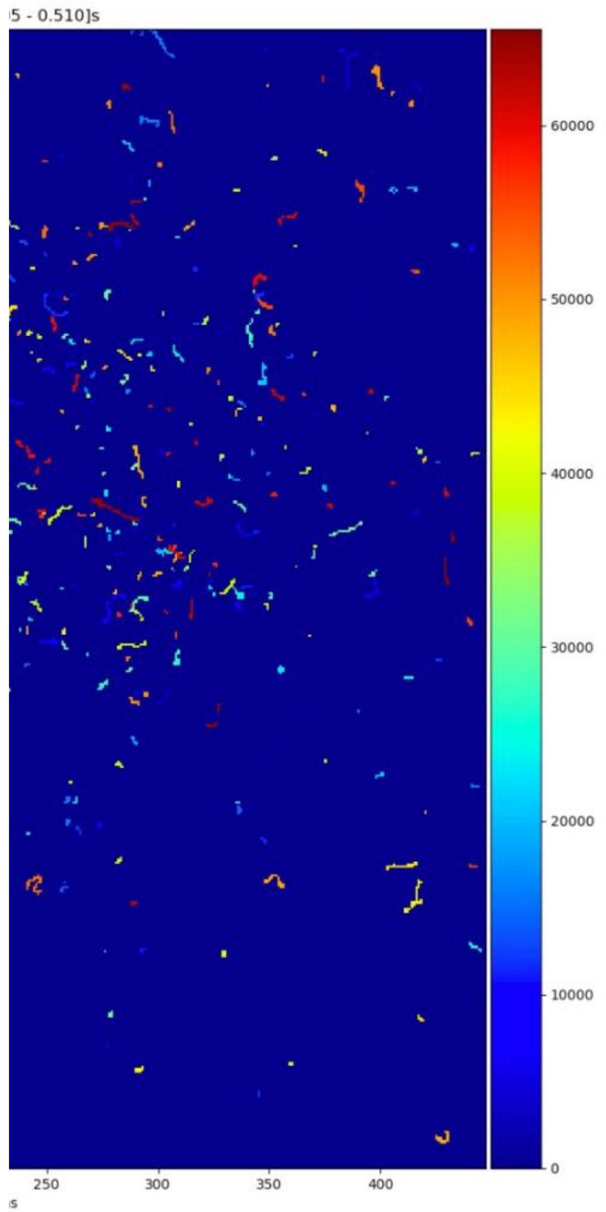
Tests at INFN on X-ray photon counting hybrid pixel detectors based on the Timepix4 ASIC

P. Cardarelli, N.V. Biesuz, R. Bolzonella, V. Cavallini, P. Delogu, A. Feruglio, M. Fiorini, E. Franzoso, R. Longo, G. Mettivier, G. Romolini, V. Rosso, A. Taibi, S. Tudisco



High Precision X-ray Measurements 2023 – June 22nd, 2023 – Laboratori Nazionali di Frascati INFN

Medipix Collaboration

- Medipix Collaboration was born to transfer the technology developed for the LHC experiments to applications outside high-energy physics
- Medipix4 Collaboration based at CERN with 18 members
- INFN is an official member of the Medipix4 Collaboration since November 2020

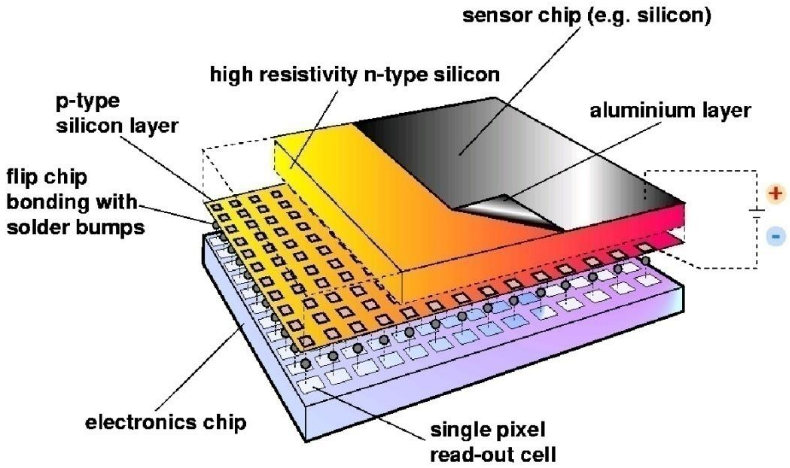
- CEA, Paris, France
- CERN, Geneva, Switzerland
- DESY-Hamburg, Germany
- Diamond Light Source, England, UK
- IEAP, Czech Technical University, Prague, Czeciah
- IFAE, Barcelona, Spain
- JINR, Dubna, Russian Federation
- NIKHEF, Amsterdam, The Netherlands
- University of California, Berkeley, USA
- University of Canterbury, Christchurch, New Zealand
- University of Geneva, Switzerland
- University of Glasgow, Scotland, UK
- University of Houston, USA
- University of Maastricht, The Netherlands
- University of Oxford, England, UK
- INFN, Italy
- Chinese Spallation Neutron Source, Dongguan City, China
- Brazilian Light Source, Campinas, Brazil

https://medipix.web.cern.ch/home

Hybrid pixel detectors

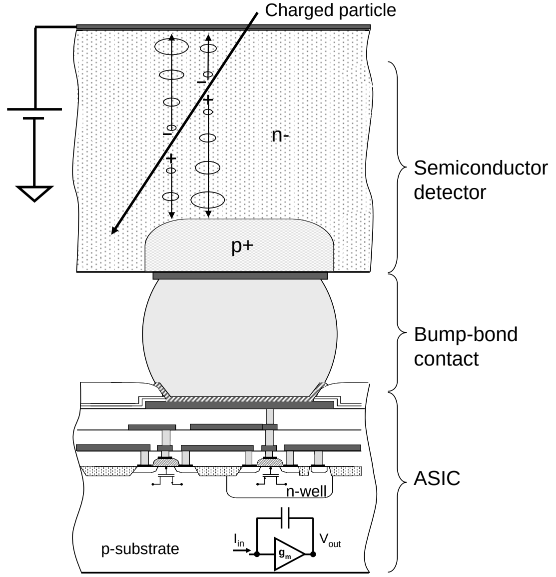
Medipix4 Collaboration is aimed at the development of innovative **hybrid pixel detectors** for particle tracking and medical imaging.

The semiconductor **sensor** and the **readout chip** (ASIC), are manufactured **independently** and later electrically coupled by means of a bump-bonding process



Advantages of hybrid approach:

- Standard CMOS can be used (follow industry)
- Sensor material can be changed (Si, GaAs, CdTe..)
- Semiconductor sensor can be replaced by a gas gain grid or MCP



Courtesy M. Campbell

Medipix4 collaboration

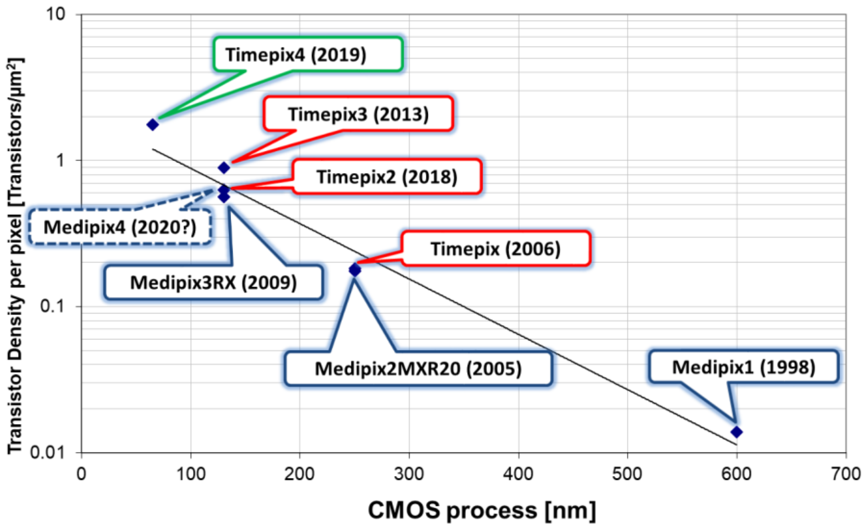
Two Application Specific Integrated Circuits (ASICs) are developed and produced by the collaboration:

Timepix4

- **Particle tracking** detector chip
- Single-threshold
- High energy and time resolution
- High-rate imaging capabilities

Medipix4

- **Spectroscopic X-ray imaging**
- Multi-threshold photon-counting
- Rates compatible with medical CT scans

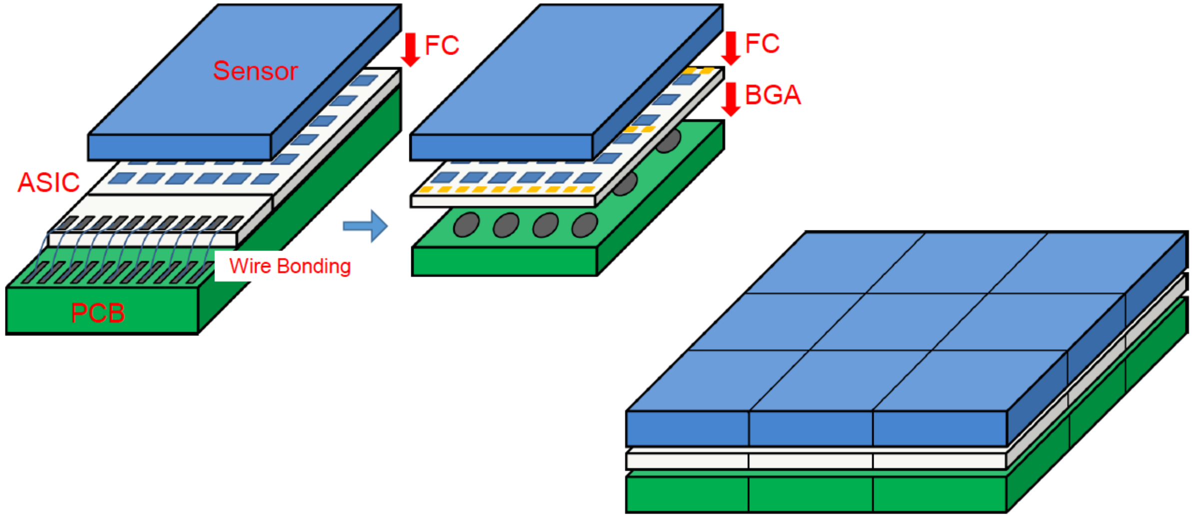


Courtesy of X. Llopart (CERN)

Through-Silicon Vias

For many applications **large area** covering is a fundamental requirement

- 4-side buttable pixel arrangement
- Target to build large area detectors by combining smaller modules
- The **Through-Silicon Vias (TSVs)** is the key technology for this paradigm shift
- **Both chips have a 4-side buttable architecture:**
  - Periphery integrated inside the pixel matrix
  - Prepare for readout using TSV (Through-Silicon-Vias)
  - Larger ASICs



Courtesy of X. Llopart (CERN)

Timepix4

Timepix4 is the new **particle-tracker and photon counting hybrid pixel detector** designed with the support of the Medipix4 collaboration

- 65nm technology
- Pixel matrix of 512 x 448 pixels (55 x 55 μm^2)
- **6.94 cm^2** sensitive area
- 4-side buttable with **<0.5% dead area**
- Readout: **Up to 160 Gbps readout bandwidth**
- **Very configurable architecture** to accommodate many different applications

			Timepix3 (2013)	Timepix4 (2019)
Technology			130nm – 8 metal	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 cm^2	**6.94 cm^2**
Readout Modes	Data driven (Tracking)	Mode	TOT and TOA	TOT and TOA
		Event Packet	48-bit	64-bit 33%
		Max rate	0.43x10^6 hits/mm^2/s	**3.58x10^6 hits/mm^2/s** 8x
		Max Pix rate	1.3 KHz/pixel	**10.8 KHz/pixel**
	Frame based (Imaging)	Mode	PC (10-bit) and iTOT (14-bit)	CRW: PC (8 or 16-bit)
		Frame	Zero-suppressed (with pixel addr)	Full Frame (without pixel addr)
		Max count rate	~0.82 x 10^9 hits/mm^2/s	~5 x 10^9 hits/mm^2/s 5x
TOT energy resolution			< 2KeV	< **1Kev** 2x
TOA binning resolution			1.56ns	**195ps** 8x
TOA dynamic range			409.6 μs (14-bits @ 40MHz)	**1.6384 ms** (16-bits @ 40MHz) 4x
Readout bandwidth			≤5.12Gb (8x SLVS@640 Mbps)	**≤163.84 Gbps** (16x @10.24 Gbps) 32x
Target global minimum threshold			<500 e$^-$	<500 e$^-$

Courtesy of X. Llopart (CERN)

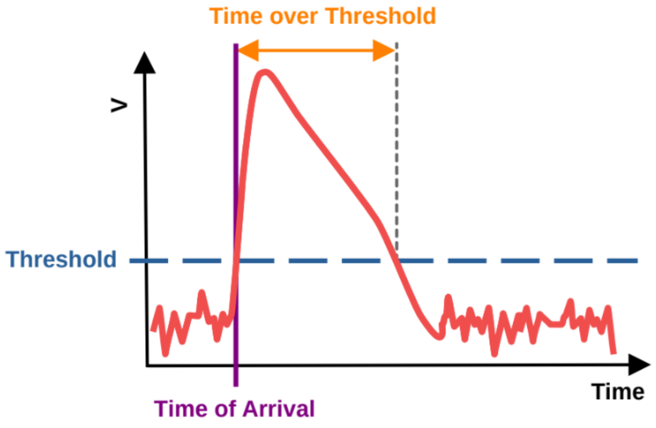
X. Llopart *et al* 2022 *JINST* **17** C01044

Timepix4 readout

Two different read-out modes:

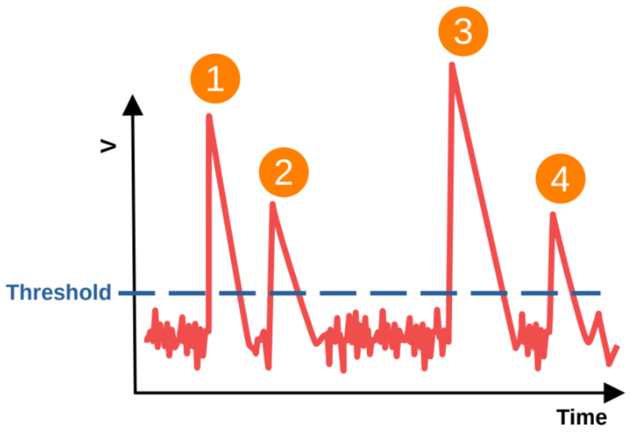
Data-driven

- Particle identification and tracking
- Zero-suppressed continuous acquisition, up to 10.8 kHz/pixel
- Time of Arrival, sub-ns time binning <200 ps
- Time over Threshold 11-bit dynamic range with ~200 e^{-}_{rms} resolution

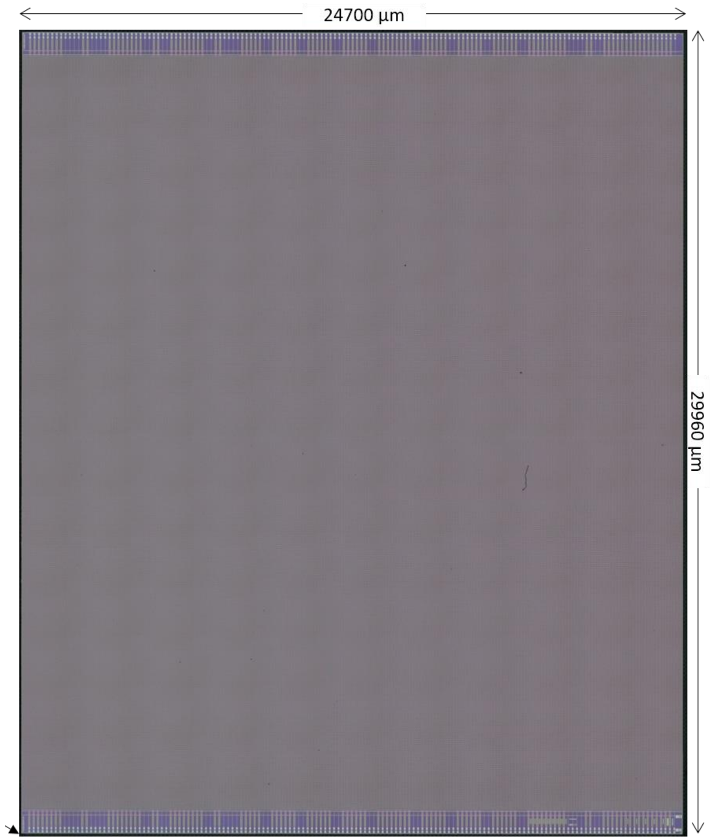


Frame-based

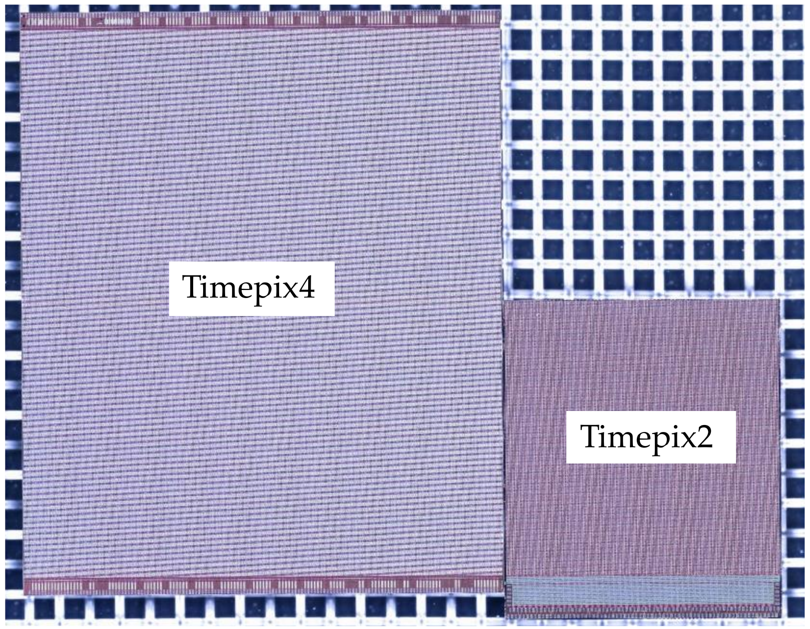
- Full frame readout with continuous read-write (CRW)
- No zero-suppression (no pixel address sent)
- 8-bits or 16-bit counter depth up to 5 x 10^9 hits/mm^2/s
- Frame rate limited by bandwidth, e.g. 44.6 kfps @ 163.84 Gbps (16 bit)

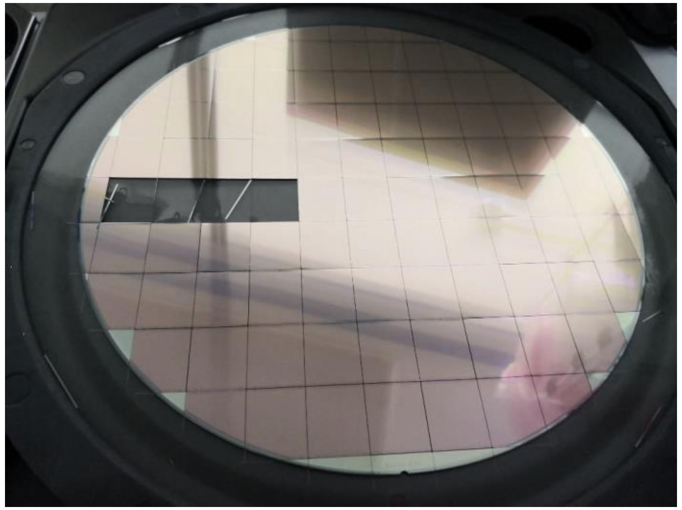


Timepix4 productions

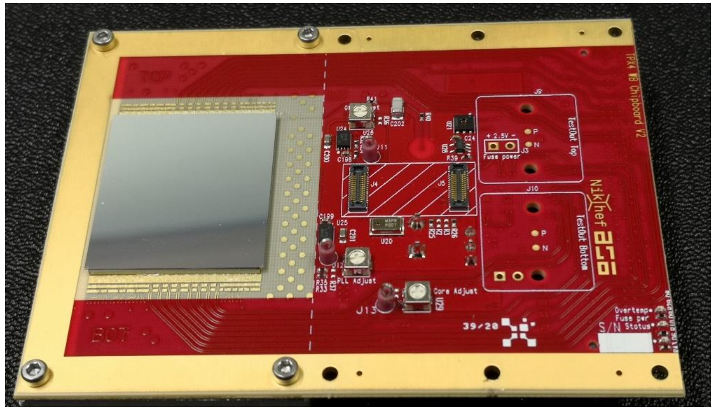


- 65 nm CMOS (TSMC)
- ASIC productions:
  - Timepix4_v0 (Q1 2020)
  - Timepix4_v1 (Q4 2020)
  - Timepix4_v2 (Q4 2021)
  - Timepix4_v3 (Q1 2023)





Diced Timepix4v0 300mm wafer



Timepix4v1 with full (512 x 448) Si sensor (March 2021)

X. Llopart (CERN)

INFN

Medipix4

Medipix4 is the latest photon processing hybrid pixel detector designed with the support of the **Medipix4 Collaboration**

- **5.76 cm²** sensitive area.
- **4-side buttable** architecture to cover **99.37% active area**.
- **2 operation mode**: Fine Pitch (75 um pixel) and Spectroscopic (150 um pixel)
- **2 thresholds** in Fine Pitch Mode and **8** in Spectroscopic Mode
- Configurable analog modes to accommodate **a large range of different applications** (from very fast to very low noise).
- **Pile-up filtering** circuit to discard tail pile-up events in the measurement.

		Fine Pitch Mode (FPM)	Spectroscopic Mode (SM)
Technology		130 nm + 9 metals	
Pixel size (µm)		75 x 75	150 x 150
Pixel arrangement		4-side buttable 320 x 320	4-side buttable 160 x 160
On-pixel thresholds		2: SPMa + CSM	8: 1 SPMa + 7 CSM[6:0]
Counter depth SRW [Full dynamic Range with overflow]		2 x [12 or 1] bits	8 x [12 or 1] bits
		2 x [24 or 2] bits	8 x [24 or 2] bits
Counter depth CRW [Full dynamic Range with overflow]		2 x [12 or 1] bits	8 x [12 or 1] bits
Operation Modes	SPM CSM	2 THR, WD, Pileup Filtering	8 THR, WD, Pileup Filtering
Output ports		1 to 16 SLVS @ 640Mbps DDR max	
Max frame Rate	1 FPM : 4 SM THRs	120 µs (8.3 Kfps) @ 12-bit CRW, 16 links @640Mbps and Split readout 10 µs (100 Kfps) @ 1-bit CRW, 16 links @640Mbps and Split readout	
	2 FPM : 8 SM THRs	240 µs (4.1 Kfps) @ 2x12-bit CRW or 24-bit, 16 links @640Mbps and Split readout 20 µs (50 Kfps) @ 2x1-bit CRW or 2-bit, 16 links @640Mbps and Split readout	
Input clocks		Readout clock up to 320 MHz (only in edge peripheries) Slow Control clock up to 40MHz	

Courtesy of X. Llopart (CERN)

First Medipix4 bonded to sensor by the end of 2023

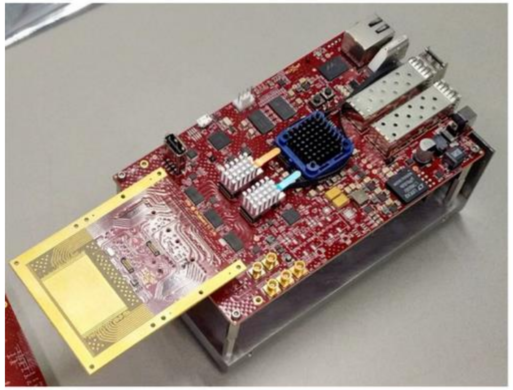
MEDIPIX4 at INFN

- Activities funded by INFN-CSN5 for technological research and interdisciplinary application
- Main goal: exploitation of the family of application-specific integrated circuits (ASICs) developed by the Medipix4 Collaboration at CERN
- Main activities and applications of interest
  - New sensors development (SiC, UV)
  - Dosimetry and Nuclear Medicine
    - Nuclear Medicine - Compact gamma camera
    - Dosimetry - Gamma-ray detector for dosimetry and MV X-rays, Diagnostic X-ray beams, charged particles
  - X-ray imaging
    - Spectral imaging
    - Phase Contrast Imaging

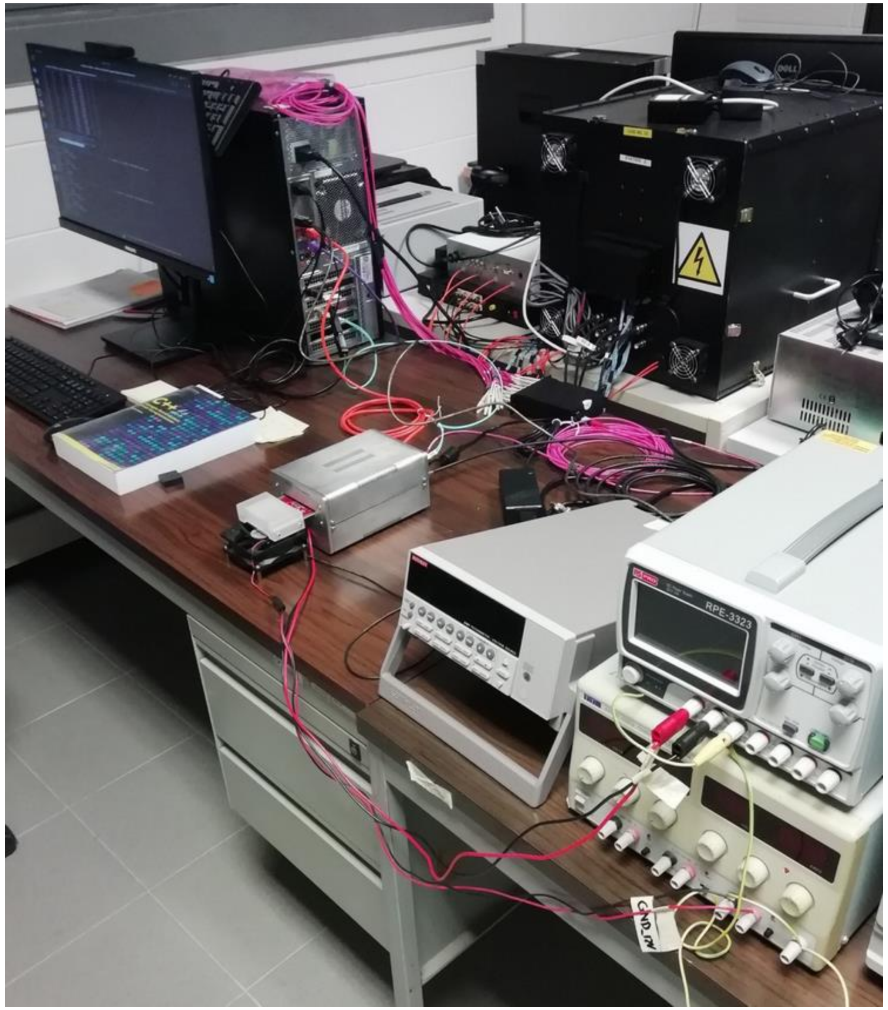
Currently ongoing: test and characterization of Timepix4 assemblies

Assemblies, Readout, Acquisition software

- Silicon bump-bonded assemblies available
- High-Z sensor bump-bonded assemblies under development
- All measurements done so far on the Timepix4 ASIC are based on the SPIDR4 read-out system developed by Nikhef
  - 1 Gb ethernet slow control, 10 Gb/s ethernet read-out and full bandwidth read-out (160 Gb/s though optical fibers and dedicated PCIe receiver board on DAQ server)
- Dedicated control and DAQ open-source software developed at INFN
- Control and DAQ FPGA-based board under development at INFN



Tests performed



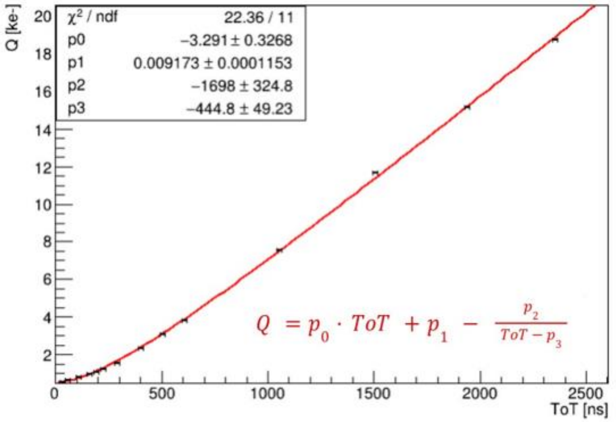
- Threshold equalization
- Noisy pixel detection and masking
- Test pulse (simulating pattern of hits on pixels) test and calibration
- Data driven acquisition tests with radioactive sources and picosecond pulsed laser
- Timing resolution measurements

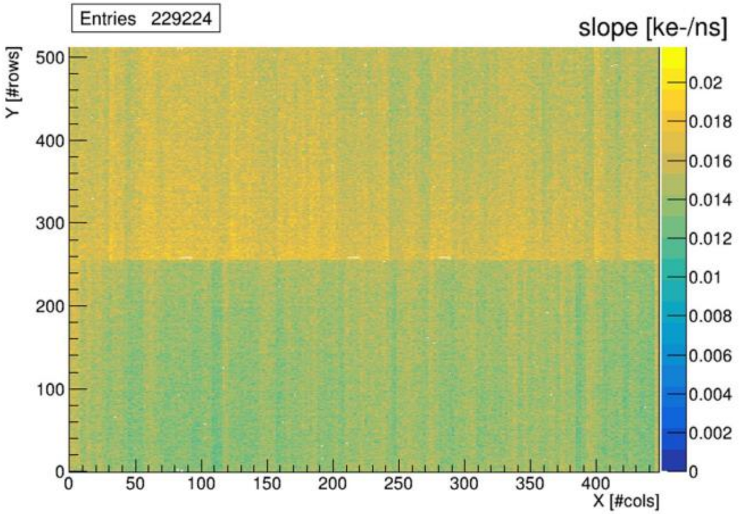
INFN

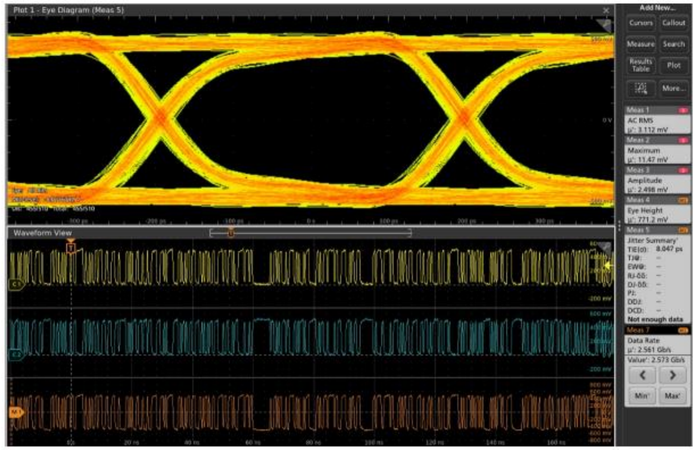
Test pulse calibration

Calibration of ToT versus charge injected

- Analog testpulse
- Per pixel calibration over the whole matrix
- Automatic algorithm exploiting 10 Gbps links
- Calibration fit parameters distribution for linear region



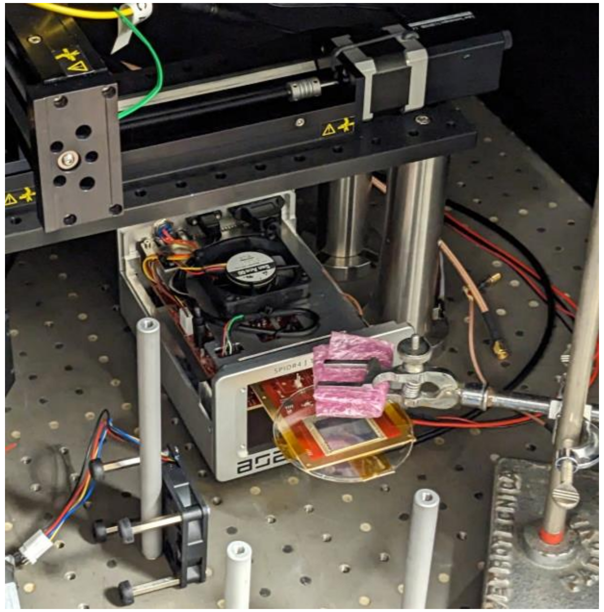




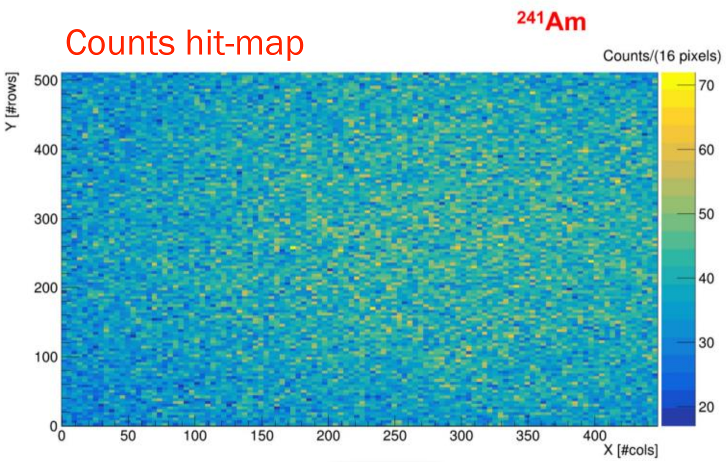
R. Bolzonella (INFN FE)

Measurements with radioactive sources

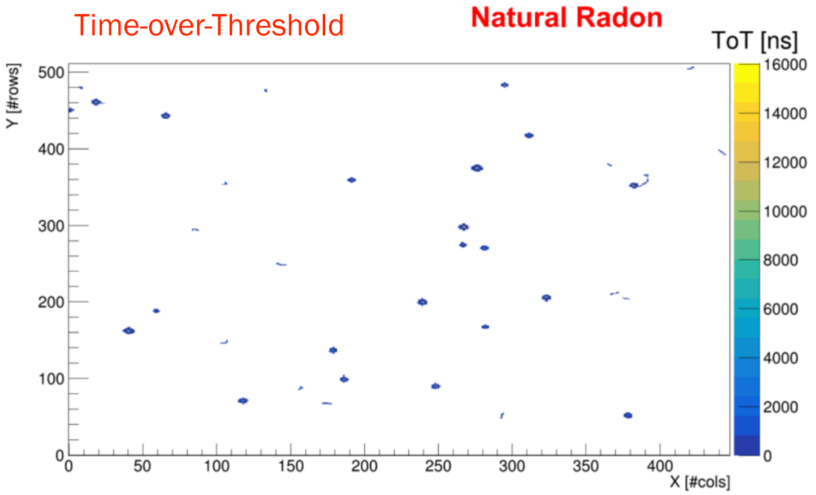
- Ongoing measurements with radioactive sources: Sr-90, Am-241 and Cs-137
- Si-sensor 300 um



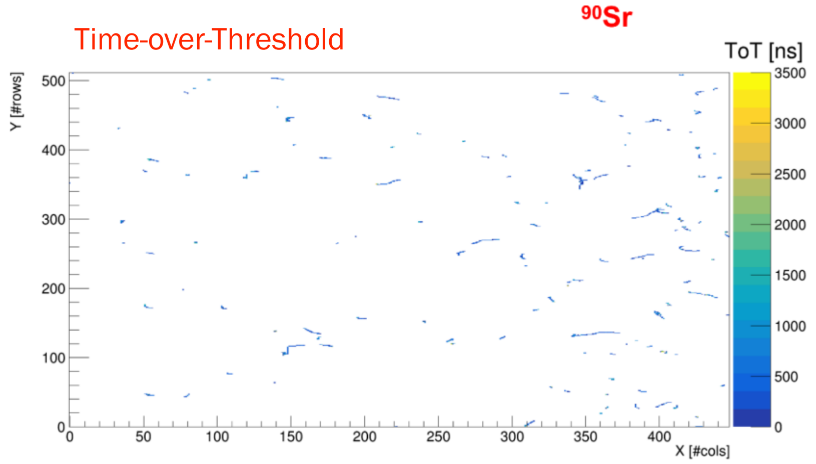
Counts hit-map



Time-over-Threshold

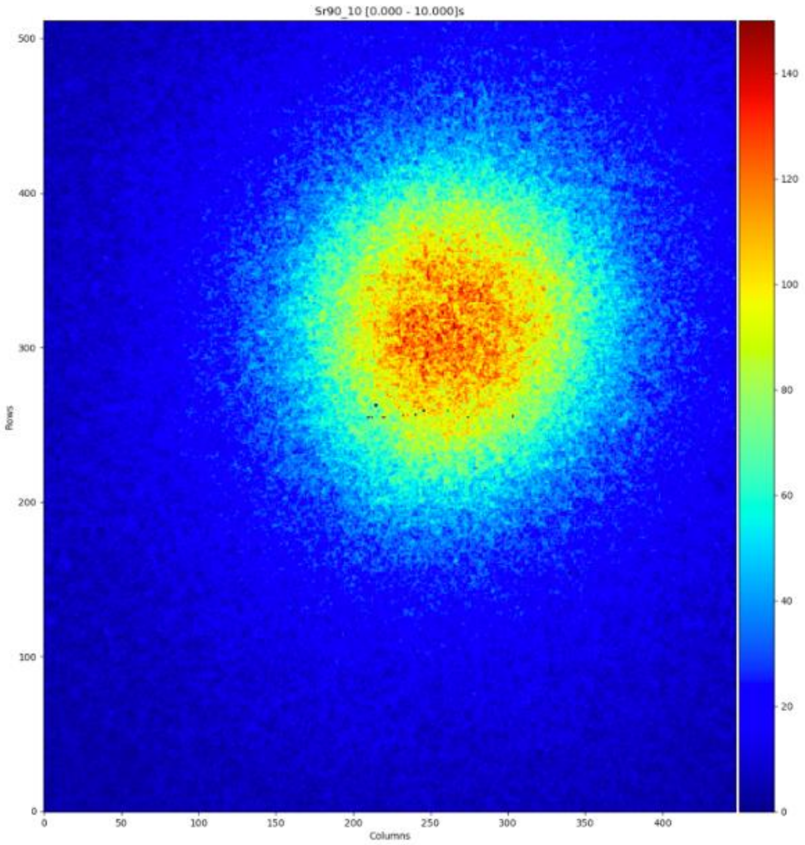


Time-over-Threshold

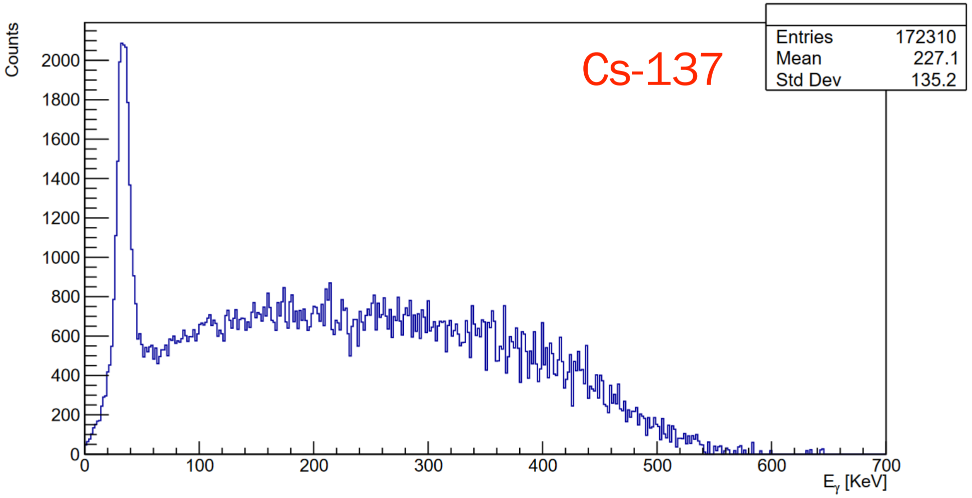


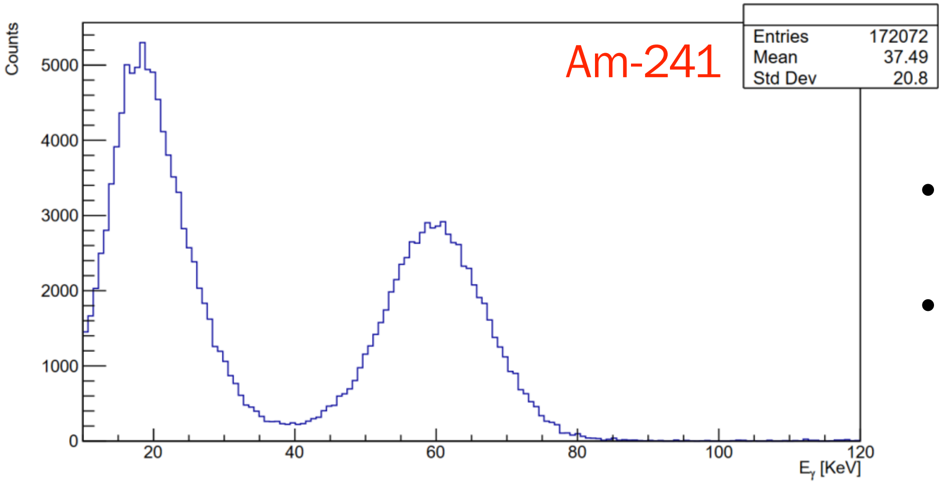
Test of Timepix4 fast data readout

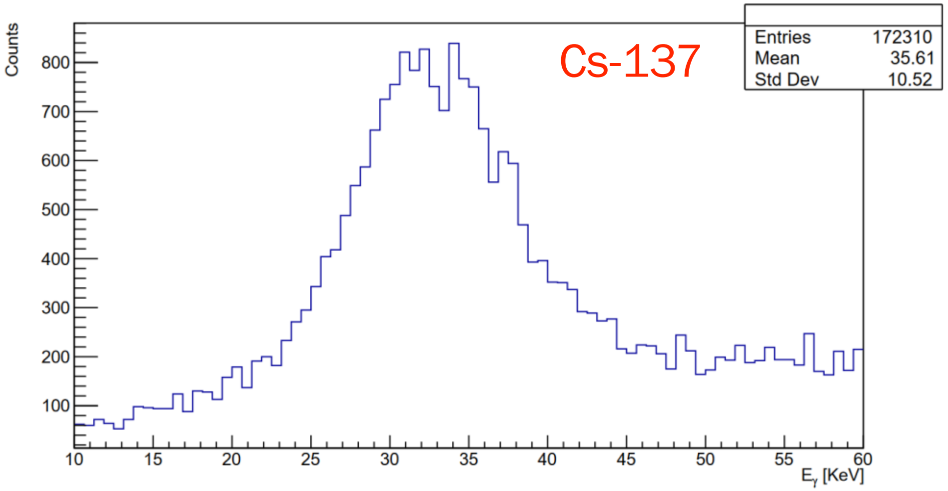
- 2 links enabled at 2.56 Gbps (5.12 Gbps total)
  - SPIDR4 system + 10 Gb Ethernet link + 1 PC
- No noticeable difference w.r.t. slow-control read-out
- Example:
  - 90Sr source, 10s acquisition with fast read-out
  - Thr =800e with ~120 pixels masked
  - ~6 M packets received without errors (link stability looks to be very good)
    - PC 1 pixel packet = 1 count

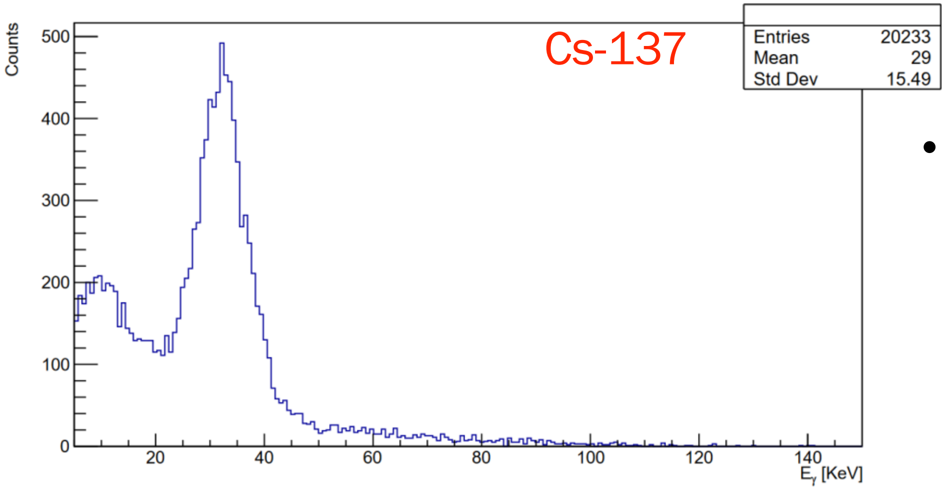


Energy distribution measure with radioactive sources







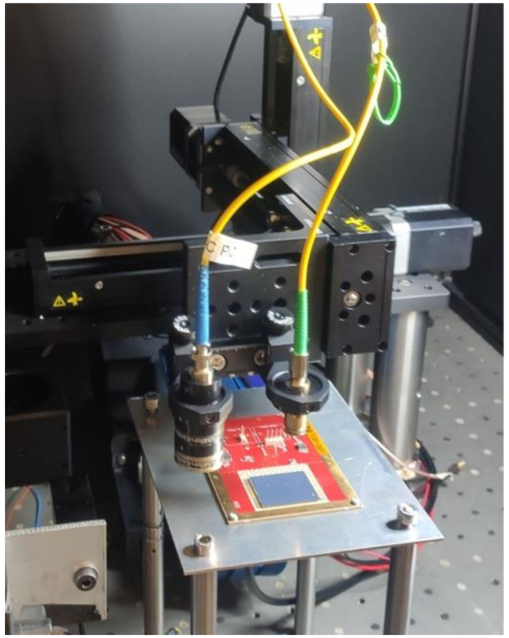


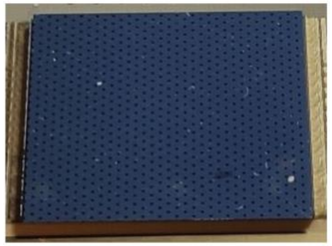
- 300 um Si Sensor
- Calibration of ToT made with emission peak energy
  - 59.54 keV Am-241
  - 32 keV Cs-137 (Ba X-ray)
- Energy resolution to be improved
- Pixel-to-pixel calibration is a work in progress

Courtesy R. Bolzonella (INFN-FE)

Timing resolution measurements of Timepix4

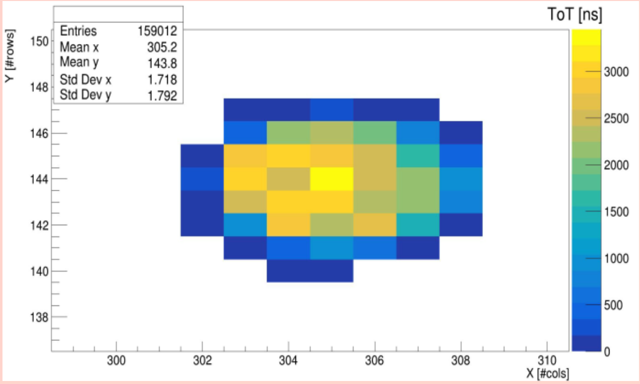
- Setup
  - Timepix4V2 bonded to a 100 µm n-on-p Si detector (borrowed from Nikhef):
    - Biased at -150 V
    - Metallization with holes pattern
  - Pulsed Diode Laser PDL 800-B:
    - 1060 nm
    - Trigger simultaneously sent to laser and Timepix4 Trigger input





- Measurement
  - After TOT timewalk correction and VCO calibration:
    - **Single pixel resolution** of 111 ± 1 ps
    - **Cluster timing resolution** of σ_{ToAAvg} = 49 ± 1 ps

Preliminary!!!

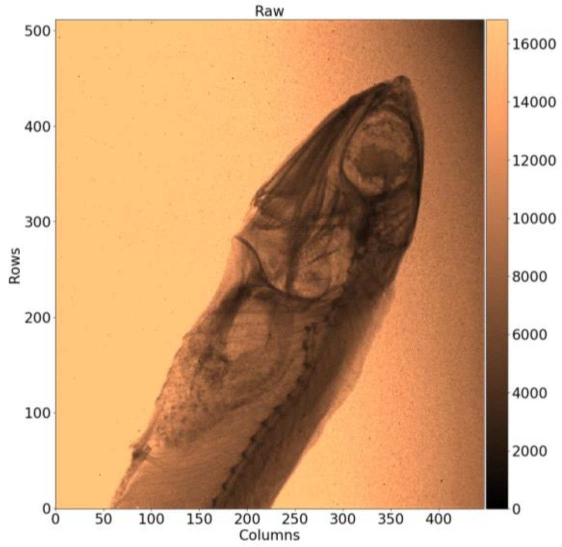


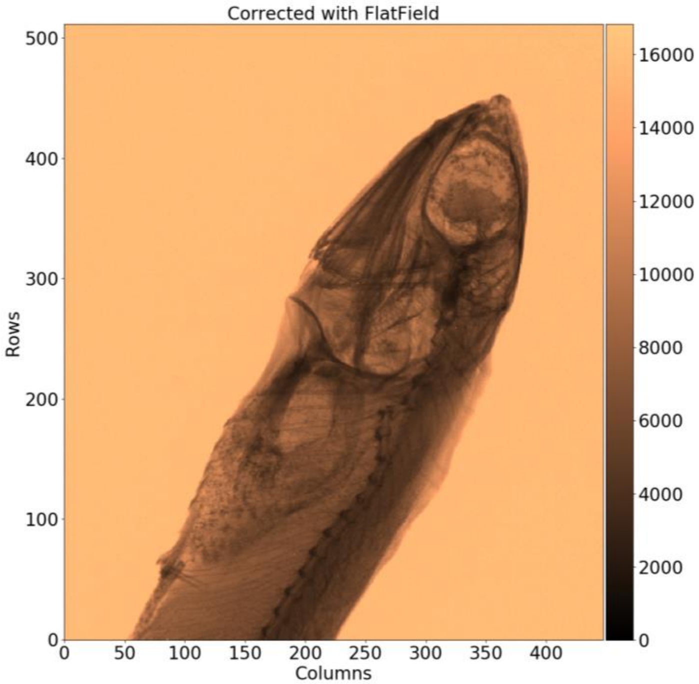
- σ = 1.4 pixel = 77 µm
- most of the charge is released in 4-5 pixels
- Wide range of released charge covered

Courtesy of R. Bolzonella (INFN-FE)

First X-ray images

- Taken with Timepix4_v1 and a full-sized (2021)
- 300µm thick Si sensor
- Excellent bump bonding quality (<10 missing pixels in 230k)
- Experimental setup at **CERN**:
  - X-ray source, Cu target, 30 kVp
  - 16-bit frame-based mode
  - exposure time = 2 s
  - Images taken using the slow control
  - approx. 20k counts per pixel
  - The flatfield map from 20 identical images





Courtesy of X. Llopart (CERN)

Conclusions

- Medipix4 ASICs family: Timepix4 and Medipix4
- First **Timepix4 assemblies with Si sensors are currently available** at INFN
- Assemblies with other sensors (high Z, high density) will be available soon
- **Testing and characterization of hybrid pixel detectors based on Timepix4 is ongoing** at INFN laboratories (data-driven mode)

Next activities foreseen

- Characterization with radiation (radioactive sources, X-ray tubes and synchrotron light) in light of possible applications
- Test of Timepix4 frame-based mode

Thanks for the attention