



Spectroscopic X-ray imaging

Lukas Tlustos
Medipix Collaboration, CERN

MEDIPIX2 Collaboration



- U INFN Cagliari
- CEA-LIST Saclay
- CERN Genève
- U d'Auvergne Clermont
- U Erlangen
- ESRF Grenoble
- U Freiburg
- U Glasgow
- IFAE Barcelona
- Mitt hoegskolan
- MRC-LMB Cambridge
- U INFN Napoli
- NIKHEF Amsterdam
- U INFN Pisa
- FZU CAS Prague
- IEAP CTU in Prague
- SSL Berkeley



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GLASGOW



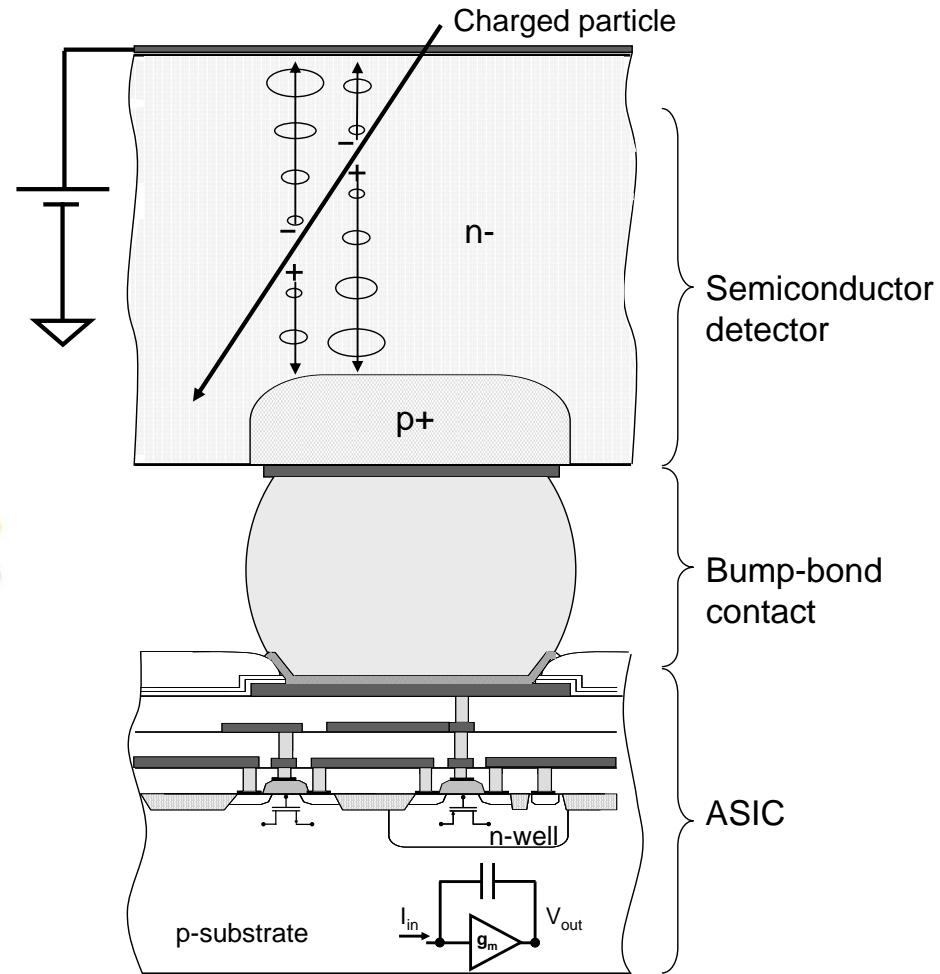
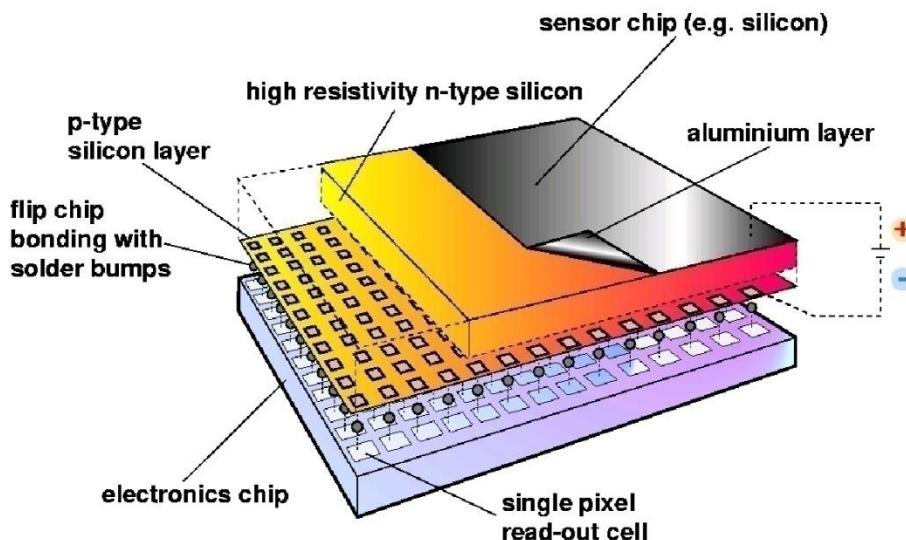
<http://medipix.web.cern.ch/MEDIPIX/>



MEDIPIX3 Collaboration

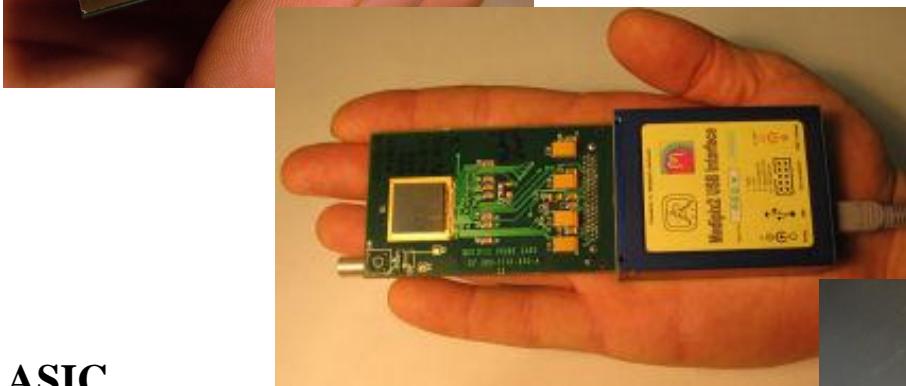
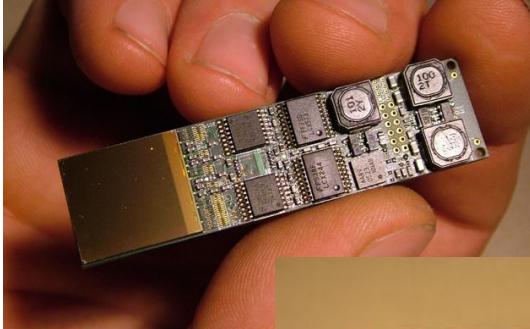
- University of Canterbury, Christchurch, New Zealand
- DRT/LIST/DeTeCS/SSTM, CEA, Paris, France
- CERN, Geneva, Switzerland,
- DESY-Hamburg, Germany
- The Diamond Light Source, Diamond House, Didcot, UK
- Freiburger Materialforschungszentrum, Albert-Ludwigs-Universität Freiburg, Germany
- University of Glasgow, Scotland, UK
- Institute for Synchrotron Radiation, ISS, Forschungszentrum Karlsruhe, Germany
- Biophysical Structural Chemistry, Leiden Univ., The Netherlands
- NIKHEF, Amsterdam, The Netherlands
- Mid Sweden University, Sundsvall, Sweden
- IEAP, Czech Technical University, Prague, Czech Republic
- ESRF, Grenoble, France
- Universität Erlangen-Nürnberg, Erlangen, Germany
- Space Sciences Laboratory, University of California, Berkeley, USA
- VTT Microsystems, Espoo, Finland
- ITER

Hybrid-Pixel Detector



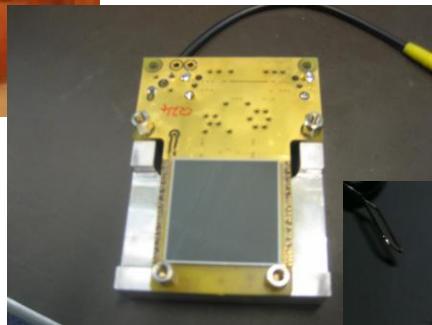


Medipix2



ASIC

- 0.25 mm CMOS
- 55 μ m Pixel, 256 x 256
- Sensitive area \sim 2 cm 2
- 3 side buttable
- Serial RO \sim 9.2ms @ 100MHz Clock
- 32bit CMOS Parallel RO \sim 300 μ s Port



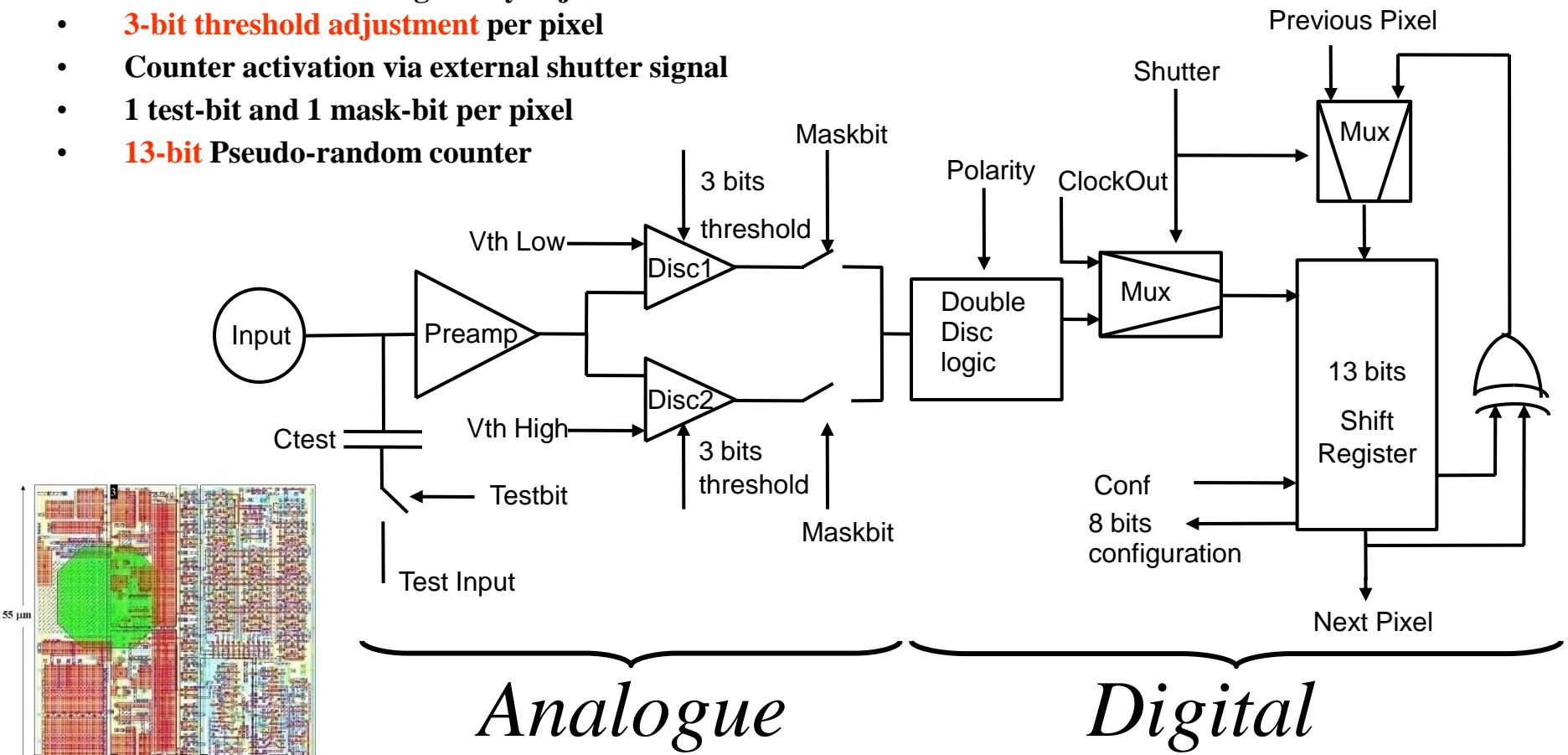
(Current) RO systems

- Standard readout: MUROS2 + NI-DIO32
- Fastest readout: PRIAM (ESRF)
 1.5 kHz frame rate
- Most compact, portable: USB1.0 based
 \leq 4Hz frame rate

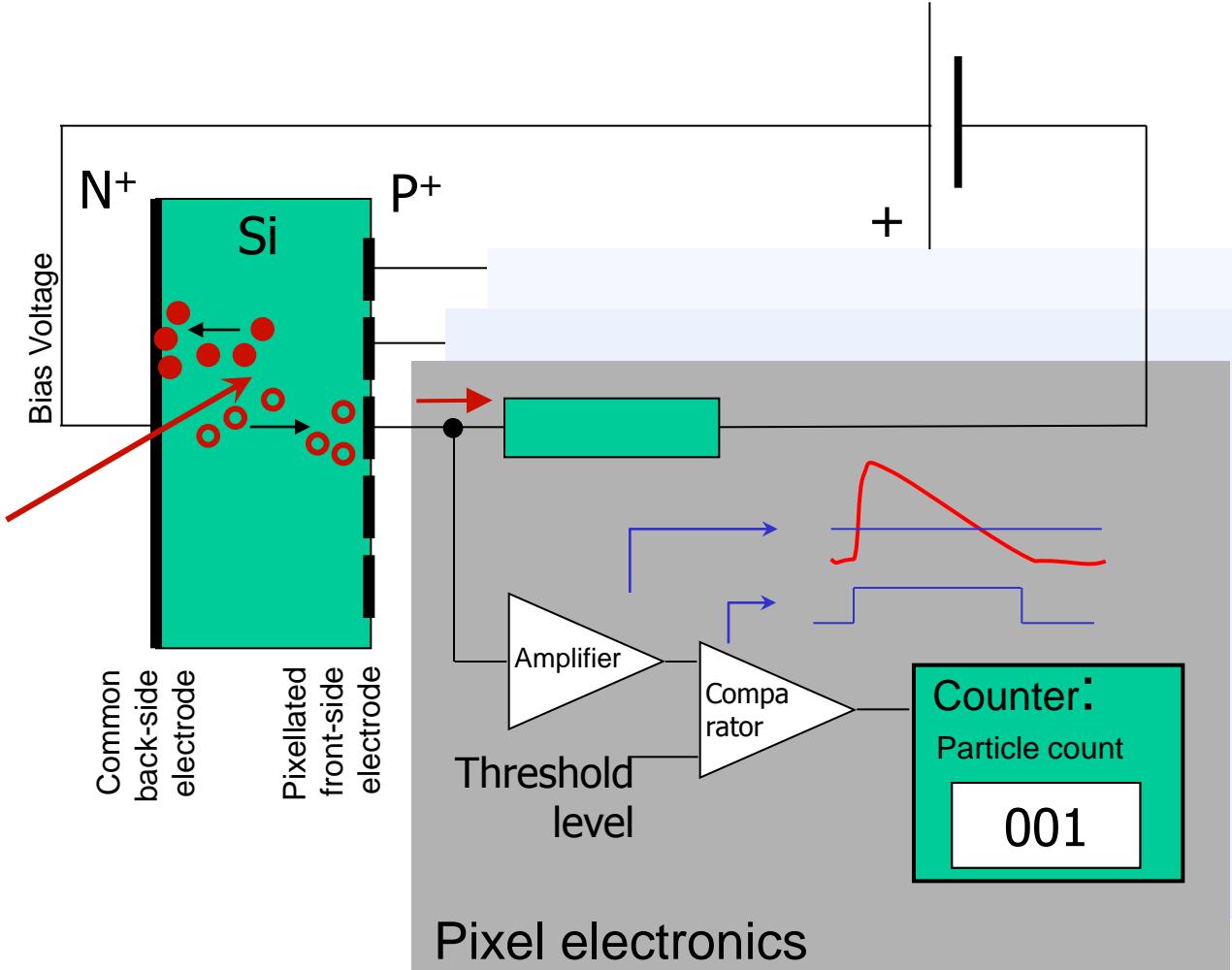
Largest assemblies
2x2 and 1x5

Medipix2 Pixel

- Positive und negative input signals → alternative detector materials (GaAs, CdTe ...)
- Charge sensitive preamplifier with leakage current compensation per pixel
- 2 Discriminators with globally adjustable threshold
- 3-bit threshold adjustment per pixel
- Counter activation via external shutter signal
- 1 test-bit and 1 mask-bit per pixel
- 13-bit Pseudo-random counter

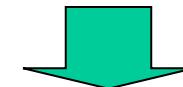


Medipix Signal Processing



Threshold level >>
electronic noise
⇒ No noise counts

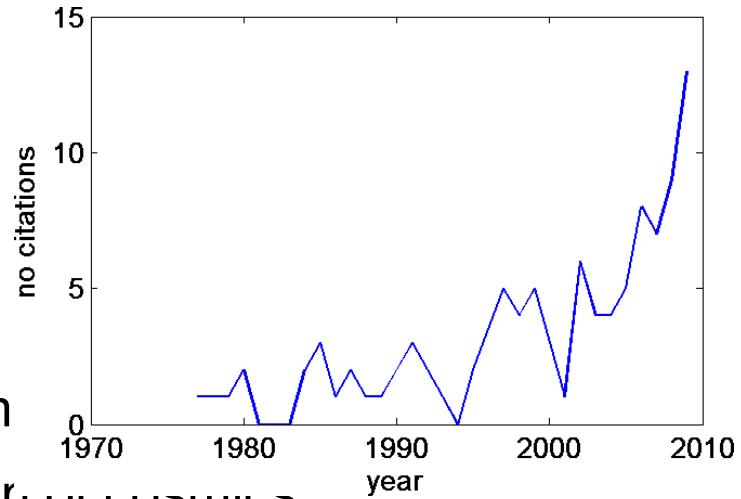
Digital integration
(counting)
⇒ No dark current.



Unlimited dynamic range
and exposure time.

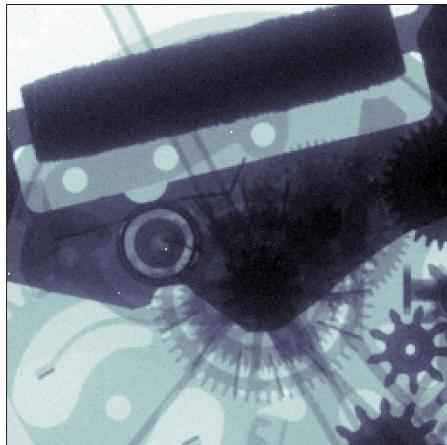
Motivation for Spectroscopic Imaging

- Use as much information contained in the X-ray beam as possible
 - Noise reduction, Energy weighting, ...
 - Material reconstruction
 - “Energy-selective reconstructions in X-ray computerised tomography”,
R. Alvarez and A. Macovski
1976 *Phys. Med. Biol.* **21** 733-744
- Particle recognition → Quantum
- Autoradiography - Discrimination of isotopes
-
- (Neuron imaging)

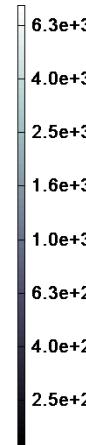
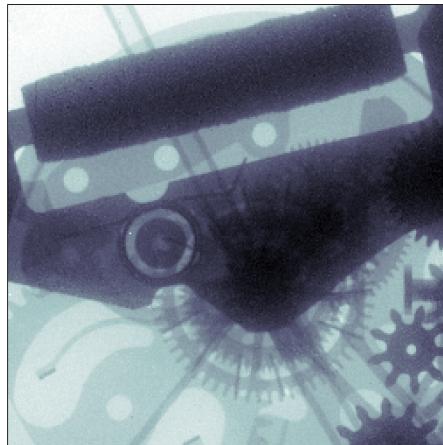


Energy Window Medipix2

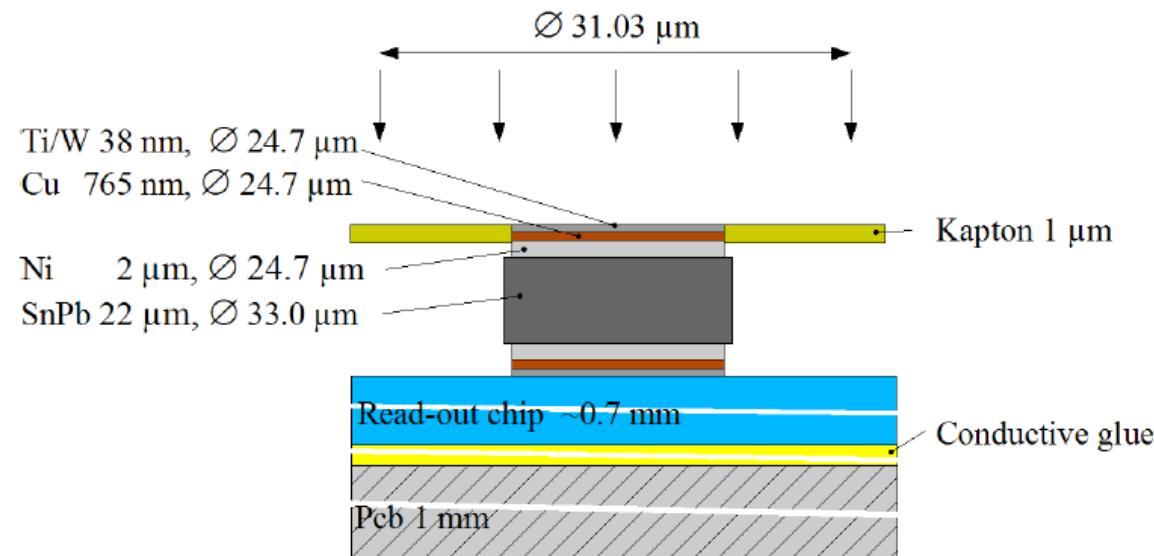
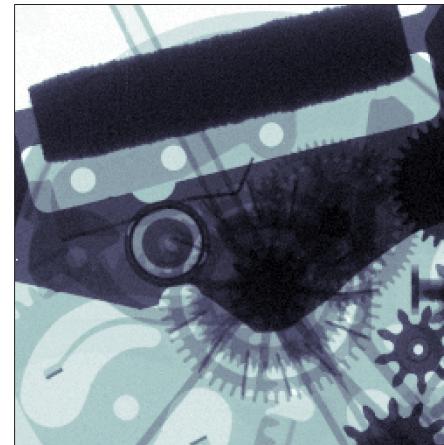
16.1-19.6 keV



21.6-25.1 keV

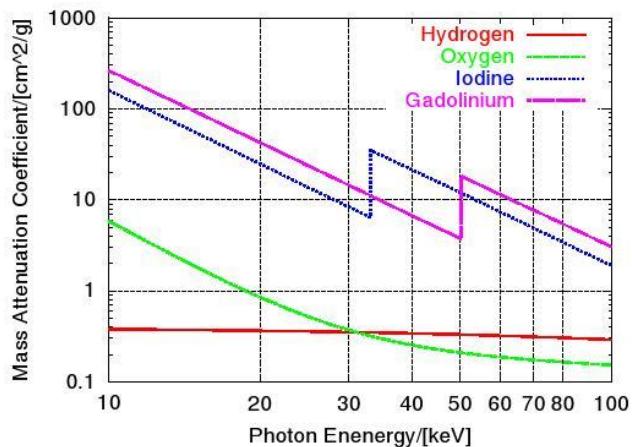


29-33.5 keV

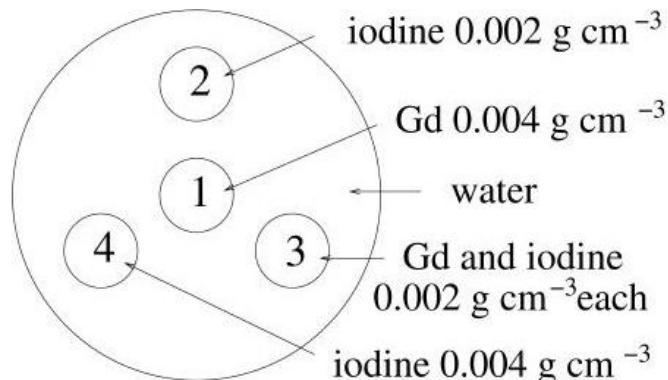




K-edge Imaging - Simulation



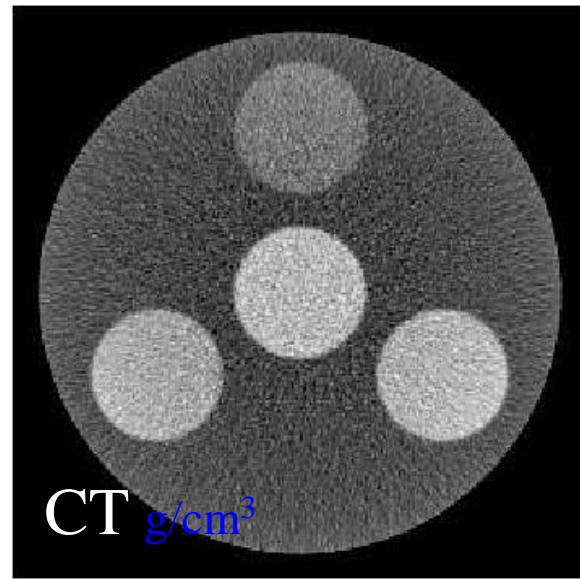
M Firsching et al. Nuclear Science Symposium Conf. Rec., 2006



- 20 cm water phantom
- W-tube 120kV, 0.6 mm Ti filter
- Ideal detector w=40 cm, 256 pixels
- Contrast agents
 - Iodine
 - Gadolinium

$$\frac{I(E)}{I_0(E)} = T(E) = \exp\left(-\sum_j \mu'_j(E) a_j\right)$$

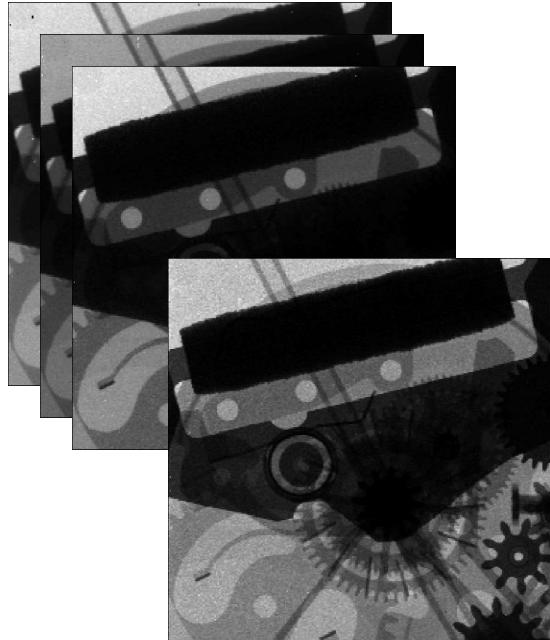
$$\begin{pmatrix} \mu_1(E_1) \\ \mu_2(E_2) \end{pmatrix} = \begin{pmatrix} \beta & \alpha \\ \beta & \alpha \end{pmatrix} \cdot \begin{pmatrix} \rho \\ \rho Z^k \end{pmatrix}.$$



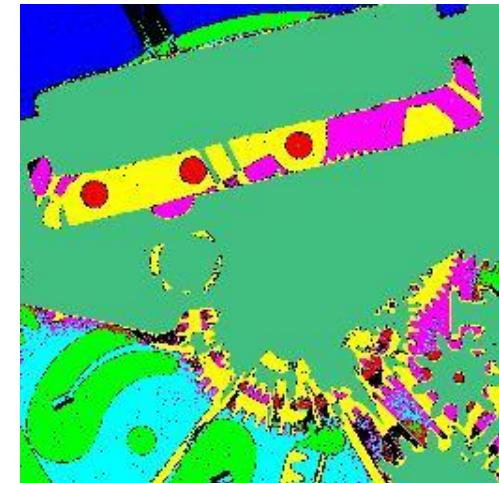
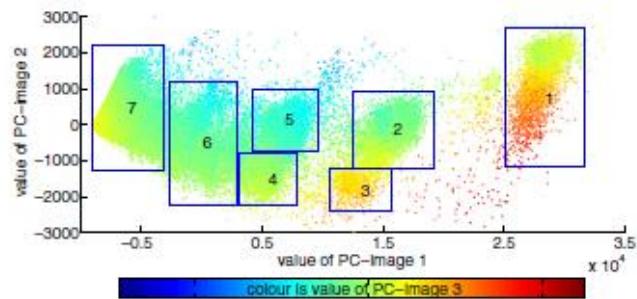


Statistical Material Recognition

- Material reconstruction using matrix inversion not always possible, matrix to be inverted tends to be close to singular
- Alternatives: Iterative methods, Statistical methods



Principal
Components
Analysis



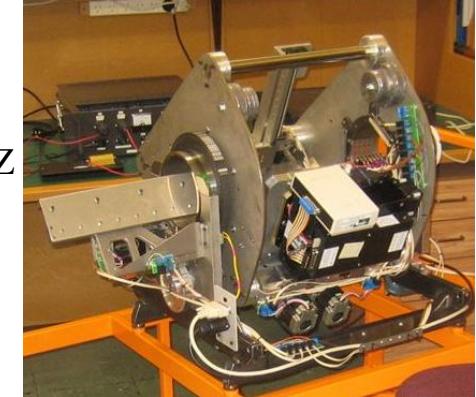
Butzer, J. et al., Image and Vision Computing New Zealand, 2008. IVCNZ 2008. 23rd International Conference



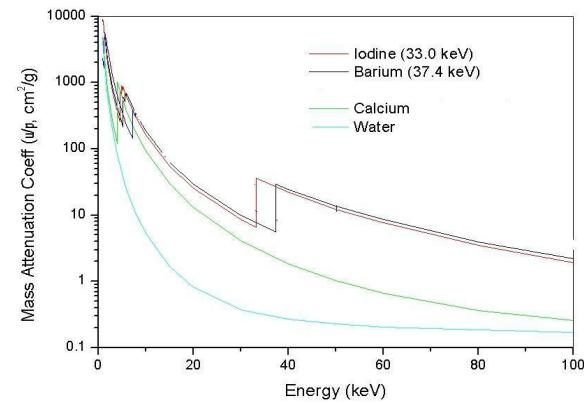
K-edge imaging



Univ. Canterbury, NZ
Mars bio-imaging
Small animal CT



- Iodine: Pulmonary circulation
- Barium: Lung
- Bone: normal structure

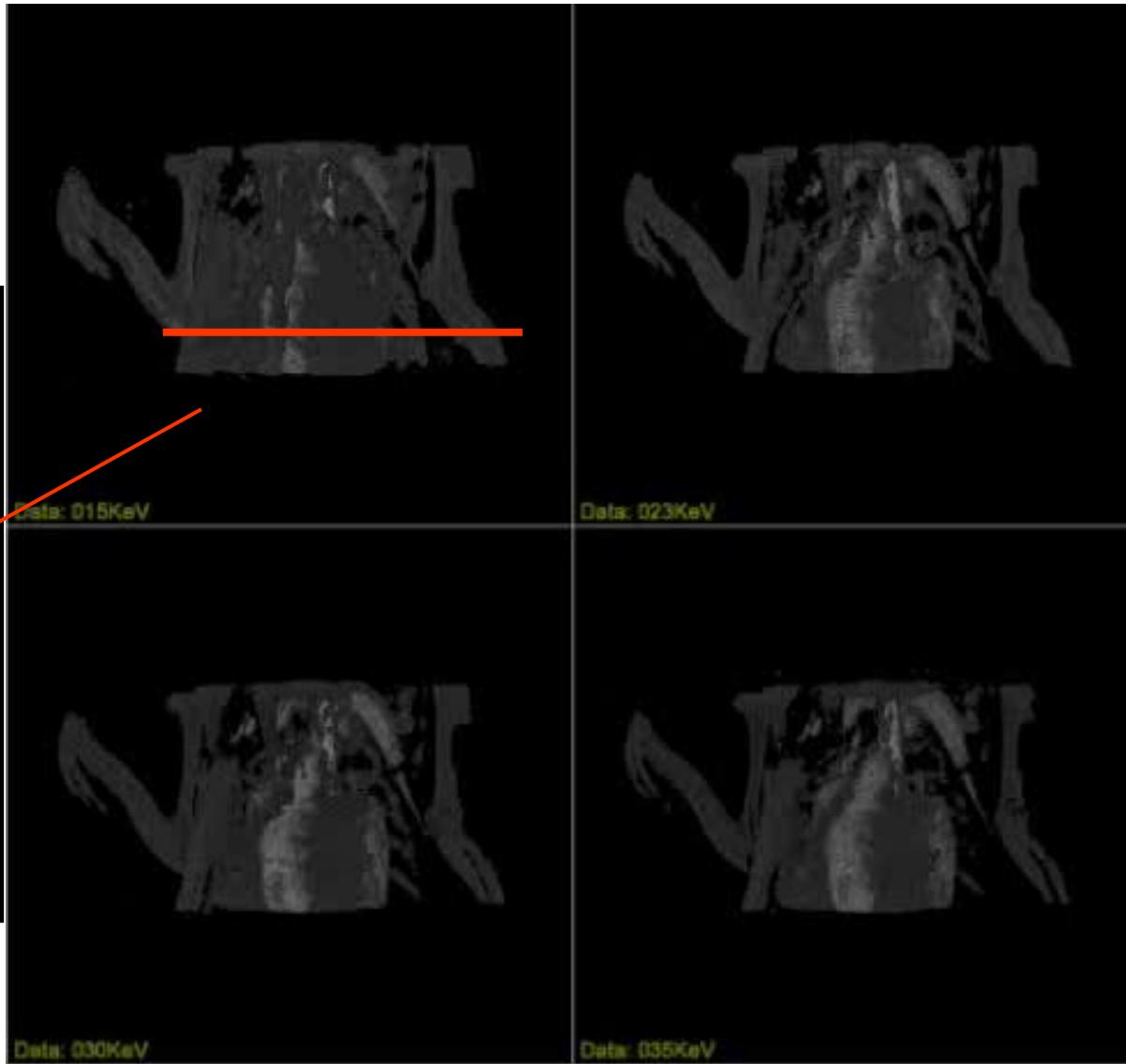
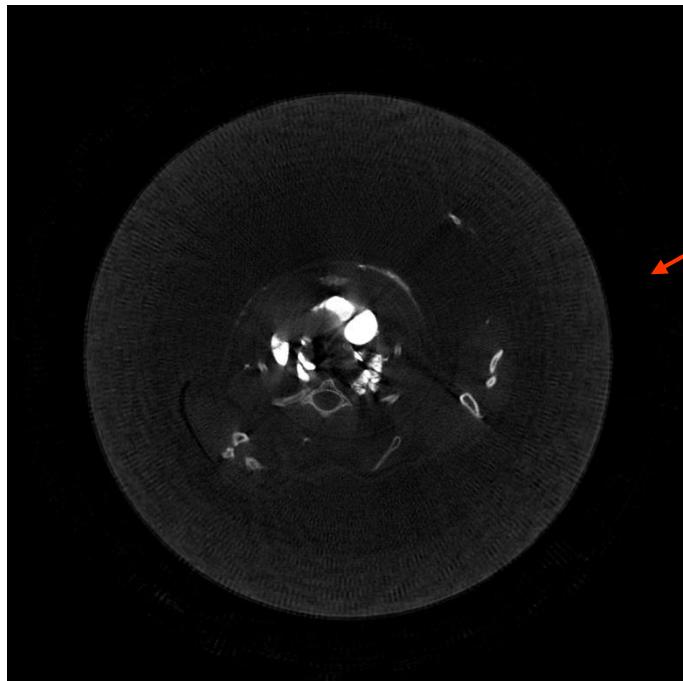




4 energy CT

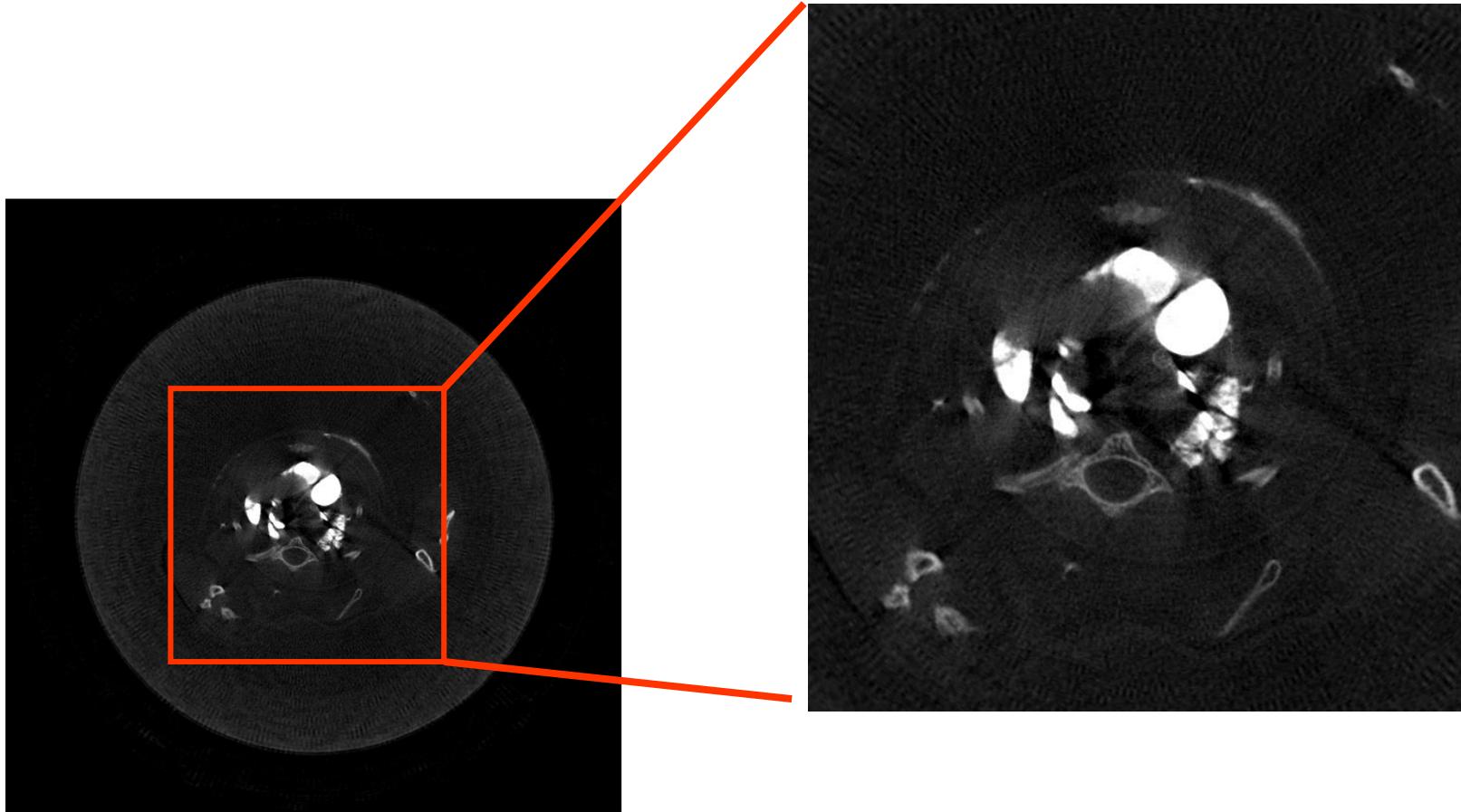


4 low thresholds chosen
(15, 23, 30, 35 keV)



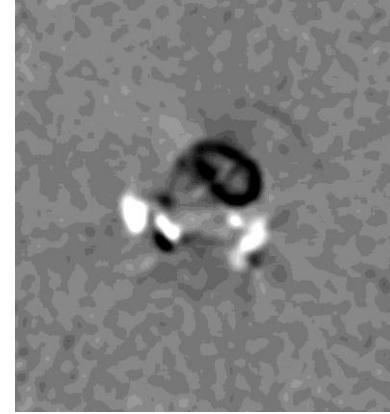
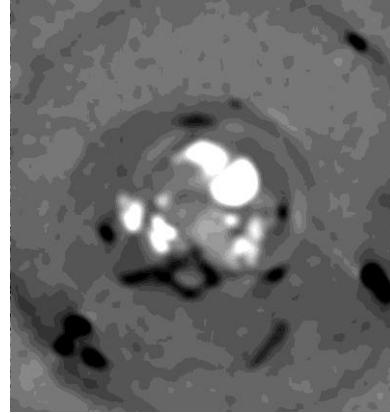
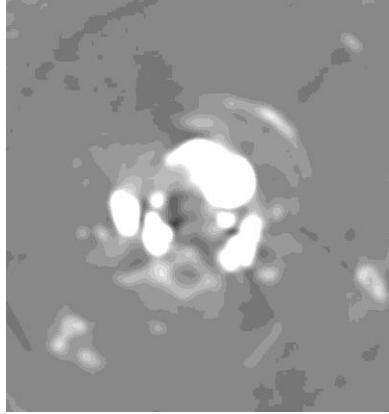


4 energy CT





PCA



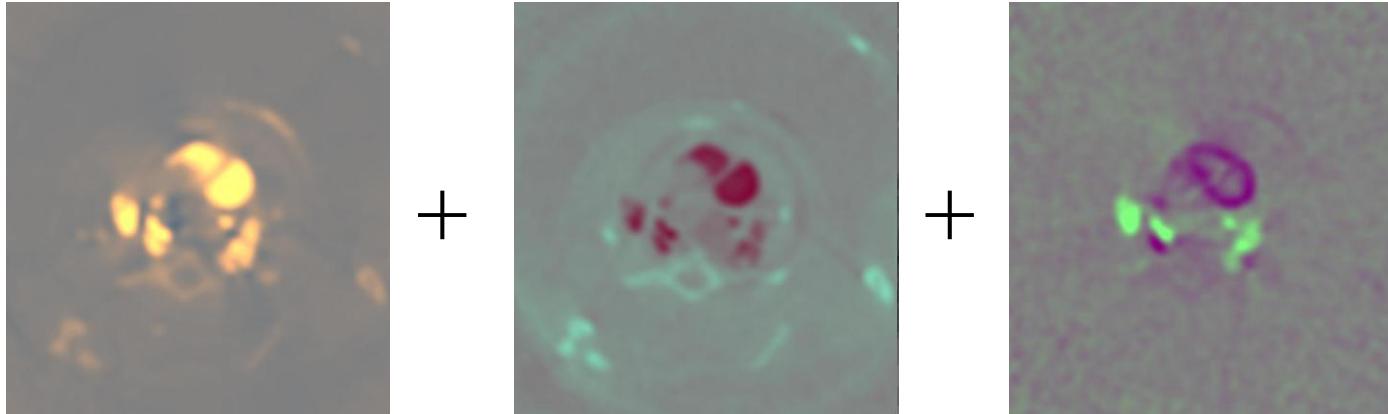
Bone = 1 -1 0

Iodine = 1 1 -1

Barium = 1 1 1

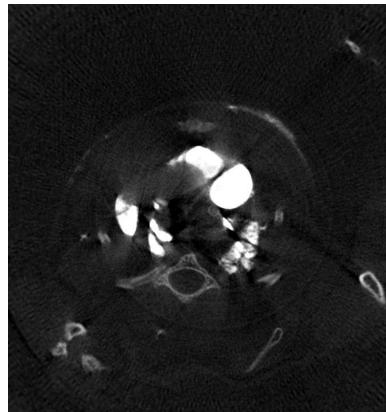


Colourise



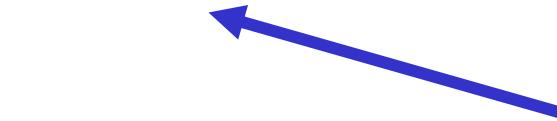
(

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X

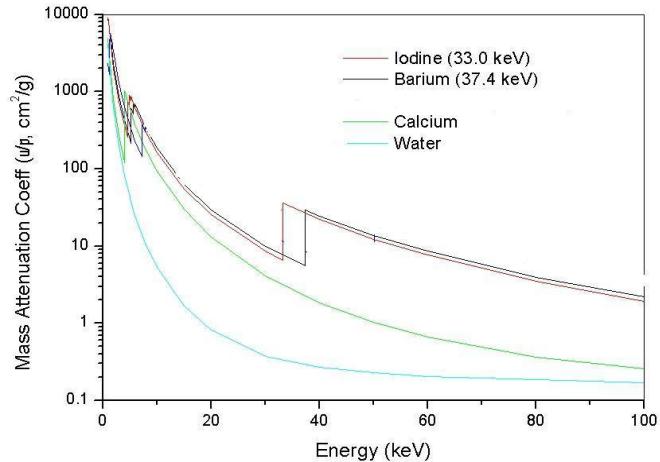
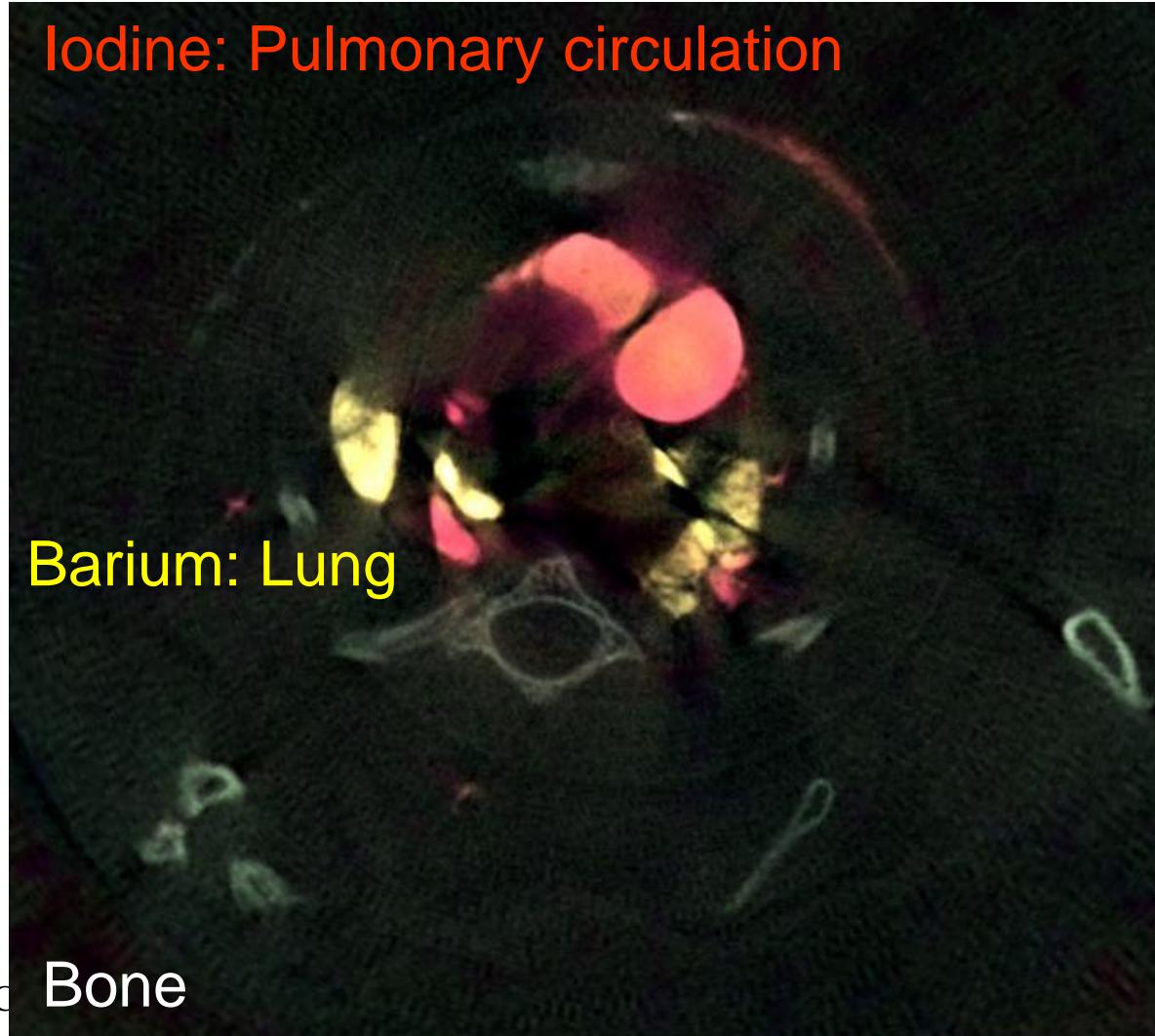
Spectral information



“conventional” information



Spectral enhancement



Butler, A., et al., *Processing of spectral X-ray data with principal components Analysis*, IWORID 2009, Prague

Possible Future Applications

- Eventually humans
- Improved material recognition
 - Ca-Phosphate vs. Ca-Oxylate
 - Fat vs. glandular tissue
 - Micro-CT in industrial context
- Nanoparticles
 - E.g. Contrast agent loaded Lipoproteines
 - Antibody labeled Lipoproteines → “functional” CT

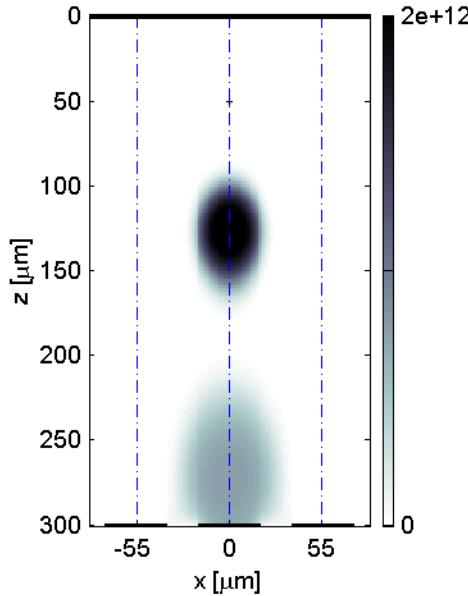




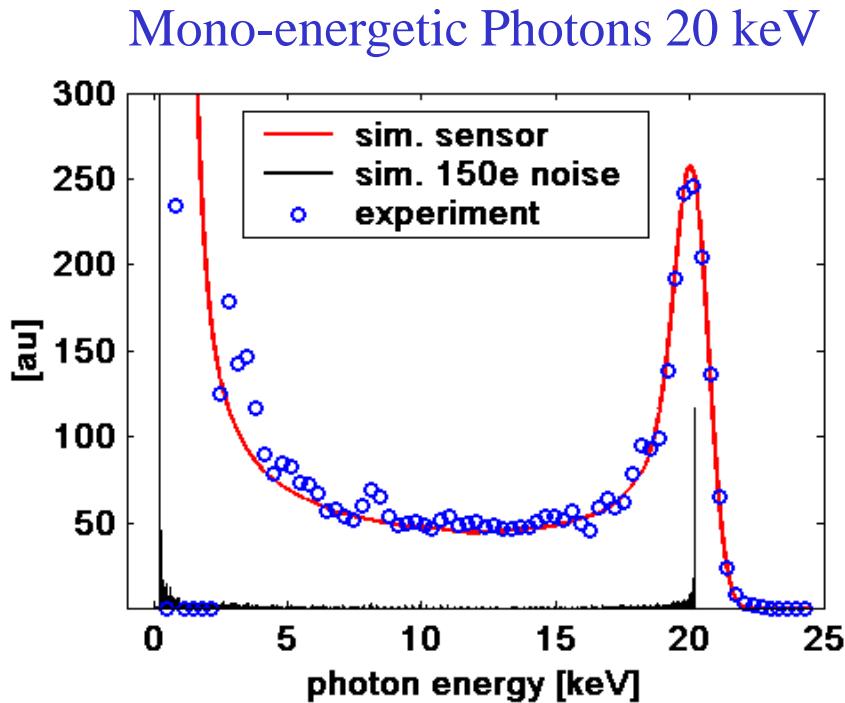
Limiting Factors

- 1) Energy dispersion due to charge sharing
 - Double counted / not counted photons, depending on threshold
 - Can be corrected for (De-convolution, Spectrum stripping), but introduces additional noise to the spectral dataset due to uncorrelated datasets - see above
 - Further amplification of noise when using matrix inversion to reconstruct mean Z and mean ρ
- 2) Only one energy window
 - Uncorrelated datasets for different energy bins
 - Reduced quantum efficiency
- 3) Fluorescence within detector (GaAs, CdTe, ...)
 - Additional distortion of the recorded spectrum

Charge Transport in Planar Si Sensor



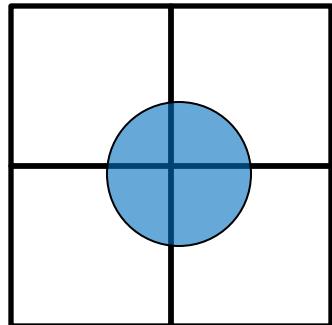
20 keV Photons
 300 μm Si Sensor
 55 μm Pixel Pitch
 120 V sensor bias



- Mono-energetic Photon spectrum \rightarrow continuous spectrum with \pm constant background and strong contribution of low pulse heights
- Even when using energy window spectroscopic information degraded

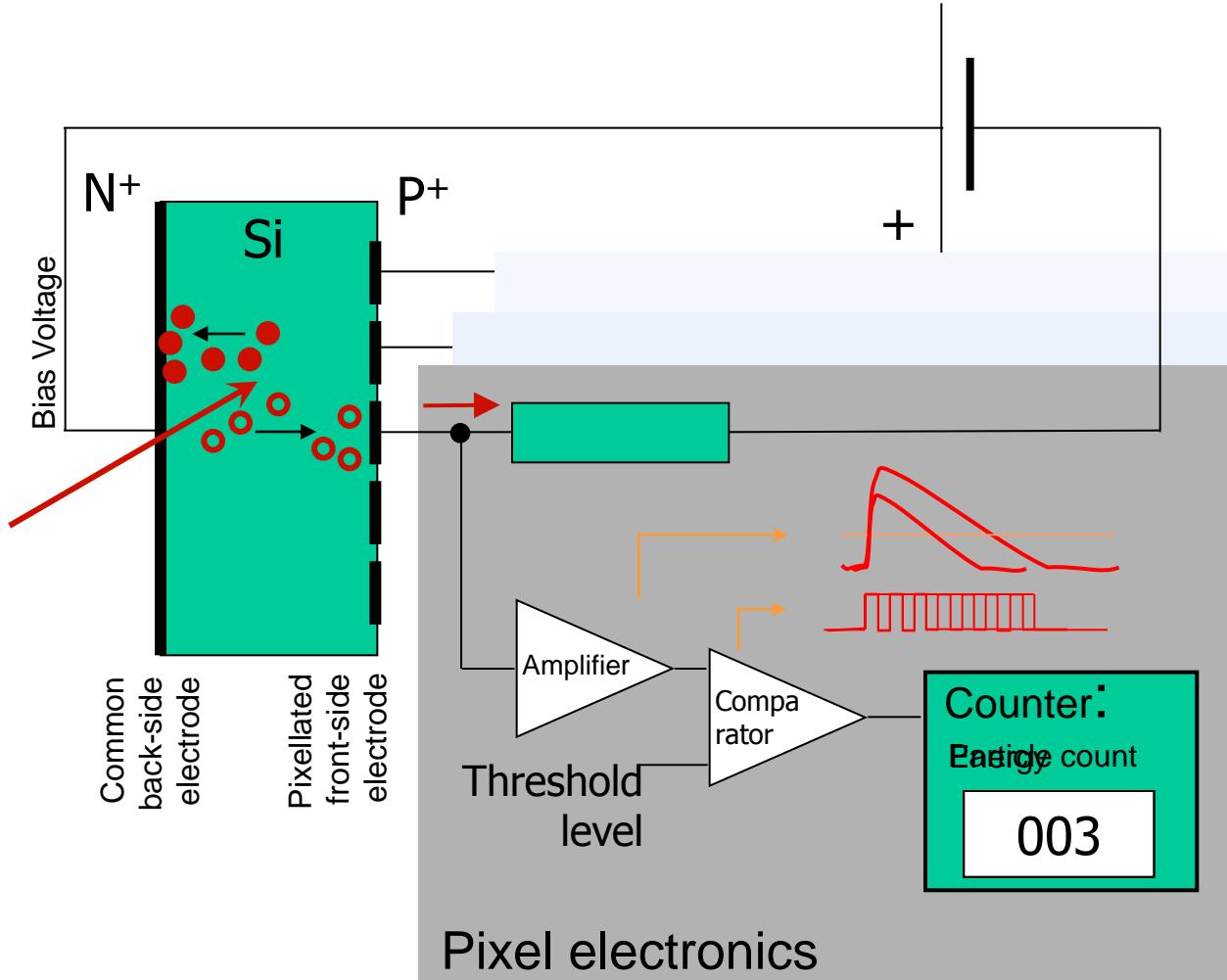


Charge Summing Implementation



- *Off chip:* **Timepix** like architecture
 - Digitization of energy deposited in pixel → TOT
 - Sparse data, no overlaps → limited particle flux
 - Fast readout necessary
- *On chip:* **Medipix3**
 - Communicating pixels
 - Dead time/pileup limit given by shaping time
 - Summing of 4 adjacent pixels
 - 2, 4 (8) Energy bins

TimePix



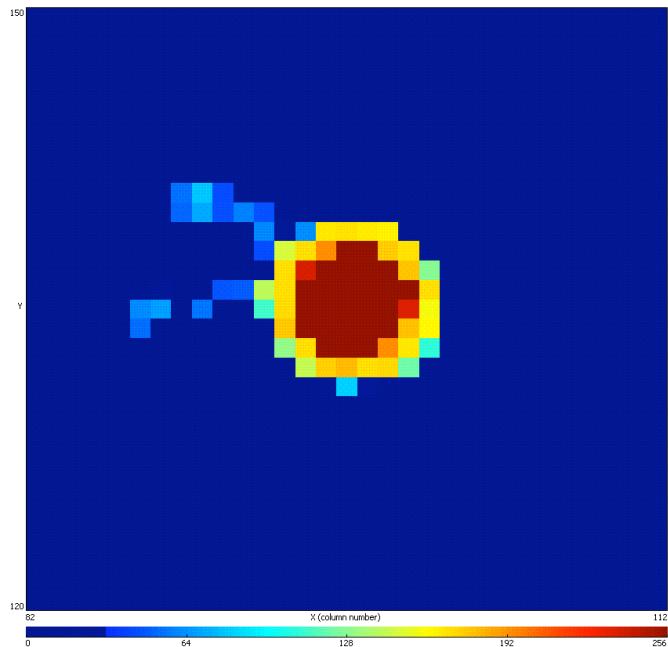
Continuous clock signal on whole chip ≤ 100 MHz

3 Modes:

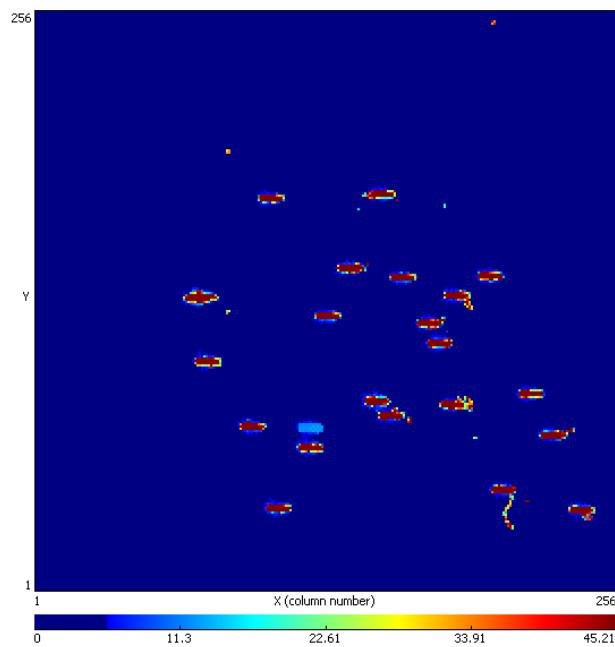
1. Counting = Medipix2
2. Time over Threshold
clock pulses counted when discriminator high.
Measure for energy deposited in pixel.
3. Time of Arrival
all clock pulses from first hit until end of shutter signal counted. Time of arrival of first particle per pixel.

^{11}B HIMAC, 290 MeV/nucleon

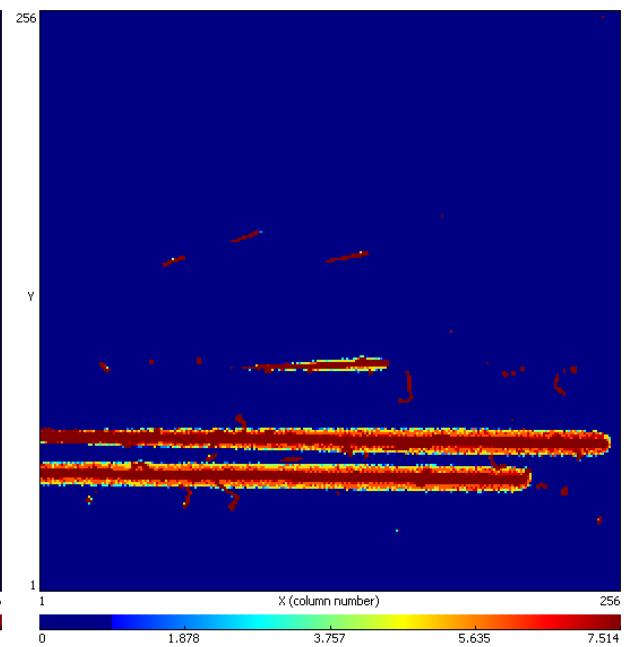
@ 0°



@ 60°



@ ~90°

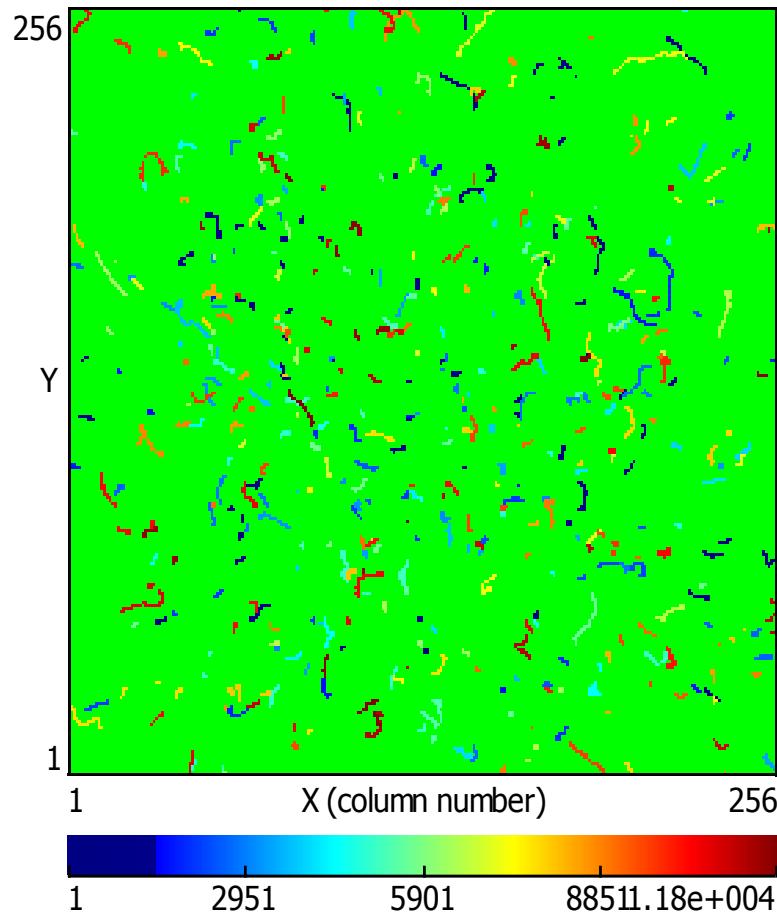


Charge deposition studies with various Isotopes → Space Dosimetry

Courtesy L. Pinsky, Univ. Houston

^{90}Sr

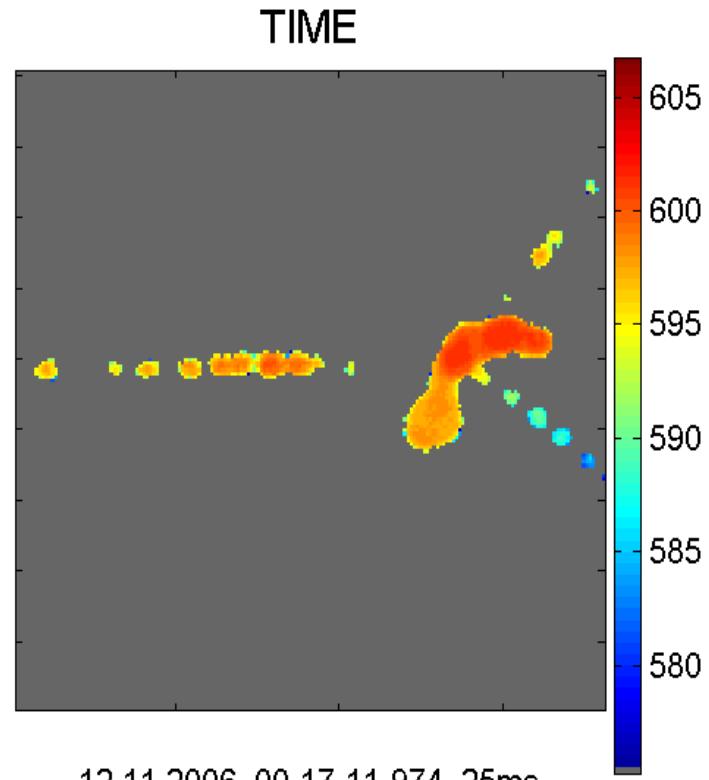
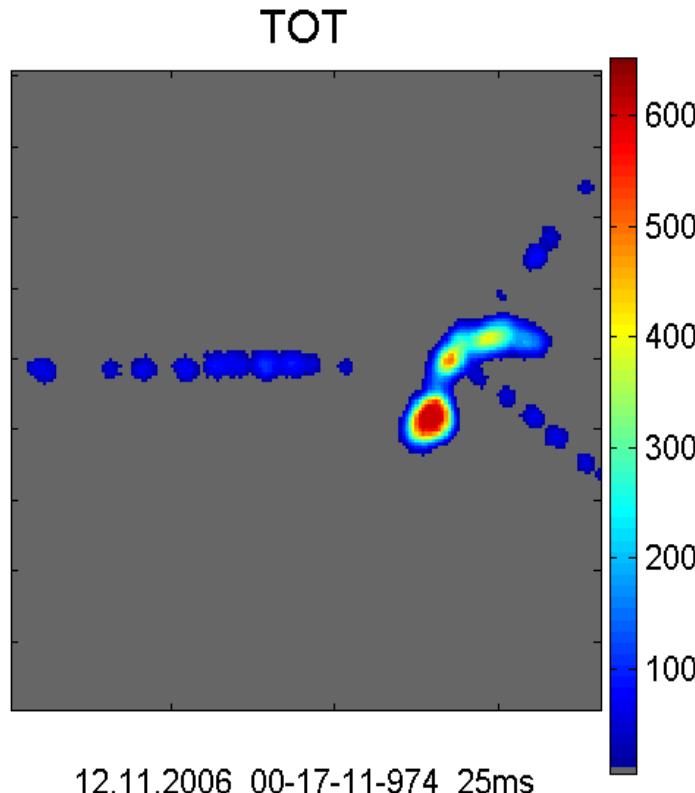
- ^{90}Sr 11 μs exposure time and $C/k_{\text{Ref}}=6.27 \text{ MHz}$ (159.3ns)
- Maximum acquisition time dynamic range of 1.88 ms



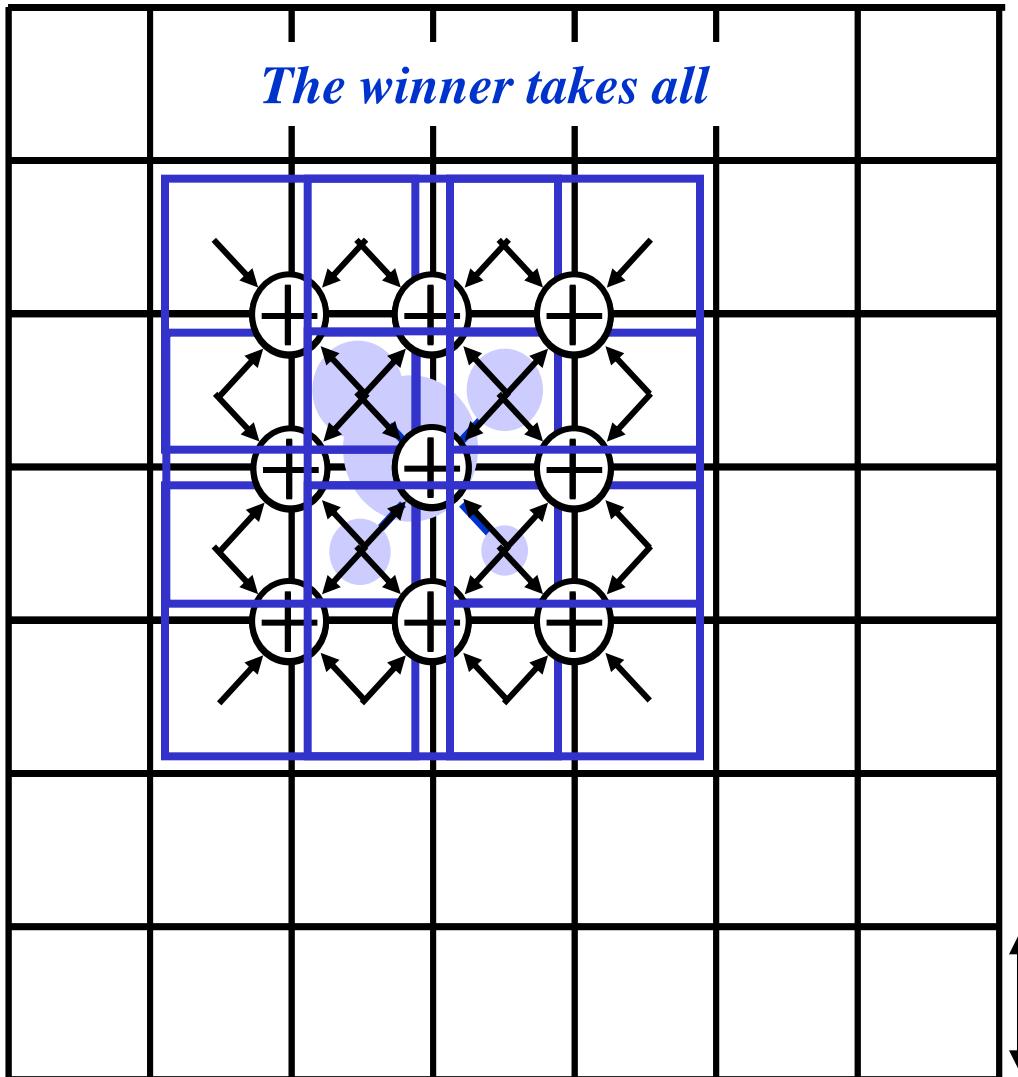


Timepix with 3-GEM detector

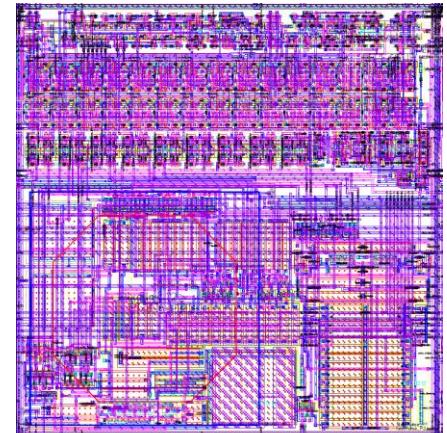
- DESY testbeam in November 2006 (A.Bamberger, M.Titov)
- 5 GeV e⁻



Medipix3 - Charge Summing Architecture



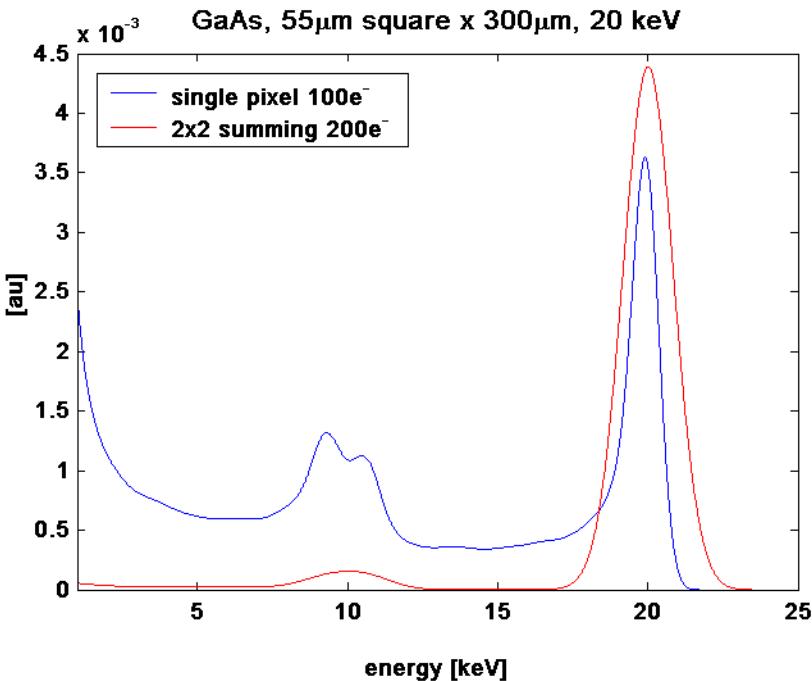
- *Charge is summed in every 4 pixel cluster on an event-by-event basis*
- *The incoming quantum is assigned as a single hit*



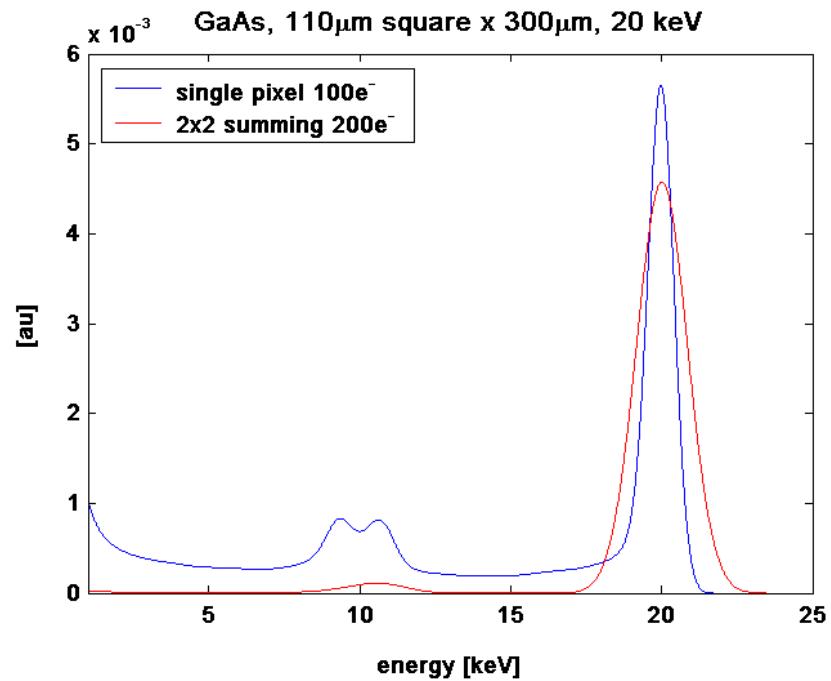


Medipix2/3 - 300 μm GaAs, 650 V

(still simulations)



$$\begin{aligned}\mu_e \tau_e & 650\text{V}/300\mu\text{m} \sim 1.7 \text{ cm} \\ \mu_h \tau_h & 650\text{V}/300\mu\text{m} \sim 0.086 \text{ cm}\end{aligned}$$



$$\begin{aligned}\text{Ga } K_{\alpha} & = 9.2 \text{ keV} \rightarrow 40 \mu\text{m} \text{ mean free path} \\ \text{As } K_{\alpha} & = 10.5 \text{ keV} \rightarrow 15 \mu\text{m} \text{ mean free path}\end{aligned}$$



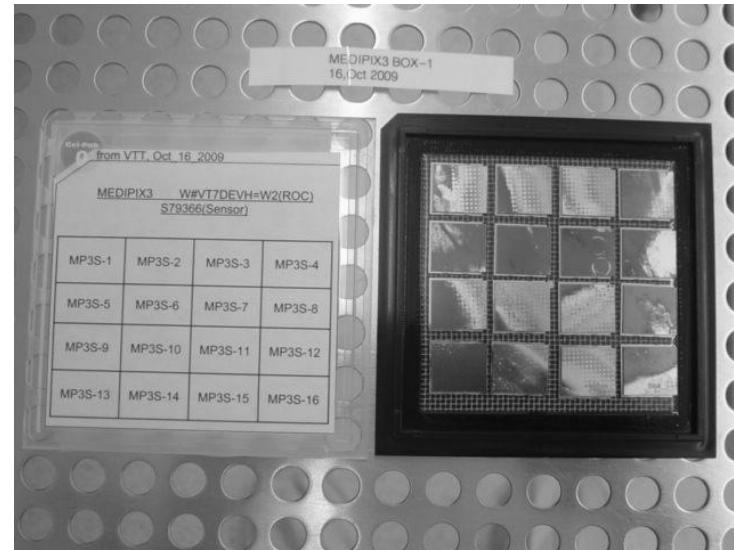
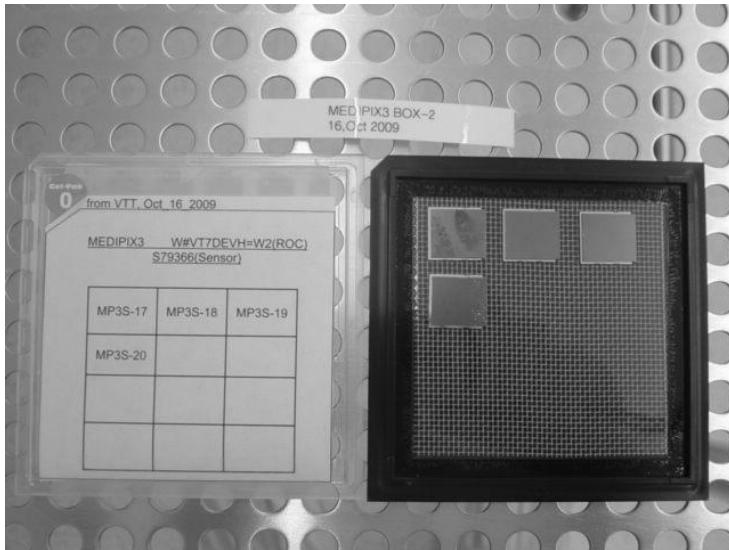
Medipix3 Modes of Operation

System Configuration	Pixel Operating Modes	# Thresholds
Fine Pitch Mode → 55 μm x 55 μm	Single Pixel Mode	2
	Charge Summing Mode	
Spectroscopic Mode → 110 μm x 110 μm	Single Cluster Mode	8
	Charge Summing Mode	
Front-end Gain Modes	Linearity	# Thresholds/Pix
High Gain Mode	~10 ke ⁻	2
Low Gain Mode	~20 ke ⁻	
Pixel Counter Modes	Dynamic range	# Counters/Pix
1-bit	1	2
4-bit	15	2
12-bit	4095	2
24-bit	16777215	1
Pixel Readout Modes	# Active Counters	Dead Time
Sequential Read-Write	2	Yes
Continuous Read-Write	1	No



First Medipix3 Assemblies @ CERN

- First 20 300 µm Si detectors bonded to single Medipix3 readout chips (VTT) arrived at CERN ~ one month ago.
- 5 assemblies have been mounted
- Extensive testing going on
 - + HW integration ...
 - + Software debugging

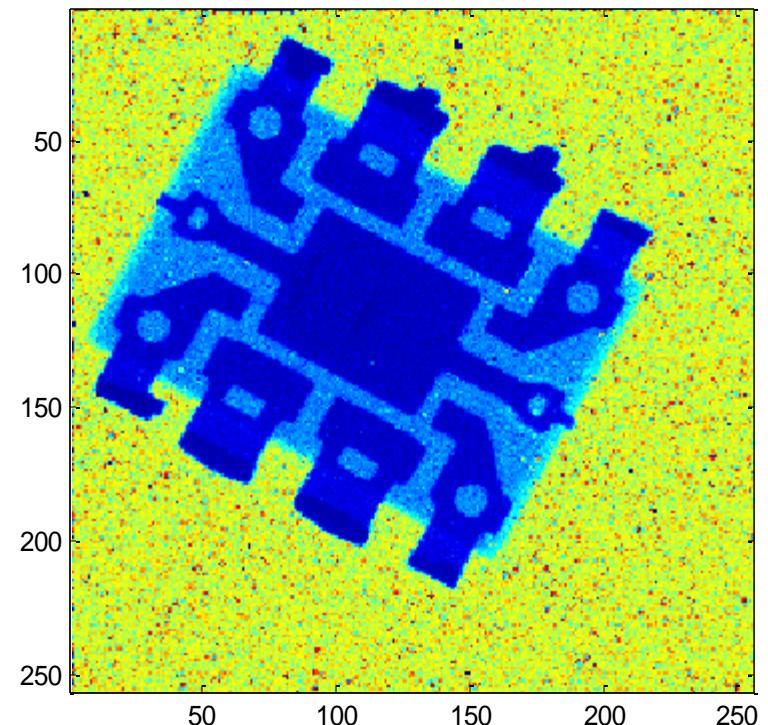


Images courtesy G  adda Akiko (VTT, Finland)

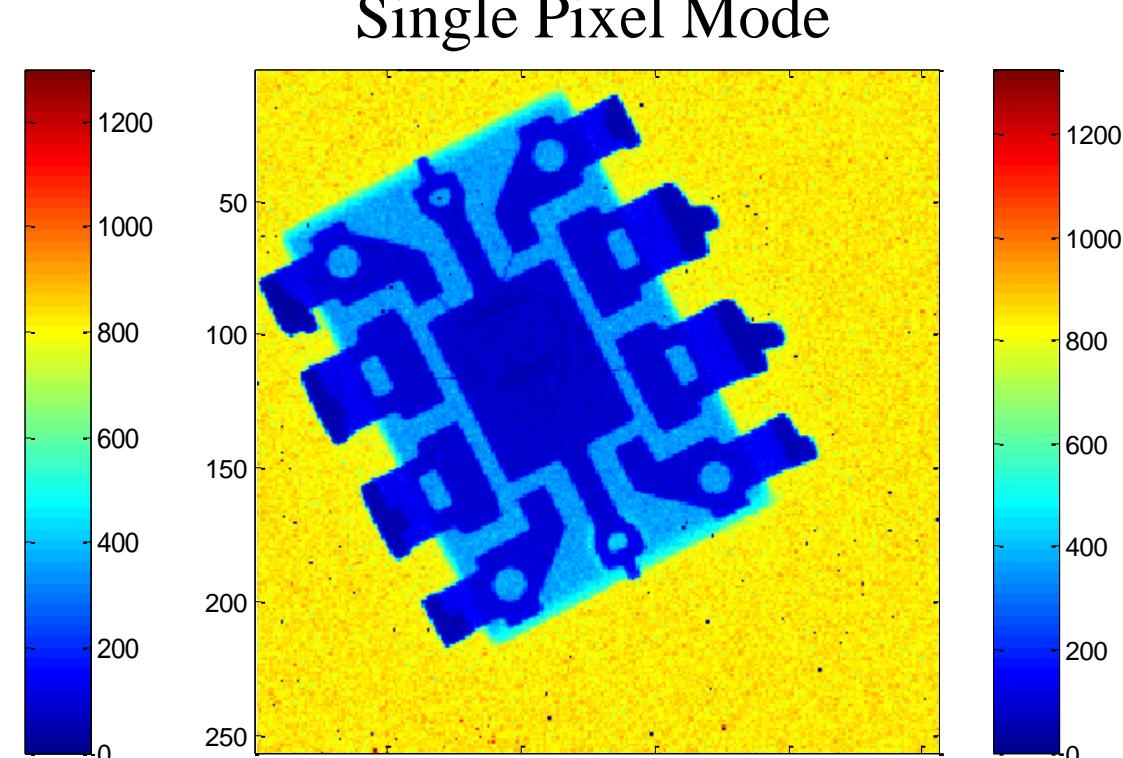


Charge Summing vs. Single Pixel

Charge Summing Mode

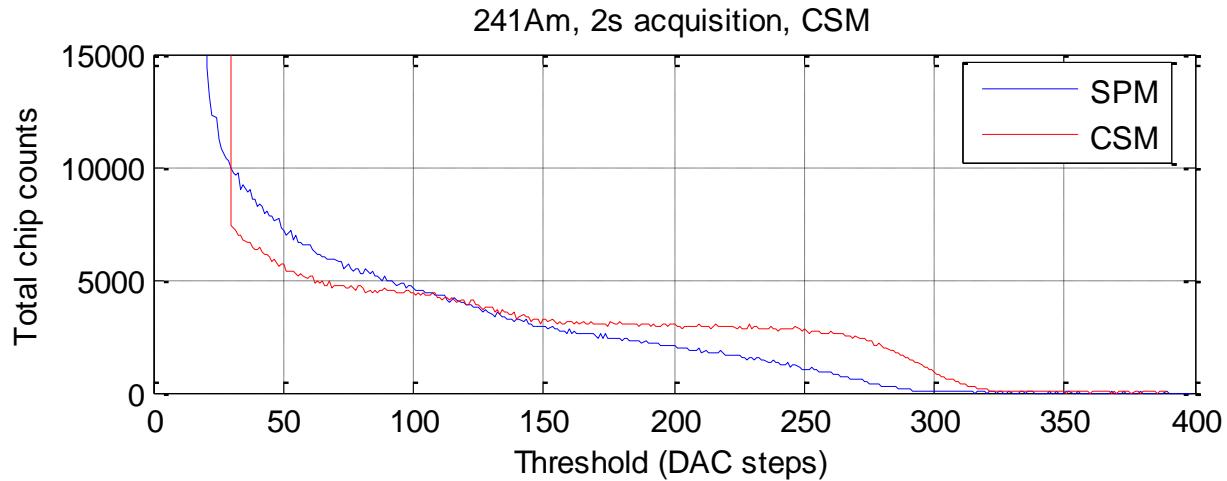


Single Pixel Mode



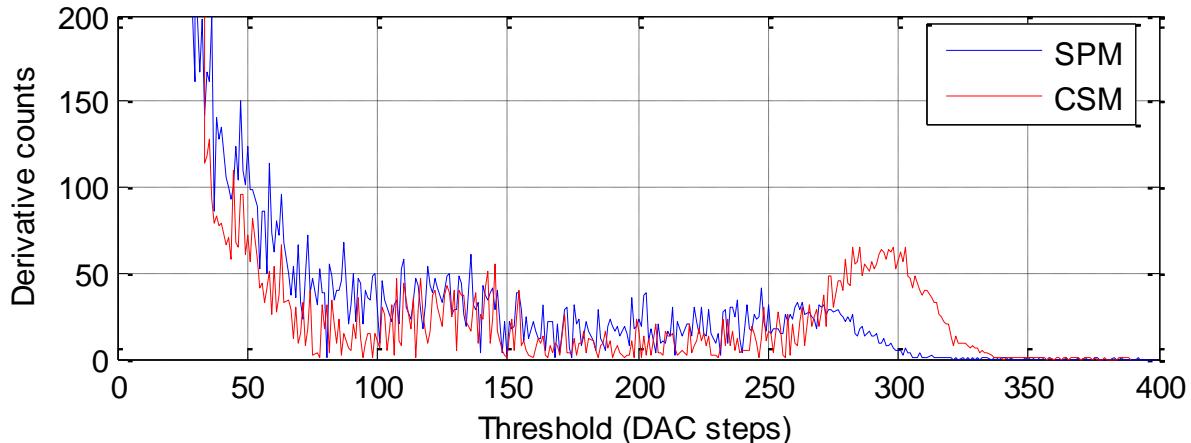
Very first images, preliminary.

Spectroscopic behavior (CSM and SPM) Am²⁴¹



- Again, very first measurements
- Low statistics ≤ 0.1 count/pixel

keV	%
13.9	9.6
17.7	5.7
17.9	1.4
20.8	1.4
59.5	35.9

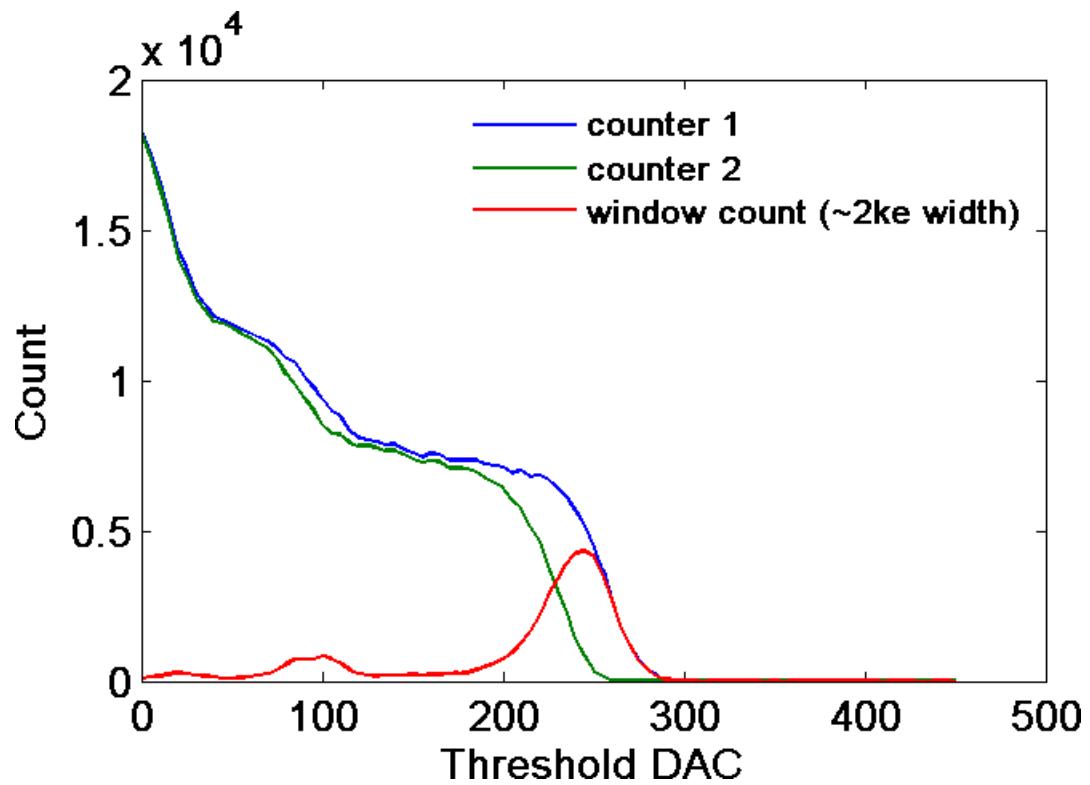


- Charge summing works !



MPX3 2nd threshold

- Preliminary
- best guess working point





Conclusions & Outlook

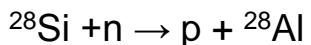
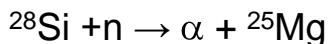
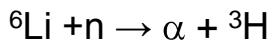
- Spectroscopic imaging has a wide range of applications
- High resolution spectroscopic X-ray imaging entered pre-clinical context
 - For the moment limited to low energies $\sim \leq 40$ keV (Si de facto standard sensor material)
- First Medipix3 production run
 - Working!
 - Verification/characterisation under way (16 modes!)
 - High Z materials
 -
- Timepix2, first discussions
 - ToA and ToT simultaneously per pixel
 -

Description of the detector

Medipix2 ASIC with 300 μ m Si sensor + USB interface

Neutron conversion structures:

- 1) LiF+50 μ m Al foil area
- 2) 100 μ m Al foil area
- 3) PE area
- 4) PE+50 μ m Al foil area
- 5) Uncovered area



Neutron efficiency calibration

Fixed HIGH threshold (~200keV)

Calibrated efficiency:

Thermal: 1.41E-2 7.11E-4 cm⁻²s⁻¹

252Cf: 1.19E-3 1.89E-5 cm⁻²s⁻¹

AmBe: 2.86E-3 5.46E-5 cm⁻²s⁻¹

VDG: 7.23E-3 5.81E-4 cm⁻²s⁻¹

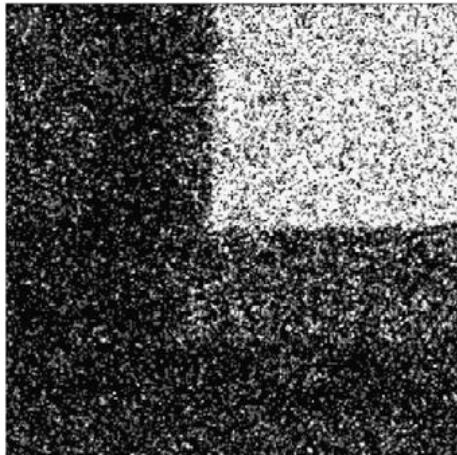
PE / PE+Al cluster count ratio:

252Cf: 10.70 0.04

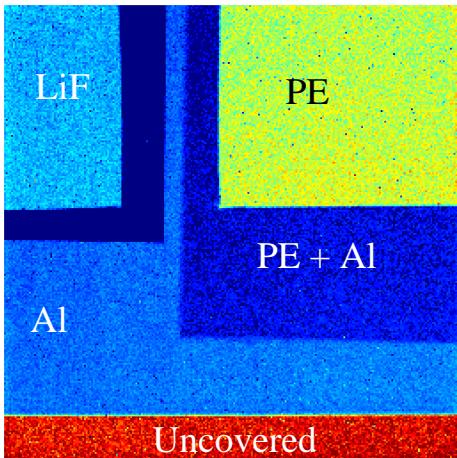
AmBe: 5.18 0.03

VDG: 2.51 0.03

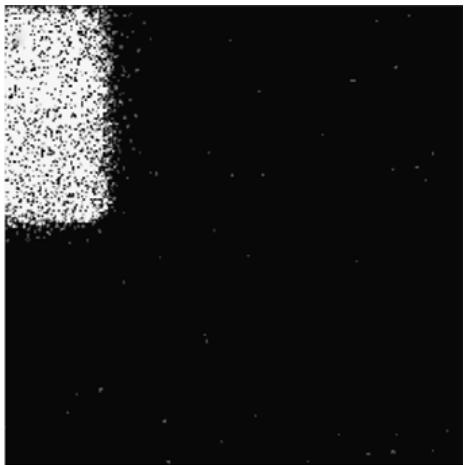
252Cf – 2000s, 2 MeV (mean)



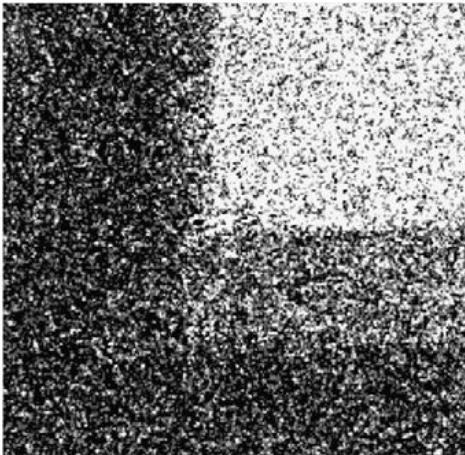
X-ray image of conversion layers



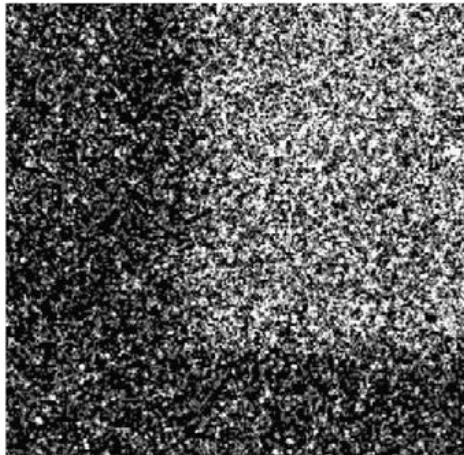
Thermal neutrons – 500s, 25meV (mean)



AmBe – 2000s, 4 MeV (mean)



Van de Graaff – 1000s, 14 MeV





Pulse processing (= energy sensitive) imaging ROCs

(tentative & incomplete listing)

Technology	MEDIPIX2	MPX3 (design)	XPAD3	Pilatus II (single)	Eiger	PIXIE (4 th , 2007)	Timepix
Type	CMOS 0.25 μm	CMOS 0.13 μm	CMOS 0.25 μm	CMOS 0.25 μm	CMOS 0.25 μm	CMOS 0.18 μm	CMOS 0.25 μm
Pixel size [um]	55	55/110	130	172	75	27.7 hexagonal	55
Matrix	256 x 256	256 x 256	80 x 120	60 x 97	256x256	600 x 800	256x256
Pixel no.	65536	65536	9600	5820	65536	480000	65536
Area mm ²	196	196	162	172	369	672	196
Max. tiled Area [cm ²]	1.4 x 7		6.8 x 6.5	43 x 44	big		3 x 3
Pixel density [mm ⁻²]	330	330	60	33	177	720	330
Pixel noise ENC [e ⁻]	140	75e / 150	160	65	135 (design)	50	90
Threshold dispersion [e ⁻]	100	55 / 100 adj.	50	85 unadj	<200 unadj	30	60
Global threshold [e ⁻]	1000 adj	1000 adj	1000 adj	730 unadj	<1250 unadj	200 auto-adj	650 adj
Counter depth	13	1/2/4/8//11/22	12	20	4/8/2012	15	13
No threshold	2	1/2/2008	2	1	1	1	1
Read-out scheme	synchronous	synchronous	synchronous	synchronous	synchronous	synchronous	synchronous
Read-out mode	full frame	full frame/ROI	full frame	full frame	full frame/ROI	full frame/ROI	full frame
		continous	continous		continous	up to 200 nodes	
Read-out time	10 ms, 300 μs	<10 ms	2 ms (continous)	3.6 ms	41/82/123 μs	?	10 ms, 300 μs
Frame rate [Hz]	103	100...	500	100	8/12/24 kHz	5 kHz	103
Event rate/pixel [Hz]	$\sim 10^6$	$\sim 10^6$	$\sim 10^6$	$\sim 10^6$	$\sim 5 \cdot 10^6$	$> 10^5$	$\sim 10^6$
Poisson event rate [Hz/cm ²]	$\sim 10^9$	$\sim 10^8 / 10^9$					$\sim 10^9$

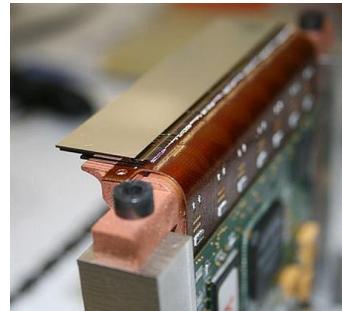
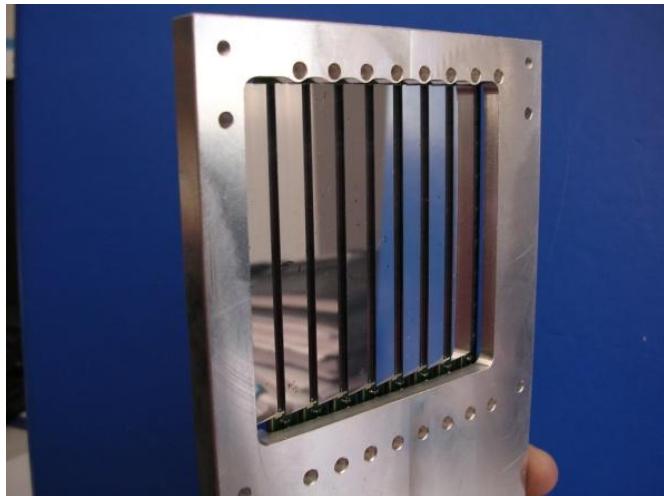
XPAD2, XPA3, Large surface X-Ray PixelDetector

XPAD2

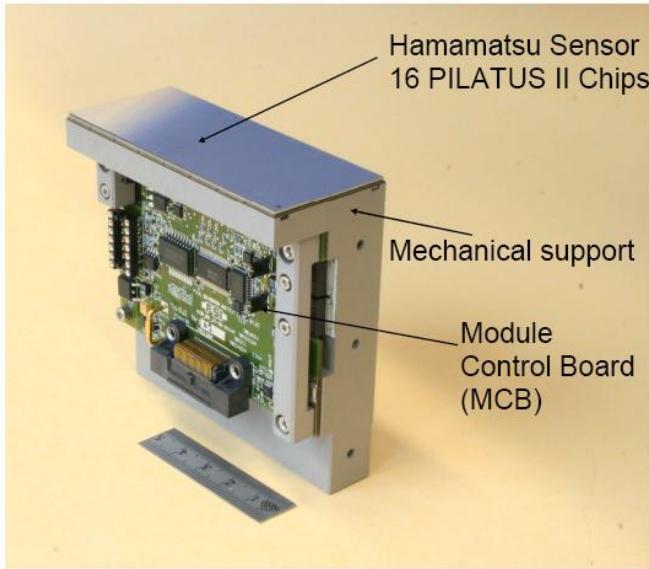
- Pixels 330 x 330 μm^2
- 15-bit Counter
- linear until $2 \cdot 10^6$ ph/sec/pixel
- 8 modules tiled
- 6,8 x 6,5 cm² HPS Detector
- Pixels size: 330 x 330 μm^2
- 400 frames, 2 ms between frames

XPAD3

- IBM 0,25 μm
- Pixels 130 μm , 120 x 80 pixels
- Radiation hard
- 13-bit counter/pixel
- Continuous readout during DAQ
- Chip size: 1 x 1.7 cm²



Pilatus



Pilatus Module - Building block of all Pilatus Detectors

- 1 Silicon Sensor
- 16 PILATUS CMOS Chips
- 487×195 pixels = 94965 pixels, active Area 83.8×33.6 mm 2
- Readout time = 3.6 ms
- Continuously sensitive: no gaps between chips
- Building Block of all Pilatus Detectors
- Frame rate: 300 Hz

Pilatus 2Module – 24 modules

- Format: 1475×1679 pixels
- Area: 254×289 mm 2
- Frame rate: up to 30 Hz

Applications:

- X-ray diffraction (XRD)
 - Small-angle scattering (SAXS)
 - Macromolecular crystallography
 - Time-resolved experiments

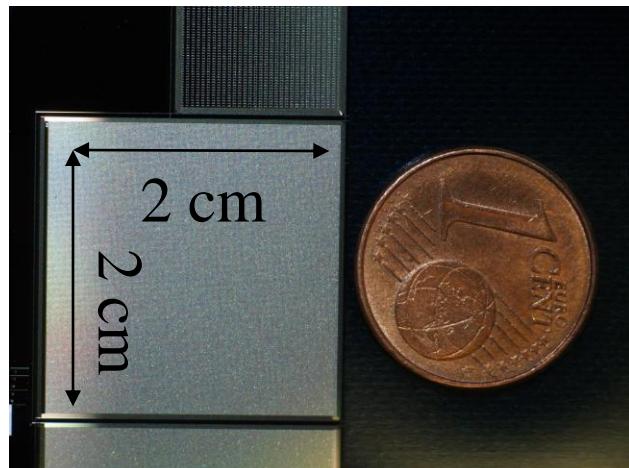
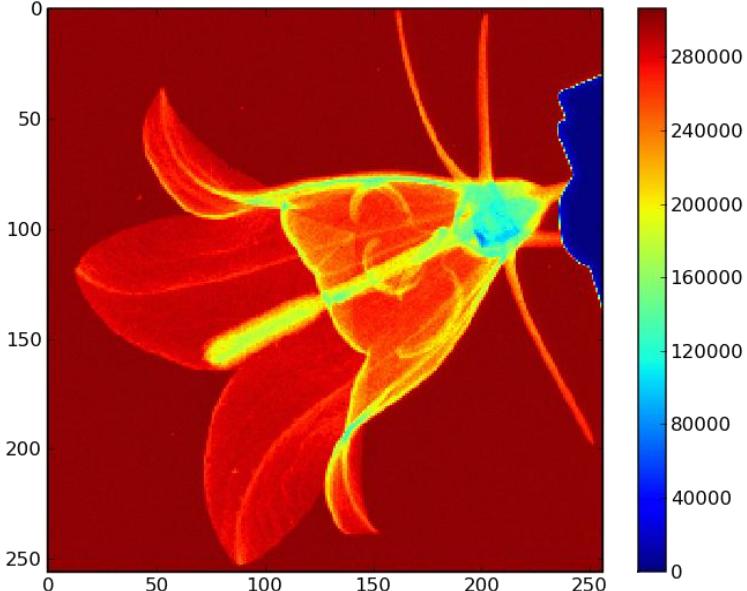


Courtesy Chr. Brönnimann, DECTRIS AG



EIGER (preliminary)

Chip count state

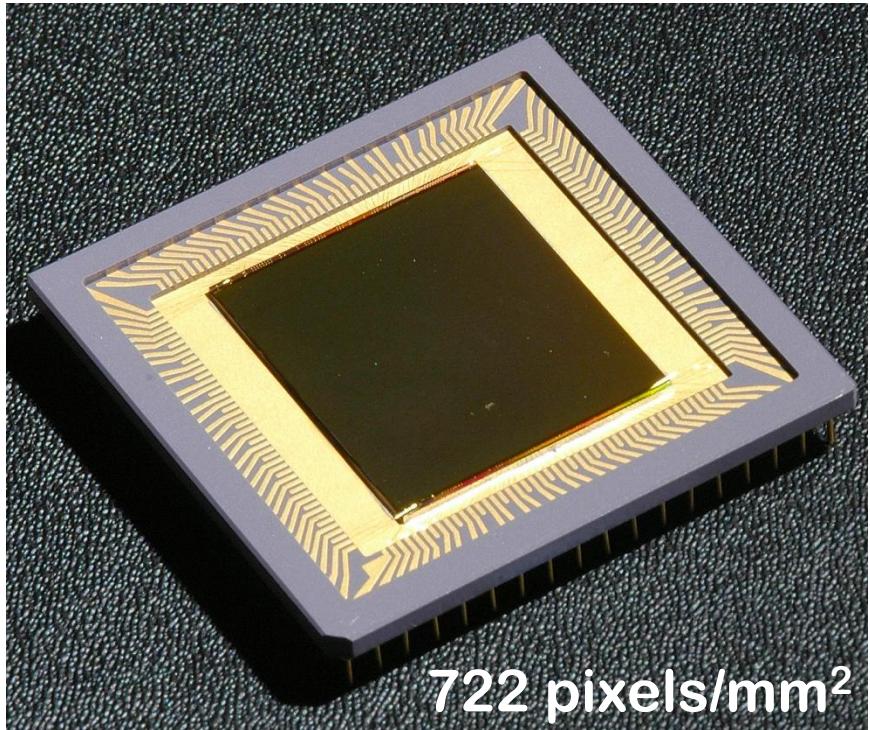


Technological process	UMC 0.25 μ m
Analog Parameters	30 ns peaking time ~150 ns ret. Zero 8.8uW/pixel Gain: 44.6 μ V/e-
Chip size	19.3 x 20.1 mm ² (active 19.2x19.2mm ²)
Pixel array	256 x 256 = 65536
Pixel size	75 x 75 μ m ²
Transistors, Matrix:	28.44M
Periphery:	>120 000
Transistors density:	430/pixel
Detector readout speed	~12.5 KHz @ 8 bit mode (Detector size doesn't matter)
Radiation tolerance	Full radiation tolerant design (>4Mrad)
Nominal power supplies	1.1 V (analog), 2V (digital), 1.8V (I/O)
Counter	12 bits, binary, configurable (4,8,12 bit mode)
Continuous readout	yes
Threshold adjustment	6 bit DAC
Overflow control	yes

~very first image, preliminary – definitely working!

Courtesy R. Dinapoli, PSI

The CMOS counting ASIC



Each pixel column can be individually configured for:

- counting the number of events during a given time slot or
- providing, with an external clock, a timestamp to the event or the time over threshold

See talk 24th Nov: R. Bellazzini, X Ray Polarimetry: a new window on the high energy sky

The chip integrates more than 259 million transistors.

It has **480k** pixels organized in a honeycomb matrix of **600 columns 800 lines** corresponding to an active area of

24mm (600x40μm) 27.7mm (800x34.64μm)

Each pixel is connected to a charge-sensitive shaping amplifier followed by a discriminator and a 15-bit shift register.

A self-calibration circuit is implemented in each pixel to reduce unavoidable DC offset variations from pixel to pixel →
a *global threshold* can be applied to the whole matrix.

Acknowledgements

Fellow members of the Medipix Consortium www.cern.ch/medipix

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