Application of the Medipix2 Technology to Space Radiation Dosimetry and Hadron Therapy Beam Monitoring

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Abstract

The Medipix2 Collaboration, based at CERN, has developed the TimePix version of the Medipix pixel readout chip, which has the ability to provide either an ADC or TDC capability separately in each of its 256 x 256 pixels. When coupled to a Si detector layer, the device is an excellent candidate for application as an active dosimeter for use in Space Radiation Environments. In order to facilitate such a development, data have been taken with Heavy Ions at the HIMAC facility in Chiba, Japan. In particular, the problem of determining the resolution of such a detector system with respect to heavy ions of differing charges and energies, but with similar dE/dx values has been explored for several ions. The ultimate problem is to parse the information in the pixel "footprint" images from the drift of the charge cloud produced in the detector layer. In addition, with the use of convertor materials, the detector can be used as a neutron detector, and it has been used both as a charged particle and neutron detector to evaluate the detailed properties of the radiation fields produced by hadron therapy beams. New versions of the basic chip design are ongoing.

Key words: Pixel Detectors, Silicon Detectors, SSDs, Medipix, charge drift

1. Introduction

The TimePix version of the Medipix2 detector technology [1] is very attractive as a basis for development of a Space Radiation personal dosimeter or even as part of a general radiation area monitor for use in spacecraft or habitats on the lunar or planetary surfaces. Any such device must be capable of sampling a radiation field that is isotropic in the sense that the incident radiation can come from any direction, and that includes a wide range of energetic charged particles from singly charged through fully ionized Fe nuclei, with the potential to also have a substantial neutron component in some situations. The general properties of a TimePix-based device with a bump-bonded Silicon detector attached have been described previously. [2]

Briefly, the TimePix is a version of the technology developed by the Medipix2 Collaboration, which is based at CERN. It is a pixel-based CMOS ASIC wherein the electronics for each of the individual 55 $\mu\,m$ square pixels is contained within the footprint of that pixel. The TimePix is distinguished from other Medipix2 versions in that after the charge-sensitive pre-amp in the front end, it possesses single discriminator whose input is delivered to a logic unit capable of being employed in one of several different modes. These modes include functioning as a simple counter for the number of times that the (externally applied common) discriminator threshold value has been exceeded (Medipix mode), as a Time to Digital Convertor (TDC) or for the application described here, similar to a Wilkinson-type (Time Over Threshold) Analog to Digital Converter ADC. The device is activated in all modes by the application of a common gate input, termed the "shutter." Each pixel has its own 14-bit shift register configured as a pseudo-random counter for data storage and transfer.

The TimePix input stage is agnostic in the sense that it accepts either positive or negative inputs and can be attached to any acceptable overlying detector input. For application to the problem of measuring the properties of the radiation field in a typical space radiation environment or in a charged particle therapy beam, a simple reverse-biased Si detector layer works as well as any alternative. This is because, as noted, the dominant components of that environment are very energetic charged particles. The Si itself is not a very good neutron detector, but when coupled with converter materials such as ^{6}Li for thermal neutrons or H for more energetic neutrons, the Si can detect the resulting ionization from the charged products produced. [7] In the versions used for the measurements reported here the detector is generally bulk n-type Si, with embedded p-type Si pads arranged to correspond to the ASIC pixel input pad connection locations. The contact between the Si detector pads and ASIC pixel inputs is accomplished through the use of the Flip-Chip bump-bonding technology. The Si detector in the measurement discussed here was nominally 300 $\mu\,m$ thick.

Currently, a robust USB interface with associated software [8] [9] that both supplies the power and HV as well as reads out the data from the chip is available, making the use of the device very convenient.

2. Charged Particle Tracks

The primary particles of interest in applications like space radiation dosimetry and hadron therapy beam monitoring are energetic charged particles. With the increasing popularity of using heavy ion beams for therapy applications, both applications require a detector that has the dynamic range to measure the properties of incident heavy ions while still being able to adequately accommodate minimum ionizing particles. For dosimetry applications current dosimetric endpoints such as dose-equivalent are dependent upon the Linear Energy Transfer (LET) by the ion to the tissue it traverses. Given the ability of a TimePix-based device with a Si detector layer to measure the total deposited charge [3] and to simultaneously estimate the angle of incidence to within a few degrees [4] the LET can be directly calculated. While this will certainly allow the measurement of the dose-equivalent in the dosimeter itself, a more interesting capability is to be able to characterize the nature of the radiation field as precisely as possible so that one can predict what the depth dose to tissues deep within the body will be and in addition to be robust in the sense that any future re-definitions of dosimetric endpoints can be easily accommodated.

In order to characterize the nature of the radiation field, at least as far as incident charged particles are concerned, one needs to be able to bin the results in terms of the charge of the incident particles and their energy spectrum. This presents a significant challenge for a single thin detector layer, as measurement of the change in energy loss rates in not possible for any but the very slowest incident particles, and momentum analyses in a magnetic field are impractical. However, for the range of particles from minimum ionizing down in energy, the ability to observe details of the track structure, specifically to obtain detailed information about the δ-ray spectrum, provides a potential mechanism by which the particles can be accurately binned in energy and charge. The exact resolution capabilities of a Si-detector TimePix device is a function of the incident angle and of the thickness of the Si detector layer as well as of individual device settings such as the choice of bias voltage, etc. The data described here has shed some initial preliminary light on these issues, but some interesting properties of the physics and the combined detector response to these heavily ionizing particles have made the development of an accurate model of the charge-cloud drift in the Si and the underlying ASIC response characteristics to it more complex than first thought.

Fig. **??** presents the images of two tracks, both of which have the same total energy deposited. They are from 100 MeV/A O and 600 MeV/A Si. The different velocity distributions of the δ-rays produced by these particles causes the pixel cluster distributions to be slightly different. Detailed fits to these shapes and the identification of the associated long-range δ-rays for the higher energy tracks provides a potential to resolve the energies and charges of these tracks within reasonably relevant bins for dosimetry purposes. Fig. **??** presents the extreme case of very high angle of incidence (85 degree) energetic (800 MeV/A) Si tracks. Note the δ-ray fields from each of the tracks, which are from particles moving from left to right, and the presence of δ-rays emanating back into the detector layer from the passage of the particle through the material in the underlying chip itself. Note also the presence of several recoils from apparent nuclear interactions. This detector has the capability to function as a virtual active nuclear emulsion-equivalent. [10]

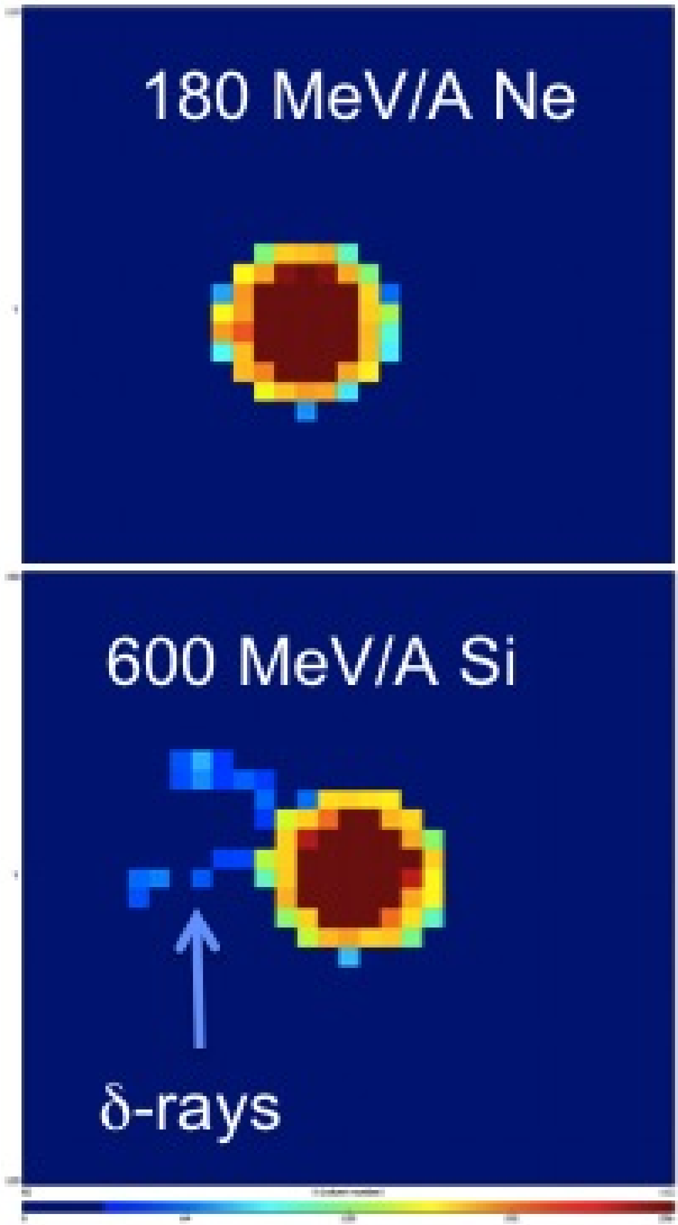

Figure 1: Tracks from normally incident O @ 100 MeV/A and Si @ 600 MeV/A, both having the same total energy deposited in the detector medium. Note the δ-ray field around the Si track.

3. Saturation Effects

Fig. 3 shows the summed cluster shape for ˜ 5000 tracks from 500 MeV/A Fe particles normally incident on the detector. All reasonable charge diffusion models give predictions that such a distribution should be smoothly centrally peaked. The very visible dip in the center of the distribution is also accompanied by a net 1̃0% deficiency in the total volume, which is a measure of

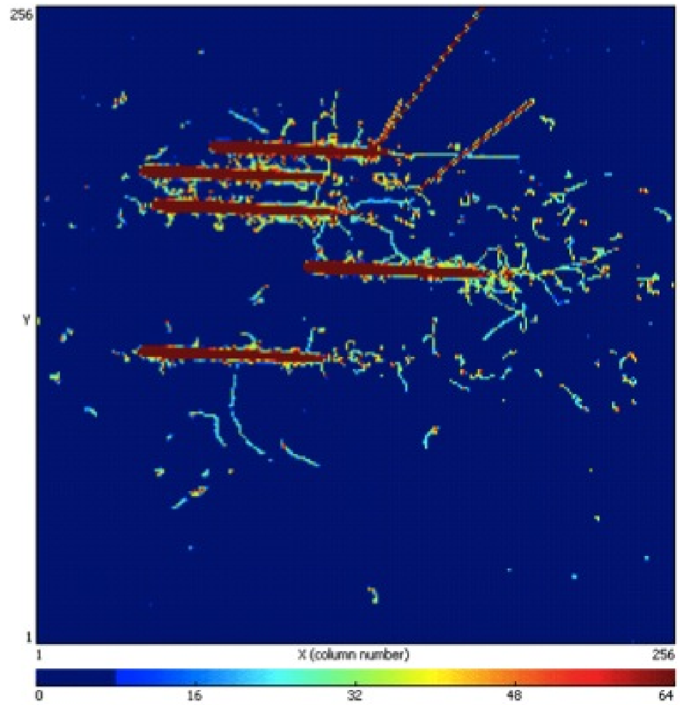

Figure 2: Tracks from Si @ 800 MeV/A and 85 degree incidence. Note the extensive δ-ray presence and the apparent nuclear interactions. This capability is similar to an active nuclear emulsion.

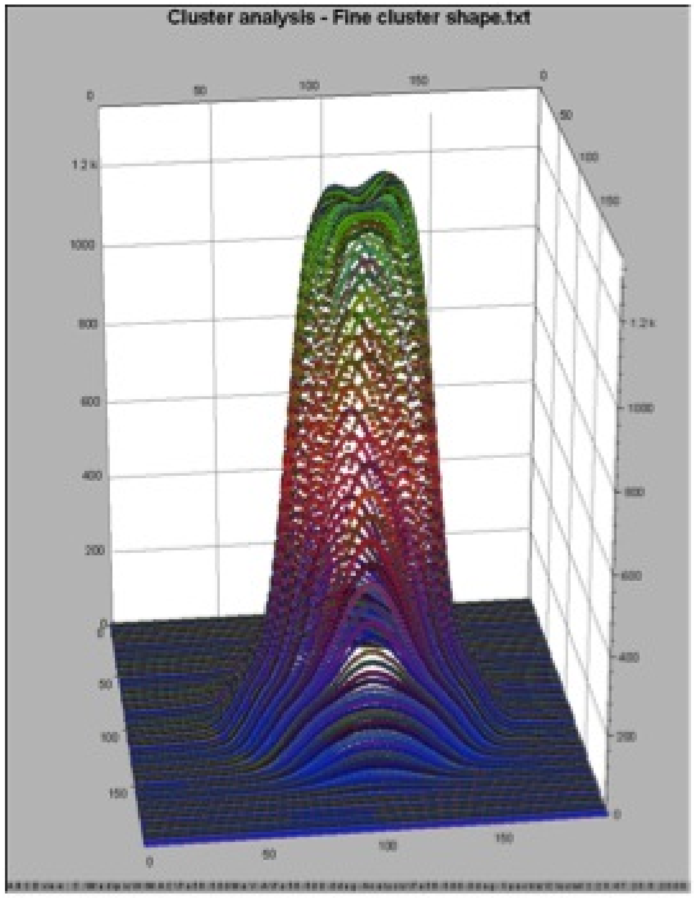

Figure 3: The shape of Fe @ 500 MeV/A for almost normally incident tracks summed over > 5000 events. Note the deficiency in the central-most region.

the total energy collected when compared to Monte Carlo predictions. These two observations suggest that the charge, which should have been present in the central region was somehow lost. There are two possible explanations that we have focussed on. The first is a saturation effect in the electronics. There is evidence that the response curve as a function of the charge collected in a given pixel changes its slope abruptly when the energy deposited in the Si detector layer contributing to that charge reaches the order of 1 MeV. Measurements of fission fragments with this same type of detector have also presented similar indications of saturation effects, which become dominant at levels around 2 MeV deposited in the detector. [5]

A further argument for saturation effects are the observation of “ghost” tracks. That is the high charge cores of tracks that have actually occurred prior to the opening of the shutter seem to be overly persistent. The discriminator will function independently of the shutter, so that if the discriminator is “high” when the shutter opens, the counter will begin counting immediately. However, if there were no electronic saturation effects, then one would expect to see “ghost” tracks with a distribution of cuts through the nominal track images. The non-linear bias in the appearance of the central core regions argues for some other effect to enhance their persistence.

An alternative, and in all likelihood a coincident effect at some level, is the prospect of increased recombination during the time the charge is drifting in the Si detector layer. For vertical tracks, where the electric field from the bias voltage is parallel to the track direction, the cloud of electrons and holes along the track will have to drift directly through each other on their way to the the anode and cathode. For heavy ions, the charge density in the central-most region of the track can create a plasma effect.[6] In effect, the creation of such high electron and hole densities in the same region can lead to a considerable recombination effect.

Fig. 4 shows a portion of the output from exposures of one of the 500 MeV/A Fe beam images. Note that the central charge densities at the core of these tracks will be far higher than those necessary to create the plasma effect. The track to the upper right is a normal track, showing evidence of the central deficiency noted in Fig. 3. The cluster to the lower left, however, is very unusual. The supposition is that this is a image from a track which occurred near the end of the shutter signal, and the shutter terminated the Time-Over-Threshold counting in all of the pixels prior to its completion and very probably prior to the completion of the charge collection process from the detector layer. The dramatic feature of this image is the lack of any counts in the central-most region. The discriminators for the pixels in that region apparently were never above threshold during the time the shutter was open. If this is the case, then this may be evidence for virtually total recombination in the earliest times during the drifting in the bias field. As the charge cloud diffuses the, the plasma effect will subside and the charge from immediately outside of this region will tend to backfill the central region, leaving it with the filled in shape seen in Fig. 3. Explanations of this event incorporating purely saturation effects is difficult, especially since the deficiency is not pronounced for tracks with significantly non-normal incident angles. In cases of higher incident angles the bias voltage field will tend to separate the electrons and holes rather than drifting them through one and other.

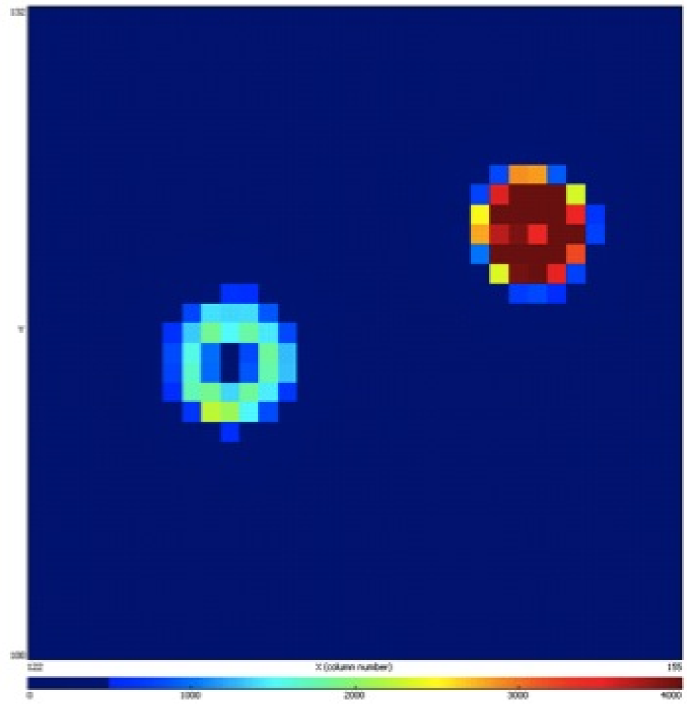

Figure 4: Two Fe @ 500 MeV/A normal incidence events. The upper righthand event is a normal event and the lower lefthand one is exceedingly unusual.

3.1. Conclusions

The TimePix version of the Medipix2 technology has proven itself to be an exceptional device for use in characterizing widely varying radiation fields, especially those containing heavy ions like space radiation and hadron therapy beams. The issues identified with respect to saturation can be accounted for with correction factors and future generations of this technology should be modifiable to overcome those aspects that are shown to be hardware-related.

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