Single-photon imaging detector with sub-100 ps and <10 μm resolutions

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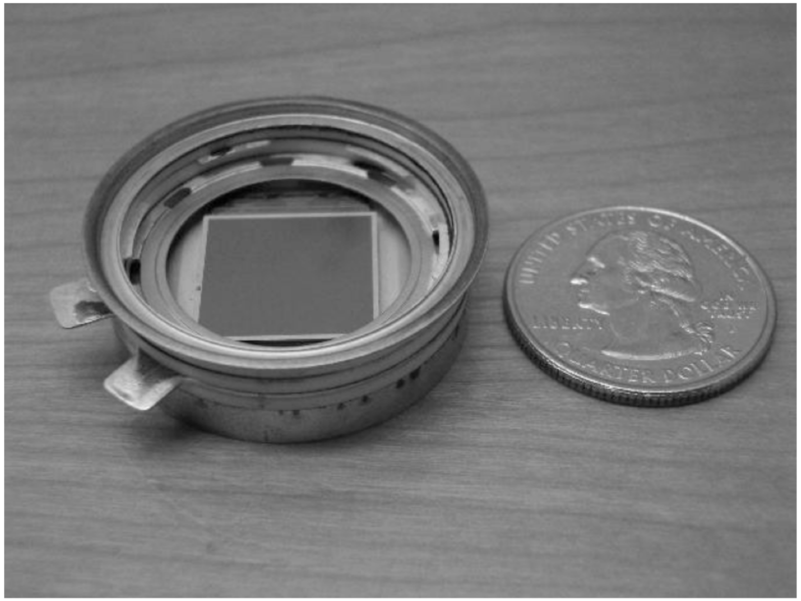
Outline

- Optical imaging tube
  - Proof of concept based on Medipix2
  - Electron tracking using a quad-Timepix
  - Detection of non-classical light
- Single-photon imager with sub-100 ps and <10 μm resolutions
  - Detector specifications
  - Timepix4-based read-out
  - Time-walk correction
  - Data acquisition system
  - Application example: high-energy physics
- Conclusions

Optical imaging tube

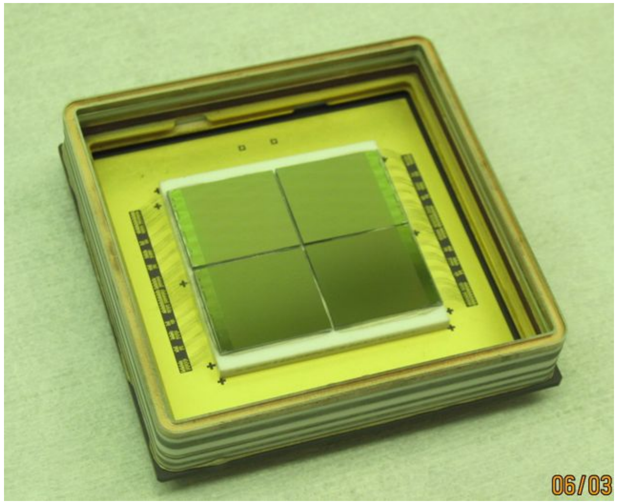
- Optical imaging tube fabricated in-house: ASIC embedded in vacuum tube (J. Vallerga, A. Tremsin et al., 2008)
- Multi-alkali photocathode S20
  - Quantum Efficiency (QE): maximum 4% at ~400 nm
- Chevron MCP pair
- Based on Medipix2 ASIC
  - 256 × 256 pixels
  - Only photon counting
  - No timing information
- Successful sealing of the tube
  - CMOS ASIC survived high-temperature processing steps
  - Proof of concept



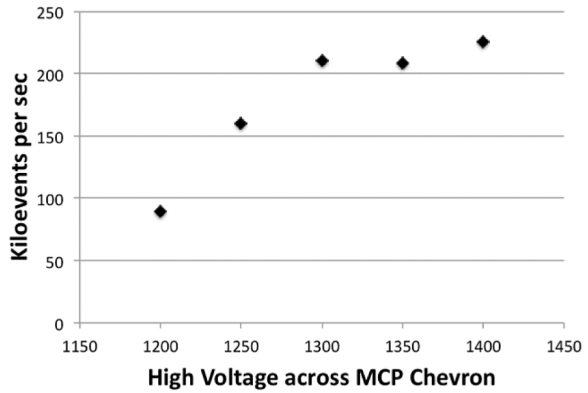
Proc. SPIE 7021 2008
(J. Vallerga, A. Tremsin et al.)

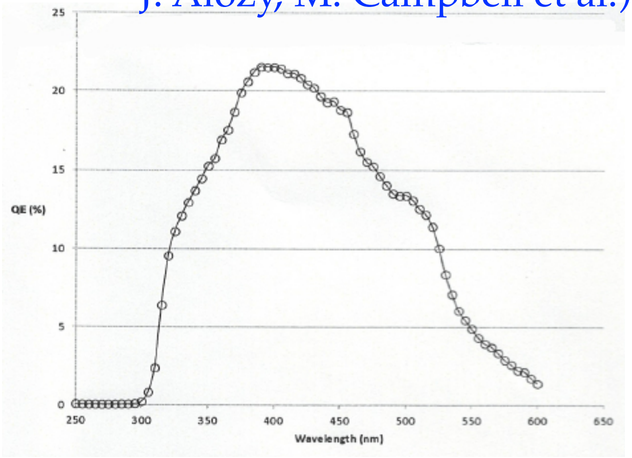
Quad-Timepix imaging tube

- Prototype optical photon counting imaging tube (development 2009-2013 by Medipix2 Collaboration)
  - 4 × Timepix (4 × 256 × 256 pixels)
  - Time-tagging of events (10 ns) or Time-over-Threshold measurement
  - 50 mm square tube (Photonis)
  - Bi-alkali photocathode (22% max QE)
  - Chevron MCP pair (25 μm pores)



JINST 9 C05055 2014
(J. Vallerga, A. Tremsin, T. Michel, J. Alozy, M. Campbell et al.)





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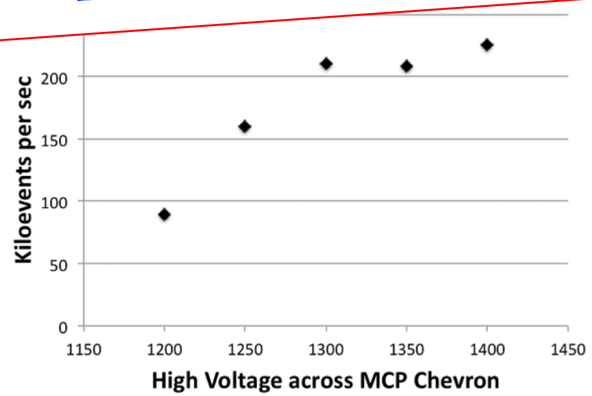
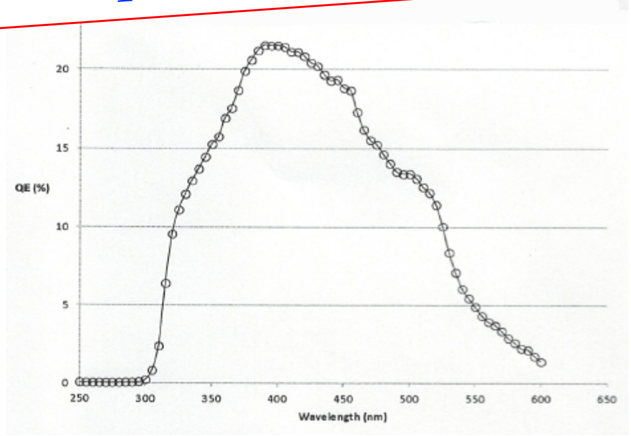
Talk by Anton Tremsin tomorrow

"Optimization of spatial resolution and detection efficiency for photon/electron/neutron/ion counting detectors with Microchannel Plates and Quad Timepix readout"

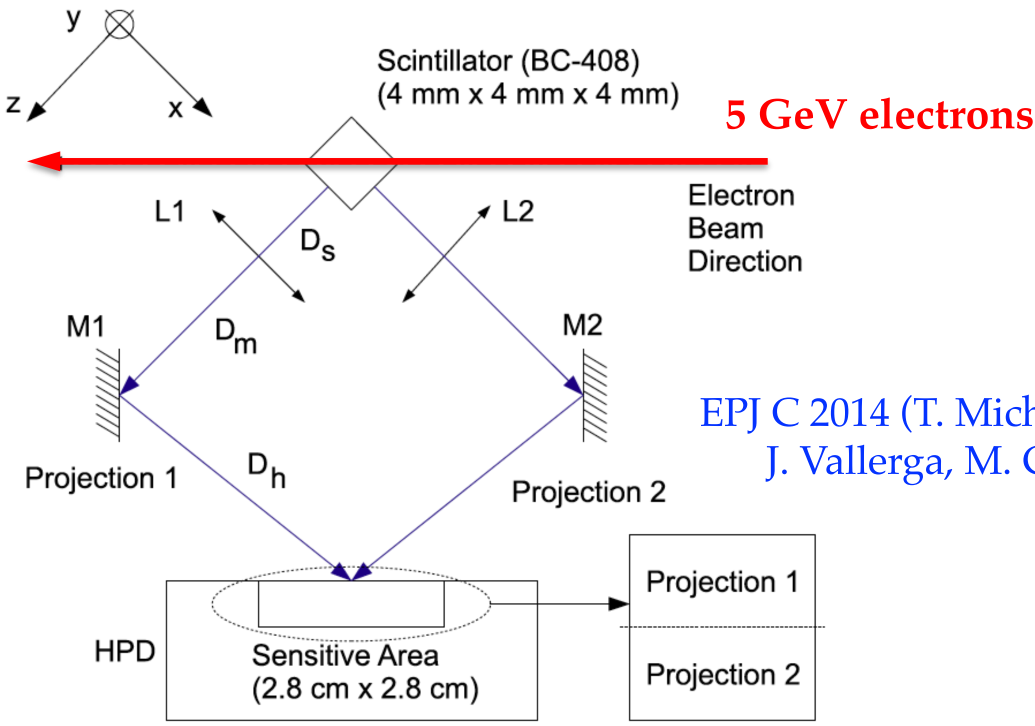
…el,

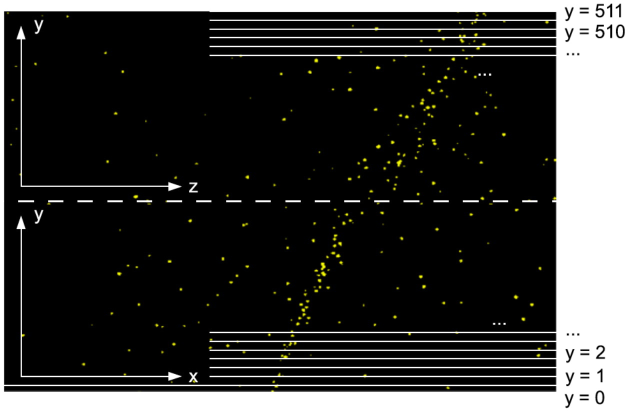




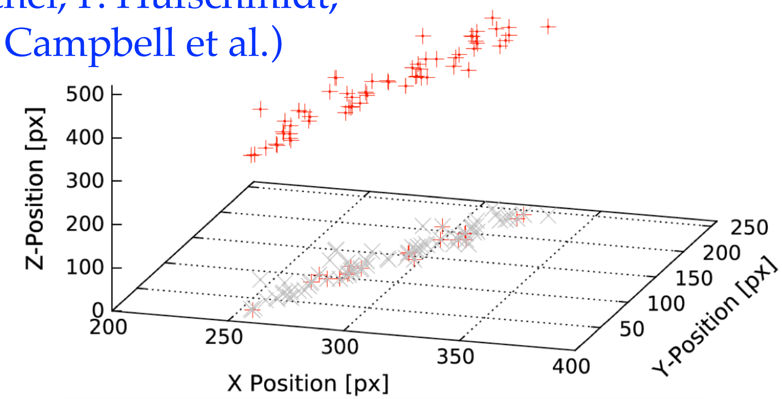
Electron tracking

- Reconstruction of particle trajectories to distinguish between charged particles (e.g. HEP and 0ν2β decay)





EPJ C 2014 (T. Michel, P. Hufschmidt, J. Vallerga, M. Campbell et al.)

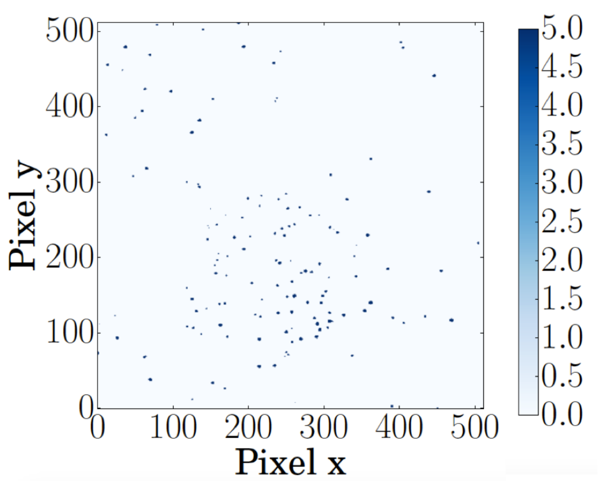


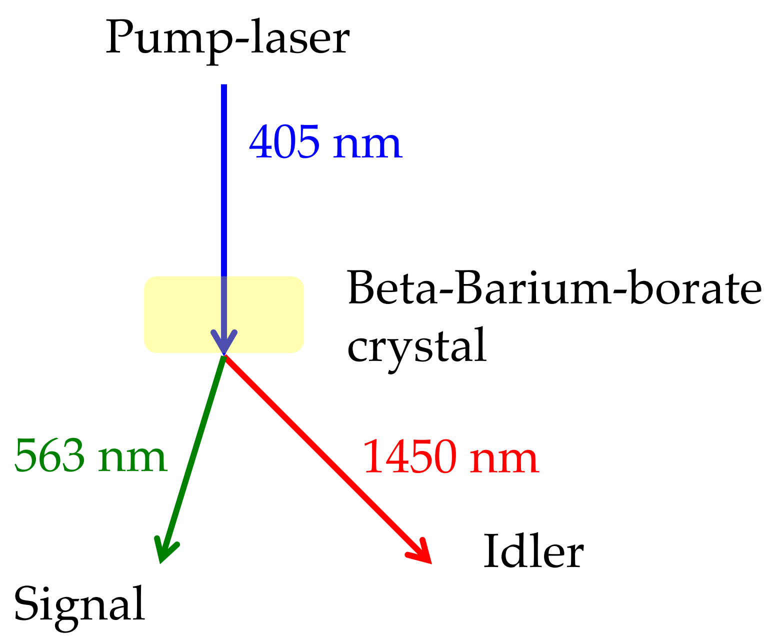
- Resolution of ~200 μm (proof of concept)

Quantum optics (1)

- Detection of non-classical light from "spontaneous parametric down-conversion"
  - Use of two-photon correlations for an absolute quantum efficiency measurement

Example of single frame



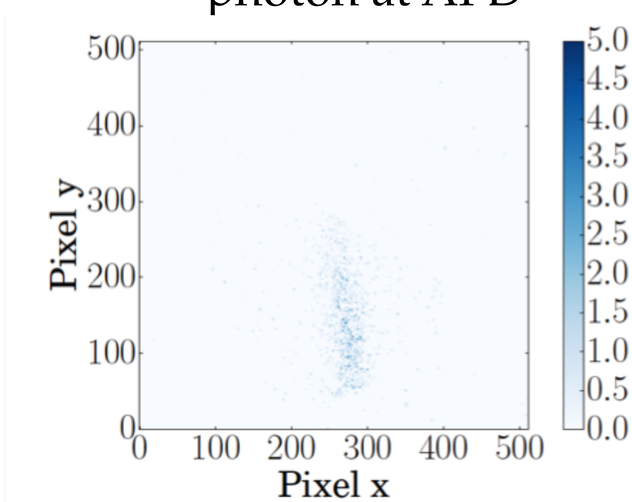


Optics Express 22 17561 2014
(T. Michel, J. Vallerga, M. Campbell et al.)

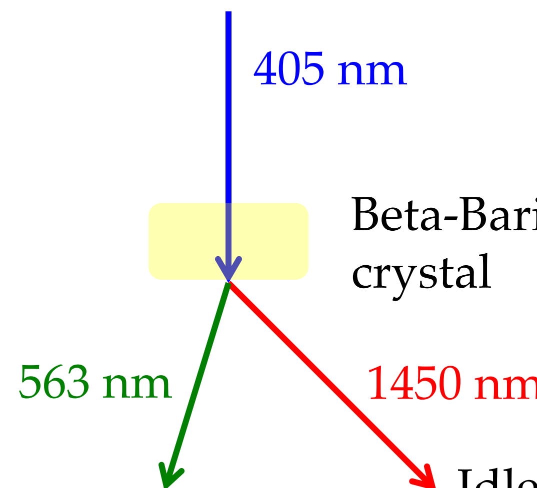
Quantum optics (2)

- Detection of non-classical light from "spontaneous parametric down-conversion"
  - Use of two-photon correlations for an absolute quantum efficiency measurement

In coincidence with idler photon at APD



Pump-laser (starts Timepix)



Beta-Barium-borate crystal

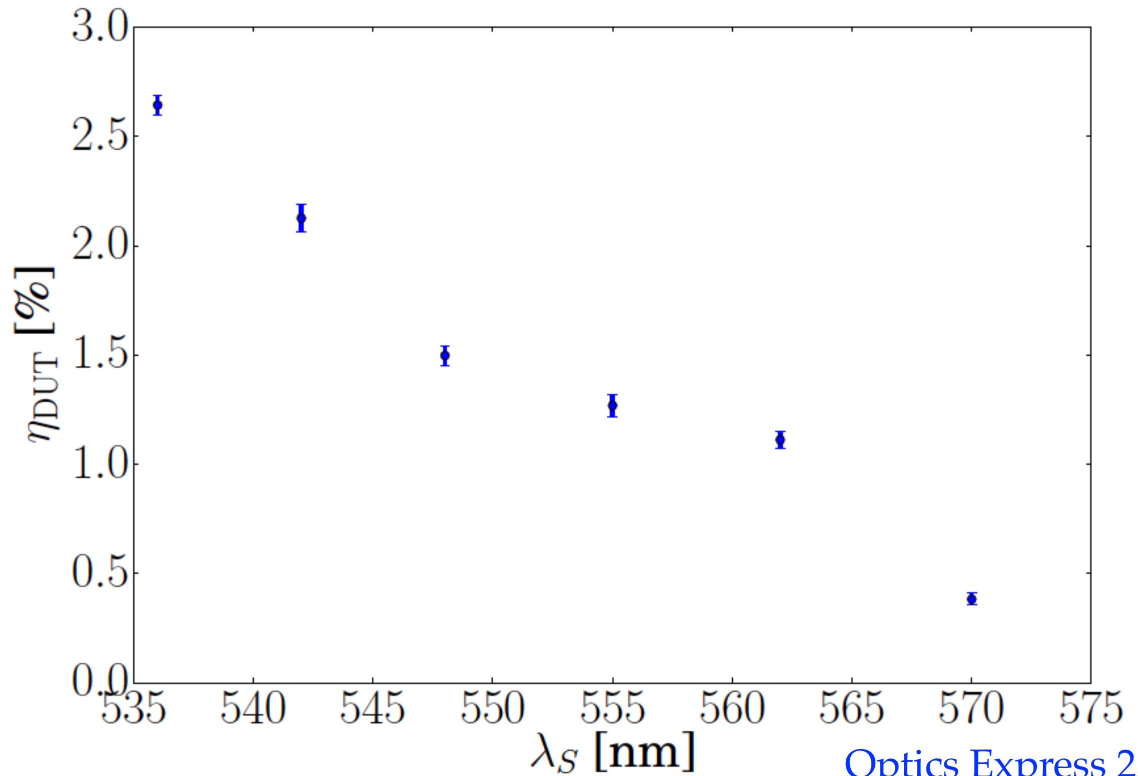
Signal: Timepix in ToA mode measures timestamp

Idler: APD stops Timepix

Optics Express 22 17561 2014
(T. Michel, J. Vallerga, M. Campbell et al.)

Quantum optics (3)

- This approach allows absolute Quantum Efficiency measurement
  - No need for a reference calibrated detector



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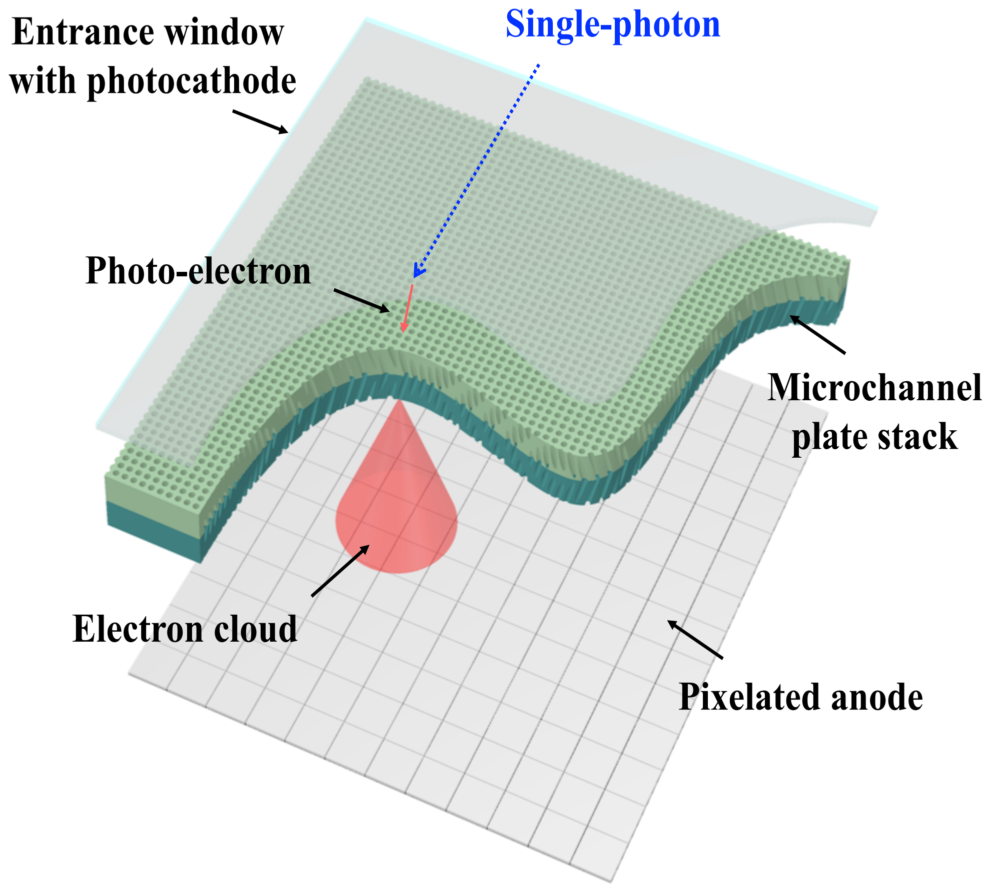
(T. Michel, J. Vallerga, M. Campbell et al.)

Single-photon imager

- Detector concept
  - Up to 10^9 individually detected photons per second, with simultaneous measurement of position (<10 μm resolution) and timing (few tens of picosecond)
  - Large active area (7 cm^2) and low dark count rate at room temperature (10^2-10^3 Hz/cm^2)
  - Pixelated anode based on the Timepix4 ASIC



Detector specifications

- Optimized bi-alkali photocathode
- MCP with 5-10 μm pore diameter, operated at low gain (a few 10^4) and with atomic layer deposition (ALD) for lifetime increase to >10 C/cm^2 integrated charge
- Photocathode-to-MCP distance preserves impact position information
- Optimized MCP-to-anode distance spreads the electron cloud over a number of pixels
  - Improve spatial resolution (ultimately limited by pore size)
  - Improve timing resolution (multiple sampling)
  - Compromise between achievable resolutions and data rate
- Key expected performances per single-photon: few tens of picosecond timing resolution, 5-10 μm position resolution

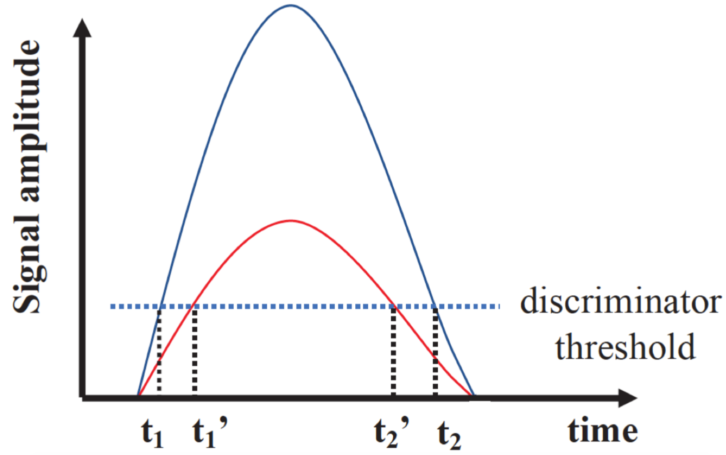
Timepix4: specifications

Technology			**CMOS 65 nm**
Pixel Size			55 µm × 55 µm
Pixel arrangement			4-side buttable 512×448 (0.23 Mpixels)
Sensitive area			6.94 cm^2 (2.82 cm × 2.46 cm)
Read-out Modes	Data driven	Mode	TOT and TOA
		Event Packet	64-bit
		Max rate	178.8 Mhits/cm^2/s
	Frame based	Mode	CRW: PC (8 or 16-bit)
		Frame	Full Frame (without pixel addr)
		Max count rate	~800 Ghits/cm^2/s
TOT energy resolution (Si sensor)			**< 1 keV**
Time resolution			**~200ps**
Readout bandwidth			≤81.92 Gbps (16× @5.12 Gbps)
Equivalent noise charge			50-70 e^-
Target global minimum threshold			<500 e^-

Adapted from X. LLopart

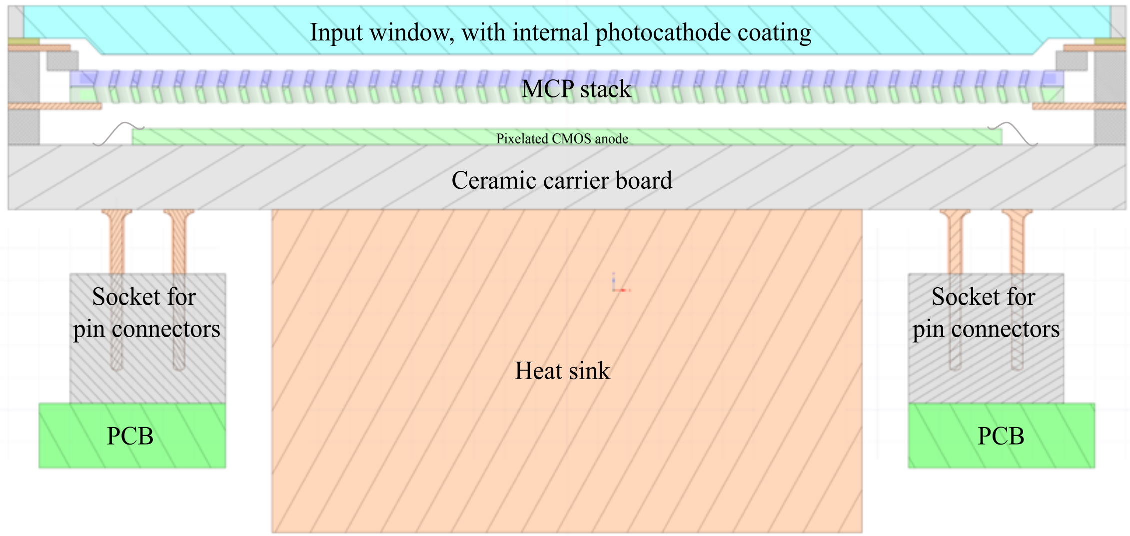
Time-walk correction

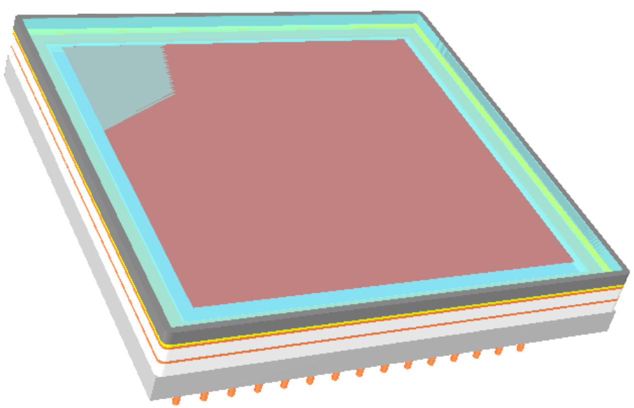
- Timepix4 allows to time-stamp leading time and measure Time-over-Threshold (ToT) for each individual pixel
  - 195 ps LSB TDC (~60 ps rms resolution for 1 pixel)
  - ToT measured with 1.6 ns precision (time-walk correction possible for each pixel hit)
- One photon creates an electron cloud that typically hits >1 pixel, and a centroid algorithm can be used to improve spatial and timing resolution
- A weighted average of the cluster pixels position can be calculated using their ToT information
  - Possible to reach 5-10 μm resolution with optimised geometry



Vacuum tube design

- Detector side-view

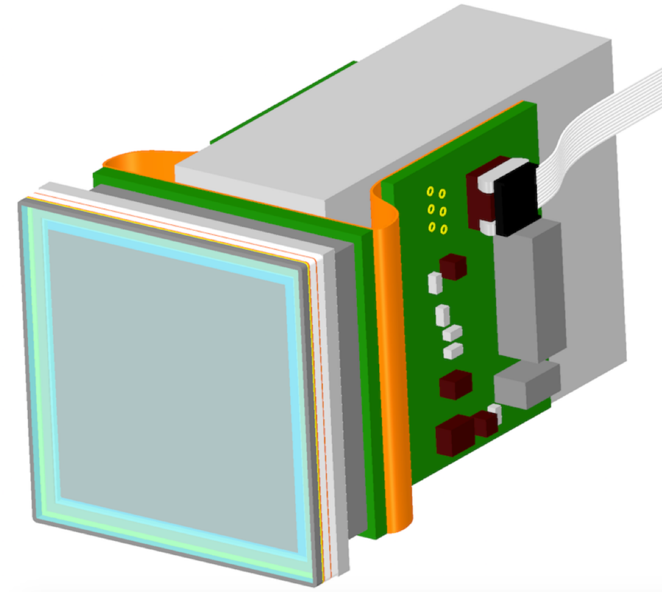




- 3D rendering

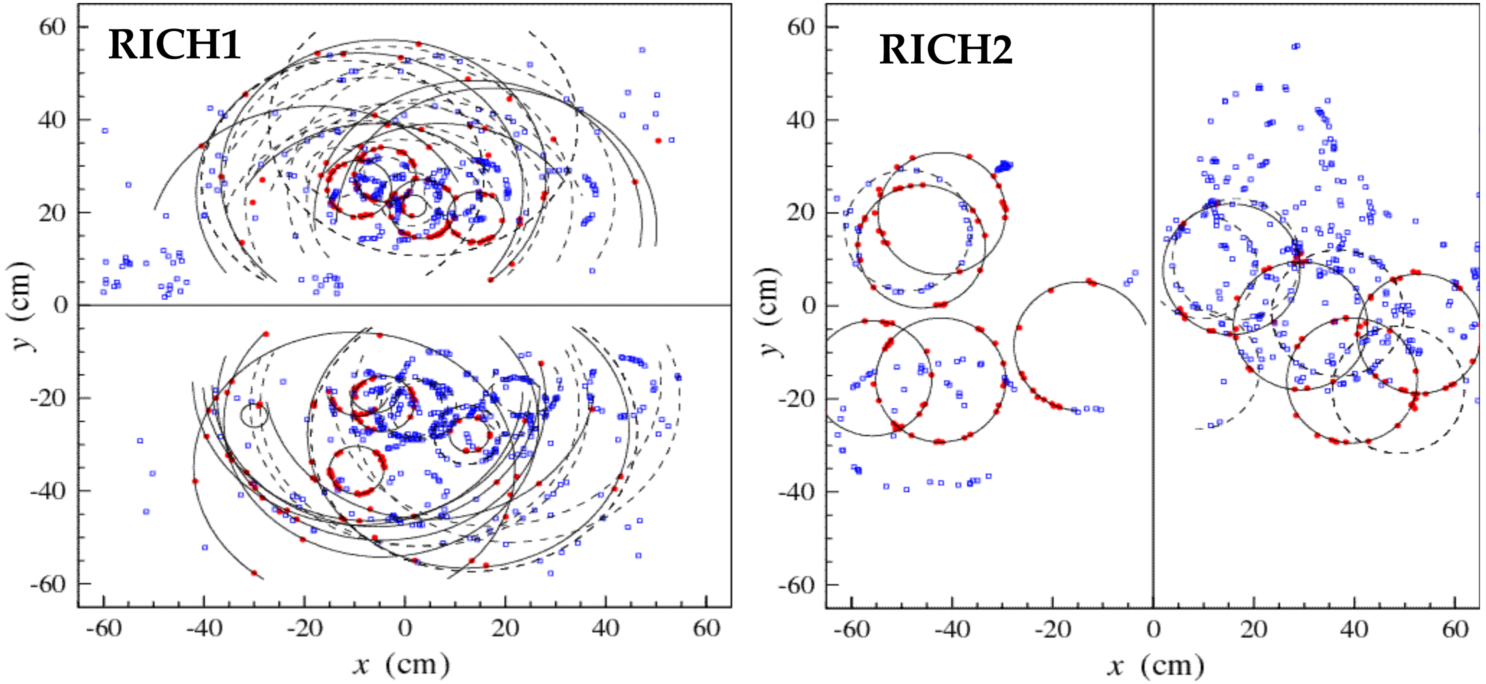
Electronics and DAQ

- Front-end electronics architecture is data driven
  - 64 bit for each pixel hit
  - 80 Gbps maximum data rate for a total photon rate of 1.2 Ghits/s
- Flexible design: electro-optical transceivers will link the ASIC to an FPGA-based board for the exchange of configuration and the collection of event data
  - FPGA far from detector
- The FPGA will perform serial decoding and send the data directly to a PC for storage using fast serial data links



Application in HEP (1)

- Single-photon detectors are crucial for fundamental research in high-energy physics (HEP)
  - Used for detection of Cherenkov and scintillation light
- For example, experiments use Ring Imaging Cherenkov (RICH) detectors for charged particle identification (PID)



LHCb Run 1

Typical event "snapshot" (1 every 25 ns)

Application in HEP (2)

- High-Luminosity upgrade of the LHC
  - Large increase in detector occupancy → pile-up (many events within 25 ns time window) → reconstruction inefficiencies
- Interactions are spread in space but also time
  - Use time-tagging detectors (few tens of ps resolution) → discriminate overlapping events exploiting time-association of the hits → timing as new handle for pattern recognition
- A RICH detector equipped with such device could deliver unprecedented information and allow efficient PID:
  - High granularity (Cherenkov angle resolution improvement), high rate capabilities, timing resolution (simplify pattern recognition improving efficiency), very small dark count rate (negligible detector-related background), robust in magnetic fields (thanks to MCP and tube geometry)

Conclusions

- The use of a bare CMOS ASIC inside a vacuum tube with a MCP has proved to be a solid approach for the detection of single photons
- A new detector concept has been presented, which will allow to detect up to 10^9 photons/s with simultaneous measurement of time and position with unprecedented resolutions (few tens of ps and <10μm respectively)
  - Fully exploit both timing and position resolutions of a MCP
  - High-performance data acquisition (up to 80 Gbps)
- Many potential applications
  - High-energy physics, quantum optics, life sciences