P27

Imaging by single quantum processing: large pixels with brains or attopixels without?

Rafael Ballabriga, Benedikt Bergmann, Michael Campbell, Vladimir Gromov, Erik Heijne, Thanushan Kugathasan, Xavier Llopart, Petr Manek, Tuomas Poikela, Stanislav Pospisil, Walter Snoeys, Viros Sriskaran, Lukas Tlustos and John Vallerga

with Medipix teams at CERN Geneva, IEAP-CTU Prague, Nikhef Amsterdam and SSL-UC Berkeley

CERN EP Department, CH 1211 Geneva 23, Switzerland
Nikhef, Science Park 105, Amsterdam, NL 1098XG, Netherlands
IEAP at Czech Technical University, Prague 1, CZ 110 00, Czech Republic
Space Sciences Laboratory at the UC Berkeley, USA CA 94720

contact Erik H.M. Heijne IEAP of Czech Technical University in Prague & CERN EP Dept CH1211 Geneva 23 Switzerland
erik.heijne@cern.ch tel +41 24 477 3152

abstract

Single quantum imaging can be achieved for visible wavelengths by using very small capacitance attopixels, so that even one electron charge produces a good signal. In different e.m. frequency domains, X-rays or gamma quanta, or quanta with mass, generate a signal of many e-h pairs in an extended semiconductor sensor volume. Imagers incorporating sophisticated signal processing then allow the precise measurement of properties of the incident quanta, such as their energy or sub-ns time of arrival in the pixel. Larger pixels of ~50μm can still process quanta at high rates, up to 10^{11}cm^{-2}s^{-1} showing material specifics. Examples are discussed from the Medipix and Timepix family, designed at CERN, based on expertise with imaging of quanta in elementary particle physics experiments at 40MHz framerate. Smaller pixels would improve precision in space and time, but lack sophistication until a CMOS multi-layer approach can result in intelligent 3D assemblies.

1. Single quanta

Imaging of photons in the visible frequency range of 430-770THz has become a major field in consumer electronics, but the use of these photons one-by-one is still a novelty. This is possible using some charge avalanche mechanism, and the alternative of detecting a single photo-electron on a tiny capacitance also becomes realistic [1, 2]. Single electromagnetic radiation quanta are widely used already at higher frequencies, besides other elementary quanta, with mass and electrical charge, such as electrons or protons. In nuclear analysis methods, at particle accelerators and at synchrotron light sources, processing of single quanta is customary, but electronic imaging for all these non-visible quanta is only just beginning. Single photon processing is little used for X-ray imaging in the medical field, while this is probably the largest application of non-visible radiation. Obviously, Positron Emission Tomography PET and Single Photon Emission Spectroscopy SPECT are medical imaging methods, fully based on single quanta.

Various single quantum detectors have existed since long, photographic plates first of all, but electronically the radiation profiles typically were produced by scanning with a single-channel device. Methods now are required for recording instantaneous images with singly incident quanta of all sorts. Several challenges are to be addressed. First: obtain from each quantum a signal that is large enough for electronic processing. Further: 100% fill-factor with imaging matrix elements, and these should also record relevant properties of the quanta. Preferably not by filtering, as today in most color imagers for visible, but by measurements on each quantum, with close to 100% efficiency. Finally, intelligent pixels would contain so much functionality that they recognize specific quanta according to characteristics measured in the pixel and provide images with specific materials information derived from energy spectra. A fairly large pixel area is currently required to accommodate such a 'brain'. If nevertheless small pixel size is needed, recent 3D chip stacking technology presents a possibility to incorporate complex functions while maintaining a limited footprint.

We describe work on imagers, primarily intended for elementary particle physics experiments, with spin-off towards a few other applications. A wider range of use is at hand, if more specific features would be included in the quantum processing electronic functions.

2. Imaging and processing of quanta: elementary ionizing particles, now and in future

Our pixelated matrices, hybrid assemblies consisting of sensor and CMOS chips, in the Large Hadron Collider LHC experiments have to cover surface areas of several m^2, in 3 or 4 concentric cylinders. Their images are sparsely filled with the 'hit' points along the trajectories of the crossing particles. These tracks have to be reconstructed in 3 dimensions (3D) with micrometer precision, so as to point exactly to the primary interaction or to a secondary decay 'vertex' which indicates the occurrence of especially sought-after physics processes [3]. The charge signal, of order 10^4 e-h pairs is proportional to the energy deposited by the particle in the depleted silicon volume of the diode matrix element. A relatively thick, high resistivity Si layer is used (between 50μm-300μm) in order to achieve good signal/noise (S/N >10) with the fast, analog amplifier in CMOS, hybridized onto each pixel. The interactions occur at 40MHz frequency, and each particle crossing point has to be tagged with its frame-time to better than 25ns. It is desirable also to digitize the signal amplitude, to improve hit coordinates by interpolation between adjacent pixels.

Data then have to be stored temporarily up to 4μs, for one or two hits, in on-pixel memory, until a 'trigger' decision is received from outside. If a frame is chosen, data readout is initiated, or otherwise data can be overwritten after 4μs. These pixel detector cylinders have proven essential to disentangle the complex track environment in the center of the LHC experiments.

For future experiments, an important improvement would be to record with ~50ps precision the time of interaction and of all its associated hits. Position coordinates with ~100nm precision will be useful, provided that the material density does not disturb too much the trajectories. Therefore, much thinner, smaller pixels are desirable. We can follow the trend in visible imaging, towards smaller pixels and back-side incidence with a 2-5μm sensitive layer. The electron transit time in a 3μm depleted Si layer would be <50ps and the signal risetime well below this, depending on shaping and applied power for the nano-amplifier circuit. The typical signal charge expected from a particle in 3 μm of Si would be ~120 e-h pairs [4]. The capacitance of such a pixel is below 1fF, with noise < 1 e^- r.m.s. but not yet in the domain of a few attofarad, which is intended for detection of single visible photons without using avalanche amplification ('jots' [1]). With 3x3x3μm^3 pixels the precision on the 3D hit coordinates is already better than 1μm, by combination of several imaging planes.

Overflow drains or deep-well separations between pixels are undesirable for physics imaging, the more so as these may be sensitive to the intense irradiation during operation. Use of a thin sensor layer would be advantageous at high dose, as characteristics of thicker, high resistivity Si prove to degrade sooner than the associated CMOS chips. Anyway, switches must be implemented to turn off noisy pixels, and up to a few % of dead pixels can be tolerated in these experiments.

The pixel size of 3x3 μm^2, revolutionary for tracking, is well in the range of current imagers for the visible. But it will be a challenge to accommodate the required functionality in signal processing, timing, digitization parallelism and data transmission inside this area. It appears necessary to use multi-layer 3D CMOS device structures, to achieve tileable assemblies without edges.

A jump to attofarad pixels with a size ~200nm would offer another large increase in rate capability and coordinate precision in physics experiments, but if the sensor thickness can not be proportionally reduced, always a number of pixels will be hit by the same particle quantum, due to the inclinations of most trajectories. Investigations are needed to ascertain that an adequate signal with 100% efficiency is generated if the Si sensor layer would be also be reduced to e.g. 500nm. GEANT4 simulations indicate that efficiency drops more than tolerable, below 2μm thickness. However, validity of this program for such conditions is uncertain, even if it is the standard tool. Signals have been measured for a range of Si thicknesses [4], but as yet no data seem to exist below 5μm.

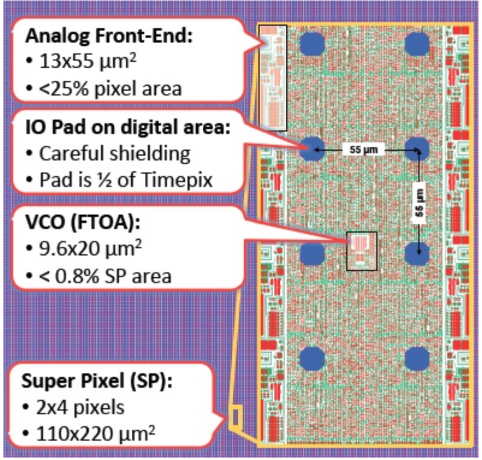


Fig.1a 8-cell superpixel of Timepix3 readout chip. The Voltage Controlled Oscillator supplies upon demand a high-frequency 640MHz clock if a cell in the superpixel is hit.

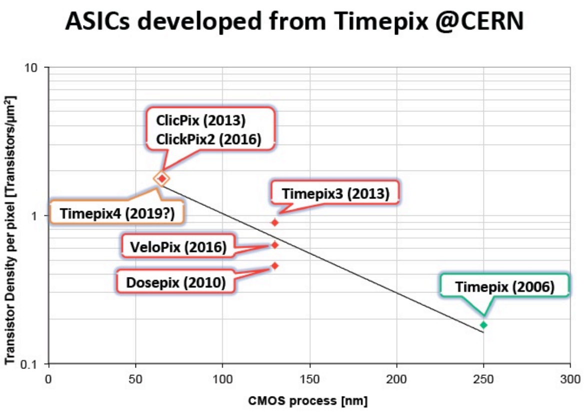
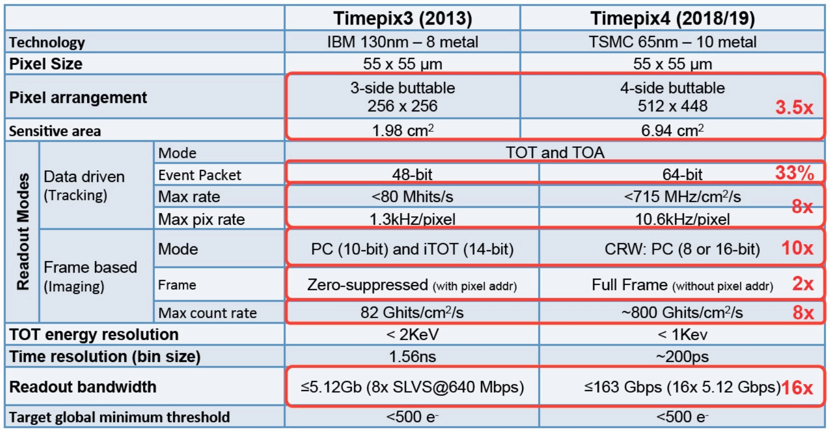


Fig.1b Transistor density in the large pixels (55x55μm^2) of the Medipix/Timepix family from 2006 until 2019 [Llopart, CERN].

3. Single quantum processing for other imaging applications

Starting from these hybridized devices for elementary particle research, the Medipix collaboration, through a series of consortia of 10-30 physics institutes worldwide, initiated development of imagers for single quanta outside particle physics, for X-rays in the first place. Some of the basic components of the physics detectors have been adapted to serve the alternative aims, while essential features of the earlier hybrids have been retained. In particular a) the hybrid approach which allows to combine with the CMOS processor chip different types of semiconductor sensors (Si, GaAs, CdTe,..), vacuum Micro-Channel Plates MCP, or gas-based sensors; b) the complete parallelism of signal processing, digitization and local storage until transmission; c) the encoding of arrival time of the quantum with (sub)ns precision. The pixels have been standardized to squares at 55μm pitch, instead of the rectangular shapes that are useful for precise tracking in a magnetic field. The signal processing has been improved for low noise and low power. The basic memory function in our circuits has been expanded to allow more data to be stored. The evolution in complexity of the Timepix readout matrices is sketched in Fig1b. Clock distribution all over the matrix with frequency between 5-80 MHz has been introduced for signal time digitization and for in-pixel ADC, using a traditional 'Time-over-Threshold' ToT method. In the most recent circuits, ever better precision has been obtained, with 1.56ns in Timepix3. Power here is kept low, by only starting a local 640MHz Voltage Controlled Oscillator VCO serving an 8-cell block, once a hit is detected by one of the comparators, as illustrated in the circuit layout in Fig 1a [5]. In the next Timepix4 imager, a precision better than 200ps is expected. In the two recent Timepix imagers, autonomous, comparator-driven data transmission from individual pixels has been incorporated, which obviates any shutter operation or dead-time, up to a quantum rate of nearly $10^9 cm^{-2}s^{-1}$. The pixel address and its corresponding measured data are sequenced to one of the output ports and transmitted off-chip. Fig. 2 compares Timepix3 with Timepix4, soon to be manufactured.



			Timepix3 (2013)	Timepix4 (2018/19)	
Technology			IBM 130nm – 8 metal	TSMC 65nm – 10 metal	
Pixel Size			55 x 55 μm	55 x 55 μm	
Pixel arrangement			3-side buttable 256 x 256	4-side buttable 512 x 448	3.5x
Sensitive area			1.98 cm²	6.94 cm²	
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	TOT and TOA	
		Event Packet	48-bit	64-bit	33%
		Max rate	<80 Mhits/s	<715 MHz/cm²/s	8x
		Max pix rate	1.3kHz/pixel	10.6kHz/pixel	
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)	10x
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)	2x
		Max count rate	82 Ghits/cm²/s	~800 Ghits/cm²/s	8x
TOT energy resolution			< 2KeV	< 1Kev	
Time resolution (bin size)			1.56ns	~200ps	
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	≤163 Gbps (16x 5.12 Gbps)	16x
Target global minimum threshold			<500 e-	<500 e-	

Fig. 2 Comparison of the characteristics of the earlier Timepix3 in 130nm CMOS and the new Timepix4 imagers in 65nm.

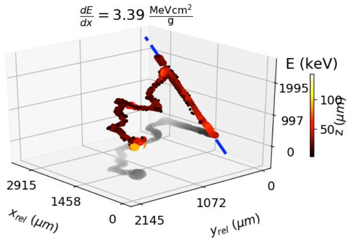
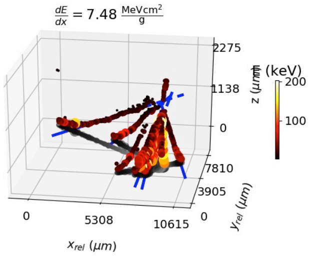


Fig.3a Tagging of arrival time allows 3-dimensional reconstruction of the trajectories inside the sensor volume. Here an incident pion with a high energy delta electron [6].

Fig.3b An incident pion makes a nuclear reaction, from which decay products can be tracked through the 2mm thick CdTe sensor volume.



A spectacular feature among the many possibilities offered by the time stamping in the individual pixels, is full 3D reconstruction of particle tracks in a single device. In a thick, 0.5 to 2mm sensor material transport of liberated charge carriers takes between 1 to 50 ns, well within the resolution of Timepix3. Then it is possible to measure the depth in the sensor from where the carriers originate, because the complete amplifier signal is generated only when the carriers come close to the final collection electrode, due to the 'small pixel effect'. Previously there was ambiguity in direction for particles that traverse the sensor at an angle, through several pixels, but time tagging solves this, and also enables reconstruction of the trajectories of secondaries such as delta-electrons, or products from a nuclear decay within the sensor [6]. This is illustrated in Fig. 3, using a 2mm thick CdTe sensor chip.

4. Remote or in-pixel quantum processing?

Reduction of pixel size results in larger data volumes, especially if the same large area has to be covered, as in these physics experiments. The transmission capability in Timepix4 reaches ~160 Gb/s and can handle $7x10^8$ hit pixels $cm^{-2}s^{-1}$ (Table/Figure 2) but this fills up Terabit storage in minutes. Remotely correlating data from adjacent pixels that are hit by the same incident quantum is current practice, but if this operation can be performed immediately in-pixel and on-chip, the photon rate can be increased to nearly $10^{11} cm^{-2}s^{-1}$. Following this approach, the Medipix collaborations implemented a series of imagers aiming at in-pixel reconstruction of the original energy of the incident quantum which is spread over a cluster of pixels. A master pixel is designated, that incorporates the sum of coincident current signals in all adjacent, lower charge pixels. The algorithm in the Medipix3 circuit is illustrated in Fig. 4a [7]. The Medipix3 circuit makes spectroscopic X-ray imaging possible, so that specific energies can be determined which indicate material composition. In Fig. 4b is illustrated the signal amplitude distribution without charge summing, and improvement in energy resolution using Charge Summing Mode CSM. With energy-resolved

X-ray imaging, for example, rust can be detected during scanning of a steel pipeline, and types of tissue can be distinguished, such as muscle or fat, in medical Computed Tomography CT scanning. Ballabriga et al. published a review [8] of the successive Medipix and Timepix processing imagers.

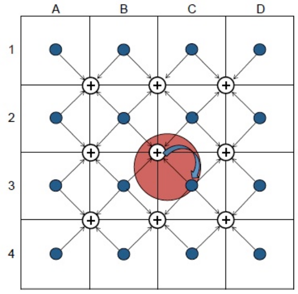


Fig.4a In the Medipix3 readout [7] the signal charge from up to 4x4 pixels can be summed on-chip in real time, and allocated to the pixel with the highest signal. This is called Charge Summing Mode.

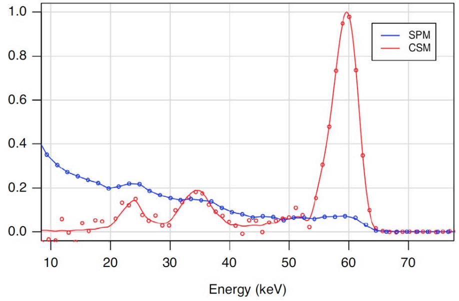


Fig.4b Exposure of a Medipix3 imager with 2mm CdZnTe sensor to a 241Am 59.5keV X-ray source. In Single Pixel Mode 'SPM' (blue) the energy spectrum can hardly be seen, but in CSM (red) the spectral energy peaks become well-resolved.

5. Small attopixels or large, complex pixels.

Extrapolating the trend from 730aF in a 110nm CMOS Image Sensor CIS process [2] to 460aF in a 65nm process [1], pixels of only ~200x200 nm^2, and 1-3 μm fully depleted thickness, with capacitance approaching a few tens of attofarads seem possible quite soon. In such attopixels, a large signal is generated even by a single electron. A crossing ionizing particle would result in tens of e-h pairs. In our physics experiments, an advantage of attopixels would be the <<μm precision and the capability to separate particles in a dense beam, such as in a jet of high-energy particles, which today is mostly impossible close to the interaction point. In other applications, however, to measure characteristics of single quanta requires complex circuitry, and extended area is needed. So, in a first approximation it seems that attopixels do not lend themselves to sophisticated measurements such as ps time-tagging, while their dimensions and low capacitance would be just very appropriate for this. A solution for this dilemma would consist in the design of a hierarchical processing system, built in superposed chip layers, with complex circuits shared in groups of pixels. This approach has been implemented in a rudimentary way in the Timepix3 and Timepix4 chips, where 'superpixels' consist of 8 basic pixels, served by a common VCO and where memory locations can be attributed at the group level. Similar approaches are underway elsewhere, and eventually this may become a succesful technology of 'More than Moore'.

6. Conclusion

Recording of single quantum elementary particles at a continuous framerate of 40MHz uses imagers that incorporate 'intelligent' functions in each pixel, in particular time tagging and amplitude digitization. Shrinking pixel size would allow sub-μm position encoding and sub-ns timing, with a trade-off in space needed for functional complexity. Very small attopixels need to be grouped in a hierarchical system, with common functions at different chip layers in a 3D assembly. Future imagers can exploit enhanced connectivity offered in the most advanced CMOS technologies, combining hybrid and monolithic approach. Single quantum imaging can be extended into many fields of application, including the visible, where attopixels or 'jot's deliver good signals for single electrons.

References

[1] Jiaju Ma, Saleh Masoodian, Dakota A. Starkey and Eric R. Fossum, Photon-number-resolving megapixel image sensor at room temperature without avalanche gain, Optica 4 (2017) 1471-1481 doi 10.1364/Optica.4.001474

[2] Min-Woong Seo et al., A 0.27 e- read noise 220-μV/e- conversion gain reset-gate-less CMOS image sensor with 0.11-μm CIS process, IEEE El.Dev.Lett. 36(2015) 1344-1347 doi 10.1109/LED.2015.2496359

[3] Erik H.M. Heijne, How chips pave the road to the Higgs particle and the attoworld beyond, IEEE Proc. ISSCC2014 paper 1.3, p. 22-28 978-1-4799-0920-9/14

[4] Stefano Meroli et al., Energy loss measurement for charged paricles in very thin silicon layers, J.Inst. JINST 6(2011) P06013 doi: 10.1088/1748-0221/6/06/P06013

[5] Tuomas Poikela et al., Timepix3: a 65k channel hybrid pixel readout chip with simultaneous ToA/ToT and sparse readout, JINST 9(2014) C05013 doi 10.1088/1748-0221/9/05/C05013

[6] Benedikt Bergmann et al., 3D reconstruction of particle tracks in a 2mm thick CdTe hybrid pixel detector, Eur.Phys.J.C 79(2019) 165 doi:10.1140/epjc/s10052-019-6673-z

[7] Rafael Ballabriga et al., The Medipix3RX: a high resolution, zero dead-time pixel detector readout chip allowing spectroscopic imaging, JINST 8(2013) 2 C02016 doi 10.1088/1748-0221/8/02/C02016

[8] R. Ballabriga, M. Campbell and X. Llopart, ASIC developments for radiation imaging applications: the Medipix and Timepix family, Nucl. Instr. Meth. A878(2018) 10-23 dx.doi.org/ 10.1016/j.nima.2017.07.029