The Medipix Photon Counting Family Of Chips

R. Ballabriga

CERN EP-ESE-ME

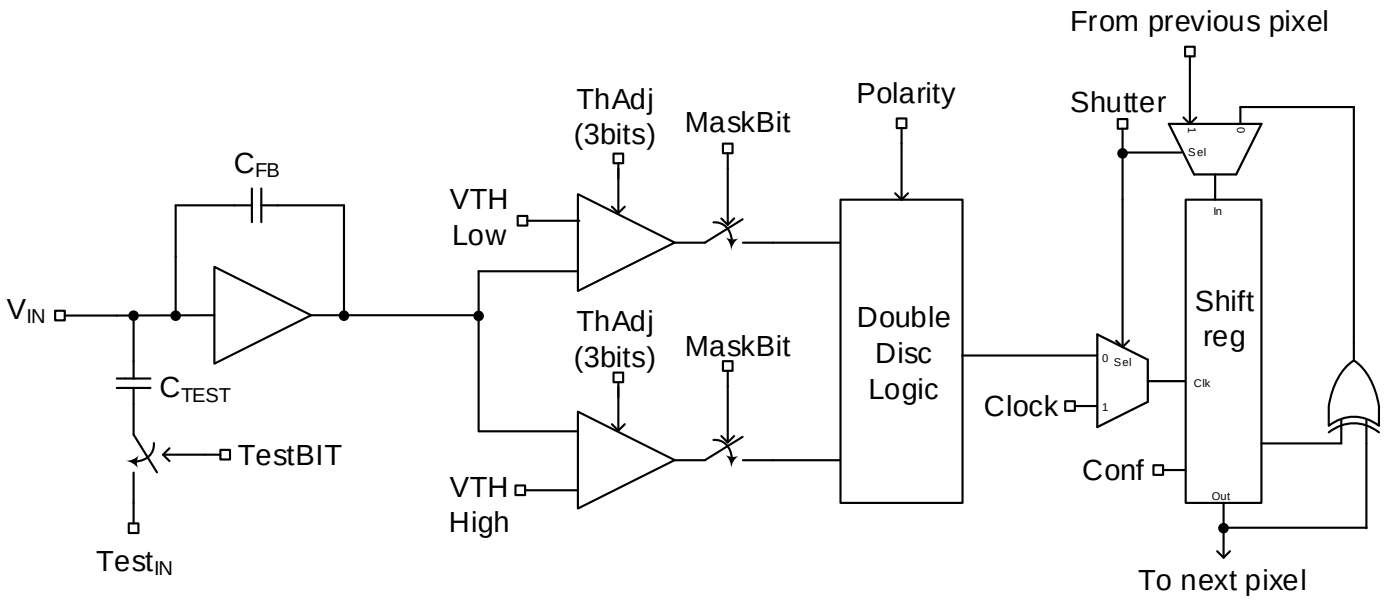
Outline

- Medipix2 chip
- Medipix3 chip
  - 1st version
  - Medipix3RX
- Towards Medipix4
- Summary and conclusions

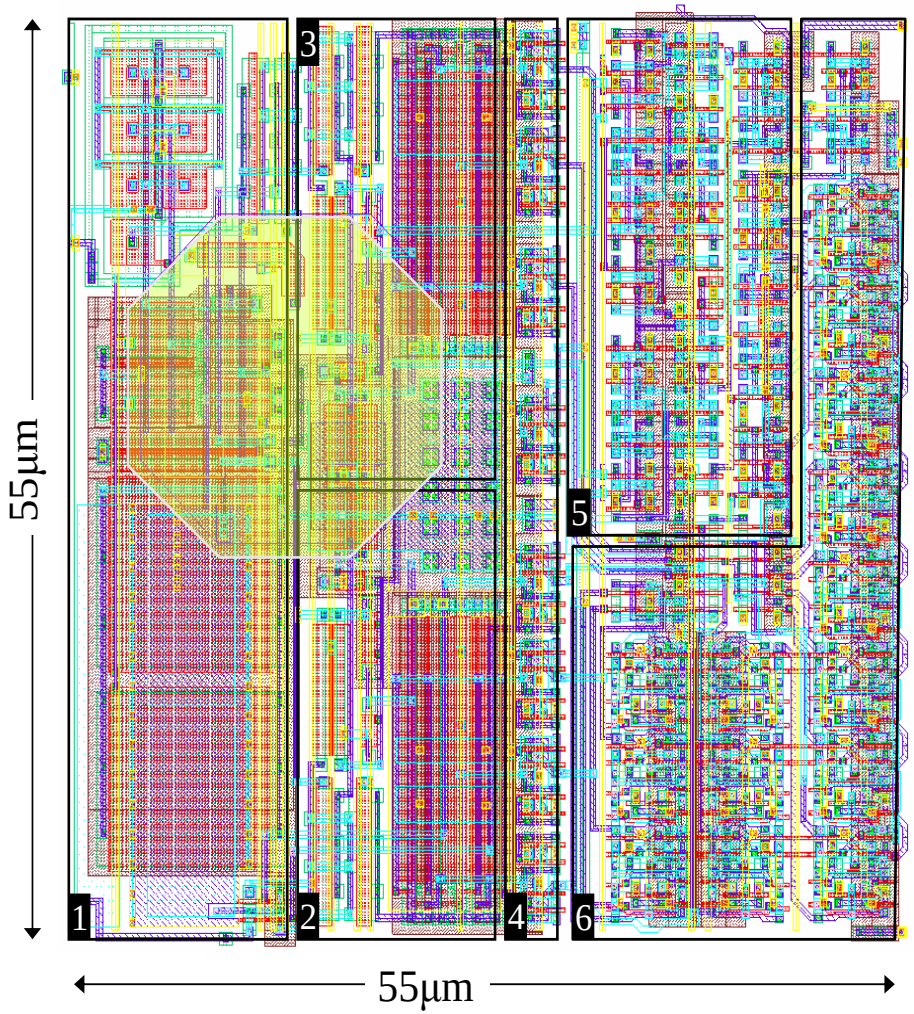
Medipix2 chip

Medipix2 chip

- Collaboration efforts started in 1999 (20 years ago!)
- Large matrix of pixels (256 x 256) with fine pitch (55μm)



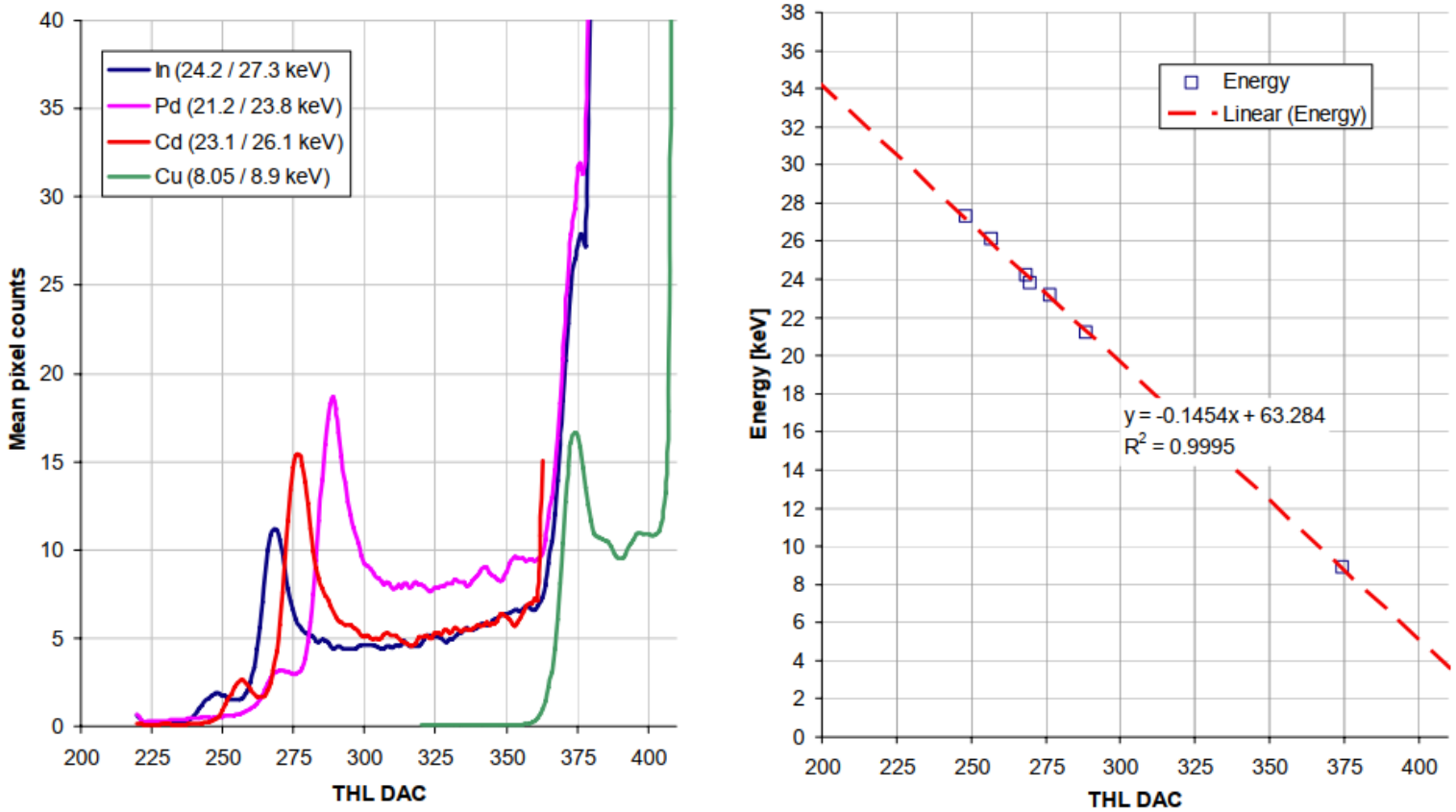
Mpix2MXR20 layout



- Camera logic (open shutter > count > close shutter > read out image)

Medipix2 chip

- Medipix2 was the first hybrid pixel detector at a pitch below 150µm
- Measurement with Si sensor
- Charge sharing tail due to charge diffusion tail: distortion in the energy spectrum
- The influence of this effect on the spectrum increases as the pixel pitch is decreased with respect to the thickness of the sensor material.

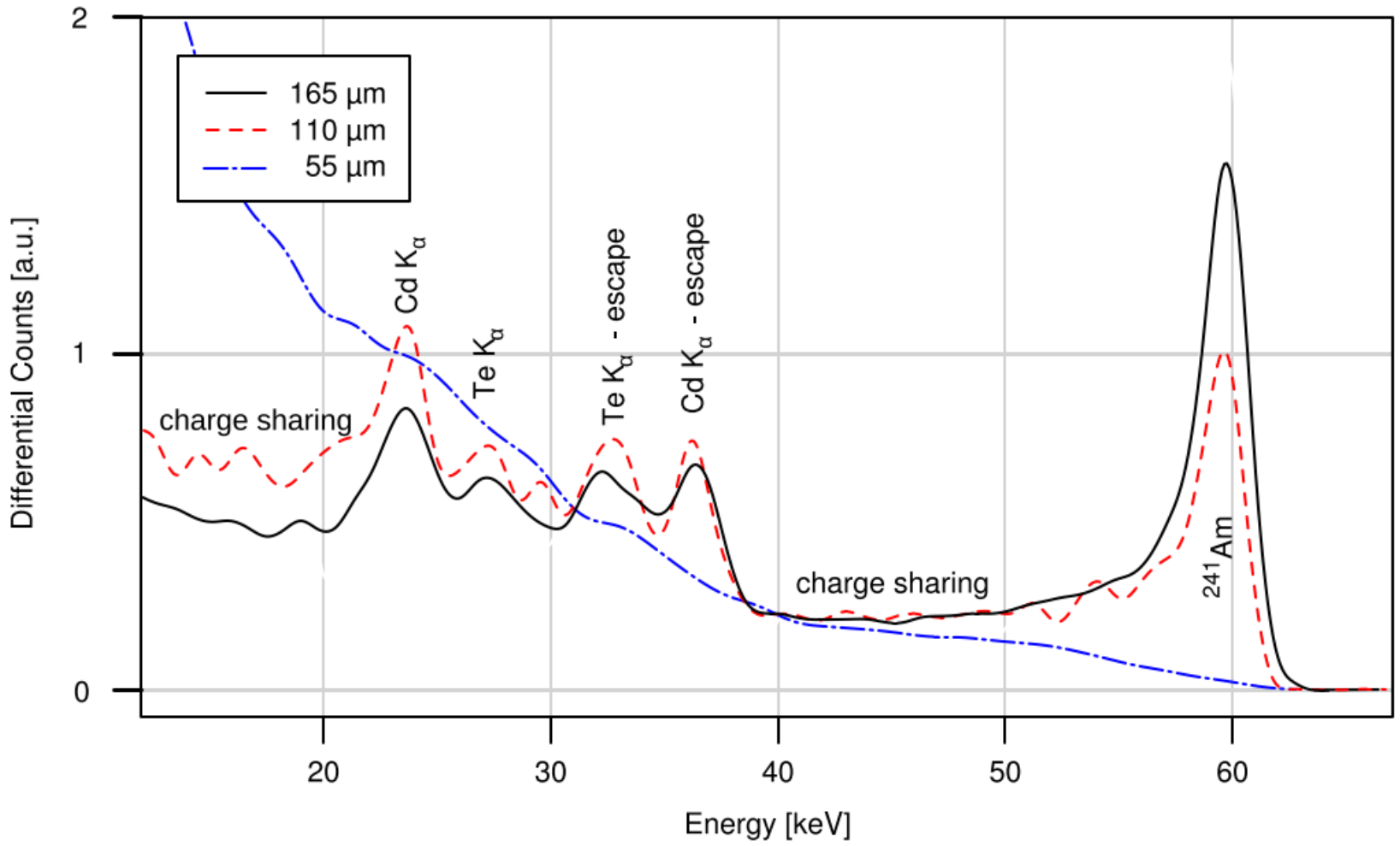


Energy calibration of Medipix2MXR (300um Si) with In, Cd, Pd and Cu fluorescence photons

145eV/DAC step, minimum detectable energy~3.8keV

Thesis X. Llopart (p. 97)

^{241}Am Spectrum with Medipix2 CdTe and 55-110 and 165µm pixels



1mm CdTe

Thesis T. Koenig

Medipix2: a 64-k Pixel Readout Chip With 55-μm Square Elements Working in Single Photon Counting Mode

X. Llopart, M. Campbell, R. Dinapoli, D. San Segundo, and E. Pernigotti

IV. Future developments

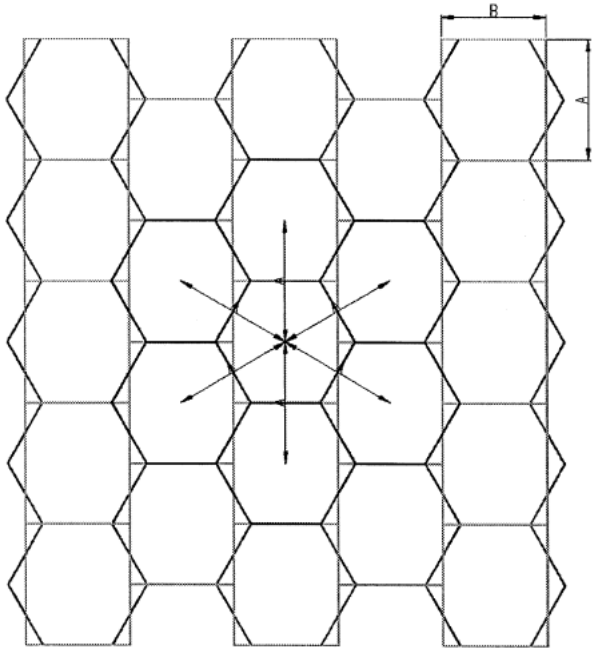


Fig. 7. Proposed detector layout $B = 3A/2\sqrt{3}$.

Detector solutions

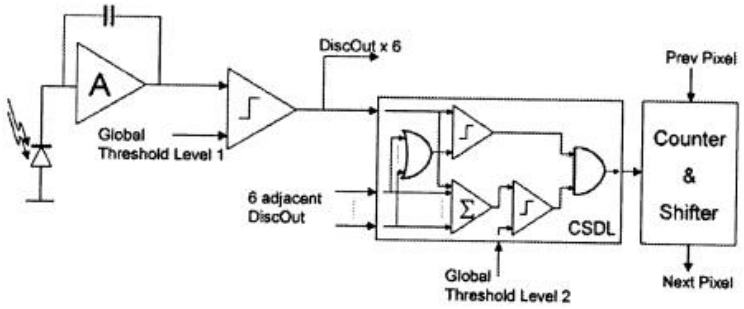


Fig. 8. Scheme of the proposed solution to take into account charge sharing effects.

Electronic solutions

This proposed system has to face two major constraints. First, the design and layout of a multipixel structure with connections between them, which must be contained in a very small pixel size (between 40–60 μm side), is very difficult to achieve with our actual design technology (0.25-μm minimum gate length and 6-metal layers). This can be overcome by moving to newer commercial CMOS deep submicron technologies with smaller gate length and more interconnection metal layers. The second constraint is the design of very low noise amplifier and discriminator cells, in order to minimize the threshold spread distribution and mismatch between adjacent channels.

Medipix3 chip

Medipix3

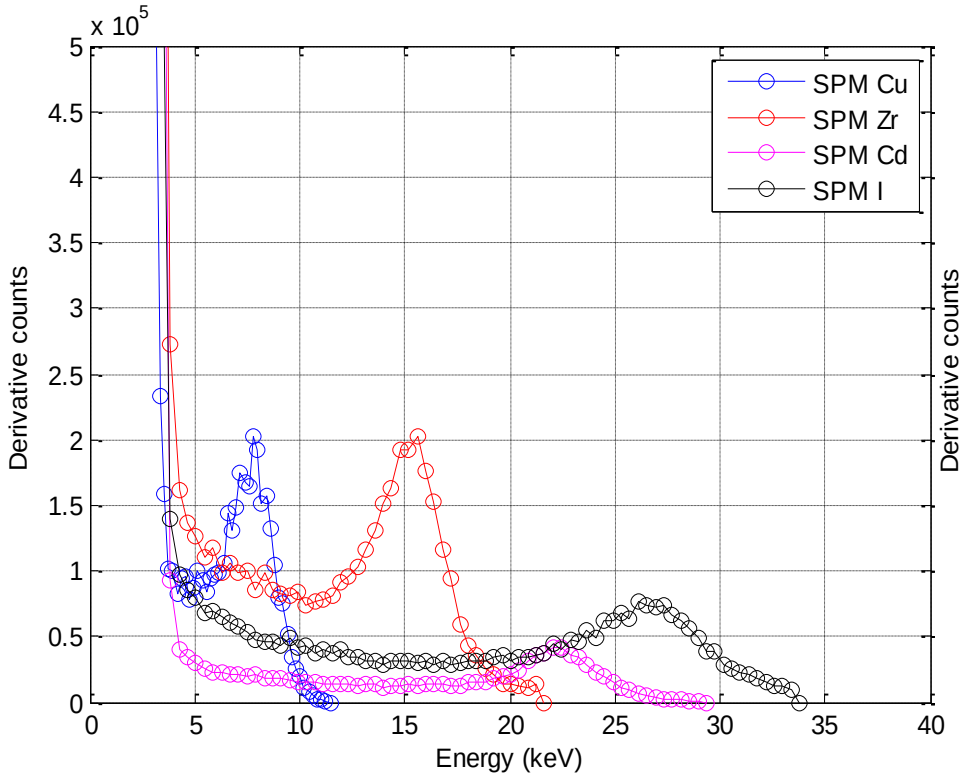
- Collaboration started in 2005

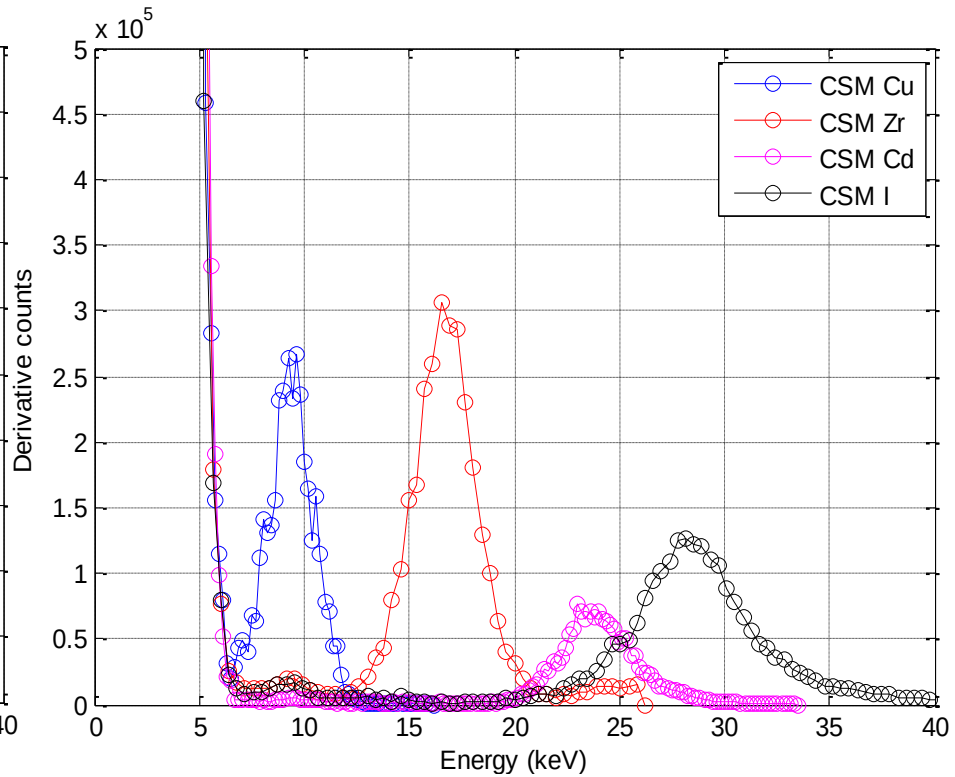
Pixel matrix	256 x 256
Pixel size	55 x 55 μm^2 or 110 x 110 mm^2
Technology	CMOS 130 nm
Measurement modes	• Single pixel • Charge summing
Gain modes	• Super low gain mode • Low gain mode • High gain mode • Super high gain mode
# thresholds	• 2 per 55 µm pixel • 8 per 110 µm pixel
Programmable counter depths	• 2 x 1-bit • 2 x 6-bit • 2 x 12-bit • 1 x 24-bit
Readout type	Frame based • Sequential R/W • Simultaneous R/W
Readout Time	Depends on counter depth used
Minimum threshold	~ 500 e-

the first large scale chip in 130nm CMOS in the High Energy Physics community

Medipix3.0 chip

Measured spectra with X-ray fluorescence photons





Single pixel mode

Noise~80 e^- r.m.s.

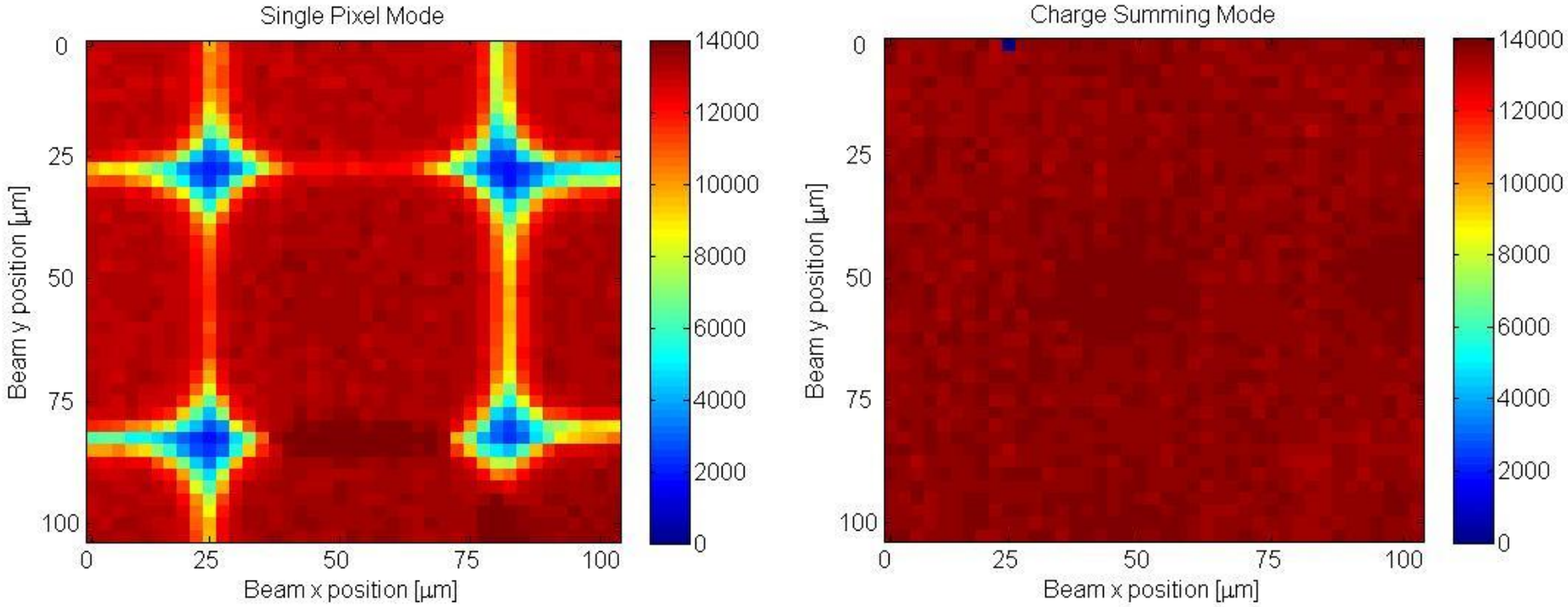
Threshold dispersion~140 e^- r.m.s.

Min detectable charge ~950 e^- r.m.s.

Charge summing mode

The energy of the photon was correctly reconstructed

Detector surface scan at a synchrotron facility



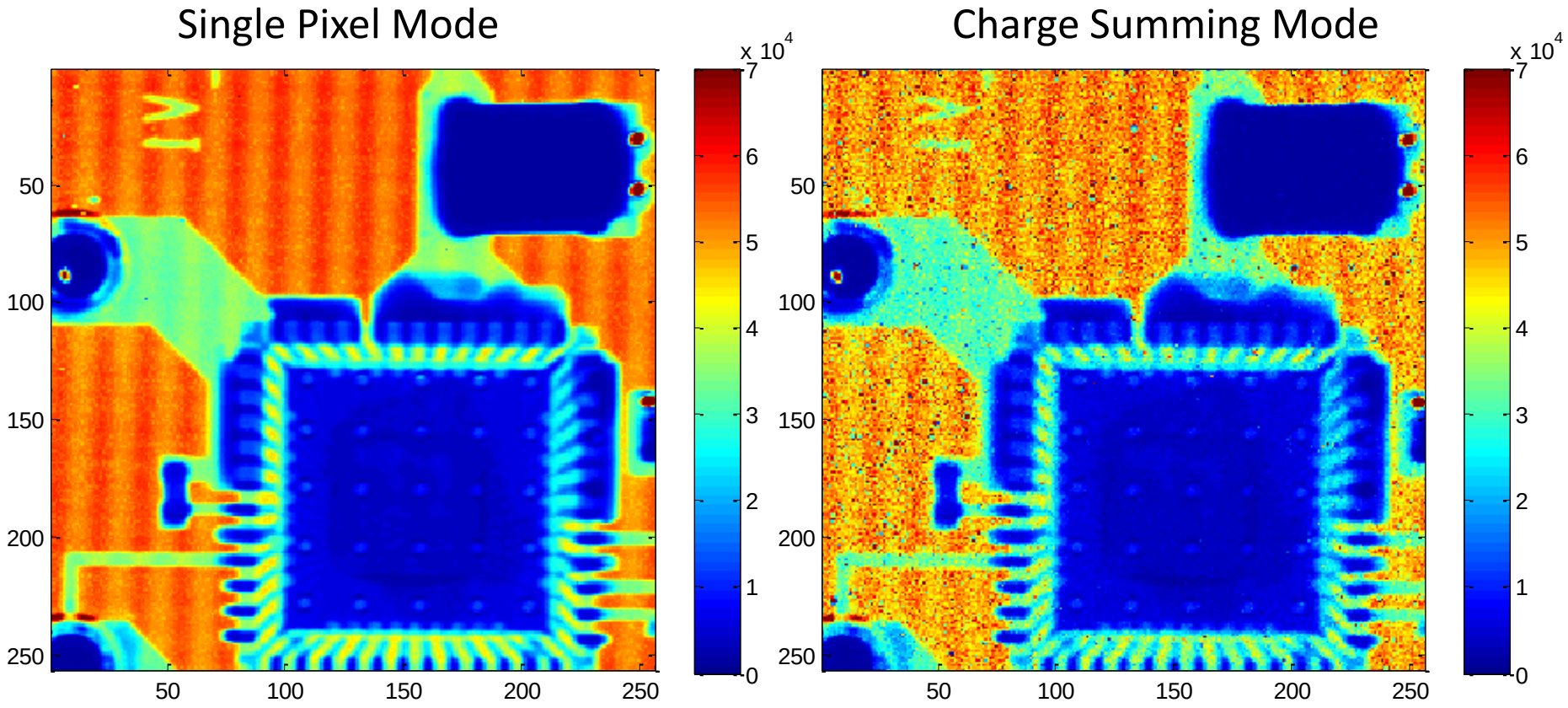
Total number of hits as a function of pencil beam x-y position

No photons lost and no double counting in Charge Summing Mode

Conditions: Scan in 100x100μm, 2.5μm steps, 15keV beam, 7.5keV threshold, 300μm Si

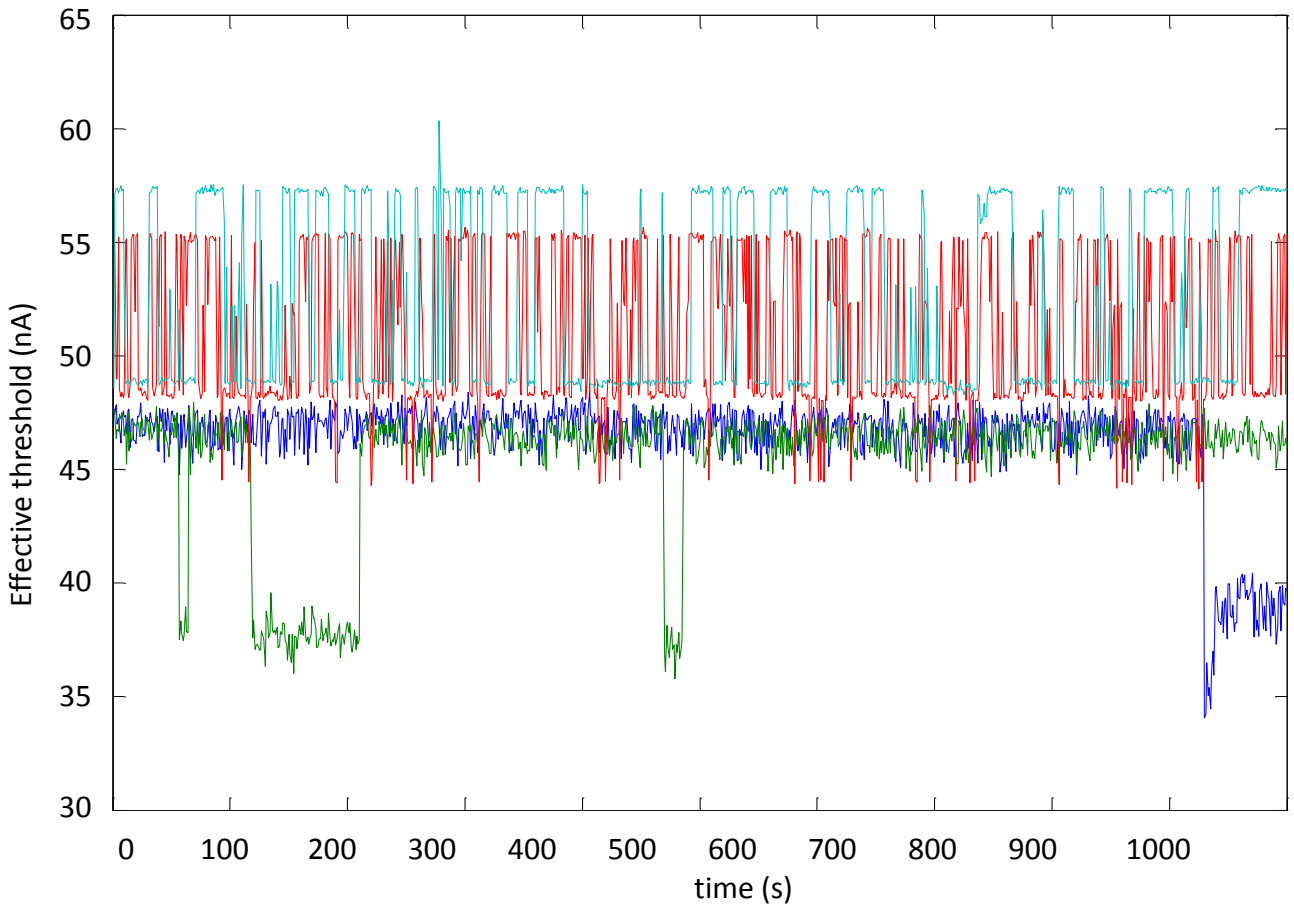
Courtesy of Eva N. Gimenez (Diamond Light Source)

Imaging in Charge Summing Mode



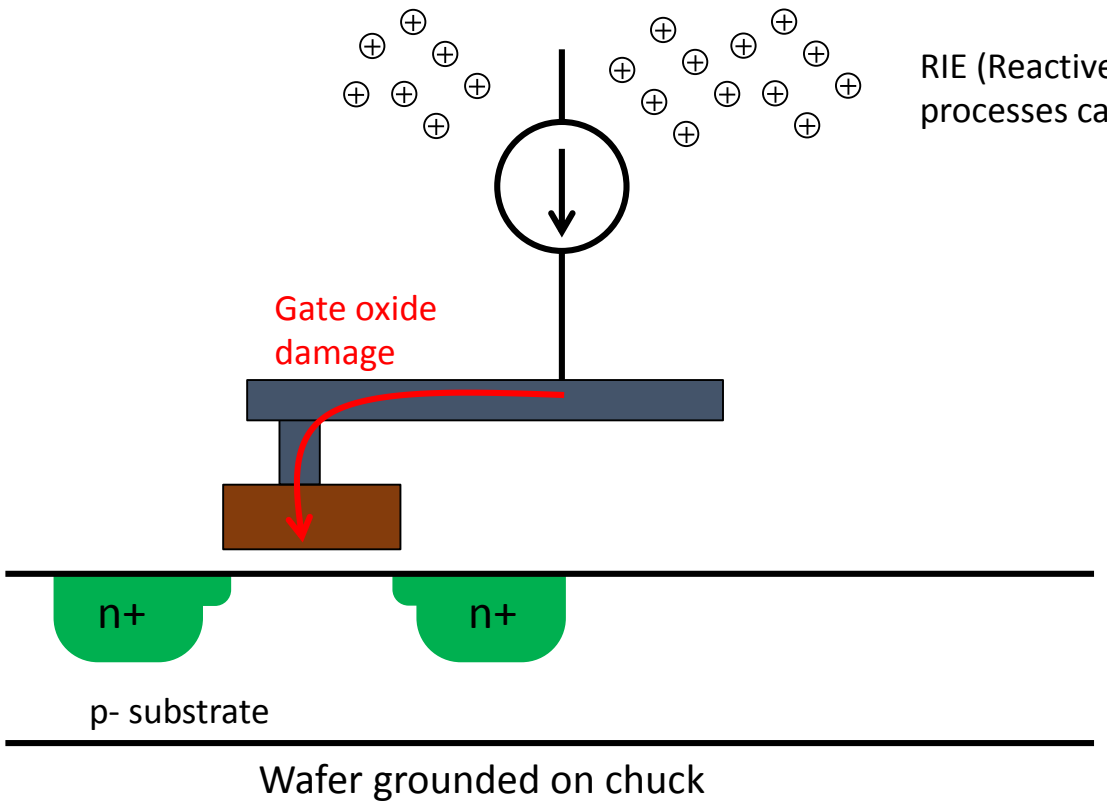
- We observed granularity in the Charge Summing Mode image due to **incorrect hit allocation**
- This was due to the sensitivity of the architecture to high threshold dispersion

Random Telegraphic Noise



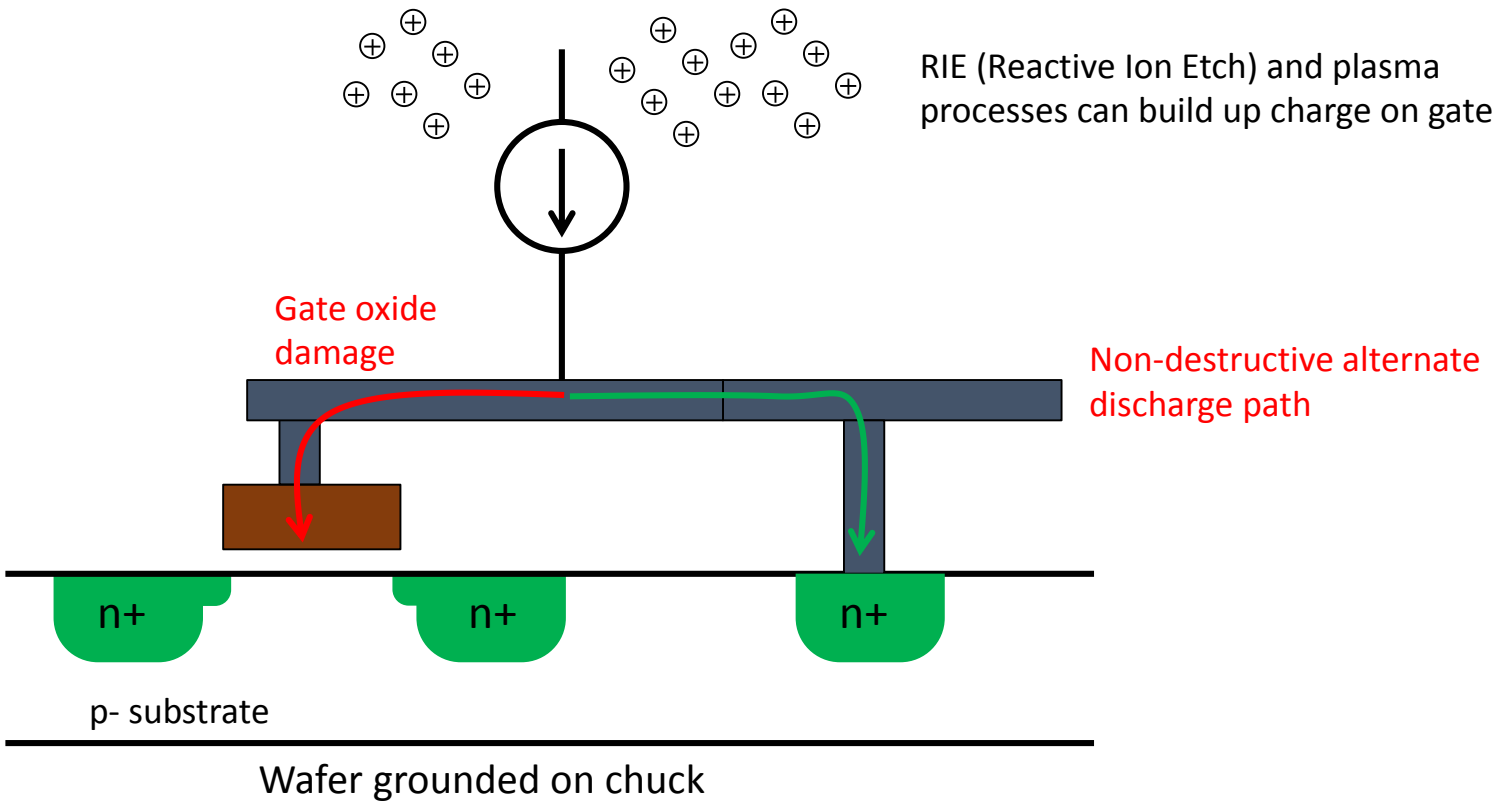
- We measured RTS on individual pixels
- Effective threshold change (in nA) vs time for ~20 minutes measurement
- 2 hour measurement RTS on less than 1% of the pixels showing RTS
- Different frequencies (changes between states from tens of second to hours)

Antenna effects



RIE (Reactive Ion Etch) and plasma processes can build up charge on gate

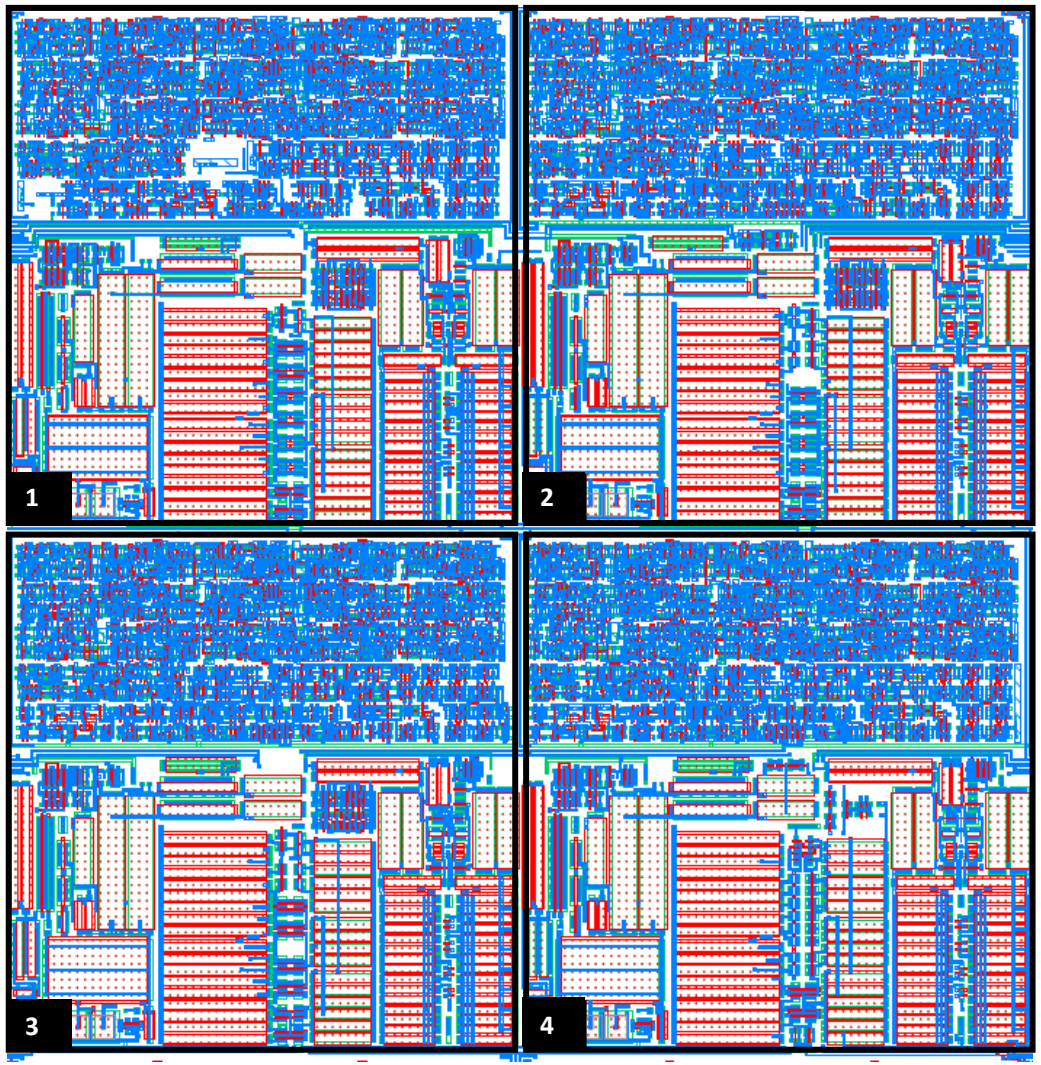
Antenna effects



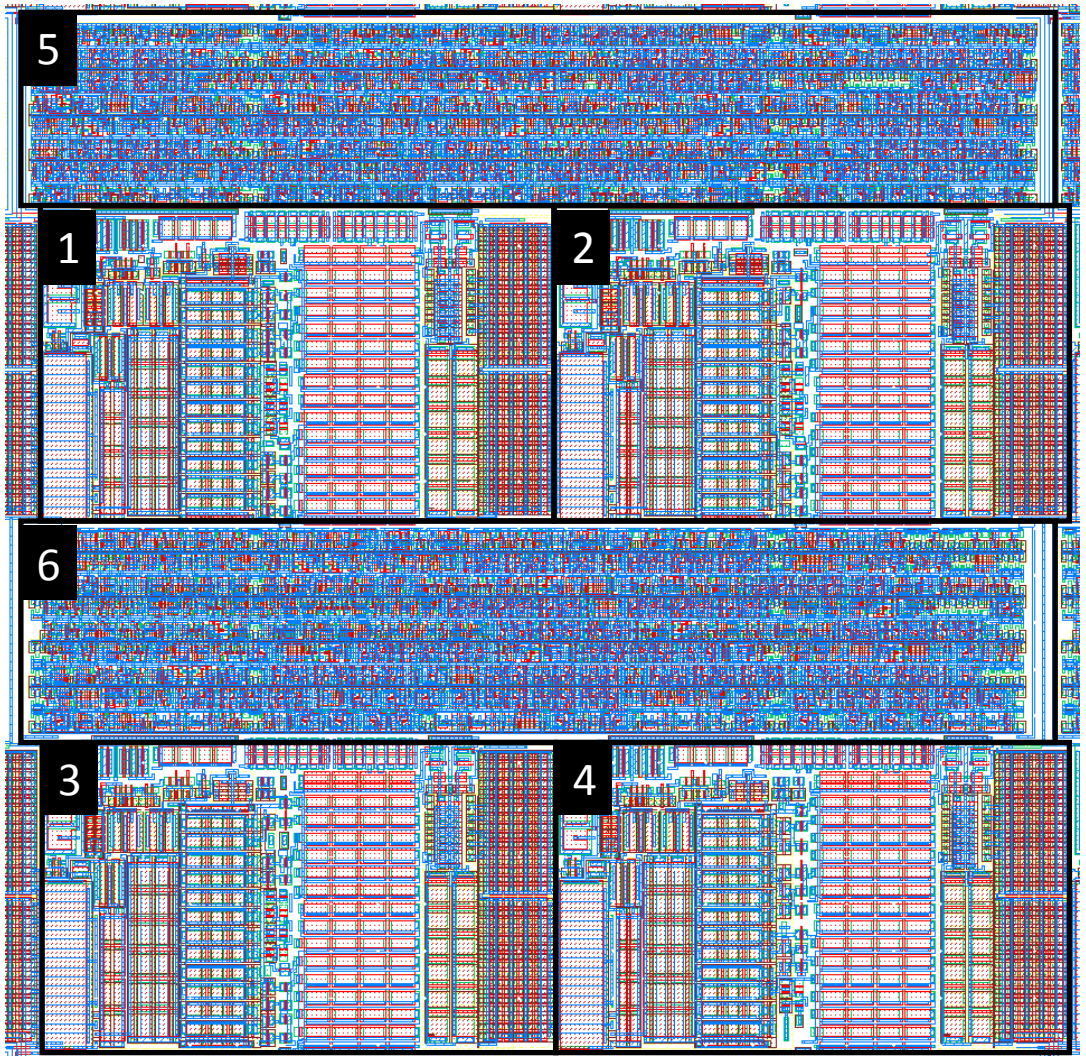
- DRC rules had been respected (but unusual design: large ASIC, mixed mode)
- The issue was addressed at architectural and device level
  - Hit allocation based on the local charge
  - Protection diodes
- Previous designs suffered less from this effect (older technologies, thicker dielectric)
  - Although not 100% immune
- The modifications resulted in a more robust design used today in demanding applications

Medipix3RX chip

Regular structure layout



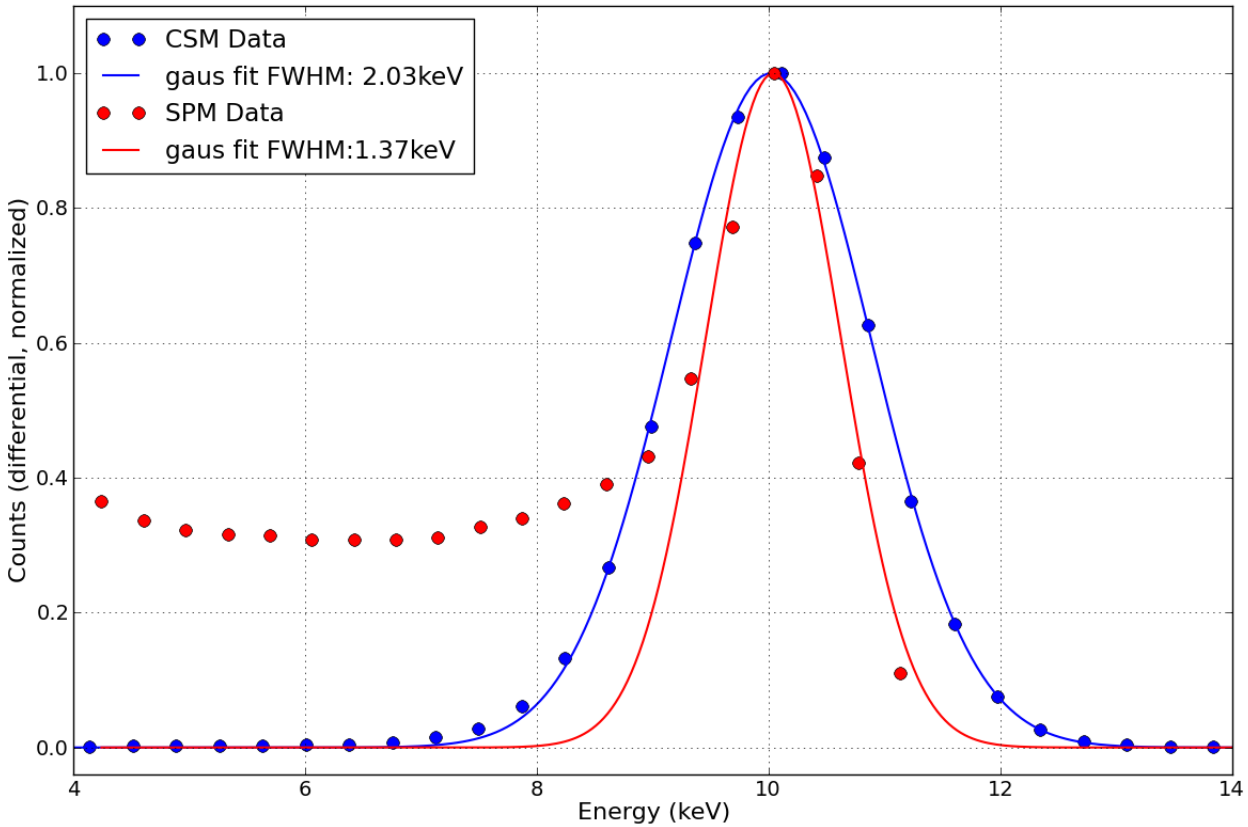
Medipix3.0 Regular Structure



Medipix3RX Regular Structure

Analog circuit improved for matching. Digital part using digital design flow techniques.

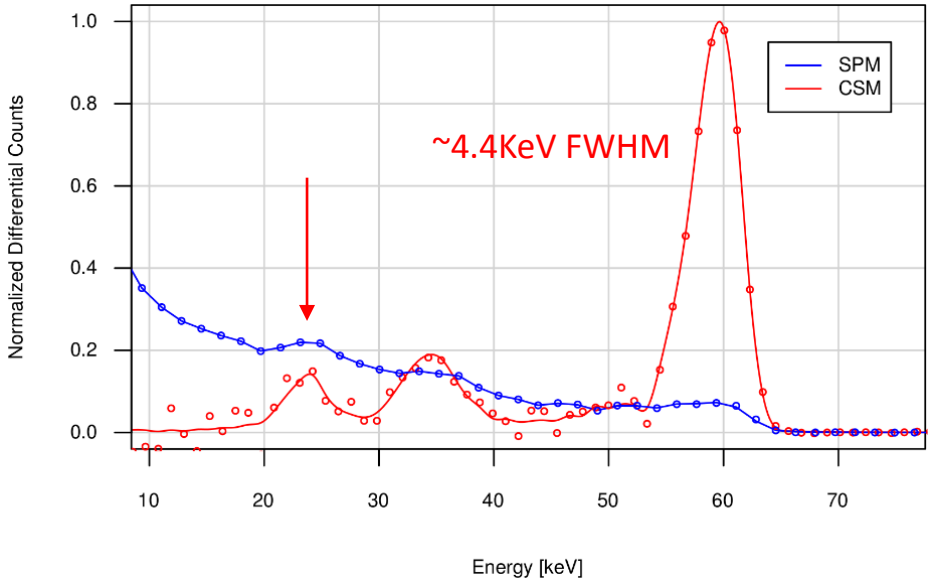
Measurement of 10KeV monochromatic light



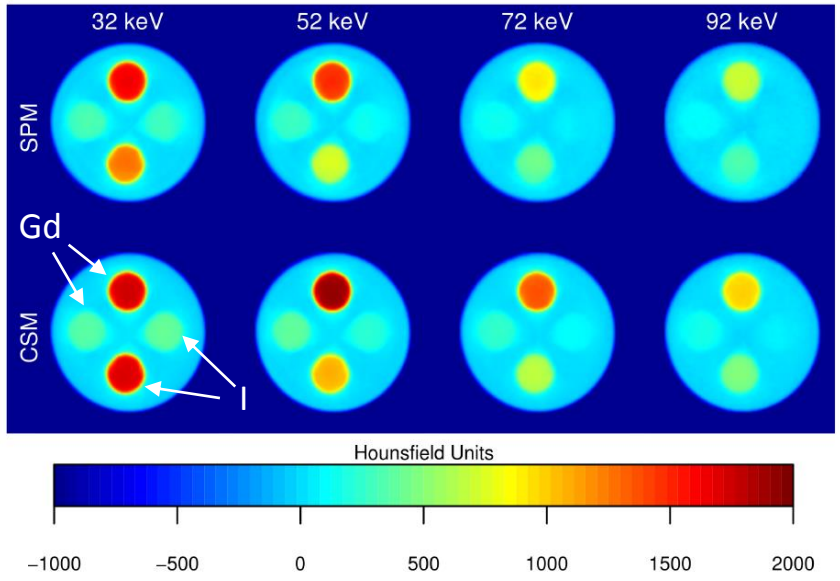
Derivative of the total number of counts in the matrix as a function of the threshold
Full matrix measurement, Raw data, No offline pixel realignment
In Charge Summing Mode the energy is reconstructed and each photon is counted once

E. Fröjdh

Measurement (60keV, 110µm pitch, 2mm CdTe)



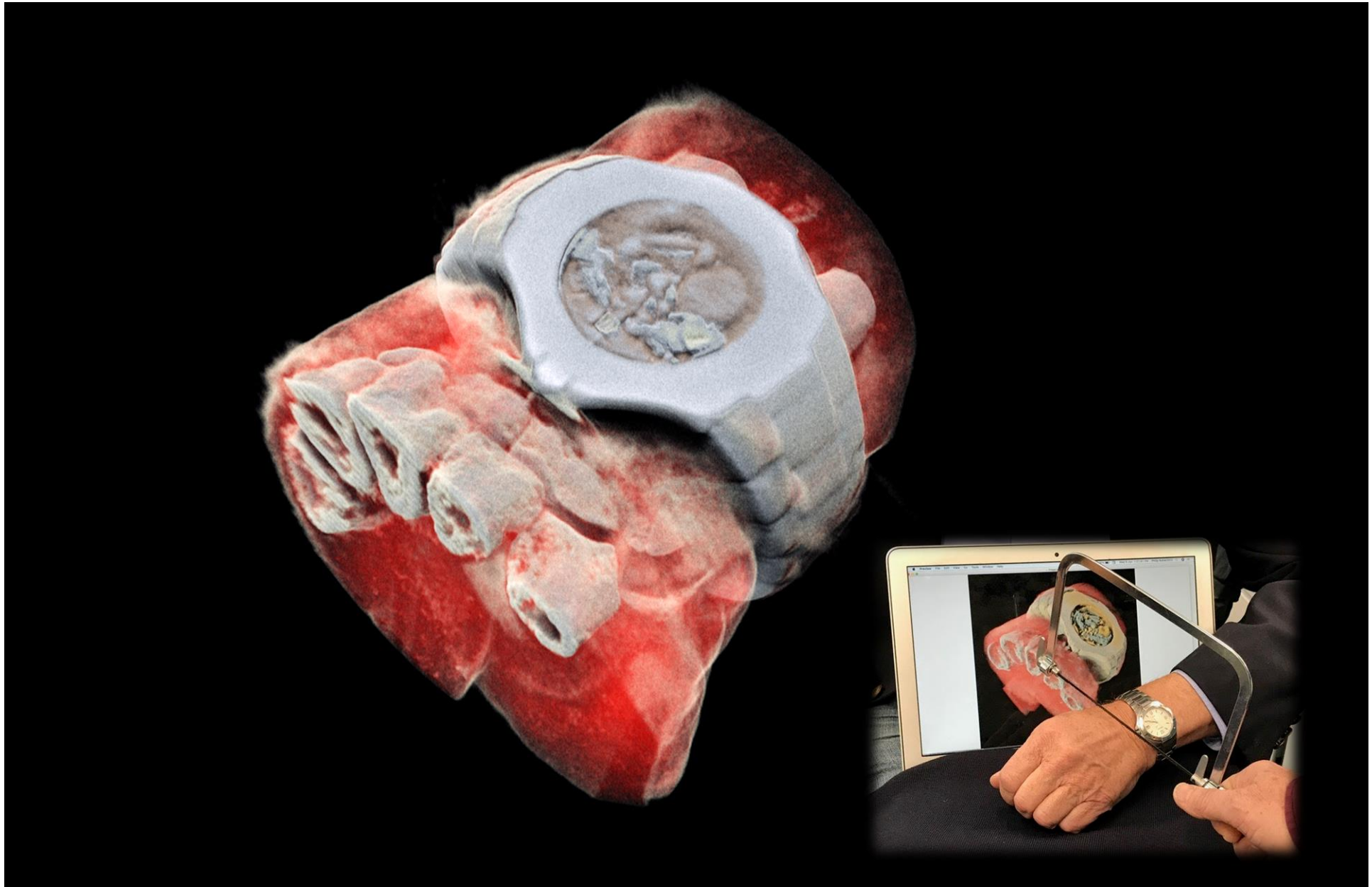
- Measured energy spectrum in Single Pixel Mode and in Charge Summing Mode
- 60keV, 2mm CdTe, 110µm pitch
- Fluorescence photons are included in charge sum if their deposition takes place within the volume of the pixels neighbouring the initial deposition



- CT scan of a PMMA phantom containing gadolinium and iodine
- Ga K-edge can be identified in CSM images
- SNR higher in CSM for the higher energy thresholds
- The gain in CSM amounts to 45% for the iodine and 30% for gadolinium solutions compared to PMMA

T. Koenig

CT image



Towards Medipix4

Review of hybrid pixel detector readout ASICs for spectroscopic X-ray imaging

(UPDATED MAY 2019)

R. Ballabriga,[a,1] J. Alozy,[a] M. Campbell,[a] E. Frojdh,[a] E.H.M. Heijne,[a,b] T. Koenig,[c] X. Llopart,[a] J. Marchal,[d] D. Pennicard,[e] T. Poikela,[a] L. Tlustos,[a] P. Valerio,[a] W. Wong[a] and M. Zuber,[c]

*2016 JINST **11** P01007*

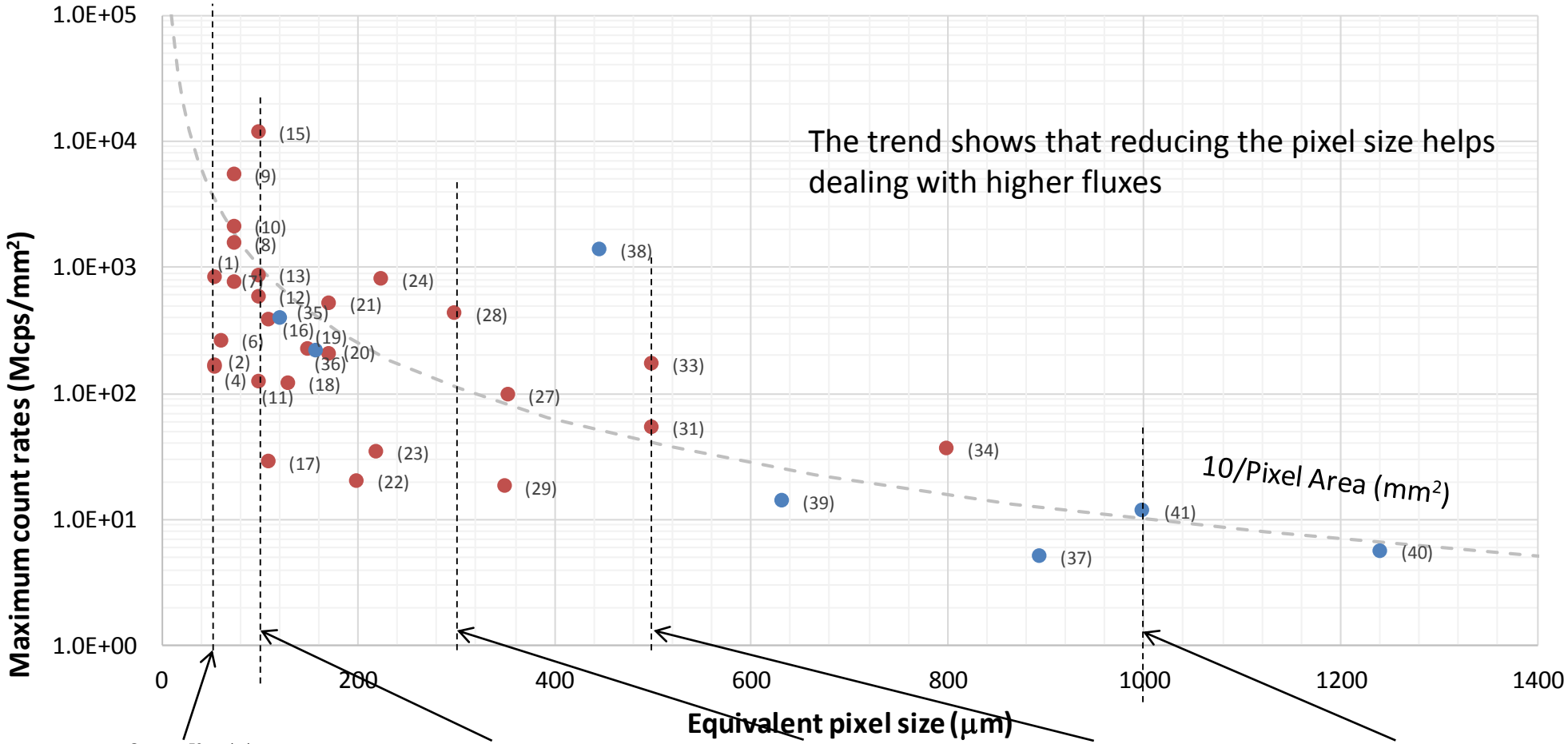
- *Tables (included for completeness) and plots updated with new developments*
- *Reported measurement values not taken as absolute values for comparison but should be used to identify trends and performance envelopes*

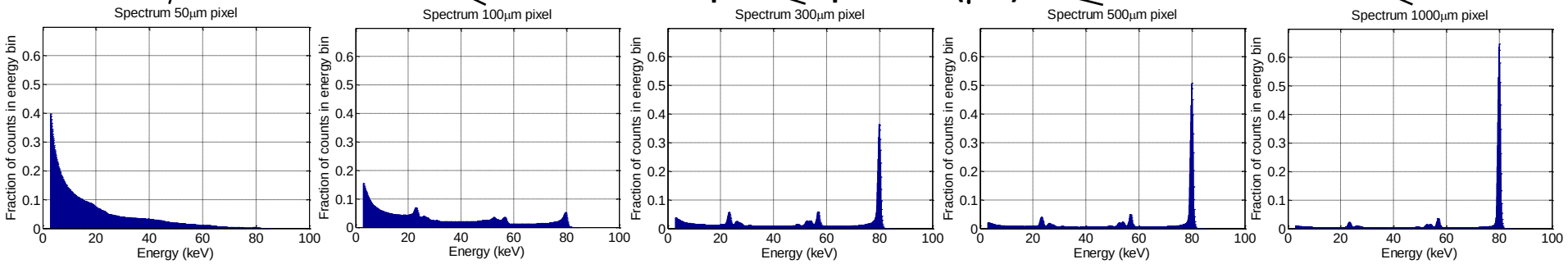
Name	Matrix	Channel size (μm^2)	Energy thresholds	Peaking time (ns)	Buttable sides	Technology (μm)	Specific information
Medipix3 *(1)*	256x256	55x55	2	120	3	0.13	Fine Pitch mode, Single Pixel mode, Compatibility with Through Silicon Vias (TSVs)
Medipix3 *(2)*	256x256	55x55	2	120	3	0.13	Fine Pitch mode, Charge summing and hit allocation algorithm, TSVs
Timepix3 *(3)*	256x256	55x55	10bits	30	3	0.13	Data push mode, Time-over-Threshold (ToT) energy measurement, charge sharing correction possible off-chip
Pixirad Pixie II *(4)*	512x476	52x60	2	300	2	0.18	Hexagonal pixels, equivalent pixel pitch of 55.6μm
Samsung PC *(5)*	128x128	60x60	3	NS	0	0.13	On-pixel successive approximation Analog to Digital Converter (ADC)
Pixirad Pixie III *(6)*	512x402	62x62	2	125	2	0.16	Large area ASIC (31.7x25mm^2), Charge summing algorithm
Eiger *(7)*	256x256	75x75	1	30	3	0.25	Radiation hard electronics design
PXD23K (AGH) *(8)*	128x184	75x75	2	48	3	0.13	
IBEX (Dectris) (9)	256x256	75x75	2	NS	3	0.11	Radiation hard electronics design, Instant retrigger technology
UFXC32K (10)	128x256	75x75	2	40	3	0.13	
X-Counter PC *(11)*	256x256	100x100	2	NS	3	NS	Charge summing algorithm
PXD18K (AGH) *(12)*	96x192	100x100	2	30	3	0.18	
FPDR90 (AGH) *(13)*	40x32	100x100	2	28	3	0.09	
AGH_Fermilab *(14)*	18x24	100x100	2	48	0	0.04	Charge summing algorithm
PXF40 (15)	18x24	100x100	1	8	0	0.04	
Medipix3 *(16)*	128x128	110x110	8	120	3	0.13	Spectroscopic mode, Single Pixel mode, TSVs
Medipix3 *(17)*	128x128	110x110	8	120	3	0.13	Spectroscopic mode, Charge summing algorithm, TSVs
XPAD3 *(18)*	80x120	130x130	2	150	3	0.25	
HEPS-BPIX (19)	104x72	150x150	1	20	3	0.13	ASIC designed for synchrotron applications
Pilatus 2 *(20)*	60x97	172x172	1	110.00	3	0.25	Radiation hard design
Pilatus 3 *(21)*	60x97	172x172	1	110.00	3	0.25	Radiation hard design, instant retrigger technology
Telesystems *(22)*	40x40	200x200	4	300-500	3	0.25	
Dosepix *(23)*	16x16	220x220	16	300	3	0.13	ToT energy measurement, 16 digital thresholds
Siemens PC *(24)*	64x64	225x225	2	20	NS	NS	Pile-up trigger method
Hexitec *(25)*	80x80	250x250	14bits	2000	3	0.35	Digitization of pulse amplitude with off-chip ADC, TSVs
D2R1 (26)	16x16	300x300	13bits	NS	2	0.18	Triggered readout, Multi Correlated Double Sampling (MCDS)
CIX 0.2 *(27)*	8x8	500x250	1	NS	1	0.35	Simultaneous charge integration and photon counting measurement
Philips ChromAIX1 *(28)*	16x16	300x300	4	20	2	0.18	
Ajat-0.35 (PC) *(29)*	32x64	350x350	1	1000	3	0.35	
Ajat-0.35 (ADC) *(30)*	32x64	350x350	64	1000	3	0.35	On-pixel ADC
DxRay-Interon *(31)*	16x16	500x500	4	10	NS	NS	
Ajat-0.5 *(32)*	44x22	500x500	2	1000-2000	3	0.35	
Philips ChromAIX2 (33)	22x32	500x500	5	10	3	0.18	
CEA-MultiX (34)	4x8	756x800	8bits	NS	2	0.13	On-pixel SAR ADC. Charge sharing, charge induction and pile-up correction

Name	Channels	Sensor pixel (μm^2)	Energy thresholds	Peaking time (ns)	Technology (μm)	Specific information
Mythen II *(35)*	128	50x300	1	NS	0.25	Si strip readout chip, edge-on orientation, designed with radiation hard techniques
Microdose Mammography *(36)*	NS	50x500	2	NS	NS	Si strip readout chip, edge-on orientation
IDEAS *(37)*	64	2000x400	6	50	NS	Optimized for Cd(Zn)Te linear sensor array
KTH_Lin_SPD *(38)*	160	500x400	8	10-20-40-60	0.18	Optimized for readout of 16-segment Si-strips oriented edge-on
Hamamatsu *(39)*	64	800x500	5	NS	NS	Optimized for Cd(Zn)Te linear sensor array
BNL *(40)*	64	2200x700	5	40-80-160-320	0.25	Optimized for CdZnTe sensors, 9th order shaper
GE-DxRay *(41)*	128	1000x1000	2	30	0.25	Connected to 2-D CdZnTe by means of interposer board, Clinical images taken with the GE lightSpeed VCT scanner

Name	Max count rates (Mcps/pixel)	Max count rates (Mcps/mm²)	Electronics noise (e^- r.m.s.)	Energy resolution (FWHM)	Power/pixel (μW)
Medipix3 (FPM-SPM) *(1)*	2.50	826	80	1.37keV @ 10keV, 300um Si	7.5
Medipix3 (FPM-CSM) *(2)*	0.50	164	174	2.03keV @ 10keV, 300um Si	9.3
Timepix3 *(3)*	$1.3\ 10^{-3}$	0.43	62	4.07keV @ 59.5keV, 300um Si	15.2
Pixirad Pixie II *(4)*	0.5	162	50	1.73keV @ 60keV, CdTe	12.5
Samsung PC *(5)*	NS	NS	68	NS	4.6
Pixirad Pixie III *(6)*	1	260	50(SPM)/100(CSM)	2keV @ 20keV, CdTe	34
Eiger *(7)*	4.2	747	121/160/185	NS	8.8
PXD23K (AGH) *(8)*	8.55	1519	90	NS	25
IBEX (DECTRIS) (9)	30	5300	90	850eV FWHM @8keV (300um Si)	8
UFXC32K (10)	11.8	2100	123	NS	26
X-Counter PC *(11)*	1.2	120	NS	10KeV @60keV, CdTe	NS
PXD18K (AGH) *(12)*	5.8	580	168	NS	23
FPDR90 (AGH) *(13)*	8.55	855	91	NS	42
AGH_Fermilab *(14)*	NS	NS	84 (SPM)/168 (CSM)	NS	34
PXF40 (15)	115	11600	185	NS	105
Medipix3 (SM-SPM) *(16)*	4.55	376	80	1.43keV @ 10KeV, Si	30
Medipix3 (SM-CSM) *(17)*	0.34	28	174	4.4keV @60keV, 2mm CdTe	37.2
XPAD3 *(18)*	2	118	127	2.3keV @59.5keV CdTe	40
HEPS-BPIX (19)	5	220	115	NS	36.6
Pilatus 2 *(20)*	6	203	123	1keV @ 8keV	20.2
Pilatus 3 *(21)*	15	507	123	1keV @ 8keV	20.2
Telesystems *(22)*	0.8	20	NS	4.88keV @ 122keV	94.4
Dosepix *(23)*	1.64	34	150	3.12keV @ 35keV	14.6
Siemens PC *(24)*	40	790	NS	NS	NS
Hexitec *(25)*	0.001	0.02	NS	0.8keV @ 60keV	220
D2R1 (26)	$40\ 10^{-6}$	$0.44\ 10^{-3}$	29	584eV FWHM @ 60keV	315
CIX 0.2 *(27)*	12	96	330	NS	3200
Philips ChromAIX1 *(28)*	38	422	400	4.7keV @60keV	3000
Ajat-0.35 (PC) *(29)*	2.2	18	NS	4keV @122keV, CdTe	390.6
Ajat-0.35 (ADC) *(30)*	$4.88\ 10^{-5}$	$4\ 10^{-4}$	NS	4keV @122keV, CdTe	390.6
DxRay-Interon *(31)*	13.25	53	NS	7keV @60keV, CdTe	NS
Ajat-0.5 *(32)*	NS	NS	NS	4.7keV @122KeV, CdTe	413.2
Philips ChromAIX 2 *(33)*	42	168	260	4.8keV FWHM @60keV	NS
CEA-MultiX (34)	23	36	NS	8.5keV @122keV, CdTe	10000

Name	Max count rates (Mcps/pixel)	Max count rates (Mcps/mm²)	Electronics noise (e^- r.m.s.)	Energy resolution (FWHM)	Power/sensor channel (mW)
Mythen II *(35)*	5.88	392	151+55.6e-/pF	NS	368.75
Microdose Mammography *(36)*	5.29	212	200 (without detector)	NS	NS
IDEAS *(37)*	4	5	105+40e-/pF	7keV @ 60keV, CdTe (10pF Cin total)	4200
KTH_Lin_SPD *(38)*	272	1360	214 @5pF Cin (40ns pk time)	1.09keV @ 15keV	80000
Hamamatsu *(39)*	5.5	14	NS	12keV @ 120keV, CdTe	NS
BNL *(40)*	4	6	170 @ 2pF Cin (40ns pk time)	5.5keV @ 40ns pk time/2.15keV @ 320ns pk time (4.6pF Cin)	4700
GE-DxRay *(41)*	11.6	12	NS	5.8keV @ 122keV, CdZnTe (5pF Cin total)	2100

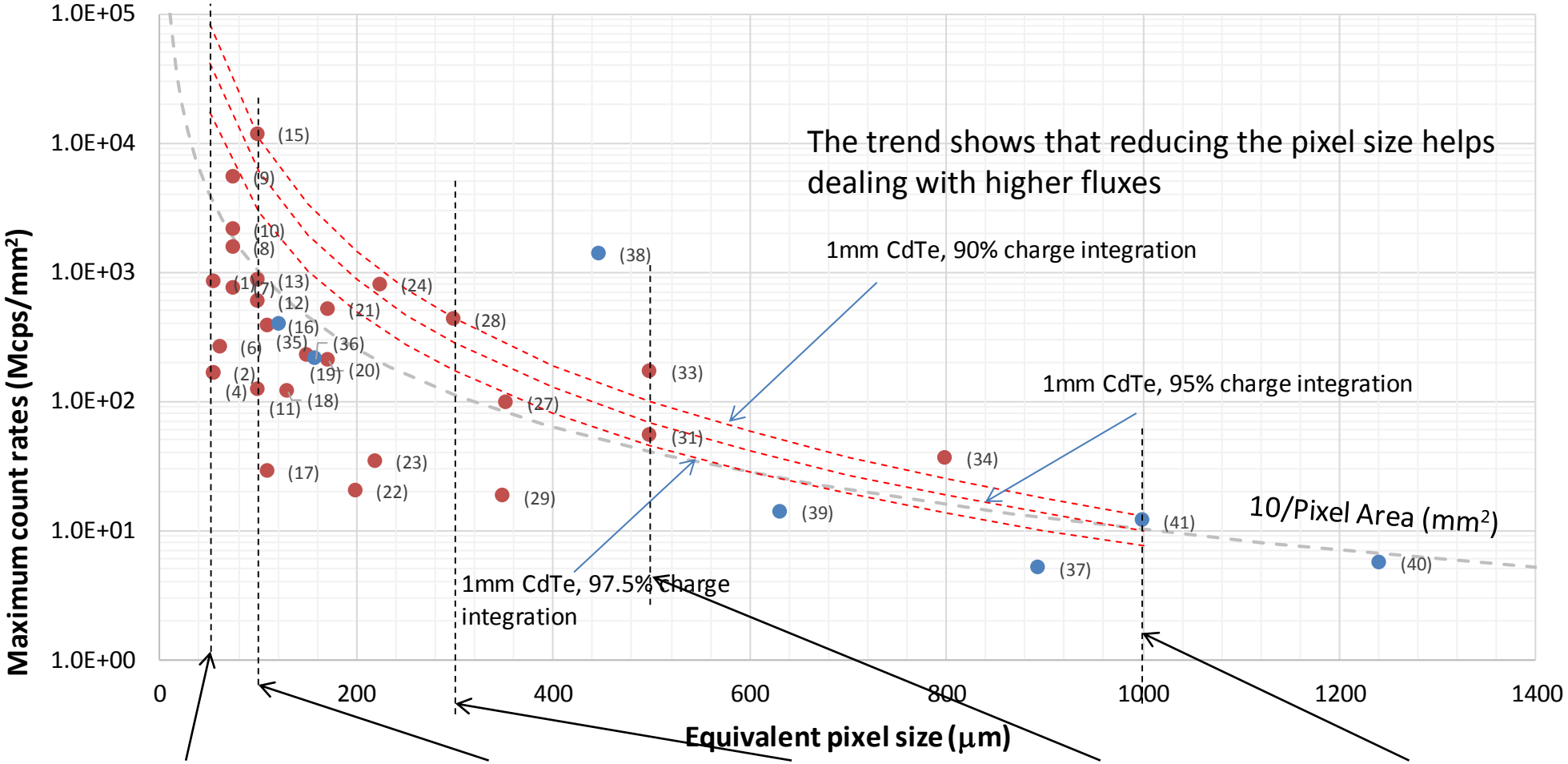


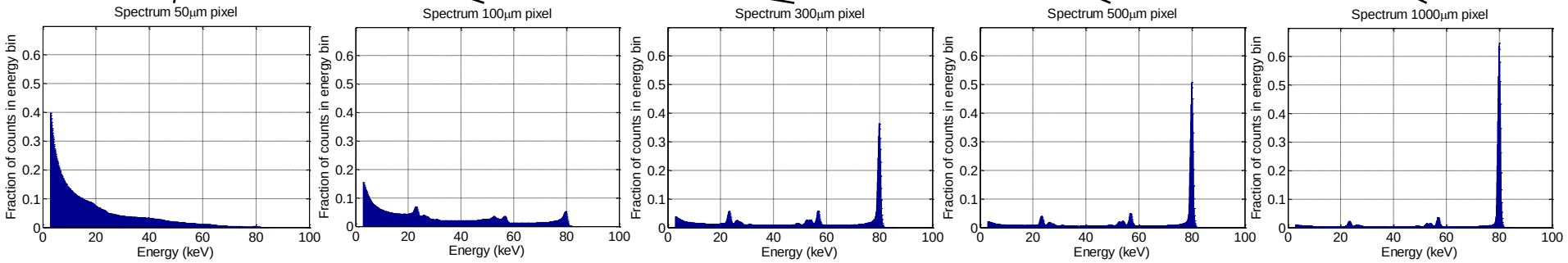


Simulation 80keV photons, 2mm CdTe, -800V, 100e- r.m.s. noise (no threshold dispersion, no charge trapping)

In order to do spectroscopy at fine pitches a charge reconstruction and hit allocation architecture is required.

Acknowledgements for simulations on sensor physics: D. Pennicard (DESY), L. Tlustos (CERN)





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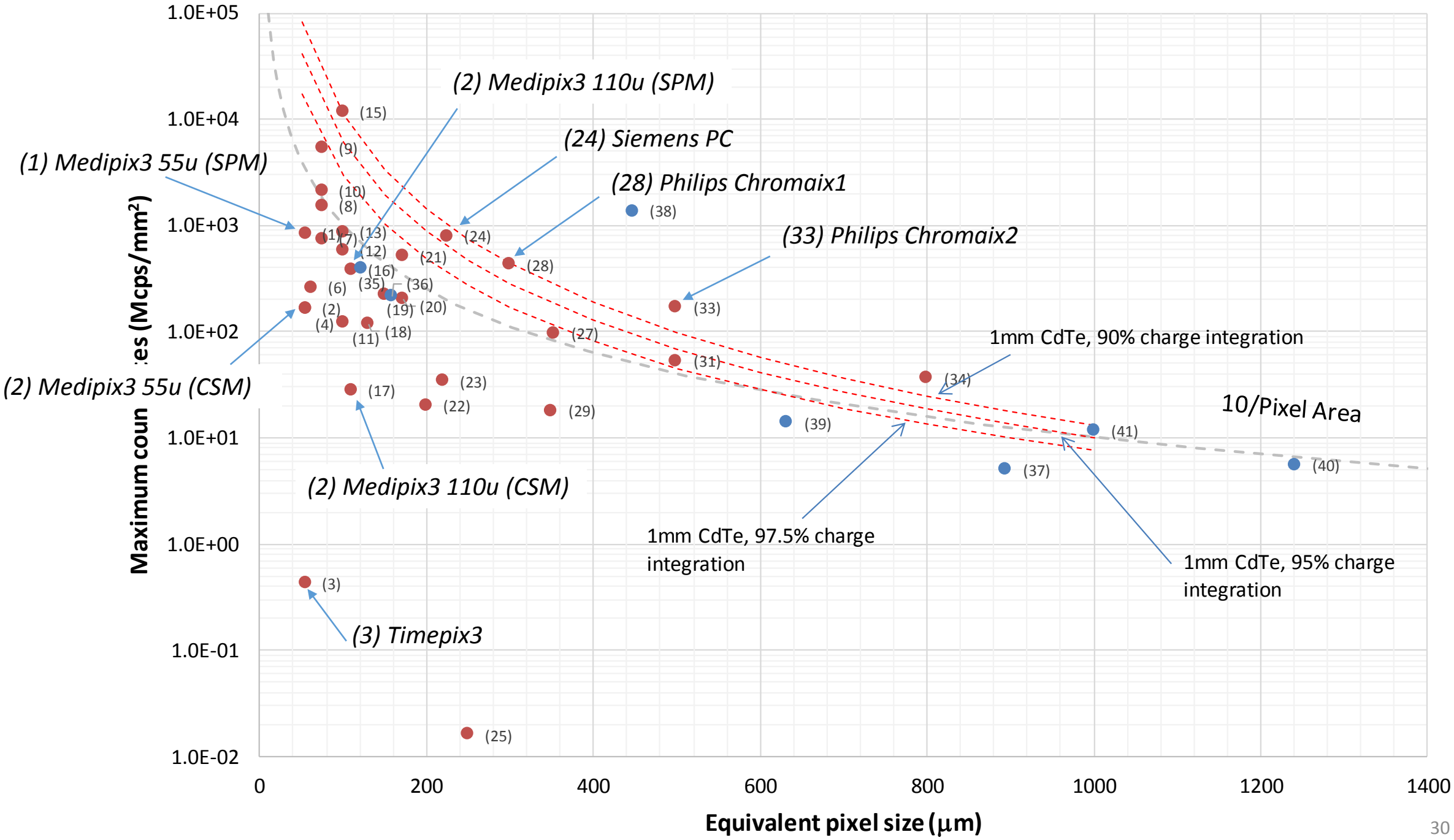
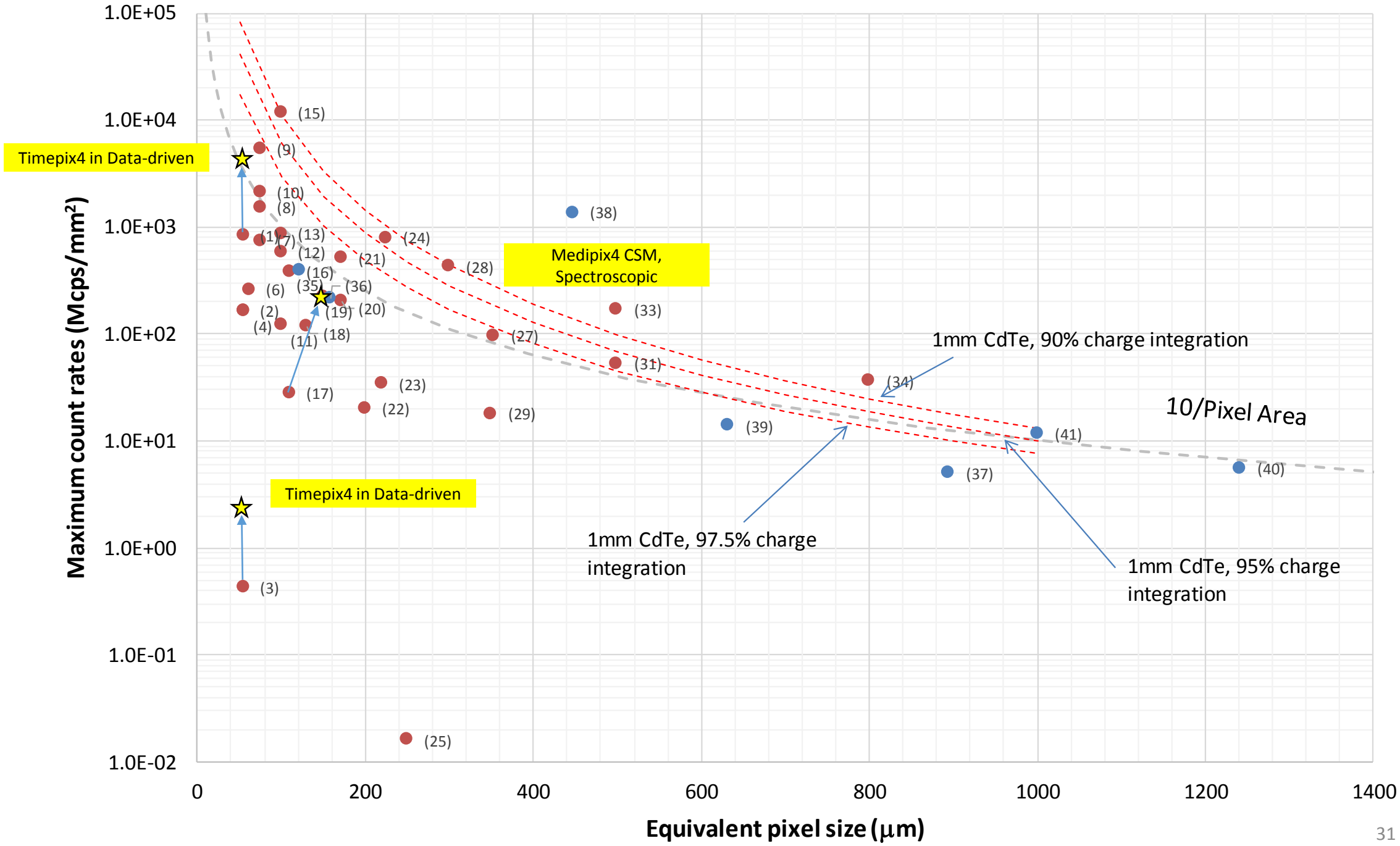
In order to do spectroscopy at fine pitches a charge reconstruction and hit allocation architecture is required.

Acknowledgements for simulations on sensor physics: D. Pennicard (DESY), L. Tlustos (CERN)


(2) Medipix3 110u (SPM)
(24) Siemens PC
(1) Medipix3 55u (SPM)
(28) Philips Chromaix1
(33) Philips Chromaix2
1mm CdTe, 90% charge integration
(2) Medipix3 55u (CSM)
10/Pixel Area
(2) Medipix3 110u (CSM)
1mm CdTe, 97.5% charge integration
1mm CdTe, 95% charge integration
(3) Timepix3
Maximum coun es (Mcps/mm²)
Equivalent pixel size (µm)
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
0
200
400
600
800
1000
1200
1400


Maximum count rates (Mcps/mm²)
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
0
200
400
600
800
1000
1200
1400
Equivalent pixel size (µm)
Timepix4 in Data-driven
Timepix4 in Data-driven
Medipix4 CSM, Spectroscopic
1mm CdTe, 90% charge integration
10/Pixel Area
1mm CdTe, 97.5% charge integration
1mm CdTe, 95% charge integration
(15)
(9)
(10)
(8)
(1)
(7)
(13)
(12)
(16)
(6)
(35)
(36)
(2)
(4)
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(11)
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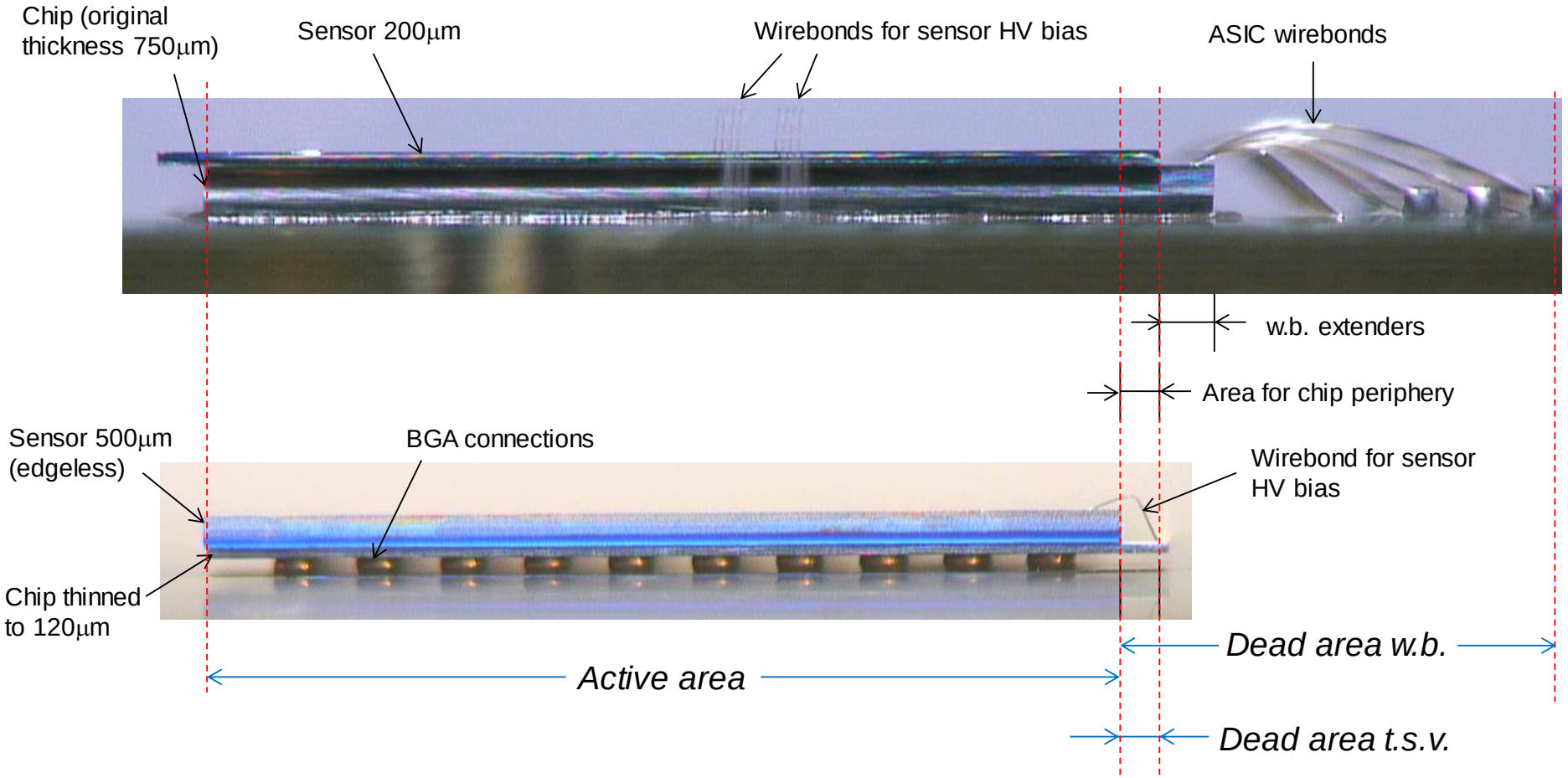
(37)
(40)
(3)

Towards Medipix4

	Medipix3	Medipix4
Technology	CMOS 130nm – 8 metal	
Pixel matrix	256 x 256 / 128 x 128	400 x 400 / 200 x 200
Pixel size	55 x 55 µm² / 110 x 110 µm²	70 x 70 µm² / 140 x 140 µm²
Matrix arrangement	3 sides buttable	4 sides buttable (TSV)
Acquisition mode	Single Pixel Mode Charge Summing Mode	
Dynamic range	25 ke^- (SLGM)	35 ke^- (150 keV with CdTe)
Maximum count rates (Si, 10% loss, Spectroscopic Mode)	SPM: 2.18 10^7 ph/mm² s CSM: 4.31 10^6 ph/mm² s **	SPM: 1.28 10^8 ph/mm² s CSM: 3.40 10^7 ph/mm² s
Energy resolution	4.4KeV (FWHM, CdTe, CSM, 60keV)	< 2.2KeV (FWHM, CdTe, CSM, 60keV)
Thresholds SPM	2/8	3/12
Thresholds CSM	1(SPM)+1(CSM) / 4(SPM)+4(CSM)	1(SPM)+2(CSM) / 4(SPM)+8(CSM)
Analog power consumption	SPM: 9 µA CSM: 13 µA	SPM: 19.5 µA CSM: 23.5 µA
Readout architecture	Frame based Continuous RW	
Minimum threshold charge	< 500e-	~ 600e^-

Through Silicon Vias on the Medipix3RX ASIC



In Timepix4 and Medipix4 the periphery dead area will be suppressed by integrating its circuitry underneath the pads.

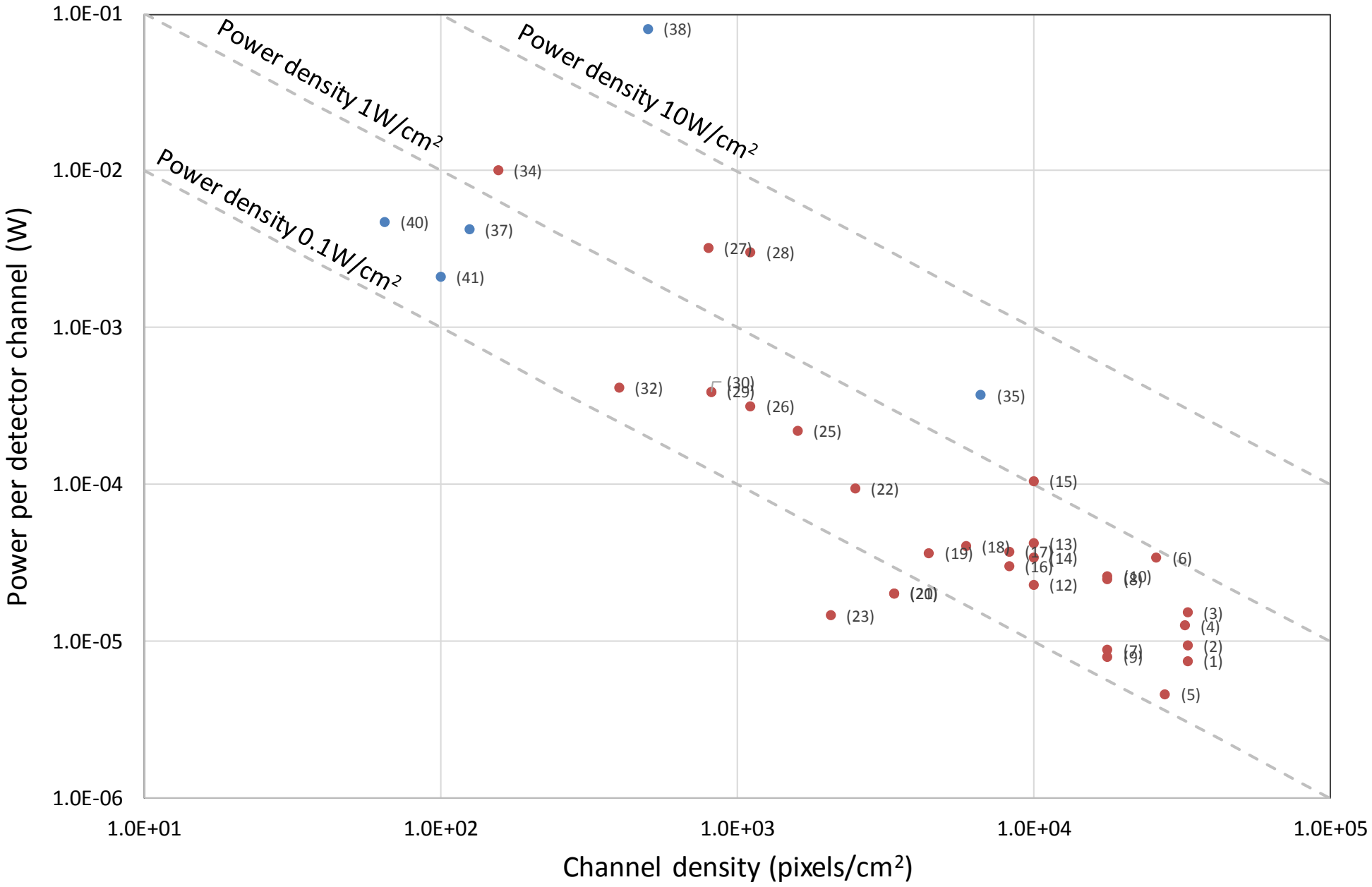
Summary and conclusions

Summary and conclusions

- Reviewed the Medipix family of counting chips
- Medipix2 was the first photon counting chip with a pixel pitch below 150um
- Its small pixel pitch motivated studies of charge sharing (diffusion/fluorescence) and circuit solutions to address their impact
- The Medipix3 chip was designed to mitigate these effects. It was the first large scale chip in 130nm CMOS in the HEP community
  - We had to invent new methods of processing the charge
  - Issues in the first version
  - Addressed in the Medipix3RX which led to a robust design
- Medipix4 is designed to read out high-Z materials allowing seamless large detection areas keeping the essence of the Medipix photon counting family of chips:

"Spectroscopic information at fine pixel pitches"

Additional slides


Power density 1W/cm²
Power density 10W/cm²
Power density 0.1W/cm²
Power per detector channel (W)
Channel density (pixels/cm²)
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E+01
1.0E+02
1.0E+03
1.0E+04
1.0E+05
(38)
(34)
(40)
(37)
(41)
(27)
(28)
(32)
(30)
(29)
(26)
(25)
(35)
(15)
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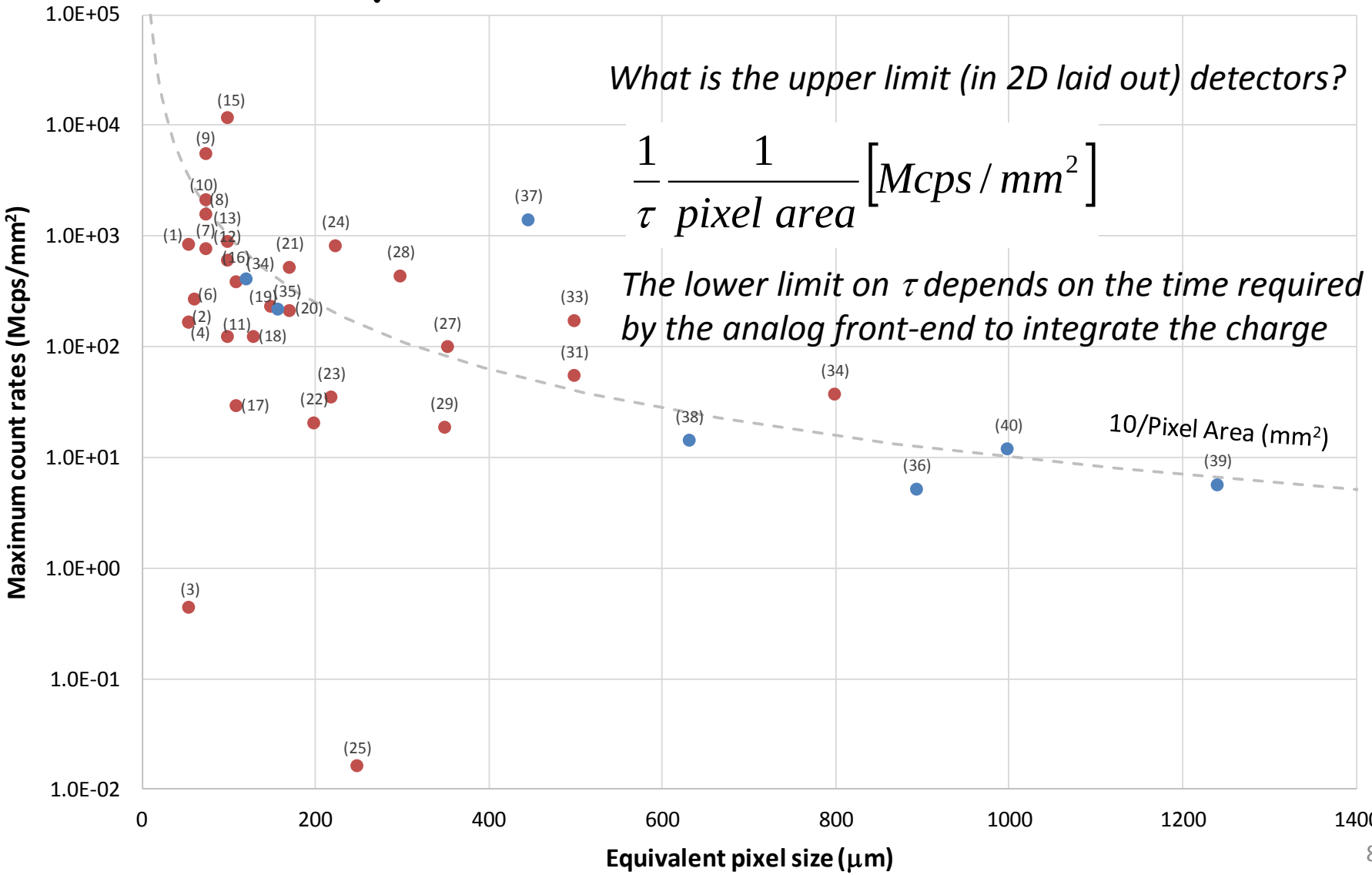
(20)
(21)
(23)
(3)
(4)
(2)
(7)
(9)
(1)
(5)

	Medipix2	Medipix3	Timepix	Timepix3
Pixel side (μm)	55	55/110	55	55
Technology (nm)	250	130	250	130
# pixels in x and y	256	256/128	256	256
Readout architecture	Frame based Sequential RW	Frame based Continuous RW	Frame based Sequential RW	Data driven/ frame based
Charge summing and allocation mode (CSM)	No	Yes	No	No
# thresholds	2 (window discriminator)	2/4/8 Seq RW 1/4 Cont RW	1	1
ToT/ToA	No	No	ToT (14 bit) OR ToA (14 bit, 10ns precision)	ToT (10 bit) AND ToA (18 bit, 1.56ns precision)
Front end noise (e^- rms)	110	80(SPM) 174(CSM)	100	62
Minimum Threshold (e^-)	900	500 (SPM) 1000 (CSM)	650	500
Peaking time (ns)	150	120	100	30
Max count rate ($Mc/mm^2/s$)* *very sensitive to exact test conditions	826	614 (SPM 55μm) 114 (CSM 55μm) 130 (SPM 110μm) 29 (CSM 110μm)	-	0.43 (data driven)

Maximum count rates (Mcps/mm^2) vs pixel size (μm)

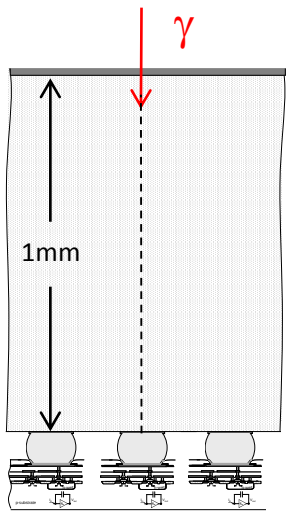


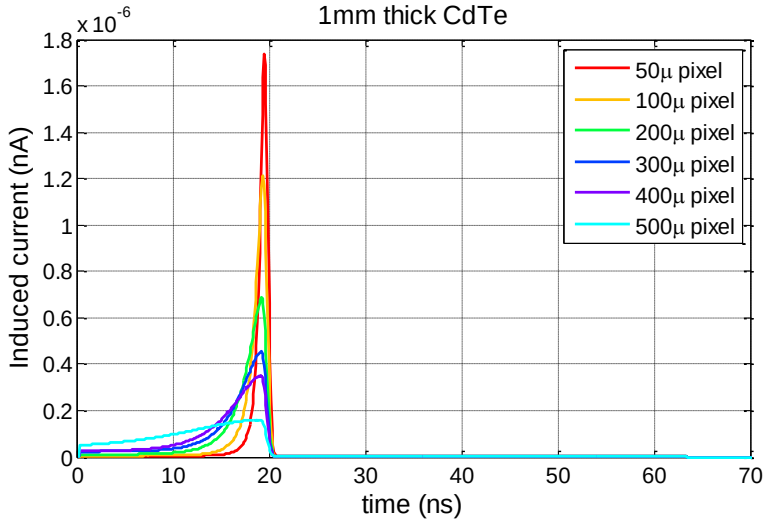
What is the upper limit (in 2D laid out) detectors?

$$\frac{1}{\tau}\frac{1}{pixel\ area}\left[Mcps/mm^2\right]$$

The lower limit on τ depends on the time required by the analog front-end to integrate the charge

Signal induction in the pixel electrodes



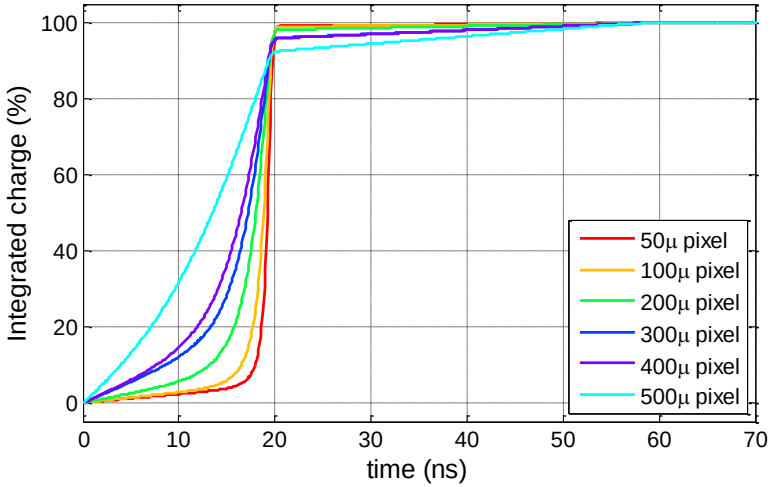


Signal shape depends on detector geometry

We calculate the maximum count-rate for a given pixel size for a given charge integration time

- 1mm CdTe
- 60keV photon
- 600V sensor bias
- Energy deposition at z=240μm

- (No charge trapping, charge sharing included in simulation)



Pixel pitch

Time to integrate a given percentage of the charge

	$t_{90\%}$	$t_{97.5\%}$
50μm	2.4ns	13.5ns
300μm	14.7ns	38.2ns

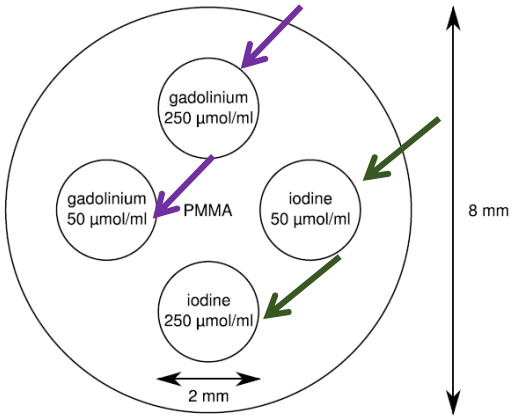
We assume $t_{X\%}=t_p$ and $\tau=2\tau_p$

$$\frac{1}{\tau}\frac{1}{pixel\ area}\left[Mcps/mm^2\right]$$

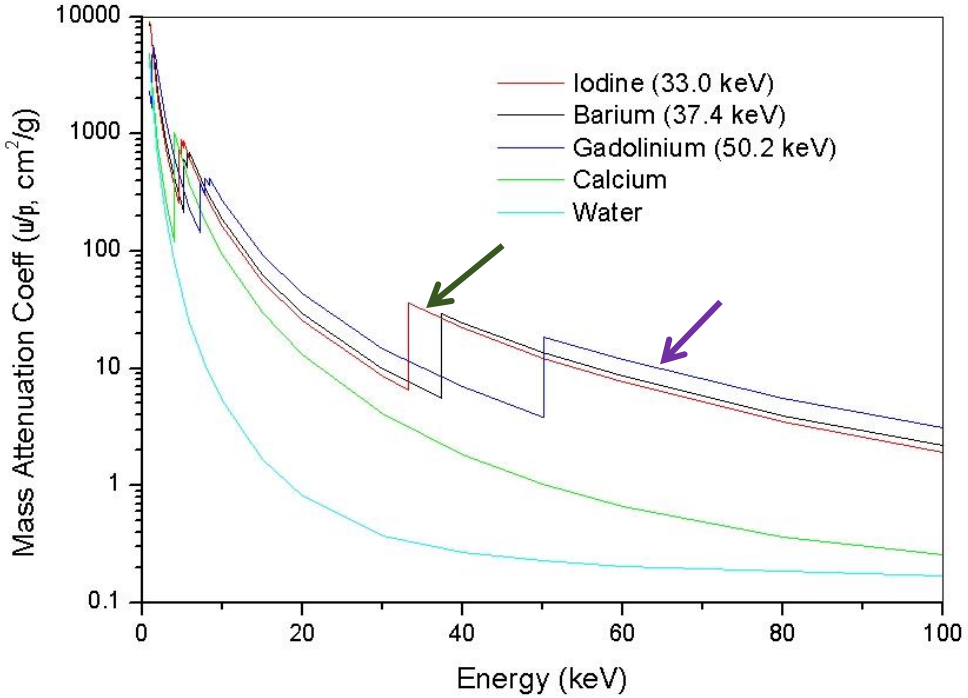
How imaging can benefit from the Medipix3 architecture:

K-edge imaging

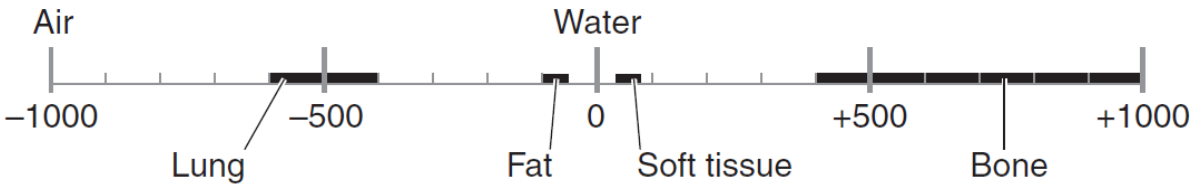
CT scan of a sample containing gadolinium and iodine



CT of a phantom
0.15s acquisition
720 projections

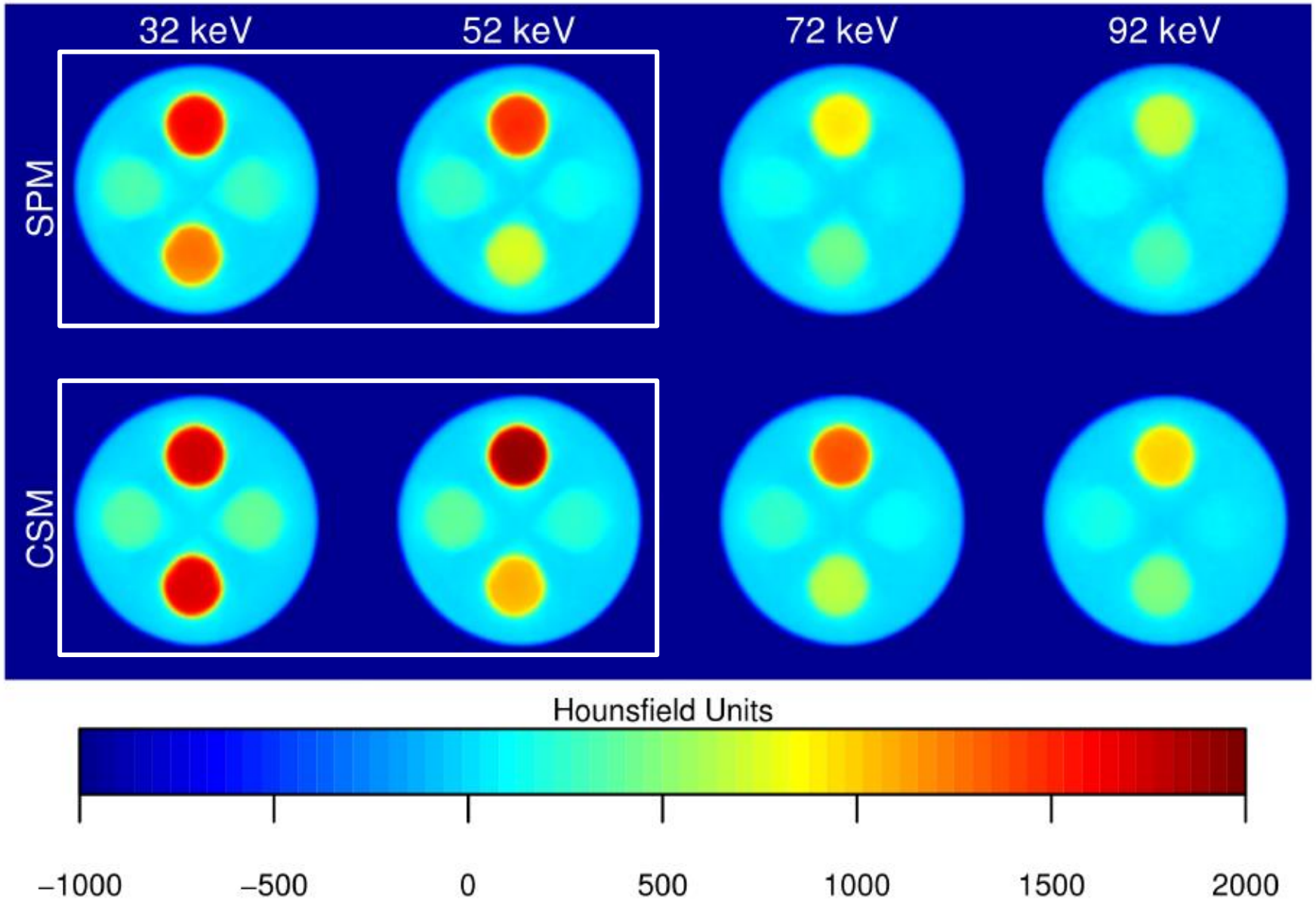


<u>Hounsfield units:</u>



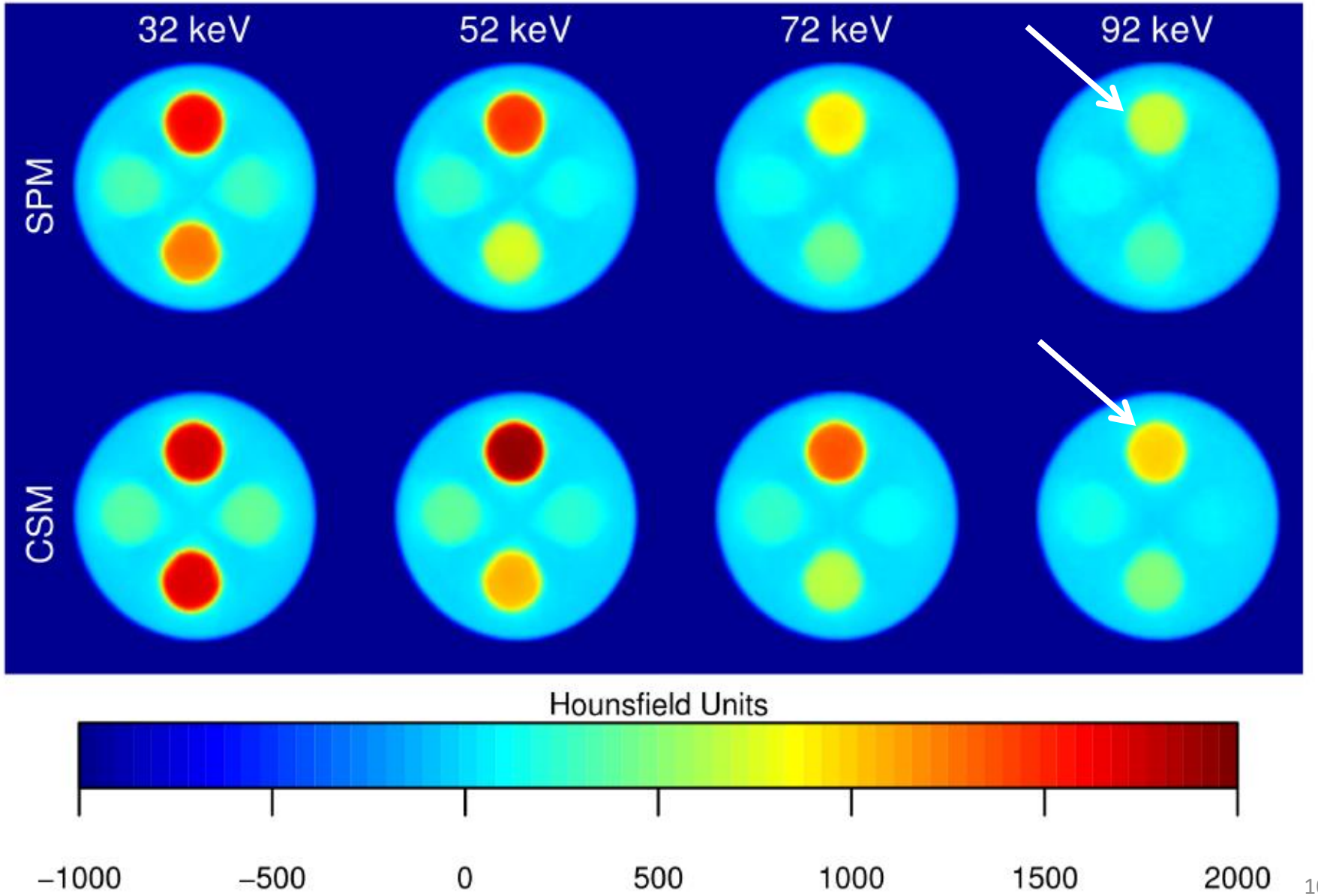
$$HU = 1000 \times \frac{\mu_X - \mu_{water}}{\mu_{water}}$$

Mass attenuation for different energies: The K-edge for gadolinium is seen in the CSM

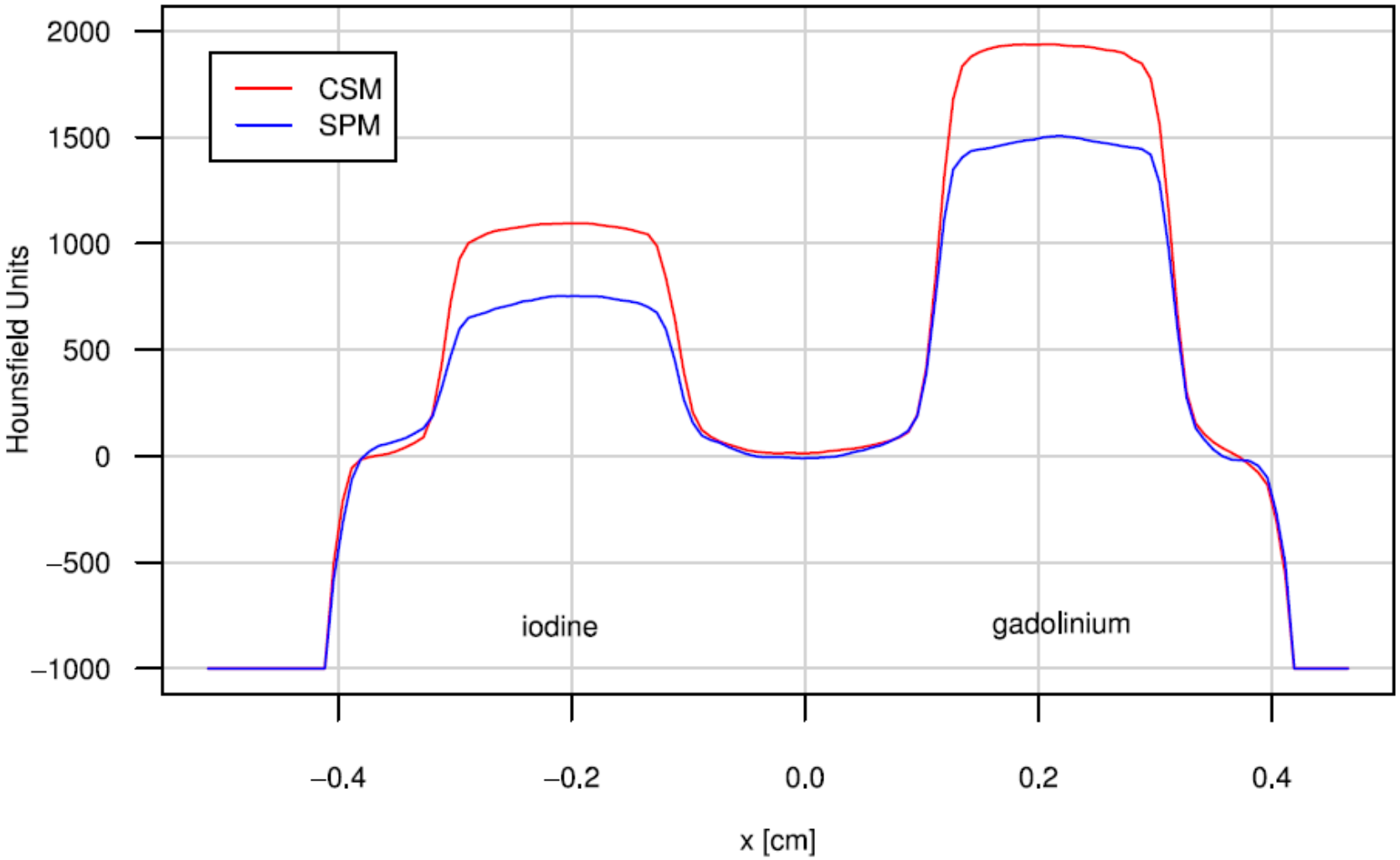


Courtesy, T. Koenig, KIT

The SNR in CSM is better for high energy photons



Courtesy, T. Koenig, KIT



Profiles through the capillaries containing 250umol/ml of Iodine and Gadolinium contrast agent (energy threshold at 52keV)
45% gain in contrast for Iodine, 30% gain in contrast for gadolinium

Fluorescence

Mean free path of fluorescence photon [μm]

Fluorescence yield [%]

Energy fluorescence photons [keV]

Z

Material	N	K_1	L_2	L_3	$K_{\alpha 1}$	$K_{\alpha 2}$	$d_{\alpha 1}$	$d_{\alpha 2}$	$\eta[\%]$
Si	14	1.84	0.10	0.10	1.74	1.74	11.86	11.86	4.1
GaAs									
Ga, 48.20%	31	10.36	1.14	1.11	9.25	9.22	40.62	40.28	50.5
As, 51.80%	33	11.87	1.36	1.32	10.54	10.50	15.62	15.47	56.6
CdTe									
Cd, 46.84%	48	26.71	3.73	3.53	23.17	22.98	113.20	110.75	83.6
Te, 53.16%	52	31.81	4.61	4.34	27.47	27.20	59.32	57.85	87.3

The fluorescence yield increases with the atomic number
The mean free path of the fluorescence photons is in the same order of magnitude as the pixel pitch
Implications: degradation of the energy measurement, blur the image

Table: L. Tlustos, PhD thesis

Table 1
A summary of the main features of the chips in the Medipix and Timepix family.

	Medipix	Medipix2	Timepix	Medipix3	Timepix3
Pixel side (μm)	170	55	55	55/110	55
Technology (nm)	1000	250	250	130	130
# pixels in x and y	64	256	256	256/128	256
Readout architecture	Frame based Sequential RW	Frame based Sequential RW	Frame based Sequential RW	Frame based Continuous RW	Data driven/frame based
Charge summing and allocation mode (CSM)	No	No	No	Yes	No
# thresholds	1	2 (window discriminator)	1	2/4 Seq RW 1/4 Cont RW	1
ToT/ToA	No	No	ToT (14 bit) OR ToA (14 bit, 10 ns precision)	No	ToT (10 bit) AND ToA (18 bit, 1.56 ns precision)
Front end noise (e^- rms)	170	110	100	80(SPM) 174(CSM)	62
Peaking time (ns)	100	150	100	120	30
Max count rate (Mc/mm^2/s)[a]	–	826	–	826 (SPM 55 μm) 164 (CSM 55 μm) 376 (SPM 110 μm) 28 (CSM 110 μm)	0.43 (data driven)
Number of sides available for tiling	0	3	3	3	3

[a] Depends strongly on exact conditions of threshold, sensor material and energy of illumination.