Straw Detector for High Rate, High Resolution Neutron Imaging

Athanasios Athanasiades, *Member, IEEE,* Nader N. Shehad, *Member, IEEE,* Christopher S. Martin, Liang Sun, *Member, IEEE,* and Jeffrey L. Lacy, *Member, IEEE*

***Abstract*— Instrument requirements in soon to be commissioned and planned neutron scattering facilities call for large area detectors that can sustain rates up to 10^8 cps and millimeter-level spatial resolution. Although ^{3}He pressurized area detectors can provide good spatial resolution, sensitivity and gamma ray discrimination, this technology cannot achieve the required rates without further development. Moreover, achieving large detection areas with pressurized ^{3}He technology is expensive because of the complexity of the pressure containing vessels required. We propose a detector technology, based on thin-walled straws, lined with a 1 μm thick sputter coating of enriched boron carbide ($^{10}B_4C$). Neutrons converted in ^{10}B generate charged particles that subsequently ionize the gas contained within each straw. Because the $^{10}B_4C$ coating is very thin, efficient escape of the reaction products can be achieved. A panel detector consisting of several thousand close-packed individual straws, which are read out independently, can easily support high event rates. We present performance testing of two 50-straw prototypes (non-enriched B_4C), including detection efficiency, spatial resolution, and two-dimensional imaging. Each straw has a diameter of 4 mm and a length of 1 m. Additional tests of a single 50 cm long straw, 2 mm in diameter are also presented.**

***Index Terms*— Boron-lined proportional counters, thermal neutron detection, neutron scattering**

I. Introduction

THE Spallation Neutron Source (SNS) facility, due for completion at Oak Ridge in 2006, will push available thermal neutron flux at least an order of magnitude above that achievable at any other neutron science facility [1]. The increased flux imposes extreme rate requirements on the neutron detectors in many of the proposed instruments. Moreover, many of the SNS experiment stations require detector areas of several square meters. Detector requirements for the Small Angle Neutron Scattering (SANS) instrument, as an example, are listed in Table I.

Although ^{3}He pressurized area detectors can provide needed spatial resolution, sensitivity and gamma ray discrimination, this technology, without fundamental developments, cannot achieve the needed high rate operation. Furthermore, large detection areas are costly, because of the complexity of the pressure vessels required.

We propose a detector technology, based on thin-walled straws, lined with a 1 μm-thick sputter coating of enriched boron carbide ($^{10}B_4C$). Neutrons converted in the $^{10}B(n,\alpha)^7Li$ reaction generate heavy charged particles that subsequently ionize the gas contained within each straw. Because the $^{10}B_4C$ coating is very thin, efficient escape of the reaction products can be achieved. A panel detector consisting of several thousand, close-packed, independently read-out straws, as shown in Fig. 1, offers a large detection area, achieves a high detection efficiency, supports high event rates, and discriminates effectively against gamma rays, as demonstrated below for small scale prototypes.

TABLE I
PROPOSED DETECTOR PERFORMANCE, AND SANS REQUIREMENTS

	proposed design	SANS [2]
dimensions	$100\times100\times4$ cm^3	100×100 cm^2
det. efficiency (80 meV)	50%	50%
position resolution	$7\times4\times4$ mm^3	5×5 mm^2
count rate (overall)	2×10^7 cps	2×10^7 cps
pixel count rate	>1500 cps	1500 cps
gamma efficiency	10^{-7}	10^{-7}

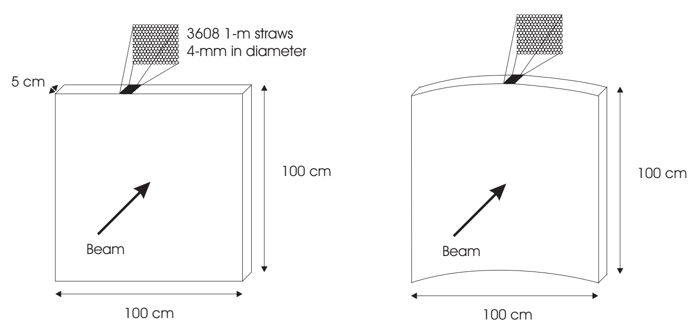


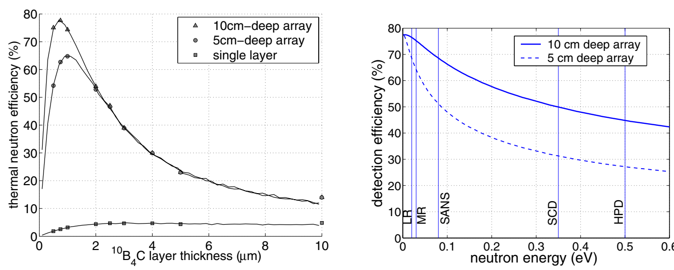
Fig. 1. Neutron area detectors composed of dense-packed $^{10}B_4C$ lined straws, showing a flat panel configuration (left) and a curved panel (right) whose curvature matches the radius of the scattering geometry.

Boron-lined proportional detectors have been employed for many years, but achieve at most a few percent efficiency, due to the fact that, if the foil thickness exceeds the range of reaction products, no escape occurs. Thus only conversions in the very thin layer near the surface are detected. This very thin layer captures only a small percentage of the incident

This work was supported by DOE SBIR grant no. DE-FG03-01ER83297, and NIH SBIR grant no. 2R44RR018053-02.

All authors are with Proportional Technologies, Inc., Houston, TX 77054 USA (telephone: 713-747-7324, e-mail: aathanasiades@proportionaltech.com).

neutrons. The proposed design employs a close-packed array of $^{10}B_4C$-lined straw tubes, and removes the low efficiency barrier, by providing many layers of very thin converters, each providing efficient reaction product escape. Using a stack of such detectors, of reasonable depth, high neutron detection efficiency can be achieved in the 1-10 Å neutron wavelength range, as determined in Monte Carlo simulations [3], shown in Fig. 2.



(a) (b)

Fig. 2. (a) Predicted thermal neutron detection efficiency of a single ^{10}B-enriched B_4C-lined straw tube (4 mm in diameter), and of arrays of such detectors, at various film thicknesses [3]. Results for a planar film of ^{10}B-enriched B_4C are included for comparison. (b) Detection efficiency as a function of neutron energy for two array depths, and with a $^{10}B_4C$ thickness of 1 μm. The vertical lines indicate the energy requirements (at 50% efficiency) of instruments at SNS [2]. LR: Liquids Reflectometer; MR: Magnetism Reflectometer; SANS: Small Angle Neutron Scattering; SCD: Single-Crystal Diffractometer; HPD: High-Pressure Diffractometer.

It is useful to compare the stopping power of the proposed detector, with the popular ^{3}He medium. The atomic density of ^{10}B in a close-packed array of straws, where each straw is 4 mm in diameter, and incorporates a 1 μm thick $^{10}B_4C$ lining, is 1.0×10^{20} atoms/cm^3. At one atmosphere, the atomic density of ^{3}He (or any gas) is 0.269×10^{20} atoms/cm^3. Correcting for the relative thermal neutron cross sections of ^{3}He and ^{10}B, the straw array has the linear stopping power of ^{3}He gas at a pressure of 2.68 atm. It is difficult to achieve this pressure safely in planar detectors of large dimension, and even in simple commercial cylindrical detectors pressures are often limited to 4 atm.

Table I lists the predicted detection efficiency, spatial resolution, count rate and gamma discrimination of the proposed design, based on prototype detector results, outlined in the following sections. A preliminary report of this development was published in [3].

II. Methods

Two prototype detector modules were fabricated according to the proposed design. Each module consisted of a close-packed array of 10×5 straws. The two modules were mated together, as shown in Fig. 3. Such close packing can be carried to as many modules as desired to produce a continuous detection volume within a secondary housing. Each straw was 100 cm long and 4 mm in diameter. Straw material was made by winding two thin strips of either aluminum or copper, incorporating a 1 μm thick layer of non-enriched boron carbide (B_4C) on the inner surface of the inner layer. A resistive anode wire (43 Ω/cm), 20 μm in diameter, was tensioned in the center of each straw. The sensitive face area of the two modules combined was 800 cm^2, and their depth in the direction of irradiation was 1.73 cm.

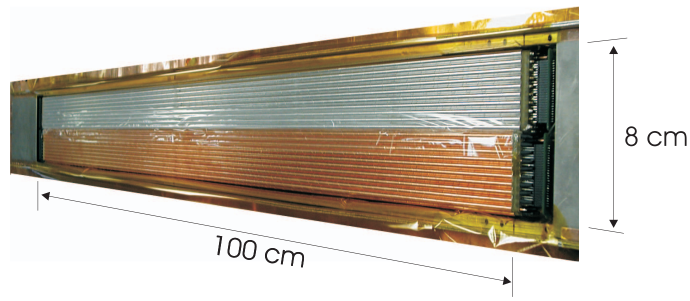


Fig. 3. Aluminum (top) and copper (bottom) prototype detector modules, close-packed to form a 100×8 cm^2 panel. Neutrons are incident on the face shown. The depth dimension, in the direction of irradiation, is 1.73 cm.

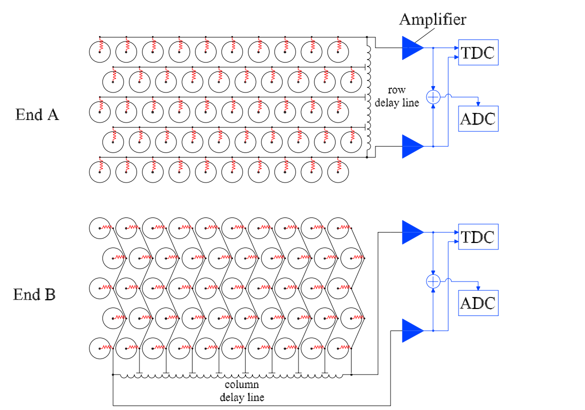


Fig. 4. Electronics setup for straw readout, showing circuitry connected to the two respective ends of each module.

Straw decoding was accomplished by connecting groups of either rows or columns of straws together into delay line taps, as shown in Fig. 4. On one end of the detector, straws were connected together in rows (row decoding end) and on the other side, they were connected in columns (column decoding end). When an event occurs in a straw, its current divides and is injected into a tap of the row delay line and a tap of the column delay line. By timing the outputs of the delay lines, both a row and column number can be obtained, thus identifying the straw in which the event was detected. Event position along the straw length was determined using a charge division method, applied to the total 50 straw readout arriving at each end. By combining straw decoding and longitudinal position, full three-dimensional positioning was obtained for each detected event. The same readout technique has been applied to a prototype PET camera made with gamma ray sensitive straw detectors [4].

The two detector modules were tested in a thermal neutron beam, at the reactor of the Nuclear Science Center at Texas A&M University (TAMU NSC). Experiments were performed using different collimators and reactor power levels. For all experiments, the detectors were biased to 1150 V, and the gas mixture employed was 90% argon, 10% methane. Due to the limited size of the neutron beam, only half of the detector length (50 cm) could be irradiated at a time. Thus, most experiments involved moving the detector to one of two positions, then repeating at the other position.

A. Gas Multiplication & Energy Resolution

The prototype detector was operated in a mode of proportional amplification, whereby maximum signal levels were achieved while maintaining adequate energy resolution. Measurement of the amplification factor was done by placing a 37 MBq (1 mCi) ^{55}Fe gamma source next to a single straw detector, filled with a gas mixture of 90% argon and 10% methane, and recording the count rate and corresponding average ionization current. The ratio of the two numbers gives the average amplified charge generated in each event avalanche.

Energy spectra were collected in one of the two 50-straw modules, with a moderated ^{252}Cf source at different bias voltages.

B. Neutron Detection Efficiency

The detection efficiency for thermal neutrons was measured with both the copper and aluminum straw modules positioned in the neutron beam of the TAMU NSC reactor in the orientation shown in Fig. 3. The intensity of the beam was characterized with a commercially available BF_3 neutron detector (N. Wood Counter Laboratory Inc., Chesterton, IN). In order to avoid counts from neutrons scattered from the beam cave walls, all sides of the modules, except the one facing the beam, were shielded with borated aluminum.

C. Gamma Efficiency & Discrimination

The response of the copper straw module to gamma radiation was determined in the following experiment. A 246 μCi ^{137}Cs source was placed 25 cm away from the face of the module. The gamma fluence Φ through the detector module was estimated using the relation $\Phi = N/(4\pi d^2)$, where N is the number of photons emitted by the source (94% at 662 keV), and d is the distance between the source and the detector. The average fluence through the detector was 500 photons/(cm^2·s), or 200,000 photons/s over its face area (400 cm^2).

D. Position Resolution & Imaging

Spatial resolution in the direction parallel to the straw axis was investigated through the use of a slit collimator. The two modules were oriented as shown in Fig. 3, and placed behind a 4.5 mm thick borated aluminum collimator (^{10}B areal density of 45 mg/cm^2, 99.9% attenuation) with ten 1 mm wide slits, 10 cm apart from one another. The energy discriminator level was set to 30 keV.

A two-dimensional neutron image was obtained using an acrylic (polymethyl methacrylate) letter target, reading "PROPORTIONAL TECH.". Each letter was 55 mm tall and 9.1 mm deep, taped onto a 1 mm thick sheet of borated aluminum, in order to lower the flux of incident neutrons, and placed 10 cm away from the detector face. Neutrons scattered within the acrylic letters at a rate of 50% before hitting the detector. The reconstructed image was adjusted for variations in straw sensitivity, and was enhanced for contrast.

E. Single 2-mm straw

We investigated the effect of straw diameter on spatial resolution by testing a single, 50 cm long aluminum straw, 2 mm in diameter. Neutron scattering instruments such as the Single Crystal Diffractometer require resolutions less than 2 mm. The straw was also tested in the TAMU NSC neutron beam. The detectors were biased to 960 V, aand were operated with a continuous flow of argon/methane (90/10) gas.

III. Results & Discussion

A. Gas Multiplication & Energy Resolution

The measured amplification factor is plotted in Fig. 5, as a function of the applied potential. Each 50-straw module showed stable operation up to a bias level of 1200 V, with a corresponding multiplication factor of 50,000, and without significant degradation in energy resolution. The breakdown point was at 1550 V.

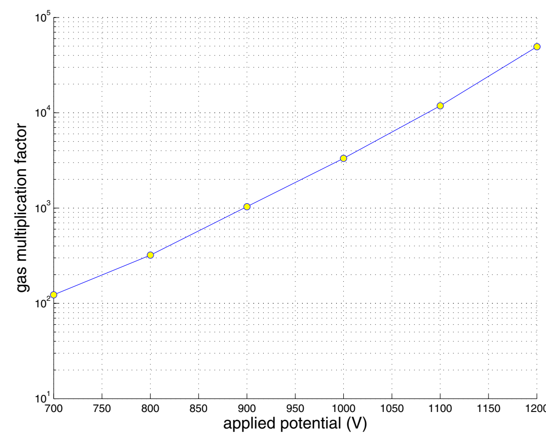


Fig. 5. Gas amplification factor in the prototype detector, filled with 90% argon, 10% methane at 1 atm, as a function of detector bias voltage.

Neutron and gamma events deposited markedly different amounts of energy, as shown in Fig. 6, with most neutron events depositing energies significantly higher than those of gamma events, as indicated in the figure (bottom panel). Gamma discrimination is easily achieved by setting an energy threshold above the gamma tail, at an energy level of about 30 keV (channel 500 in figure).

B. Neutron Detection Efficiency

The measured thermal neutron flux at the location of the detector modules was 58 nv (nv ≡ neutrons/(cm^2·s) at a reactor power level of 10 W, and 290 nv at 50 W. It increased linearly

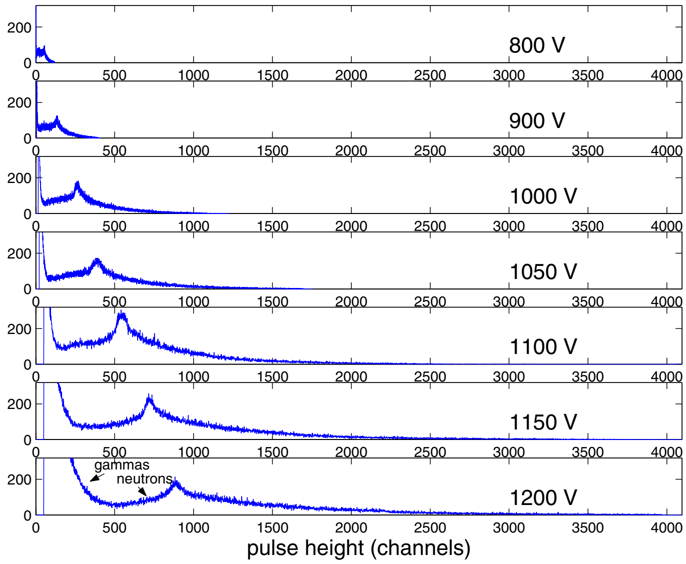


Fig. 6. Energy spectra collected in the 50-straw detector from a moderated ^{252}Cf source. The detector cathode was biased to the voltage indicated in each panel. The gas mixture was argon-methane (90-10).

at higher power levels. The neutron count rate recorded at a reactor power level of 50 W, and above a threshold of 30 keV, was 29 cps/cm^2 in the aluminum module, and 45 cps/cm^2 in the copper module. The resulting thermal neutron detection efficiencies are 10% (=29/290) for the aluminum module, and 16% (=45/290) for the copper module. If the straws were to be lined with ^{10}B-enriched boron carbide, the efficiencies would be aproximately 3.5 times higher.

The difference in efficiency between the two modules is probably due to a difference in the thickness of the boron carbide (B_4C) layer that lines each straw in the two modules. The fully developed detector will be 5 cm deep, will incorporate enriched rather than natural boron carbide, and will have an estimated thermal neutron efficiency close to 70% [3], as shown in Fig. 2.

C. *Gamma Efficiency & Discrimination*

The number of photons counted above a threshold of 30 keV was 0.0607 cps. The resulting gamma detection efficiency was 3.0×10^{-7} (=0.0607/200,000). The gamma discrimination factor, defined as the ratio between the neutron and gamma efficiencies, was 0.53×10^6 (=$0.16/3.0\times10^{-7}$). The aluminum straw module, due to its lower density, has a significantly lower gamma ray efficiency, and thus better gamma ray discrimination.

D. *Position Resolution & Imaging*

Figure 7 shows the spectrum of interaction positions in each of the two meter-long modules, and in the two modules combined, with the reactor power set to 50 W. The mean full-width-at-half-maximum (FWHM) of all peaks in the aluminum-straw module was 7.4 mm, and in the copper module it was 9.1 mm. In the third panel of Fig. 7, the two module position spectra are added together, producing a mean resolution of 9.3 mm, demonstrating good inter-detector calibration. The minimum values measured were 6.54 mm in the aluminum module, and 7.27 mm in the copper module.

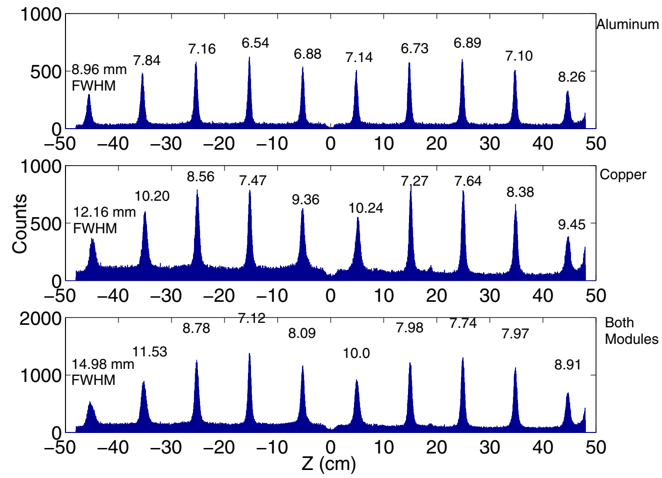
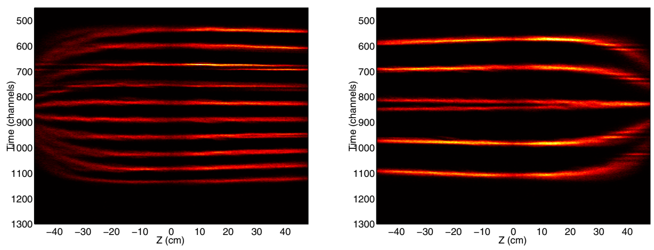


Fig. 7. Position spectra in the direction along the straw axis (z direction), collected in the prototype detector, using a collimator, and at a reactor power level of 50 W. The detector was operated with an argon-methane gas flow, at 1150 V. The full-width-at-half maximum (FWHM) is indicated above each peak. The absence of counts at 0 cm is due to the presence of a fitting that supports the anode wire at the center of each meter-long straw.

A substantial degradation of resolution was observed at the edges of the neutron beam, which is not inherent to the detector. As the neutron beam was only 50 cm in diameter, the detector was irradiated in two steps, one covering the section from -50 cm to 0 cm, and the other covering the section from 0 cm to +50 cm. The resolution was worse towards those end points. In another experiment (not shown here), the detector was positioned such that a different, central section from -25 cm to +25 cm was irradiated. The resolution degraded towards the new end points ($\pm$25 cm), and it was optimal in the center.

Figure 8(a) shows the correlation between the time of arrival of signals, and the corresponding location of interaction events. Events are widely separated in narrow bands, except for the left end of the detector, where the bands begin to merge, but are still separable. A similar plot of the timing of signals in the direction of the module rows was constructed and is shown in Fig. 8(b). Good separation between the five rows is clearly shown over the entire extent of the detector.

Figure 9 shows the image created with the letter target. The image shows very good linearity, but resolution degrades significantly in the center. This likely is a result of combined effects of beam edge degradation previously discussed, and probable effects of the plastic sleeving used in the center twisters. Whereas the presence of fittings at the two ends of each straw is required and will not interfere if the straw ends are shielded, the central support will be eliminated in the future in order to minimize neutron scattering.



(a) (b)

Fig. 8. (a) Correlation between the timing of signals and the corresponding location of neutron interactions along the length of the prototype detector. Each band represents events from one of the ten columns making up the module. (b) Correlation between the timing of signals and the corresponding location of neutron interactions along the length of the prototype detector. Each band represents events from one of the five rows making up the module.

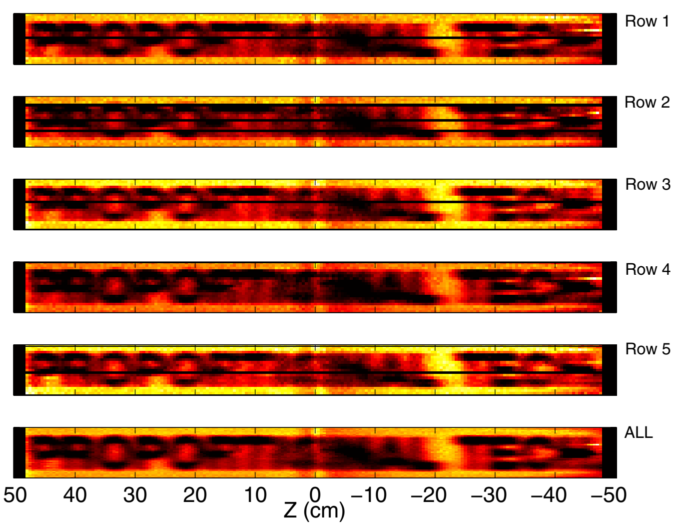


Fig. 9. Two-dimensional image created in the prototype detector, using an acrylic letter target. Separate images are shown for each row in the detector (group of 20 straws), and for all rows combined. Row 1 is the row on the front face of the detector.

E. Single 2-mm straw

Fig. 10 shows the position spectra collected with the 2 mm straw placed behind a slit collimator (0.5 mm wide slits). The mean FWHM of all peaks, excluding the two falling inside the plastic supports, was 1.73 mm. The FWHM of the four peaks closer to the center was 1.64 mm. A 50×50 cm^2 close-packed array of these smaller straws would support both high rates and high resolution. Exclusion of 18% of events with highest energy deposition (longest alpha tracks) produced a resolution approaching 1.3 mm FWHM in the center of the detector.

IV. Conclusion

Table II summarizes the measured performance parameters of the two straw modules. Results indicate that a 1 m^2 panel detector, made up from 58 such modules, will satisfy the neutron detector requirements of many of the instruments proposed for the Spallation Neutron Source (see Table I).

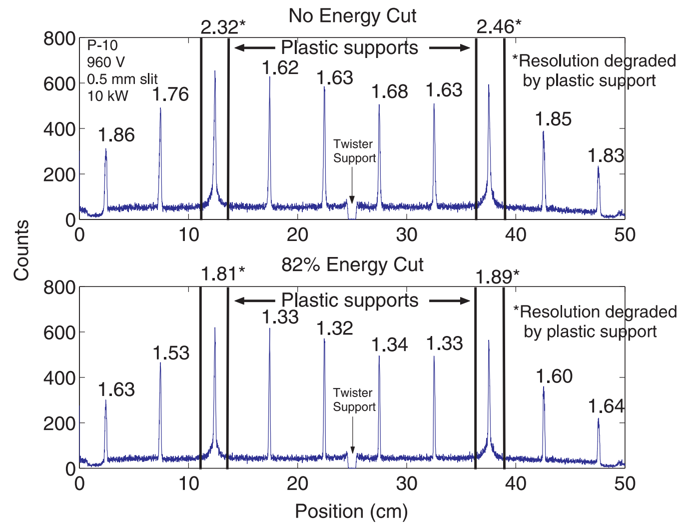


Fig. 10. (*top*) Position spectra collected in a single, 50 cm long straw, 2 mm in diameter, using a slit collimator. (*bottom*) The same spectrum with an upper discriminator level that rejects high energy events (18% of events rejected), resulting in improved resolution. Note the peak broadening in the two peaks positioned over plastic supports, and the clean, narrow inefficient spot in the center, produced by the central wire support.

The prototype readout electronics were not designed to accommodate high count rates (a new amplifier is currently under development), and, thus, it was not possible to test performance at count rates higher than those listed in Table II. However, because of the segmentation afforded by the straw array, high rate capabilities are straightforward to achieve.

TABLE II
Performance Summary of Two Prototype Modules

	aluminum straws	copper straws
dimensions	100×4×1.73 cm^3	100×4×1.73 cm^3
number of straws	50	50
det. efficiency (thermal)	10%	16%
position resolution	7×4×4 mm^3	9×4×4 mm^3
max count rate tested	9547 cps	14120 cps
max pixel count rate tested	49 cps/mm	75 cps/mm
timing resolution	25 ns	25 ns
gamma efficiency		3×10^{-7}

References

[1] Spallation Neutron Source, http://www.sns.gov, 2005.

[2] R. Cooper, I. Anderson, C. Britton, K. Crawford, L. Crow, P. DeLurgio, C. Hoffmann, D. Hutchinson, R. Klann, I. Naday, and G. Smith, "A program for neutron detector research and development," March 2003, http://www.sns.gov/nov04rev/.

[3] J. L. Lacy, A. Athanasiades, N. N. Shehad, R. A. Austin, and C. S. Martin, "Novel neutron detector for high rate imaging applications," in *IEEE Nuclear Science Symposium Conference Record*, 10-16 Nov. 2002, vol. 1, pp. 392–396.

[4] N. N. Shehad, A. Athanasiades, C. S. Martin, L. Sun, and J. L. Lacy, "Novel lead-walled straw pet detector for specialized imaging applications," in *IEEE Nuclear Science Symposium Conference Record*, 23-29 Oct. 2005.