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

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OMA project – ViALUX GmbH

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PSI

3D scanners in the radiotherapy environment

Image courtesy of ViALUX GmbH

3D/4D DLP based scanners for:

- Industrial application
- Medical application

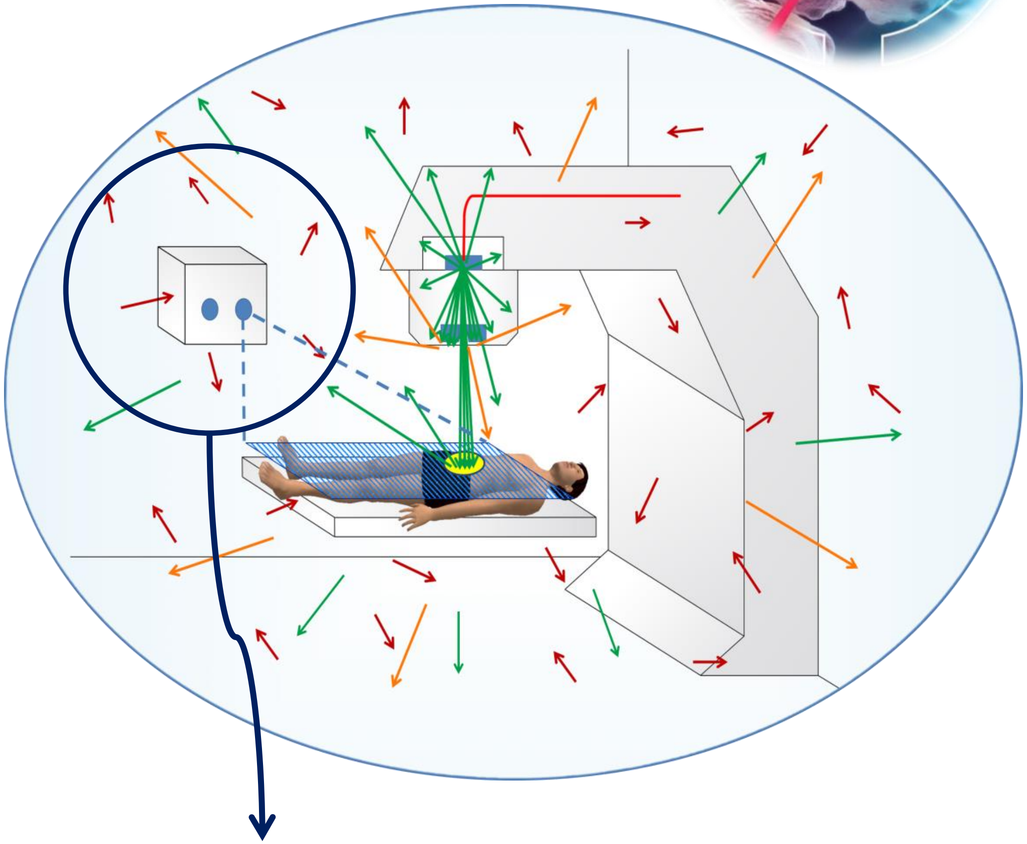
Used in radiotherapy to:

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

Development of a radiation-hardened 3D scanner

Radiation resistant 3D body scanners ➡

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

Study the irradiation conditions in radiotherapy environment and the possible effects on electronics

1. Evaluate of the sensitivity to radiations for all the electronics components
2. Apply hardware and/or software improvements to the device design
3. Test the final device

How do the scanners work?

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

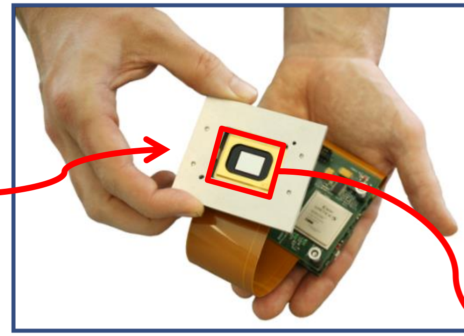
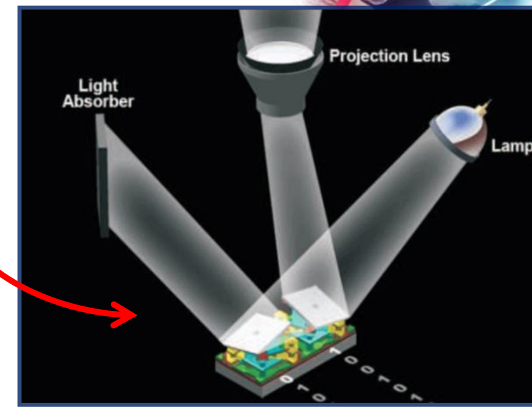


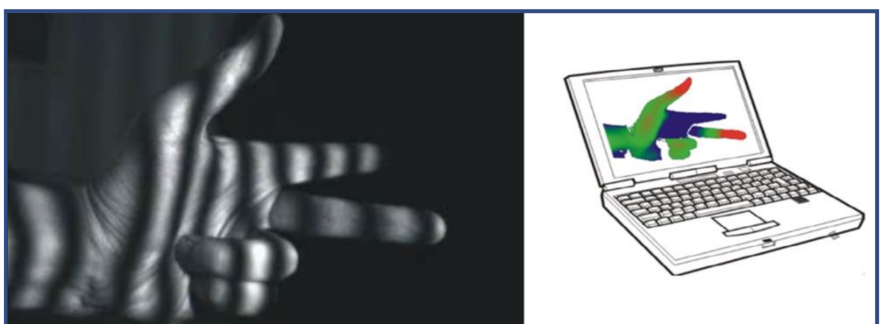
Image courtesy of ViALUX GmbH



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



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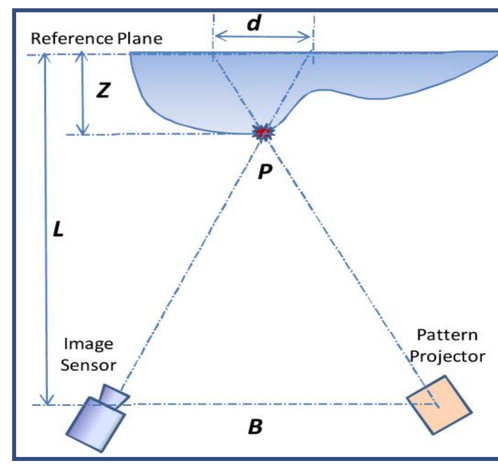
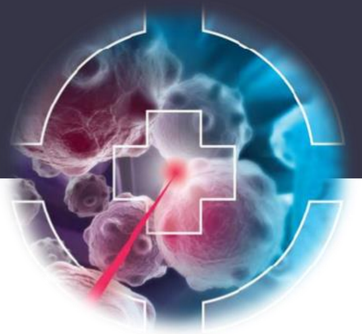


J. Geng. Structured-light 3D surface imaging: a tutorial. Advances in Optics and Photonics 3, 128–160 (2011)

Secondary photons in conventional radiotherapy



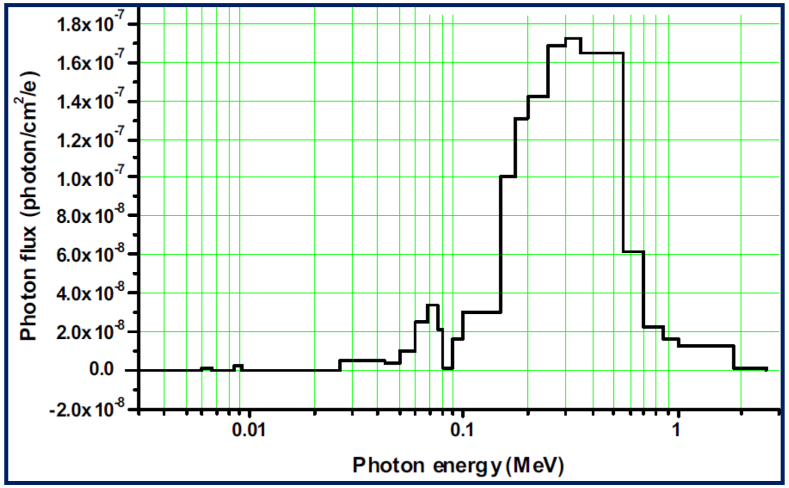
Scattered photons

- 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)

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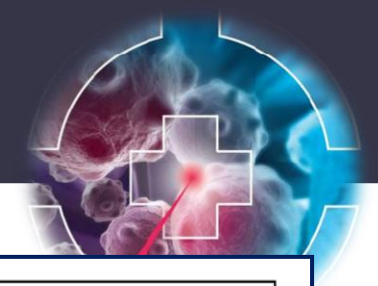
Photoneutrons in conventional radiotherapy

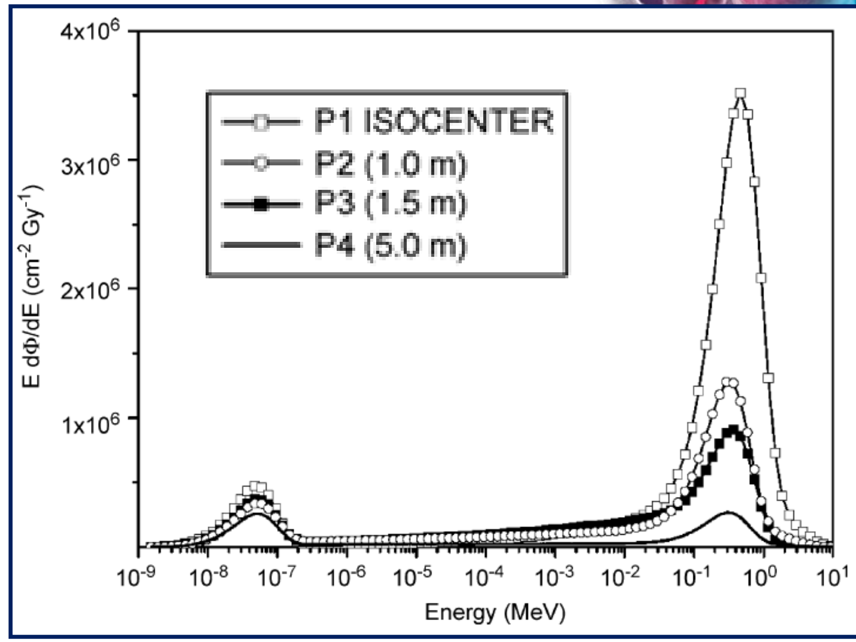


Fast component (~ 1 MeV)

- Neutrons produced through **GDR process**
- Flux α **$1/r^2$** (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

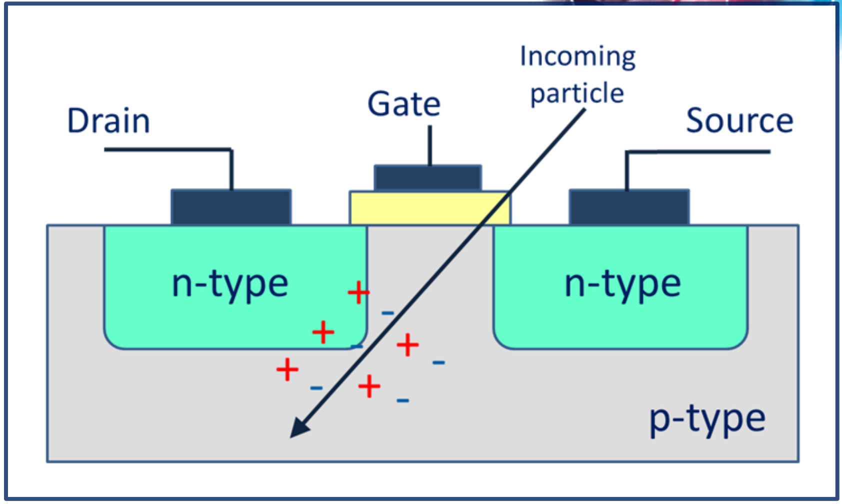


The photoneutron flux is negligible with energy beam < = 6 MeV

Dist. from isoc. (m)	Φ (cm^{-2} 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 on electronics



1) Interaction between the radiation and the device

2) Creation of e-/hole pairs

3) Possible temparary/permanent damages on the device:

Single event effects (SEE)

Caused by a single interaction

↓

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

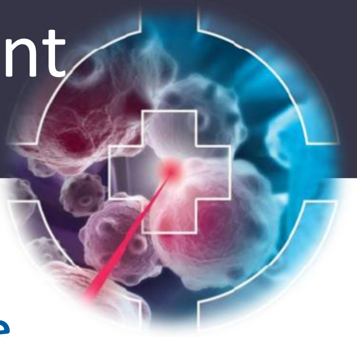
Displacement damages (DD)

Progressive damage

↓

Displacement of an atom
+
interstitial defect

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)

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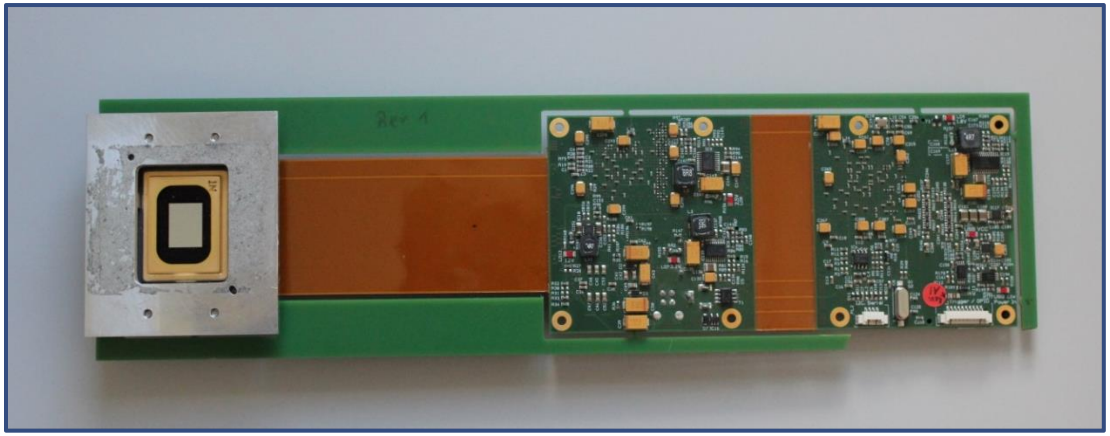
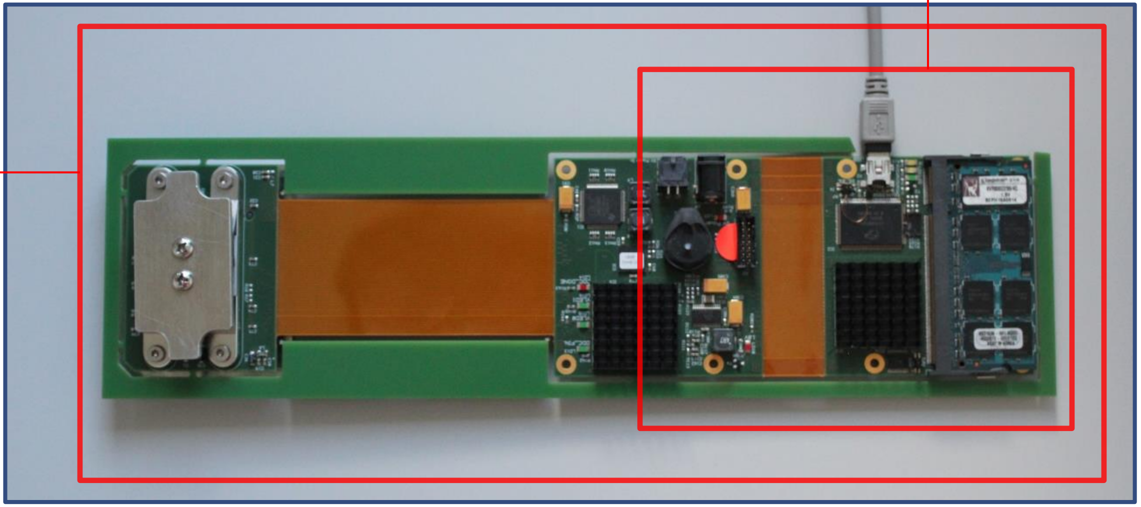
Evaluation of the electronic components – the projection board



1st test

Detect SEU via software in:
- DRAM (data corruption)
- FPGA (functionality interruption)



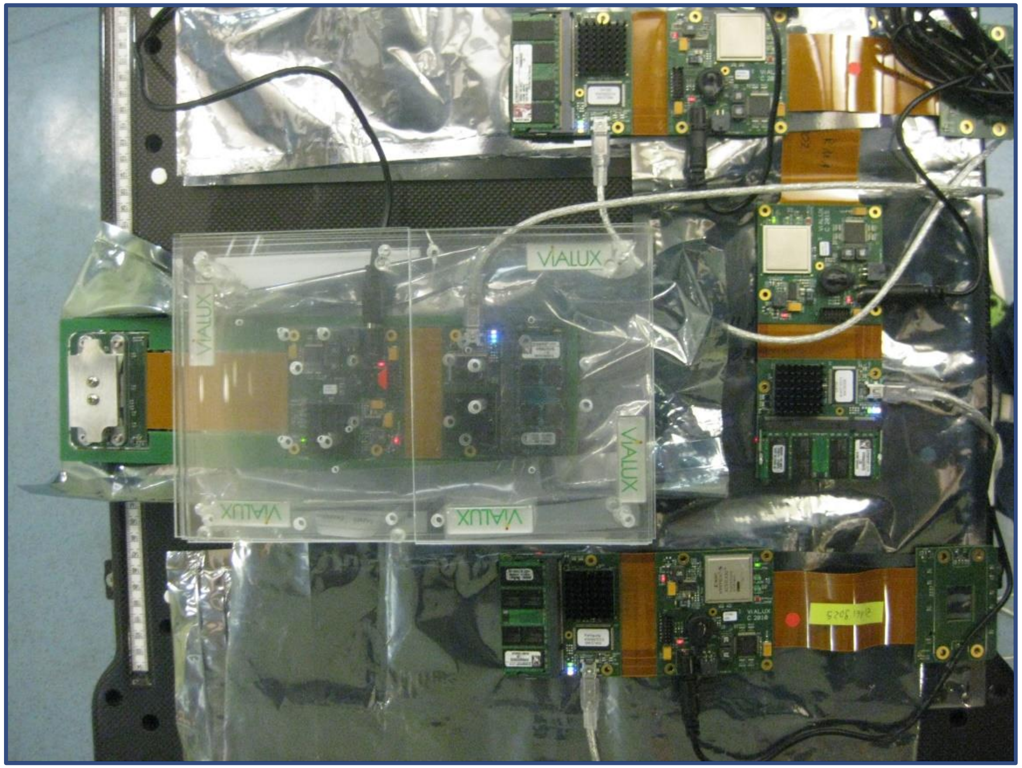
Possible 2nd test

Detect SEU via software and optical techniques in:
- DLP projector (errors in the projection)

The setup

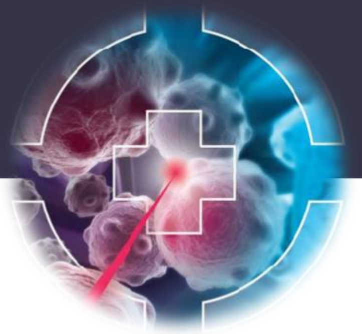
4 boards on the patient couch:

- 1 board at the isocenter
- 3 boards at 15 cm from isocenter



Plexiglass around the central board to enhance the thermal neutron flux

The test algorithm



SEU detection in:

- FPGA configuration memory — Cyclic Redundancy Check (CRC) readback function

- DRAM — load a memory state in DRAM and read it in search of bit flips

Dynamic test: use only part of the memory and read during irradiation

✓ More similar to the real use

✗ Lower probability to see an error

✗ It is possible to see if a particle cause multiple errors

Static test: use the whole memory and read it only after irradiation

✓ Higher probability to see an error

✗ Not possible to detect multiple errors

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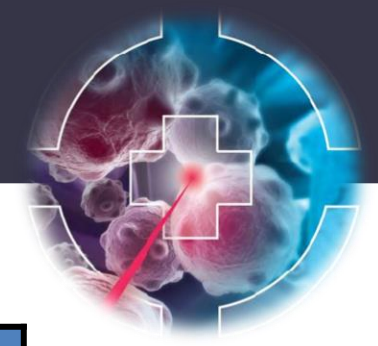
First test results & next steps



Städtisches Klinikum Dresden

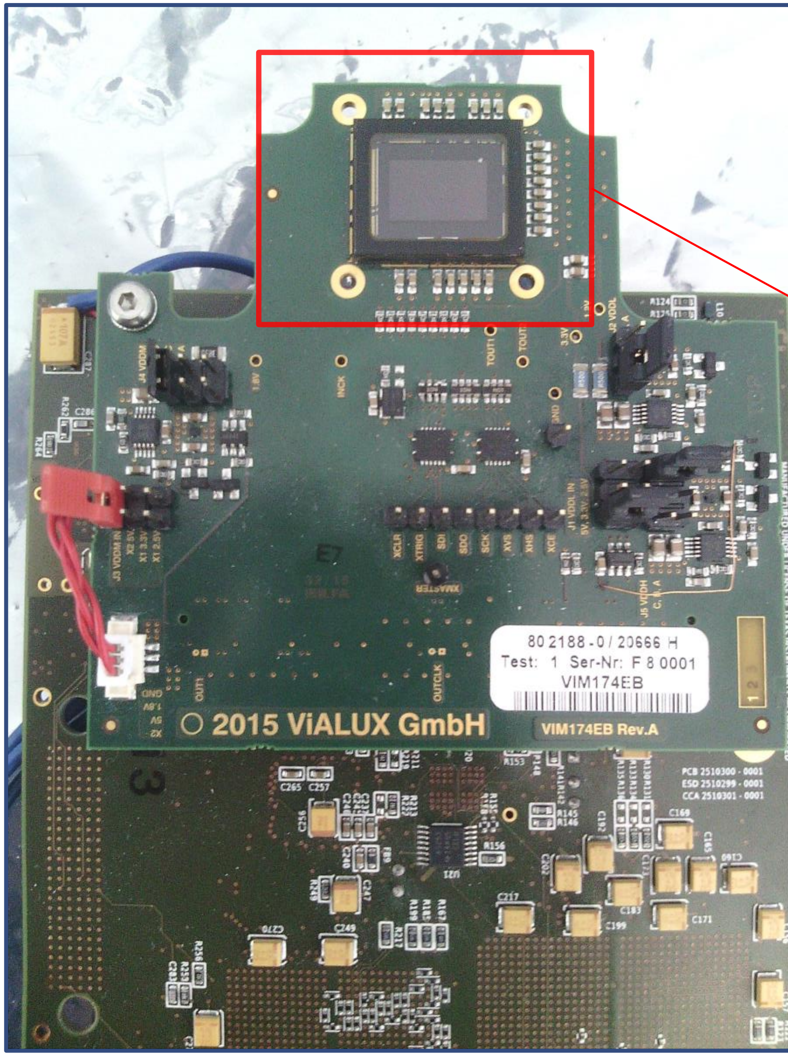
* Daily Monitor Units ~ 18000 MU

	Test A	Test B
Beam energy	15 MeV	15 MeV
Irradiation field	10x10 cm^2	0,5x0,5 cm^2
Monitor units*	1800 MU	3000 MU

No SEU detected : Board under test reliable with normal operation condition

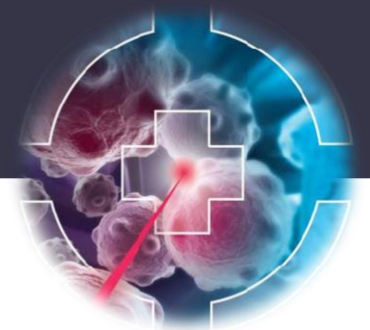
- Check that the algorithm is working as expected →
  - Force SEUs exposing the board to harsher conditions
- Perform a longer test to prove the first results →
  - Longer tests in the radiotherapy environment
  - Tests in a test beam facility to simulate aging

Evaluation of the electronic components – the CMOS sensor



Evaluate the progressive **performace degradation** of a CMOS exposed to radiation

Radiation effects in CMOS sensors



Single Event Effects

- Produce a signal in the pixels (as visible light)
- High amount of energy can saturate one or more pixels

Total ionizing dose

- Effect on the dielectrics (SiO_2)

Displacement damages

- Effect on the sensitive area (Si)

- Increase of dark current in the pixels (noise in the pixel output)
- Decrease of Quantum efficiency (efficiency in visible light detection)

↓

White pixels
Black pixels

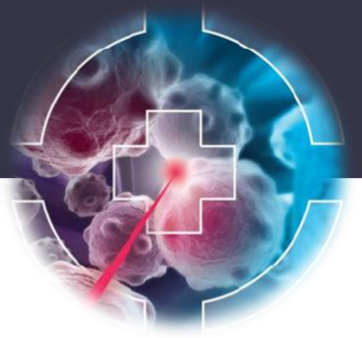
CMOS test

1. Characterization of the CMOS sensors in terms of output
    - find White and Black pixels
    - observe CMOS output in reference conditions (mean output)

2. Irradiation of the sensor
    - measure the dose absorbed by the CMOS

3. Repeat the characterization to observe the effects of radiation
    - new White and Black pixels
    - enhamncement of the difference between White and Black pixels and the mean output value
    - Increase in the mean output value in reference conditions

CMOS characterization



Acquisition of pictures in different conditions, changing:

- Incoming light
- CMOS exposure time
- CMOS gain

Analysis of the 10-bit grayscale PNG pictures

Board A	
Black pixel position (row ; column)	White pixel position
212 ; 1197	396 ; 635
736 ; 766	462 ; 642
799 ; 777	1111 ; 1036
952; 1593	1151 ; 1028

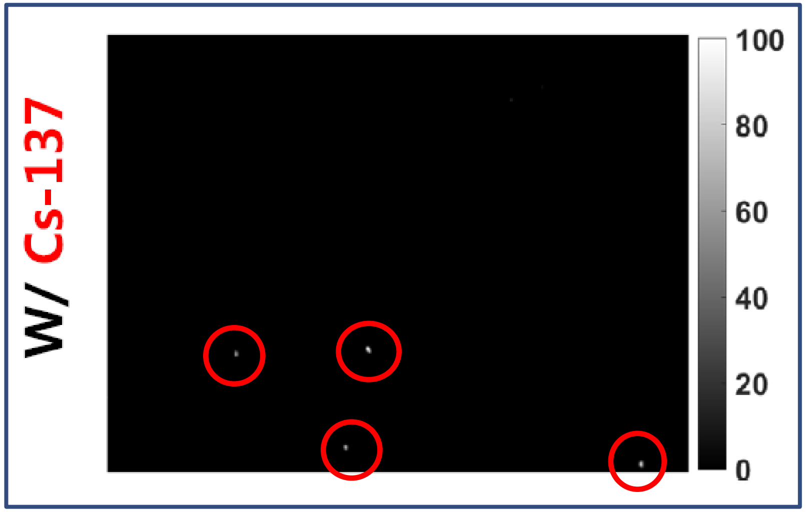
Board B	
Black pixel position	White pixel position
133 ; 1316	816 ; 367
134 ; 1316	945 ; 942
141 ; 1330	1186 ; 195
900 ; 390	

CMOS irradiation

a) Passive irradiation

a) Active irradiation: data acquisition with the CMOS during the irradiation

CMOS output (in dark conditions) → dose absorbed in the sensor (Si) → dose absorbed in the dielectrics (SiO_2) (via simulations)



e.g. Irradiation with Cs-137 (662 keV photons)

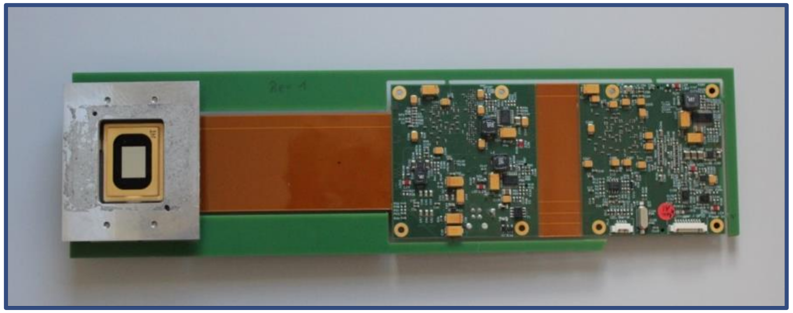
Kang et al. *An investigation of medical radiation detection using CMOS image sensors in smartphones*
Nuclear Instruments and Methods in Physics Research A823 (2016) 126–134

Summary

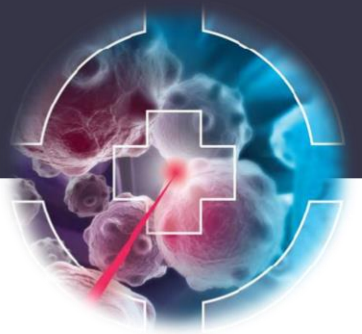
- High precision technology for patient positioning and monitoring
- No extra dose to the patient

- Requires radiation-hardness evaluation:

Projection board
- reliable in radiotherapy environment



CMOS sensor
- still under study



Thank you for your attention

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