IFAE Experience with Radiation Pixel Photon counting Sensors

Mokhtar Chmeissani

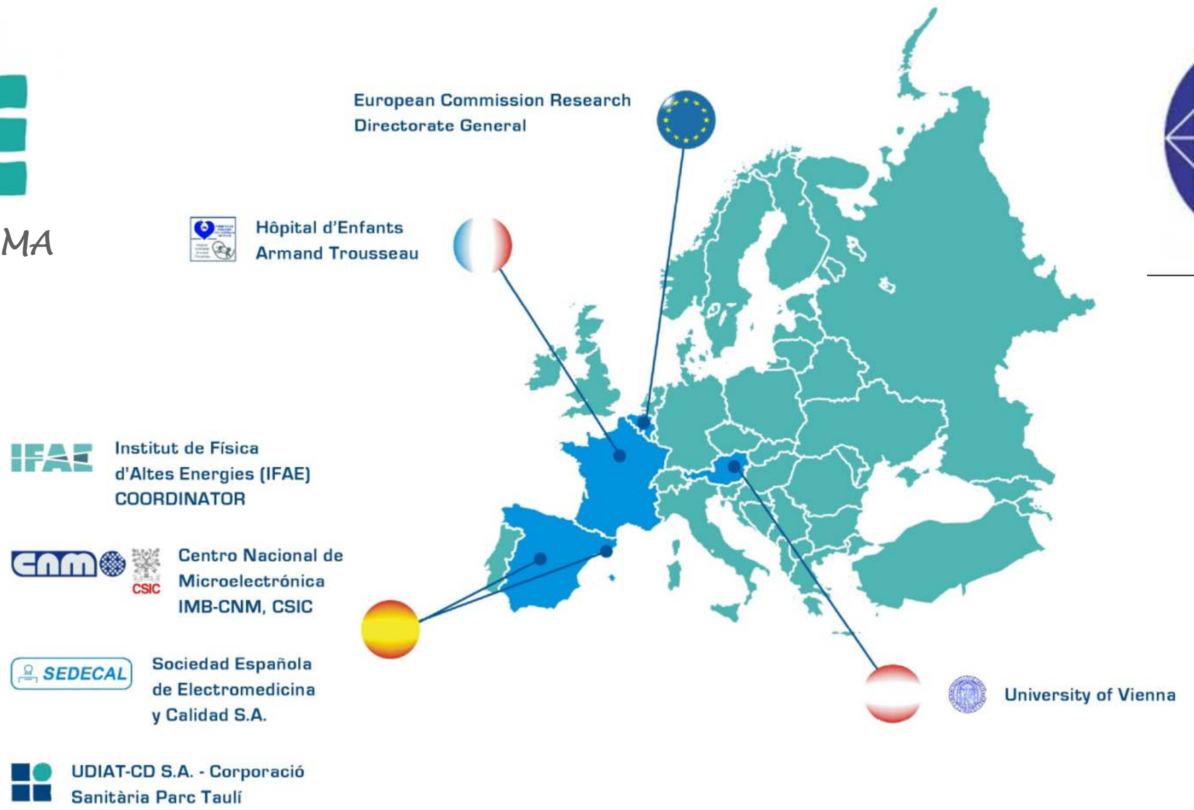
- Introduction
- Dear-Mama (FP5-2001)
- Voxel Imaging PET (VIP) (ERC-2009)
- LINDA (RETOS +Producte)
- New pixel sensors Fit for Photon Counting

Charge Integration vs Photon Counting

	Charge integration (CI)	Photon Counting (PC)	Comment
High photon flux	+	-	
Noise	-	+	PC is excellent for long exposure Real time dosimeter
Less sensitive to charge sharing	+	-	PC either it double count the photon ot it loses it
Fast readout	-	+	PC is by far much faster as the data is intrinsically digital
Multi-energy bins	-	+	PC has no rivalry with MEB
Pixel size	+	-	

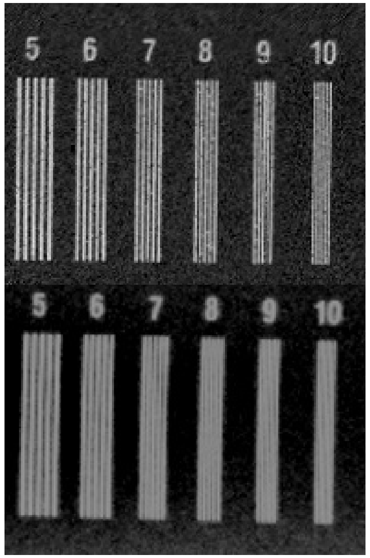
Dear-Mama Project (FP5)

DEAR MAMA

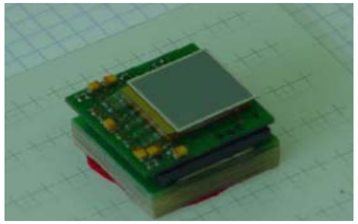


Dear-Mama-I Machine

The photo of the prototype Dear-Mama X-ray machine in CORPORACIÓ SANITÀRIA PARC TAULÍ (Sabadell)



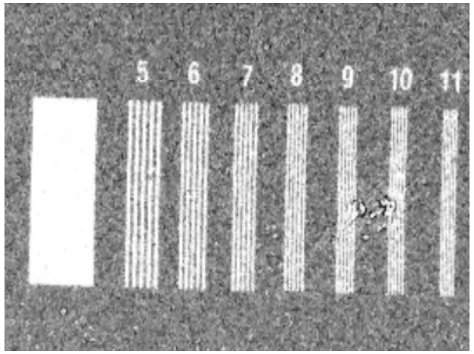
Top lines of the phantom were imaged with Dear-Mama machine while the bottom lines were images with Hologic Selenia machine



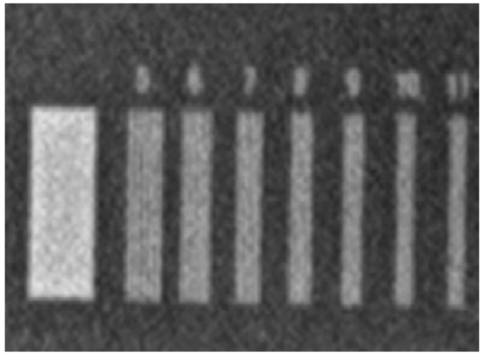
Dear-Mama kernel senor with Si on Medipix2

Dear-Mama-II Machine

Dear-Mama-II machine for general radiology. First Digital machine with CdTe detectors

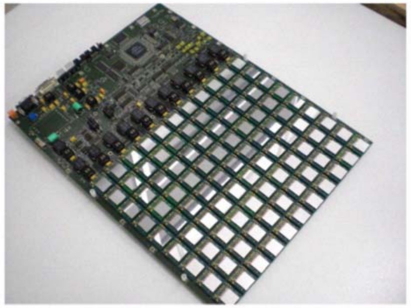


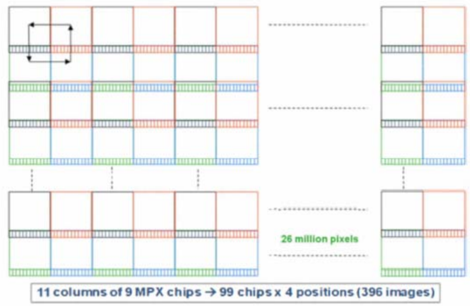
Radiography of a phantom with Dear-Mama-II machine using 40kV and 2mAs dose which corresponds to **5.7µGy**. One can see easily the separation of 8 lines per mm.

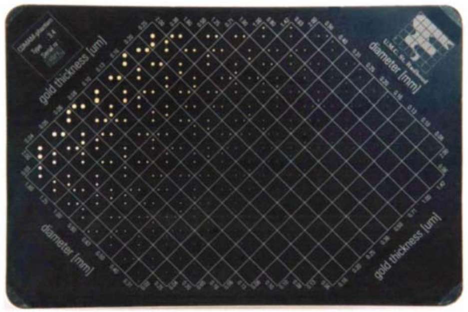


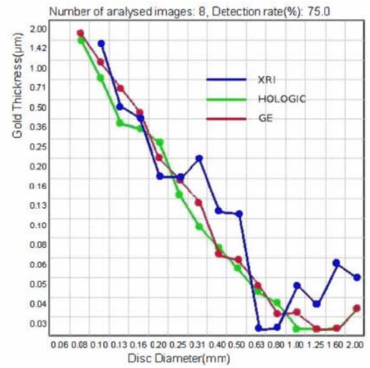
Radiography of the same phantom with AGFA CR 75.0 system using 40kV and 5mAs dose which corresponds to **35.7µGy**. One can hardly see any line at such dose.

XRI Prototype



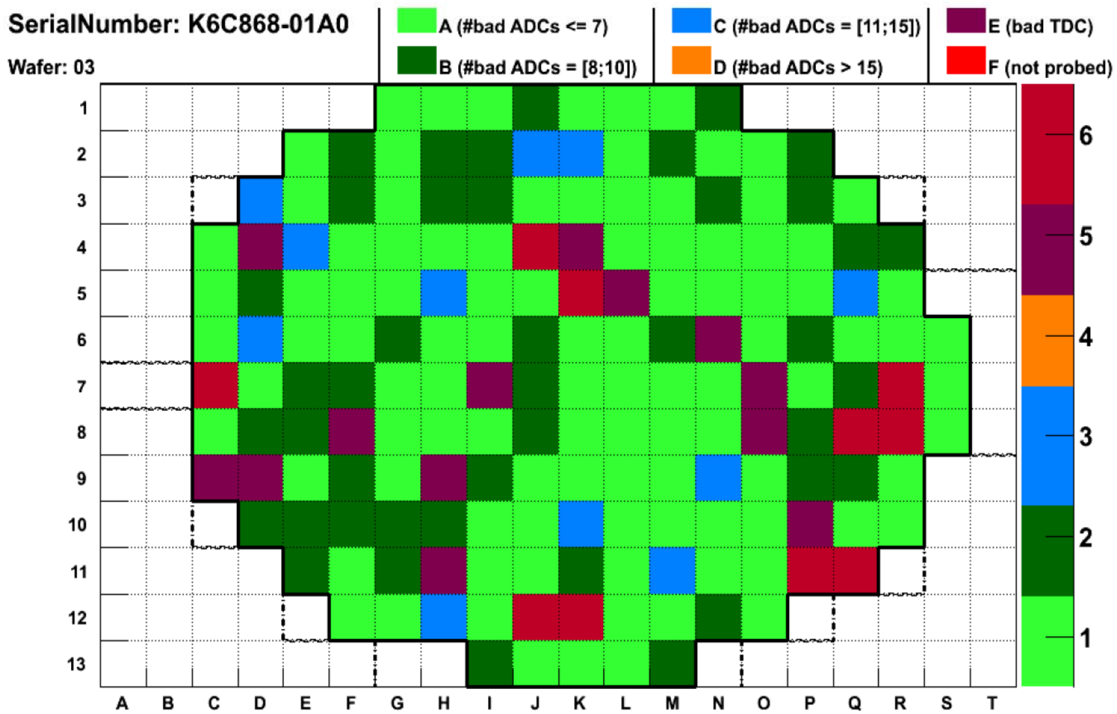






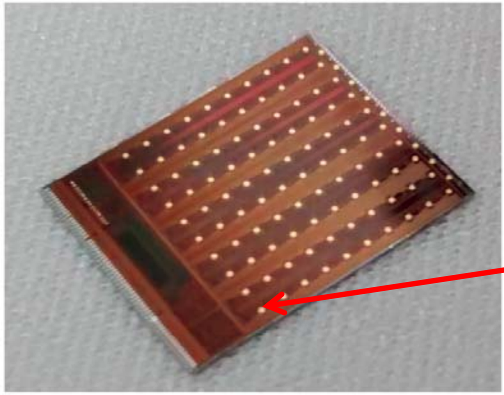
Voxel Imaging PET Pathfinder

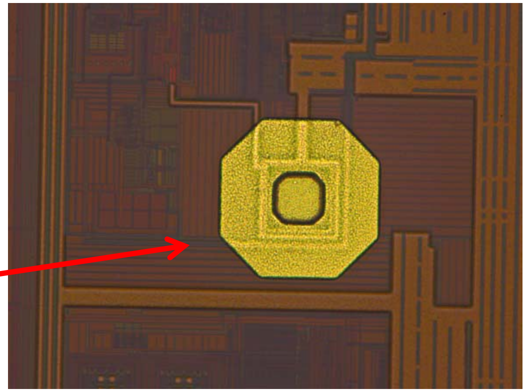
VIPPIX Wafer

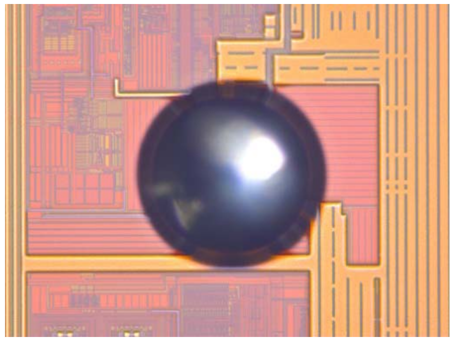


We did our own chip design, production and characterization of the wafer/chip. We produced 12 wafers. We have defect in the ADC design. We had enough chips with light green

BiSn Solder Ball deposition

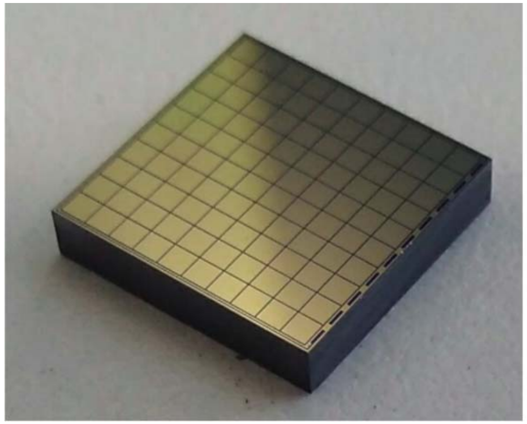


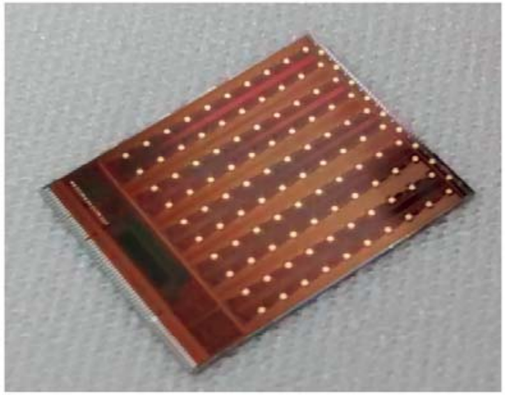


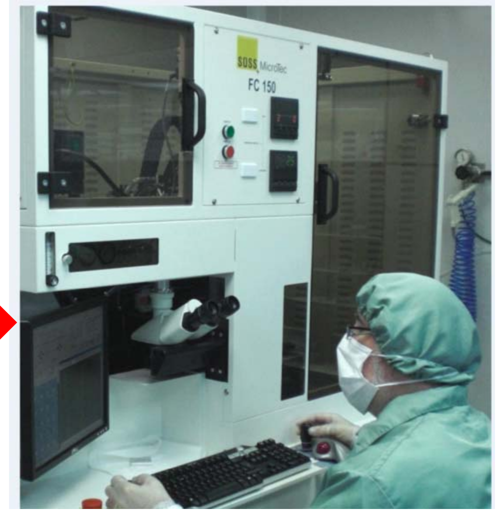


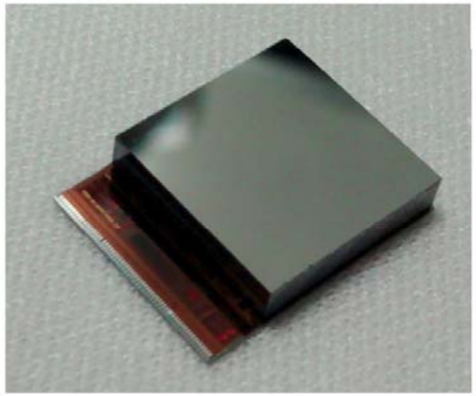
The wafers were processed at IZM with Under Metal Bump (UBM), then thinned down from 725um to 200um, and then diced. With Pactech SB^2–SM machine we deposited the 250um BiSn solder ball, one by one, for flip-chip in later stage.

CdTe Pixel Detector



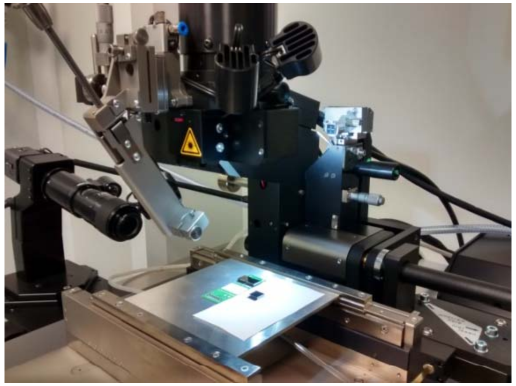


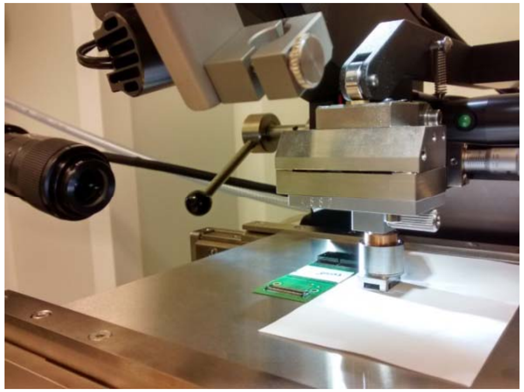


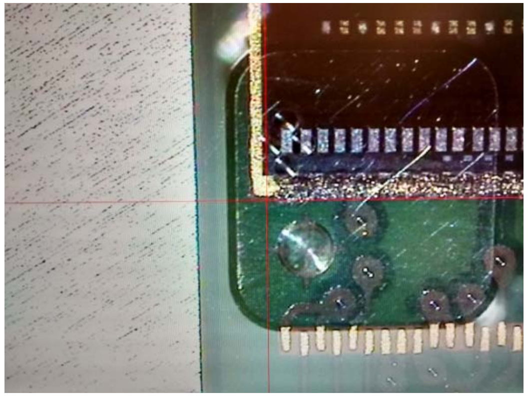


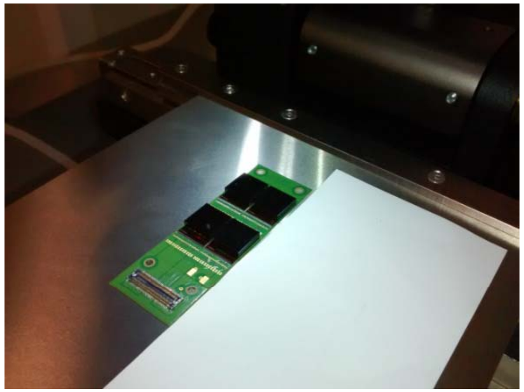
The pixel CdTe is fabricated by Acrorad (Japan) with Schottky electrodes to reduce the leakage current/pixel. Pixel pitch is 1mm and the detector thickness is 2mm. The detector is bonded to VIPPIX using FC150 with reflow arm at 150 ^{o}C. The Cd(Zn)Te detector is very sensitive to temperature and the bonding process should not exceed 160 ^{o}C.

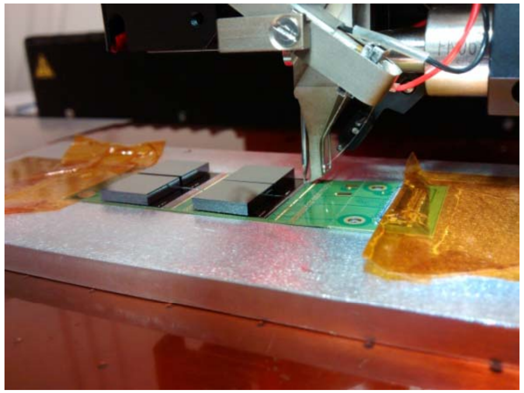
Single Layer Pixel CdTe



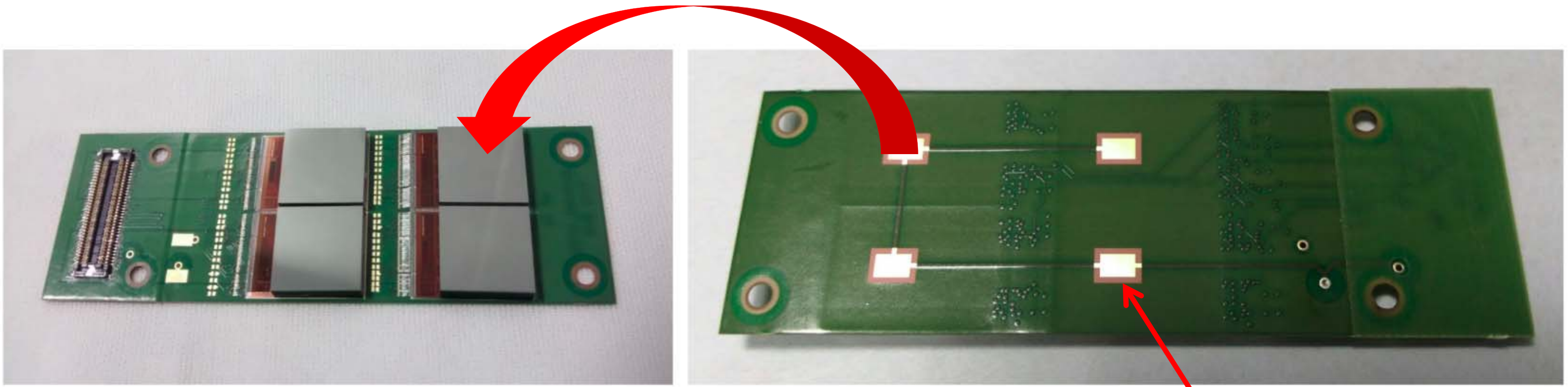


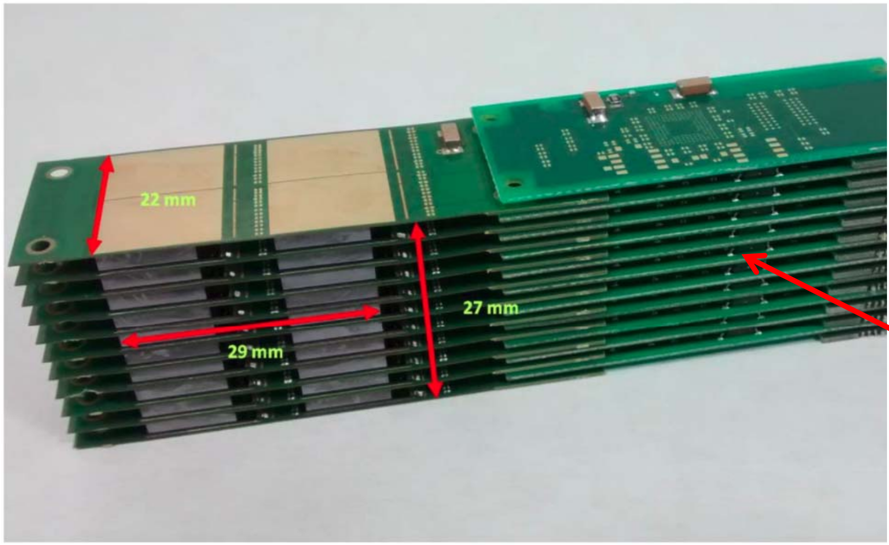






Detector Module (4000 voxel)

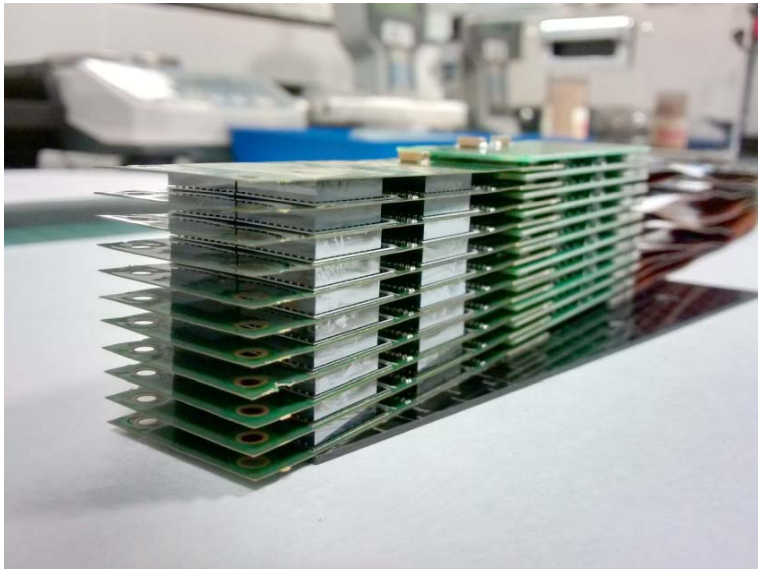




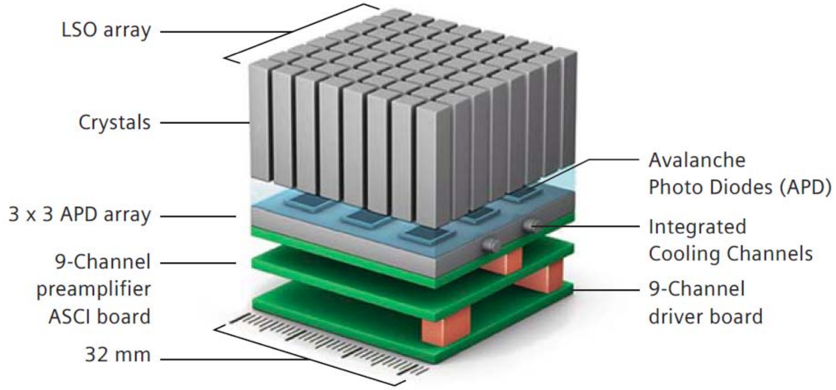
HV is provided by this bus to the 4 CdTe sensors of the layer underneath via 50um thick double adhesive conducting tape.

Every layer has it is own small FPGA to control/read/write to the 4 VIPPIX chips.

VIP detector module



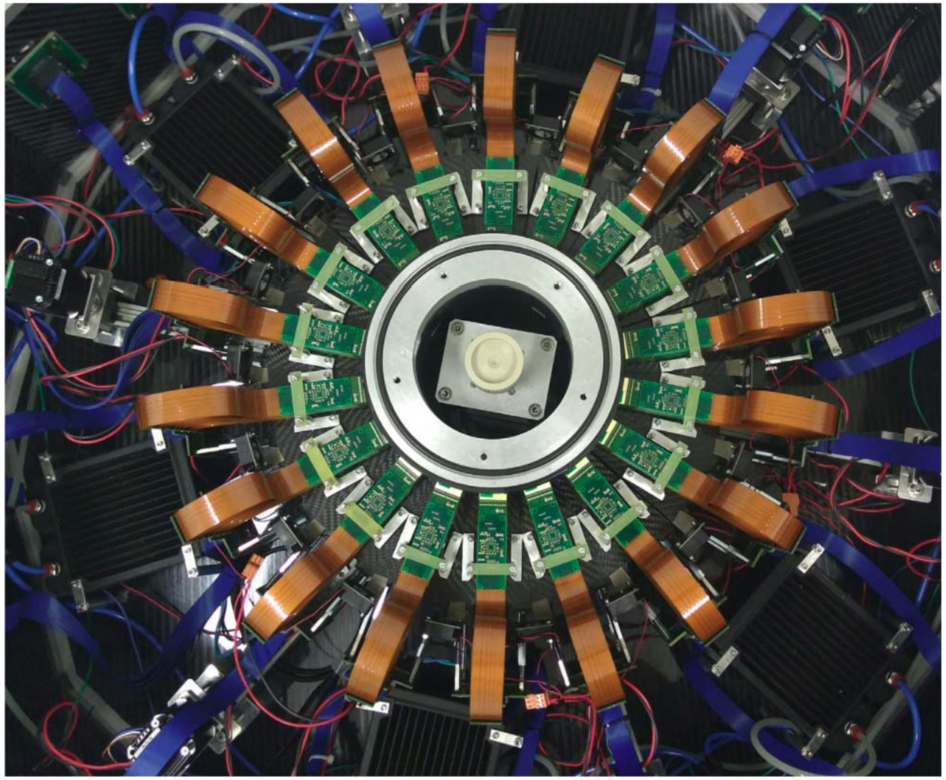
64 crystals each is 4mm x 4mm x 20mm



From Siemens Biograph mMR brochure

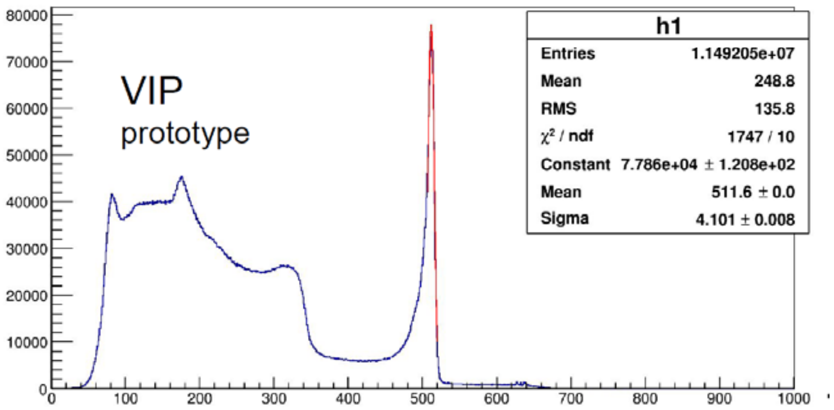
2cm x 2cm x 2cm of CdTe The module has **4000** independent pixels, each **1mm x 1mm x 2mm** , provides precise Depth Of Interaction (DOI) information regardless its radial length, excellent energy resolution and adequate detection efficiency

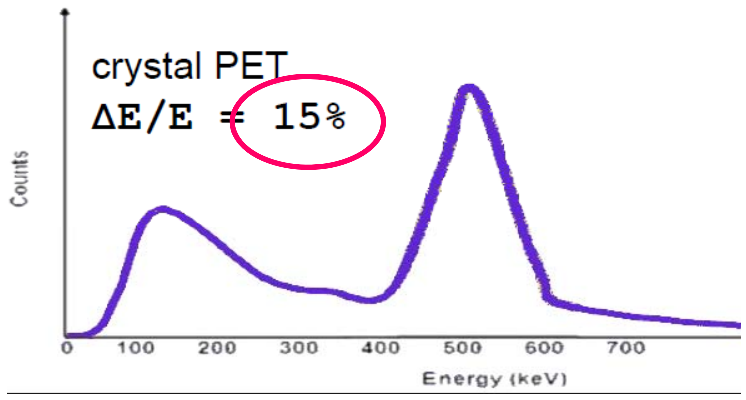
18 VIP detector modules



Top view of the VIP-PET scanner (proof of concept) with 72000 voxel CdTe, each has the volume of 1mm x 1mm x 2mm. Its axial view is **27** mm and it trans-axial view is **130 mm** . It is a sort of small animal PET

Spectroscopy Coincidence events with 2 hits only



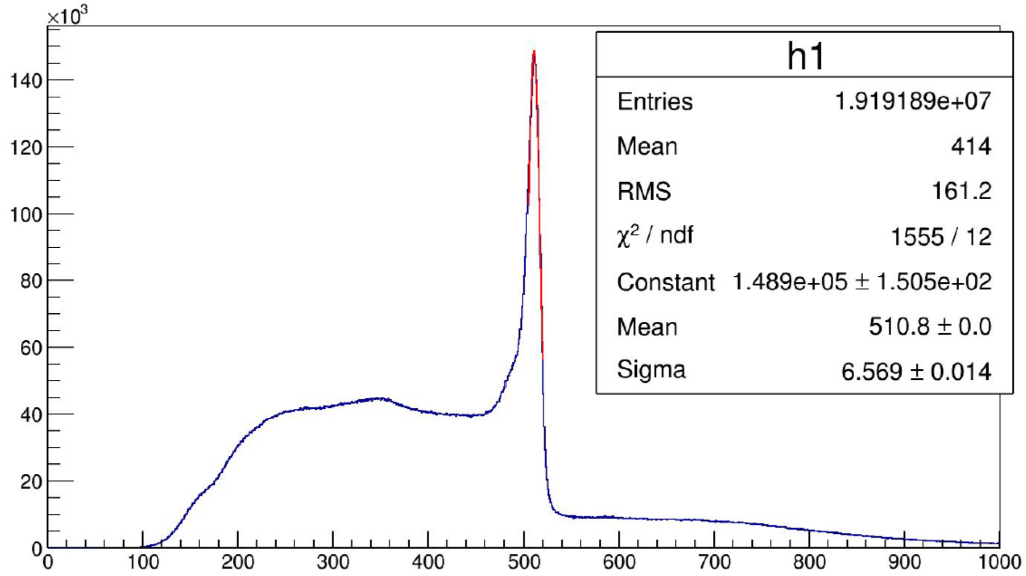


Energy Resolution (FWHM) @ 511 keV = 2%

Scatter fraction about **30-40%**

➔ Scatter fraction about **4-6 %**

Energy Spectrum of Compton Events



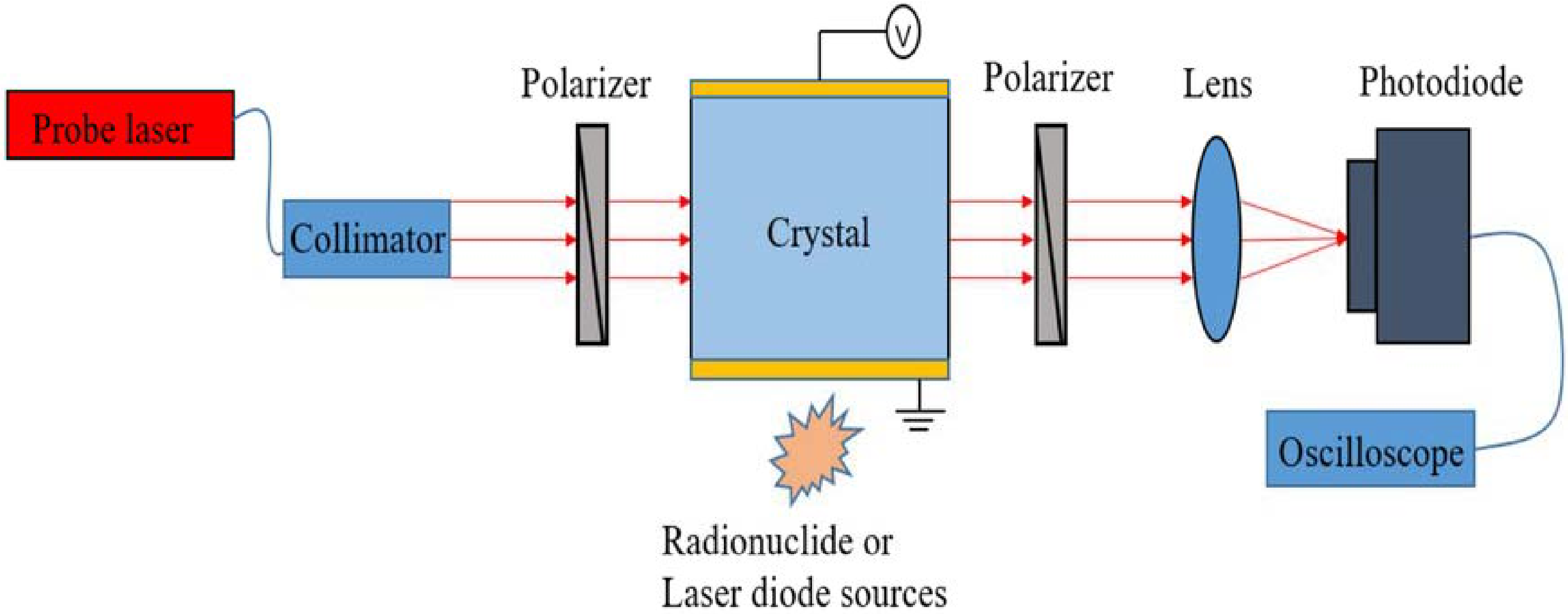
Energy Resolution (FWHM) @ 511 keV is **3%**

Excellent energy & position resolutions

⇩

High Resolution Compton Gamma Camera

Timing resolution of Cd(Zn)Te



The timing resolution of Cd(Zn)Te is **few ns** at best. However one can reach **100 ps** by using the Pockels effect property of the CZT crystal under radiation

X-ray LINe Detector with novel photon counting ASIC

LINDA

GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

AGAUR
Agència de Gestió d'Ajuts Universitaris i de Recerca

Unió Europea
Fons Europeu de Desenvolupament Regional

Introduction

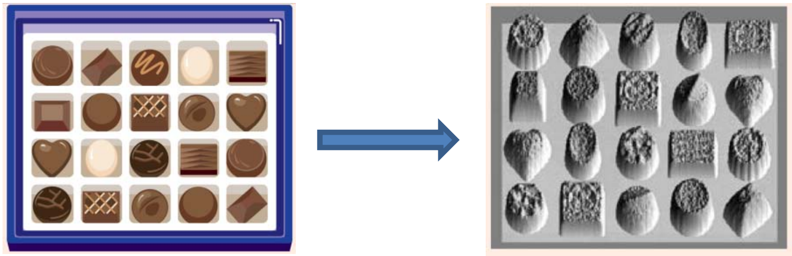
Industrial Quality Control based on X-ray scanner is a growing market and has bright prospective due to the increasing demands for:

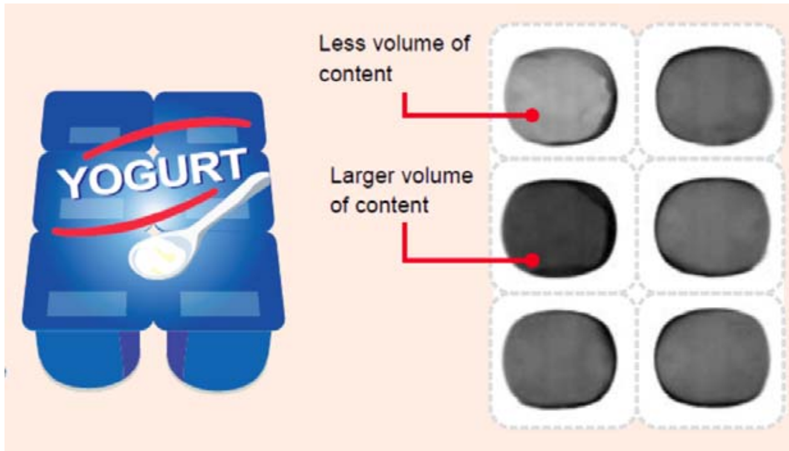
1-better quality product

2- reduced cost

This can be achieved by optimization of the production process (reducing the machinery errors with feedback from the processed images)

Applications for X-ray Linear Scan

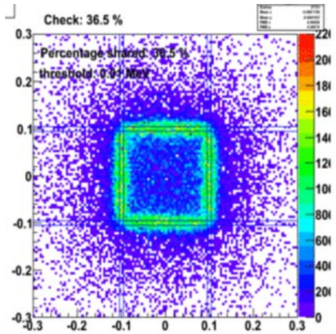


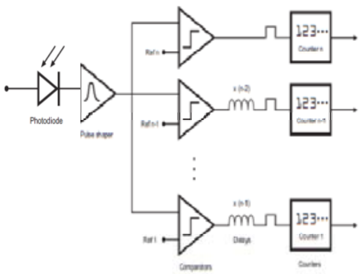


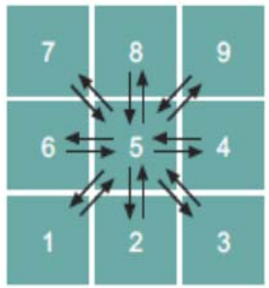
To sell 
in Japan, one needs to insure it does not have an air-bubble bigger than 1 cm

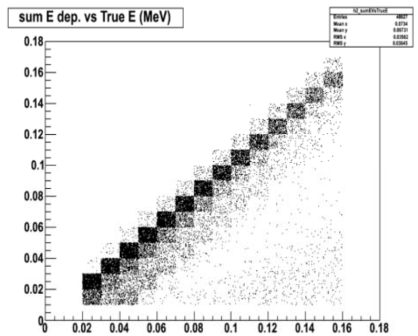
LINDA sensor

A Spectral X-ray Photon Counting Pixel Semiconductor Detector With Fast Algorithm to Sum Charge Sharing

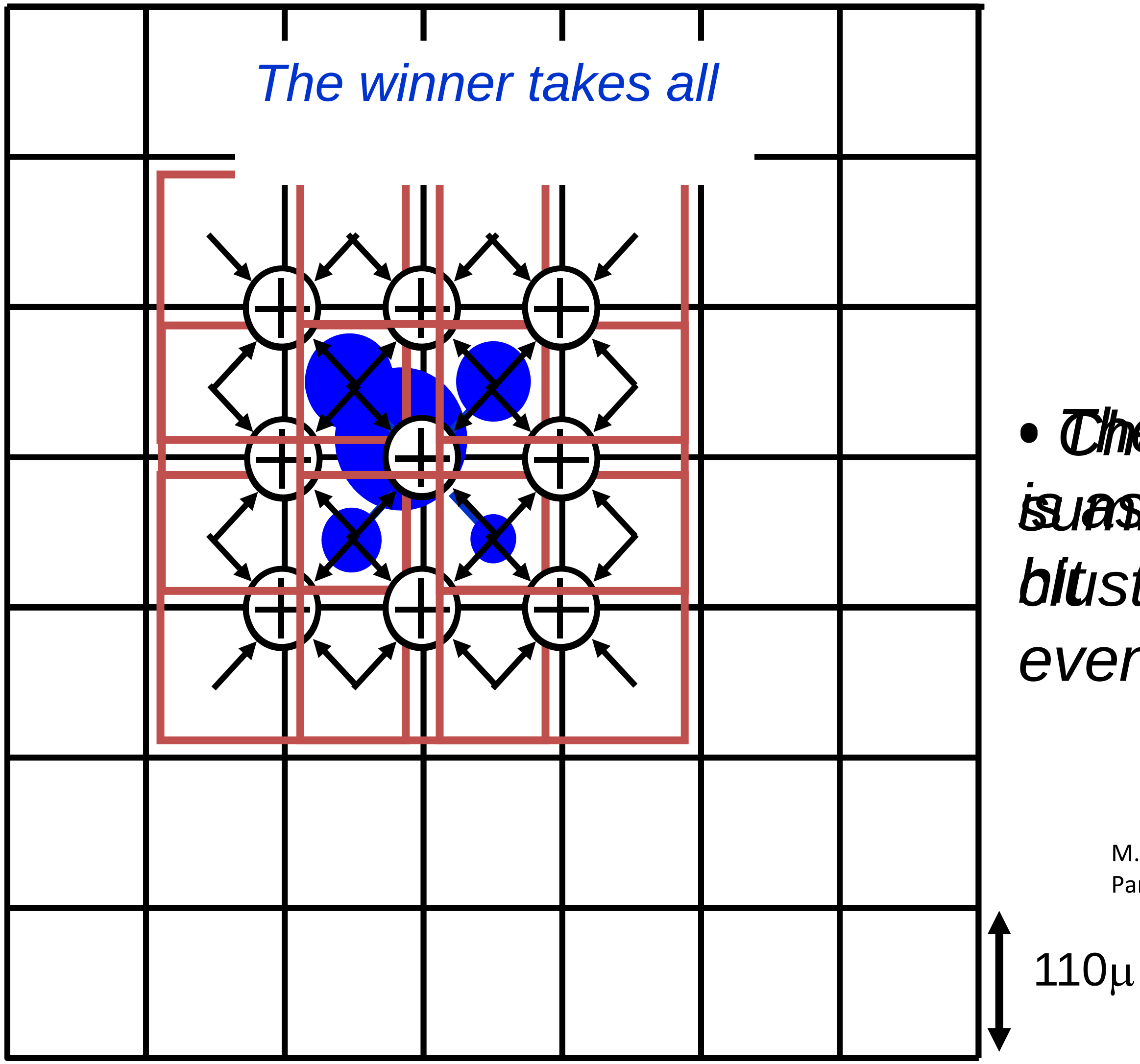








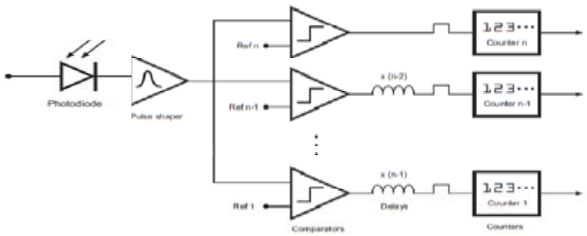
Medipix3 – charge summing concept

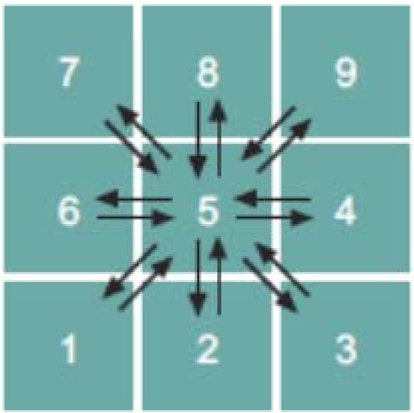


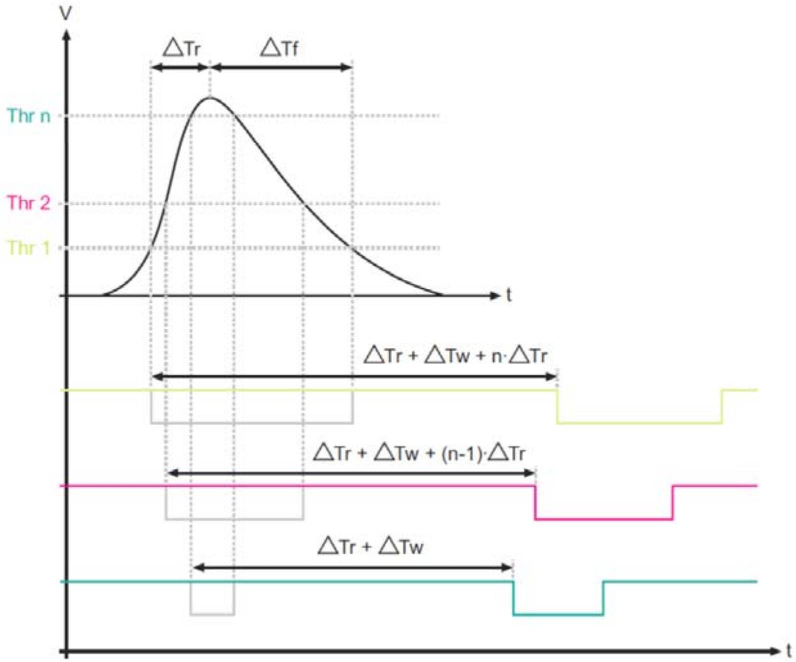
- *The incoming quantum is assigned as a single hit*
- *Charge processed is summed in every 4 pixel cluster on an event-by-event basis*

M. Campbell et.al , EUDET Annual Meeting 2007, Paris

LINDA Solution Charge Summation Algorithm Simple and Fast

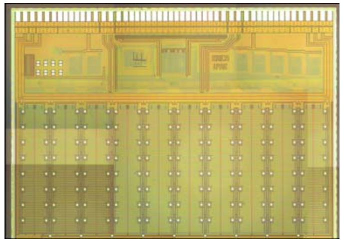


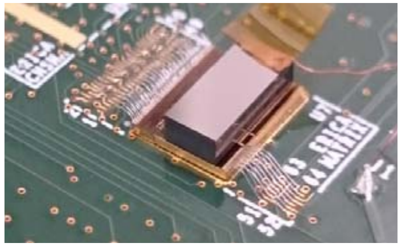


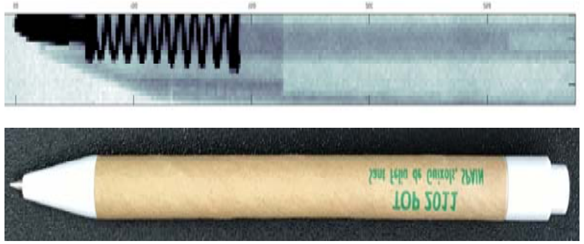


Patent Title: Energy Sum with Photon Counting . Priority date: 23 February 2015. Publication number: WO2016135106A1. Inventor(s): M. Chmeissani, J .G .Macias, M. Kolstein

Status







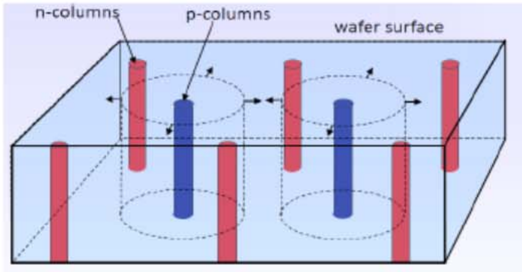
Work done
Left: An ASIC has been designed with a matrix array of 8 x 20 pixels. Each is 330um x 330um and each pixel has 6 energy counters. It has zero dead-time and can be used to acquire images in Time-Delay-Integration (TDI) mode
Center : LINDA sensor. The ASIC has been bump-bonded to 1mm thick and mounted on PCB. Active area 2.64 mm x 6.6 mm
Left : X-ray scan image of a pen. One can see the detailed image of the spring and the tube one part filled ink and the part with no ink

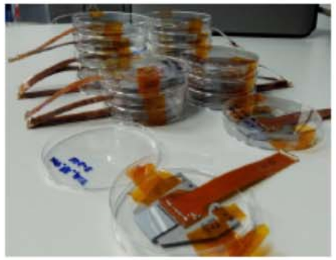
Work in progress
Embarked on the development of 200 mm line camera, using 30 LINDA sensors, to get integrated in X-ray scanner machine provided by **Multiscan Technologies SL**.

New Pixel Sensors fit for Photon Counting

3D pixel Sensor

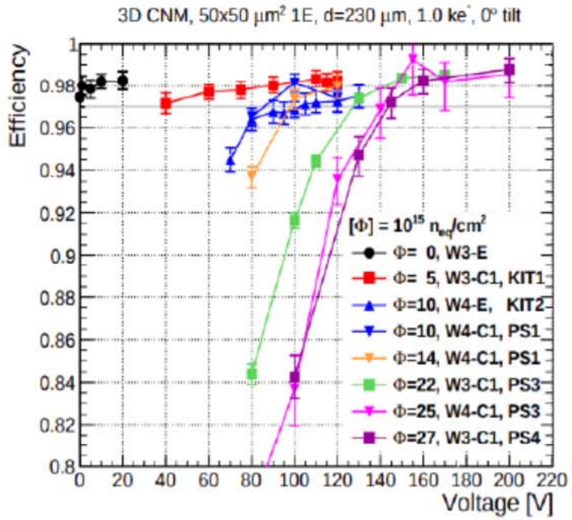
- In 3D sensors, the electrodes penetrate the silicon bulk
  - Charge has less distance to travel, less trapping, more radiation hardness
- IFAE qualified the 3D sensors for the ATLAS HL-LHC pixel detector upgrade
- Already tested 3D sensors with 50x50 μm² pixels using the new RD53A chip after irradiation





3D sensors bump-bonded and assembled by IFAE

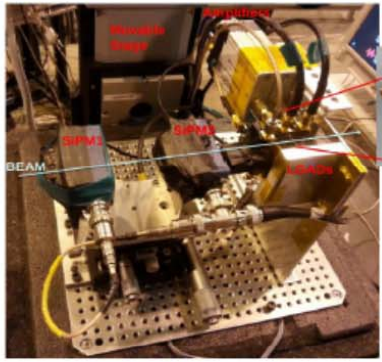
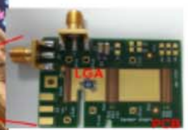
*Excellent **radiation hardness** of new generation of 3D sensors for the HL-LHC (JINST 13 (2918) P09009)*



3D sensors baseline for innermost layer of the HL-LHC ATLAS pixel upgrade

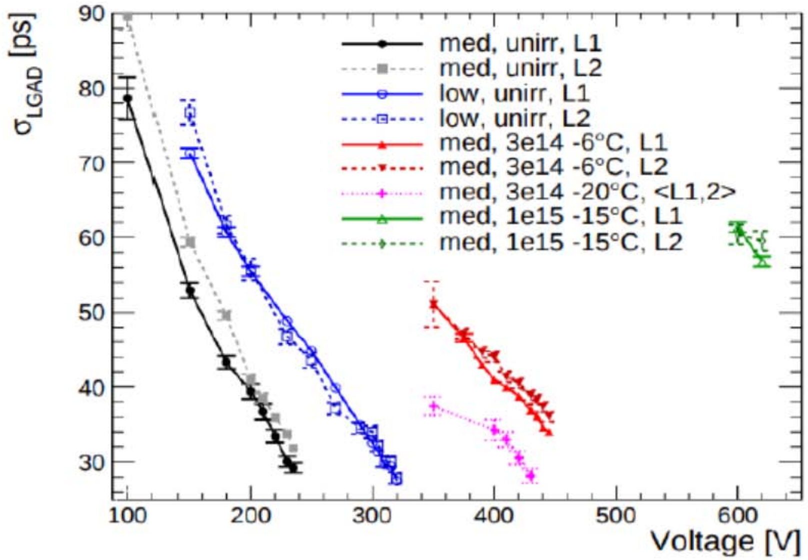
Timing With Silicon Sensor

- Development of silicon detectors with low gain (LGAD) with CNM-Barcelona
  - Moderate multiplication layer and thin devices result in excellent timing
- First results of timing performance before and after irradiation
  - 25 ps before irradiation and 60 ps after 1E15 neq/cm2 measured in beam tests

First test beam of irradiated LGADs

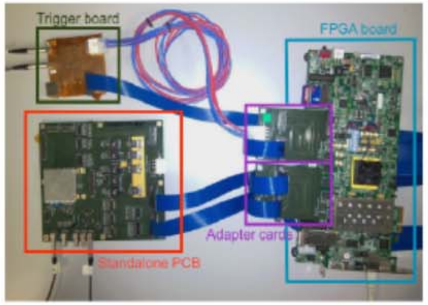
JINST 12 (2017) P05003



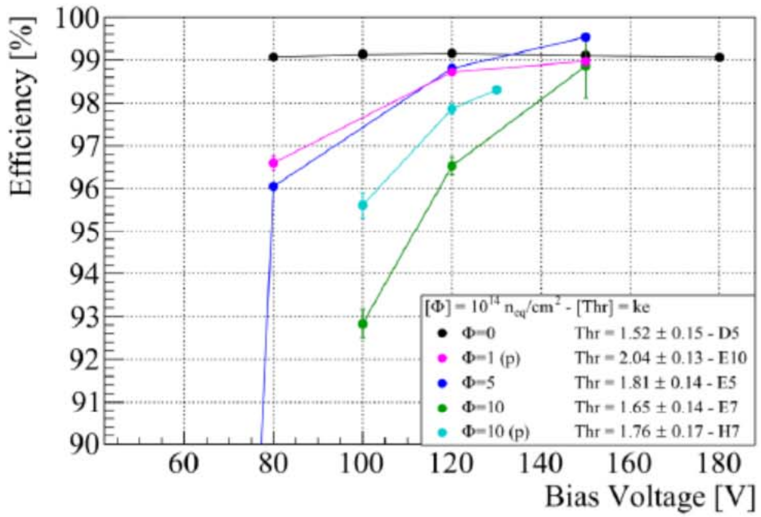
Technology adopted by High Granularity Timing Detector (HGTD) of ATLAS HL-LHC upgrade, TDR in preparation (April 2020)

IFAE: Monolithic Depleted-CMOS

- IFAE participated in the design and led the characterization of the first full size monolithic depleted CMOS prototype for the HL-LHC ATLAS pixel upgrade
- Excellent performance before [1] and after irradiation [2] up to 1E15neq/cm2
  - Compatible with outer pixel layer of HL-LHC ATLAS pixel detector
- In a second stage, a small pixel size (50x50 μm^2) prototype was produced and is being tested



IFAE readout system



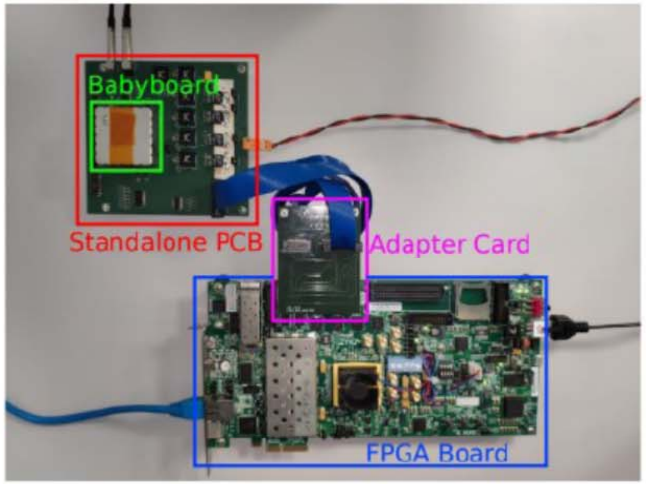
[1] JINST 12 (2017) C07023

[2] JINST 14 (2019) P02016

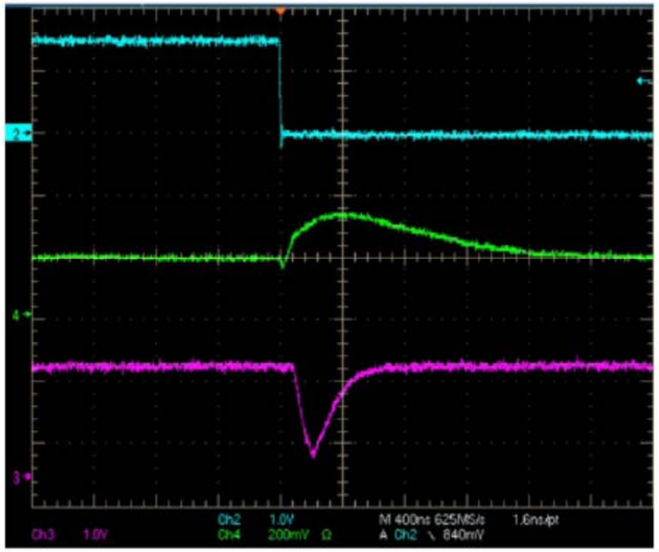
Technology being explored for LHC upgrades and future accelerator experiments

IFAE: Monolithic Photon Counter

- IFAE exploring the usage of monolithic devices for soft X-ray applications
- Photon counting matrix (75x75 μm^2) with a 16-bit counter
- Developed readout system and verified basic operation



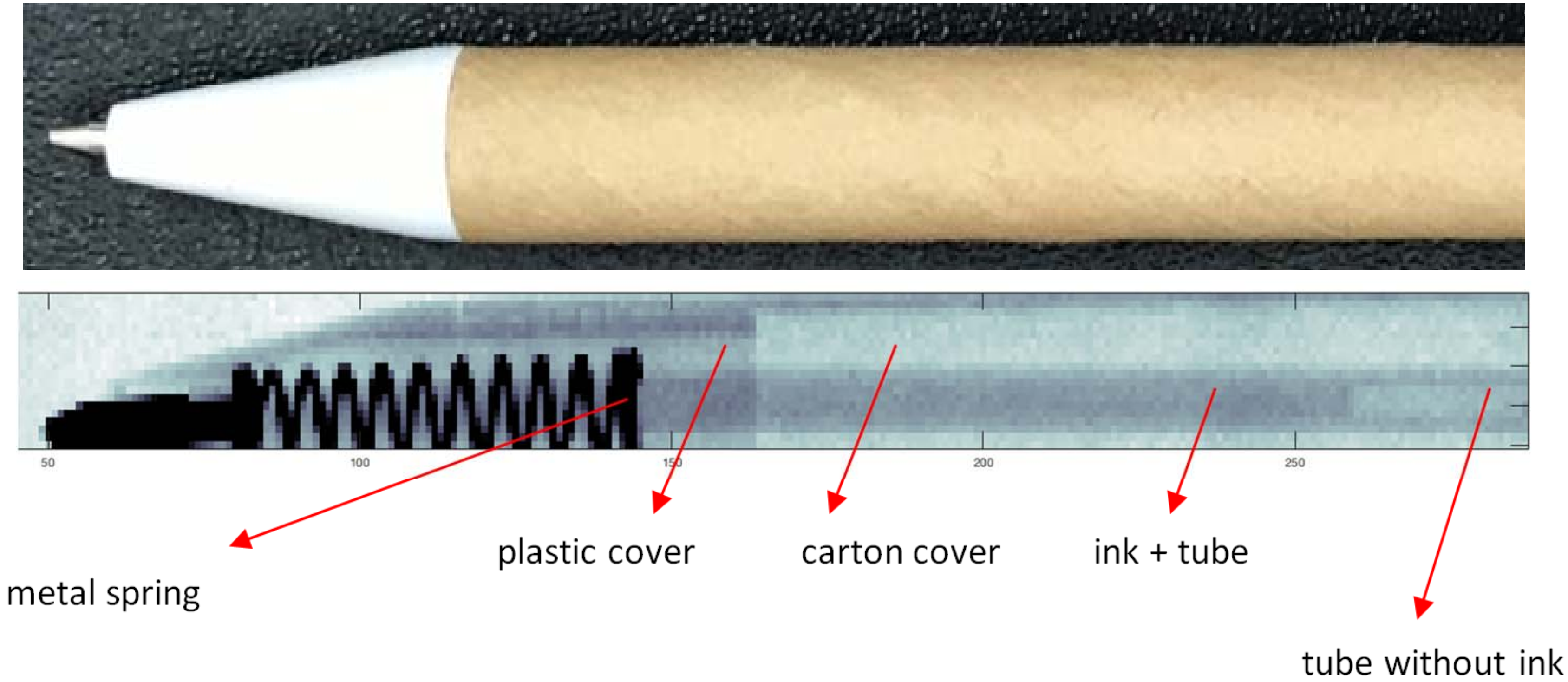
(b) LF2 readout system



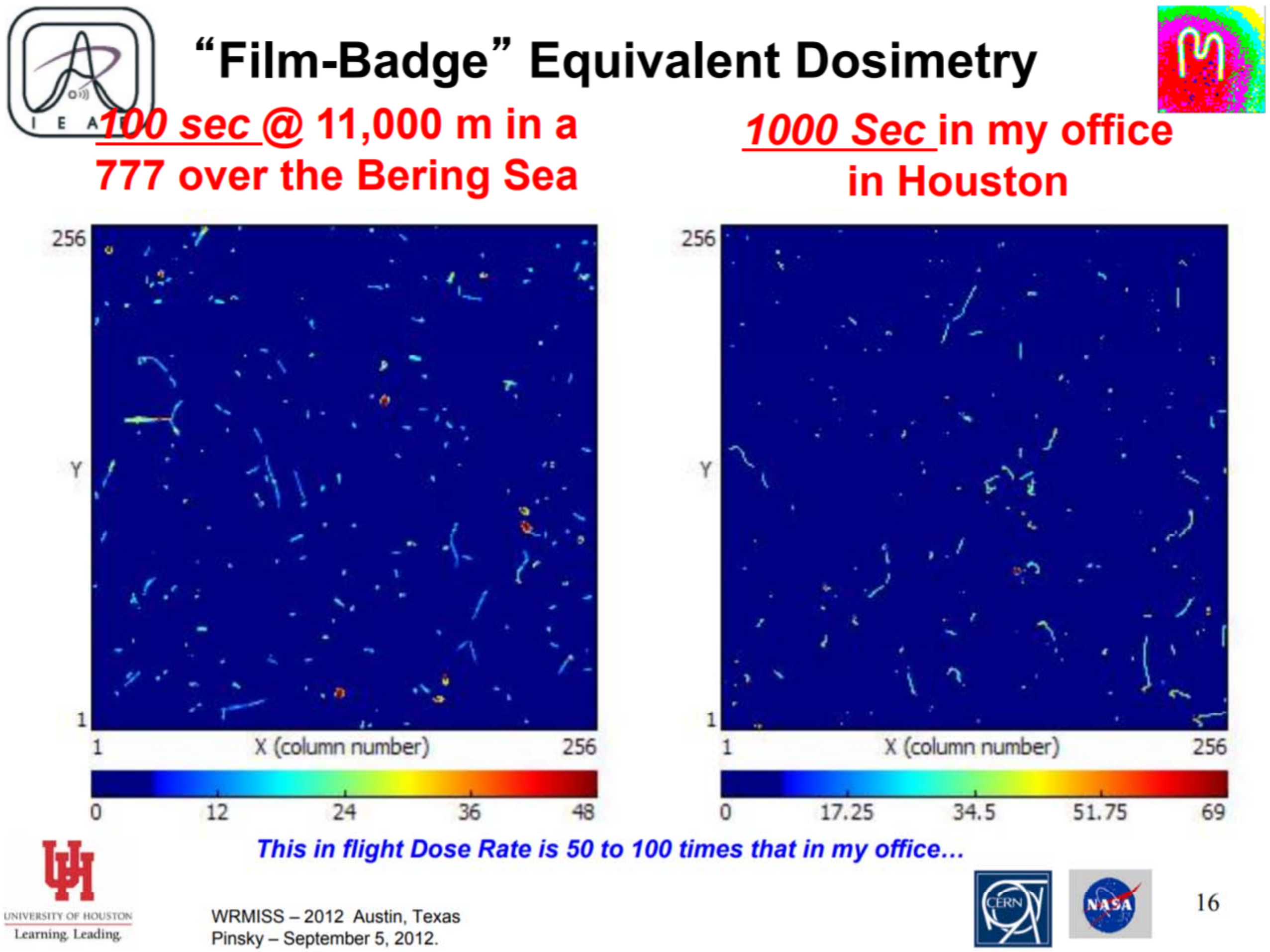
PoS (TWEPP-17) 039

Depleted Monolithic Active Pixel Sensors are an interesting and cost effective technology for photon counters

Thank you for your attention


50
100
150
200
250
metal spring
plastic cover
carton cover
ink + tube
tube without ink

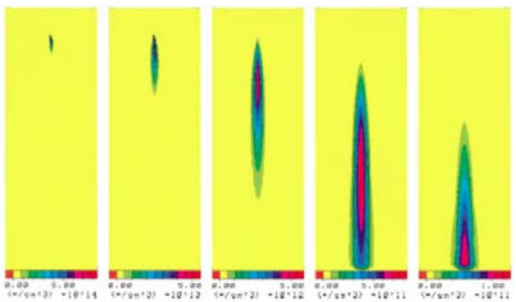
It can be used a real time Dosimeter



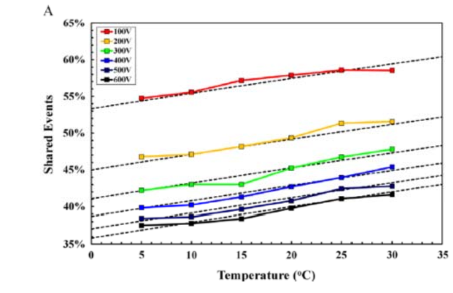
These sensors were produced by XRI

Charge Sharing

Charge sharing among neighboring pixels is the natural consequence of the diffusion (Fick´s law) of the charge cloud as it moves toward the electrodes. The diffusion process on many parameters and namely on the drift time (e-h mobility, HV, thickness of the detector). Temperature, and the initial size of the cloud, which in its turn depends on the Energy of the X-ray photon Energy.

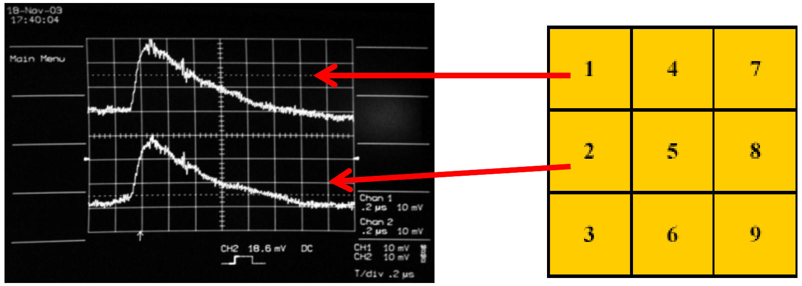


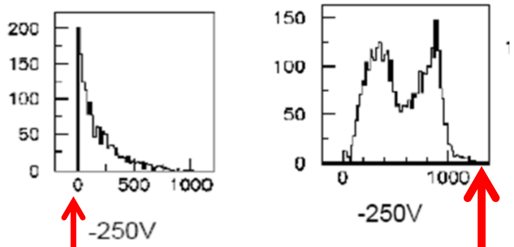
$$r = r_0 + 1.1d\sqrt{\frac{2k_\beta T}{qV}}$$



M.C. Veale et al. Measurement of charge sharing in small pixel CdTe detectors. Nucl. Instrum. Nucl. Mehtods in Phys. Res. A 767 (2014) 218-226

Problem: Charge sharing destroys the spectral information in Photon Counting sensor with **small pixel size**



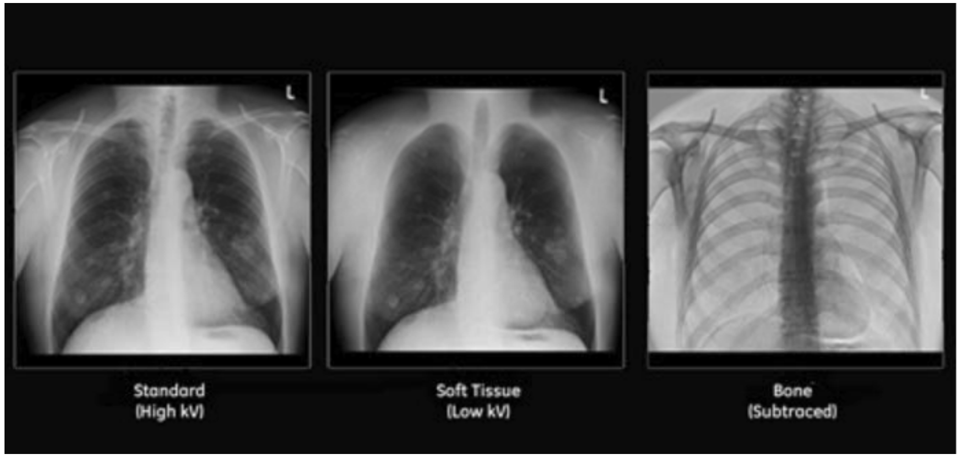


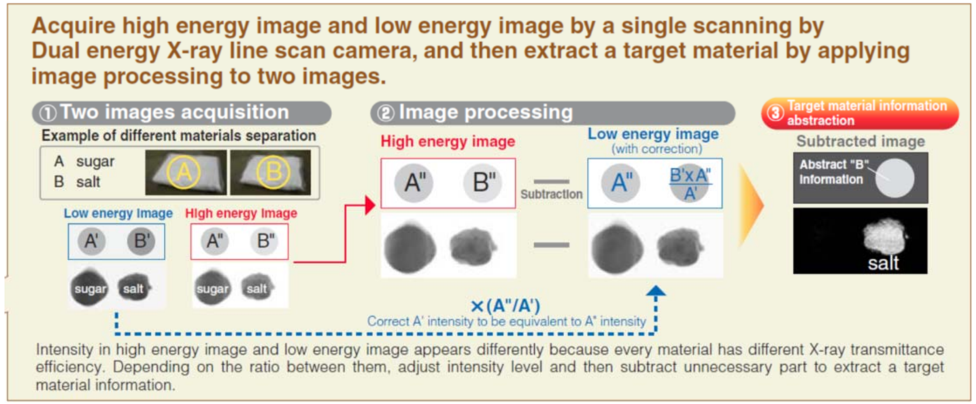
When an X-ray photon from Am241 hits one pixel , it could generate a signal in the neighboring pixel due to charge sharing

As a consequence the spectral energy of Am241 measured by any pixel (1 to 9) is lost

When the maximum energy of the photon is deposited in pixel 5 (central) and the energies of all the surrounding pixels are added to 5, the spectral energy of the total sum has recovered the profile of Am241

Dual-Energy Subtraction without photon counting sensor





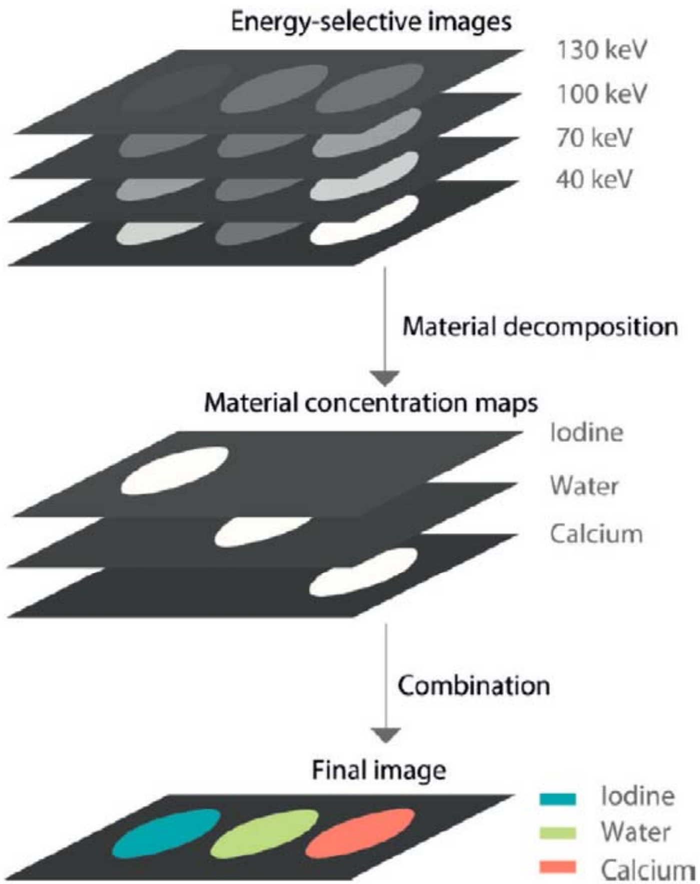
Technique widely used in Medical imaging. This is achieved **using 2** shots of X-ray one at High kV and one at Low kV

And

Used as well in linear scanner to detect two different materials. This is achieved by **using 2** line detectors one is set to detect Low and High X-ray Photons

With Photon Counting Sensor this can be achieved **by 1 X-ray Shot** and **1 detector** and with **multi-energy bins**

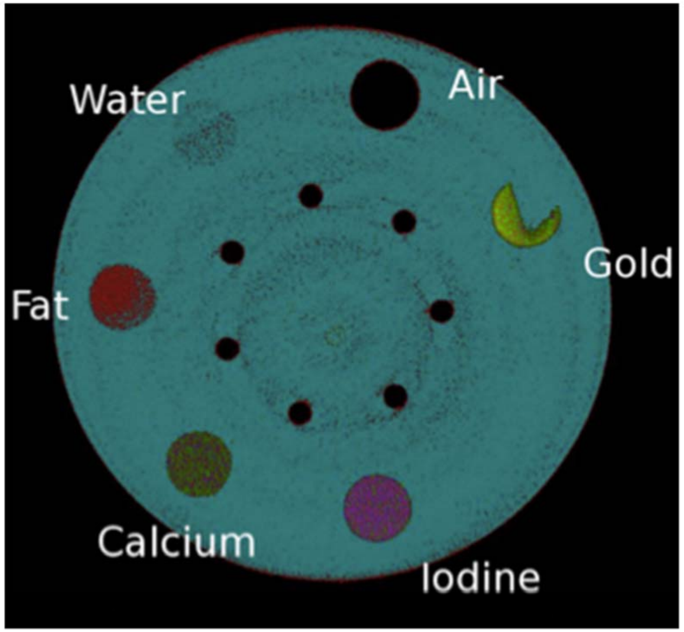
Photon Counting Multi-Energy Bins



Photon counting X-ray sensor with multi-bin energy thresholds will allow to decompose the object into different materials depending on the profile energy absorptions in every pixel.

The new generation of CT-Scanners developed by Siemens, Philips, GE, and Hitachi will be based on Cd(Zn)Te material and **with 4 energy levels** to achieve better diagnostic

CT scan with Medipix3



spectral image of a five-material decomposition obtained using Medipix3.1 GaAs detector assembly. Clockwise from 1 o'clock: black, air; yellow, gold (30 mg ml1); purple, iodine (20 mg ml1); green, calcium (338 mg ml1); red, fat; cyan, Perspex and water

Clinical applications of spectral molecular imaging: potential and challenges. By Nigel G. Andersona, and Anthony P. Butler. Published in Contrast Media Mol. Imaging 2014,93–12

Scatter and Parallax