Expected feedback from 3D IT for imaging

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Outline:

- ✓ Underline the expected benefits of 3D IT in imaging
- ✓ Do the exercise on the realistic case of single optical photon detection

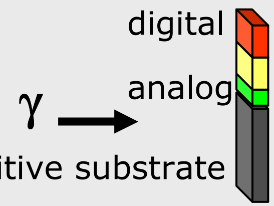
It is not a review about all imaging systems but …
conclusions of this talk could be easily extended to other imaging systems

- ✓ NIR optical and Xray Astrophysics …
- ✓ Autoradiography
- ✓Electron Microscopy
- ✓Neutron imaging
- ✓ commercial and military imaging VIS-IR

General remark

3D IT offers two levels of possible breakthrough in imaging system design

Sensor design



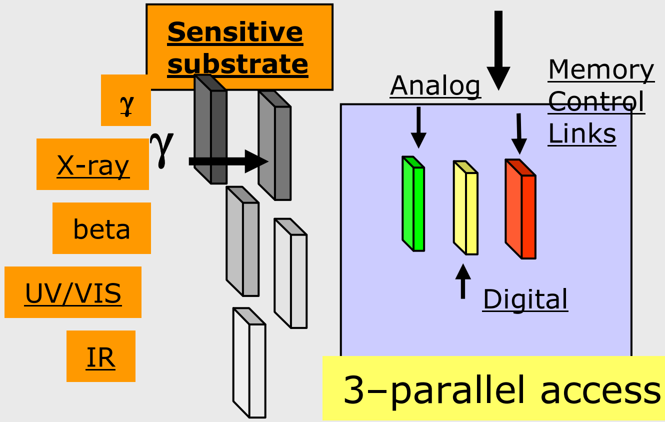
2D
Same substrate for conversion and analog readout

Fill factor is reduced

3D IT

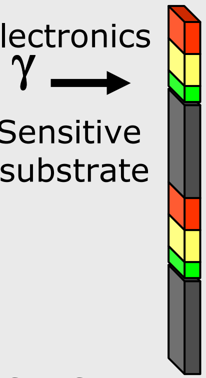
1- Substrate selection

2-Each layer can be optimized separately



3–parallel access to the pixels

Imaging system design:

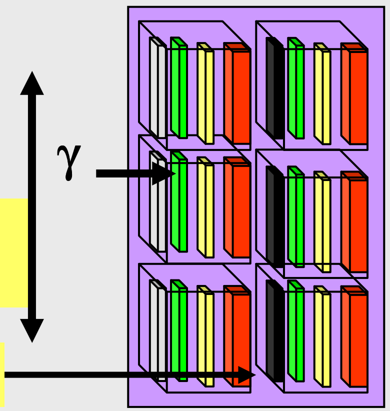


fill factor of the system is reduced

3D IT

1. 4-edge buttable => large surface

2. stacked sensors



VIS/Xray-SPECT

New multi-modality possibilities

Are R&D trends equivalent ? Yes … for most of them but for different reasons !

• HEP experiment detectors	• Imaging Systems
Granularity-Spatial Resolution	
Tagging particles, trajectory	Imaging from molecule (μm) to the organs (mm)
Sensitivity & Fill factor	
Reduce dead material – slim sensors	reduce the dose or the photoxicity (fluor. Im.)
Identification & Energy resolution	
Increase efficiency and purity of the selection	Increase the contrast of the image Imaging with more than one probes
Fast Readout	
Minimize dead time - increase signal statistics	Dynamical imaging - gating - large volume

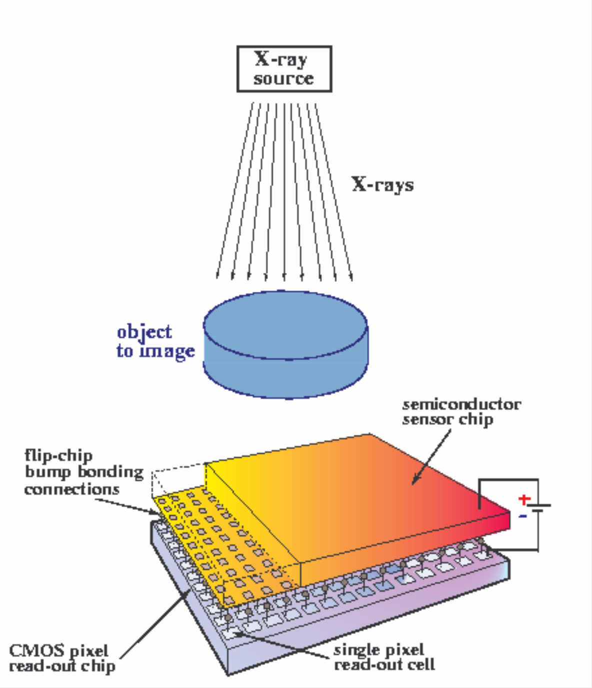
Bandwidth trade-off

fast readout (MHz) / granularity (# channels) / energy resolution (n bits)

On chip processing / memory / links

Reduce the data rate down to what is possible to extract from the sensors
Use memory for local processing to take a decision on event rejection

X-ray Computed Tomography is a transmission imaging



MEDIPIX from CERN
XPAD3 from CPPM

D Brasee IPHC

Two categories:

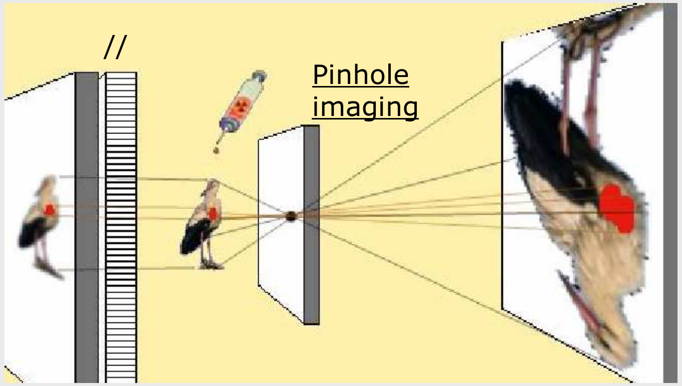
- Crystal+Photo-detector : CsI cry. + FOP + CCD
- Direct γ conversion detector : CdTe/CdZnTe/GaAs/Si

Hybrid pixels was the first generation of this type of sensors

Trends :

- Photon counting
=> decrease noise – reduce dose
- Increase dynamical range: contrast
- Keep resolution: < 50 μm pixel pitch;
- Increase the FOV: 5x5-20x20 cm2
- High count rate: 1 Mph./pixel/s
- gating capability (cardiac …) 100ms
- typical readout time: 500 ms

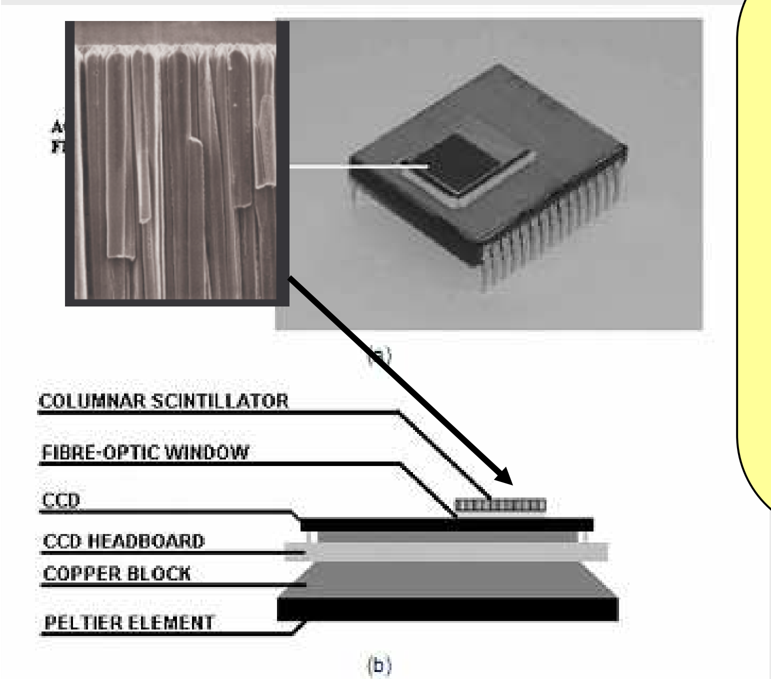
Single Photon Emission Computed Tomography



Single mono-energetic γ emission imaging

Radiotracers 99Tc-125I

Detection devices:
- ✓ crystals + FOP+ optical pixel sensor
- ✓ CdZnTe substrate: direct conversion

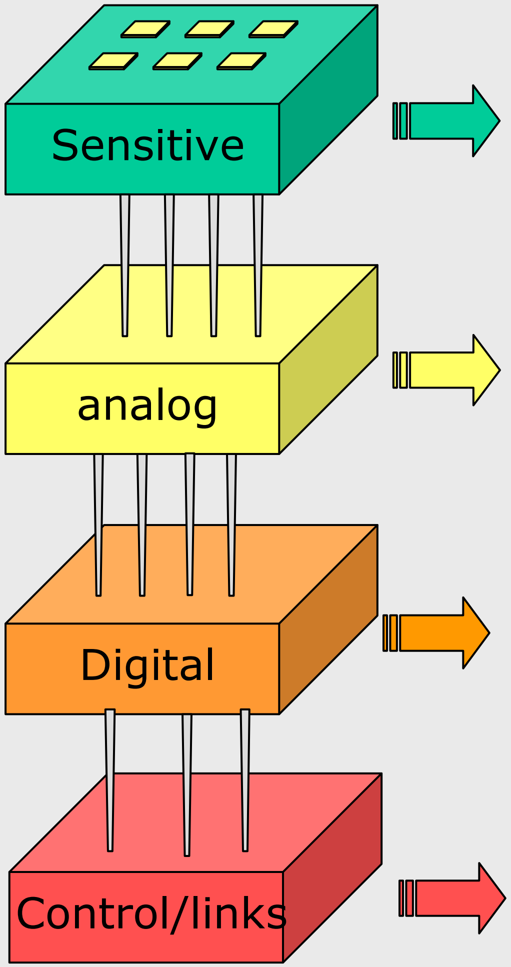


CsI needle crystals +FOP+CCD

SPECT Trends :
- High Resolution 2mm -> 100 μm
- Keep sensitivity
- decrease Noise
- ✓ Large surface of detection increase resolution
- ✓ Photon counting capabilities increase resolution
- ✓ Energy resolution or different threshold selection Two or more radio-labelled probes simultaneously
- ✓ low count rate no bandwidth trade-off compare with Xray

What we expect !

Large surface FOV=20x20 cm2
Megapixel Sensor



✓ Direct γ conversion CdZnTe/CdTe…
✓1-10 Megapixels – Pitch < 50 μm

✓ Amplifier
✓ Discriminator: two thresholds for “energy selection” or windowing for two simultaneous tracer imaging

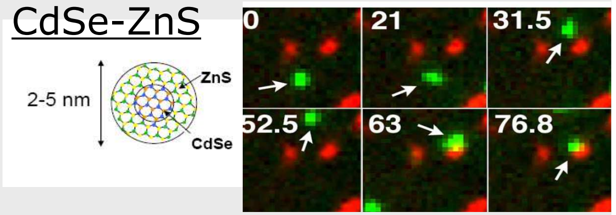
✓ Fast readout-Photon counting strategy : ~10^6 ph/pixel/s for X-ray; Medipix or XPAD3 like architecture
✓ Time stamping

✓ Gating capability for X-ray and
✓Fast readout for dynamical imaging (cardiac movements)

- One of the major goal in Fluorescence imaging is the single molecule tracking at millisecond
- New fluorescent tracers : Quantum dots

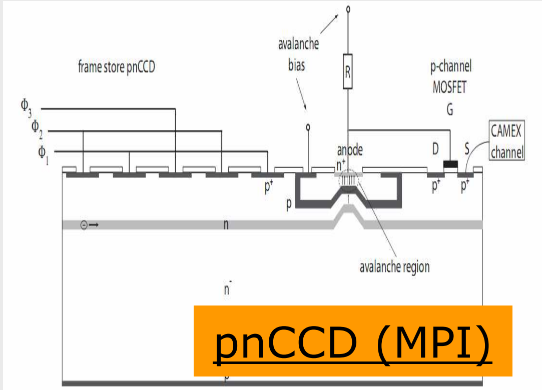
-> ~10 ph./ms/pixel on the sensor

-> the photon signal is a Poisson distribution



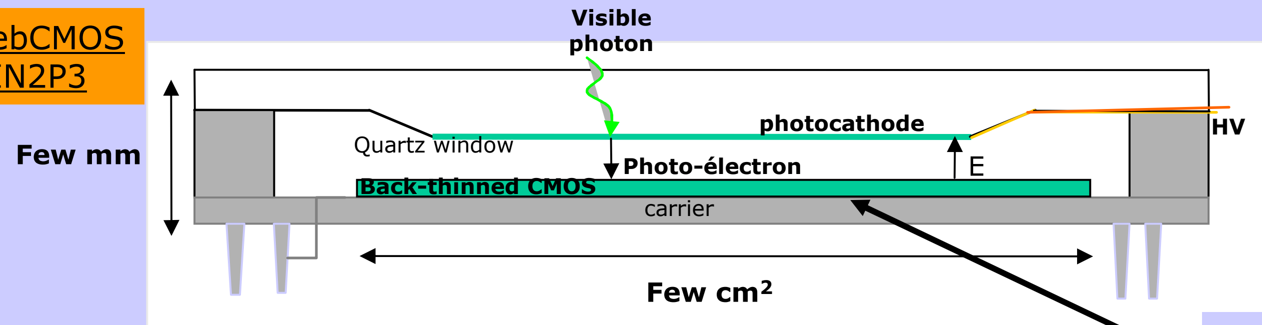
Synaptic activity

- Standard EMCCD: 512x512 Pixels - Pitch 10 μm - 30 fps
  - ✓ Single photon sensitivity with EMCCD (impact ionisation in shift register) or EBCCD (ph.e imaging)
  - ✓ but no in pixel photon counting !
- New generation of single photon sensitive pixel detectors:
  - direct conversion (avalanche mode in pn junction) -> pnCCD
  - Photo-electron and acceleration or multiplication -> Hybrid vacuum tubes
    - EBCMOS (Back thinned CMOS)
    - EB-MCP-CMOS (Front pads+CMOS readout)



pnCCD (MPI)

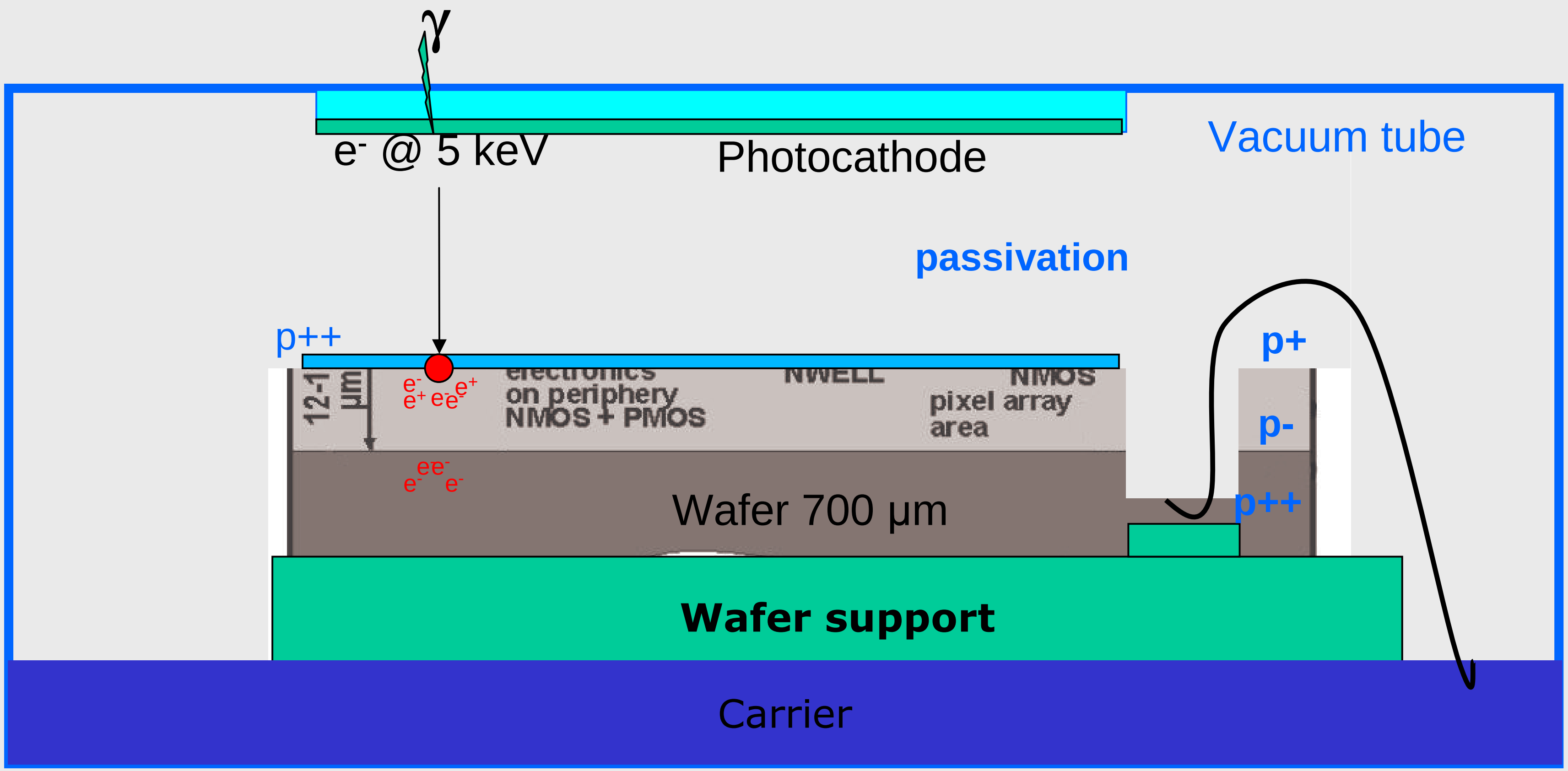
ebCMOS IN2P3



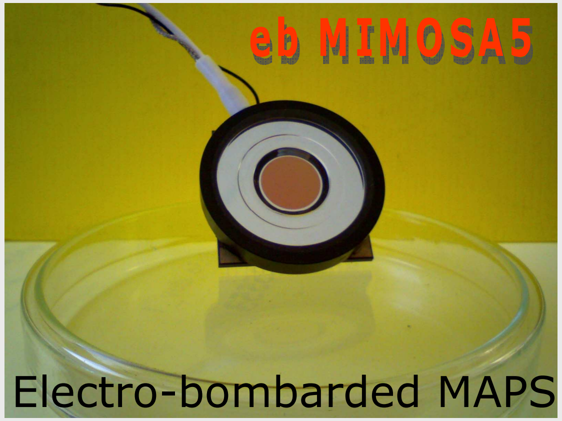
A photo-electron tracker

Integration issue :

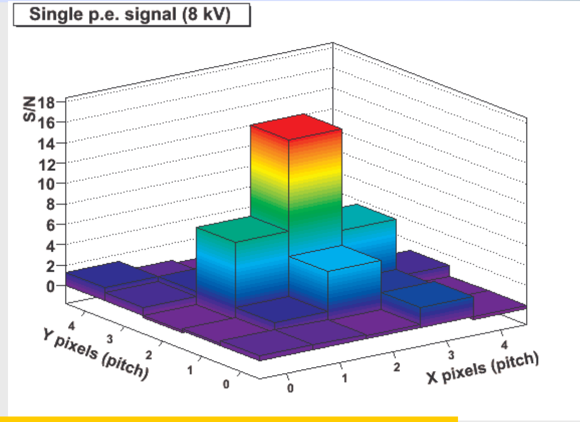
1. Back thinning of the CMOS down to the epilayer !
2. Post processing of the epilayer !
3. Bonding into deep pads
4. cathode processing: 350°C during 2 hours !



Single photo-electron tracking : demonstrator EBMIMOSA5



Single photo-electron:
Charge sharing
-> Resolution by clustering
-> keep 9 pixels or more if multi-hits



- Frame size: 1 Megpixels
- Pixel size: 10 μm
- Frame rate 10 Hz (slow)
- Data rate 4Mb/frame
- In cluster photon counting capability
- position sensitive inside the cluster

2 μm light spot focused on the cathode

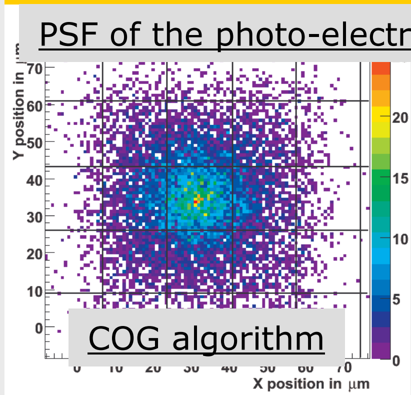
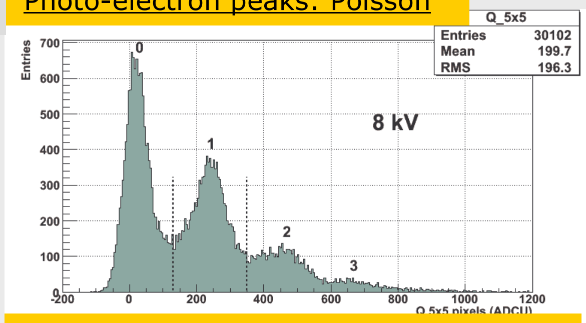
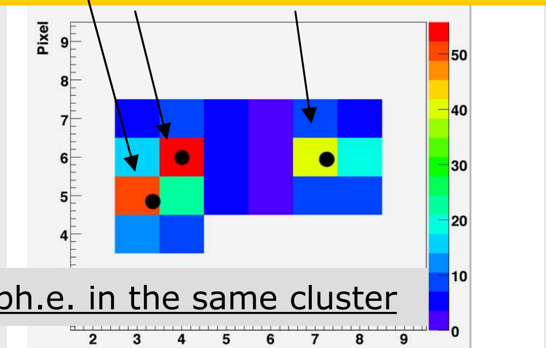


Photo-electron peaks: Poisson



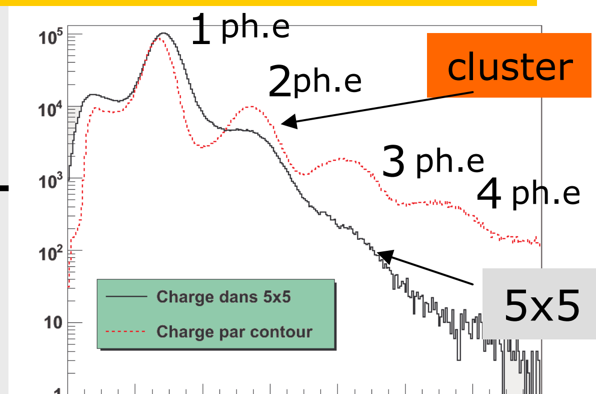
Counting capabilities in cluster !

Reconstructed. energy and position



Deterministic annealing to process multi-hits

When the fill factor of hits increases (5%= 50000 hits) Multi-hits has to be processed !

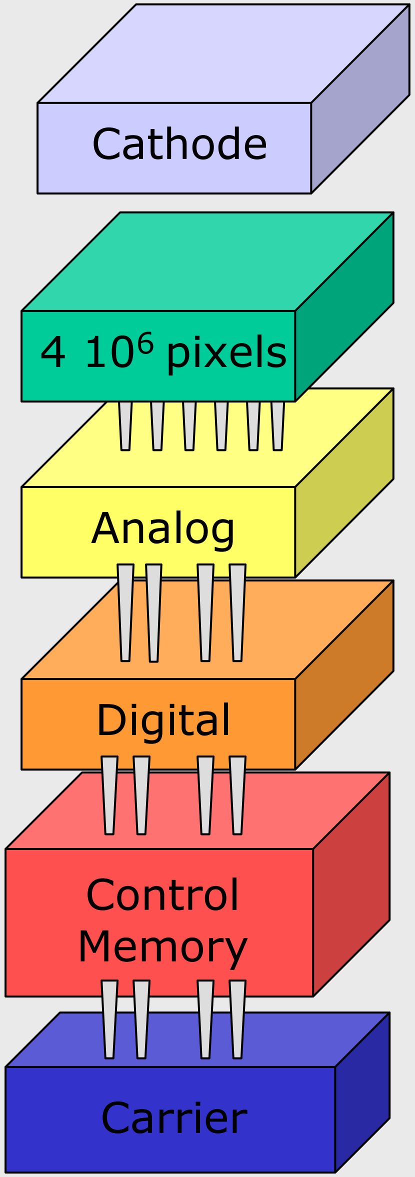


Energy resolution depending on the clustering method

What could we expect from 3D IT for EBCMOS ?

3D IT could bring pixel-by-pixel parallel access to the MAPS array

It’s a close to ILC vertex requirements !



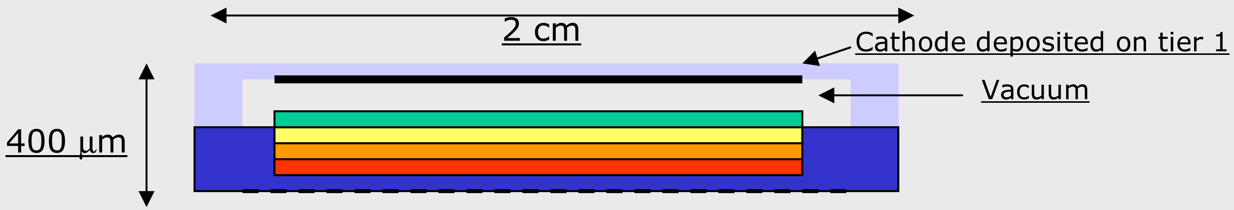
In pixel electronics for ph.e. tracking:

- ✓ Amplifier-CDS
- ✓ Threshold for the seed pixel
- ✓ adjustable threshold above 1-2-3 ph.e. cut at 2 ph.e.= No Dark count !
- ✓ Self-triggered pixel - time stamping (asynchronous architecture) ?

- ✓ Discriminator with cluster selection around the seed ? - Sum over neighbour pixels - spatial filtering
- ✓ Analog memory
- ✓ Contour for cluster in case of multi-hits (10% Fill factor)

- ✓ ADC (4-8 bits) of the pixels of the selected clusters
- ✓ Reduce the number of ADC to the maximum of expected number of clusters

- ✓ Memory for integration mode on few frame (temporal tracking)
- ✓ Carrier connections
- ✓ HV control/gating



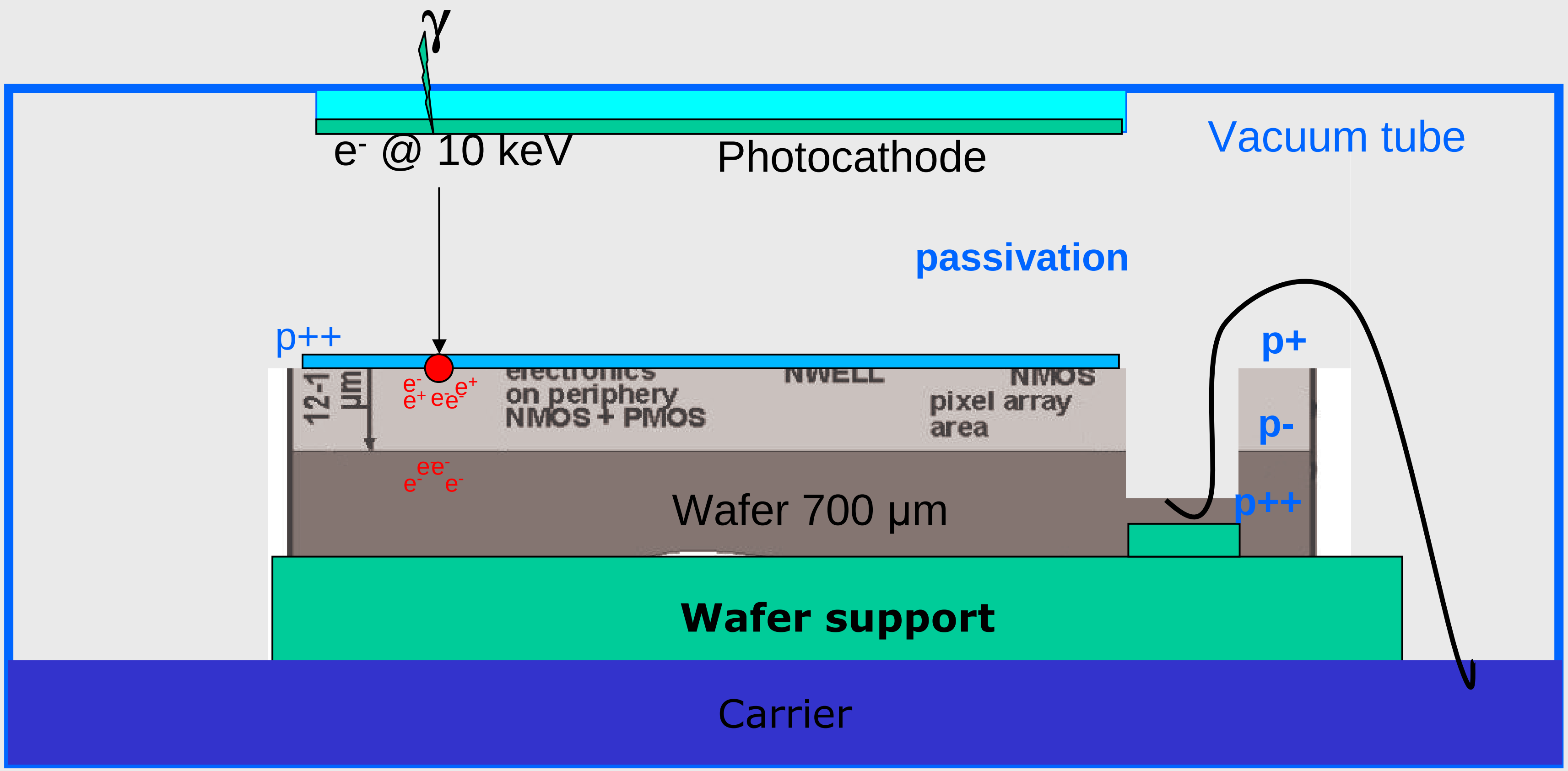
My personnel view of the full 3D integrated ebCMOS

Conclusion

- 3D IT will give new possibilities to imaging system integration
- The capability of changing only the tier 1 (sensitive volume and amplification) and keeping the others will reduce the cost of imaging systems developments
- 3D IT brings pixel-by-pixel parallel access to the array keeping the maximum information on charge but we need analog signal processing to reduce the ADC number
- 3D IT will offer improvements from IR to X-ray energy scale detection
- Impact on imaging applications will be important in Life science but also in other fields: astrophysics at millisecond time scale, segmented crystals readout with FOP (reduction of the cost/channel), security-night vision applications …
- Thanks

Integration issue :

1. Etch the MAPS down to the epilayer !
2. Post process on the epilayer: few tenth of nm !!
3. Do the bonding into a deep and small pad thinnest Layer M3
4. Resist to the cathode process: 350°C during 2 hours !!!
5. 63 I/O from the backside of the MAPS through the ceramic base plate



Molecular imaging systems : trends and trade-offs

X-ray CT scanners
Principle: Transmission imaging
Key points :
Increase dynamical range to keep contrast
16 bits : 1M ph./pixel/s
Keep resolution :
around 50 micron Pitch
4 Mega Pixels
Photon counting mode :
Keep sensitivity
2 detectors types :
Crystal + VIS pixelised detectors
100% silicon X-ray detector Flat panel Xray detector

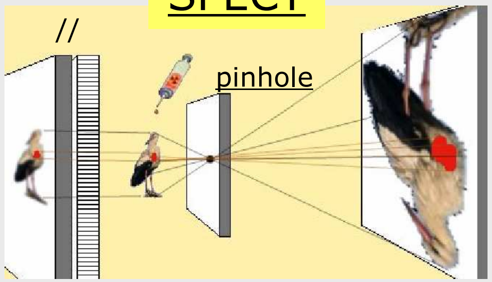
SPECT system
Emission imaging : mono-energetic gamma imaging

Resolution 3mm down to 100 microns
Ultra-high resolution requires segmentation and photon counting capabilities
Large field of view
Main Goal is to find a compromise between spatial resolution and sensitivity
Low data rate 1000 cps/MBq

PET system
Emission imaging : beta range 1-2 mm
Acollinearity 0.25°
coincidence of two gammas
Time stamping < 500 ps
Energetic resolution for compton events (detectors or bodies scattered)
Pushing spatial resolution to the intrinsic limit crystal segmentation of the Radial – parallax error (DOI limitation of Resolution) or Longitudinal (energy resolution)
Sensitivity 1-5% -> 10-15%

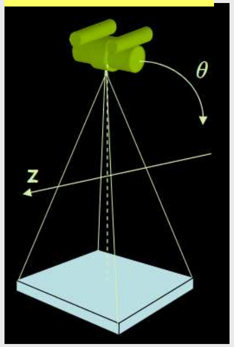
Optical Microscopy
Emission : fluorescence GFP - Quantum dots bioluminescence
Increase reaout speed 50 fps -> ms
Spatial resolution 10 microns Pitch
Sensitivity to one photon
Large FOV 4D
Quantum dots tracking as cellular GPS !
Reach the millisecond time scale
Calcium imaging in neurons
In molecular motor

SPECT



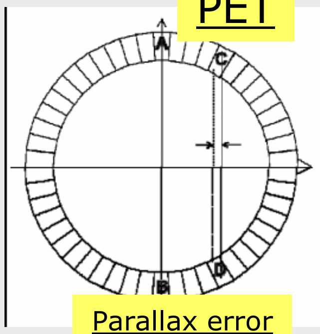
$$\int_L \mu_E(x,y,z)\,dL = \ln\frac{I_0}{I}$$

X-ray source

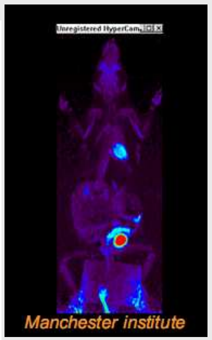


D. Brasse IPHC

PET

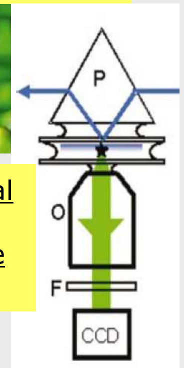


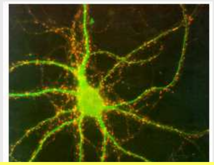
Parallax error



CT

Single Molecule Tracking (GFP)





Total Internal Reflection Fluorescence Microscopy

Synaptic activity

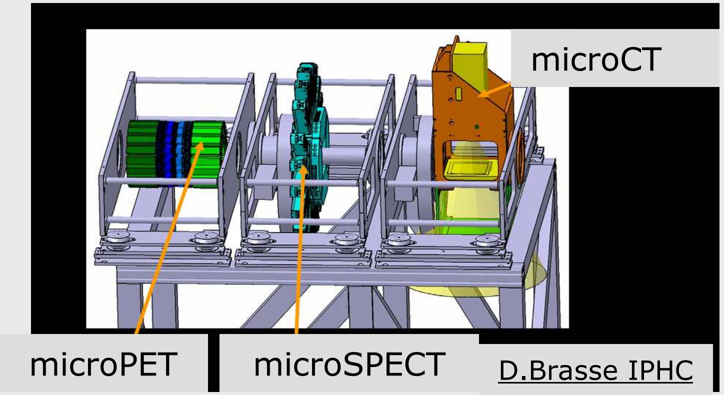
Small Animal Imaging

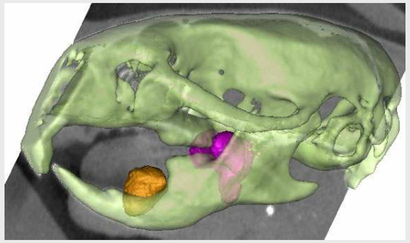
Benefits of 3D Integration imaging system design

Multimodality systems handle functional imaging provided by the SPECT and/or PET and/or Optics modalities fused with high-resolution anatomical imaging provided by X-ray CT.

Two categories of multimodality :

The three modality are aligned along the axis of translation of the bed
Trade off : Software fusion of the images

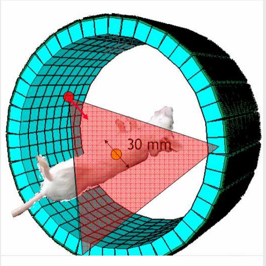


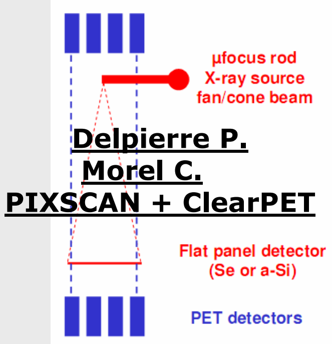


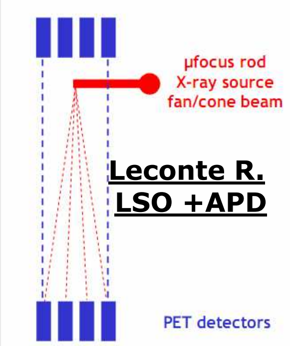
Offline Image fusion SPECT/CT

Two modalities are integrated in the same barrel detector; Simultaneous acquisition
Trade off : keep the sensitivity for both detectors

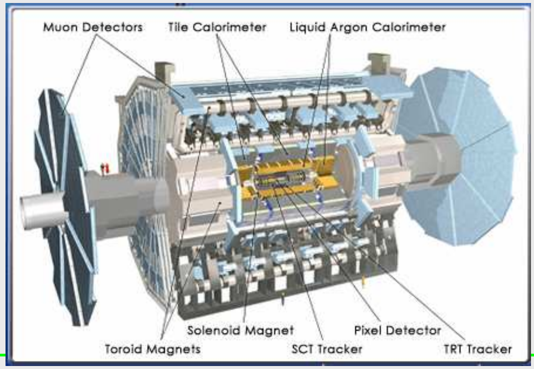
- PET/CT
- SPECT/CT
- Optical/PET





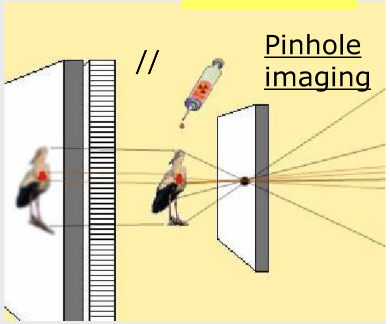


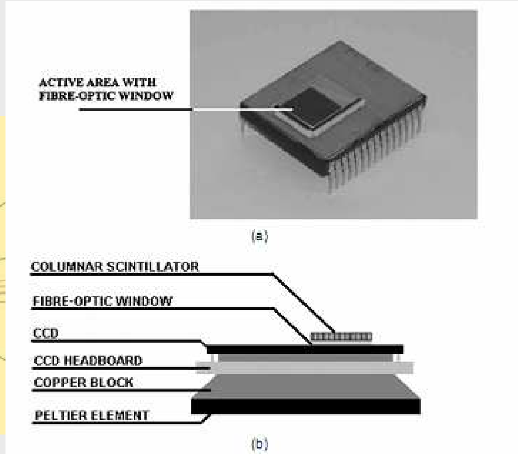
HEP detectors are always multi-modality imaging systems !



SPECT/PET for small animal imaging

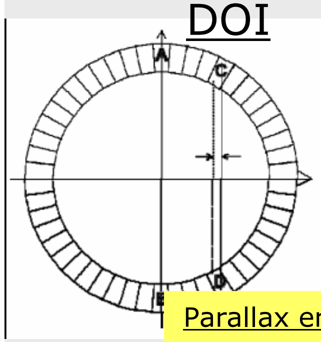
SPECT

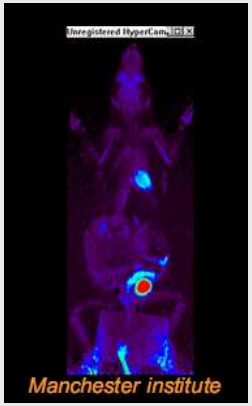




PET

DOI





Single mono-energetic γ imaging

- 2 categories:
  - Crystal+Pixel Photodetector : most commonly used
  - Direct γ conversion detector : CdZnTe …
- Key points: increase resolution keeping sensitivity
- Low data rate 1000 cps/MBq
- Two or more radio-labelled probes simultaneously using energy discrimination !

beta source -> 2 γ - coincidence

Crystal & Pixelised Photodetectors s=1-4mm^2

- Key points :

Time stamping < 500 ps

Energetic resolution for compton events (detectors or bodies scattered–axial PET)

Spatial resolution is already at the intrinsic limit : beta range 1-2 mm

Trends : High Resolution SPECT down to 100 μm
- MegaPixels with 10-50 μm pitch
- photon counting capabilities
- energy resolution : ^{125}I spectrum

Trends :
TOF PET
Time stamp < 500 ps
Sensitivity : 2% -> 10%
It's more a sensor integration issue:
Crystals / APD / GAPD -> SiPM

- ✓ Increase the number of channels -> Mega Pixels
- ✓ Parallelize the readout channels for fast readout
- ✓ Thresholds / Self trigger capability
- ✓ Keep energy information -> ADC / Counters
- ✓ Time Stamping / pixel or cluster
- ✓ Local processing to decrease the bandwidth
- ✓ I/O Communication to the system -> Trigger/control/gating

What could do 3D IT to answer to these requirements ?