The Vienna Conference on Instrumentation

A new X-Ray imaging system based on *Chromatic Photon Counting technology*

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PiXirad Chromatic Photon Counting

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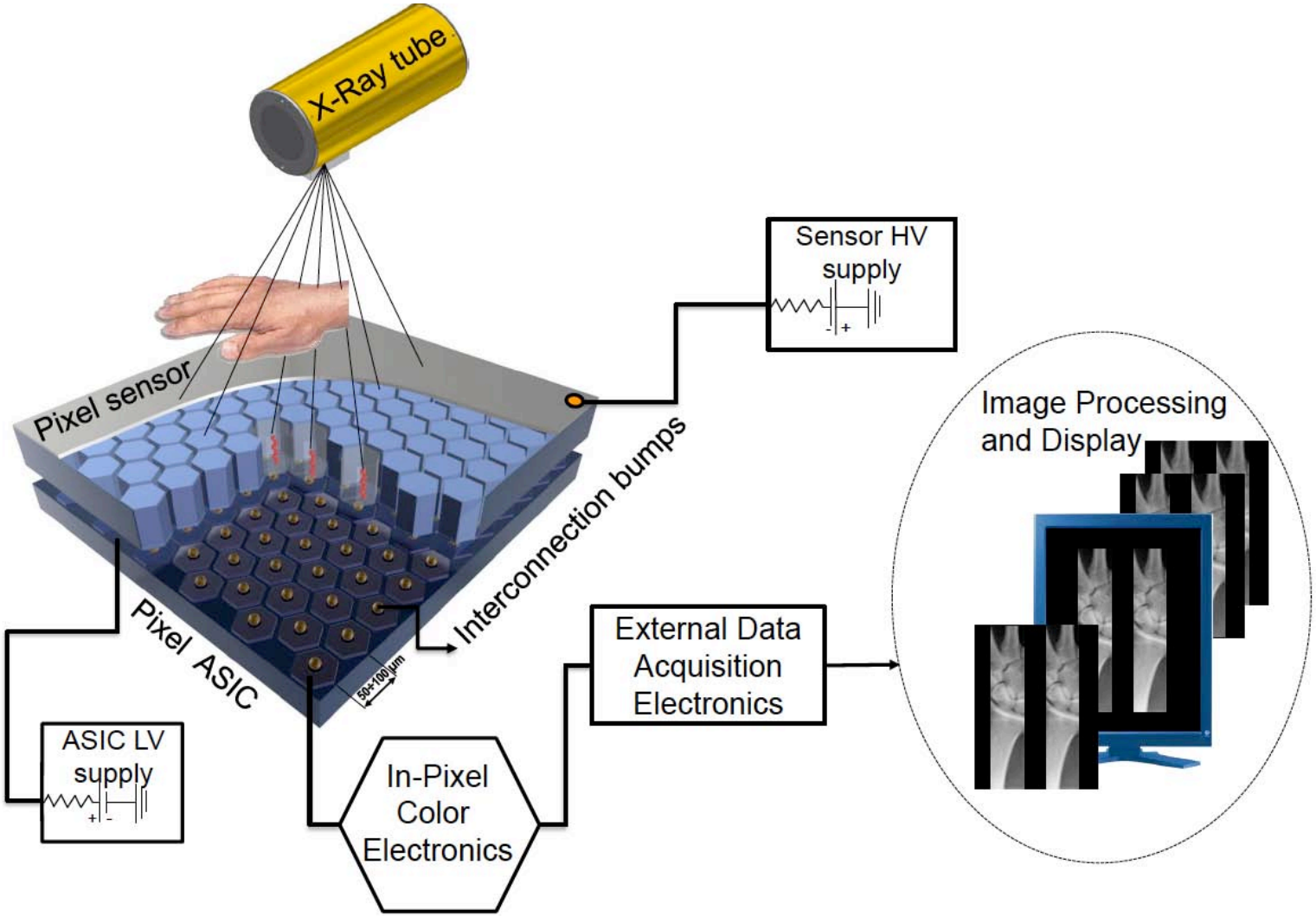
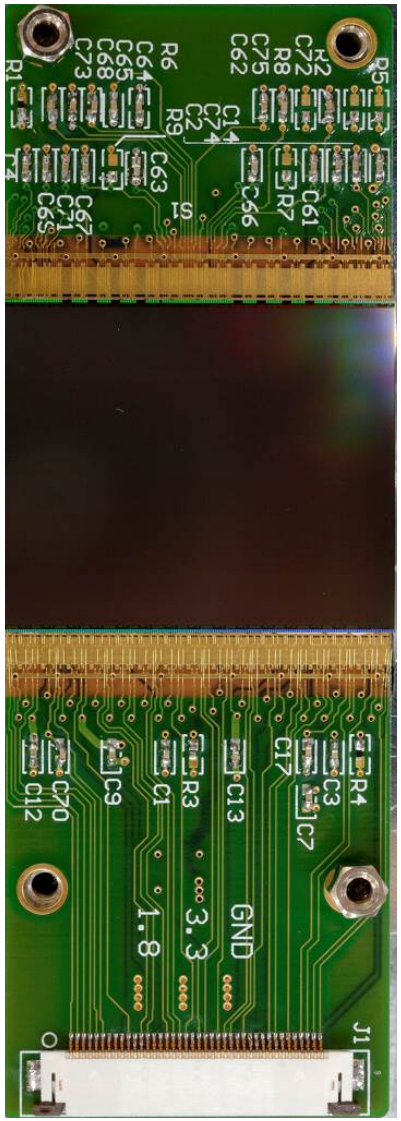
Principle of operation



The building block of the X-ray Imaging Sensor



Base block of PIXIRAD.
Hybrid architecture, obtained by
coupling, with the *flip-chip bonding* technique:

- a CdTe X-ray sensor (30 × 25 mm^2, electron collection type)
- a pixellized CMOS ASIC (512×476 pixels, at 60 µm hex. pitch)

Main characteristics:

- color capability (2 counters / thresholds in each pixel)
- largest ASIC ever built on planet
- largest CdTe sensor with pitch finer than 100 µm ever built
- buttable on two sides
- very low global threshold
- automatic offset compensation

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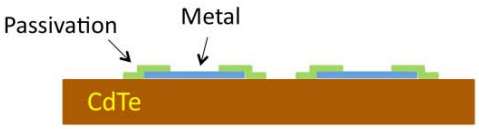
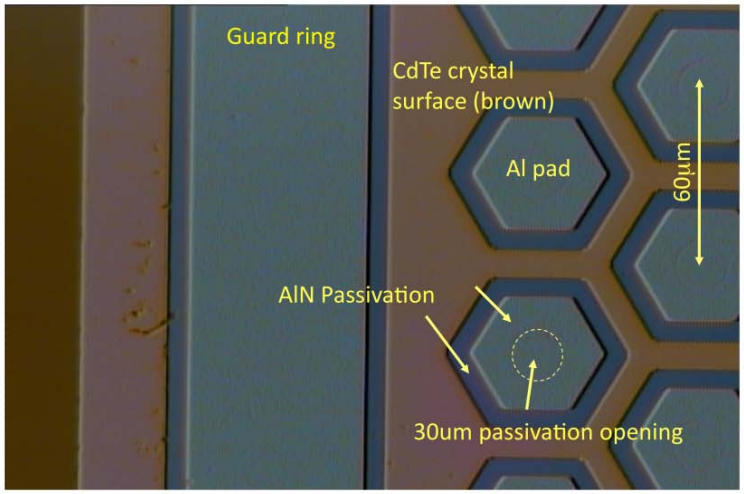
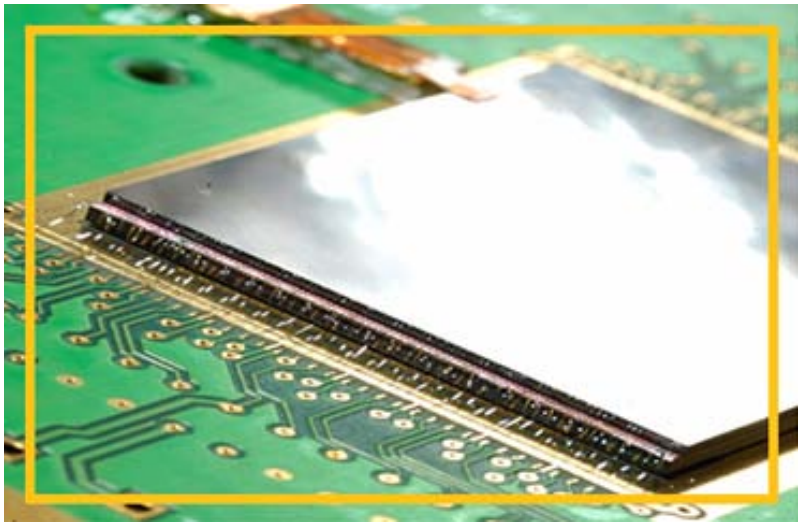
The CdTe Sensor







CdTe semiconductor characteristics:	
Atomic numbers	48, 52
Effective atomic number	50
Density ρ(g/cm³)	5.85
Band energy (eV)	1.5
Dielectric constant	11
Ionizing energy (eV)	4.43
Resistivity ρ(Ωcm)	10^9
Electron mobility μ_e (cm²/Vs)	1100
Electrons mean lifetime τ_e (s)	$3x10^{-6}$
Hole mobility μ_h (cm²/Vs)	100
Holes mean lifetime τ_h (s)	$2x10^{-6}$
$(\mu\tau)_e$ (cm²/V)	$3.3x10^{-3}$
$(\mu\tau)_h$ (cm²/V)	$2x10^{-4}$

The CdTe pixel sensor (ACRORAD Co., Ltd.) is a Schottky type diode with electron collection on the pixels
Large area: 30.96 × 24.98 × 0.65 mm
Pixel pitch: 60 µm (on hexagonal matrix)
Very low leakage current @400-500V working voltage (5 nA/cm²)

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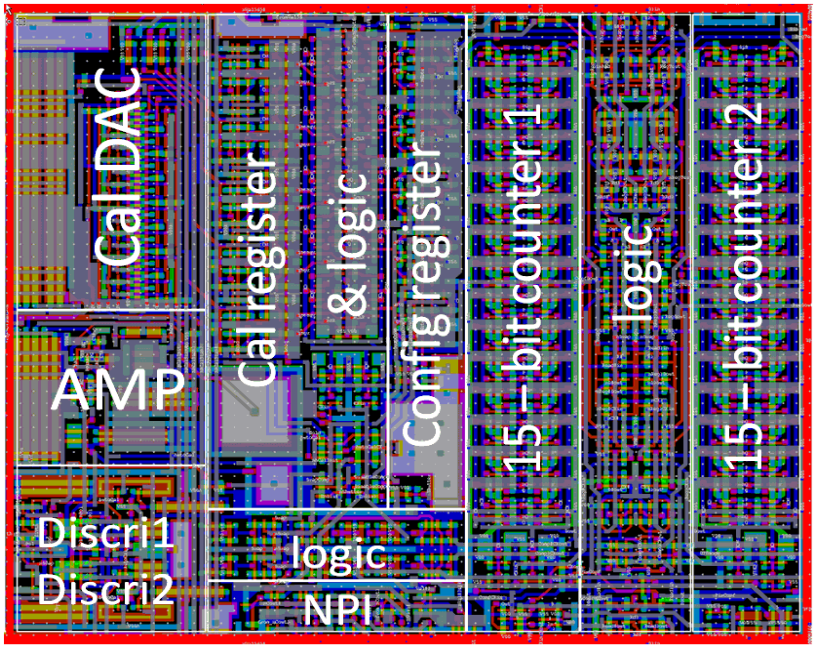
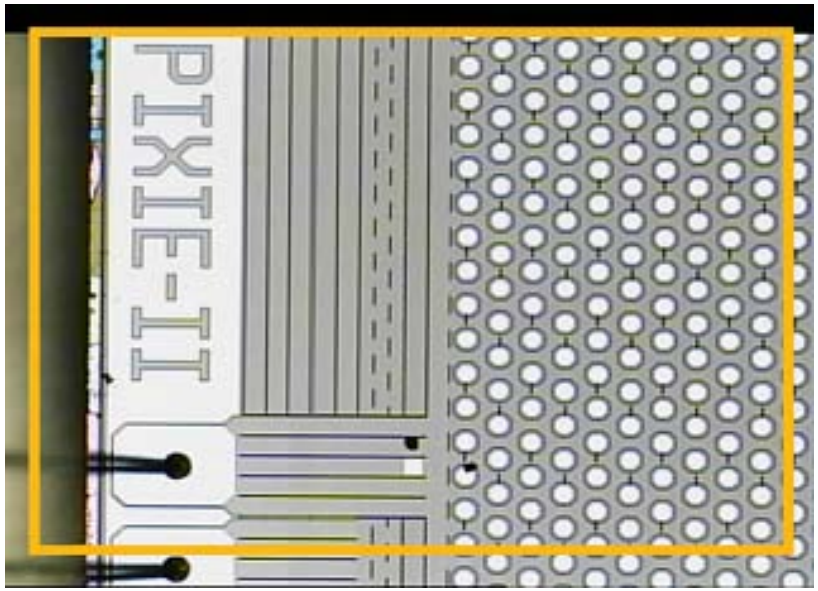
The CMOS large area ASIC





Pixel characteristics	
Shaped pulse duration (at the base)	1 µs (adjustable)
Linear range	> 3000 electrons
Saturation level	> 6000 electrons (>30 keV for CdTe)
Equivalent noise (ENC)	50 electrons (rms)
Residual offset after auto-calibration	± 30 electrons
Maximum number of counts before reading	32768
Input signal	positive or negative
Possibility to disable, swap, by pass, pixels	user selectable
Pixel reading	
Serialization of columns for best readout time	16, 32, 64, 128
Typical readout clock frequency	50 MHz
Readout time for 32 data outputs = 16 columns serialized (16 columns × 476 pixels × 15 bits × 20 ns)	2.3 ms
Readout time for 16 data outputs = 32 columns serialized	4.6 ms
Readout time for 8 data outputs = 64 columns serialized	9.2 ms

Data acquisition: 2 *color* reading (2 thresholds, 2 counters) or, alternatively, counting in one counter while reading the other one (dead-time free mode).

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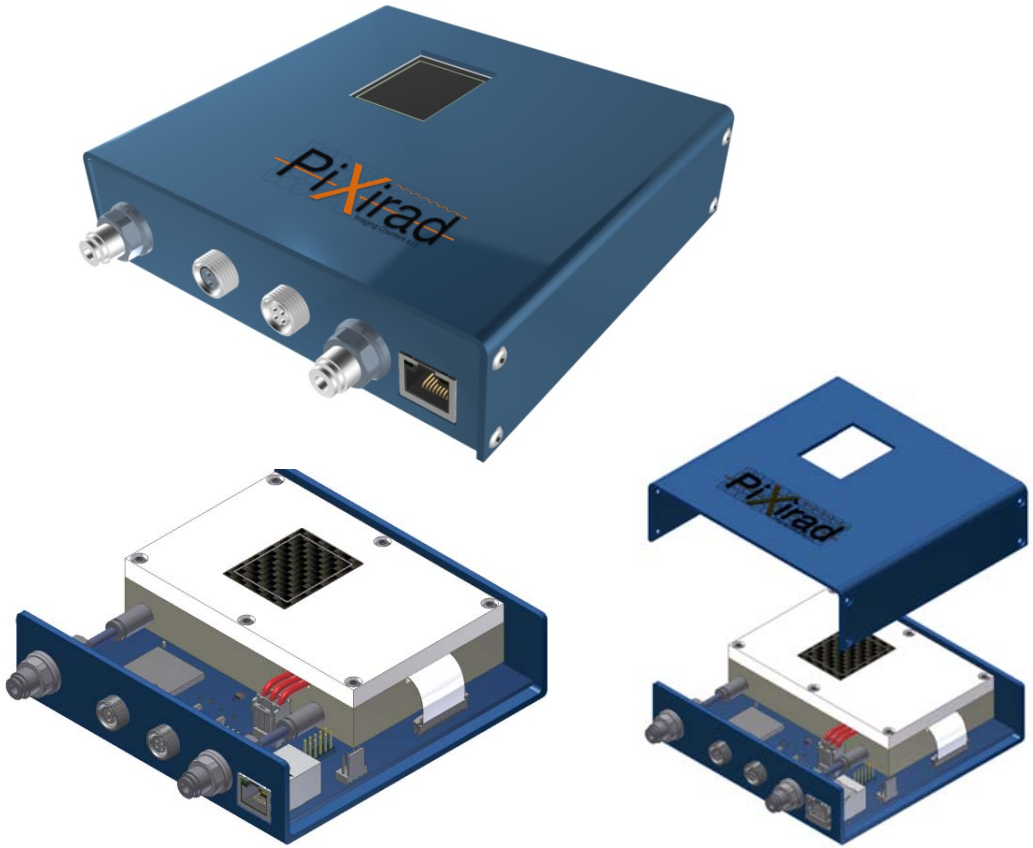
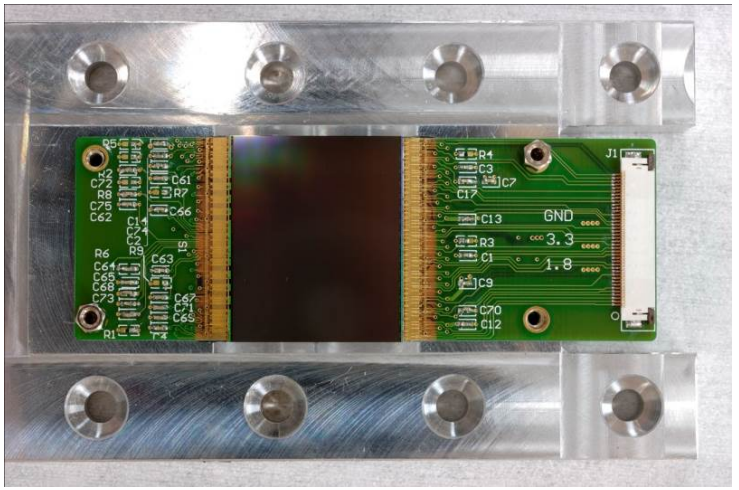
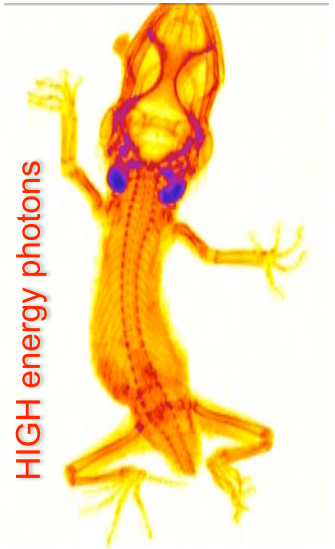
PIXIRAD-1 design concept



A single unit system (3×2.5 cm²)





Inside the module:

- 1 Gbit Ethernet DAQ
- Generation of High and Low Voltage Supply
- Distribution and cooling control

Externally: only 12V power supply (laptop type)

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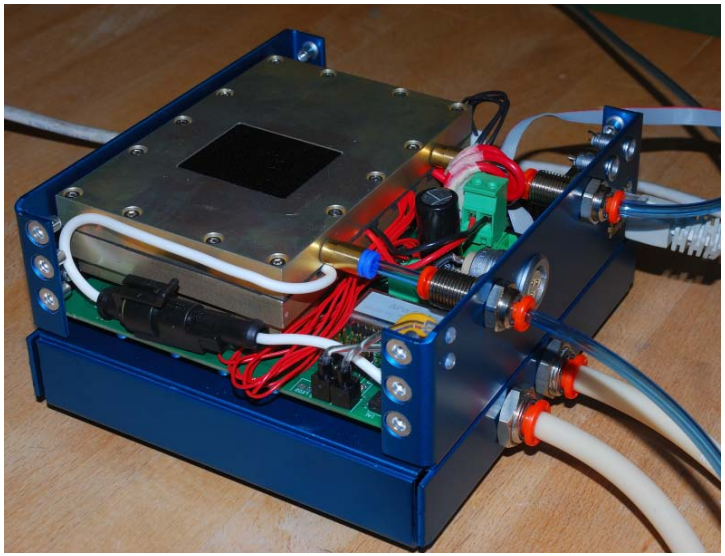
PIXIRAD-1: The module and the specs



Sensor specs:	CdTe, 650 µm, 30.9 × 25.0 mm² Schottky type diode Electron collection at pixel
ASIC+CdTe base block	512 × 476 pixels
Number of blocks	1
Global active area	31 x 25 mm²
Total number of pixels	243712
Total number of counters	487424
Pixel size	60 µm hexagonal arrangement
Pixel density	323 pixels/mm², equivalent to 55 µm on square arrangement
Pixel rate capability	10^6 counts/pixel/s (after dead-time correction)
Global rate capability	$2.4x10^{11}$ counts/s
Pixel dead-time	300 ns
Position resolution	11 line pairs/mm at MTF 50%
Reading while taking data	possible
Energy range	1-100 keV
Detection efficiency @10 keV, 25 keV, 50 keV	100%, 100%, 98%
Counters depth	15 bits
Read-out time @50 MHz clock	5 ms/counter
Frame rate	200 readouts/s
Minimum applicable global threshold	200 electrons
Sensor bias voltage	200 ÷ 400 V
Leakage current density	5 nA /cm² at 400 V, -20 °C
Typical number of defective pixels	less than 1%
Number of independent thresholds (colors)	2 set of two (swappable in real time)
Camera specs:	
Size (W×L×H)	14×14×7 cm³
Weight	< 2Kg
Power consumption	60 Watts (typical)
Cooling	liquid or forced air
Operating temperature	+40 -40 °C

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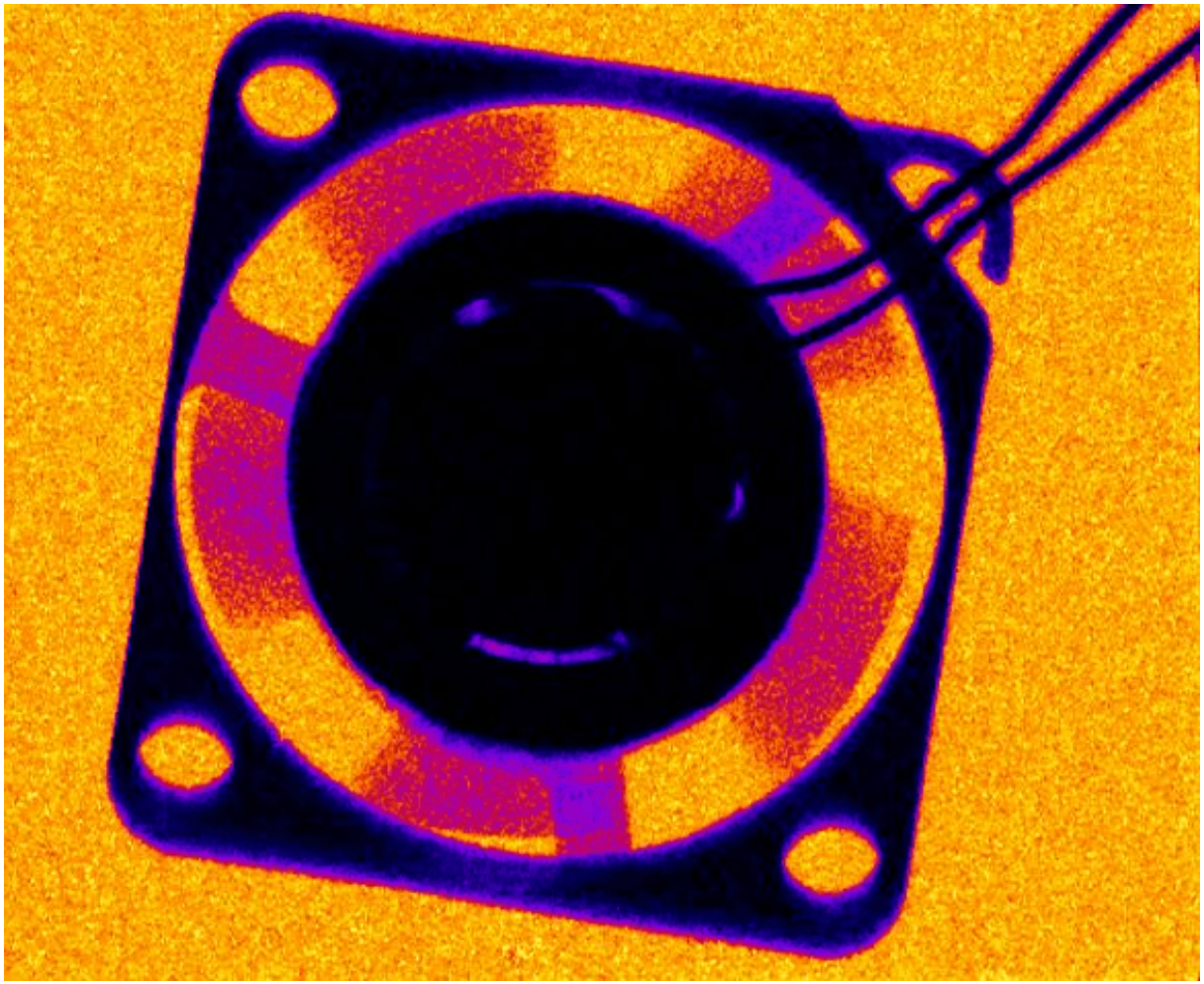
Dynamic Imaging

Image of a small fan spinning at around 4000 rpm.

The image was taken in Dead-Time Free mode (DTF), i.e. data are acquired in one counter while reading the other one.

The acquisition speed was 100 frame per second, shutter width was 1 ms and counting rate was 4×10^5 counts per pixel per second



PIXIRAD-2

A 2 unit system (6×2.5 cm²)

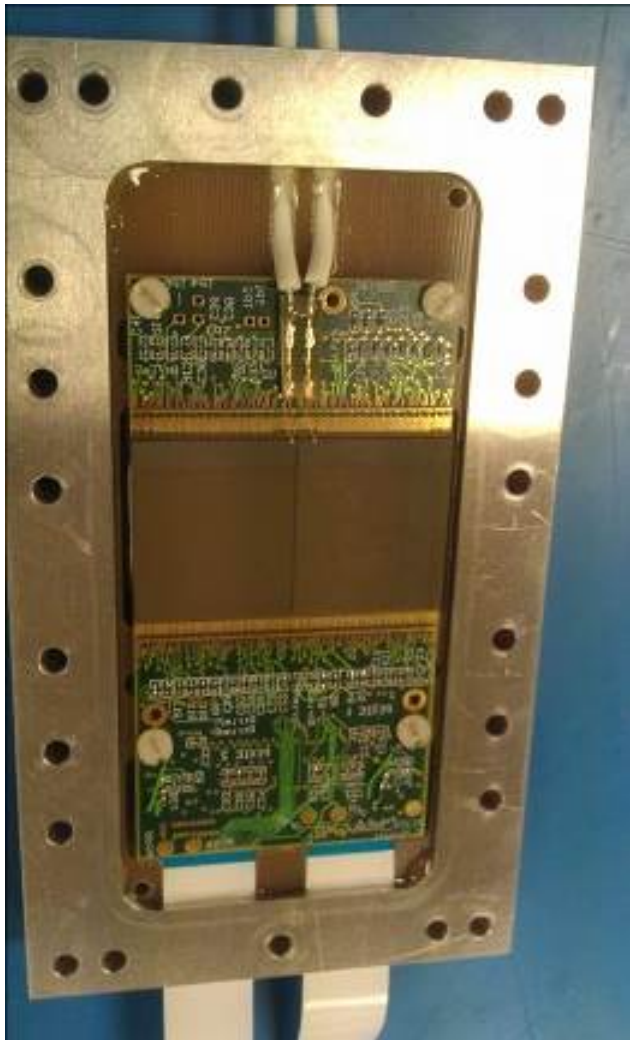
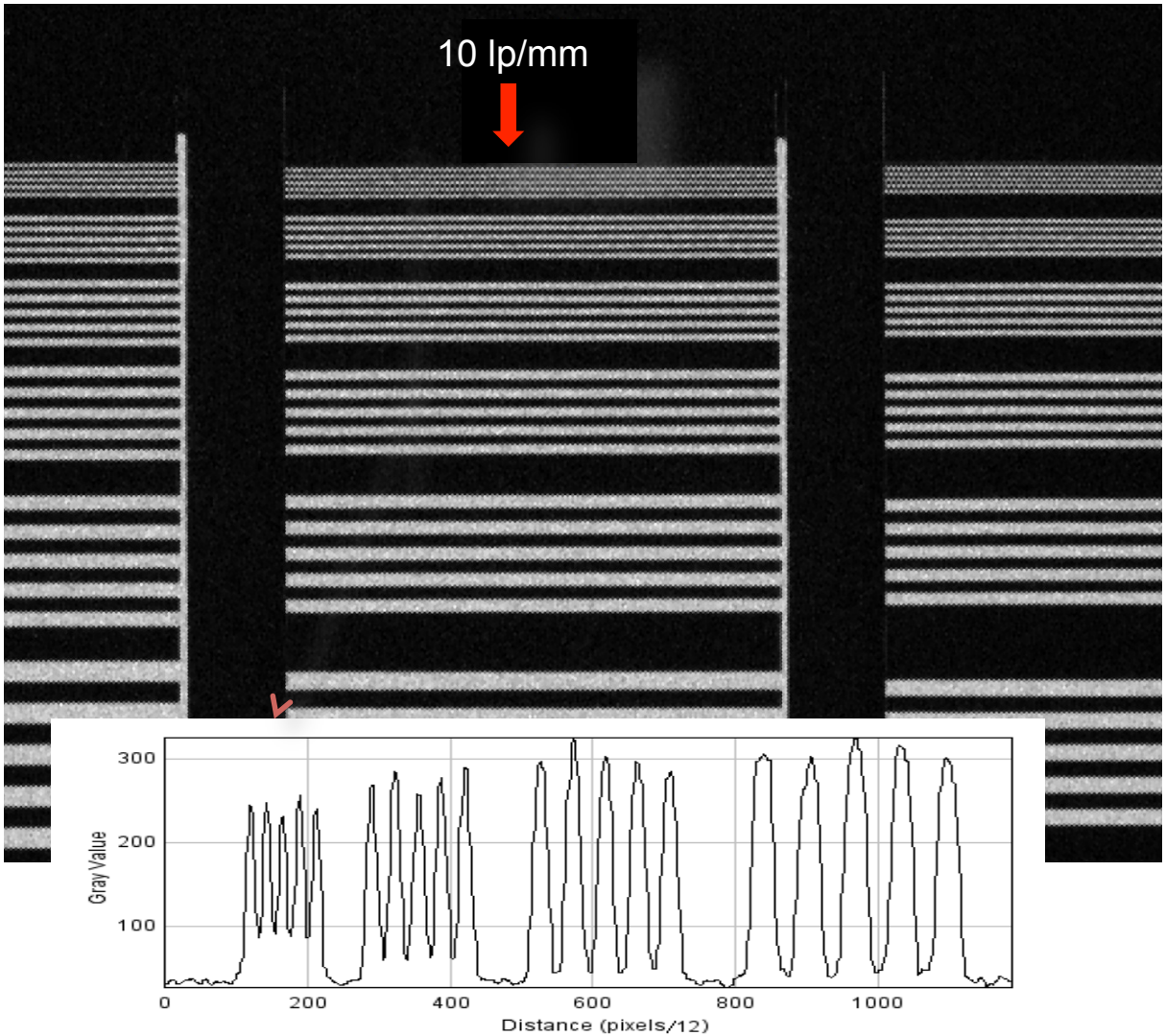


Image of a Hüttner mask to measure the resolving power



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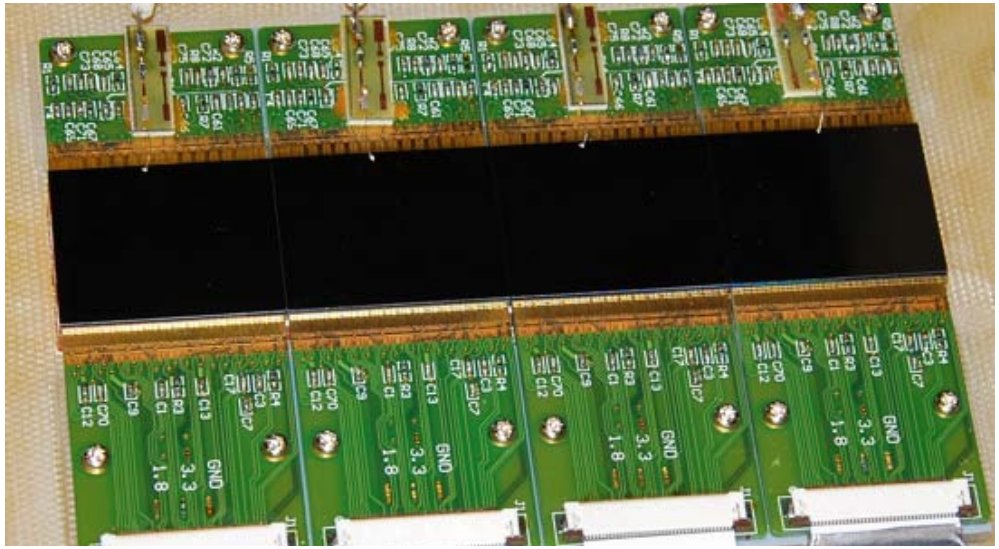
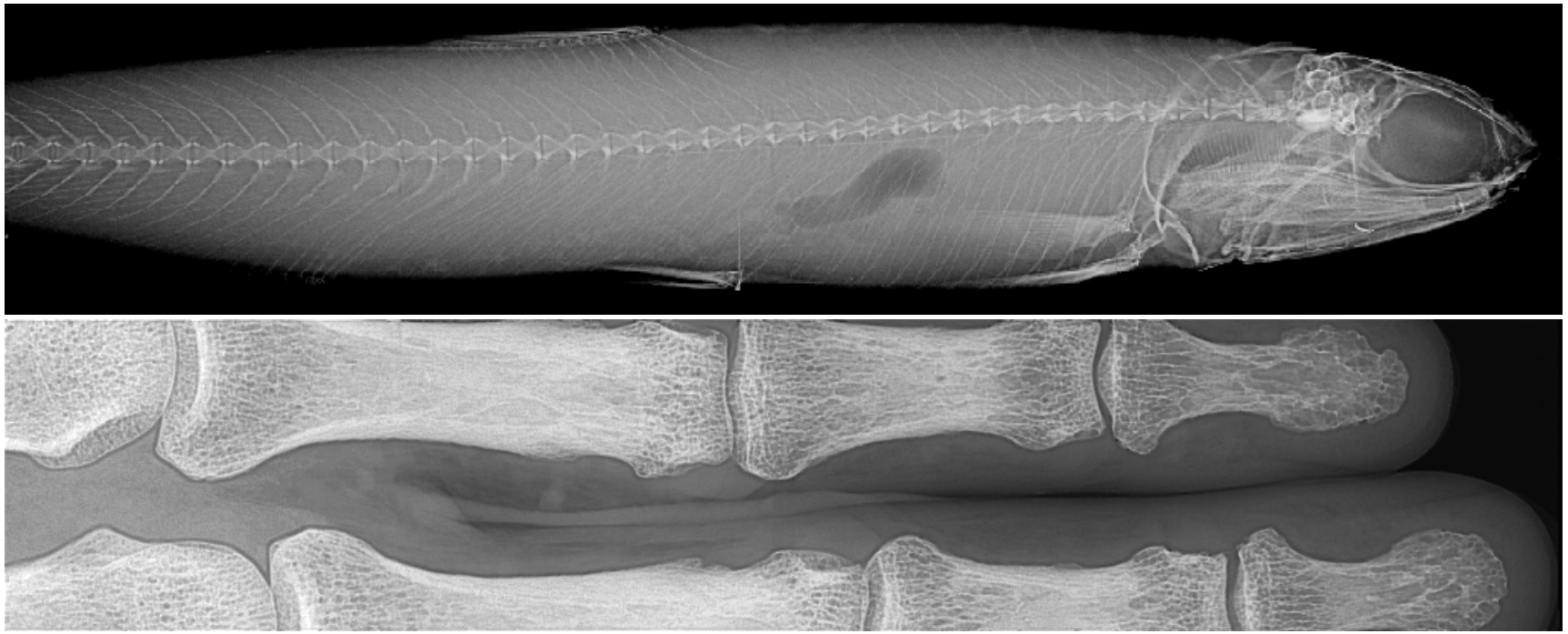
PIXIRAD-4



A 4 unit system
1M pixels, 2M counters,
12.1×2.5 cm² active area



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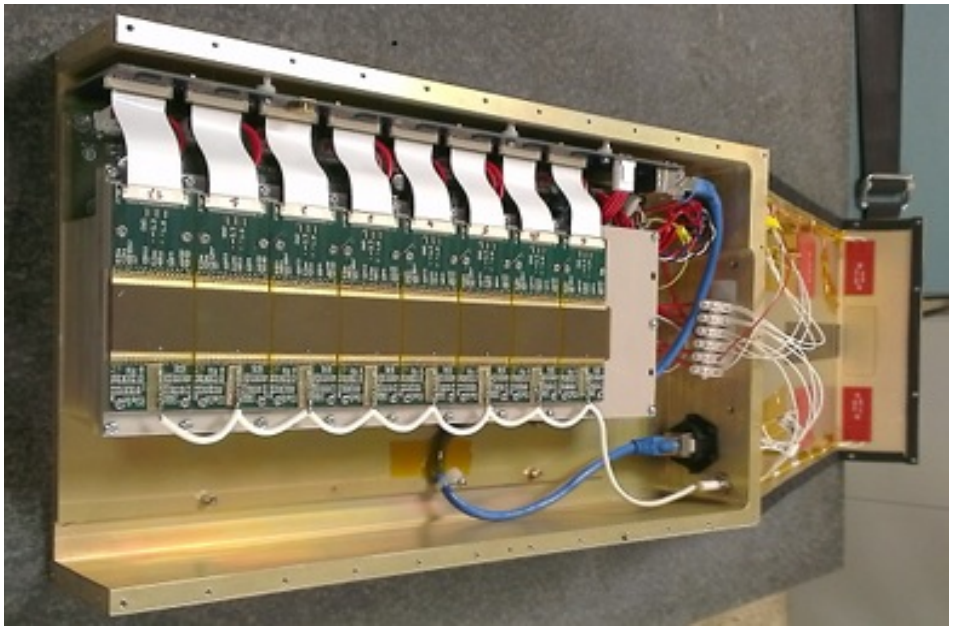
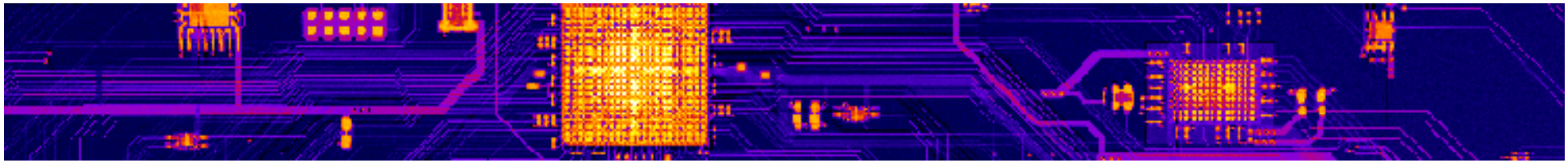
The giant PIXIRAD-8

A 8 unit system 2M pixels, 4M counters
25×2.5 cm² active area

Sensor type:	CdTe, 650 µm, 30.9 × 25.0 mm² Schottky type diode electron collection at pixel
ASIC+CdTe base block	512 × 476 pixels
Number of blocks	8
Global active area	250 x 25 mm²
Total number of pixels	1,949696
Total number of counters	3,899392
Pixel size	60 µm hexagonal arrangement
Pixel density	323 pixels/mm², equivalent to 55 µm on square arrangement
Pixel rate capability	10^5 counts/pixel/s
Global rate capability	$2x10^{11}$ counts/s
Pixel dead-time	300 ns
Position resolution	11 line pairs/mm at MTF 50%
Reading while taking data	possible
Dead-space between blocks	2 columns (to be reduced to 1 column)
Energy range	1-100 keV
Detection efficiency at 50 keV	98%
Counters depth	15 bits
Read-out time at 50 MHz clock	0.073 s
Frame rate	13.6 fps
Minimum applicable global threshold	200 electrons
Cooling	liquid or forced air
Operating temperature	+40 -40 C
Sensor bias voltage	200 ÷ 400 V
Leakage current density	5 nA /cm² at 400 V, -30 C
Typical number of defective pixels	less than 10^{-2}
Number of independent thresholds (colors)	2 set of two (swappable in real time)





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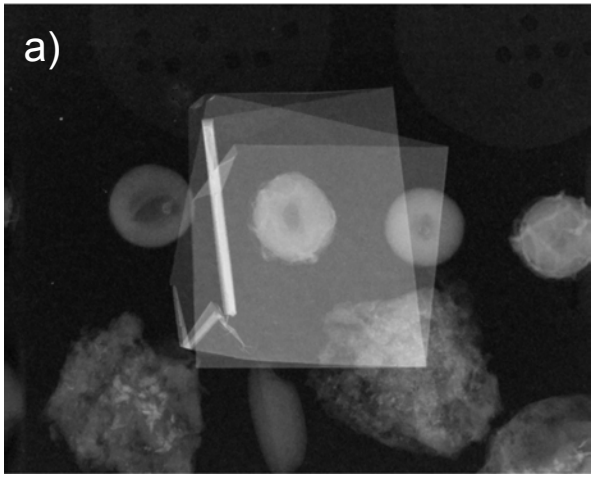
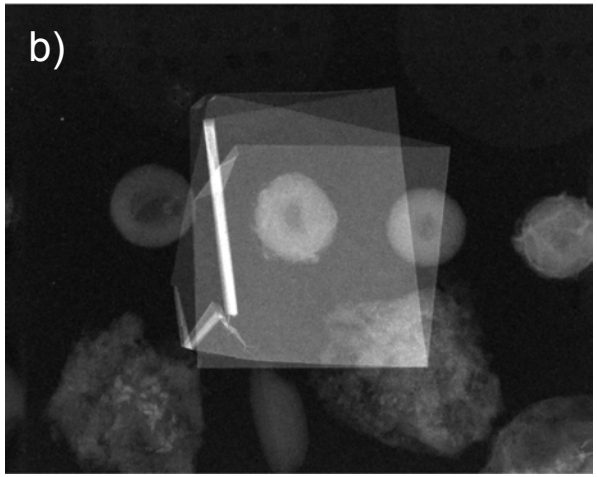
Chromatic photon counting

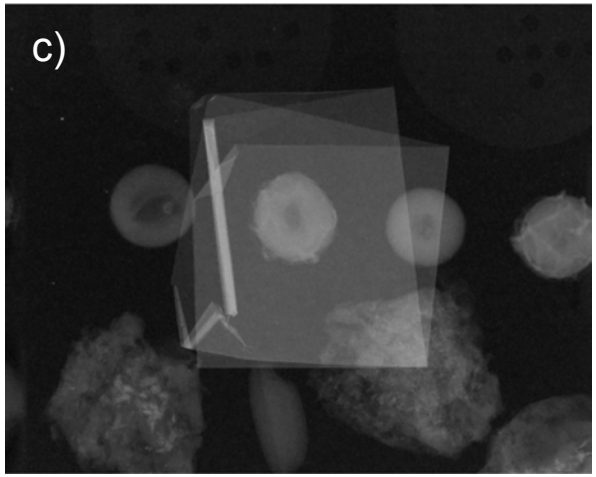
All energies photons image

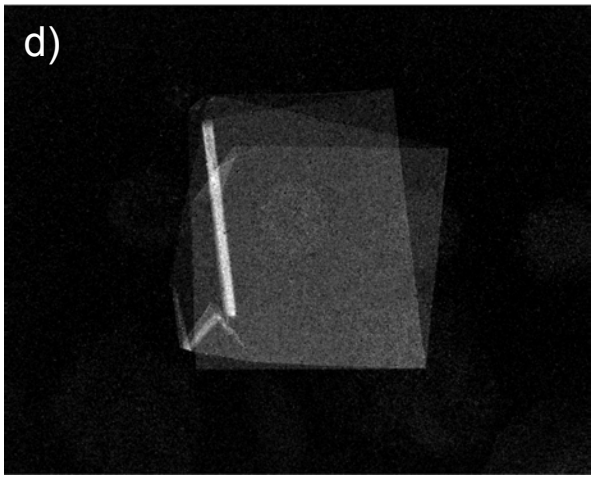
High energy photons image.
High thresh just > Zr K edge

Low energy photons image:
a) – b) (En < Zr K edge)









Ackermann phantom superimposed with a 2 µm Zr sheet.
The Zr foil has been irregularly folded to simulate different thicknesses (2-8 µm).
Kedge Zr: 17.9 KeV

Image d) =b) - 0.7 c)
The Ackermann phantom structures disappear, leaving visible the Zirconium sheet. The factor 0.7 is chosen to roughly equalize the counts in the Low and High energy image.

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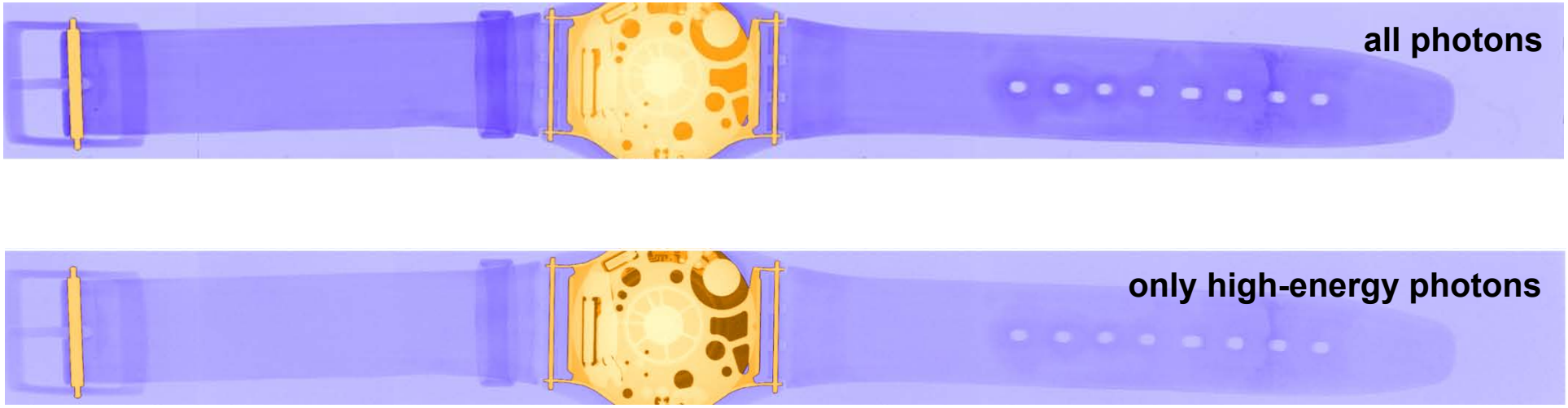
Chromatic photon counting

Single shot X-ray image of a man watch with its leather band



The watch is made of plastic and metal parts. The top image better visualizes low absorbing materials (plastic, leather), the bottom image better visualize the metal parts

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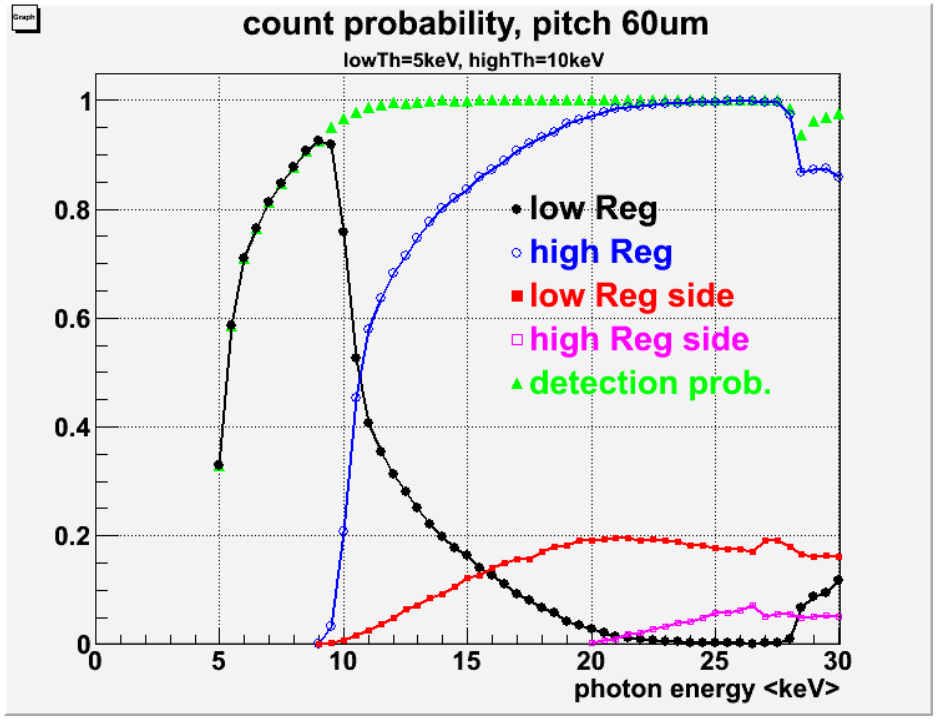
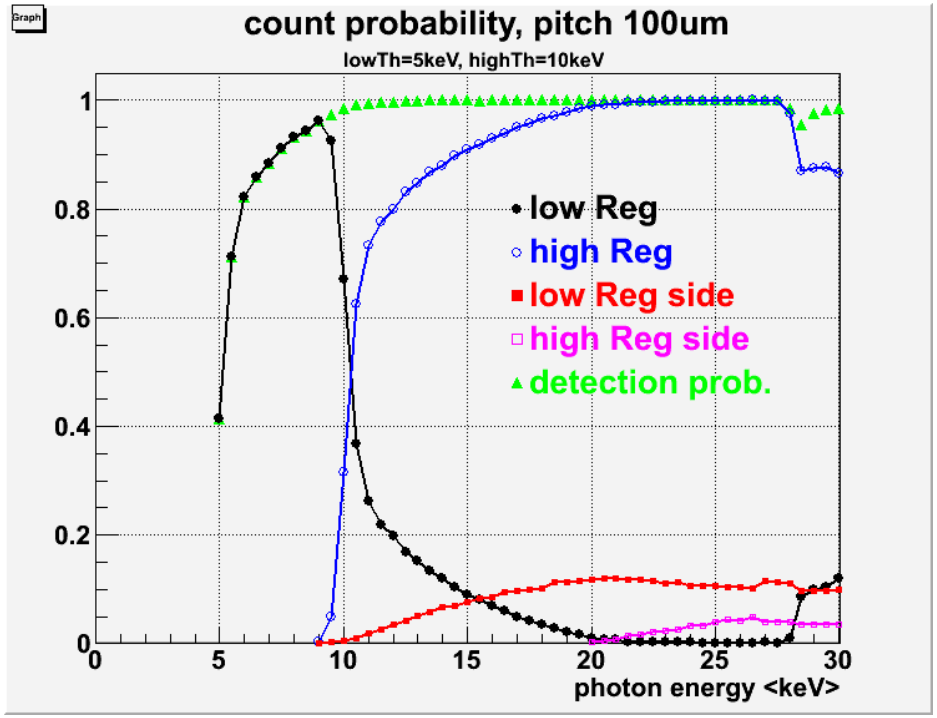
Two thresholds detector count probability



low Register: 5keV < Energy < 10 keV
high Register: Energy > 10 keV



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Sensitivity to low energy photons

Images of a *very low contrast objects*

200 electrons global threshold
corresponding to 1 keV
(all photon, LOW counters)

1200 electrons global threshold
corresponding to 6 keV
(high energy photons, HIGH counter)

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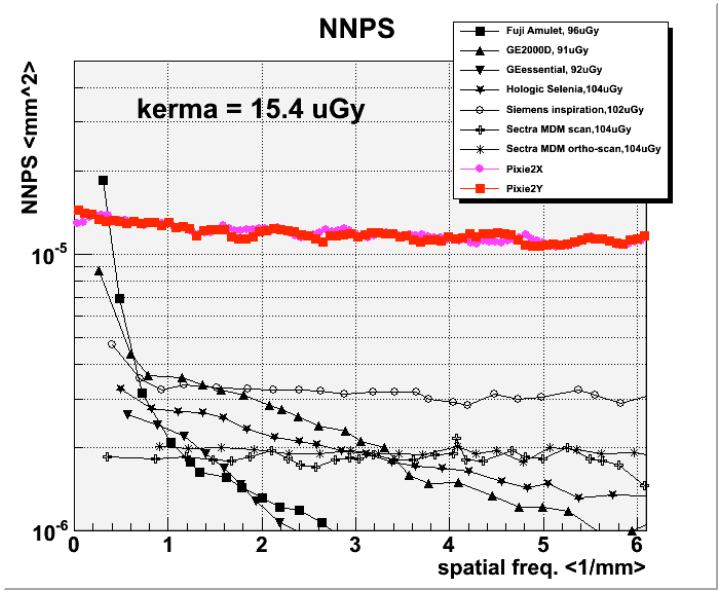
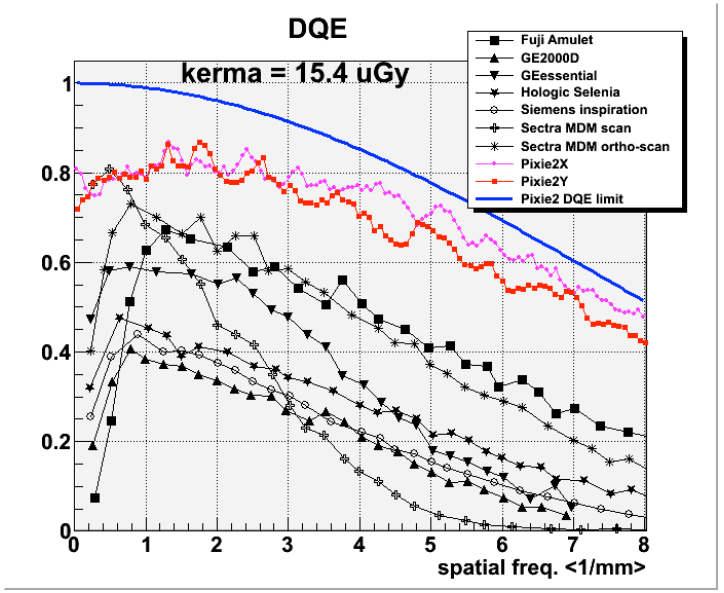
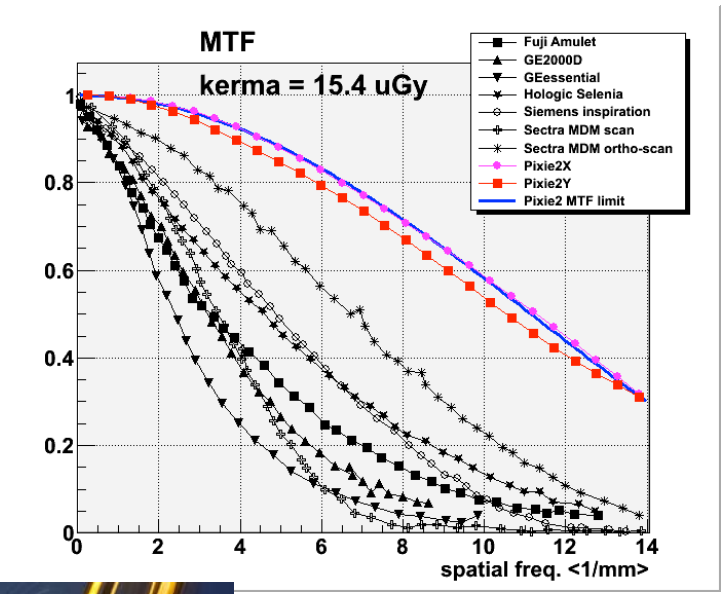
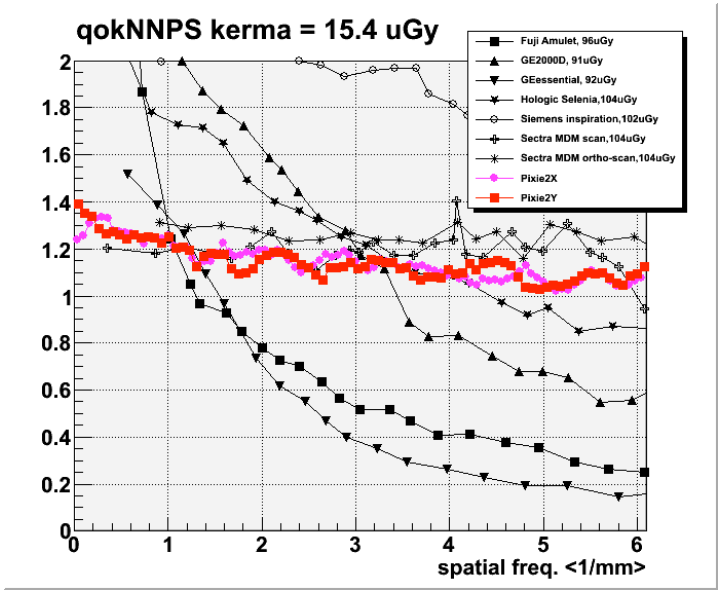
PIXIRAD characteristics for digital mammography









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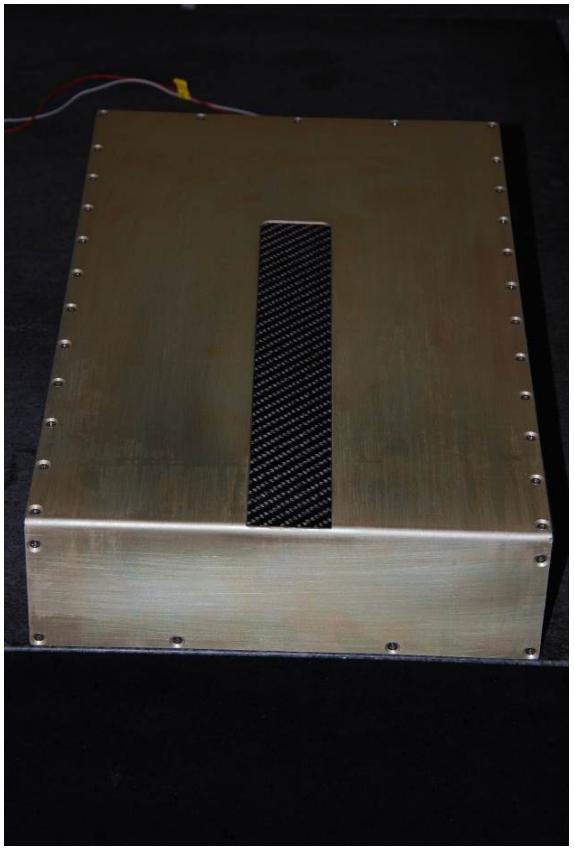
PIXIRAD-8 application to digital mammography



Complete module includes;

- 8 unit sensor
  - 25×2.5 cm² active are
  - 2 M pixel – 4M counters
  - 2 pixel inter-modules spacing
  - almost edge less toward the breast
- DAQ electronics
- Cooling system
- 1 Gbit Ethernet connection

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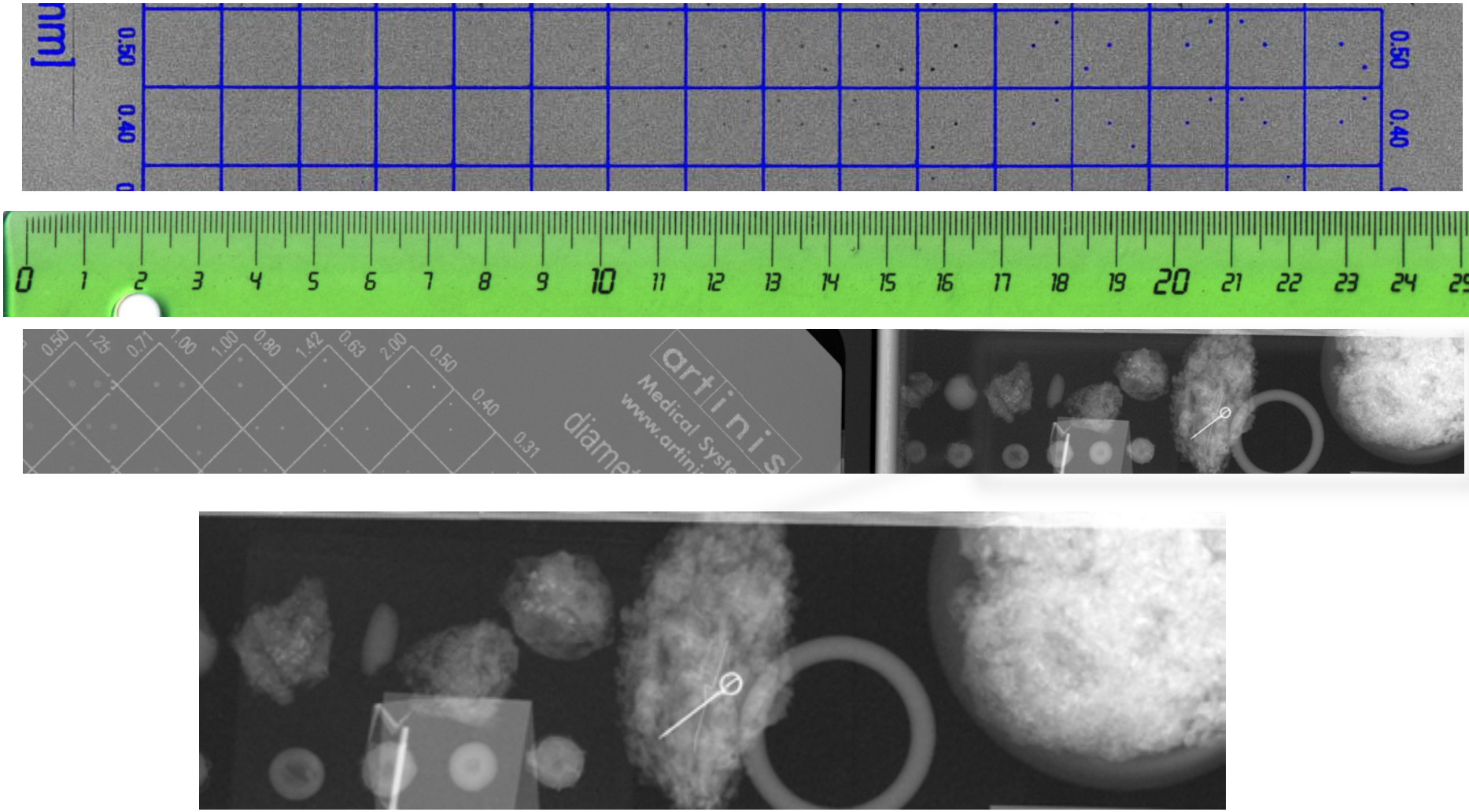
PIXIRAD-8 application to digital mammography

Images of CDMAM and Ackermann mammographic phantoms



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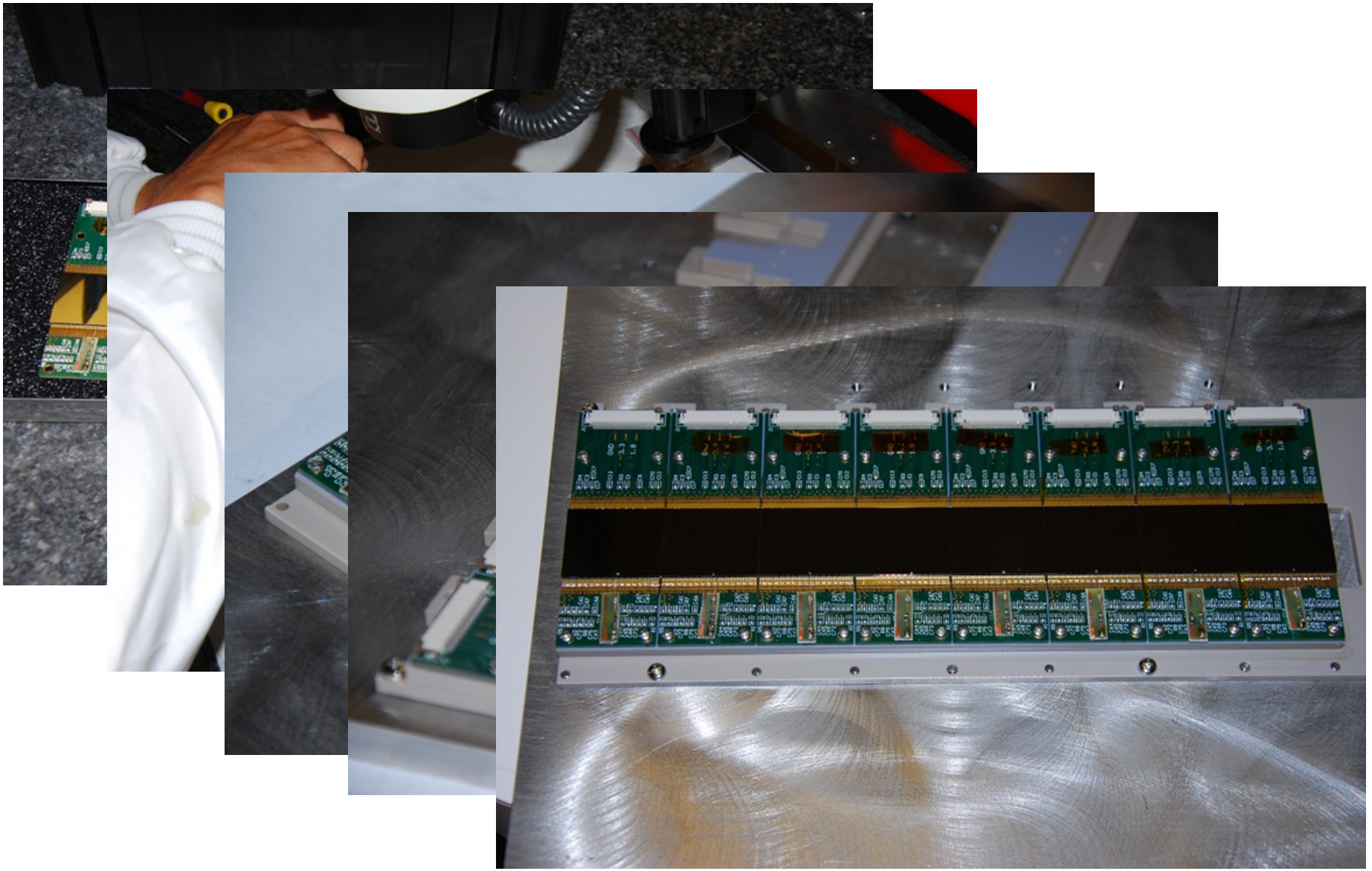
PIXIRAD-8 assembling phases



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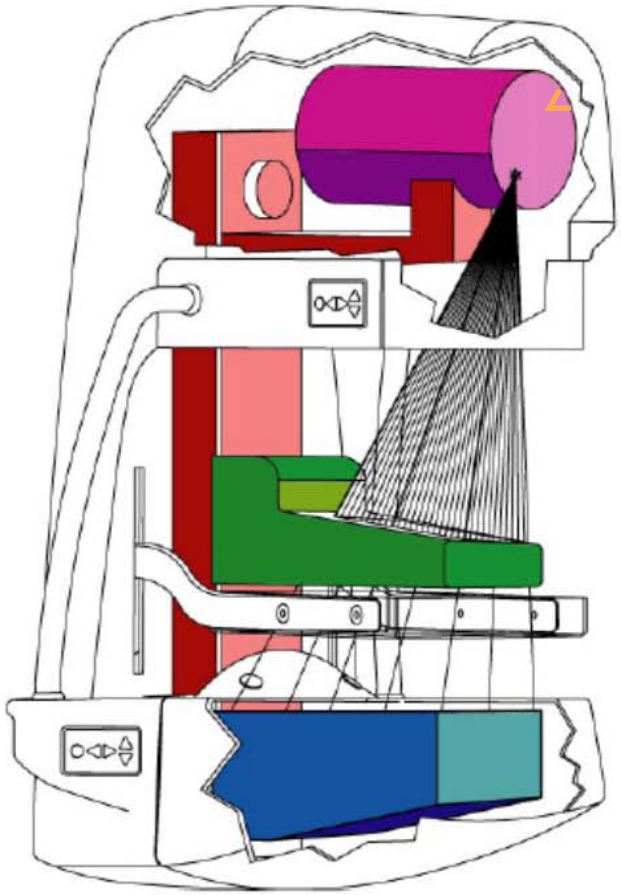
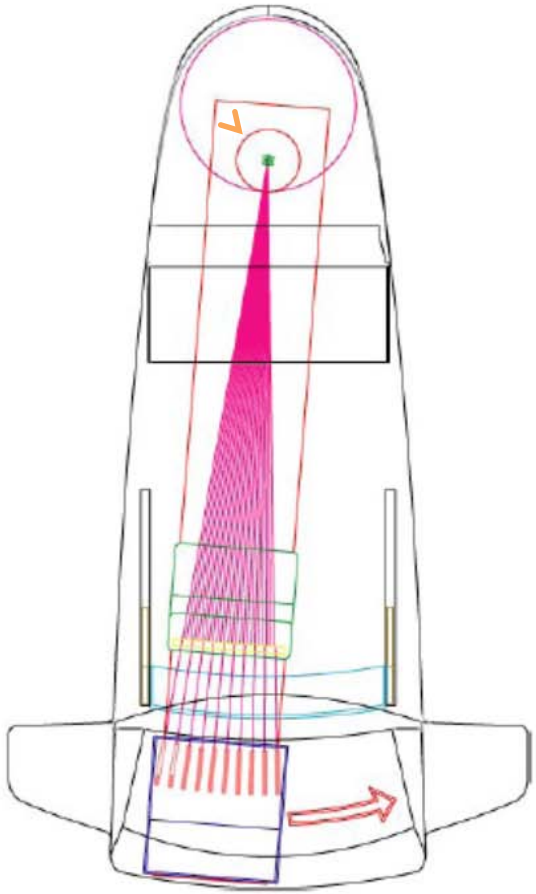
The X-ray slot-scanning imaging system

X-ray tube





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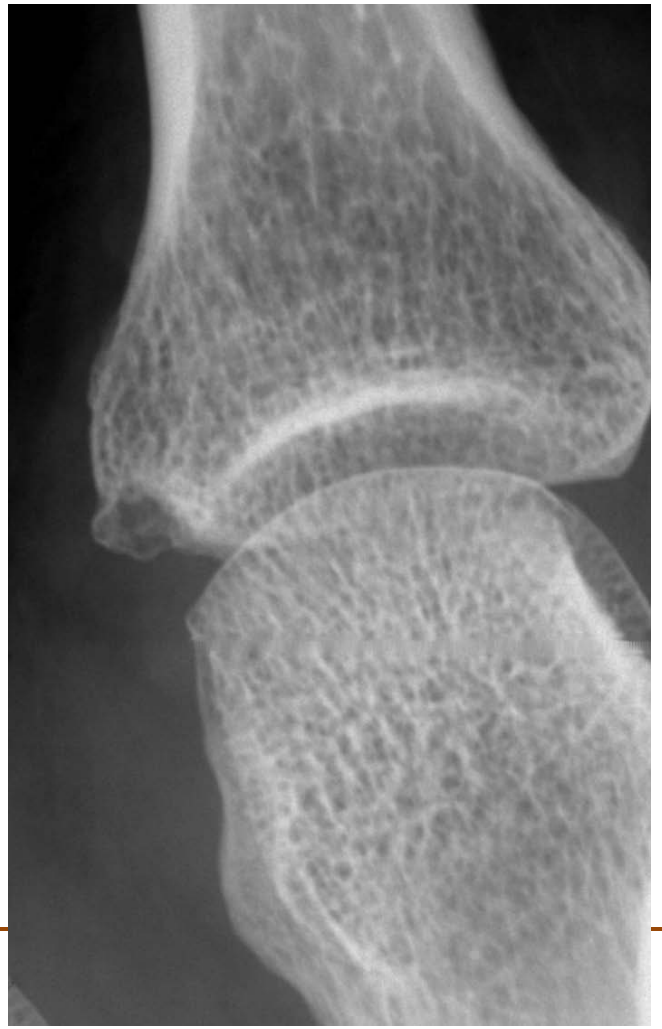
Images taken with the slot-scanning device

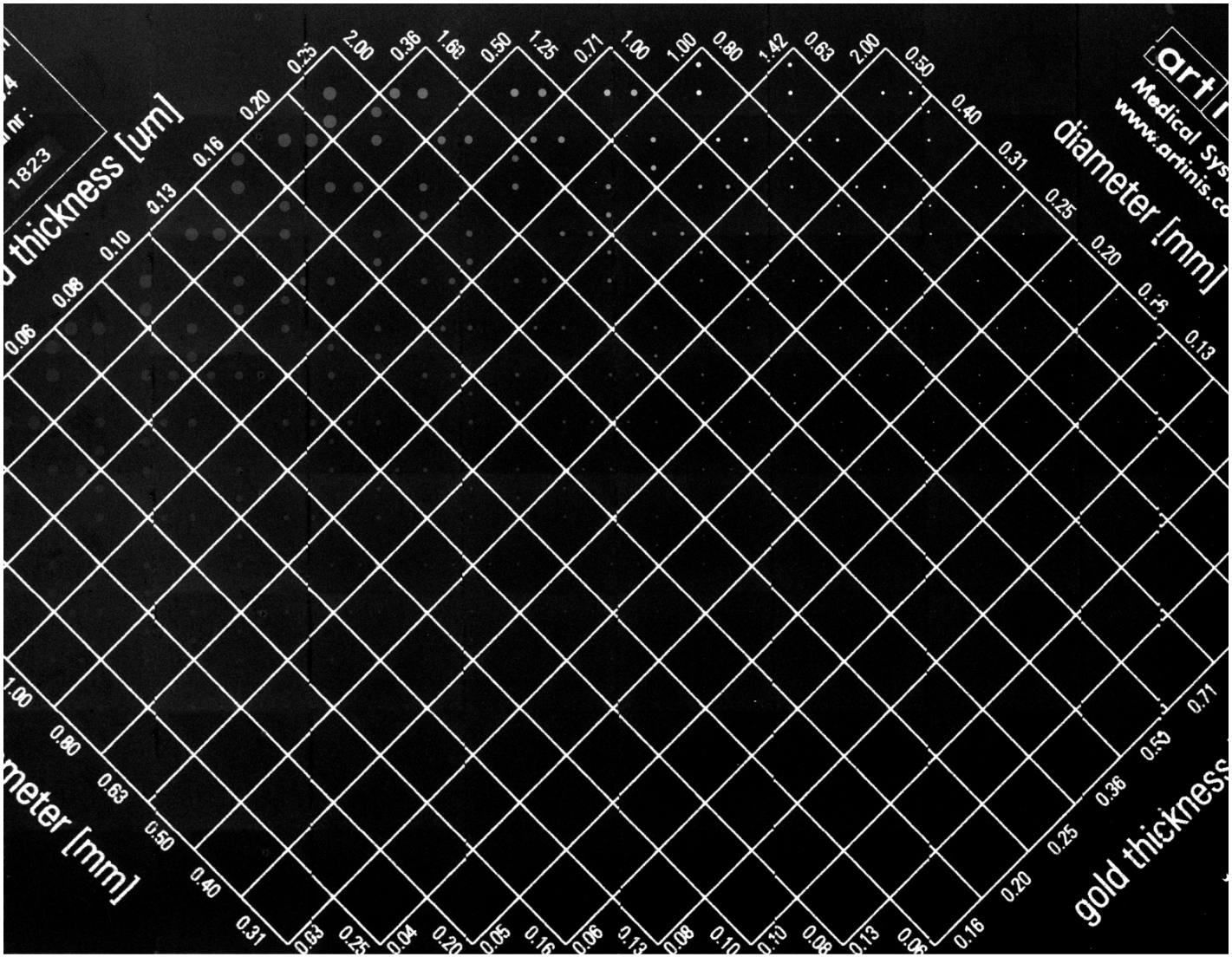
Image of a human hand (no image treatment) taken in slot-scanning mode at 35 kVp tube voltage and with a silver filter and a detail of a finger junction.



Images taken with the slot-scanning device

A large area (25x20 cm^2) image of a sea-bass fish and two anchovies taken in slot-scanning mode and a detail of mouth and teeth

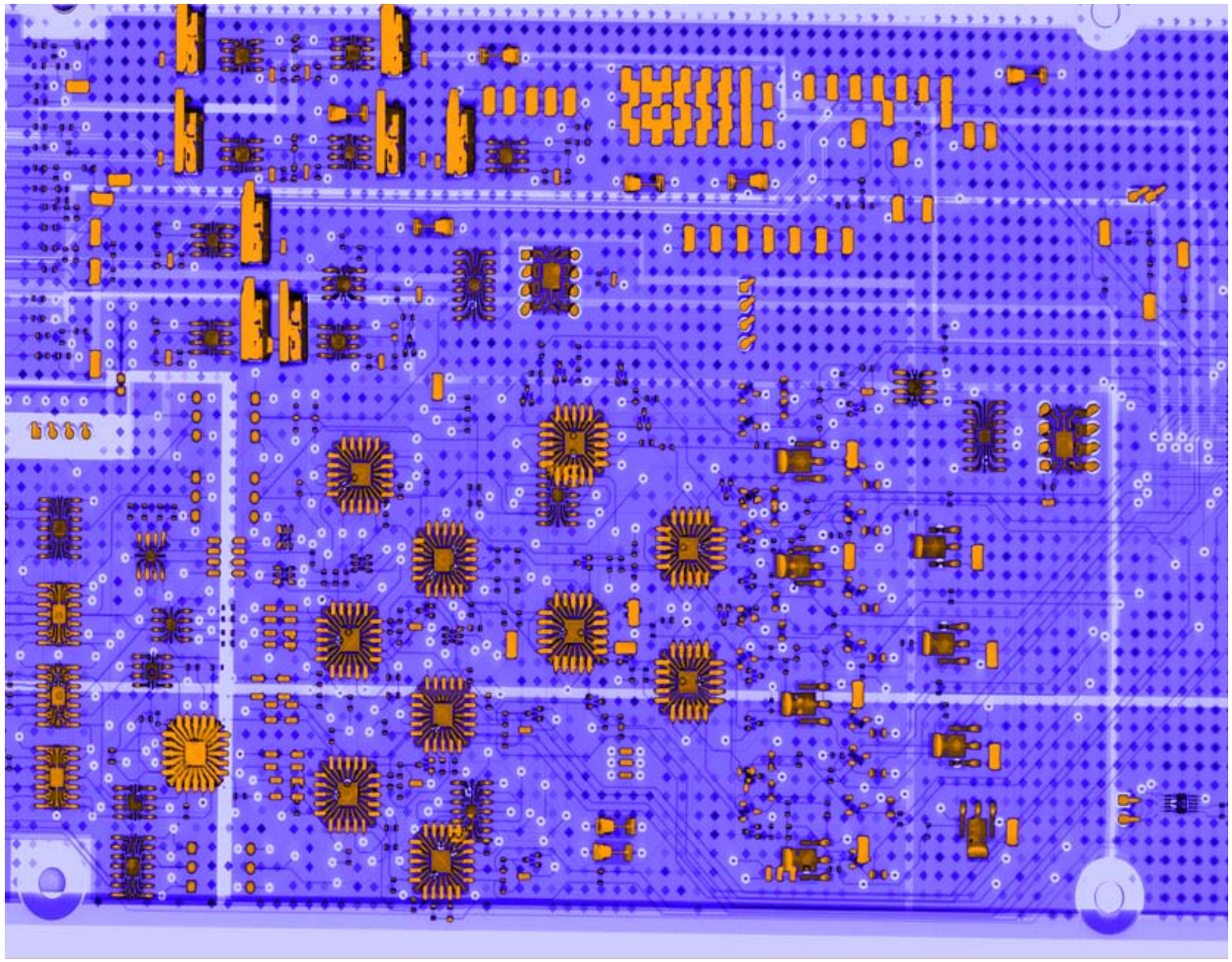
Images taken with the slot-scanning device

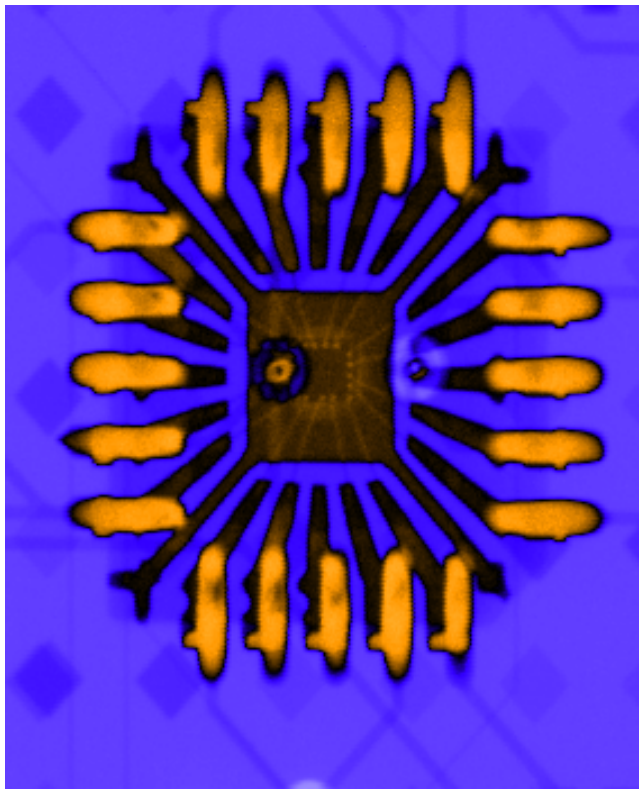


A CDMAM contrast-detail phantom image.
The image has been taken in a configuration equivalent to a 32 mm thick breast (27kvp, 50mas, no filtration).

We can detect the 0.5 mm diameter detail down to 0.05 µm thickness, the 0.25 mm down to 0.08, the 0.1 mm down to 0.36

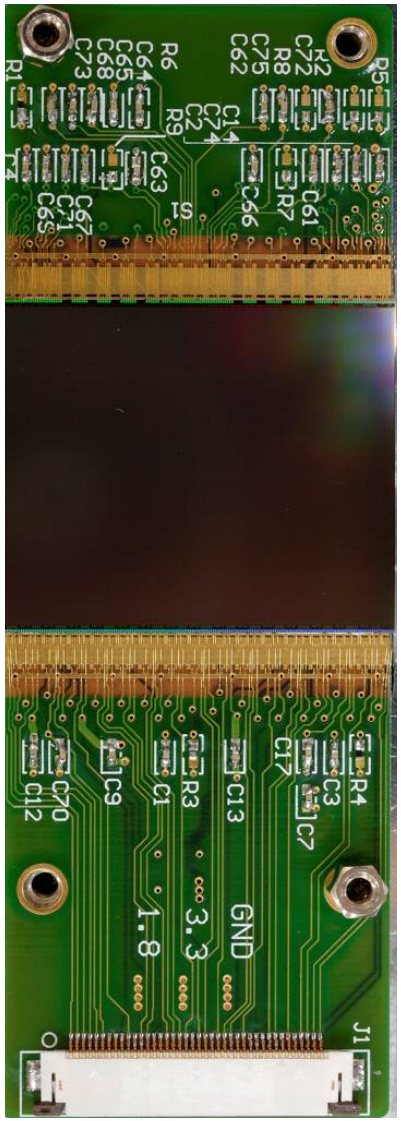
Images taken with the slot-scanning device





Large PCB imaged in slot-scanning mode. In the detail on the right the wire bondings inside an electronic package are neatly visible

Conclusions



An innovative X-ray Imaging Sensor based on Chromatic Photon Counting technology has been presented.
The detector can deliver extremely clear and highly detailed X-ray images for medical, biological, industrial and scientific applications in the energy range 1-100 keV.

Photon counting, *color* mode and very high spatial resolution (11 lp/mm at MTF50) allow to obtain an optimal image quality/absorbed dose ratio.

1, 2 , 4, 8 tiles modules units with almost zero dead space between the blocks have been built.
A complete X-Ray camera based on PIXIRAD-1 single module assembly is available for customers in scientific and industrial markets .

A dedicated machine to perform X-ray slot-scanning imaging has been designed, built and is currently under test. The system utilizes the PIXIRAD-8 module and is able to produce very large area images, with fine position resolution. This system has been designed for Digital Mammography, one of the most demanding X-ray imaging applications.

The X-ray Imaging System is the technological platform of PIXIRAD Imaging Counters s.r.l., a recently constituted INFN spin-off company.
PIXIRAD web site: http://pixirad.pi.infn.it

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