An Update on Medipix in Space and Future Plans (Medipix2, 3 & 4)

L. Pinsky[a] , T. Campbell-Ricketts[a], A. Empl[a], S. George[a], L. Tlustos[a], D. Turecek[a], D. Fry[b], M. Kroupa[b], R. Rios[b], E. Semones[b], N. Stoffle[b], S. Wheeler[b], C. Zeitlin[b]
H. Kitamura[c], & S. Kodaira[c]

[a]University of Houston, 77204 Houston, TX, USA
[b]NASA, 77058 Houston, TX, USA
[c]HIMAC, QST-NIRS, 4-9-1 Anagawa, Inage-Ku, Chiba-Shi 263-8555, Japan

pinsky@uh.edu

Abstract

Medipix technology in the form of Timepix chips from the Medipix2 Collaboration have been in continuous operation in LEO (Low Earth Orbit) externally (in vacuum) on satellites and internally within the ISS for over three and half years. To date no failures of the Timepix chips themselves have occurred during any of the more than 30 combined exposure-years, although there have been a few minor failures in the supporting electronics. These exposures include numerous single devices powered and readout via ISS onboard laptops, self-contained battery-powered units on the first test of NASA's new Orion MPCV during the EFT-1 flight, as well is dedicated satellite based devices including the 5-chip LUCID (Langton Ultimate Cosmic-ray Intensity Detector) device on the UK's TechDemoSat mission. A summary of the functional information and the data gathered from these missions are presented along with the recent evaluation of n-in-p Si sensors on both Timepix and Timepix3 chips in comparison with the baseline results using the nominal p-in-n Si sensors.

Future plans include flying additional single units as radiation monitors inside the ISS and the upcoming test of the inflatable Bigelow Expandable Activity Module (BEAM) module as well as deploying a multiple Timepix stack to evaluate its potential to improve incident particle ID capability. In the longer term the primary charged particle radiation monitors to be flown on the next few flights of the Orion, called the HERA (Hybrid Electronic Radiation Assessor), is undergoing the final verification process. Evaluation of the Data-Driven Timepix3 from the Medipix3 Collaboration is underway as well, and it will be used in the verification process for the frame based Timepix and Timepix2-based devices from the Medipix2 Collaboration. The Timepix2 is in the final design process at CERN, and will be evaluated for replacement in the HERA hardware for eventual operational Orion missions. The Medipix4 Collaboration has just formed and is in the process of developing the design concept for the Timepix4 chip. The University of Houston, with support from NASA and the University, is one of the founding members of the Medipix4 Collaboration, which will hopefully ultimately provide the basis for future long term radiation monitoring and active personal dosimeter devices.

Table 1: Medipix Chips, Past, Present and Future. (P.C. =(Photon Counting, and * = Not yet available). Note only the final versions in the development of each chip line are listed.

Name	**# & Pixel size/ CMOS Tech.**	**Modes**	**Read-Out**
Medipix1			
Medipix1	64 x 64 170μm/ ~1μm IBM	P.C.	Frame
Medipix2			
Medipix2	256x256 55μm/ 250nm IBM	2 Threshold P.C.	Frame
Timepix	256x256 55μm/ 250nm IBM	TOT, TOA or P.C.	Frame
Timepix2*	256x256 55μm/ 13nm TSMC	TOT+TOA or P.C.	Frame
Medipix3			
Medipix3RX	256x256 55μm 128x128 110μm/ 130nm IBM	2 Threshold P.C. 4 Threshold P.C.	Frame 2 Regis
Timepix3	256x256 55μm/ 130nm IBM	TOT+TOA or Continuous PC	Frame or Data Driven
Medipix4			
Medipix4*	TBD/ (65nm TSMC)*	TBD	Frame or Data Driven
Timepix4*	TBD (65nm TSMC)*	TBD	Frame or Data Driven

I. The Medipix Collaborations

The sequence of CERN-based Medipix Collaborations had their start with the initial efforts of Michael Campbell, Eric Heijne, Walter Snoeys and others in the in the early 1990's using the experience from the RD19 Collaboration and earlier efforts in the development of radiation sensing pixel detectors[1], [2], [3] [4]. The constant design characteristic of all of the Medipix Collaborations has been the employment of the hybrid design whereby the readout chip and the overlaying sensor volume were separate, typically connected using the Flip-Chip® "solder-bump bonding technology [5]. The Medipix2 Collaboration formed in the late 1990's, and set the tone for the subsequent incarnations in the sequence. Each Medipix Collaboration is an aggregation of member institutions that each pay an initially set collaboration fee to join, with that initial infusion of funding sustaining the collaborations activities until supplemented by royalties from the licensing of their products. The membership is only partially overlapping, as are the associated access rights to the products of each collaboration. Medipix3 formed in 2006 and Medipix4 has just formed in late 2015. The three latter Collaborations are all still active. Table 1 lists the chips produced by each collaboration and their essential design characteristics. All of the past and present space flight units have been based on the Timepix chip from the Medipix2 collaboration. Bare Timepix assemblies and various control and readout interfaces have been licensed to a number of vendors for sale to the public along with licenses to sell the Medipix2 chip by the Medipix2 collaboration. The Medipix3 collaboration have licensed distribution Medipix3RX chips and at some point in the not too distant future, they will likely license the distribution of the Timepix3.

II. The Medipix2 Timepix Chip

The Timepix chips contain 256 x 256 pixels, each 55 µm on a side, providing an effective area of the chip that is 1.982 cm2 [6]. The full chip is 16.120 x 14.111 mm, which includes a service area on one side of the chip that contains 127 input/output wire-bond pads for control, readout and power. Each pixel contains the circuitry within its footprint to digitize the output. As such, only digital data is transferred out of the pixels, unlike CCDs and monolithic CMOS detectors. The input to each pixel is through a conducting solder pad on the upper surface of the chip.

To fabricate a charged particle detector employing a Timepix, one must attach a semiconductor sensor to the top surface of the pixels as shown in Figure 1. Different sensor materials may be used for various applications, but for charged particle detection, silicon is the semiconductor of choice. Sensors with thicknesses from 50 µm to 1.0 mm have been fabricated; with 300 and 500 µm thick sensors used on the ISS REM units, and exclusively 500 µm thick sensors employed on all additional NASA projects to date. The sensors are fabricated so that the bulk volume is doped as either p-type or n-type, with opposite doping implants on the lower surface. The REM units employ bulk n-type sensors. The implants are in contact with conducting solder pads on the lower surface of the sensor, which allows the bulk sensor volume to be reverse-biased to deplete it of free charge carriers. As noted previously, the sensor is attached to the Timepix chip using the FlipChip® solder-bump technology. The bias voltage also serves to collect any free electron-hole pairs created by the passage of charged particles in the sensor volume. The presence of free charges in the sensor volume causes images charges to appear on the sensor's solder pad. The return path for the bias voltage runs through the solder-bump and the pixel's analog front-end circuitry. Thus the current induced in the solder bumps by the formation of the image charges is amplified and shaped by the analog front-end circuitry in each pixel. The current flow created in the front-end electronics is generally proportional to the energy deposited in the sensor volume, and the digital portion of each pixel digitizes that value for readout. The digital section of each pixel can be set to function as a charge-summing Wilkinson-type Analog-to-Digital-Convertor (ADC) using the Time-Over-Threshold (TOT) technique where the time is referenced to an external clock signal with a maximum frequency of 100 MHz.

In operation, the Timepix is controlled by providing discrete inputs to the internal Digital-to-Analog-Convertors (DACs) to set various working parameters such as the threshold to suppress noise. In addition, data-taking is activated by providing an external gate or "shutter" signal. This shutter can be set to a very wide range of time values from microseconds to minutes or more. As a practical matter for measuring the energy deposited by charged particles, the minimum shutter time should be an order of magnitude or two longer than the longest anticipated digitization time using the TOT method, which for space radiation situations is on the order of a millisecond. The Timepix and related devices produced by the Medipix2 Collaboration are also capable of being configured to measure the properties of the incident neutron flux[7],[8],[9], but this paper will focus solely on the detection and measurements of incident charged particles. Each detector in use has been individually calibrated pixel-by-pixel to yield an accurate correlation between the TOT counts recorded and the energy deposited in the sensor volume that was responsible for that pixel's response [10].

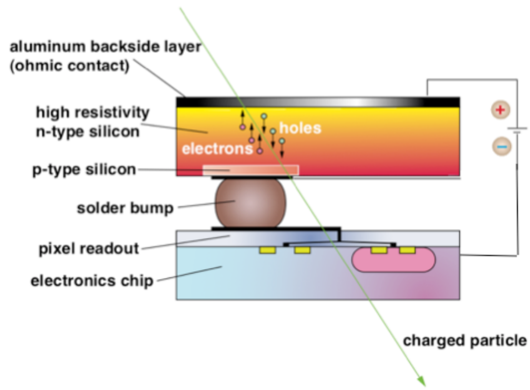

Figure 1: Timepix Hybrid Assembly. Each pixel in the underlying chip is connected to a bulk semiconductor sensor through a solder-bump as shown. The bulk sensor volume is separated from the sensor's ohmic contact with an opposite polarity doped implant to allow the formation of a p-n junction in the sensor for each pixel. (Courtesy of the Medipix2 Collaboration)

Generally speaking, the cluster of pixels produced by a penetrating charged particle has a clearly defined core of contiguous pixels that can be geometrically identified [11], [12], [13]. For slower particles (e.g. protons, He and heavier ions with kinetic energies below a few hundred MeV/u) there are rarely any disconnected pixels. However, for higher velocity particles, the production of δ-rays can lead to geometrically discontiguous pixels. With low occupancy frames, the association of these separated pixels can be recovered, but in busier frames such correlations can become ambiguous.

II. The Medipix3 Timepix3 Chip

The Timepix3 chip[14] is still in the evaluation phase of its development, and has not yet been deployed in space. It differs from the Timepix in a number of important characteristics. Although it has the same pixel size and number as the Timepix, and can be operated in a "Frame" mode with summing TOT measurements in each pixel for the duration of the frame's live time, one of its primary distinguishing capabilities is to be operated in a "Data-Driven" mode. For readout purposes, the individual pixels are ganged into super-pixels of 4 by 4 pixels in adjacent columns. The readout path runs down to the output buss between every other column of pixels with a token passing along the super-pixel interface every 40ns. If data are present in a super-pixel, the token shifts out the contents of that super-pixel, which are added to the serial stream being continuously readout from the chip. With an appropriately fast interface, this mechanism will support the recovery of all data without significant loss for random hits on the pixel matrix up to ~81 MHz. Compact USB 3.0 based interfaces have been demonstrated to function at rates of up to half that value.

Another major difference between the Timepix and Timepix3 is the addition of a "Time-Of-Arrival" (TOA) recording by each pixel of the time of threshold crossing to an accuracy of ~1.6 ns. This is accomplished by giving each pixel access to a global 40 MHz clock and a local 4-bit high-speed divider in each pixel to enable recording of the TOA to the stated accuracy. This data is included with the TOT in the output stream.

This Data-Driven output capability comes at the cost of increased power consumption with respect to the Timepix when the interface electronics power consumption is included. Currently, the available Timepix3 USB interfaces power requirements slightly exceed the capability of typical laptop USB powering ability and require external power supplies. One can, of course operate the Timepix3 in the Frame mode to reduce the power consumption and still take advantage of first-hit TOA information. Plans by the Medipix2 Collaboration to produce a Timepix2 replacement for the current Timepix will be close to a "plug-&-play" replacement from the control standpoint, but it include the addition of the TOA capability in several operating modes. Full details of this addition to the Medipix2 family will be forthcoming from the Medipix2 Collaboration.

III. Present and Planned Timepix Deployments In Space

Table 2 lists the present and future planned deployment in space[15], [16], [17] [18]. It is important to note that while some of the COTS ("Commercial Off The Shelf") interfaces that were employed in the first uses in space did suffer some long term parts failures, post failure analysis has determined that none of these failures were due to the Timepix chip itself. In all cases where the Timepix chips have been recovered after up to 3 years in space (in LEO), no measurable degradation of performance has been observed. This level of robustness has encouraged NASA to proceed to plan future on-board active radiation monitoring based on the continuing Medipix technology. To date, Timepix devices have been deployed in vacuum in polar orbits (LUCID and SATRAM) as well as internally in manned spacecraft (ISS and Orion/MPCV) in various orbits, with the EFT-1 mission penetrating the more intense regions of the Earth's trapped radiation [15]. Further, multiple exposures of Timepix devices for hours in intense heavy ion accelerator beams over several years has continually built confidence in the ability of these chips to operate successfully in the harshest of radiation environments. One recent test of a Timepix3 detector was demonstrated in a sustained proton beam flux of > 4 x 10^5 /cm^2 s without loss of data or any perceived damage.

IV. Acknowledgments

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V. References

All bibliographical references should be numbered and listed at the end of the paper in a section called "REFERENCES". When referring to a reference in the text, place the corresponding reference number in square brackets [1], [2], [3], etc...

Example:

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Table 2: Summary Past, Present and Planned Medipix deployments in Space

Mission/Project Launch Date	Agency (Country)	Number of Timepix Detectors	Exposure Time In Space to Date	Timepix Failures to Date	Orbital Parameters (altitude/Inclination)
ISS/REM Aug. 2012	NASA	7 total	Max time chip 3 yre 10 months	0	~400 km/ 51°
ProbaV-SATRAM May, 2013	ESA	1	3 yrs 1 month	0	820 km/96° Sun Sync.
TechDemoSat/LUCID July 2014	(UK)	5	1 yr 11 months	0	500 km/98° Sun Sync.
MPCV-EFT-1/BIRD Dec. 2014	NASA	2	~4 hours	0	400-5910 km/28.6°
RISESat/Timepix (2016)	JAXA (Japan)	1	TBD	TBD	~700 km/Sun Sync.
ISS/JSC X-Project (2017)	NASA	2	TBD	TBD	~400 km/ 51°
Biosentinel/HERA (EM-1)	NASA	1	TBD	TBD	Parasitic EM-1 Payload
MPCV-EM-1/HERA (2020)	NASA	3-5	TBD (2-3 Weeks)	TBD	Trans-Lunar
MPCV-EM-2/HERA (2022)	NASA	3-5 (Timepix2 or Timepix4?)	(2-3 Weeks)	TBD	Trams-Lunar