Optimization of high-performance 3D/4D surface scanning technology for patient monitoring in radiotherapy environment

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CERN

3D scanners in the radiotherapy environment

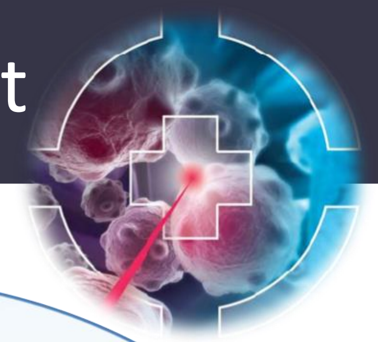


Image courtesy of ViALUX GmbH

3D/4D DLP based scanners for:

- Industrial application
- Medical application

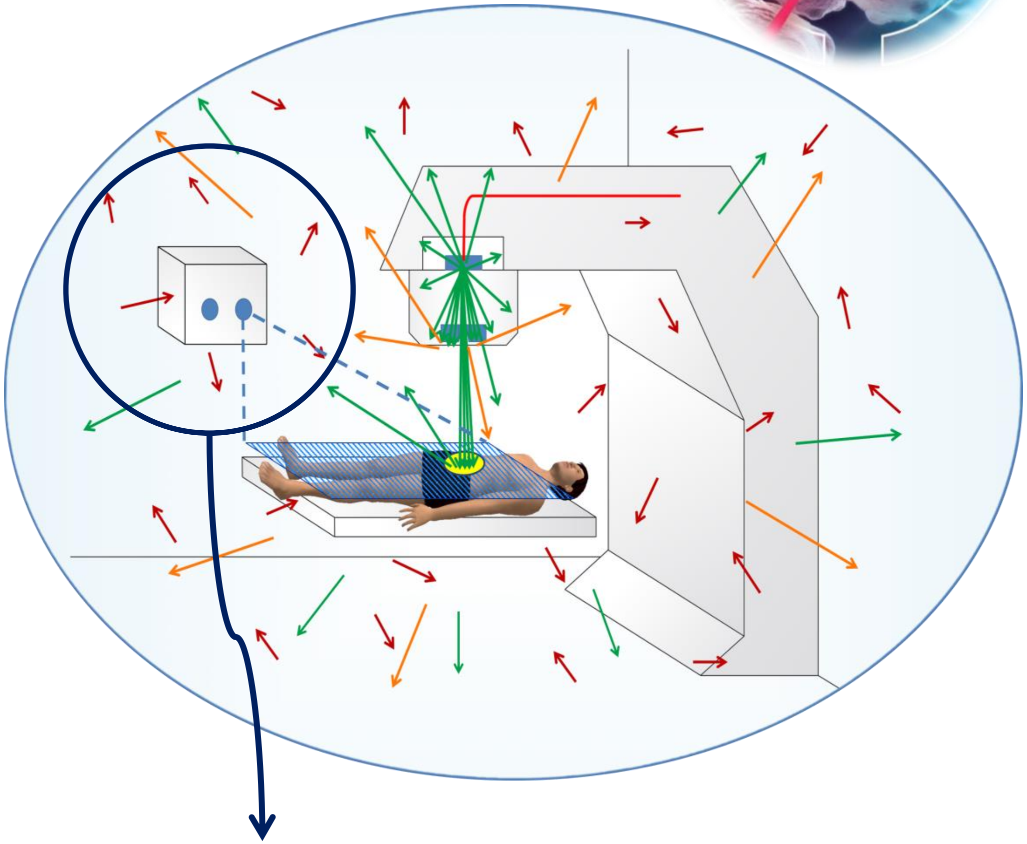
Used in radiotherapy to:

Position the patient before the therapy

Monitor the patient position during the therapy for:

a) stopping the therapy if the patient is in the wrong position

b) treating moving tumors



Secondary radiation can cause errors and/or damages in the scanners

Radiation hardening

Aviation

Space

Accelerators

Automotive

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Radiation effects on electronics

Interaction between the radiation and the device

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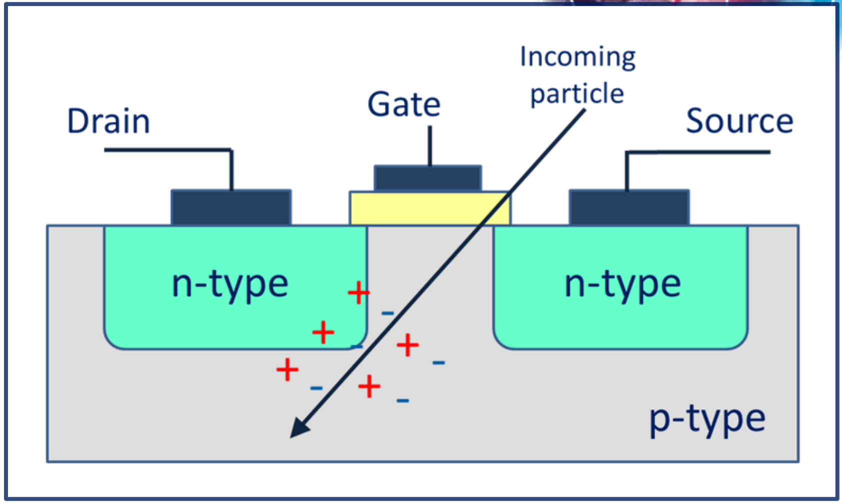
Possible temparary/permanent damages on the device:



Single event effects (SEE)

Caused by a single interaction

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Hard effects -> permanent damage
Soft errors -> temporary effects

e.g. Single Event Upset (SEU): change of bit values in the memory

Total Ionizing Dose (TID)

Progressive damage

↓

Defects in the insulating layers in the junctions

Displacement damages (DD)

Progressive damage

↓

Displacement of an atom
+
interstitial defect

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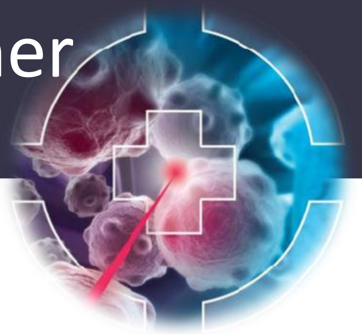
A famous example: Qantas flight 72 (2008)

Development of a radiation-hardened 3D scanner



Radiation resistant 3D body scanners ⇨

- Secure and accurate treatment
- Improve patient's experience
- Increase uptime

1. Study the irradiation conditions in radiotherapy environment and the possible effects on electronics
2. Evaluate of the sensitivity to radiations for all the electronics components
3. Define the best strategy to deal with the possible issues (e.g. hardware and/or software improvements to the device design)

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Secondary photons in conventional radiotherapy

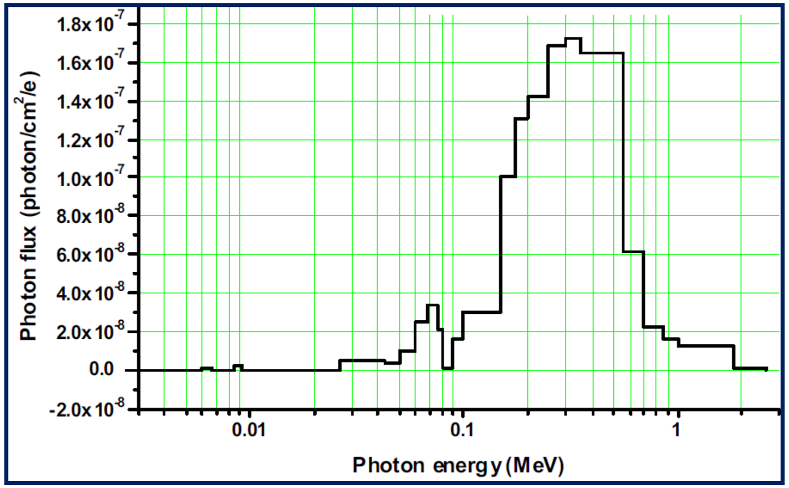
Scattered photons

- Produced by the interaction of the primary photons with the patient
- Emitted in all directions, but the most of them with small scattering angles

+

Leakage photons

- Bremmstrahlung photons not stopped in the LINAC head shielding or in the collimator
- Photon energy up to primary photon energy
- Leakage flux ~ $1/r^2$



Simulated photon spectrum near the room walls

Beigi et al. *Safe bunker designing for the 18 MV Varian 2100 Clinac.* Rep Pract Oncol Radiother (2016)

Photoneutrons in conventional radiotherapy

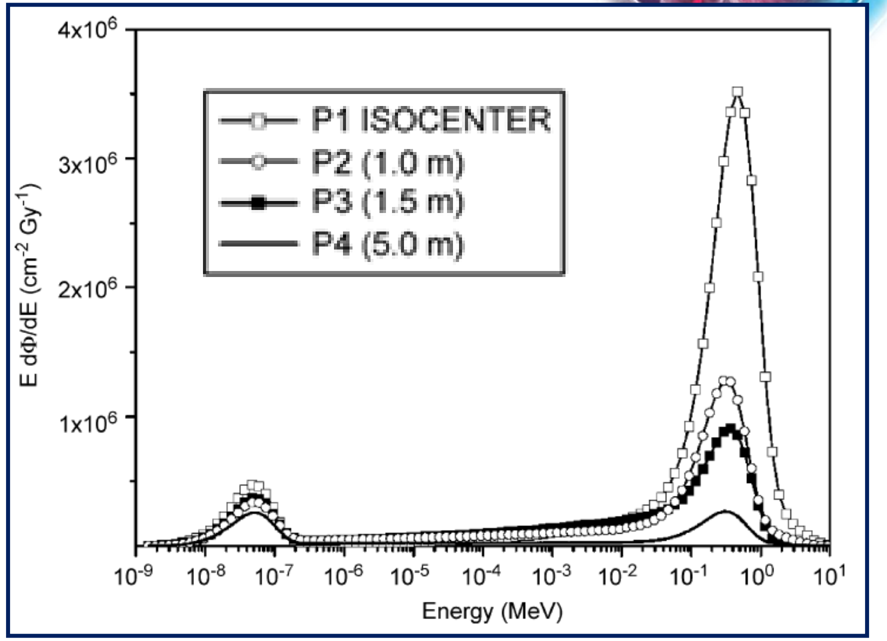
Fast component (~ 1 MeV)

- Neutrons produced through GDR process
- Flux α 1/r²   (r = distance from LINAC head)

Thermal component (< 1 eV)

- Neutrons scattered in the room
- ~ uniform distribution in the room
- Flux depends also on room dimensions

The photoneutron flux is negligible with energy beam < = 6 MeV



Dist. from isoc. (m)	Φ $(\mathrm{cm}^{-2}\,\mathrm{Gy}^{-1})$	P_{ev} (%)	P_{epi} (%)	P_{th} (%)
0	$9.11 \times 10^6 \pm 2.1\%$	64	27	9
1	$4.36 \times 10^6 \pm 2.1\%$	48	38	14
1.5	$3.98 \times 10^6 \pm 2.4\%$	36	47	17
5	$1.35 \times 10^6 \pm 4\%$	33	33	34

Esposito et al. *Determination of the neutron spectra around an 18MVmedical LINAC with a passive Bonner sphere spectrometer based on gold foils and TLD pairs.* Radiation Measurements 43 (2008)

Radiation effects in the radiotherapy environment

	Characteristics	Particle involved in the radiotherapy environment
Single Events Upsets	Caused by high energy deposition in a short path (high LET particles)	Thermal neutrons • Indirectly through neutron capture process in Boron $^{10}B + n \rightarrow {}^{7}Li + \alpha$
Total ionizing dose	Related to the total absorbed dose	Secondary photons and photoneutrons
Displacement damages	Proportional to Non Ionizing Energy Loss (NIEL)	Fast neutrons (E ~ 1 MeV)

How do the scanners work?

1. Precise high-speed projection of sinusoidal light patterns using DLP micro-mirror arrays

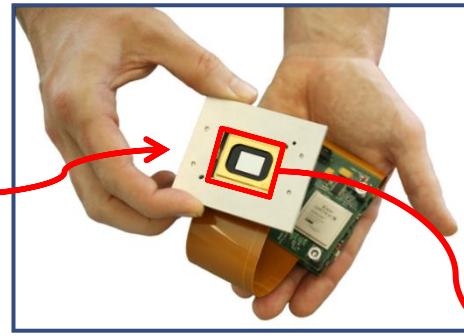
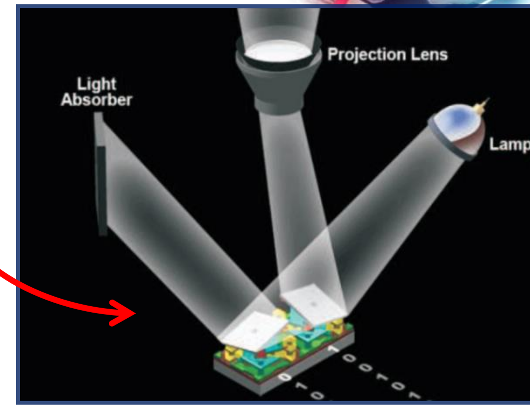


Image courtesy of ViALUX GmbH



Introduction to Digital Micromirror Device (DMD) Technology Texas Instrument Inc.

2. Image acquisition through the camera

3. Reconstruction of the 3D body surface by photogrammetry software

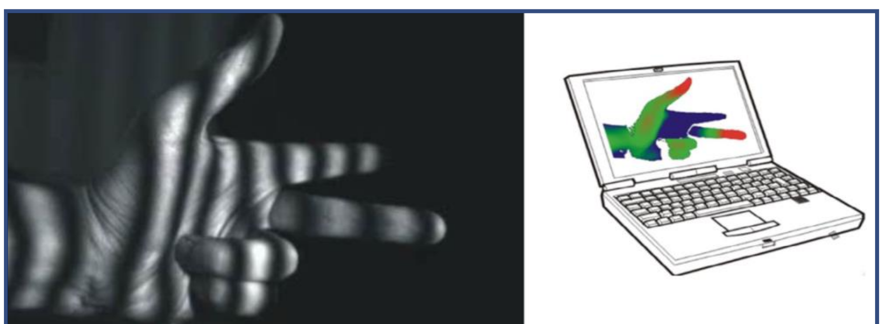
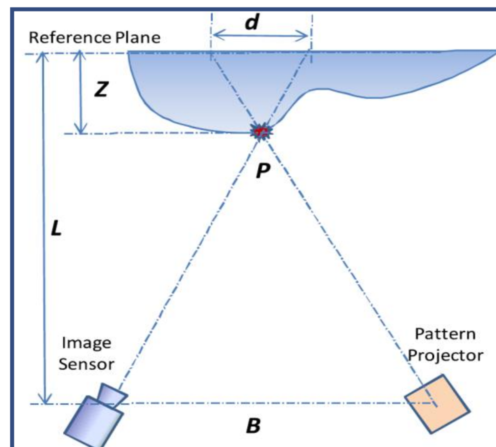


Image courtesy of ViALUX GmbH



J. Geng. Structured-light 3D surface imaging: a tutorial. Advances in Optics and Photonics 3, 128–160 (2011)

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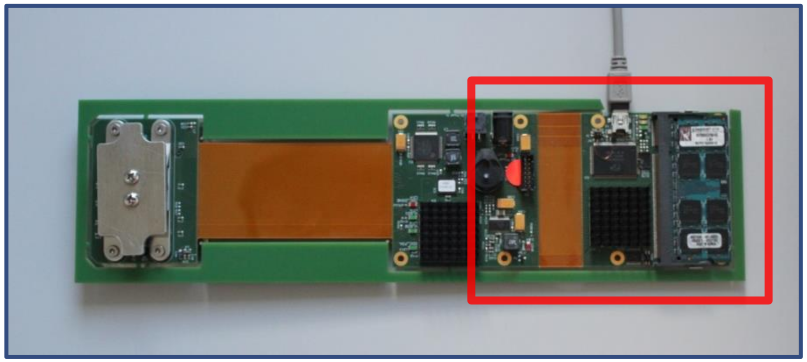
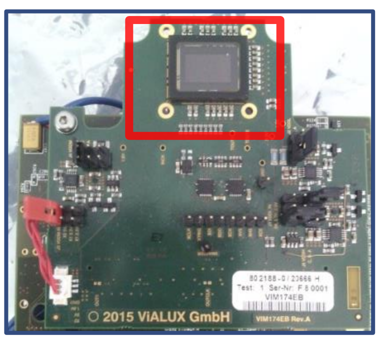
Which are the possible issues?

Single Event Upsets in FPGA configuration memory → Single Event Functionality Interruption (SEFI)

- the scanner stops to work and must be reset



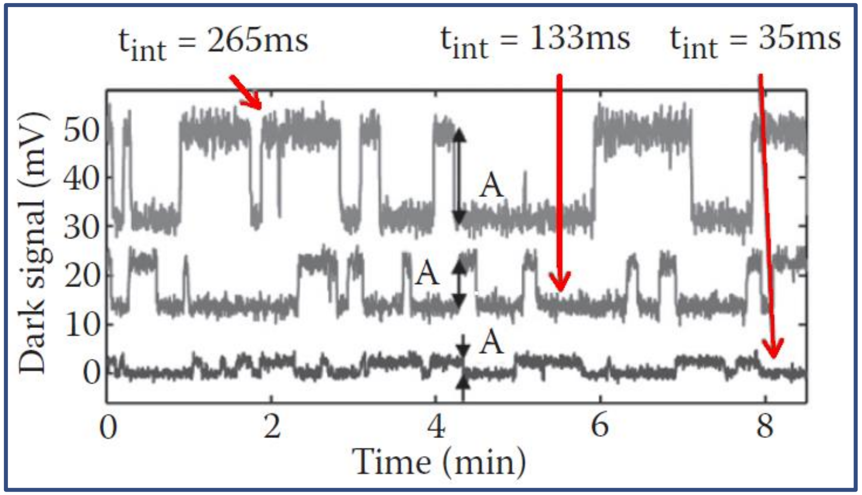
Total Ionizing Dose in CMOS image sensor → Progressive degradation of CMOS performance



Effects of TID on the CMOS image sensor

Effect on the dielectrics (SiO_2)

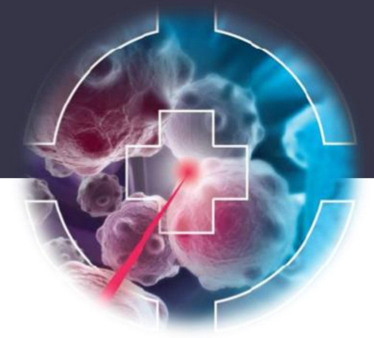
1) Increase of dark current in the pixels (noise in the pixel output)
   - Bright pixels
   - Pixels with Random Telegraph Noise



M. Bagatin and S. Gerardin. *Ionizing Radiation Effects in Electronics: from Memories to Imagers*, CRC Press, 2015

2) Decrease of Quantum efficiency (efficiency in visible light detection)

CMOS tests



1) CMOS sensor acquire data in dark conditions

   a) Short exposure time (below 100 ms)

      Real working conditions

   b) Long exposure time (several seconds)

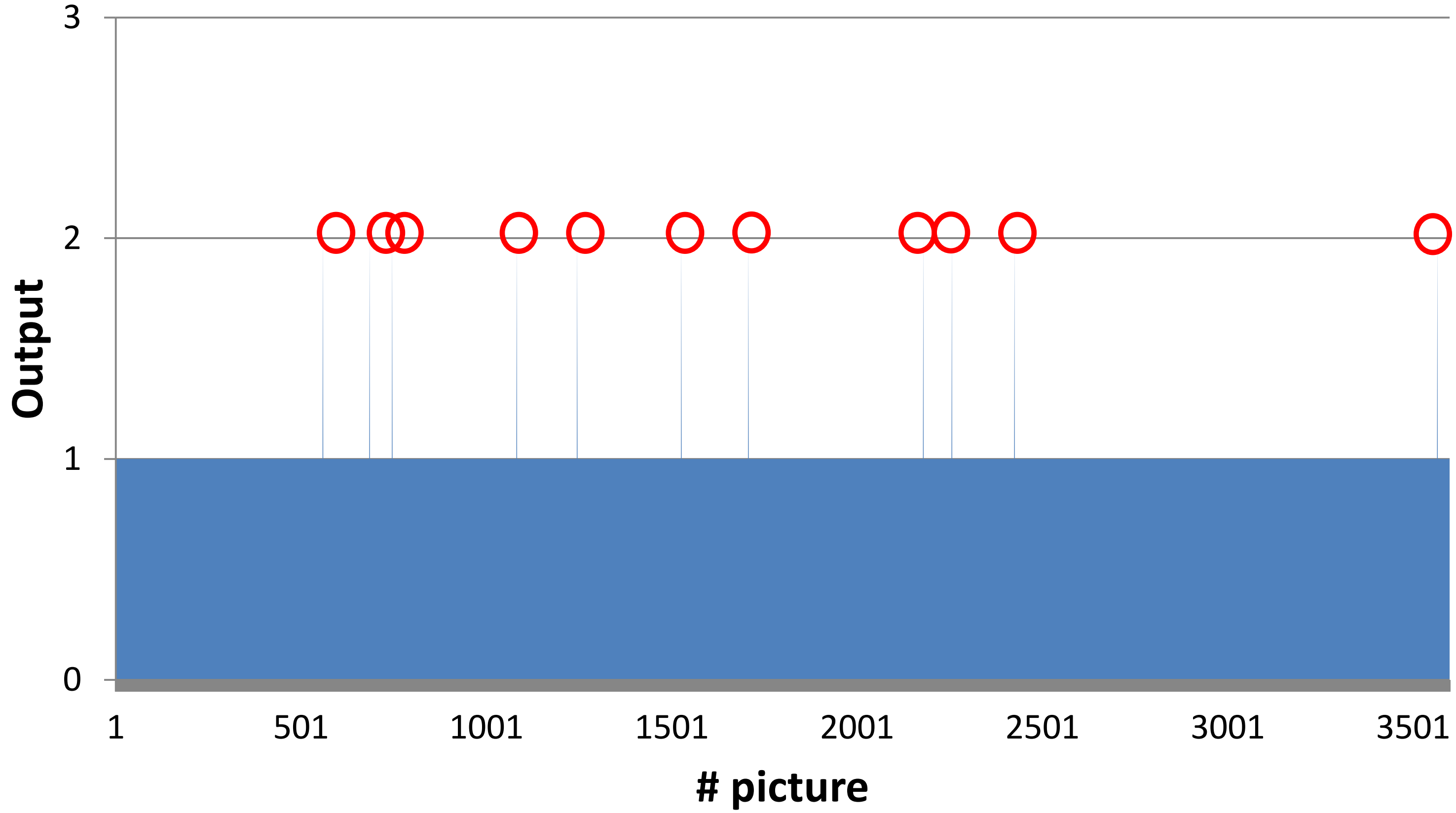
      Possibility to see also small effects

2) Analysis of the output

   10-bit PNG pictures → output signals

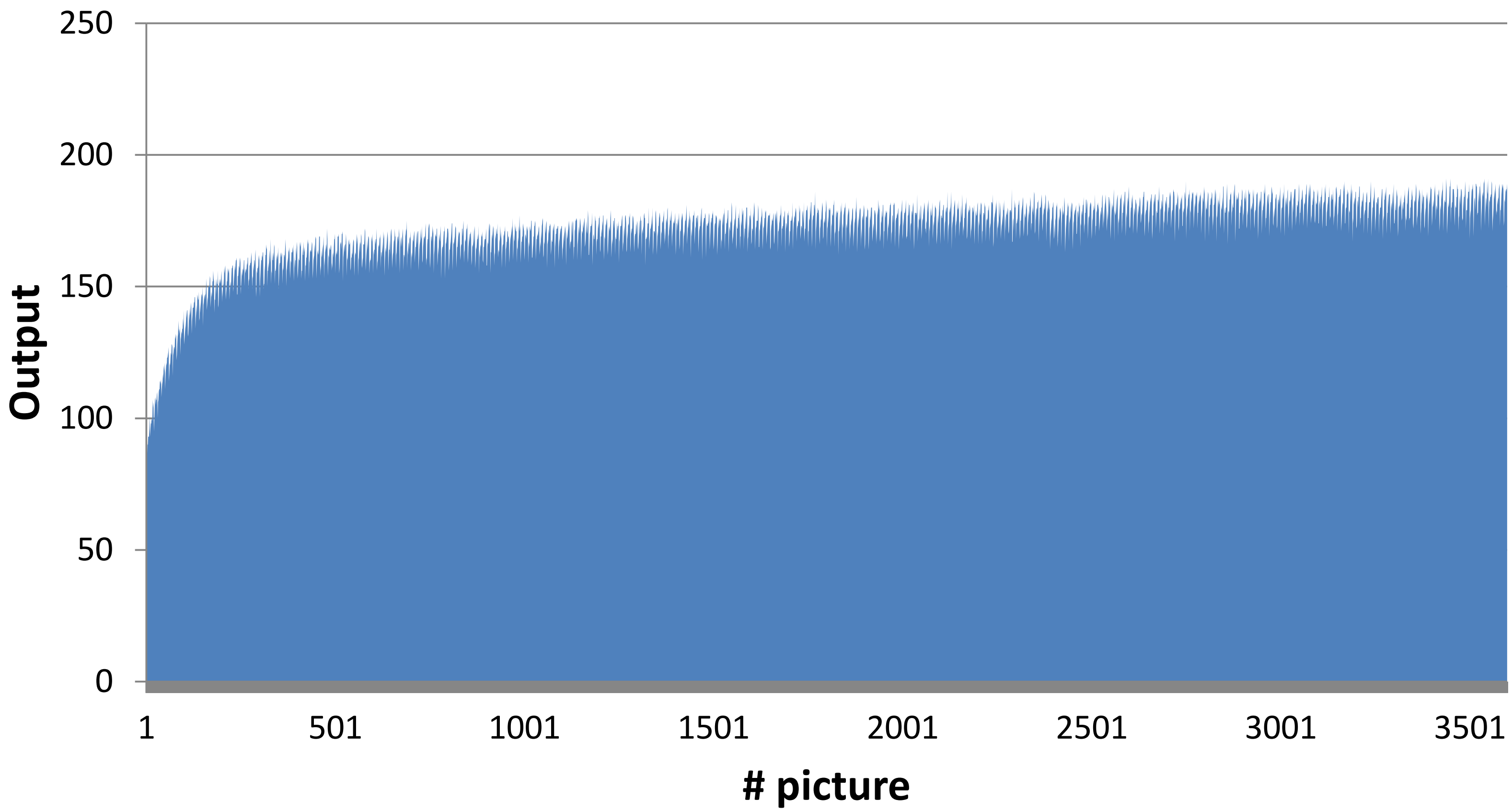
The CMOS before the irradiation

Regular pixel



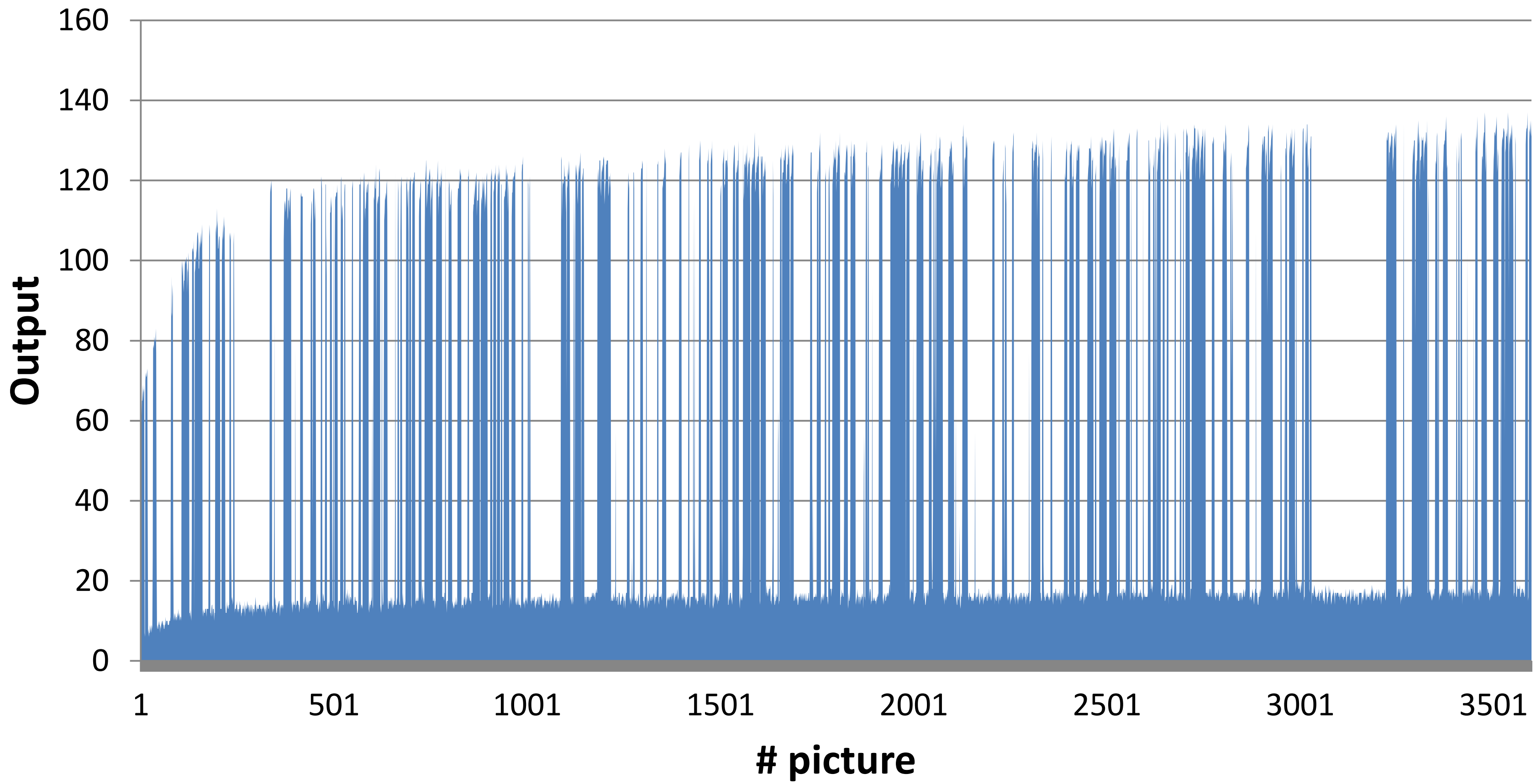
The CMOS before the irradiation

Bright pixel



The CMOS before the irradiation

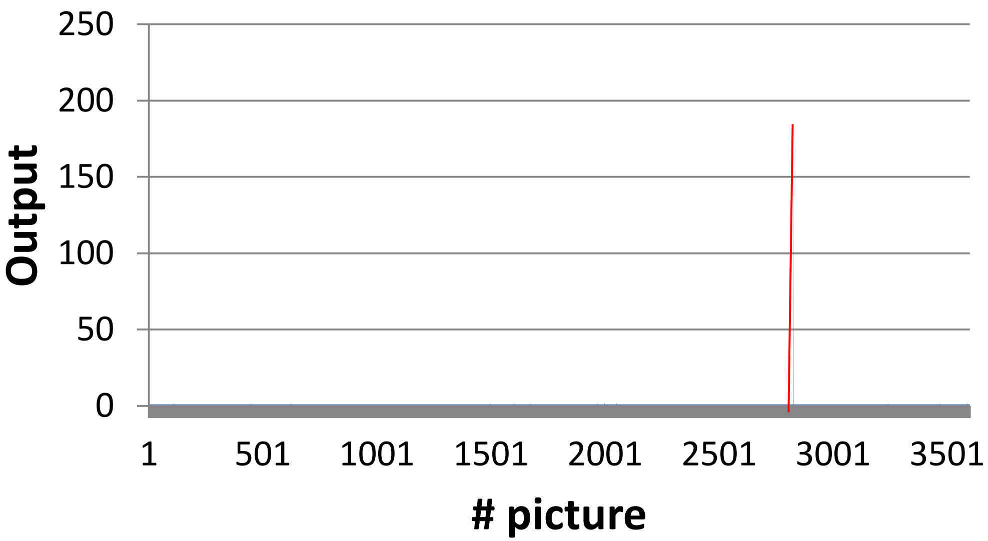
Pixel with telegraph noise



CMOS “active” irradiation

The CMOS sensor is biased during the irradiation

1. Real working conditions
2. TID effects are enhanced
3. CMOS used also to measure the dose that it absorbes



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Preliminary test with radioactive sources

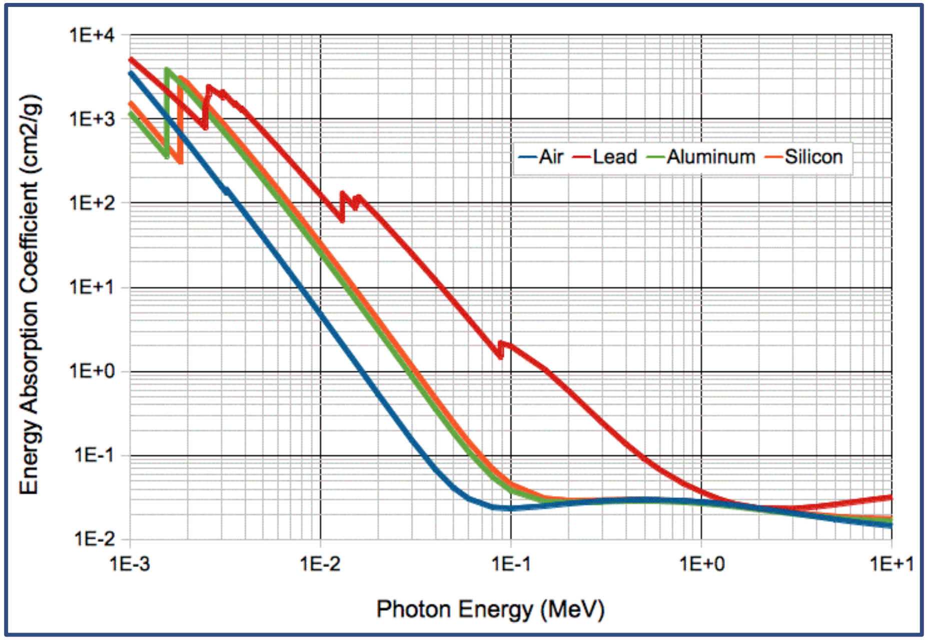
Study the response of the CMOS with photons in the range 100 keV - 1 MeV

Radionuclide	Photon Energy (keV)
Americium-241	59.54
Barium-133	81 303 356
Cesium-137	662
Sodium-22	511 (Annihilation) 1275
Cobalt-60	1173 1330

Preliminary test with radioactive sources

- Measure the dose absorbed in the CMOS (dose in Silicon)
- Compare dose measured with other tecnique (e.g. Gafchromic films)

Dose in Silicon vs Dose in Air/Water



Data from NIST: https://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html

Future steps

Test in the radiotherapy environment

- evaluate reliability of the CMOS for 3d scanner in typical working conditions

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  apply possible improvements

- observe the small effects due to low doses

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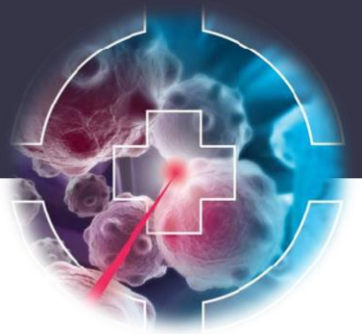

Thank you for your attention

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