Reliability of a CMOS image sensor for a 3D scanning device in the radiotherapy environment

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A 3D scanner for the radiotherapy

- **Optical 3D scanners** represent a valid solution for **patient positioning and monitoring,** delivering **no extra dose to the patient** since they work only with visible light.
- The **ViALUX 3D scanners** perform this task with [1]:
  - **high precision** (≤ 1 mm Δ(x,y,z) point accuracy)
  - **high resolution**
  - **high speed** (latency ≤ 20 ms)
- The **key components** of the ViALUX 3D scanners are (see Fig.1):
  - a Digital Light Processing (**DLP**) **projector**, which projects a sinusoidal light pattern on the object to scan [2]
  - a **CMOS image sensor** which acquires the image with high speed and high resolution
  - a dedicated **phase-shifting photogrammetry software**, which reconstructs in real-time the object surface, generating 3D points with the x,y,z coordinates.

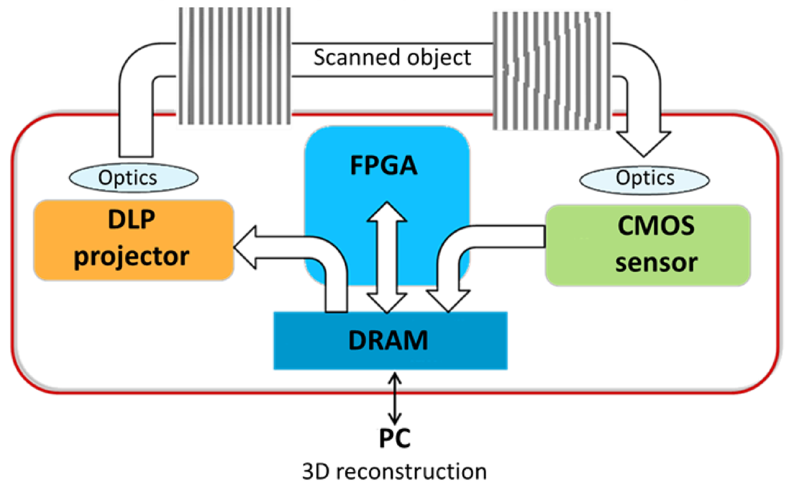

Fig.1: The main components of the 3D scanners made at ViALUX [1].

The radiotherapy environment

- Besides the primary beam used for treating the patients, **secondary radiations** are produced during the radiotherapy. These radiations are object of studies because they can cause secondary tumors in the patients [3], but they can also generate **failures and/or damages in the electronics** [4].
- 3D scanners used in the conventional radiotherapy environment are subject to (see Fig.3):
  - **Scattered and leakage photons** coming from the LINAC head and from the patient
  - **Fast neutrons** (~ 1 MeV) produced via GDR in the LINAC head
  - **Thermal neutrons** (~ 25 meV) scattered all around the room

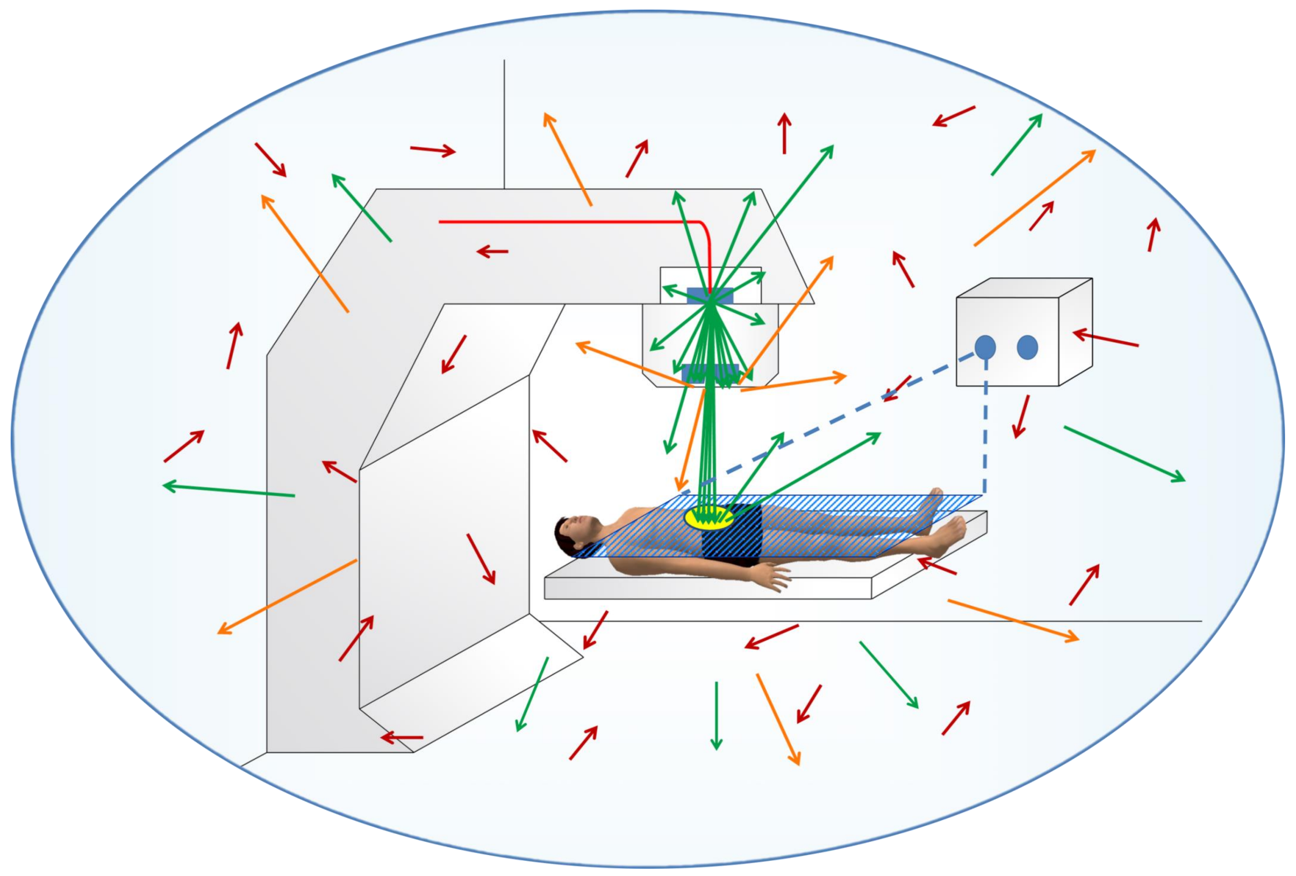

Fig.2: typical irradiation conditions inside a conventional radiotherapy treatment room.

The radiation effects on a CMOS image sensor

- The secondary radiations in a conventional radiotherapy treatment room can damage gradually and permanently a CMOS image sensor through these mechanisms [4]:
  - **Total Ionizing Dose (TID) effects**: the effects caused by the total dose absorbed by the device under test due to ionizing interactions. In our case we should consider the dose deposited by the **neutrons** through ionizing process and the dose deposited by the **gamma**
  - **Displacement Damages (DD)**: these effects are proportional to the Non Ionizing Energy Loss (NIEL). In this case we should consider mainly the non-ionizing interactions of the **fast neutrons**.
- The TID effects and the DDs cause an **increase in the pixels noise**, which leads to the creation of the so-called **Bright Pixels** (see Fig.3).
- The bright pixel noise is **enhanced with a longer exposure time and a higher gain.**
- The bright pixel noise acts as an **offset in the pixel output** and it can cause a pixel to always be saturated.
- Many Bright pixels cause a **degradation of performance in the CMOS sensor** which can affect its reliability

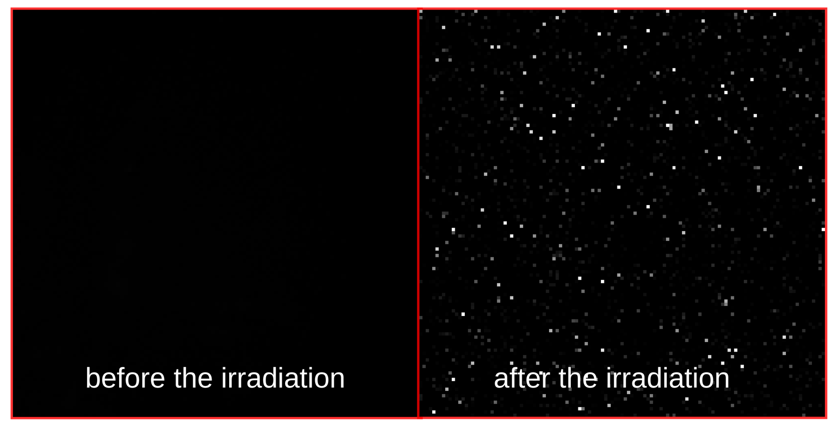

Fig. 3: a 125x125 pixels area from two pictures taken by the CMOS image sensor under test before and after the radiation test. The image sensor was isolated from any light source in order to evaluate the number of Bright pixels.

The radiation test at the FRM II nuclear reactor

- We performed a **radiation-hardness test** at the FRM II nuclear reactor in Munich.
- The tests were performed at the **MEDAPP instrument**, which provides [5] [6]:
  - a **thermal neutron** flux of about 2x10^9 n/(cm²s)
  - a 3.2x10^8 n/(cm²s) **neutron flux with fission spectrum** (Fig. 4a), obtained using Uranium converter plates and a boron filter to reduce the thermal neutrons. This spectrum is similar to the typical neutron spectrum in the treatment rooms (Fig.4b).

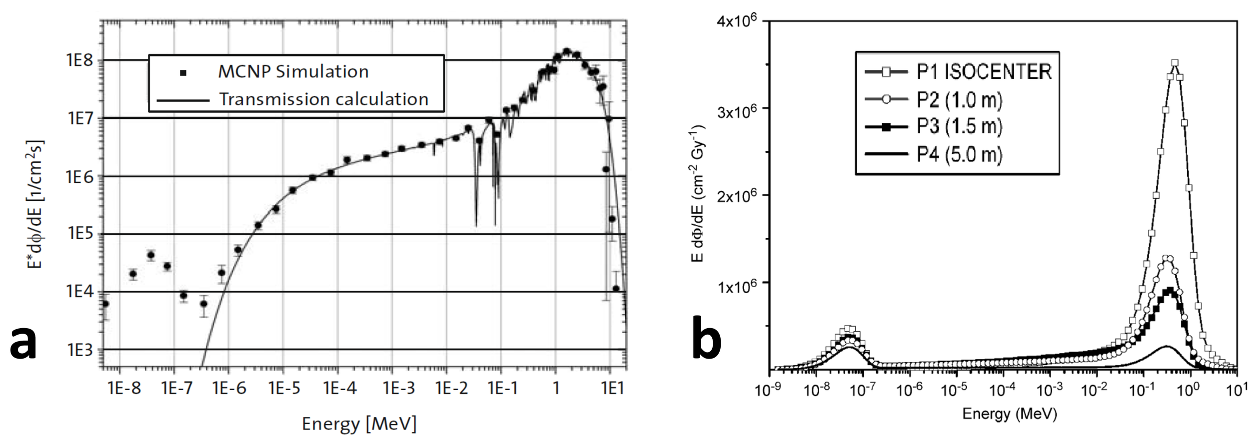

Fig.4: neutron spectrum at MEDAPP when the Uranium converter plates and the boron filter are used (a). Neutron spectra in a conventional radiotherapy treatment room at different distances from the isocenter [7].

- The goals of this test were:
  - investigating the **reliability of the 3D scanner** during the irradiation (e.g. detecting interruption of functionality due to the radiations)
  - evaluating the **CMOS performance in 3D scanning** after the irradiation
- Considering the typical neutron flux in the conventional radiotherapy treatment rooms (~10^5 n/(cm²s) [7]) and the irradiation time, we can estimate that during the radiation tests the scanner was subject to a flux comparable to **more than 1000 hours of irradiation in the treatment room.**

Evaluation of the CMOS performance after the radiation test

- After the radiation test we observed an **increase in the number of Bright pixels** in the CMOS sensor (see Fig. 3 and Tab. 1)

	Number of Bright pixels	
Pixel output (grayscale from 1 to 1022)	Before the irradiation	After the irradiation
>10 (saturation capacity reduced by 1%)	38 pixels	~9% (~ 200k pixels)
> 100 (saturation capacity reduced by 10%)	2 pixels	~0,5% (~ 12k pixels)
>150	No pixels	~0,1% (~2500 pixels)
1022 (saturated)	No pixels	4 pixels

Tab. 1: number of Bright pixels before and after the irradiation test, considering different Bright pixel thresholds.

Fig. 5: 3D scanner under test after the radiation test.

- Can the bright pixels affect the quality of the 3D pictures?
  a) Bright pixels with a **simple offset**: the 3D algorithm evaluates consecutive pictures and removes the offset ⟶ **not a concern**
  b) **Saturated pixels**: cause missing 3D points in the final 3D image (as the overexposed and the underexposed pixels) ⟶ **further analysis required**
- We acquired several 3D images of a body model (see Fig. 5), combining different parameters:
  - exposure time (5-250 ms)
  - gain (1x – 5x)
  - resolution (full CMOS resolution or 2x2 pixel binning)
- The 3D images didn't show **any missing 3D point due to the Bright pixels with the typical parameters** used for 3D scanning in radiotherapy (2-10 ms exposure time, 1x gain and 2x2 binning resolution).
- We can observe that the Bright pixels can actually affect the 3D scanning process only when „extreme" parameters are set, e.g. exposure time 50 ms, gain 5x and full resolution (see Fig. 6c).

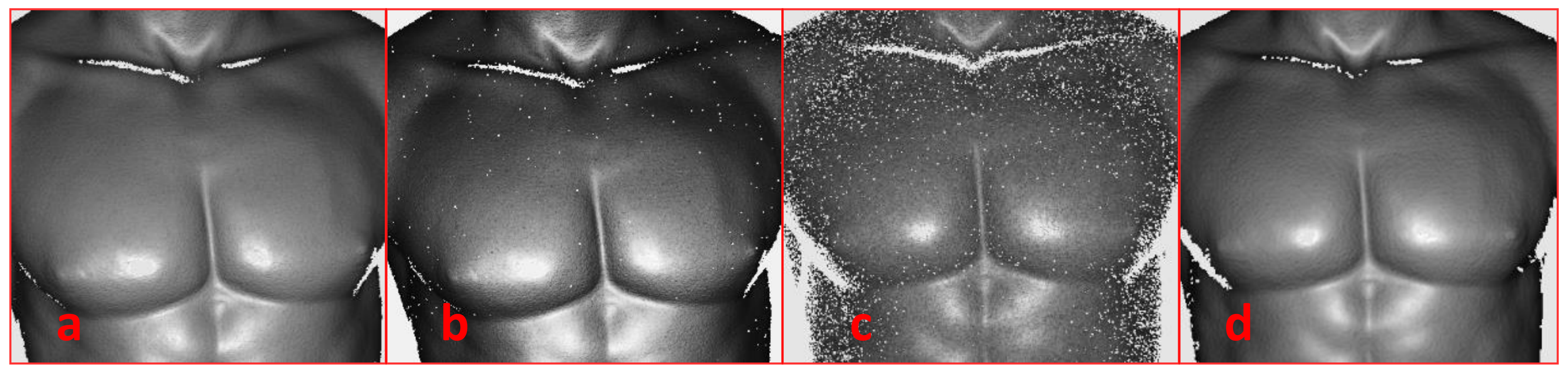

Fig. 6: 3D images acquired with the following parameters:
a) 5 ms exposure time, 1x gain, full resolution
b) 250 ms exposure time, 1x gain, full resolution
c) 50 ms exposure time, 5x gain, full resolution
d) 50 ms exposure time, 5x gain, 2x2 binning resolution

Conclusions

- The radiations can cause a **performance degradation in the CMOS image sensors**, mainly increasing the number of Bright pixels.
- Considering the ViALUX 3D scanner technology and the typical irradiation conditions in a conventional radiotherapy treatment room, we estimated that the **3D scanning process is not significantly affected** when a CMOS sensor is exposed to a radiation comparable to more than 1000 hours of operation in a treatment room.
- A methodology needs to be implemented in order to set a threshold (e.g.in terms of number of Bright pixels) beyond which the CMOS sensor cannot be considered reliable anymore.
- Further tests will estimate after how many hours of treatment room operation the CMOS image sensor will overcome such a threshold.

References

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Acknowledgments

This work is based upon experiments performed at the MEDAPP instrument operated by FRM II at the Heinz Maier-Leibnitz Zentrum (MLZ), Garching,Germany. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 675265, OMA – Optimization of Medical Accelerators.