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Current Status of the Medipix2, Timepix, Medipix3 and Timepix2 Pixel Readout Chips

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These proceedings describe the current status of the Medipix family of pixel readout chips. The current chips, Medipix2, Timepix and Medipix3 are described and their applications briefly summarised. A future readout chip Timepix2 is also discussed and two possible implementations are explored.

The Medipix2 and Timepix chips have allowed a wide variety of fields to access hybrid pixel technology where it would otherwise have not been financially viable. This has lead to a very broad range of applications, including material analysis, medical imaging, sensor development, dosimitry, neutron monitoring and education. The success and maturity of the technology has also led to the chips being used to develop future systems within HEP, particularly the future LHCb pixel vertex tracker.

The move to 0.13μm CMOS technology for Medipix3 has provided many benefits in terms of functionality and radiation tolerance but has also produced some unexpected difficulties which are being addressed. It is hoped to continue using this technology within the Medipix3 collaboration to develop Timepix2, a device targeted towards the simultaneous readout of analogue and fast timing information.

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1. Introduction

The development of the Medipix family of chips has been motivated by the desire to provide research communities beyond High Energy Physics (HEP) with access to the hybrid active pixel detectors developed for particle tracking systems. These devices combine fast, high resolution imaging of ionising radiation with a noise free operation that makes them very attractive in many fields. The Medipix2 and Medipix3 collaborations encompass a wide range of disciplines including medical imaging, materials analysis, bio-imaging, astronomy, dosimetry and particle physics. The Medipix devices themselves provide pixilated readout for a variety of sensor systems, either bump bonded to a solid state sensor to form a hybrid, or directly collecting electrons from gas or micro channel amplification systems.

This proceeding also reports on the status of the development of the new Medipix3 spectroscopic imaging chip which is undergoing evaluation and testing as well as plans for a new Timepix2 device that is currently under discussion. Medipix3 is designed to perform high rate multi spectral imaging and to overcome the charge sharing limitations to the spectral resolution.

2. Medipix2 and Timepix

Medipix2 [1] and Timepix [2] are the current generation of readout chips developed by the Medipix2 collaboration. They share a similar architecture and are fabricated in the IBM 0.25μm CMOS process. Both chips have a 256 by 256 matrix of 55μm square pixels and are three side tileable with an inactive readout periphery 2mm deep on the fourth edge.

Medipix2 was originally conceived as a photon counting, X-ray imaging detector that would make use of the active pixel device's superior noise performance over charge integrating systems. Medipix2 is driven by an external shutter signal that determines whether the pixel matrix is taking data or reading out. When the shutter is open the pixels individually count the number of incident particle to pass a threshold. When the shutter is closed the matrix is read out as a shift register. Each pixel contains separate analogue and digital circuitry that amplify the signal, apply one or two thresholds and provides a 14 bit pseudo-random counter. The pixel also contains test circuitry and a four bit threshold trimming system to compensate for variations in fabrication. This allows an accurate global threshold to be applied with an overall variation of just 95e^-. The small pixel size and low power of the system contribute to a low electronics noise per channel of 110e^-rms, this combined with the equalised threshold variation means a minimum detectable charge of 900$e^-$is possible. The pixels have an instantaneous dead time of up to a microsecond and so the chip is able to sustain a counting rate of up to 300kHz per pixel. Medipix2 also incorporates a second threshold level to allow an energy windowing mode to demonstrate the utility of multi-spectral medical imaging.

The Timepix chip was derived from Medipix2 at the request of, and supported by, the EUDET collaboration. Its layout and operation are largely similar, although the second threshold of Medipix2 has been removed and replaced with a clock that can be propagated to every pixel. The presence of the clock allows two new modes of operation to be implemented alongside a particle counting mode similar to that in Medipix2. These two modes, designated Time over Threshold (ToT) and Time of Arrival (ToA), provide a measurement of the charge deposited in the pixel and the time at which the pixel was hit respectively. Individual pixels within the matrix can be separately programmed to operate in any of these three modes. The ToT mode uses the clock and counter to determine the time the amplifier pulse has been over threshold, as this pulse is essentially triangular the value counted is, to first order, linearly proportional to the energy deposited. The ToA mode measures the time between the first particle's arrival in the pixel and the shutter closing. The electronic noise in the pixel is slightly lower than Medipix2 at $100e^{-}$rms, the threshold variation after trimming is only $35e^{-}$and the minimum detectable signal on all pixels is $650e^{-}$.

3. Overview of Current Applications

The versatility of the Medipix2 and Timepix chips has lead to them being adopted in a very wide variety of applications, in both the academic and commercial sectors. In particular Medpix2 has been successfully commercialised by PANalytical, who produce an X-ray diffractometer for materials analysis that uses Medipix2 as the principal imaging system. Several additional commercial partnerships are planned in the fields of X-ray imaging and education. Timepix, has not yet been adopted for a commercial purpose but is used in a variety of research applications.

3.1 X-Ray Imaging

The Medipix2 design was primarily targeted at the development of noise free, high dynamic range X-ray imaging, and this field has found the broadest range of applications. PANalytical, (Almelo, NL) have based their X'Pert [3] X-Ray Diffraction (XRD) materials analysis suite around the detector, primarily due to the high dynamic range offered. Phase contrast imaging with micro-focus X-ray tubes [4] have made significant use of the ability of Medipix2 to use very low rates to provide very clear images of biological structures. The high dynamic range has allowed the chips to operate in environments such as Computed Tomography (CT) and Micro-CT[5] where very high rates are encountered. In the field of medical imaging the chips have been used as prototype digital readouts for mammography [6], dental imaging [7], and multi-spectral CT imaging. Multi-spectral imaging will be discussed further in section 4.1.

3.2 Electron Microscopy

Recent work has demonstrated the effectiveness of Medipix2 silicon detector assemblies in electron cryo-microscopy [8] and in Low Energy Electron Microscopy (LEEM) [9]. In LEEM applications it is possible to simply replace the conventional Micro-Channel Plate (MCP) and CCD imaging system with a Medipix2 assembly and produce images of a significantly improved quality, as shown in Figure 1. This is again due to the low noise and high dynamic range of the Medipix2.

3.3 Visible Single Photon Imaging

Work to encapsulate the Medipix2 and Timepix chips in vacuum phototubes has progressed in two main branches; an electrostatically accelerated Hybrid Photon Detector (HPD) [10] and an MCP based electron multiplication tube [11]. The HPD has a simpler construction than the MCP based system but requires a significantly higher voltage to operate, greater than 7kV compared with 1kV. The MCP based system has the advantage of not requiring a silicon sensor to be bump bonded

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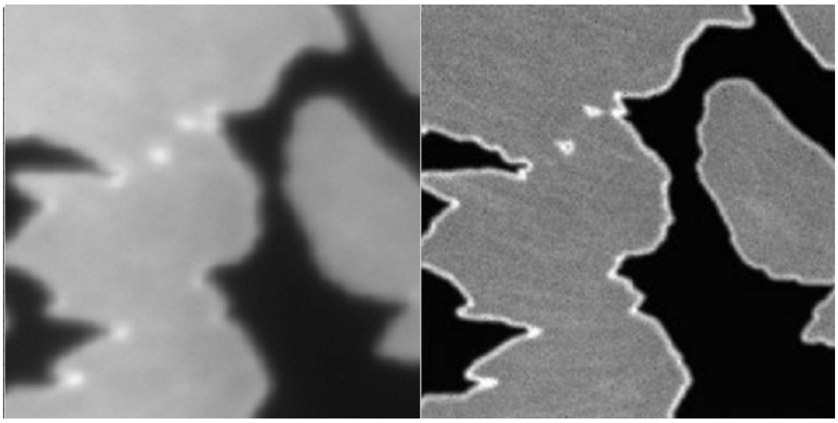

Figure 1: LEEM images of graphene flakes produced by the University of Leiden [9]. The image on the left was produced using the standard technique of electron multiplication with an MCP, read out with a CCD. The image on the right was produced using a silicon Medipix2 assembly, and clearly shows the increase in sharpness and resolution attributable to the high dynamic range of the device.

to the readout chip, however the MCP has a significantly more limited lifetime due to the eventual depletion of the MCP doping. These two designs of phototube have been investigated in the context of bio-imaging, astronomical adaptive optics and as a readout system for Cherenkov light systems in HEP experiments.

3.4 Neutron Monitoring

It is possible to detect a wide spectrum of neutrons at relatively high efficiency using a silicon sensor coupled with a converter layer of either plastic, ^{6}Li or ^{10}B. The neutron is captured in the converter layer and produces highly ionizing particles such as alphas which can be readily detected by a Medipix assembly. By coating different parts of the sensor with different converter and filter layers it is possible to gain some insight into the spectrum of the neutron flux. This approach has been extensively used in the ATLAS experiment [12] where 15 devices are positioned throughout the detector to monitor the instantaneous radiation field. A similar system of detectors is situated around the CMS experimental cavern. There has been significant work to qualify the Medipix2 as a neutron detector for flux monitoring in the LHC tunnel. A series of experiments in the CERF and CNGS areas at CERN have been used to prove the detectors ability to monitor relatively complex neutron fields. A different method of detecting neutrons with a Medipix system is the use of a ^{10}B doped MCP to generate an electron cloud that can be detected by a bare readout chip [13].

3.5 Tracking and Vertexing

Medipix2 and Timepix have been extensively used as HEP tracking readouts both in solid state and gas detectors. Timepix was specifically developed at the request of EUDET [14] with the ToA mode that would let it operate as the readout to a Time Projection Chamber (TPC). This development has continued with detectors like the Gridpix system [15] developed by NIKHEF. A number of Medipix2 detectors have been installed in several locations in the SPS accelerator as diagnostic tools as well as being used in the UA9 crystal collimator experiment.

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In parallel with this activity there has been strong interest from the LHCb VELO Upgrade community into making use of a Timepix like readout chip with a solid state sensor. This would make use of the ToT information to allow cluster centroiding, providing sub pixel resolution as well as taking advantage of the benefit to forward tracking systems of the square pixel configuration. A number of tests in CERN's North Area beamlines have been carried out using an array of Timepix chips as a particle telescope [16]. There has also been interest from the LCD project [17] for a highly accurate time stamping layer to be part of the vertex detector for a future CLIC experiment.

3.6 Mass Spectrometry

Medipix2 and Timepix have been used in two different mass spectrometry applications. Timepix has been used in prototype Time of Flight (TOF) mass spectrometers [18] where additional information from the distribution of the velocities of the ion fragments is used. This requires precise time resolution which can be provided by Timepix operating at its highest frequency, 100MHz, in ToA mode. The compact readout systems available for the Medipix2 and Timepix have also made them of interest to groups miniaturising molecular imaging mass spectrometry systems [19]. These have been operated both with a silicon sensor, and with a bare readout chip collecting the ionised fragments on the bond pads.

3.7 Education

The convenience and portability of the Medipix USB readout system and the Pixelman software, both developed by CUT Prague, make the Timepix an excellent aid in the teaching of radiation, both in schools and at undergraduate level. The ability to visually distinguish the signals of alpha, beta and gamma particles, and the video style frame rate makes it a significantly compelling demonstration tool. The ability to record data with the system directly onto a PC means that students can be introduced to computer aided data analysis relatively easily. Providing schools with these devices is the aim of the CERN@School [20] program and of the CERN Education department who also use them as a demonstration in their popular teachers program.

The CERN@school program is linked to the LUCID experiment, where Timepix assemblies instrument a space based cosmic ray detector. This has been conceived by the Simon Langton Grammar School (Kent, UK), and developed in partnership with SSTL.

3.8 Sensor Development

Medipix2 and Timepix have been used extensively as a test bench for developing new sensor materials. These include double sided 3D [21] and edgeless silicon devices, amorphous silicon and higher atomic mass detector materials such as GaAs [22] and CdTe [23] favoured for detecting higher energy X-rays. The analogue information provided by the ToT mode of Timepix allows a significant level of characterisation and deep investigation of the sensor properties.

3.9 Dosimetry

The high dynamic range and low background of the hybrid pixel design, coupled with the energy sensitivity of the Timepix ToT mode, make this a very interesting device for dosimetry. Significant characterisation efforts by the University of Houston [24] mean that Timepix is now a leading device for the next generation of space based dosimetry. In particular, studies at charged ion beams have been used to demonstrate its ability to differentiate between various species that are not found in standard ground based radiation fields.

4. Medipix3

Medipix3 [25] is a new design for a photon counting chip that can provide multiple thresholds and compensate for the effect of charge sharing distorting the spectrum with a charge summing mode. It has been designed and fabricated in the IBM 0.13μm CMOS process and has been undergoing extensive characterisation for the past year. It has been designed with a continuous readout mode to remove the dead time seen in Medipix2 and Timepix. Each pixel in Medipix3 has two thresholds and two 12 bit binary counters which are able to operate linked or separately in a variety of modes. To make maximum use of the charge summing ability Medipix3 has a spectroscopic mode, where four pixels are linked to provide larger pixels, each with eight independent threshold levels. Each pixel also contains five bits of threshold trimming information used in a similar manner to that in Medipix2 and Timepix. In single pixel mode the noise in a pixel is 60e^-, in charge summing mode it is 130e^-.

4.1 Multi-Spectral Imaging

The benefits of multi spectral imaging have been demonstrated using Medipix2's charge windowing mode to build up composite images [26]. An example of this is Figure 2 where a CT scan of a rat has been constructed at multiple energies. The calcium of the bones as well as barium and iodine markers are clearly viable as different X-ray absorption lengths. This type of functional identification of different systems combined with the future use of smart markers able to target specific proteins gives rise to the possibility of 3D functional imaging with the resolution of current CT systems.

4.2 Charge Sharing and Spectral Correction

It is often the case that an incoming particle falls on the boundary between two or more pixels and the charge it deposits is shared between these pixels. The energy then reconstructed in each pixel is only a fraction of the true energy deposited by the particle. This leads to a spreading of the energy below a peak as shown in Figure 3. Medipix3 can be optionally correct this by enabling the charge summing mode. This mode reallocates all the charge in a hit shared between up to four pixels to the pixel with the highest charge. To avoid losing charge to threshold effects, this occurs in the analogue part of the pixel before the threshold is applied. Charge summing mode is available when operating with standard 55μm pixel configuration or when groups of four pixels are linked together in spectroscopic mode described below.

4.3 Spectroscopic Mode

Spectroscopic mode allows the bonding of the chip to a 110μm sensor matrix and the functionality of the four pixels to be linked together to provide a larger number of thresholds for the larger pixel. Individually the pixels contain two thresholds and counters allowing the 110μm pixel to operate with eight of each. This provides the primary method of spectroscopic imaging in Medipix3.

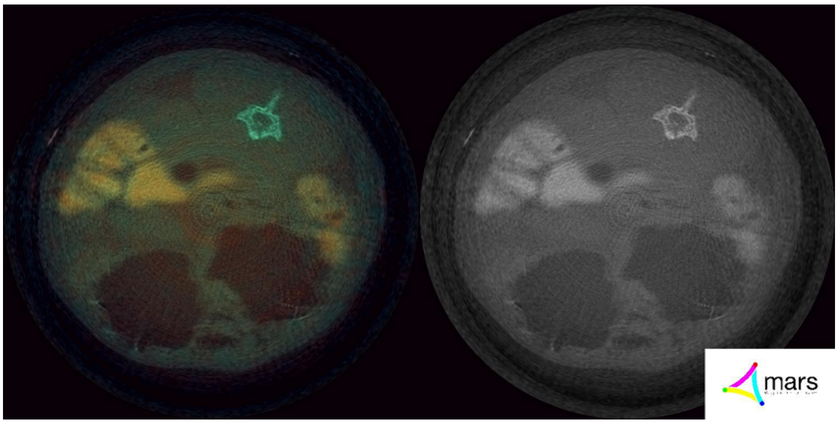

Figure 2: A multi-spectral CT slice through a rat treated with iodine and barium markers [26]. The right image shows a broad spectral counting response made with a Medipix2. The left image shows the same measurement but using the charge windowing mode to make a multi-spectral 'colour X-ray' measurement. The different colours of the various markers can be clearly seen. This measurement was made by the University of Canterbury MARS team.

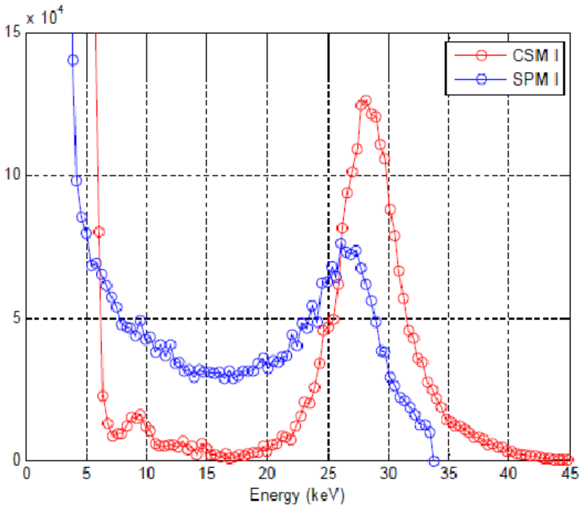

Figure 3: The effect of running with and without the charge summing mode in Medipix3 is shown in this threshold scan measurement of a ^{109}Cd X-ray source. The measurement taken in single pixel mode shows the effects of charge sharing at a threshold value below the peak, whereas in charge summing mode this is almost completely absent. These measurements were taken at CERN by R. Ballabriga and L. Tlustos.

Essentially eight matrices of counts are recorded for each different threshold simultaneously. The threshold levels can be programmed individually to lie at appropriate points between desired markers and it is possible to use charge summing mode in conjunction with spectroscopic mode.

4.4 Continuous Readout

It is also possible to set the two counters in each pixel to operate in such a way that the chip behaves as a Medipix2 but is continuously sensitive. This is achieved by using one counter to accumulate data whilst the other is shifting the data off the chip matrix. This cannot be used in conjunction with the modes that use the second counter for other purposes, like spectroscopic mode.

4.5 Radiation Tolerance

As the Medipix3 has been fabricated in 0.13μm CMOS it is intrinsically more tolerant to radiation then chips fabricated in 0.25μm . In particular, Medipix3 has been demonstrated to operate after a total ionising dose of 500Mrad[27]. This has a number of implications for the usefulness of the chip in applications such as synchrotron light sources and CT scanners where a long lifetime in a high flux environment is required.

4.6 Current Status

At the time of writing, the first Medipix3 engineering run has been completed and the chips are showing some problems associated with adapting to using the 0.13μm process, and the aggressive nature of the design. Foremost amongst the issues identified is a variation in the threshold which is too great for the trimming circuitry to properly correct. This leads to a reduction of the resolution of the image when working in charge summing mode, as one of the four pixels is always allocated the charge of the others. There is also an issue with the leakage current drawn by the pixels, which suffers a much higher then expected variation with irradiation and temperature. This leads to one of the digital to analogue converters on the chip being unable to supply the required voltage across the chip, impairing its operation, and making the chip difficult to operate in an optimal way. To compensate for these problems work with the manufacturer, IBM, is ongoing, as is a redesign effort to overcome the effects seen. It is anticipated that a new chip will be submitted in the first quarter of 2011.

4.7 Applications of Medipix3

The main application foreseen for Medipix3 is multi-spectral X-ray imaging. This has already begun the process to commercialisation with the MARS[28] project in collaboration with the University of Canterbury, NZ. Medipix3 is also expected to be employed in synchrotron light source applications due to its high radiation tolerance and ability to readout continuously, as well as in detector development situations where its ability to overcome charge sharing will be its main asset. It is also seen as being able to operate in any application that currently employs Medipix2.

5. Plans for Timepix2

Timepix2 is a chip that is currently in the design phase and is supported by the Medipix3 collaboration. It is foreseen as being able to perform both ToT and ToA measurements simultaneously to a high degree of accuracy, as well as being based on the radiation tolerant 0.13μm technology node. Other details, such as its pixel size, readout scheme and other functionality are still being

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decided by the collaboration. Currently two leading contenders for the design have come forward, a data driven design and one based on highly configurable, linked small pixels.

5.1 Data Driven Readout

The data driven readout of Timepix2 is based on the proposed design for the LHCb VELO Upgrade pixel chip. VELOpix is intended to handle very high data rates and deliver all the data off the chip. It was thought that with an appropriate readout system a lower bandwidth version of the design would be suitable for Timepix2, as in any case ToT and ToA have to have a sparse particle rate to be used effectively. In the data driven scheme a particle falling on a pixel triggers that pixel to react, acquiring the timestamp from the global clock and starting the local ToT counter. When the amplifier level falls below threshold again the ToT is stopped and the ToT and ToA values are shipped down the pixel column along with address information for the pixel. In this manner each particle hit will cause a packet to be generated on the chip which will be read off the chips periphery. The chip will be limited by the speed of the data drivers on the periphery to send data to the readout system. In this scheme the pixels will remain relatively standard at 55μm and the ToA will be accurate to 1ns. In this design it is though that the chip will be able to deal with a 1Mhz particle rate across the chip.

5.2 Programmable Small Pixels

An alternative design concept that has been proposed is based on pixels a quarter the previous size, with each pixel containing an amplifier, threshold and counter that can be grouped together into two or four pixel structures that share resources. This would allow a simultaneous ToT and ToA pixel to be configured using two of the constituent pixels and allow a matrix with half the current pitch. The strong advantage oft his system is the enormous flexibility it would bring in the configuration of the chip, however studies of its technical feasibility are still ongoing.

5.3 Timepix2 Applications

It is hoped that the fast time resolution of Timepix2 along with the simultaneous readout of ToT and ToA will make it a strong chip for particle tracking systems using both gas and solid state detector mediums. In particular the LHCb collaboration intends to use it as a development step towards the final readout chip for their upgrade programme. The analogue information coupled with the high radiation tolerance of the technology node should make Timepix2 a very useful chip for specific synchrotron applications where an energy spectra is important but a high rate is not. It is also thought that the increase in time resolution will make the chip very applicable to future TOF mass spectrometry systems.

6. Conclusions

The Medipix2 and Timepix chips support a very broad range of applications. Their success appears to be based upon their flexibility and the willingness of collaborators from a large number of different fields to come together and use the same devices in different ways, helping each other overcome common problems. The success of the commercial partnership with PANalytical is extremely encouraging and it is hoped that this will continue into the Medipix3 era.

The Medipix3 chip has undergone a long period of debugging since the completion of the engineering run and several issues that need to be addressed have been identified. This notwithstanding the initial indications for the charge summing and spectroscopic modes indicate that when the gain variation and leakage current problems are overcome the chip will perform as expected.

The development of the Timepix2 chip is ongoing and several design concepts are being investigated. It is hoped that a chip capable of simultaneous ToT and ToA measurements, as well as a very high data rate.

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