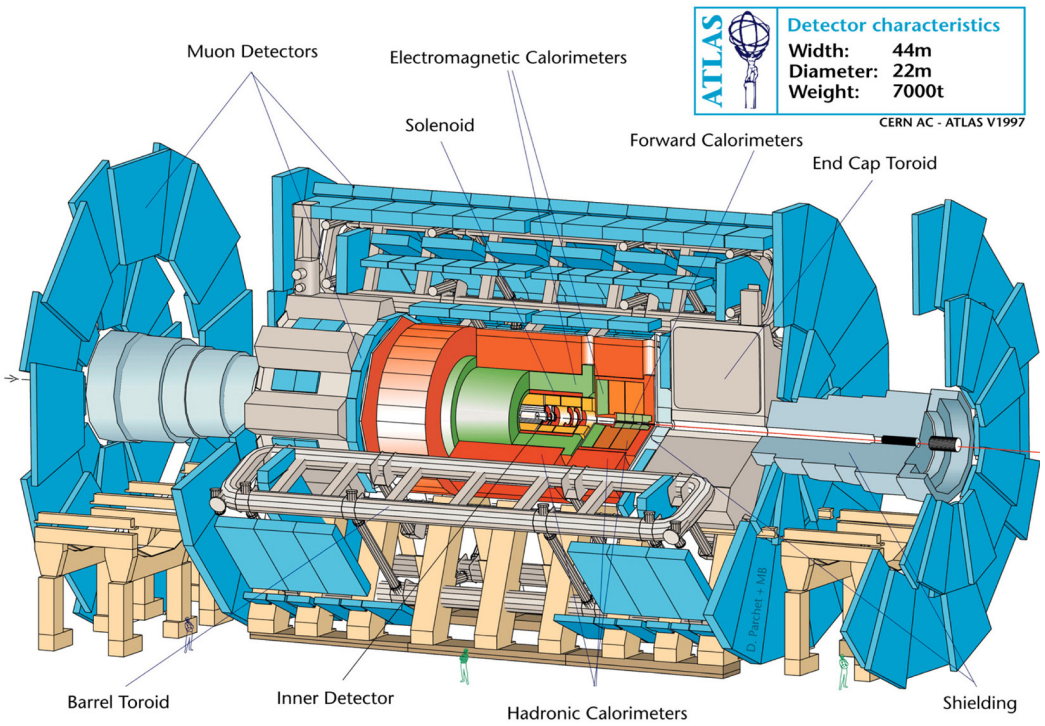
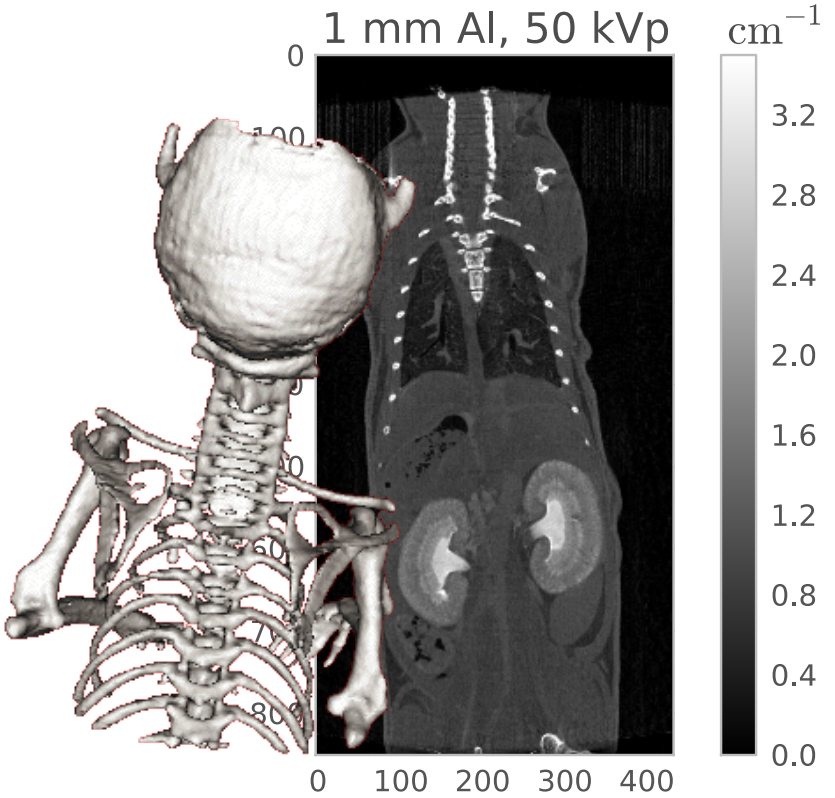
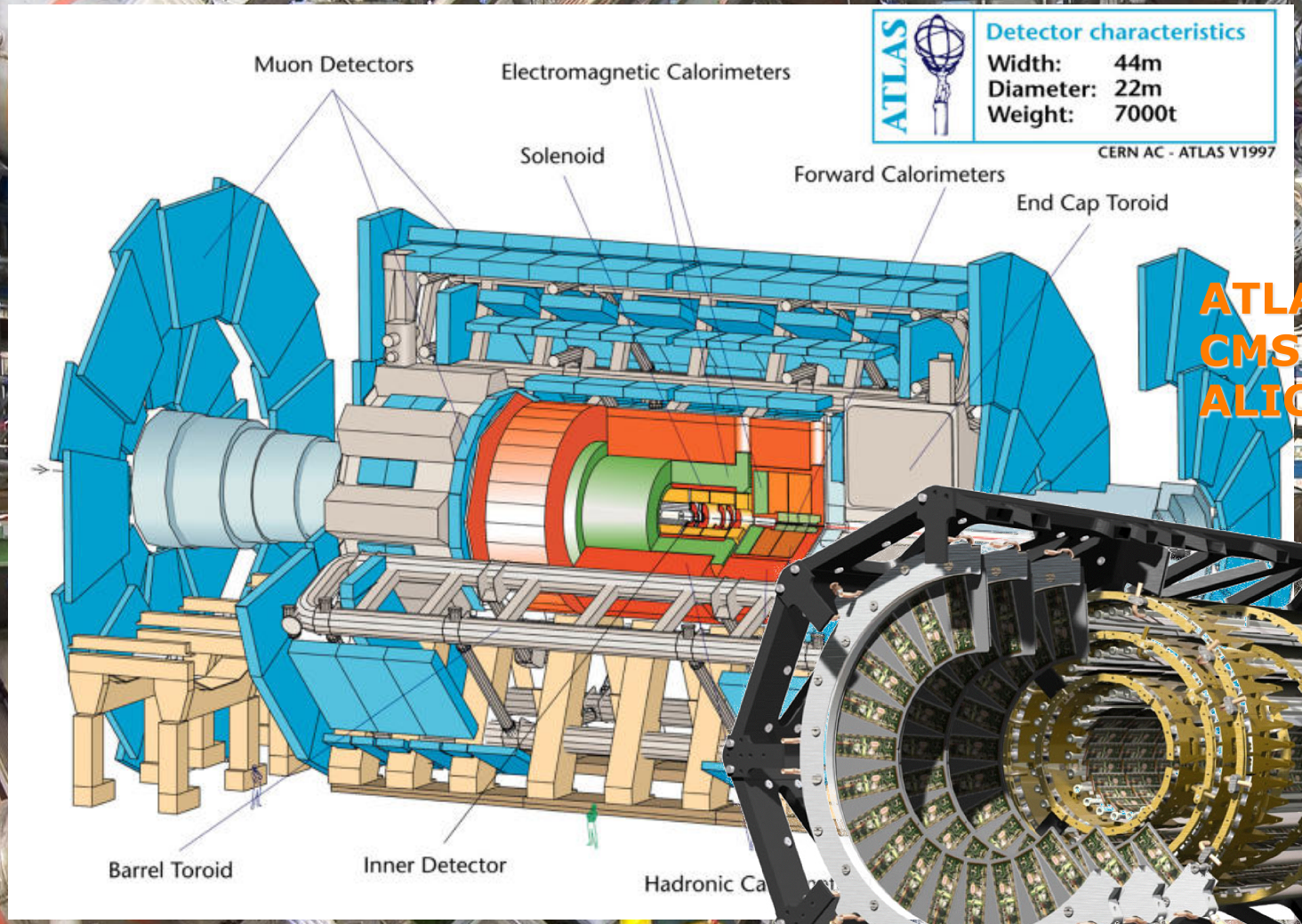
Les pixels hybrides : des expériences du LHC à la tomodensitométrie spectrale de petit animal



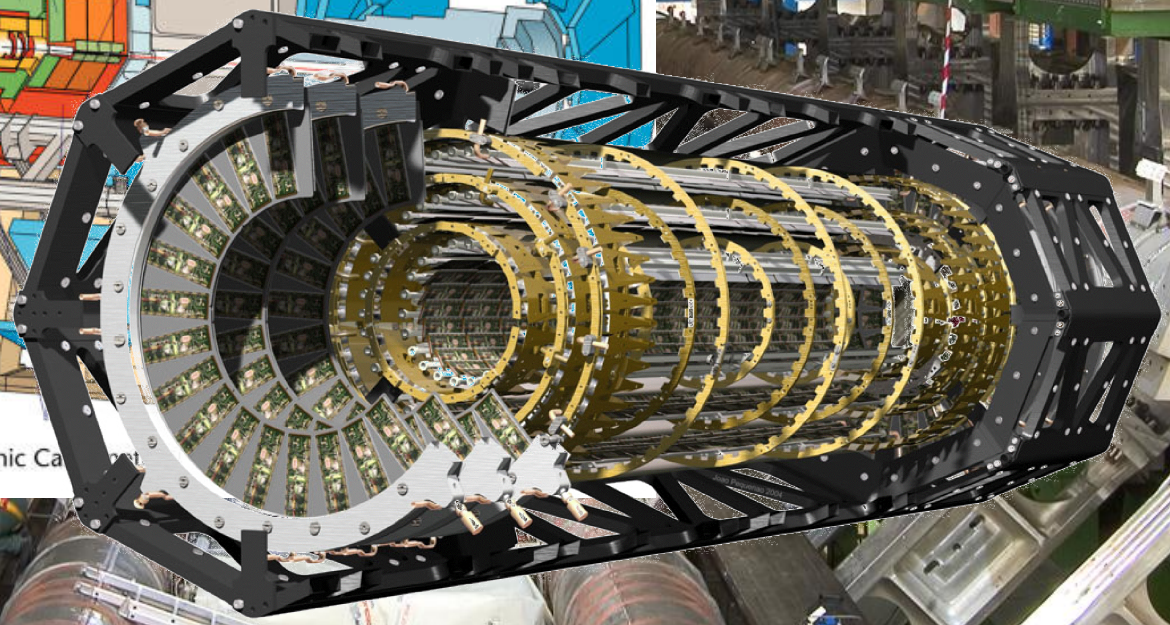


Hybrid Pixel detectors for High Energy Physics

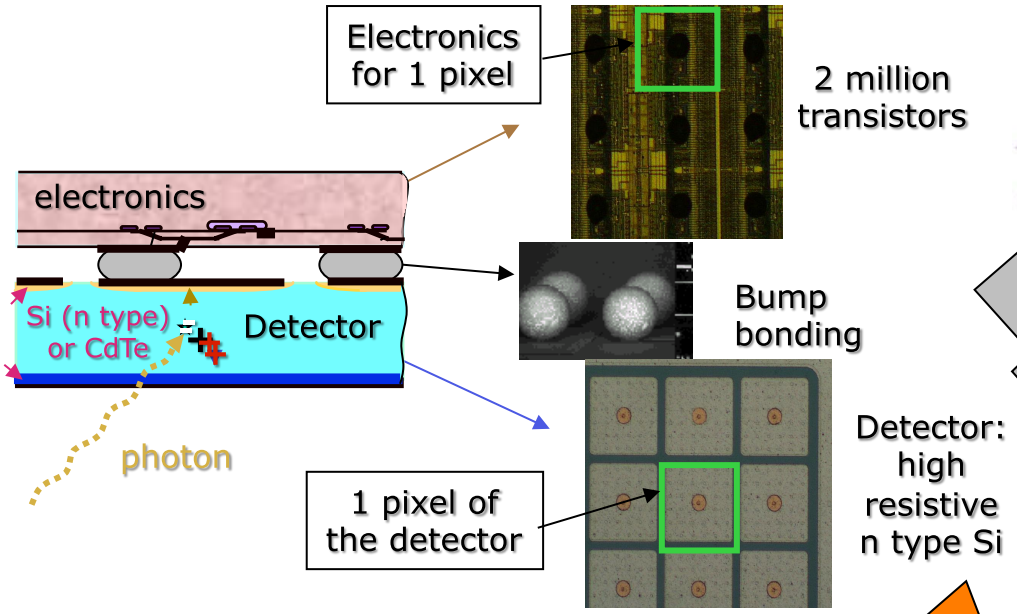


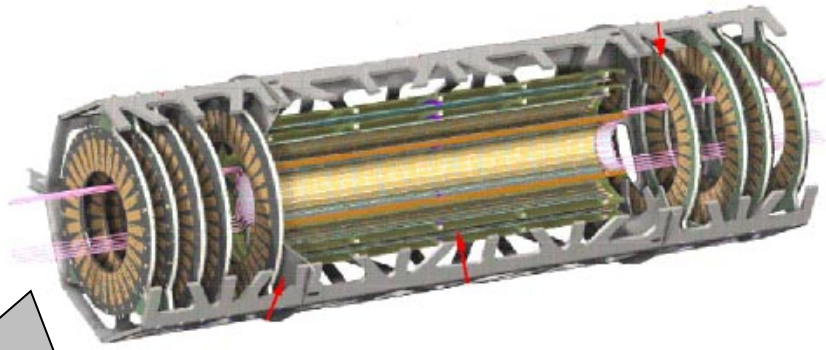
Inner Detector:
100 million
hybrid pixels
400 x 50 µm²

ATLAS ~ 100 Mpixels
CMS ~ 100 Mpixels
ALICE ~ 10 Mpixels



Hybrid Pixels for X-ray Cone-Beam CT





- Very fast data acquisition
- Choice of the sensor (Si, CdTE, AsGa)
- Optimized efficiency

- Noise suppression
- Energy selection
- Very high dynamics

Reduce radiation dose
Improve contrast
Perform spectral analysis

Research & Development on Hybrid Pixels at CPPM

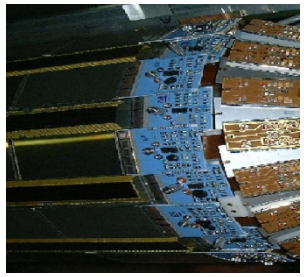
Start of the hybrid pixel project

1991

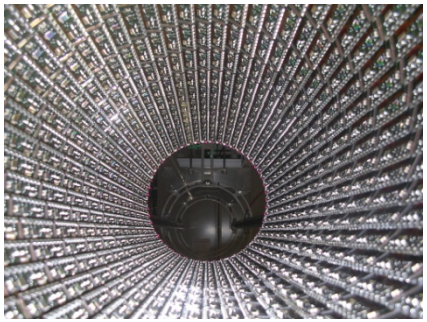
1996

DELPHI:

World premiere



1998

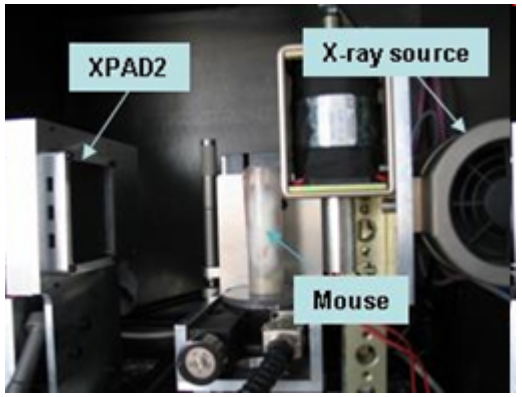


ATLAS: 50 x 400 μm^2 pixels

1999

XPAD1: first hybrid pixel detector for X-ray applications

2001



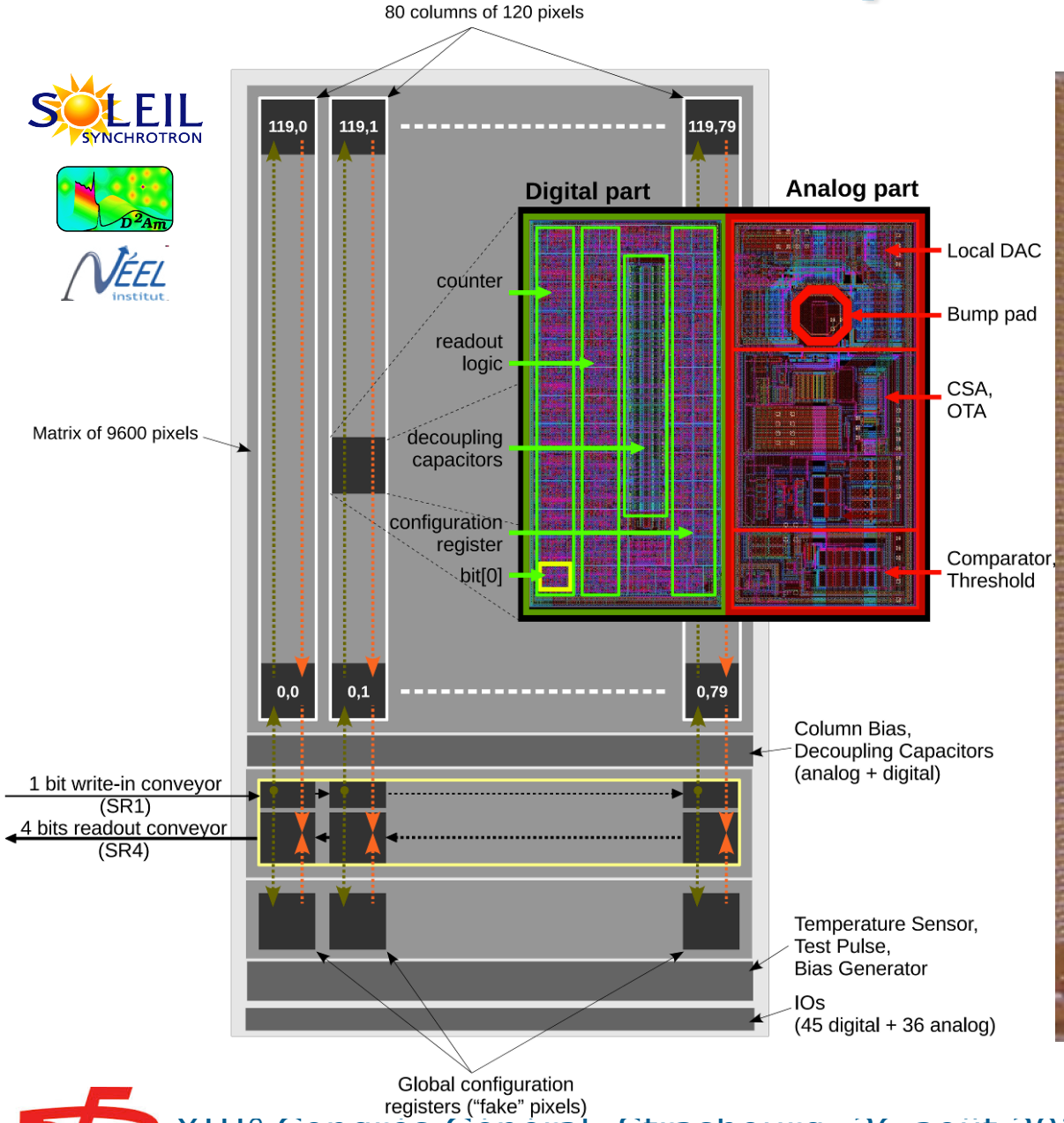
XPAD2: 330 x 330 μm² pixels

2006

XPAD3 : 130 x 130 μm² pixels

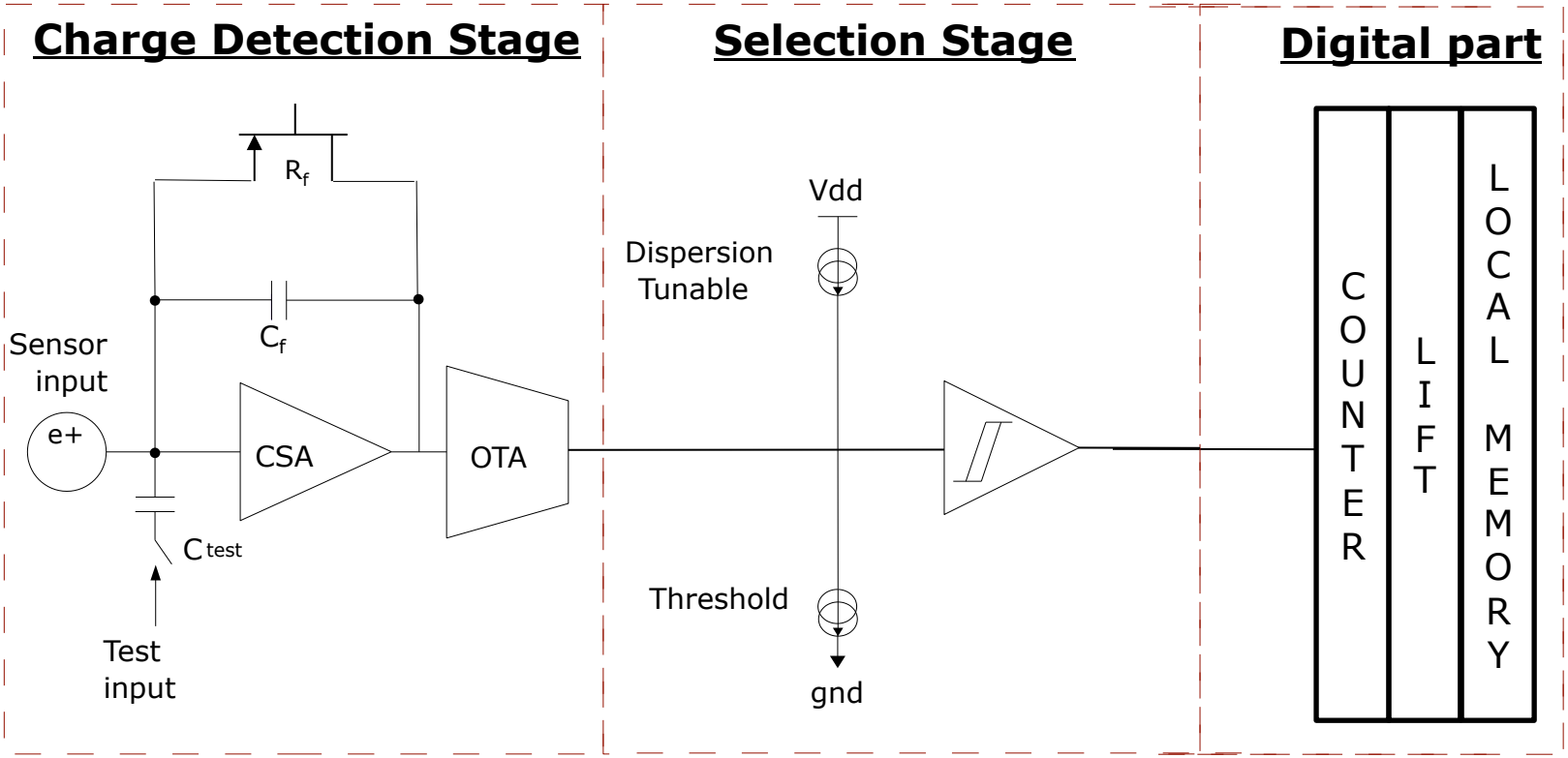
Delpierre, JINST **9** (2014) C05059

XPAD3: Si and CdTe Hybrid Pixels for X-ray



- 0.25 µm IBM CMOS technology
- (130 x 130) µm^2 pixels
- 80 x 120 = 9600 pixels
- 12 bit counter + overflow
- Count rate up to 10^6 ph/pixel/s
- < 1 ms readout time
- 5-35 keV adjustable thresholds

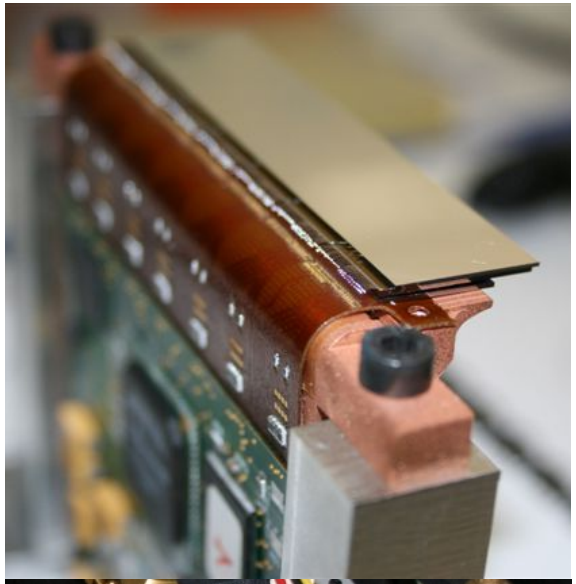
XPAD3 pixel architecture

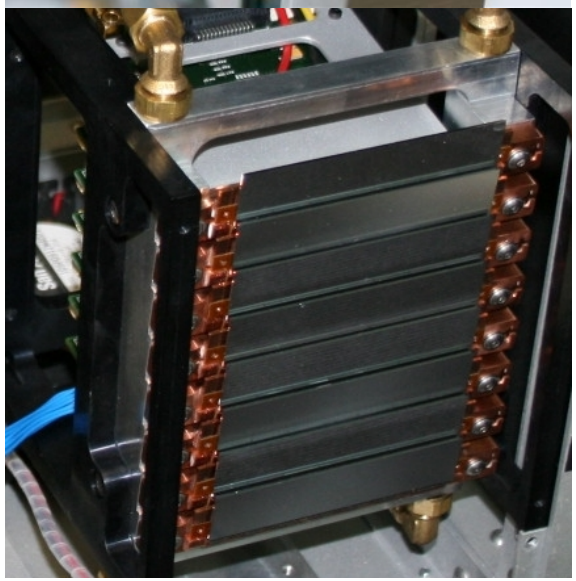


Gain : 89 nA/keV
Noise : 127 e- rms
Linearity : < 10% @ 35 keV

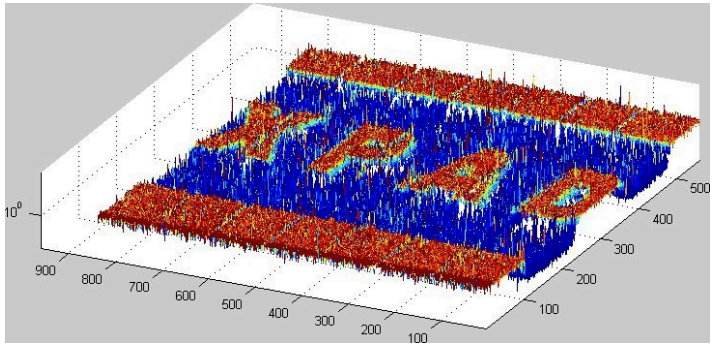
Power consumption : 40 µW/pixel
Threshold adjustment resolution : 57 e-
Minimum threshold: < 4 keV

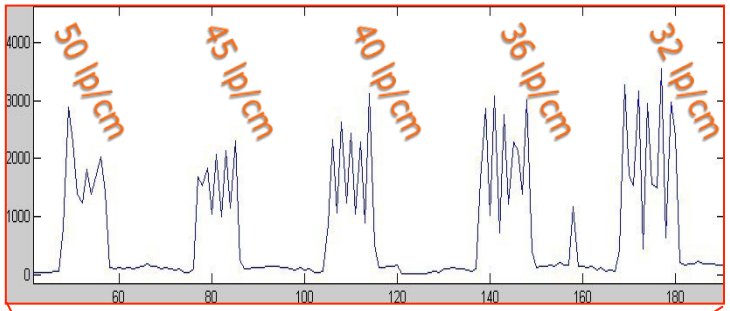
XPAD3: Si and CdTe Hybrid Pixels for X-ray detection

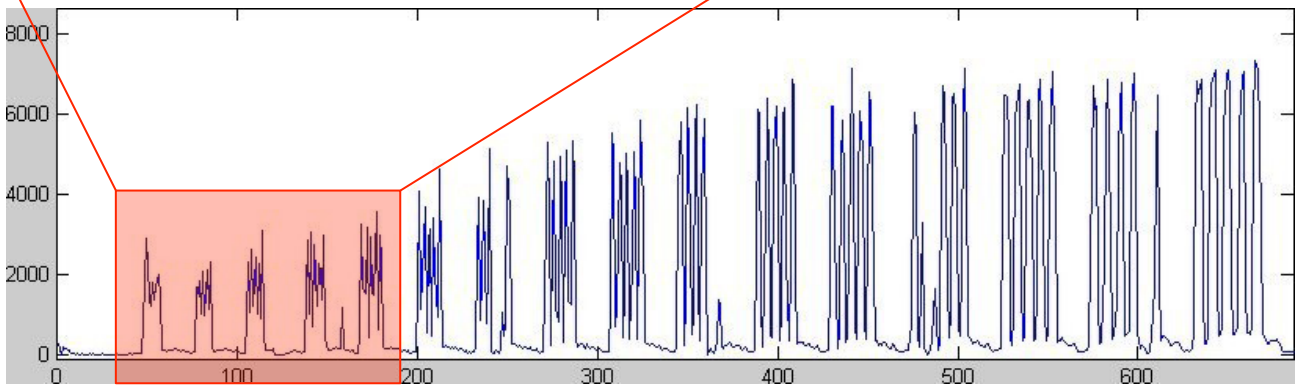




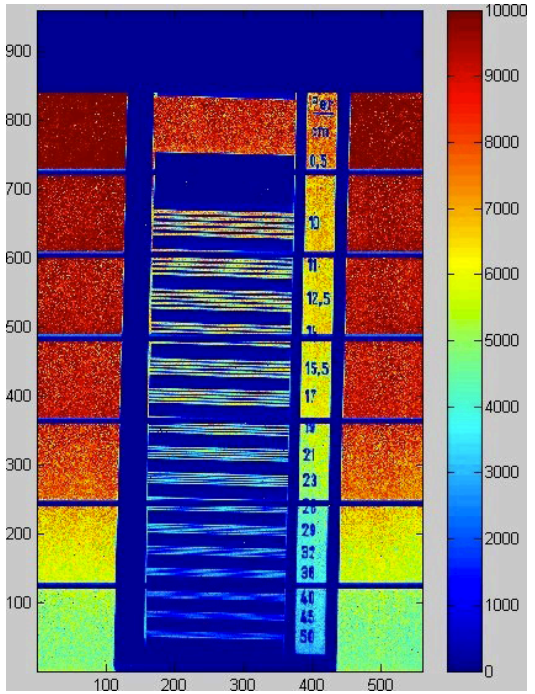
5 keV



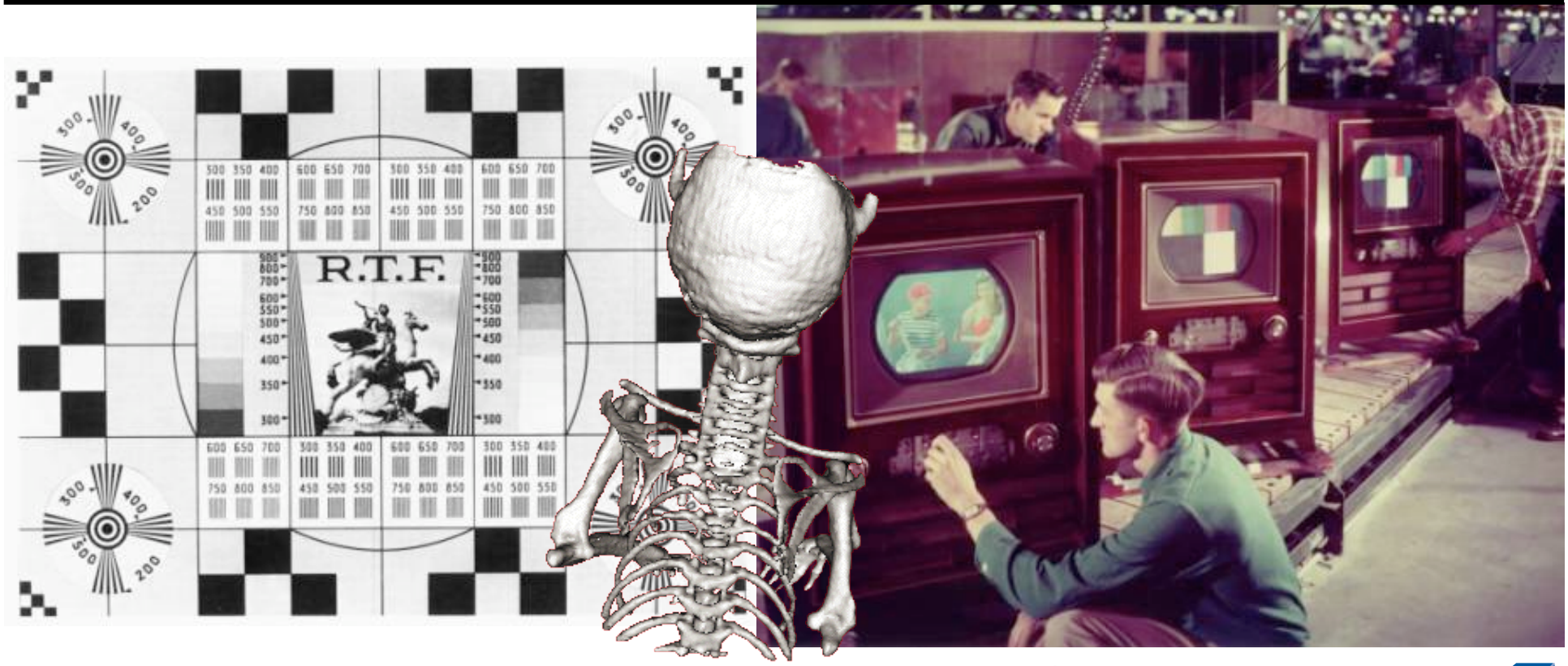




14 keV



X-ray spectral CT: from black & white to colour



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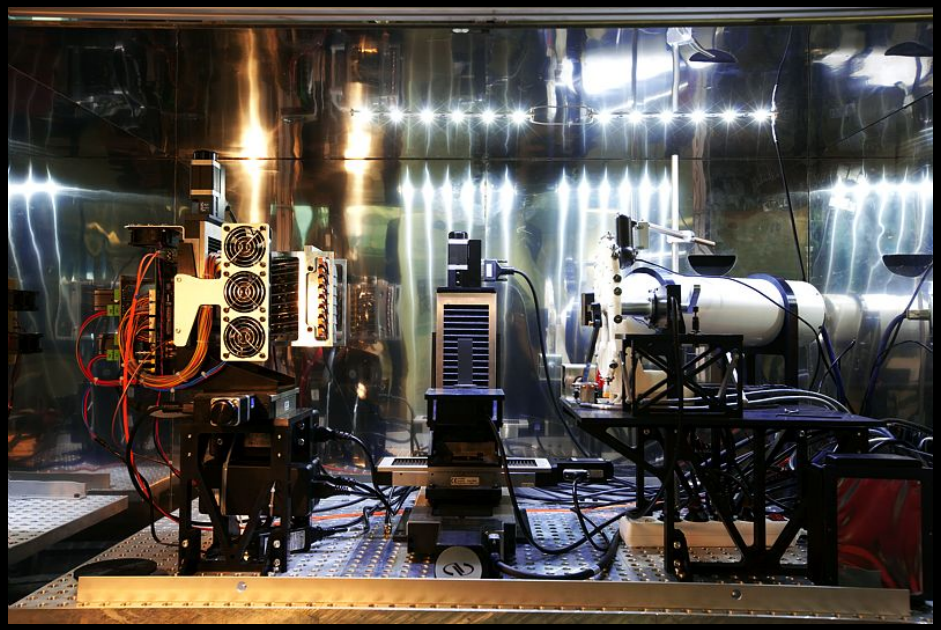
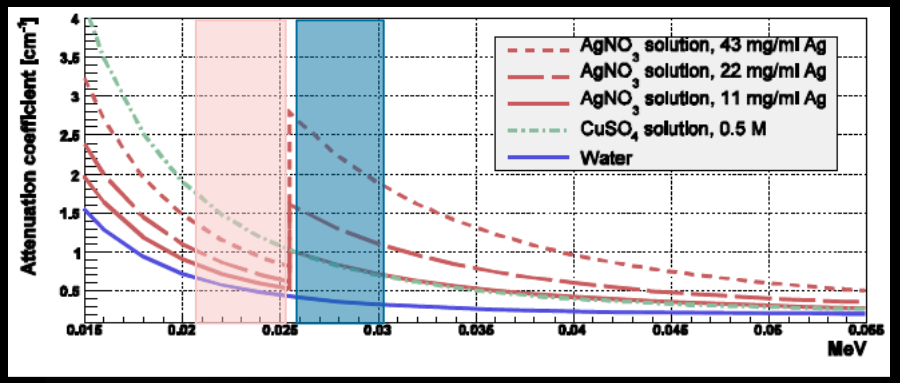
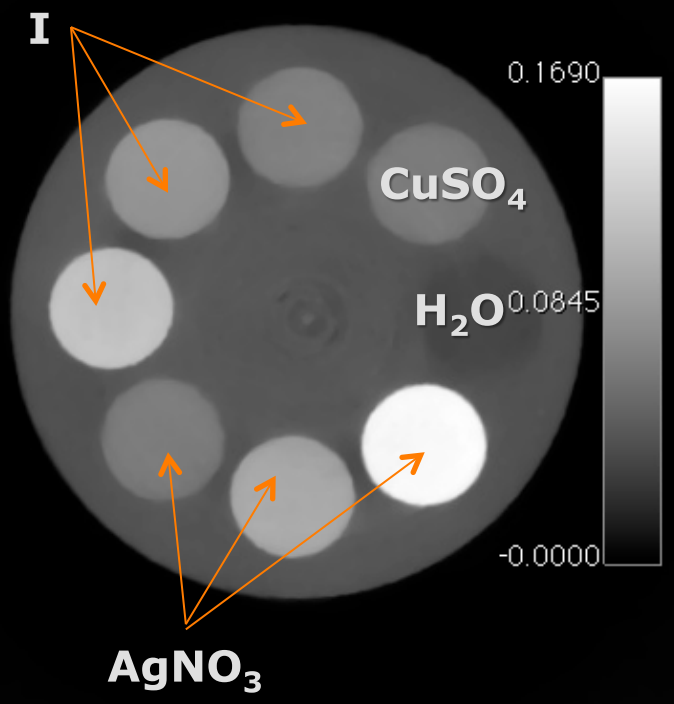
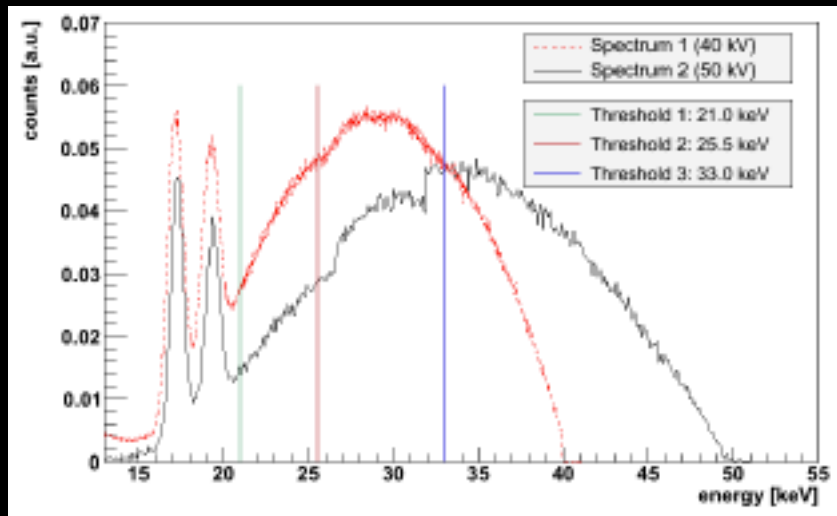
cnrs IN2P3 Les deux infinis
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM




Attenuation coefficient [cm⁻¹]
AgNO3 solution, 43 mg/ml Ag
AgNO3 solution, 22 mg/ml Ag
AgNO3 solution, 11 mg/ml Ag
CuSO4 solution, 0.5 M
Water
MeV

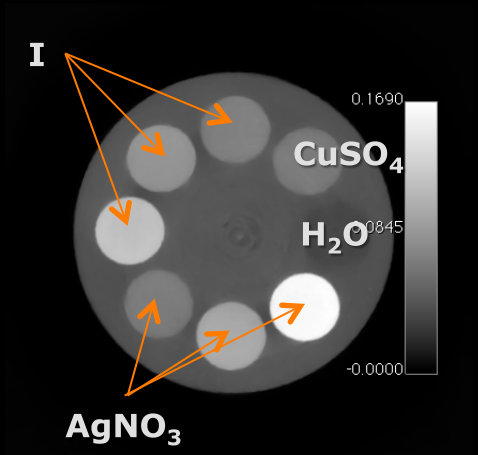

I
0.1690
CuSO4
H2O
0.0845
-0.0000
AgNO3

X-ray spectral CT using XPAD3

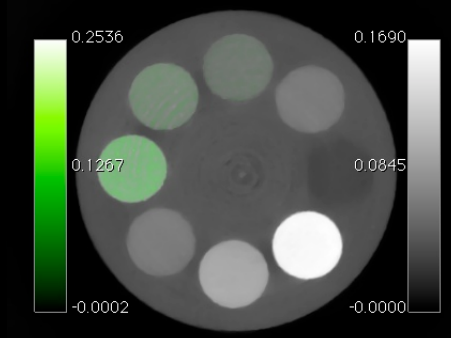


Silver	Iodine
$E_{1Ag} = 21$ keV	$E_{1I} = 25.5$ keV
$E_{2Ag} = 25.5$ keV	$E_{2I} = 33$ keV
$E_{3Ag} = 33$ keV	$E_{3I} = 40/50$ keV

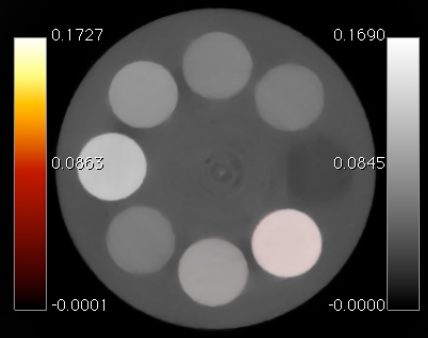
Standard CT



Iodine and Silver K-edge imaging



$(E_{2I}-E_{3I}) - (E_{1I}-E_{2I})$



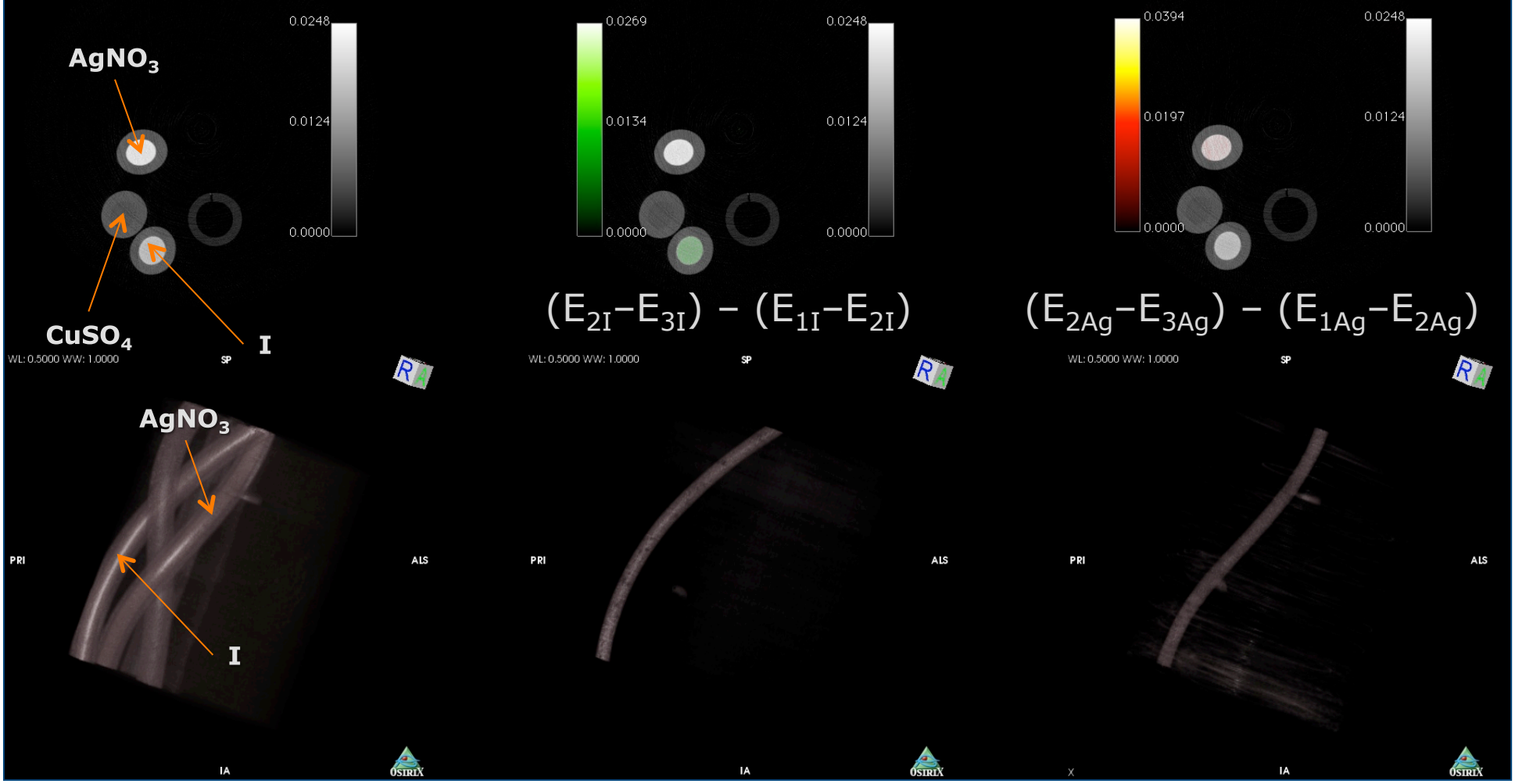
$(E_{2Ag}-E_{3Ag}) - (E_{1Ag}-E_{2Ag})$

Cassol *et al.*, IEEE Trans. Nucl. Sci. **60** (2013) 103

X-ray spectral CT using XPAD3

Standard CT

Iodine and Silver K-edge imaging



Cassol *et al.*, IEEE Trans. Nucl. Sci. **60** (2013) 103

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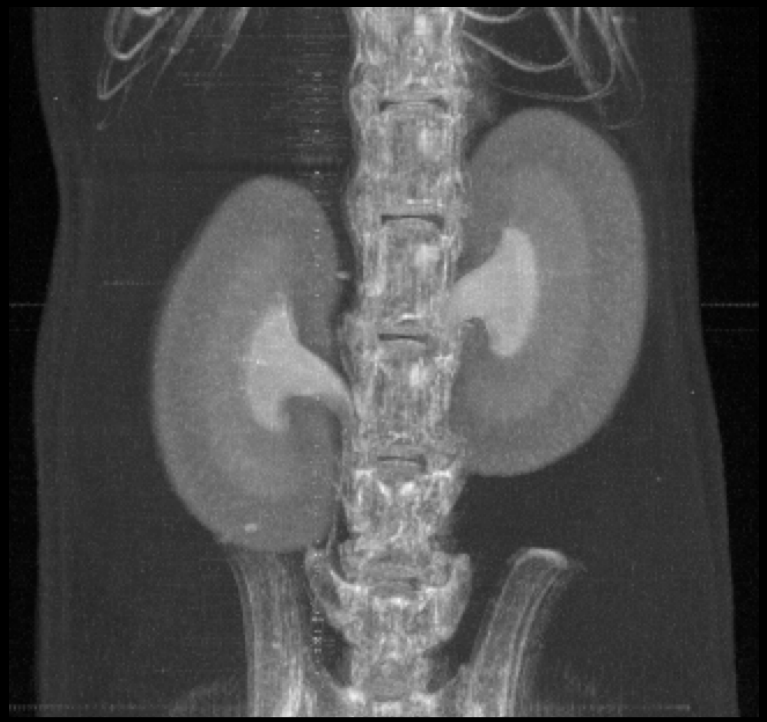
X-ray spectral CT using XPAD3

Standard CT

Maximum intensity projection



- Injection of 200 µL Iomeron
- Molybden anode X-ray tube
- 50 kVp, 30 W

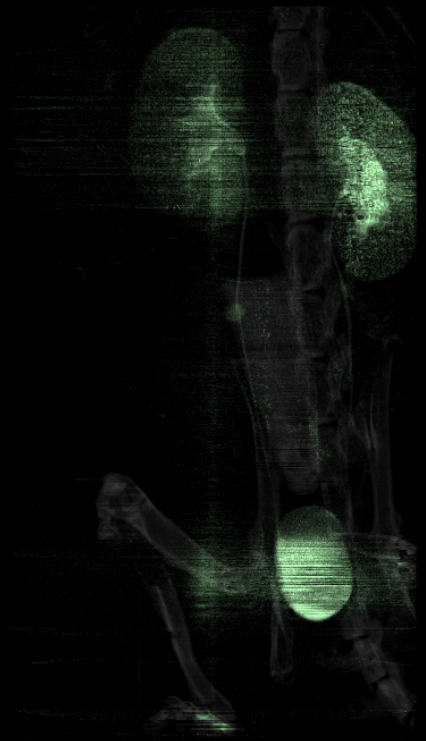
Iodine K-edge image

Maximum intensity projection

- 100 µm Cu filtering
- 5 s/image
- 360 projections

X-ray spectral CT using XPAD3

beta = 0



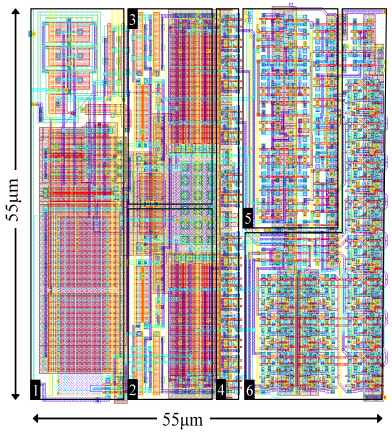
- Injection of 200 µL Iomeron
- Molybden anode X-ray tube
- 50 kVp, 30 W
- 100 µm Cu filtering
- 5 s/image
- 360 projections

Concurrent Hybrid Pixel designs

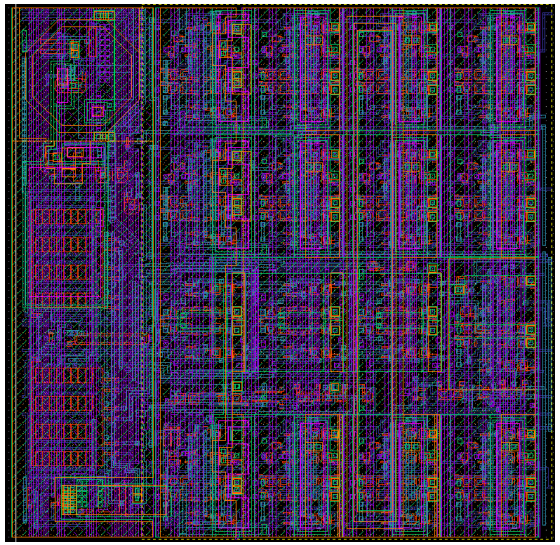
Name	Matrix	Pixel side (μm)	Energy thresholds	Peaking time (ns)	Maximum count rates (Mcps/pixel)	Maximum count rates (Mcps/mm²)	Electronics Noise or energy resolution	Power per channel (μW)	CMOS node
Medipix3 (FPM-SPM)[1]	256x256	55	2	120	2.5	826.5	1.37keV FWHM @ 10KeV	7.5	0.13μm
Medipix3 (FPM-CSM)[2]	256x256	55	1+1	120	5.0E-01	163.5	2.03keV FWHM @10KeV	9.3	0.13μm
Timepix3 (CERN)[3]	256x256	55	10bits	30	1.6E-03	0.53	4.07kev FWHM at 59.5keV	15.2	0.13μm
Pixirad Pixie II[4]	512x476	55.6	2	300	5.0E-01	161.5	1.45keV FWHM @ 20keV	12.5	0.18μm
Samsung PC[5]	128x128	60	3	NS	NS	NS	68 e- r.m.s.	4.6	0.13μm
Pixirad Pixie III[6]	512x402	62	2	125	1.0	260.1	6.6% FWHM @ 60keV	34	0.16μm
Eiger[7]	256x256	75	1	30	4.2	711.1	121e- r.m.s. (low noise settings)	8.8	0.25μm
PXD23K (AGH)[8]	128x184	75	2	48	8.5	1519.5	89e- r.m.s.	25	0.13μm
X-Counter PC (PDT25-DE)[9]	256x256	100	2	NS	1.2	120	8.3keV FWHM @20keV 10keV FWHM @60keV	NS	NS
PXD18K (AGH)[8]	96x192	100	2	30	5.8	580	168e- r.m.s.	23	0.18μm
FPDR90 (AGH)[8]	40x32	100	2	28	8.5	854.7	106e- r.m.s.	42	90nm
AGH_Fermilab[10]	18x24	100	2	48	NS	NS	84e⁻ (Single pixel), 168e⁻ (Charge summing)	34	40nm
Medipix3 (SM-SPM)[11]	128x128	110	8	120	4.5	375.7	1.43keV FWHM @ 10keV	30	0.13μm
Medipix3 (SM-CSM)[12]	128x128	110	4+4	120	3.4E-01	28.1	2.2keV FWHM @10keV	37.2	0.13μm
XPAD3[13]	80x120	130	2	150	2.0	118.3	127e- r.m.s.	40	0.25μm
Pilatus 2[14]	60x97	172	1	110	6.0	202.8	1keV FWHM @ 8keV	20.2	0.25μm
Pilatus 3[15]	60x97	172	1	110	15.0	507.0	1keV FWHM @ 8keV	20.2	0.25μm
Telesystems [16]	40x40	200	4	300-500	8.0E-01	20	5.36keV FWHM @ 122keV	94.4	0.25μm
Dosepix (CERN)[17]	16x16	220	16	287	1.6	33.9	150 e- r.m.s.	14.6	0.13μm
Siemens PC[18]	64x64	225	2	20	40.0	790.1	NS	NS	NS
Hexitec[19]	80x80	250	14bits	2000	1.0E-03	0.016	800eV FWHM @ 60keV, 1.1keV @ 141keV	220	0.35μm
Philips Chromaix [20]	4x16	300	4	20	38.0	422.2	4.7keV @60keV (1 channel)	3000	0.18μm
Ajat-0.35 (PC)[21]	32x64	350	1	1000	2.2	18.0	4keV FWHM @122keV	390.6	0.35μm
Ajat-0.35 (ADC)[22]	32x64	350	64	1000	4.9E-05	4.0E-04	4keV FWHM @122keV	390.6	0.35μm
CIX 0.2 (Bonn)[23]	8x8	353.6	1	NS	12.0	96	330e- r.m.s. (counting channel)	3200	0.35μm
KTH_Lin_SPD [24]	160 ch.	447.2	8	10-20-40	272.0	1360	1.09keV @ 15keV (measured at 40kcps)	80000	0.18μm
DxRay-Interon[25]	16x16	500	4	10	13.3	53	7keV FWHM @60keV, Min TH20keV	NS	NS
Ajat-0.5[26]	44x22	500	2	1000-2000	NS	NS	4.7keV @122keV (1 channel)	413.2	0.35μm
Hamamatsu[27]	64 ch.	632.5	5	NS	5.5	13.75	12keV FWHM @ 120keV	NS	NS
IDEAS[28]	64 ch.	894.4	6	50	4.0	5	7keV FWHM @60keV	4200	0.35μm
GE-DxRay [29]	128 ch.	1000	2	30	11.6	11.6	4.75% at 122keV, CZT, 5pF Cin (1 Channel noise= 4.8keV FWHM)	2100	0.25μm
BNL [30]	64 ch.	1241.0	5	40-80-160-320	4.0	5.5	5.5keV at 40ns peaking time/2.15keV at 320ns peaking time	4700	0.25μm

Courtesy: R. Ballabriga, CERN

Concurrent Hybrid Pixel designs



- MEDIPIX @ CERN
- PILATUS and EIGER @ PSI (Switzerland)
- XPAD3 @ CPPM/IN2P3 (France)



	Num. of pixels	Pixel size $[\mu m^2]$	Count rate $[ph/px/s]$	Counter depth	Readout time	Energy range $[keV]$	CMOS techn. $[\mu m]$
PILATUS II	60×97 $5'820$	172×172	2×10^6	20 bits	2.85 ms	3-30	0.25
EIGER	256×256 $65'536$	75×75	16×10^6	12 bits (4, 8, 12 mode)	85 μs 8-bit mode	-	0.25
MEDIPIX2	256×256 $65'536$	55×55	10^6	13 bits	8.5 ms in serial 266 μs in parallel	5-300	0.25
XPAD3	80×120 $9'600$	130×130	10^6	12 bits + OVF	1 ms	5-35	0.25

Spin-off activity on Hybrid Pixels

2003 — DxRay — www.dxray.com

2006 — DECTRIS® — www.dectris.com

2010 — imXPAD — www.imxpad.com

2011 — PiXirad (Chromatic Photon Counting) — pixirad.pi.infn.it

FUNCTIONS \ APPLICATIONS	Crystallography Laboratories	Crystallography Synchrotron	Preclinical Scanner	Clinical Angiography	Clinical Scanner	Waste Sorting	Homeland security
Noise suppression	X	XX	X	X	X	X	X
Energy selection	X		XX	XX	XX	XX	XX
Dose reduction			XX	XXX	XXX		X
Large dynamic range	XX	XXX	X	X	X		X
No readout dead time	X	X					
On the fly readout		X		X		XX	
Frame rate = 1 kHz		X	X	X	X		X
Accurate time window		XX					

2006 — XRAY IMATEK (Pixelated X-Ray Detectors) — www.xray-imatek.com

2011 — AMSTERDAM SCIENTIFIC INSTRUMENTS — www.amscins.com

2003 — kromek (detect image identify) — www.kromek.com

2007 — mars (Medipix All Resolution System) — www.marsbioimaging.com

2012 — ADVACAM (IMAGING THE UNSEEN) — www.advacam.com

2011 — XIE X-RAY IMAGING EUROPE — www.xi-europe.com

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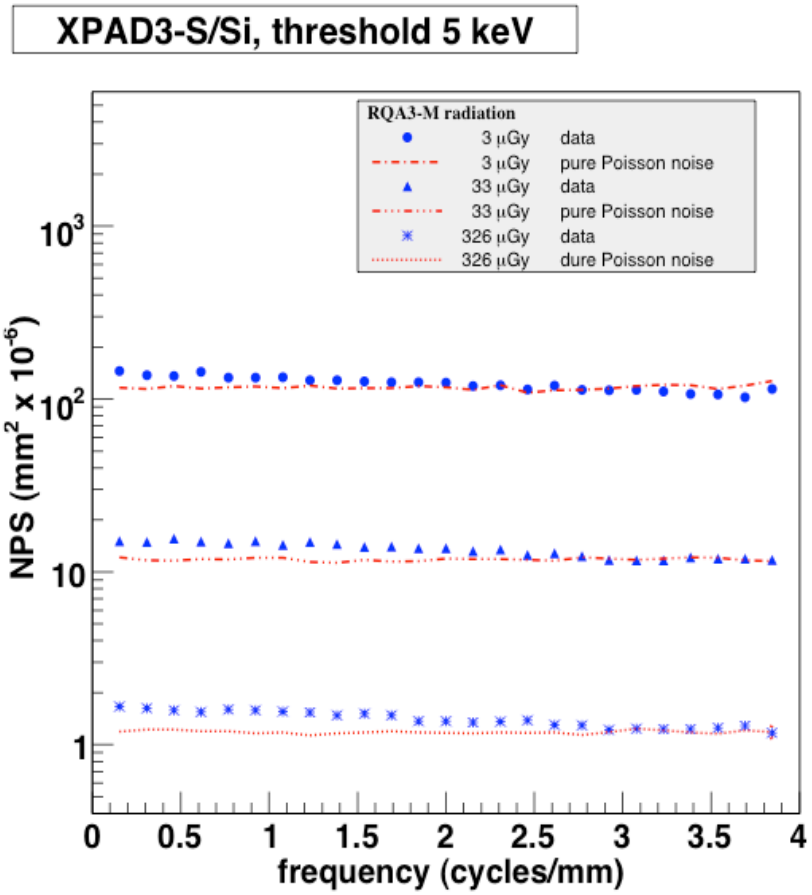
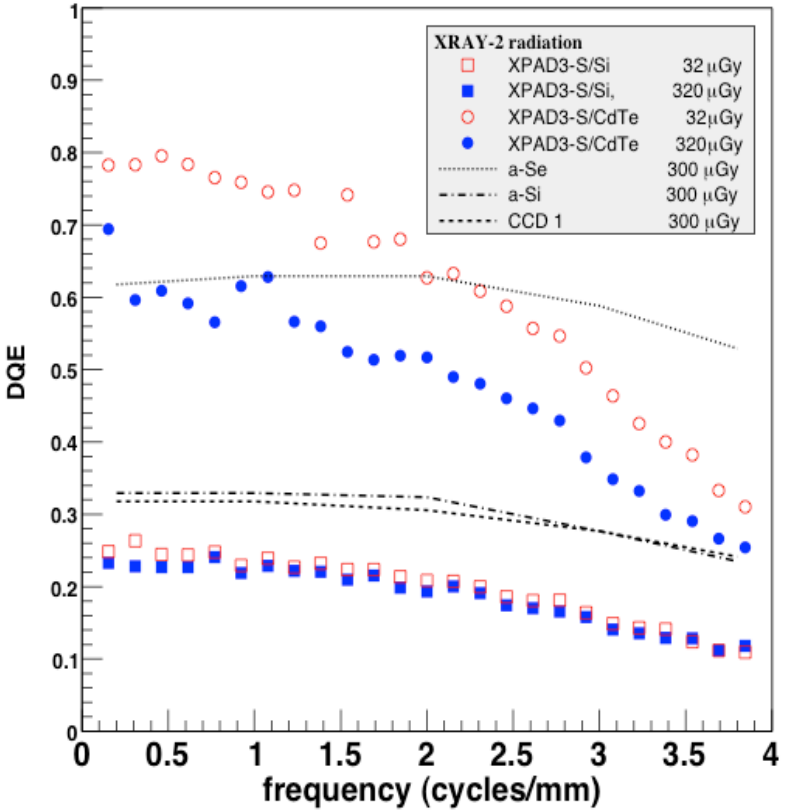
Single chip XPAD3 Si et CdTe detector characterisation

Noise Power Spectrum



Detective Quantum Efficiency



Goertzen *et al.*, Phys. Med. Biol. **49** (2004) 5251
Cassol *et al.*, Phys. Med. Biol. **54** (2009) 1773

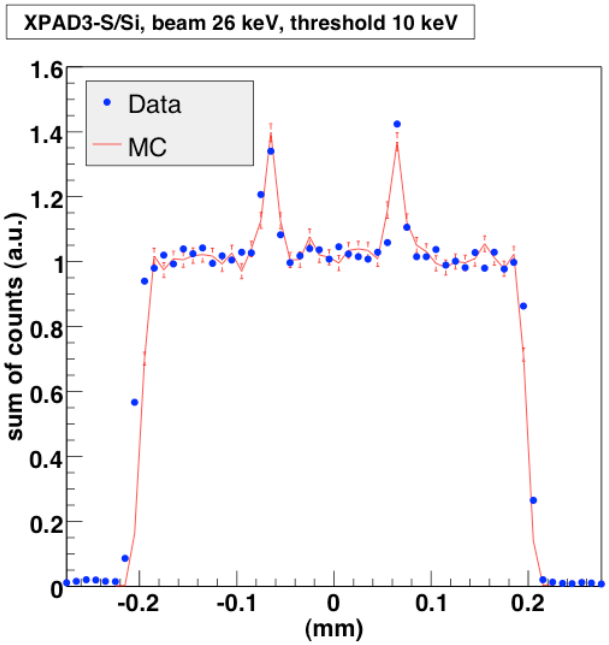
Study of charge sharing with XPAD3 Si and CdTe

Beam of E_0 = 26 keV $\quad n(E_{th},E_0) = (1-k)n_p(E_{th},E_0) + kn_{cs}(E_{th},E_0)$

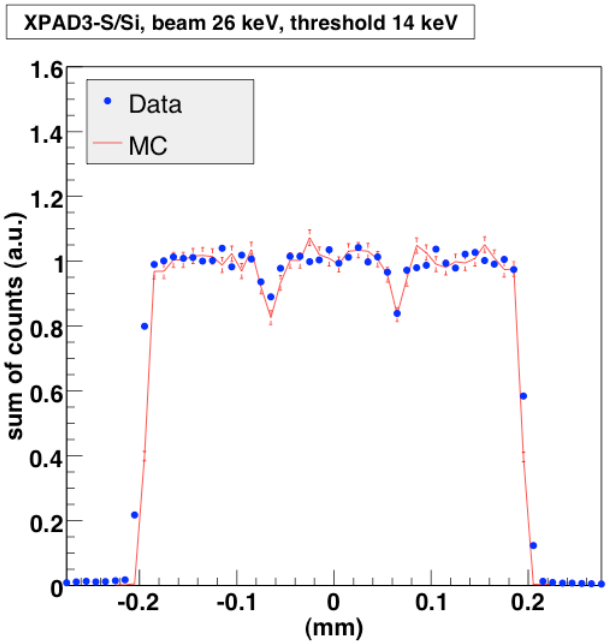
$n_p(E_{th},E_0) = N(E_0,\Delta E_0) \quad n_{cs}(E_{th},E_0) \sim 1/E_0$

Charge sharing probability: k = 0.75 (measured), 0.76 (simulated)

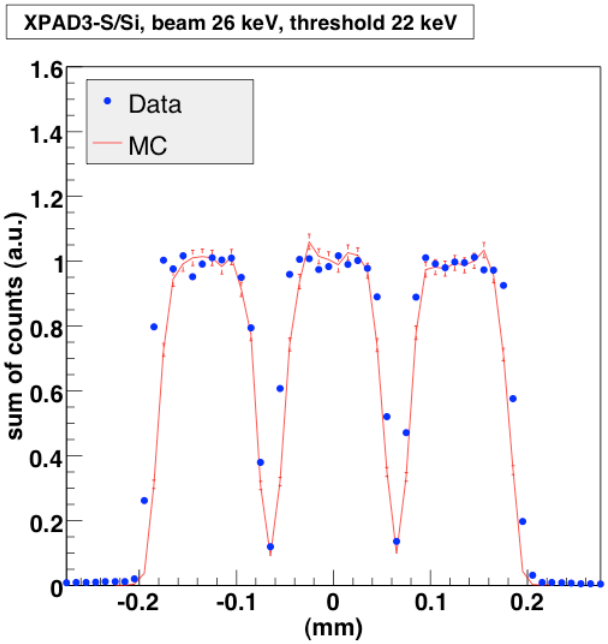
$eff_p(pixel) = 1/(1\text{-}eff_{cs}) \quad eff_{cs} = k\,(E_0/2-E_{th})/E_0$



10 keV threshold



14 keV threshold

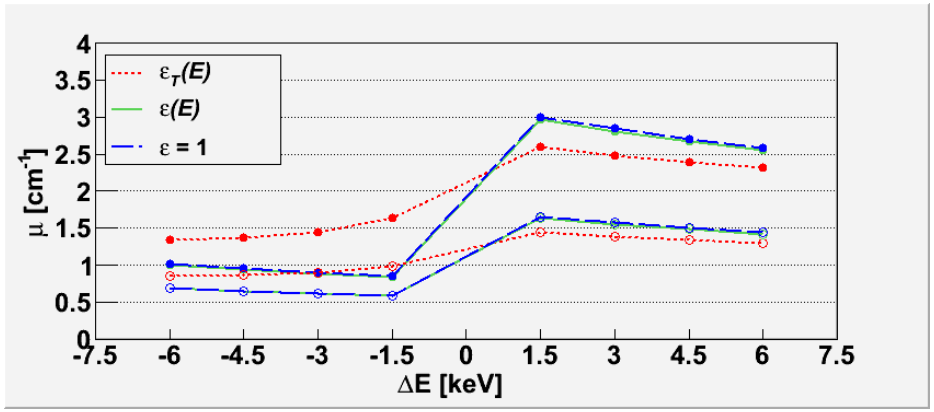


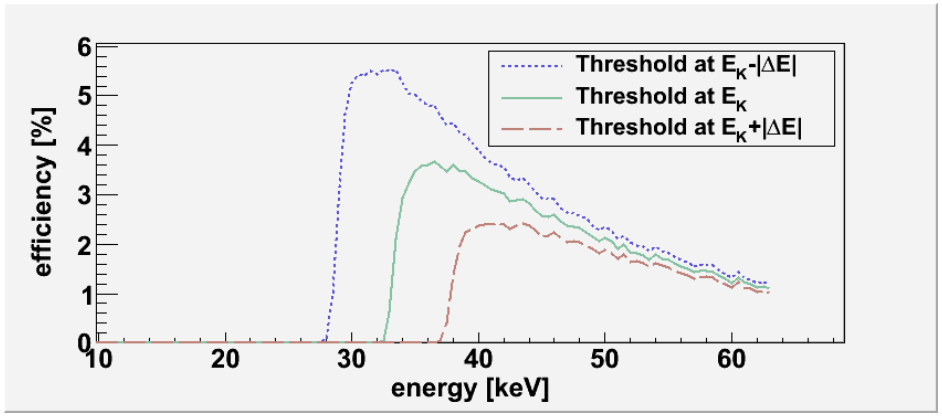
22 keV threshold

Cassol *et al.*, Nucl. Intstrum. Meth. A **633** (2011) 111

Effect of charge sharing on spectral contrast

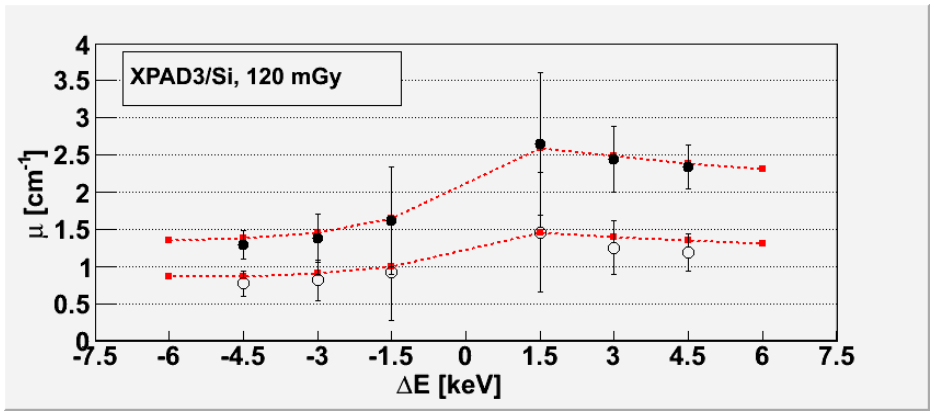
Simulation of Si sensors (full marker: 0,630 M, empty marker: 0,315 M)



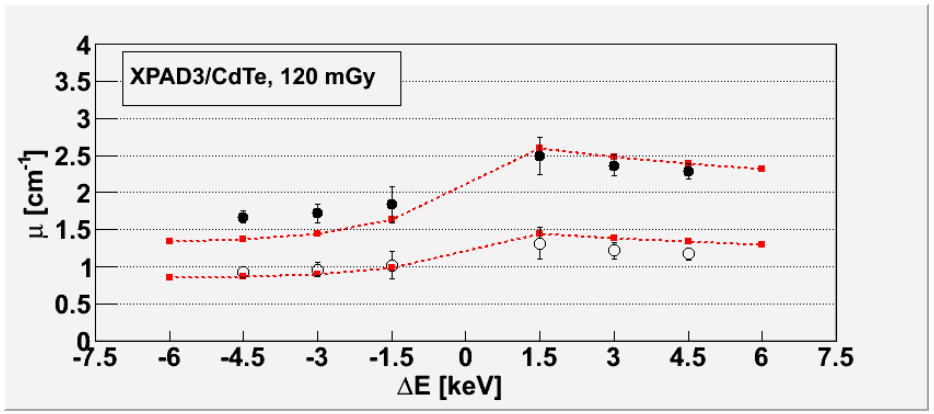


Measured data

Si



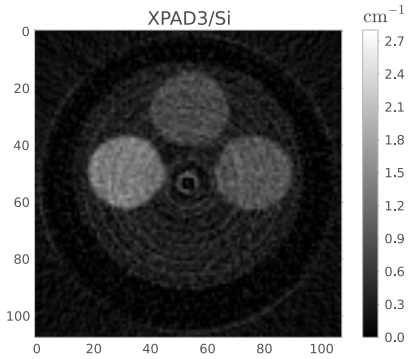
CdTe



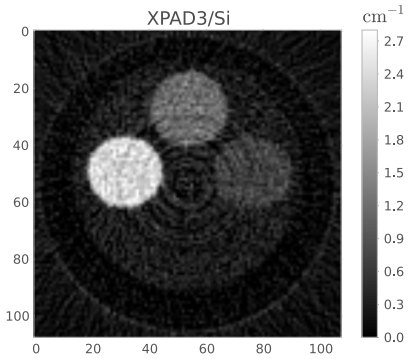
Cassol *et al.*, Phys. Med. Biol. **60** (2015) 5497

Comparison of K-edge imaging between Si and CdTe hybrids

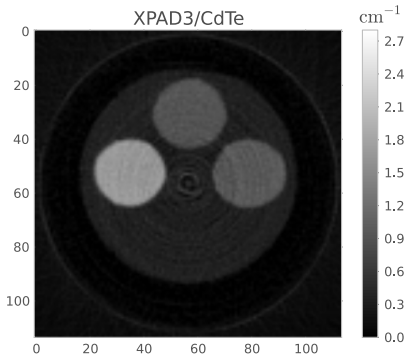
ΔE ≈ −4.5 keV



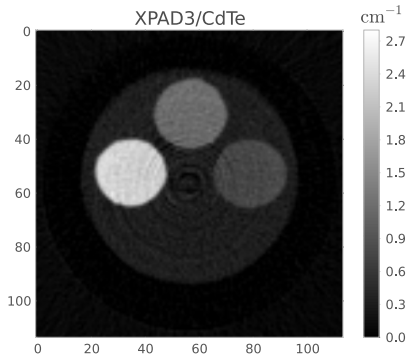
ΔE ≈ +4.5 keV

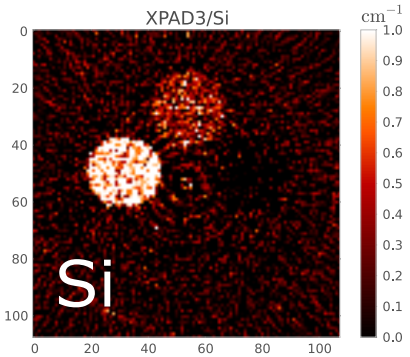


ΔE ≈ −4.5 keV

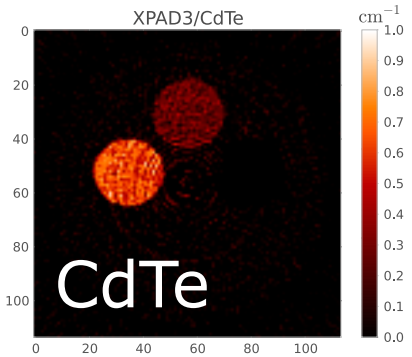


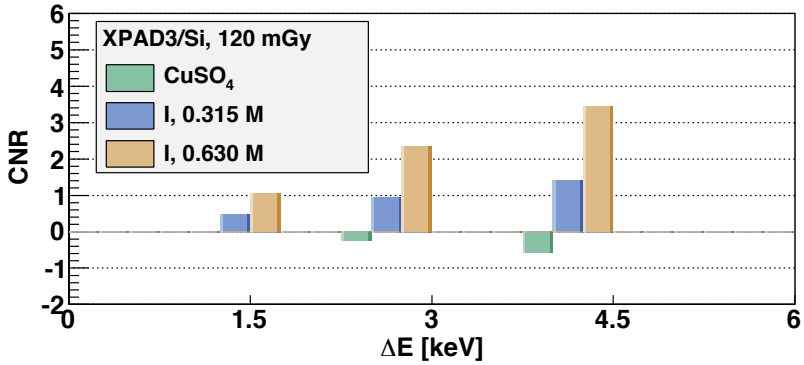
ΔE ≈ +4.5 keV

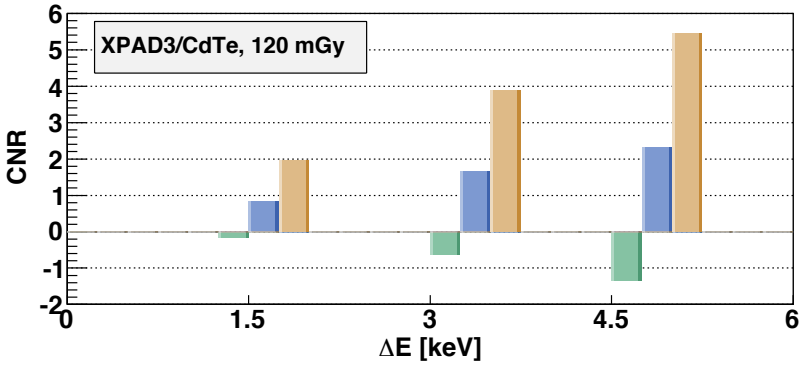




Contrast to Noise Ratio (CNR) at equivalent dose



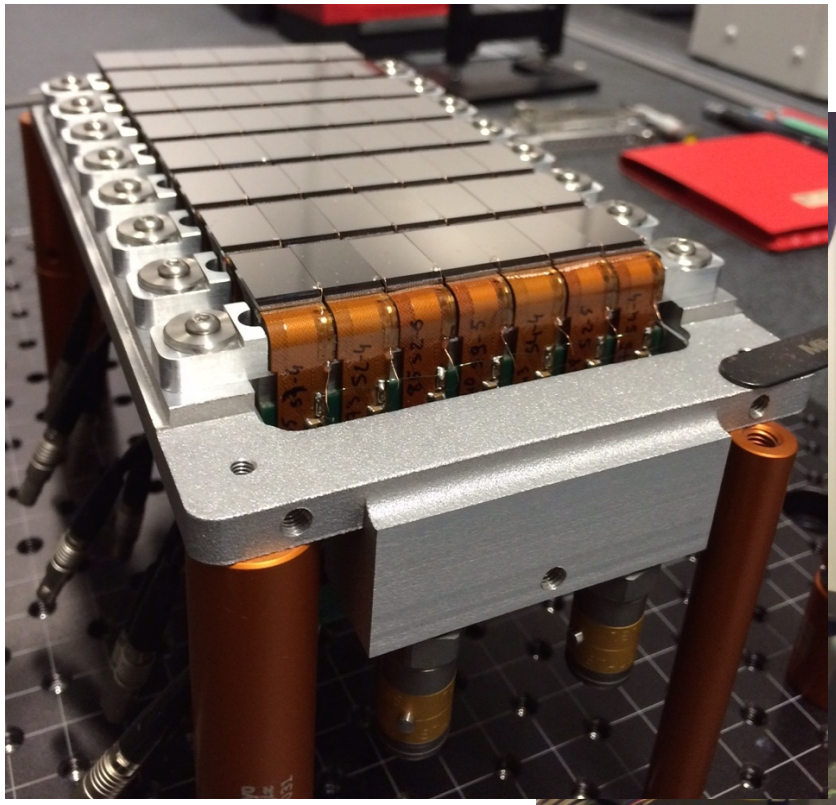


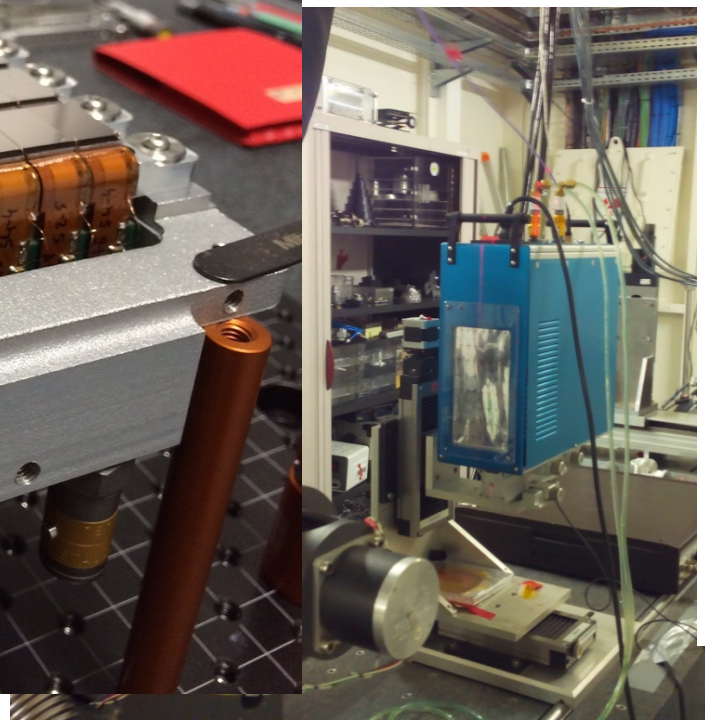


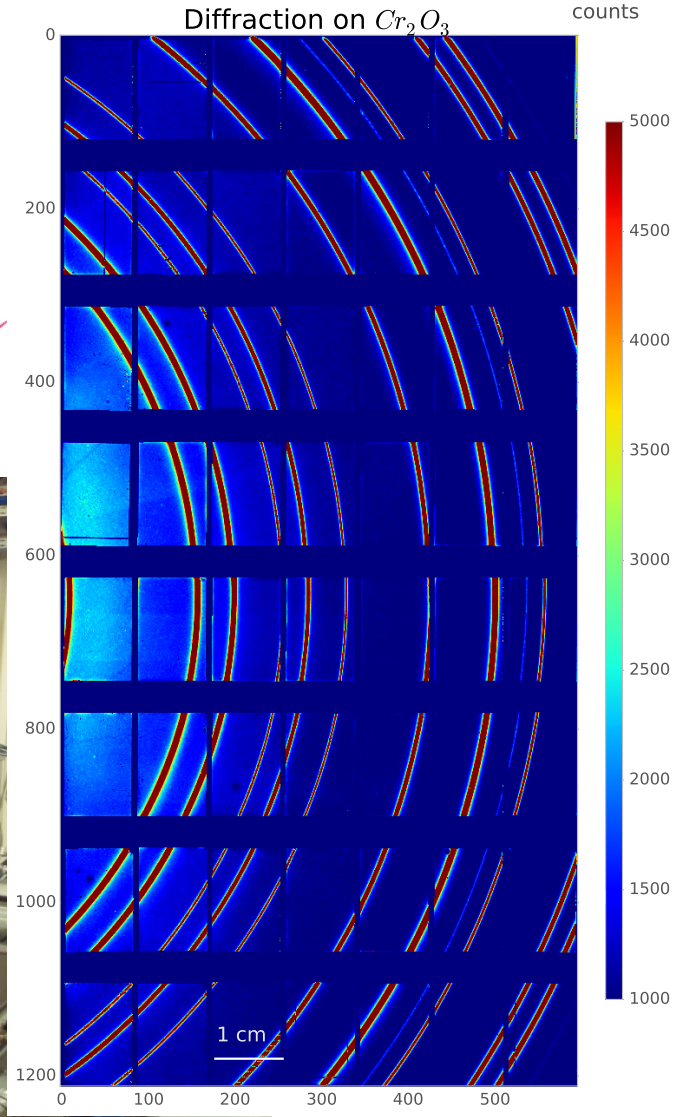
Cassol *et al.*, Phys. Med. Biol. **60** (2015) 5497

The CHiPSpeCT project (PhysiCancer 2012)

- Sensor type: hole collection with Schottky contacts
- CdTe sensor thickness: 700 µm
- Sensitive area: 150.9 x 77.6 mm^2
- Total number of pixel: 537 600
- Dead area: < 23%
- Defective pixels: < 0.17 %







Cassol *et al.*, Proc. iWoRiD 2015, DESY

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- Eric Vigeolas

Aix*Marseille université cnrs IN2P3 Les deux infinis CPPM CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE