Neutron beam monitor based on a boron-coated GEM

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Abstract: A new thermal neutron beam monitor with a Gas Electron Multiplier (GEM) is developed to meet the needs of the next generation of neutron facilities. A prototype chamber has been constructed with two 100 mm×100 mm GEM foils. Enriched boron-10 is coated on one surface of the aluminum cathode plate as the neutron convertor. 96 channel pads with an area of 8 mm×8 mm each are used for fast signal readout. In order to study the basic characteristics of a boron-coated GEM, several irradiation tests were carried out with α source ^{239}Pu and neutron source ^{241}Am(Be). The signal induced by the neutron source has a high signal-to-noise ratio. A clear image obtained from α source ^{239}Pu is presented, which shows that the neutron beam monitor based on a boron-coated GEM has a good two-dimensional imaging ability.

Key words: boron-coated, GEM, neutron beam monitor, spallation neutron source

PACS: 29.40.Gx, 29.40.Cs, 28.20.Cz **DOI:** 10.1088/1674-1137/35/7/012

1 Introduction

Neutrons are used to investigate the structure and dynamics of a material. In particular, slow-neutron scattering is one of the key tools for studying condensed matter. Many efforts have recently been devoted to the development of the next generation of neutron facilities, which include SNS in USA, J-PARC in Japan, ISIS in UK, CSNS (China Spallation Neutron Source) in China and ESS in Europe. At present, CSNS and ESS are under construction. The advent of high current pulsed spallation sources ($>10^{16}$ n/cm^2·s) applied to high time resolution experiments will create a need for new detectors [1, 2].

In China, CSNS [3], with a power of 100 kW and a pulse repetition frequency of 25 Hz, is scheduled to begin operation in September 2016, and CARR (China Advanced Research Reactor, CIAE) will be operative this year, with a power of 60 MW and a intensity of 8×10^{14} n/cm^2·s. The majority of the beam lines will be used for neutron scattering instruments, each of which operate an incident beam monitor to measure neutron beam intensities at various points in the beam line. This is in order to correct the experimental data of a neutron scattering experiment in accordance with the intensity fluctuations of the incident beam due to accelerator or reactor power changes. The detectors used in these instruments, in particular the beam monitor, must not only have the capabilities of distinguishing between wavelengths of incoming neutrons and of producing a two dimensional readout, but they must also be able to achieve a high counting rate and have good capability of γ discrimination for high beam intensity. Due to the continuous measurement of the incident beam to provide the integrated intensity as a function of flight time applied in TOF, the beam monitor needs to have good timing resolution in order to determine the wavelengths of incoming neutrons. Because the beam transmitted through the monitor for the scattering experiment is downstream of the sample, it should have high transmission factors and low efficiency, and must produce minimal perturbation to the incident beam and minimize the production of

Received 15 September 2010, Revised 26 January 2011

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background by the monitor itself. The position-sensitive beam monitor will allow more accurate determination of the corrections for sample absorption and will permit the collimation-defining beam line components to be more accurately placed. Detailed requirements for the new generation neutron beam monitor are summarized in Table 1.

Table 1. Requirements for the next generation neutron beam monitor.

parameter	requirement
type of operation	real-time
thermal neutron intensity	$>10^9$ n/cm^2·s
spatial resolution	1~10 mm
timing resolution	~ 1 μs
detection efficiency (1.8 Å)	~ 1%
gamma to neutron separation	well
counting rate	10^6 Hz/cm^2
active area	50 mm×50 mm
stability	long term

The currently employed neutron beam monitors do not fulfil all of the requirements in Table 1 very well. To overcome these limitations, intensive R&D efforts with micro-pattern gas detectors are recently being made by numerous groups such as the GEM-based monitor [4] with ^{10}B at J-PARC, the micromegas-based monitor with ^{10}B and ^{6}Li at CERN [5] and at the University of Tennessee [6] for SNS, the MSGD-based monitor filled with ^{3}He in ISIS [7]. Various types of slow-neutron detectors are under development. Since the GEM is a gaseous detector with a high counting rate capability ($>10^7$ Hz/cm^2), the GEM-based detector is highly suitable for a high-intensity beam line monitor.

The GEM[8] was invented by Sauli in 1997. It is a Kapton foil coated on both sides with a thin layer of Cu metal. The foil is perforated by a compact array of small open holes that can act as multiplication channels. A GEM can achieve enough gain and it can be operated in a harsh environment. With a neutron sensitive convertor such as ^{10}B, ^{6}Li and ^{155,157}Gd, it is convenient for a GEM to detect neutrons, especially with a low efficiency. To overcome the size limitation, a compact readout system for a GEM has been under design, which will be small, simple and cost-effective, and can be moved, constructed and easily used. The investigation of a neutron beam monitor based on a boron-coated GEM is reported in this paper. A simple prototype chamber has been constructed. The latest experimental results of several irradiation tests carried out with α source ^{239}Pu and neutron source ^{252}Cf are presented.

2 Detector design

2.1 Convertor

The detector mainly consists of the neutron convertor, the double GEM, the special electronics for pad readout, the gas cycle system and shielding for neutron and electromagnetism. Compared with the highly reactive and expensive ^{6}Li, a solid ^{10}B layer seems to be much more favourable and suitable for use as a neutron converter. It can easily be produced in reasonable sizes using evaporation or sputtering techniques. ^{10}B (enrichment >99%) is commercially available. The enriched boron-10 is coated on one surface of an aluminum cathode plate. Neutrons are detected by the following neutron reactions:

$\mathrm{n} + {}^{10}\mathrm{B} \longrightarrow \alpha + {}^{7}\mathrm{Li} + 2.79\ \mathrm{MeV}$ 7% $E_\alpha = 1.78$ MeV $E_{\mathrm{Li}} = 1.0$ MeV

$\mathrm{n} + {}^{10}\mathrm{B} \longrightarrow \alpha + {}^{7}\mathrm{Li}^* + 2.31\ \mathrm{MeV}$ 93%

$\alpha + {}^{7}\mathrm{Li} + \gamma + 2.31\ \mathrm{MeV}$ $E_\alpha = 1.47$ MeV $E_{\mathrm{Li}} = 0.84$ MeV

When the thermal neutron induces the ^{10}B (n, α) ^{7}Li reaction, 93 % of all the reactions lead to the first excited state of ^{7}Li*, which decays spontaneously (~73 fs half-time) to the ground state of ^{7}Li by emitting the 0.48 MeV gamma ray, and 7% of the reactions result in the ground state of ^{7}Li. When the reaction proceeds to the first excited state of ^{7}Li, 0.84 MeV ^{7}Li and 1.47 MeV α particles are generated. The thermal neutron (0.0253 eV) cross section of the ^{10}B (n, α)^{7}Li reaction is 3840 barn and it drops rapidly with an increase in thermal neutron energy. Due to multiple Coulomb scattering, the range of 1.47 MeV α in boron is 3.6 μm and that of 1 MeV ^{7}Li is 2 μm calculated by the SRIM (Stopping and Range of Ions in Matter). The maximum conversion efficiency is

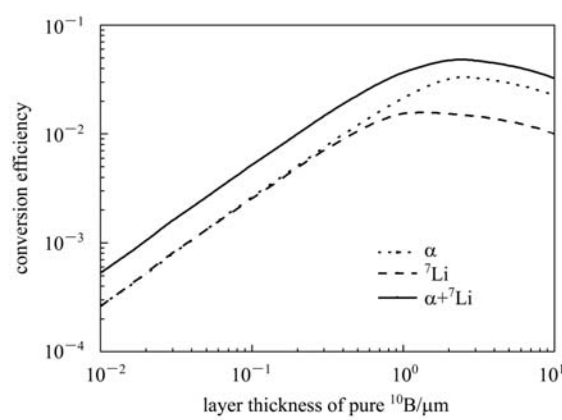

Fig. 1. Conversion efficiency for the incident thermal neutron going through a single pure ^{10}B-layer varies with its thickness. ^{7}Li contributes to the dashed line, and α contributes to the dotted line. The solid line refers to the total contributions.

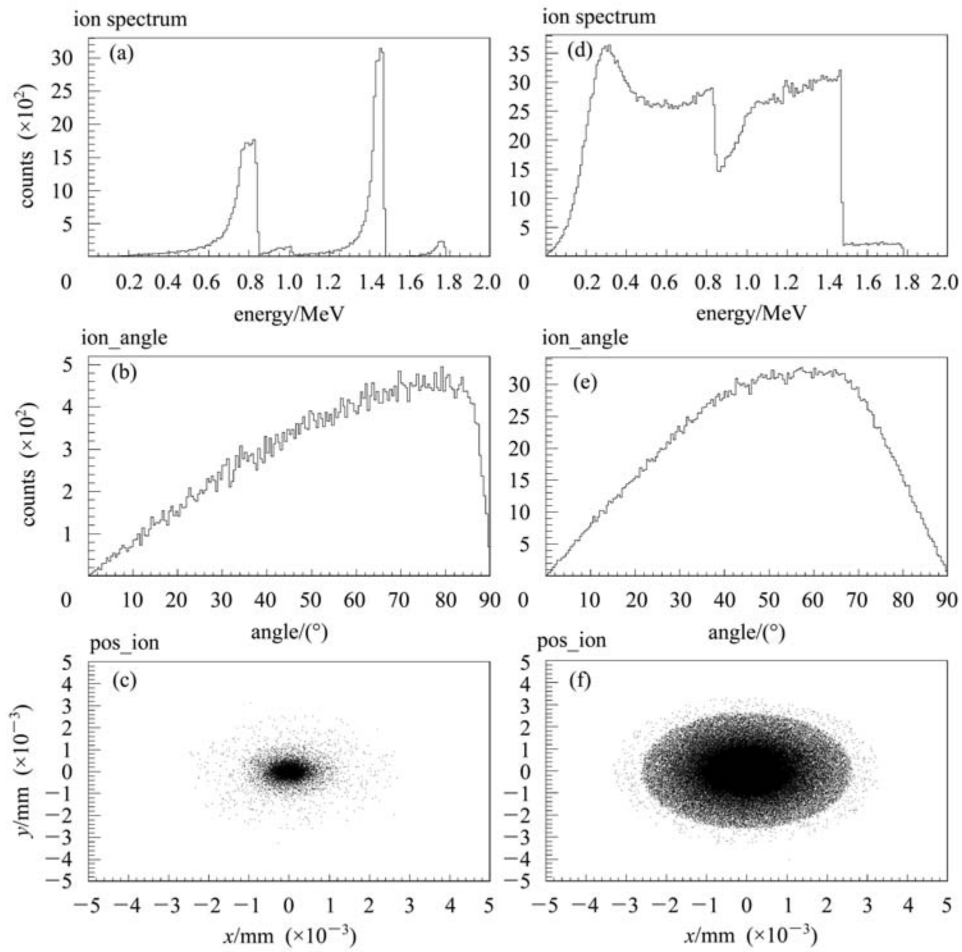

Fig. 2. Emission states of ions induced by thermal neutrons in a ^{10}B layer.

about 5% for thermal neutrons through a single pure ^{10}B-layer with a thickness of 2.5 μm. With respect to the requirement of the low efficiency ($\sim$1‰) in the beam monitor, the thickness is approximately 0.02 μm (calculated with Geant4). See Fig. 1 and Fig. 2 for more details.

A pencil beam of thermal neutron goes vertically to the surface of the ^{10}B layer. Geant4 is employed to simulate the reaction induced by the thermal neutron and coulomb interaction of ions and boron atoms. Fig. 2(a), (b), (c) are the energy spectrum, zenith angle distribution and points of emitted ions (α & ^{7}Li) from the other surface of the 0.1 μm ^{10}B layer with a conversion efficiency of 5.2‰ and Fig. 2(d), (e), (f) are images for the 1 μm ^{10}B layer with a conversion efficiency of 3.7%. Compared with Fig. 2(d), Fig. 2(a) shows that there is almost no energy slowing for very thin convertor ($\sim$0.1 μm). A suitable threshold can be set to cut out the other small signals induced by γ rays that are not caused by ions so as to improve the γ discrimination ability. Fig. 2(b) and Fig. 2(e) shows the cone emission of ions and the thicker layer has a smaller cone emission angle. A small cone emission can reduce the transverse diffusion of ions, which can improve the spatial resolution. Fig. 2(c) and Fig. 2(f) shows that ions escaping from the convertor surface are very close to the origin location of the incident neutron (several microns), which can be ignored.

2.2 GEM

With a thin conversion layer, the time and location of the emitted α or ^{7}Li can be considered as those information of the incident neutron. Here, the GEM is employed to detect these charged particles to determine the information of the incoming neutron. Due to the high energy of the charged conversion products, it is sufficient for the double GEM to obtain the gain ($\sim$10^3) to achieve a total charge of 0.1–1 pc, which is easy to read out. The standard GEM foils produced at CERN are employed, which have holes of 70 μm in diameter with 140 μm pitch and consist of three layers: a polyimide insulator 50 μm thick and copper electrodes 5 μm thick. The detector is operated in flow mode with Ar/CO_2 (70/30) mixtures at atmospheric pressure. A continuous purge of a cheap counting gas avoids the ageing effects encountered in other detectors. This solution actualizes long-term stability as well as a long lifetime. When a neutron is captured, either an α ion or a ^{7}Li ion is emitted into the drift gas volume, where it releases a large number of Secondary Electrons (SE) along its track, which is proportional to the energy deposited in the drift gas volume ($\sim 3\times10^4$ SE for 1 MeV). Whilst the other ion is emitted in the opposite direction, i.e. into the cathode plate, and therefore lost for detection. The range of 1.47 MeV α in the mixture gas is 7 mm calculated by the SRIM. Fig. 3(a) is energy loss and Fig. 3(b) is the range distribution of 1.47 MeV α in the gas mixture. If a thicker drift gap is chosen, which is greater than the range of the ions, then all of the SEs are released into the drift gas volume, and the neutron can be detected with a maximal pulse-height related to good γ discrimination. If the pulse-height is high enough, the signal-to-noise ratio will be better and a higher threshold can be set in order to discriminate the signals induced by γ. A drift gap thickness of about 5–7 mm will be chosen to accord with the ion range for improving γ discrimination ability [9]. A combination simulation for the convertor and the GEM will be needed in order to obtain more detail.

2.3 Readout and electronics

In order to fulfil the counting rate of 1 MHz/cm^2 required for fast readout, an array of pads is used and the special electronics are being designed, each channel of which is completely independent (Fig. 4). Each one is made with an analogue section with a voltage sensitive amplifier to read the charge from the detector and a shaper to change the rise and fall time of the output analogue pulse from the preamplifier. In the cascade there is a comparison section and a discriminator with DAC to regulate the threshold. The system time is driven by FPGA. The next stage is a fully custom digital section with a bulk counter register to count the number of input pulses for each channel, which provides the beam intensity profile. The spatial resolution is related to the size of the pad. Additionally in the digital section, there is another counter register to count the number of signals arriving in sequence of all the channels with a time window of 2 μs, applied to TOF for wavelength measurement. ASIC is the best and the ultimate solution.

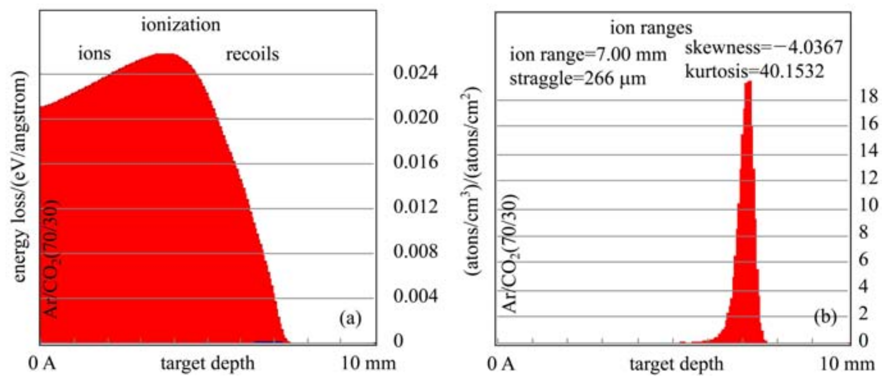

Fig. 3. Energy loss of 1.47 MeV α in drift gap.

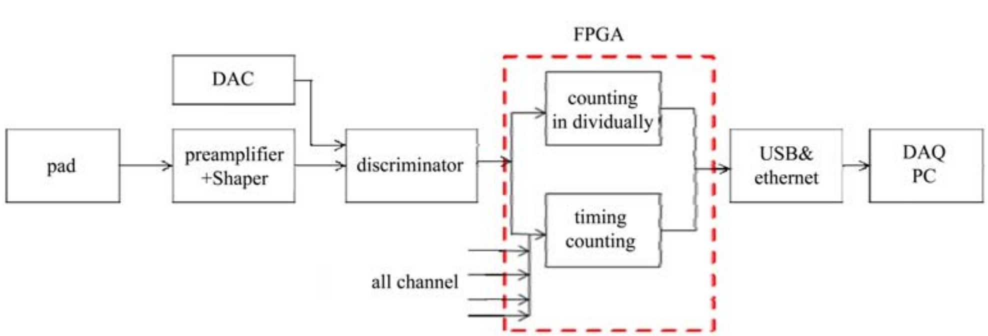

Fig. 4. Scheme of the electronics.

2.4 Shielding and background

The shielding of the electronics mainly consists of two parts. One is an Al shell for interference reduction from outer electromagnetism to improve the ratio of signal to noise. Another is for absorbing neutrons with a boron-rich plastic and Cd mounted outside the Al shell to protect the electronic components from the radiation damage of scattering neutrons. With a low total cross section with neutrons and no neutron activation, Al is widely used in neutron instruments. The whole mechanical supports of the beam monitor will use Al. However, the total thickness of Al covering the active area for beam penetration is smaller than 5 mm thick, which produces about 5% loss of the incident beam.

Since the low-Z material is used as a neutron converter and the working gas is of low density, the background induced by γ rays should be very low in the monitor. Moreover, it must also be noted that 93.6% of all neutron capture events in ^{10}B emitting 478 keV X-rays can induce energetic secondary electrons from all materials. However, the photon's capture by photo effect or its Compton scattering occurs with low probability in thin, low-Z materials, and the resulting photo-electrons deliver a very dilute background, which is not visible in the presence of lots of SEs released from the α and ^{7}Li ions [10].

Due to the use of a low Z material, thin gas detector thickness and much higher energy deposited by α &^{7}Li than that induced by γ rays, the beam monitor should be insensitive to γ background.

3 Prototype chamber

In order to study the basic characteristics of the whole system, a simple prototype chamber (see Fig. 5) with an active area of 100 mm×100 mm has been constructed with standard foils from CERN at IHEP [11] for neutron beam monitor R&D, which consists of two GEM foils sandwiched between two conductive planes. The 90% enrichment of boron-10 (mass thickness 1 mg/cm^2) is coated onto one surface of the aluminum cathode plate as the neutron convertor by electrophoresis at the Beijing Nuclear Instrument Factory so as to obtain the maximum conversion efficiency for irradiation tests. The signal collection plane is a printed circuit board with 96 square pads with each area being 8 mm×8 mm.

The high voltage is provided by a CAEN SY-127 multi-channel power supply and the detector is operated in flow mode with Ar/CO_2 (70/30) mixtures at atmospheric pressure. The gain is about 200.

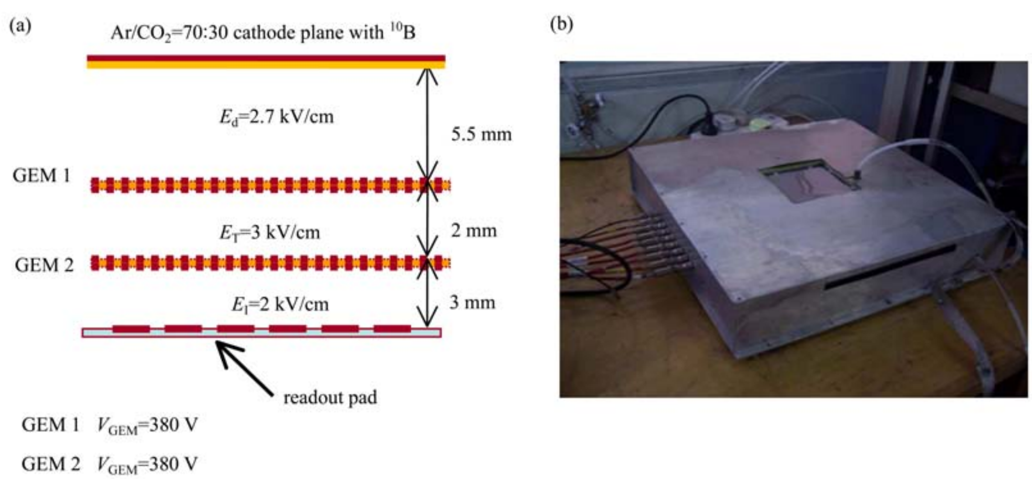

Fig. 5. (a) is the scheme of the GEM; (b) is the prototype chamber.

4 Experimental setup and results

4.1 Signal induced by the neutron source ^{241}Am(Be)

The prototype chamber was first tested by the neutron source ^{241}Am(Be) (5×10^5 Bq), which is placed in a special cylinder shielding with an open hole with a diameter of 4 cm (see Fig. 6(a)). The chamber was inverted and mounted on a shelf with the window aiming at the hole of the shielding. A polyethylene stick of ϕ4 cm×8 cm was inserted into the hole as a neutron moderator. One channel of the output signals from the readout pad (see Fig. 5(a)) was directly connected to a charge sensitive amplifier (made in IHEP) with a sensitivity of 0.5 mV/fC. The signal is shown in Fig. 6(b) The majority of amplitudes is about 100 mV corresponding to the probability 93% of the emitted particles with lower energy and the minority of that is above 200 mV, relating to the probability 7% of those with higher energy. The pulse is about 1.5 μs wide with the rise time about 400 ns. The noise is smaller than 3 mV. The counting rate of one channel is about 3.5 per minute.

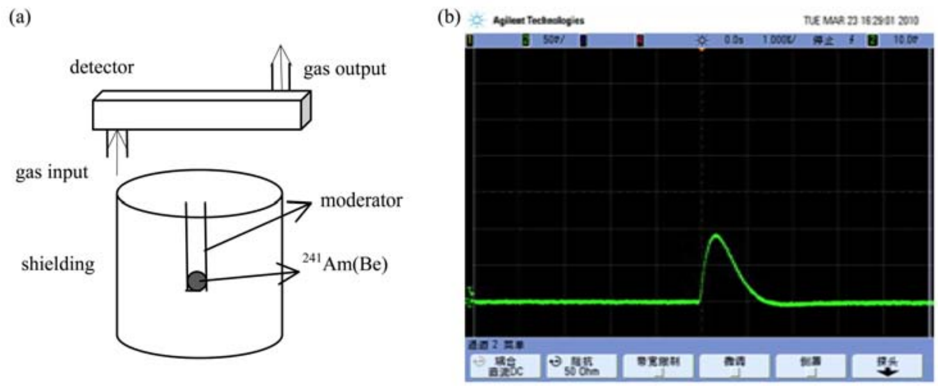

Fig. 6. The layout of the experimental setup and signal induced by thermal neutrons.

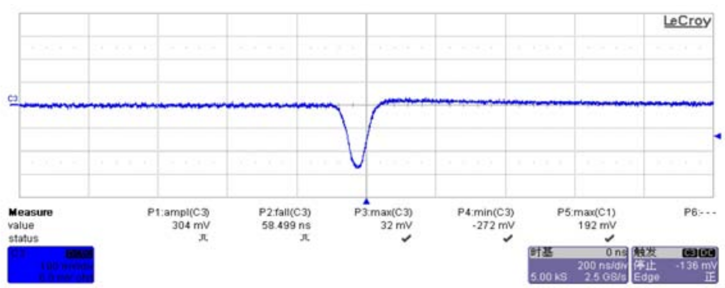

Fig. 7. The signal induced directly by a Pu α source.

4.2 Image by scanning ^{239}Pu source

Due to the very low neutron sensitivity (0.03 cps/nv, cps-count per second, n-neutron density, in the unit cm^{-3}, v-average neutron flying velocity in sensitive volume, cm/s) of the small pad area and the low conversion efficiency (∼5%) for each channel, the image test was carried out by scanning ^{239}Pu α source (1.0×10^6 Bq, 5.2 MeV α-ray) instead of the neutron source. The signal induced directly by the α ions of one channel with a current preamplifier (FBPANIK) is shown in Fig. 7. The amplitude is about 250 mV with the pulse 150 ns wide, which can fulfil the high counting rate of 1 MHz/channel. The noise is smaller than 30 mV.

For imaging, each pixel of 96 pads is connected individually to a current preamplifier (FBPANIK), with the current amplification about 30 and the impedance 390 Ω. The output pulse of the preamplifier is fed to the discriminator with a threshold −100 mV and the digital pulses from the discriminator are counted by a Lecroy Scaler based CAMAC system for DAQ.

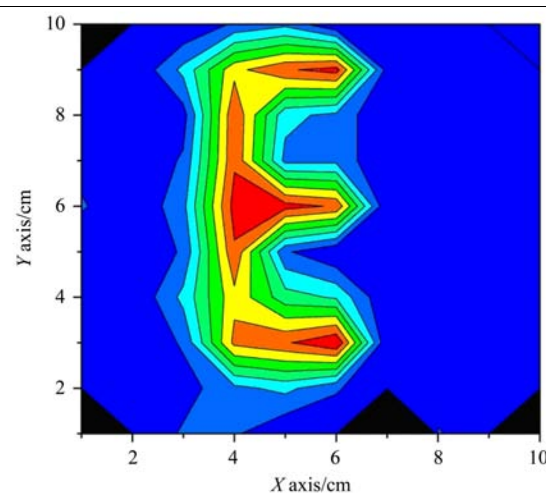

Fig. 8. The image of the letter E obtained by scanning ^{239}Pu α source.

The image of the letter E is shown in Fig. 8.

A block of 3 mm thick steel with a hole of 2 mm in diameter was used to collimate the emitted α. The image is shown in Fig. 9.

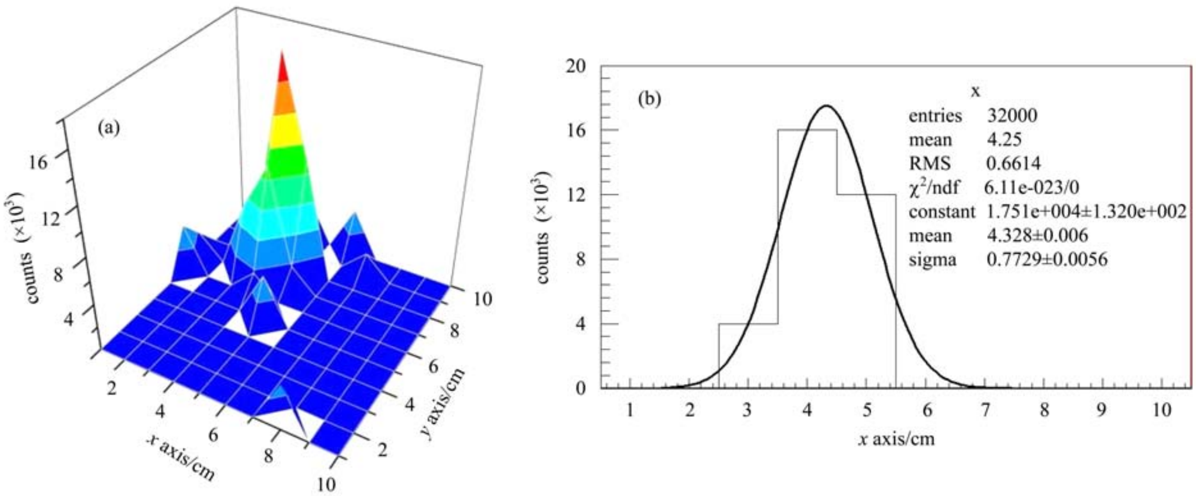

Fig. 9. Image of the ^{239}Pu source emitted α particles after collimation.

Figure 9(a) shows the counting rate distribution of 2-dimensional pads, and Fig. 9(b) is its distribution from x-axis. The single peak is fitted with a Gaussian function. Sigma is 7.7 mm. Due to 8 mm×8 mm pad and 2 mm gap for each pad, the counting bin of x-axis is set to 10 mm.

5 Conclusion

A neutron beam monitor based on a boron-coated GEM is being designed at IHEP for the next generation of neutron facilities. A prototype chamber has been constructed for investigation with pad readout. The double-GEM response to the neutron is measured. The pulse width is about 150 ns. Further work will be continued, such as how to coat the ^{10}B film perfectly, simulation for the detector design, smaller pads and special electronics for high speed readout.

We are grateful to Professors Xie Yigang, Lu Shuangtong, Ou Yangqun and Chen Yuanbo for their support and helpful discussions.

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