ERIK FRÖJDH
CERN

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HYBRID PIXEL DETECTORS

-Basic principles and applications

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ME

- PhD Student at Mid Sweden University
- Full time at Miun 2010-2011
- Moved to CERN for a 3 year fellowship contract within the ARDENT project.
- Working in the microelectronics division together with the Medipix design team
- Chip characterization and applications for imaging and dosimetry

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OUTLINE

- CERN
- Hybrid Pixel Detectors
  - Timepix
  - Medipix3RX
- Applications
  - Color X-ray imaging
  - Particle identification and dosimetry
- New detectors
- Summary

CERN

The world's largest particle physics research laboratory

An international effort of:

20 European Member States

7 Observer or Acceding States

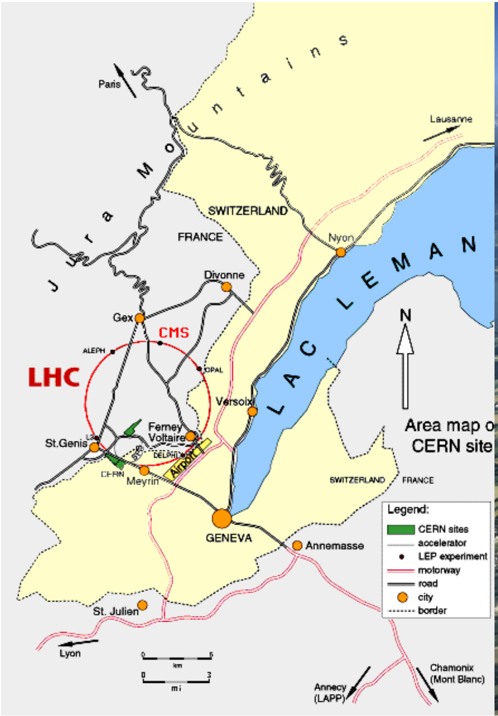
28 Non-Member States involved in particular projects

~ 2 400 staff members (75% are applied physicists, engineers and technicians)

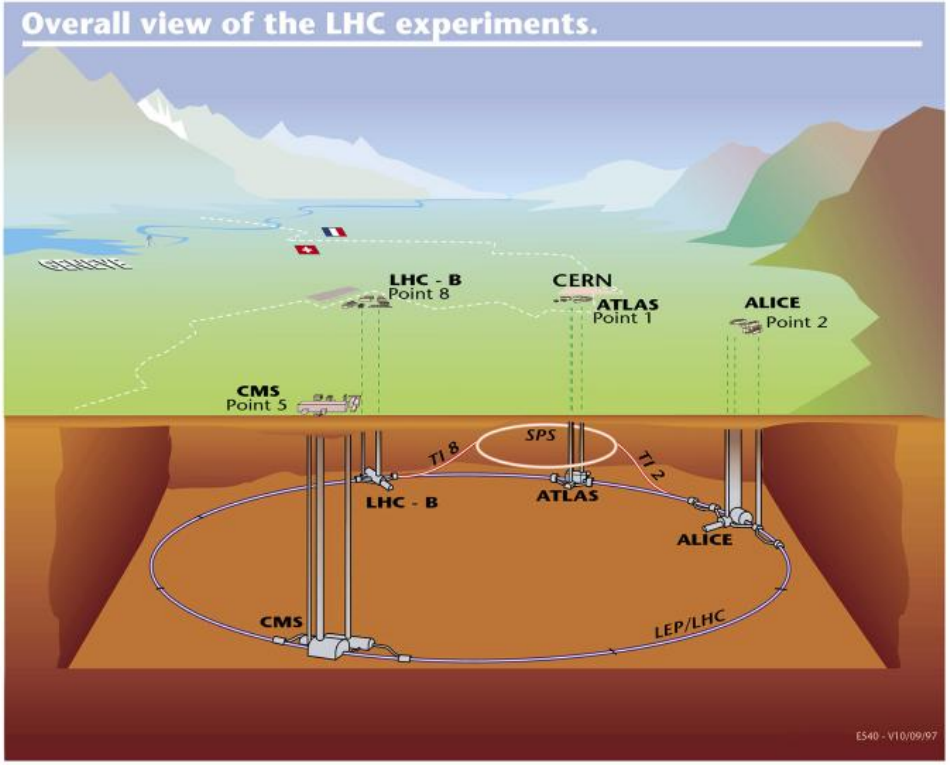
~ 11 500 users from all over the world (mostly physicists)

Annual budget ~ USD 1 000 000 000

AN AERIAL VIEW OF CERN AND THE LARGE HADRON COLLIDER ACCELERATOR COMPLEX



THE LARGE HADRON COLLIDER



Two counter rotating proton beams on 27km circumference ring

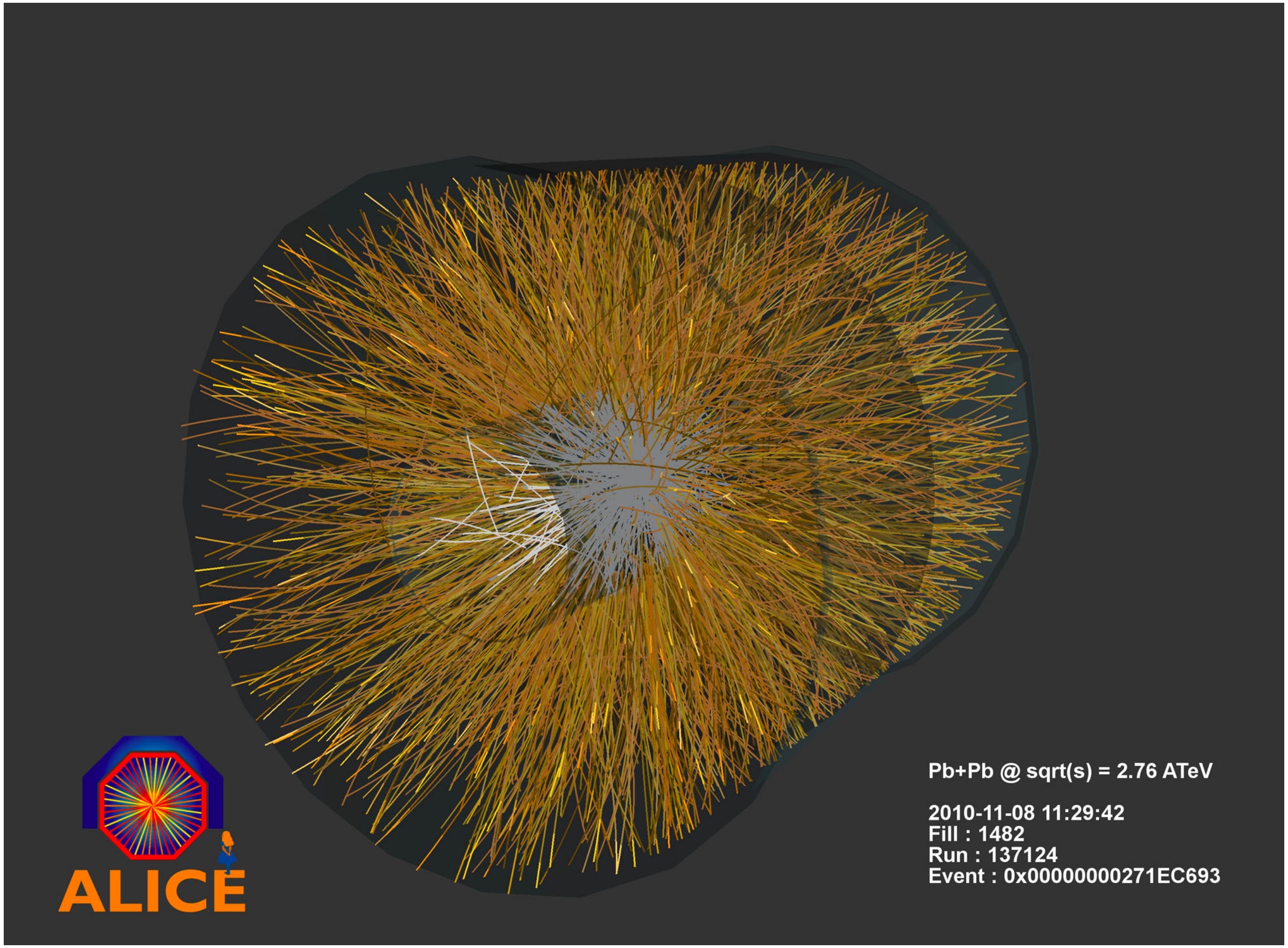
Particle bunch crossings 40 M times per second

100 billion particles in each bunch

Several 1 000 particles created per bunch crossing

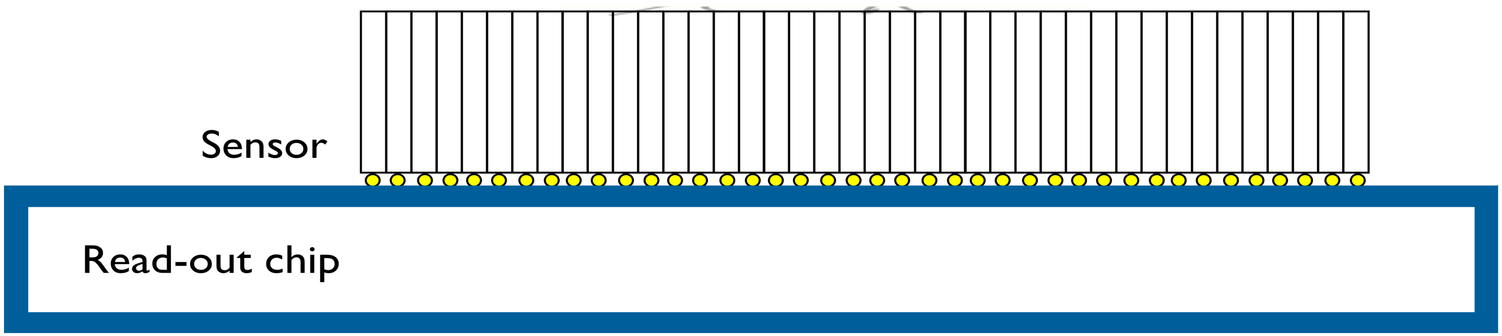
7 TeV on 7 TeV Collisions

Entire magnet ring cooled to 1.8K



Lead-Lead Collision at ALICE

HYBRID PIXEL DETECTORS



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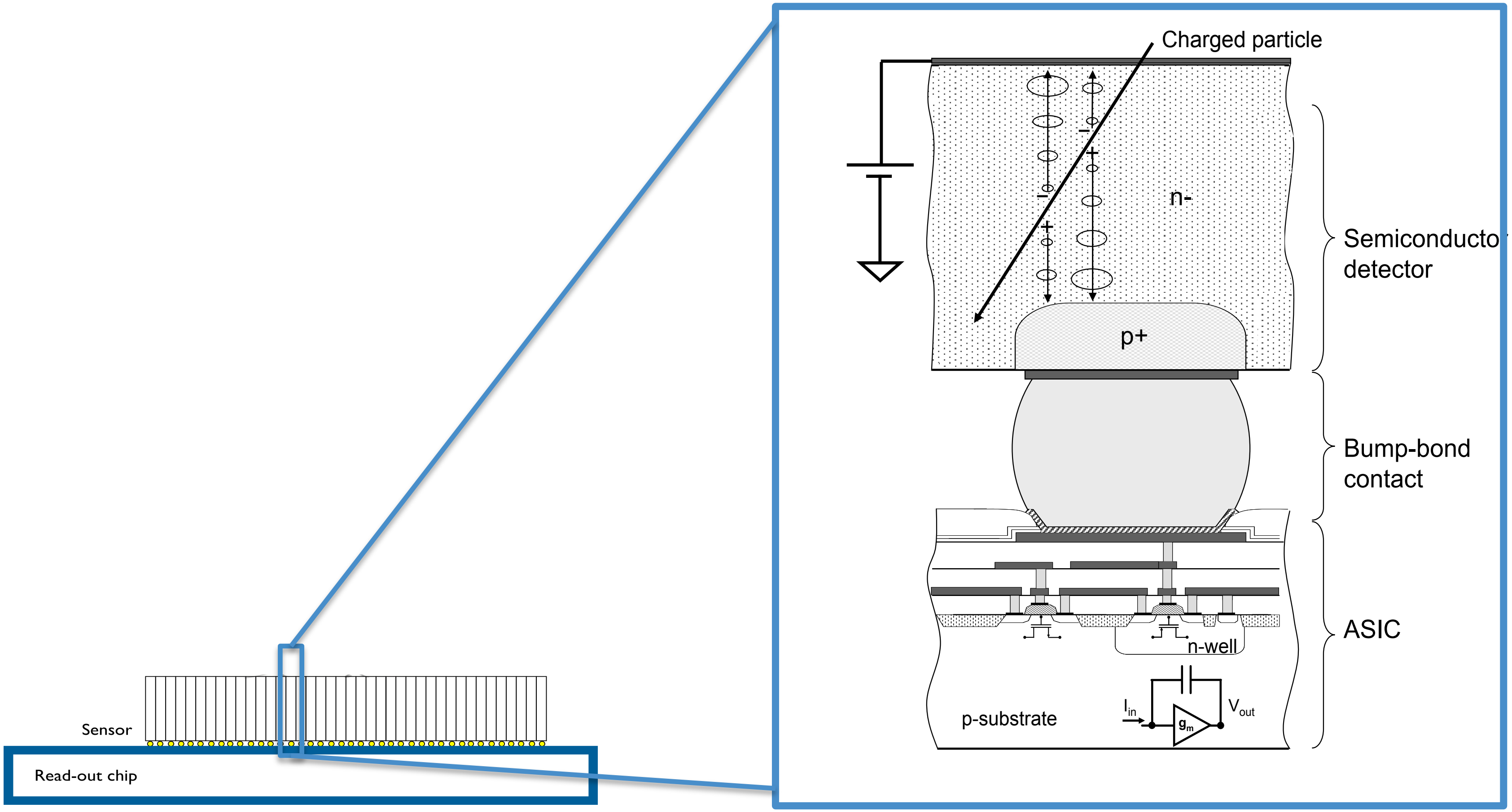
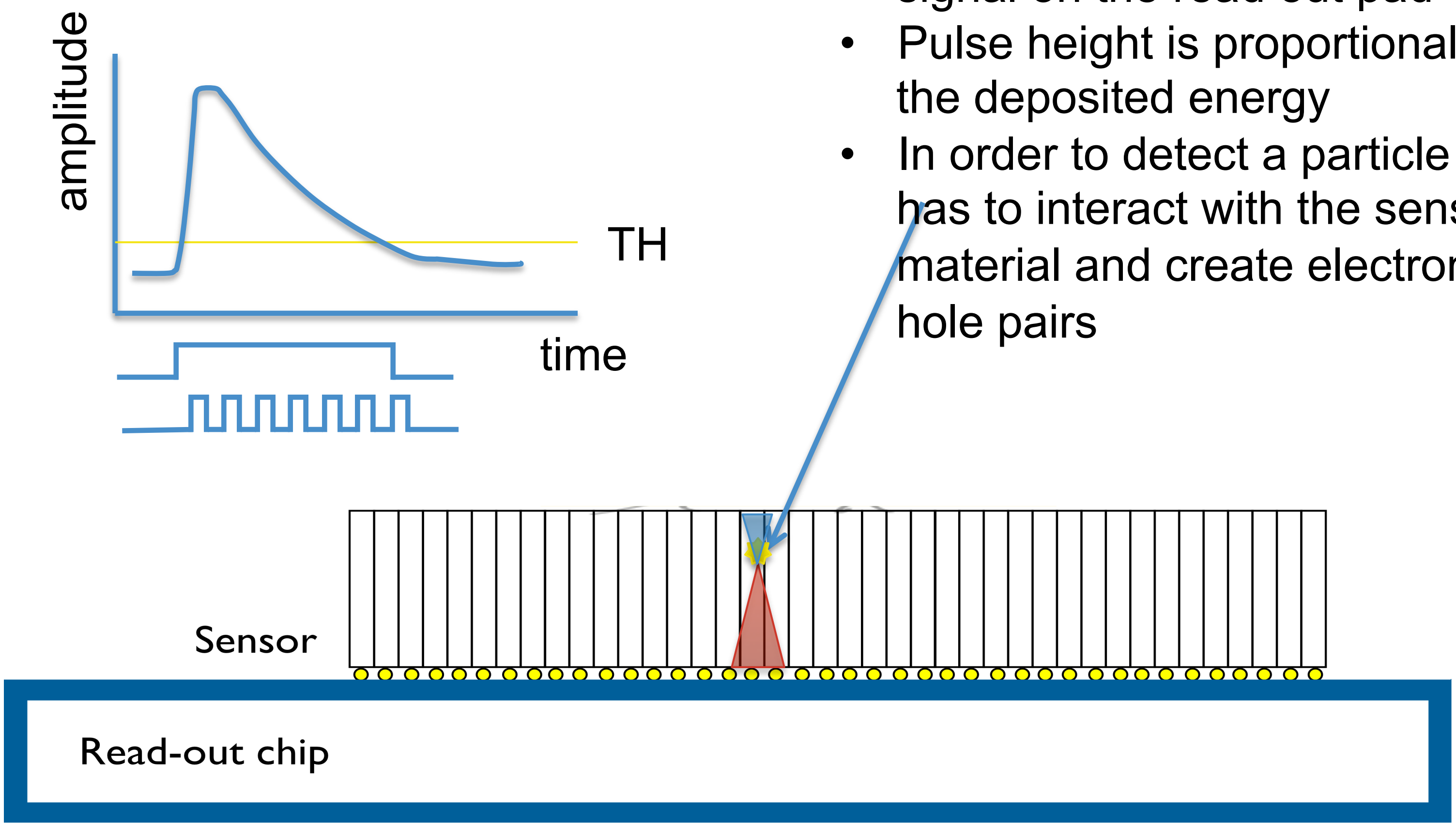
HYBRID PIXEL DETECTORS

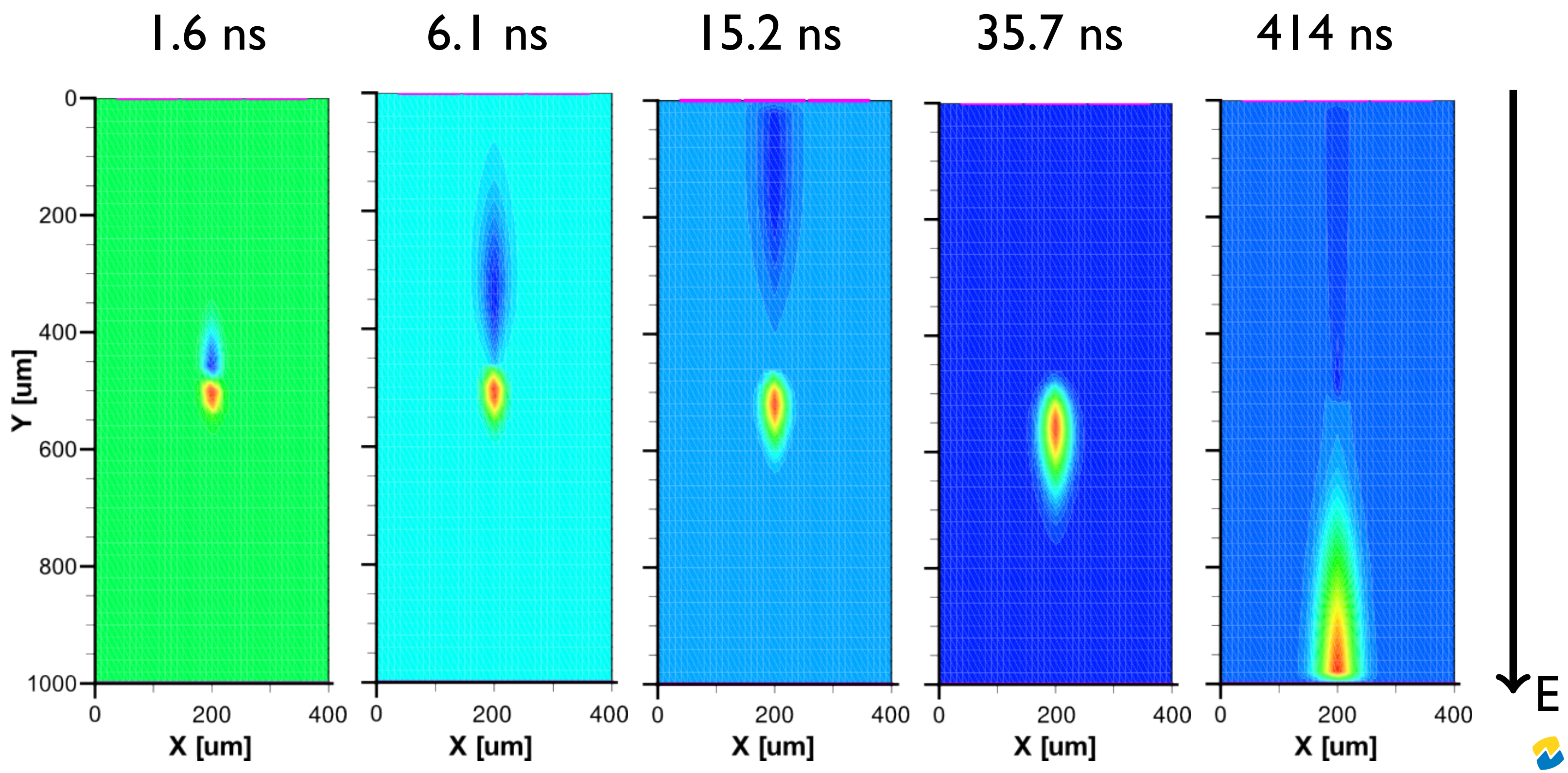


SIGNAL FORMATION



- Moving charge induces a signal on the read out pad
- Pulse height is proportional to the deposited energy
- In order to detect a particle it has to interact with the sensor material and create electron-hole pairs

CHARGE CARRIER SIMULATION CDTE



By David Krapohl, Mid Sweden University

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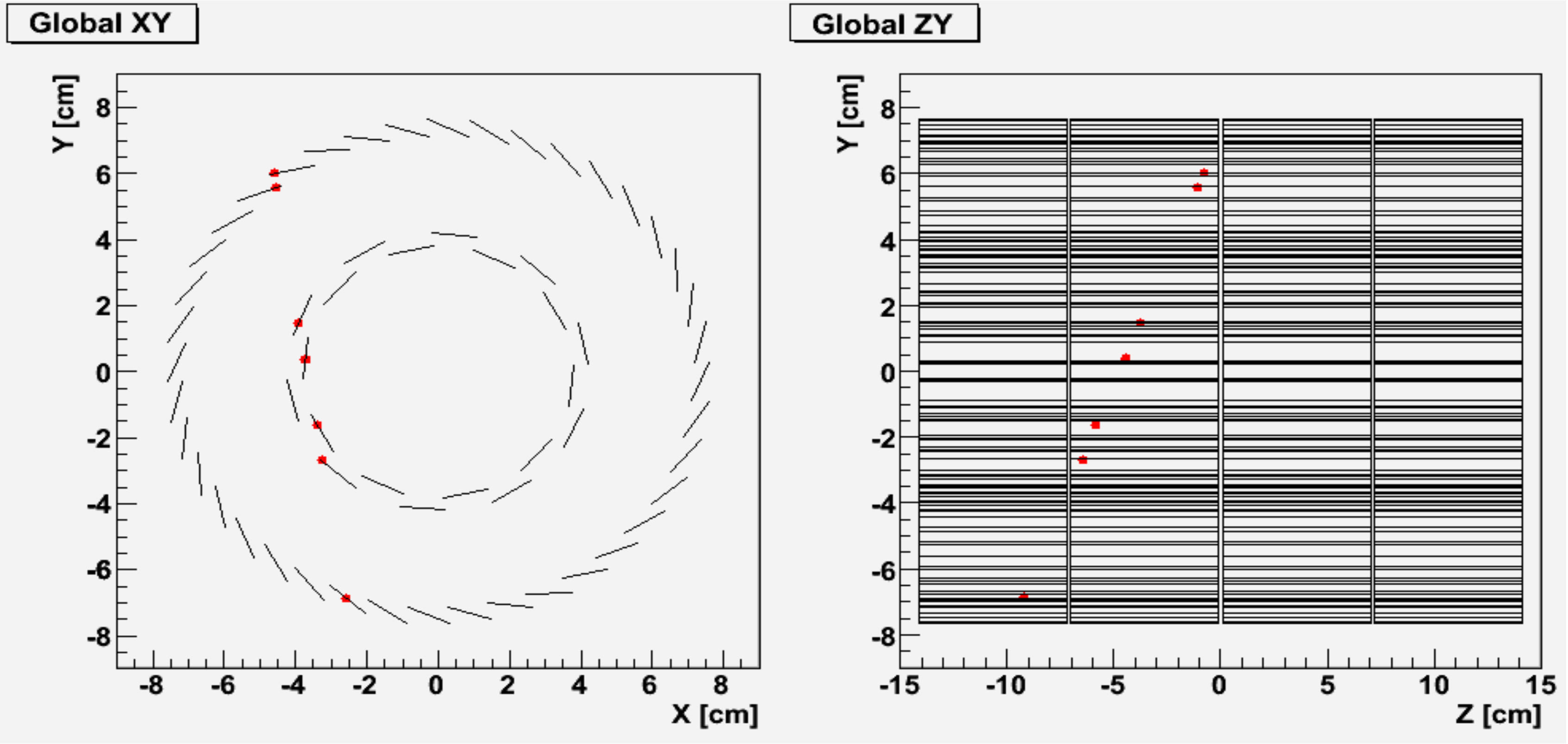
NOISE FREE IMAGES



Cosmic particles seen by ALICE

CAN THIS BE USED FOR SOMETHING ELSE?

- The idea of using the single photon counting principle with hybrid pixel detectors for X-ray imaging dated back to late 80s
- The Medipix collaboration was formed to use the knowledge gained in the design and fabrication of hybrid pixel detectors to make a single photon counting system for X-ray radiography.
- Initial partners of the collaboration were CERN, the University of Freiburg (Germany), the University of Glasgow (Scotland) and the INFN of Pisa and Napoli
- Mid Sweden University joined the collaboration 1999

MEDIPIX 2/3 COLLABORATION

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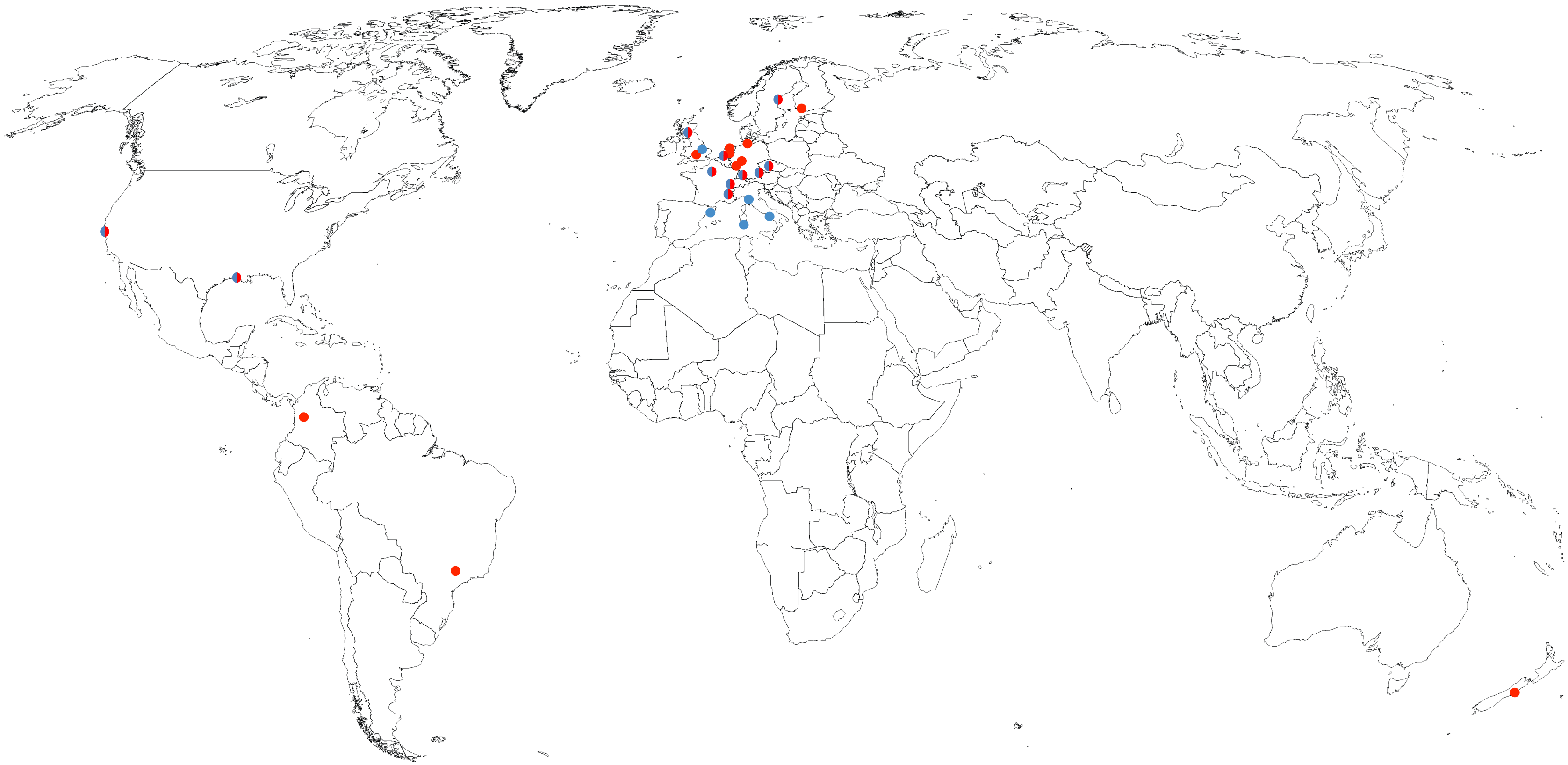

- Medipix2 collaboration member
- Medipix3 collaboration member
- Medipix2 and 3 collaboration member

www.cern.ch/medipix

Drawing: R. Ballabriga

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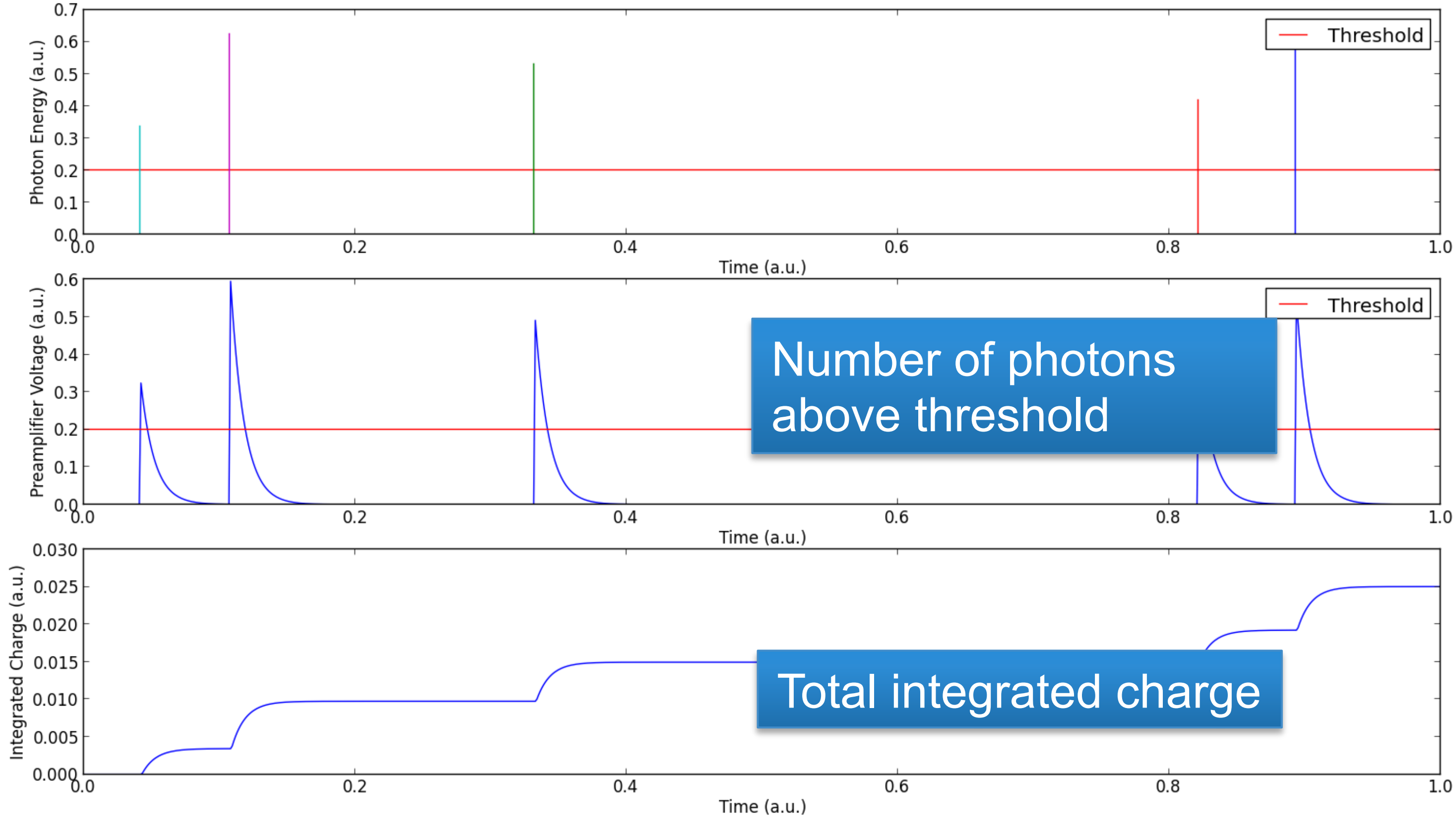
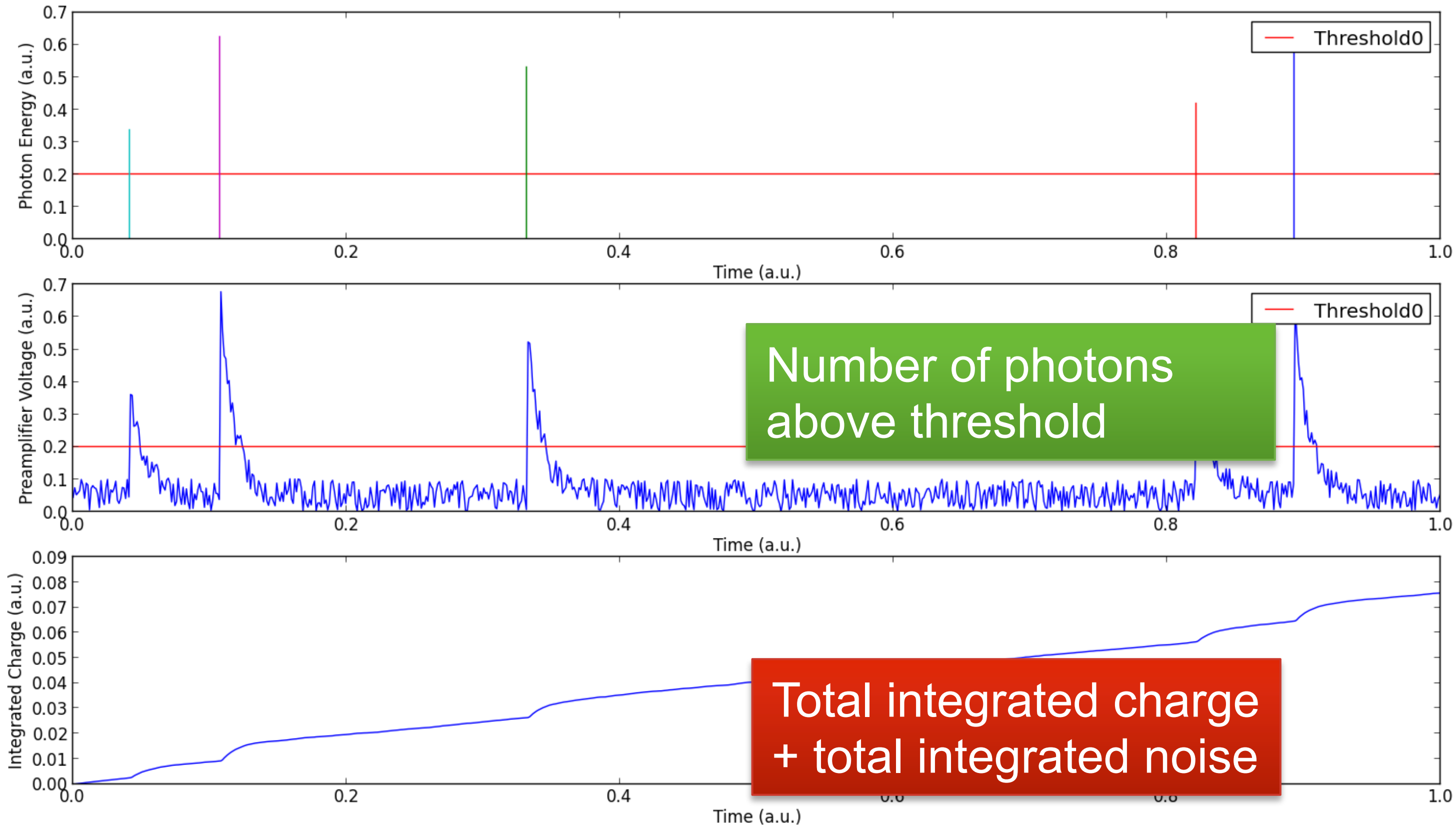
ADVANTAGES OF HYBRID PIXEL DETECTORS FOR X-RAY IMAGING

PHOTON COUNTING VS. INTEGRATION



PHOTON COUNTING VS. INTEGRATION



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Optimal weighting for low contrast objects: $W \sim E^{-3}$

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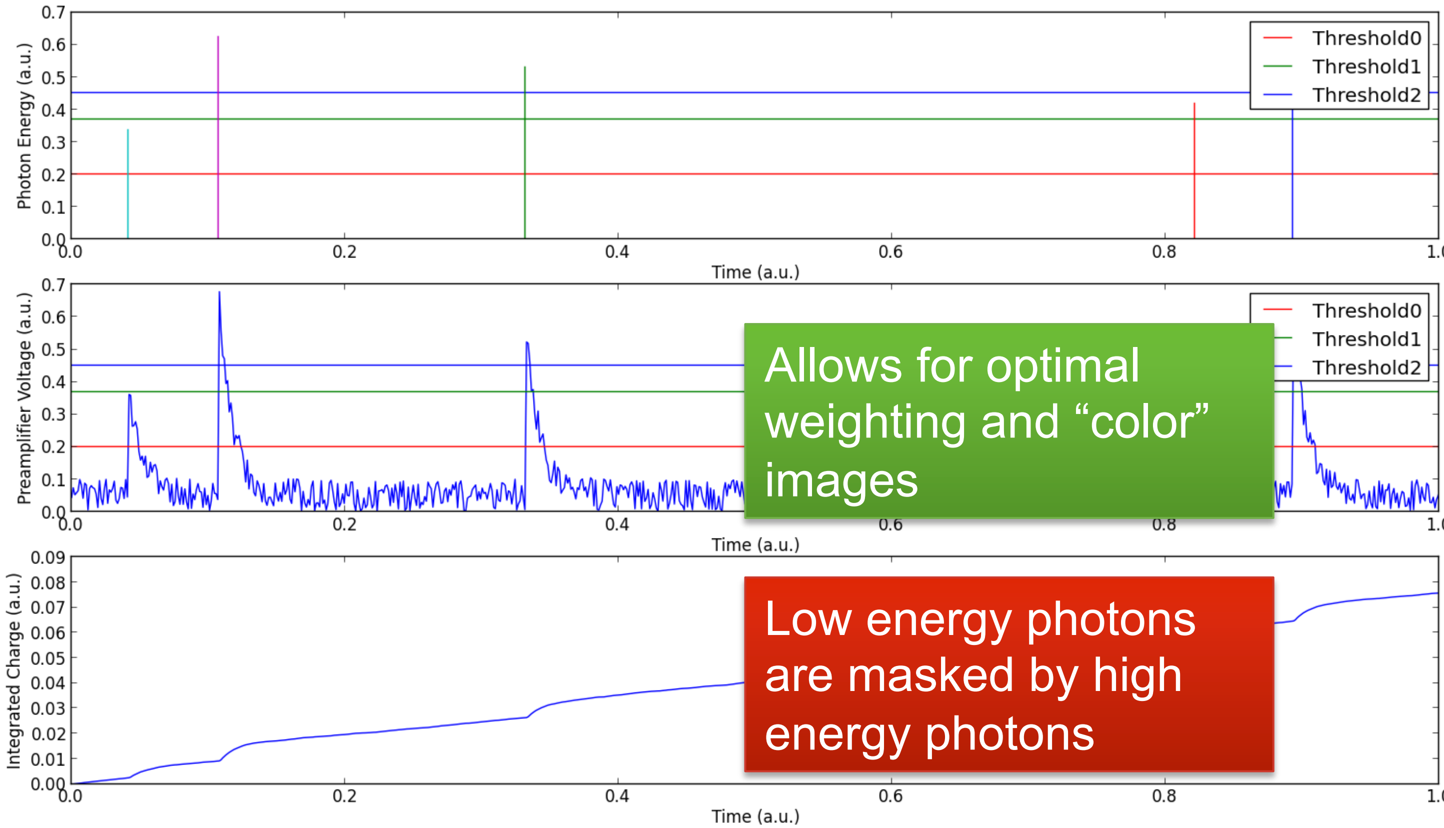
PHOTON COUNTING VS. INTEGRATION



Allows for optimal weighting and “color” images

$W = 1$

Low energy photons are masked by high energy photons

$W \propto E$

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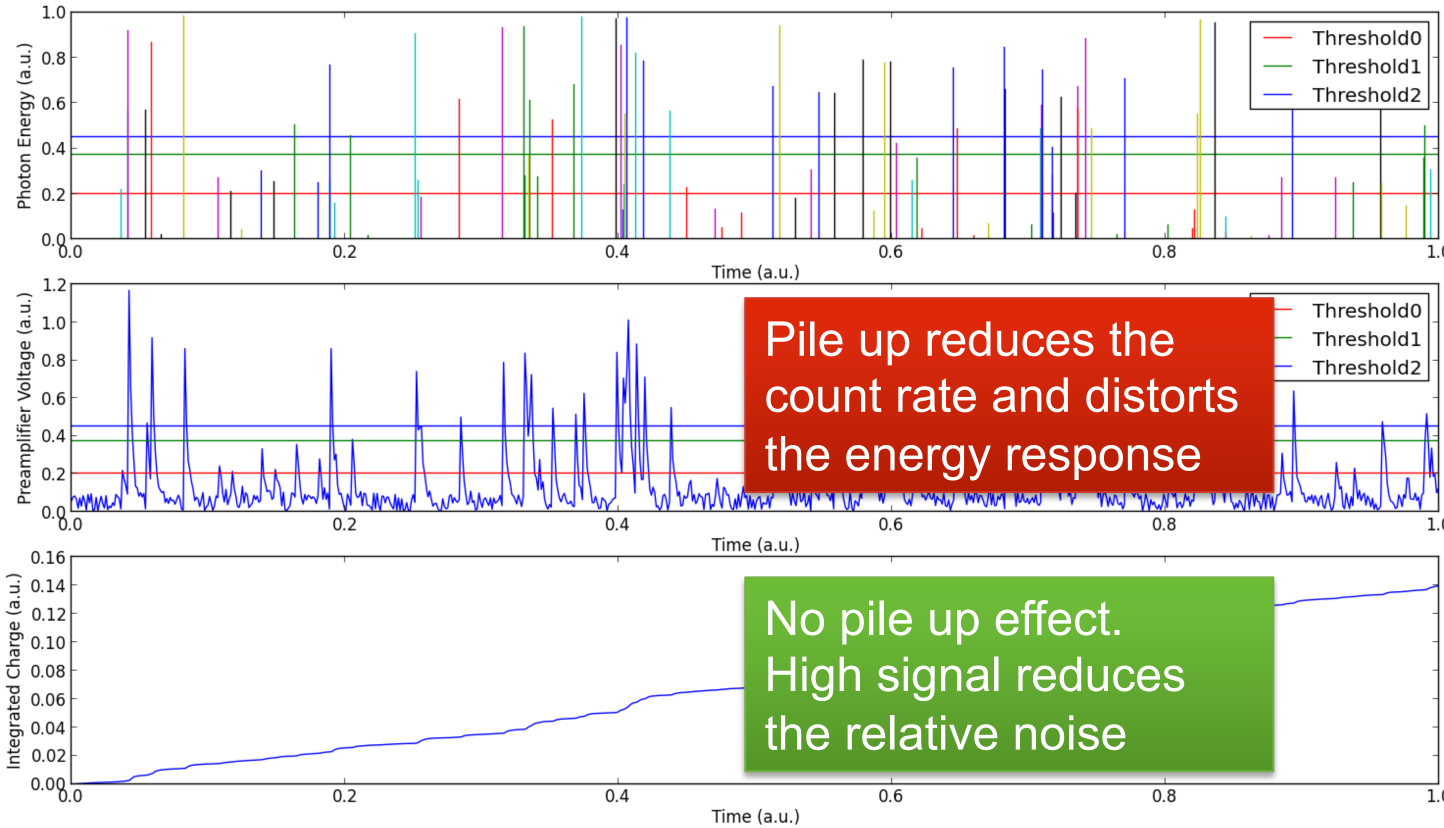
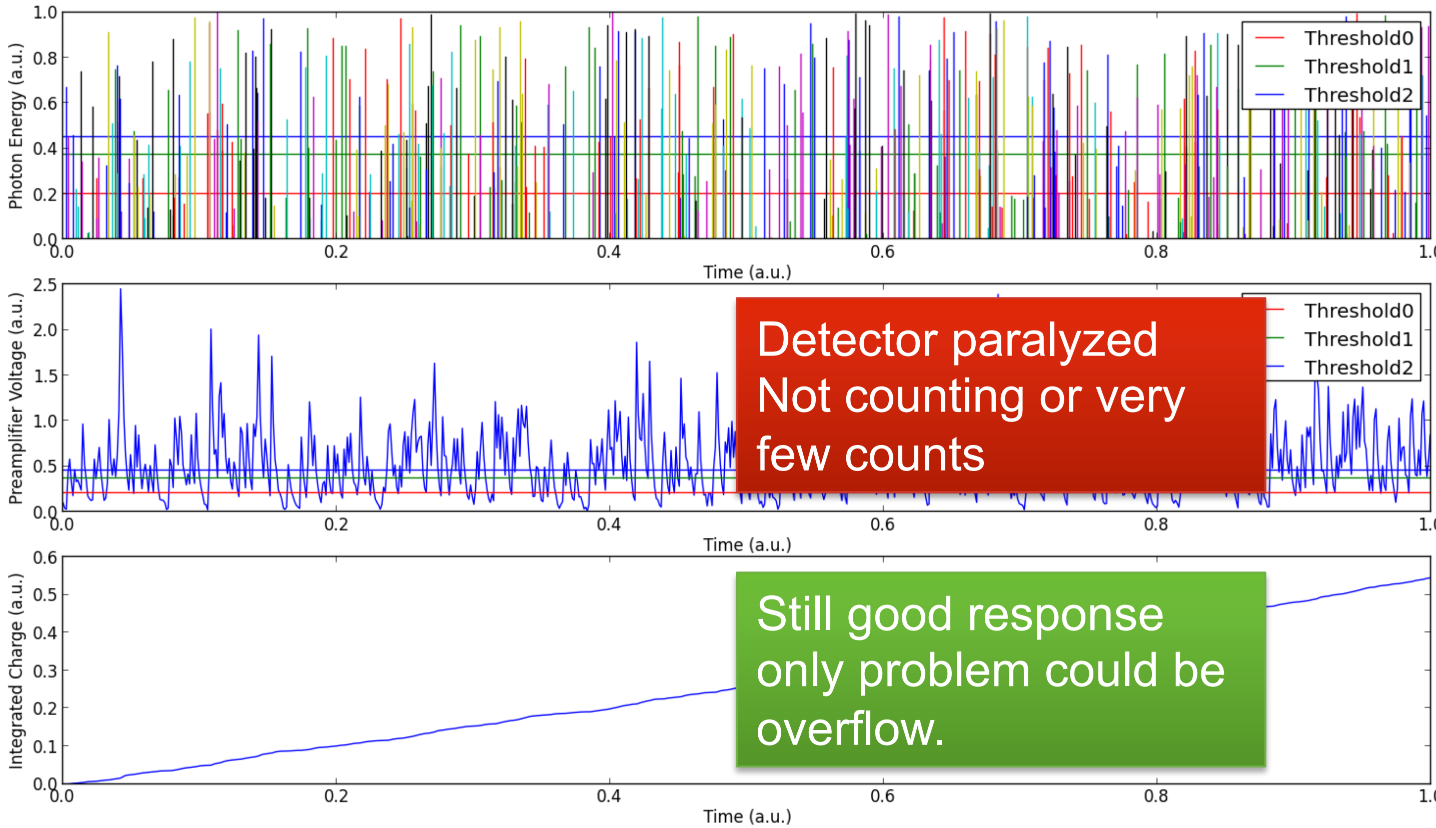
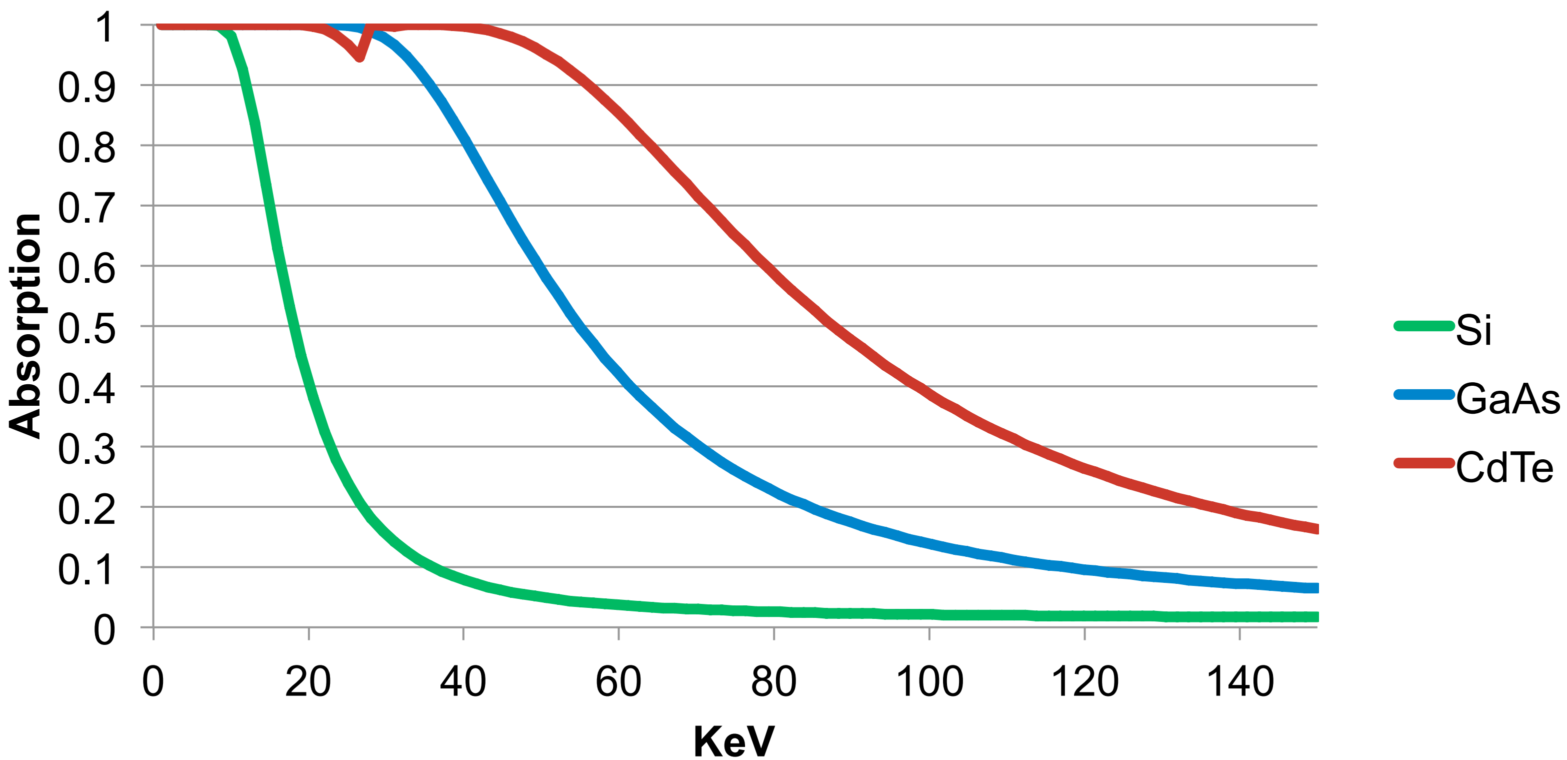
PHOTON COUNTING VS. INTEGRATION



PHOTON COUNTING VS. INTEGRATION



STOPPING IN 0.5 MM LAYERS



SUMMARY HYBRID PIXEL DETECTORS

- Developed for high energy particle physics
- Advanced processing capabilities on pixel level
- Sensor layer can be optimized for a specific application
- “Noise free” images due to photon counting
- Spectral sensitivity for increased contrast and/or lower dose

DESIGNED CHIPS

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Medipix1 (1998)	*1μm SACMOS, 64x64 pixels, 170x170μm^2* *PC / Frame based readout*
Medipix2 (2001)	*0.25μm CMOS, 256x256 pixels, 55x55μm^2* *PC / Frame based readout*
Timepix (2006)	*0.25μm CMOS, 256x256 pixels, 55x55μm^2* *PC, ToT, ToA / Frame based readout*
Medipix3 (2009)	*0.13μm CMOS, 256x256 pixels, 55x55μm^2* *PC / Frame based readout* *Event by event charge reconstruction and allocation*
Dosepix (2011)	*0.13μm CMOS, 16x16 pixels, 220x220μm^2* *ToT, PC / Rolling shutter (programmable column readout)* *Event by event binning of energy spectra (16 digital thrs)*
Timepix3 (2013)	*0.13μm CMOS, 256x256 pixels, 55x55μm^2* *PC; ToT, ToA (simultaneous)/ Data driven readout*
Smallpix	*0.13μm CMOS, 512x512 pixels, 40x40μm^2 (TBD)* *PC, iToT; ToA, ToT1 (simultaneous)/ Frame based (ZC)* *TSV compatible design*
Clicpix prototype	*65nm CMOS, 64x64 pixels, 25x25μm^2* *ToA, ToT1 (simultaneous)/ Frame based (ZC)*

DESIGNED CHIPS

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Medipix1 (1998)	*1µm SACMOS, 64x64 pixels, 170x170µm²* *PC / Frame based readout*
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Clicpix prototype	*65nm CMOS, 64x64 pixels, 25x25µm²* *ToA, ToT1 (simultaneous)/ Frame based (ZC)*

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TIMEPIX

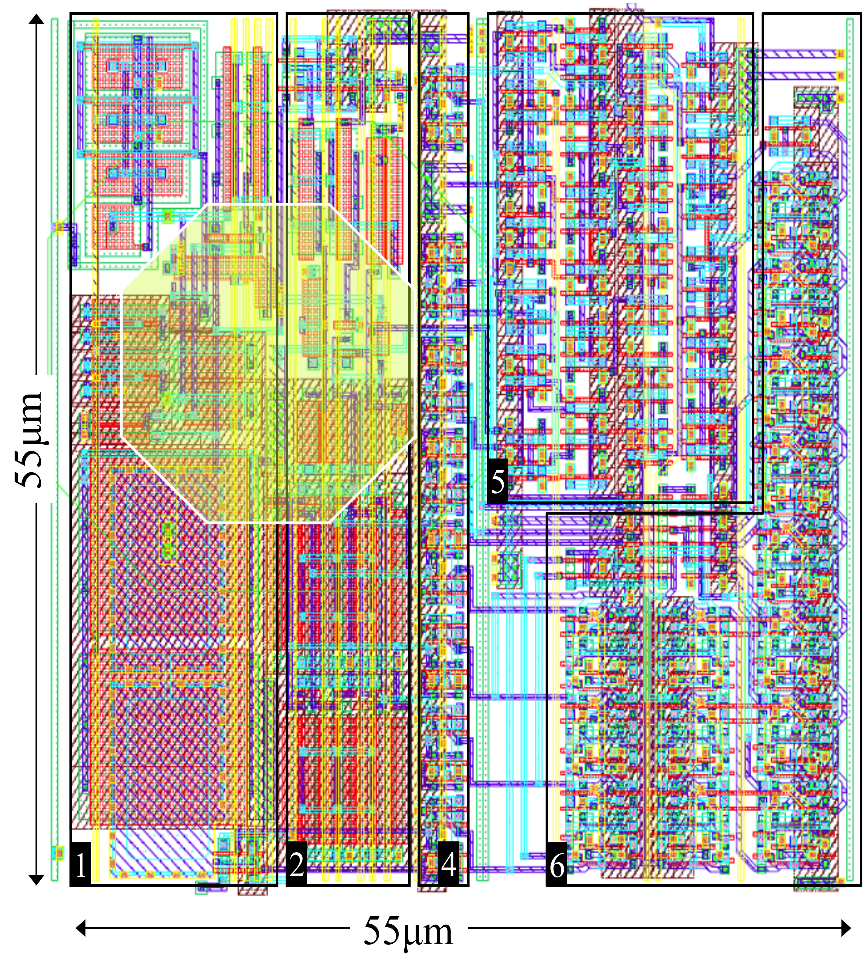
- Hybrid Pixel Detector
- 256x256 pixels
- 55um pixel pitch

- Single Photon Processing
  - Time-over-Threshold
  - Time of arrival
  - Photon Counting

Capable of operating in both electron and hole collection mode

Multi purpose chip

~ 500 transistors / pixel



DIGITAL BACK-END ELECTRONICS

Photon counting mode

Medipix1, 2, 3

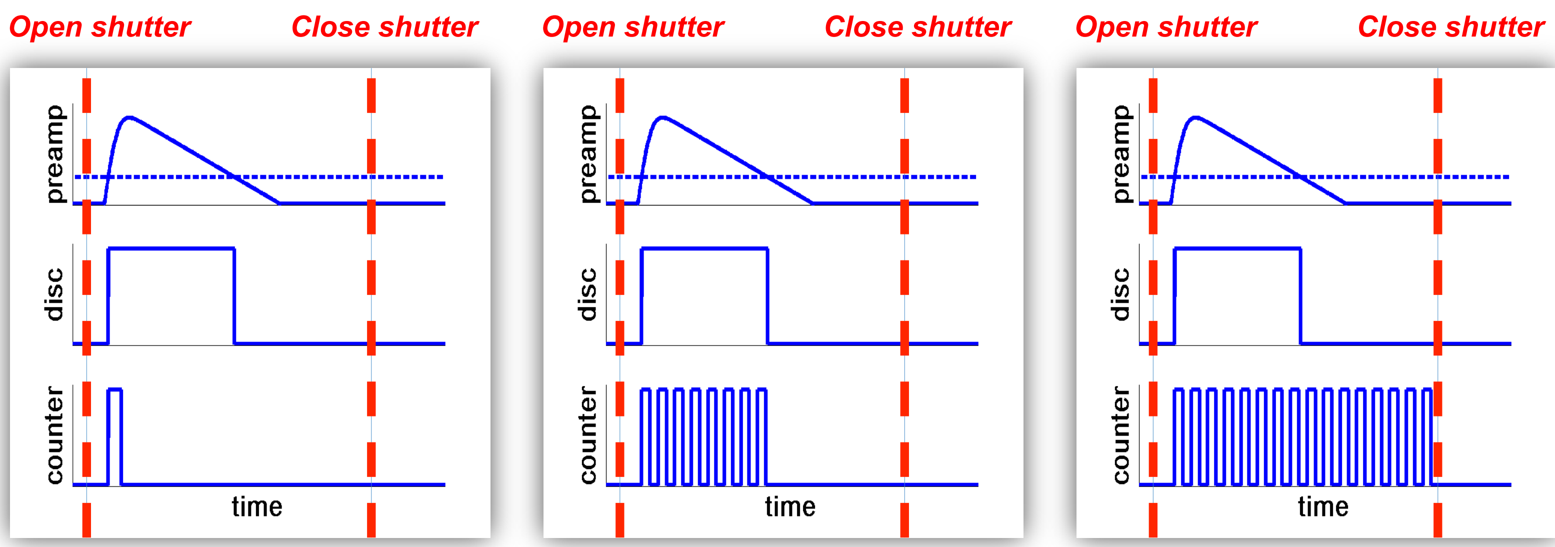
Timepix

Time over Threshold mode

Timepix

Time of Arrival mode

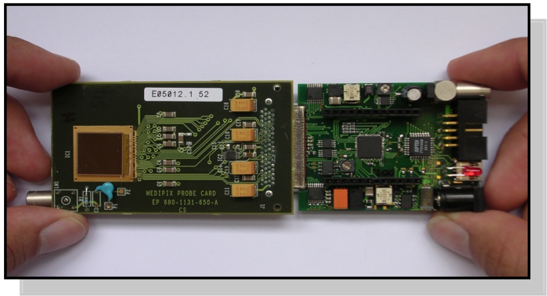
Timepix



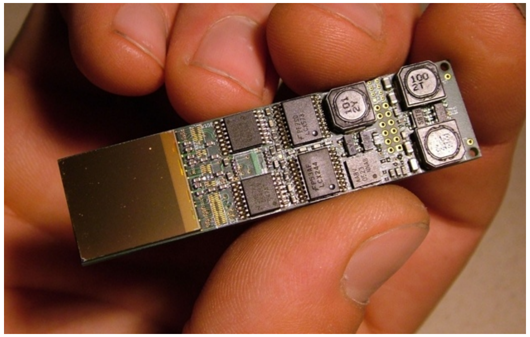
Drawing: W. Wong

TIMEPIX

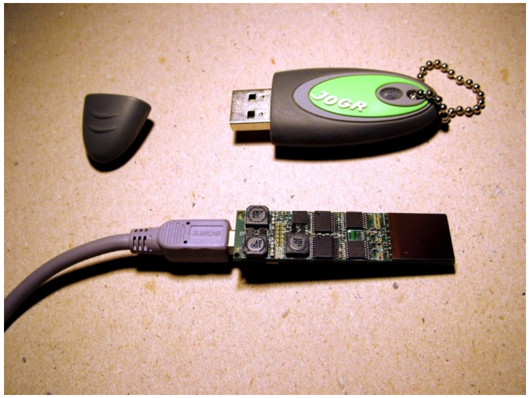
- Compact system 15x60mm for the USB Lite read out including sensor
- USB Connection to standard PC
- Pixelman control software allowing scripting and plugins



Usb read out

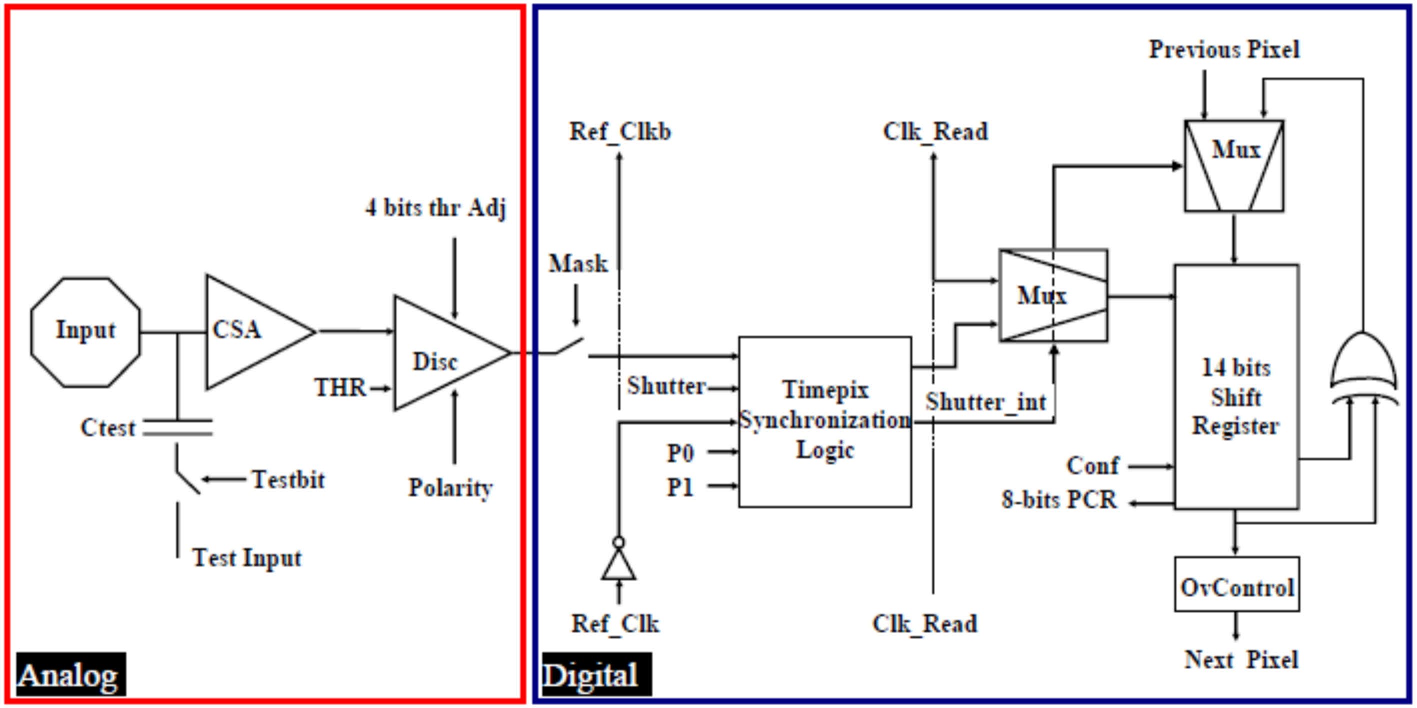


Usb lite



Pictures courtesy of IEAP Prague

TIMEPIX PIXEL CELL SCHEMATIC



X. Llopart, et al., "Timepix, a 65k programmable pixel readout chip for arrival time, energy and/or photon counting measurements" NIM A 581 (2007) 485-494.

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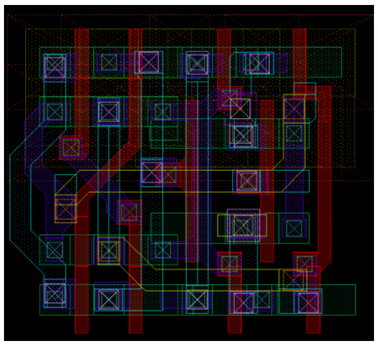
TIMEPIX

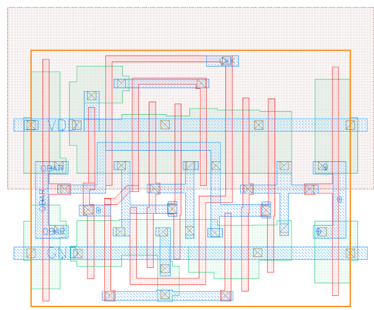
	Holes [h^+]	Electrons [e^-]
Electronic noise	$99.4 \pm 3.8\ e^-$ rms	$104.8 \pm 6\ e^-$ rms
Gain	~16.7 mV/ke^-	~16.3 mV/ke^-
Threshold DAC step gain	$24.7 \pm 0.7\ e^-$	$25.4 \pm 1.2\ e^-$
CSA linearity [0-20 ke-]	>99.9%	
TOT dynamic range	> 200 ke^- (measured up to ~40 ke^-)	
ΔTOT/TOT (Qin>Thr + 1 ke-)	<5%	
Time-walk	<50 ns	
Threshold variation before adjustment	~240 e^- rms	
Threshold variation after adjustment	~35 e^- rms	
Minimum detectable charge	~650 e^-	
TOT energy resolution after correction	1300 e^- FWHM	
Static pixel analog consumption	~6.5 μW	
Static pixel digital consumption	~7 μW @ Ref_Clk =80 MHz	

HOW CAN WE ADD MORE FUNCTIONALITY TO NEW DETECTORS?



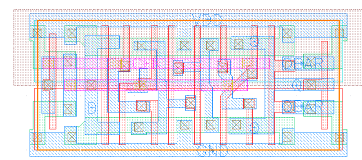
DFF_skt
Medipix2_lib
250nm

1

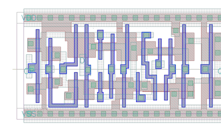


DFF_A
cmos8rf
130nm

1.5x



DFF_A_XL
cern_cmos8rf_hd
130nm
3.2x

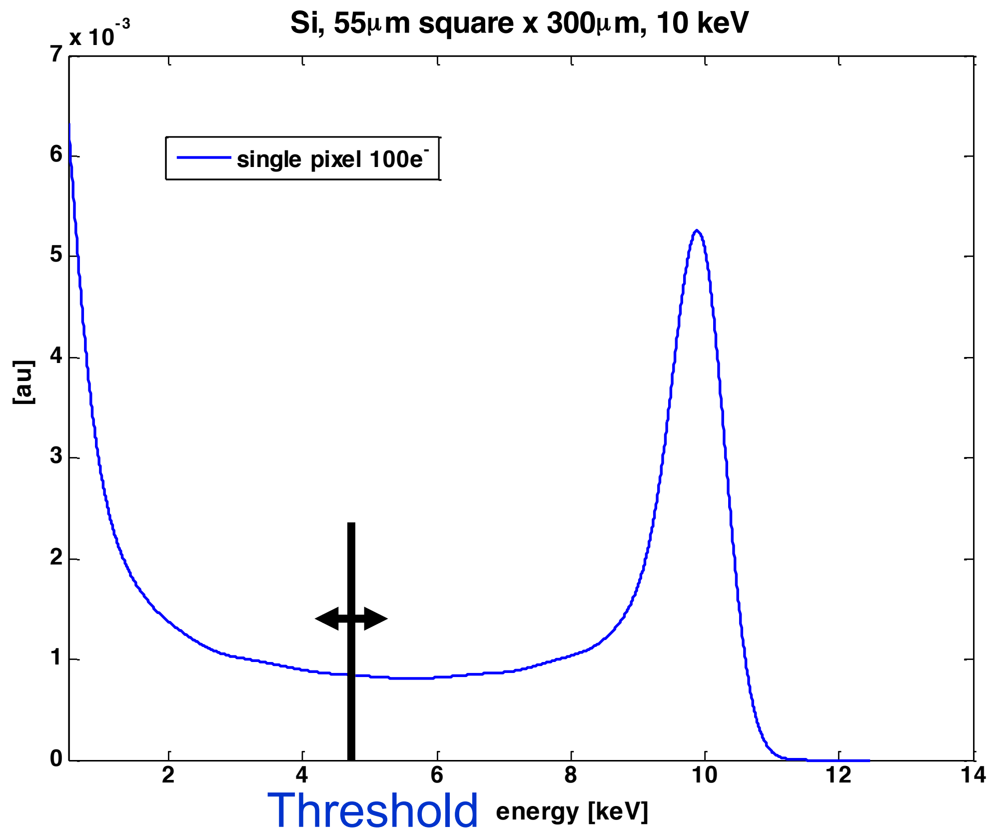


DFQD1
tcbn65lp
65nm

6.4x

This applies only to digital components

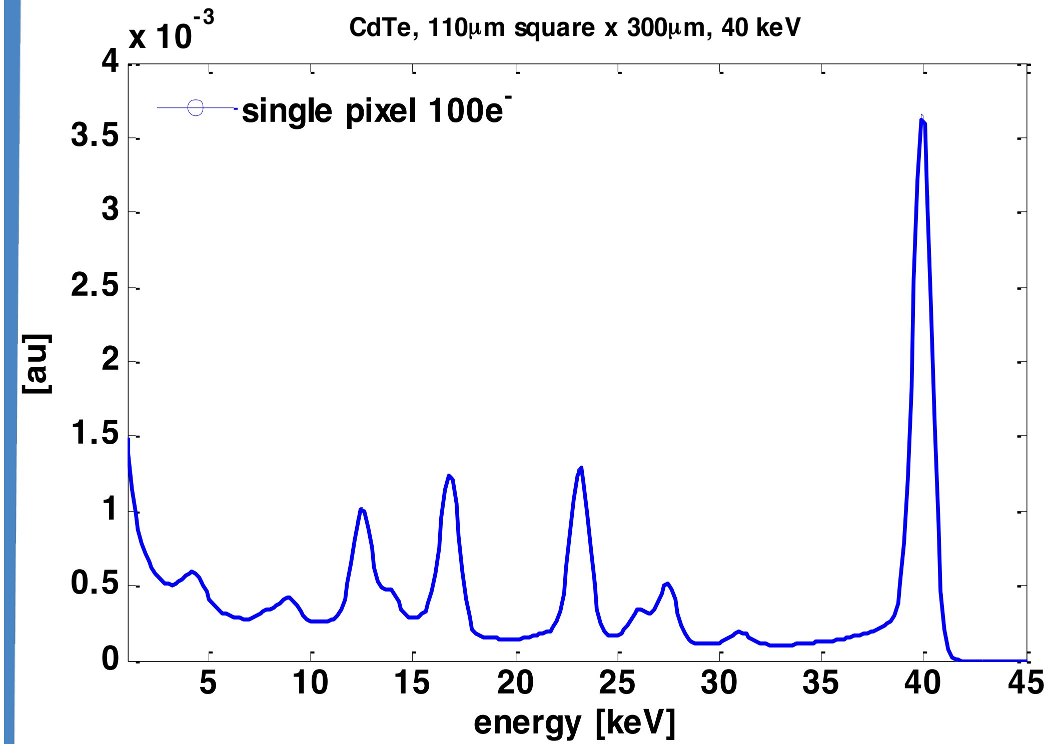
MOTIVATION FOR THE MEDIPIX3 CHIP



- Simulated Data
- Si 300mm, 55mm pixel
- 10keV monochromatic photon beam
- Charge diffusion produces "charge sharing" tail
- Threshold variations produce fixed pattern noise
- Energy information is reduced

Simulation: L. Tlustos

MOTIVATION FOR THE MEDIPIX3 CHIP



- Simulated data
- CdTe 300mm
- 110mm pixel pitch
- 40keV monochromatic beam
- The influence of fluorescence photons in the energy spectrum is seen

Simulation: L. Tlustos

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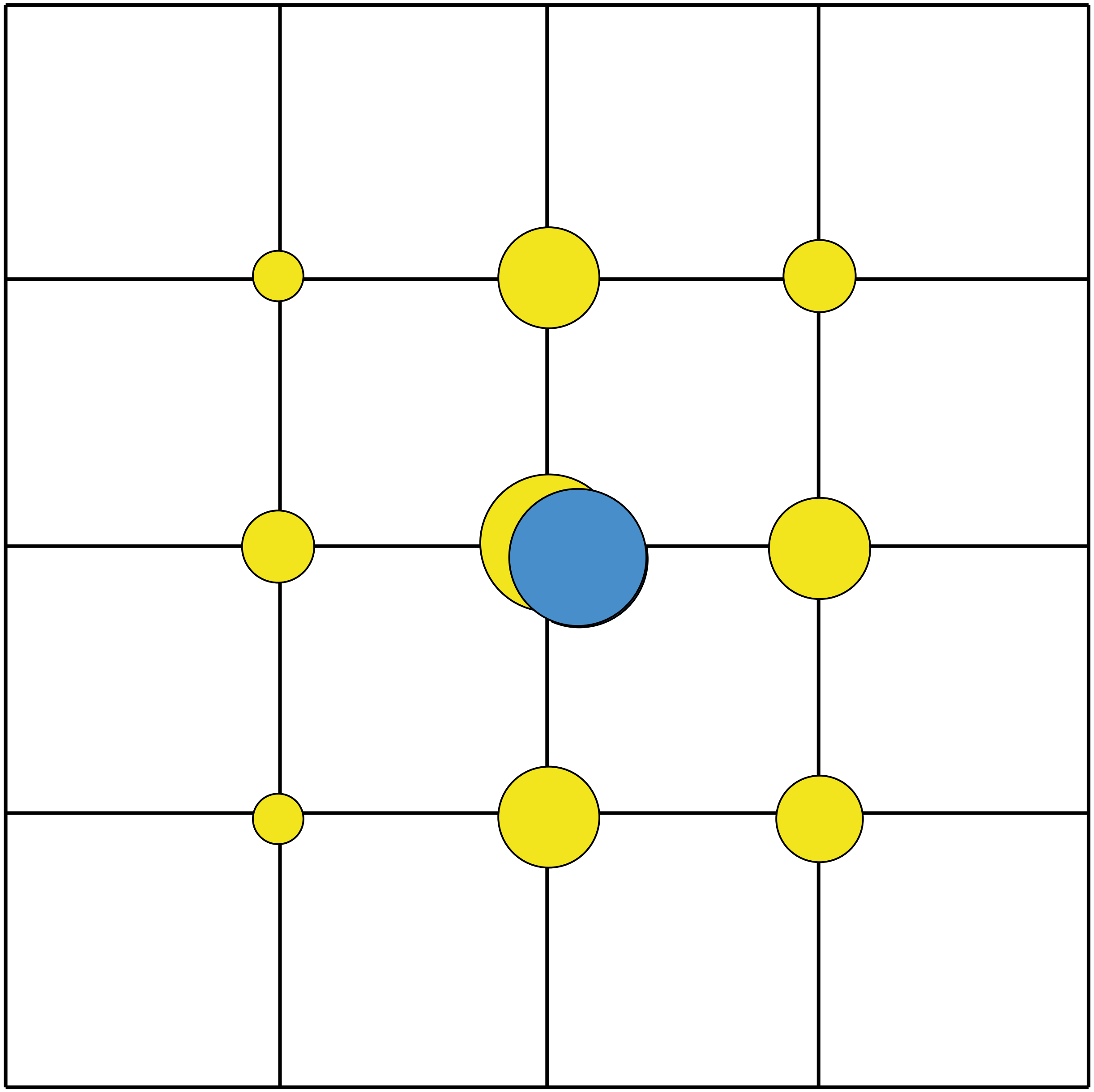
CHARGE RECONSTRUCTION AND HIT ALLOCATION



1. TH_0 is applied to the local signal

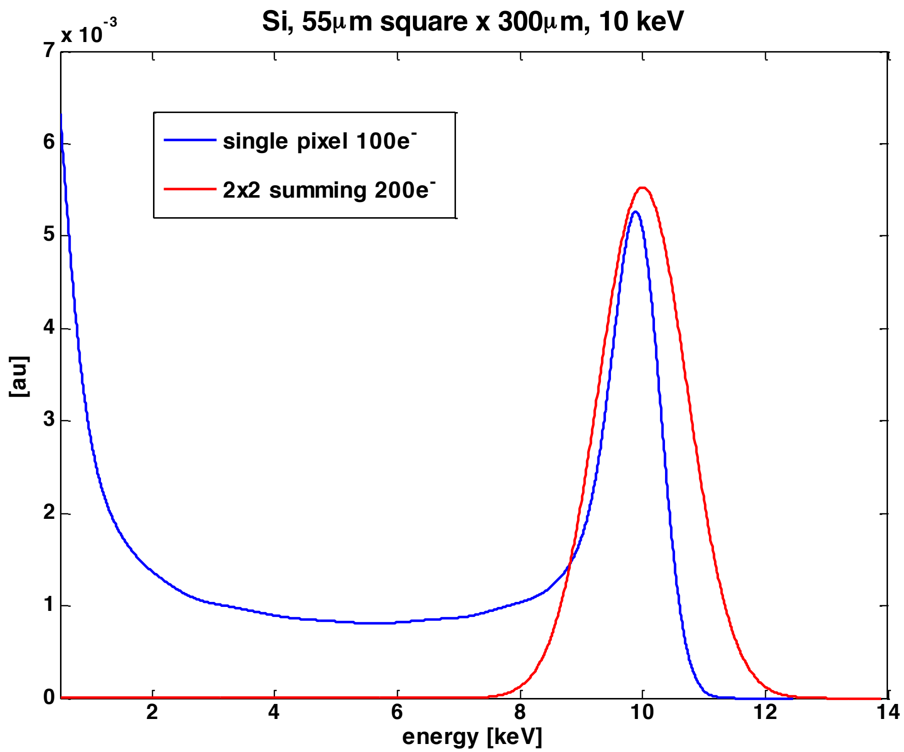
2. Arbitration circuitry identifies the pixel with largest charge and supresses the pixels with lower signal

3. In parallel, the charge has been reconstructed in the analog summing circuits

4. The pixel with highest charge checks the adjacent summing circuits to see if at least one of them exceeds TH_1

Slide by R. Ballabriga

MOTIVATION FOR THE MEDIPIX3 CHIP



- Simulated Data
- Si 300mm, 55mm pixel
- 10keV monochromatic photon beam
- In the new architecture charge sharing tail is eliminated

Simulation: L. Tlustos

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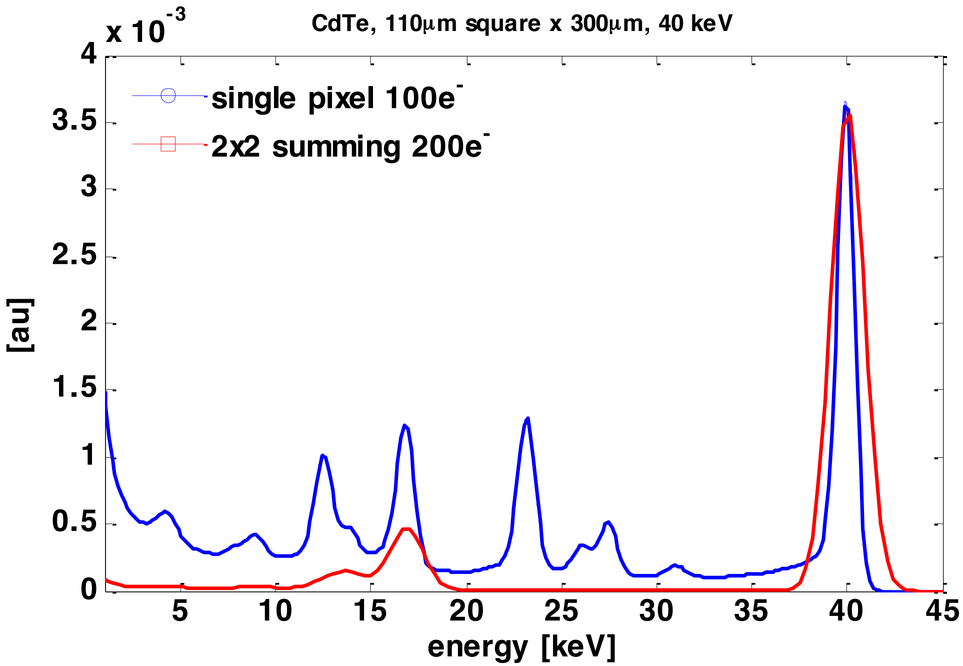
MOTIVATION FOR THE MEDIPIX3 CHIP

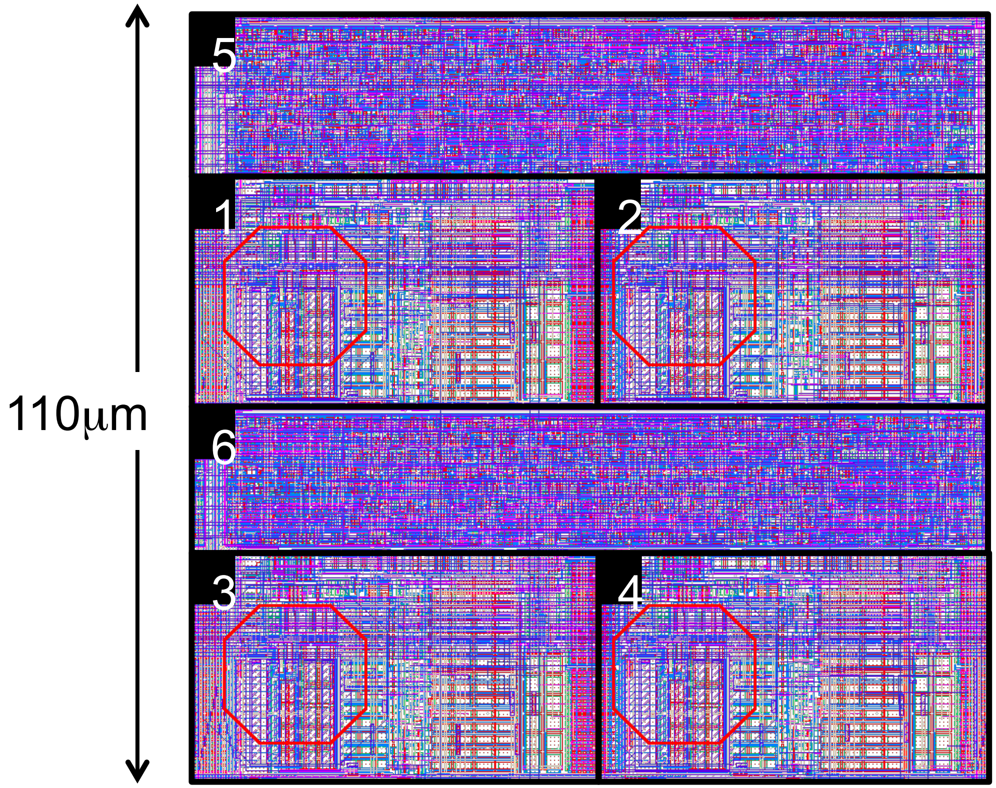


- Simulated data
- CdTe 300mm 110mm pixel pitch
- 40keV monochromatic beam
- Fluorescence photons are included in charge sum if their deposition takes place within the volume of the pixels neighbouring the initial deposition

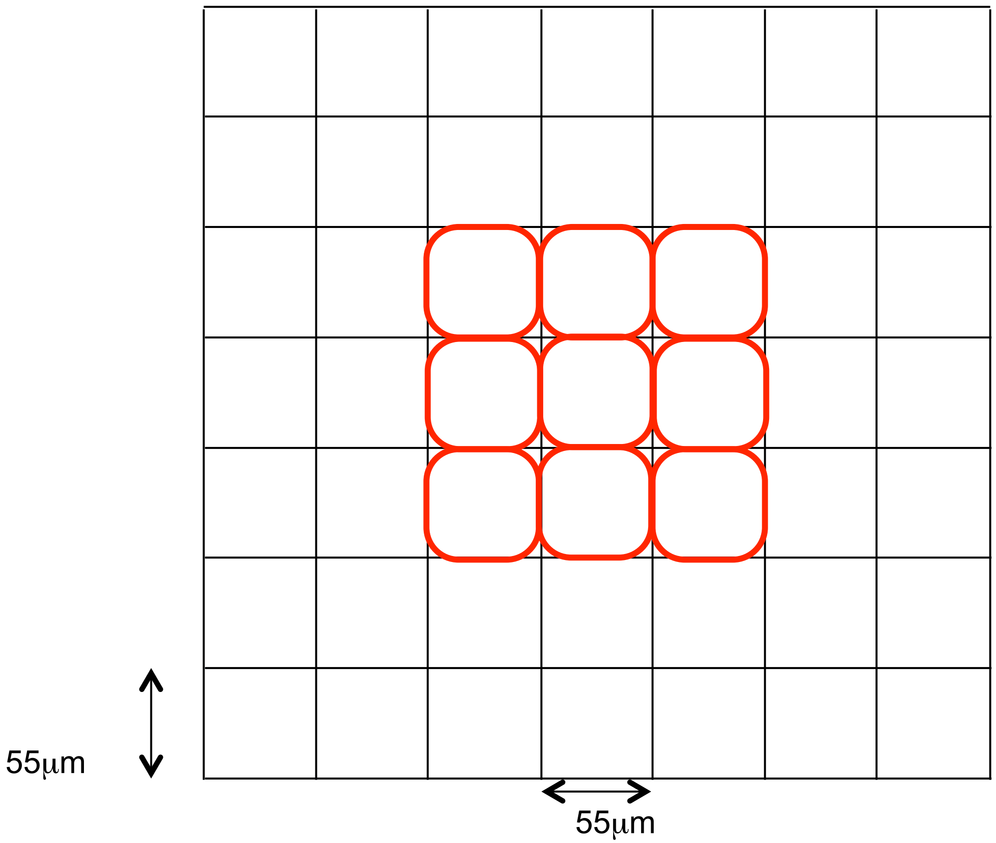
Simulation: L. Tlustos

MEDIPIX3RX OPERATING MODES

MEDIPIX3RX PIXEL LAYOUT



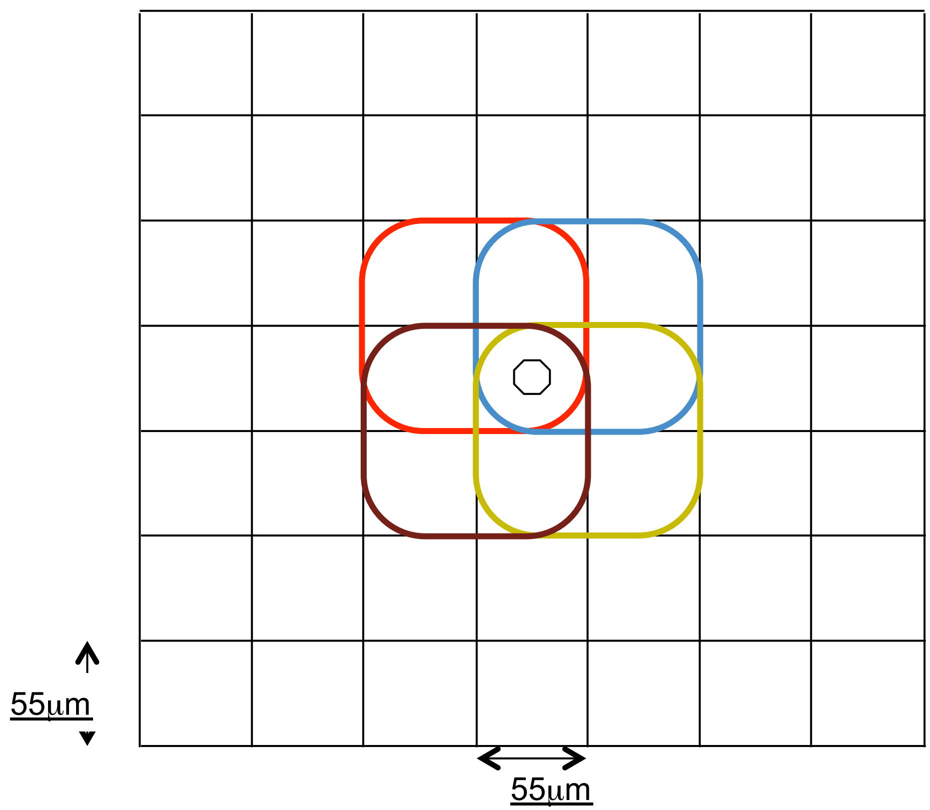
FINE PITCH, SINGLE PIXEL MODE



- 55mm pixel pitch
- 2 thresholds/pixel
- 2 counters

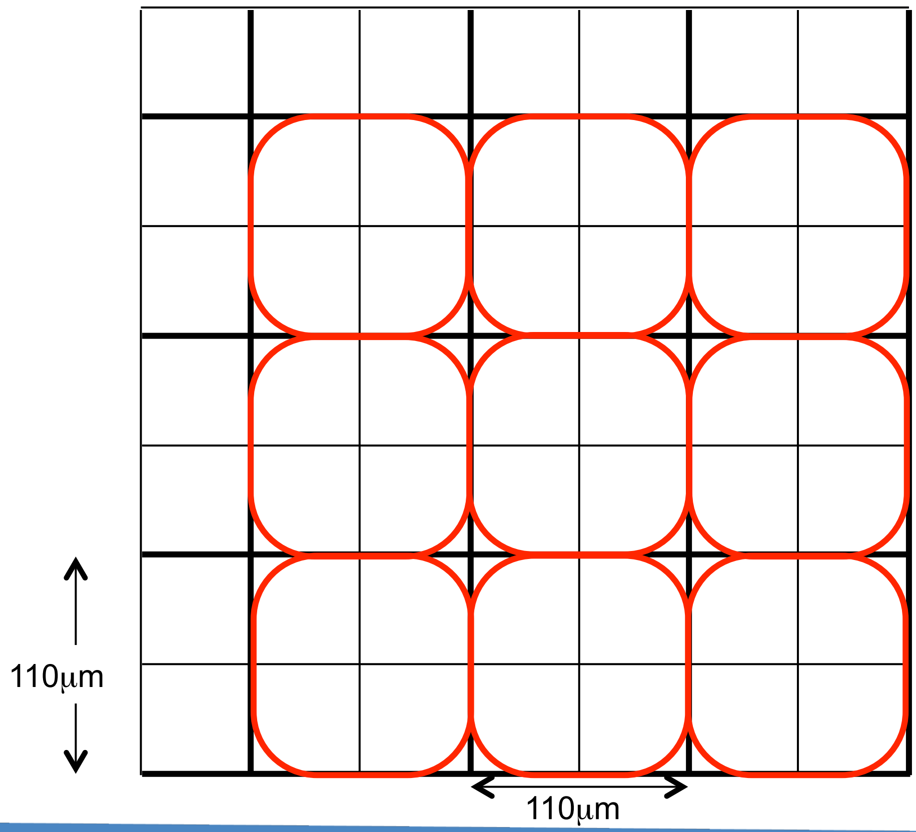
- Pixels work independently from one another

FINE PITCH, CHARGE SUMMING MODE



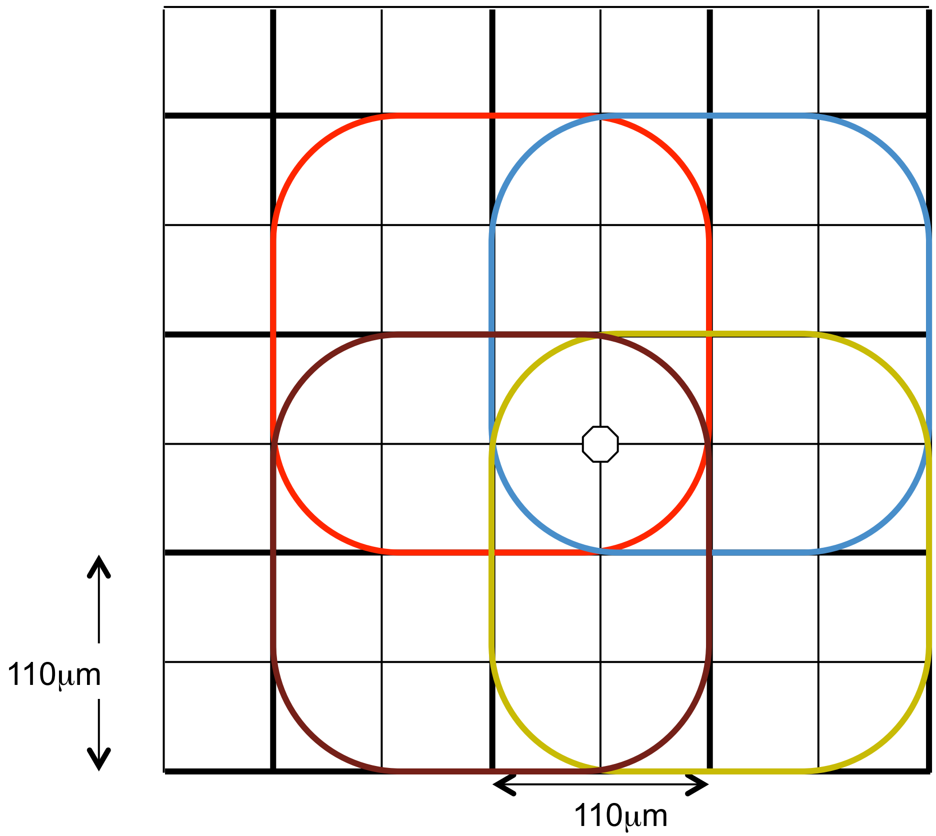
- 55mm pixel pitch
- Reconstruction over overlapping 110mm x 110mm areas
- 2 thresholds/pixel (1 for local charge/1 reconstructed charge)
- 2 counters
- Advantage of small pixels without disadvantage of charge sharing

SPECTROSCOPIC, SINGLE PIXEL



- 110mm pixel pitch
- 8 thresholds/pixel
- 8 counters

SPECTROSCOPIC, CHARGE SUMMING

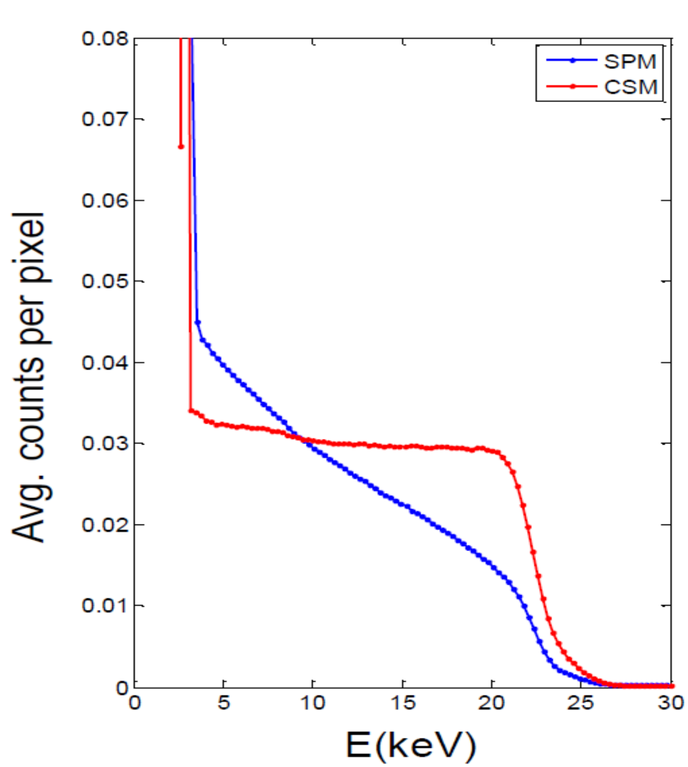


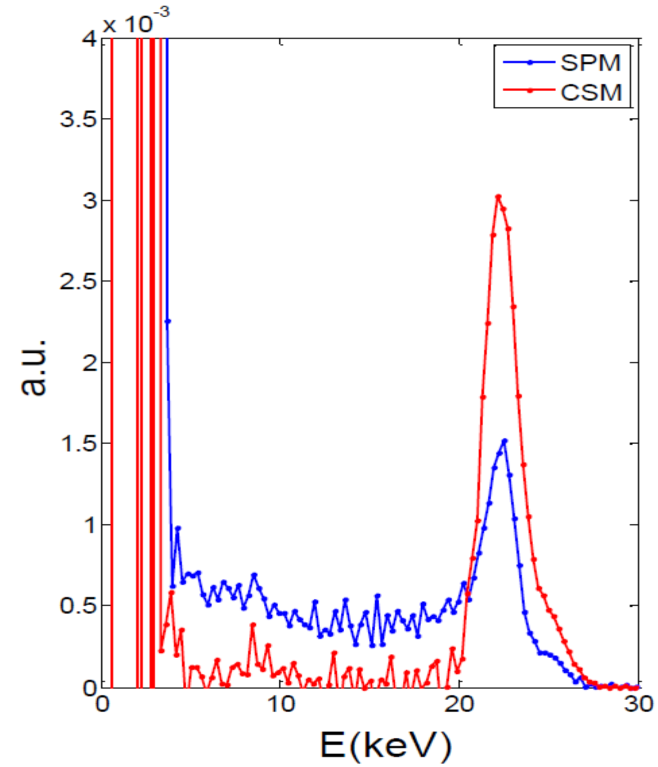
- 110mm pixel pitch
- Reconstruction over 220um x 220um area
- 8 thresholds/pixel (4 for local charge/4 reconstructed charge)
- 8 counters

Common to all configurations:

- 4 selectable gain mode
- Possibility of Continuous Acquisition/Readout

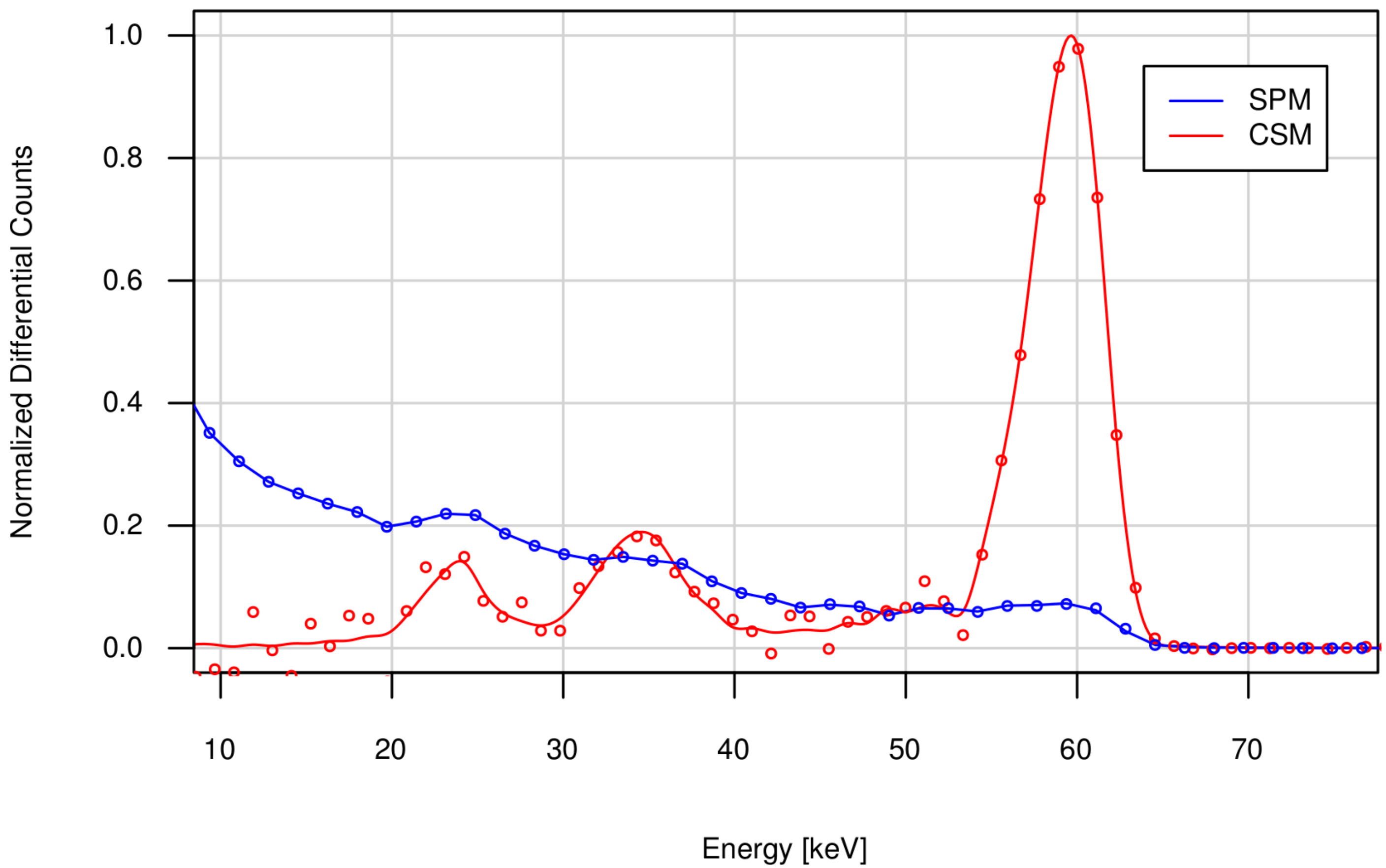
^{109}Cd 55um, 300um Si





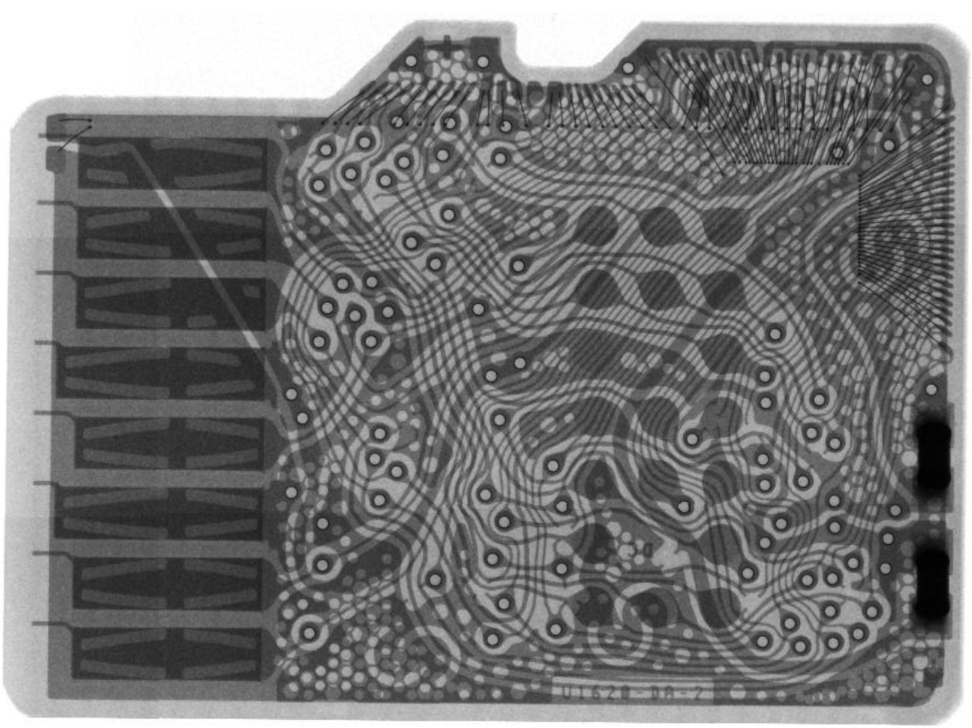
Measurement in HGM @ very low flux conditions
Raw data, No realignment in data, by R. Ballabriga

60keV, 110um 2mm, CdTe



Energy spectra measurements by T. Koenig

IMAGING A uSD CARD IN CSM



μSd card
4x3 tiles,
magnification 3.2x
X-ray tube voltage: 30 kVp,
Tube current: 100μA,
1mm Al filtering,
5s acquisition

Courtesy of S. Procz (Freiburger Materialforschugszentrum FMF, Germany)

MEDIPIX3RX ELECTRICAL CHARACTERIZATION

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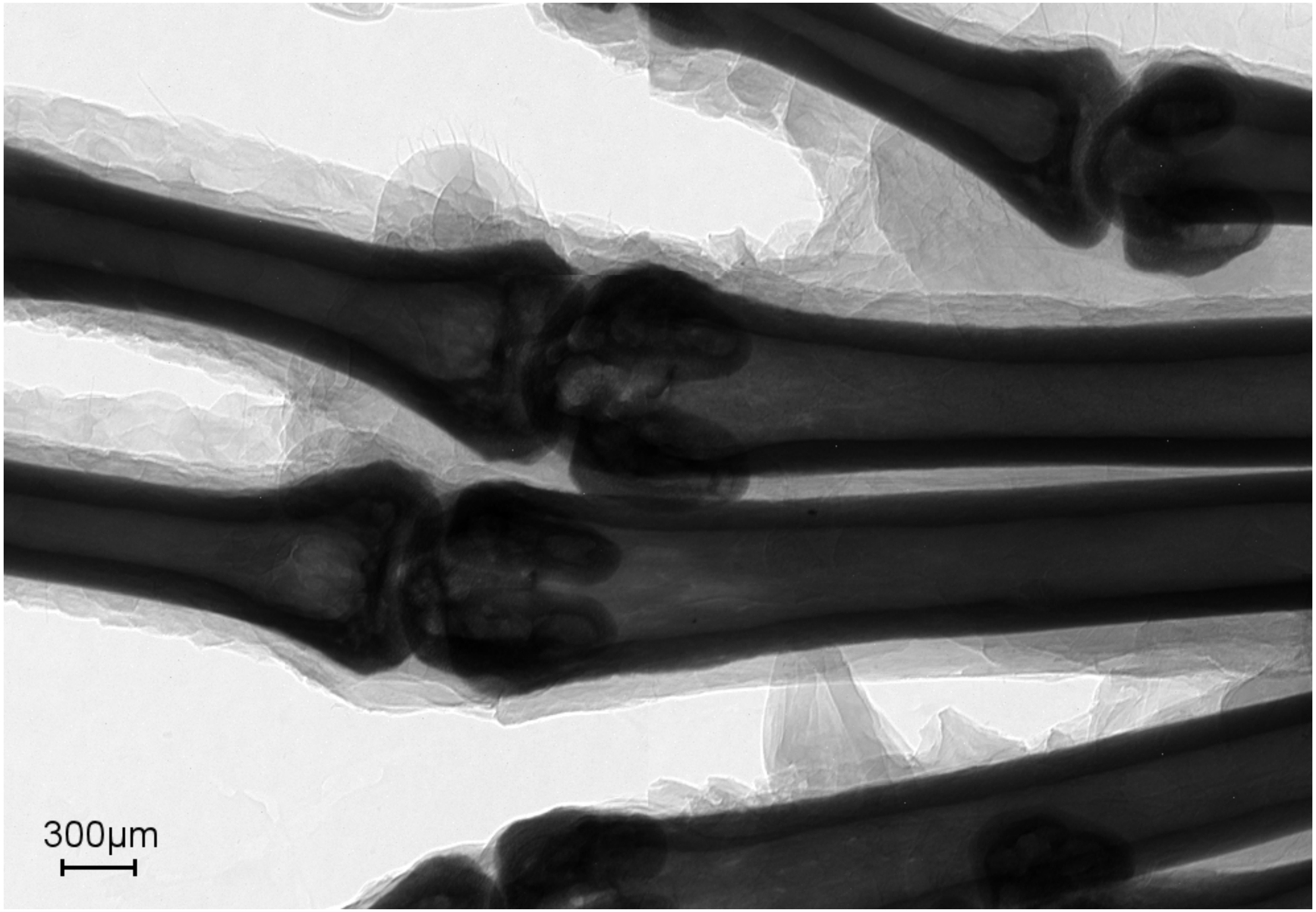
	SPM	CSM	Units
Gain (SHGM)	25	55	e^-/DAC step
ENC (SHGM)	75	150	e^- r.m.s.
Threshold dispersion (SHGM)	37.5	85.5	e^- r.m.s.
Peaking time	120	120	ns
Power consumption	0.78	1	W/chip
Dead time/channel*	0.22/4.5	2.94/0.34	μs/MHz
Count rate*	375	28	Mc/mm^{2}s

*Measurements with CdTe, 2mm thick at 110μm pitch (paralizable model fit)

APPLICATIONS



Mouse paw 10x (25s acq / 15 tiles) (Entire dynamic range)
energy: 30 kVp, power: 3.0 W threshold 0: 50 (DAC value)
magnification: 10x (~5µm pixel resolution)

Courtesy of S. Procz (*Freiburger Materialforschugszentrum FMF, Germany*)

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Mouse paw 10x (25s acq / 15 tiles) (Entire dynamic range)
energy: 30 kVp, power: 3.0 W threshold 0: 50 (DAC value)
magnification: 10x (~5µm pixel resolution)

Courtesy of S. Procz (*Freiburger Materialforschugszentrum FMF, Germany*)

ENERGY SELECTIVE, PLANAR IMAGING

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Piezo Lighter

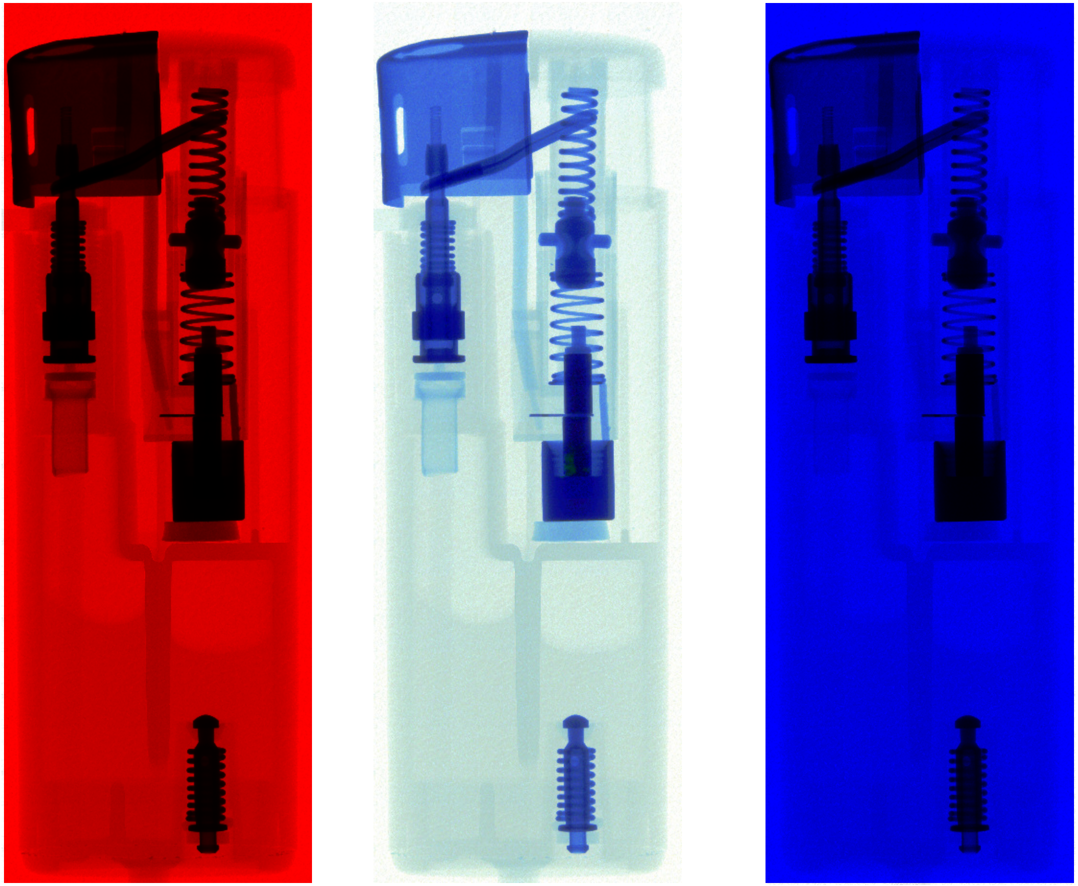
Magnification: 1.3x

Bias: -320V

MPX3 CdTe 1mm
Color Mode
4x11 tiles

1 acquisition, 4
thresholds

Courtesy S. Procz



9-14 keV
14-23 keV
23-50 keV

RGB: 9-50 keV

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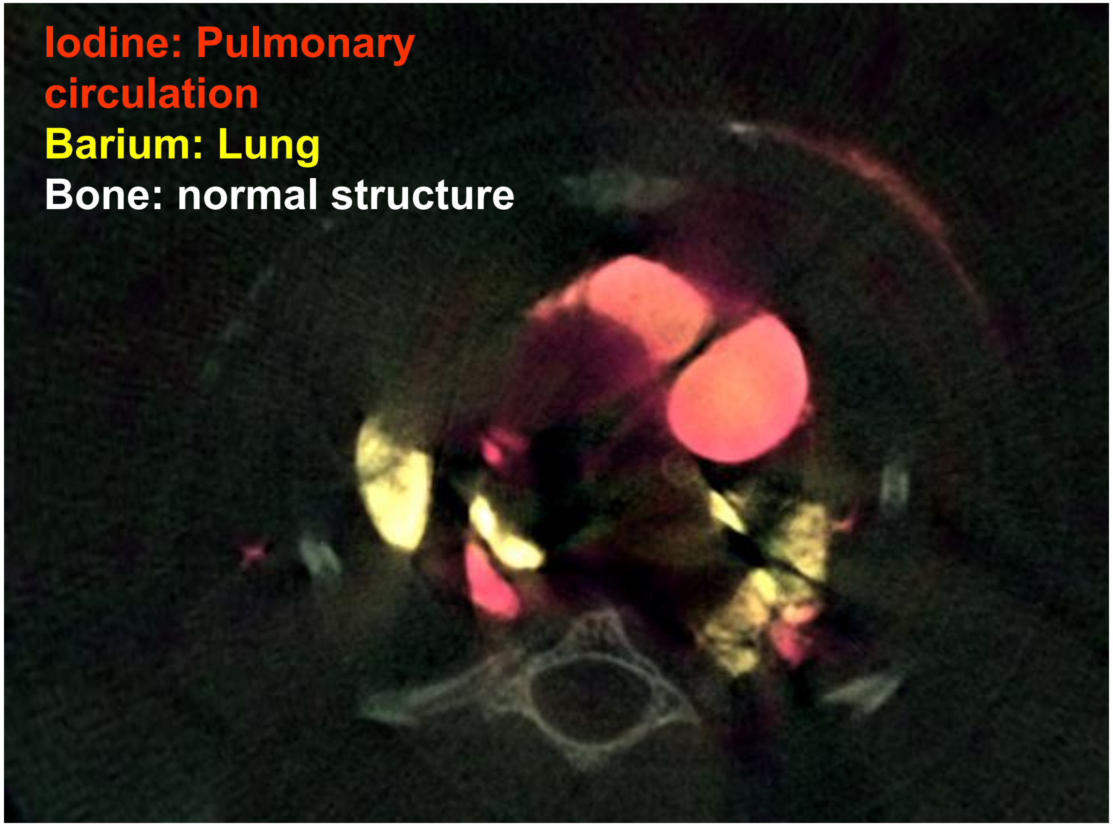
SPECTROSCOPIC COLOUR IMAGING



Courtesy: A. Butler

BASIC PARTICLE IDENTIFICATION

- Mixed radiation fields poses problems for dosimetric measurements.
- An advantage of a pixelated detectors is that particles can be identified by their track shape.
- This is based on the different ways the particles interact in the sensor.

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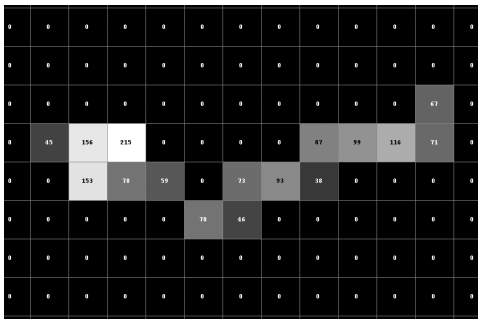
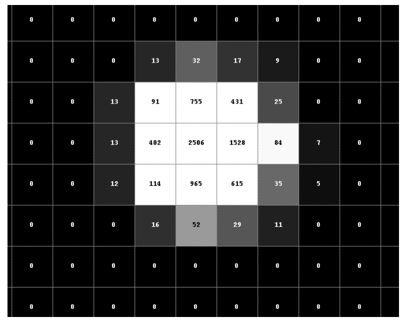
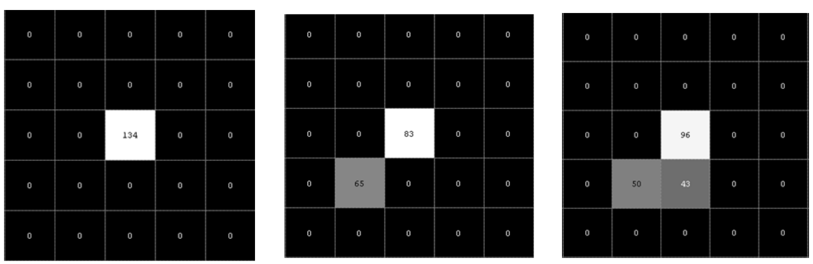
EXAMPLE OF PARTICLES



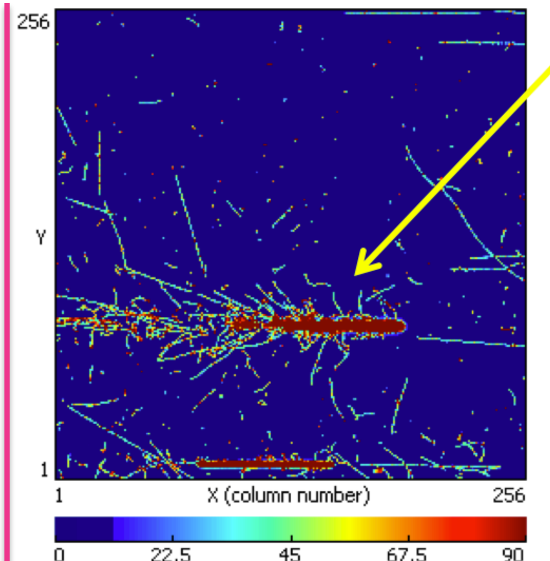
0.5MeV Electron (^{90}Sr)



5.5MeV Alpha (^{241}Am)



60keV Photons (^{241}Am)



Pb ion with delta rays
Erik Heijne [2]

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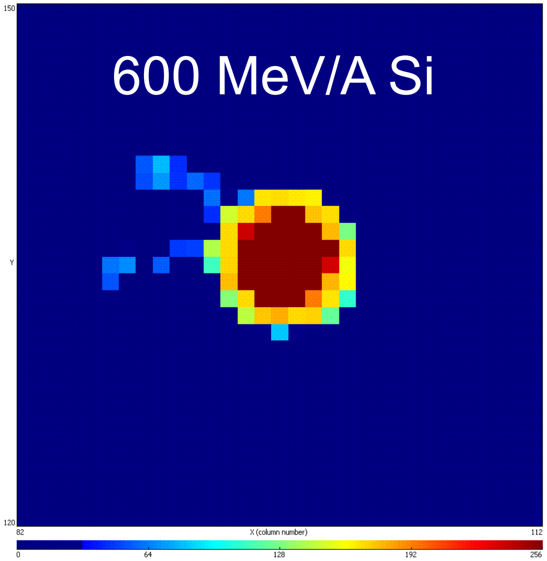
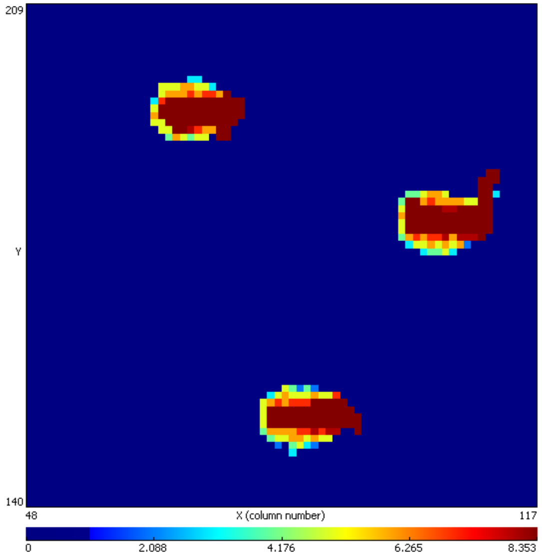
EXAMPLE OF PARTICLES

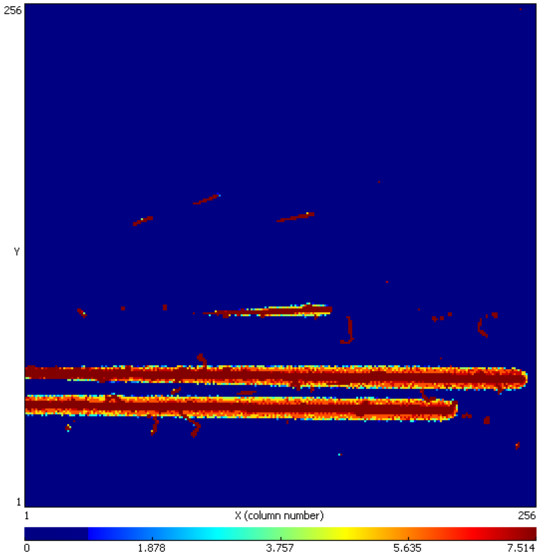
0º



60º



90º



L. Pinsky et al., Proc. IEEE Aerospace Conf., 2007.

TIMEPIX DETECTORS AT ISS

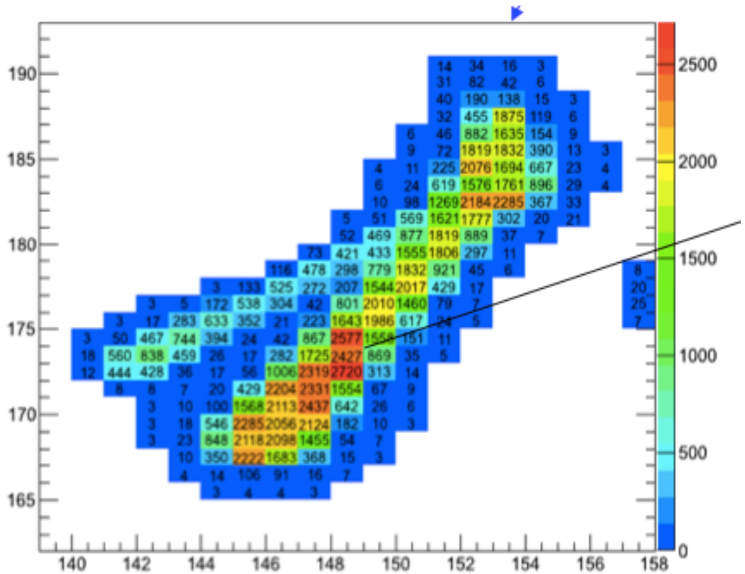
- 5 Timepix Usb Lite detectors with 300um Si sensors are currently in operation at the ISS
- Evaluated as an option for radiation field monitors and personal dosimeters
- Mixed radiation field
- Important to get the right quality factor for heavy ions

UNIVERSITY of HOUSTON

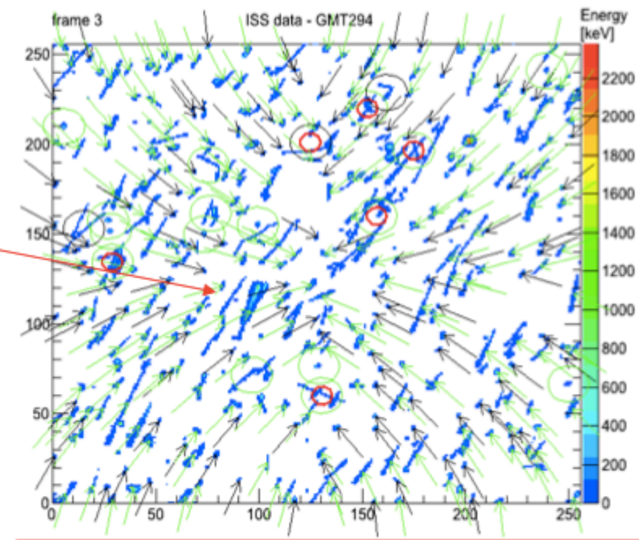
NASA


EMERGENCY USE
FIRE PORT
NOD1P3_H1

TIMEPIX DETECTORS AT ISS



Heavy Ion fragment, Q factor ~ 25

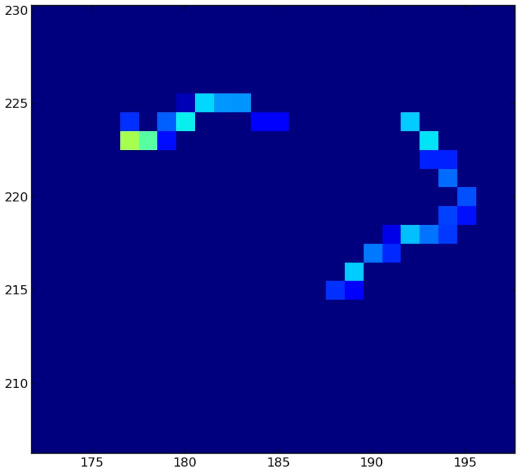


Heavy fragment found in a very busy frame.

DEMONSTRATION

BASIC PARTICLE IDENTIFICATION: CONCLUSIONS

- Possible to categorize particles using track and energy information
- Some types of particles are hard or impossible to separate
- Additional convertors and filters improve the detection specificity



β^- radiation or Compton electrons?

OUTLINE AND HIGHLIGHTS FROM MY RESEARCH

- Characterization of CdTe sensors bump bonded to Timepix (in collaboration with Glasgow University and Diamond Light Source) []
- Investigation of excess noise in Timepix ToT mode.
- Long time stability of Timepix
- Radiation hardness characterization of Medipix3RX
- Count rate linearity and energy response of Medipix3RX in high flux conditions

PUBLICATIONS

1. Frojdh, E.; et al., *Probing Defects in a Small Pixellated CdTe Sensor Using an Inclined Mono Energetic X-Ray Micro Beam, Nuclear Science, IEEE Transactions on* , vol.PP, no.99, pp.1,1, 0doi: 10.1109/TNS.2013.2257851
2. FRÖJDH, C.; NORLIN, B.; FRÖJDH, E. Spectral X-ray imaging with single photon processing detectors. *Journal of Instrumentation*, 2013, 8.02: C02010.
3. BALLABRIGA, R., et al. The Medipix3RX: a high resolution, zero dead-time pixel detector readout chip allowing spectroscopic imaging. *Journal of Instrumentation*, 2013, 8.02: C02016.
4. E. Fröjdh, C. Fröjdh, E.N. Gimenez, D. Maneuski, J. Marchal, B. Norlin, V. O'Shea, G. Stewart, H. Wilhelm, R.M Zain and G. Thungström, *Depth of interaction and bias voltage depenence of the spectral response in a pixellated CdTe detector operating in Time-OverThreshold mode subjected to monochromatic X- rays*. 2012 JINST 7 C03002 doi:10.1088/1748-0221/7/03/C03002
5. D. Maneuski, V. Astromskas, E. Fröjdh, C Fröjdh, E.N. Gimenez, J. Marchal, V. O'Shea, G. Stewart, N. Tartoni, H. Wilhelm, K. Wraight and R.M. Zain *Imaging and spectroscopic performance studies of pixellated CdTe Timepix detector* 2012 JINST 7 C01038 doi:10.1088/1748-0221/7/01/C01038
6. S. Reza, W.S. Wong, E. Fröjdh, B. Norlin, C. Fröjdh, G. Thungström and J. Thim *Smart dosimetry by pattern recognition using a single photon counting de- tector system in time over threshold mode* 2012 JINST 7 C01027 doi:10.1088/1748- 0221/7/01/C01027
7. E. Fröjdh, B. Norlin, G. Thungström and C. *Fröjdh X-ray absorption and charge transport in a pixellated CdTe detector with single photon processing readout* JINST 6 P02012 doi:10.1088/1748-0221/6/02/P02012
8. E. Fröjdh, A. Fröjdh, B. Norlin, C. Fröjdh, *Spectral response of a silicon detector with 220µm pixel size bonded to MEDIPIX2*, NIM-A:, Volume 633, Supplement 1, May 2011, Pages S125-S127, ISSN 0168-9002, doi: 10.1016/ j.nima.2010.06.143.
9. A. Fröjdh, E. Fröjdh, G. Thungström, C. Fröjdh, B. Norlin, *Processing and characterization of a MEDIPIX2-compatible silicon sensor with 220µm pixel size* NIM-A, Volume 633, Supplement 1, May 2011, Pages. S78-S80, doi: 10.1016/j.nima.2010.06.128.

List does not include non-refereed conference proceedings

What are the future chips expected from the Medipix Collaboration?

OUTLOOK

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TIMEPIX3

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- Design effort shared between CERN, Bonn university and Nikhef
- Applications: Particle tracking by time stamping and total deposited charge measurement
- 256x256 pixel matrix, 55x55μm^2 pixels
- CMOS 0.13μm technology
- Simultaneous measurement of ToA and ToT per event (48bits/event)
- Packet-based data-driven readout (readout associated dead time of 375ns)
- Maximum dead time free hit rate of 40 10^6 hits/s cm^2 (randomly distributed hits)
- Programmable shutdown/wake-up feature for the front end (analog domain) and/or general clock gating (digital domain)

X. Llopart, T. Poikela, M.De Gaspari

PIXEL REQUIREMENTS

Pixel size	55 μm x 55 μm
Global Time stamp (bunchID)	40 MHz (25ns)
Global Time stamp range	14bits (409.6 μs)
Accurate Time stamp per pixel	4bits → 1.56ns resolution (640 MHz)
Local Oscillator frequency	640 MHz (shared by 8 pixels)
On-pixel local oscillator tuning	Locked using periphery PLL
TOT range	10 bits (@ 40 MHz)

PIXEL OPERATION MODES

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Readout Operation Modes	Op_mode	
ToA & ToT	00	Fast Time (4b @ 640 MHz) ToA (14b @ 40 MHz) ToT (10b @ 40 MHz) Pixel coordinate 16b
		Double hit resolution: 375ns
Only ToA	01	Fast Time (4b @ 640 MHz) ToA (14b @ 40 MHz) pixel coordinate 16b
		Double hit resolution: 375ns
Event Count & Integral ToT	10	Event count 10b Integral ToT (14b @ 40 MHz) pixel coordinate 16b
		Shutter-controlled operation
		Non-continuous with Zero Suppression
		Full chip readout time: 1.6 ms @ 320MHz and 8 SLVS lines

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SMALLPIX

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- Developed in the framework of the Medipix3 collaboration
- Applications: Particle tracking by time stamping and total deposited charge measurement
- 512x512 pixel matrix, ~40x40mm^2 pixels
- CMOS 0.13mm technology
- Simultaneous measurement of ToA + ToT1 or PC + iToT
- Frame based readout with zero compression (on-pixel and per-column)
- Fast OR
- Shutdown/wake-up feature for the front end
- Design compatible for Through Silicon Via technology

CLASSICAL 3-SIDE BUTTABLE ARCHITECTURE

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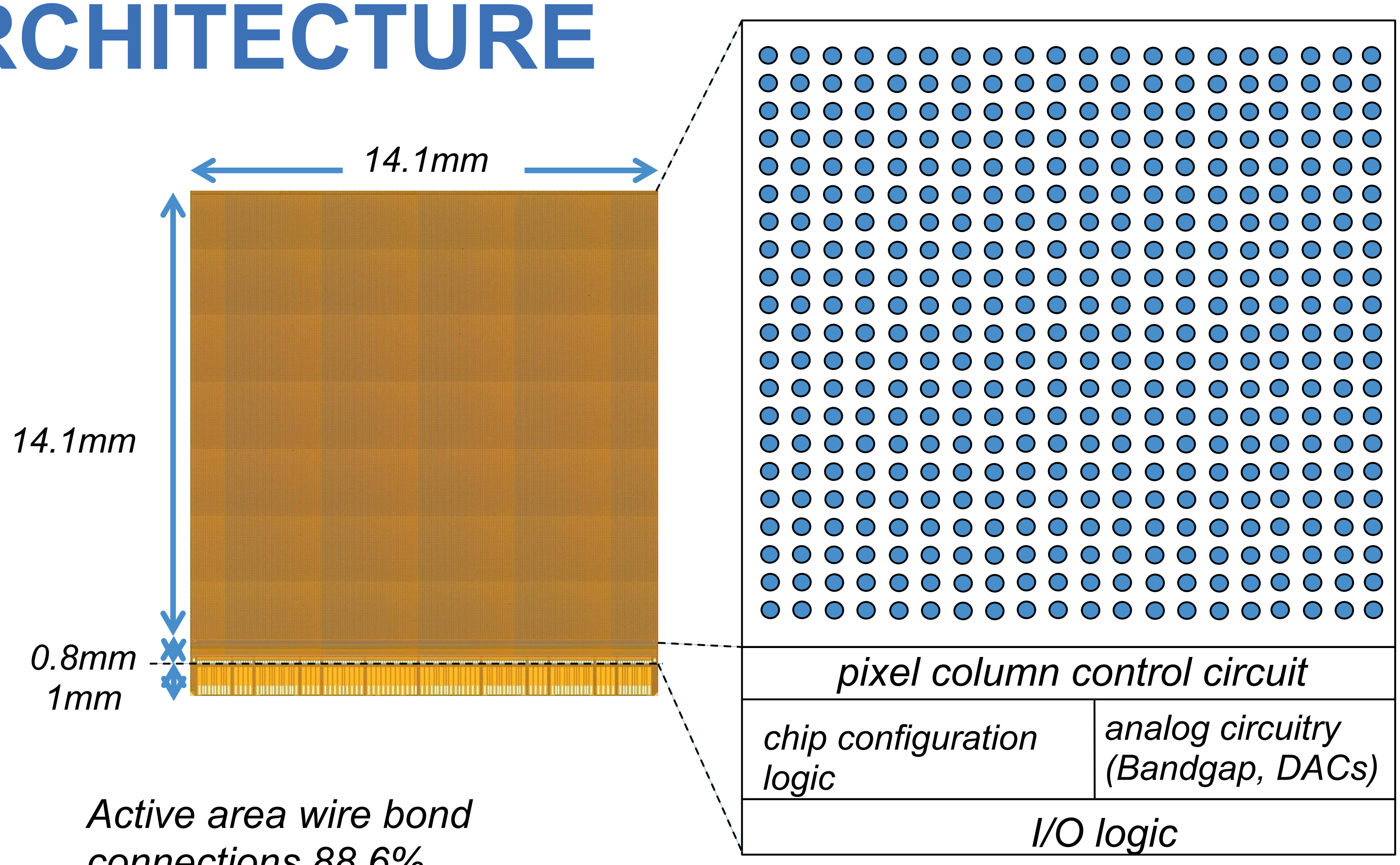

Active area wire bond connections 88.6%
Active area TSV connections 94.3%

SMALLPIX ARCHITECTURE

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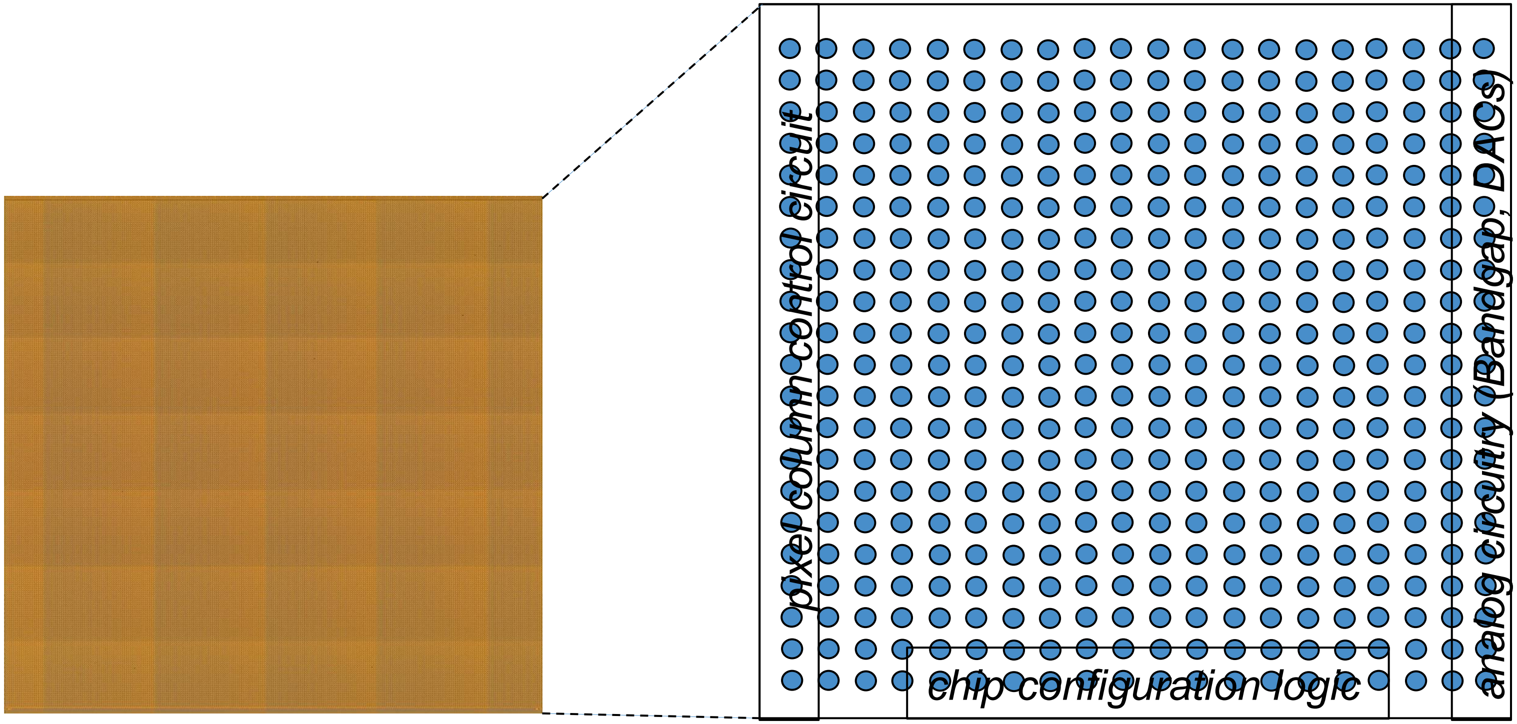
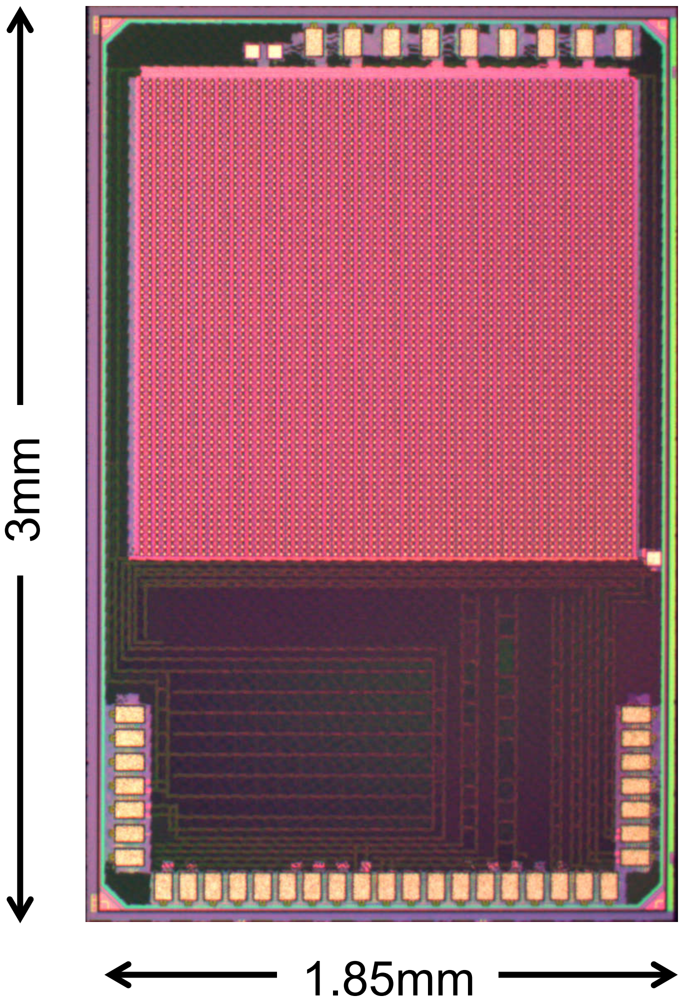


Target Active area TSV connections ~100%
Chip can be tiled on 4 sides

CLICPIX PROTOTYPE



Designed in collaboration with the CERN Linear Collider Detector group

ASIC in 65nm CMOS technology designed to fulfill the specifications for the future CLIC vertex detector

- $25 \times 25\ \mu m^2$ pixel, 64x64 pixel matrix
- Simultaneous 4-bit ToA and TOT measurement @100MHz
- Frame based with zero suppression
- Power pulsing

Preliminary characterization on the 65nm CMOS technology done

First prototype chip with full pixel functionality to be tested in coming weeks

TRENDS FOR NEW DETECTORS AND FUTURE RESEARCH

- More complex processing on chip
- Faster communication
- Larger systems
- Increased costs
- Moving into medical applications
- ….