The 8th International Conference on Micro-Pattern Gaseous Detectors

Ceramic GEM neutron detector and its applications at China Spallation Neutron Source

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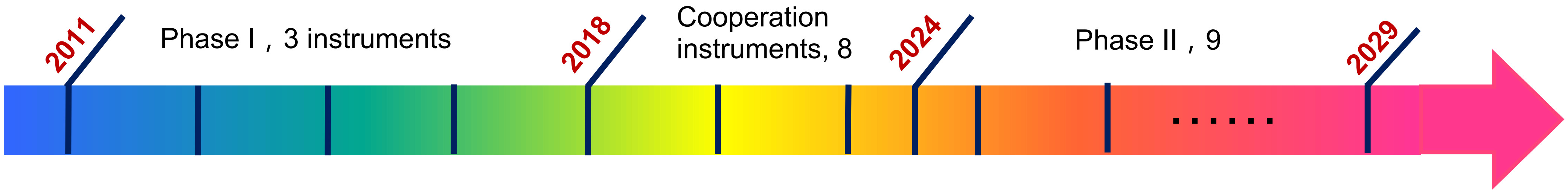
Outline

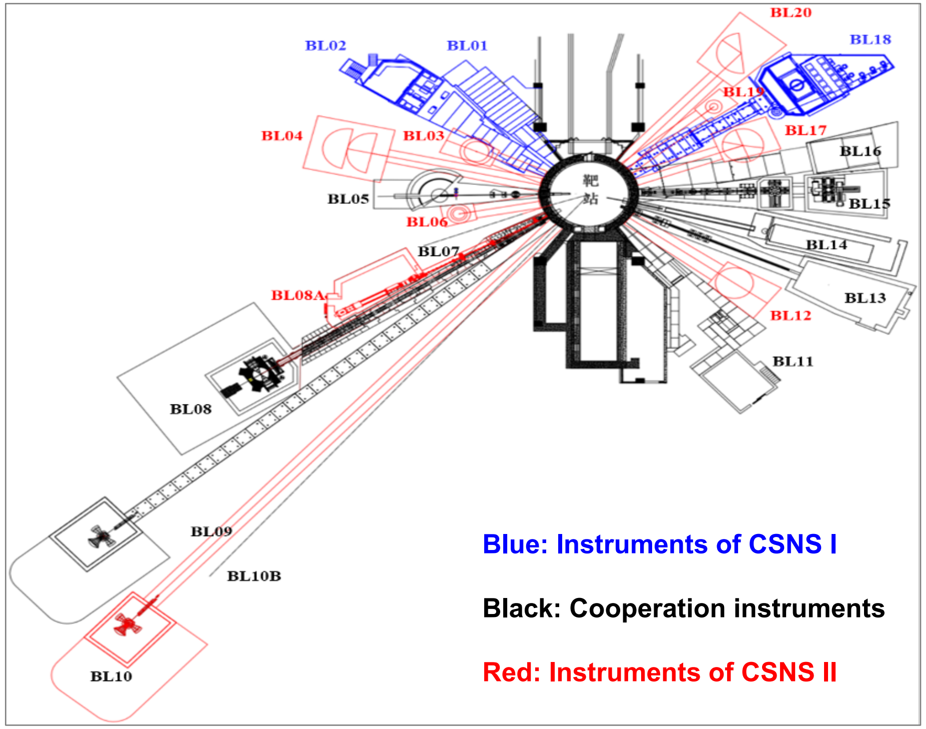
Contents

China Spallation Neutron Source (CSNS)

A multidisciplinary frontier research platform to study the structure and dynamics of matter

- 8 instruments operated, 3 instruments under commissioning, 9 instruments planned in CSNS II





Blue: Instruments of CSNS I

Black: Cooperation instruments

Red: Instruments of CSNS II

BL01. Small Angle Neutron Scattering Instrument

BL02. Multi-functional Reflectometer

BL03. Liquid Neutron Reflectometer

BL04 Cold Neutron Direct Geometry Inelastic Spectrometer

BL05. High-Energy Inelastic Spectrometer

BL06. Inverse Geometry Molecular Vibrational Spectrometer

BL07. (Reserved)

BL8A. Neutron Technology Development Beamline

BL08. Engineering Materials Neutron Diffractometer

BL09. 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

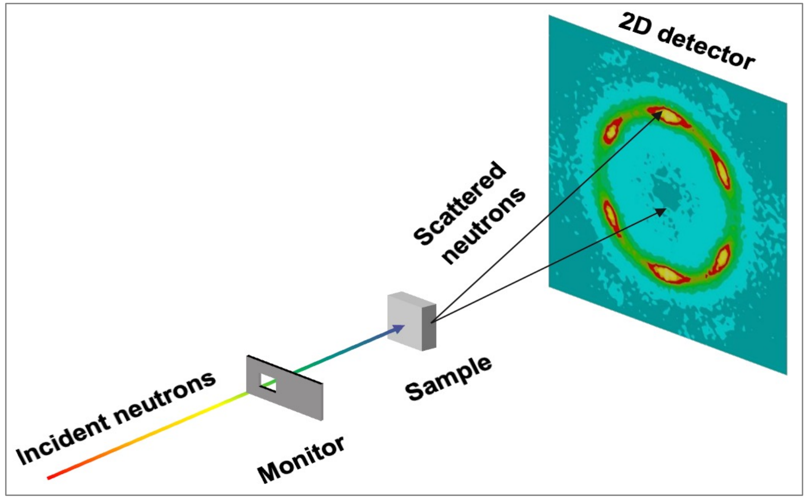
BL19. Single Crystal Neutron Diffractometer

BL20. Direct Geometry Polarized Inelastic Spectrometer

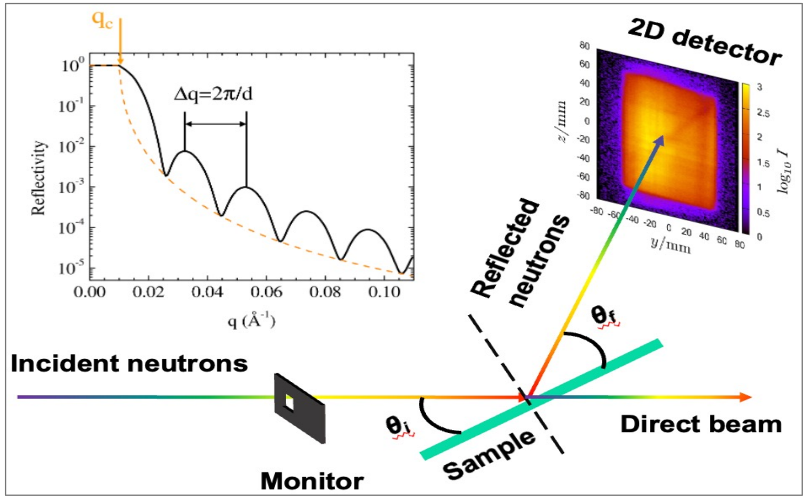
Challenge on direct & approaching beam measurements

Demand very high flux measurement with wide dynamic range：0.1Hz - 1MHz

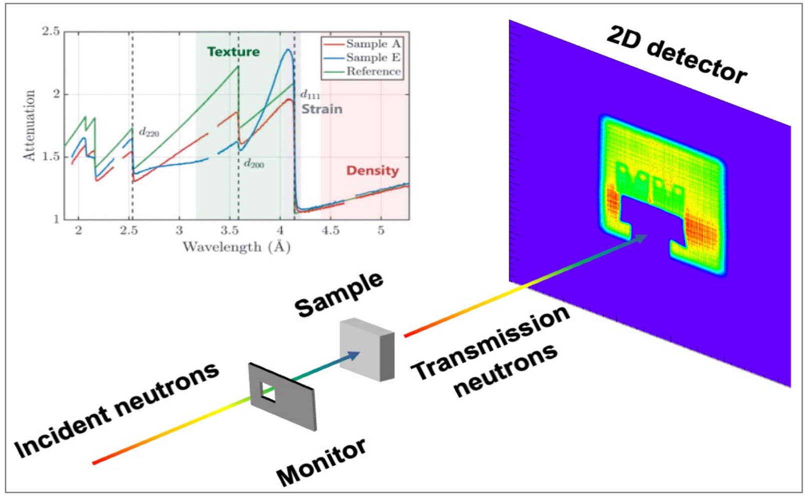
Small-angle neutron scattering



Neutron reflection



Neutron bragg-edge imaging



Beam monitor

Parameters	Requirement
Effective area	50 mm × 50 mm ~ 100 mm × 100 mm
Spatial resolution	~ mm
Time resolution	~ μs
Dynamic range	0.1Hz ~ 1MHz

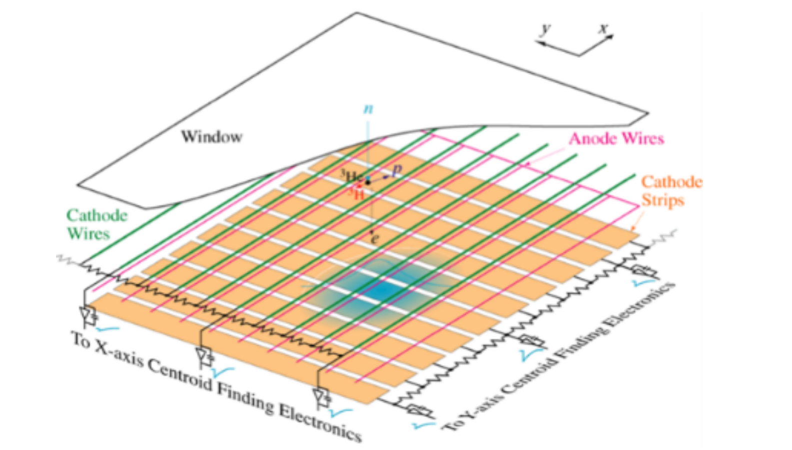
Small angle scattering/Neutron Reflection/Neutron imaging

Parameters	Requirement
Effective area	200 mm×200 mm ~1000 mm×1000 mm
Spatial resolution	~ mm
Time resolution	~ μs
Dynamic range	0.1Hz ~ 1MHz

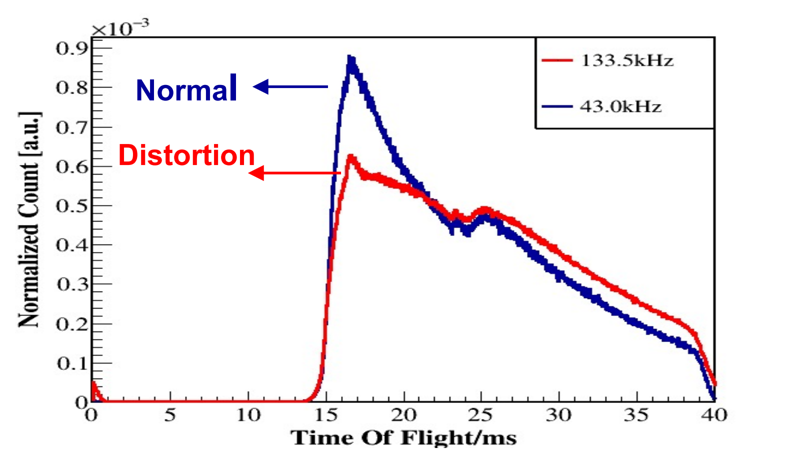
Challenge on the traditional neutron detection technology

Widely used wire-structure detector cannot satisfy high flux measurement

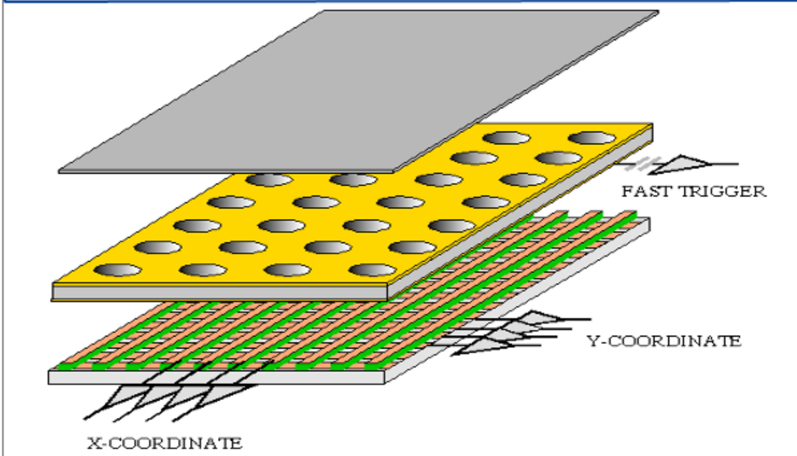
Multi- Wire Proportional Chamber(MWPC)



Exceeding 100 kHz @ MR of CSNS



Gas Electron Multiplier (GEM)

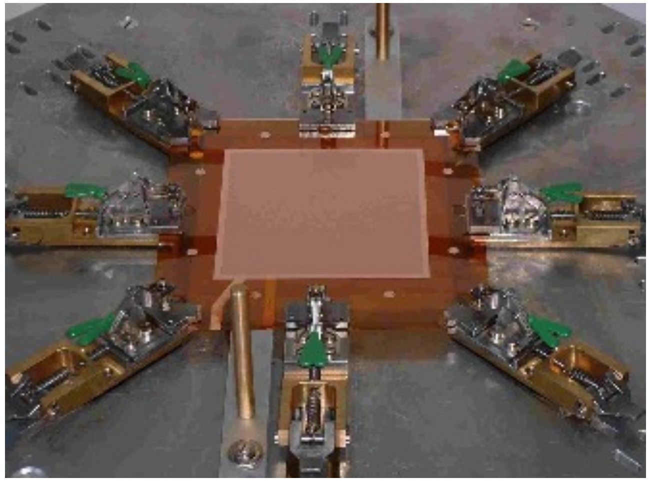


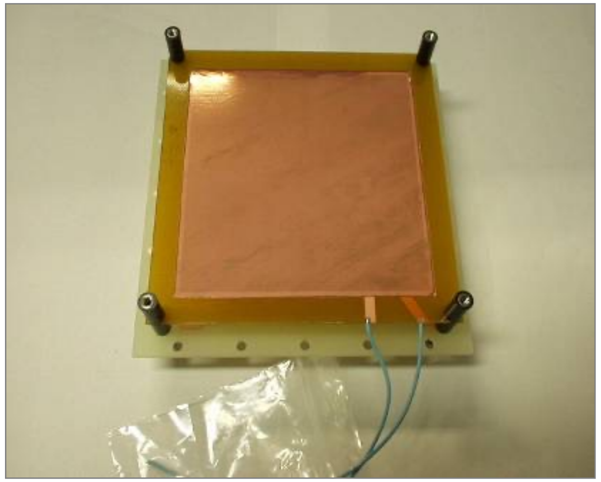
Parameters	Traditional Wire- Structure Detector	Micro-Pattern Gas Detector
Dead time	Wired-structure electrode, slower drift velocity of ion, Long dead time (> 10μs)	Micro-structure electrode, fast drift velocity of electron Short dead time (~ 0.1μs), decreased by 2 orders of magnitude
Counting rate	Lower count rate (< 100kHz); Smaller dynamic range of neutron flux measurement	Higher counting rate (~10 MHz) , Wide dynamic range improved by 2 orders of magnitude

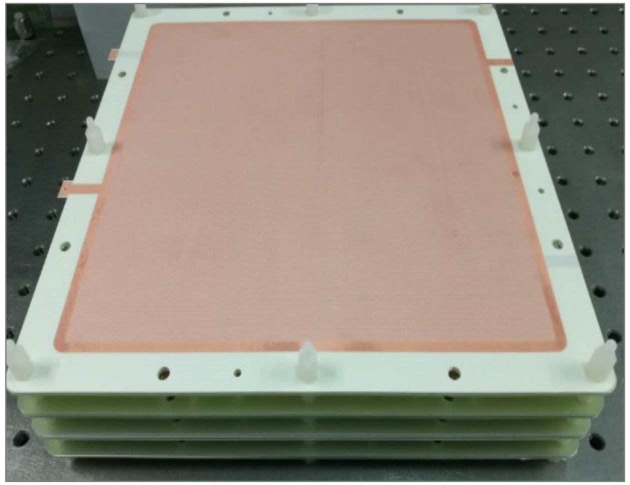
Micro-pattern gas neutron detector booming

GEM (Gas Electron Multiplier) applied in neutron detection

Martin Klein, **Kapton GEM@CERN**, NIMA 628(2011) **LCP GEM@KEK**, NIM A 525(2004) **Ceramic GEM@CSNS, CPC 407(2016)**







Institution	GEM type	Insulating Material	Hole diameter d(μm)	Pitch between holes (μm)	Copper layer thickness (μm)	Total thickness (μm)	Copper Coverage Ratio η
Uni. Heidelberg	nGEM	Kapton	70	210	5	60	90%
KEK	GEM	LCP	70	140	5	100	77%
CSNS-IHEP	**Ceramic GEM**	**Ceramics**	**200**	**600**	**20**	**200**	**90%**

Outline

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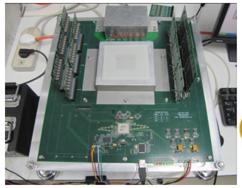
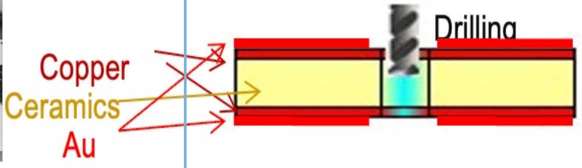
The development timeline of ceramic GEM neutron detectors

2009

Start research on GEM neutron detector





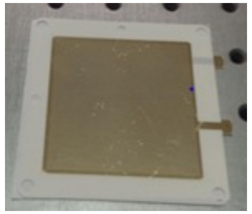
2012

A standard GEM-based neutron detector achieved

2013

Ceramic GEM for neutron detection proposed and designed

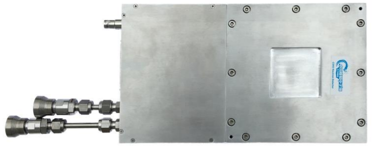
2015



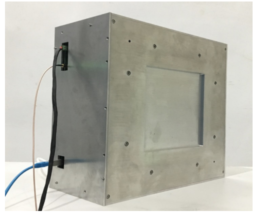
Small-area ceramic GEM realized

2017

GEM-based beam monitor applied at CSNS



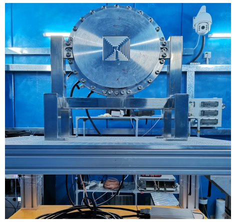
2019



High-efficiency and large-area GEM detector developed

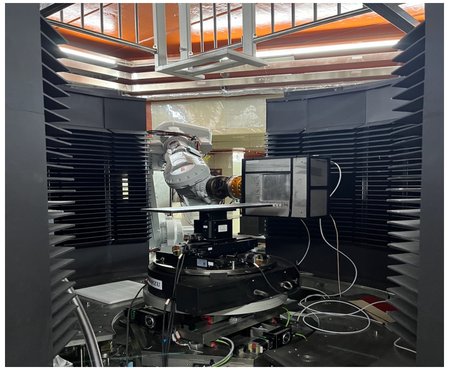
2020

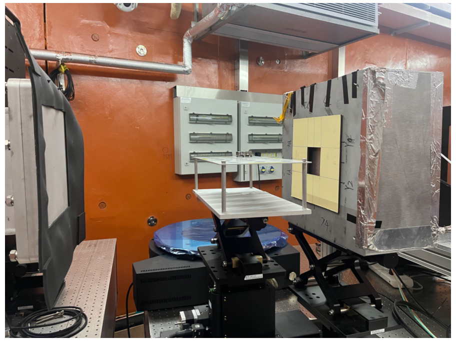
Sealed GEM detector developed

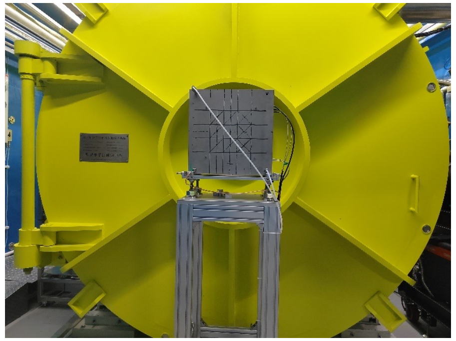


2022

Multiple applications for instruments







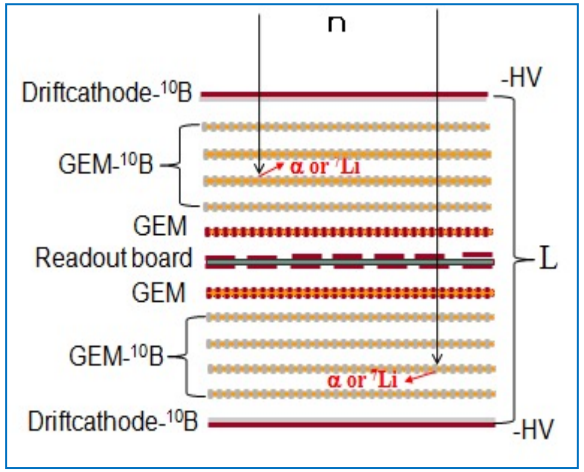
Ceramic GEM neutron detector

CHINESE ACADEMY OF SCIENCES

Study content: ① Detector design ② Research on the key technologies ③ Engineering applications

Focusing on engineering applications based on ceramic GEM, promote R&D on detector design and key technologies.

Principle of the detector



1-10 layers of GEM

$^{10}B + n \rightarrow {}^{7}Li + \alpha + 2.792\ MeV$ 3840 b

$^{7}Li^{*} + \alpha + 2.310\ MeV$

3 key-technologies

Developing high-performance large-area ceramic GEM

- Less neutron scattering, lower scattering background
- New methods and techniques to improve quality and qualified rate

Fabrication of large-area boron coating for neutron conversion

- Large area with strong adhesion
- High purity and good uniformity of thickness

High-speed readout electronics and data acquisition software

- High-speed front-end ASIC chip
- High-speed data acquisition system and software

Engineering applications

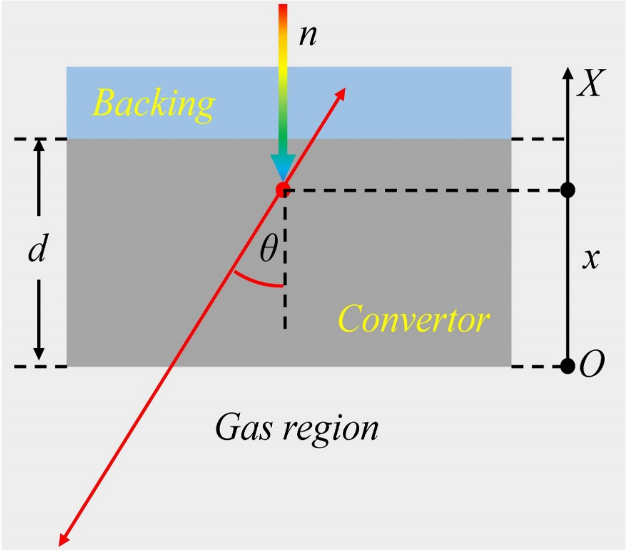
Physical requirement → Model Specification → Engineering Design → Scandalization

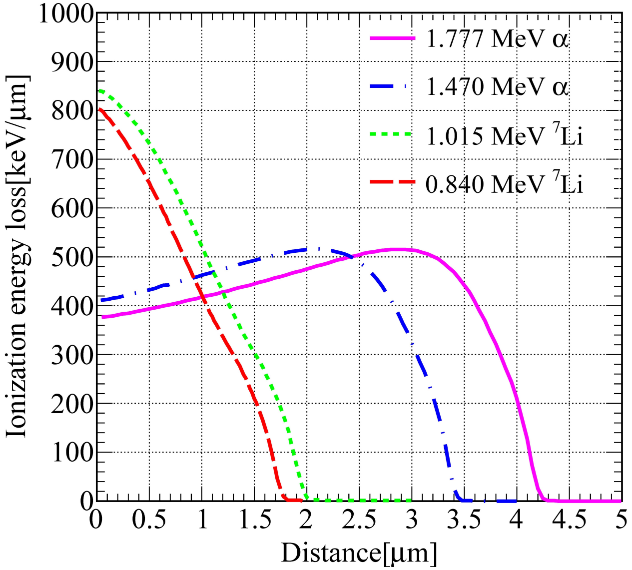
Simulation and optimization

Neutron converter B_4C coating (^{10}B 96%)

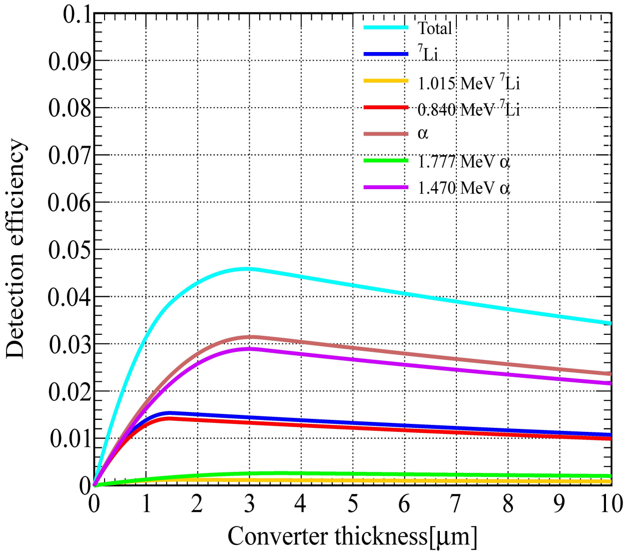
- Max. efficiency ~ 4% at 2.5 μm thick for single coating
- 20 layers of converters required to improve detection efficiency to 40%(very difficult)
- Ionization energy loss in gas ~ 200 keV/mm
- Primary electrons ~ 30000(5fC) and gas gain ~100 enough for neutron detection

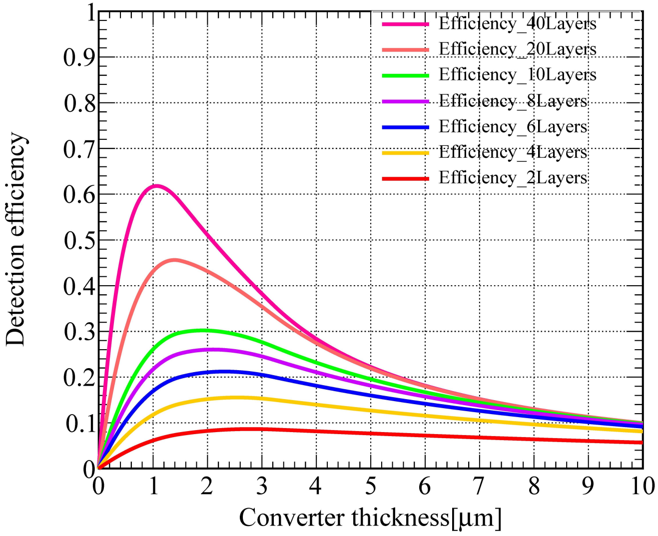
Analysis model and geant4 calculation





Detection efficiency

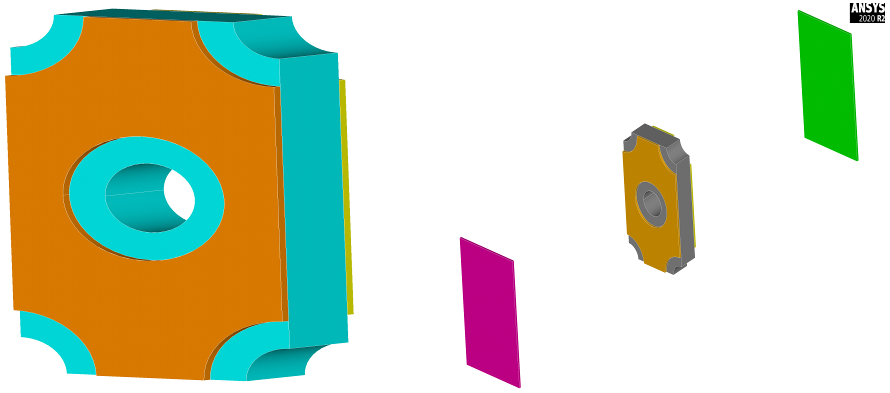


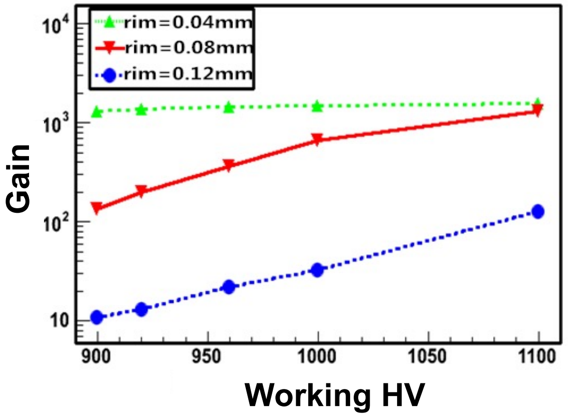


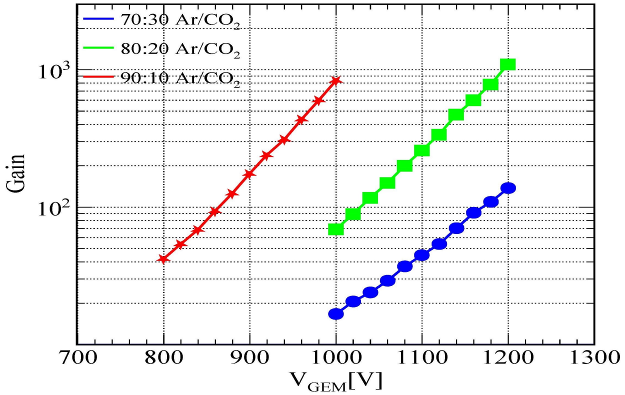
Simulation and optimization

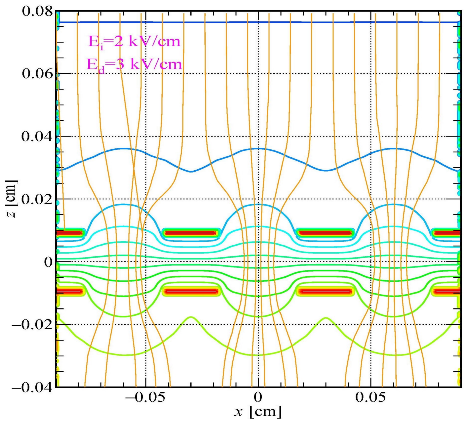
Ceramic GEM design

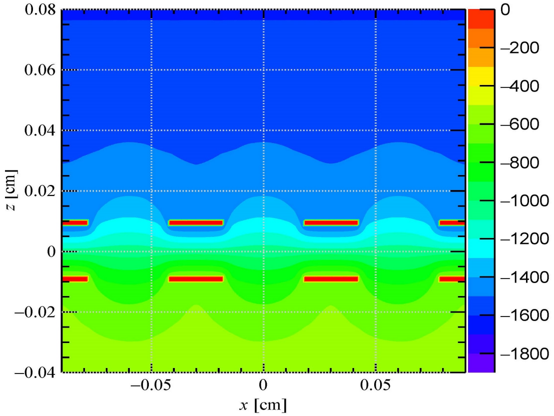
- Hole dia. 200μm, pitch 600 μm, total thickness 200μm, Rim 80μm
- Working gas: Ar/CO_2(90:10), drift electric field ~1 kV/cm and induction electric field ~3 kV/cm
- Gas gain: 10-1000, Signal width(σ): ~ 65ns

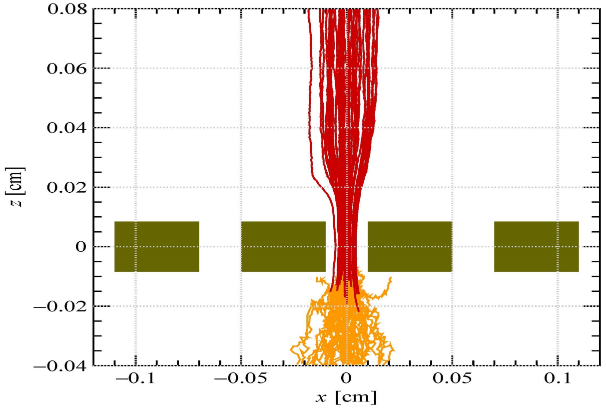


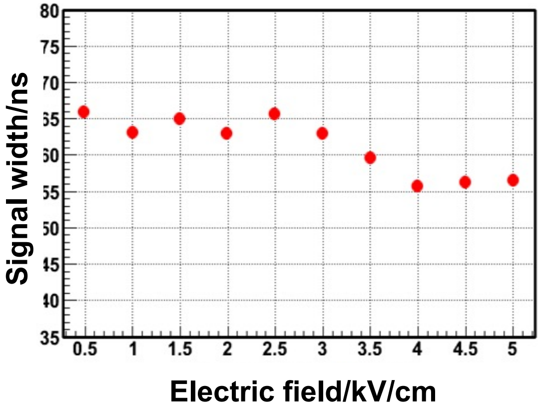








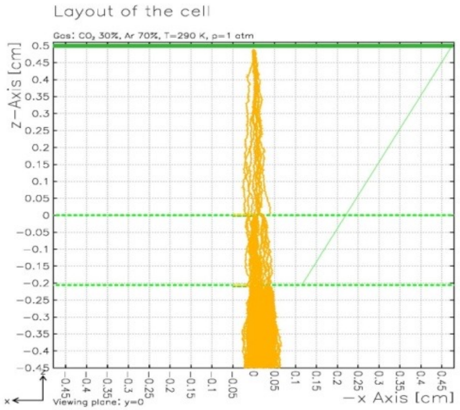


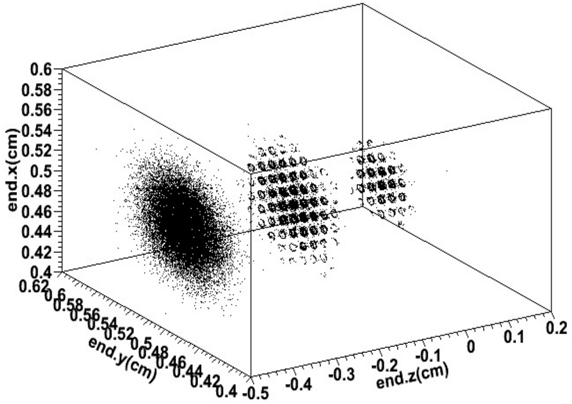


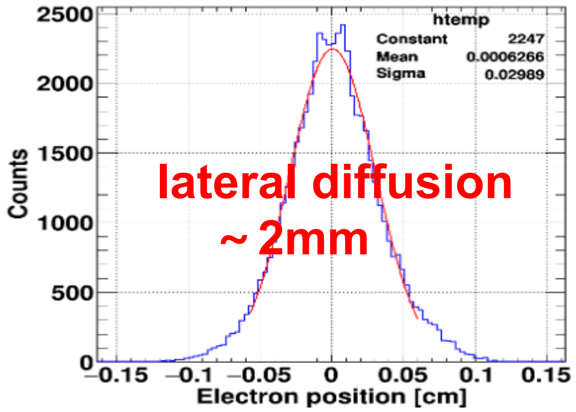
Simulation and optimization

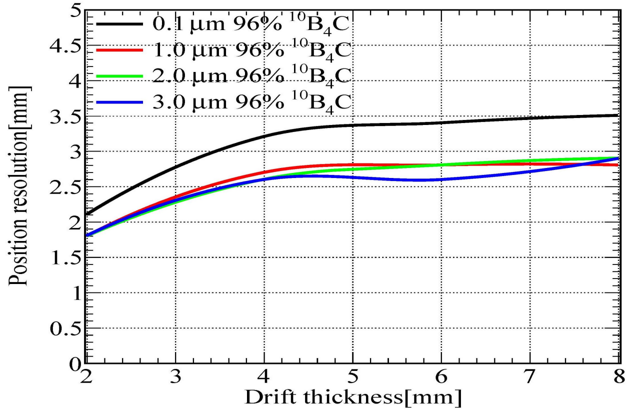
Spatial resolution ~2mm

- Determined by emitted angle, ion range, drift distance and electron lateral diffusion



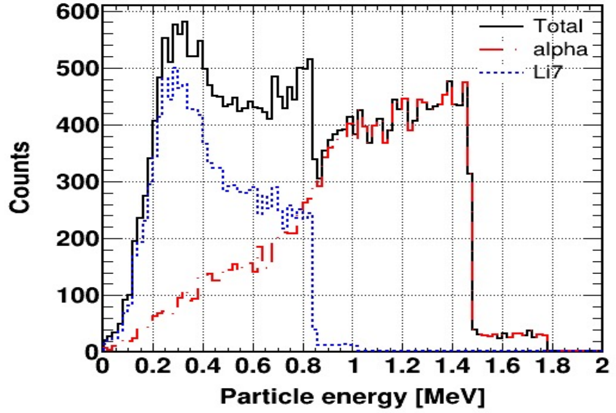


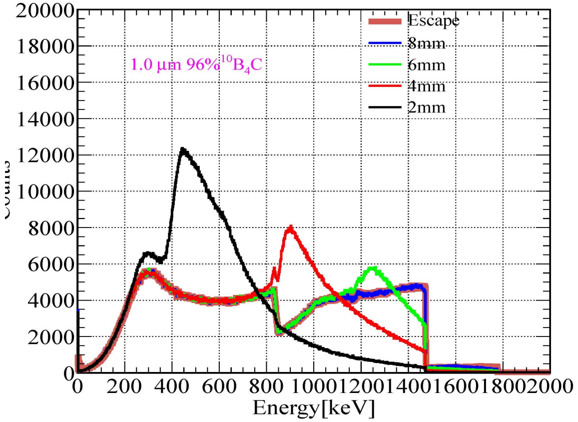


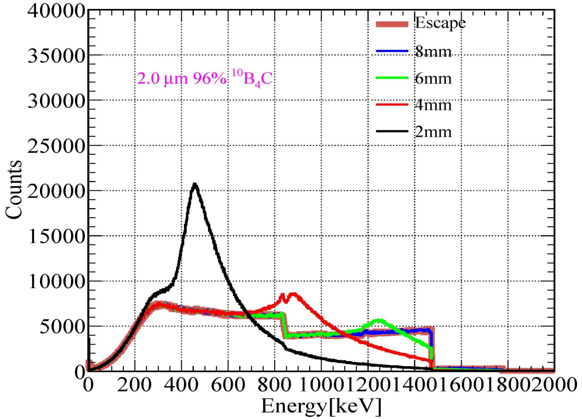


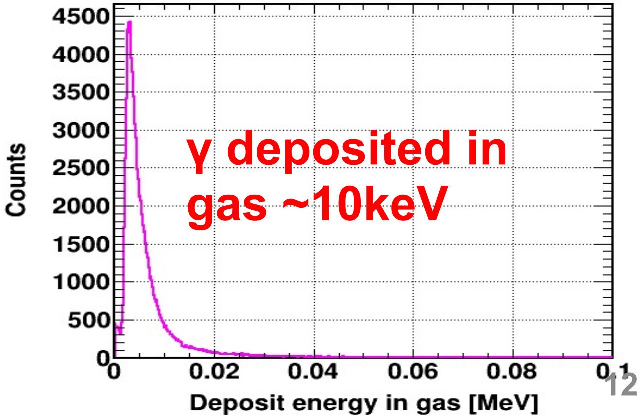
High neutron-gamma discrimination capability

- due to energy deposited in gas by ions ~1MeV, while γ ~10keV





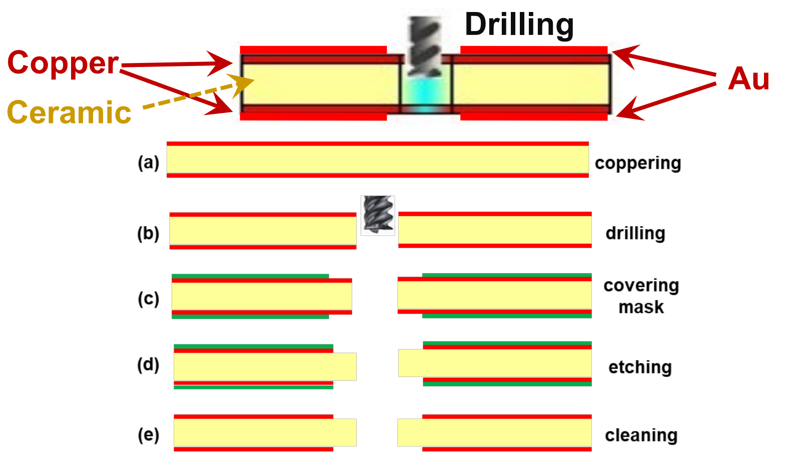




Ceramic GEM for neutron detection

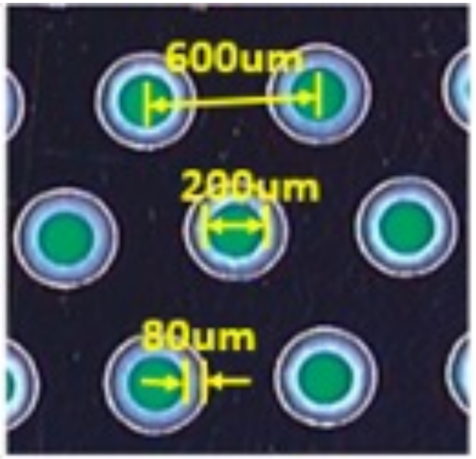
Almost no hydrogen, low neutron scattering, radiation hardness, withstands baking

Ceramic GEM — mechanical drilling



Specification of GEM:

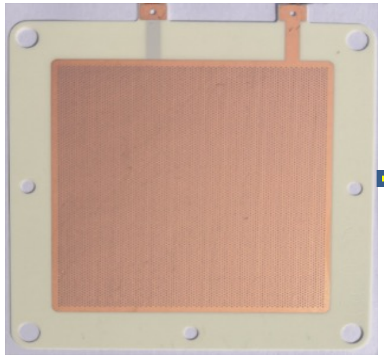
thickness: 200 μm, hole diameter: 200 μm, pitch: 600 μm, Rim of 80 μm.



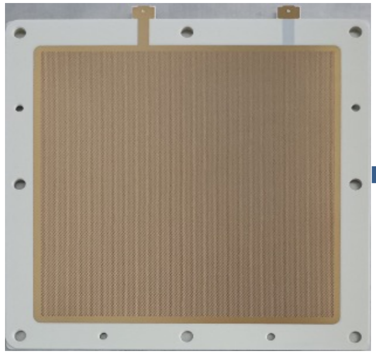
Fabrication process :

- **Substrate material: composite ceramic by standard PCB mechanical drilling process**
- **Drilling speed: ~300 holes/min**
- **Drilling accuracy: ~50 μm**
- **Qualified rate: over 90% for small area, with rapid decreasing for large area due to drill wear**

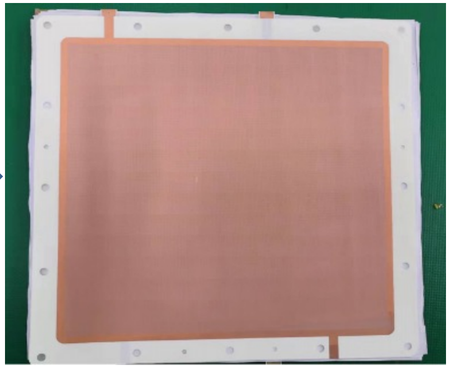
Four types of ceramic GEM realize mass industrial production(Yuguang Xie)



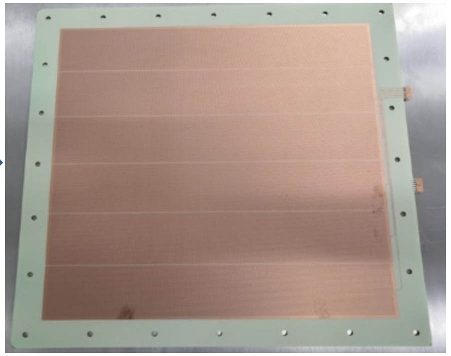
50mm× 50mm



100mm × 100mm

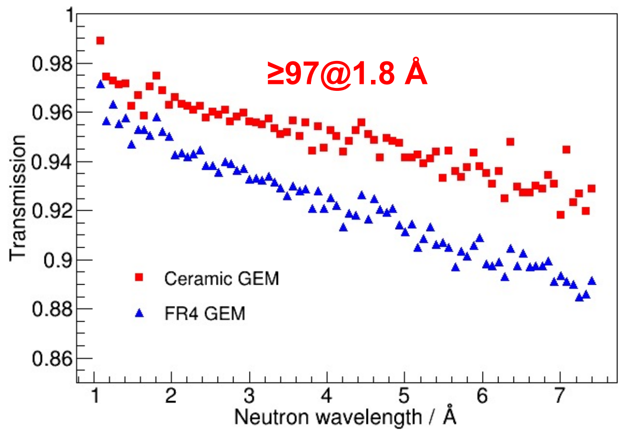


200mm× 200mm



300mm × 300mm

Neutron transmission



NET, 52(6):1277-1281, 2020

Large-area neutron conversion coating

Develop a large-area boron coating facility and a set of coating techniques (Tongji University)

- Thickness: 0.01 ~ 5μm, accuracy control: < 5 nm, single-sided, double-sided coating, RF and DC mode
- Maximum coating area: 1500mm × 500mm, thickness: 1μm and its uniformity better than ±1.32%.

Dedicated facility for large-area boron coating by magnetic sputtering

Sample of high-performance large-area B_4C film

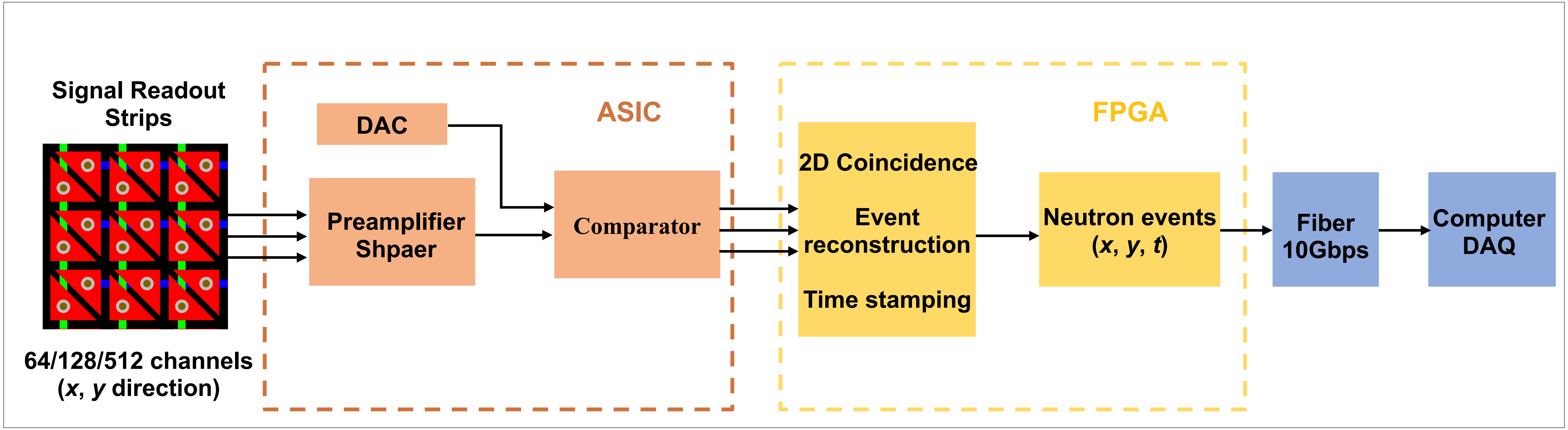
Fund supported by the State Key Laboratory of Nuclear Detection and Nuclear Electronics

Rev. Sci. Instrum. 94, 093901, 2023

Fast readout electronics and the method

Detect neutron position by 2D signal coincidence method

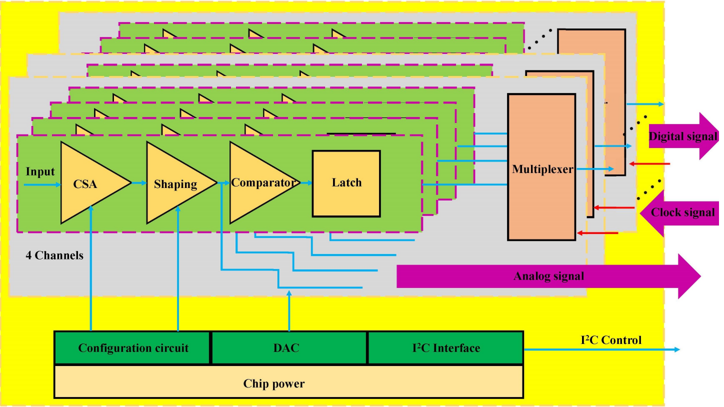
- **2D signal readout strip: flexible circuit board (0.5mm thickness, 6-layers and strip period 0.78mm) for signal extraction**
- **Analog front-end: 64-channel fast analog to digital ASIC chips, output digital pulse above threshold**
- **Digital part: based on high-speed FPGA, achieving high count rate readout and high spatial resolution by 2D signal coincidence method and event reconstruction algorithm**



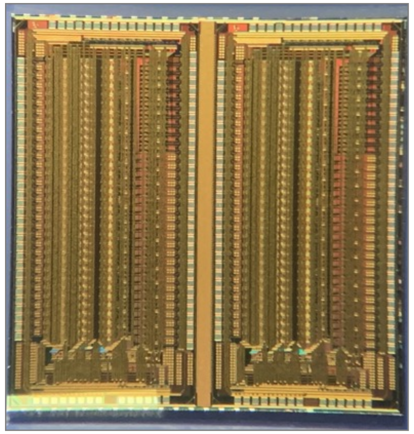
Front-end ASIC chip development

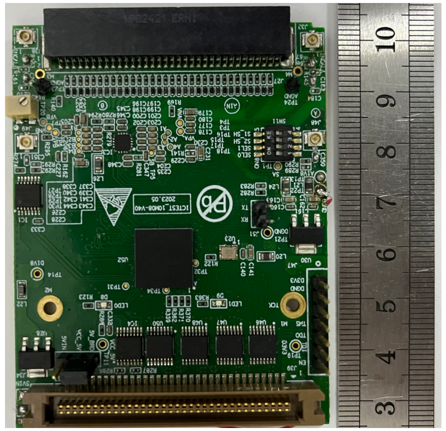
A dedicated high-speed front-end ASIC chip (by Ma Yi Chao)

Parameters	Specification
Input charge	±10 fC ~ ±400 fC
Counting rate	≥ 1.0 MHz/ch
Number of channels	32 × 2
Output	2.5V TTL signal over threshold
Threshold	Externally adjustable DAC

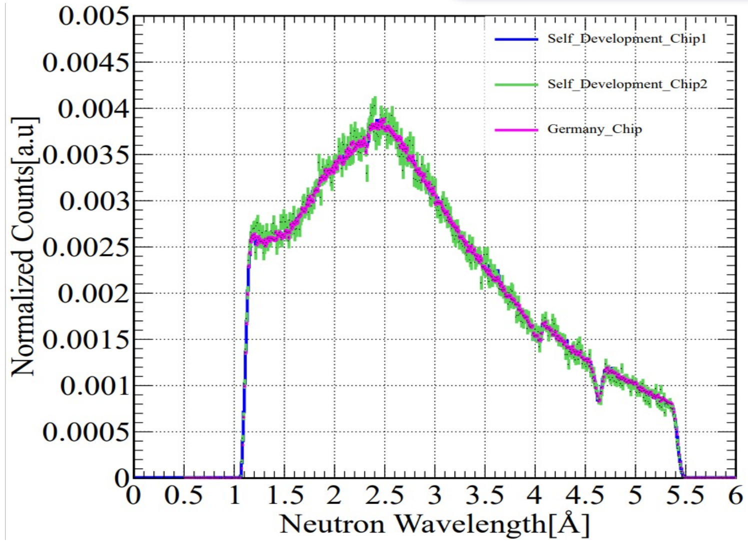


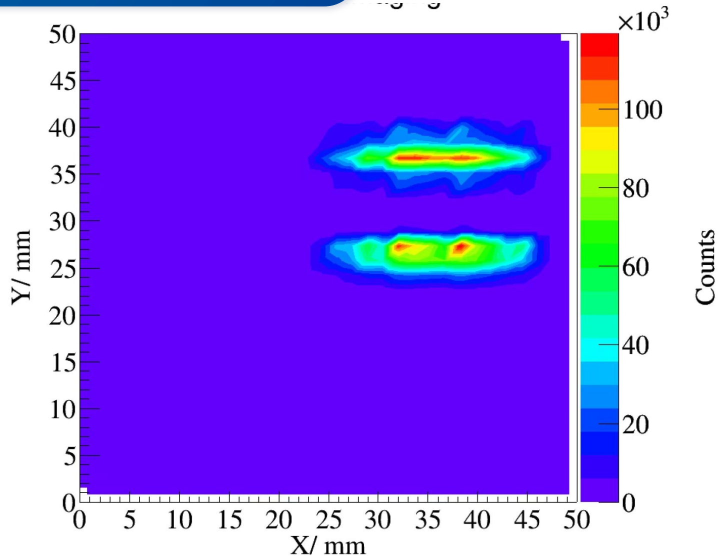
Two ASIC chips are packaged onto a board





Beam tests at CSNS BL20



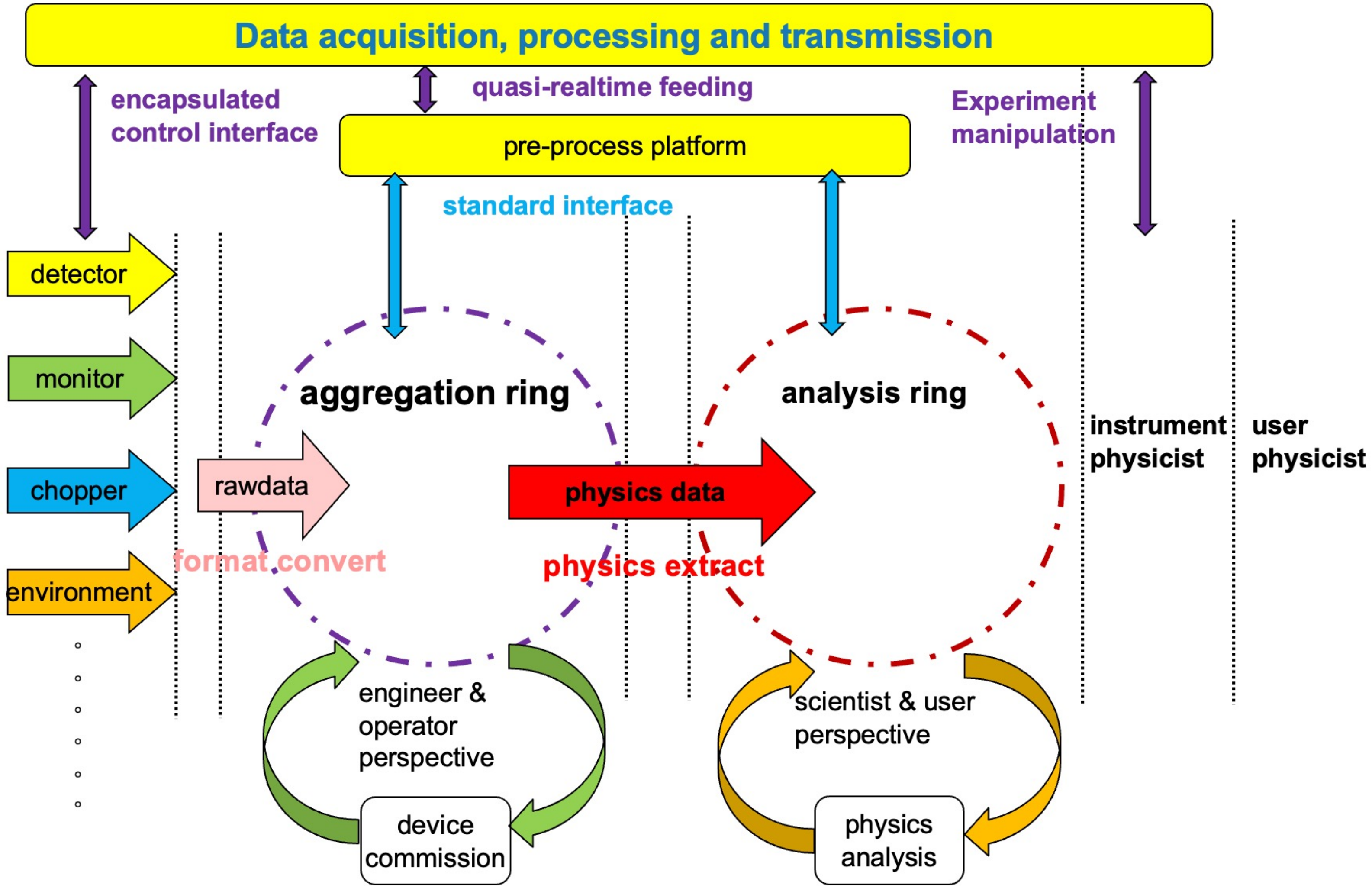


Progress of the ASIC

- **Difficulties:** multi-channel, low power consumption, high speed, and radiation hardness
- 2020: the first version of design and tape-out
- 2021: packaging and tests, relatively high noise.
- 2022: V2 with optimized design, poor channel consistency.
- 2023: V3 worked well but with low speed
- 2024: new design under the way

Data acquisition system software

- Develop a data-driven detector data acquisition system, based on the open-source platform Kafka , enable the implementation of high-performance, highly reliable data processing and sharing, finally improving the experimental efficiency.



Outline

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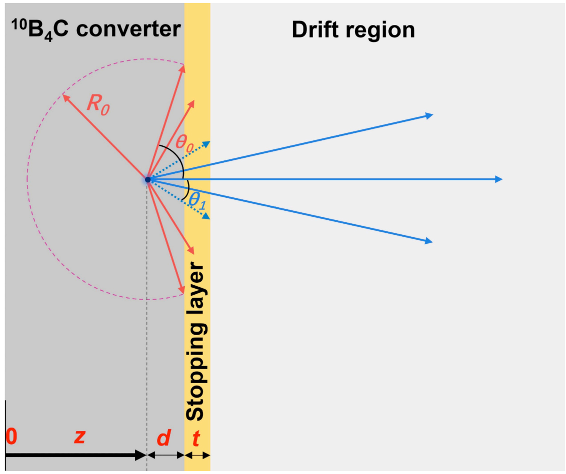
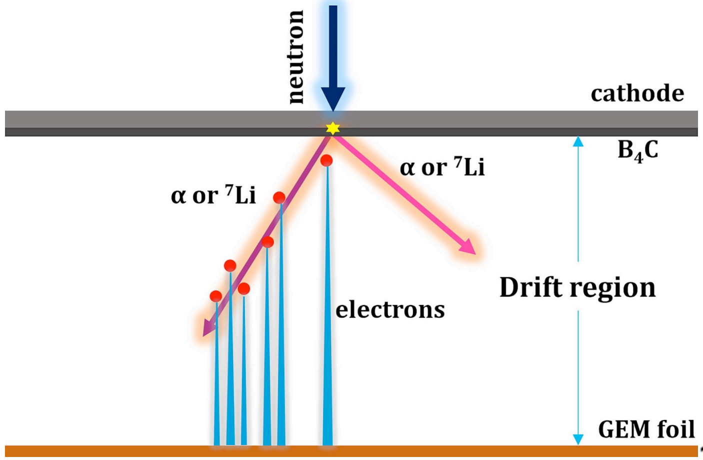
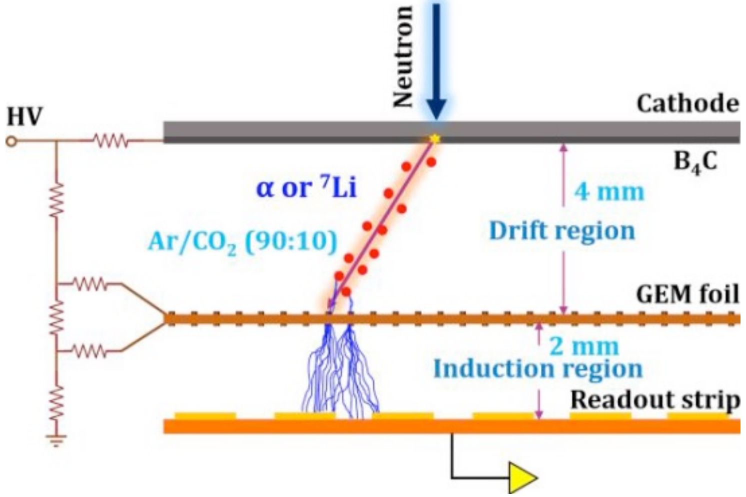
High spatial resolution detector

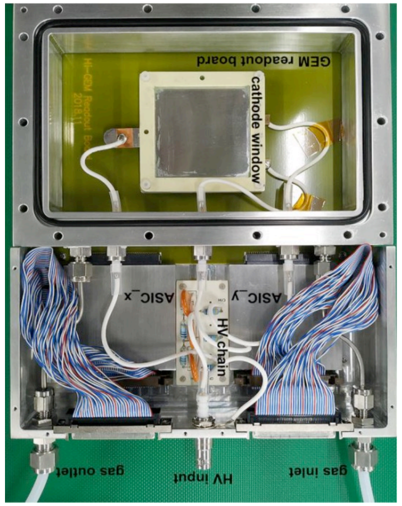
- **Improve the spatial resolution to 0.8mm with a Ti/Al stopping layer**
  - **Absorb and reduce the emitted particle with large angle**

Principle concept

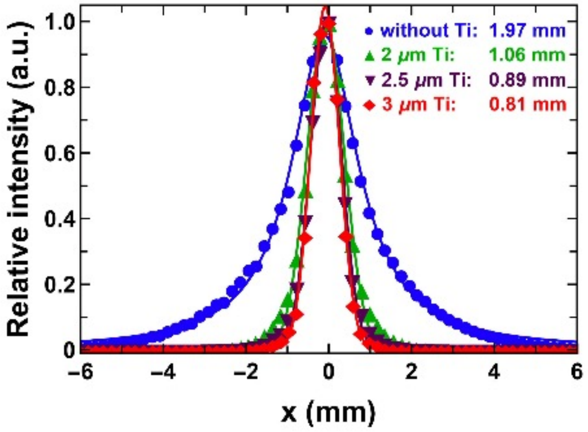


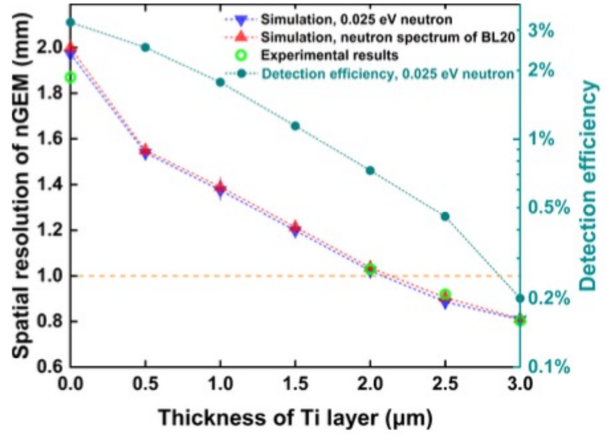




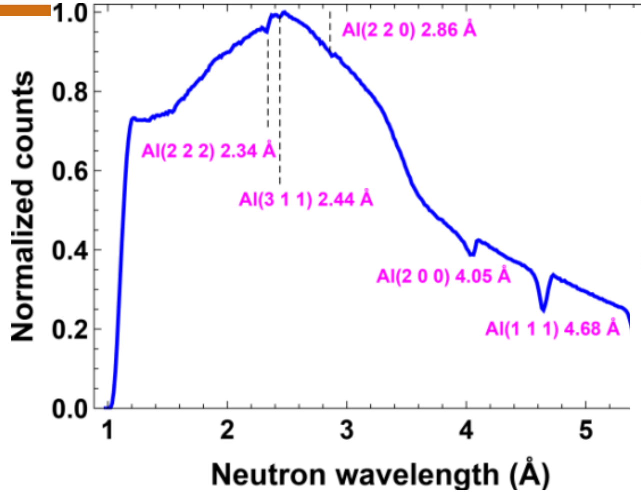


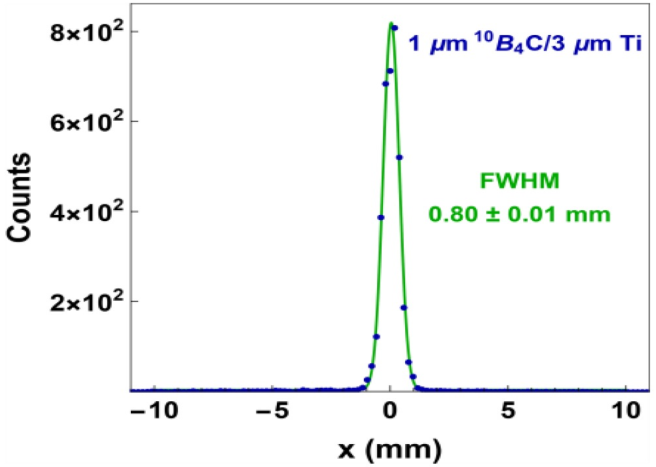
M.C. simulations





Beam tests at BL20





IEEE TNS, 99:1, 2021   Rev. Sci. Instrum. 94: 103304, 2023

High efficiency detector

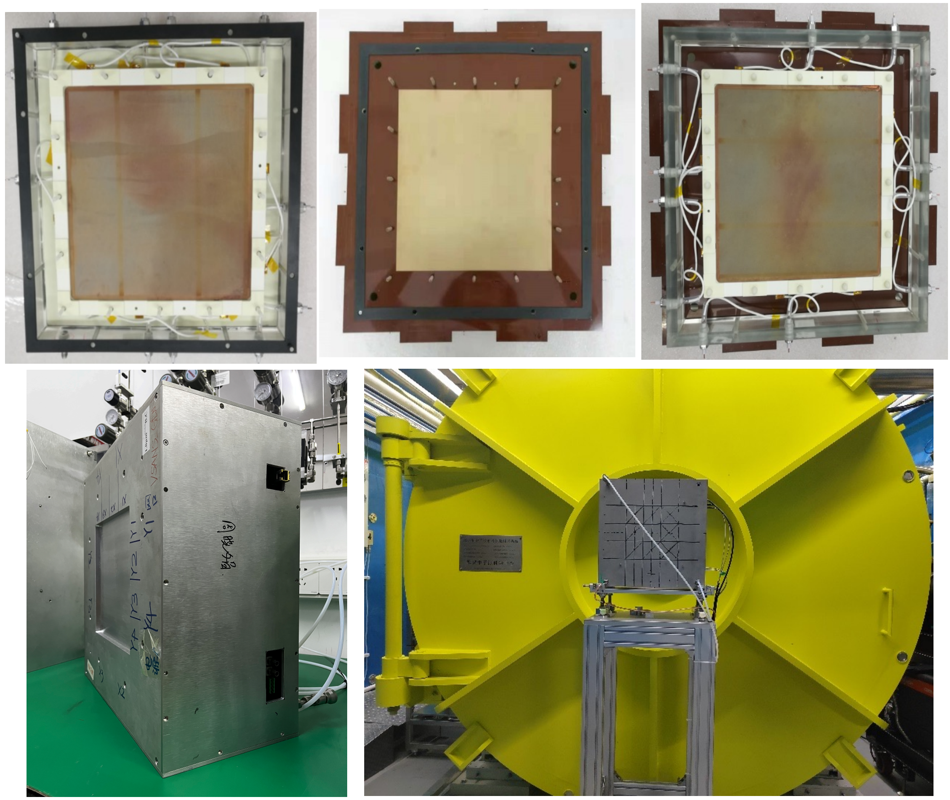
High detection efficiency and large area, operated at VSANS instrument from Oct. 2023

- **Effective area: 200mm*200mm**
- **Detection efficiency: 43%@4.8Å, spatial resolution: 2mm**

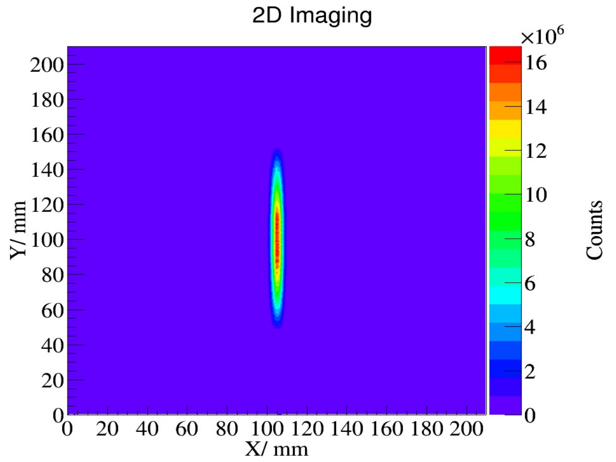
Design specifications

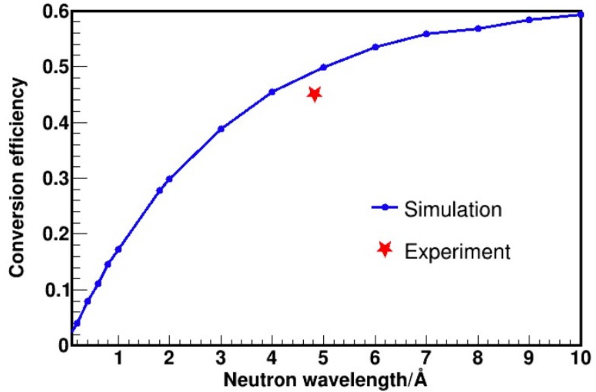
parameters	specifications
Effective area	200 mm × 200 mm
Spatial resolution(FWHM)	≤ 2mm
Detection Efficiency @ 4.8Å	≥ 40%
Maximum counting rate	≥ 1 MHz
Neutron converter	10 layers of $^{10}B_4C$ 1.2 μm
Working gas	Ne/iC_4H_{10}
Strip period	0.8 mm
Readout channels	256(X) + 256(Y) = 512
Readout electronics	8 × 64 channels ASIC + Digital electronics

Photos of detector



VSANS experiment



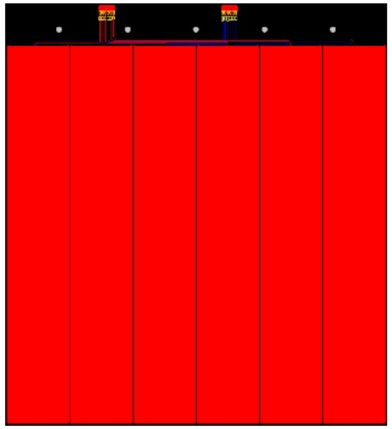


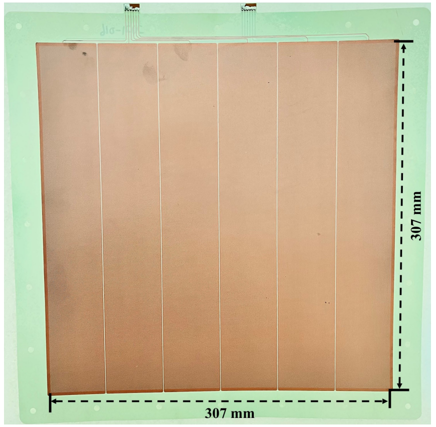
Large aera detector

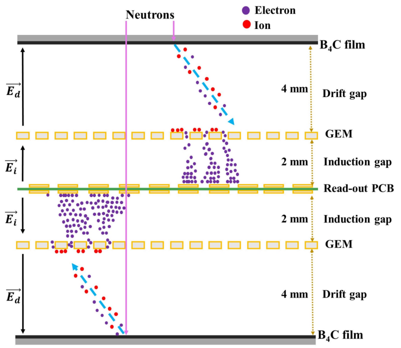
Continually develop large aera ceramic GEM detector

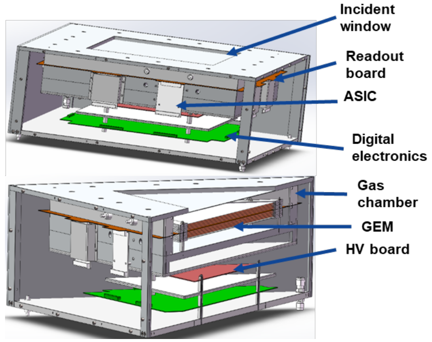
- **Active area: 300 mm × 300 mm, with 6 sub-regions decreasing discharge probability**

GEM foil and detector design

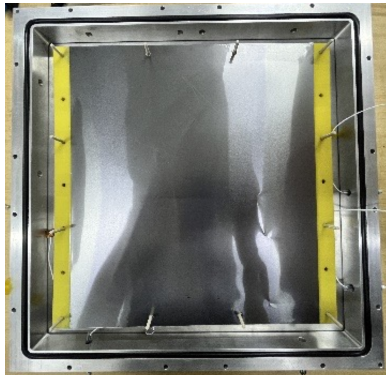


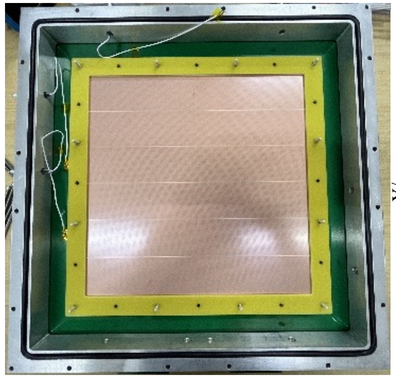


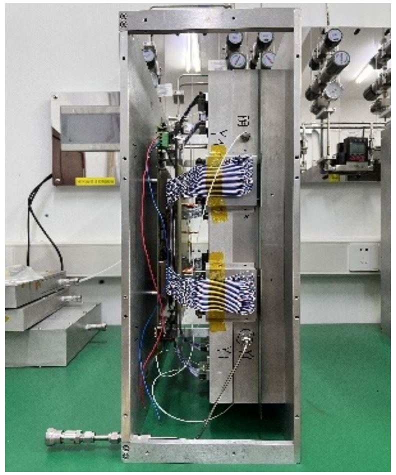


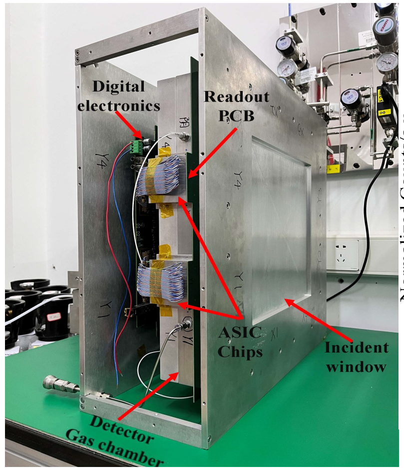


Detector Assembly

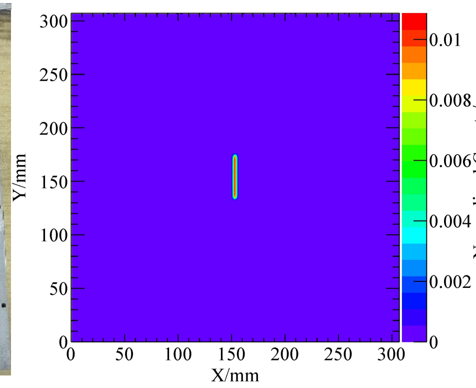


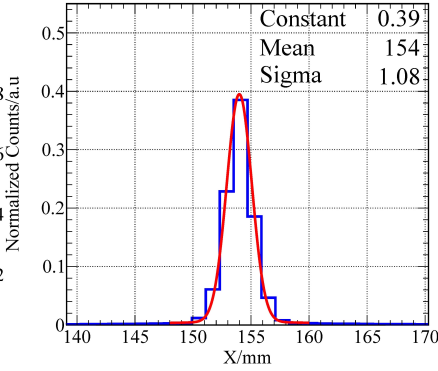


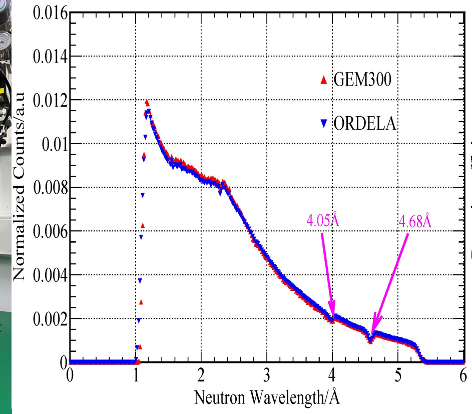


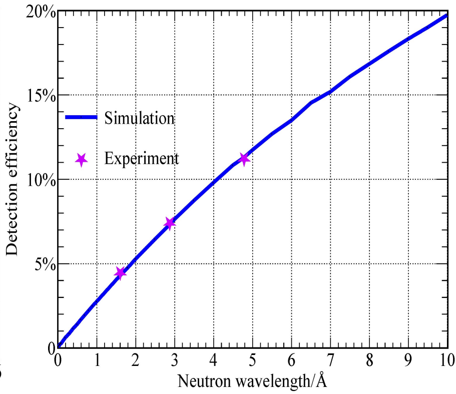


Beam tests at BL20









Imaging detector with large FOV

Large FOV for large-size object imaging, operated at ERNI instrument from Oct. 2023

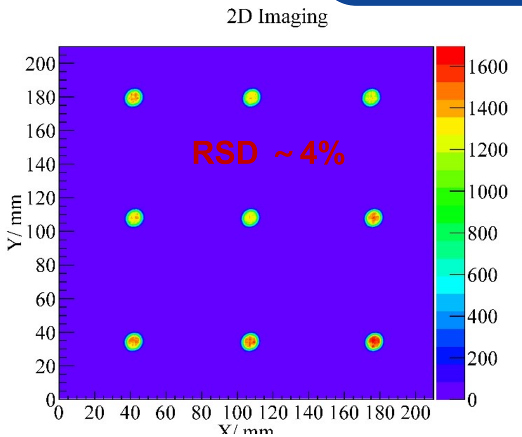
- Effective area (FOV): **200mm*200mm**
- Area uniformity: ~4%(RSD), spatial resolution: 1.8mm
- Bragg-Edge Imaging: **Δλ/λ= 0.3%**

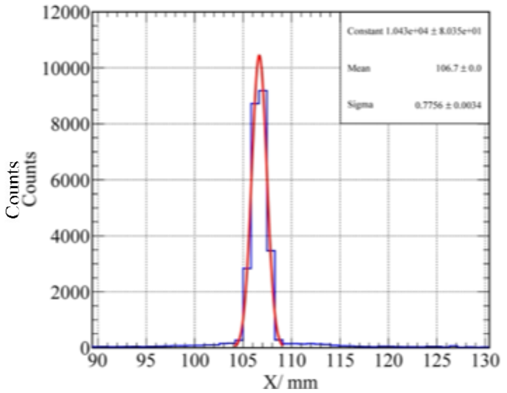
Specifications

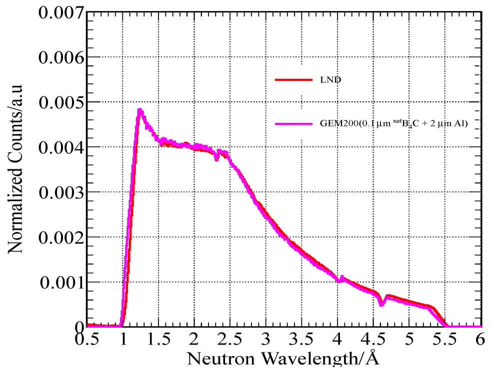
Parameters	Specifications
Neutron converter	0.1μm $^{nat}B_4C$ +2μm Al
Effective area (FOV)	200 mm × 200 mm
Spatial resolution/fwhm	1.8 mm
Detection Efficiency @1.8Å	10^{-4}
Maximum counting rate	≥ 1 MHz
Maximum neutron flux	10^{10} n/s

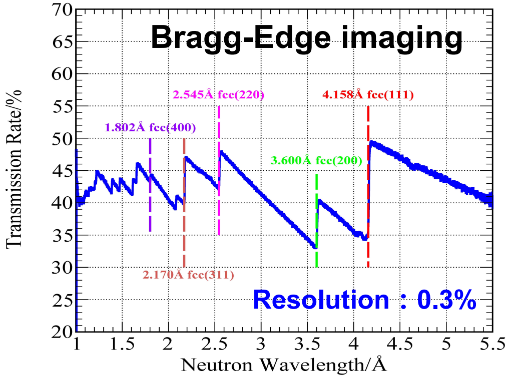
JINST, 2023, 18，P01033

Beam tests at BL 20

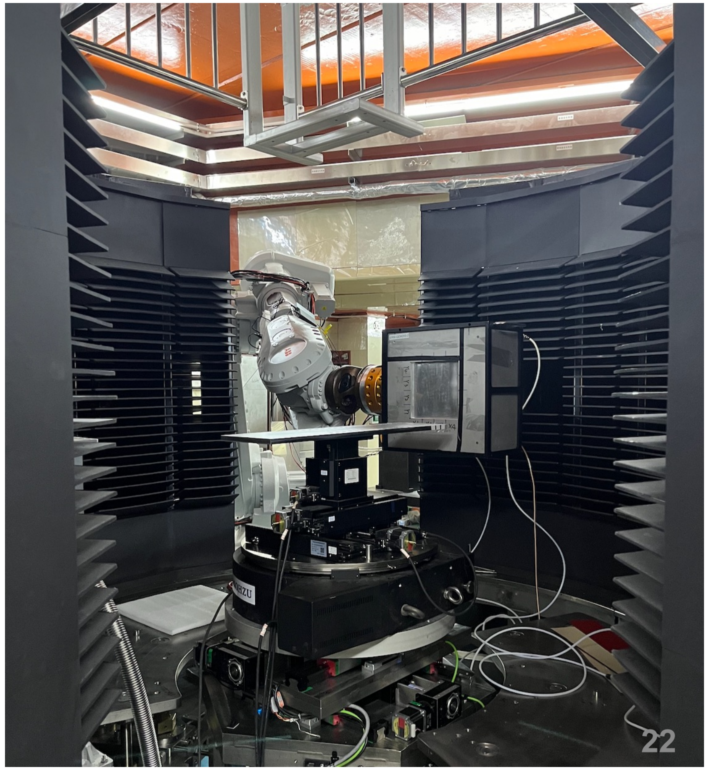








Site photo at ENRI



High-flux 2D position-sensitive beam monitor

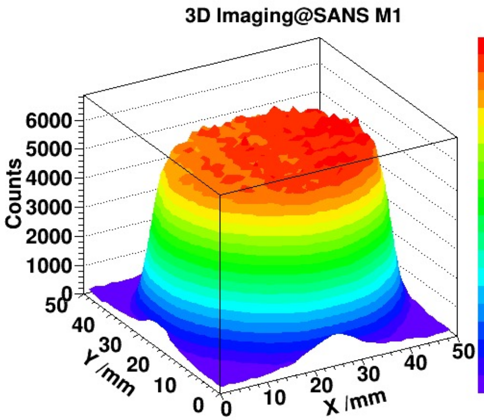
6 monitors were installed in CSNS I, operating stably for 6 years. totally 21 monitors used for instruments.

Design specifications

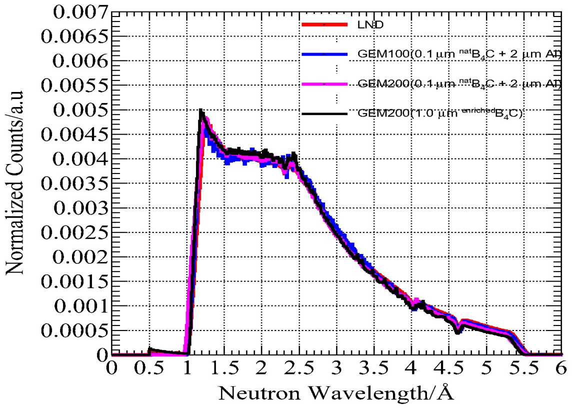
Parameters	Specifications
Neutron Converter	B_4C、C_2H_4，^{238}U
Effective area	50mm*50mm，100mm*100mm
Spatial resolution(fwhm)	~ 2mm
Detection Efficiency @1.8Å	10^{-4}~10^{-2}
Maximum count	1.2 MHz
Maximum neutron flux	10^{10} n/s

30 monitors produced

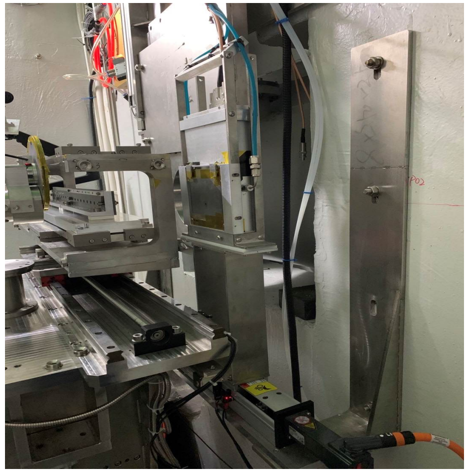
The first beam on SANS M1

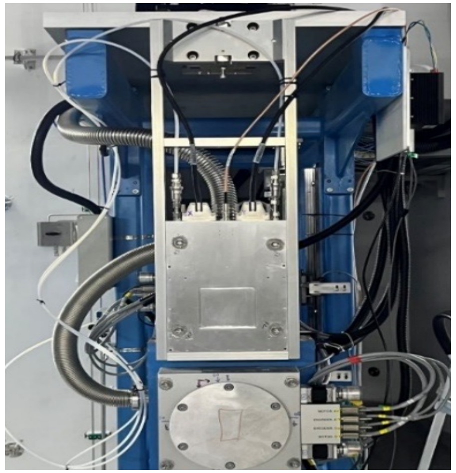


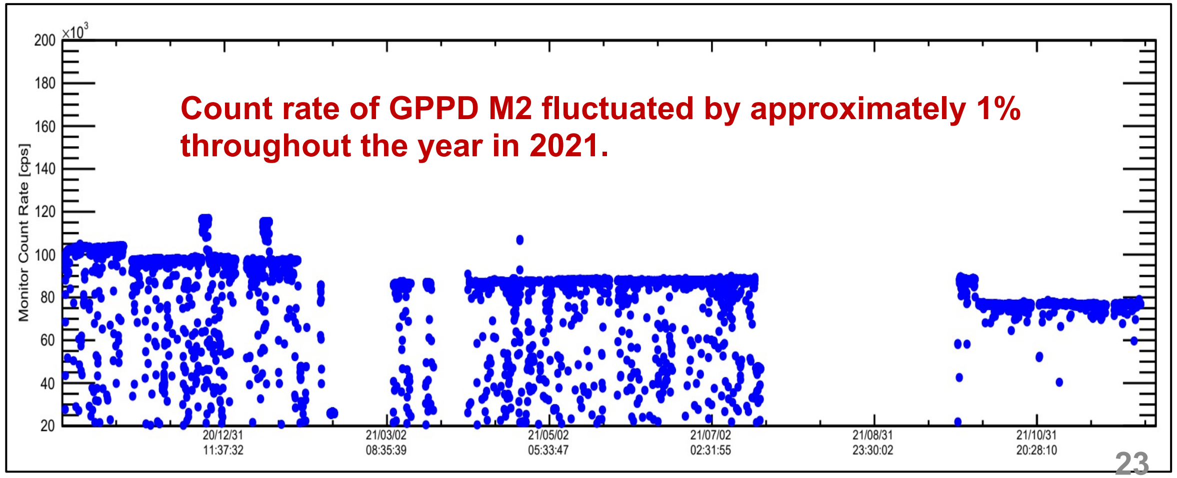
NIMA, 2020, 962:163593.



JINST, 18:P010333,2023

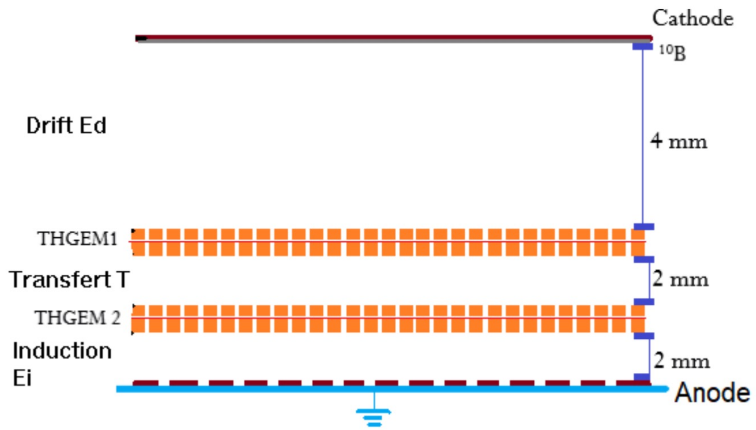


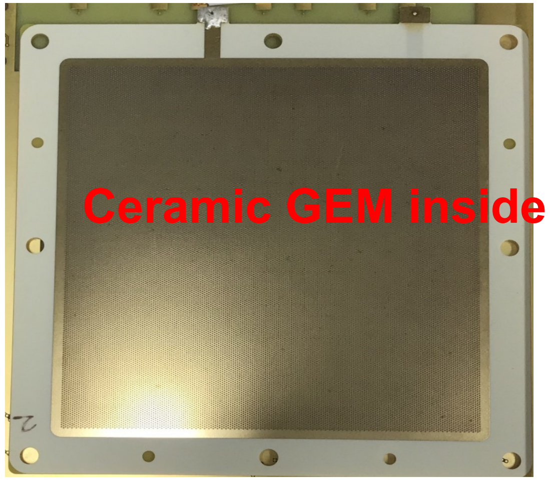


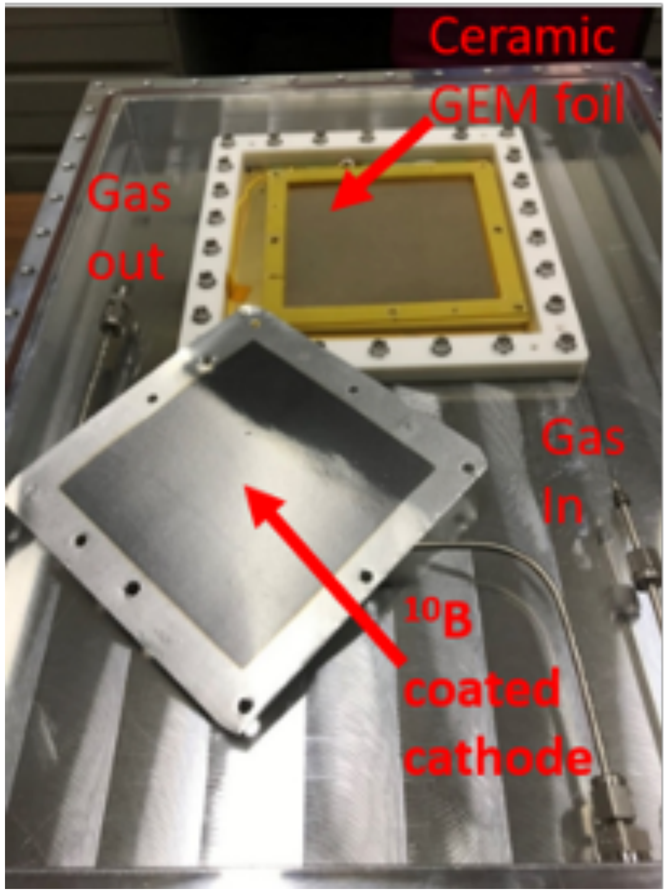


Double ceramic-GEM detector by University of Milano-Bicocca

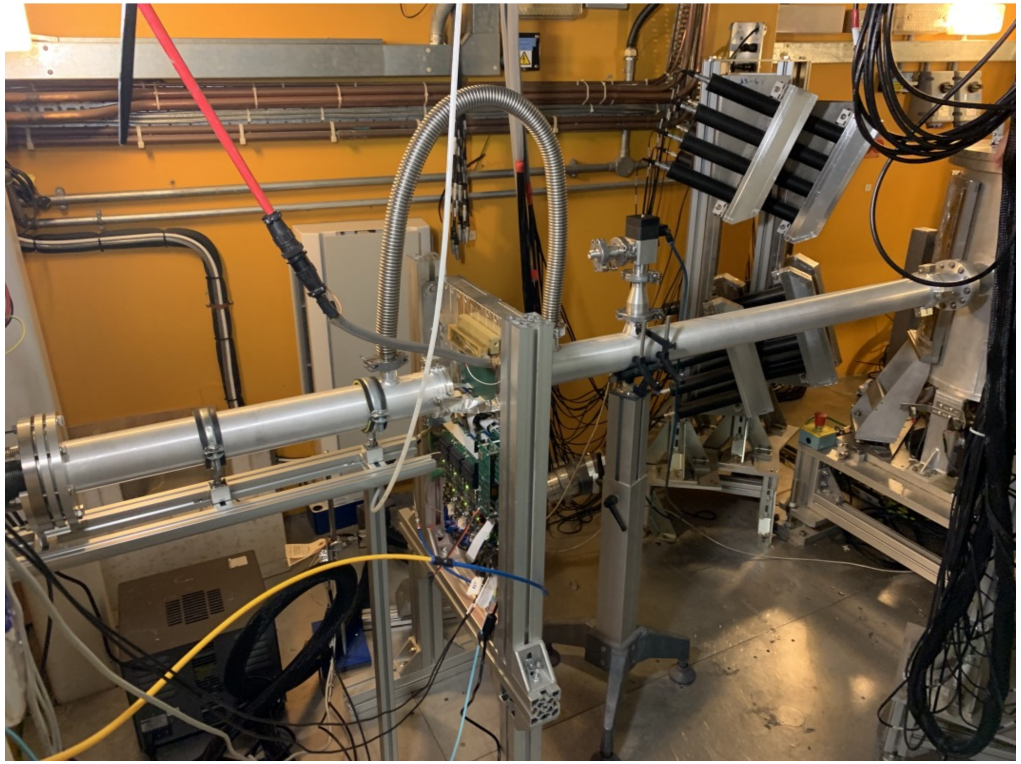
- **Operated at the VESUVIO instrument of ISIS, UK from 2021**
  - **provided accurate measurements of the neutron total cross section of samples**
  - **converter: 1.2 μm $^{10}B_4C$, active area: 100mm*100mm, readout by 2D pads**







VESUVIO instrument



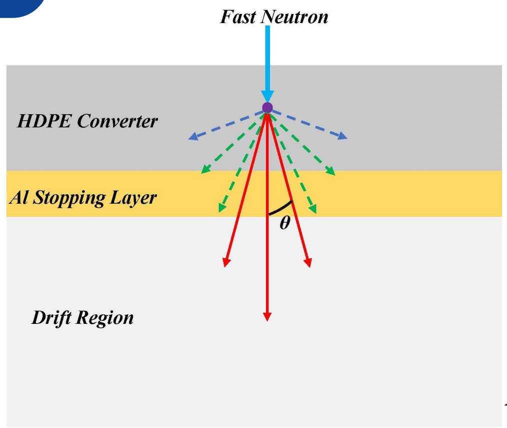
JINST, 2021, 16: P06003， NIMA, 2021, 988: 164907

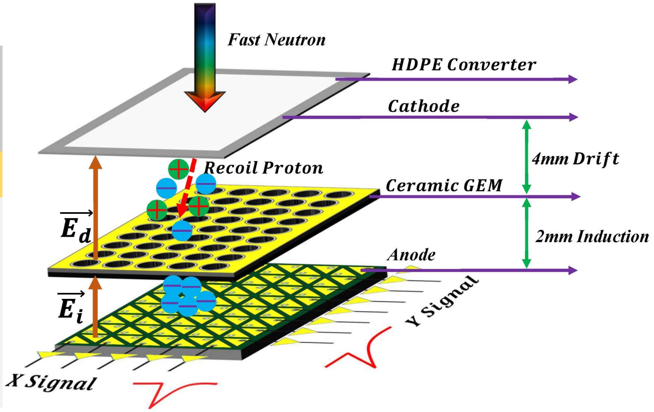
Fast neutron detector with polythene

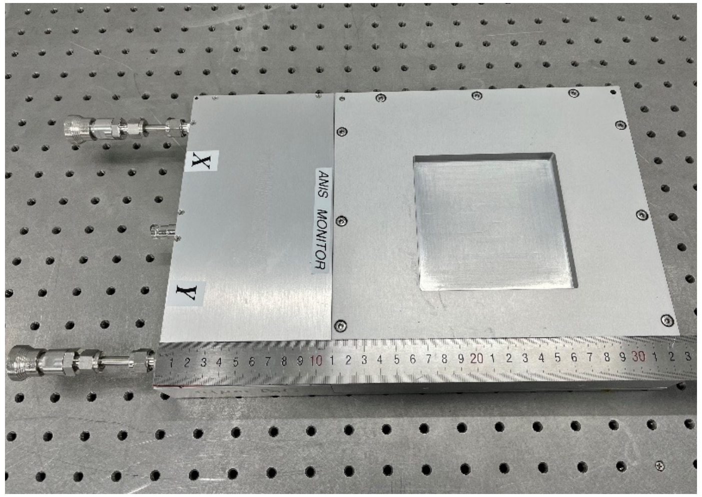
- **Operated in Atmospheric Neutron Irradiation Spectrometer for monitoring from April 2022**
  - a stopping layer of 0.2mm Al to absorb and reduce the emitted proton with large angle
  - improve spatial resolution from 5mm to 2mm(FWHM)

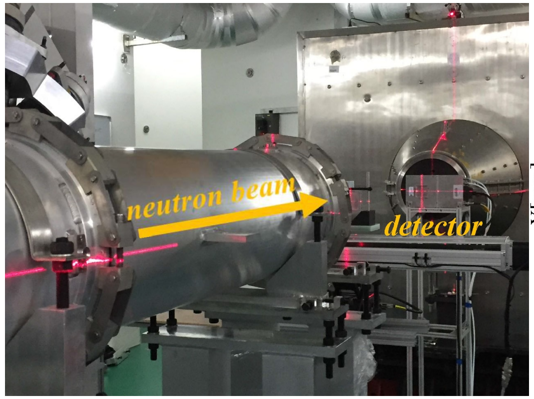
Detector design

Parameter	Specifications
Converter	2 mm C_2H_4+0.2mm Al
Effective area	100 mm × 100 mm
Pixel size	1.56mm
Detection Efficiency@1 MeV	~10^{-4}
Counting rate	1 MHz

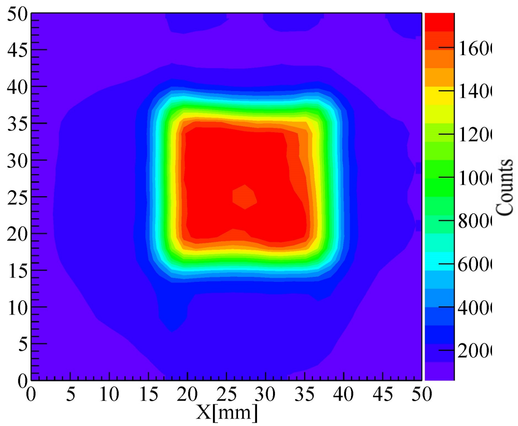


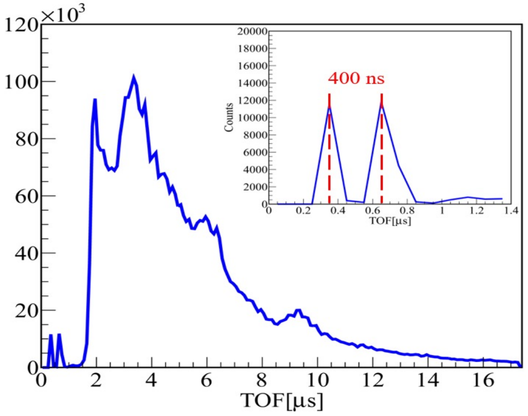


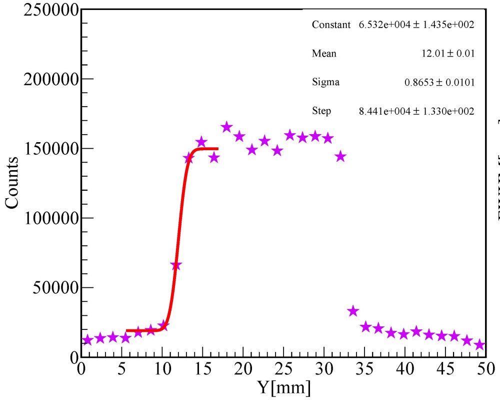


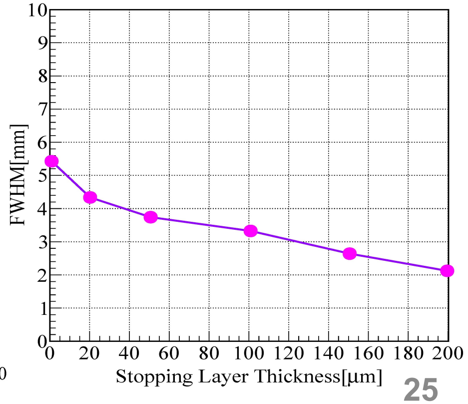


2D Imaging









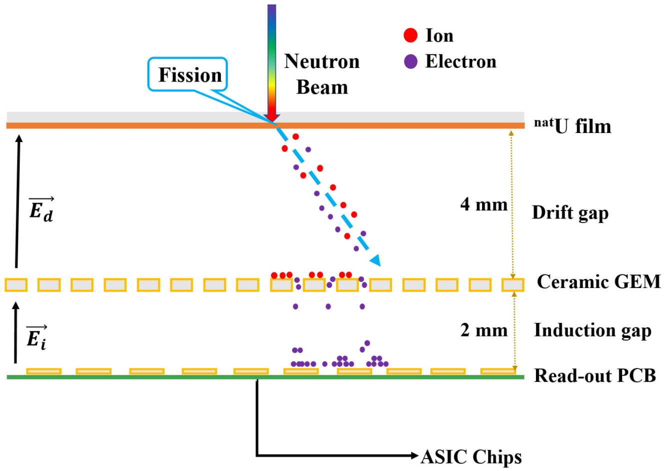
Fast neutron detector with ^{238}U

Operated in Atmospheric Neutron Irradiation Spectrometer for monitoring from April 2022

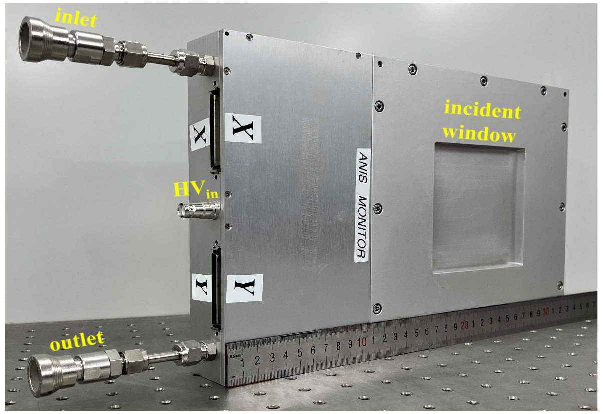
- advantage: large ionization energy loss of fission fragment to **improve n/ γ discrimination**
- spatial resolution 4.3mm(FWHM)

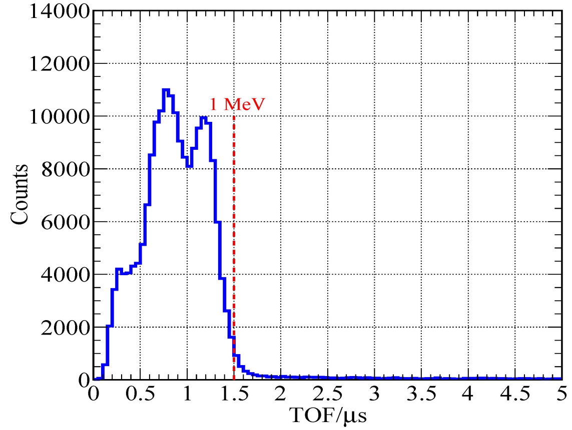
Detector design

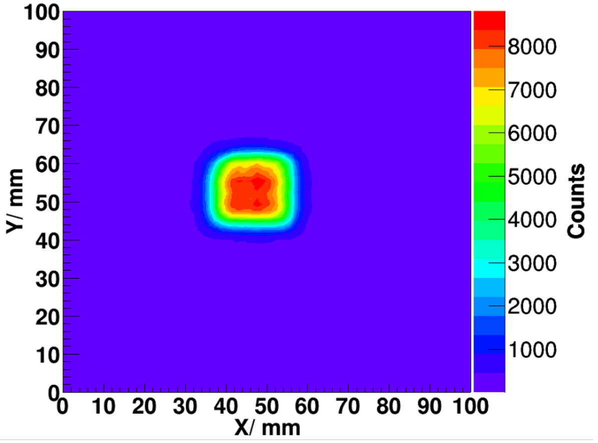
Parameter	Specifications
Converter	1 mg/cm2 ^{238}U
Effective area	100 mm × 100 mm
Pixel size	1.56mm
Detection Efficiency@1 MeV	~10^{-5}
Counting rate	1 MHz

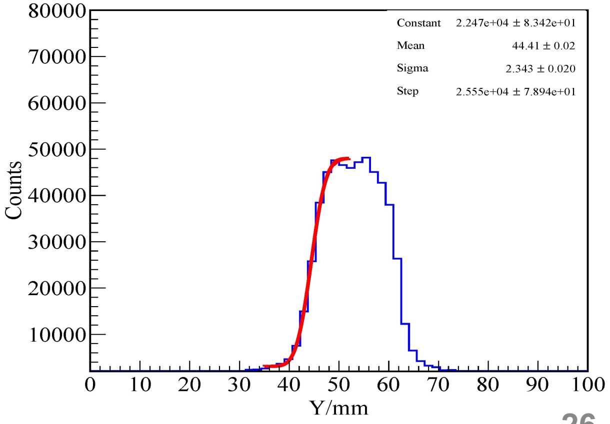


Beam tests









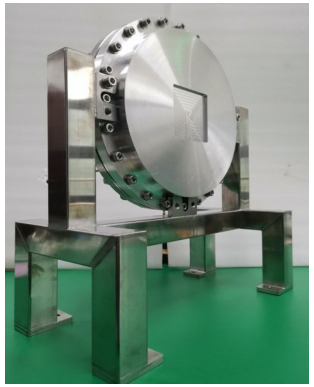
Sealed GEM neutron detector

Sealed detector suitable for the vacuum environment and more compact without gas flow

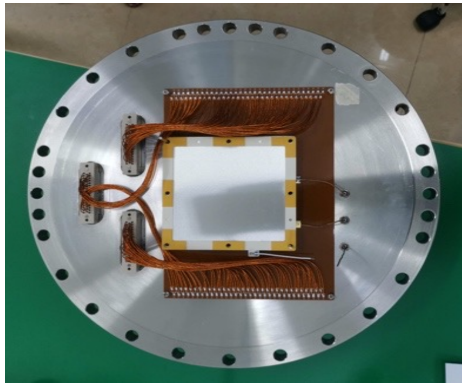
- ceramic GEM with high-temperature resistant over 100°C for outgassing
- improve the working life and long-term stability

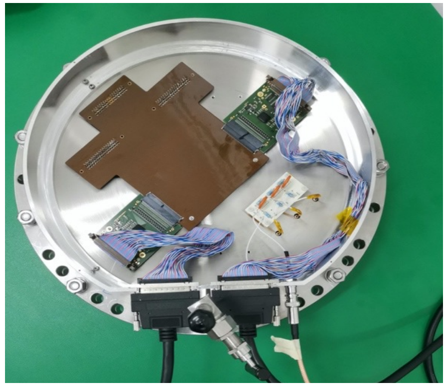
Detector design

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

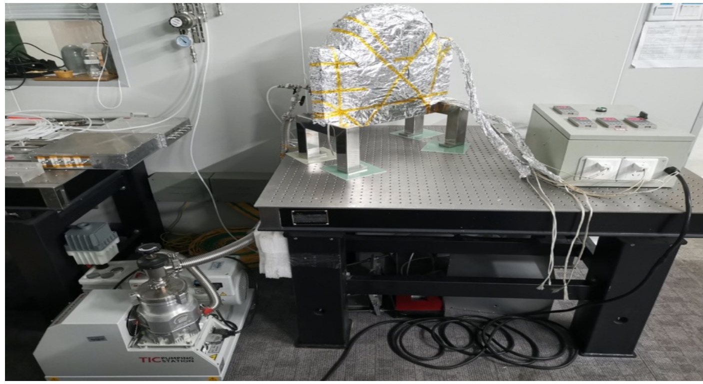


Detector assembly

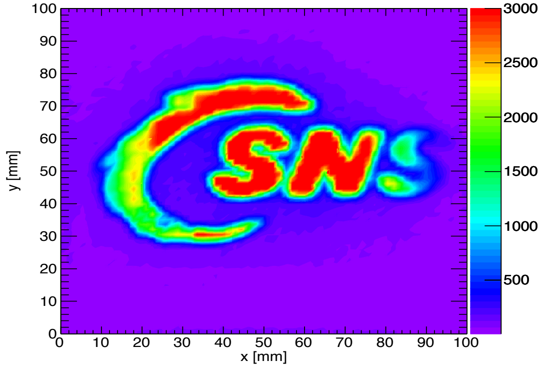




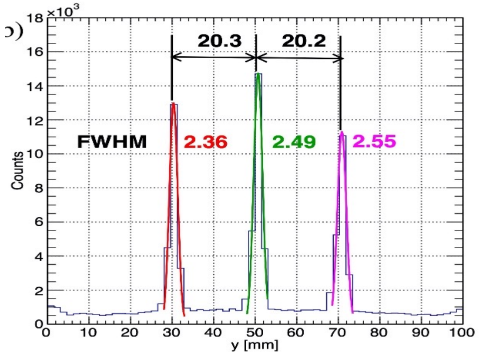
Outgassing baking system



2D imaging

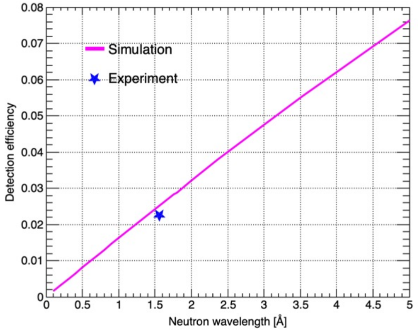


Spatial resolution



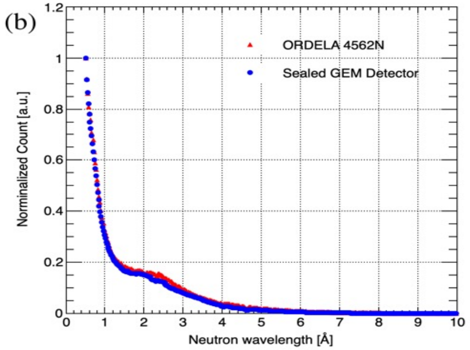
NIMA, 2021,995:165129 .

Detection efficiency

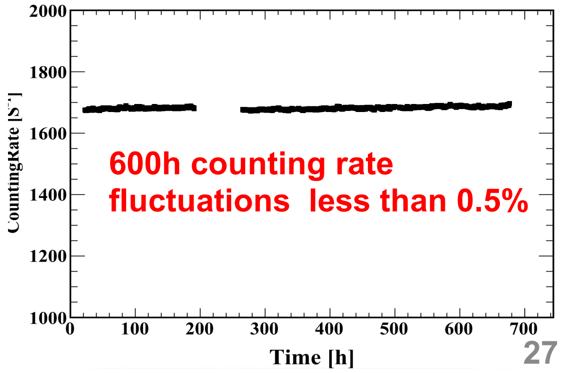


NIMA, 2021,1024:166076

Neutron wavelength



Long-term stability

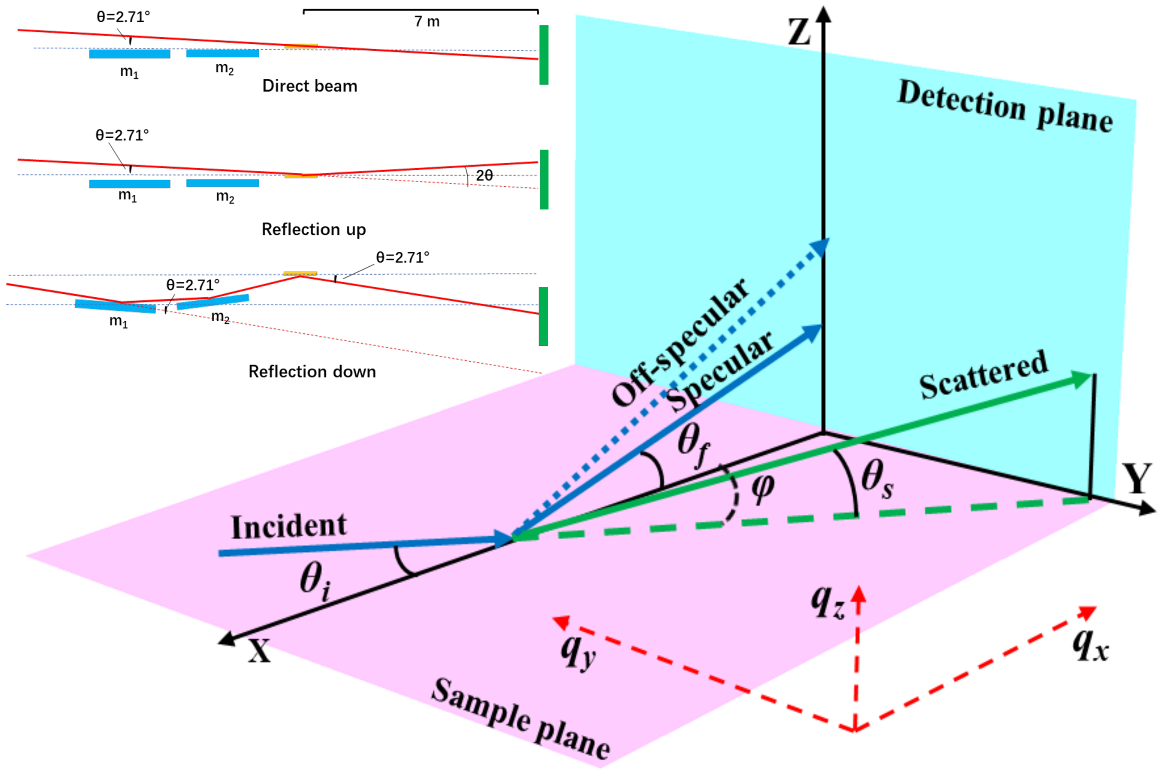


^{3}He+ GEM detector For CSNS II

A high count rate, high efficiency detector required by liquid reflection instrument(CSNSII)

- critical demand: wide measurement dynamic range： 0.1Hz - 1MHz
- ^{3}He + GEM may potentially achieve high efficiency and high counting rate

Liquid neutron reflection experiments



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

Key technologies:

- develop large area ceramic GEM
- fabricate high pressure ^{3}He detector

Large-area ceramic GEM by laser drilling

New technology for the production of the large-area ceramic GEM

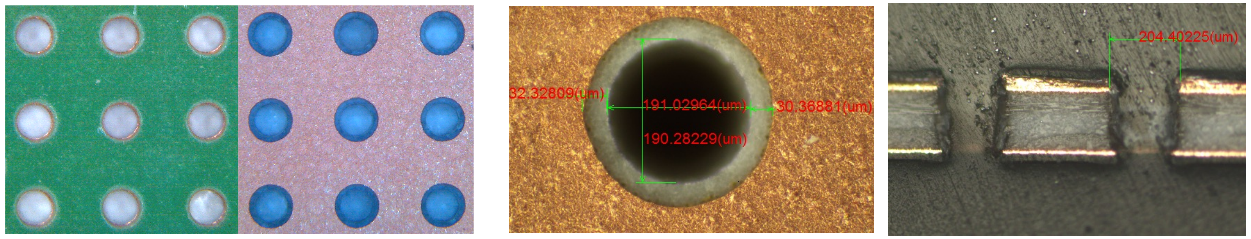
1. Disadvantages of mechanical drilling:

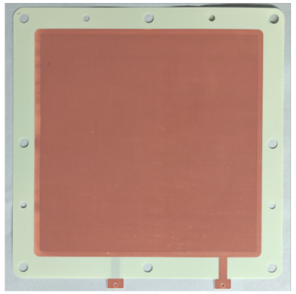
- drill wear reduces the quality of holes
- frequently replace the drill for the large-size GEM

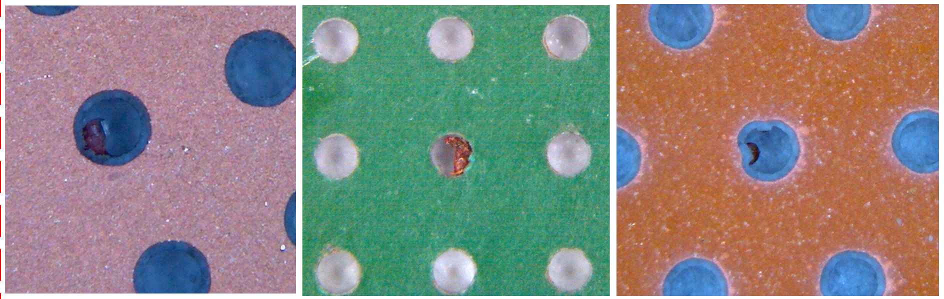
2. Advantages of laser drilling:

- high speed & non-contact machining
- good flexibility & higher positioning accuracy

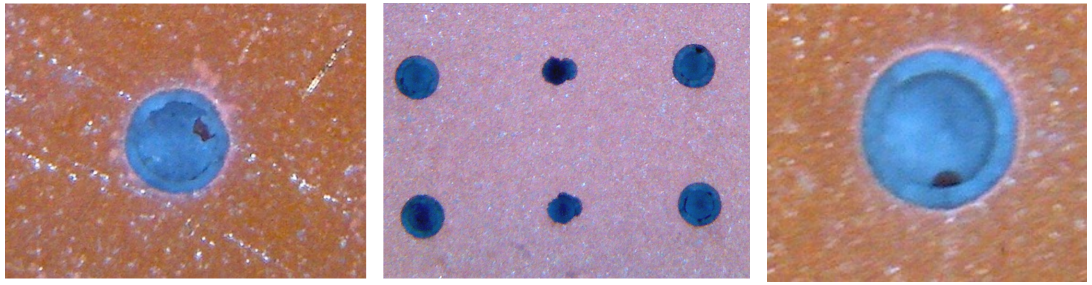
Samples of 100 mm × 100 mm ceramic GEM



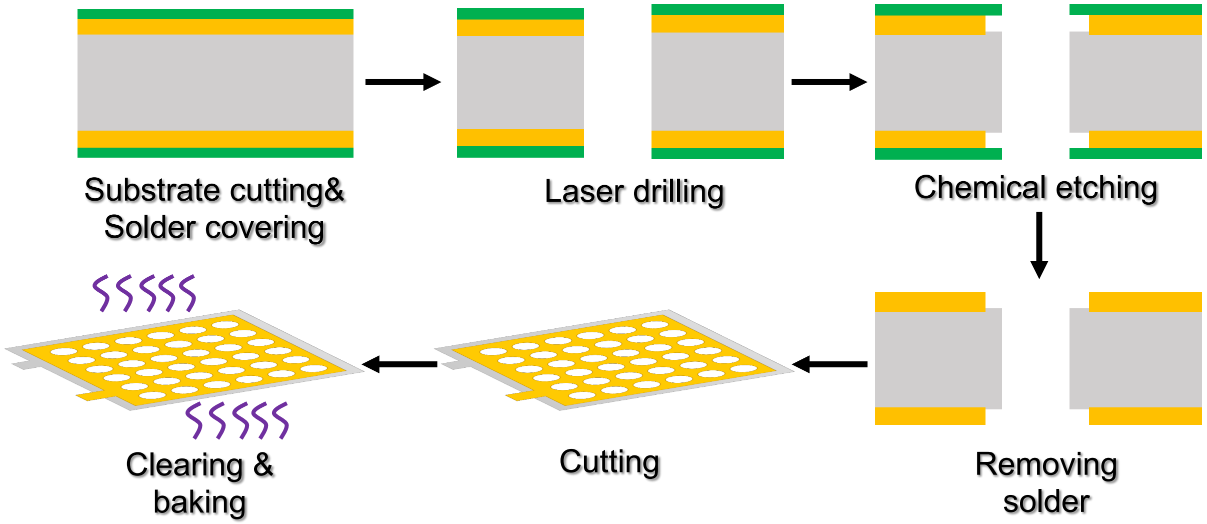




existing problems: irregular shape



Fabrication process

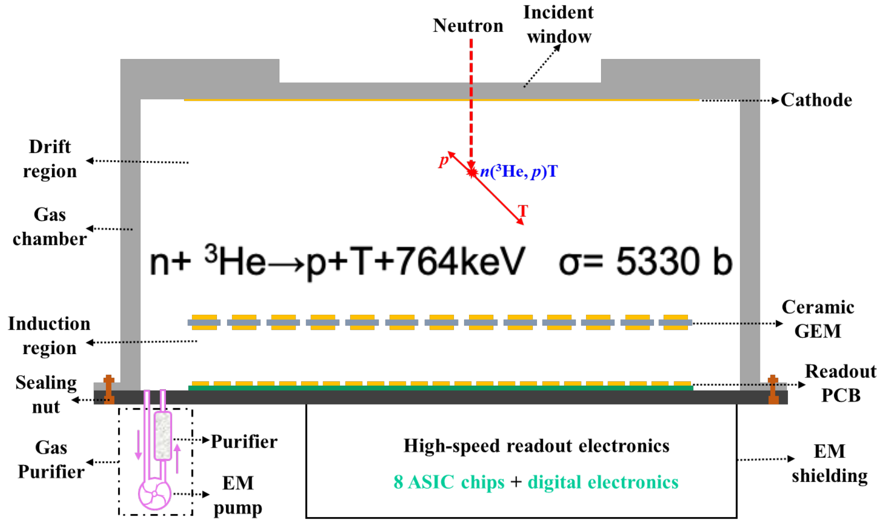


The technique and methods under further improvement

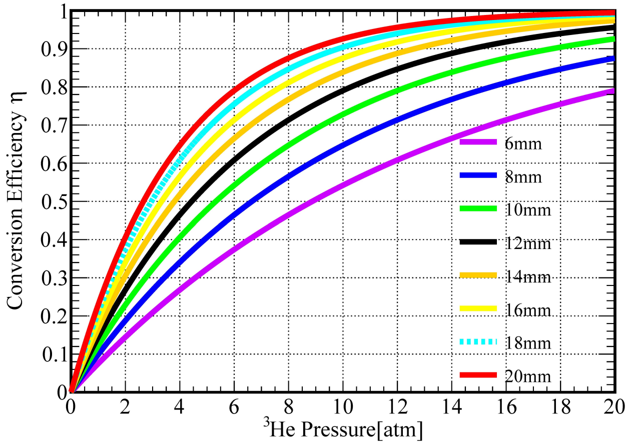
^{3}He+ GEM detector Prototype

A high-counting-rate and high-efficiency GEM neutron detector for LR in CSNS II

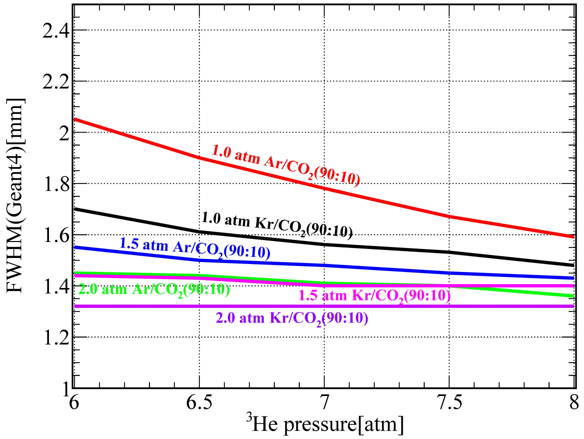
Diagram of detector



Detection efficiency

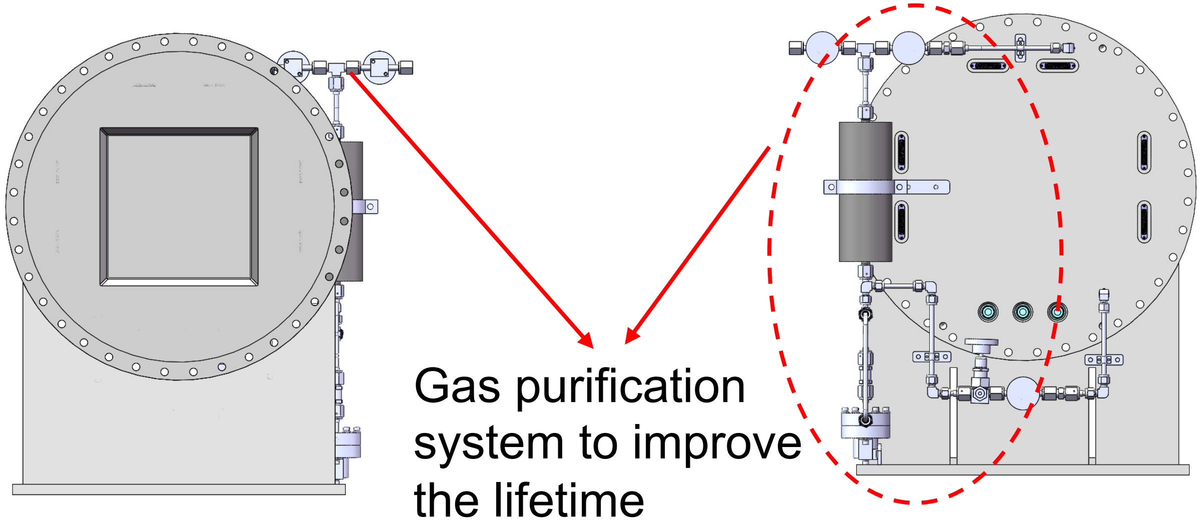


Spatial resolution in different gases



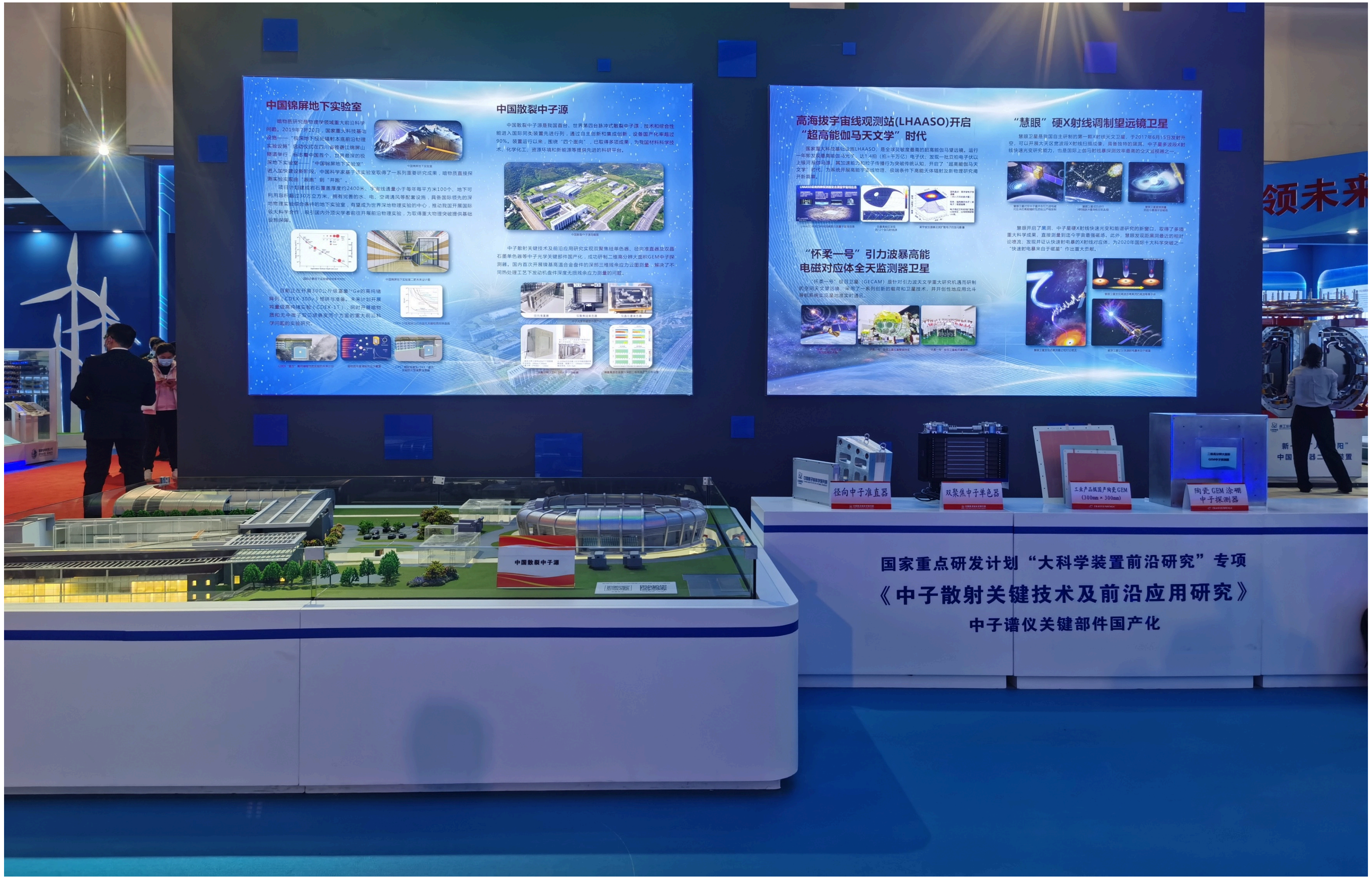
Parameters	Specification
Active area	200 mm × 200 mm
Detection efficiency@1.8Å	≥ 80%@ 6atm ^{3}He+Ar/CO_2
Spatial resolution	≤ 2.0 mm
Maxi. Counting rate	≥ 1.0 MHz
Readout electronics	8 × 64chns ASIC + Digital electronics + Fiber
Readout channels	256(X) + 256(Y) = 512
Strip size	0.78 mm × 0.78 mm

Mechanical design



National Innovation Achievement Exhibition

- **In 2021, ceramic GEM detector selected for the National “13th Five Year Plan” Science and Technology Innovation Achievement Exhibition in Beijing**



Outline

Contents

Summary and outlook

Summary:

- **developed a family of ceramic GEM neutron detectors and successfully applied in many instruments.**

Outlook:

- **fabricate large area(1 m^2 level) and high quality ceramic GEM by laser drilling**
- **design high-speed ASIC chip of 10MHz for GEM detector**
- **develop detector with 1 m^2 area, high detection efficiency(80%) and high resolution(sub-mm)**


Thank you !