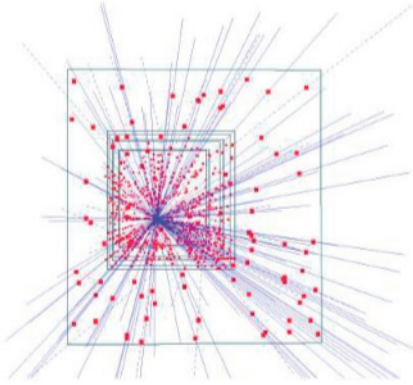




MEDIPIX



This picture was taken in 1995 and demonstrated the potential of hybrid silicon-pixel detectors for tracking applications in high-energy physics. It shows 153 high-energy particle tracks flying through a telescope of half a million pixels.

Introducing Medipix

The high-energy physics community in general, and CERN in particular, is constantly looking for ways to do things faster, better and more accurately, as well as for opportunities to implement its innovations in society at large. Medipix, a family of successive generations of hybrid pixel detectors, has made the journey from experiments at the Large Hadron Collider (LHC) to applications in places such as the International Space Station, classrooms, and medical devices.

In essence, Medipix is an integrated circuit composed of thousands of identical channels each of which is connected to a sensitive element to form a small 2-dimensional particle detector. Its ability to count single photons enables it to produce X-ray images that are high resolution and noise-free, making it excellent for use in medical imaging and a broad range of applications involving radiation detection.

Hybrid pixel technology enables the detection of charged particles with high resolution, high contrast and almost no noise, all reasons that drove most of the LHC experiments to adopt the technology for their vertex detectors. The detectors are so sensitive that they can detect individual X-ray photons. Researchers from CERN and some external collaborating groups saw the opportunity to transfer the technology used in the LHC experiments to applications outside the field of high-energy physics, thus the Medipix project was born.

The strong link between high-energy physics and medicine has always been one that inspires innovation. Medipix is a spin-off from the electronics developed for the detectors used at the Large Hadron Collider.

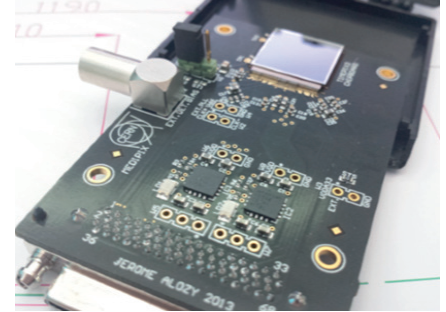
The History of Medipix

The very first Medipix chip was produced in the 1990's when an informal collaboration of four institutes demonstrated the potential of the new technology to provide noise-free single-photon counting. The result was the Medipix1 chip.

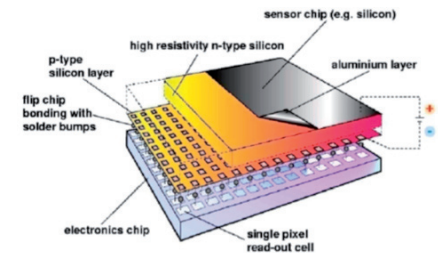
Since then, the Medipix family has expanded to include the Medipix2 chip with improved spatial resolution and Timepix which is a modified version of Medipix2 with the additional functionality of time or amplitude measurements. Last but not least are Medipix3 and Timepix3 which, as well as counting photons, can determine the energy level of each individual photon detected.

The Medipix2 Collaboration was formed in 1999. It was supposed to end after four years, but still meets on a regular basis more than 15 years later. This is in large part a result of the number of applications to which the technology has been applied. In 2005 the EUDet Collaboration approached the Medipix design team to request that each pixel be adapted to measure particle arrival time instead of the number of impinging photons: the Timepix chip was launched. A direct evolution from the Medipix2 chip, it allows measurement of arrival time, "time-over-threshold" (ToT) or event counting independently in each pixel. The Timepix chip was launched in 2006 and its immediate success led to another wave of new applications.

The Medipix3 Collaboration was formed in 2005 to develop the Medipix3 chip, which makes it possible to mitigate the effects of charge-sharing by allowing pixels to communicate with each other on an event-by-event basis. Moreover, by using a more advanced CMOS technology, it became possible to integrate two counters on a single small pixel, permitting one image to be taken while the previous one is being read out. The Timepix3 chip was developed by the same collaboration with the aim of producing a general-purpose integrated circuit suitable for readout of both semiconductor detectors and gas-filled detectors. It has been used in test beams in experiments at CERN with excellent results.

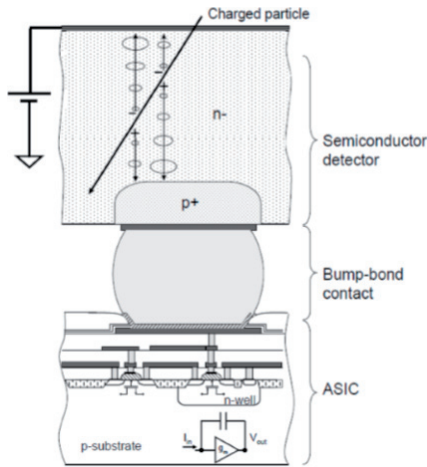


Timepix3 chip, a multipurpose hybrid pixel detector developed within the Medipix3 Collaboration.



Technical Introduction

The Medipix ASICs (application specific integrated circuits) are high spatial resolution, high contrast CMOS pixel-read-out chips. Together with a detection medium – typically a semiconductor such as silicon, GaAs or CdTe – these chips form hybrid pixel detectors. The read-out chip is composed of a matrix of pixels with signal-processing circuitry. The electrode at the bottom face of the detection medium is pixelated as well and connected to the read-out chip pixel by pixel. A technique called bump-bonding is used, in essence creating a very small ball-like solder joint between the detection medium and the read-out chip, one for each pixel.



Cross-section of a single pixel, showing the detection medium, the ASIC and the bump-bond connecting them.

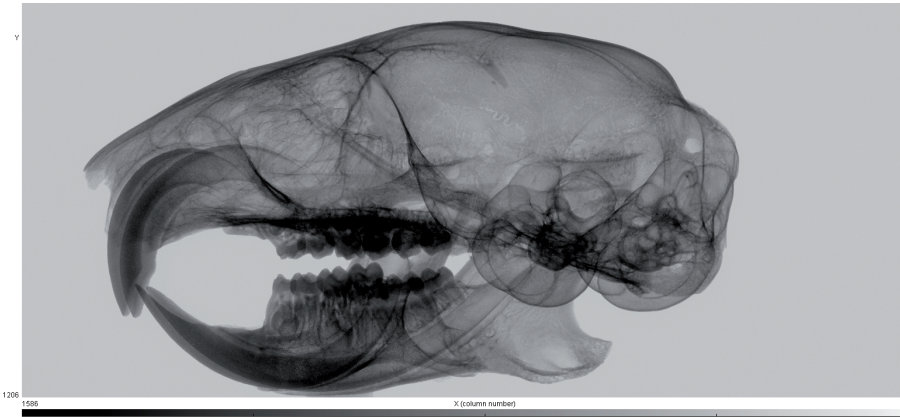
Charged particles interact with the semiconductor, resulting in the creation of electron-hole pairs. The charge is then transferred through the bump-bond of each pixel and, in counting mode, the electronics adds up the number of particle hits per pixel. The separation of the detection medium and the read-out chip allows for noise-free detection of photons and the possibility to optimize the detection medium for different types of particles and energy ranges. The number of charge-carriers created is proportional to the energy of the incident particle, making it possible also to quantize the energy of the particle.

The dimensions of the most commonly used chips, Medipix2, Timepix and Medipix3, are $1.4\text{ cm} \times 1.6\text{ cm}$ and the pixel matrix contains 256×256 pixels of $55\text{ }\mu\text{m} \times 55\text{ }\mu\text{m}$ each. The chips are 3-side buttable, which means that an array of $2 \times N$ chips can be assembled on a single large detector slab. The largest commercially available Medipix-based detector has 6.5 million pixels and uses 10×10 single Timepix chip assemblies with roof-tile mechanics covering $14\text{ cm} \times 14\text{ cm}$ almost seamlessly.

Application Areas and Commercialization

The Medipix technology is one of CERN's most successful technology-transfer cases. Each collaboration has triggered a significant number of commercial activities in widely different application areas. Industrial X-ray imaging, medical imaging and material analysis are just some of the arenas in which Medipix chips are operating today. The industrial partners and licence holders commercializing the Medipix technology range from established enterprises to young start-up companies. Thus, the technology is contributing to value creation, not only in its application areas, but also through business creation.

More than 32 organizations, institutions and companies have been involved with the development of the family of Medipix chips.



A tiled X-ray image of a mouse skull

Application Area: Medical Imaging

Radiography and computed tomography (CT) use X-ray photons to study the human body. The Medipix chips that implement on-pixel single photon counting provide many advantages for use in these fields. The technology has been applied in X-ray CT, in prototype systems for digital mammography, in CT imagers for mammography and for beta- and gamma-autoradiography of biological samples. Moreover, with the Medipix3 chip, the images are no longer black and white – they have colours to indicate different energy levels of the photons. The colour X-ray imaging technique produces clearer and more accurate pictures that should help doctors give their patients more accurate diagnoses.

In July 2015, CERN had ten active Medipix licences with commercial actors: six licences for Medipix2/Timepix and four licences for Medipix3. Seven of these are held by young start-up companies, most of them having spun out from the collaborating institutes.

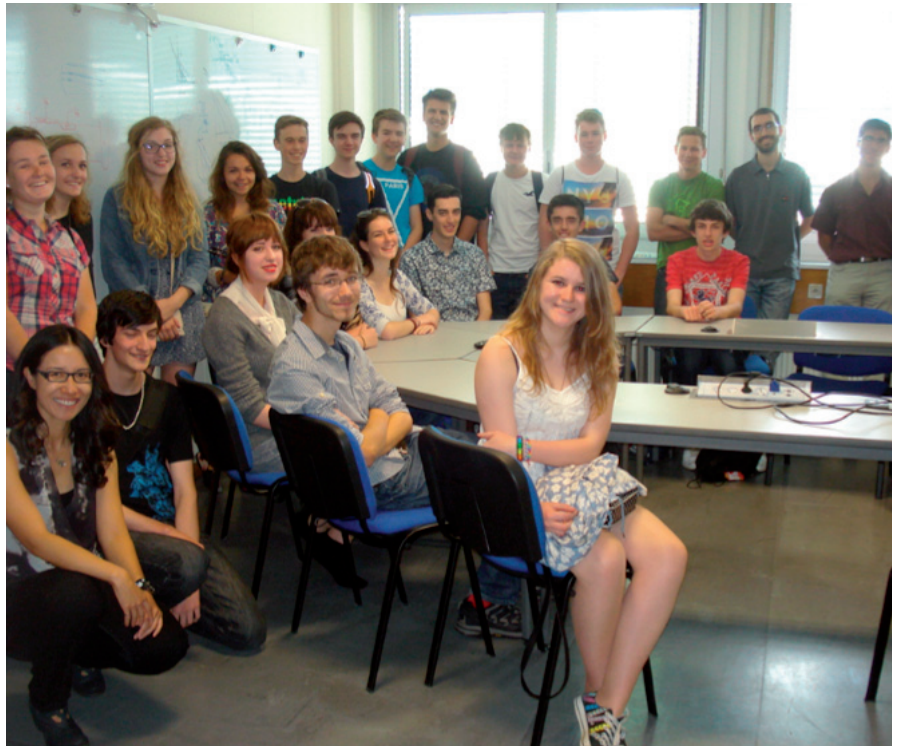
Application Area: Education

In 2013, a kit especially designed for classroom-use based on Timepix was put on the market. The kit consists of a user-friendly particle detector that can detect ionizing radiation in real time. The students can then observe the particles arriving on the detector on a computer screen. The ability to visually distinguish the signals of alpha, beta and gamma particles and the video-style frame-rate makes it a compelling demonstration tool for educators teaching about radiation. Students also learn about computer-aided data analysis by using the USB-based read-out system.

A pilot project, called CERN@School, has been launched by the Simon Langton School in Canterbury, England, with the aim of delivering kits, together with the associated teaching material, to a large number of schools. High-school students are encouraged to initiate their own research projects using the kits.



Langton student Katherine Evans presenting at the CERN@School symposium.

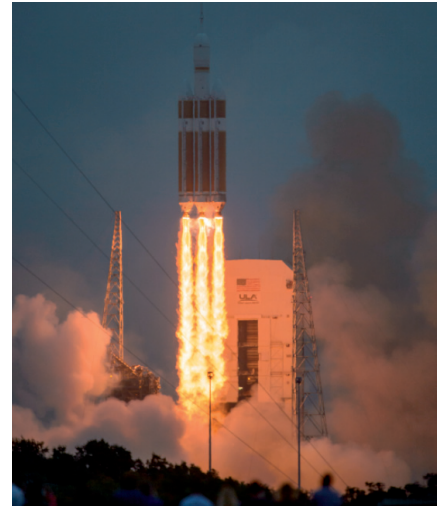


Students from the Thomas Hardy School, Dorchester, England visiting CERN.

Application Area: Space Dosimetry

In 2012 the Timepix chip arrived at the International Space Station. This was the culmination of efforts by collaboration members at the Institute of Experimental and Applied Physics in Prague and the University of Houston, Texas, to use the chip for monitoring the radiation environment of the station. Five chips were plugged into the USB ports of the station laptops and immediately started delivering data to the Earth-based team in Houston. This team is now carefully analysing the data and comparing it with data from the more conventional but rather bulky area-monitors.

In December 2014, two Timepix chips were incorporated into a battery-operated system that flew on the NASA Orion rocket. The development, which was driven by the University of Houston, provides a very compact and low-power solution to measure the radiation field to which astronauts are exposed. The approach has been adopted as the baseline for radiation measurements for the Orion project.



There are two Timepix chips inside the BIRD (battery-operated independent radiation detector) that was used on the NASA Orion Rocket.



The astronaut Chris Cassidy working near the Timepix USB on the International Space Station.

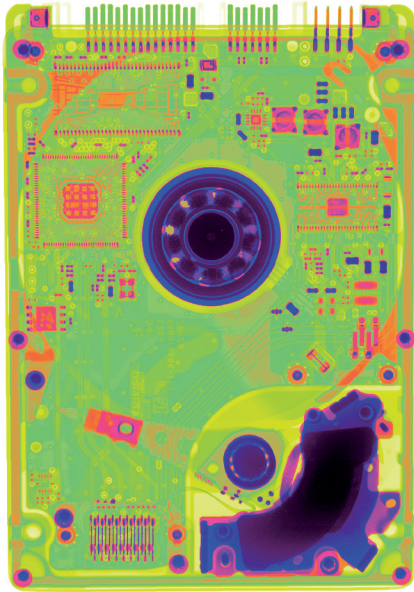


Image of a hard disk.

Application Area: Material Analysis

The Medipix2 and the Medipix3 chips are both being used for commercial X-ray of materials analysis. The Dutch company PANalytical use Medipix for their cutting-edge X-ray diffractometers. These instruments are being used for a myriad of purposes such as the characterization of pharmaceuticals, evaluation and synthesis of new materials, and the detection of counterfeit drugs. This is possible because of the extended dynamic range provided by the single-photon counting approach.

The single-photon counting technique provides outstanding images at very low rates enabling high-resolution phase-contrast imaging with micro-focus X-ray sources. In low rate environments it is possible to perform X-ray polarimetry measurements with the Timepix chip using either silicon as the sensing material or gas.

Back to High-Energy Physics

The Medipix family's roots extend deep into the tunnels of CERN's LHC and high-energy physics. Originally developed for particle physics, they found their way to medical imaging and then came back for the second run of the LHC.

As an example, the chips are now being used in the ATLAS experiment to provide independent, real-time information about the radiation environment in the experimental cavern – in principle the same task that Timepix does at the International Space Station. A direct 'spin back' to high-energy physics is VELOpix, based on Timepix3. Benefiting from developments made in the framework of the Medipix3 consortium which were not originally intended for high-energy physics, VELOpix will serve as the read-out chip in the new vertex detector of the LHCb experiment, which is planned for installation in 2018.

Other Application Areas

The Medipix and Timepix chips are also being used in other application areas such as:

- X-ray detection and imaging at synchrotron light sources
- Gamma cameras
- Low-energy electron microscopy
- Focal planes for electron microscopes
- Single visible photon imaging with microchannel plates
- Axion search TPC readout using GridPlix
- Neutron imaging (combined with B-doped microchannel plates)
- Time-of-flight mass spectrometry



X-ray image of a small flower, acquired with Medipix3. The capability of Medipix detectors to use low-energy X-ray photons (< 20 keV) for radiography enables high contrast even for objects with low X-ray attenuation. The blossom and the tiny hairs on top of the calyx (closed flower) are visible as well as the inner parts, e.g. the stigmas. The colours represent different intensities.

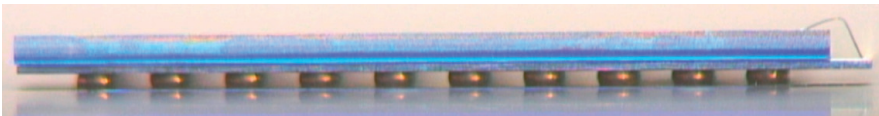
The Next Step: Medipix4

Up until now it has been possible to make pixel detector read-out chips that can be abutted on three sides only. The fourth side is used for on-chip peripheral logic and wire-bond pads that permit electronic read-out. Because of this structure, large detector areas can be covered, but only with gaps in the coverage, or by using complicated roof-tile mechanics. Through-silicon-via (TSV) technology provides the possibility of reading the chips through copper-filled holes that bring the signals from the front side of the chip to its rear. Recent developments based on the Medipix3 chips have demonstrated that this has now become a viable option for pixel detector read-out. However, the TSV processing of Medipix3 only allows a reduction in the peripheral area by avoiding the use of wire bonds. The peripheral logic is still present.

A new collaboration, called Medipix4, is in formation with the aim of designing pixel read-out chips that for the first time are fully prepared for TSV processing and may be tiled on all 4 sides. In other words, all of the communication with the pixel matrix will now go through the rear of the chip – the peripheral logic and control elements will be integrated inside the pixel matrix. This will not only enable large areas to be covered seamlessly, but will also permit the development of new read-out architectures by avoiding the need to send all of the data to one side of the chip for read-out. Two new chips are foreseen: Medipix4, which will target spectroscopic X-ray imaging at rates compatible with medical CT scans, and Timepix4, which will provide particle identification and tracking with higher spatial and timing precision.



Image of a wild bee, Medipix3.



Side view of a Medipix3 silicon detector assembly connected to a printed circuit board using a ball grid array. TSV's are used to connect the ball grid array to the front side of the ASIC.

Contact Information

CERN Knowledge Transfer Group

cern.ch/kt

mail-KT@cern.ch

Picture credits

Front page: Simon Procz, University of Freiburg, Medipix flower I

Page 2: CERN, 1995

Page 3: CERN, Timepix3 chip; CERN, Illustration

Page 4: CERN, Cross section

Page 5: Simon Procz, University of Freiburg, Mouse skull

Page 6: Becky Parker, Katherine Evans; Judith Wardlaw, Thomas Hardy School

Page 7: NASA, Orion; NASA, ISS

Page 8: Simon Procz, University of Freiburg and Elias Hamann, KIT, Hard disk

Page 9: Simon Procz, University of Freiburg, Medipix flower II

Page 10: Simon Procz, University of Freiburg, Wild bee; CERN, Medipix3

Collaboration Partners

Medipix1

CERN; University of Freiburg; University of Glasgow; Istituto Nazionale Di Fisica Nucleare of Pisa and Napoli.

Medipix2

CERN; Institut de Física d'Altes Energies, Barcelona; University of Cagliari; Space Sciences Laboratory, University of California, Berkeley; Commissariat à l'Energie Atomique; Czech Academy of Sciences; IEAP, Czech Technical University in Prague; ESRF; Universität Erlangen-Nürnberg; Friedrich-Alexander-Universität Freiburg-i.B.; University of Glasgow; University of Houston; Laboratory of Molecular Biology, Medical Research Council, Cambridge; Mid-Sweden University; Università di Napoli Federico II; NIKHEF; Università di Pisa.

Medipix3

CERN; Brazilian Synchrotron Light Laboratory; University of Canterbury; Commissariat à l'Energie Atomique; Deutsches Elektronen-Synchrotron; Diamond Light Source; Albert-Ludwigs-Universität Freiburg; University of Glasgow; IPS, Karlsruhe Institute of Technology; Leiden University; NIKHEF; Mid-Sweden University; IEAP, Czech Technical University; ESRF; Universität Erlangen-Nürnberg; Space Sciences Laboratory, University of California, Berkeley; VTT Technical Research Centre of Finland; University of Houston; Universidad de los Andes; University of Bonn; FOM Institute for Atomic and Molecular Physics; Technical University of Munich.



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