Geant4 simulations of STIX Caliste-SO detector's response to solar X-ray radiation

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ABSTRACT

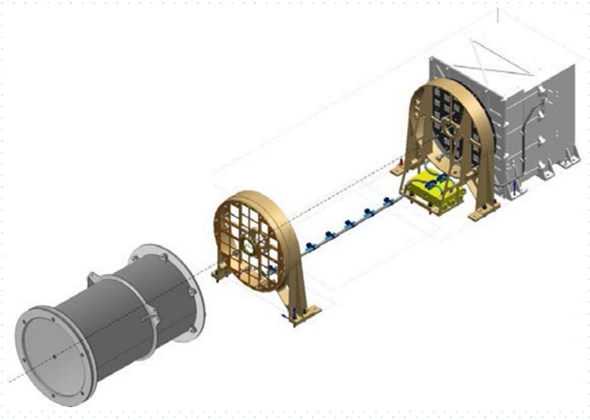
Spectrometer/Telescope for Imaging X-rays (STIX) is a part of Solar Orbiter (SO) science payload. SO will be launched in October 2018. After three years of cruise phase, SO will reach final orbit with perihelion distance equal 0.3 a.u. STIX is a Fourier imager equipped with pairs of grids that comprise the flare hard X-ray tomograph. Similar imager types were already used in the past (eq. RHESSI, Yohkoh/HXT), but STIX will incorporate Moiré modulation and a new type of pixelized detectors with CdTe sensor. We developed a method of modeling these detector's response matrix (DRM) using the Geant4 simulations of X-ray photons interactions with CdTe crystals. Taking into account known detector effects (Fano noise, hole tailing etc.) we modeled the resulting spectra with high accuracy. Comparison of Caliste-SO laboratory measurements of ^{241}Am decay spectrum with our results shows a very good agreement. The modeling based on the Geant4 simulations significantly improves our understanding of detector response to X-ray photons. Developed methodology gives opportunity for detailed simulation of whole instrument response with complicated geometry and secondary radiation from cosmic ray particles taken into account. Moreover, we are developing a Geant4 simulations of ageing effects which decrease detector's performance. As an example we present predicted Caliste-SO X-ray spectra of a solar flare obtained for several levels of detector's degradation.

Solar Orbiter (SO) & Spectrometer/Telescope for Imaging X-rays (STIX)

The main objective of the SO, first M-class mission of ESA's Cosmic Vision2015-2025 programme, is investigation of the connection between the Sun and the heliosphere. SO orbit will be heliocentric with perihelion equal 0.28 AU. Simultaneous in-situ measurements, remote high-resolution imaging and spectroscopic observations of the Sun will be performed with a broad suite of instruments. One of them is the STIX which provide us with images and spectra of the Sun in 4-150 keV range with high spatial and spectral resolutions.

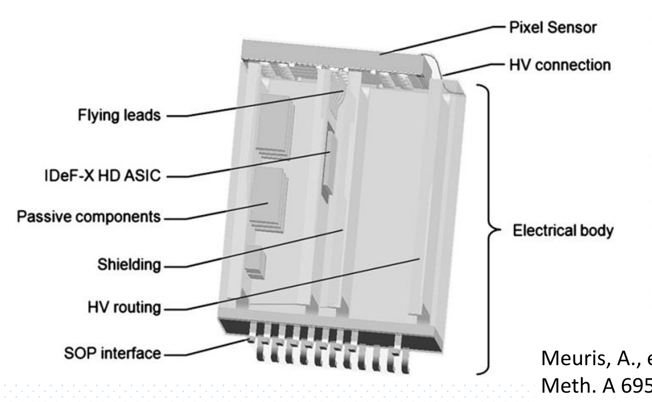
There are three modules in STIX:

- X-ray window, which provide thermal shielding and rejection of low-energy X-ray photons,
- Imager – 30 pairs of grids with different pitches and orientations which provide Fourier components of solar X-ray emission sources distribution,
- Detector Electronics Module – set of 32 Caliste-SO detectors with IDPU.



Caliste-SO detectors

Caliste-SO consist of a CdTe sensor and a dedicated front-end electronics. They are manufactured in 3D Plus technology. There are four printed circuit boards in the electronic part of the detector: first for ASIC, second and third containing discrete parts for power supply filtering and local decoupling, and fourth for routing the sensor high bias voltage



Meuris, A., et al., Nucl. Instrum. and Meth. A 695, 288-292 (2012).

The sensor (CdTe crystal) area is 100 mm^2 and it's thickness is 1 mm. Sensor is divided into 12 pixels, which are grouped into four stripes. This arrange allows to detect Moiré pattern shape, which is produced by pairs of grids located before each detector, with high accuracy . Moreover, pixels allow to limit too high photon flux observed during large solar flares by disabling some of them which reduce active area. Additionally, entire crystal is surounded by guard ring that eliminates edge effects.

There are two electrodes in the CdTe sensor. The entrance electrode – cathode made of 15 nm thick platinum layer. On the opposite side, the multilayer anode, consisting of 50 nm thick aluminium, 15 nm titanium and 80 nm gold layers, is placed .

The Caliste-SO is developed by CEA/Irfu (France) and Paul Scherrer Institute (Switzerland).

Geant 4

Geant4 is a toolkit for simulation of particle interaction with matter. There are many software components, which can be freely selected, in the package. This tool is useful for simple simulations as well as analysis of whole large experiments like the Large Hadron Collider.

The Geant4 package collects knowlegde about Monte Carlo simulations and physical process, which is used in many fields of science like nuclear physics, particle physics, accelerators, space engineering, and medical physics.

This package cotains a broad suite of physical models (including electromagnetic, hadronic and optical), which covers a wide range of energies from around 250 eV up to several TeV. Existing physical models are being improved and extended continuosly.

Detector effects

Photons are absorbed in a detector crystal and generate electron-hole pairs. Next, carriers are transported to electrodes where total charge is counted. Several effects may influence number of carriers reaching electrodes:

1. *Hole tailing*. Holes are characterized by low mobility and life time due to impurities and defects present in crystal. Therefore, not all of them reach electrode which lowers counted total charge and produce a low energy tail for each measured spectral feature. Hole tailing depends strongly on photon absorption depth. Therefore, the tail will be longer for higher energy photons. Hole tailing is described by Hecht equation:

$$\eta(x) = \frac{\lambda_h}{D}\left(1 - e^{-\frac{x}{\lambda_h}}\right) + \frac{\lambda_e}{D}\left(1 - e^{-\frac{D-x}{\lambda_e}}\right)$$

where: $\lambda_{h,e}$ – mean free path of holes (h) and electrons (e), D – crystal thickness, x – photon absorption depth.

2. *Fano noise*. Even if absobed photons have exactly the same energy they create different number of carriers. This produce a broadening of measured spectral features. The full width at half maximum (FWHM) of this broadening is equal:

$$FWHM(E) = \frac{1}{\sqrt{\frac{F \cdot w}{E}}}$$

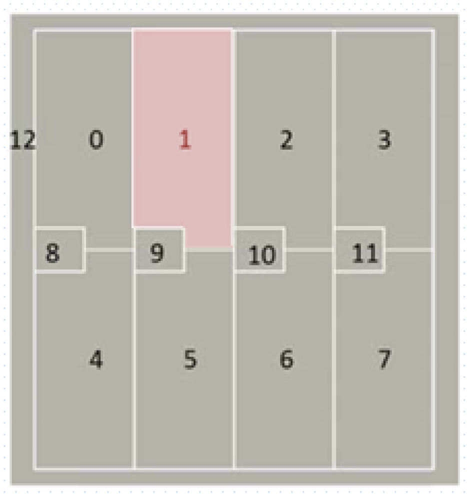
where: F – Fano coefficient, w – mean energy of elctron-hole pair, E – energy of absorbed photon.

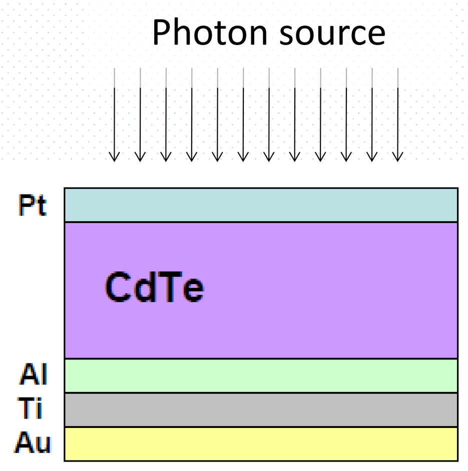
3. *Electronic noise*. The result is broadening of spectral features, but it does not depend on photon energy.

4. *Damage layer*. It is observed in Caliste-SO sensor front part. Photons absorbed at depth lower than 5 μm produce less signal than expected. The result is similar to hole tailing, but this effects does not depend on photon energy.

Geant4 simulations of Caliste-SO

We considered CdTe sensor with electrodes divided into pixels. Geometry details are given in pictures below.





Simulations were performed assuming monoenergetic photon source with energy changing from 4 keV to 180 keV in 0.1 keV steps. The photon source was planar with a size equal to a size of CdTe sensor. Photons felt at right angle to the crystal surface and their distribution was uniform. For each energy we simulated 1 milion photons.

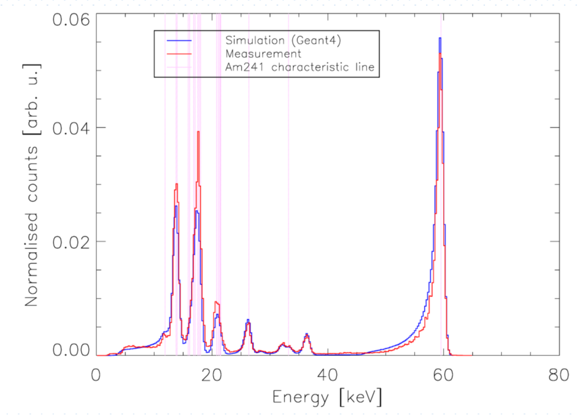
We use Livermore physics list, which is dedicated to low energy physics. Following physical processes were included in our simulations:

- for photons:
  - Photoelectric effect,
  - Compton scattering,
  - Gamma conversion,
  - Rayleigh scattering,
- for electrons:
  - Multiple scattering,
  - Coulomb scattering,
  - Ionisation,
  - Bremsstrahlung.

Comparison with laboratory measurements

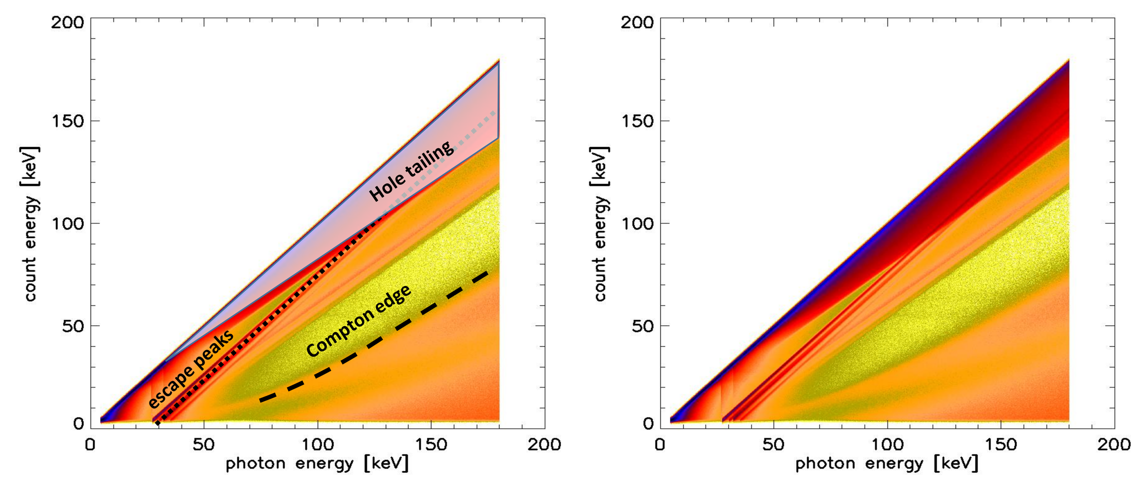
Simulated spectrum was compared with laboratory measurements of ^{241}Am performed with Caliste-SO.

The radioactive data from LBNL Isotopes Project database has been used [Firestone 2004] .



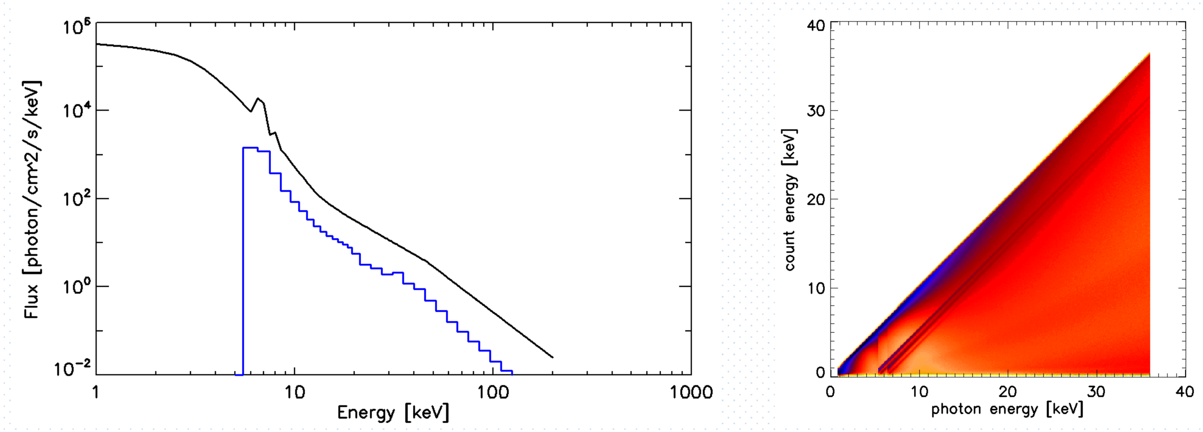
Detector Response Matrix (DRM)

Simulations performed enabled us to calculate DRM for Caliste-SO. Most of the response is in the diagonal elements of the matrix (the blue line). The non-diagonal response contains: escape peaks (four lines parallel to diagonal marked by dotted line), hole tailing (red triangle beneath diagonal), Compton scattering visible below edge marked by dashed line.



Count spectrum of new and aged Caliste-SO

Assuming that detector's ageing mainly affects carriers lifetime we may simulate response of aged Caliste-SO. For 1% of carriers original lifetime we observe significant change in detector's response (right figure) visible in off-diagonal values mainly. Left figure presents solar spectrum (black curve), and spectrum restored from aged instrument with a use of original DRM. Restored spectrum is shown with STIX's energy binning scheme (blue curve).



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