Monolithic Pixel Detectors

Some examples and practical considerations

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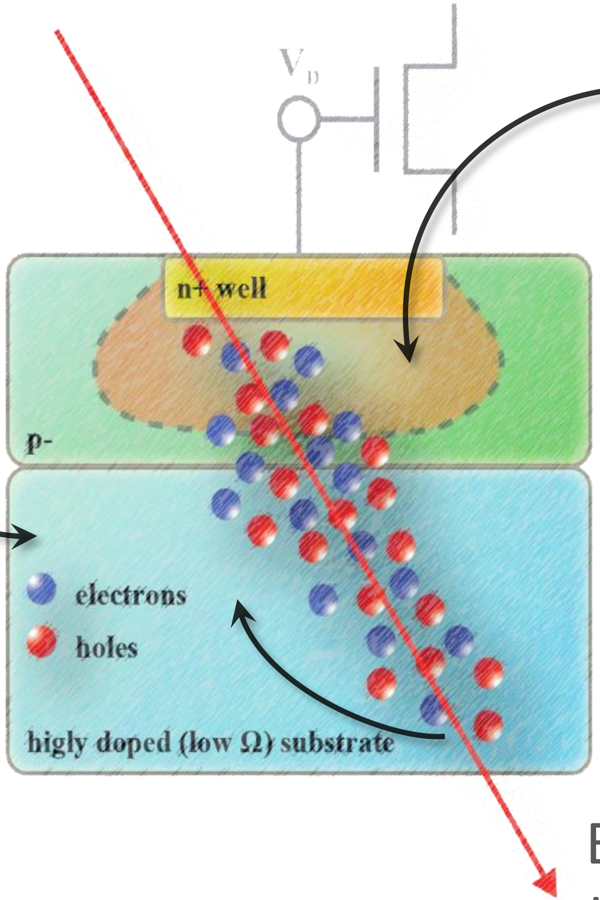
26/11/2013
Torino

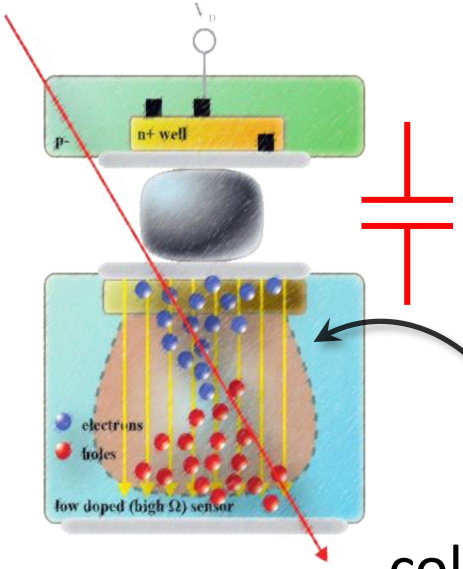
Introduction – standard CMOS monolithic pixels

Usually a standard (opto) CMOS process, low Ω substrate



Charge collection by diffusion. Collection time of tens of ns.

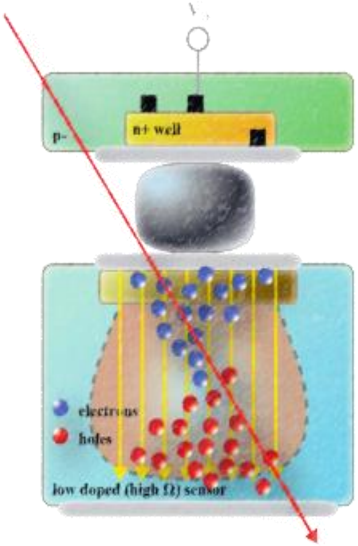
Effective collection depth limited to the epitaxial layer (~10µm)



Fast, deep collection volume

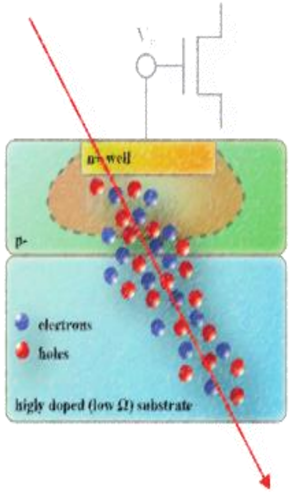
capacitance, cost, complexity

Introduction – monolithic vs hybrid pixel detectors



- Established, proven, effective technology.
- Unique possibility to use the best sensor depending on the radiation to track.

- Plenty of room for extremely advanced in-pixel electronic.
- Cost, complexity, mid power consumption, material budget.
- Producing small (< 20 µm) pixels still a challenge for bump bonding.



- Young technology
- Sensing material limited to silicon
- No room in pixel for advanced signal processing

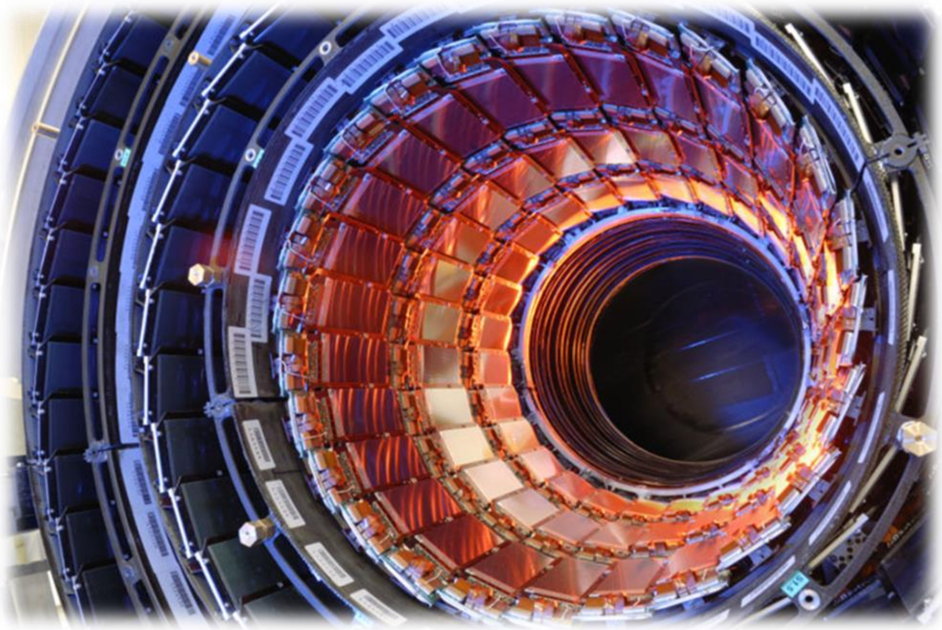
- Radiation tolerance could still be an issue for high doses applications
- Cost effective, simple, low power and low material budget
- High resolution (pixels < 5µm)

Do we really need monolithic?

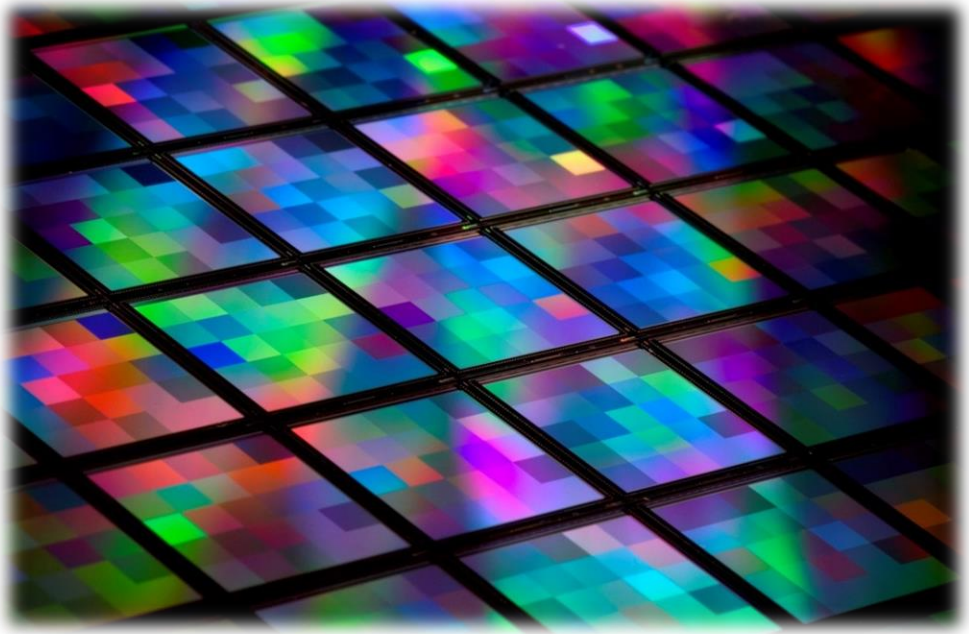
1. Monolithic pixel detectors are not the Holy Grail of pixelated radiation imagers!
2. Actually, they have severe limitations when compared to other technologies!
3. We need strong motivations to get real advantages by using them.

Motivations – sheer quantity

The quantity of detectors to produce is large enough to call for costs saving both for production and assembly.



CMS tracker – 200 m^2

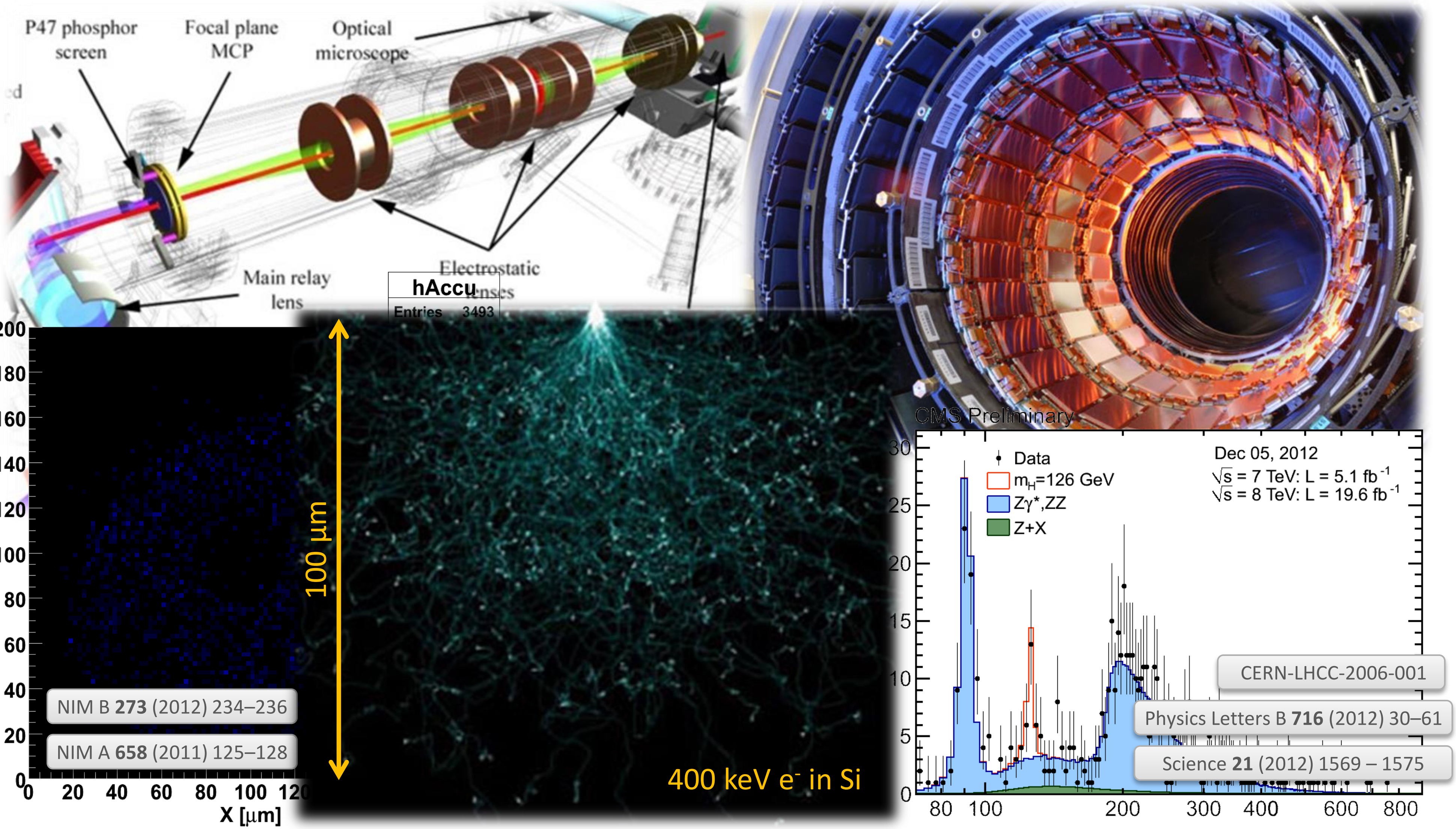


Imagers – Mpieces/year

In such cases using a standard CMOS process could save the day.

Motivations – passing particles

The radiation passing trough the detector must stay unaffected as much as possible. Ultra-thin detectors (less than 50 µm) required.



NIM B **273** (2012) 234–236

NIM A **658** (2011) 125–128

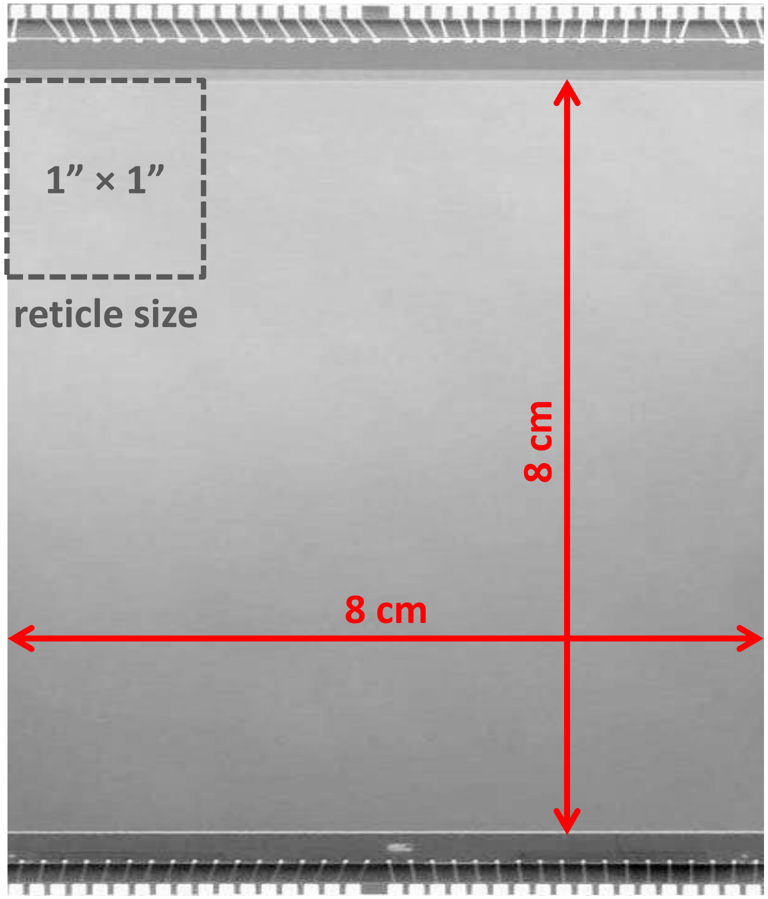
CERN-LHCC-2006-001

Physics Letters B **716** (2012) 30–61

Science **21** (2012) 1569 – 1575

Motivations – passing particles 2

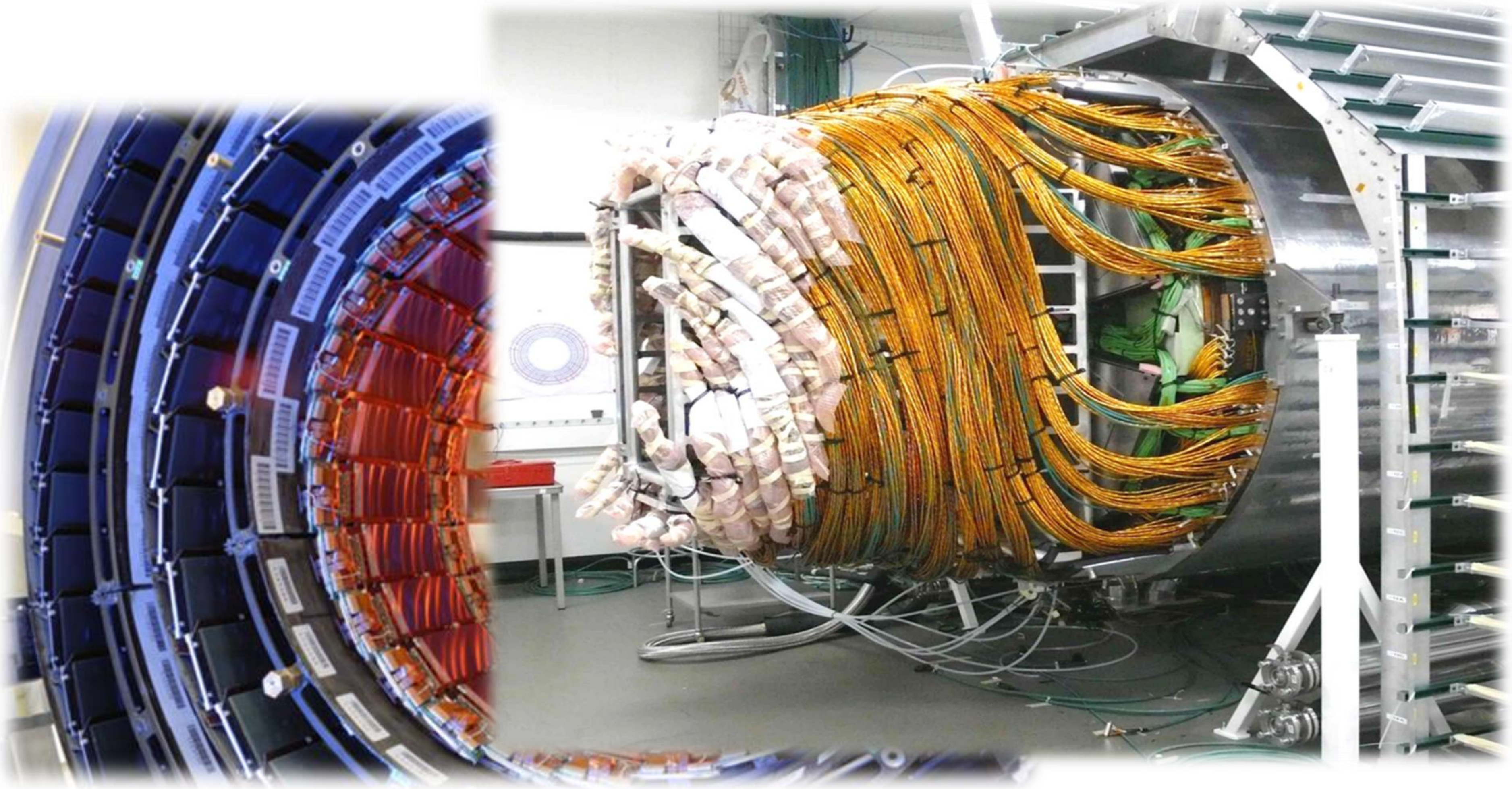
Ancillary constraint of minimizing the device thickness to the technical limit is that it is **not possible to use any backbone** to supply / support / connect tiled large area detector. This implies using **very large** (many 10 cm^2) dies realized by stitching, i.e. **sensors larger than the reticle size**. Bump-bonding is not practical for such oversized detectors.



4096 × 4096 pixels   20 × 20 µm^2 pixels

Motivations – ultra low power (<≈10 mW/cm^2)

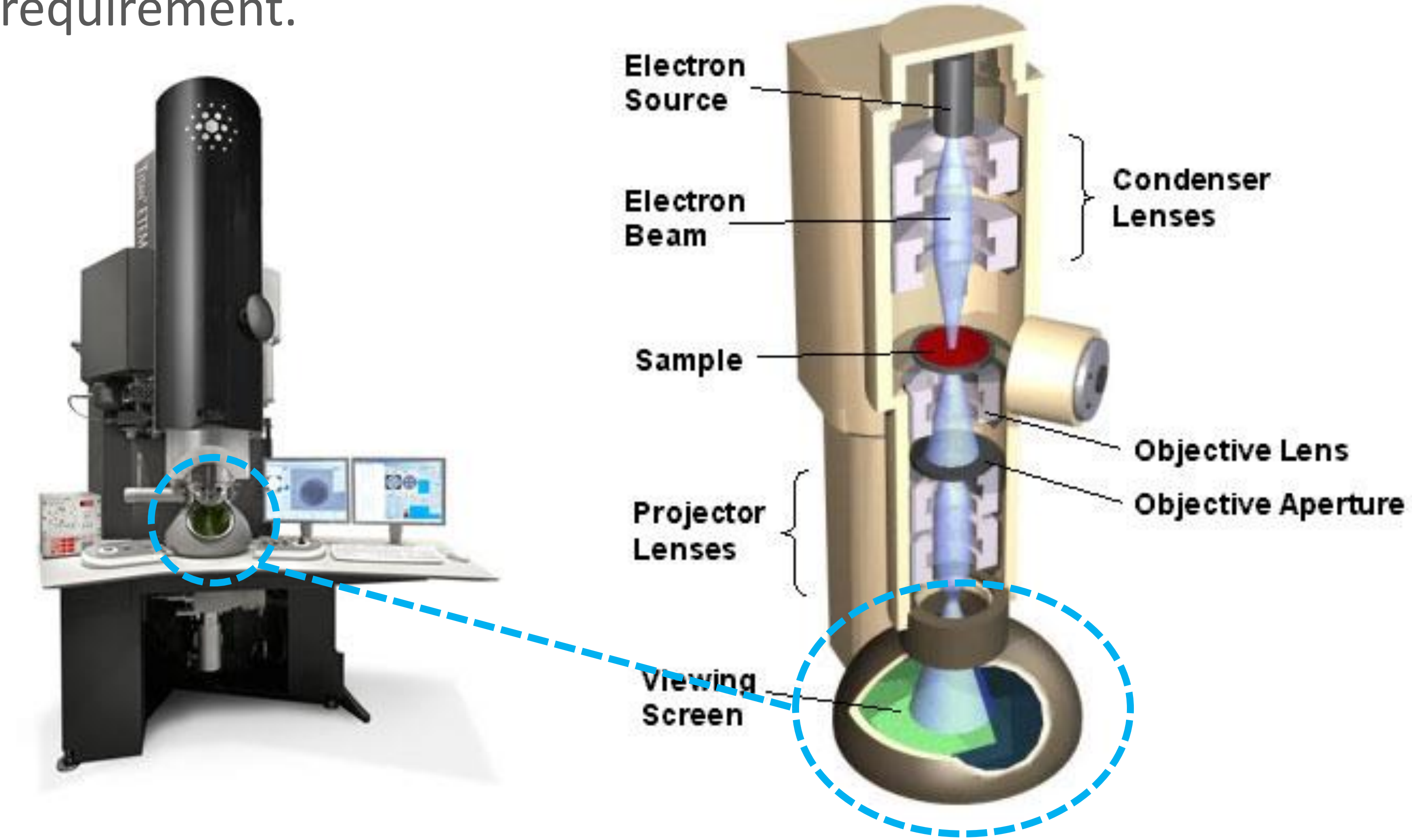
For real low mass very low power is mandatory in large area systems (think about cooling, supply lines…)



33 kW in the detector and… 62 kW in the cables !

Motivations – ultra low power (<≈10 mW/cm^2)

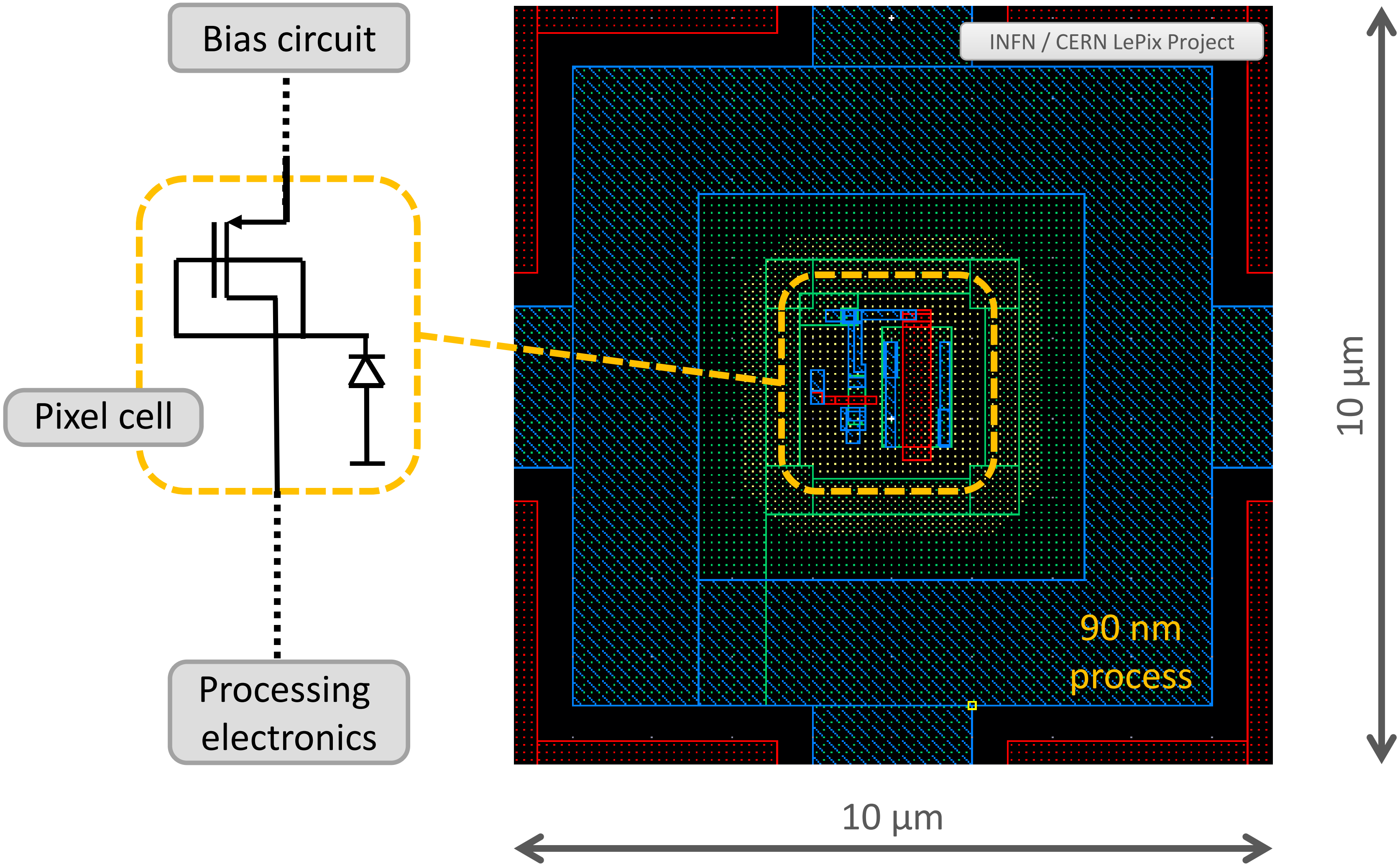
Also for small and medium sensors operated in vacuum with no cooling (the detector must stay very thin, no support allowed) ultra low power can be a mandatory requirement.



The sensor must be **large**, **ultra thin**, and sits in the **vacuum**

Motivations – very small pixels

Whenever the pixel pitch has to go below 10 um, the room for electronics in the pixel cell, even in hybrid detectors, starts to be in shortage.



Reasons for going monolithic:

Ultra low power budget (thanks to sensor capacitance)

Low material budget (thin device, small clusters)

Small pixels (no room for bonding and/or complex in-pixel electronics)

Very large areas (stitching)

All these requires very specific architectures and technical solutions! Low transistors count (per pixel), ultra low power, on chip data reduction, etc…

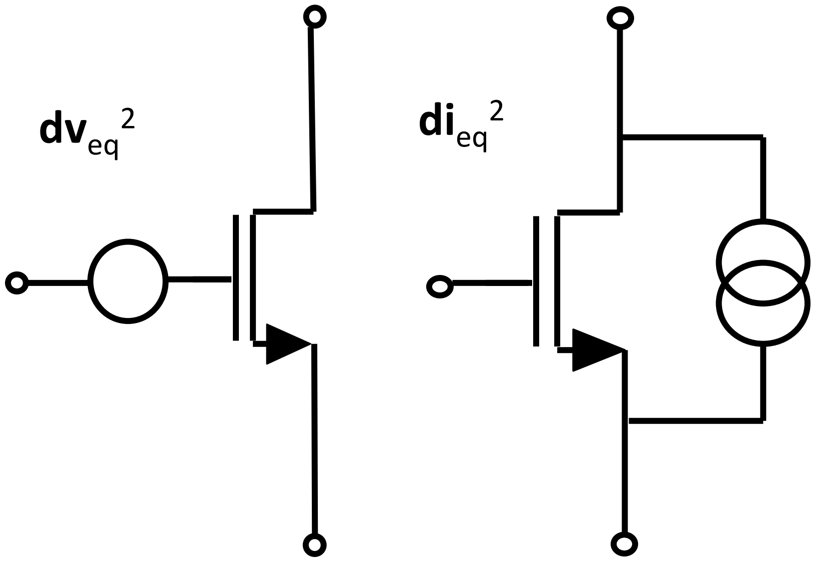
Common ground – power consumption factors

1. **Analog**: determined by collected charge over capacitance (Q/C) in the pixel: pixel sensor optimization.

2. **Digital**: determined by on-chip architecture & cluster size Standard is Rolling shutter, studies on architectures with in-pixel binary front-end.

3. **Data transmission** off-chip: determined by cluster size and required bandwidth unless data reduction by clustering algorithm

Common ground – low capacitance to low power 1



$$di_{eq} = g_m \cdot dv_{eq}$$

Transconductance g_m is related to power consumption, hence **higher current** (power) in the first stage improves **performances** and **noise.**

Noise, **Weak** inversion

flicker $(^1/_f)$

$$dv_{eq}{}^2 = \left(\frac{K_F}{WLC_{ox}{}^2 f^\alpha} + \frac{4K_B T n}{g_m}\right) df \quad g_m \sim I$$

thermal

Noise, **strong** inversion

$$dv_{eq}{}^2 = \left(\frac{K_F}{WLC_{ox}{}^2 f^\alpha} + \frac{2K_B T \gamma}{g_m}\right) df \quad g_m \sim \sqrt{I}$$

K_F	technology dependent constant
W, L	transistor width and length
C_{ox}	gate oxide capacitance per unit area
g_m	transistor transconductance
K_B	Boltzmann constant
T	absolute temperature
n	weak inversion slope
ϒ	often around ½ - 2/3 in strong inversion

Common ground – low capacitance to low power 2

$$S = \frac{Q}{C}$$

signal

$$N \sim \frac{1}{\sqrt{g_m}}$$

noise

$1 \le a \le 2$

$1 \le a \le 2$

$$\frac{S}{N} \sim \frac{Q}{C}\sqrt{g_m} \sim \frac{Q}{C}\sqrt[2a]{I} \sim \frac{Q}{C}\sqrt[2a]{P} \Rightarrow P \propto I \propto \left(\frac{S/N}{Q/C}\right)^{2a}$$

Assuming $\frac{S}{N} = cost \Rightarrow \boldsymbol{P \propto \left(\frac{C}{Q}\right)^{2a}}$

Good detection Parameter, say 25

Power to meet S/N goal

$1 \le a \le 2$

Weak inversion

Strong inversion

Analog power is very strongly dependent on Q/C => we wants low C

Common ground – Q/C in monolithic visualized

Assuming input noise $v_{eq} = 0.16\,mV$

$\begin{pmatrix}\text{Transistor noise at 40 MHz BW for 1 µA} \\ \text{(1 µA/100x100 µm pixel = 10 mW/cm}^2\text{)}\end{pmatrix}$

$\Downarrow$

$$\frac{S}{N} \geq 25 \rightarrow \frac{Q}{C} \geq 4\,mV$$

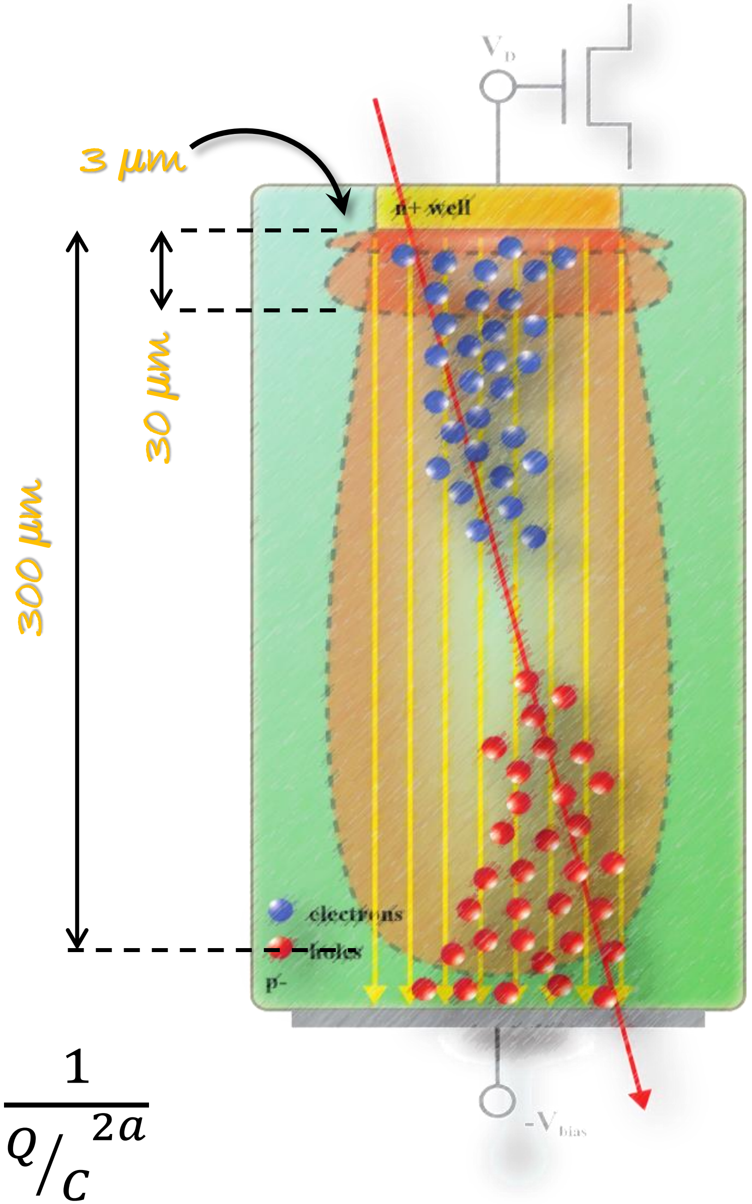
$\Downarrow$

25 ke$^-$ 2500 e$^-$ 250 e$^-$

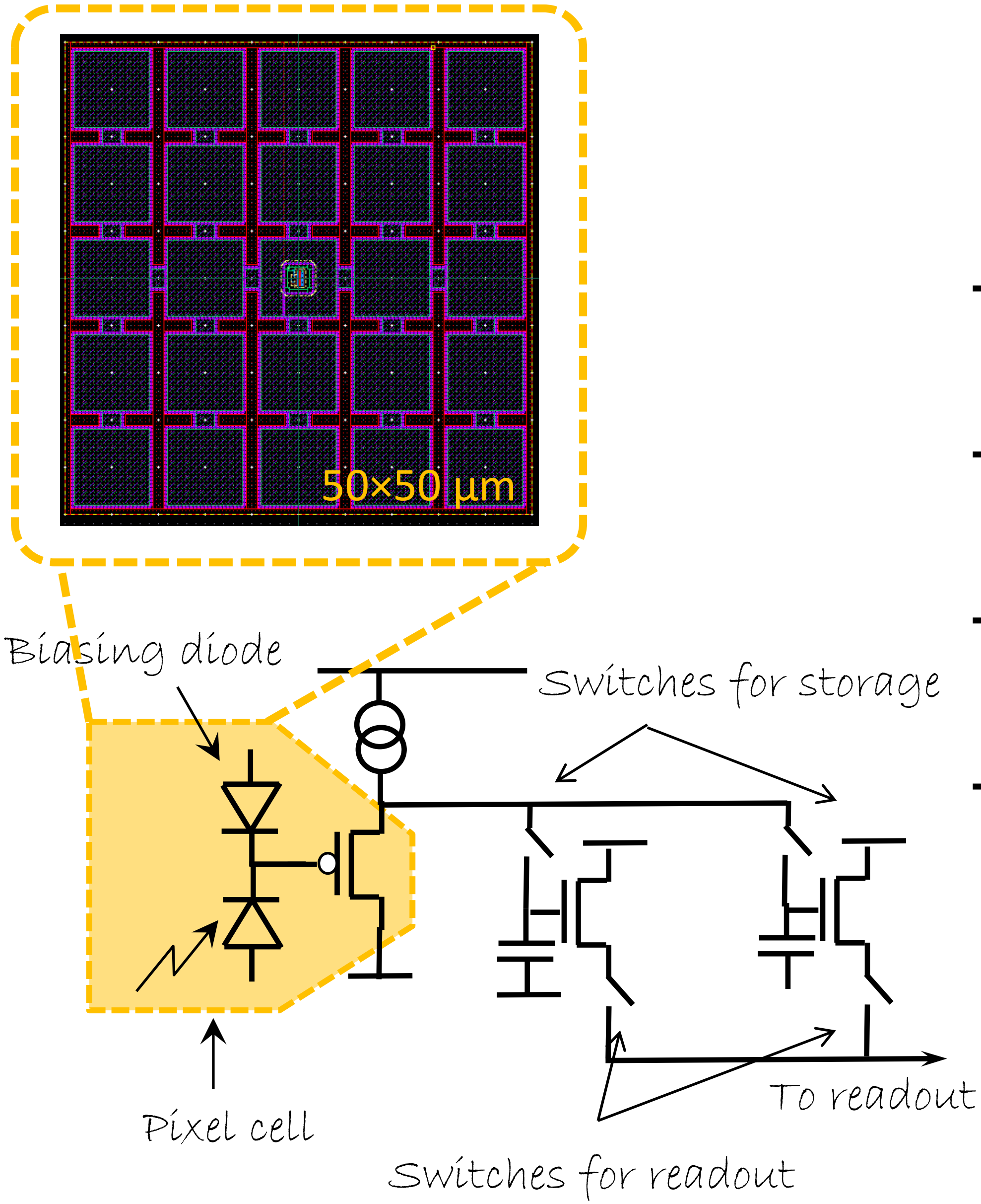
$$\frac{4\,fC}{1\,pF} \equiv \frac{0.4\,fC}{100\,fF} \equiv \frac{0.04\,fC}{10\,fF}$$

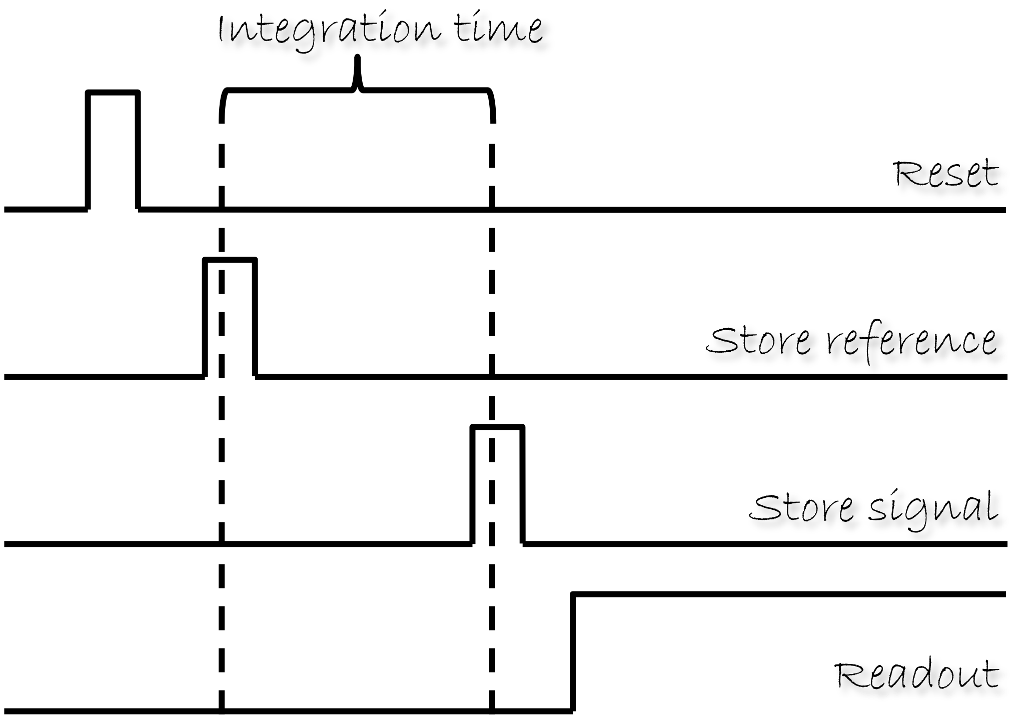
300 µm 30 µm 3 µm

For the same $\frac{S}{N}$ power consumption $\propto \frac{1}{Q/C^{\,2a}}$



Common ground – how to keep C very low (LePix)



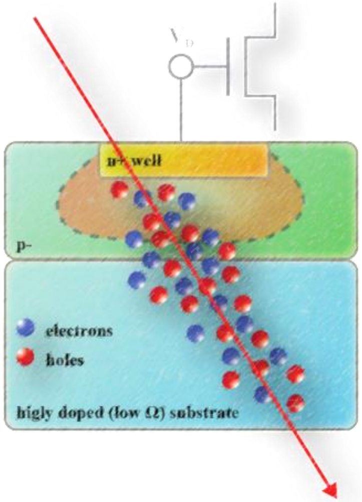


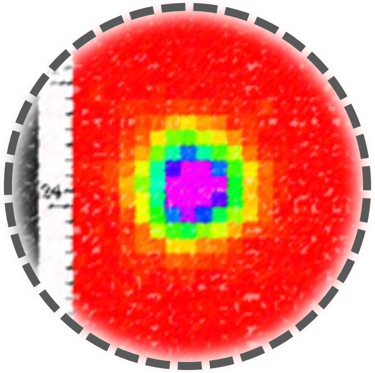
On periphery CDS. Parallel storage for all pixels: no rolling shutter, synchronous integration time independent from readout time.

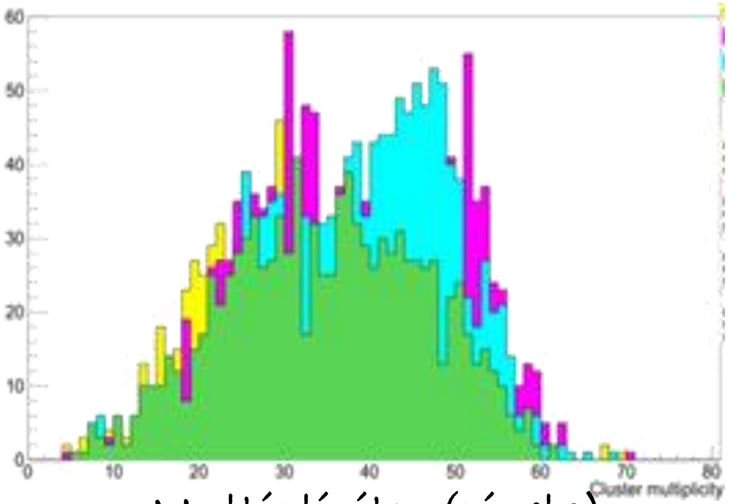
Common ground – depletion to reduce data and increase S/N

300 MeV protons beam
50 µm pixel (LePix detector)

No bias

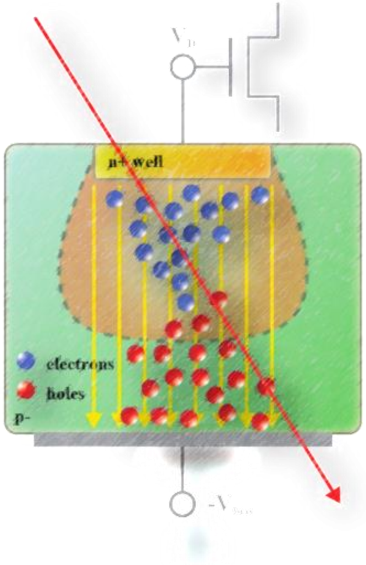


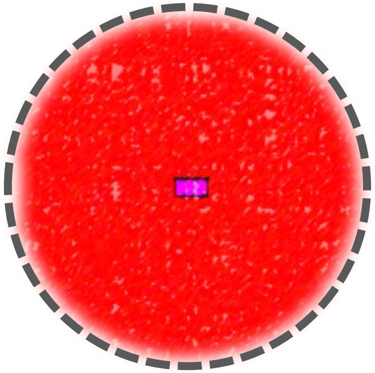


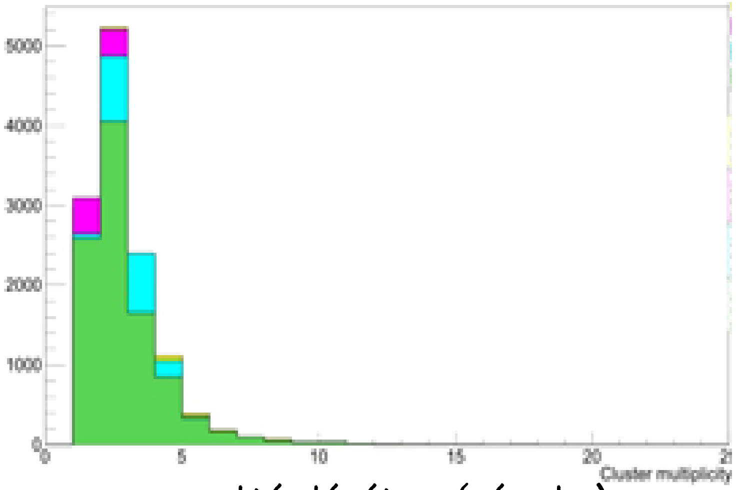


Multiplicity (pixels)

60V bias

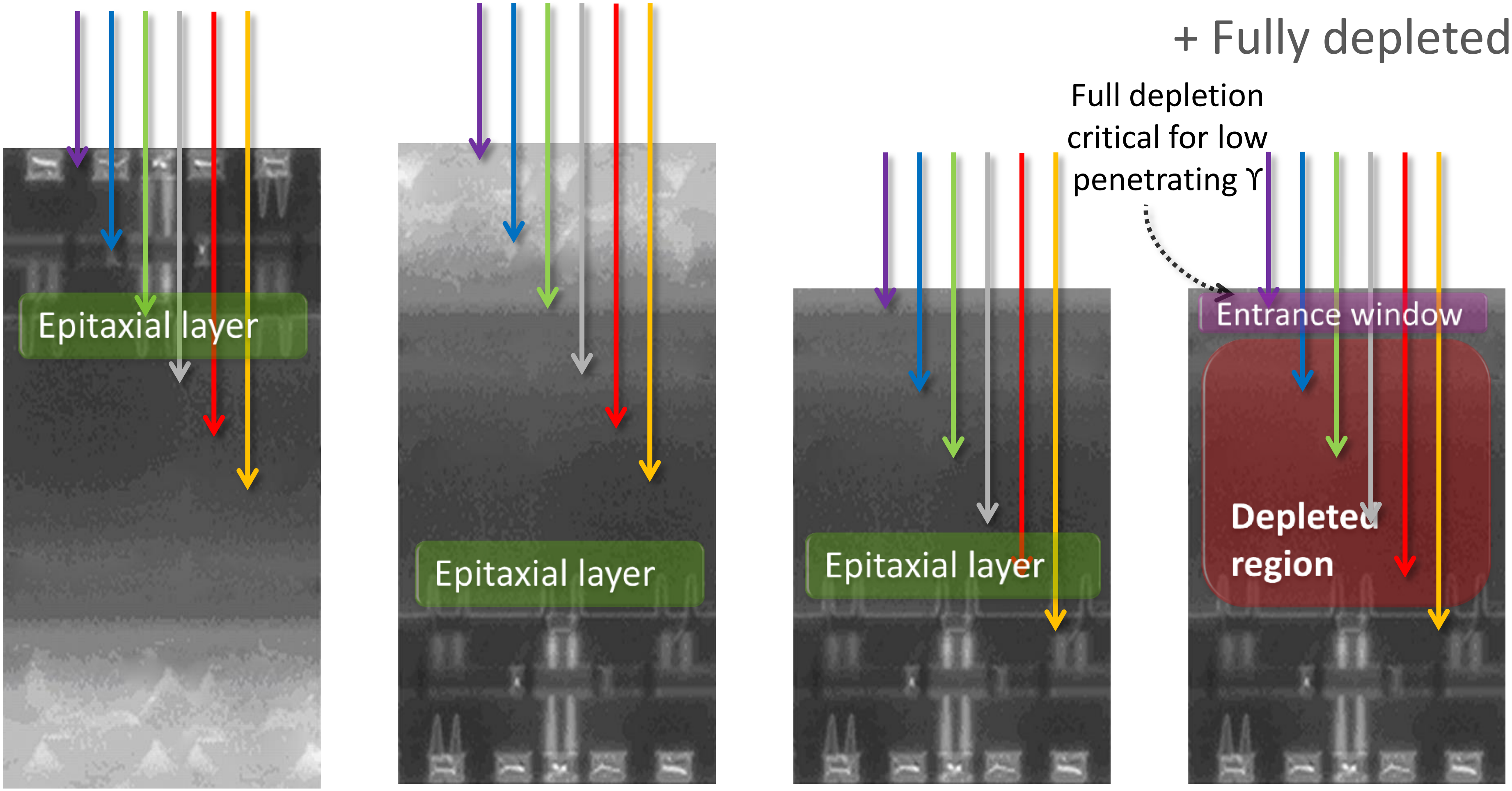






Multiplicity (pixels)

Common ground – backlit + thinning to increase S/N



Standard

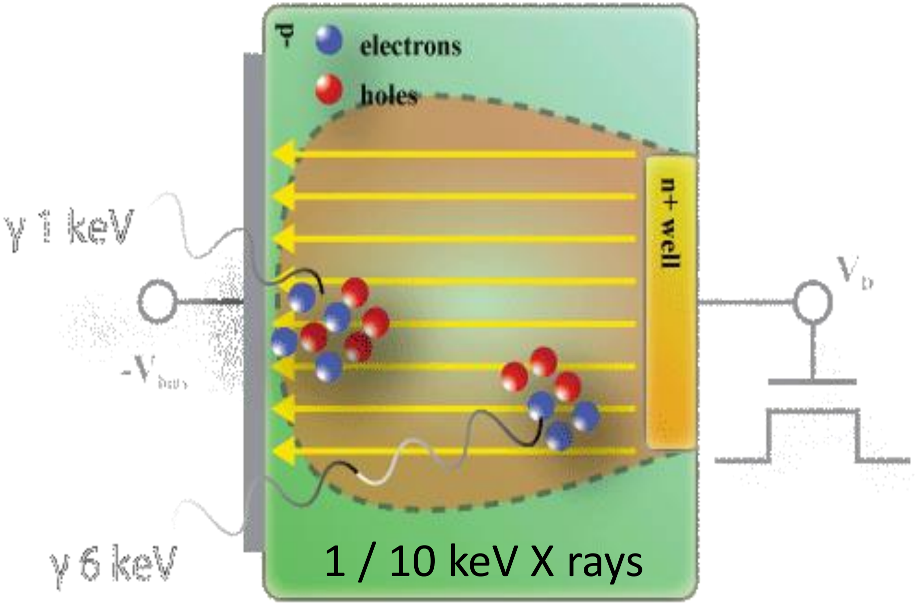
Back-lit

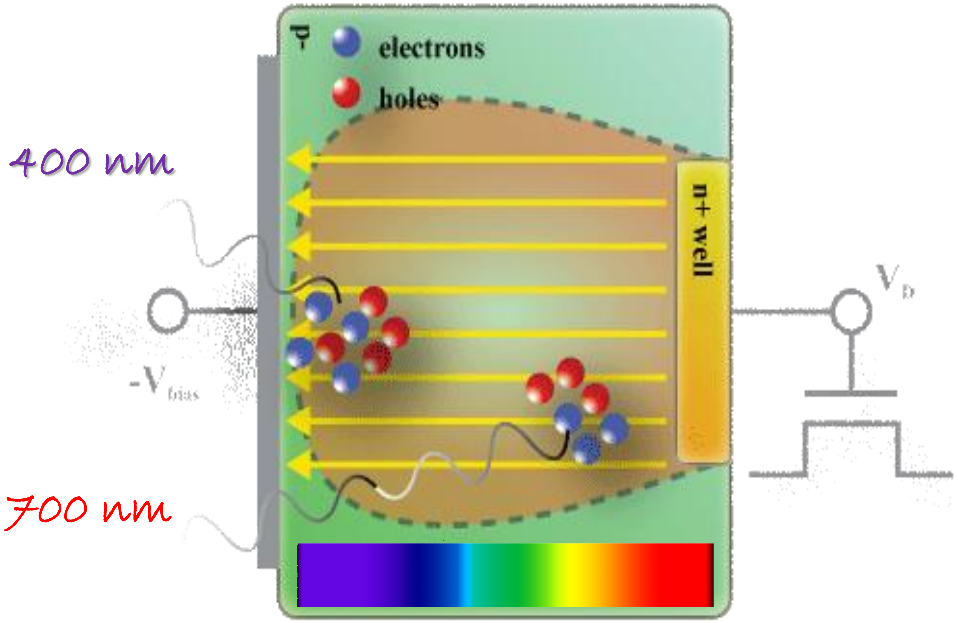
Back-lit
+ Thinning

Back-lit
+ Thinning
+ Fully depleted

Full depletion critical for low penetrating ϒ

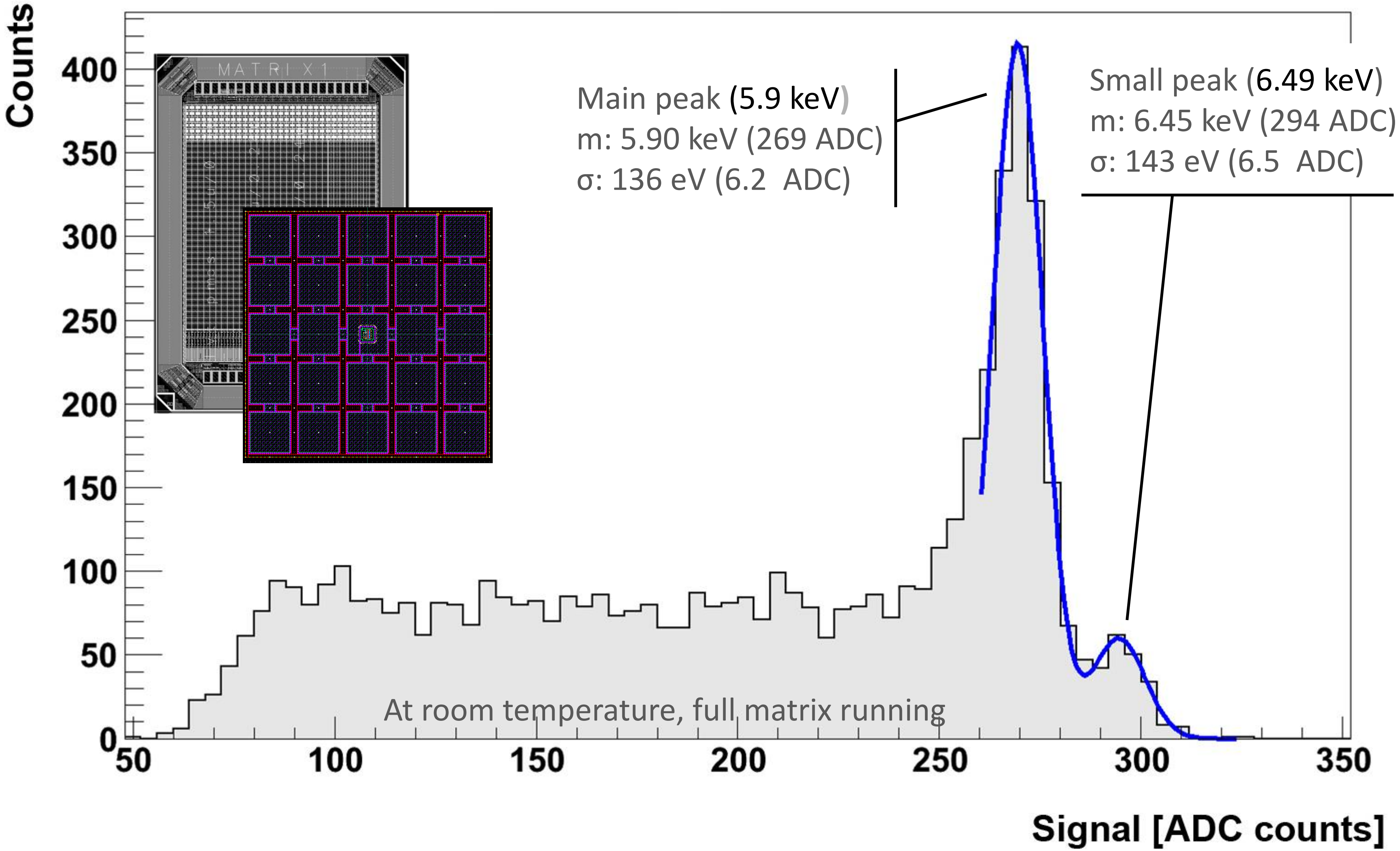
Common ground – depleted + thinned + backlit to maximize S/N





- Back-illuminated, fully depleted could see the whole spectrum.
- **Spectroscopic capabilities** over full detection range thanks low noise.
- Soft X-Rays (**0.5 keV – 10 keV**) absorption length **1 µm – 100 µm**.
- Visible range **0.05 µm – 7 µm** color imaging without filters.
- Large area (up to 20 x 20 cm^2) and small pixel pitch (down to 1 µm) are key characteristics for **Synchrotron Light Sources** and **Free Electrons Lasers**.

Common ground – ^{55}Fe (5.9 keV) with depleted MAPS (LePix)



Main peak (5.9 keV)
m: 5.90 keV (269 ADC)
σ: 136 eV (6.2 ADC)

Small peak (6.49 keV)
m: 6.45 keV (294 ADC)
σ: 143 eV (6.5 ADC)

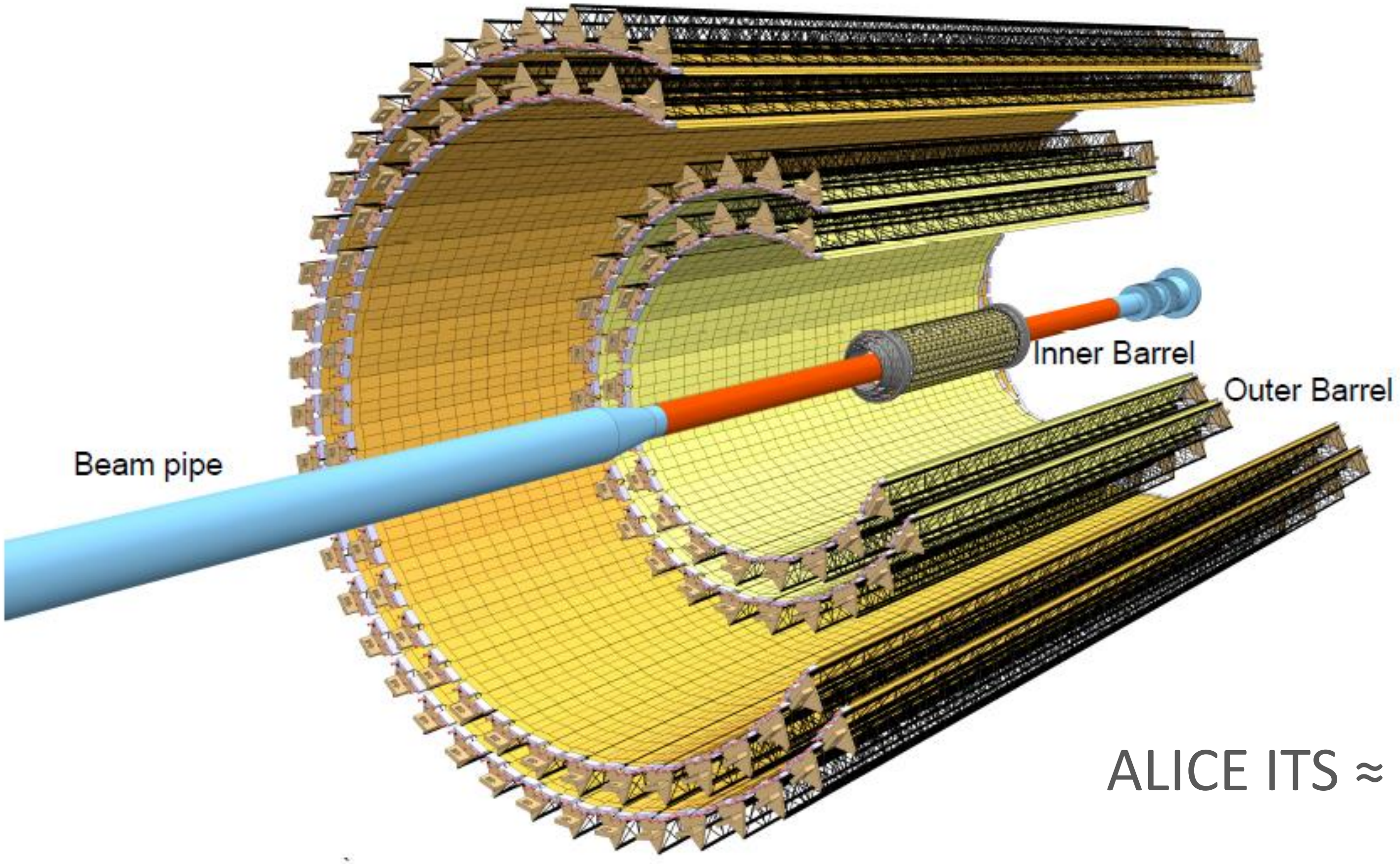
At room temperature, full matrix running

Clever architecture

Assuming we implemented all previous technical tricks and squeezed the ultimate S/N out of our pixels, how can we effectively retrieve all data out of the matrix maintaining the low power goal?

1. ALICE Inner Tracking System pALPIDE prototype.
2. Ultra low power – large area OrthoPix prototype.
3. I'm sure no time for this: large TEM detectors.

pALPIDE pixel detector

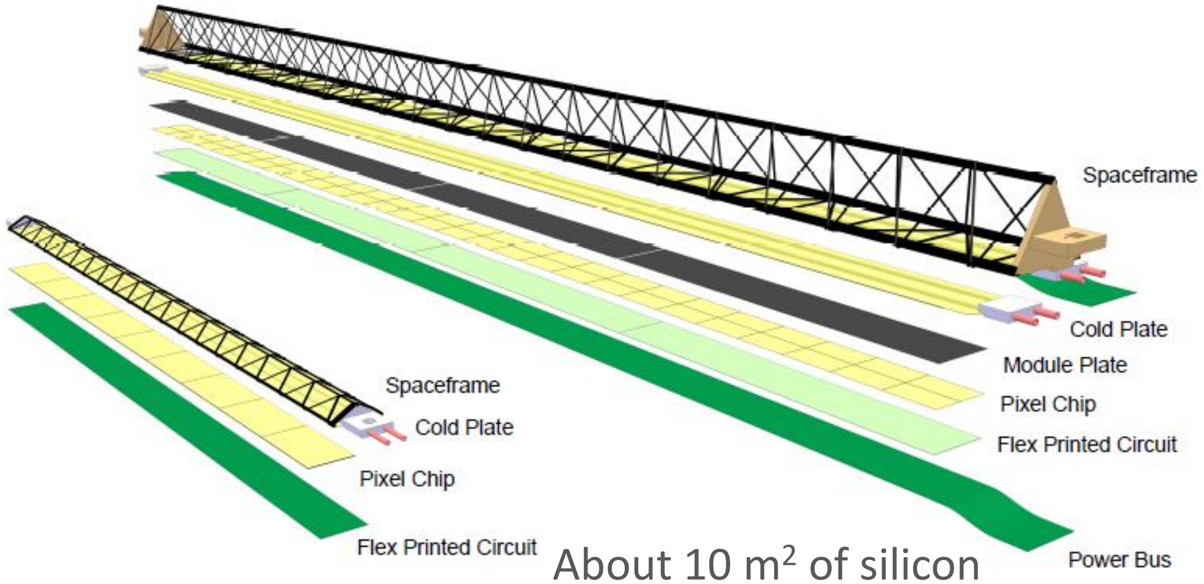


ALICE ITS ≈ 10 m^2

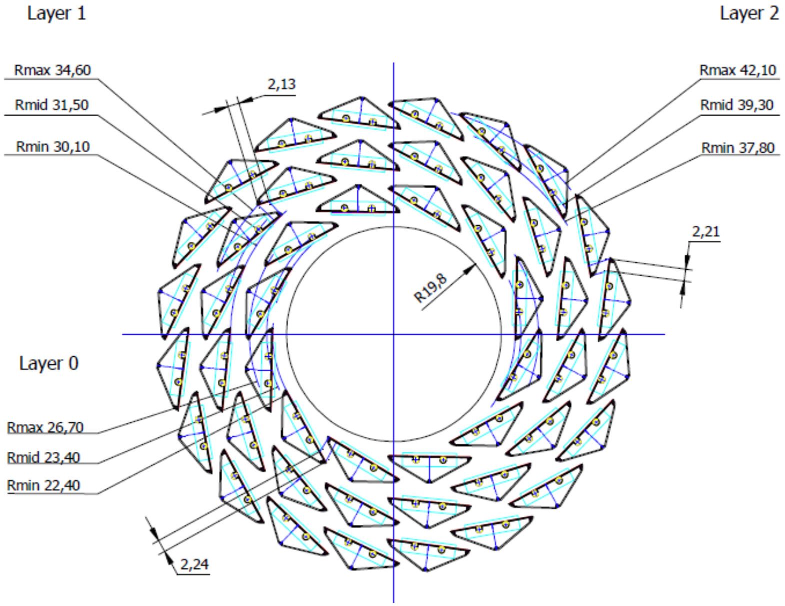
pALPIDE – ALICE Inner Tracking System specifications

- Improve impact parameter resolution by a factor of ≈ 3
- Get closer to IP (position of first layer): 39 mm to 22mm
- Reduce material budget: X/X_0 per layer: from 1.14% to 0.3% (inner layers)
- Reduce pixel size (currently 50 µm x 425 µm) by using to monolithic pixels: foreseen size ranging from 20 µm x 20 µm to 40 µm x 40 µm (roughly).
- Improve tracking efficiency and resolution at low pT
- Increase granularity, reduced pixel size: from 6 to 7 layers
- Fast readout of Pb-Pb interactions at > 50 kHz and pp interactions at ~ MHz.
- Fast insertion/removal for yearly maintenance.
- Possibility to replace non functioning detector modules during yearly shutdown

pALPIDE – ALICE Inner Tracking System specifications



About 10 m^2 of silicon

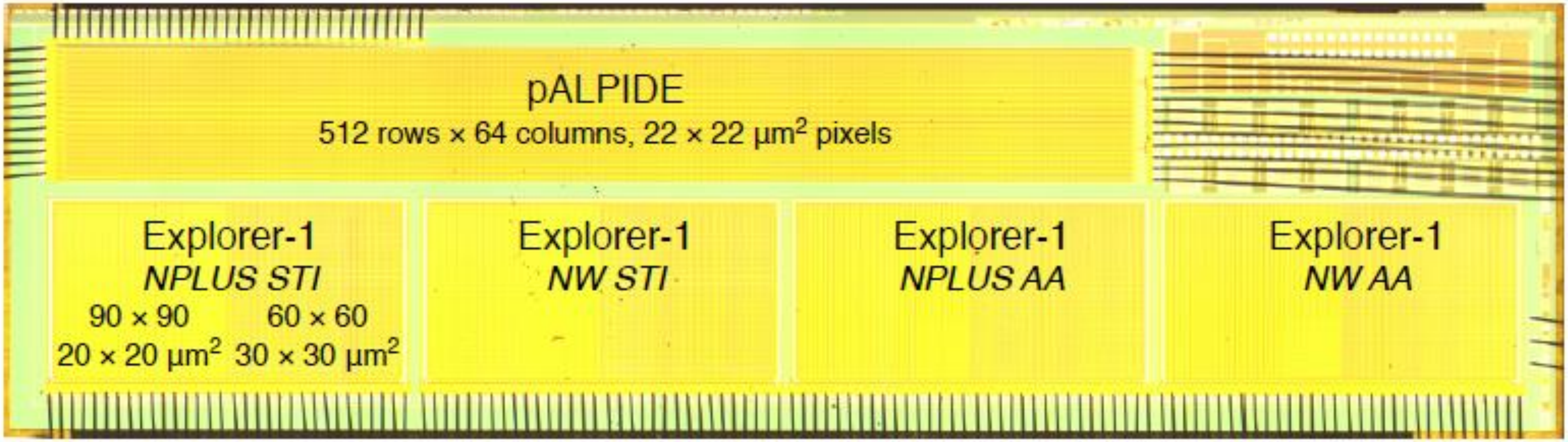


	Inner			Middle		Outer	
Layer	0	1	2	3	4	5	6
Position [mm]	23	32	39	196	245	344	393
Particles [10^{-5}s cm^{-2}]	30	20	15	1	0.7	0.3	0.3
NIEL [1 Mev n cm^{-2}]	9.2×10^{12}	6×10^{12}	3.8×10^{12}	5.4×10^{11}	5.0×10^{11}	4.8×10^{11}	4.6×10^{11}
TID [kGray]	6.46	3.8	2.16	0.15	0.1	0.08	0.06
Material [X_0 %]	0.3% X_0			0.8% X_0			
Data [Mbit chip^{-1}s^{-1}]	284	174	121	14	12	11	10

pALPIDE – overview

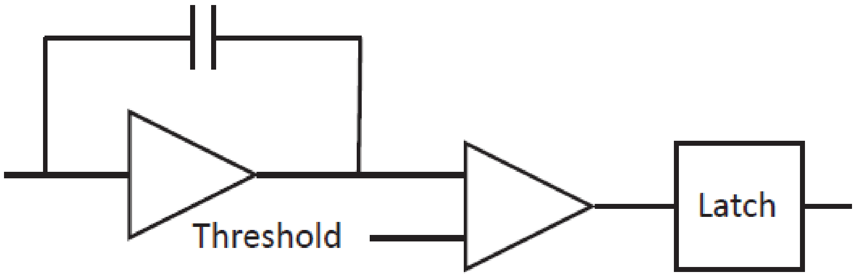
Developed jointly by Wuhan, INFN, and CERN, is one of the prototypes under evaluation to equip the ALICE Inner Tracking System.

- Tower-Jazz 0.18 µm process, deep p-well, high Ω epitaxial layer.
- New low-power in-pixel discriminator front-end.
- Data-driven digital read-out (“priority encoder”).

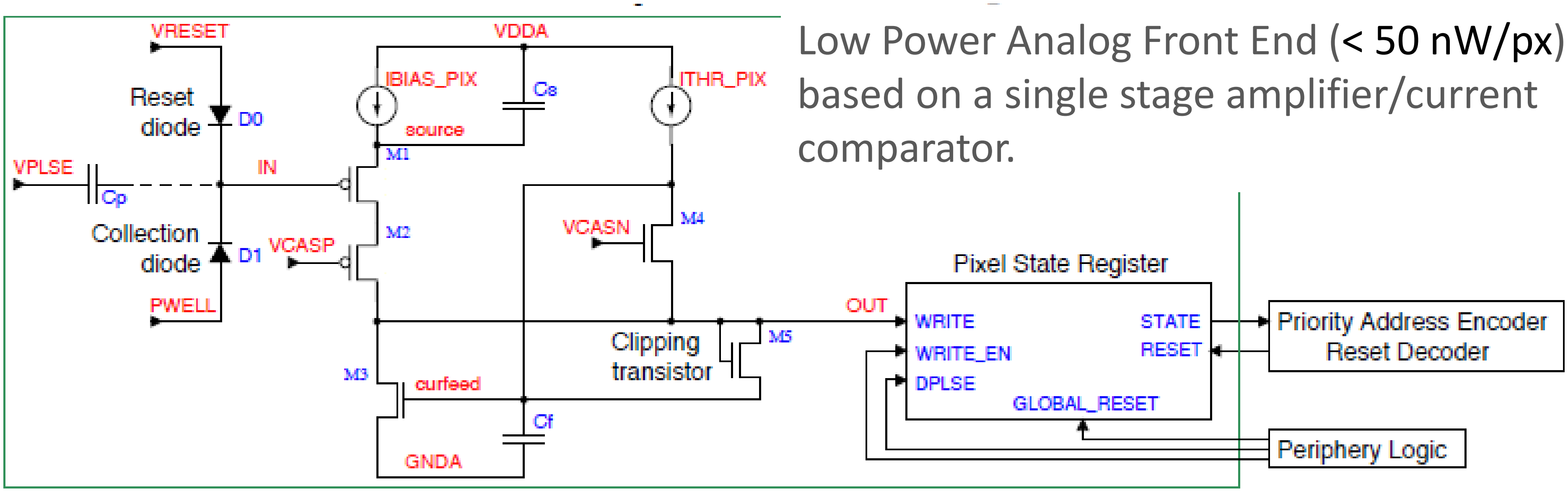


- 32 678 pixels of 22 µm × 22 µm (+ a few test pixels).
- Active area: 11.3 × 1.4 mm².
- Prototyped in four different versions and on seven different substrates.

pALPIDE – pixel cell schematic (simplified)



- AC sensitive circuit, always active.
- “Shaping time” ≈ 3 to 5 µs (in fieri).
- Hit latch inside each pixel (one).
- Global shutter capable (`WRITE_EN`).



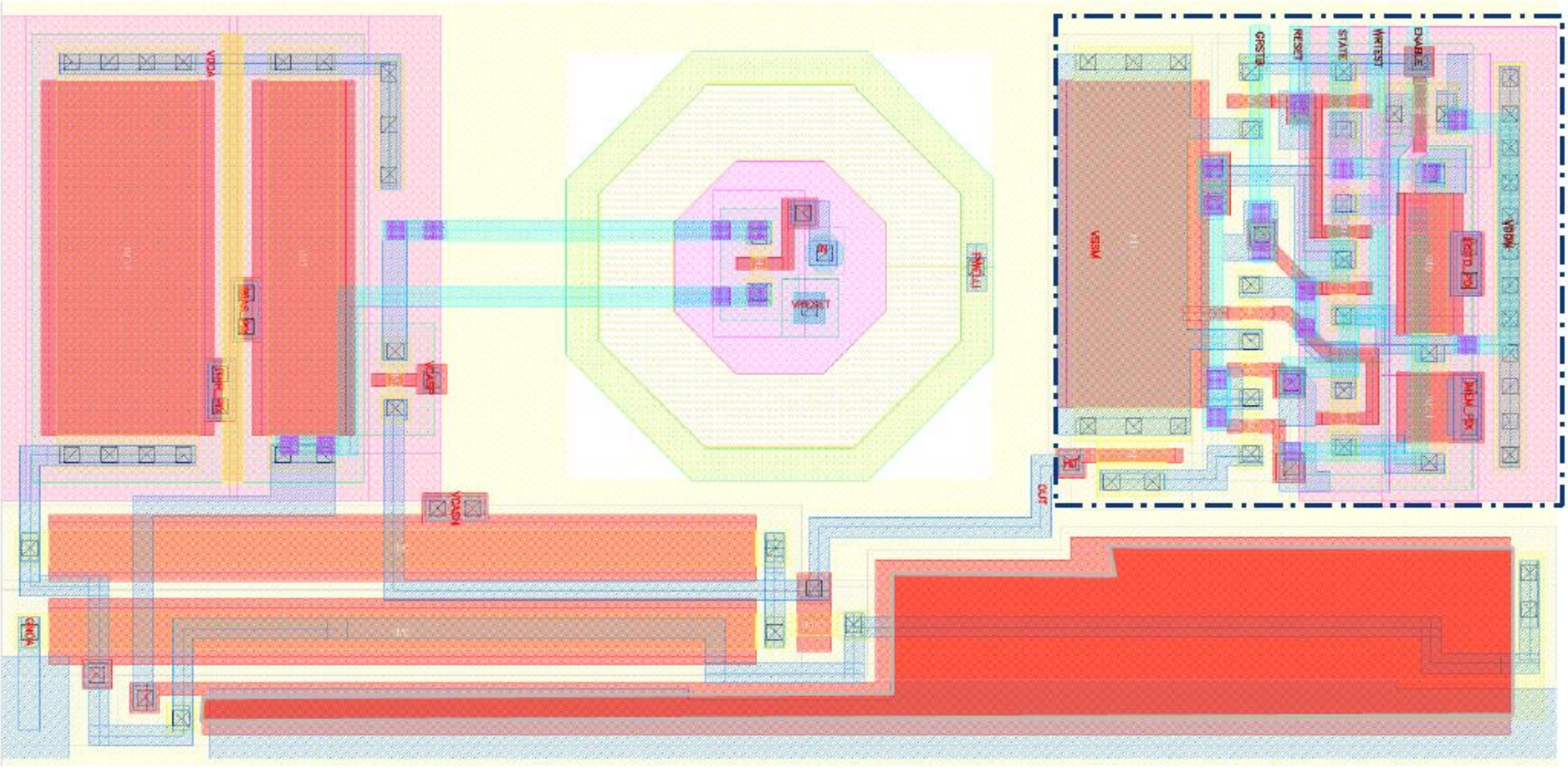
Low Power Analog Front End (< 50 nW/px) based on a single stage amplifier/current comparator.

pALPIDE – pixel cell layout

T. Kugathasan

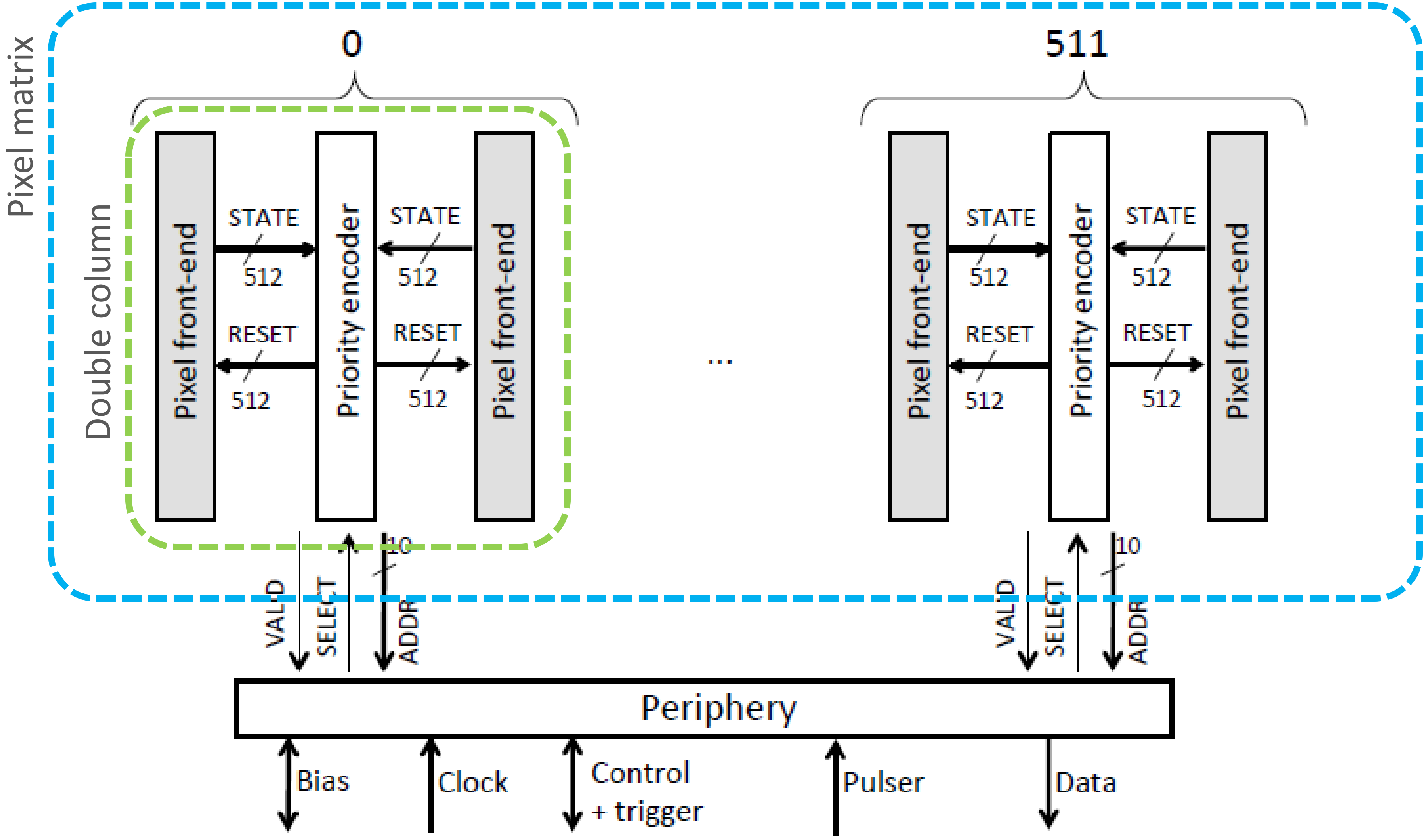
Block Size: 10.5 x 22.0 µm²

Memory size: 6.9 x 7.3 µm²



All circuitry in deep p-well, except for the collection node.

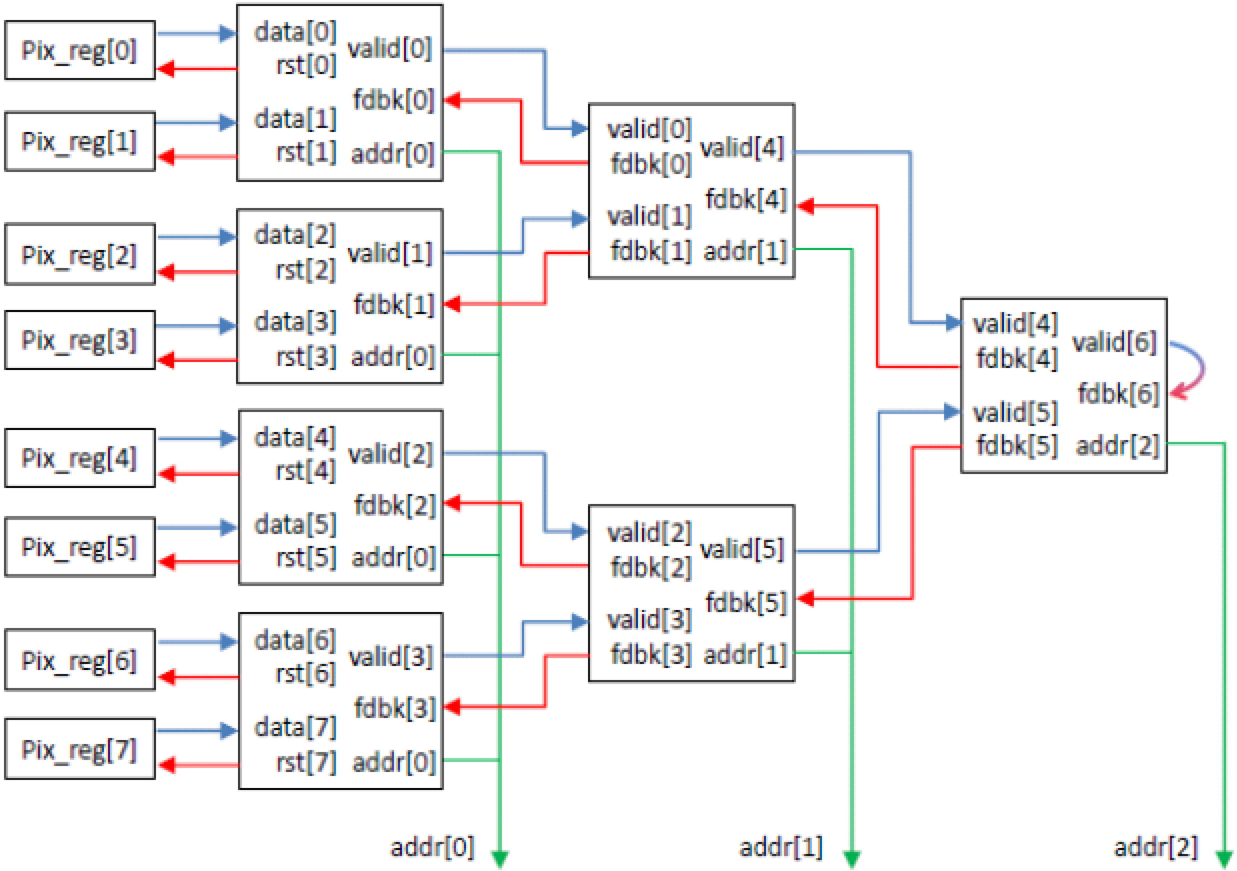
pALPIDE – global architecture



- Double column with mixed analog/digital cells.
- Asynchronous matrix readout through “priority encoder” (see next slides).

pALPIDE – priority encoder addressing

T. Kugathasan



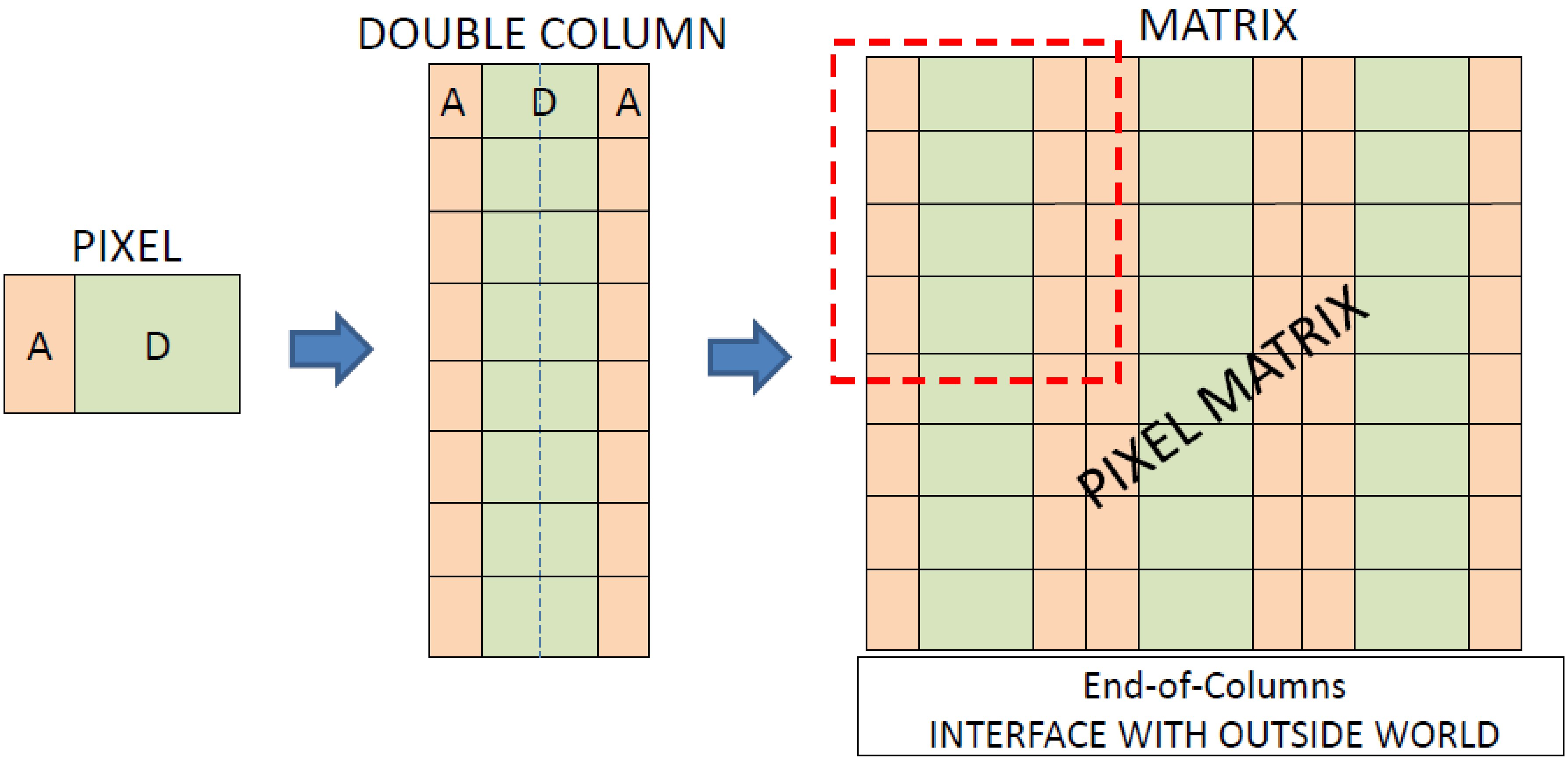
$$N_{stages} = log_b(N)$$

$$N_{blocks} = \frac{N-1}{b-1}$$

N is the total number of pixels to read and b is the basic block inputs

- Each clock cycle the highest priority pixel address is read out (and reset).
- Pixel address readout time: 20 ns / address (@ 50 MHz)
- Asynchronous circuit with no clock propagation into the pixel matrix (combinatorial logic to manage the reset): power & noise reduction.

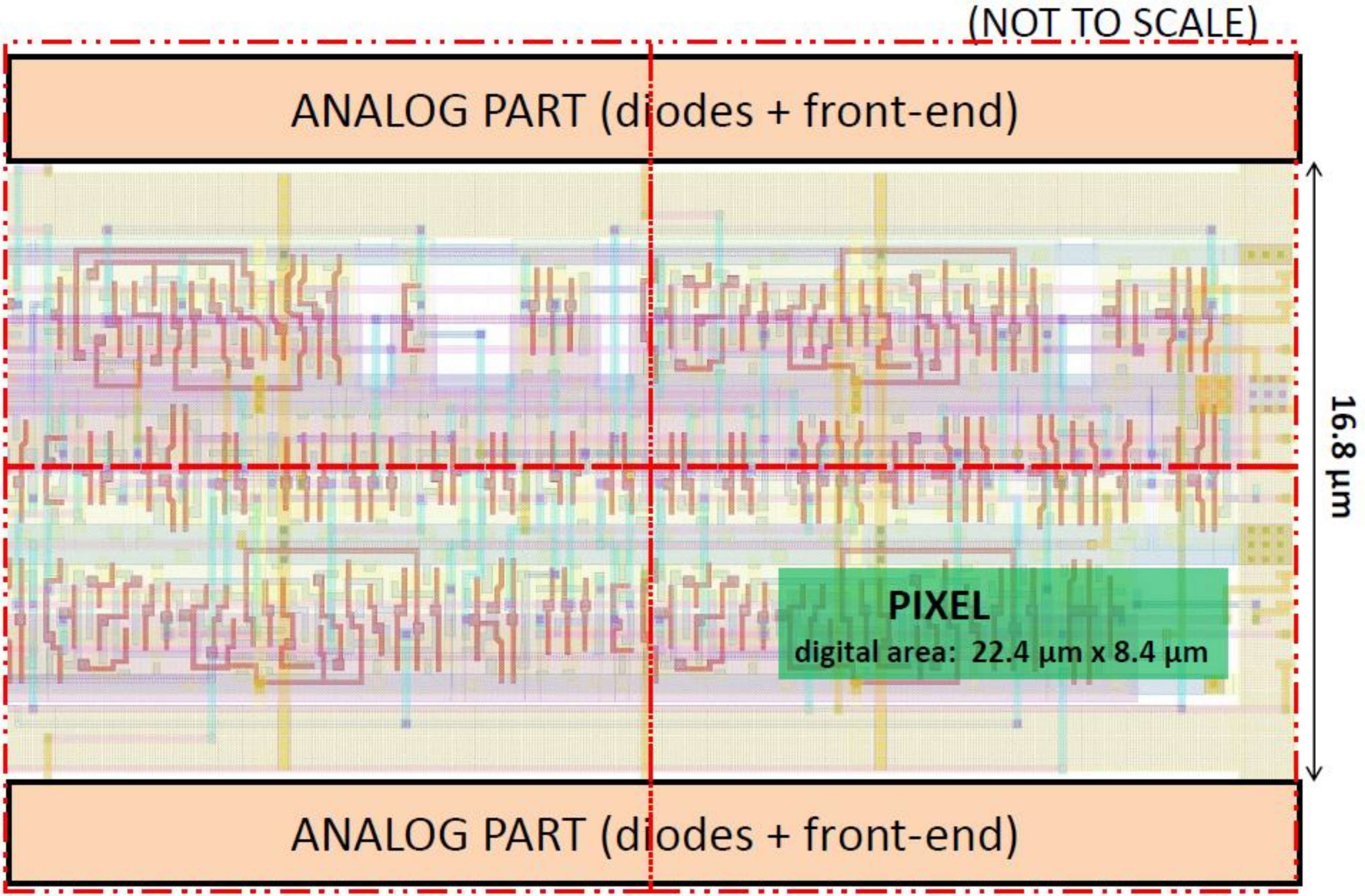
pALPIDE – matrix structure



Pixels arranged in columns: 2 adjacent, mirrored, columns share the same digital area. After a trigger, read only the active pixels, then reset them. Possible readout architecture with priority encoder: basic cell of 4 pixels repeated.

pALPIDE – pixel cell analog/digital in pixel cell

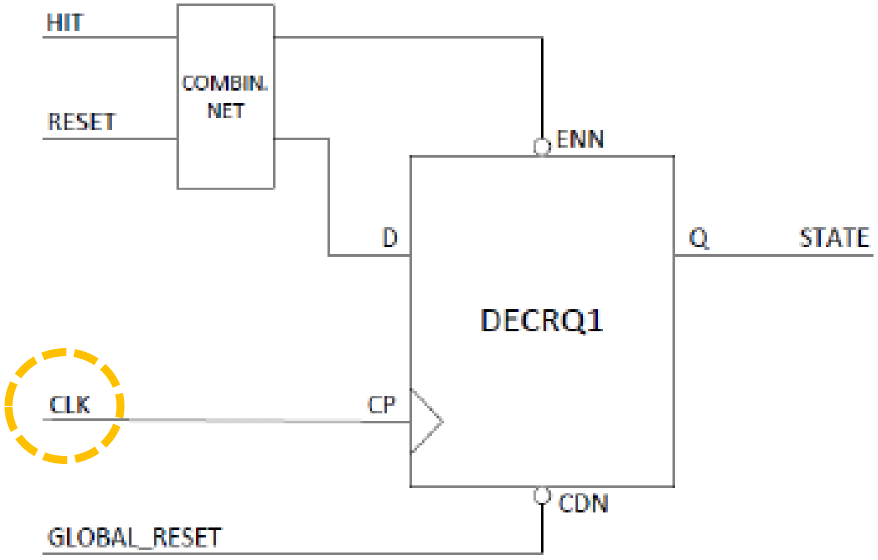
T. Kugathasan



pALPIDE – priority encoder synch or asynch implementation

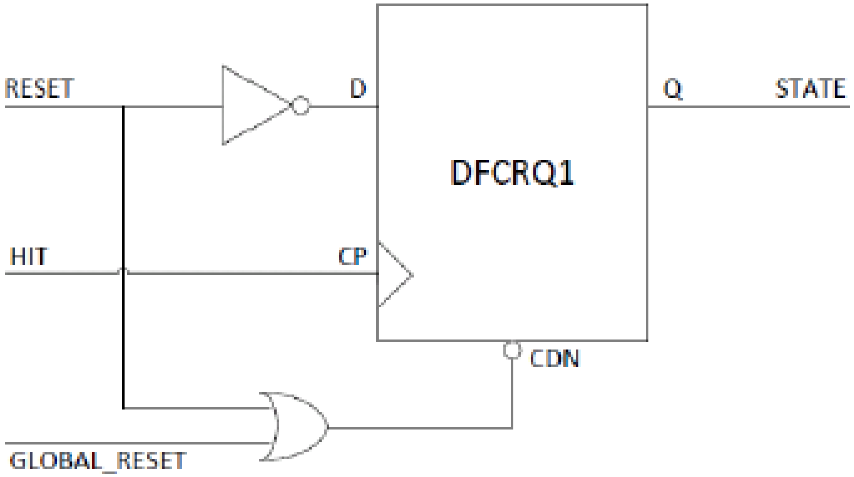
T. Kugathasan

Synchronous



- **Easy encoding** of hit data
- Few logic (**smaller pixel area,** 1 FF)
- Clock through the matrix: switching problems, power consumption

Asynchronous



- No clock propagation: **lower power**
- Asynchronous hit encoding
- Needs more logic to ensure proper reset: larger pixel area

pALPIDE – priority encoder synch or asynch power consumption

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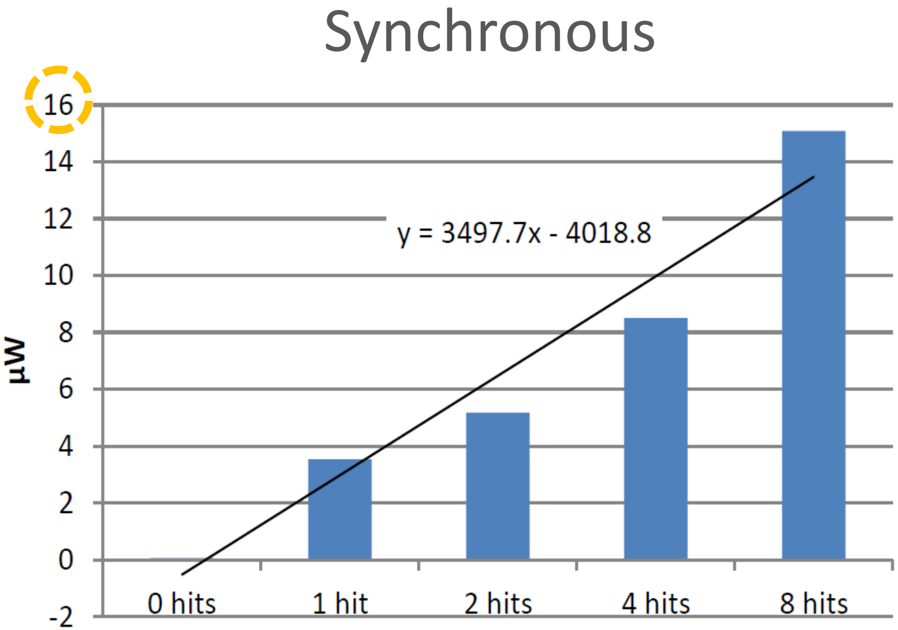
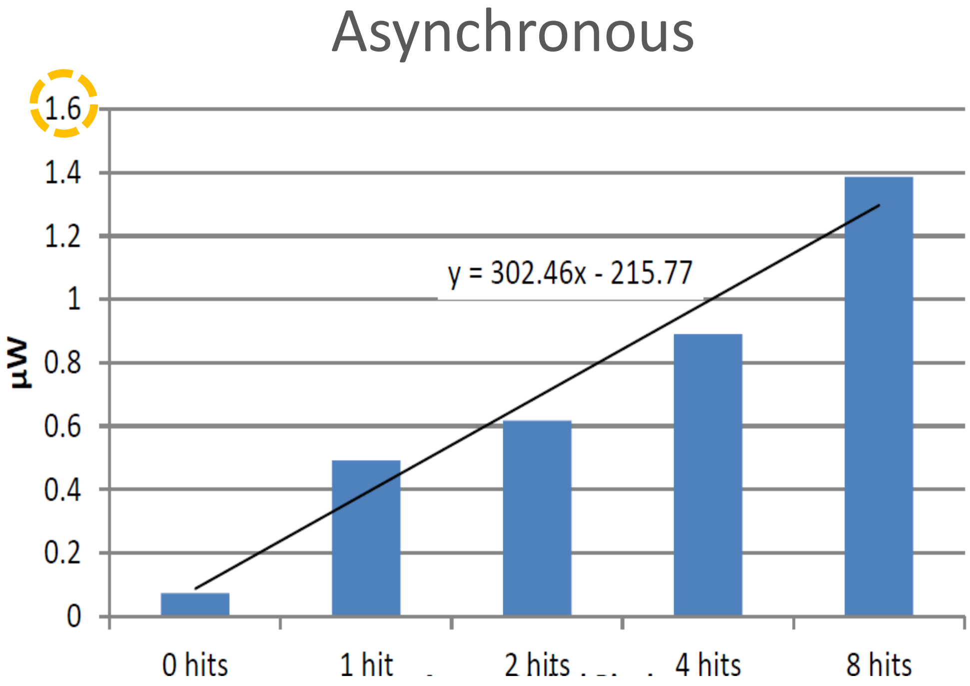


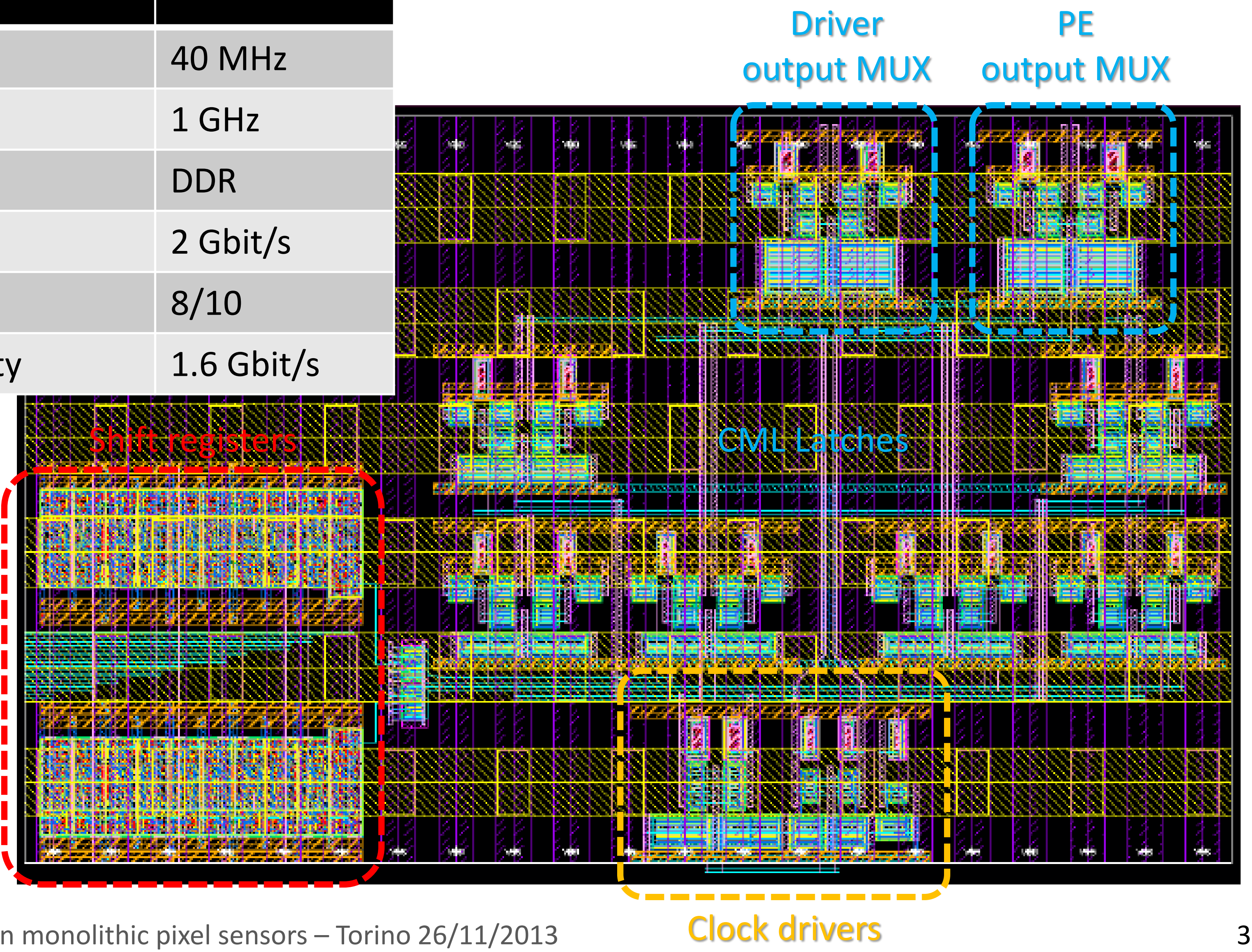


- Always reset the pixel with higher priority (less significant bit).
- Asynchronous combinatorial logic to manage the reset.
- Readout time logarithmically dependent on pixel count.

pALPIDE – serializer and driver at the periphery

G. Mazza

Ask people here!	
Input clock	40 MHz
Transmission clock	1 GHz
Transmission type	DDR
Line rate	2 Gbit/s
Line encoding	8/10
Effective line capacity	1.6 Gbit/s



pALPIDE – temporary summary

Power

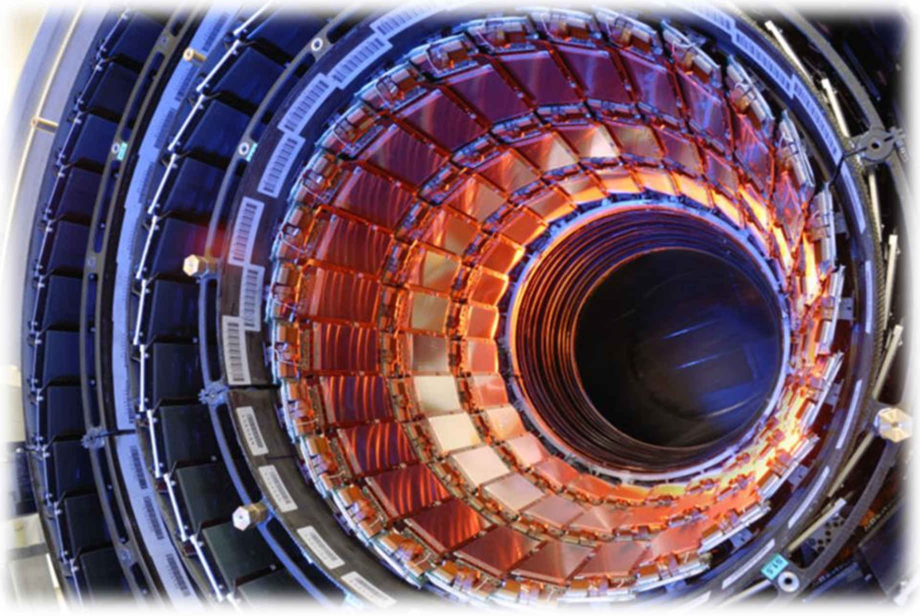
Source	Power
Analog front end: 40 nW * 250000 pixels	10 – 15 mW cm^{-2}
Digital readout (simulations)	10 – 20 mW cm^{-2}
Data transmission (simulations)	5 – 15 mW cm^{-2}

Trying to approach 50 mW cm^{-2}

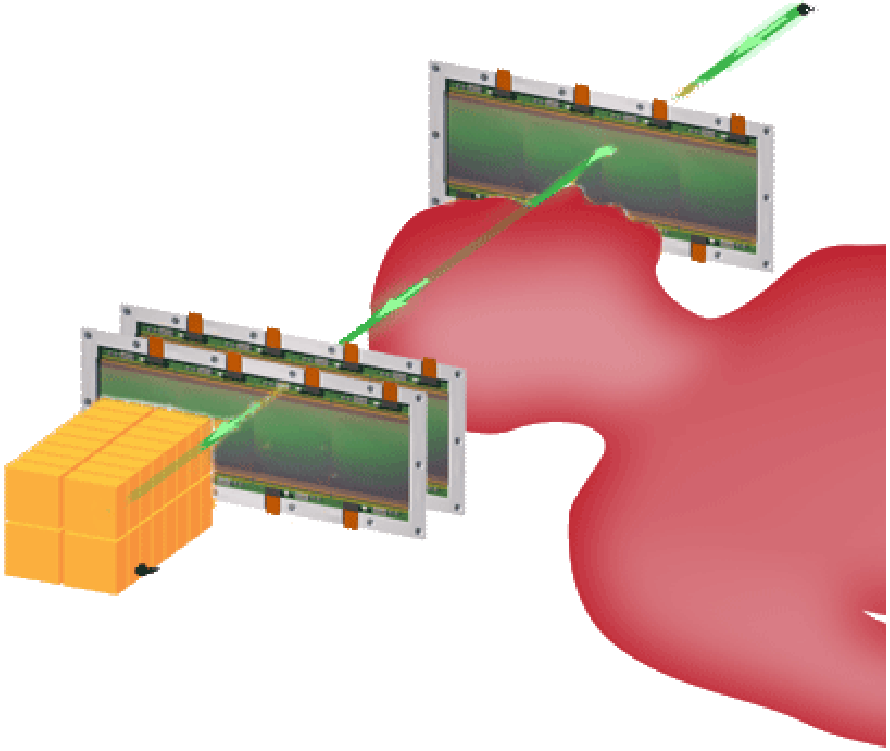
Speed

Region	Time
Rolling shutter, full matrix (@ 50 MHz)	≈20 µs
Priority encoder, 2 hit pixels over 512 × 32	≈40 ns
Priority encoder, 80 hit pixels over 512 × 32	≈1.6 µs

Pushing the limit: OrthoPix



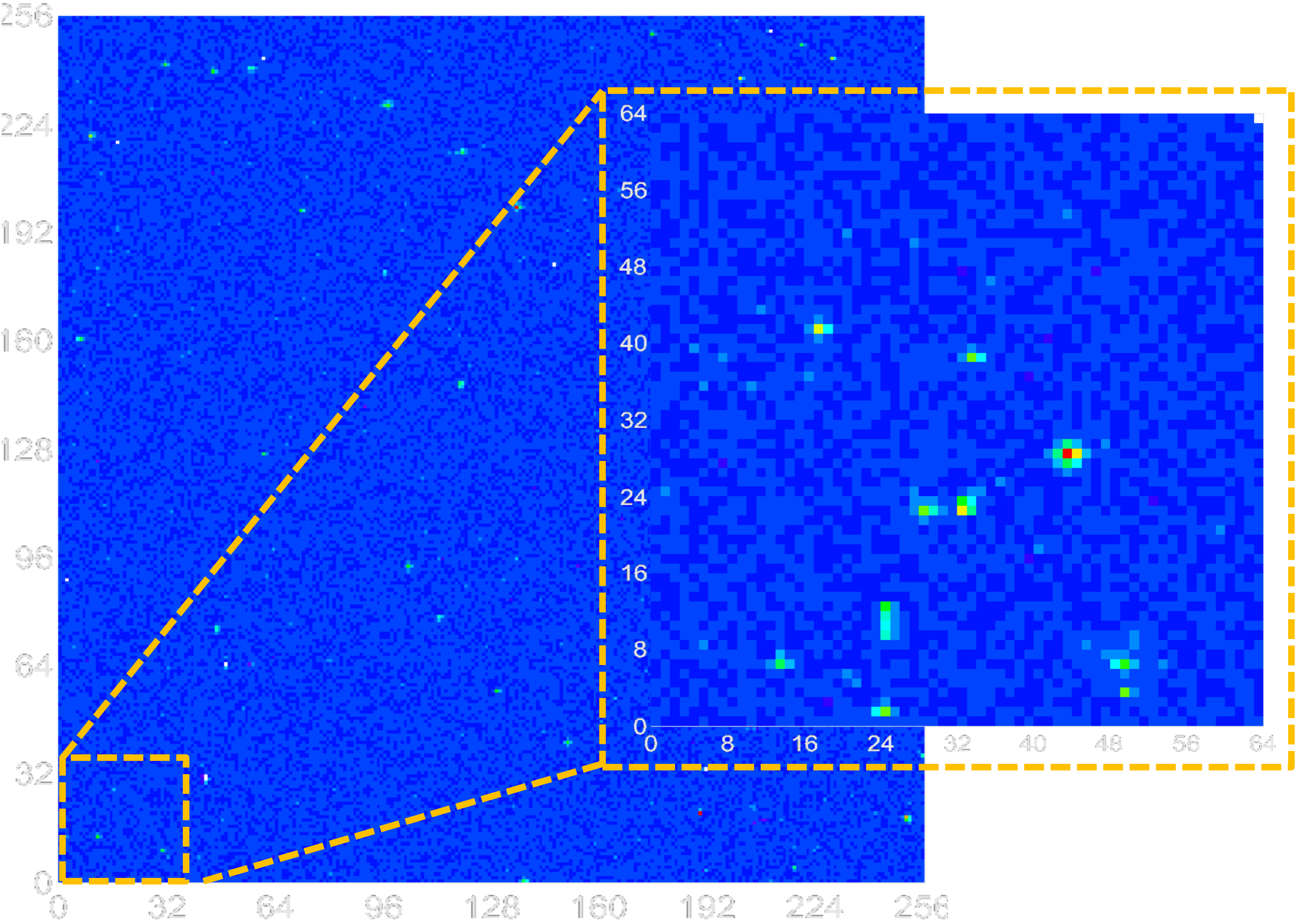
CMS tracker – 200 m^2



10^9 protons/s pCT

OrthoPix – the case: sparse populated "images"

Sparse populated image: only few % interesting pixels



High Energy Physics

Medical Imaging

Electron Microscopy

Many Others….

OrthoPix – zero suppression (sparsification) overview

! Current pixels (mostly hybrids but also monolithic) can do that

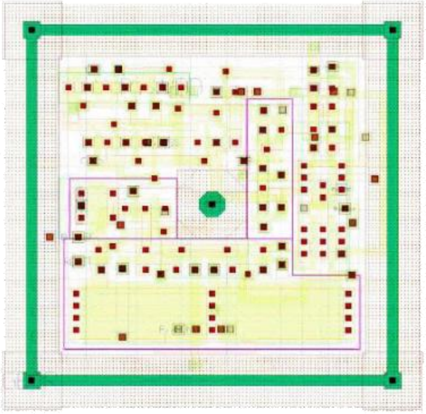
- Millions pixels and frame/s
- Counting, suppressing, compression, … in pixel!!
- Many successful applications (HEP, medical, light, …)

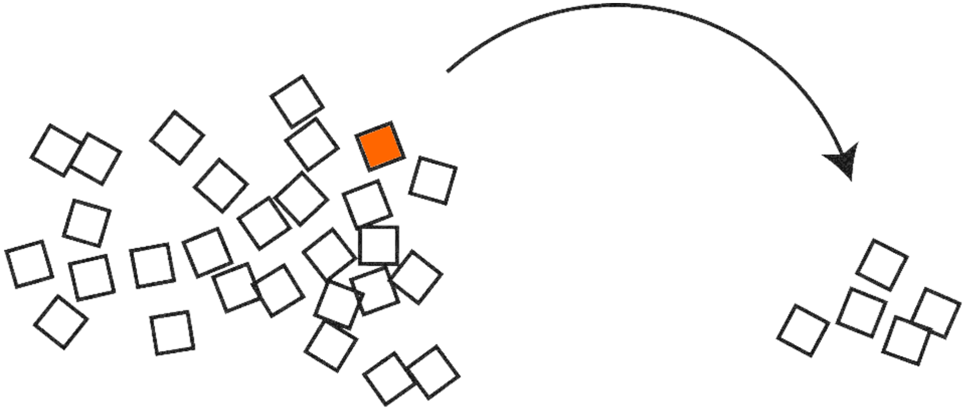
? But what if we need also any (combination) of the following?

- Very very large area detector (many m^2 scale)
- Low power consumption (<10 mW/cm^2)
- Low material budget (<50 µm thick)
- Small pixel pitch (<< 20 µm)
- Assembly simplicity and low cost

OrthoPix – zero suppression (sparsification) approaches

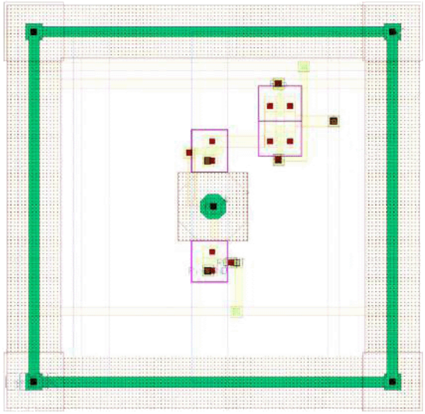
Intelligent pixels
(hybrid or not)

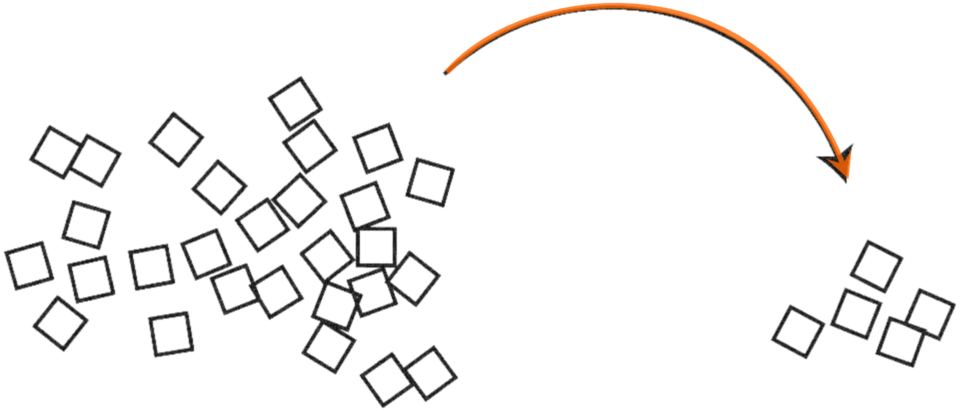




The pixel decides whether or not it is carrying data for the periphery. This requires **space and power.**

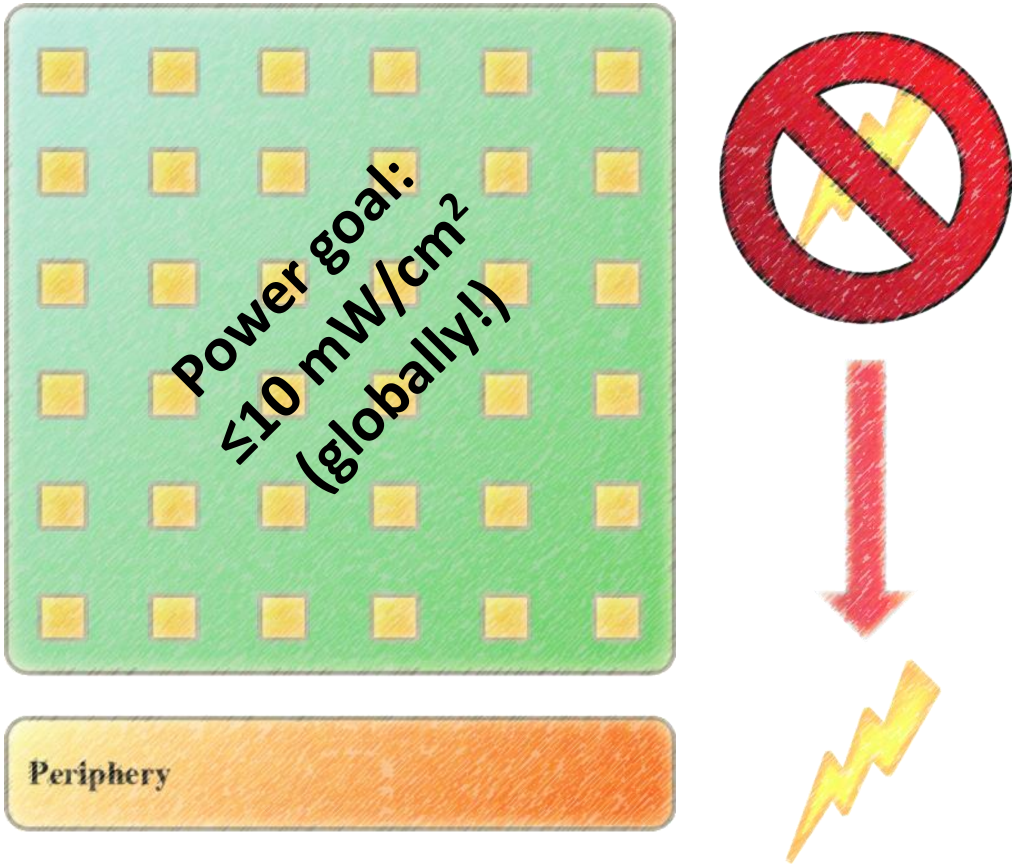
Dummy pixels





Pixel are connected to the periphery in a static way, and they are brainless. **Neither space nor power required.**

OrthoPix – reshaping power geography



Sparsification to limit the output bandwidth for high count and/or speed.

BUT

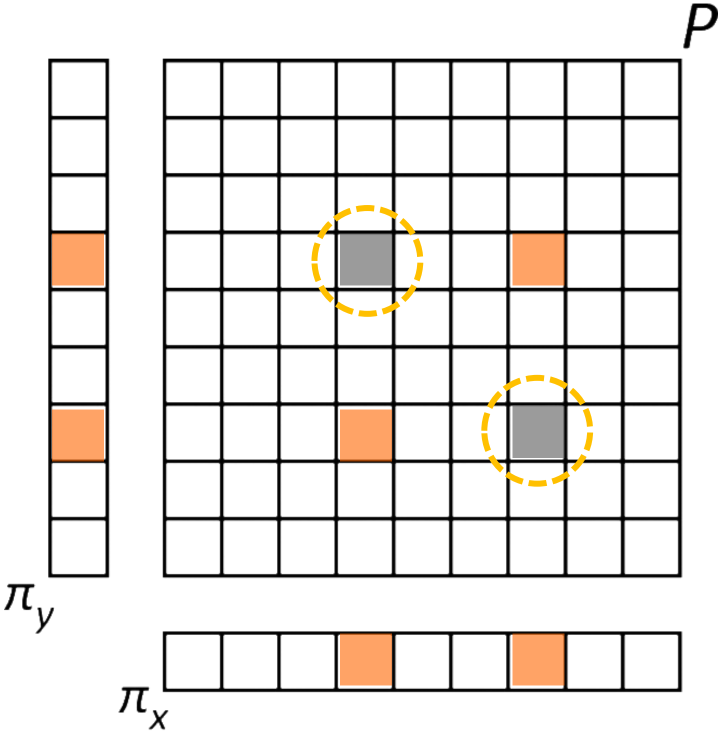
Carrying clock/data through the sensitive area is a power nightmare. (50 MHz clock over 2 cm easily 5-10 mW/cm^2)

IDEALLY

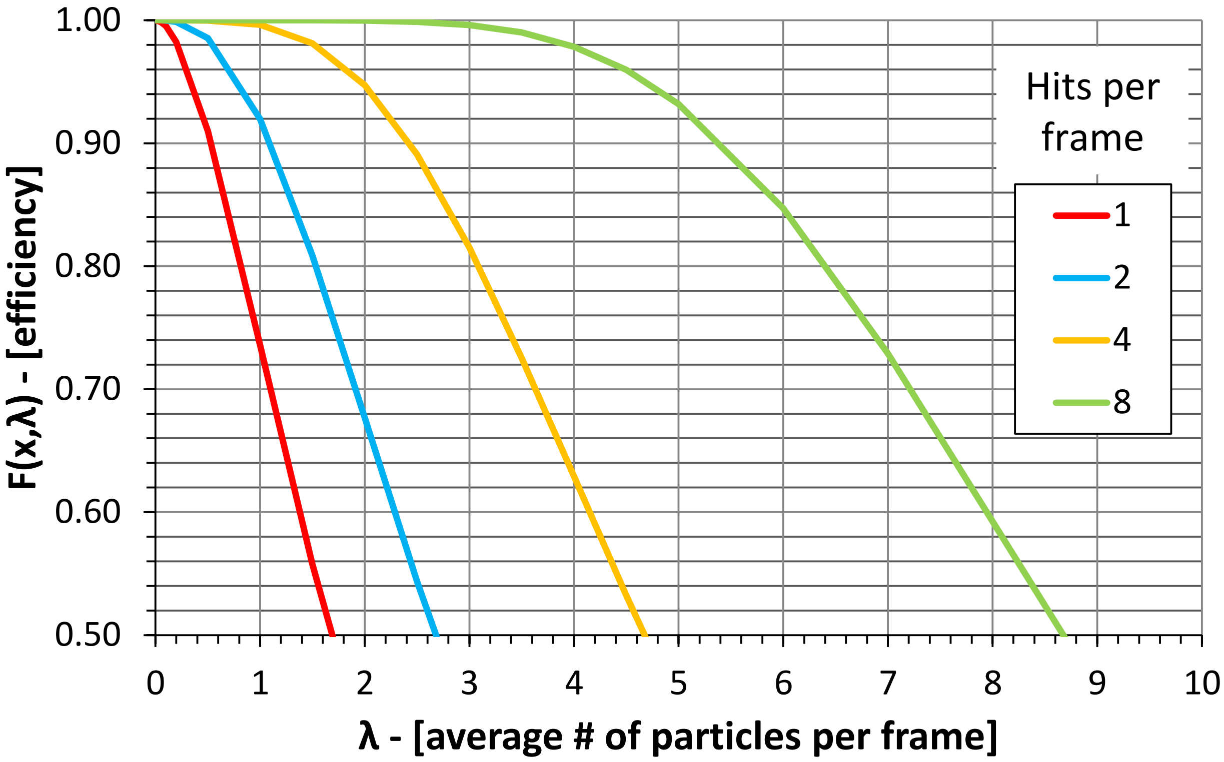
Everything should happen in the periphery. No clock around!

Moving power (and data) to the periphery allows for an easier and more effective cooling, hence for lower power consumption and material budget.

OrthoPix – starting point: xy projections and the Poisson limit



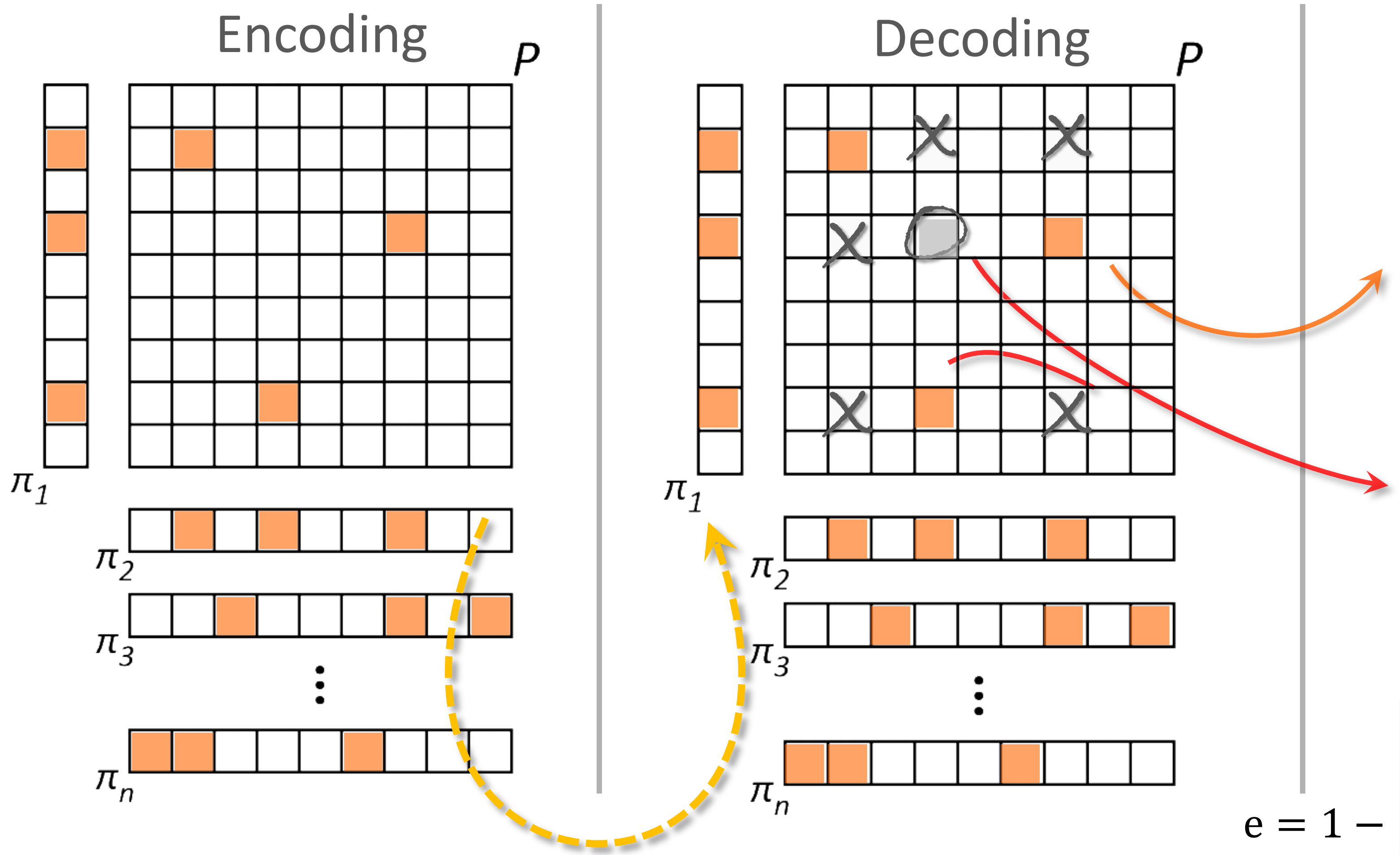
$$A = H^n - H$$



$$F(x,\lambda) = \sum_{i=0}^{x} \frac{e^{-\lambda}\lambda^{i}}{i!} = e^{-\lambda} \sum_{i=0}^{x} \frac{\lambda^{i}}{i!}$$

XY projections offer classic “static” compression, with the limit they fail in case of multiple hits: even at low occupancies Poisson stat is against you!

OrthoPix – using π_n: xy projections and the Poisson limit



Efficiency

(x_1,y_1)
(x_2,y_2)
…
(x_p,y_p)
(x_{p+1},y_{p+1})
(x_r,y_r)
…
(x_n,y_n)

$$e = 1 - \left[1 - \left(1 - \frac{1}{H}\right)^{\frac{(H^2-H)^{\frac{n}{2}}}{N^2}}\right]^n$$

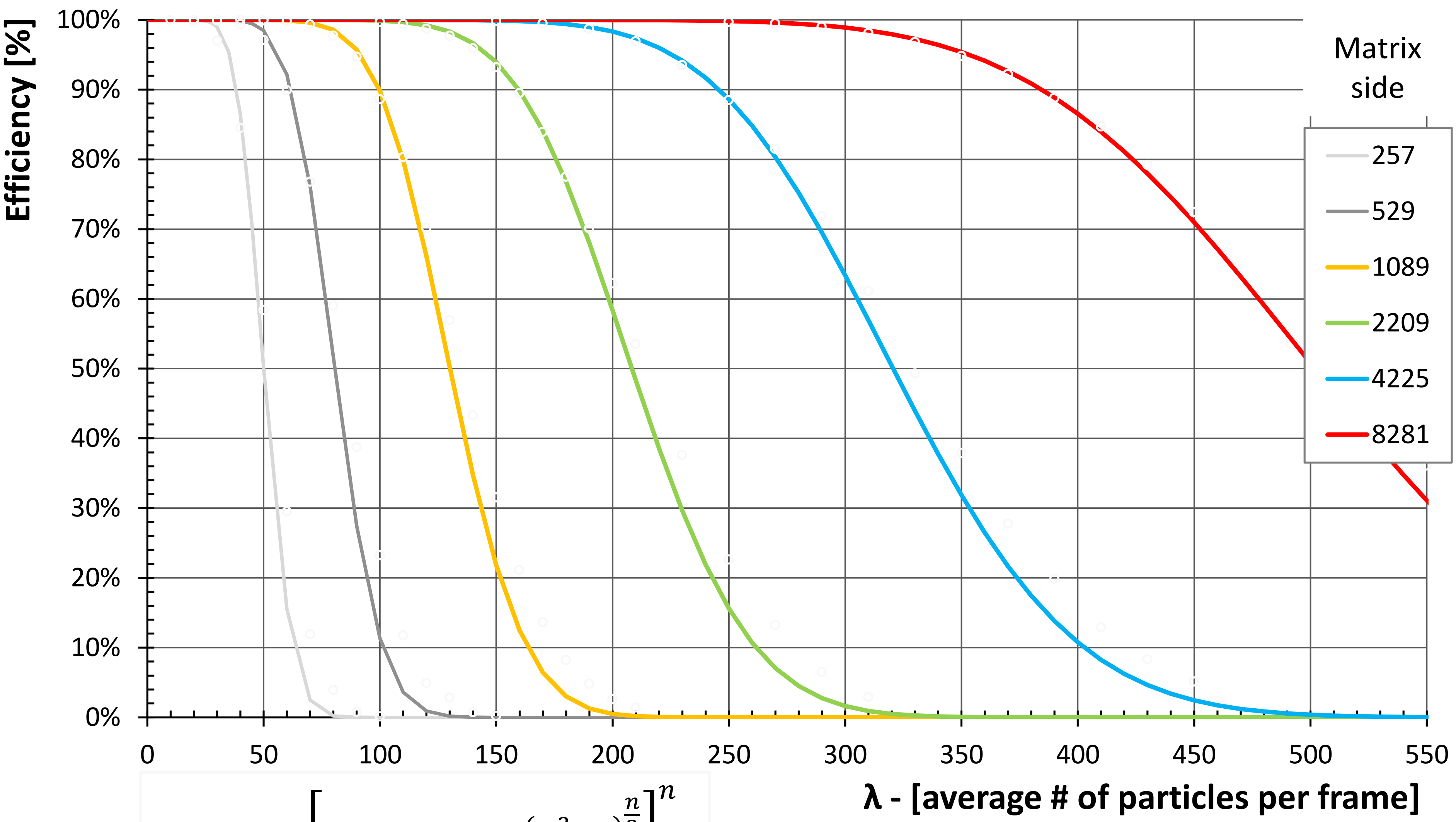
 # side pixels

$$compression = \frac{N}{n}$$

 # projections

We have a **math model** which states our maximal efficiency depending on the number of projections π implemented in the system.

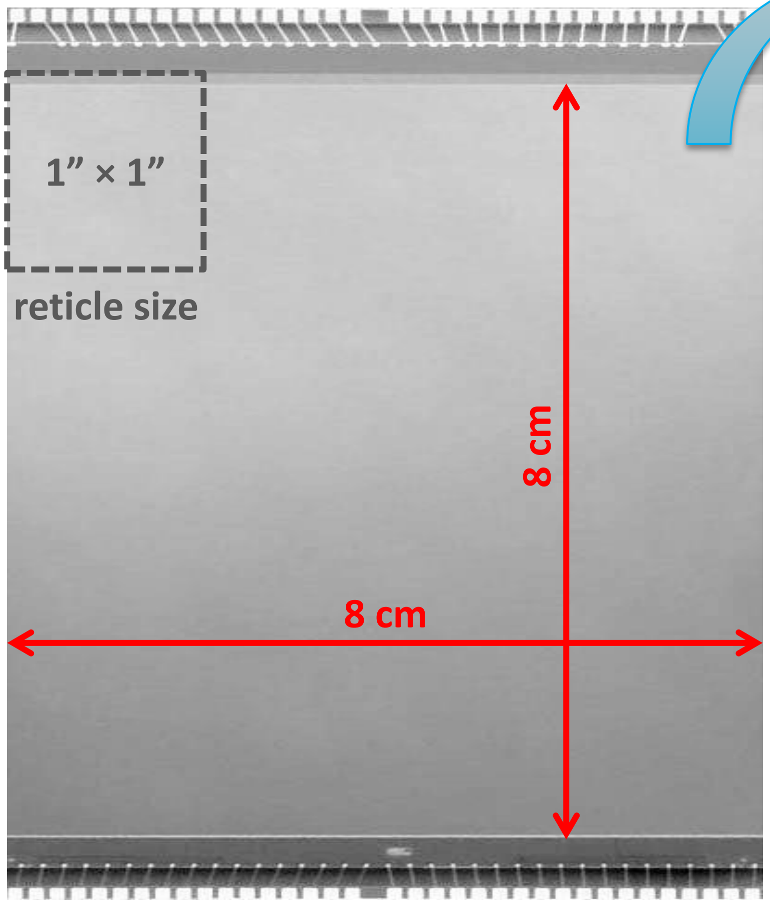
OrthoPix – using π_n: xy projections and the Poisson limit



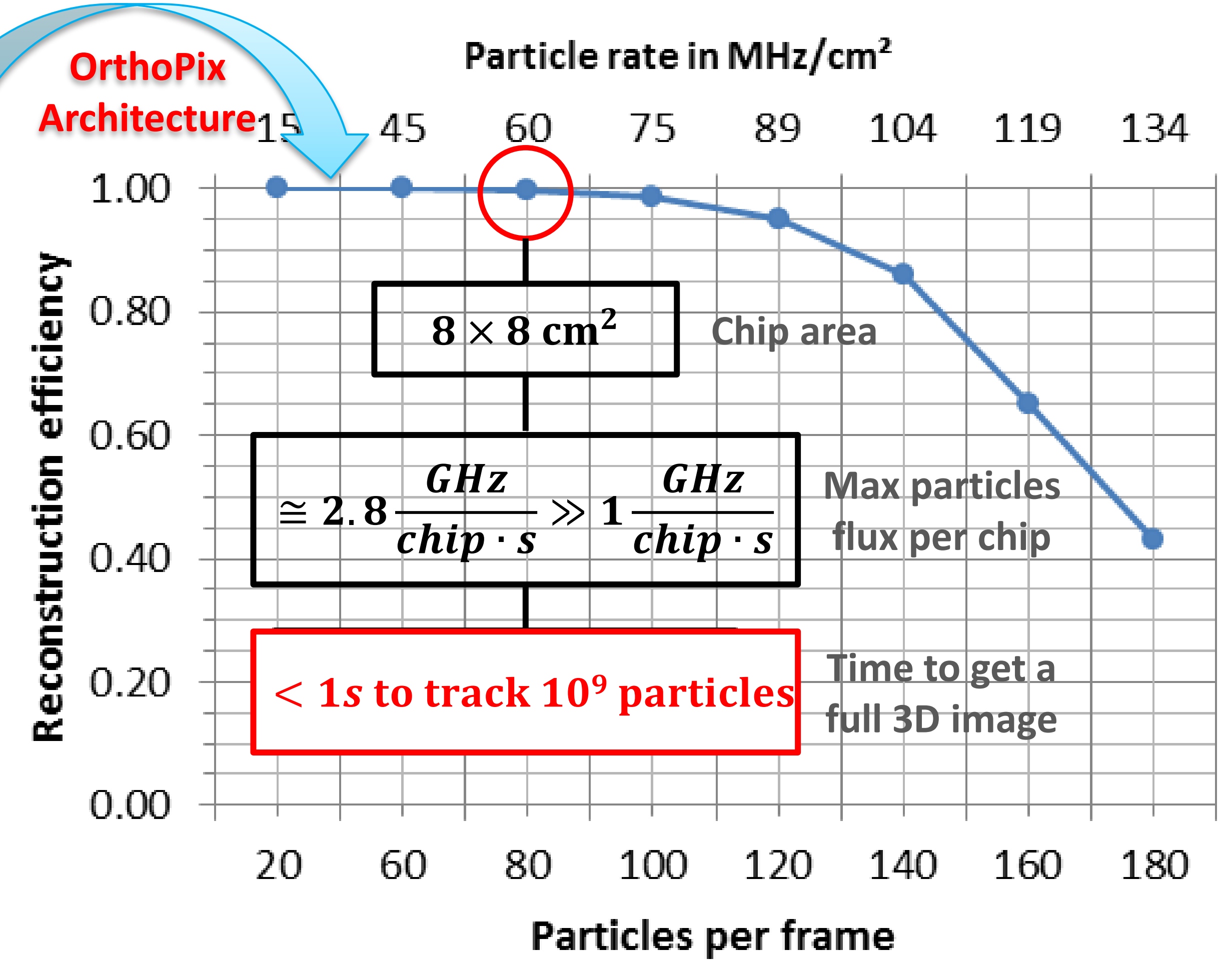
$$p = 1 - \left[1 - \left(1 - \frac{1}{H}\right)^{\frac{(H^2-H)^{\frac{n}{2}}}{N^2}}\right]^n$$

OrthoPix – what does it mean in practical applications?

To produce large area detector in a convenient way, big size chips are necessary. Stitching allows to produce single piece detector up to 10 cm side. OrthoPix can read them at **GHz speed** with **minimal power** (10 mW cm^{-2}) consumption.



4096 × 4096 pixels   20 × 20 µm^2 pixels

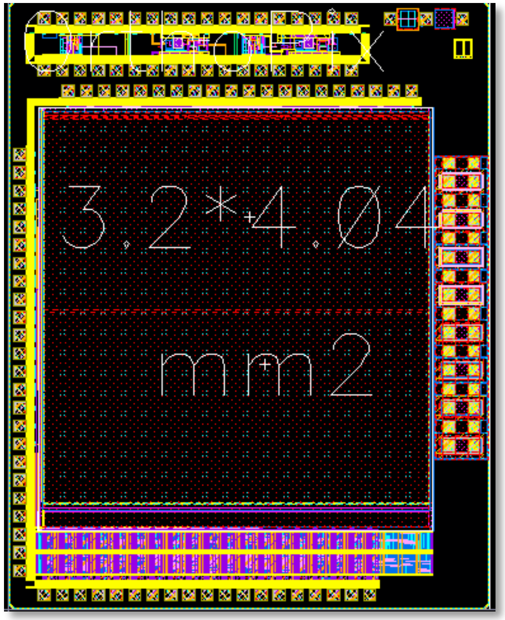


$8 \times 8\ \mathrm{cm}^2$ Chip area

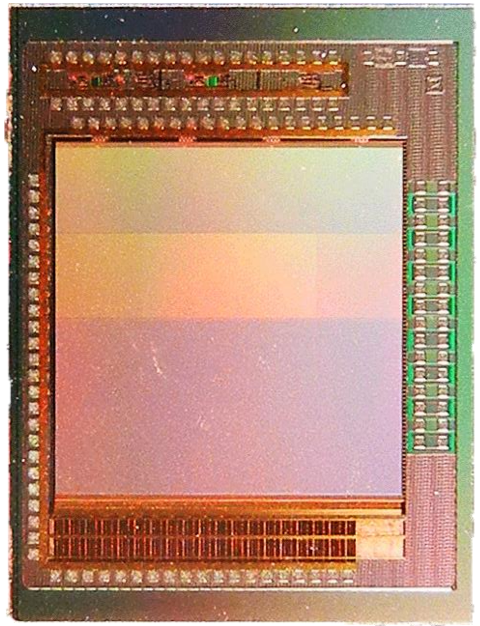
$\cong 2.8 \frac{GHz}{chip \cdot s} \gg 1 \frac{GHz}{chip \cdot s}$ Max particles flux per chip

$< 1s$ to track 10^9 particles Time to get a full 3D image

OrthoPix – a foolish dream? Actually no!



Designed in both standard **CMOS** and “specialty” **BJT** layout



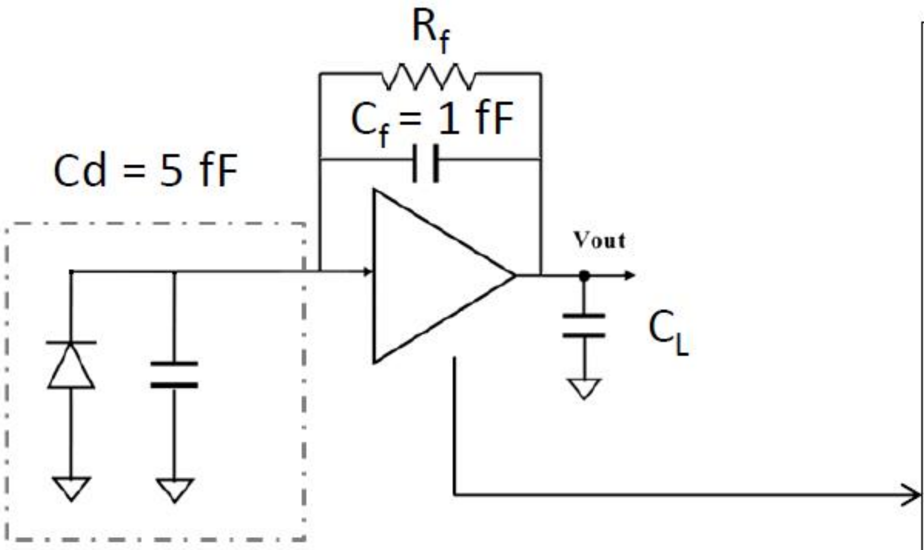
Realized in **Tower-Jazz 0.18** µm, various substrates thickness/resistivity.

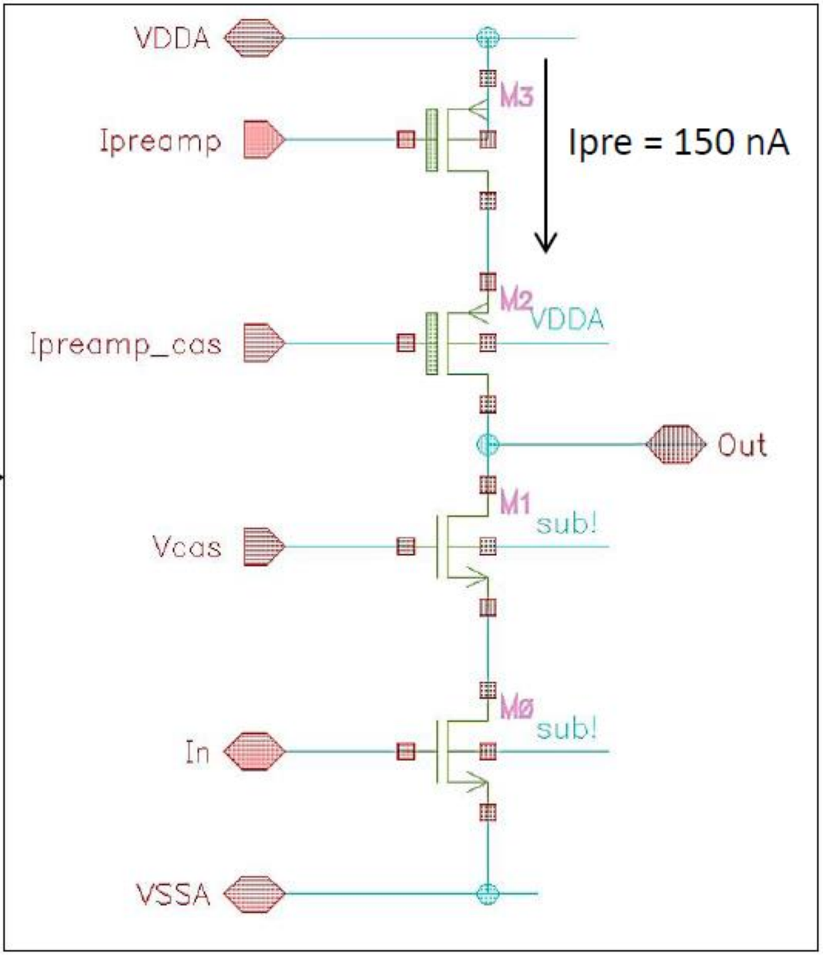
Just seen “**first light**” yesterday… a lot of testing to come!

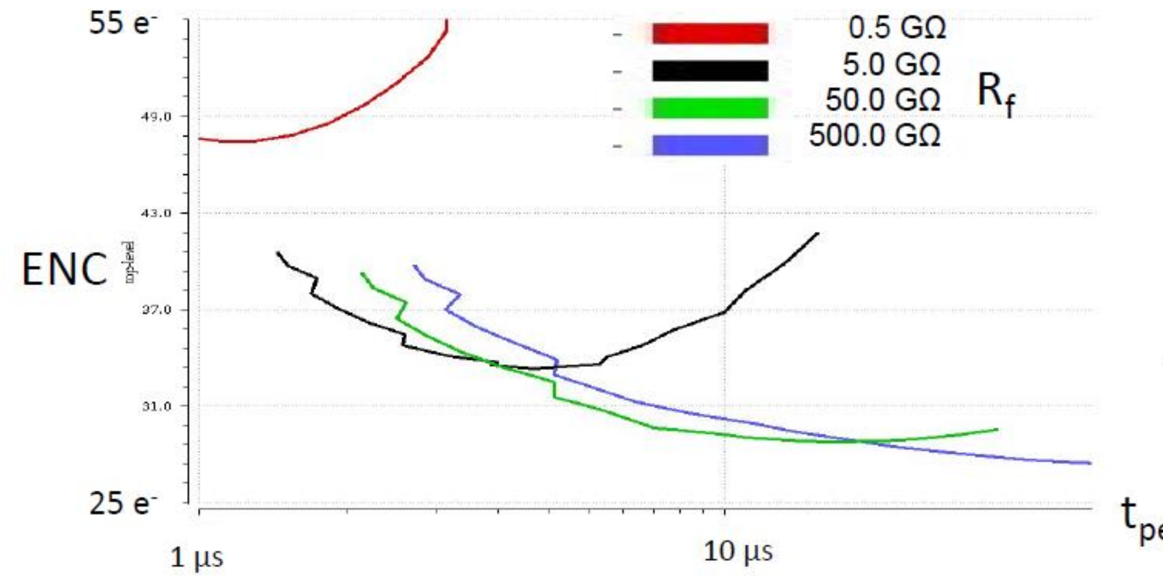
Backup slides

pALPIDE – pixel cell cascode amplifier details

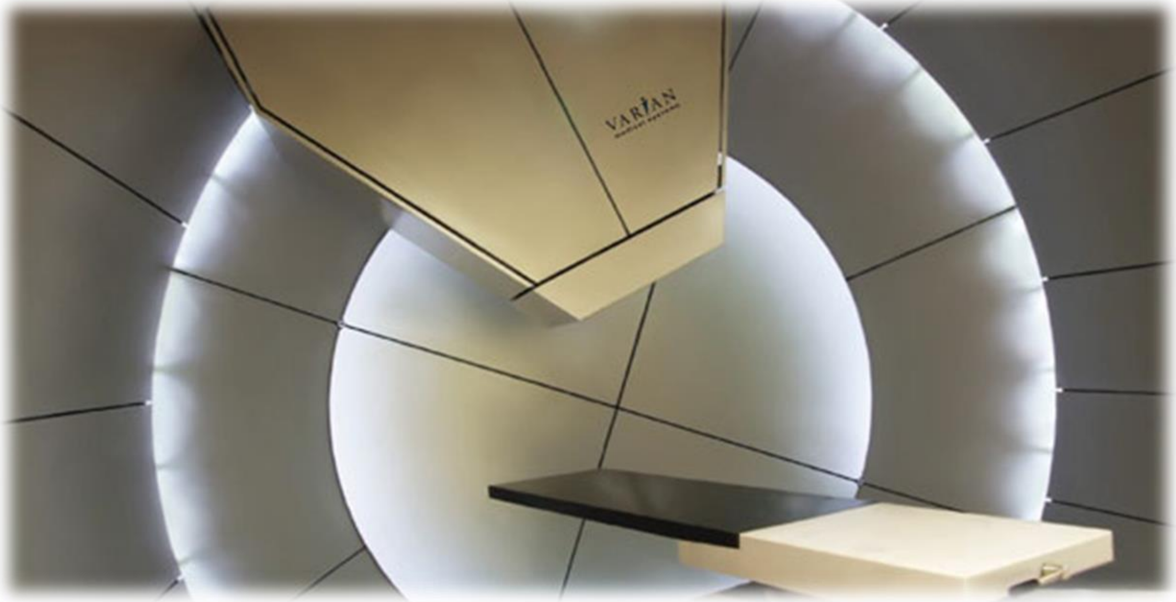
T. Kugathasan







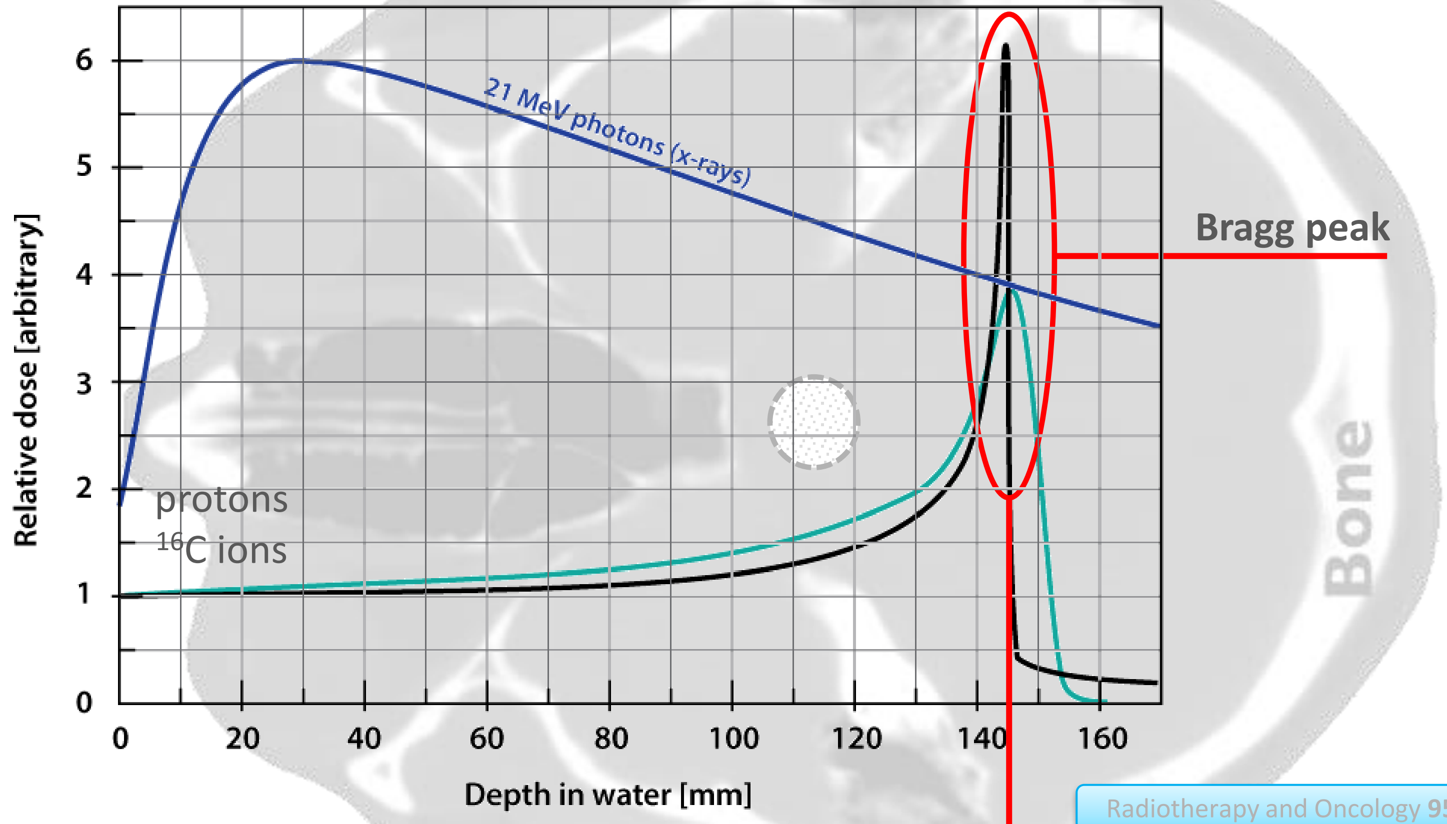
Rad hard CMOS for proton imaging



Proton therapy – physics rationale

Proton (ion) energy transfer is highly localized (Bragg peak): greater effectiveness and much lower collateral damage respect to traditional x-rays th

ionizing radiation



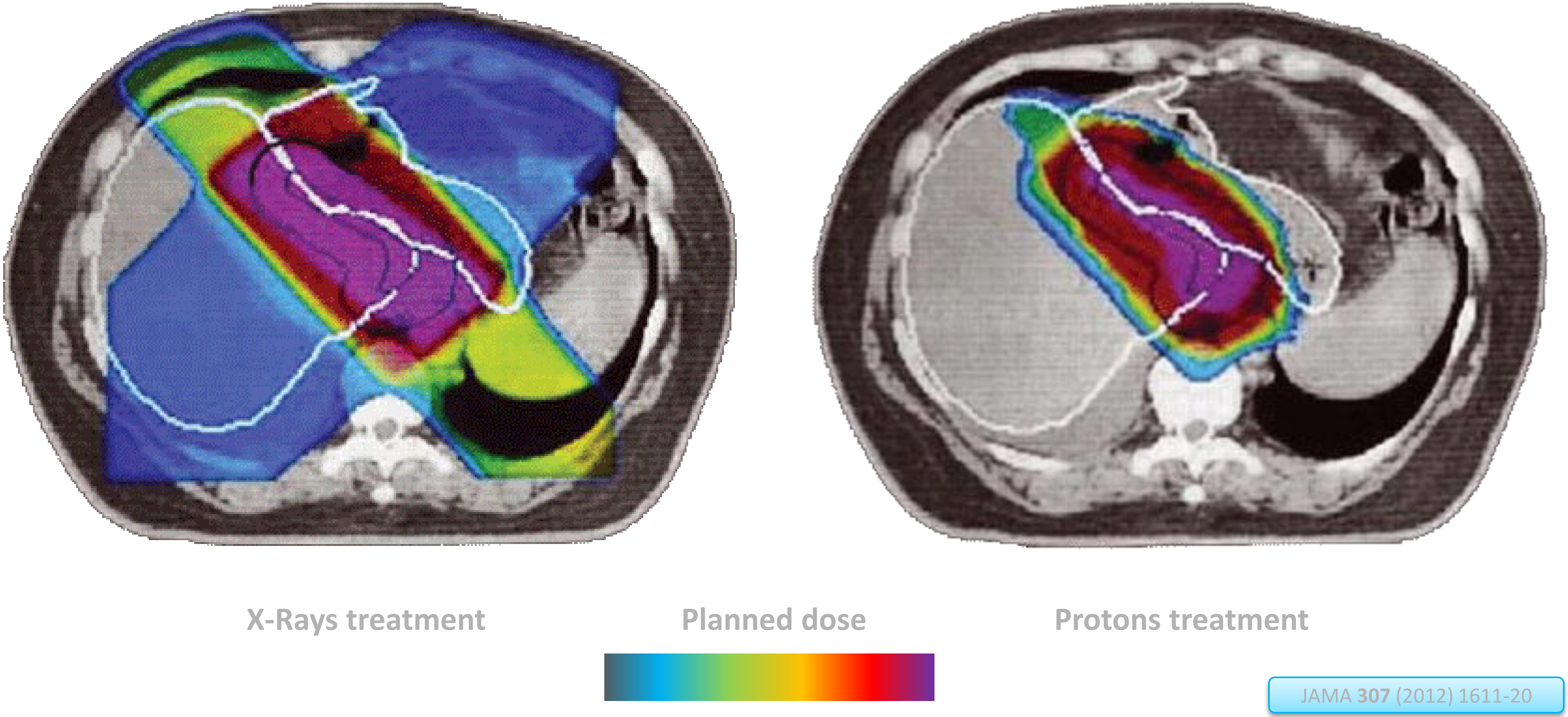
Radiotherapy and Oncology **95** (2010) 3–22

Radiation Oncology*Biology*Physics **83** (2012) 1549–1557

The Bragg peak position (depth) in the body depends on the ion energy and the tissue density it traverses. Changing energy determines the aiming depth.

Proton imaging – Bragg peak to reduced collateral damage

Much lower collateral damage respect to photons due to the focused energy deposition: less damage to surrounding tissues, less chance of secondary tumors.

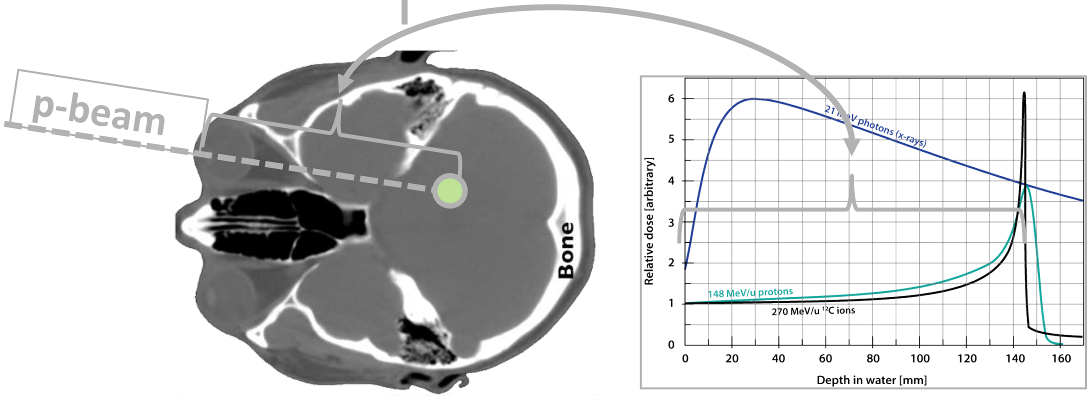


JAMA **307** (2012) 1611-20

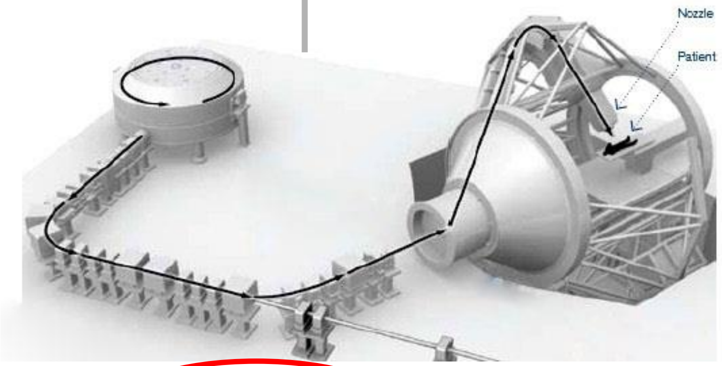
Radiation Oncology*Biology*Physics **83** (2012) 1549–1557

Proton therapy – aiming limits

Aiming the Bragg peak requires fine tuning of the proton energy to account for the tissue densities they have to traverse to reach the tumor.



Poor tissue density resolution from X-Rays CT



Fine energy tuning better than 0.5%

NIM B **268** (2010) 3295–3305

Eur. Phys. J. Plus (2011) **126**: 78

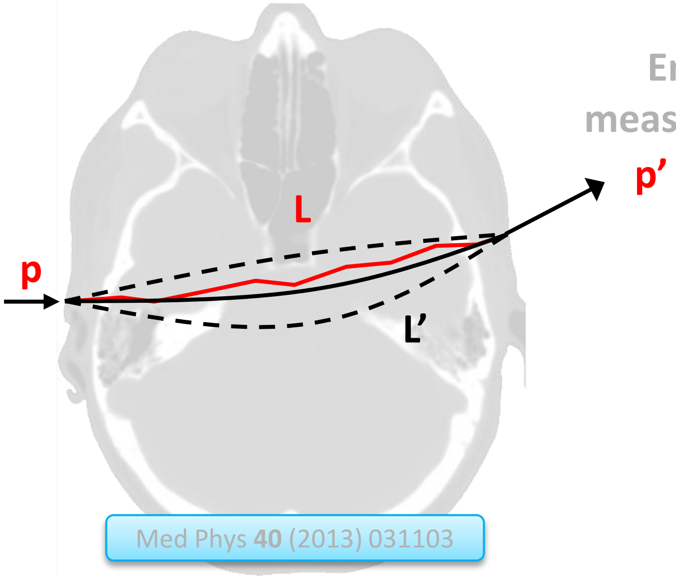
X-ray 3D CTs cannot distinguish tissue densities with the required precision, leading to Bragg peak aiming errors much worse than the Bragg peak intrinsic spread. But protons actually can (and with much less dose).

Phys. Med. Biol. **56** (2011) 2407–2421

Proton imaging – state of the art

The pCT works on the same principle as a "standard" x-rays CT: recording particles passing through the target from different angles to reconstruct a 3D image. Main difference is that, while photons are simply absorbed, protons also scatters.

Proton true trajectory

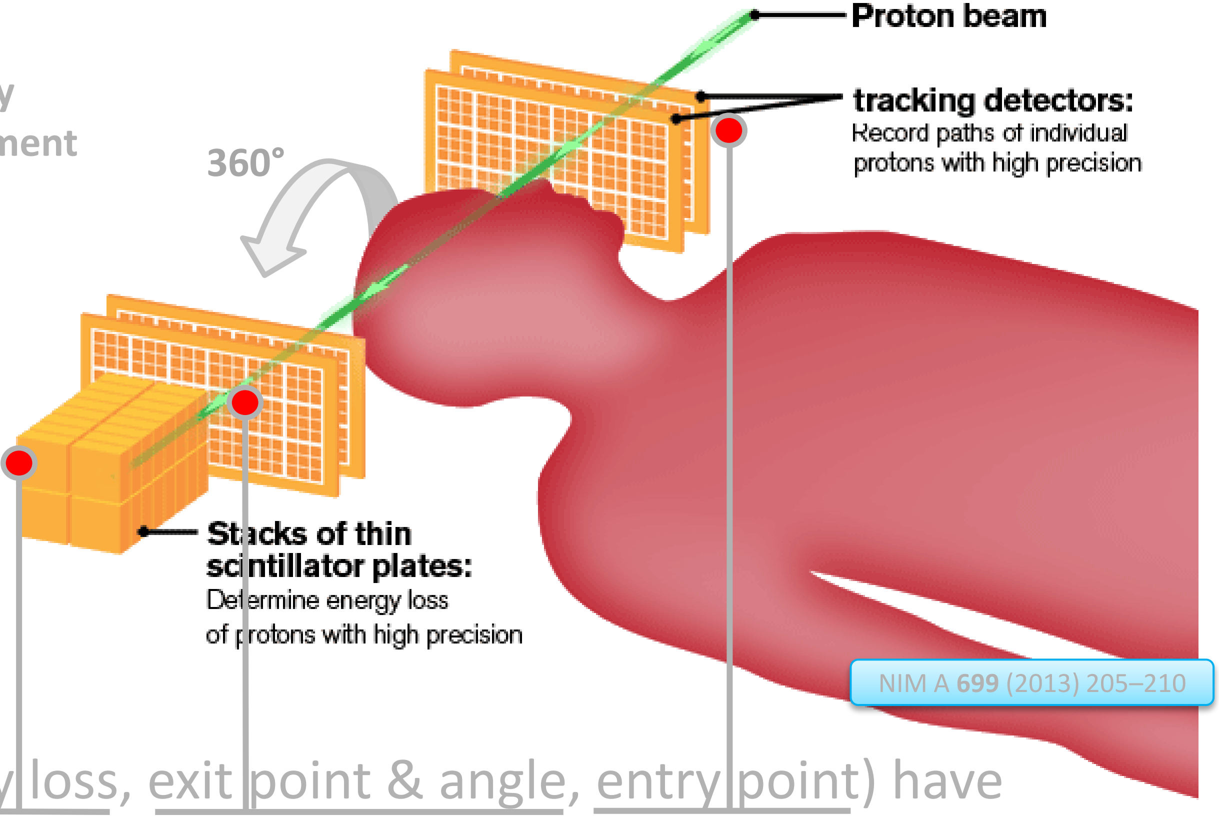


Med Phys **40** (2013) 031103

Entry and exit points + angle

Most Likely Path calculation

Energy measurement



tracking detectors:
Record paths of individual protons with high precision

Stacks of thin scintillator plates:
Determine energy loss of protons with high precision

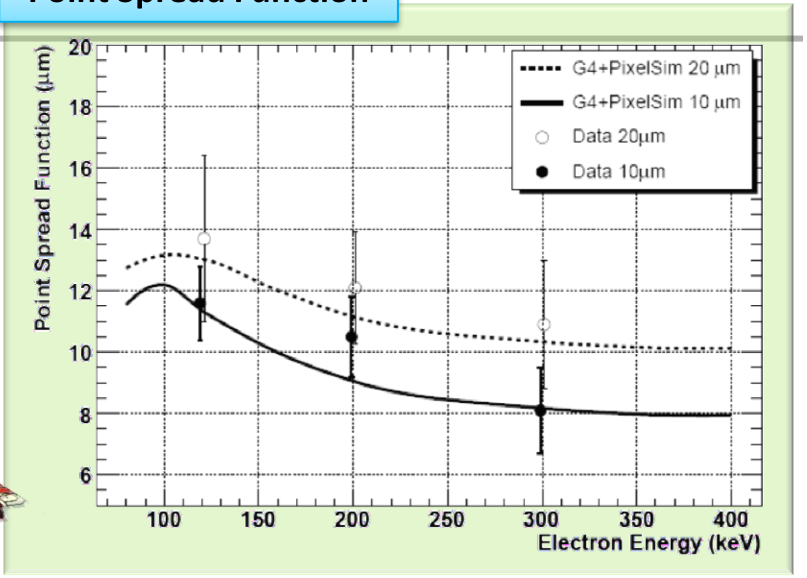
NIM A **699** (2013) 205–210

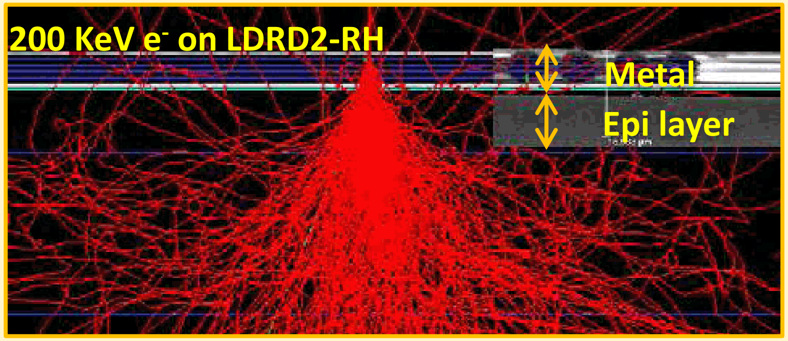
At least 10^9 proton tracks (energy loss, exit point & angle, entry point) have to be recorded to provide a detailed enough image. This leads to long exposure time (some 10s minutes) even with the best current state of the art prototypes.

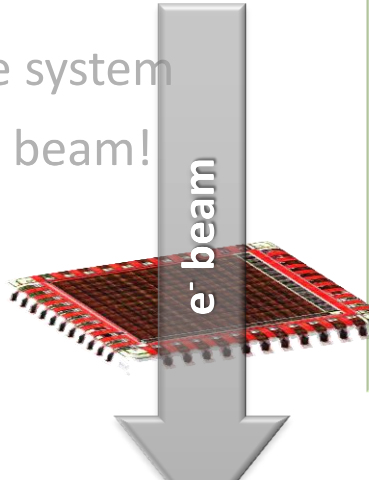
Microscopy – bulk rad-hard MAPS

- MAPS can provide a powerful detector for Electron Microscpy (**50-300 KeV e$^-$**)
- High resolution, high efficency, simple system
- Need to be rad-hard to withstand the beam!

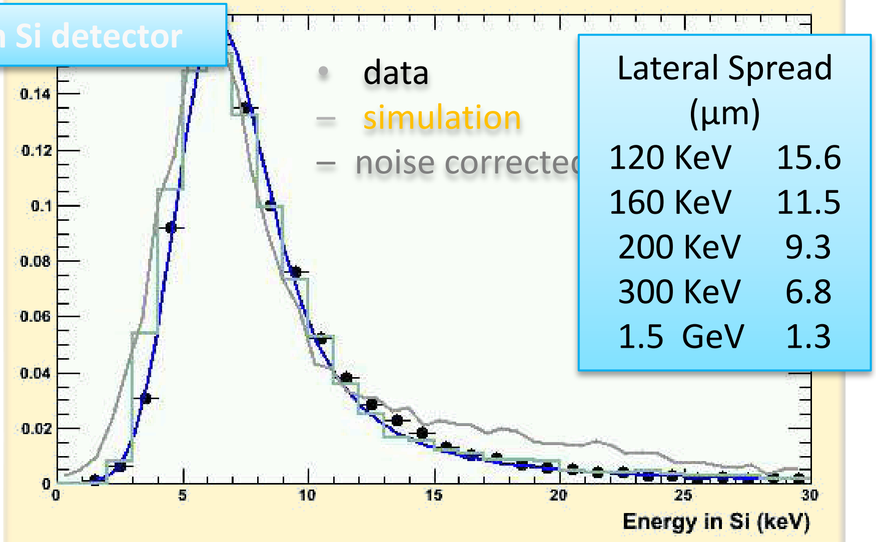
Point Spread Function







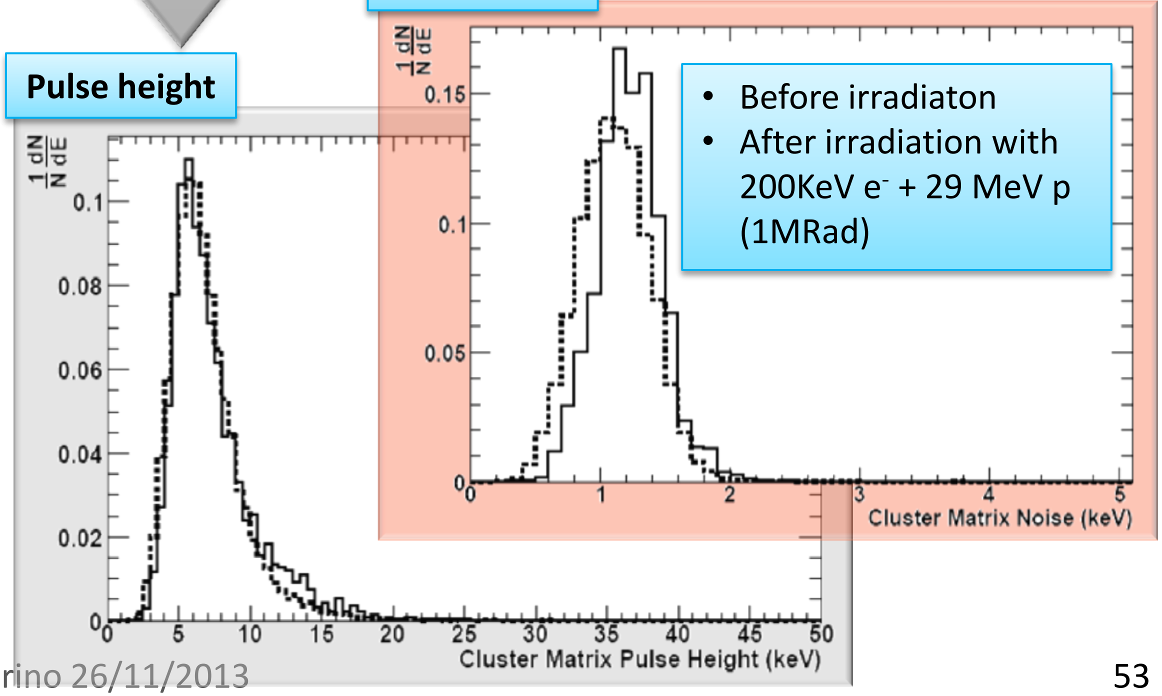
on Si detector



Lateral Spread (µm)	
120 KeV	15.6
160 KeV	11.5
200 KeV	9.3
300 KeV	6.8
1.5 GeV	1.3

Noise

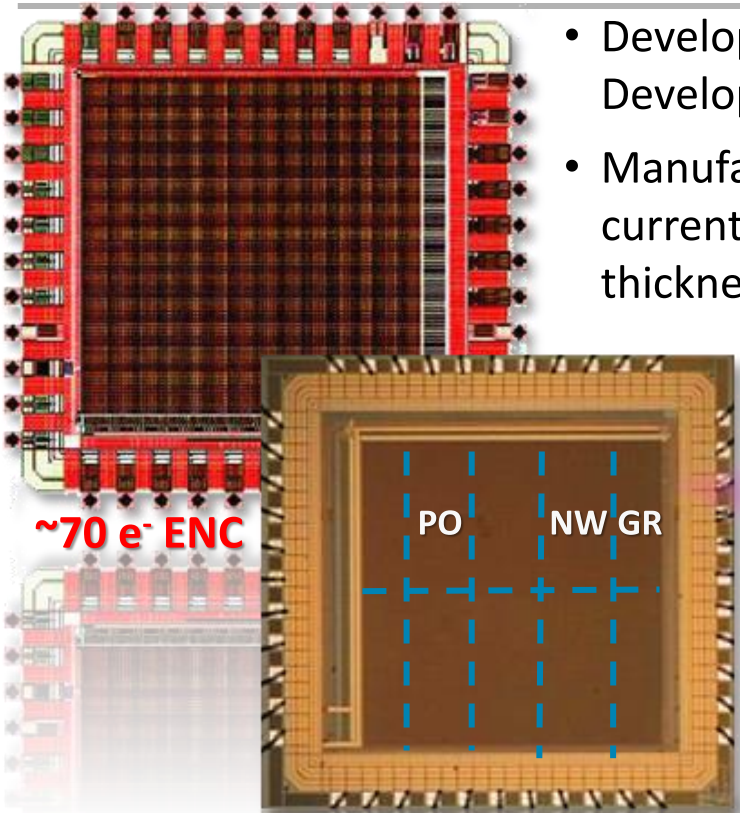
Pulse height

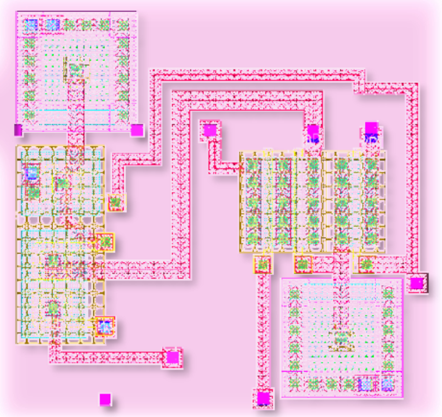


- Before irradiaton
- After irradiation with 200KeV e$^-$ + 29 MeV p (1MRad)

Microscopy – a lot of R&D toward rad-hard MAPS in past years

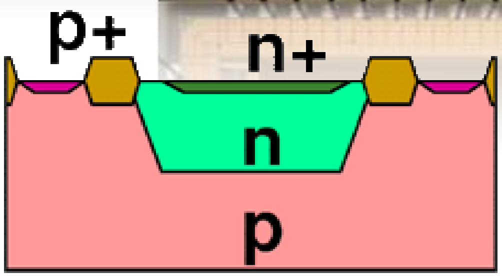
- Developed in the frame of LBNL Laboratory Directed Research & Development (LDRD) grant.
- Manufactured in AMS 0.35 µm CMOS-OPTO (optimized low leakage current, 5 metal layers)process, with 14 µm nominal epitaxial layer thickness.



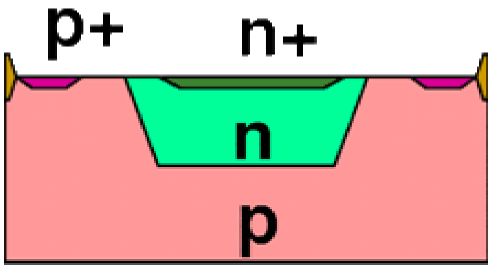


- 96x96 pixels, 20x20 µm^2, arrayed in several sub-sectors implementing different transistor layouts and different configurations of the charge collection diode.
- Simple 3-transistor (3T) pixel architecture.
- 2 sub-pixels with and without **ELT layout**.

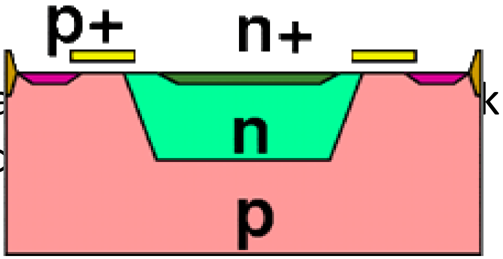
Serial rea k frequenc



GR layout
n-well diode with enclosing p+ guard-ring



NW layout
n-well diode with p+ guard-ring and thin oxide on top

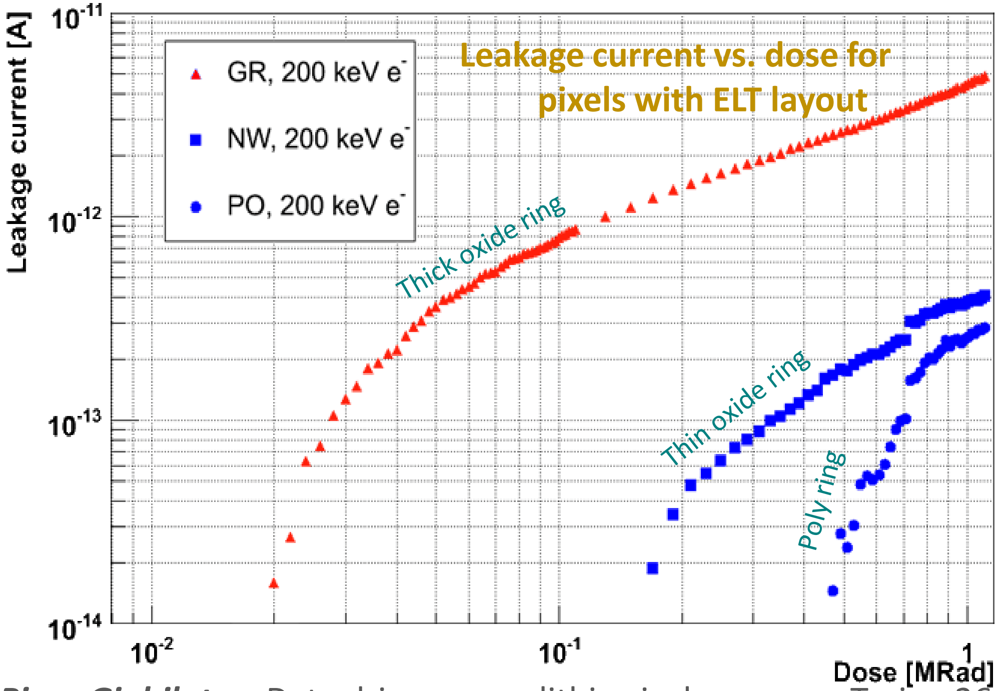


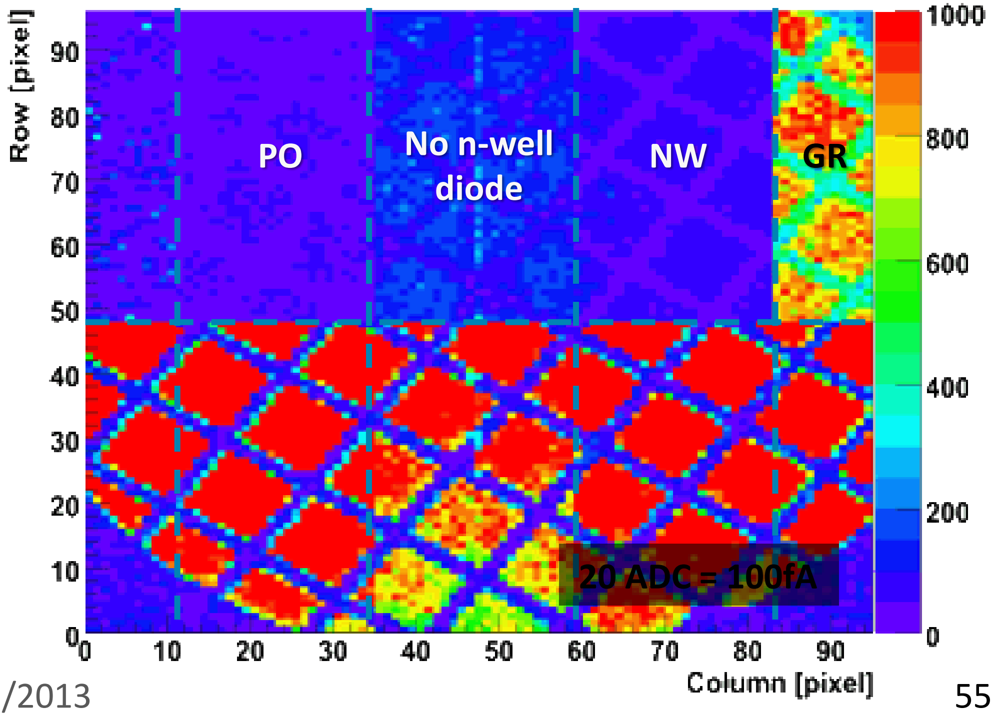
PO layout
n-well diode with p+ rings, thin oxide on top and polysilicon ring

Microscopy – 200 keV electrons irradiation results

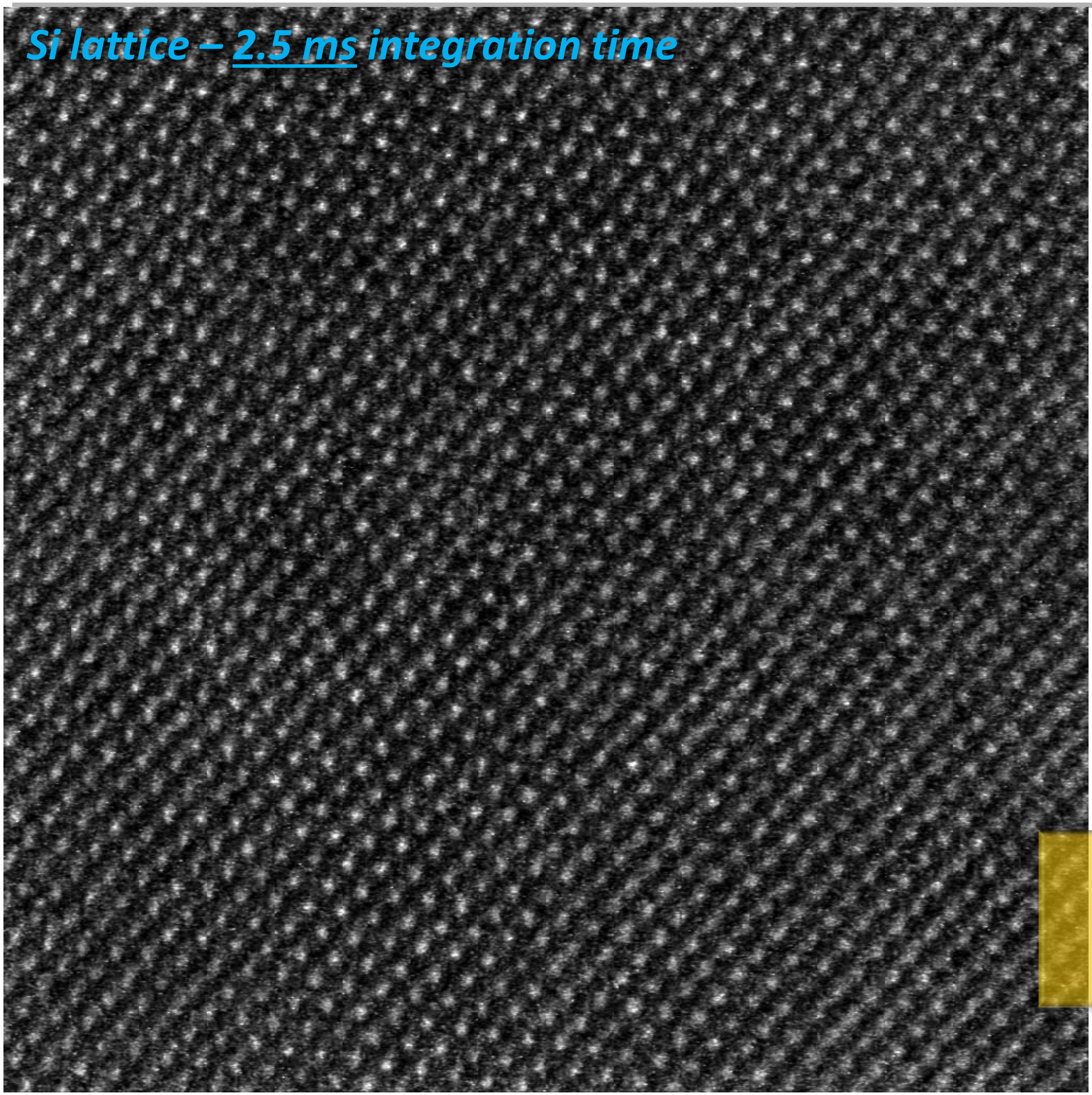
- **200 keV electrons** are expected to cause only ionising damage in Si (thr. energy for DD is 260 keV).
- Electron flux of ~2300 $e^{-}\mu m^{-2}s^{-1}$ ~9×10^{5} e^{-}/pixel/s (e.g. diffraction mode).
- Irradiation performed in steps up to a total dose of **1.11 MRad**. Dark levels monitored as dose function.

- After irradiation, the increase of leakage current in the exposed pixels gives a latent image of the mesh wires.
- Measurement of PSF ~30 μm possible, but e^{-} scattering on mesh borders spoils the actual figure.



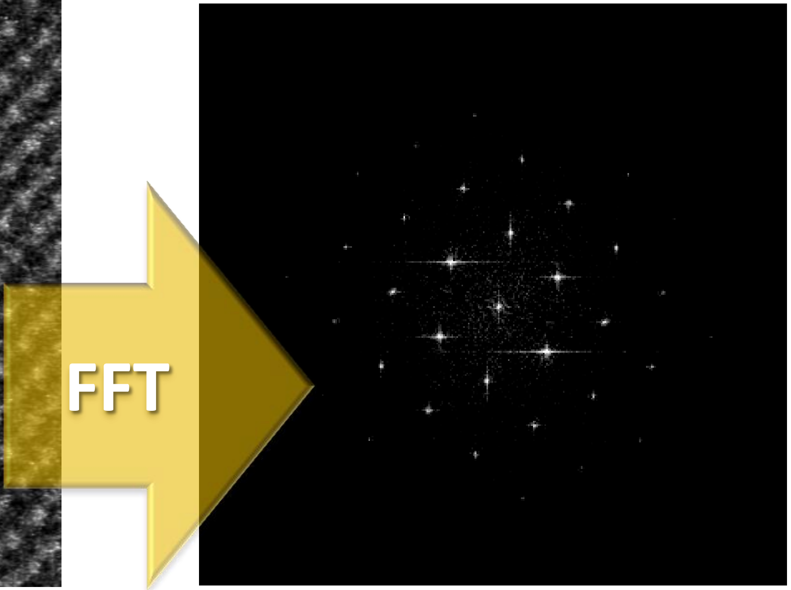


Microscopy – atoms e$^-$ imaging with 1 MPixel



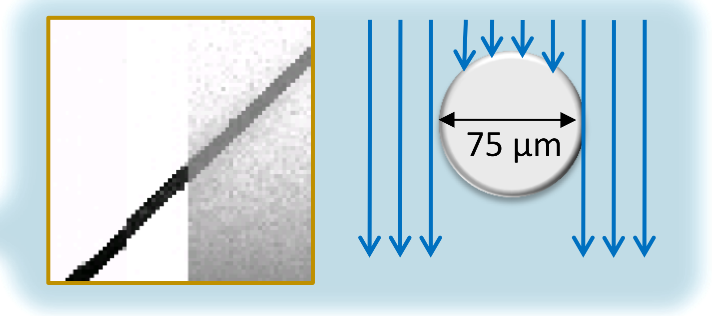
TEAM 1K detector

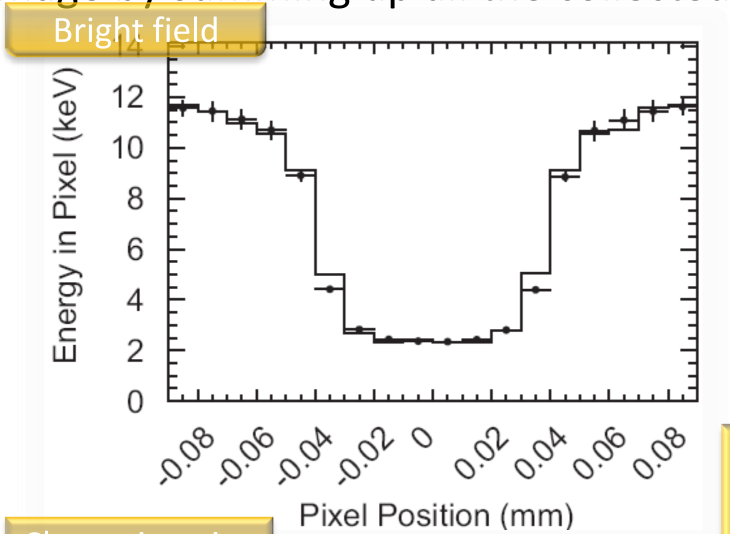
- 0.35 AMS opto process.
- *1M* pixel, 9.5 um pixel pitch
- Rad-hard design.
- *25 MHz* readout speed
- *16* parallel analog outputs
- Up to 400 Frames/s.
- Thinned down to *50µm* to reduce backscattering.

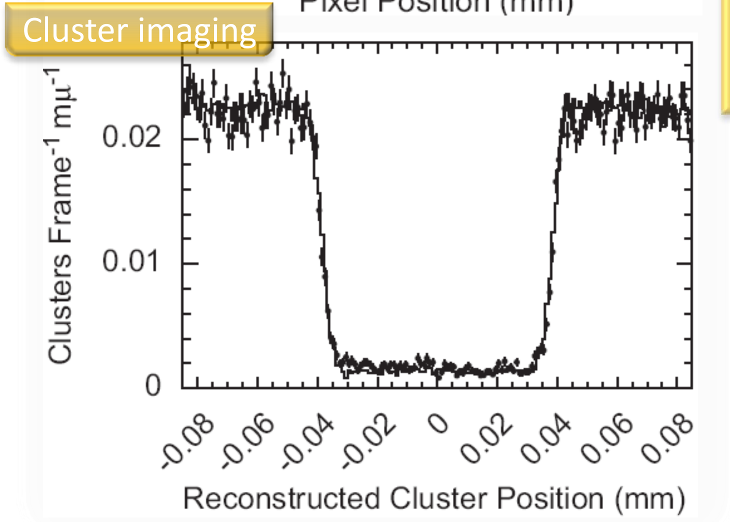


Microscopy – cluster imaging for high resolution imaging

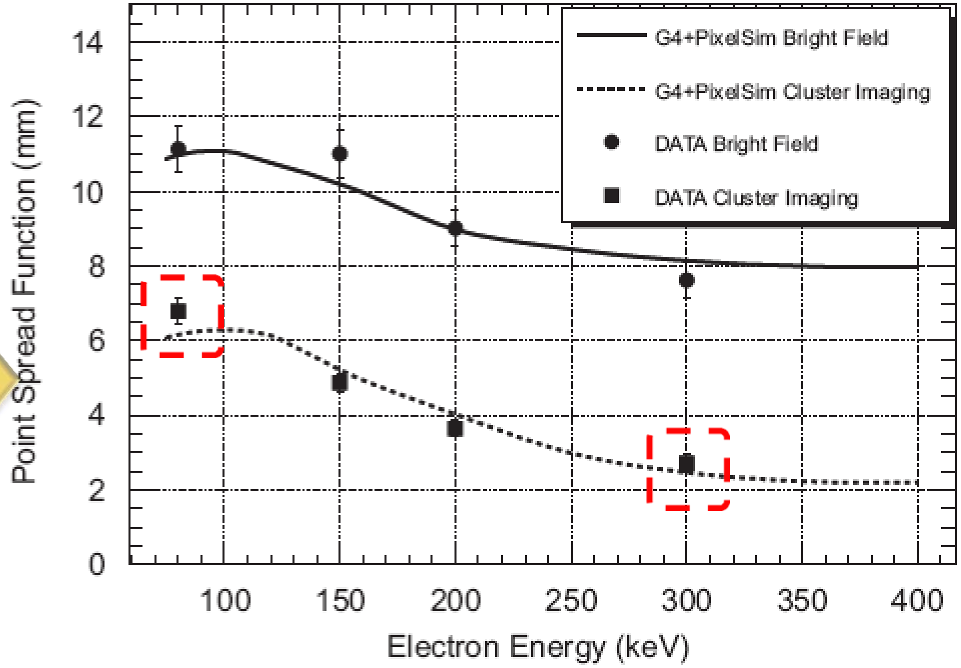
Cluster imaging: instead of integrating the e$^-$ flux into the detector, operate it in “single particle” tracking mode, retrieving each e$^-$ impact generated cluster. Reconstruct the image by summing up all the collected clusters coordinates.





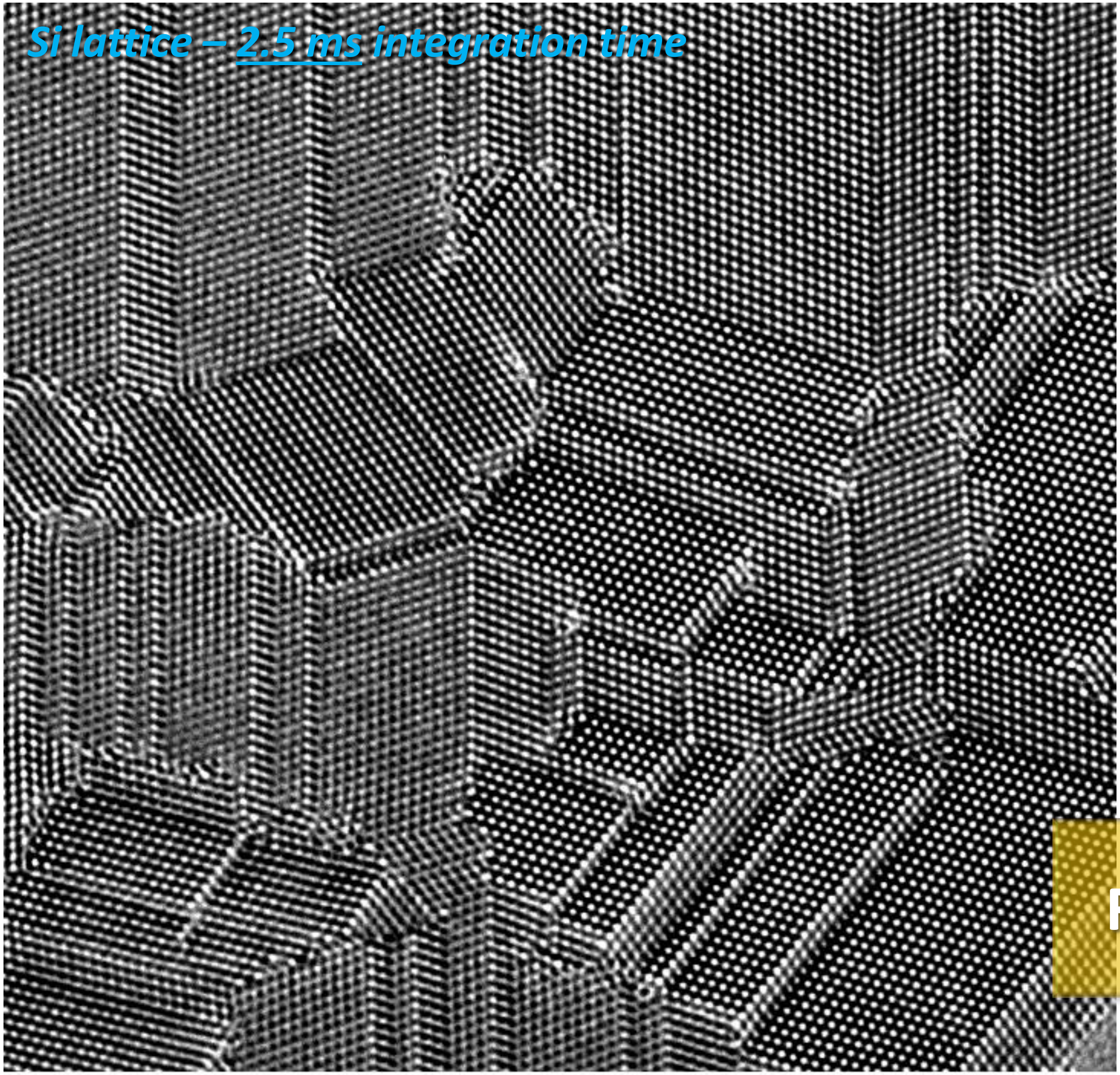


NIM A 608 (2009) 363-365



Energy (KeV)	Bright field	Cluster imaging
80	***11.1*** ± 0.6 µm	***6.8*** ± 0.35 µm
300	***7.6*** ± 0.5 µm	***2.7*** ± 0.25 µm

Microscopy – atoms e⁻ imaging with 4 MPixel



Atomic resolution micrograph of multiply-twinned nanocrystalline film of Si. (C. Song)

TEAM 2K detector

- 0.35 AMS opto process
- *4M* pixel, 9.5 um pixel pitch
- Rad-hard design
- *25 MHz* readout speed
- *64* parallel analog outputs
- Up to 400 Frames/s
- Thinned down to *50μm* to reduce backscattering

Microscopy – TEAM in 4MPixel counting mode

A recent reconstruction of the 20S Proteasome from K2 Summit™ Counting data shows estimated to be at 4.4 Å resolution (0.5 FSC). Å resolution shows both beta sheet and alpha helices.