Development of a Medipix2-based space radiation dosimeter

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ABSTRACT—NASA funding has enabled research into the development of space radiation dosimeter hardware based upon existing Medipix2 technology. The UH research cluster, in collaboration with the European Organization for Nuclear Research (CERN), has begun work on a portable, active dosimeter comparable in size and weight to current passive devices. The Medipix2 collaboration will bring a robust technology to bear on a low-risk program that promises significant, rapid advancement in radiation-monitoring equipment available for space flight.

INTRODUCTION AND BACKGROUND

ISSO funding was sought to support the creation of a cluster-based proposal to the NASA-SBIR program for the development of a portable, active space radiation dosimeter based upon the Medipix2 technology. The funding resulted in the submission of an SBIR proposal, which, in turn, was also funded, and the proposed research is now being executed. The proposal effort included a cluster team of individuals from the Physics and Computer Science Departments at UH, the Space Radiation Analysis Group at NASA/JSC, and the UH-sponsored spin-off company Nano EnerTex, Inc. Professor Lawrence Pinsky of the Physics Department is the PI. Professor Alex Ignatiev, from the Physics Department and also from Nano EnerTex, Inc., is a co-I along with Professor Ricardo Vilalta from the Computer Science Department. The Space Radiation Analysis Group, the primary organization within NASA charged with development of the dosimeter hardware, served in a consultative capacity. Physics and computer science graduate students participated in the proposal effort and are now involved in the funded research.

NASA is actively exploring leading-edge technologies to provide the basis for the design and development of an active, portable space radiation dosimeter that can assess the radiation environment during solar particle events (SPEs).[1] But while NASA targets high-risk technologies that might be applicable to the problem, the Medipix2 technology is already mature and better positioned for development. Our goal is to seek NASA funding to proceed from an exiting, mature, and proven technology to developing actual flight hardware for direct evaluation on near-term space missions.

Medipix2 is a robust technology based on electronics developed for use in the harshest radiation conditions in the Large Hadron Collider (LHC) at CERN in Geneva, Switzerland. It provides an opportunity to embark on a rapid, low-risk program geared toward providing critical advancements in the equipment available for space flight dosimetry monitoring. Our goal is to develop hardware that is comparable to current passive dosimeters in size and weight. Prototypes of current Medipix2-based devices are essentially the size of a typical USB flash memory stick and, like those USB smart drives, can be fully powered and read out electronically via standard USB interfaces such as those found on most laptops. Furthermore, work is progressing on integrating industry-standard wireless read-out capability into existing interfaces.

A consortium of institutions at CERN is responsible for developing the Medipix2 technology. In January 2008, Pinsky's group at UH succeeded in formally joining the consortium for the express purpose of developing a space radiation dosimeter based on the CERN technology. This will guarantee access to the technology for the purposes stated in this proposal. None of the funds will be used to directly support any foreign research by the consortium or by any other foreign entity, although the specific procurement of sole-source hardware from foreign entities is ultimately contemplated as part of this project and is permitted under U.S. regulations.

While size and ease of readout are clearly of great importance for potential flight hardware, the most impressive credentials of this technology are related to its demonstrated radiation detection and measurement capabilities. Using a silicon-based detector version, we have demonstrated that this technology possesses enormous dynamic range, with the capacity to record energy deposition rates from minimum ionizing muons through KeV/μm heavy ions greater than 10,000. Beyond this, the resolution also provides the distinction of the linear energy transfer (LET) and the ability to analyze the influences of the actual track structure of traversing ions. This, in turn, provides a direct measure of information about the dosimetric effects of a specific incident.

Versions of these detectors have been fitted with ^{6}Li and ^{10}B neutron converters. These provide efficiencies and energy resolutions sufficient to perform neutron dosimetry over a wide range of neutron energies. We have participated in recent test runs of these prototypes at the Neutron Standard Reference Facility (CERF) at CERN with mixed neutron fields similar to those found at high altitudes in the Earth's atmosphere (which are quite similar to the neutron spectral field found in Low Earth Orbit (LEO)). While the data analy-

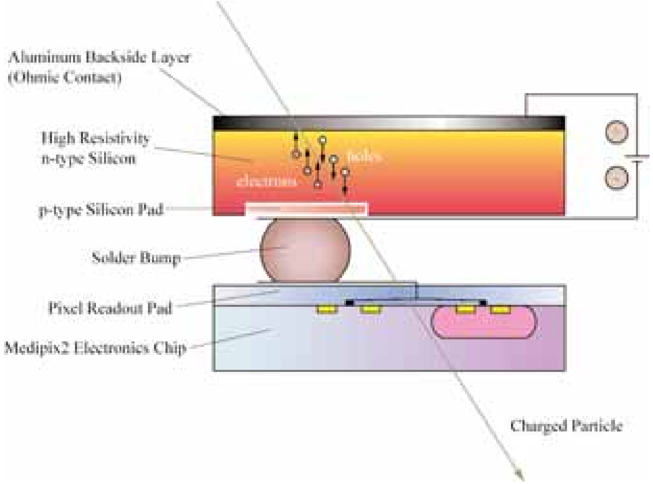

Figure 1. A schematic representation of a Medipix2-based particle detector with a depleted n-type silicon overlying sensitive detector layer and solder bump bond connecting the chip to p-type pads on the detector layer. Note that this drawing is not to scale, the active electronics layer being hundreds of times thinner than the typical detector layer, and the solder bump being negligible as well.

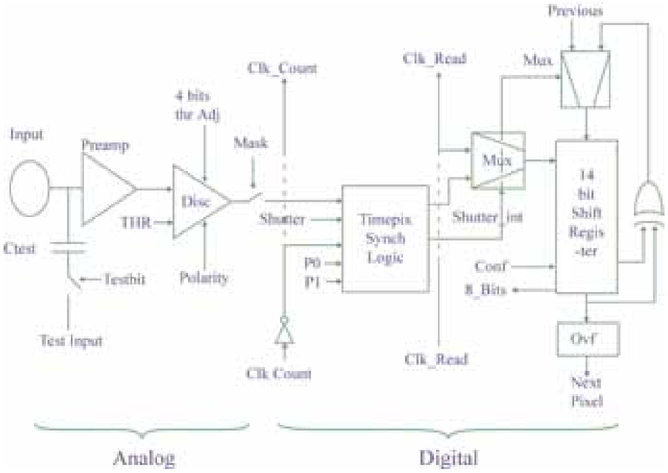

Figure 2. The logic diagram of the electronic circuitry within each TimePix pixel is shown in block schematic form. The clocks, shutter, and the threshold are global, but the four-bit threshold offsets, the mask bits, and the test bits are set pixel by pixel. Readout is by shift registers in columns. The TimePix logic input is also set independently pixel by pixel and can be specified as either time-over-threshold (ADC mode–count clock pulses while input is over threshold), TimePix (TDC mode–count clocks from first hit over threshold until shutter closes), or Medipix (i.e., count number of hits over threshold while shutter is open).

sis is in progress at present, preliminary results indicate a promising capacity for effective neutron dosimetry measurement in the space radiation environments expected to exist behind shielding and as albedos from nearby surfaces during intense SPEs, as well as from the normal galactic cosmic ray (GCR) background. It is in working with the neutron conversion coatings that Professor Ignatiev's expertise will be brought into play on this project, along with the capabilities of Nano EnerTex, Inc. Additional details are given in the next section.

Another impressive aspect of this technology is its functional dynamic range in the very high fluence environments of SPEs. The electronics can be set to stop down in time to acceptance windows ("shutters") as short as 10 ns. This capability is required for their application in the inner detectors at the LHC, where separate events due to successive collider bunch-crossings at 20 ns intervals need to be distinguished. Exposures of Medipix2-based detectors at the M.D. Anderson Proton Cancer Therapy Center in Houston have demonstrated the ability to resolve from several hundred to 1,000 proton tracks simultaneously in a single detector field. With a 10 ns shutter, this corresponds to a fluence approaching 10^{11}/cm^2/s. This fluence exceeds that expected to exist in the most intense SPE. However, by integrating the collected charge rather than counting individual tracks, the detector could continue to provide fluence estimates up to fluences of 10^{14}/cm^2/s. Further, the Medipix2 chip itself has been demonstrated capable of surviving and performing for extended periods in such radiation fields. The ability to directly monitor background rates means the device can respond within milliseconds to significant increases in dose and can provide local alarm capability based on logical combinations of sophisticated dose-related factors.

The raw output from a Medipix2-based dosimeter will be a pixel image of the detector integrated over the shutter open time. The operational method will be to control the shutter time to produce a roughly constant pixel occupancy situation to keep the pattern recognition problem constant. This is where the expertise of Professor Vilalta's group in the Computer Science Department comes into play. A significant portion of the dosimeter development effort will be devoted to the design and validation of analysis software needed to produce a radiation field description from the raw detector pixel output. For example, for SPEs, the proposed Medipix2-based devices will have not only the ability to measure the proton fluence and energy spectrum, but also to clearly distinguish ^{3}He and ^{4}He fluences and energies, as well as any heavier ion presence.

MEDIPIX2

The basis of the Medipix2 technology is the Medipix2 chip. It is a 256 × 256 pixel readout, CMOS-based integrated circuit with a 55 μm × 55 μm pixel pitch in which the readout circuitry for each pixel is embedded within the footprint pixel area. This property allows multiple Medipix2 chips to be tiled seamlessly to create larger sensitive areas with no gaps. Note that the sensitive area of each chip is almost exactly 2 cm^2. It is also important to note that this electronic chip design is quite versatile and is not tied to the use of any particular attached radiation-sensitive material. Rather, the input to each separate pixel readout circuit is accomplished through pick-up pads on the upper surface of the chip. This allows one to overlay any desired sensitive material, for example by using the solder bump-bonding technique to make electrical contact, as shown in Figure 1 for the case of an overlying silicon detector layer.

One of the currently available Medipix2 chip pixel electronics circuitry schematics is shown in Figure 2. Each pixel contains a front-end, charge-sensitive amplifier followed by a digital discriminator. In addition, there is a four-bit offset register to allow equalization of the response sensitivity of each pixel with respect to the other pixels on the chip. A logic control circuit can set each pixel to respond with an output that can provide one of several functions described below. Interfaces have been demonstrated with the ability to read out full 256 × 256 images (frames) at up to 1,000 Hz.

The prototype USB 1.1-based interface generally in use at this time is typically limited to a maximum of 25 Hz. This implies that with the current USB interface, for relatively short shutter times, one can extract up to about 25 frames per second. Obviously, if the shutter is open for very long, the frame readout rate will be reduced proportionally, but with higher bandwidth interfaces up to 1,000 frames per second can be extracted and permanently stored. The preliminary results presented in this report are all based on recent measurements taken with the new TimePix version of the Medipix2 base chip configuration. The TimePix chip provides a full equivalent ADC measurement capability for each pixel separately, as well as the possibility for TDC measurements. Each pixel is independently programmable to function in either mode.

The TimePix chip has a charge-sensitive pre-amp at the input along with a shaping amplifier whose characteristics can be globally adjusted. The clock counter is applied externally to the entire chip and can be set to frequencies as high as 100 MHz. With the output shift register bit depth the maximum count can be as high as 11,810 (decimal) with an additional bit to indicate an overflow situation. Most applications of interest to space radiation dosimetry will employ the TimePix in a time-over-threshold (ADC) mode. Figure 3 displays the functioning of the chip in this mode. The output shift register will be incremented whenever the shaped input is above the threshold, so it is important to set the shutter gate to a sufficiently small value so that only a single input pulse gives any input to the pixel in question. For overlaps in very high rate situations, the pixels can be programmed in a checkerboard fashion in order to better distinguish locally coincident tracks that are separated in time.

For use as charged particle detector, the overlying silicon must be depleted of charge carriers with a reversed biased voltage. This is supplied using a COTS chip that is normally employed to bias the Avalanche Photo Diodes (APDs) in use by the fiber optic industry, and can supply bias voltages up to 100 VDC with a 5 VDC input, and as such it can be supported as a normal part of the USB-powered interface unit. This allows us to employ silicon detector layers up to ~1 mm thick. The threshold can be set high enough to essentially suppress all of the noise and still respond efficiently to inputs as low as a single x-ray photon or a minimum ionizing cosmic ray muon. For example, when using a 700-μm-thick Si detector layer, the layer thickness is ~13 times the pixel pitch. When a penetrating heavy ion traverses the Si and produces a core of charge carriers surrounded by a halo of carriers associated with the track structure δ-rays, the diffusion of the collected charge by the time it reaches the Medipix2 pixels is generally cone-shaped. In this scenario, the charge from the most distant part of the track is the widest-disbursed, while that from the nearest pixel contact remains closest to the track itself (Figure 4). Models of this diffusion predict—and measurements affirm[2]—that the result is an analog-amplified picture (albeit not linear) of the track structure cross-section.

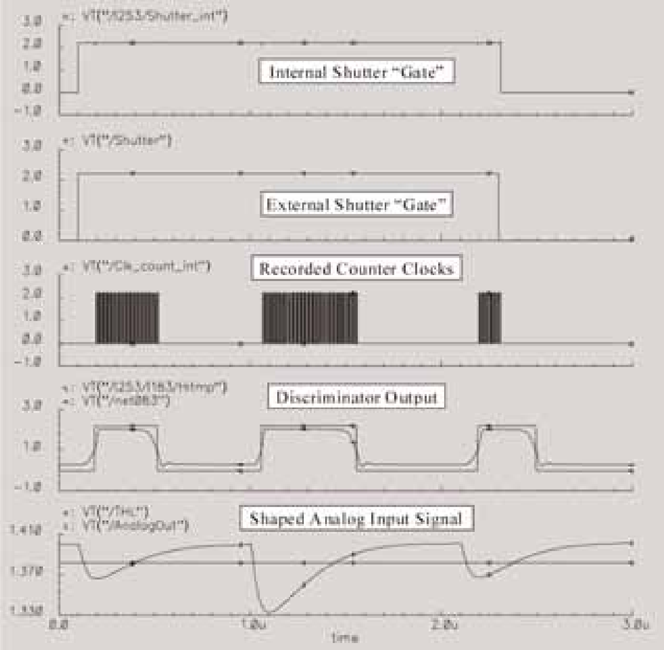

Figure 3. The functional timing diagram of the electronic circuitry within each TimePix pixel in the time-over-threshold mode. When the shaped analog input signal is above the universally set threshold, the counter clock pulses are sent to the output shift register. So the value stored in each output shift register is the number of counter clock pulses that occurred while the shaped input signal was above the threshold. Assuming only one input pulse occurs, then the output will be proportional to the total charge in that pulse.

Figure 5 shows a TimePix frame taken in January 2008 at the Heavy-ion Medical Accelerator Complex (HIMAC) at the National Institute of Radiological Sciences in Chiba, Japan. The frame shows a normally incident ^{10}B beam at 290 MeV/A and a blow-up of several of the track images. The software uses a color scale to indicate the charge count in each pixel. The raw data file, of course, contains the exact individual counts for each pixel. Prior data taken with an earlier version of the Medipix2 chip has indicated a sensitivity that will enable a charge resolution of better than one charge for all nuclei, and even isotopic resolution for some cases. The individual pixels that appear as background spots in Figure 5a are actually individual photons from de-excitations and the decay of radioactive fragments in the detector itself, as well as in the surrounding material, due to the passage of earlier beam particles. These data were taken with a 300 μm Si detector layer that was bump-bonded to the underlying Medipix2 TimePix chip.

The program proposed in the SBIR submission called for the assistance of Nano EnerTex, Inc., in depositing detector layers directly on the Medipix2 wafer without employing the solder bump-bonding technique. This also will allow researchers to investigate alternative layer materials such as GaN, including composites of interlaced detector and neutron converter materials and the nominal configurations with silicon topped with conventional materials.

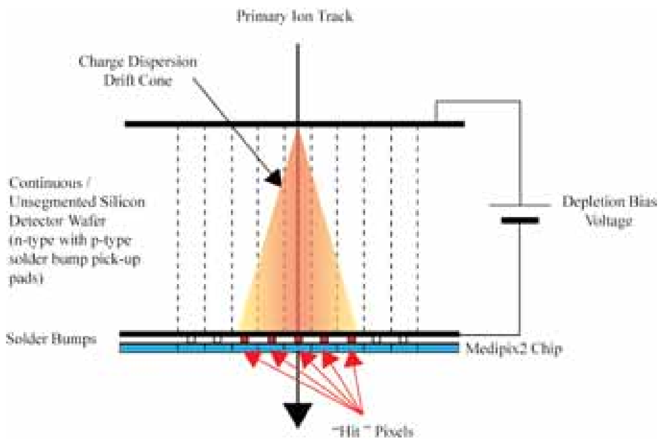

Figure 4. A schematic view of the formation of a pixel image of the track structure of an incident traversing charged particle. The "drift cone" of charge is dependent on the LET and the track structure of the particle, and the "footprint" of the image on the pixels is, in general, distributed in a conic section depending upon the angle of incidence of the particle. Upward-moving particles will yield very slightly modified "footprints," depending upon their energy.

Previous exposures at the M.D. Anderson Proton Therapy Center with an earlier version of the Medipix2 detector have demonstrated the capability to clearly distinguish individual protons at relatively intense fluences and with energies comparable to those expected in SPEs. While the analysis is ongoing, preliminary evaluations indicate an excellent potential capability in the TimePix mode to resolve proton energy differences below a few hundred MeV. Figure 6 shows single frames from the proton therapy beam at 219 MeV and at 72.5 MeV for comparison, along with a frame taken with an ^{241}Am (~5.5 MeV) α source as an example of the raw resolution capability for these crucial components of SPEs in the Medipix2 base mode. These frames show only the pixels that had charge collection values between two adjustable thresholds. Figures 6a and 6b also illustrate examples of the benefit of being able to adjust the shutter exposure time window width to control the frame occupancy hit density. Note that the beam passed through an upstream moderator in each case, and as such there was a gamma contamination, which is clearly noticeable as the intermingled single pixel "hits." These frames were taken using only the single lower threshold. Threshold scans verified that when using the full TimePix mode, the proton LET resolution should be limited only by the inherent Landau fluctuations in the Si.

The α particles in Figure 6c appear as annular "doughnuts" because the "two-threshold" mode was employed. Again, the single pixels are from the 59.5 KeV γ-rays emitted by the ^{241}Am source. Threshold scans have confirmed that in the full TimePix mode, the separation of α's from p events should be easily attainable for any SPEs.

Besides having the ability to accurately measure the proton and heavy ion contributions to the radiation field, as noted, these detectors have been shown to be effective neutron detectors as well. One can use the same general design for neutron detection by the introduction of a layer of appropriate neutron converter material over or within the Si detector layer. Material containing ^{6}Li, ^{10}B, or polyethylene has been shown to work with reasonable efficiencies (~5%) as a neutron detector in the typical LEO neutron energy ranges. Statistical energy resolution for neutrons over a wide range of energies using this technique is promising. Recent data taken at CERF are currently being analyzed, along with a number of mono-energetic neutron exposures. Figure 7a shows an example of neutron events with a spectrum similar to that found in a high-altitude Earth atmospheric spectrum as produced at CERF. This is quite similar to the albedo neutron spectrum seen in LEO. Figure 7b is a frame from that same run where a Medipix2-based device with a bare 700 μm Si detector layer was placed inside the CERF production target enclosure in the primary beam just downstream from the production target at the hadron maximum.

While these two images may look similar at first glance, they represent fluences that differ by more than five orders of magnitude. The image in 7b contains the downstream "spray" of all kinds of particles—protons, neutrons, gammas, pions, etc.—that result from the impact of a $\sim 10^{7}$ particles/cm^{2}/s 120 GeV/c mixed hadron (~60% π+ and ~35% p) beam incident on a 50 cm-thick Cu target. Note that this Medipix2-based device ran in that location for an entire eight-hour shift and did not suffer any permanent loss of functioning of any of its > 65,000 pixels. The shutter time was still set four orders of magnitude above the device's minimum. The ability to shift rapidly to short shutter times ensures the ability to function during SPEs.

An ultimate Medipix2-based space radiation dosimeter would most likely be a hybrid device with multiple Medipix2 chips, each of which would be coupled with different detector layers optimized for different components of the space radiation environment.

When it comes to being able to sustain operation during an intense SPE, the Medipix2 technology is already a proven high-rate and high-radiation device. Medipix2 devices have been placed directly in accelerator beams and have performed for hours in those environments. As noted, with a minimum frame shutter as small as 10 ns, the Medipix2 technology has the ability to resolve individual protons at fluxes of up to 10^{11}/cm^{2} s. This exceeds the highest fluxes ever recorded for >10 MeV protons during an SPE. Further, using the full range of the charge collection, a Medipix2-based device could be used to assess the flux during an SPE-like event up to as high as 10^{14}/cm^{2} s. At such high fluxes, the concern would be the radiation-hardness of the supporting electronics rather than that of the Medipix chip itself.

The USB interface can supply the needed power, as well as the bias voltage and the readout connection. This implies that an upper limit to the power needed is within the standard USB power specifications, and the typical laptop is all that is needed to power and read out this configuration. Alternative configurations that have local battery power and also include a wireless interface are possible within the size envelope of today's industrial passive personal radiation badges. For space applications, several such wireless devices could easily be built into EVA suits with minimal physical size, mass, and

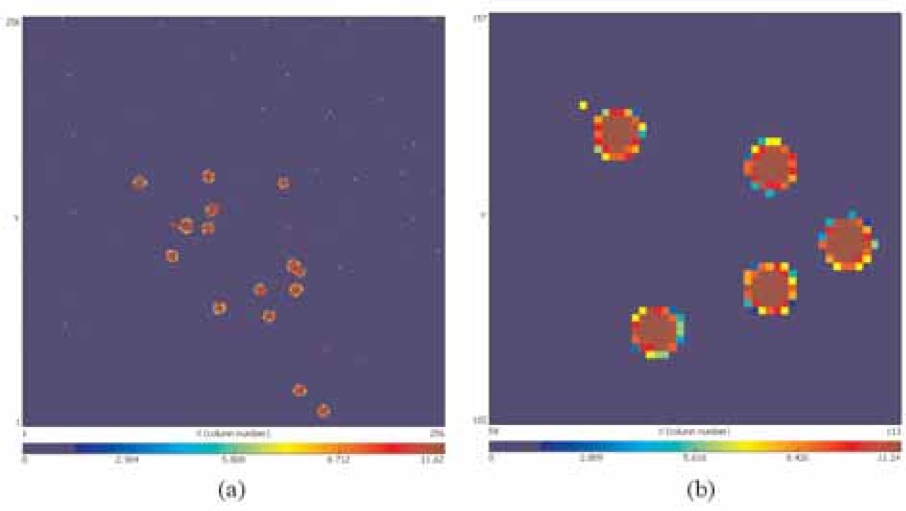

Figure 5. (a) This shows a frame image from an incident Boron-10 heavy ion beam at 290 MeV/A taken at the HIMAC facility in Chiba, Japan, with a TimePix detector at normal incidence to the beam. The shutter gate was set to a short enough time window to limit the number of ions in the frame to a manageable quantity, in order to minimize track image overlaps. (b) Shows an enlarged image of several Boron-10 hits. The color coding represents the counts for each pixel. The high values toward the center of each hit indicate the large amount of charge collected from these highly ionizing traversals of the detector.

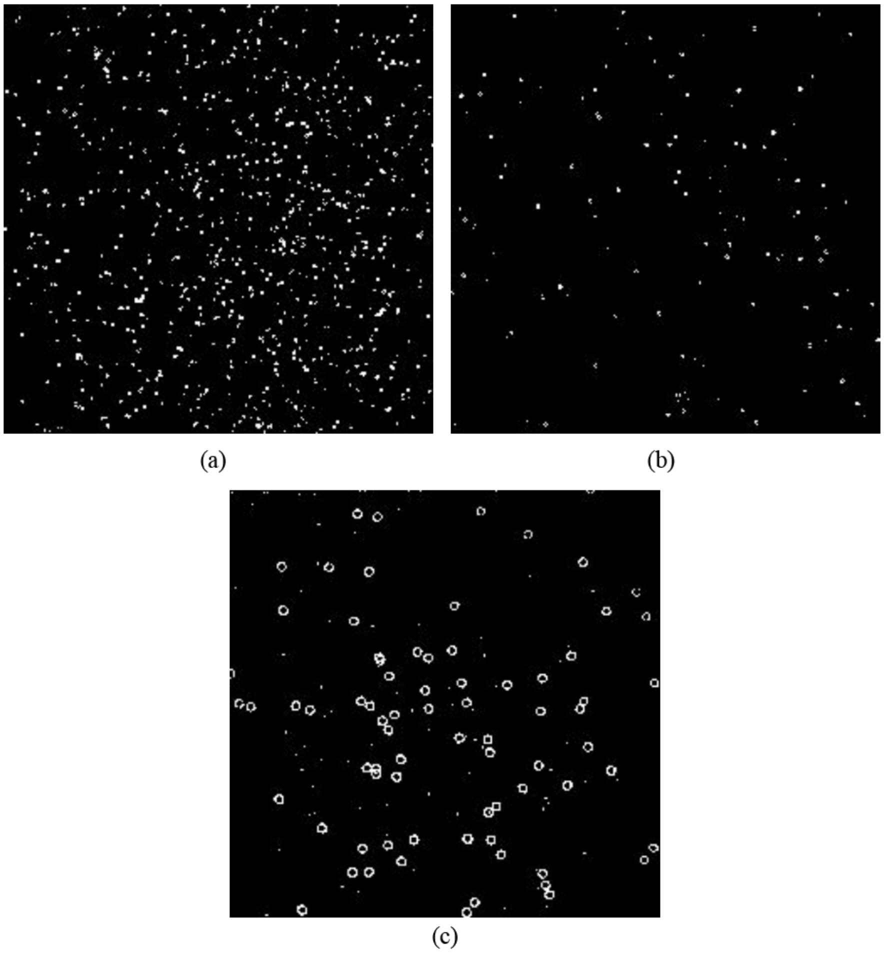

Figure 6. Frames (a) and (b) were both taken at the M.D. Anderson Proton Therapy Center in Houston, Texas. Frame (a) was in a 219 MeV proton therapy beam, and (b) was in a 72.5 MeV beam. The intermingled single pixel “hits” are due to contamination γ-rays from the immediately upstream material in the beams. These data were taken using only a single lower threshold in the Medipix2 base mode. These two frames also provide an example of the benefit of being able to control the frame “hit” density by adjusting the shutter time window width. Frame (c) is from an ^{241}Am α source with the detector in the two-threshold Medipix2 base mode, so that the α particle images appear as annular “doughnuts” where the hole in the middle of each image is actually above both thresholds, the ring being between them. Note, too, the γ-ray hits intermingled with the α particle images.

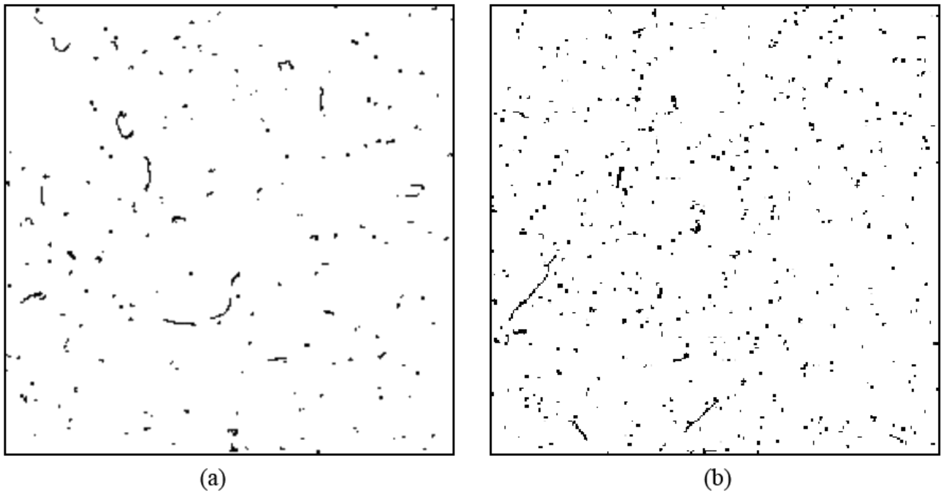
(a) (b)

Figure 7. (a) An example frame from a 1.0-second exposure of a 1.3-mm polyethylene converter over a 700 μm Si detector layer equipped Medipix2-based detector in the CERF neutron reference field (similar to the neutron spectrum seen at high altitudes in the Earth's atmosphere). Essentially all of the "hits" are the result of neutron interactions. (b) A 100 μs frame taken with a bare 700 μm Si detector layer-equipped device deployed behind the production target directly in the 120 GeV/c beam at CERF. This represents at least five to six orders of magnitude greater fluence with respect to the image in (a).

power footprints. These could be deployed with onboard memory and signal processors capable of running the pattern recognition codes developed to minimize the download bandwidth requirements. The power consumption is dominated by the supporting electronics and by actual particle fluence rates in the sense that it is proportional to the charge measured. Typical maximum power draws for "hit" pixels in the Medipix chip itself are in the 5-10 μW/pixel range. If one assumes a reasonable fluence maxima, the upper limit for the Medipix chip is not likely to exceed 100 mW, with normal use being considerably below that value.

SUMMARY

The funding supplied by ISSO led to the creation and submission of a successful proposal to NASA for an initial SBIR grant to pursue the development of techniques for directly depositing detector layers onto the Medipix2 chip. This initial phase is six months in length and has provided the cluster PIs with $100K. The purpose of this funding is to allow the development of a full SBIR proposal in which funding will be sought for formal implementation of the proposed research. That funding would be at the level of $1M/year. That proposal is in preparation at this time.

The Medipix2 technology is a mature technology ready to be adopted to applications such as space radiation dosimetry.

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PUBLICATIONS

Pinsky, L. and Chancellor, J. Status of the development of a new active personal dosimeter for use in space radiation environments. *Proceedings* of the IEEE Aerospace Conference, Big Sky, MT, March 3–10 (2008).

PRESENTATIONS

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FUNDING

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