Simulation of a silicon sensor edge-on illuminated with an X-ray beam

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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. This phenomenon is described by the Lambert-Beer law: $I = I_0 \cdot e^{-\mu t}$. The attenuation coefficient μ depends on the energy of the photons as well as on the density ρ and atomic number Z of the material. Therefore, knowing the intensity of the beam before (I_0) and after (I) the analyzed sample, it is possible to retrieve information about the materials of the sample itself.

Most of the detectors are not energy sensitive; therefore, in conventional CT, the X-ray beam is considered monochromatic when it is, actually, polychromatic. This simplification causes a deterioration of the reconstructed image (artifacts) and ignores a useful part of the information carried by the photons. Aim of this project is to exploit also the energy information, using an energy sensitive detector, capable of working in photon counting while handling the high fluxes required in CT. This technique, in which also the energy information is used, is called spectral CT.

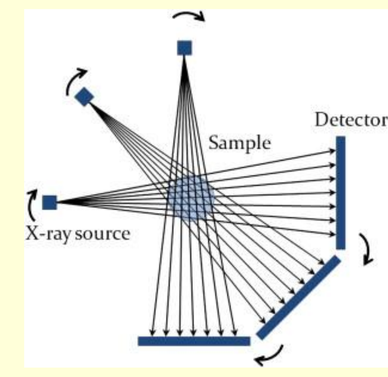


Figure 1. CT scan schematic.

Edge-on illumination

When using a semiconductor detector, several choices are available for the sensor material. Among them, Si, GaAs and CZT are the most common. Silicon has several advantages, like low concentration of impurities, relatively low cost and large availability. The main drawback is that its attenuation coefficient drops at the high energies used in Computed Tomography, due to its low atomic number. On the other hand, the manufacturing of high Z materials is not as mature as the one of silicon is; this causes non-uniform electric fields and severe charge trapping in these materials. Therefore in this project Si is used. The solution adopted here to solve the problem of low attenuation efficiency is to increase the thickness of the detector, using it in edge-on configuration [1], as shown in Figure 2.

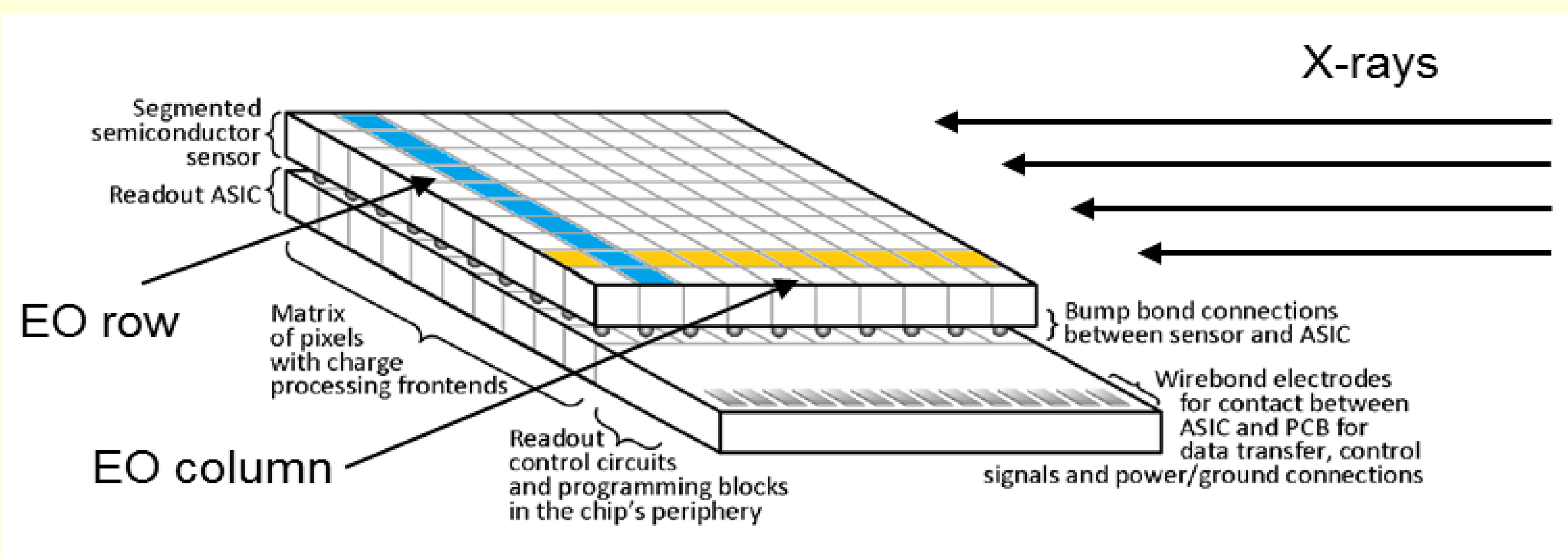


Figure 2. Schematic of the edge-on (EO) illumination.
Usually the detector is used in face-on, with the X-rays coming from above, perpendicular to the detector matrix. Here the detector is rotated by 90°, with the X-rays impinging on the side of the sensor.

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

1. higher absorption efficiency: with the detector thickness increasing from 0.5 mm (face-on) to 14.08 mm (edge-on), the percentage of absorbed photons rises from 4% to 66%, for E = 60 keV;
2. energy discrimination: on average, low energy photons interact in the top EO rows, while high energy photons interact deeper in the sensor; the results of this phenomenon is shown in the following plot.

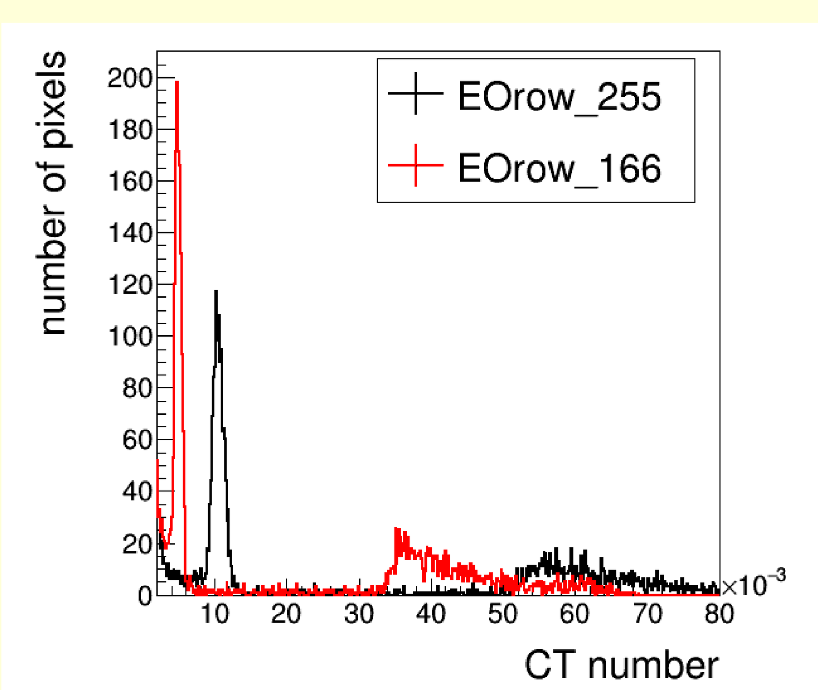


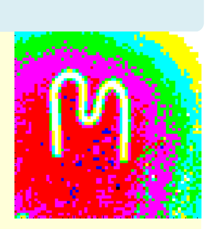
Figure 3. CT number histogram for two different EO rows; the peak from the same material appears translated. The CT number (or Hounsfield Unit) is a function of the energy of the photons, the density and the atomic number of the material. Since the two histograms belong to the same sample, the shift is due to the energy.

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

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

Obtaining the number of photons for different energy ranges is the key step for performing a spectral CT reconstruction [2].

The detector



For this project two hybrid detectors are used, the Timepix (TPX) and the Medipix3 (MPX3) [3]. Both have a pixelated Si sensor, constituted by 256 x 256 pixels (55 µm side), as shown in Figure 2. Every pixel has, within its area, its own front-end electronics, consisting of analog and digital processing blocks.

The Timepix chip can be used in 3 different operational modes:

- photon counting (one energy threshold available),
- Time over Threshold (ToT) and
- Time of Arrival (ToA).

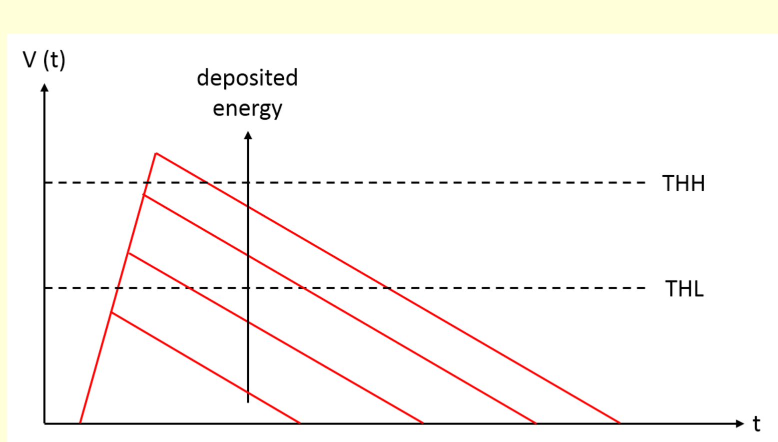


Figure 4. The charge produced by the incoming particle produces a triangular signal, which height is proportional to the energy deposited by the particle itself.

The Medipix3 chip can be operated in two modes:

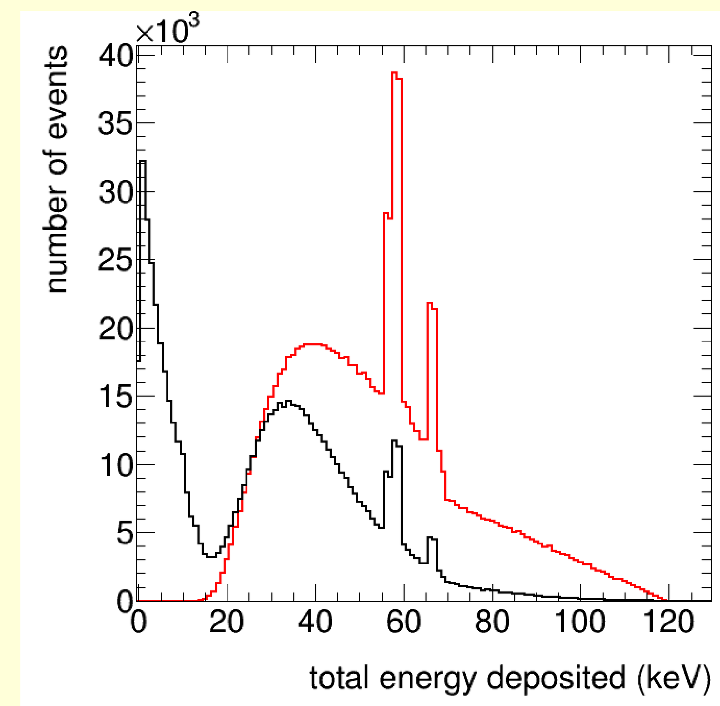
- Fine pitch mode, where each 55 µm readout pixel is connected to a sensor element of the same dimension and
- Spectroscopic mode, where only one over 2 x 2 readout pixels is connected to a sensor area of 110 µm; in this case the pixel can have up to 8 thresholds (Spectroscopic mode)

Moreover, the design of this last version of the Medipix chip, is aimed to reduce charge sharing [4]. With the Medipix3 chip, in addition to the normal photon counting mode (each pixel working independently from its neighbours), the Charge Summing (CS) mode can be used. In this case, the charge in every cluster of 4 pixels is added and assigned to the pixel with the largest charge deposition. The CS mode can be enabled in either the fine pitch mode or in the spectroscopic mode.

Simulations

In red the energy spectrum of the source (tube voltage: 120 kV), in black the detected energy spectrum.

The difference between the two histograms is due to the limited size of the detector and the way the X-ray beam interacts with it.



Photons (indirectly) deposit their energy through two processes:

- Photoelectric effect: the incoming photon gives all its energy to a photoelectron that deposits its energy in the sensor through a series of collisions with the orbital electrons;
- Compton scattering: the incoming photon scatters inelastically with an electron (recoil electron), giving to the latter only a small percentage of its energy, which is deposited locally; the scattered photon can interact again inside the sensor.

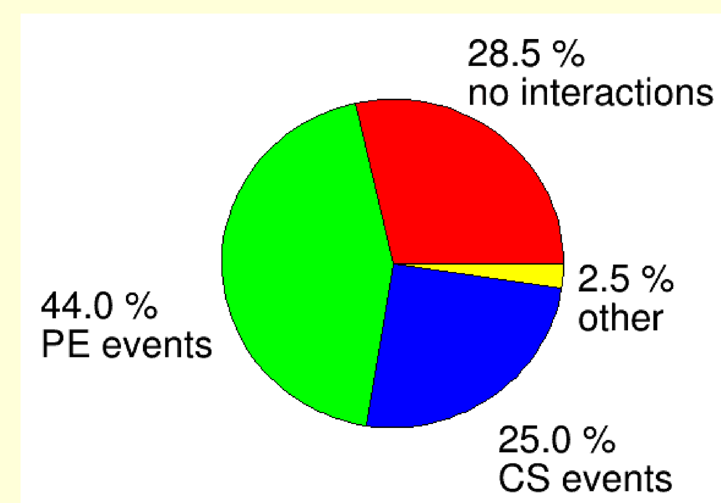


Figure 5. PE = PhotoElectric events (all the energy is deposited), CS = Compton Scattering events (the scattered photon escapes), other = photoelectrons that escape (1.7%) + Compton scattered photons that interact again in the sensor (0.8%)

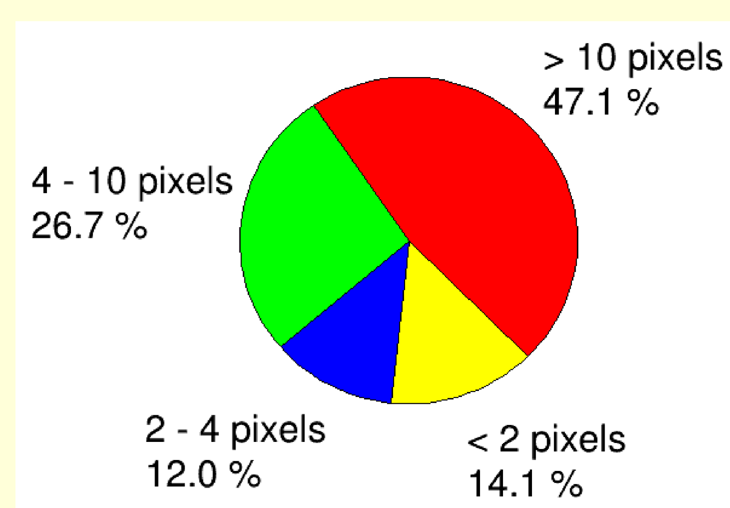


Figure 6. Distance (in pixel units) traveled by the scattered photon before it interacts again in the sensor. This interactions produce fake events.

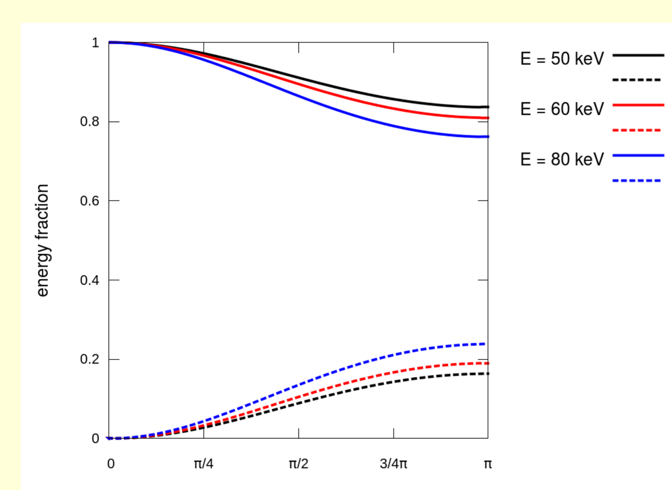


Figure7. Energy fraction (energy transferred over energy of the incoming photon) deposited in a Compton scattering event for different energies of the incoming photon. The continuous line is for the scattered photon, the dashed one for the recoil electron.

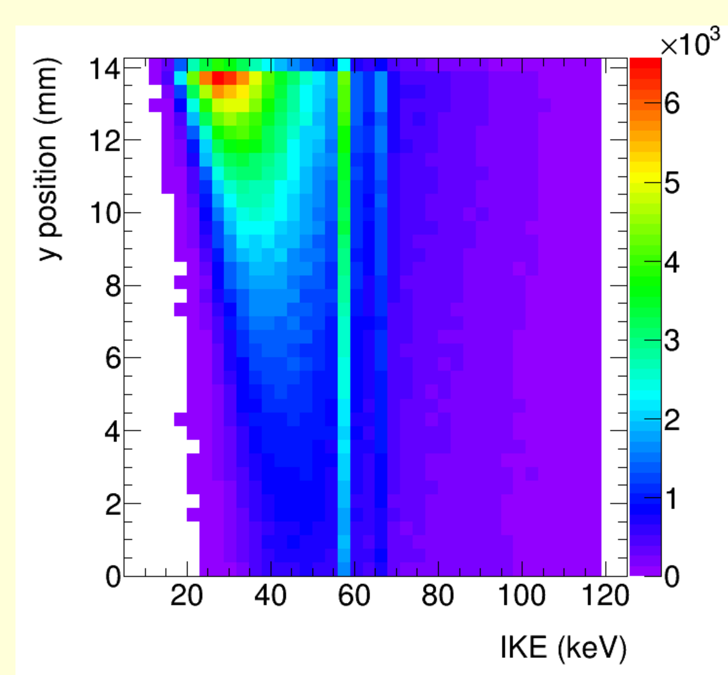


Figure 8. Number of interactions as a function of the depth in the detector (y = 14.08 mm corresponds to the EOrow 255 and y = 0 mm to the EOrow 0) and of the Initial Kinetic Energy of the incoming photon. It is clear, especially from the upper part, how the energy of the interacting photons increases with decreasing the EO row. This phenomenon, i.e. the energy discrimination, allows the spectral reconstruction to be performed.

Future work

- Quantify the Compton scattering contribution and try to compensate for it
- Sum the number of counts of the EO rows, improving the CT number histograms
- Try to differentiate between 2 or more soft materials using the energy information

References

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Acknowledgments

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