceramic GEM based detector design and key technology development

Detector design



Ceramic GEM development



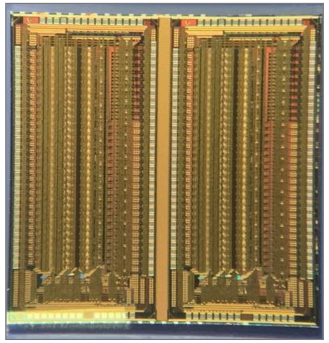
CPC, 40(7):076002,2016

Large-area boron coating by magnetron sputtering

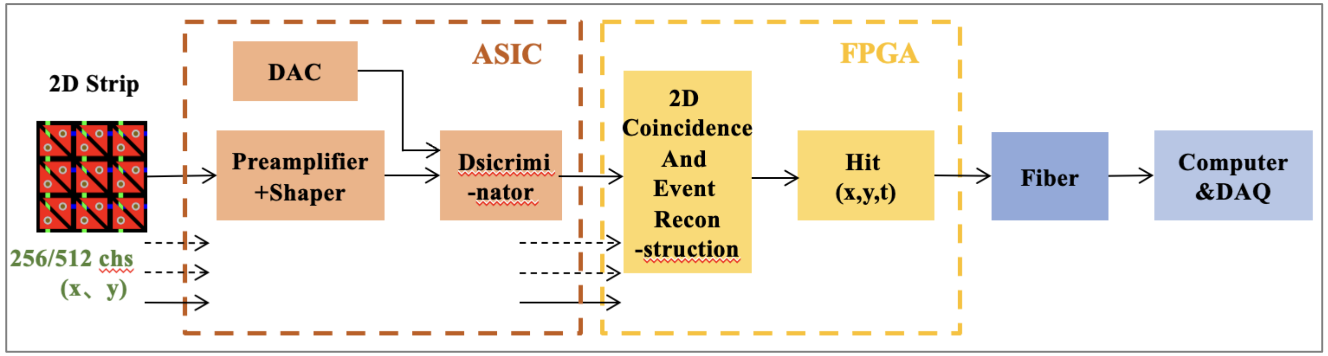
Rev. Sci. Instrum. 94, 093901， 2023

R&D of multi-channel ASIC chip

Parameter	Specification
Input charge	±10fC ~ ±400fC
Counting rate	1MHz/ ch
Channels	32*2
Output	2.5V TTL
Threshold	DAC adjustable



Fast digital readout electronics



Ceramic GEM - Beam Monitor

High flux 2D position sensitive neutron beam monitor

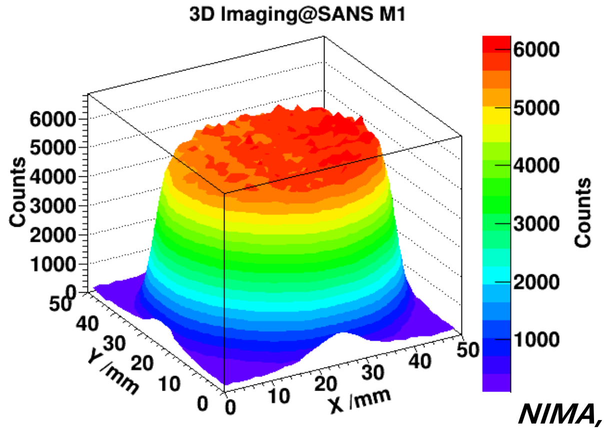
6 monitors were installed in CSNS I, operating stably for 6 years. 21 monitors totally used for instruments

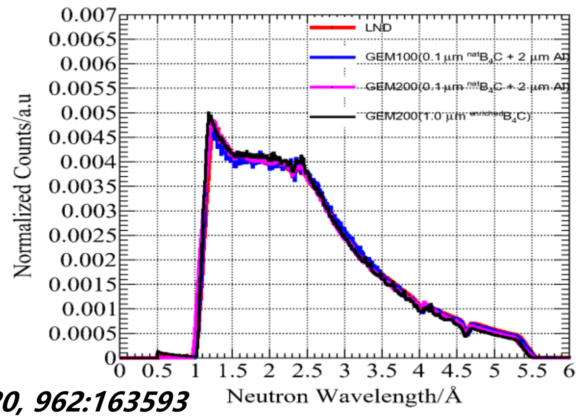
Monitor design parameters

Indicators	Specifications
Conversion layer	B_4C、C_2H_4，U
Effective area	50mm*50mm, 100mm*100mm, 200mm*200mm
Detection Efficiency @1.8Å	10^{-4}~10^{-2}
Counting rate	1 MHz
Neutron flux	10^{10} n/s

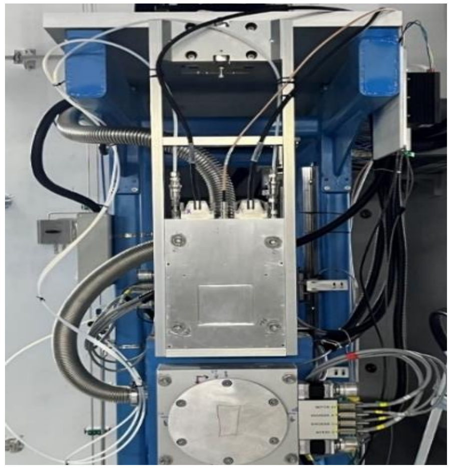
30 monitors have been mass-produced

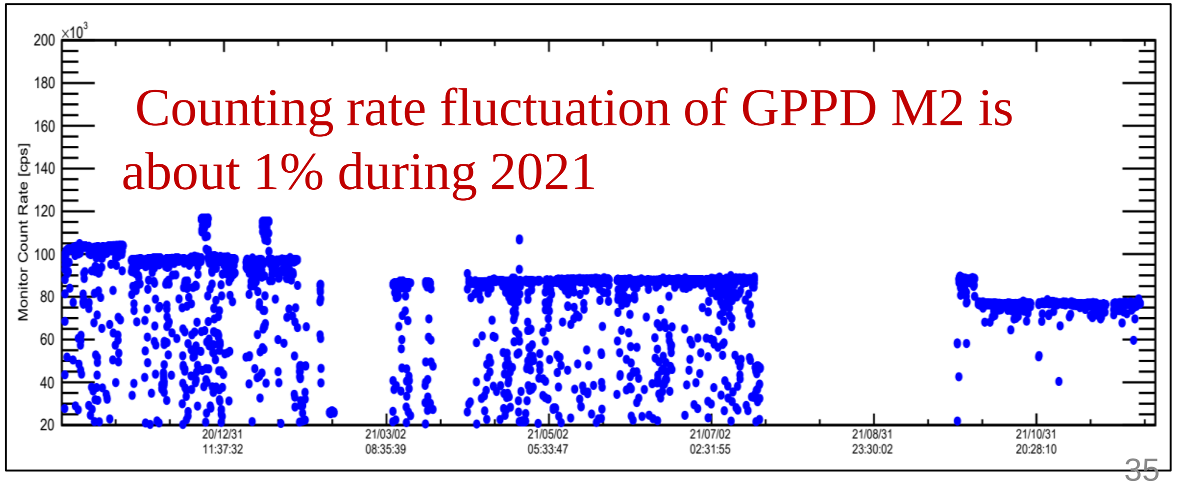
Monitor Operation Test Results





NIMA, 2020, 962:163593



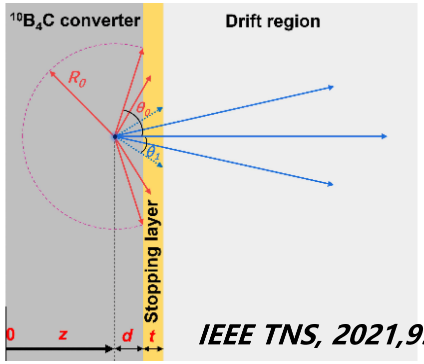


Ceramic GEM - Imaging Detector

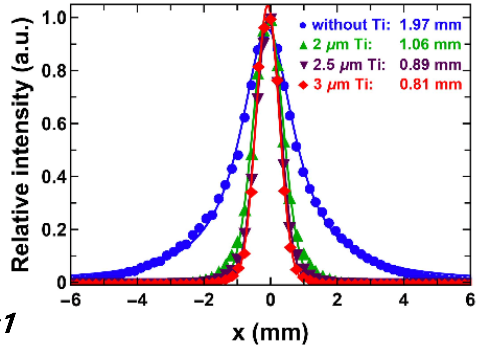
Large FOV GEM neutron detector for ERNI

Al/Ti film is used as a stop layer. Spatial resolution is improved to 0.8mm, and it has been installed at ERNI for bragg-edge imaging experiment.

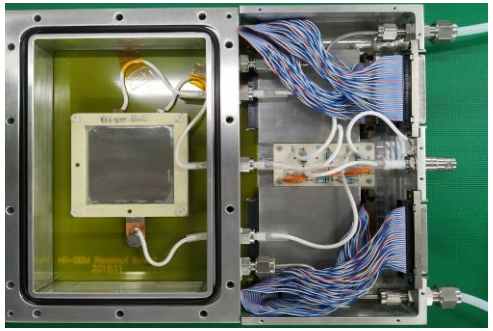
M.C. simulation



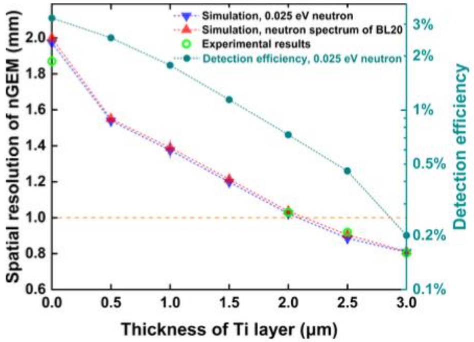
IEEE TNS, 2021,99:1

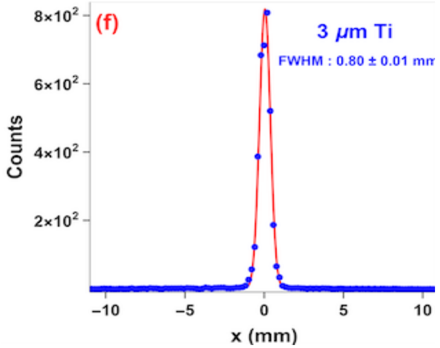


Prototype development



Test results of neutron beam test



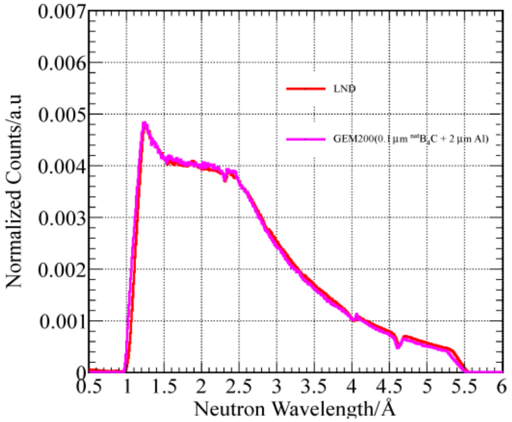


Detector design

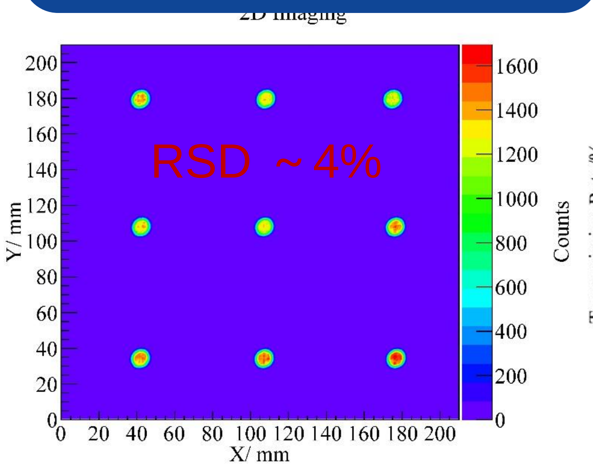
Indicators	Specifications
Conversion layer	0.1μm ^{nat}B4C+2μm Al
Effective area	200mm*200mm
Pixel size	0.8mm
Detection Efficiency@1.8Å	10^{-4}
Counting rate	1 MHz
Neutron flux	10^{10} n/s

Detector photo

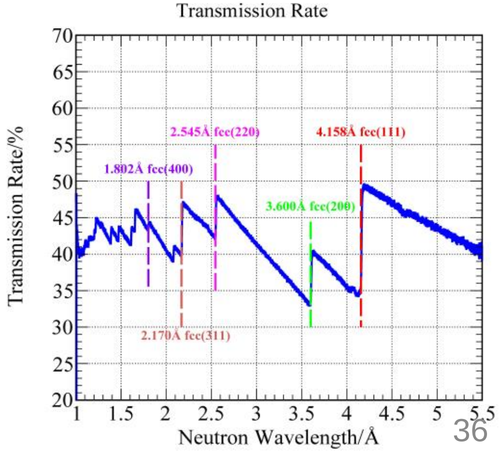
Neutron wavelength



Detecting surface uniformity



Bragg-Edge Neutron Imaging



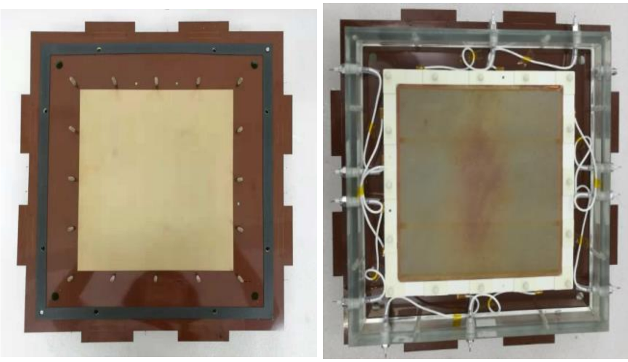
Ceramic GEM - High Resolution Detector

High Resolution Detector for VSANS

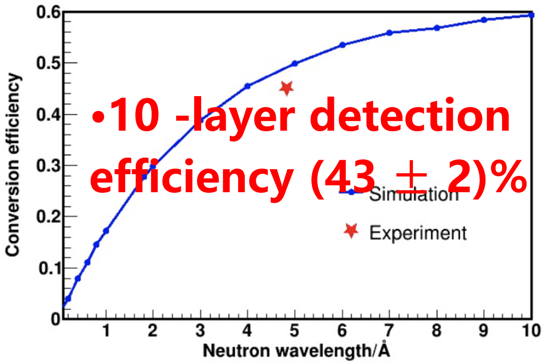
Multi-layer BGEM structure is used to improve the detection efficiency, and it has been installed at VSANS for very small angle neutron scattering experiment.

Detector design

Detector prototype development

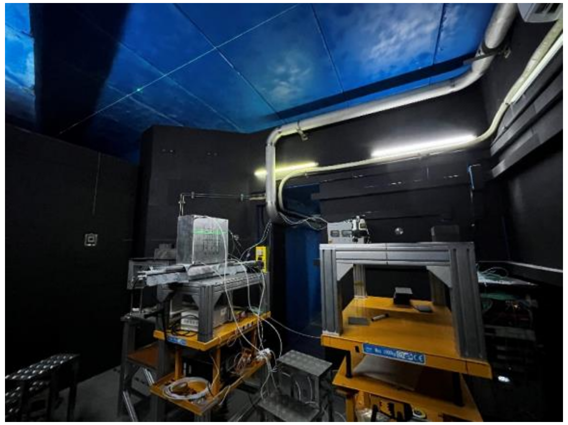


Project Acceptance by CAS@2019

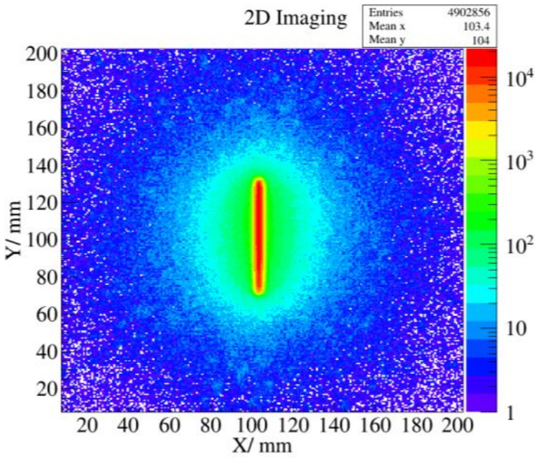


Detector photo

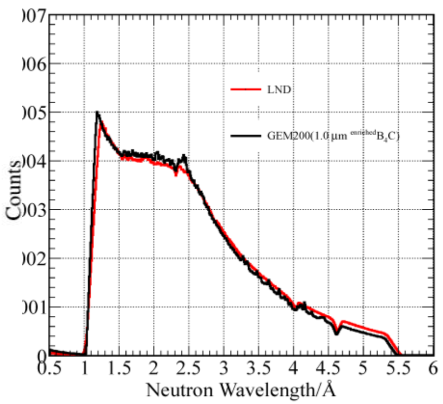
Neutron beam test



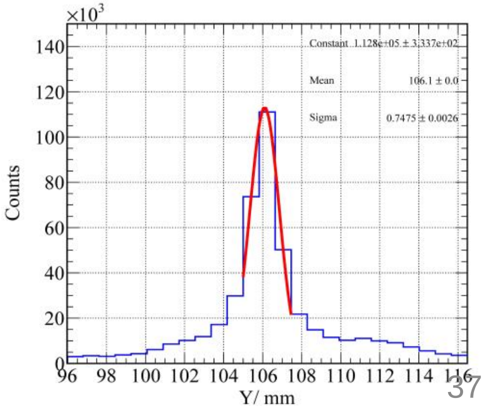
2D beam profile



Neutron wavelength



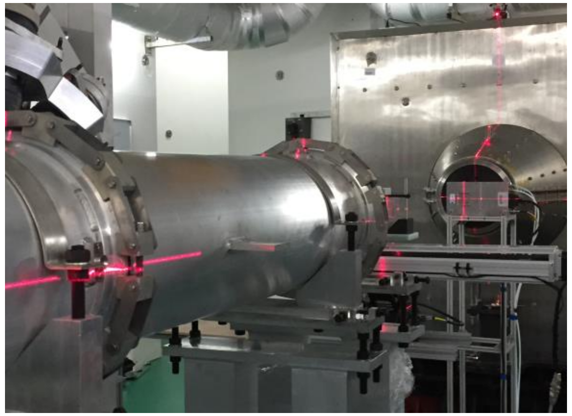
Spatial resolution

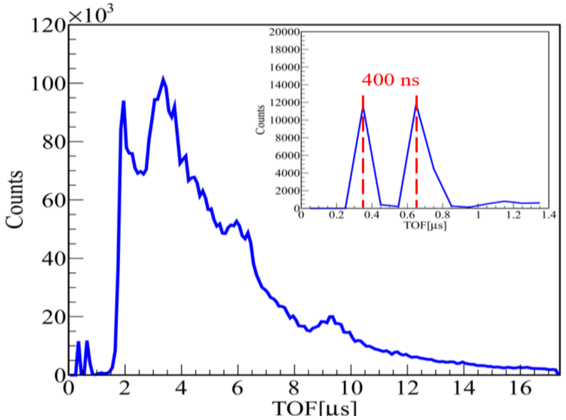


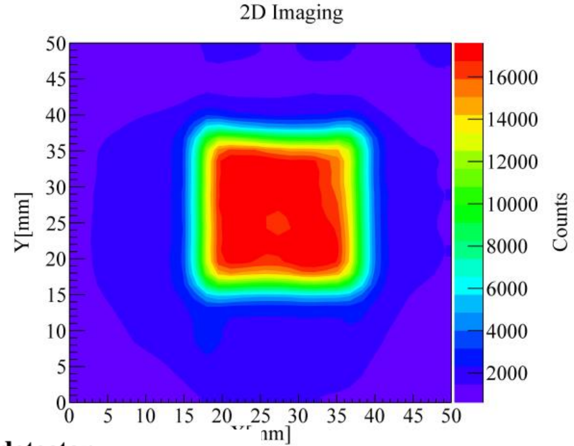
Ceramic GEM - Fast Neutron Detector

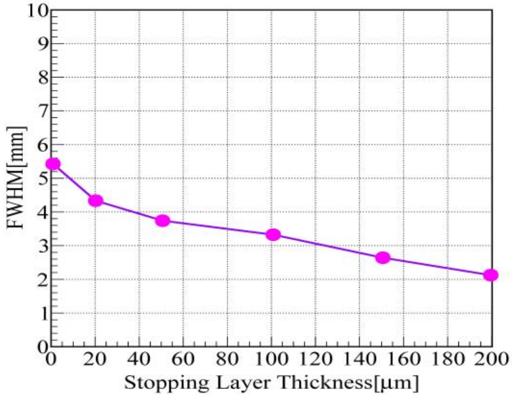
Atmospheric Neutron Irradiation Spectrometer 2D position sensitive detector

Use aluminum as stop layer and spatial resolution of fast neutron improved from 5mm to 2.1mm, has been installed at ANIS for fast and thermal neutron beam monitoring



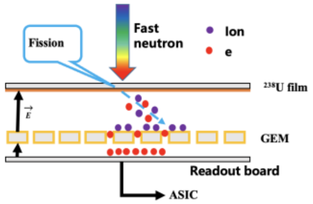






1. ^{238}U-GEM fast neutron detector

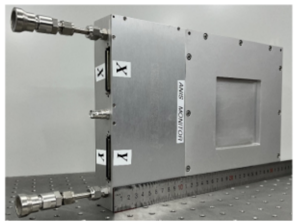
Schematic diagram



Specifications

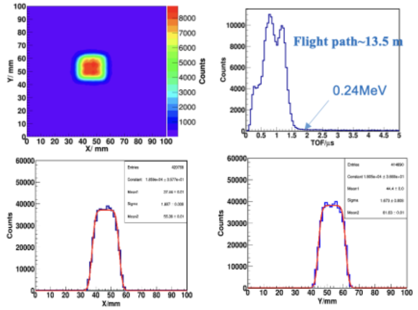
- Active area： 100mm×100mm
- Readout chanels： 64(X)+64(Y) = 128
- Pixel： 1.56mm×1.56mm
- Convertor： ~1 mg/cm² ^{238}U镀层
- Spatial resolution： 5 mm (FWHM)，HV= - 700V
- Energy range： Above 0.1MeV，Efficiency~10^{-5}

Detector photo



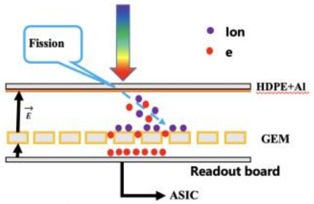
Spatial resolution 4.3 mm (FWHM)

Beam test@BL20，20mm collimator @2021.11.15-21



2. C_2H_4-GEM fast neutron detector

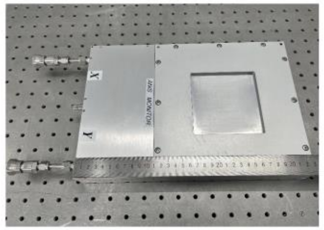
Schematic diagram



Specifications

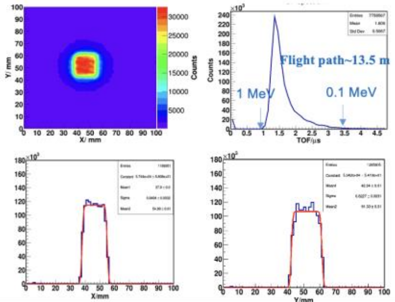
- Active area： 100mm×100mm
- Readout chanels： 64(X)+64(Y) = 128
- Pixel： 1.56mm×1.56mm
- Convertor： 2 mm C_2H_4+0.2mm Al
- Spatial resolution： 2 mm， HV= -1500V
- Energy range： Above 0.1MeV， Efficiency~10^{-4}

Detector photo



Spatial resolution 2.1 mm (FWHM)

Beam test@BL20，20mm collimator @2021.11.15-21



Ceramic GEM – Frontier Exploration

Sealed GEM neutron detector.

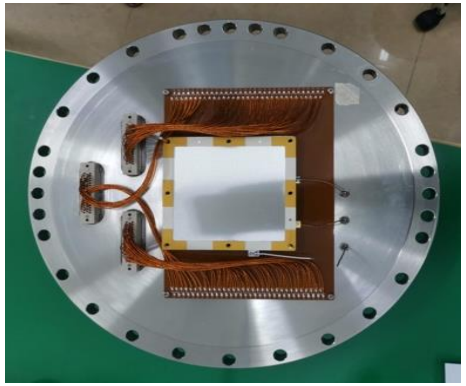
NIMA, 2021,995:165129

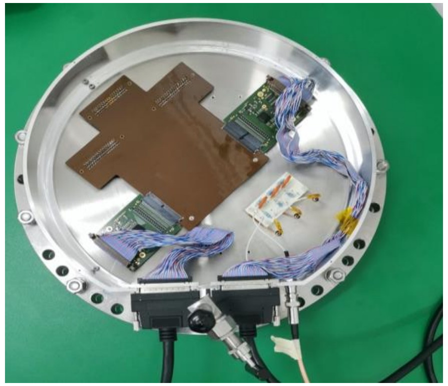
- Developed high-temperature resistant (100°C) ceramic GEM to meet baking outgassing.
- Enhancing detector stability, suitable for vacuum environments, future direction.

Detector design

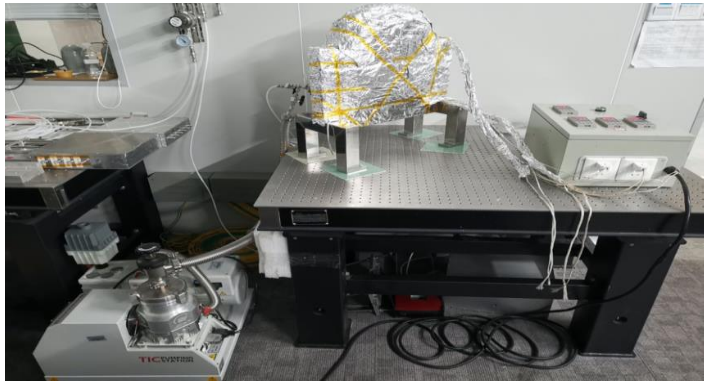
Indicators	Specifications
Conversion layer	1μm B4C
Effective area	100mm*100mm
Pixel size	1.56mm
Detection Efficiency@1.8Å	~3%
Counting rate	1 MHz

Detector assembly

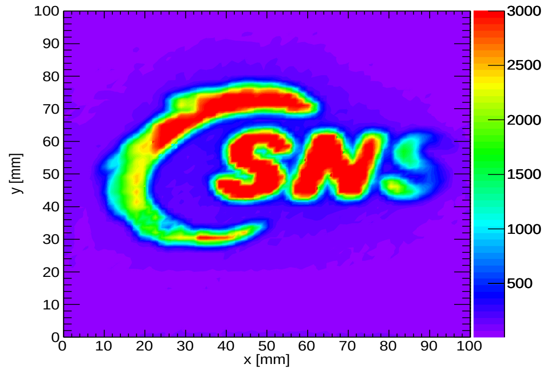




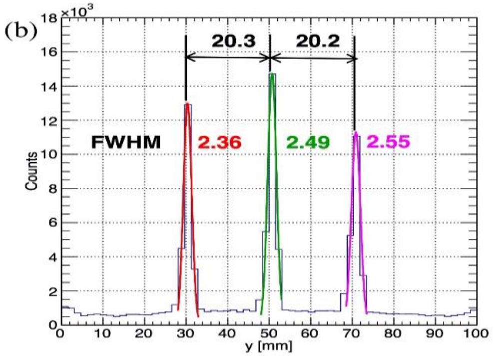
Detector baking outgassing system



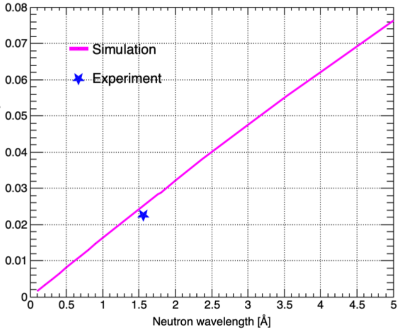
2D imaging



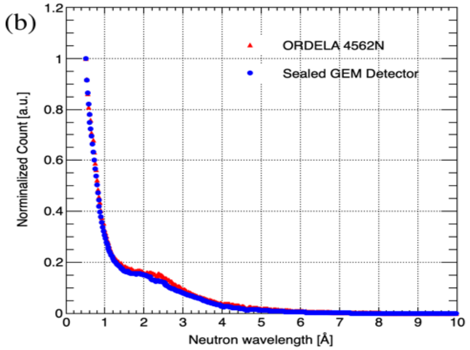
Spatial distortion



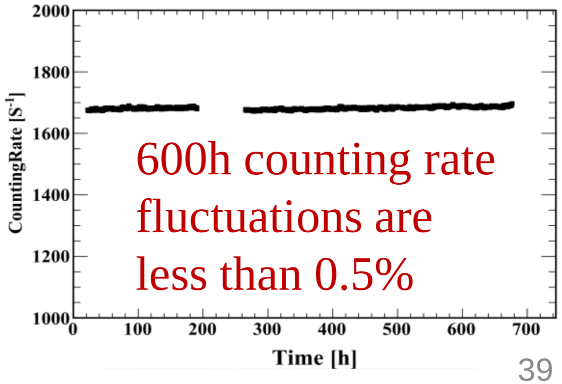
Detection efficiency



Neutron wavelength



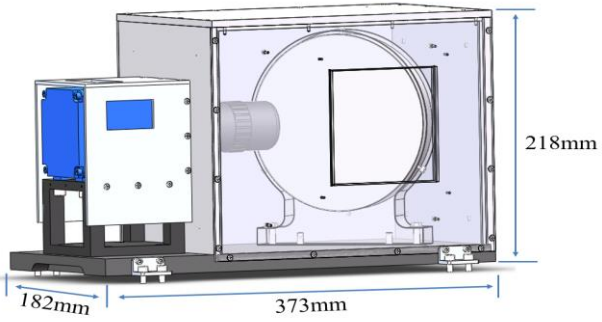
Long-term stability

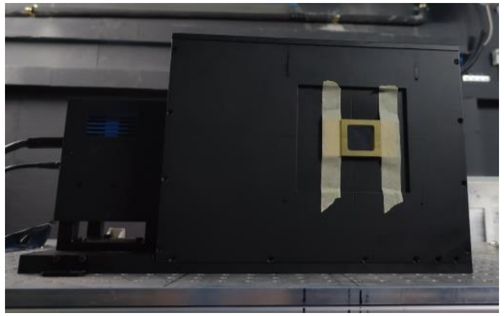


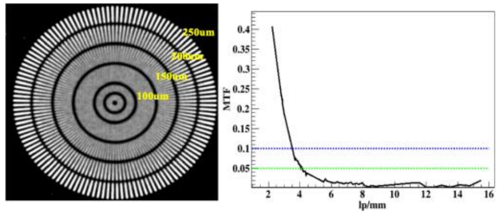
Neutron Imaging Detector

Aiming at the neutron imaging demands of CSNS and international frontiers, developing a variety of **high spatial resolution** and **high timing resolution** imaging detectors

Compact imaging detector



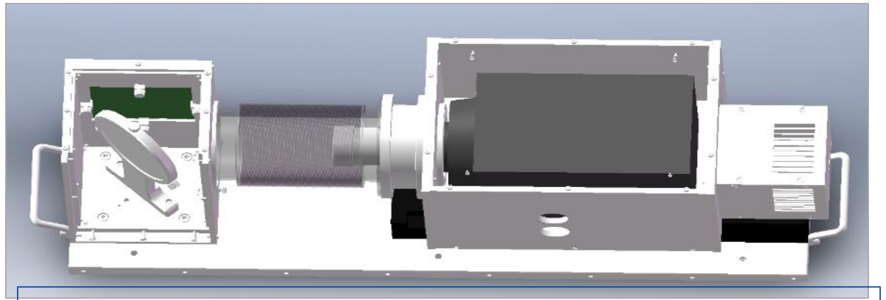




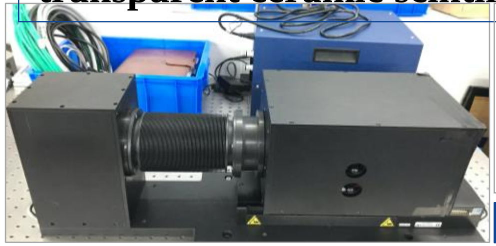
Latest beam test results: 122 μm@4.1LP/mm

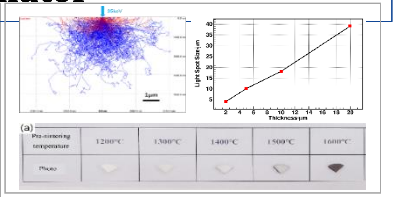
NET, 2021, 53(6):1942-1946

High-resolution imaging detector

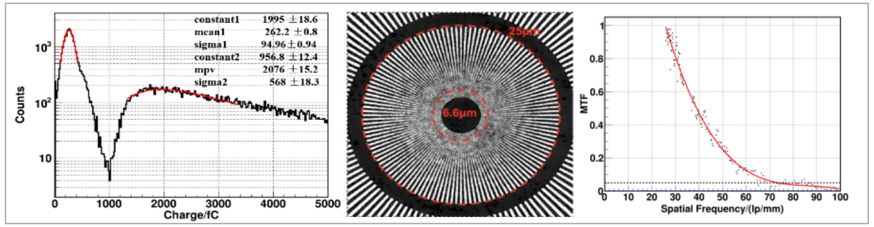


Micrometer ultra-high resolution neutron imaging detector with ultra-thin GOS: Tb transparent ceramic scintillator





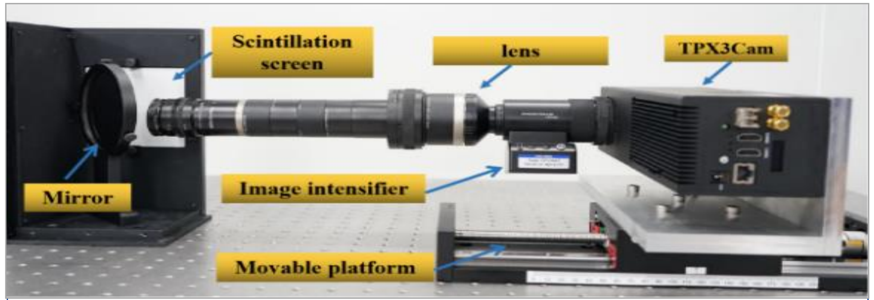
GOS Scintillator Simulation



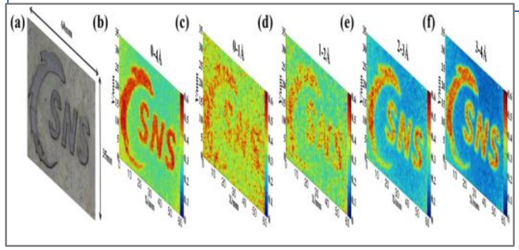
Latest beam test results: 6.6 μm @ 74 LP/mm

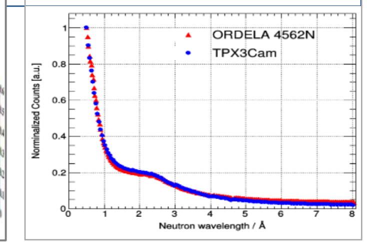
Optical Materials, 2020, 105: 10990 (cooperated with the Lijiang team of the Shanghai Institute of Ceramics)

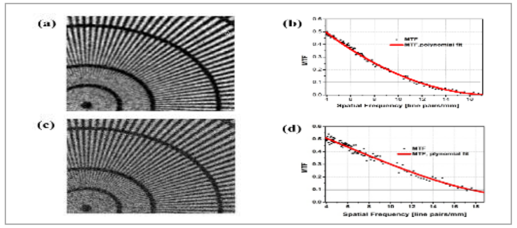
Energy resolution neutron imaging detector

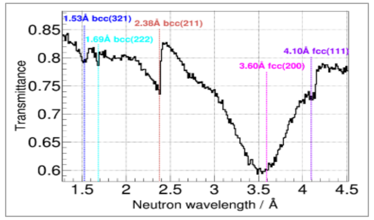


Energy resolution neutron imaging detectors can achieve high time resolution and high spatial resolution at the same time.









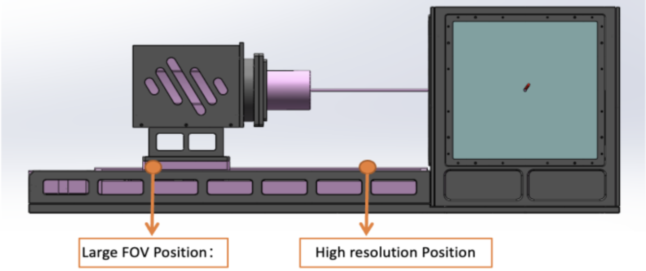
Latest beam test results: 20 μm (25 LP/mm), Δλ/λ= 0.3%

NIMA, 2021, 1003: 165322

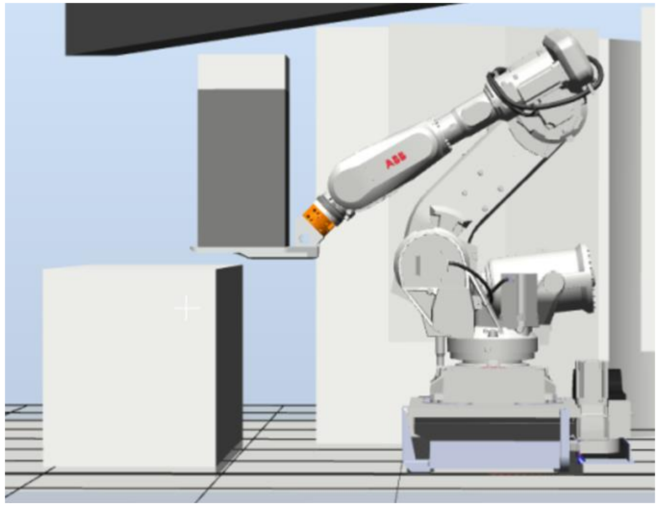
Neutron Imaging Detector - Large FOV

ERNI—Large FOV Imaging detector. Operating stably for 1 year.

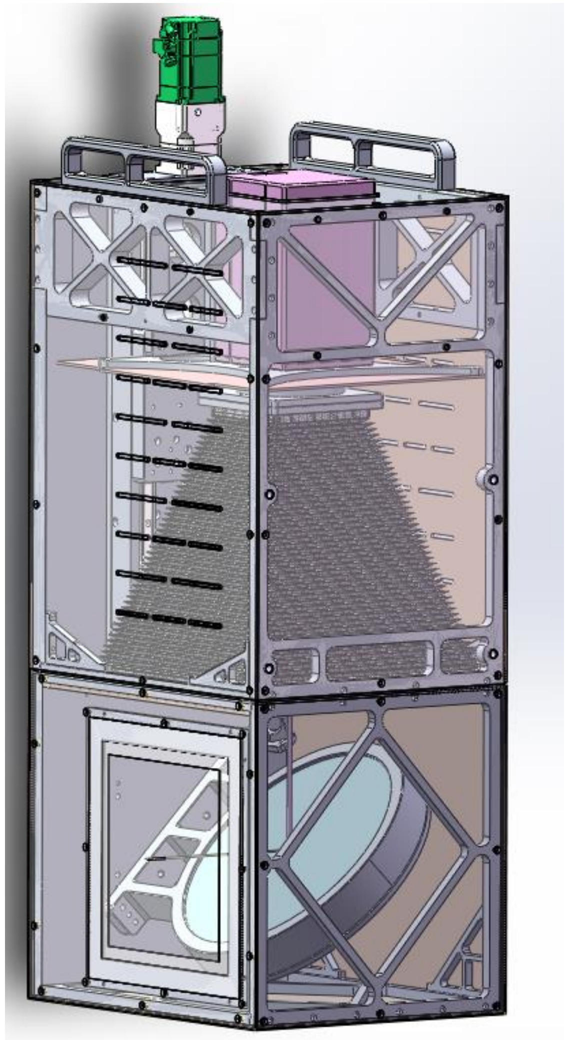
Detector engineering design



Lens	Magnification	FOV	Distance	Spatial resolution
Nikon AFSVRMICR O60_2.8	0.15	200mmX200mm	484mm	200μm
	0.3	100mmX100mm	242mm	100μm
Nikon AFSVRMICR O105_2.8	0.3	100mmX100mm	500mm	100μm
	0.5	60mmX60mm	423mm	60μm
	1	30mmX30mm	343mm	30μm

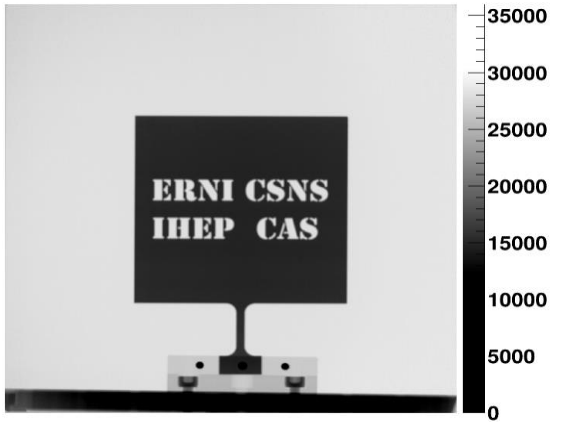


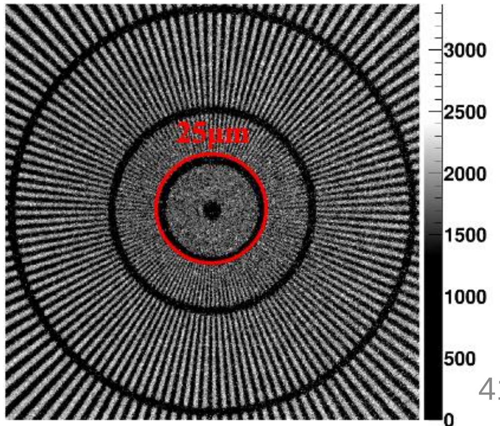
Large FOV Imaging detector



Neutron beam test @ ERNI

The maximum FOV is 220mm*210mm, and the best spatial resolution is 25 μm measured at ENRI

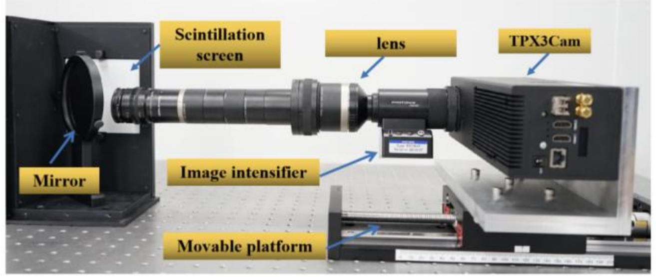




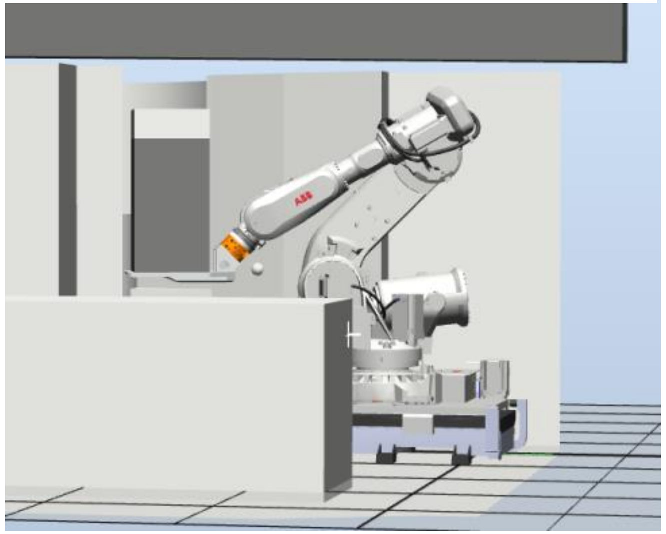
Neutron Imaging Detector-Energy Resolution (TOF)

Energy resolved imaging detector. Operating stably for 1 year.

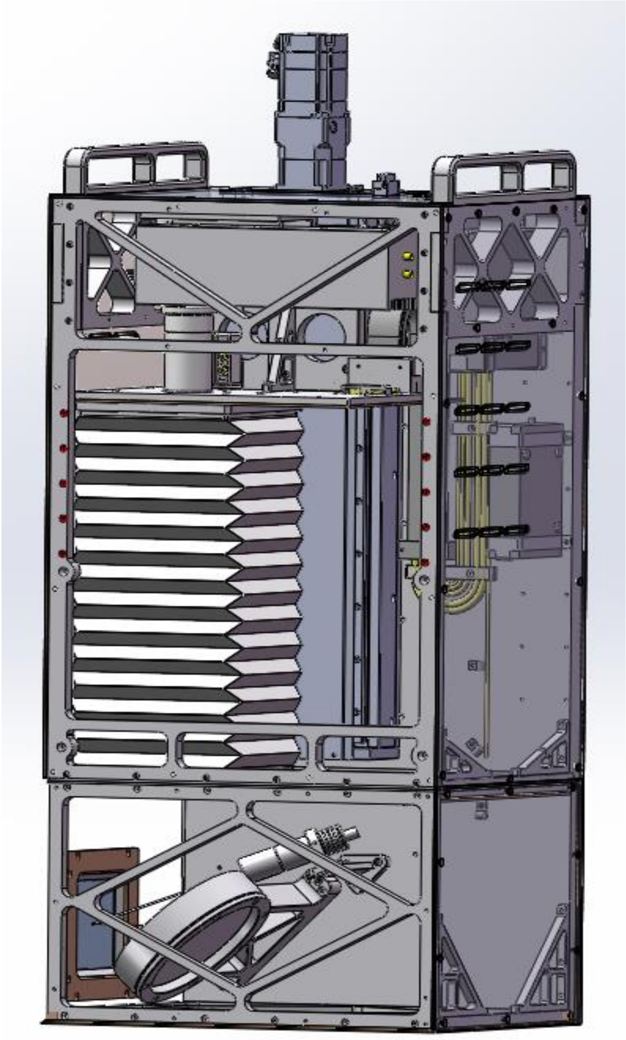
Detector engineering design



Lens	Magnification	FOV	Distance	Spatial resolution
Nikon AFSVRMIC RO60_2.8	0.12	100mmX100mm	622mm	458μm
	0.14	90mmX90mm	507mm	393μm
	0.3	42mmX42mm	302mm	183μm
Nikon AFSVRMIC RO105_2.8	0.3	42mmX42mm	519mm	183μm
	0.5	25mmX25mm	399mm	110μm
	1	12.7mmX12.7mm	299mm	55μm

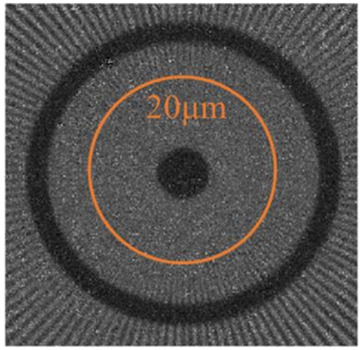


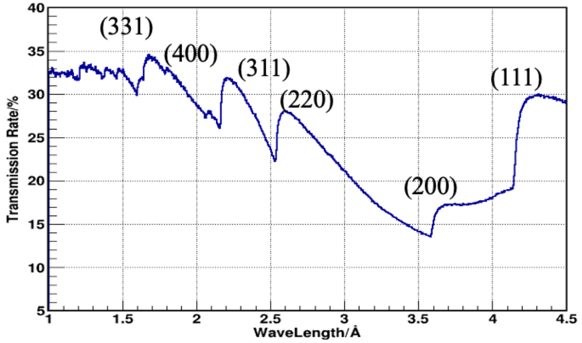
Energy resolved neutron imaging detector



Test and commissioning at the ERNI

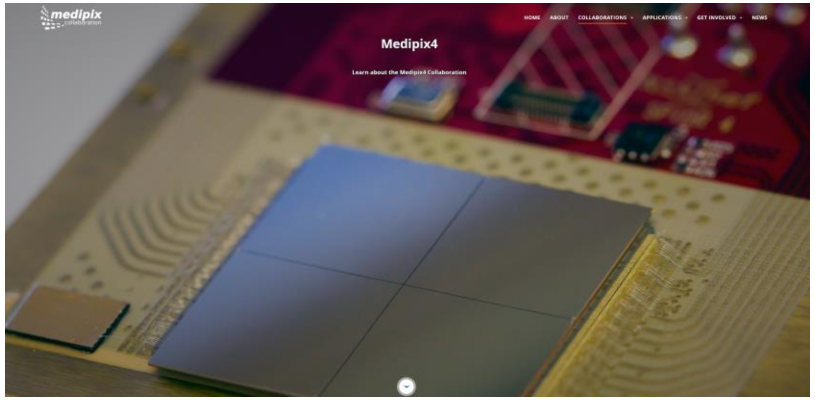
Preliminary test results of ENRI





High Speed Readout Electronics for Neutron Imaging

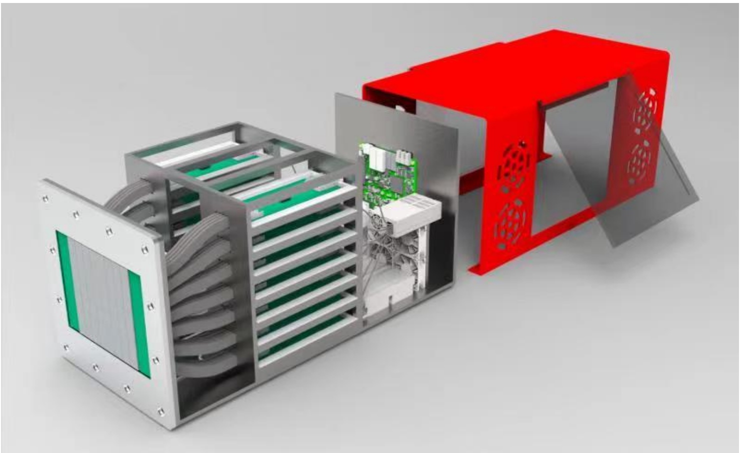
Joined the Medipix4 international collaboration group



- Medipix International Collaboration Group
  - Led by CERN, established for over 20 years, CSNS officially joined in 2022.
  - Dedicated to the R&D and promotion of pixel detector chips.
  - Latest pixel detector chip - Timepix4
  - Pixel Size/Time Resolution: 55um/200 ps
  - Maximum Count Rate: 3.5M hit/mm^2/s
  - Utilizes TSV (Through Silicon Via) technology to minimize dead zone.

Conducting key technology research for high-performance energy-resolved neutron imaging detector based on Timepix4 detector modules.

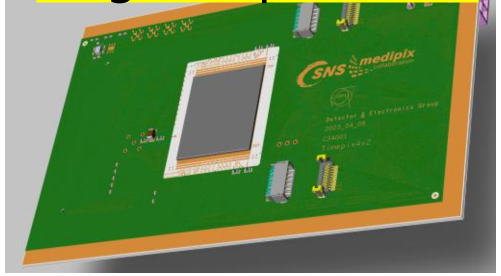
Long term goal: Large area high speed neutron camera



- High-efficiency, high-resolution scintillation screens.
- Large FOV
- High time resolution: < 1ns
- High spatial resolution: < 50 um (CoM algorithm)

Readout based on single-chip module

Single chip module



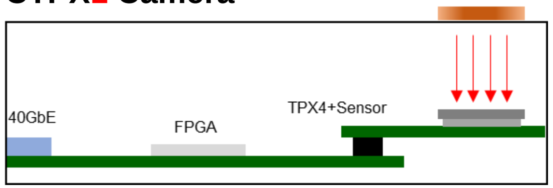
ZU + Readout Platform

High-speed readout and data compression research based on the latest SOC platform

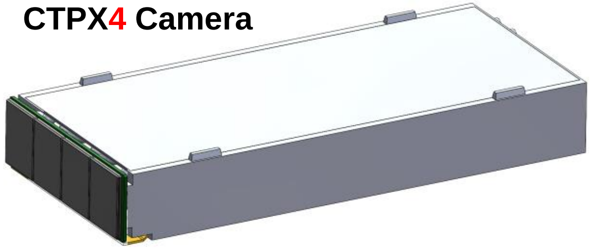
Neutron Imaging High Speed Camera Development

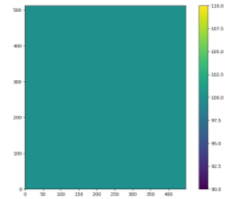
			Timepix3 (2013)	Timepix4 (2019/20)	
Technology			IBM 130 nm – 8 metal	TSMC 65 nm – 10 metal	
Pixel size			55 x 55 µm	55 x 55 µm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable (TSV) 512 x 448	3.5 x
Sensitive area			1.98 cm^2	6.94 cm^2	
Readout modes	Data driven (tracking)	Mode	ToT and TOA		
		Event packet	48-bit	64-bit	
		Max rate	< 43 $Mhits/cm^2/s$	357.6 $Mhits/cm^2/s$	8 x
		Pix rate equiv.	1.3 kHz/pix average	10.8 kHz/pix average	
	Frame Based (imaging)	Mode	Count: 10 bit + iToT	Count: 8 or 16 bit CRW	
		Frame	Zero suppressed (with pix addr)	Full frame (no pix addr)	
		Max count rate	82 $Ghits/cm^2/s$	~ 800 $Ghits/cm^2/s$	10 x
		Max frame rate	N/A (worst case: 0.8ms readout)	80 kHz CRW	
TOT energy resolution			< 2 keV	< 1 keV	2 x
Time resolution			1.56 ns	~ 200 ps	8 x
Readout bandwidth			≤ 5.12 Gbps (8 x 640 Mbps)	≤163.8 Gbps (16 x 10.2 Gbps)	32 x
Target minimum threshold			< 500 e^-	< 500 e^-	

CTPX1 Camera

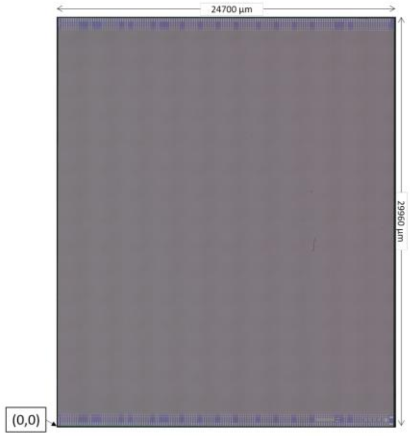


CTPX4 Camera

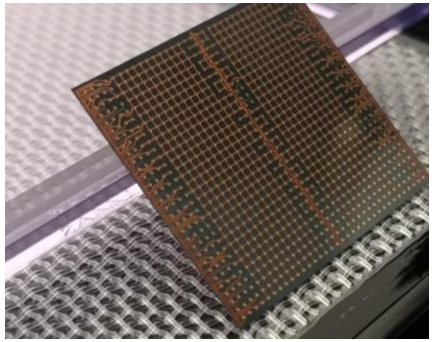




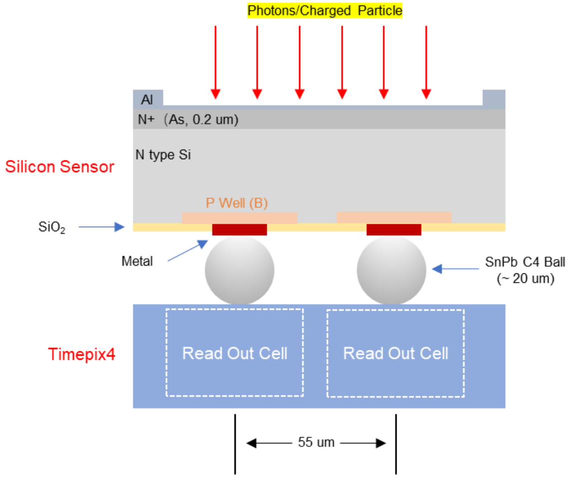
Zynq Ultrascal+ Timepix4 Readout Demonstrator



Timepix4



Timepix4 with TSV



Timepix4 + Optical Silicon Sensor

- Scintillation screen Optical Silicon Pixel Sensor + Timepix4 based neutron imaging being developed at CSNS
- Two prototypes: CTPX1, CTPX4
- Key Specifications
  - Sensor: Si
  - *Pixel Array: 512 x 448 (CTPX1), 1792 x 512 (CTPX4)*
  - *Pixel Size: 55 um x 55 um*
  - *Maximum rate: 89 kfps (frame mode), 3.56 x $10^6/mm^2/s$*
  - *Real time buffering: 32 GB/Timepix4*
  - *Readout interface: 40GbE*
- Timeline for commissioning
  - *CTPX1: 2024Q1*
  - *CTPX4: 2024H2*

Neutron Imaging High Speed Camera Development

~ 2025

Experimental Room

Control Room

Scalable Detector Unit

- Composed of CTPX4
- Target for 7 x 8 Timepix4 (or 2 x 7 CTPX4 module)
- Detection Area: ~ 20 cm x 20 cm
- < 10% dead are with TSV

High Density Fiber

300 Gb/s per CTPX4

MPO/MTP Fiber Patch Panel

Colling Liquid

Return Liquid

12V DC

CDU

LVPS

Local Service Unit

Remote Electronics Unit

Data Processing Accelerator Board

- MTP48
- MTP48
- Virtex FPGA
- DDR
- GPU
- DDR

Disk Array Access Board

- MTP12
- FPGA
- NVMe SSD
- NVMe SSD
- NVMe SSD
- NVMe SSD

System Management Board

- MTP12
- MTP12
- ZYNQ SOC
- GbE
- T0
- Clk in

Raw Data

Compressed Data

Storage Data

Fetch Data

T0, SC, Clk

Monitoring

Readout Data

Ethernet Switch

Control/DAQ Server

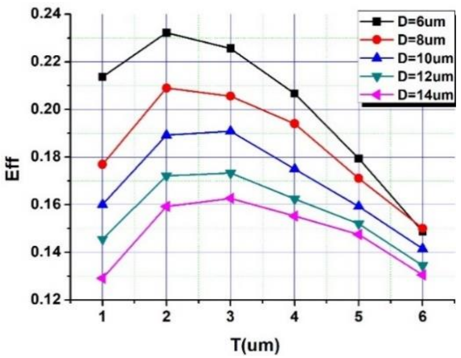
Neutron Imaging Detector-Energy Resolution (TOF)

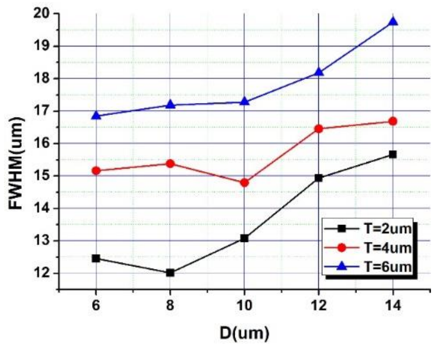
Development of neutron sensitive Micro Channel Plate (nMCP)

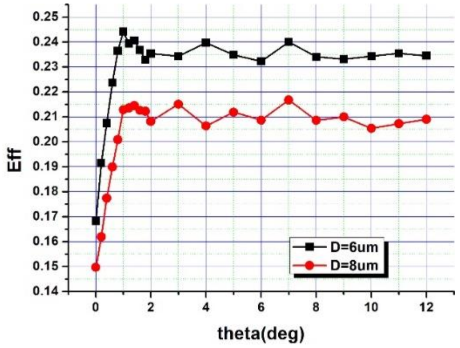
- **Challenges: Low γ sensitivity and high boron-doped concentration in nMCP, reducing high Z materials.**
- **Achieved 20 mole% boron-doped nMCP, successfully applied in GPPD**

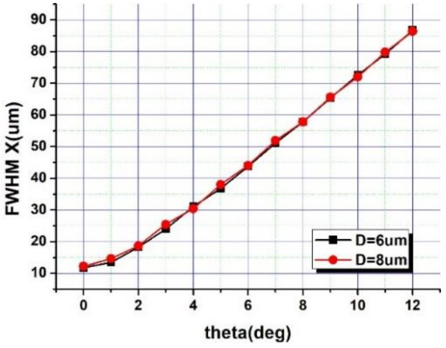
NIMA , 2022, 167828

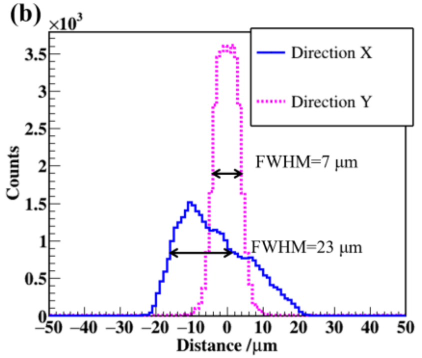
Design and optimization of nMCP based on Geant4 simulation



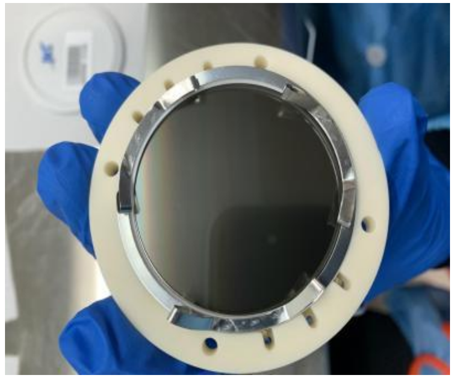




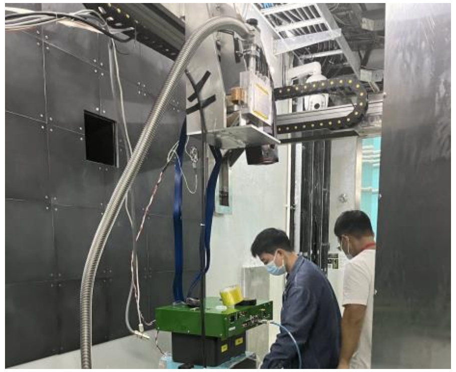




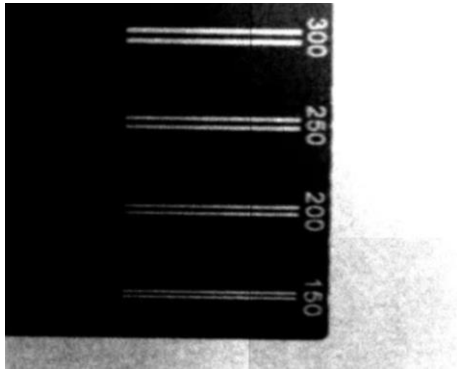
B-nMCP photo



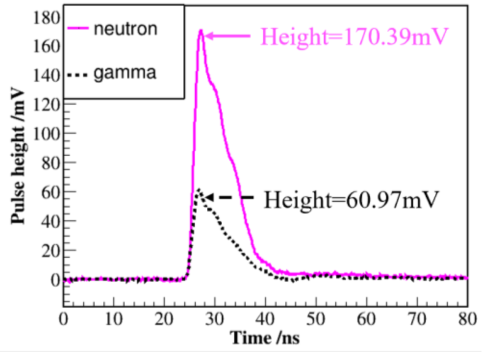
GPPD application



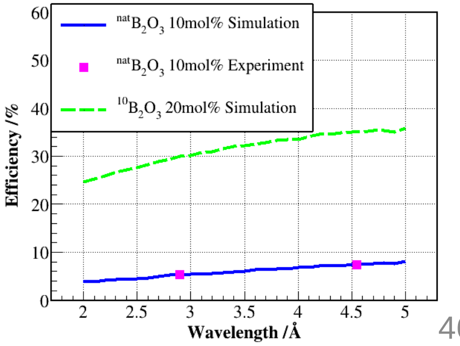
Spatial resolution



n/γ discrimination



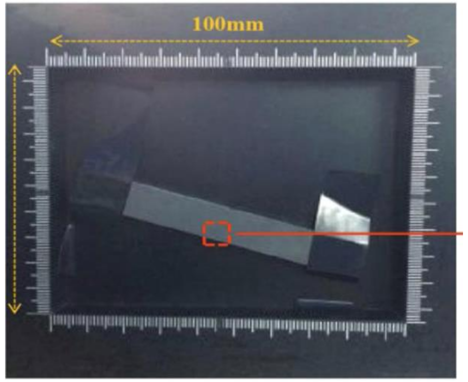
Detection efficiency

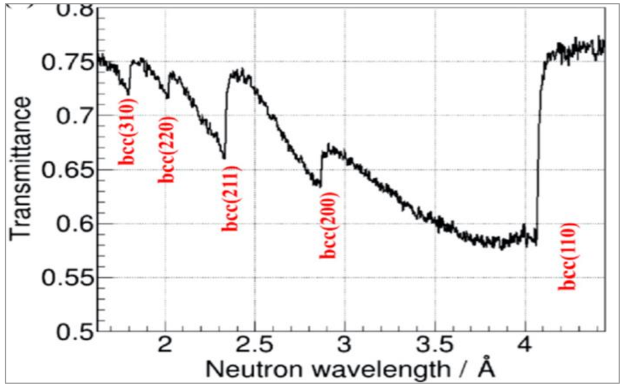


Neutron Imaging Detector-Applications

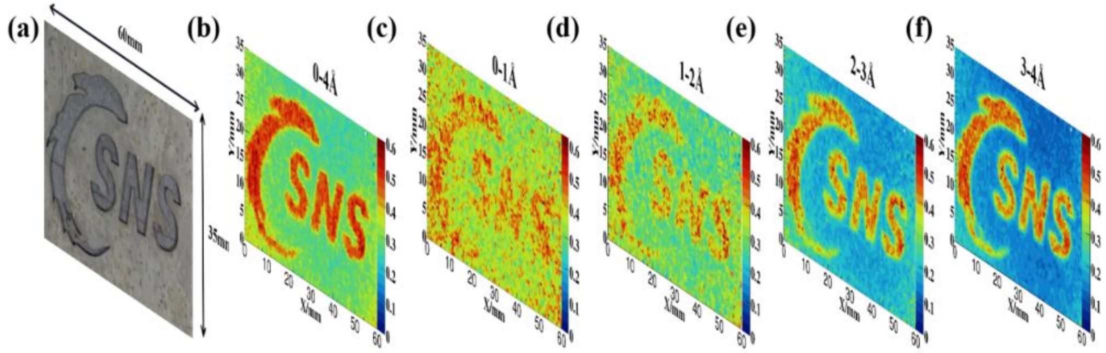
Successfully carried out several applications in multi fields at CSNS

Bragg Edge Neutron Imaging Experiment (Chen Jie)

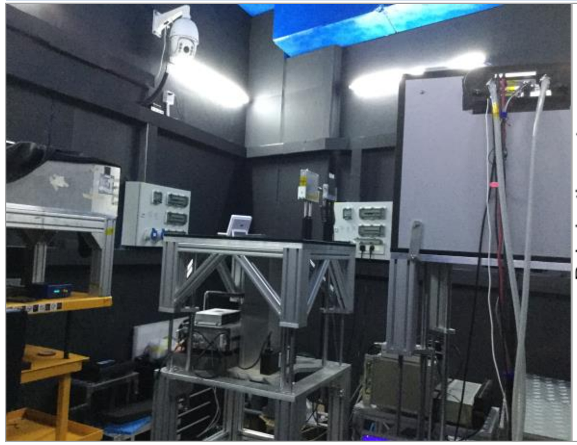


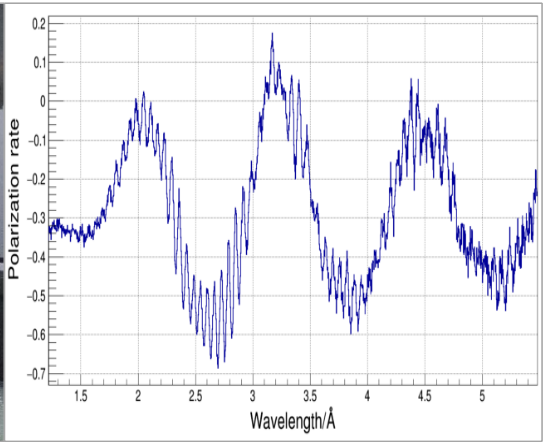


Energy Selective Neutron Imaging

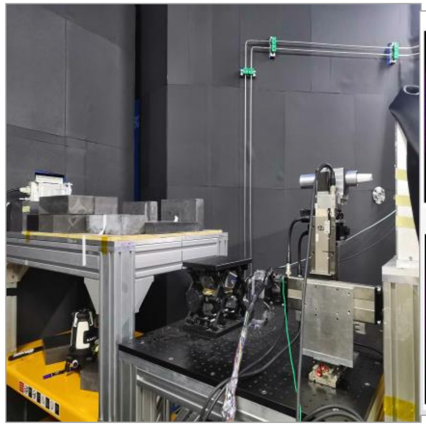


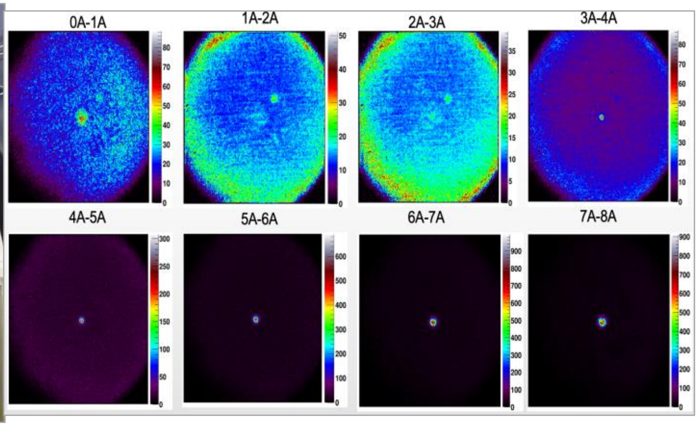
Polarized Neutron Imaging (Wang Tianhao)





Polycapillary (Yi Tiancheng)





Contents

Outline

I China spallation neutron source

II Status of the detectors development

III R&D for CSNS Phase II

IV Summary

Future development for neutron instruments

- **Addressing Engineering Issues of Neutron Instruments:**
  - **Enter "Vacuum"**
    Solve challenges like vacuum discharge, electronics cooling, space limitation, system noise, and channel consistency
  - **Moving towards High Bandwidth + Large Scale:**
    High count rate, high dynamic range, distributed independent modules

- **Enhancing Performance of Neutron Instruments:**
  - **Moving towards "Quasi" Real-Time**
    Distributed information flow, data-driven, front-end physics analysis in real-time
  - **Moving towards High Resolution (Spatial, Temporal):**
    Wavelength resolution, spatial resolution.

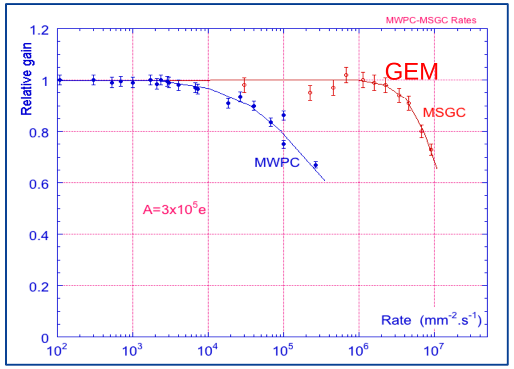
^{3}He based GEM neutron detector

Develop high count rate, high efficiency GEM detector to meet the requirements of liquid reflection instrument

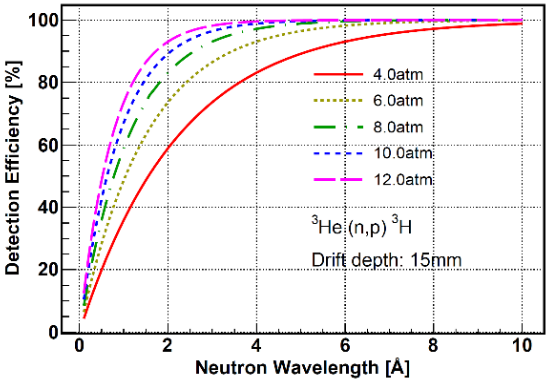
- **Bottleneck: traditional detector based on wire chamber can't meet the high flux measurement**
- **^{3}He + GEM may potentially achieve high efficiency and enhance high count rate by two orders of magnitude**

Parameter	^{3}He MWPC	^{3}He GEM needed
Effective Area	200mm × 200mm	600mm × 1000mm
Spatial resolution	≤ 2mm (FWHM)	≤ 2mm (FWHM)
Detect efficiency	≥ 80% @ 1.8Å	≥ 80% @ 1.8Å
Counting rate	≤ 100kHz	≥ 1MHz
n/γ discrimination	10^{-7}	10^{-7}

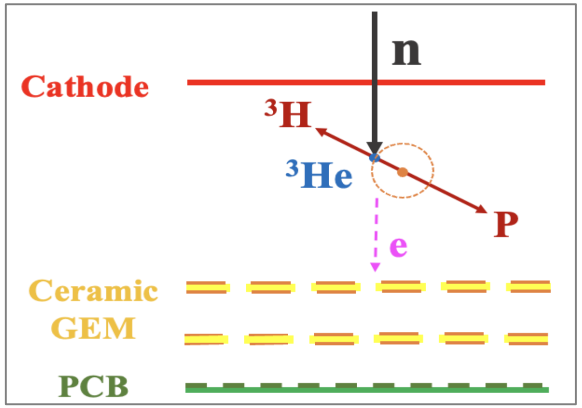
GEM counting rate 10 MHz



^{3}HE gas advantage

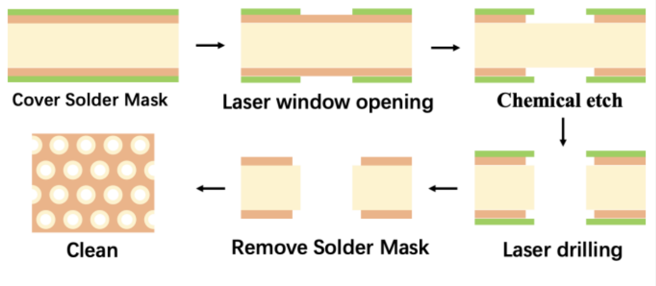


GEM neutron detector with ^{3}He

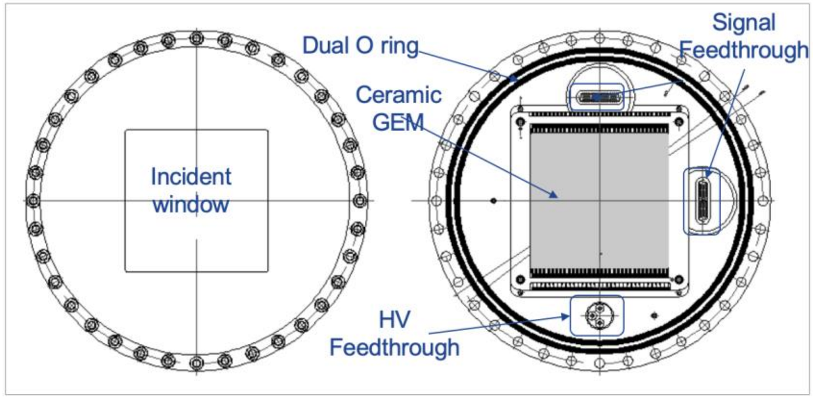


Laser drilling for ceramic GEM

- Laser preparation new technologies and methods
- Research ion feedback physics for new design



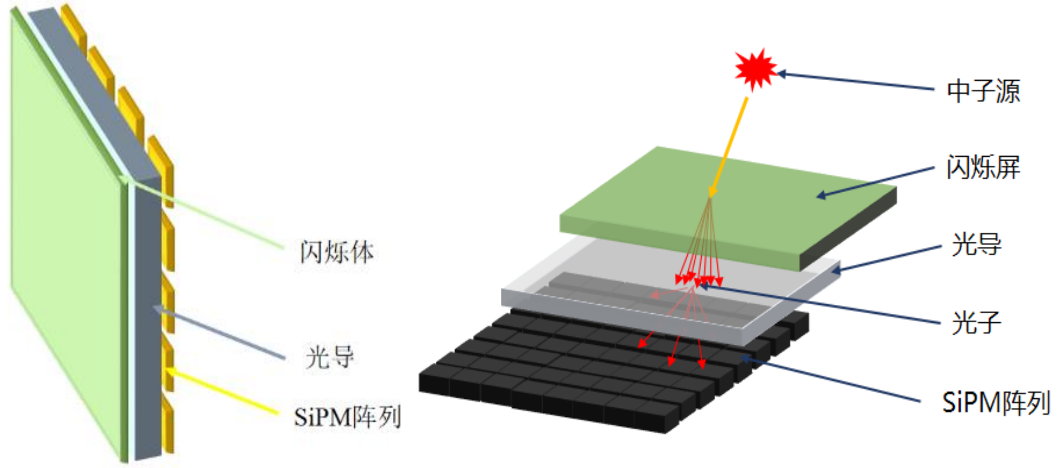
Detector high-pressure chamber design

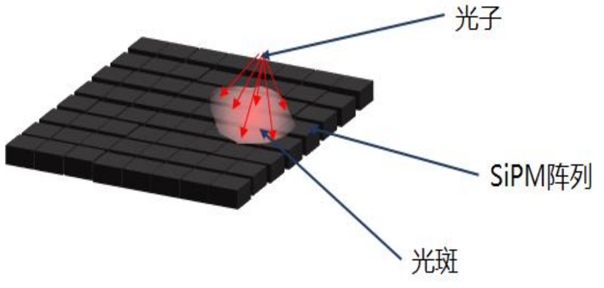


Large-Area Scintillator Detector – 3rd generation

High-Resolution Scintillation Detector

- Aiming at the urgent needs of high -performance neutron detector for CSNS II

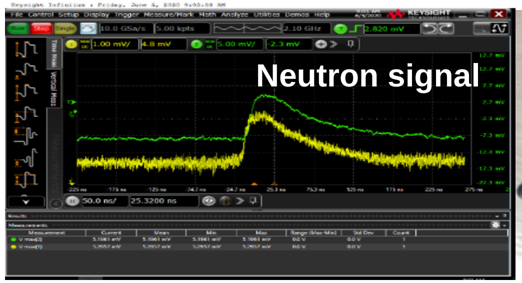


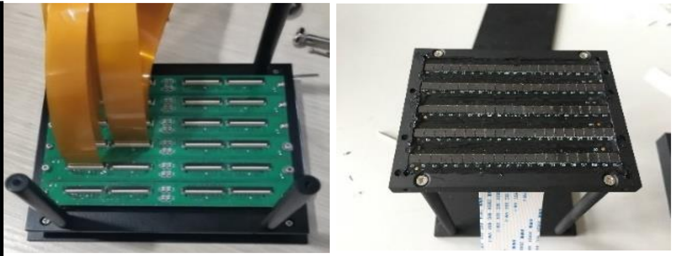


$$x = \frac{x_1 \times w_1 + x_2 \times w_2 + \cdots x_n \times w_n}{w_1 + w_2 + \cdots w_n}$$

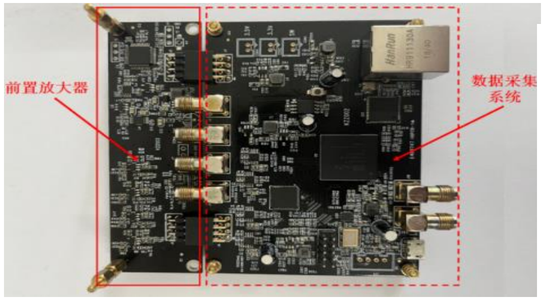
$$y = \frac{y_1 \times w_1 + y_2 \times w_2 + \cdots y_n \times w_n}{w_1 + w_2 + \cdots w_n}$$

Detector module design

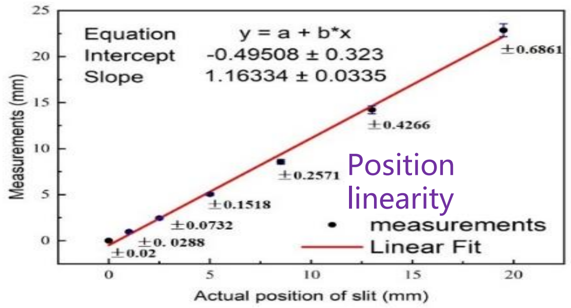


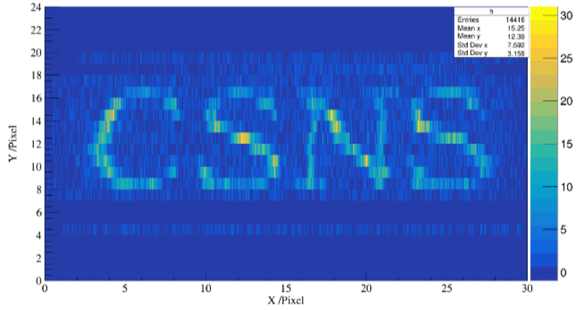


Prototype (10cm*10cm)

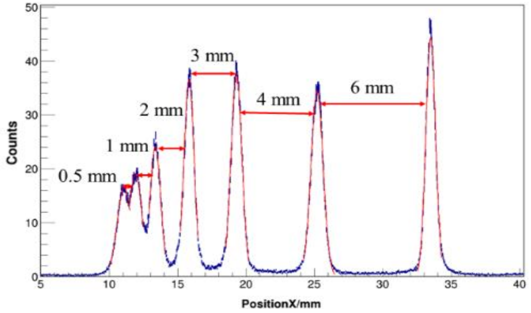


•Electronic readout system





2D imaging



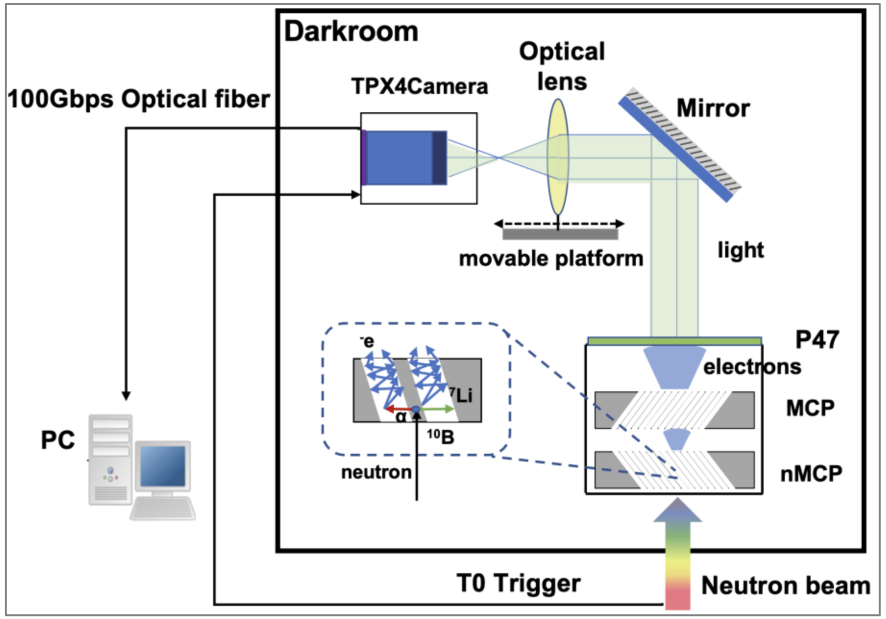
0.5mm position resolution

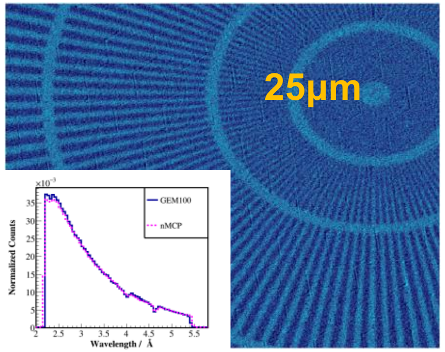
Neutron imaging detector with ultra high spatial resolution

Microsecond-level time resolution, and micron & even sub-micron level spatial resolution

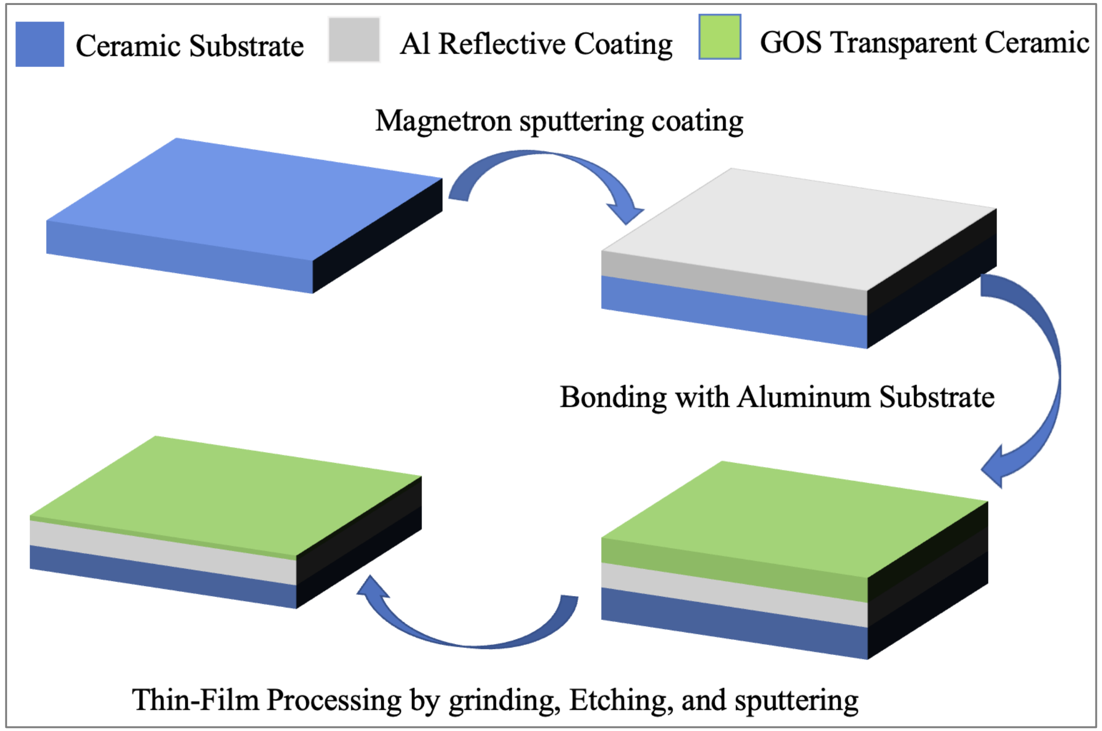
- Researching neutron image intensifiers, integrating neutron conversion and intensifier into a single vacuum device to improve integration.
- Developing ultra-thin transparent ceramic scintillators and TimePix4 cameras (already authorized by CERN).

Neutron image intensifier





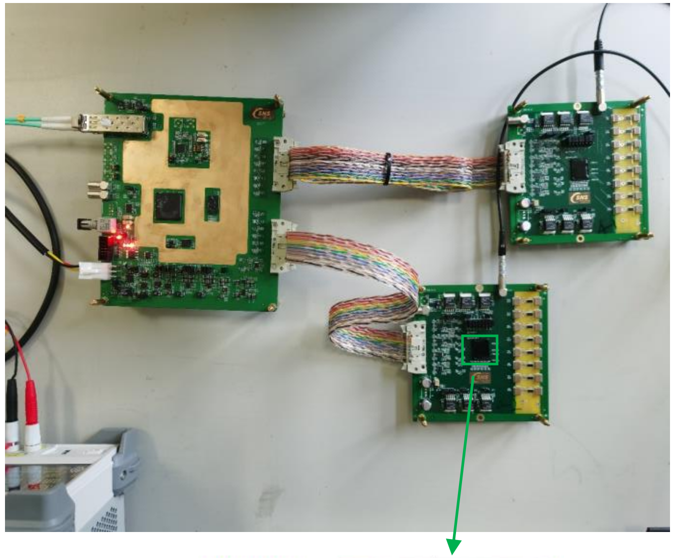
Ultra-thin transparent ceramic scintillator

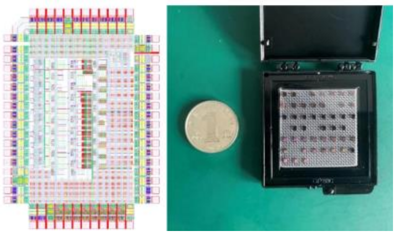


Readout Electronics – ^{3}He PSD Tube Array Detector

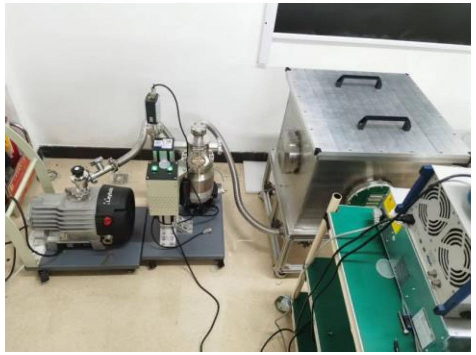
Key Specifications

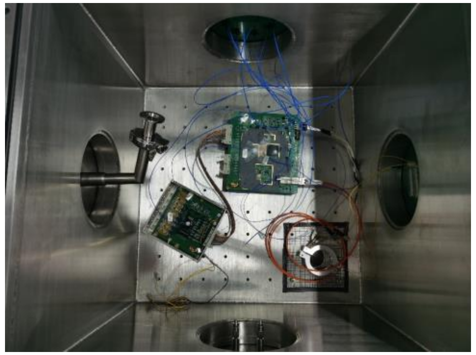
- Readout Method: Waveform sampling
- Ultra low power FPGA + ADC
- Customized ASIC (GF 180nm process)
- Modular design: 8 tube / set
- Remote firmware update
- Low power (< 3W/8 tube readout) for vacuum operation without climate chamber





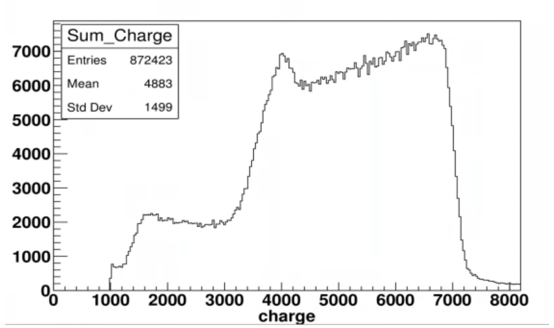
HEROC1 ASIC



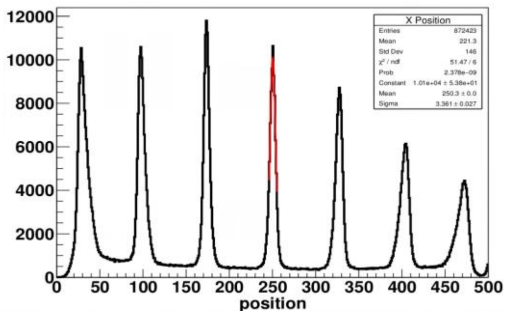


Vacuum Test Setup

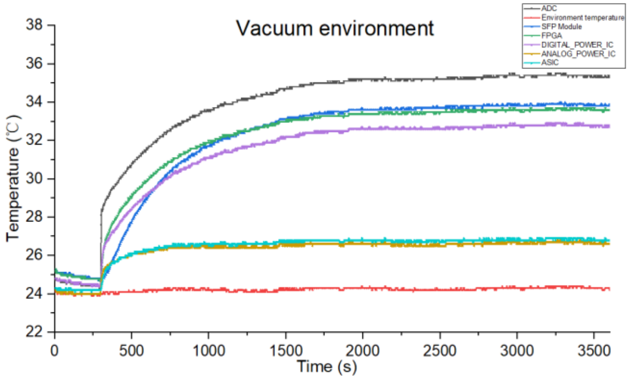
	Voltage	Current	Power (W)
Front-end Board	3.5V/-3.5V	0.075A/0.015A	0.315
Digital Board	3.5V/-3.5V	0.668A/0.001A	2.342
Subtotal			2.972



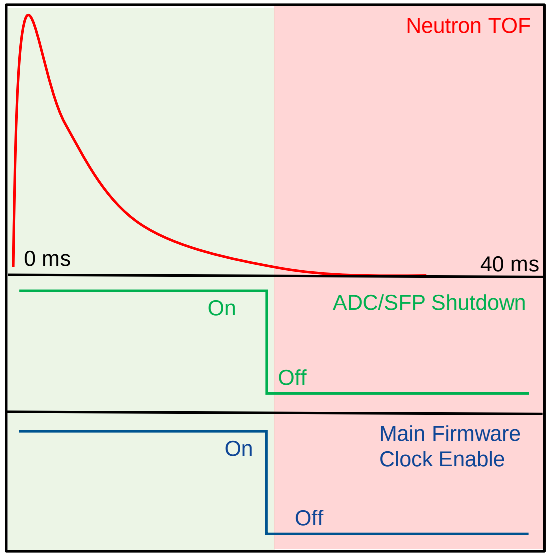
Sum charge spectrum in testbeam



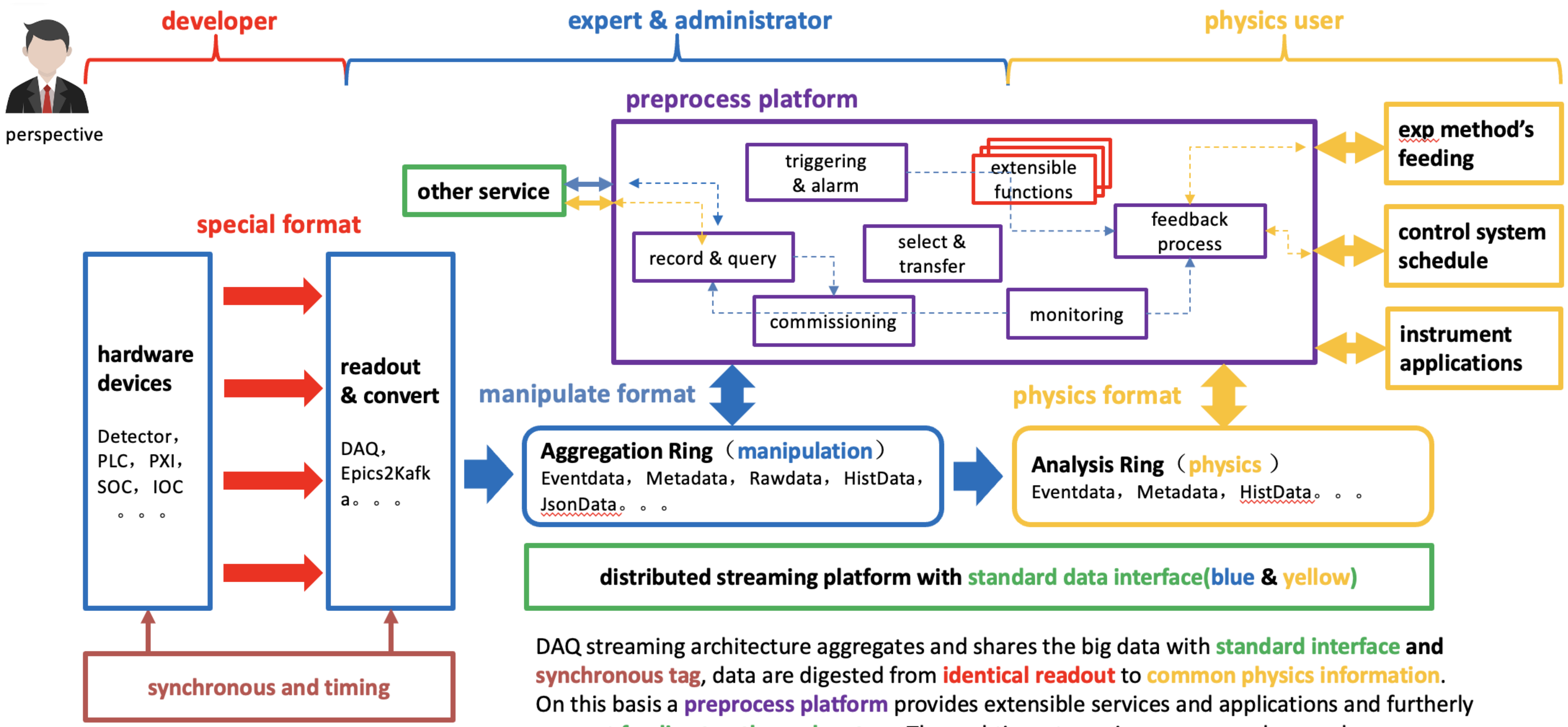
< 8 mm position resolution achieved



- Hottest component (ADC) stabilized @ ~ 35 °C in vacuum
- Use TOF gating further reduce dynamic power consumption

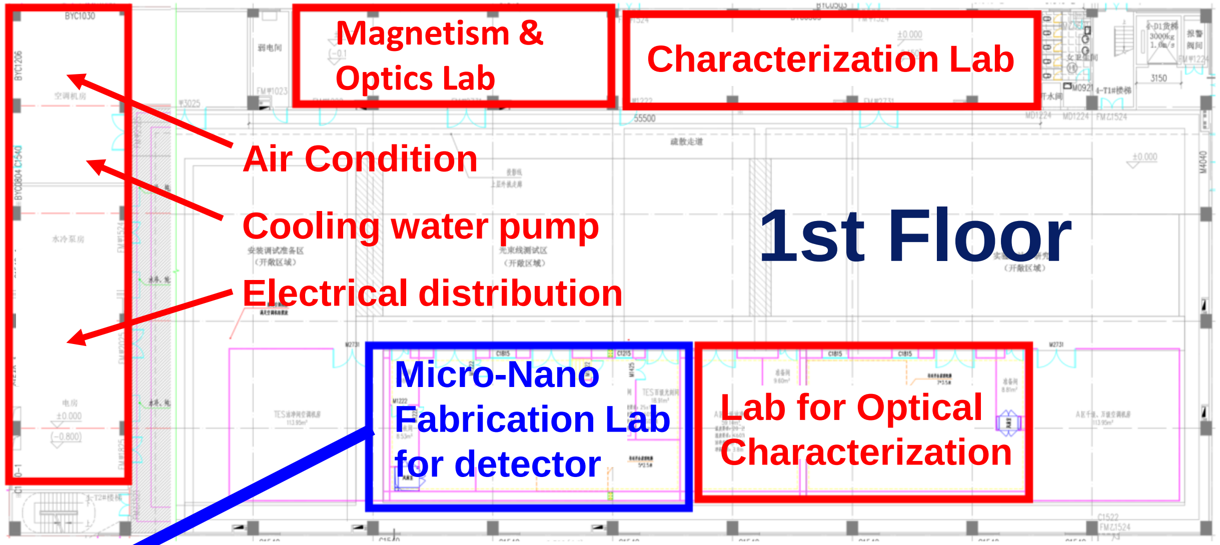


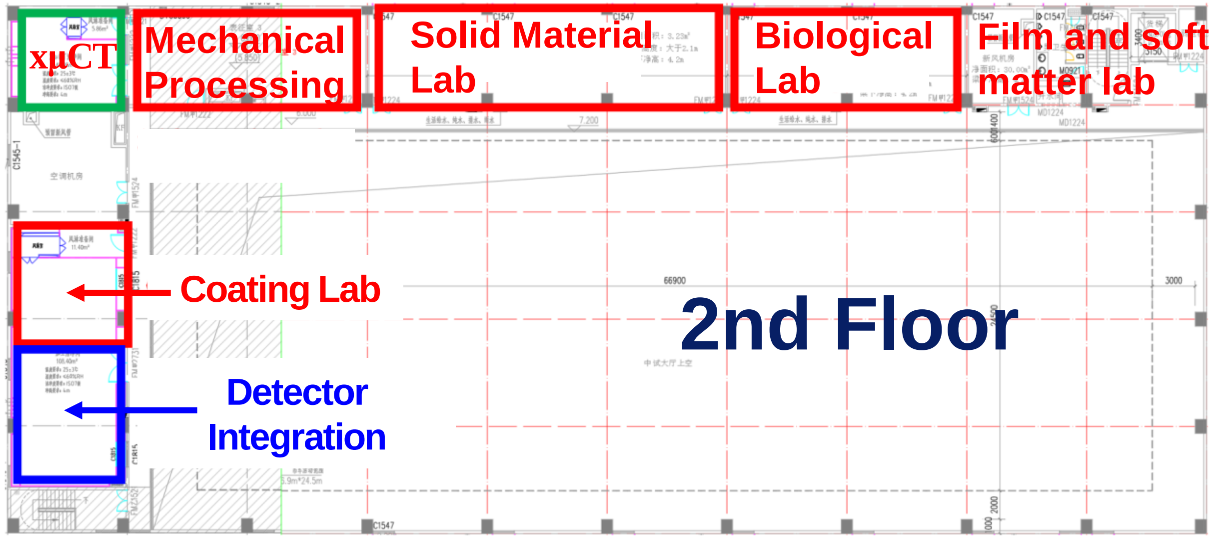
Data-driven System for Neutron Instruments (DSNI)



DAQ streaming architecture aggregates and shares the big data with **standard interface** and **synchronous tag**, data are digested from **identical readout** to **common physics information**. On this basis a **preprocess platform** provides extensible services and applications and furtherly connect **feeding to other subsystem**. The real-time streaming process and open-share manipulation characteristic **benefit various future advanced experiment methods**.

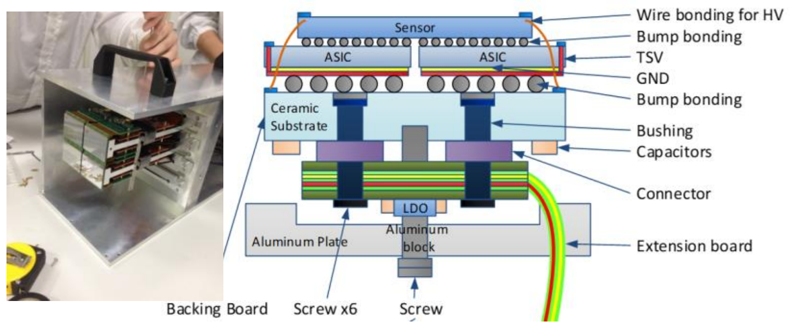
Southern Advanced Photon Source (SAPS) Testing Platform



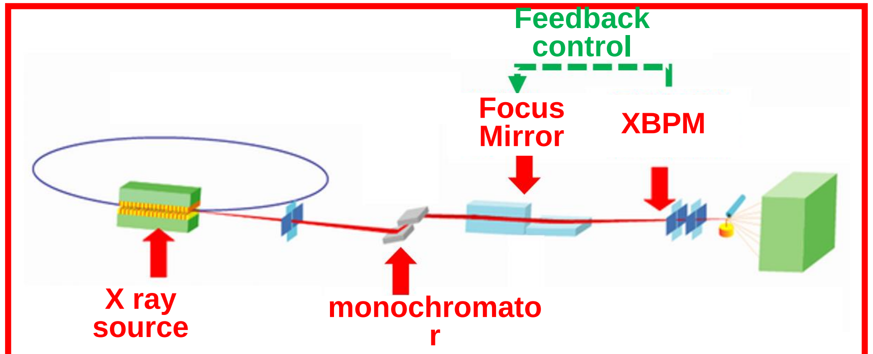


Nanofabrication Lab for Detector Development

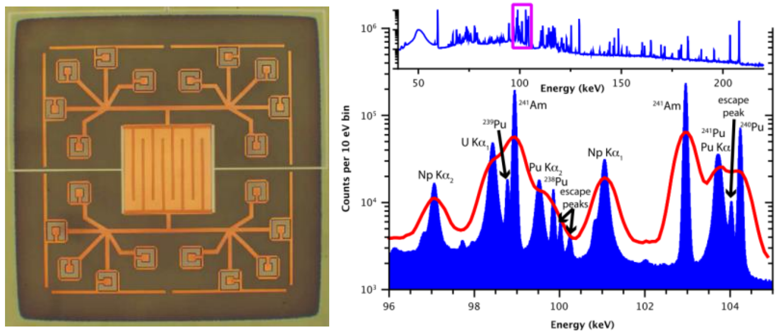
Research feilds:



Multi-threshold photon counting pixel array detector



Beam position stabilization system based on diamond detectors



Ultra-high energy resolution detector based on TES

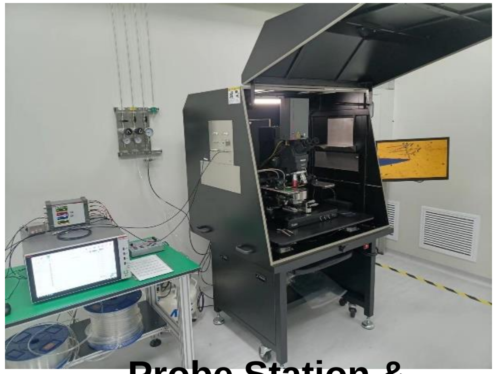
Supporting Conditions:

Laser Direct Writing Lithography Machine

Magnetron Sputtering Coating machine

Reactive Ion Etching Machine

Wire bonding



Probe Station & Semiconductor Analyzer

Microscope

Micro-Nano Fabrication：

- Minimum critical dimension: 300nm
- Overlay alignment accuracy: 500nm
- Maximum substrate size：6 inch

Packaging Integration：

- Maximum wire length：8mm
- Bonding accuracy：3μm
- Bonding Wire Range：56mm*90mm

Testing and Calibration：

- I-V、C-V Curve, Voltage range：-210V~210V
- High-Bandwidth Oscilloscope, Bandwidth: 36GHz

Summary

- Tightly around the requirements of neutron instruments, establish a neutron detectors family, promote engineering construction and exploration of new technologies.
- Based on engineering and R&D requirements, establish various functional testing and development platforms.
- Set up a micro-nano structure detector R&D platform.
- In the future, will focus on the demands of major scientific projects:
  - Solve engineering challenge, conducting engineering technical R&D (vacuum, magnetic field, electromagnetic interference, background suppression).
  - Exploring new technologies to enhance the performance of instruments

Acknowledge

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1986
NATIONAL NATURAL SCIENCE FOUNDATION OF CHINA

核探测与核电子学国家重点实验室
State Key Laboratory of Particle Detection and Electronics

中物院中子物理学重点实验室
Key Laboratory of Neutron Physics,CAEP

中国科学院青年创新促进会
Youth Innovation Promotion Association CAS

中国原子能科学研究院
China Institute of Atomic Energy

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1909
LANZHOU UNIVERSITY

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1953
HARBIN ENGINEERING UNIVERSITY

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UNIVERSITY OF SOUTH CHINA

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1907
TONGJI UNIVERSITY

陕西科技大学
SHAANXI UNIVERSITY OF SCIENCE & TECHNOLOGY

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Thanks for your attention!