A Circuit Topology Suitable for the Readout of Ultra Thin Pixel Detectors at the SLHC and elsewhere

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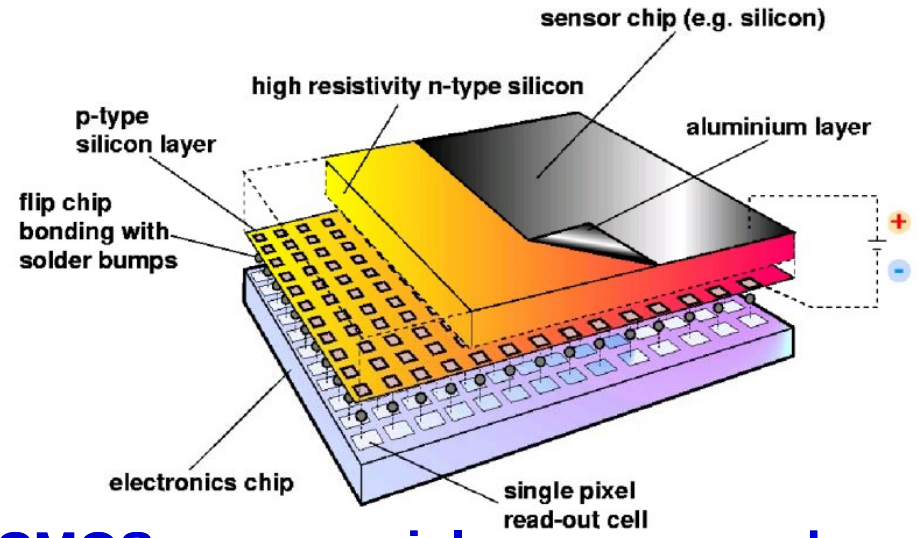
TWEPP 2007, Prague

Outline

- Why hybrid pixels?
- Performance and limitations
  - The example of Medipix2
- Improving spectral resolution for X-ray imaging
  - The charge summing and allocation architecture (Medipix3)
- Vertex tracking in thin detectors
- Design study of new architecture for SLHC
- Summary and conclusions

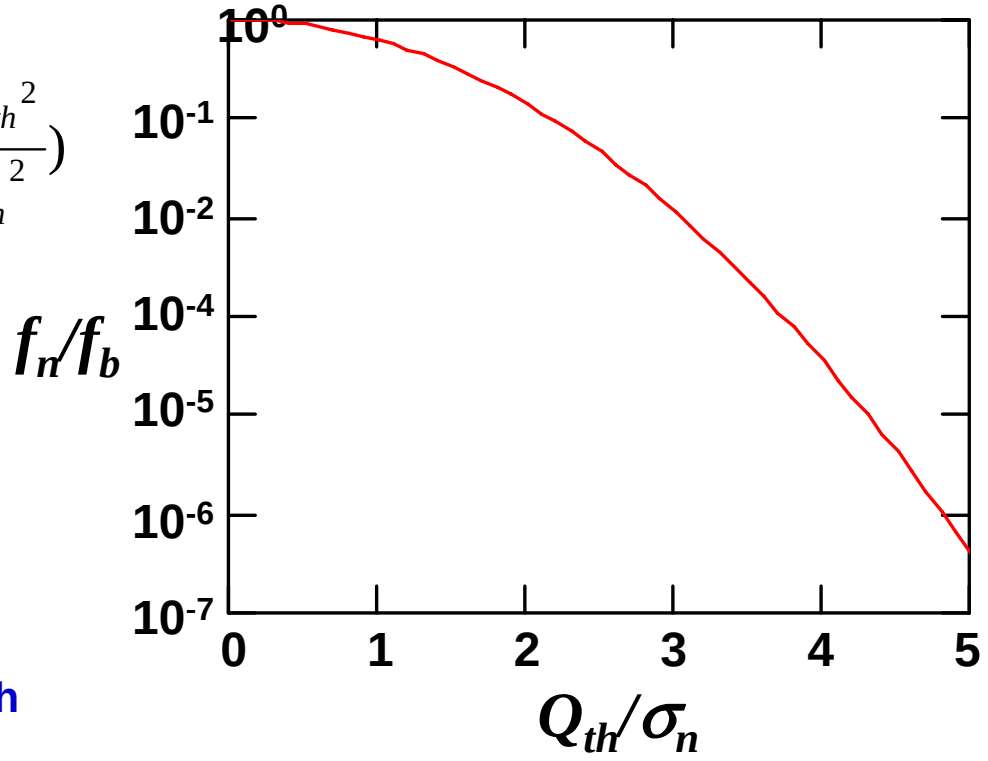
Why hybrid pixels?



- Any CMOS commercial process can be used
- The detector can be optimised for application
  - thin EPI or 3D Si for SLHC
  - Diamond
  - GaAs for mammography etc..
  - Gas….
- Sensor is usually fully depleted – prompt charge collection
- Optimal signal to noise at high rates – essential for clean pattern recognition….

Noise hit rate for a discriminator

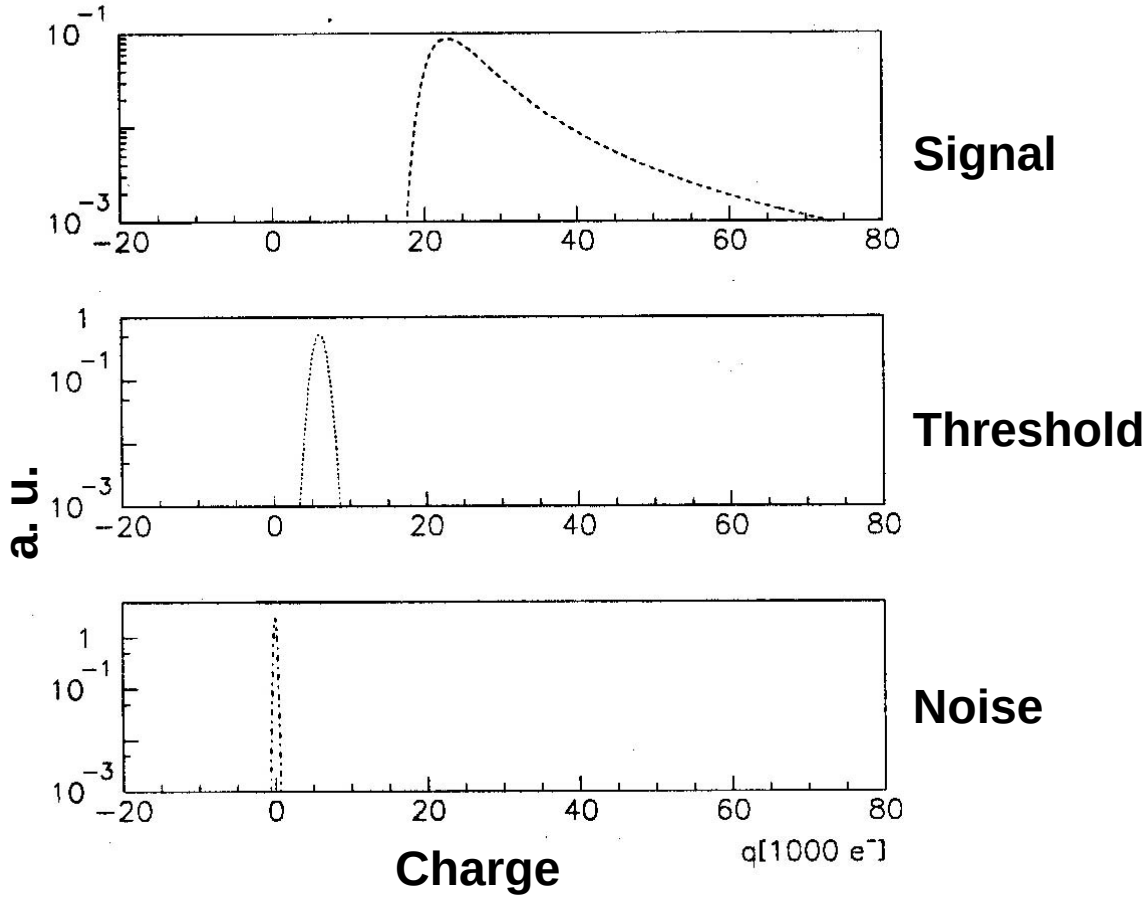
$$f_n = \frac{1}{\sqrt{3}} f_b \exp\left(\frac{-Q_{th}^{\,2}}{2\sigma_n^{\,2}}\right)$$



f_n = noise hit rate
f_b = system bandwidth
Q_{th} = threshold
σ_n = noise

In a large bandwidth system (such as an HEP experiment) noise and threshold variation must be kept very far from the threshold to produce clean event information.

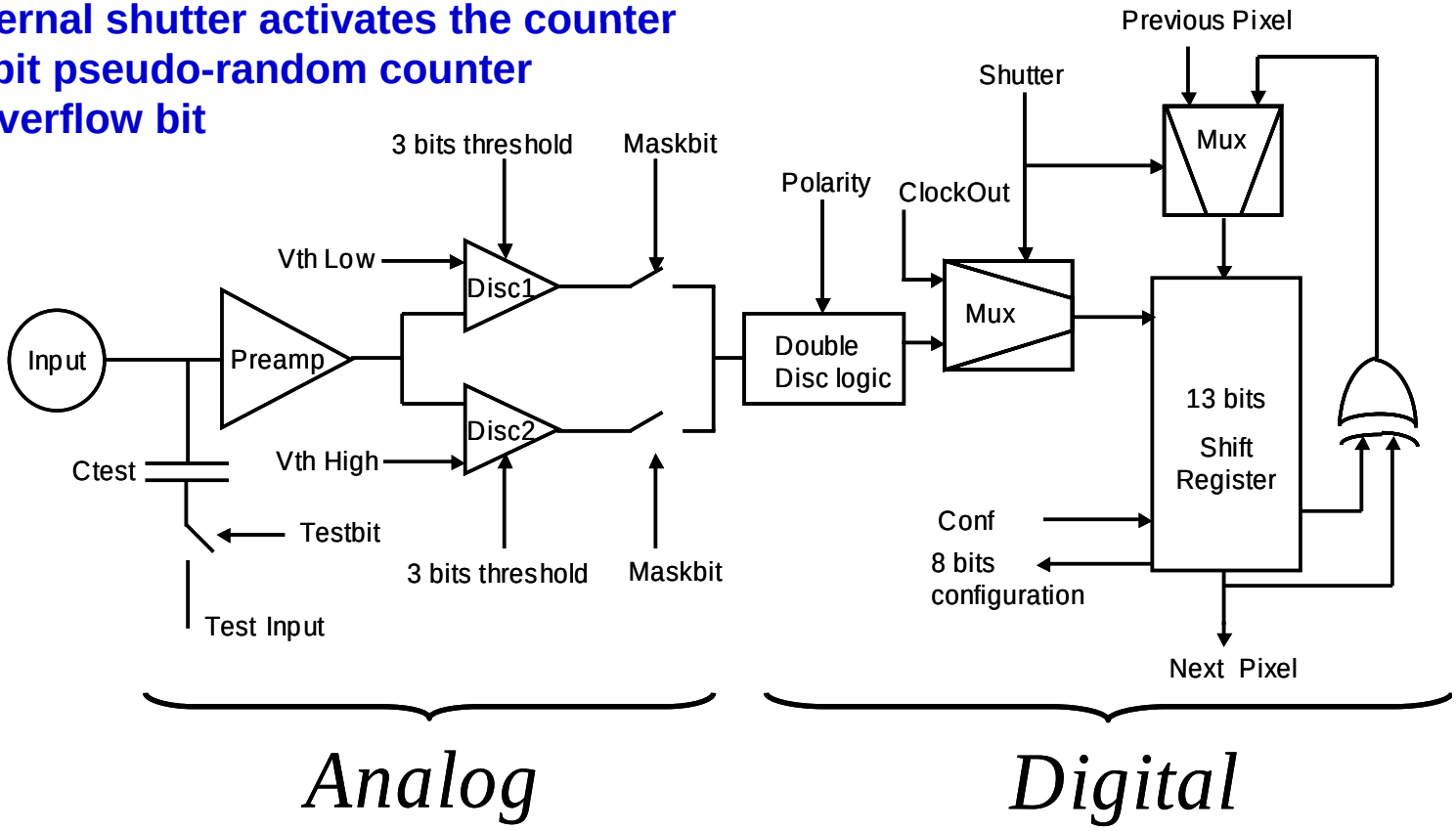
Signal, Threshold, Noise



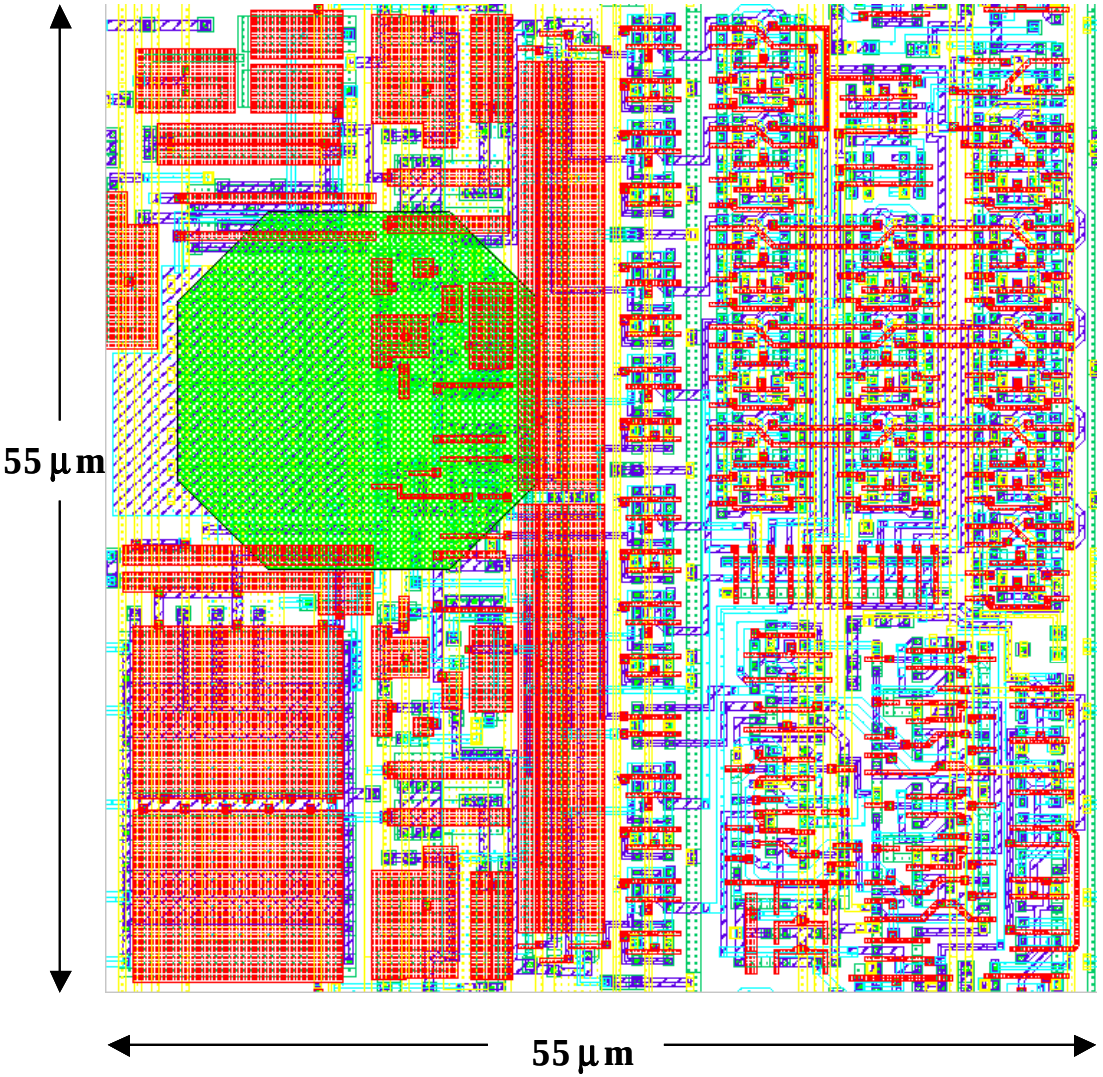
A good separation of signal, threshold and noise is achieved with hybrid pixels.
However, this argument does not take charge sharing into account…

Medipix2 Cell Schematic

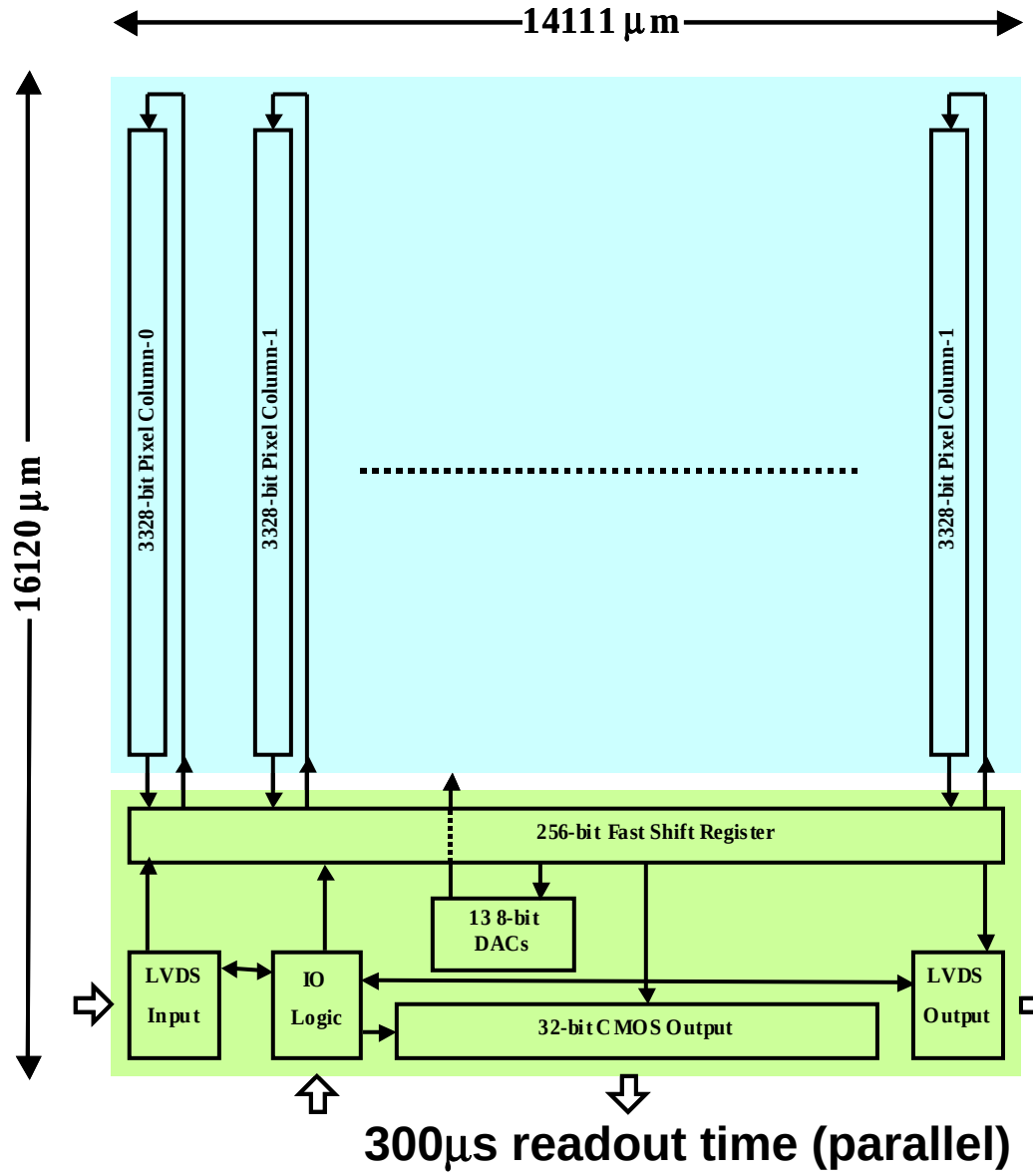
Charge sensitive preamplifier with individual leakage current compensation
2 discriminators with globally adjustable threshold
3-bit local fine tuning of the threshold per discriminator
1 test and1 mask bit
External shutter activates the counter
13-bit pseudo-random counter
1 Overflow bit



Medipix2 Cell Layout



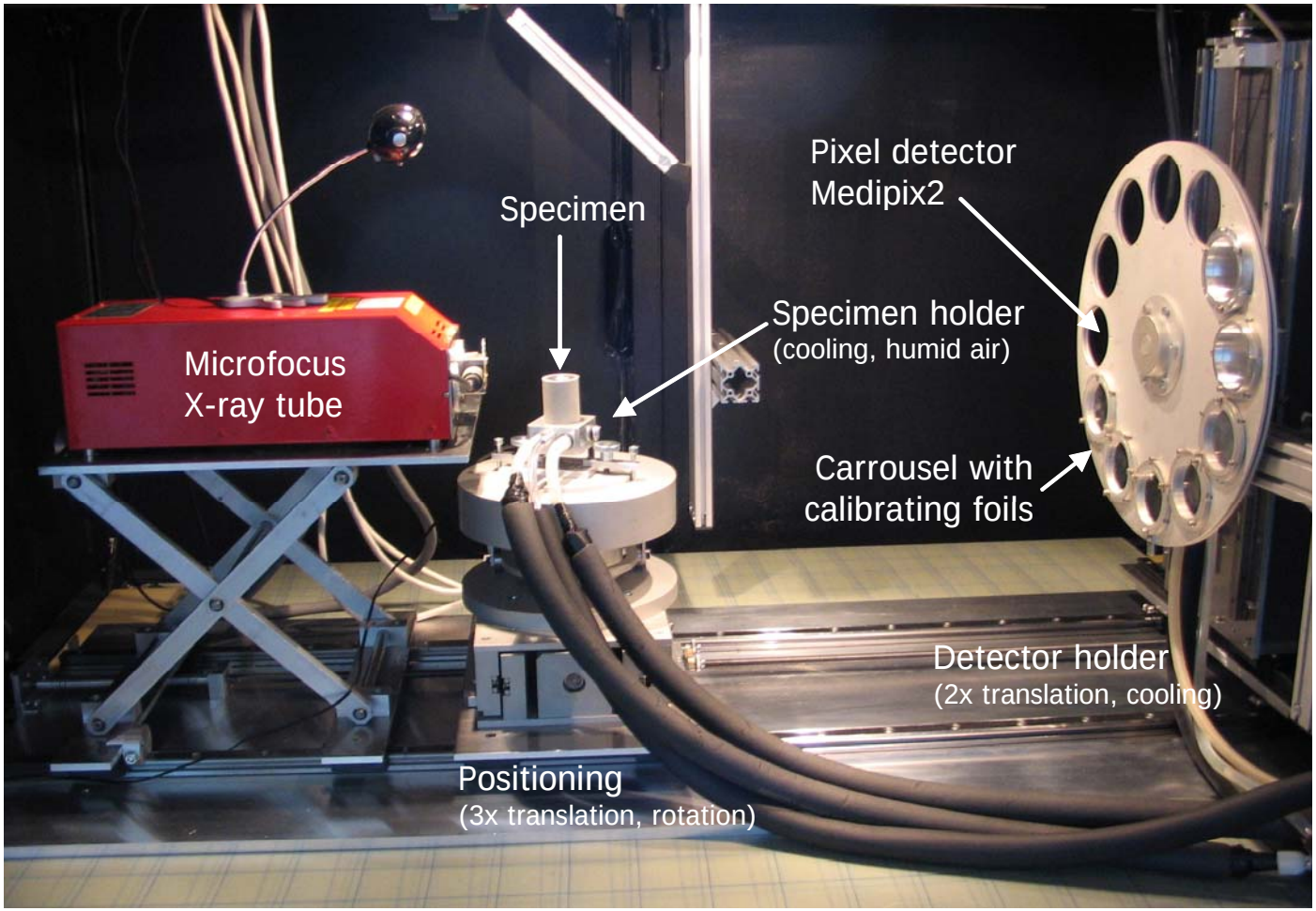
Medipix2 Chip Architecture



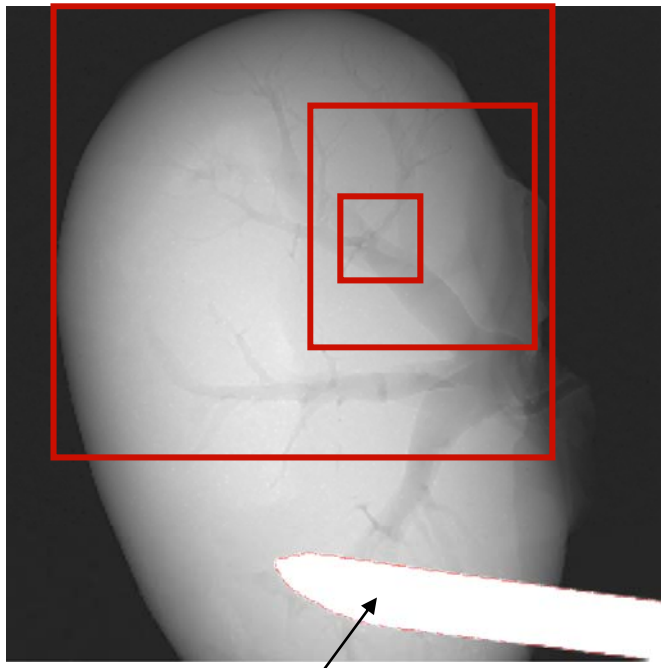
256 x 256 pixels

10ms readout time (serial)

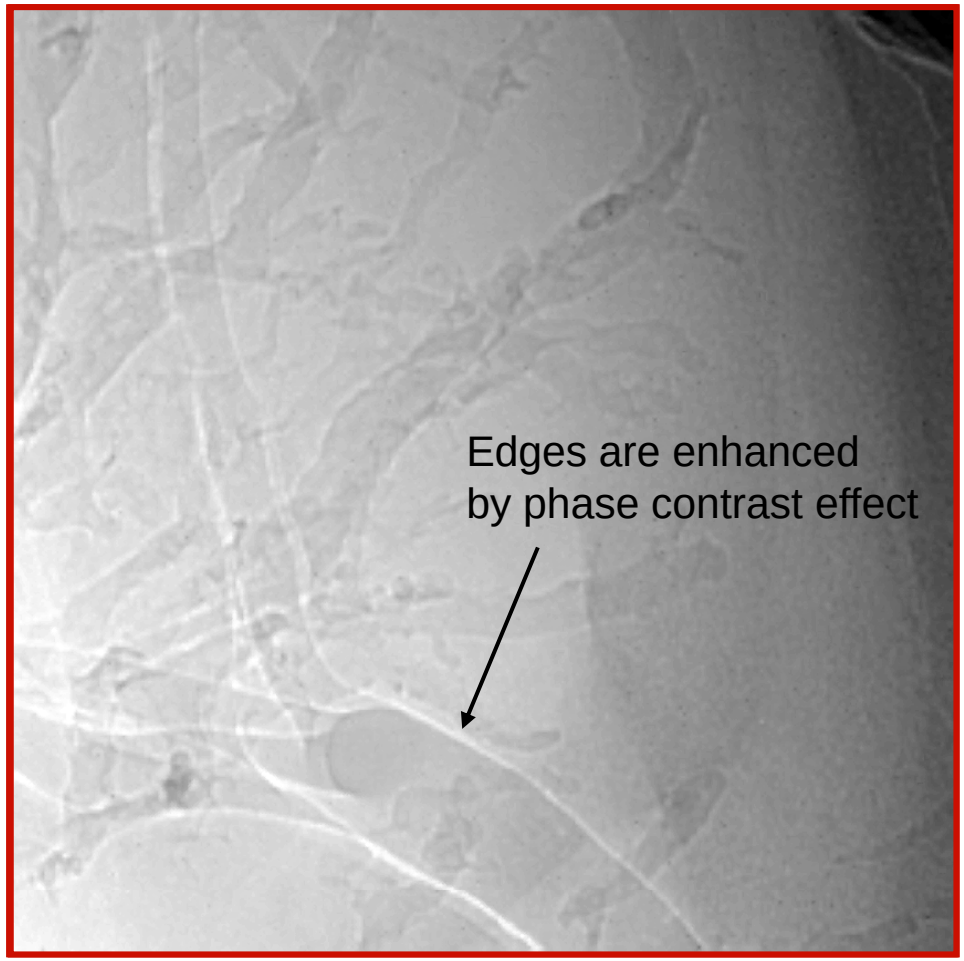
High resolution X-ray imaging using a micro-focus X-ray source(1)



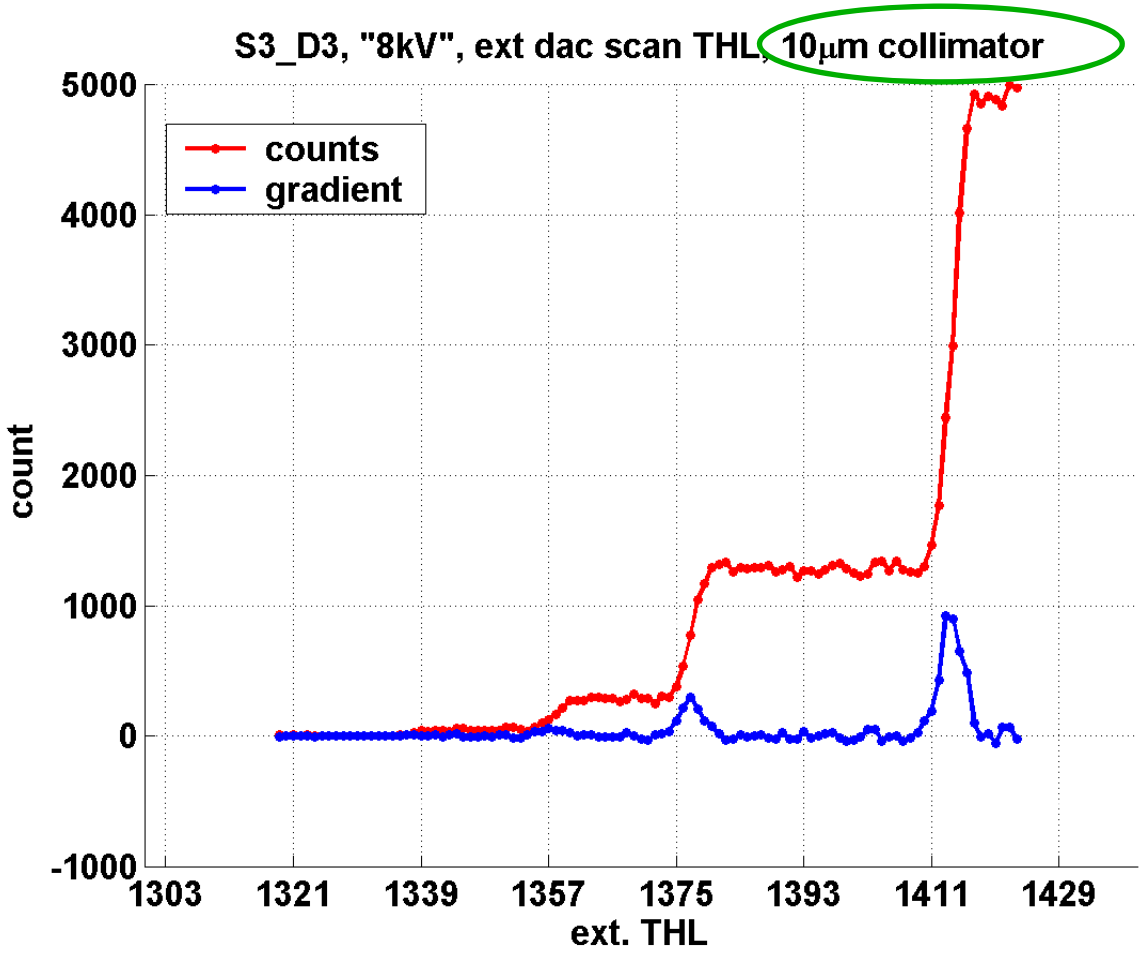
High resolution X-ray imaging using a micro-focus X-ray source(2)



Needle holding the sample



Calibration at ESRF – monochromatic pencil beam at pixel centre



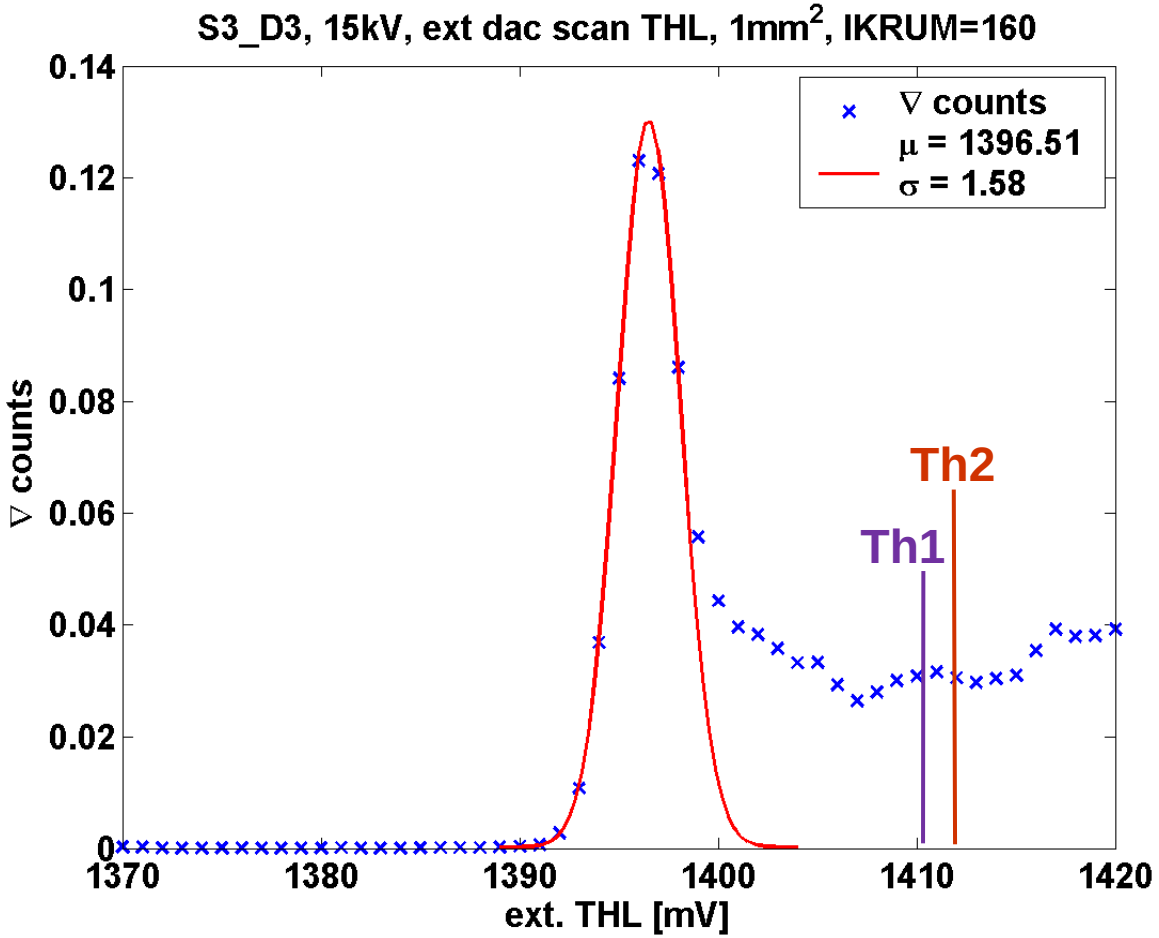
Increasing threshold

8kev plus harmonics….

Effect of Charge Sharing on Energy Resolution – monochromatic 1mm^2 beam

Increasing threshold

Effect of Charge Sharing on Energy Resolution – monochromatic 1mm^2 beam



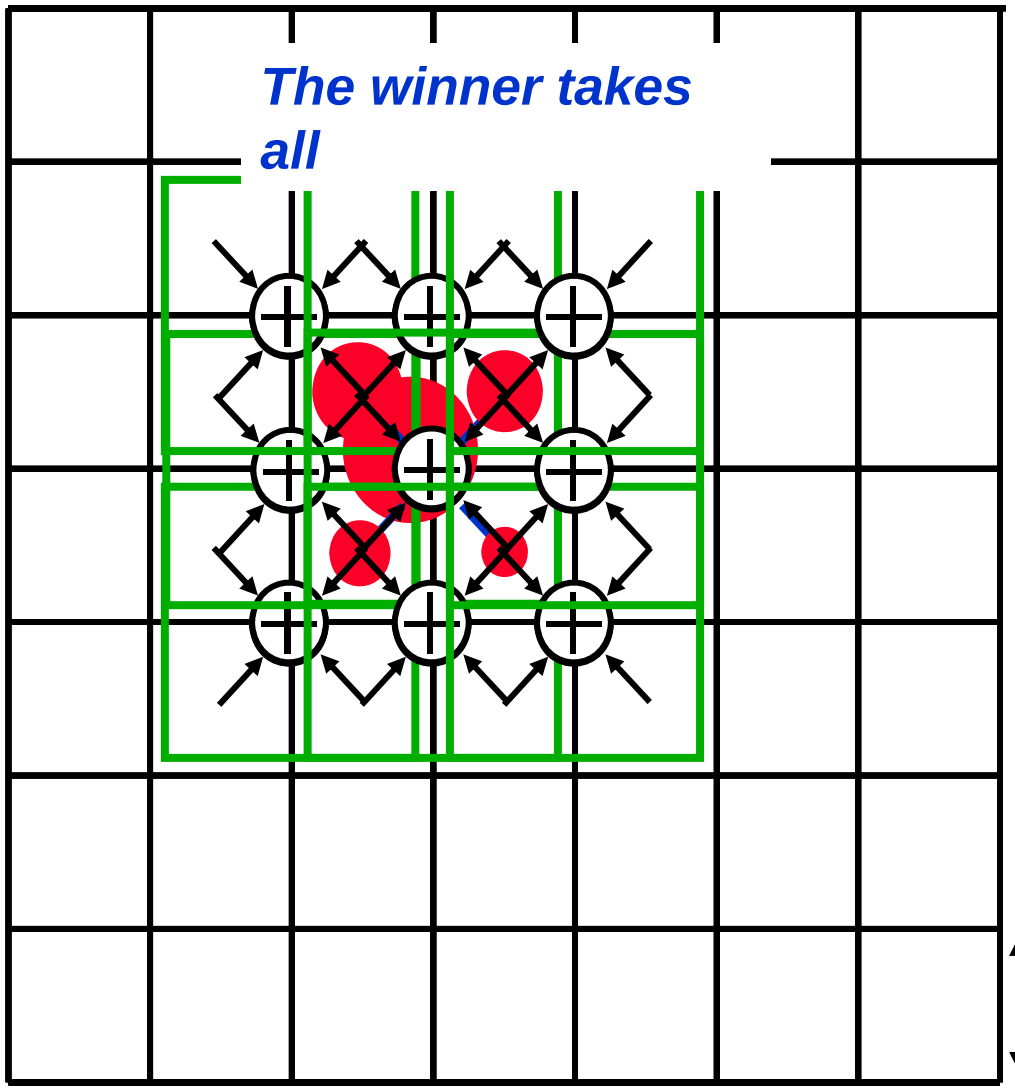
Increasing threshold

Performance and limitations of Medipix2 as an X-ray sensor

- **Single photon counting provides excellent noise free images**
- **Ideal in photon starved situations**

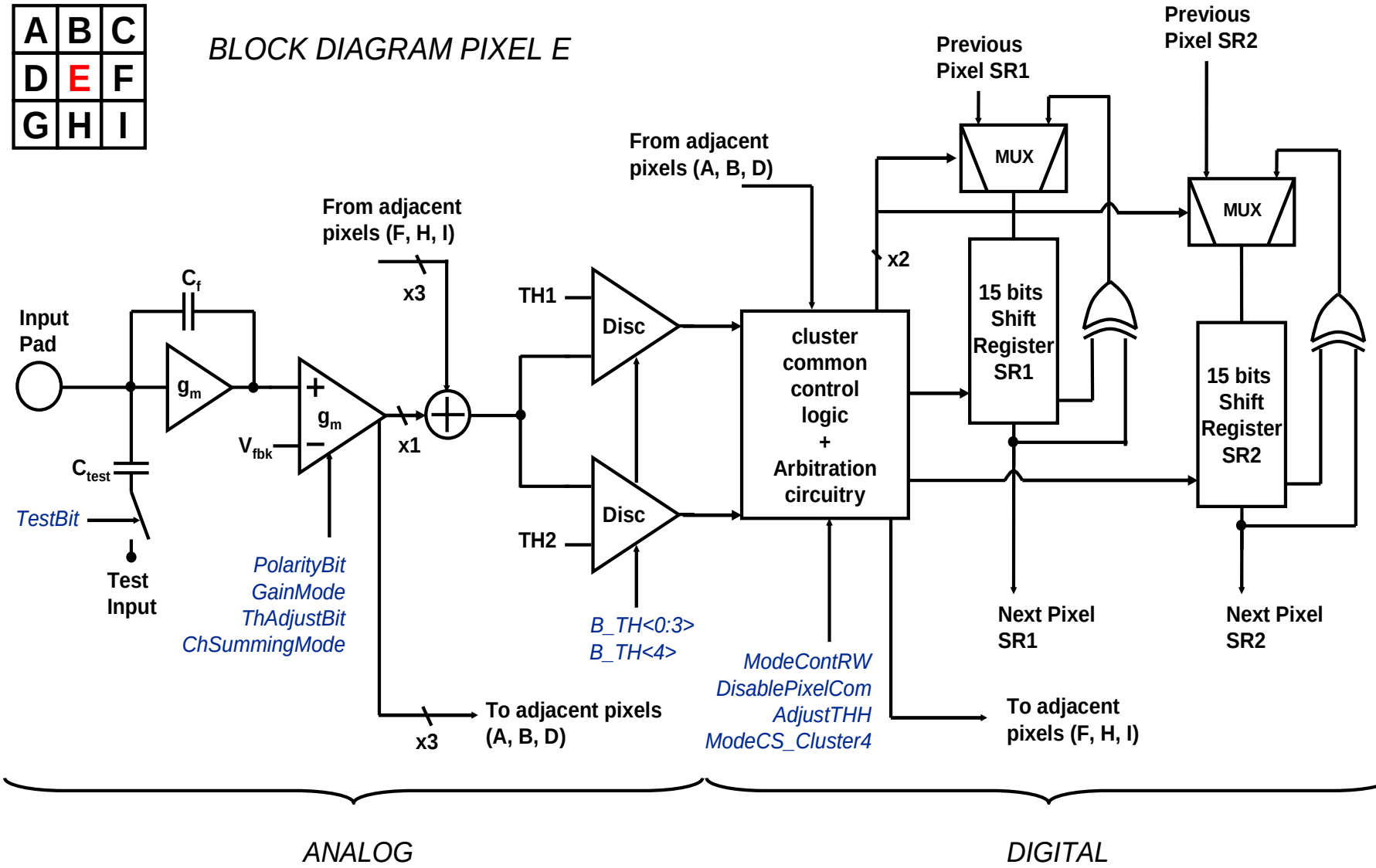
- **However, charge sharing in the sensor is an issue:**
  - **Flat field correction is sensitive to incoming spectrum**
  - **Energy resolution is limited by charge sharing tail**

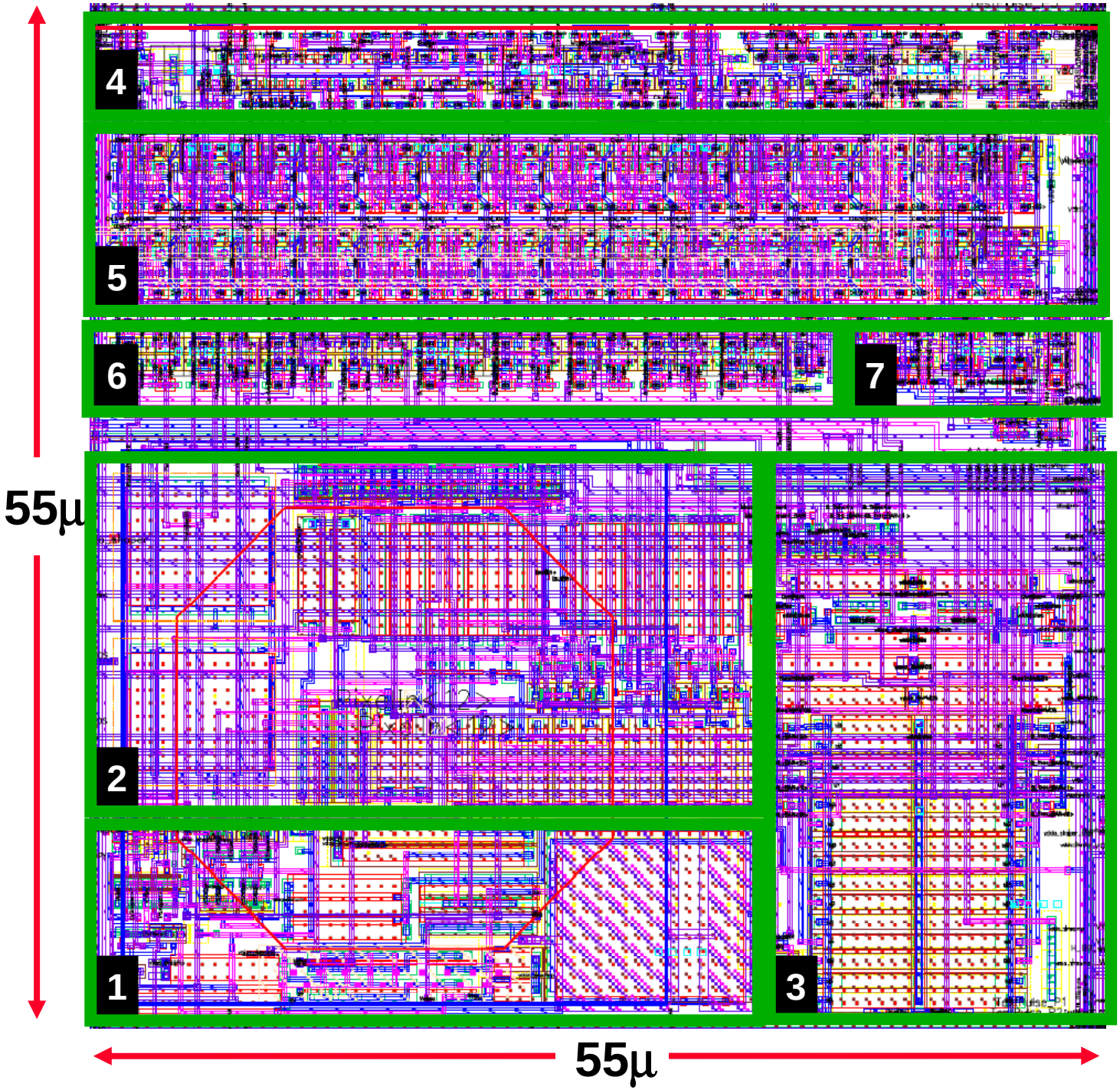
Medipix3 – charge summing concept



- *The incoming charge processed is summed in every 4 pixel cluster on an event-by-event basis*

Medipix3 – pixel block diagram





DIGITAL CIRCUITRY

4. Control logic (124)
5. 2x15bit counters / shift registers (480)
6. Configuration latches (152)
7. Arbitration circuits (100)

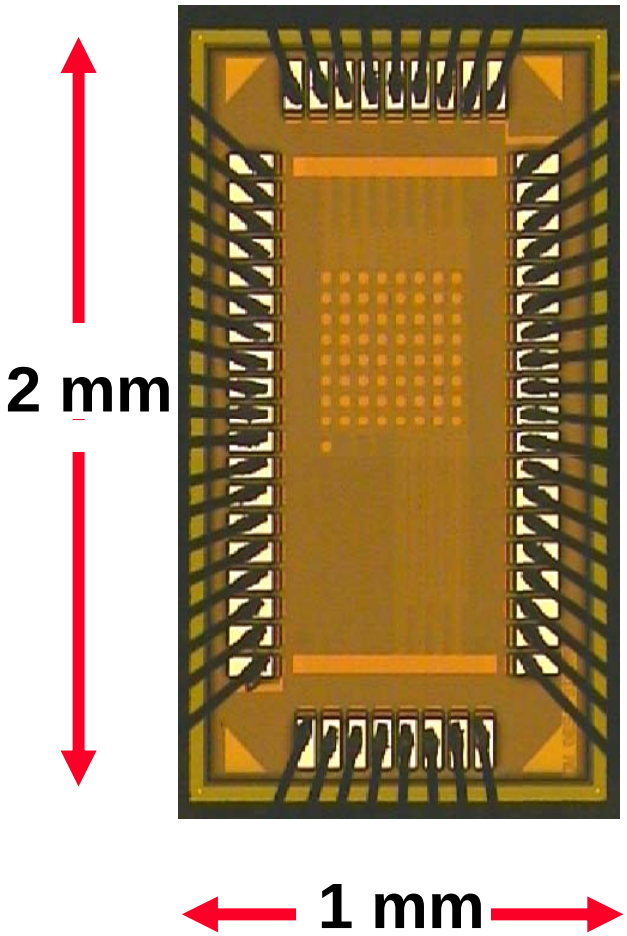
Total digital 856

ANALOG CIRCUITRY

1. Preamplifier (24)
2. Shaper (134)
3. Discriminators and Threshold Adjustment Circuits (72)

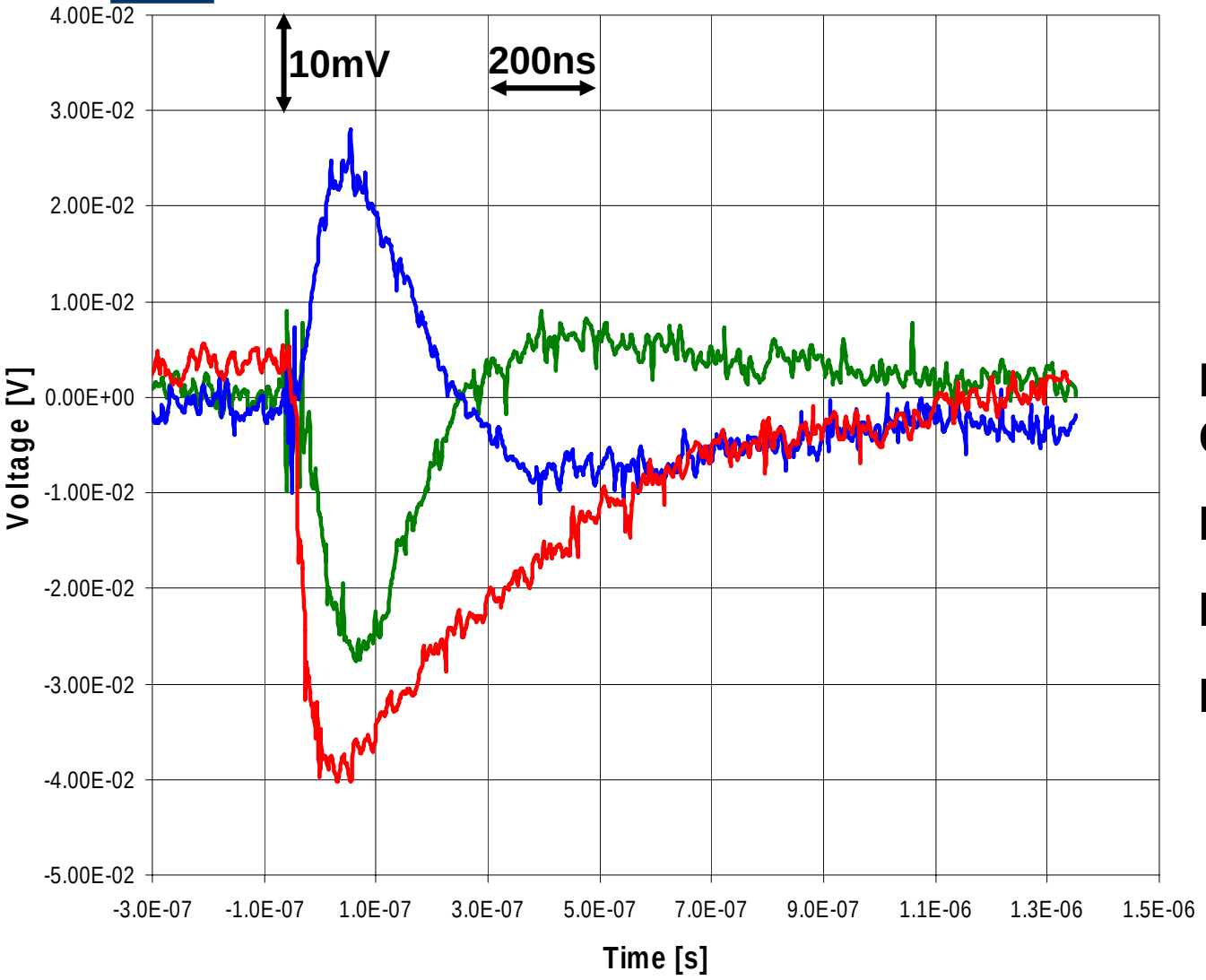
Total analog 230

The Medipix3 prototype chip



- 0.13μm technology
- 8 metal layers
- 8x8 pixel matrix

Pre-amp and shaper measurements



Response to a 3.71 Ke- input charge

Nominal Conditions

I_{CSA}=2μA

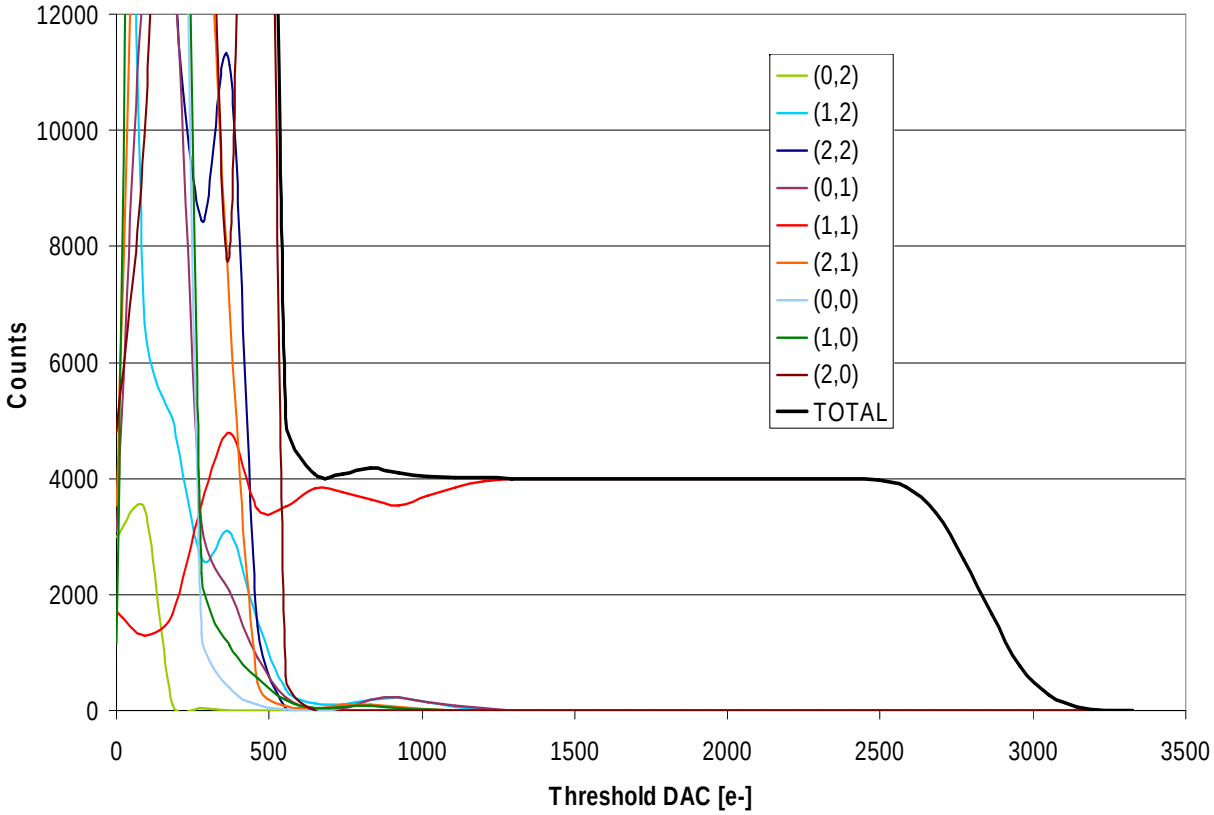
I_{RESET}=2.5nA

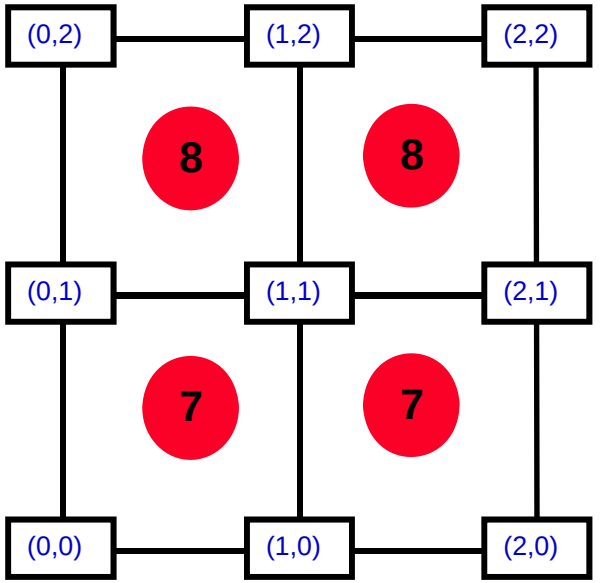
I_{SHAPER}=500nA

Medipix3 – charge summing measurements

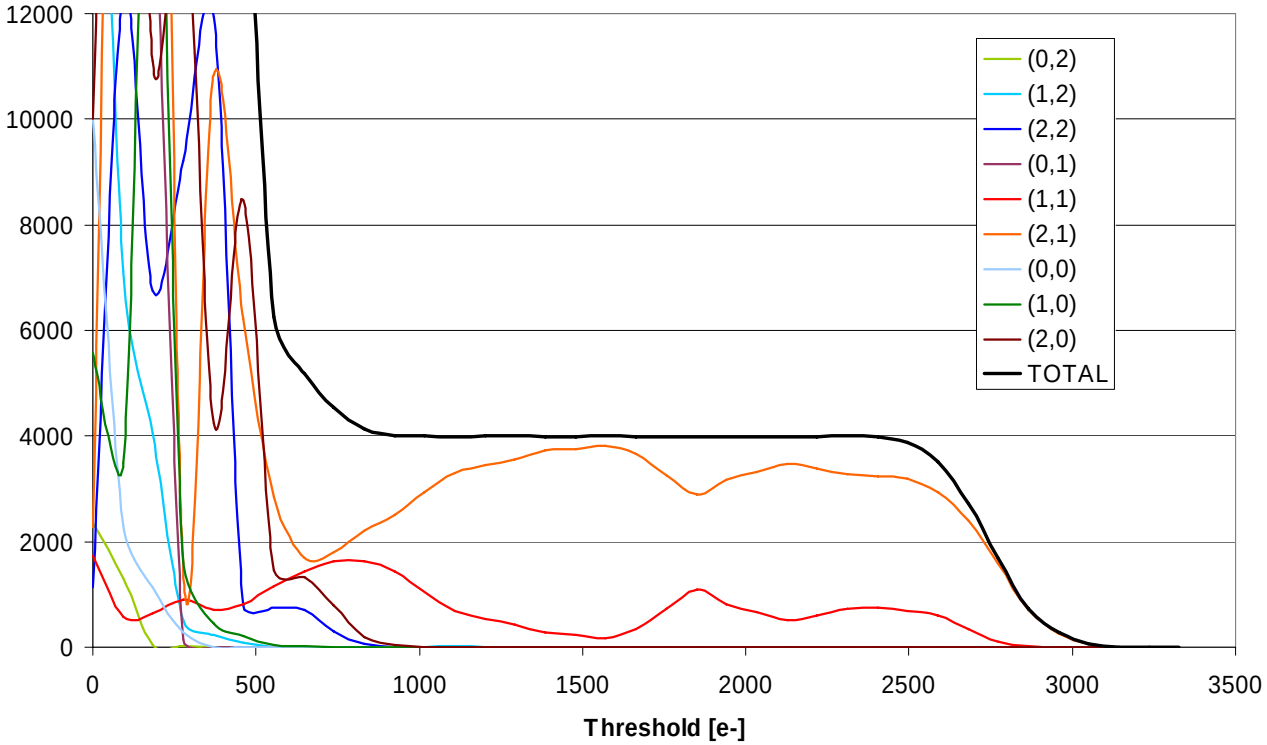
Input charge: 2.78Ke-
(30 DAC pulses)

4000 pulses





Medipix3 – charge summing measurements



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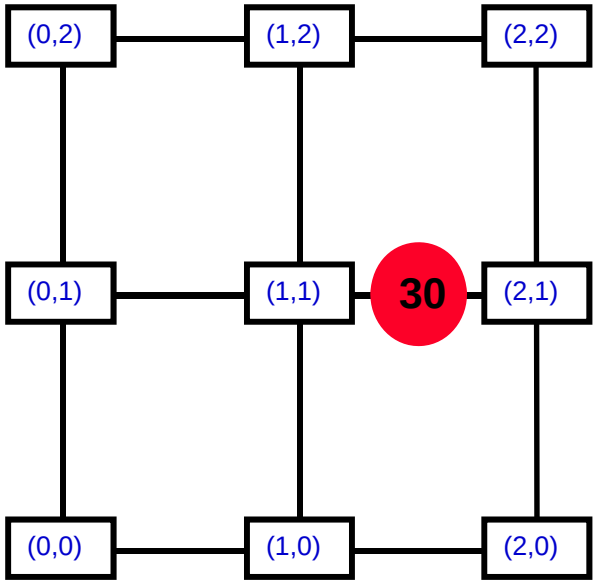

Medipix3 – charge summing measurements

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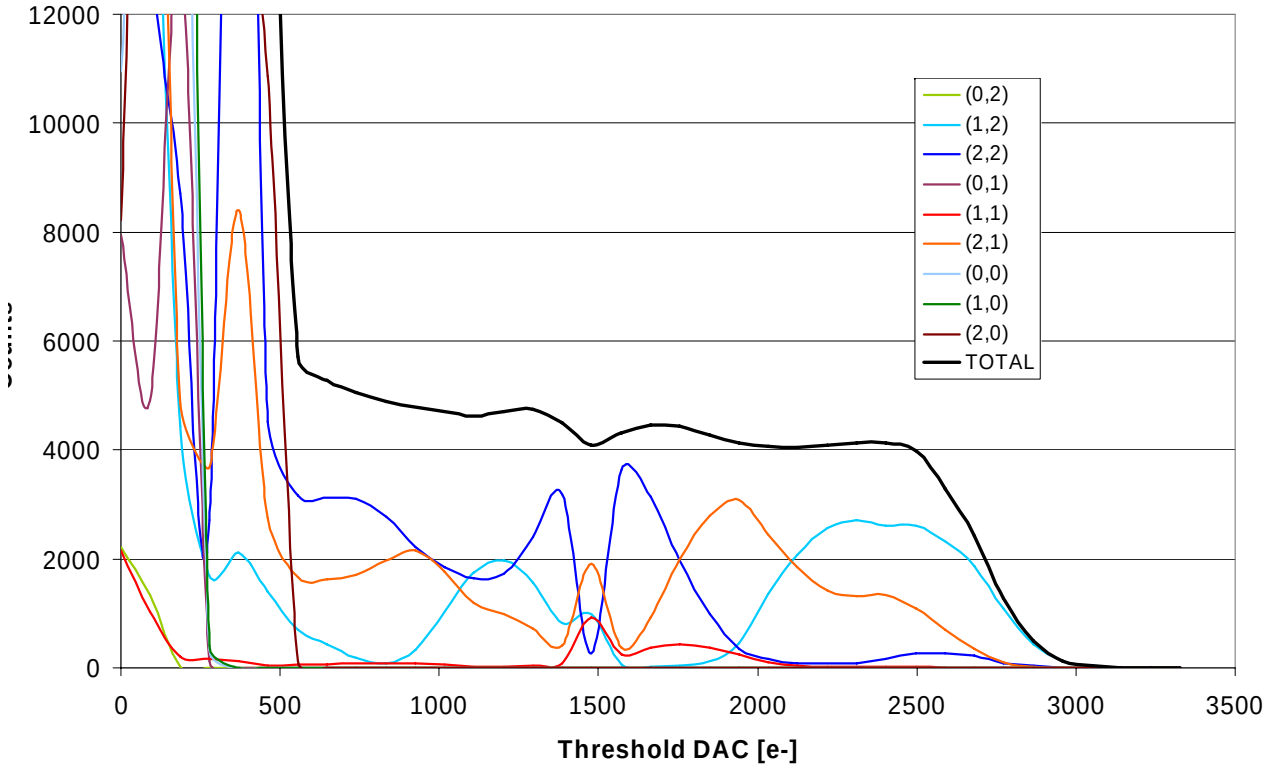
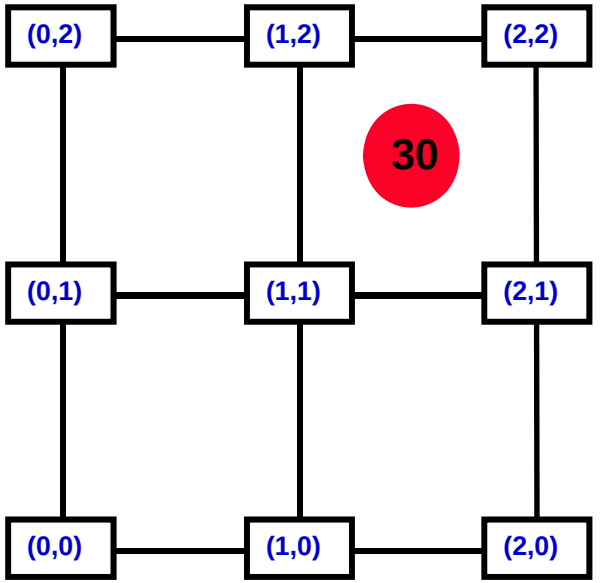


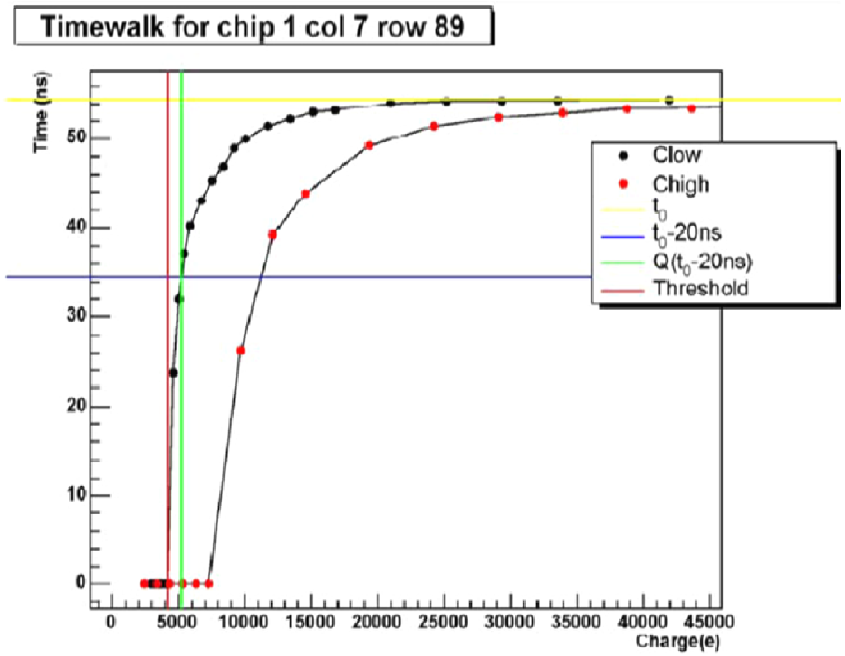


Medipix3 – electrical measurements summary

Front End Operating Mode	Single Pixel Mode	Charge Summing Mode
CSA Gain (C_F)	11.4mV/Ke- (C_F=14fF)	
CSA-Shaper Gain	65nA/Ke- (High Gain Mode), 30nA/Ke- (Low Gain Mode)	
Non linearity	<5% 9Ke- (High Gain Mode) , <2% 22Ke- (Low Gain Mode)	
Peaking Time	~100ns	
Return to baseline	<1μs for 4Ke- (nominal conditions), <300ns (tuning R_F)	
Electronic noise	72e^- r.m.s.	144e^- r.m.s.
Analog power dissipation	16.2μW (nominal conditions)	

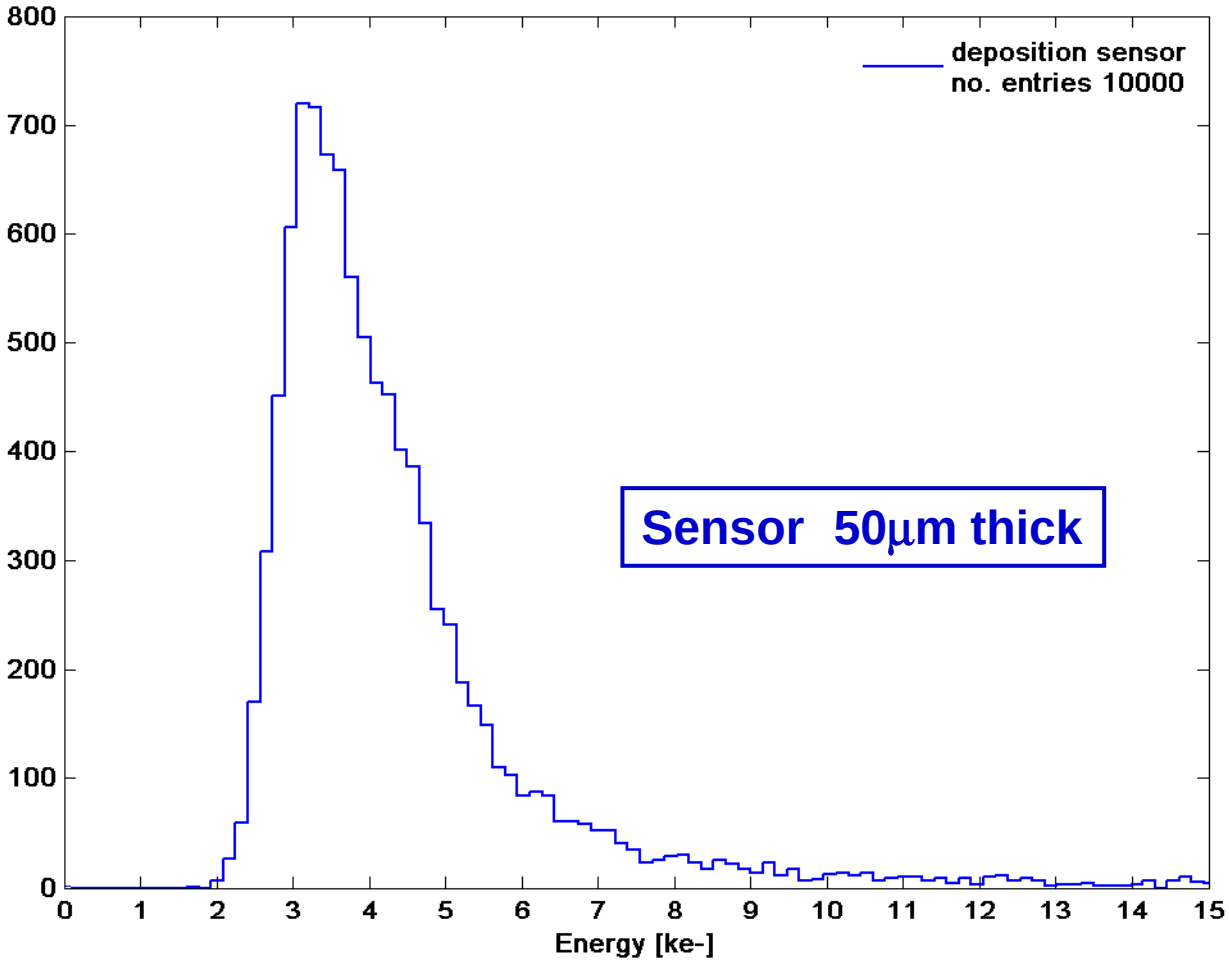
How about tracking at SLHC?

- Thin sensors desirable – less mass better spatial resolution
  - Low thresholds
- Clean readout still essential
  - Good separation threshold-noise
- Time walk can be an issue:



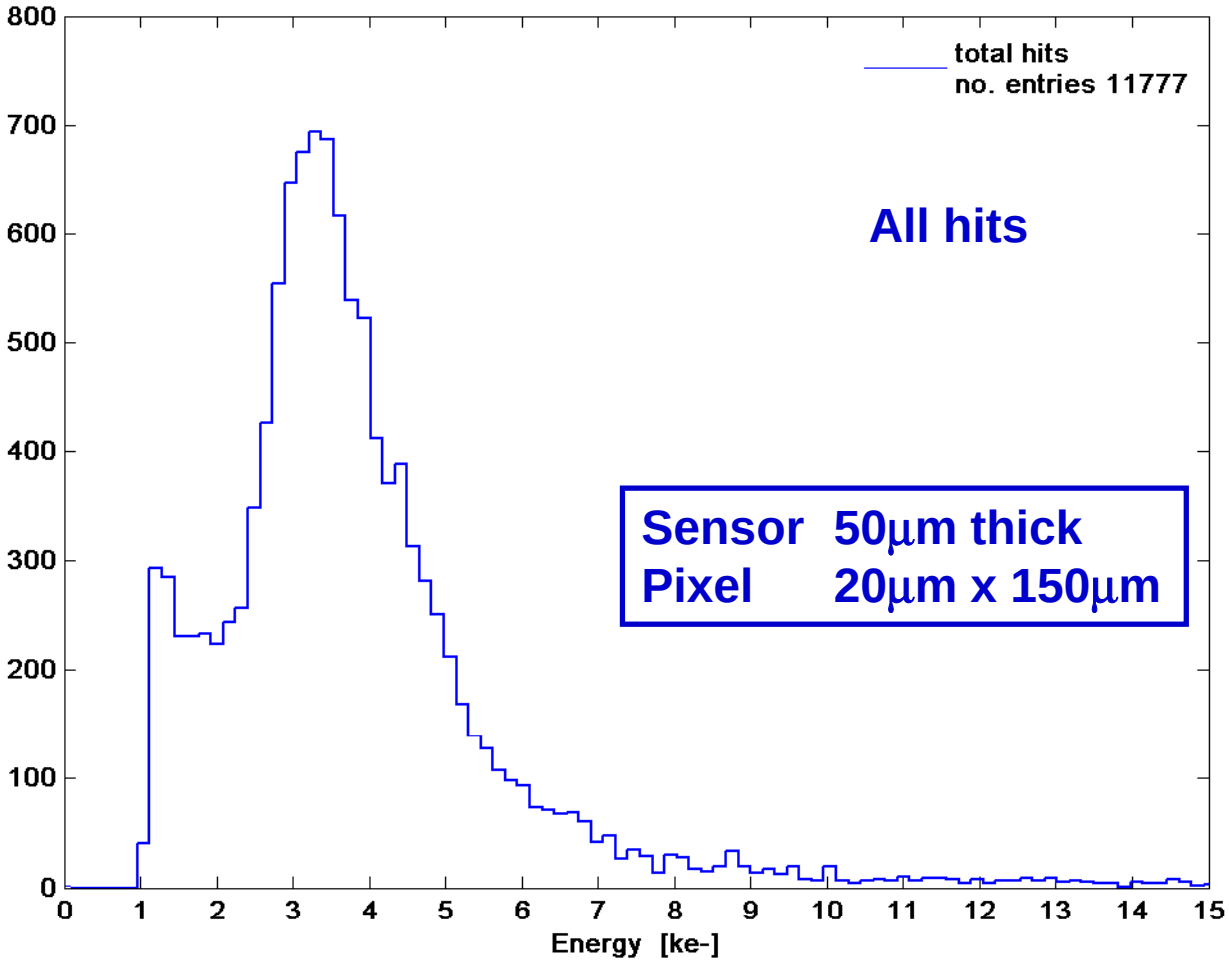
K. Einsweiller, ATLAS Pixel Detector, LBL Instrumentation Colloquim , 13 April 2005
See: http://instrumentationcolloquium.lbl.gov/The_ATLAS_pixel_detector.pdf

Charge deposition with MIPs – unsegmented Si

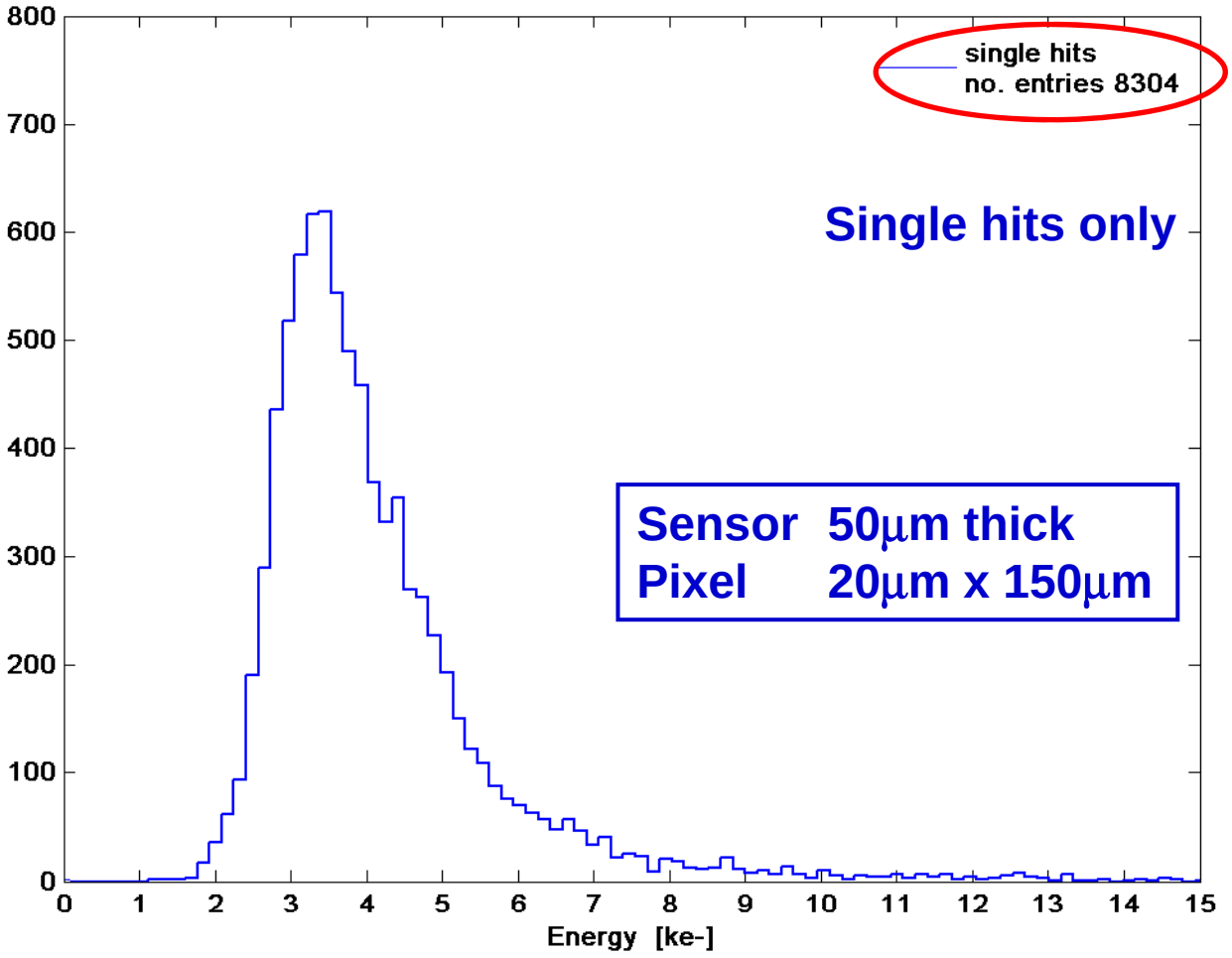


10 000 electrons 20MeV **0 deg angle of incidence**

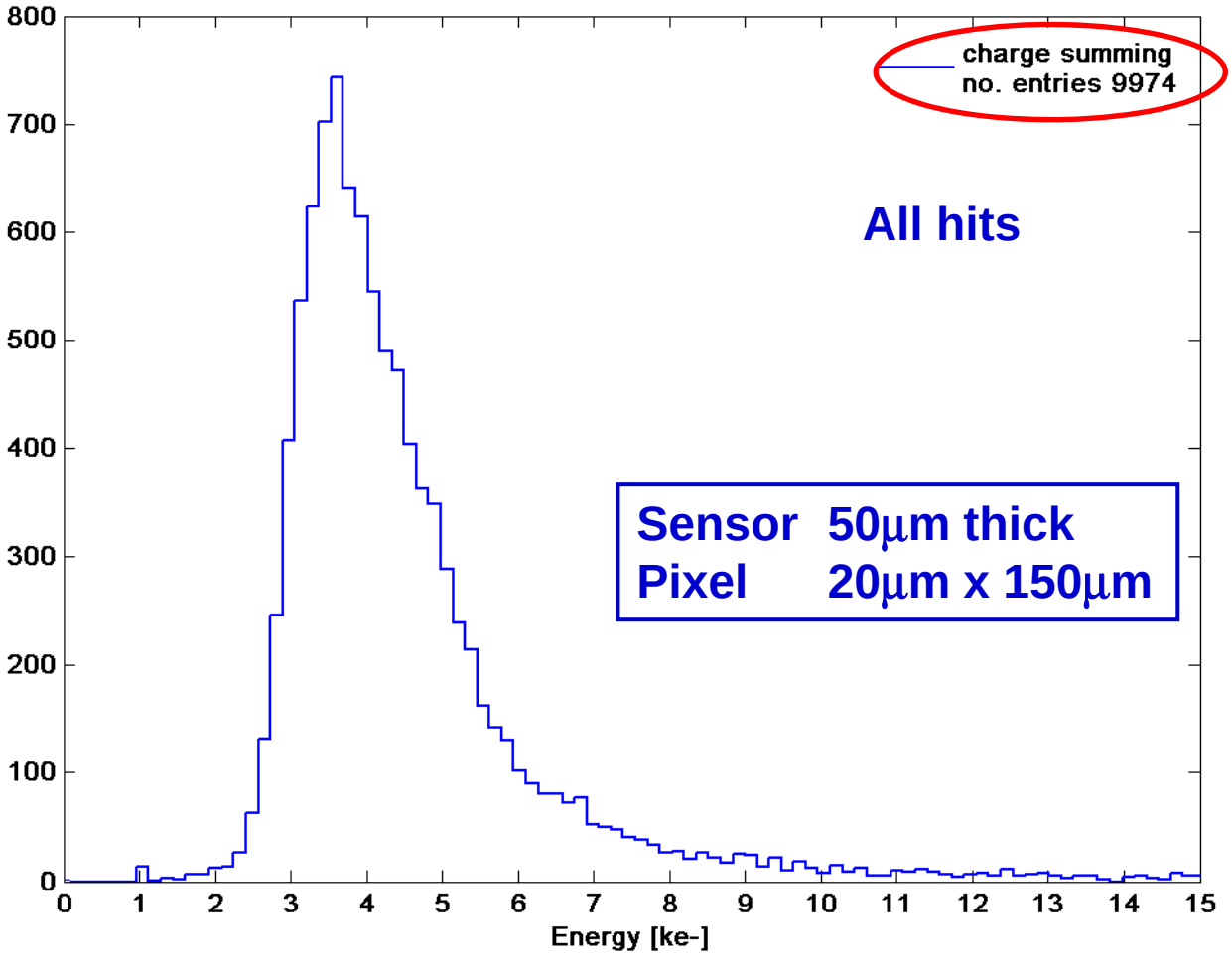
Charge detection – Conventional Readout



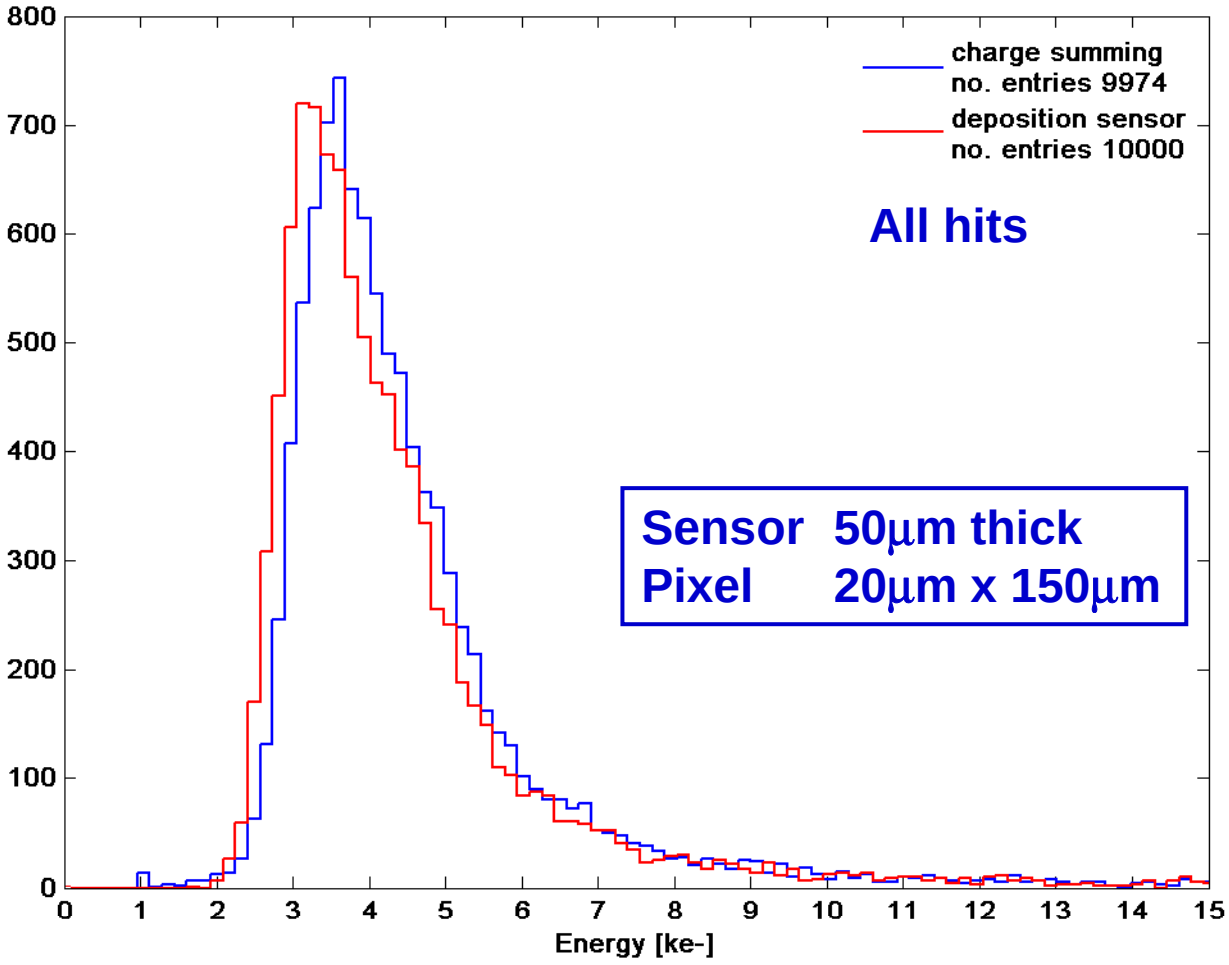
Charge detection – Conventional Readout



Charge detection – Charge summing Readout



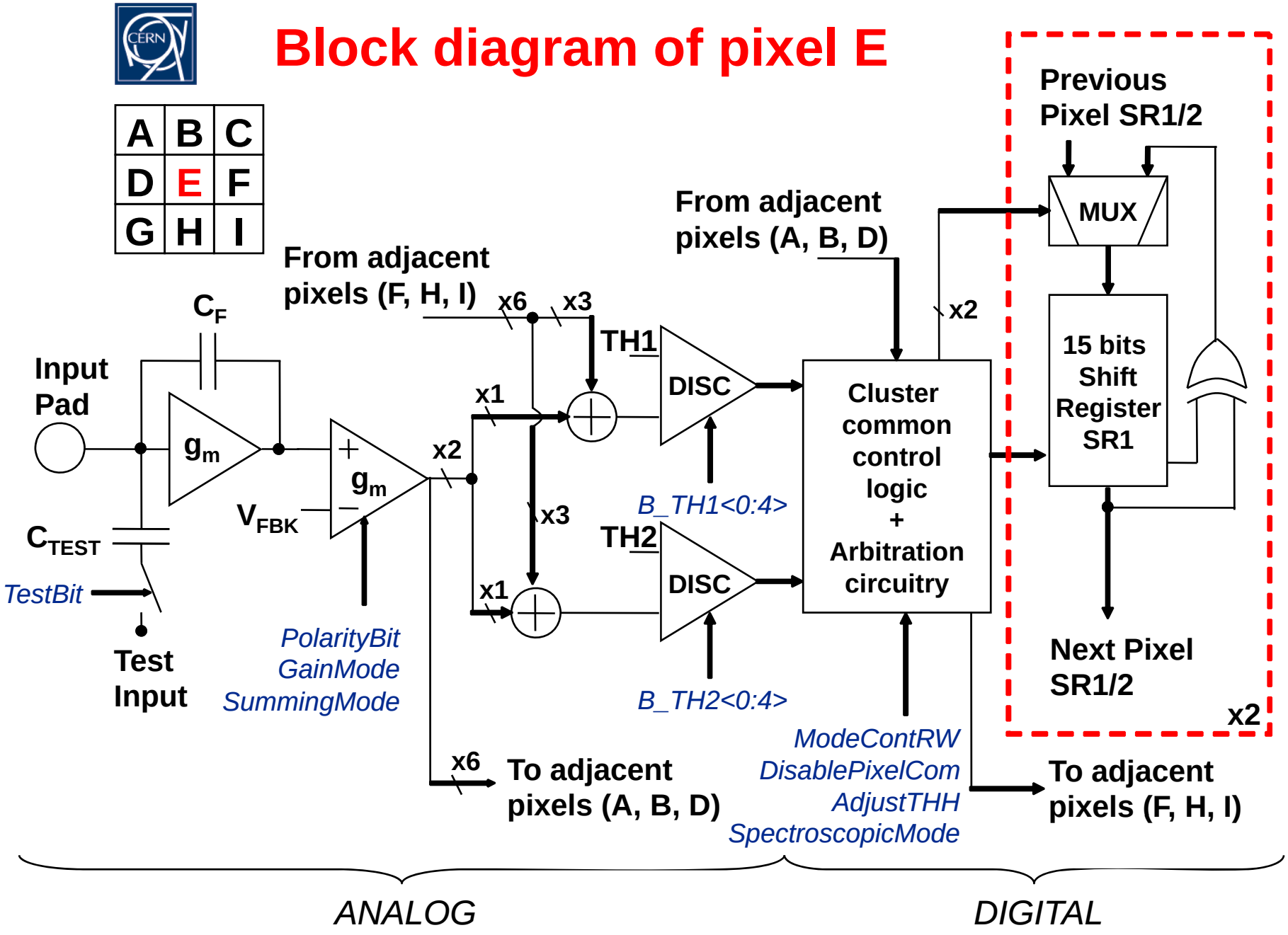
Comparison
Charge deposition – Charge summing Readout



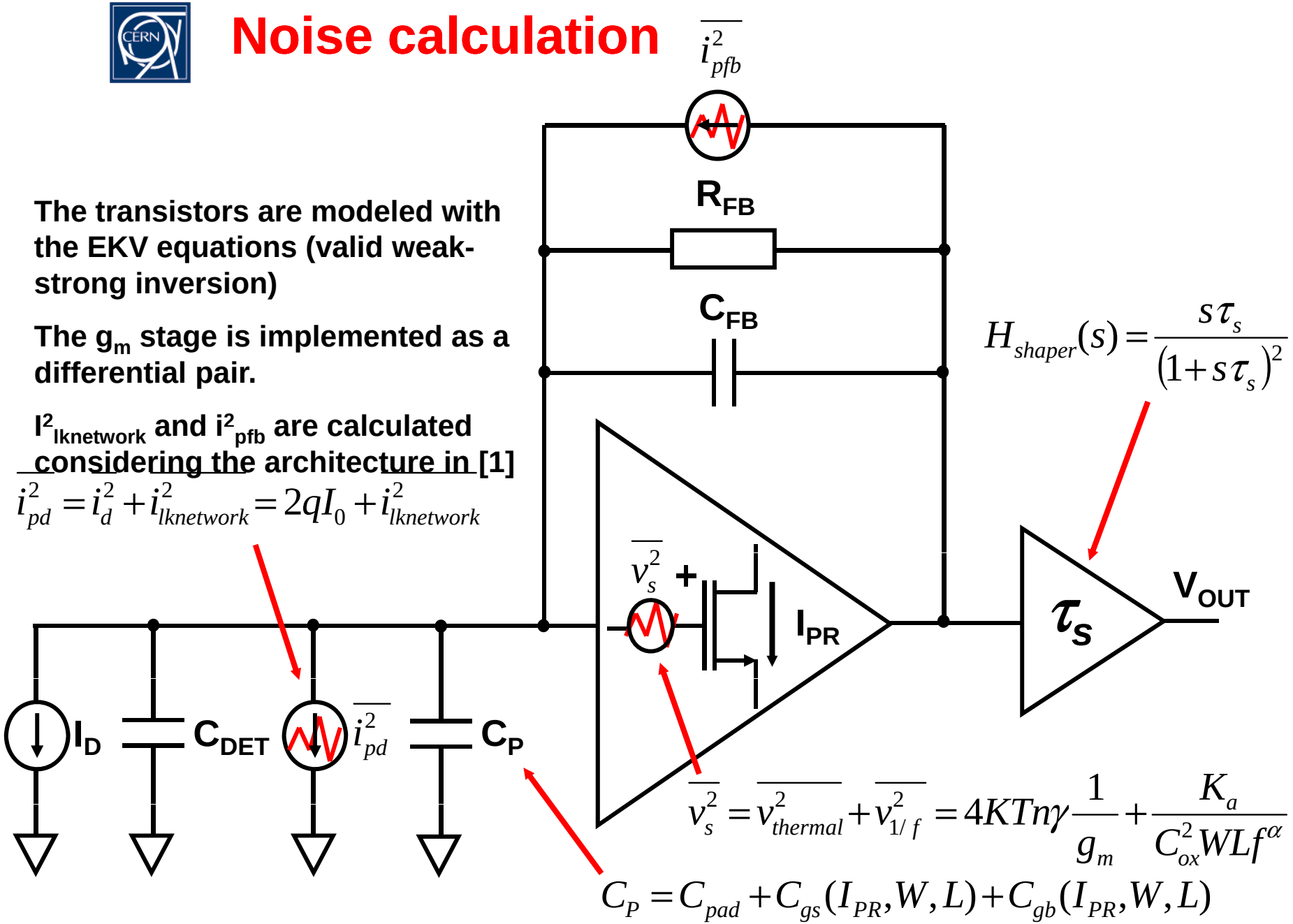
Is such an approach feasible at SLHC?

- Design example
- Assumptions:
  - 25 ns shaping time
  - Power budget 1 W/cm^2
  - ½ of power budget for analog
  - Pixel dimensions 55μm x 55μm (equivalent in area to 20μm x 150μm)
  - Therefore 10μA available for analog
  - Noise 100 e$^-$ rms per channel (200 e$^-$ rms after charge summing)

Block diagram of pixel E



Noise calculation



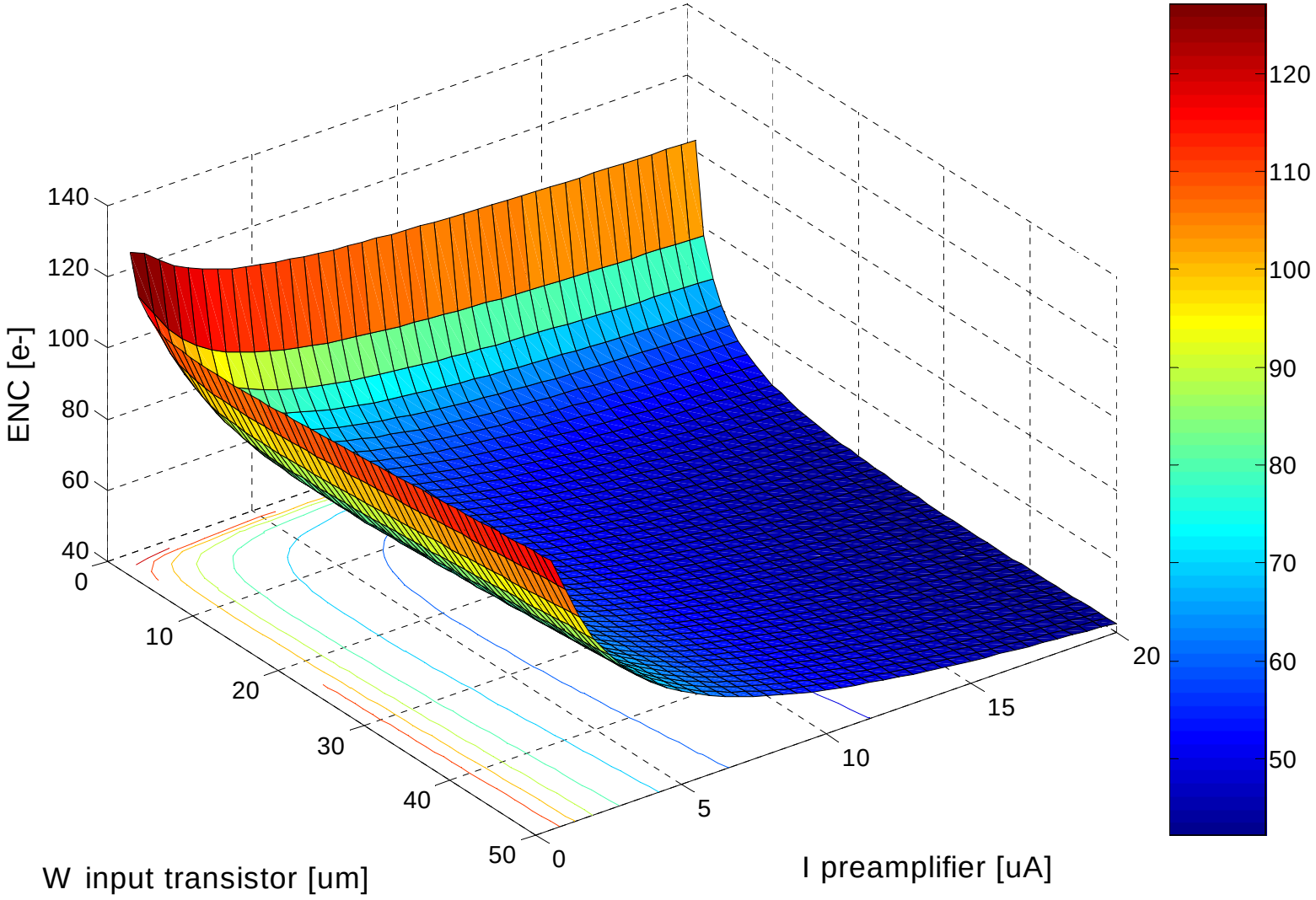
The transistors are modeled with the EKV equations (valid weak-strong inversion)

The g_m stage is implemented as a differential pair.

$I^2_{lknetwork}$ and i^2_{pfb} are calculated considering the architecture in [1]

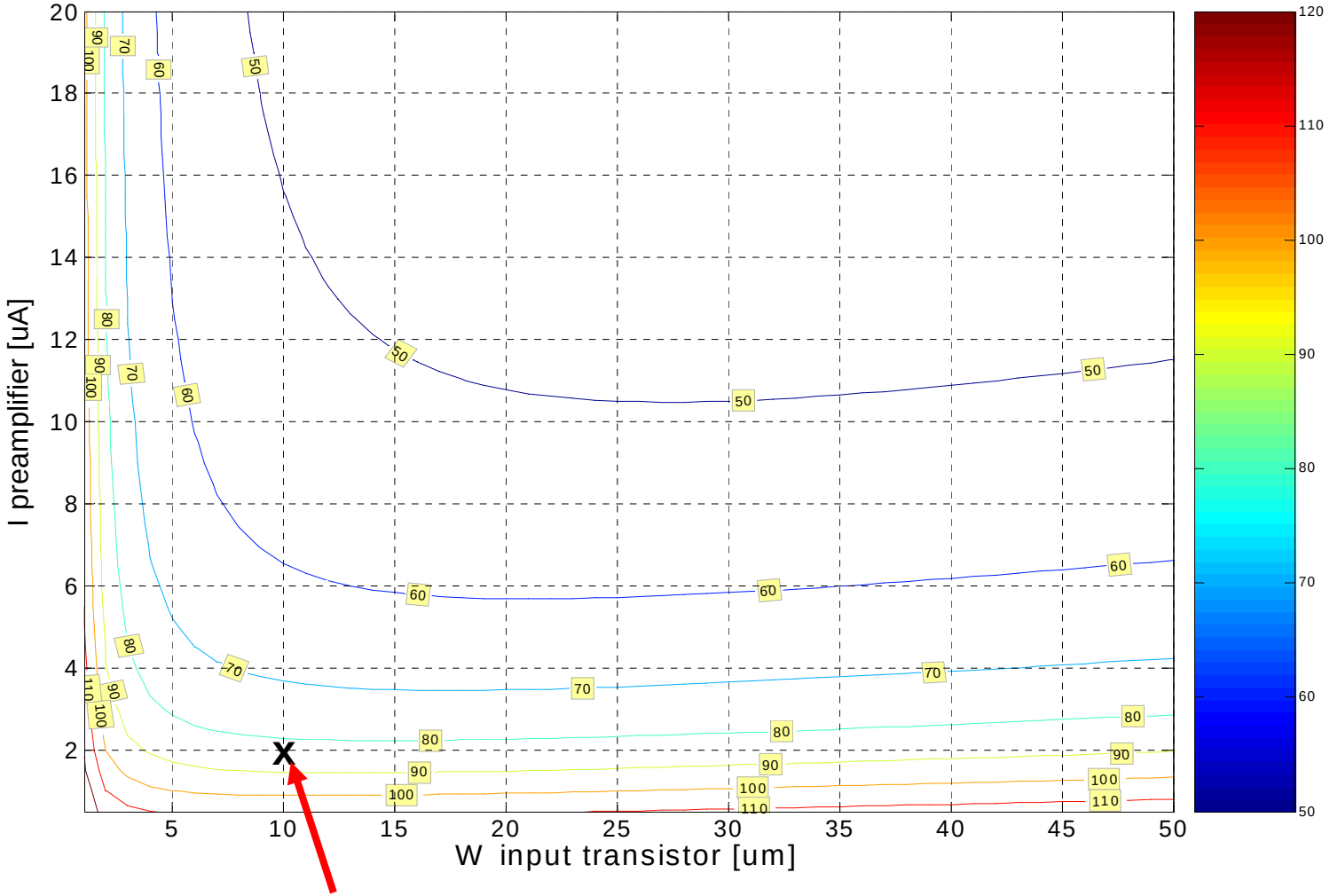
$$i_{pd}^2 = i_d^2 + i_{lknetwork}^2 = 2qI_0 + i_{lknetwork}^2$$

ENC vs preamp Current and W of IP transistor



C_{in} = 80fF

ENC vs preamp Current and W of IP transistor

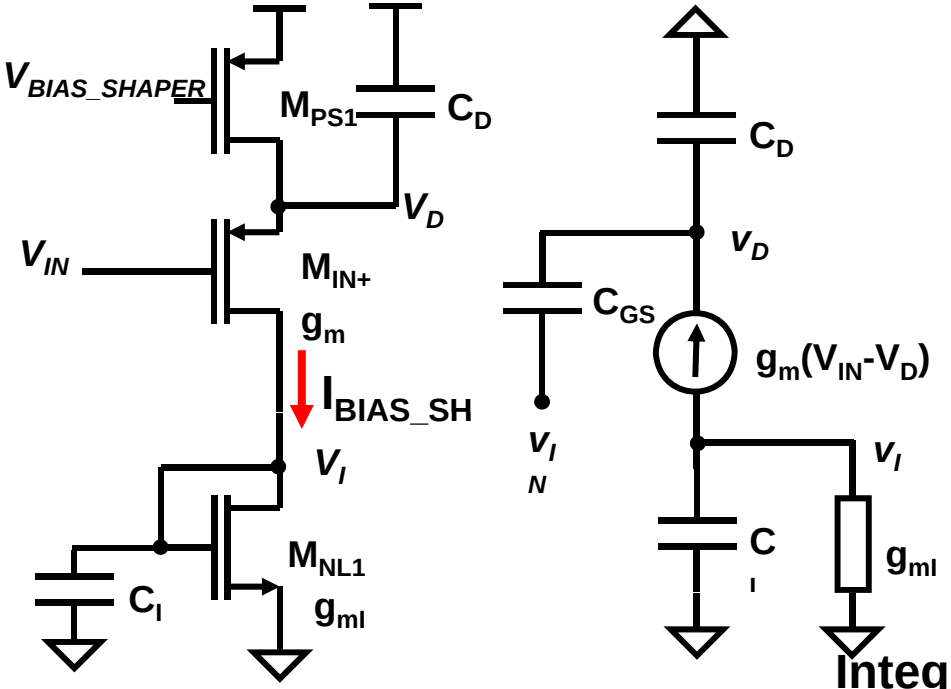


Possible design value for a target ENC of 200 e^- rms after summing

I_{PR}=2μA, I_{SH}=10μA-I_{PR}=8μA

Shaper calculations

The Shaper Circuit calculation



$$I_{SH} = 8\mu A$$

Differential version

$$I_{BIAS_SH} = \frac{8\mu A}{2\cdot(NT+1)} = 0.8\mu A$$

N: Number of neighbours (4 in rectangular pixels)

T: Number of thresholds

Transfer Function Equation

$$\tau_{p1} = \frac{C_I}{g_{mI}}$$

$$\tau_{p2} = \frac{C_D + C_{GS}}{g_m + g_{pz}} \approx \frac{C_D}{g_m}$$

$$K = \frac{C_D}{g_{mI}}$$

$$\frac{v_I(s)}{v_{IN}(s)} = \frac{-Ks}{(1+s\tau_{p1})(1+s\tau_{p2})}$$

Integrator Transistor Size Calculation

$$C_I = 5\cdot C_{gs}(I_{BIAS_SH}, W_{MNL1}, L_{MNL1}) + 5\cdot C_{gb}(I_{BIAS_SH}, W_{MNL1}, L_{MNL1})$$

$$g_{mI} = f(I_{BIAS_SH}, W_{MNL1}, L_{MNL1})$$

1µ/7.7µ

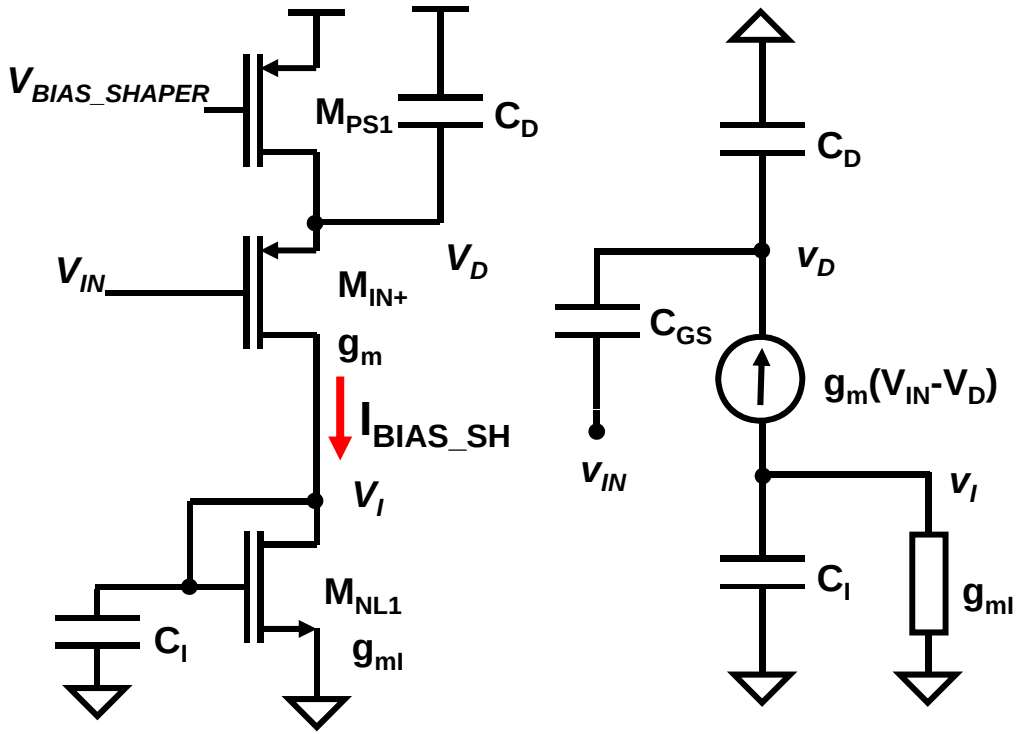
$$\frac{C_I}{g_{mi}} = 25ns$$

0.8µA

Calculated based on op point

Shaper calculations (contd)

The Shaper Circuit calculation



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$$K = \frac{C_D}{g_{mI}}$$

$$\frac{v_I(s)}{v_{IN}(s)} = \frac{-Ks}{(1+s\tau_{p1})(1+s\tau_{p2})}$$

Differentiator Transistor Size Calculation

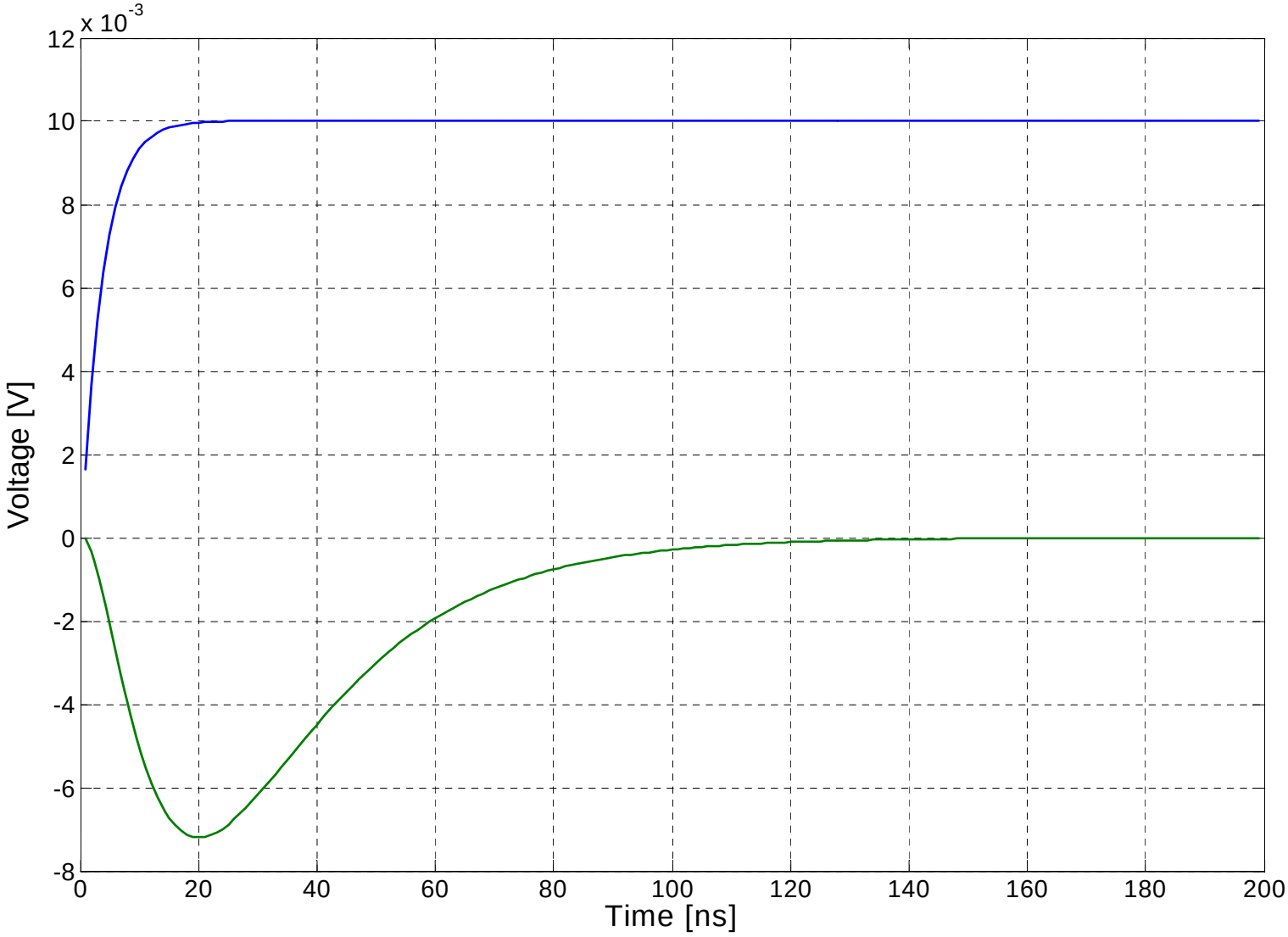
$$\frac{C_D}{g_m} = 25ns$$

$$g_m = f(I_{BIAS_SH}, W_{MIN+}, L_{MIN+})$$

C_D = 600fF (300fF in differential version)

W/L = 11µ/0.12µ

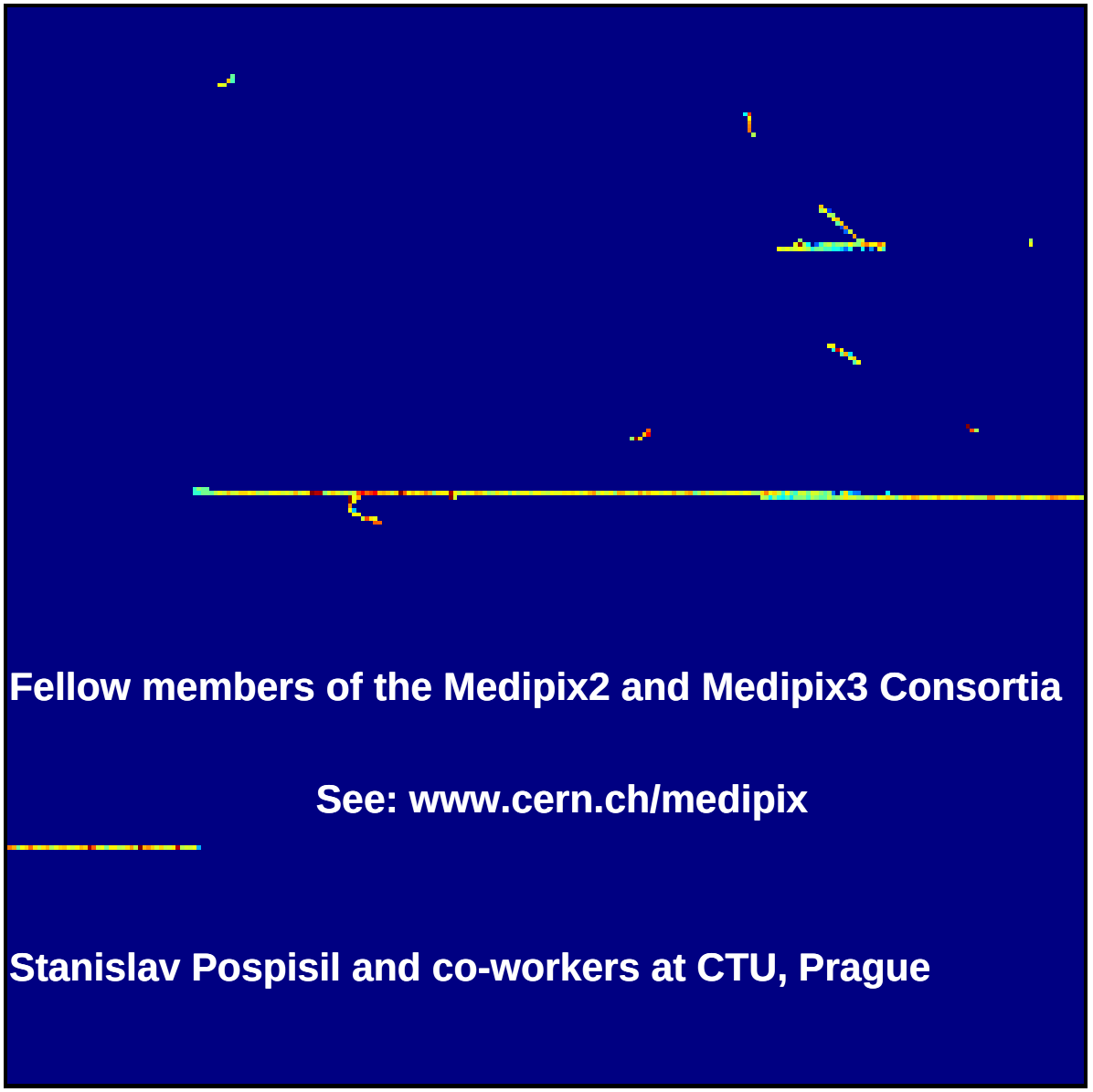
Preamplifier and Shaper Time Waveforms



Summary

- Hybrid pixels enable the separate optimisation of sensor and readout and permits the use of the most advanced CMOS process available
- Charge sharing caused by diffusion distorts the spectrum seen by segmented sensors
- This applies to single photon counting systems such as Medipix2 as well as to the MIP spectrum at an HEP experiment
- A new architecture (Medipix3) is proposed whereby a clean spectrum is reproduced prior to a YES/NO decision being taken - improved energy resolution
- This same approach should enable the use of highly segmented and very thin (rad hard?) sensors to for vertex tracking
- For HEP the YES/NO decision could be used to ‘freeze’ the analog hit info in the 4 pixels concerned
- A preliminary design study suggests that the architecture is suitable for SLHC within a reasonable power budget

Acknowledgements



Fellow members of the Medipix2 and Medipix3 Consortia

See: www.cern.ch/medipix

Stanislav Pospisil and co-workers at CTU, Prague