A silicon detector in edge-on configuration for (spectral) computed tomography: experimental setup, simulation and reconstruction algorithm

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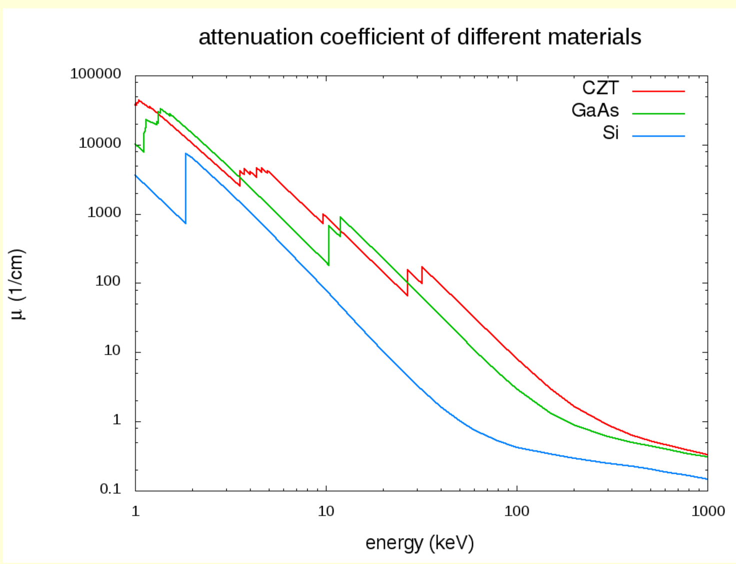
"INtelligent Fast Interconnected and Efficient Devices for Frontier Exploitation in Research and Industry"

Introduction: spectral X-ray Computed Tomography

Computed Tomography (CT) is a diagnostic technique that allows to see the inner structure of an object, exploiting the attenuation of an X-ray beam. The key component of a CT scanner is the X-ray detector.
This project focuses on a semiconductor detector working in Photon Counting mode. This setup has been shown [1] to bring remarkable improvements with respect to scintillation crystals - indirectly converting the photon - coupled to silicon photodiodes working in Charge Integrating mode. The benefits brought by photon counting detectors allow to reduce the patient's exposure to radiation, which can lead to damage in the tissues. The challenge nowadays is to switch to this new type of detectors while having the same absorption efficiency of the scintillators and handling the high photon flux impinging on the sensor. Moreover, some photon counting systems are energy sensitive, i.e. they can bin the incoming photons in different energy windows, allowing the energy information to be exploited. The technique performing this operation is called Spectral Computed Tomography [2].
In conclusion, a new family of detectors could transform the current CT technique, allowing a new era to start.

The edge-on configuration

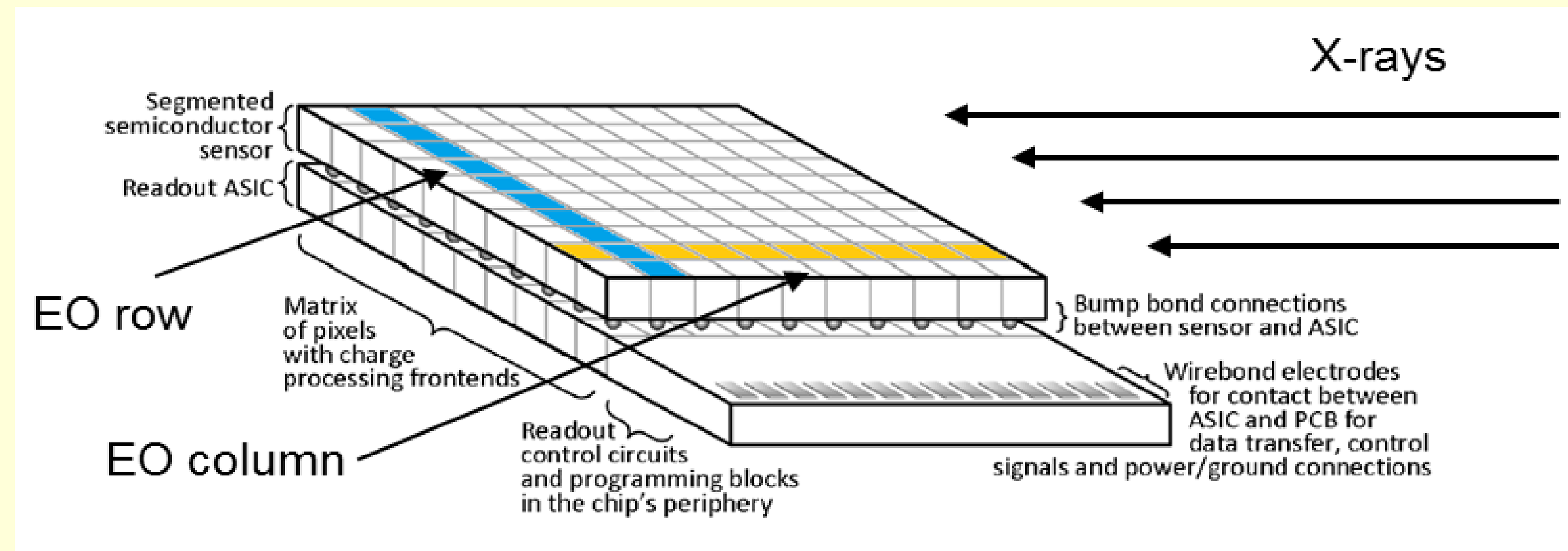
An explanatory sketch of the hybrid pixel detector used in this project is shown in the figure on the right. The semiconductor sensor (upper block) is bump-bonded to the readout chip (lower block). Several choices are available for the sensor material.



Obstacles for compound semiconductors:

- manufacturing not mature
- bump bonding difficult
- high cost
- low reliability

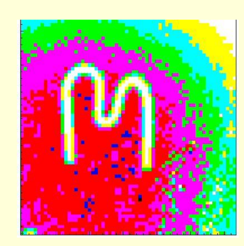
Therefore in this project **Si is used**. The solution adopted here to solve the problem of the low attenuation efficiency is to increase the thickness of the detector, using it in edge-on (EO) configuration [3] [4], as shown in the sketch on the right.



Schematic of the detector edge-on (EO) illuminated.
Usually the detector is used in face-on, with the X-rays coming from above, perpendicularly to the detector matrix. Here the detector is rotated by 90°, with the X-rays impinging on the side of the sensor.

Illuminating the sensor in this new geometry brings **two major improvements**:

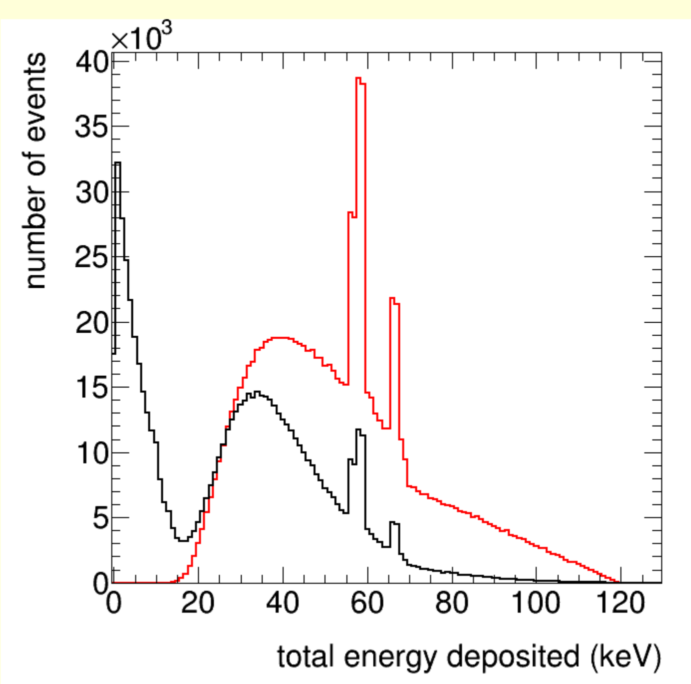
1) **higher absorption efficiency**: the percentage of absorbed photons significantly rises (e.g. for E = 40 keV, it goes from 8% to 90%)
2) **energy discrimination**: low energy photons interact in the top EO rows, while high energy photons interact deeper in the sensor



Chip: **Medipix**. Matrix of 256x256 square pixels, 55 µm side.
Thanks to the fine segmentation, this system is able to work in photon counting mode while handling high photon fluxes.

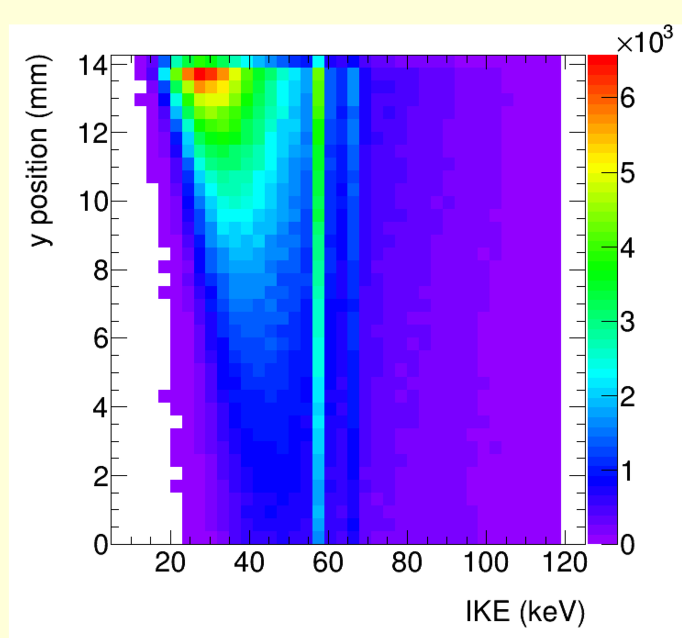
Simulations and experimental results

In order to evaluate the performance of the detector in this new configuration, some **simulations** have been run. Following, the results for a 500 µm thick sensor illuminated by a diagnostic X-ray tube (120 kVp) are shown.



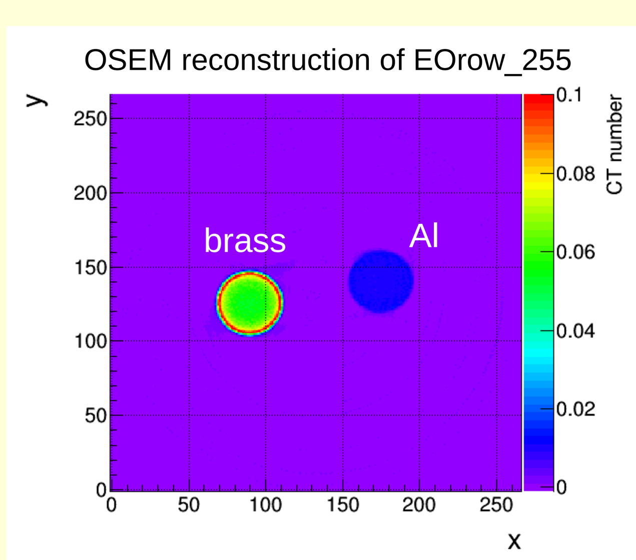
On the left, in red the energy spectrum of the source, in black the detected energy spectrum are plotted. The difference between the two is due to the limited volume of the detector and the way the X-rays interact with it.
~ 29% of the photons lost
~ 27% fake events due to Compton Scattering

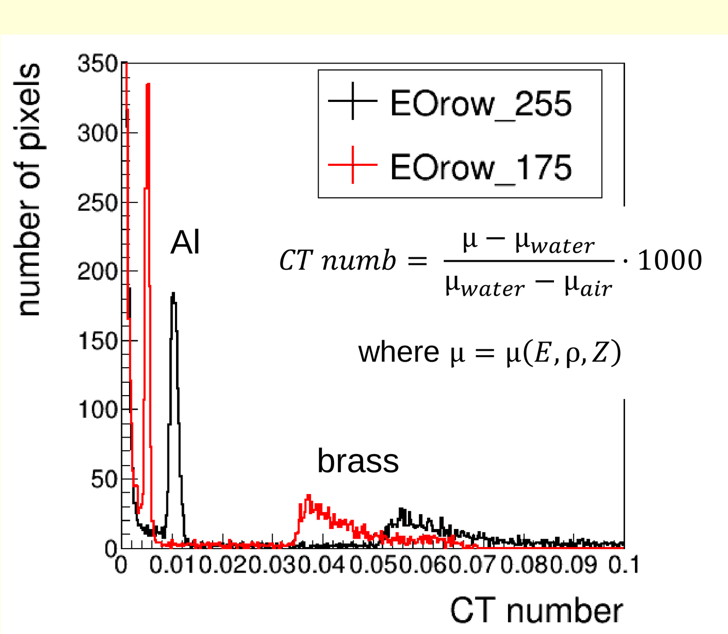
On the right, number of interactions as a function of the depth in the detector (y = 14.08 mm corresponds to the EO row 255 and y = 0 mm to the EO row 0) and of the Initial Energy of the incoming photon. The energy of the interacting photons increases with decreasing the EO row.



Measurement: CT scan of two bars (Al and brass)
On the right, reconstructed image for one Edge-On row.
Below, CT number histogram for two different EO rows. The peak from the same material appears translated, as highlighted in the last plot. This shift might be due to the different energy of the photons that interact in different EO rows.

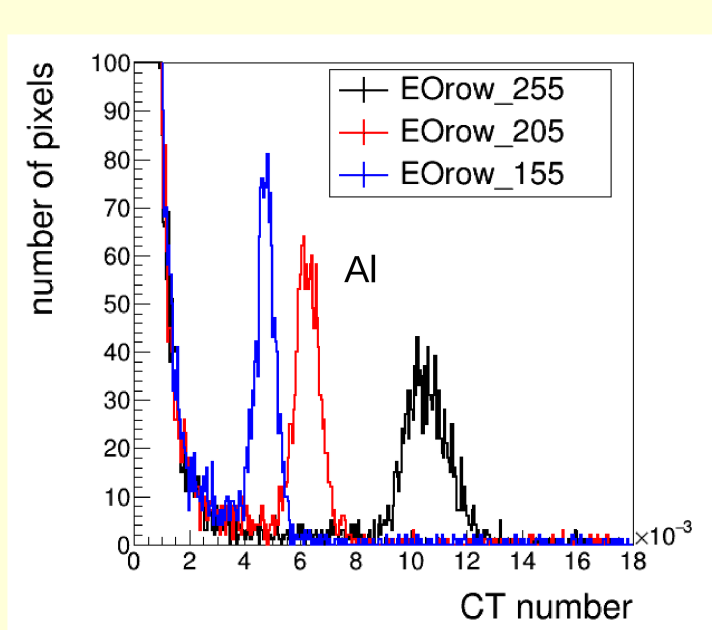
These results have been obtained with the reconstruction run EO row by EO row independently and without taking into account the beam attenuation by the detector.





$$CT\ numb = \frac{\mu - \mu_{water}}{\mu_{water} - \mu_{air}} \cdot 1000$$

where $\mu = \mu(E, \rho, Z)$



Custom reconstruction algorithm

To understand the experimental results and to exploit the features of this new configuration, a new reconstruction algorithm is under development. The platform used in this work is the ASTRA Toolbox [5], developed by iMinds-Vision Lab of the University of Antwerp with the contribution of CWI (Amsterdam).

guess matrix: x^k

forward-projection: $\mathrm{F}(x^k)$
input: energy spectrum and sample matrix
output: number of counts as a function of the spatial position, the EO row and (optionally) the energy bin

For all the angles used in the CT scan

difference with real data*: $p - \mathrm{F}(x^k) = r^k$

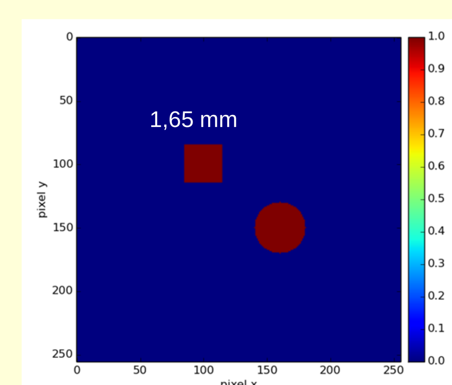
residuals sinogram: $s^k = \sum r^k$

back-projection: $B(s^k) = u^k$
(backprojector is provided by Astra)

new guess matrix: $x^k + \lambda u^k = x^{k+1}$

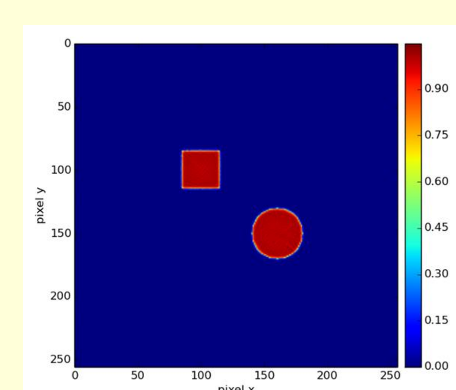
* After normalization for the Direct Beam

In order to test it, some data have been simulated and reconstructed



2D sample
material: Al

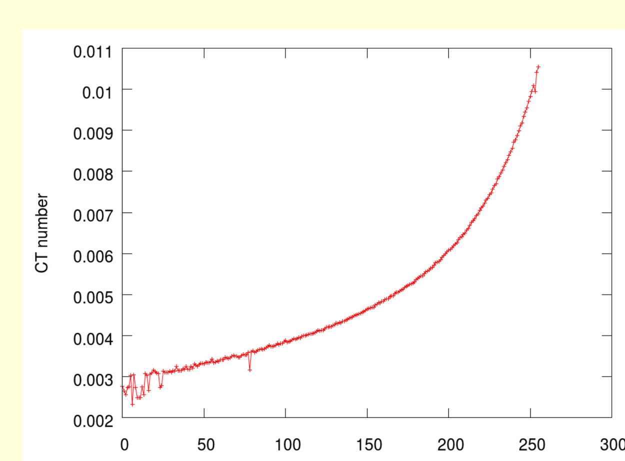
reconstruction
EOrow_255
iteration 100



This algorithm assumes that the non linearities in the forward model can be neglected, in first approximation.
At the moment, only one material can be simulated and the projector does not include the detector response function.

Discussion & future work

From the simulations, we have observed the energy discrimination phenomenon. This might be the (main) reason why the CT number shifts in the reconstruction of the experimental data. In that case, the curve representing this trend (in the plot on the right) can be used to identify materials in an unknown sample.
The custom reconstruction will help us in finding an answer to this question and in improving the results quality.



The **next steps** in the reconstruction process are:

- to test the algorithm with simulated data;
- to upgrade it, adding a second material;
- to include the detector energy response function in the forward projector;
- to validate the algorithm using real data.

The Compton scattering inside the detector remains a factor of noise. Even if a correction mask - calculated through simulation - is used, this contribution is hard to reduce.

References

[1] R. Ballabriga et al., "Review of hybrid pixel detector readout ASICs for spectroscopic X-ray imaging", 2016 JINST 11 P01007
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[3] M. Doni et al., "Edge-on illumination photon counting for medical imaging", 2015 JINST 10 C08011
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[5] W. J. Palenstijn et al. "The ASTRA tomography toolbox." *13th International Conference on Computational and Mathematical Methods in Science and Engineering, CMMSE*. Vol. 2013, 2013.

Acknowledgments

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