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A New Pad-Based Neutron Detector for Stereo Coded-Aperture Thermal Neutron Imaging

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Abstract— A new generation of coded aperture neutron imagers is being developed at Brookhaven National Laboratory. The detector of the camera is a position-sensitive thermal neutron chamber. The new device is a ^3He -filled ionization chamber, which uses only anode and cathode planes. The anode is composed of an array of individual pads. The charge is collected on each of the individual $5\times 5\text{ mm}^2$ anode pads, (48x48 in total, corresponding to $24\times 24\text{ cm}^2$ sensitive area) and read out by application specific integrated circuits. The new design has several advantages for the coded-aperture applications in the field, compared to the previous generation of wire-grid based neutron detectors. Among these are its rugged design, lighter weight and use of non-flammable stopping gas. The pad-based readout is event by event, thus capable for high count rates, and also to perform data analysis and imaging on an event-by-event basis. The spatial resolution of the detector can be better than the pixel size by using charge sharing between adjacent pads. In this paper we report on the development and performance of the new, prototype pad-based neutron camera, and present the first stereoscopic coded aperture images of thermalized neutron sources.

I. INTRODUCTION

THE concept of imaging non-focusable radiation by coded aperture was introduced more than 50 years ago [1]. Whereas pinhole cameras can produce images with non-focusable radiation, the intensity loss due to the small aperture is prohibiting for practical applications. The coded aperture devices are essentially pinhole cameras with a large number of pinholes, arranged in a specific way, so that the reconstruction of the original image is possible using decoding algorithms. A specific case using uniformly redundant arrays has been patented [2] by Fenimore et al. in 1980.

Coded aperture devices have seen many applications, mainly in the field of astrophysics. The principles of coded aperture imaging, however, are applicable to other radiations as well, where it is possible to realize the pinhole patterns and create transparent and radiation blocking pixels. Thermal neutrons have very high capture cross section in cadmium, so a coded aperture neutron camera using cadmium sheet to realize the non-transparent pixels is possible.

Brookhaven National Laboratory (BNL) developed a coded aperture thermal neutron imaging device in the late nineties [3]. It consists of a ^3He -filled position sensitive wire chamber

in a cadmium-lined enclosure. The front of the enclosure is a coded aperture mask. The distance of the mask from the detector is variable, and the mask could be rotated by 90° for mask-antimask measurement pairs. There were three masks fabricated with different pixel sizes in order to achieve higher or lower spatial resolution.

More recently, a new two-dimensional thermal neutron detector type has been developed at BNL [4]. Its operation is still based on neutron conversion in ^3He , but instead of wire grids, it uses only a cathode and an anode plane and works as an ionization chamber (unity gas gain). While the cathode is the entrance window foil, the anode plane is made of tightly placed discrete copper pads, each having individual readout electronics.

Recent interest in coded-aperture imaging with multiple cameras prompted us to build two new coded-aperture neutron imagers based on the novel pad based design. In the present paper, we will compare the advantages and possible drawbacks of the new design for coded-aperture neutron imaging and present the first stereoscopic coded aperture images of thermalized neutron sources.

II. CODED APERTURE IMAGING WITH WIRE CHAMBER

A. Wire chamber operation

The wire chamber based position sensitive neutron detector development at BNL has been described in detail by Yu et al. [5]. For the completeness of the present paper, we cite some key highlights.

Multi-wire chambers operating with ^3He use the conversion reaction



This generates the primary signal of $\sim 25 \times 10^3$ electrons. The position readout is realized by resistive-capacitive (RC) charge division. For large area detectors, the performance was greatly improved by applying a multi-node, continuous interpolating resistive charge division electrode and an analog centroid finding system [6].

The thermal neutron detector used for coded aperture studies was originally fabricated for structural biology and material science studies [7] using neutron diffraction. The detector's active area is $17 \times 20\text{ cm}^2$. A position resolution of 1.3 mm (FWHM) and integral non-linearity of $\pm 0.1\%$ was achieved using a 6.3 atm ^3He and 3.0 atm C_3H_8 gas mixture. The propane quenching gas reduces the range of the protons, thereby improving the position accuracy. The readout electronics has been upgraded using a custom-made board that reads out the individual node signals, calculates the position

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and generates and stores x and y histograms of the data. Readout is performed by a National Instruments data acquisition card through a LabVIEW virtual instrument.

B. Coded aperture imaging

Numerous papers containing results of coded aperture neutron imaging have been published and presented at conferences [e.g. 8]. To illustrate the capability of the wire chamber based coded aperture neutron camera, we present a more recent measurement where five thermalized ^{252}Cf neutron sources were imaged simultaneously. In Fig. 1, the left picture shows the sources separated in a circular configuration, while the right image shows them in a linear, close-packed configuration. The inserts above the images are photographs of the two setups where the polyethylene thermalizer blocks containing the fast neutron sources are shown.

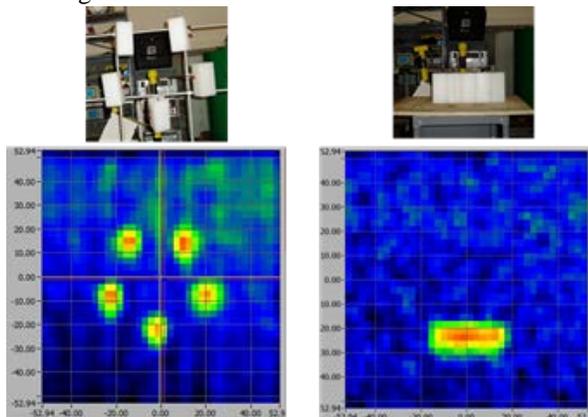


Fig. 1. Wire chamber images of five ^{252}Cf sources. Scales are in cm. (See the text for details.)

The superior position resolution achieved is an undoubted advantage of the wire chamber technique. There are certain aspects, however, which have to be addressed.

C. Detector spatial response

The multi-node interpolating readout method generates a periodic non-uniformity in uniform irradiation response. This can be accurately measured by uniformly irradiating the detector's face with thermal neutrons. The non-uniform response of the detector was observed to be fairly stable; that is, the response is not changing until the operating conditions are changed (gas pressure is the most decisive factor). Therefore, for the measurements, an empirical non-uniformity correction can be applied by dividing the x and y histograms by the corresponding uniform irradiation histograms.

D. High detector pressure and flammable quenching gas

The original position sensitive wire chambers were permanently installed in experimental halls that had strong neutron beams (reactors or spallation neutron sources). For coded-aperture applications, the portability of the device becomes an important issue. The high gas pressure with the added flammable propane gas prevented transporting the device on aircraft with the gas fill present in the detector. Also, the high pressure required a heavy pressure vessel.

III. PAD-BASED THERMAL NEUTRON DETECTOR

A. The prototype detector

The heart of the new neutron detector is a 48 x 48 pad board with 36 ASICs (64 channels each) on the back of the pad board (see Fig. 2). Each pad is connected to an individual ASIC channel. The ^3He -filled detector chamber is operated as an ionization chamber, i.e., with unity gas gain. The $\sim 25 \times 10^3$ electrons created by the $^3\text{He}(n,p)^3\text{H} + 764$ keV conversion reaction are collected on the anode pads. From there the signals are filtered and digitized by the ASIC channels and are sent to a digital data acquisition card. If the charge is picked up by more than one neighboring pad, a weighted average is calculated, and this charge division results in a spatial resolution which is less than the 5 mm pad-size. This technique is made possible by the extremely low noise characteristics of the ASIC design.

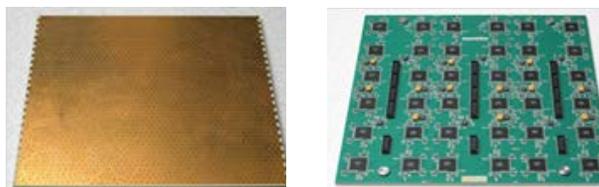


Fig. 2. Pad board (left) and 36 ASICs mounted on the back of the pad array (right).

In order to achieve a good spatial resolution, the path lengths of the proton and triton have to be reduced by mixing a stopping gas [5] with the ^3He . Traditionally, propane has been used, but more recently, comparably good results were achieved in test measurements using non-flammable CF_4 stopping gas.

A prototype detector with a gas depth of 4 cm has already been built and tested. The large conversion depth requires only two to three bar ^3He pressure to achieve high detection efficiency. This low pressure combined with the non-flammable stopping gas increases margins of safety in a variety of environments and will allow for shipment via air without restriction. The prototype chamber pressure vessel is shown in Fig. 3.

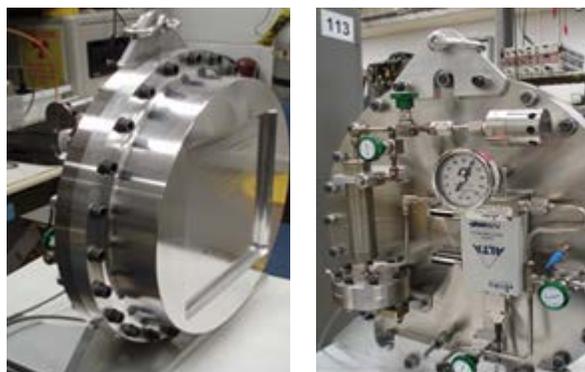


Fig. 3. Fully assembled prototype pad detector (front and back).

B. Signal readout in pad detector

The back of the pad plane (ASIC side) contains the 36 custom made ASICs (64 channels each) [10]. Each ASIC channel contains an amplifier, shaper, a peak/time detector and ADC. The output channels are read out by a data acquisition card.

The data acquisition card sequentially reads out the ASIC and sends the data to a computer through gigabit Ethernet. Each event contains an address (which ASIC, which ASIC channel had the event), time and digitized charge information. The computer stores the data for further analysis. The design is capable of handling very high data rates useful, for example, in spallation neutron sources or other accelerator-driven applications. The pad detector signal path is schematically shown in Fig. 4.

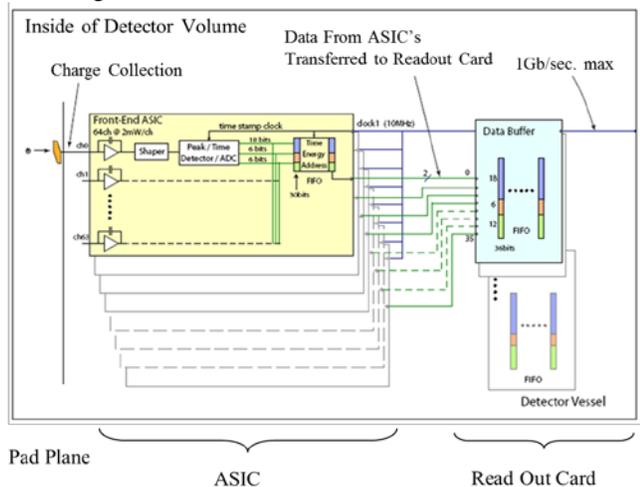


Fig. 4. Pad detector signal path. The charge collected on the pad is read, shaped and digitized by an ASIC channel, and a time stamp is added. The information along with the ASIC and channel number is sent to a data buffer which is read out through gigabit Ethernet. All the electronics are located inside the pressure vessel.

C. First coded aperture image with pad detector

The first coded aperture image using the prototype pad detector is shown in Fig. 5. The left side displays a reconstructed image of one ^{252}Cf source taken by a 19 x 19 pixel (coarse resolution) mask. The right panel is a threshold cut image where only pixels at 3σ above background level are shown.

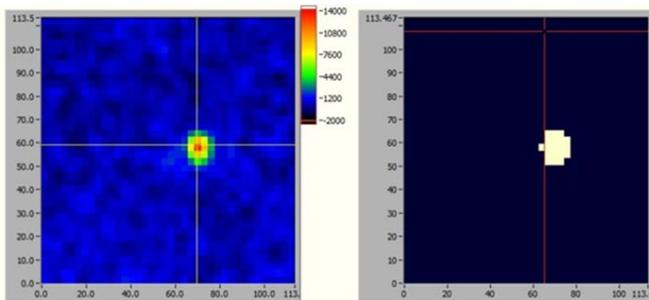


Fig. 5. First coded aperture image produced by the prototype pad detector. Left: reconstructed image. Right: threshold cut image (see the text for details).

D. Redesigned detector for coded aperture application

The new design minimizes the internal volume (and therefore the gas volume) by adapting the shape of the pressure vessel to the square active area of the detector. The pressure vessel will be square with rounded corners. This results in a substantial weight reduction (the new detector's mass will be about 25 kg, which is half that of the prototype detector).

The wire chamber required an external rack of electronics, which included the data acquisition unit, the high and low voltage power supplies and the gas purifier pump power supply. In the new detector, all these will be built into the detector. A 24 V DC power supply (power "brick", similar to those of the laptop computers) will be the only off-detector component required. The data acquisition card will be inside the detector and mounts directly to the pad board. A control card and a high voltage power supply will be attached to the back of the detector. The device will communicate with a laptop computer through a Gigabit Ethernet line.

The data acquisition card, which is in the gas volume of the prototype detector, will be extended by adding a control card on the exterior of the pressure vessel. The control card will include a high speed analog to digital converter, so the analog signals from the shaper amplifiers can be individually sent to the computer in a digitalized form. It will also control the operation of the gas purifier pump.

IV. STEREO IMAGING

Although we foresee many possible application of coded aperture imaging using the new pad based neutron detector, in the present paper we concentrate on only one of these uses, namely the stereo neutron imaging of multiple thermal neutron sources. Counting and identifying the location of thermalized neutron sources is important for treaty verification applications.

We performed preliminary stereo imaging experiments using the prototype camera. Since we used only one camera, the stereo imaging was simulated by setting up the multi-source scenario on a rotating table, and rotating the scenario by well-defined angles. Fig. 6. shows the rotating table with four polyethylene thermalizers. The ^{252}Cf neutron sources were placed in these thermalizers, and the table was rotated by well defined (0° , 15° and 30°) angles. The coded aperture camera and mask is visible in the background of the picture.



Fig. 6. Rotating table with four thermalizers. (See the text for details.)

Three exposures were taken, at 0° , 15° and 30° rotation angles. The resulting images are displayed on Fig. 7.

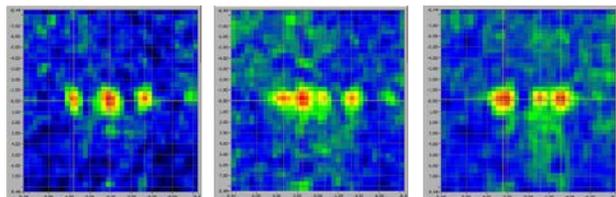


Fig. 7. Exposures at 0° (left), 15° (center) and 30° (right).

On the 0° exposure only three sources are visible, the bigger spot in center corresponds actually two sources which are behind each other in this view. In the middle picture all four sources are visible, whereas on the 30° (right) exposure again two sources are not resolved because of the geometry.

We have developed a LabVIEW based image reconstruction program to process these images. The program calculates the back projection lines based on the focal point of the camera and the image points. The crossing points of the back projection lines determine the source position.

The results of this calculation are shown in Fig. 8. The left side is a photograph of the source scenario (the sources are removed for taking the photograph, only the thermalizers are visible), the right side displays two sets of calculated data. One set was using the ($0^\circ, 15^\circ$) image pair, the other one was using the ($0^\circ, 30^\circ$) pair. The four sources are marked with differently colored symbols, and we have two calculated positions for each source from the two image pairs. The observable difference of the two sets is due to the uncertainty in the image point determination, caused by the finite pixel size.

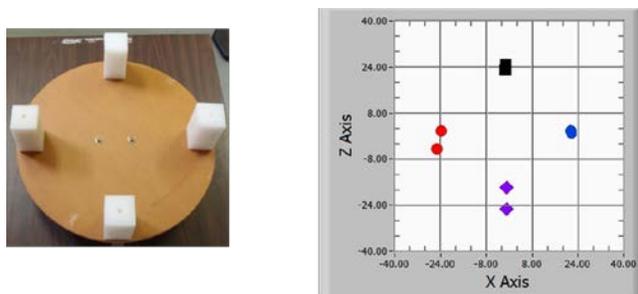


Fig. 9. Photograph of the setup (left) and calculated source positions for two exposure pairs. (See the text for details.)

V. SUMMARY

Brookhaven National Laboratory is in the process of building a new pad based coded aperture thermal neutron imager. The new design will have several advantages over the traditionally used wire chamber camera. Its efficiency will be considerably higher, yet it will have less mass. It will have a lower gas pressure, with gas that is not flammable or toxic, and a robust design enabling easy shipment for field applications of the camera. The new imager will have many uses in homeland security and treaty verification application. In the

present paper we have shown preliminary stereo imaging results using the prototype camera.

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