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Section A

A scintillating plastic fiber tracking detector for neutron and proton imaging and spectroscopy

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Abstract

We report on a prototype detector system designed to perform imaging and spectroscopy on 20–250 MeV neutrons. The detection techniques employed can be applied to measurements in a variety of disciplines including solar and atmospheric physics, radiation therapy and nuclear materials monitoring. The detector measures the energy and direction of neutrons by detecting double neutron–proton scatters and recording images of the ionization tracks of the recoil protons in a densely packed bundle of scintillating plastic fibers stacked in orthogonal layers. The scintillation tracks are detected and imaged by photomultipliers and image intensifier/CCD camera optics. By tracking the recoil protons from individual neutrons, the kinematics of the scatter are determined. This directional information results in a high signal-to-noise measurement. The self-triggering and track imaging features of a prototype for tracking in two dimensions are demonstrated in calibrations with 14–65 MeV neutrons, 20–67.5 MeV protons, and with cosmic-ray muons. Preliminary results of phantom imaging measurements using a proton beam are also presented. We discuss several applications for this detector technique and outline future development work. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Prototype detector system; SONTRAC; Proton beam

1. Introduction and motivation

Directional neutron telescopes based on double scatters have been used for many years [1,2]. They are particularly effective in high background environments. The neutron telescope described here, known as SONTRAC, the SOlar Neutron TRACking telescope, is under development to study the high-energy processes associated with solar flares [3]. When high-energy charged particle reactions occur on the surface of the Sun, neutrons carry away information about the spectrum of ions that produced them and can be used as diagnostic measures of that spectrum [4].

A number of other applications have been identified. In the earth's atmosphere neutrons above

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10 MeV produce the so-called soft error upsets in microcircuitry and they represent a radiation hazard for personnel at high-altitudes [5–7]. Neutron telescopes can be used to accurately determine the properties of the neutron background. Neutron tracking detectors can also be employed to accurately locate nuclear materials (waste, spills).

The success of proton radiotherapy (PRT) is based on the precision with which the dose is deposited in the tumor volume [8]. The tracking detector described here can be used to directly detect incident protons and precisely image the absorbing material to properly register a patient within the proton beam.

2. Tracking detector concept

The tracking detector employs a closely packed bundle of square cross-section plastic-scintillator fibers. The fibers are arranged in stacked planes with the fibers in each plane orthogonal to those in the planes above and below. This alternating orientation allows one to record stereoscopic images and track ionizing particles in three dimensions in the scintillating fiber block.

The tracking detector measures the energy and direction of incident neutrons by imaging the ionization tracks of recoil protons. Non-relativistic neutrons undergo elastic scattering off hydrogen within the organic plastic-scintillator fibers, scattering at right angles with respect to the scattered proton at non-relativistic energies. The Bragg peak, resulting from greater ionization near the end of the track, is used to determine proton track direction. A second proton scatter of the scattered neutron provides spatial information that is necessary and sufficient to determine the incident neutron energy and direction. With sufficient event statistics, an image and spectrum of the neutron source can be constructed. The energy and angular resolution are dependent upon the ability to measure the scintillation light and precisely track the recoil protons.

A functional diagram of an experiment utilizing the SONTRAC concept is shown in Fig. 1. The detector's spectroscopic, track detection and imaging components cover the entire light emitting area of the scintillating fiber bundle and are duplicated in the orthogonal dimension (not shown). The scintillation light signal is collected and processed at both ends of the fiber bundle. At one end a signal above threshold from a photomultiplier tube (PMT) fires a discriminator that in turn provides a signal to the trigger logic circuitry. At the other end of the fiber bundle, fiber-optic tapers and a pair of image intensifiers demagnify, capture and hold the scintillation-light image of the ionization track(s) for readout by the CCD camera. The first image intensifier in this chain is always ON. Its phosphor holds the image for approximately 1 ms. The second image intensifier in this chain is normally in the gated-OFF condition and no image signal is passed to the CCD sensor. However, when the trigger logic registers the proper coincidence, the track image and PMT pulse-height data are acquired and passed to an event builder and combined with auxiliary information for subsequent event-by-event analysis.

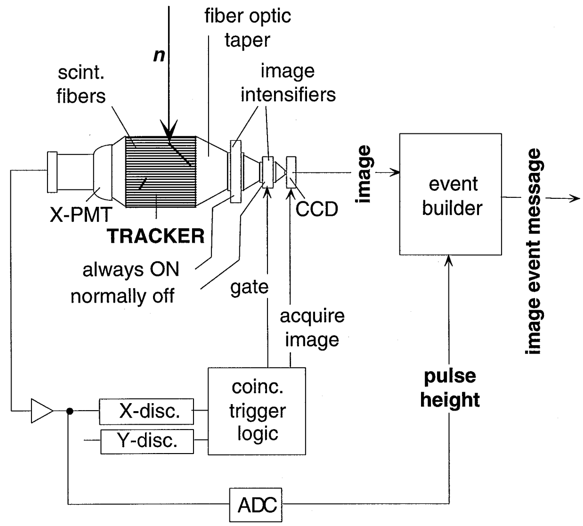

Fig. 1. Functional diagram illustrating the detector concept and the signal processing logic.

3. Prototype description and performance

The fundamental instrument design was studied extensively with Monte Carlo simulations [9,10]. It suffered at the time from a lack of technology and existed in simulations only. This technology has been applied to high-energy physics experiments [11], and has since become available at a reasonable price. We have developed a tracker prototype to demonstrate the tracking capabilities and to address fundamental science and engineering issues related to the calibration and design of space flight instrumentation [12–14]. To save cost it is small and limited to tracking in two dimensions.

The prototype has a 10 cm long bundle of 250 μm square (230 μm active) multiclad organic scintillating plastic fibers (Bicron BCF-99-55) within a 12.7 mm square envelope. The fiber pitch is 300 μm (including cladding and EMA).

The SONTRAC prototype was exposed to 14 MeV neutrons at San Diego State University and to high-energy neutrons and protons at the Crocker Laboratory cyclotron facility at the University of California at Davis. Fig. 2 shows the raw CCD image of a double scatter event displaying two recoil proton tracks from a single neutron ($\sim$65 MeV) incident from the top of the figure. Note that the Bragg effect, resulting in greater ionization at the end of the track, is evident thus permitting determination of the track direction.

Fig. 3 shows the track of a $\sim$20 MeV proton incident from the left of the figure. The CCD pixel intensity was averaged over individual fibers and the calibration mask of the fiber bundle is superposed on the track image. Note again the evidence of track direction. Note also that the track of the incident proton, unlike those from incident neutrons, starts at the edge of the bundle permitting discrimination of the incident particle type.

Fig. 4 is a histogram of the track lengths measured for 650–20 MeV protons incident normal to the fiber bundle surface. This demonstrates that track length can be used as a sensitive measure of proton energy. The measured track length is consistent with calculated predictions.

More recent tests used a variety of phantom absorbers placed between a 65.7 MeV proton beam and the tracking detector to demonstrate its spec-

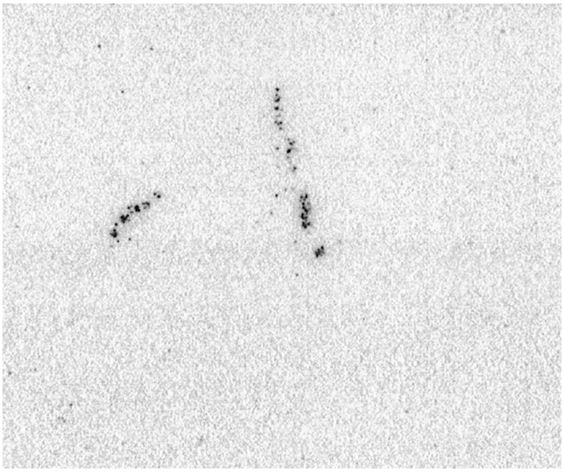

Fig. 2. Raw CCD image of double neutron–proton scatter from $\sim$65 MeV neutron incident from above.

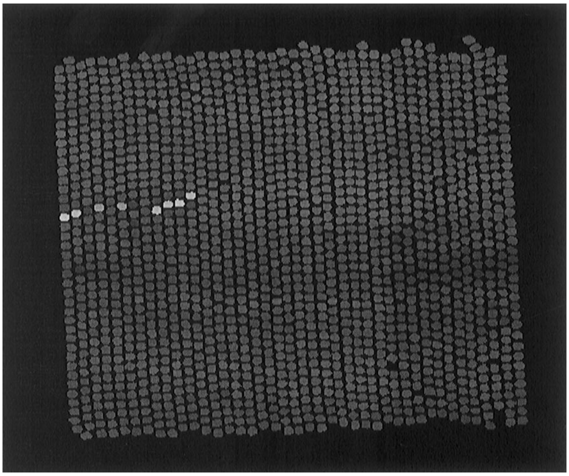

Fig. 3. Track of $\sim$20 MeV proton incident from left. The image is superposed on the mask of the scintillating fiber bundle.

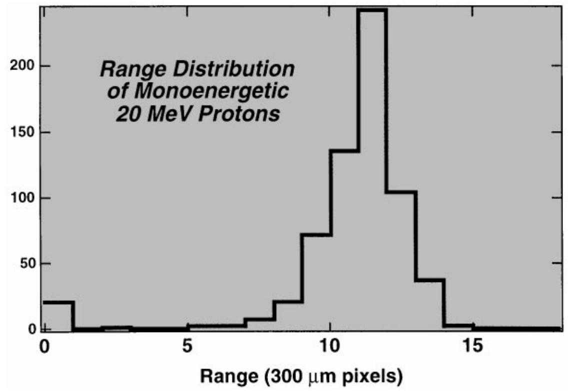

Fig. 4. Histogram of track lengths for monoenergetic protons.

troscopic and imaging capabilities for proton radiotherapy (PRT) applications. The geometry for one such test is illustrated in Fig. 5. The phantom absorber is a 20.9 mm thick acrylic block (1.18 g/cm^3) with 4 mm deep, 3 mm wide slots on 6 mm centers. The slots run parallel to the scintillating fiber axis. The prototype's scintillating fiber bundle is 12.7 mm wide (42×42 fibers on 0.3 mm pitch) thus spanning slightly more than two pitch lengths of the phantom pattern.

Fig. 5 also shows the sum of the raw CCD images from only 46 random events. The white box indicates the position of the fiber bundle within the image frame. No attempt was made in this preliminary analysis to subtract the flat field background for each event before computing the sum or to bin the CCD pixels with the fiber mask. That work is in progress and will be reported later. The figure nonetheless clearly illustrates the signature of two pitch cycles of the phantom slot pattern. Measured track length is ~ 27 fibers for protons passing through the slots, ~ 14 fibers for protons passing through the full thickness of the acrylic block, the difference being 3.9 mm in agreement with the depth of the slots in the phantom.

Images of cosmic-ray muon tracks are also clearly observed with the prototype tracker. This result was reported earlier [12] and demonstrates the detector's ability to track minimum ionizing radiation. As such it can serve to track conversion electrons in high-energy (>20 MeV) gamma detectors.

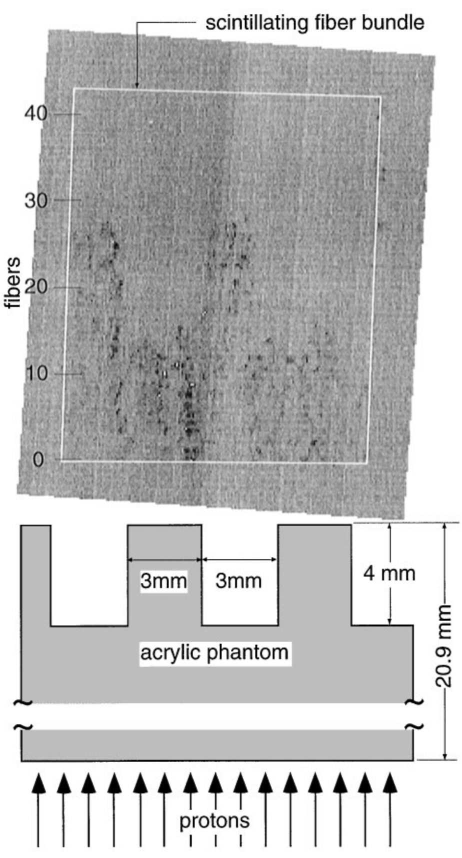

Fig. 5. Preliminary image analysis: The sum of the raw CCD images from 46 random proton events. The protons are incident through the phantom absorber whose profile is recognizable in the image.

4. Future work

We will continue to study the performance of the existing prototype tracker. We will also pursue development of a larger prototype tracker with orthogonal layers of scintillating fibers and matching electro-optics. This larger prototype will be representative of a flight instrument permitting us to address the engineering issues associated with construction, assembly and operation of a large orthogonal-layer tracker. We will develop algorithms for track identification and reconstruction in three dimensions, perform calibrations at higher energies with neutrons protons and gammas and continue to develop detector response models.

5. Conclusions

The SONTRAC laboratory prototype has demonstrated the important features of the detection technique: self-triggered track imaging, particle discrimination (neutron, proton), and measurement of the energy deposit and direction for each event. Self-triggered images of tracks of >20 MeV protons, recoil protons from 14 to ~ 65 MeV neutrons and minimum ionizing tracks of cosmic-ray muons are clearly resolved. The track images and associated pulse-height information provide good resolution measurements of both the direction and energy of the incident radiation. Preliminary analysis of the data from recent phantom imaging measurements indicate promising performance for the proton radiotherapy application. The prototype is limited, however, to tracking in two dimensions. An extension to three-dimensional tracking promises to provide unprecedented measurement capabilities for studies in a variety of fields.

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