A large-area ceramic GEM neutron detector with high efficiency at the CSNS

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Abstract

With the development of neutron sources towards higher fluxes, higher counting rates are required for detectors to remain suitable, especially for straight-through (direct) beam or small-angle scattering measurements. Gas electron multiplier (GEM) detectors have emerged as a suitable option because of their high counting rate, high resolution, and large area production advantages. This paper presents a prototype multilayer boroncoated ceramic GEM detector developed at the China Spallation Neutron Source (CSNS). The ceramic GEM, developed by the Institute of High Energy Physics (IHEP), was used in the detector to reduce neutron scattering owing to its high transmittance and low self-scattering. To date, a multilayer ceramic GEM detector has been produced and tested. The active area of the detector is 200.7 mm × 200.7 mm, the spatial resolution is less than 2.5 mm (full width at half maximum, FWHM), the highest counting rate of the system is greater than 1 MHz, and the neutron detection efficiency at a wavelength of 4.8 Å is approximately 43%. Moreover, the detector has good imaging ability and can be used for large-volume imaging. The good performance of the detector makes it suitable for use at Very Small Angle Neutron Scattering Instrument (VSANS) and Energy-resolved Neutron Imaging Instrument (ERNI) at the CSNS.

Full Text

Preamble

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Abstract

development neutron sources towards higher fluxes, higher counting rates required detectors remain suitable, especially straight through (direct) small-angle scattering measurements. electron multiplier (GEM) detectors emerged suitable option because their counting rate, resolution, large production advantages. paper presents prototype multilayer boron-coated ceramic detector developed China Spallation Neutron Source (CSNS). ceramic developed Institute Energy Physics (IHEP), detector reduce neutron scattering owing transmittance self-scattering. date, multilayer ceramic detector produced tested active detector spatial resolution width maximum FWHM), highest counting system greater neutron detection efficiency wavelength approximately Moreover detector imaging ability large volume imaging. performance detector makes suitable Small

Angle Neutron Scattering Instrument (VSANS) Energy-resolved Neutron Imaging Instrument (ERNI) CSNS.

Keywords

neutron detector, ceramic multilayer, efficiency

1. Introduction

ideal probe studying structure dynamics matter, neutron scattering widely fields.

Compared other techniques, neutron scattering irreplaceable advantages, strong penetrability, light element sensitivity, isotope resolution magnetic microscopic analysis.

Therefore, scientists recognized important spallation neutron sources provide higher neutron utilization efficiency modern science technology.

High-performance comprehensive experimental devices neutron science actively developed, spallation sources power megawatt range constructed. neutron produce hundreds times greater reactors, providing powerful platform innovative research materials science. present, pulsed spallation neutron sources currently operation worldwide include Spallation Neutron Source (SNS) Neutron Source (ISIS) Japan Proton Accelerator Complex (J-PARC) Japan China Spallation Neutron Source (CSNS) China European Spallation Source (ESS) Europe.

China spallation neutron source, first spallation neutron source developing country, construction successfully passed national acceptance powerful research platform multidisciplinary fields materials science, physics, chemistry chemical engineering, sciences, resources environment, energy. first phase project mainly included construction negative hydrogen linear accelerator, cycle proton synchrotron accelerator, target station, three spectrometers, supporting facilities. working principle first generate negative hydrogen through source series linear accelerators accelerate negative hydrogen

Afterwards, negative hydrogen stripped electrons converted protons, which injected cycle synchronous accelerator accelerate proton energy Subsequently, proton extracted collides tungsten target through transmission line.

Finally, spallation reaction occurs tungsten target produce neutrons, which directed neutron spectrometer through moderator, neutron guide tube, etc., users conduct experimental research recent years, neutron spectrometers developed. 2024, second phase project launched, accelerator target power increased neutron spectrometers constructed time. proton pulses steady repetition average power reaches improvements performance generation neutron scientific facilities, neutron becoming increasingly high, detectors close centre counting resolution suppression ability, Small Angle Neutron Scattering Instrument (VSANS), Multipurpose Reflector (MR), Liquids Neutron Reflector (LNR) Energy-resolved Neutron Imaging Instrument (ERNI), urgently needed. decades,

3 He-based

multiwire proportional chambers (MWPCs) because their efficiency thermal neutrons.

Owing limitation intrinsic counting kHz), traditional structure detector cannot requirements high-throughput measurement. decade, scientists worldwide trying neutron detection technologies. electron multiplier (GEM), first developed Sauli 1997, detector actively developed recent years, technology becoming increasingly mature Compared traditional chambers, detectors evolved changing electric field distribution working through special porous conductive foil, thereby improving electron amplification factor. basic component polyimide (Kapton) coated copper sides etched holes.

During operation, voltage applied copper surfaces sides, generating extremely electric field strength

holes. working primary ionized electrons drift holes under influence electric field undergo avalanche multiplication high-intensity electric field holes. independent proportional amplifier, single-layer reach detectors, signal induced anode arises electrons produced avalanche amplification holes, which drift towards anode induction area. copper electrodes sides prevent moving towards cathode, slowly drifting contribute final induction signal. electron induction signal anode, induction narrow.

Therefore, induction signal detector orders magnitude faster chamber signal, signal width approximately signal response fundamental reason detectors achieve counting performance detectors strong: spatial resolution, counting rate, radiation resistant, flexible readout produced large areas relatively cost. coupled boron, which ideal thermal neutron conversion material, detectors applied neutron detection, scientists research efforts regard.

Around 2000, Schmidt Klein Heidelberg University Germany first proposed concept basic structure neutron detector basis boron conversion layer. 2004, successfully developed first small-area neutron detector, named CASCADE detector, which several arranged cascaded configuration increase detection efficiency 2012, Italian National Laboratory (INFN) developed GEM-based thermal neutron monitor successfully applied spallation source VESUVIO beamline above detectors standard produced CERN, which employ polyimide insulator. addition, Energy Accelerator Research Organization (KEK) Japan developed neutron monitor multilayer detector effective around 2010, which successfully J-PARC (NOVA) foils these

systems produced Japanese company, which liquid crystal polymer (LCP) insulator.

Given neutrons sensitive hydrogen, 2013, unique ceramic neutron detection proposed Institute Energy Physics (IHEP), successfully applied neutron detection Owing ceramics insulators, ceramic better radiation resistance stability, selfabsorption self-scattering neutrons Ceramic GEM-based neutron detectors successfully applied time-of-flight neutron monitors operating stably years prototype ceramic GEM-based neutron detector large efficiency developed tested, VSANS paper describes performance

results

obtained (BL20) CSNS.

2. Detector

principle ceramic neutron detector symmetrical structure consists multilayer cascaded boron-coated ceramic foils serve neutron conversion carrier ceramic amplification. information neutron events readout electrode. detector divided three parts: neutron conversion, multiplication signal collection, which independent other. working mixture (97%) (3%), atmospheric pressure supply ensure stability detector extend service life. boron isotope ideal solid thermal neutron conversion material because chemical activity because obtain concentrated large amounts boron.

Neutrons interact follows: =1.78 =1.47 =0.84 alpha produced reaction interact boron atoms through Coulomb interactions gradually energy.

Owing limited range

alpha ions, increasing thickness single boron layer beyond improve neutron conversion efficiency achieve conversion efficiency, boron coated drift electrode surface multilayer laminated structure employed. configuration ensures alpha emitted conversion allows incident neutrons through sufficiently thick conversion achieve conversion efficiency. incident neutron captured boron, alpha produced opposite directions. these absorbed boron-coated substrate directly, whereas other enters working producing primary electron-ion pairs.

Under drive drift electric field, electrons through drift region smoothly through layer boron-coated approximately configuration allows neutron interaction information carried original electrons through conversion layers without distortion. amplification carried bottom layer (with approximately several tens), finally, neutron interaction position determined two-dimensional readout structure, shown Since neutron intensity decreases exponentially increasing thickness transfer layer, total conversion efficiency increase linearly

increasing number layers. number layers reaches certain value, conversion efficiency tends saturate.

Considering conversion efficiencies different conversion layer numbers thicknesses obtained Monte Carlo simulations, layers cathode plate coated layer isotope-enriched enrichment layers single-side boron-coated ceramic (ceramic coated layer isotope-enriched enrichment selected neutron conversion. boron-coated ceramic layer serves neutron conversion provide amplification referred

Figure 2

Figure 1: Figure 2

conversion layer layer located two-dimensional readout circuit board, which serves neutron conversion amplification functions, referred amplification layer electric field between drift electrode first conversion layer defined drift electric field, electric field between ceramic defined transmission electric field, electric field between amplification layer two-dimensional readout circuit board defined collection electric field.

Without reducing number boron-coated layers decrease conversion efficiency, symmetrical installation detection units layer cathode layers single-side boron-coated ceramic sides adopted, readout electrode reads signals sides middle, which reduce voltage half.

3. Detector

prototype

3.1 Ceramic

neutrons sensitive hydrogen, easily scattered hydrogen atoms, which affects spatial resolution measurement accuracy detector. reduce scattering between neutrons foils, especially multilayer structure total thickness approximately developed ceramic whose neutron absorption dimensions, making suited neutron detection. insulating substrate consists ceramic glass fibres. components

ceramic oxygen, silicon aluminium, whose ratios 48.5%, 34.3% respectively, total neutron cross-sections respectively. other hand, total neutron cross section hydrogen whereas hydrogen accounts almost elements ceramic substrate Therefore, influence ceramic itself performance neutron detector reduced. ceramic manufactured economically using printed circuit board technology. thickness ceramic including ceramic substrate double-side copper holes formed mechanical drilling holes minute (Fig. 2

(a)). diameter holes distributed pitch formed etching. ceramic subsequently cleaned, shaped, baked, tested obtain intact samples, shown present, ceramic active number holes nearly 128000) produced. increase neutron conversion efficiency, isotopic boron coated single ceramic neutron conversion.

Mechanical drilling, (b) 200 mm × 200 mm ceramic GEM

Detector design multilayer ceramic detector designed standalone block. detector chamber consists chambers, upper chamber lower chamber, containing cathode boron-coated ceramic layers. multilayer stack structures, maintaining flatness uniformity interlayer spacing crucial. ensure accurate alignment between foils, ceramic substrate support frame placed between layer foil. support frames processed using high-precision digital machine tools, flatness processing accuracy exceeding ensure installation positioning accuracy layer foil. thickness ceramic substrate support frame grooves formed frame provide support facilitate dimensions drift transfer induction respectively. upper lower chambers separated two-dimensional readout circuit board sealed sealing rings. present, commonly

methods

signal readout include two-dimensional strip readout, which ionization point position determined calculating centre gravity charge, two-dimensional

signal matching

methods

determine ionization point position.

methods

employ two-dimensional strip readout structure, number electronic circuits operate within achievable range.

Owing different readout methods, former provides accurate positioning accuracy requires charge measurement, leading lower readout speed latter. latter digital readout higher counting rate.

Therefore, choose two-dimensional signal matching

method

determine neutron position achieve counting application targets. two-dimensional readout circuit board fabricated flexible Kapton material total thickness minimize neutron scattering, pixel achieve consistency between readout strips direction direction one-dimensional readout strip connected triangular through interlayer wiring, other designed completely symmetrical. upper lower symmetrical readout strips directly connected share channel, signal extraction achieved through multilayer interlayer wiring. readout board adopts multilayer board wiring, avoid crosstalk between signal lines, shielding layer added between every wiring layers. high-voltage distribution board, front-end ASICs acquisition board located device directly improve system integration. resistor chain apply different voltages different sections detector. reduce neutron scattering activation, material detector mechanical mainly aluminium alloy, thickness neutron entrance window addition, neutron shielding carefully implemented.

Boron-aluminium alloy plates thickness installed around detector bottom chamber prevent direct neutron irradiation electronics. detector operates flowing atmospheric pressure avoid ageing effects.

Detector assembly Before detector assembled boron-coated ceramic undergo voltage testing working ensure normal operation.

Afterwards performance testing conducted using source obtain versus voltage curve, which serves basis selecting voltage distribution resistors voltage distribution board.

During assembly, lower chamber detector first installed cathode layer, boron-coated ceramic layers, ceramic support frames installed sequence.

Notably, layers boron-coated ceramic layers, boron-coated surface faces readout board, whereas boron-coated ceramic layer readout board, boron-coated surface faces readout board amplified strong electric field hole.

Afterwards two-dimensional readout circuit board installed upper chamber installed following procedure lower chamber. reads signals through connectors, shielding cover installed reduce interference. detector adopts resistor chain method, which provides multiple voltages symmetrical ceramic through voltage channel. resistances drift region, transfer region, induction region, conversion layer ceramic amplification layer ceramic respectively.

Under normal operating conditions, applied voltage drift electric field strength kV/cm, transfer electric field strength kV/cm, induction electric field strength kV/cm, conversion layer ceramic amplification layer photograph detector

shown Photograph detector.

3.4 Readout

electronics and data acquisition system

counting significant advantage detectors. application requirements detector, 512-channel counting readout electronics system developed. front-end readout circuit AS20Board developed CASCADE group University Heidelberg Germany perform analogue sampling, signal amplification, filtering shaping detector output signals. integrates low-noise charge-sensitive preamplifier channels, highest trigger reach readout clock frequency During readout clock cycle, signals channels transmitted, complete triggered transmission cycle completed readout clock cycles. readout requirements channels, AS20Board front-end readout circuits used. improve efficiency system signal

analysis

processing, pipelined working

method

process data. logic block diagram shown Figure requirements multichannel interface, high-speed

analysis

transmission reception, XC7K-325TFBG676 Kintex-7 series control chip.

abundant on-chip resources device requirements system resource configuration logic analysis.

First, realizes configuration circuit through interface.

Afterwards, signals consecutive readout clock cycles according control signal output AS20Board, 64-channel signal recombined.

Finally,

analysis

performed direction, groups 64-channel signal combined obtain channel signals directions detector. obtain neutron event information, coincidence

analysis

space coincidence

analysis

applied during processing. coincidence

analysis

required because neutron signal duration (usually between easily exceeds integration comparator front-end circuit.

Under these conditions, digital signal appears position, there multiple triggers short time.

Therefore, coincidence algorithm considers neutron signal triggered multiple times within coincidence neutron signal filters multiple useless trigger signals.

Spatial coincidence

analysis

performed because, channel signals directions, multiple channels simultaneously contain signals, herefore, signals appear multiple continuous channels, adopts central

method

merging. signals multiple discontinuous channels time, these cases handled exceptions. effective neutron events obtained through coincidence

analysis

space coincidence

analysis

correspond two-dimensional coordinates neutron reconstructed readout

strips. Then, neutron events formed adding timestamp relative using clock. inally neutron events stored uploaded computer TCP/IP protocol.

4 R

esults

discussion

study performance detector, detailed experimental study carried CSNS, including measurements neutron imaging performance, wavelength, counting capability, spatial resolution detection efficiency. decoupled poisoned hydrogen moderator (DPHM) provide neutron beams different pulse structures neutron wavelength ranges.

4.1 Neutron

imaging wavelength spectrum First, verify multilayer boron-coated ceramic detector system operates properly, imaging wavelength spectra measured using time-of-flight (TOF) method. distance between detector During testing, limiting placed front detector image profile, which consistent neutron considering neutron divergence, shown 6(a), indicating neutron distribution uniform.

Moreover, wavelength spectrum distribution obtained distribution, shown 6(b). wavelength spectrum distribution, distinct Bragg edges observed which correspond Al(200) Al(111) crystal faces, respectively originate neutron interactions aluminium components moderator detector.

These findings demonstrate multilayer boron-coated ceramic detector excellent neutron imaging capabilities accurately measure neutron wavelengths using information. evaluate uniformity detector, conducted detailed tests. detector placed movable platform, diameter boron-aluminium alloy limiting front effective detector divided regions. moving detector, neutron counts tested separately time, monitor normalize fluctuations area. relative standard deviation (RSD) regions obtained 4.3%, indicating uniformity achieved effective addition, accurately measure effective detector area, detector placed high-precision moving platform moved right. detector moved moving platform while scanning spot. maximum detection displacement differences directions detector respectively, indicating effective detector imaging neutron wavelength spectrum.

4.2 Counting

capability

counting capacity system important specification detectors since counting significant advantage detectors, detector intended high-flux instruments. counting capability evaluated CSNS. neutron operates pulse frequency number neutrons arriving detector varies different times within pulse cycle.

method

follows: detector faces exit, spectrum measured; after count channel spectrum divided effective pulse number width, instantaneous counting spectrum obtained, highest counting detector system spectrum. highest counting multilayer boron-coated ceramic detector greater

4.3 Spatial

resolution Spatial resolution, usually defined width maximum (FWHM) peak, among essential parameters position-sensitive detector obtained Gaussian fitting projected position distribution. measure spatial resolution, cadmium plate thickness thick three slits widths pitch placed front detector. cadmium plate rotated degrees, spatial resolution direction direction measured separately. shown spatial resolutions direction direction (FWHM), respectively. uncertainty position resolution measurements mainly arises statistical errors system uncertainties, alignment accuracy divergence. reduce system uncertainties, before measurement, laser level ensure neutron precisely aligned coplanar centre slit, minimizing systematic error caused mechanical misalignment.

During experiment, sensitive detector outside measurement region (i.e., outside slit) shielded cadmium plate, effectively preventing divergence affecting measurement results. respect statistical errors, counts within effective

measurements exceeded 10000, ensuring relative statistical error Poisson fluctuations Spatial resolutions direction direction

4.4 Detection

efficiency described Section cathode layers boron-coated ceramic layers increase detection efficiency. detection efficiency determined comparison counts measured standard (LND252299, diameter, under conditions.

During test, low-pressure monitor (Ordela 4560N) placed measure fluctuations neutron intensity subsequent

processing could normalized eliminate interference. monochromator select monochromatic neutrons wavelength standard tube, detection efficiency centre close neutrons. increase measurement accuracy, placed shielding small diameter, centre facing small ensure monochromatic neutrons entering small could detected. standard neutron stationary removed, response neutrons passing through small detector tested. addition,

background

detector subtracted further increase measurement accuracy. detection efficiency calculated using following formula: where represent

background

counts multilayer boron-coated ceramic detector, respectively, represent

background

counts standard tube, respectively, represent counts monitor under different testing conditions, respectively.

During testing process, low-pressure monitor, monochromator, standard tube, multilayer boron-coated ceramic detector sequentially placed exit.

Based neutron time-of-flight spectrum measured standard tube, obtained.

Next, keeping experimental conditions unchanged, standard removed channel, testing multilayer boron-coated ceramic detector began, resulting Through calculation, detection

efficiency neutrons wavelength comparison between experimental

results

simulation

results

obtained Geant4 shown efficiency simulation wavelength which consistent experimental results. deviation efficiency mainly arises angle deviation small absorption wall.

Detection efficiency neutron wavelength obtained Geant4 simulation (curve) experimental (dotted dots).

5 Conclusion

outlook Faced high-throughput neutron measurement requirements spectrometer, neutron detector advantage counting developed. prototype multilayer ceramic neutron detector cathode layers boron-coated ceramic layers developed CSNS. active detector spatial resolution (FWHM), neutron detection efficiency wavelength highest counting system greater Moreover, detector capable measuring wavelength spectra exhibits imaging performance.

results

indicate detector highly suitable measuring direct beams beams. accordance detector design, dedicated detectors developed VSANS ERNI, running

stably years, providing users high-quality data. develop larger-area neutron detectors, currently researching advanced ceramic manufacturing technologies, mainly focusing laser drilling technology, utilizing advantages micrometre-level positioning accuracy, drilling speed holes/min, noncontact processing achieve high-performance, metre-level ceramic detectors.

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