DE LA RECHERCHE À L'INDUSTRIE

Modelling of the influence of the CdZnTe substrate thickness on the response of IR HgCdTe photodetectors under proton irradiation

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CEA - LETI/Optronics Department (Grenoble, France)

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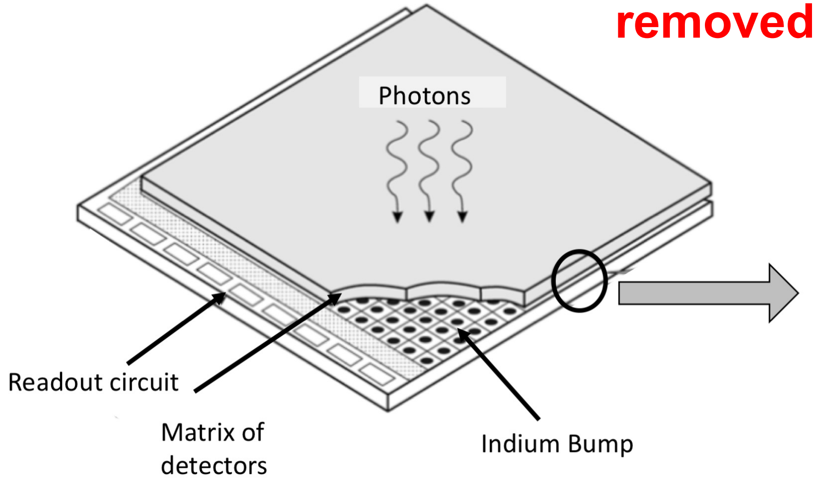
DeMo – June 2020

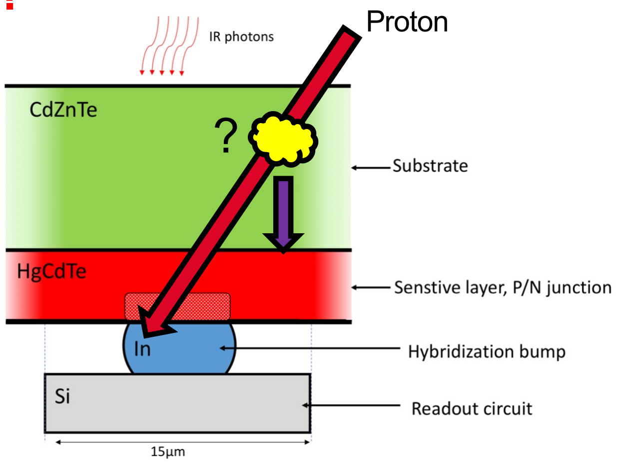
ALFA (Astronomical Large Format Array) detector : equip Europe with high performance IR detectors for space applications and astrophysics

- **Development :**
  - Lynred + CEA-Leti
- **Characterisation :**
  - Astrophysics Department, CEA
- **Funding :**
  - ESA, FOCUS

- **ALFA Specifications:**
  - HgCdTe
  - 2048x2048 with a pixel pitch of 15µm.
  - **Spectral domain 0.8µm to 2.1µm.**

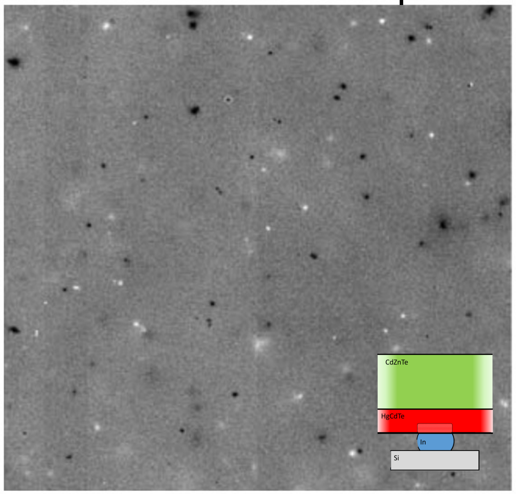
What happens under irradiation when the CZT substrate is not removed ?



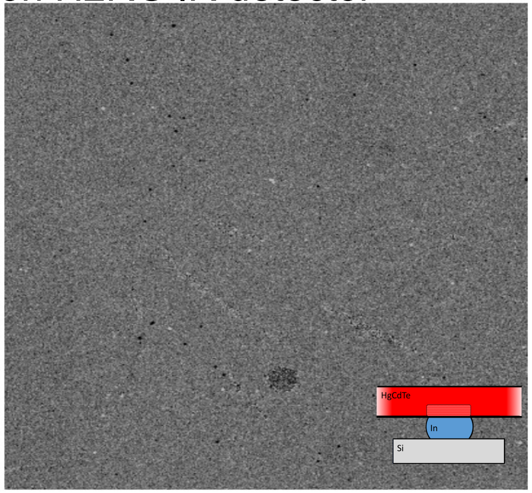


Effects of 63MeV proton irradiation on H2RG IR detector

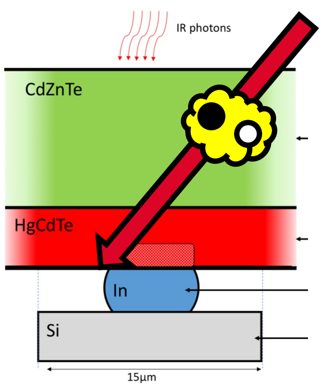
<u>H2RG (Teledyne) :</u>
2048x2048, 18µm pixel pitch.
$$\lambda_c = 1.7\mu m$$



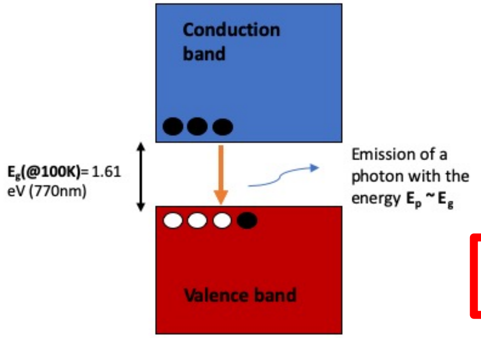
Intact Substrate CdZnTe(*). Substrate Thickness 800µm



CdZnTe Substrate removed (*)



Radiative recombination



<u>Proton irradiation on substrate intact IR detector:</u>
1 – Induce large cluster of pixels
2 - Increase in the detector background (suspected to be linked to CZT luminescence)

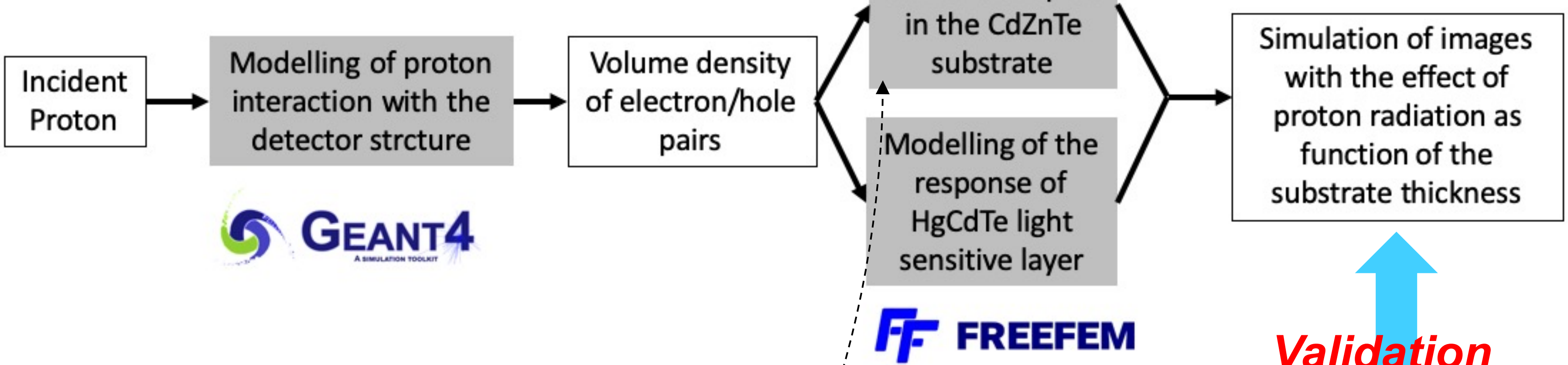
However, substrate removal is a tricky step in the fabrication process.

Which substrate thickness can we keep?

(*)*Noise and Zero point drift in 1.7um cutoff detectors for SNAP*, Smith et al. Proceeding of SPIE (2006)

- **Modelling**

Pichon et al. (2020). JEM, 49(11), p. 6918



Validation

- **Experimental campaign:**

Material properties

Measure material optical properties on CdZnTe samples, to use it as input for the simulations.

Pichon et al. (2021). To be published

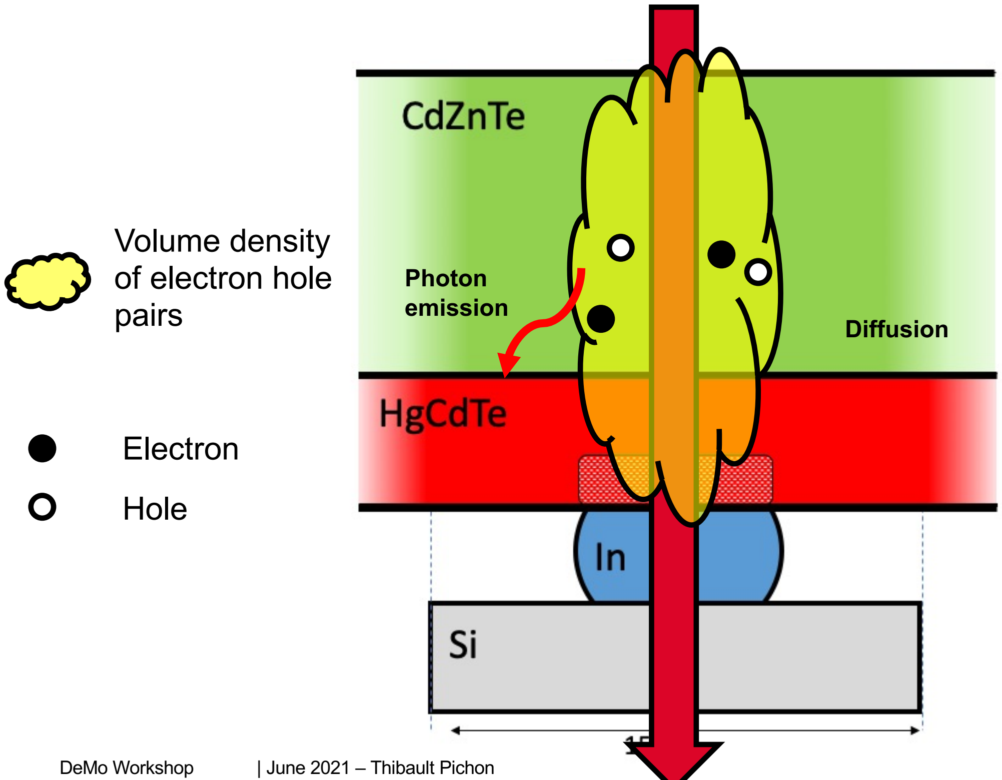
Irradiation campaign

Perform an irradiation campaign on real detectors to validate the model.

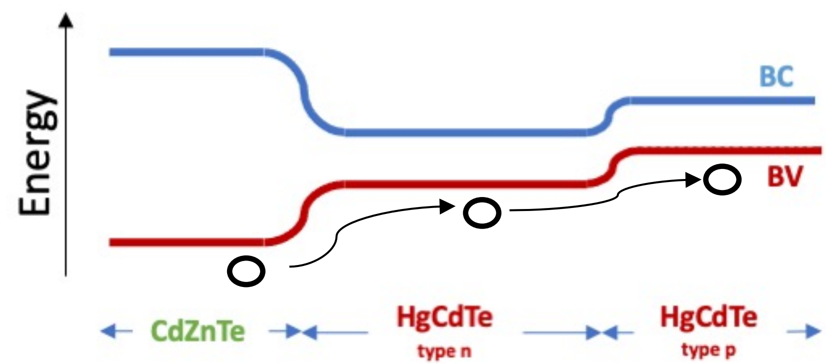
Pichon et al. (2020). SPIE n° 11454-25

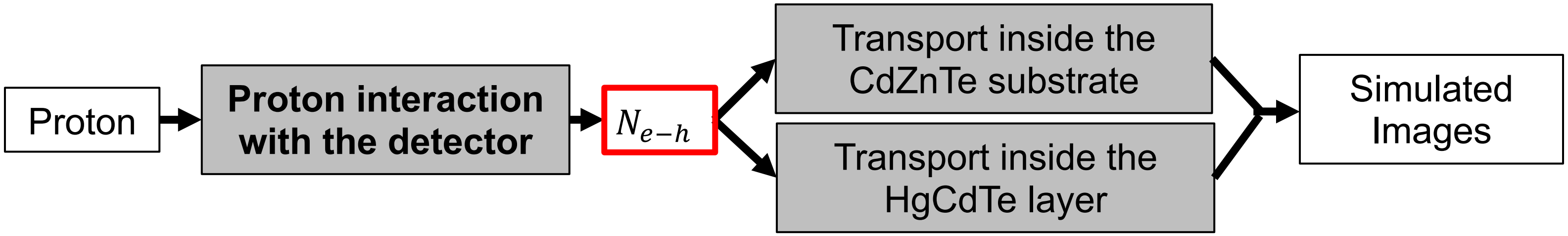
• Modelling

Incident Proton → Modelling of proton interaction with the detector materials (GEANT4) → Volume density of electron/hole pairs → Modelling of carrier transport in the CdZnTe substrate (python) / Modelling of the response of HgCdTe light sensitive layer (FREEFEM) → Simulation of images with the effect of proton radiation as function of the substrate thickness



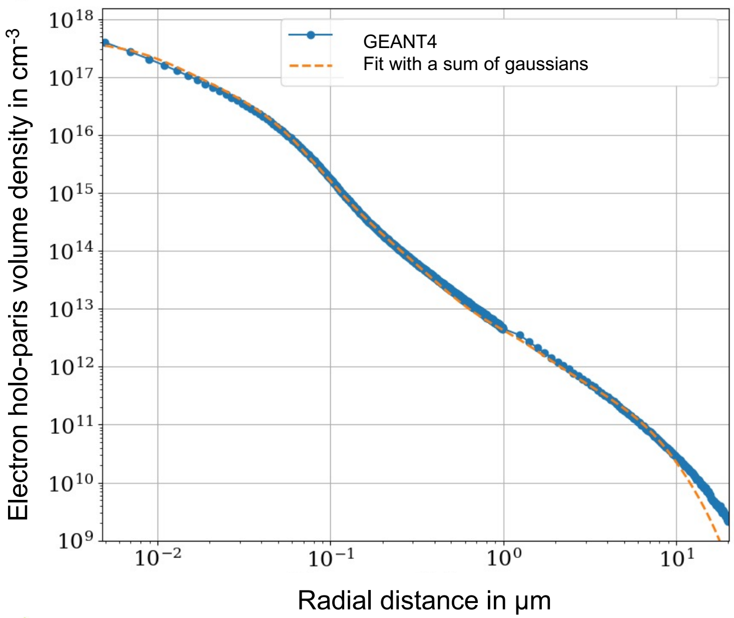
Band Diagram

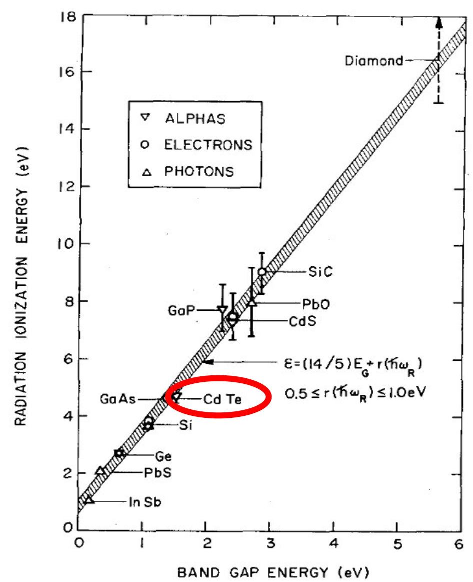




GEANT4 : **GE**ometry **AN**d **T**racking **4**. Monte Carlo calculation tool.

Method : Localization of energy deposited as a function of radial distance from proton impact → Fiitted with a sum of gaussian functions.





Evolution of E_{e-h} as a function of E_g. Taken from (*).

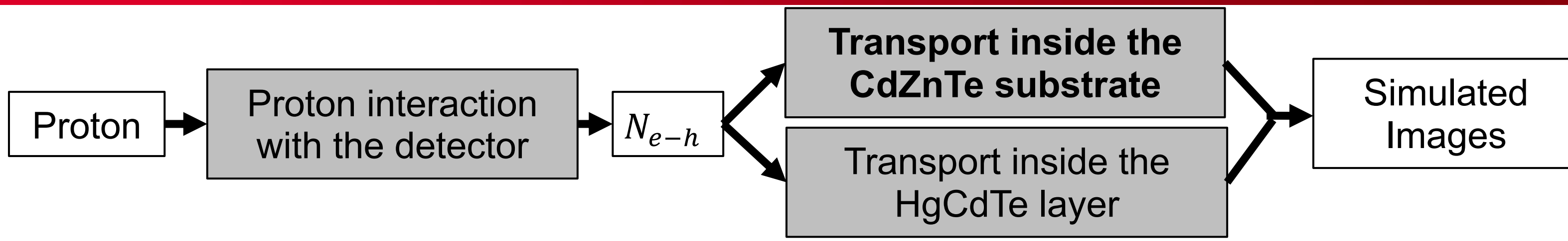
Electron-hole pairs volume density is calculated using the mean energy of creation of one electron hole pair E_{e-h}.

$$E_{e-h} \sim 3E_g$$

$$N_{e-h} = \frac{E_{deposited}}{E_{e-h}}$$

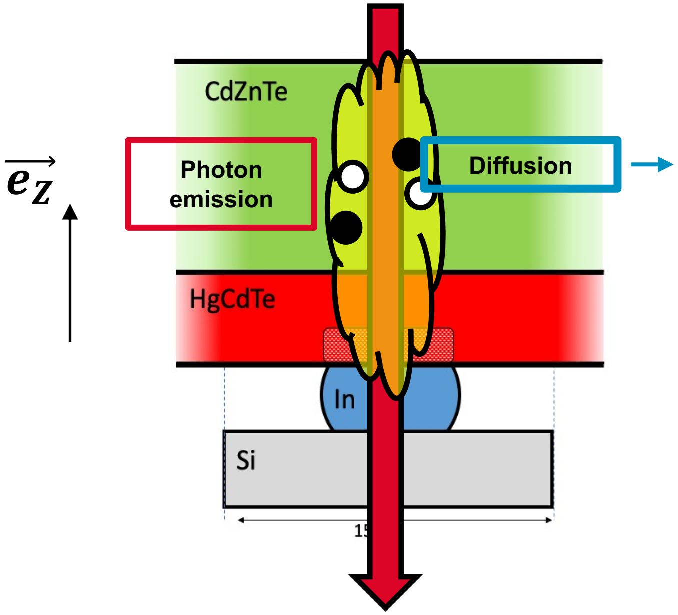
GEANT4 A SIMULATION TOOLKIT

(*) KLEIN, Claude A. Bandgap dependence and related features of radiation ionization energies in semiconductors. Journal of Applied Physics, 1968, vol. 39, no 4, p. 2029-2038.



→ Electron-hole pairs are generared **close to the proton trajectory**
→ Hence we have a **gradient in the carrier concentration**
→ **Carriers will diffuse**

Solving the diffusion equation, enables us to know the carriers density, $\Pi(\vec{x}, t)$, at any time and any point in the CdZnTe substrate.



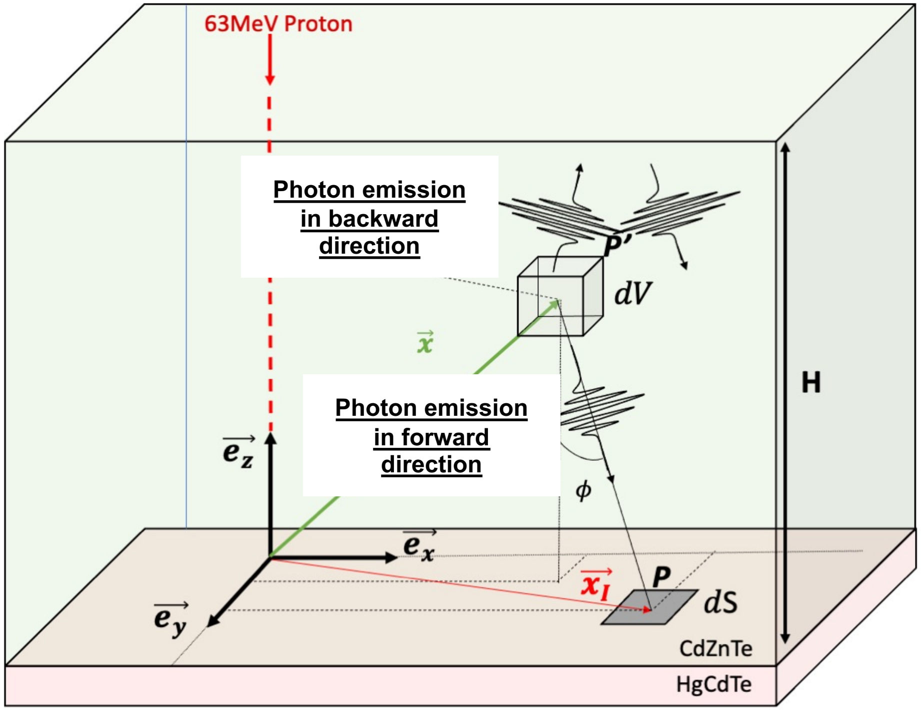
Diffusion current density expresses as :

$$J_{\text{diff}}(\vec{x_I}, t) = -D^* \, \overrightarrow{\text{grad}}\left(\Pi(\vec{x_I}, t)\right).\vec{e_Z}$$

The total number of charge at the CdZnTe/HgCdTe interface expresed in e-h/cm2 is then :

$$Q(x_I) = \int_t J_{diff}(x_I, t)dt$$

Modelling of the luminescence of the CdZnTe substrate



Phenomenological model:
Let's calculate the number of photons emitted at point P' and received at point P $d\psi(P', P, \lambda)$

1. Count **the number of photons** emitted by radiative recombination
2. Take into account **the wavelength of these photons** (emission spectrum)
3. Consider photon emission in the **solid angle $d\Omega$**
4. Take into account **optical losses** (absorption and reflection/transmission)

The **total number of photons recieved at the point P**, in unit of photons/cm2 is then written as follows :

$$\psi(P) = \int_{P'} \int_{\lambda} d\psi(P', P, \lambda)$$

$$d\psi(P',P,\lambda) = \frac{\eta_{in}}{\tau}\pi(\vec{\boldsymbol{x}})\gamma_{spon}(\lambda)\frac{\cos(\phi)}{4\pi|\vec{\boldsymbol{x}_I} - \vec{\boldsymbol{x}}|^2}\exp(-\alpha(\lambda)|\vec{\boldsymbol{x}_I} - \vec{\boldsymbol{x}}|)\,T_{HgCdTe}(\vec{\boldsymbol{x}},\vec{\boldsymbol{x}_I},\lambda)d\lambda$$

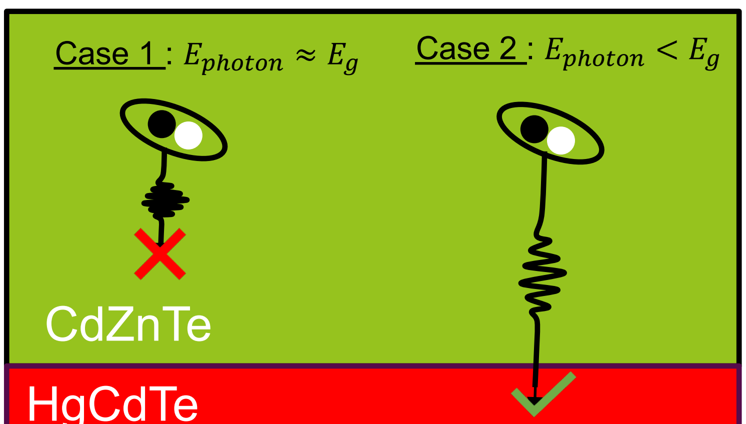
Determination of the energy of the emitted photons.

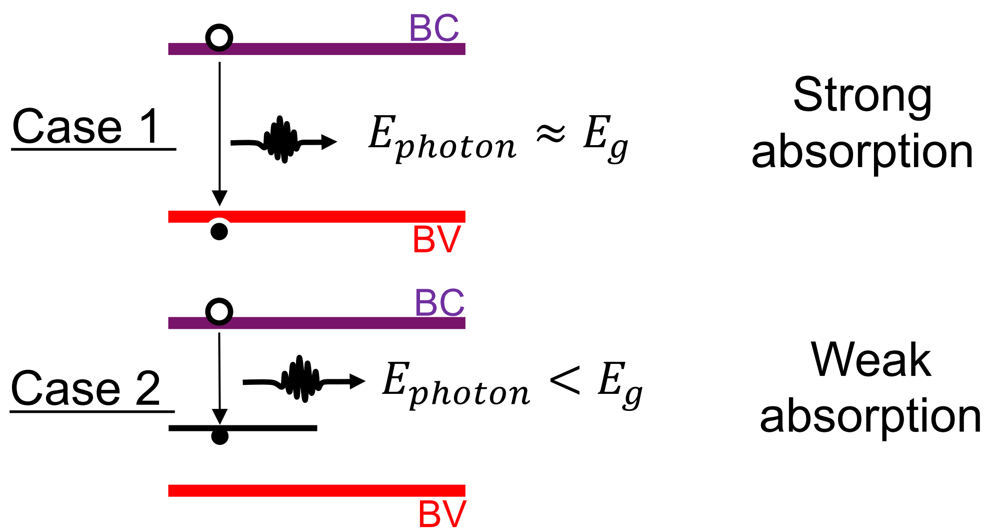
Determination of the dielectric function to calculate the absorption coefficient and the complex refractive index.

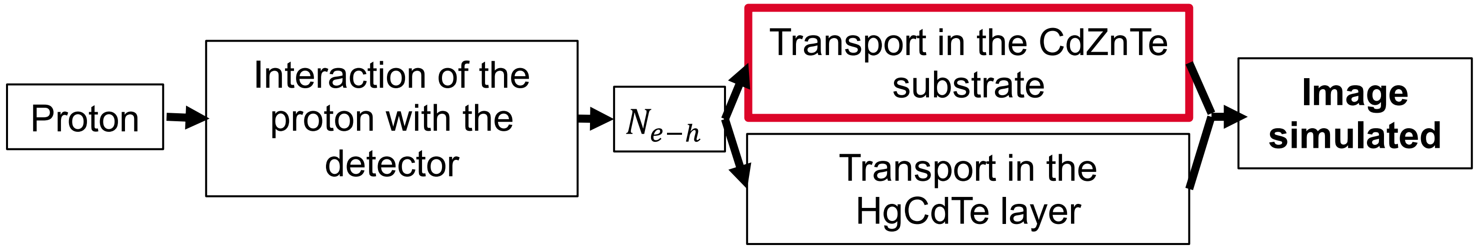
These data:

1. Depend one the material quality
2. Cannot be found in the literature at 80 K and 100 K

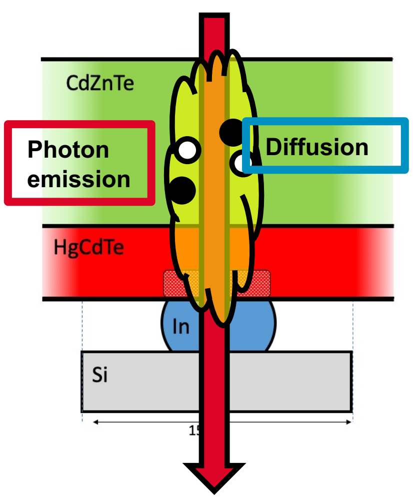
Luminescence and ellipsometry measurements were done on CdZnTe representative samples.





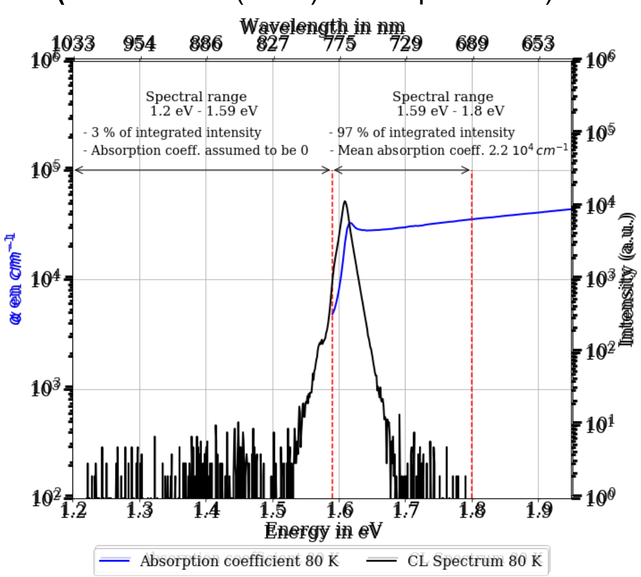


Different contributions	Measured optical properties	Application of the model with experimental material properties

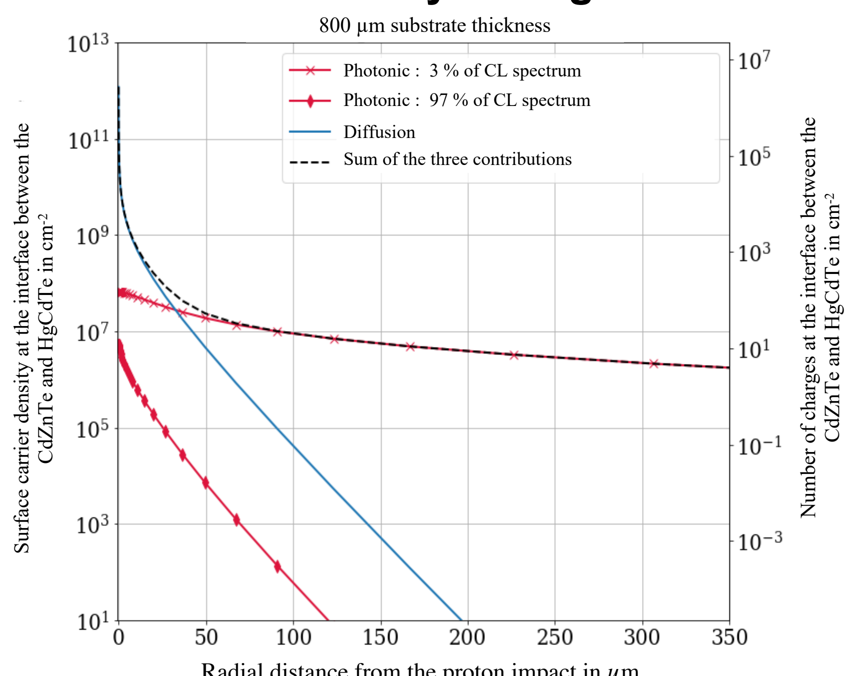


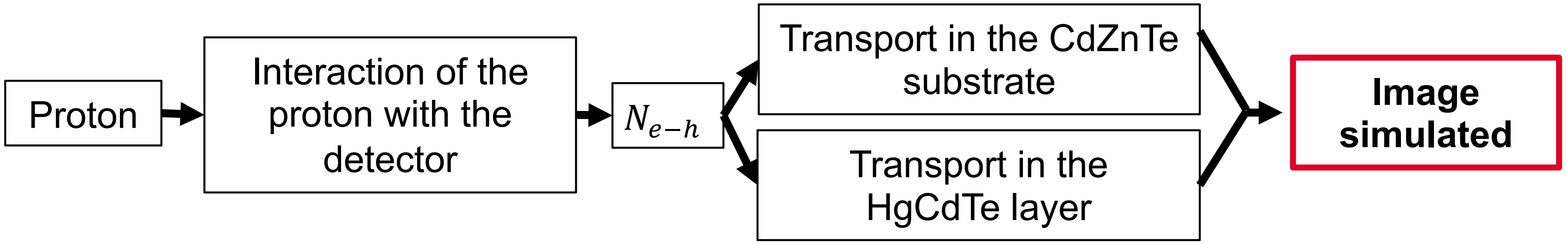
Luminescence properties of the CdZnTe

(Pichon et al. (2021). To be published)

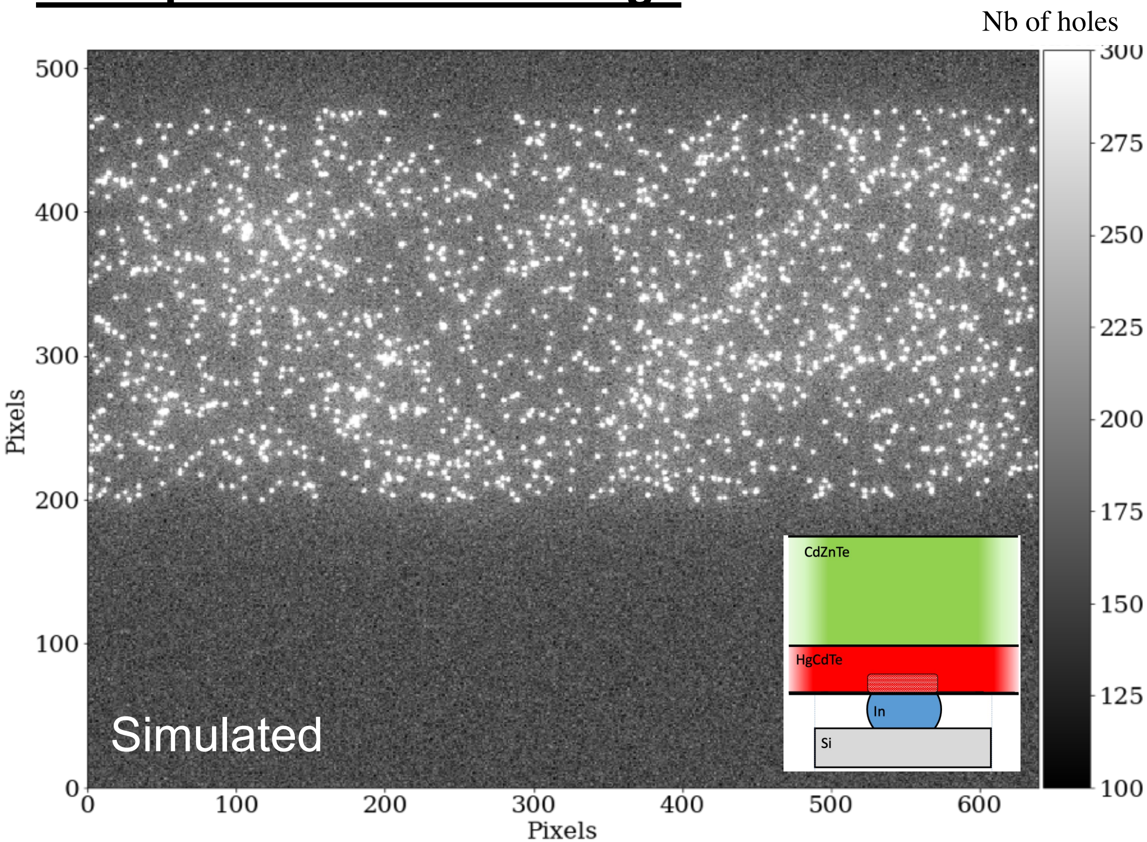


Contributions to the signal collected by the HgCdTe

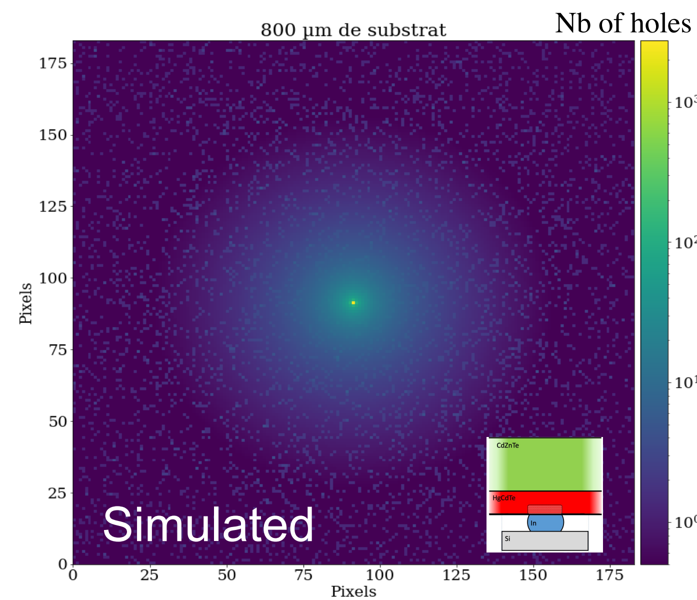




Example of simulated image



One proton impact simulated

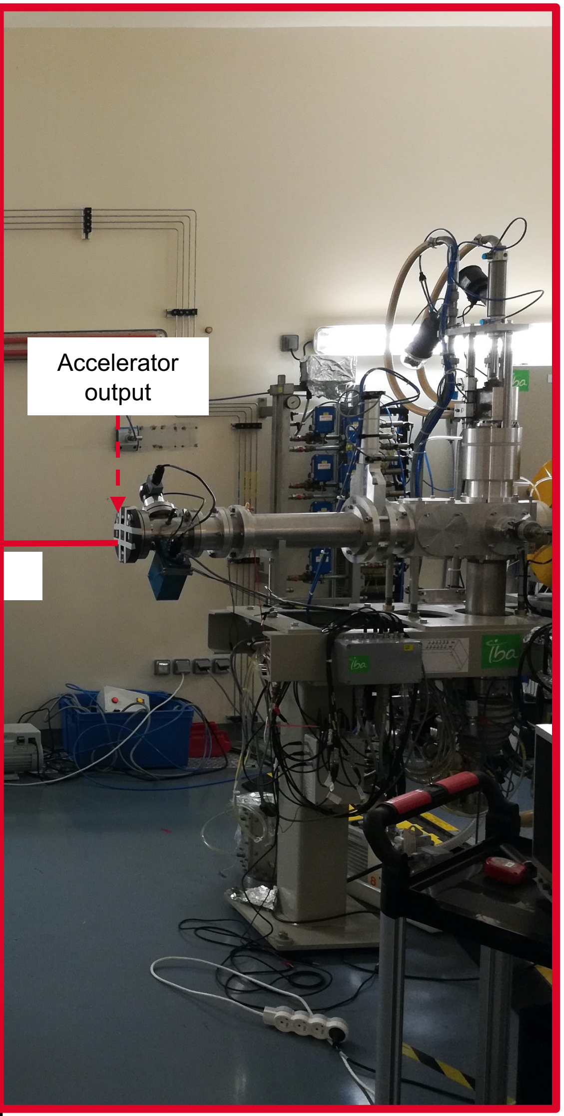


Arronax cyclotron in Nantes (France)

Arronax aims at producing innovative radionuclides for research in **nuclear medicine** and at performing research in radiochemistry on radiolysis.

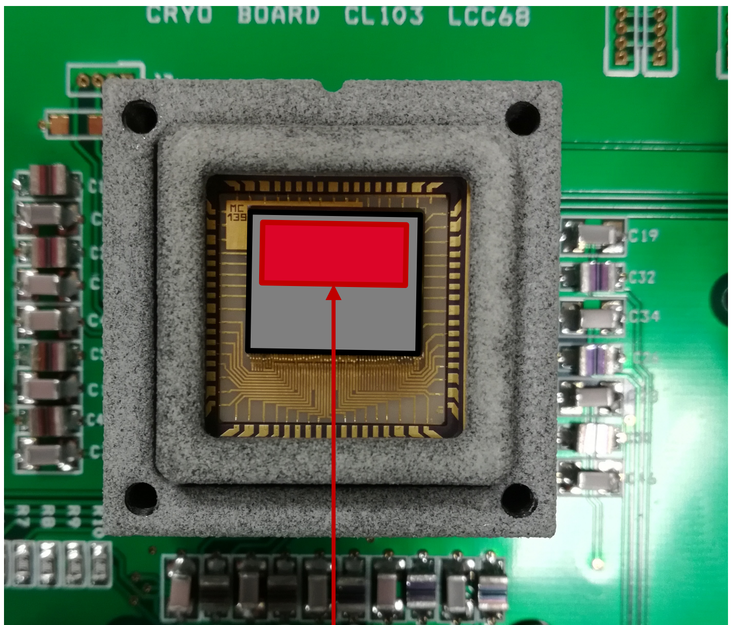
Features of the irradiation facility

- Particles: protons, alphas et deutons ✓
- Proton energy: de 30 MeV à 70 MeV ✓
- Very low flux < 100 protons/s/cm^2 ✓

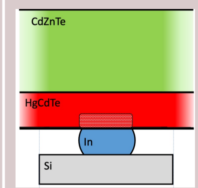
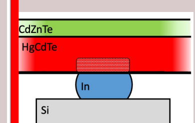


Two test detectors have been manufactured at CEA-Leti

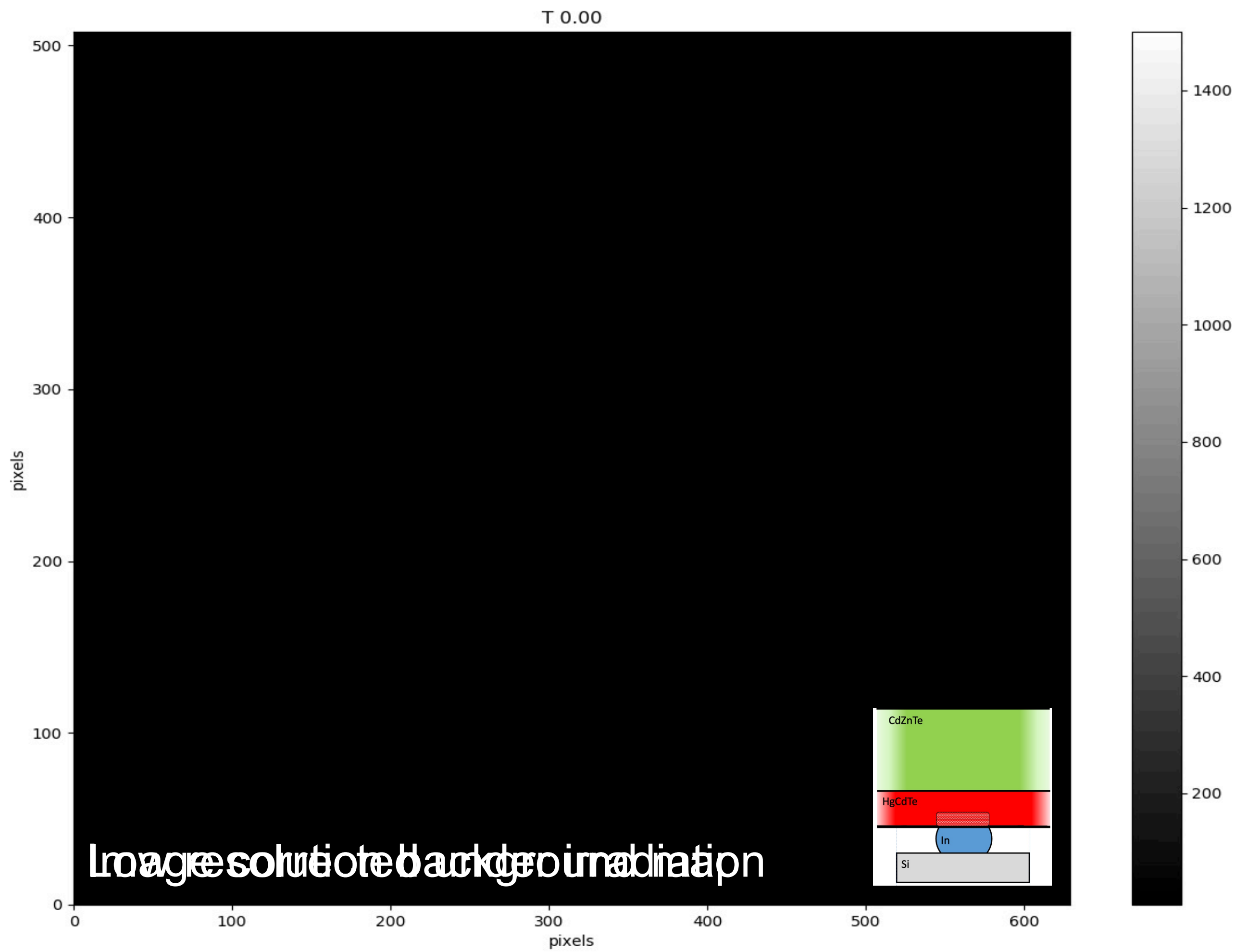
Picture of 1903 (NIR800) detector



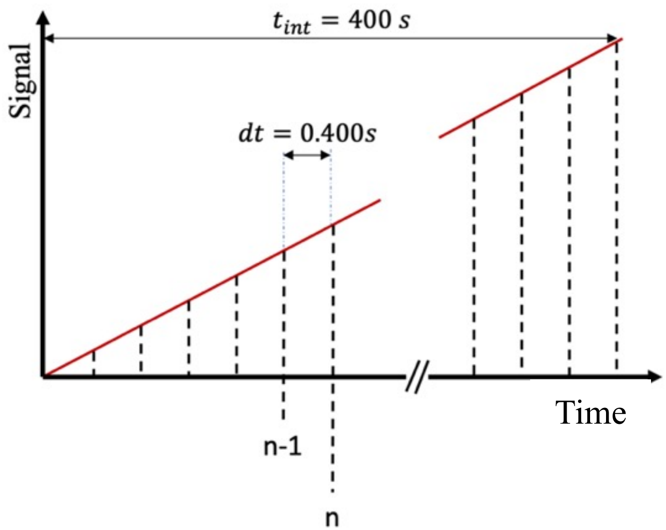
Unshielded area

	NIR50	NIR800	ALFA
Name	1901	1903	-
Absorbing material	HgCdTe	HgCdTe	HgCdTe
Format [pixels × pixels]	640x512	640x512	2048x2048
Pixel pitch	15 µm	15 µm	15 µm
Cut off wavelength	2.1 µm	2.1 µm	2.1 µm
CdZnTe substrate thickness	**50 µm**	**800 µm**	**< 30 µm**
Scheme			
Underfill	Yes	No	Yes
Diode technology	p/n	p/n	p/n
ROIC	SFD	SFD	SFD
Readout time	400 ms	400 ms	1.31 s
Operating temperature	80 K	80 K	100 K

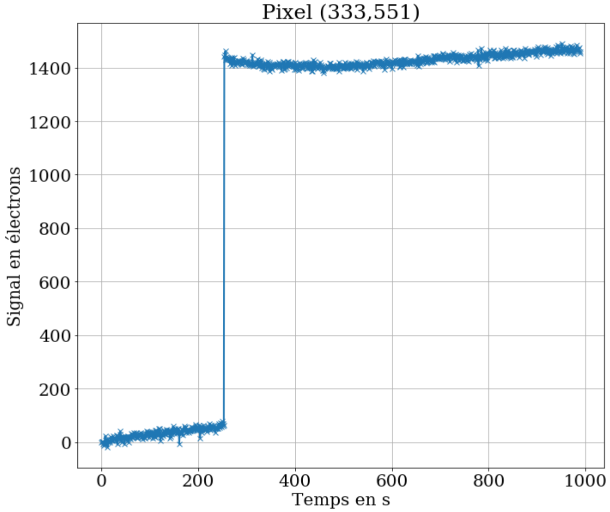
Détecteur NIR800



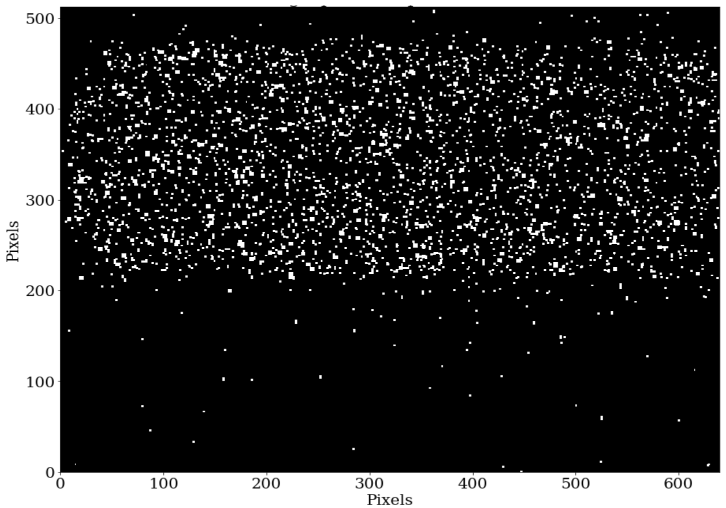
Non-destructive readout (FUR mode, Following Up the Ramp)



Example of pixels affected by a proton

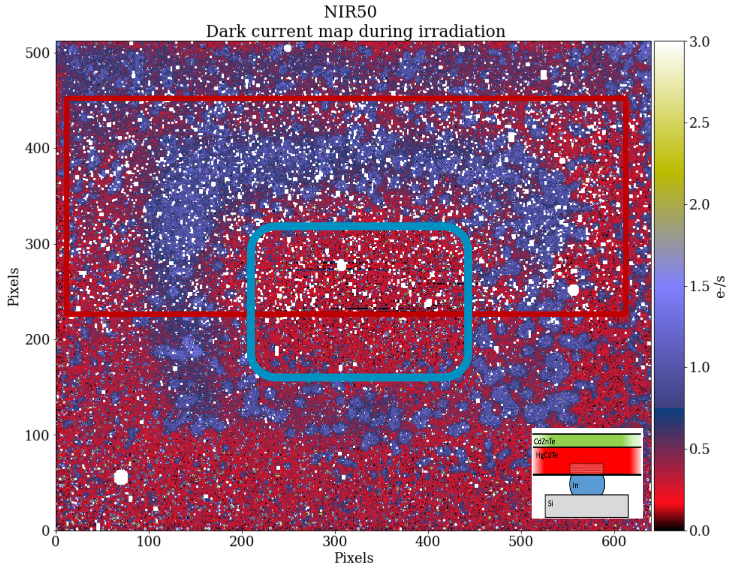


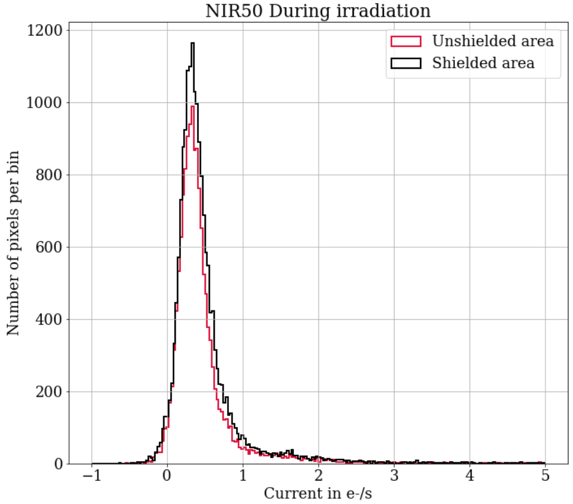
Map of proton impacts detected by SExtractor



Proton impacts are detected with **SExtractor** (Source Extractor) applied to the difference of two consecutives images

Pixels **marked as affected by a proton** = signal **3σ higher than the background signal**

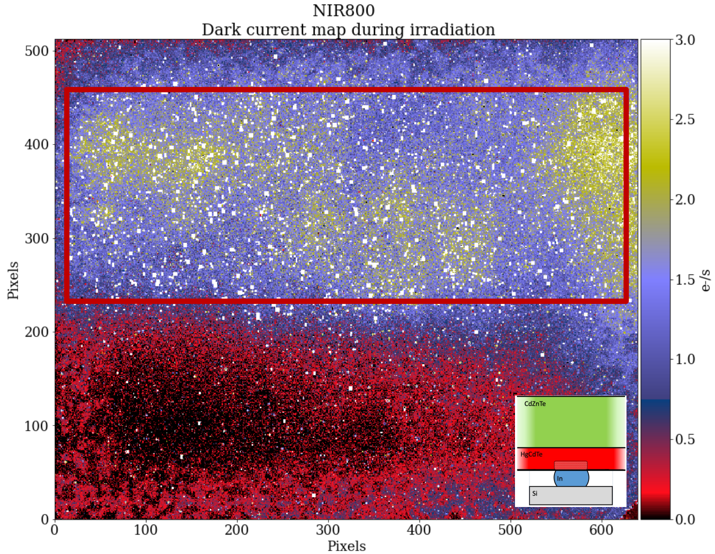


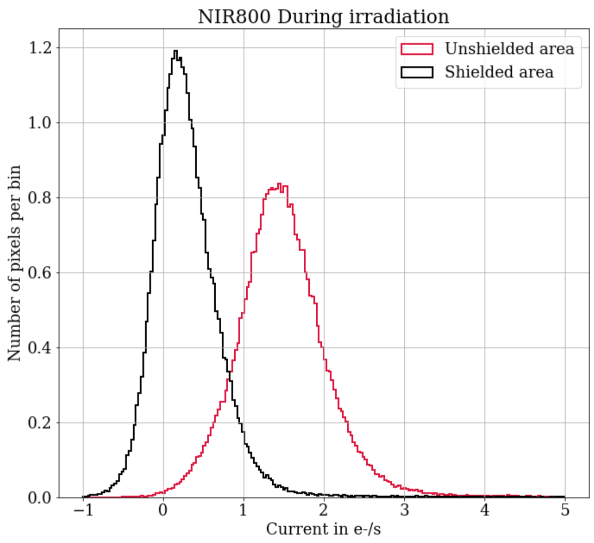


Median current in dark conditions under irradiation:

Unshielded area
0.53 ± 0.23 e^-/s/pixel

Shielded area
0.54 ± 0.24 e^-/s/pixel



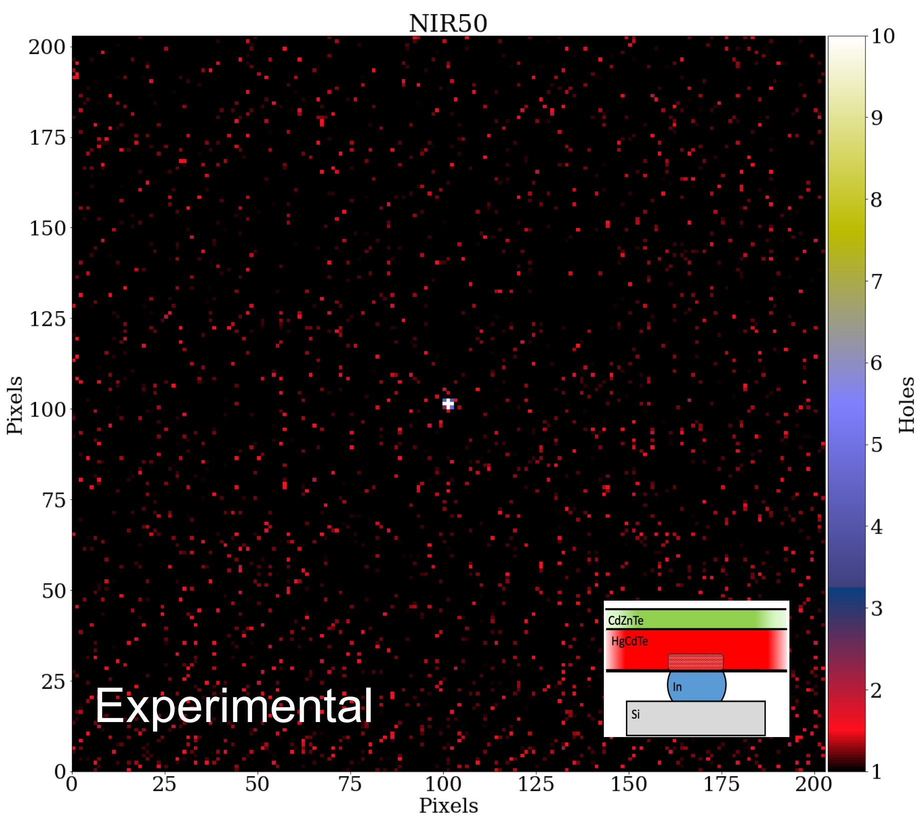


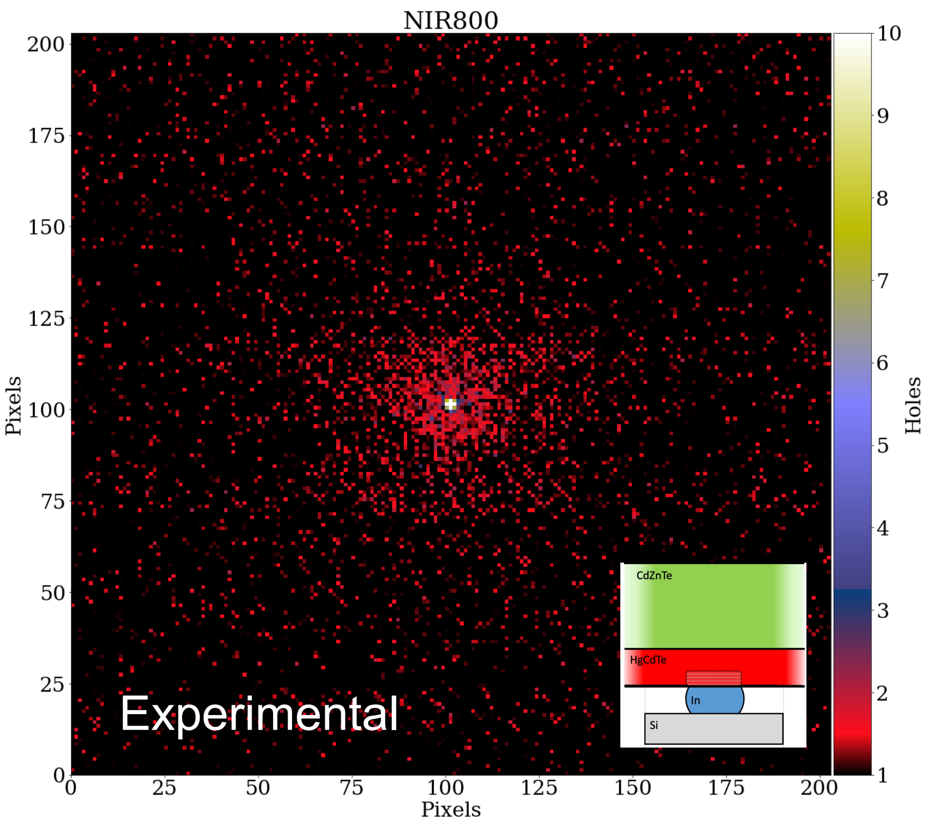
Median current in dark conditions under irradiation:

Unshielded area
1.57 ± 0.30 e^-/s/pixel

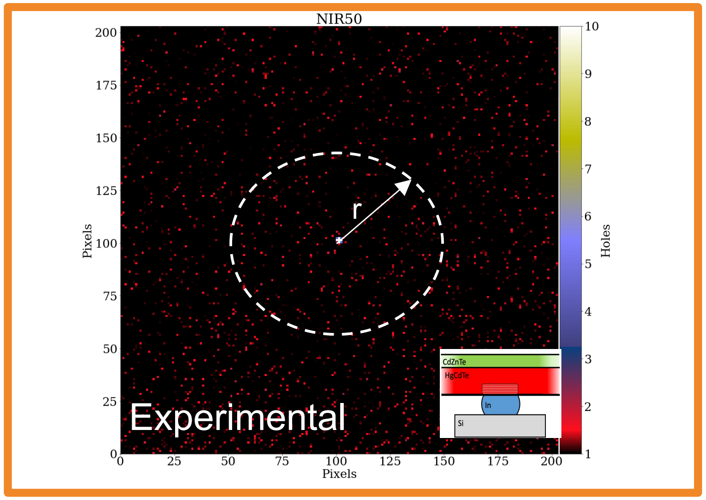
Shielded area
0.43 ± 0.23 e^-/s/pixel

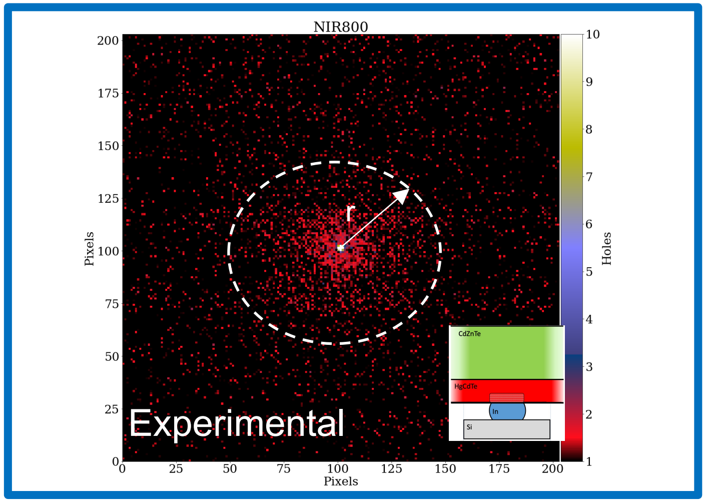
Mean clusters

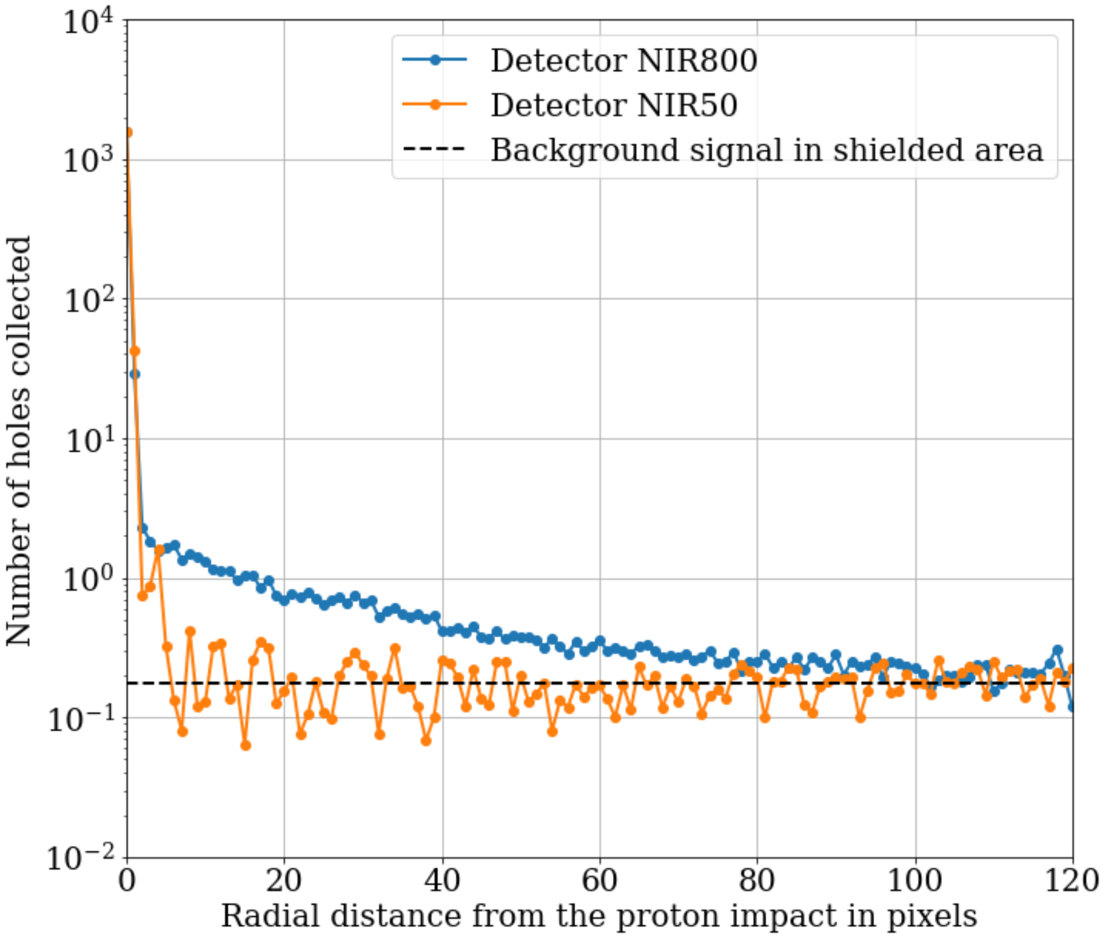


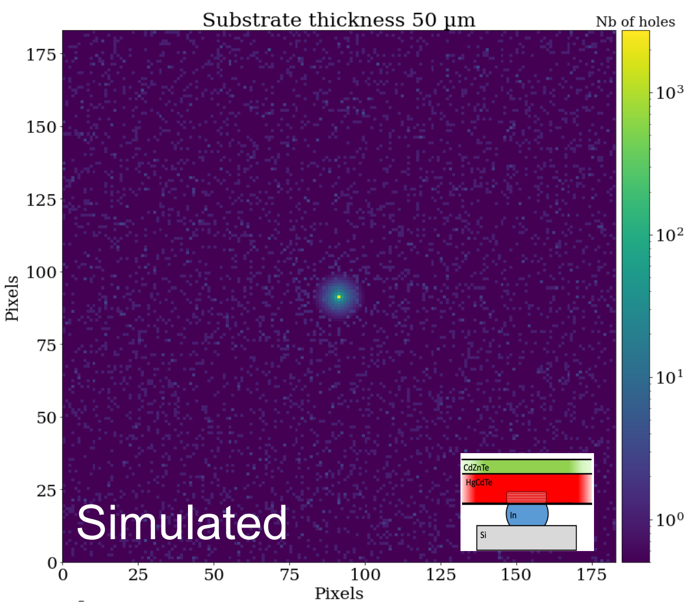


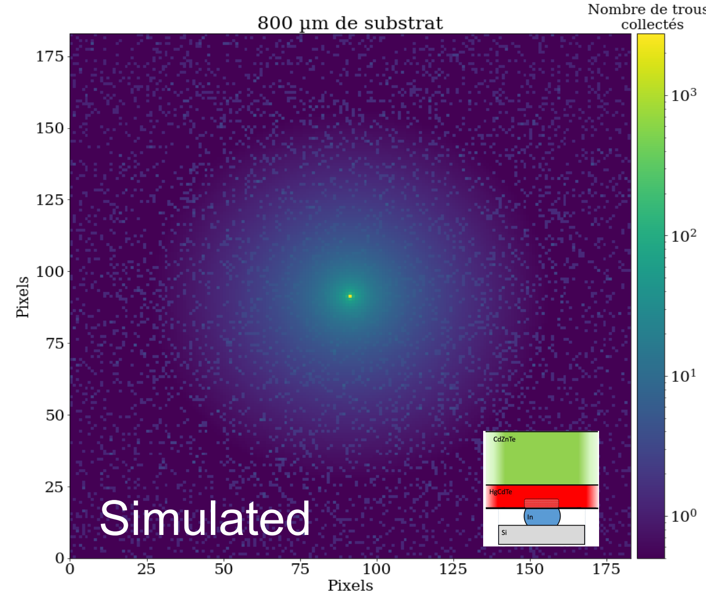
Radial profile: Average of the pixels at equidistance of the proton impact

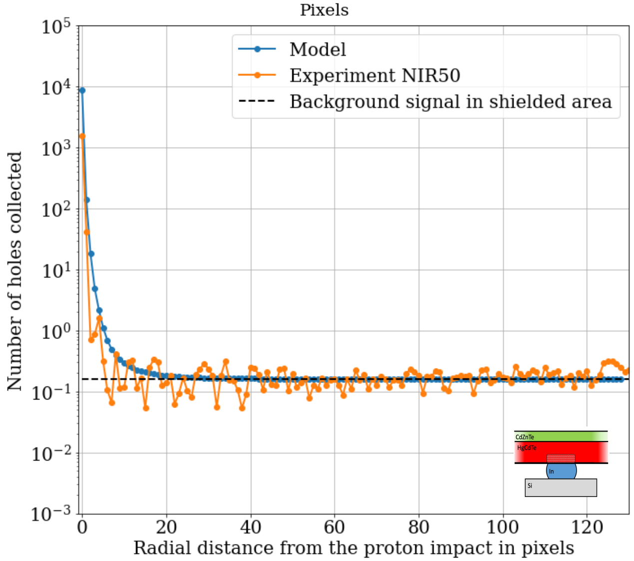




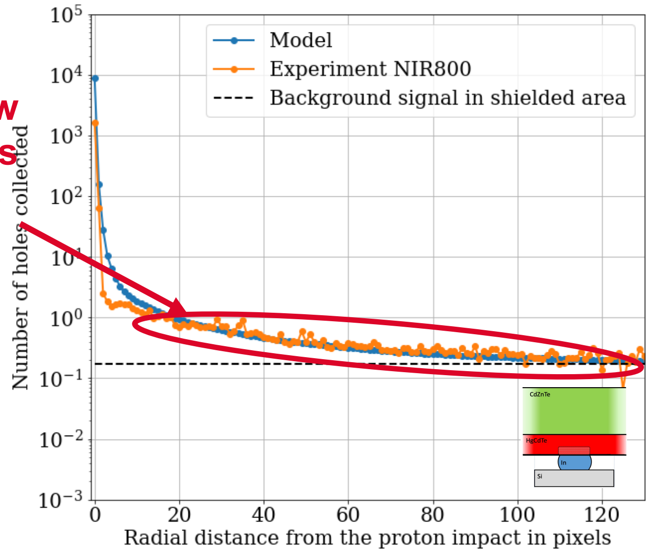






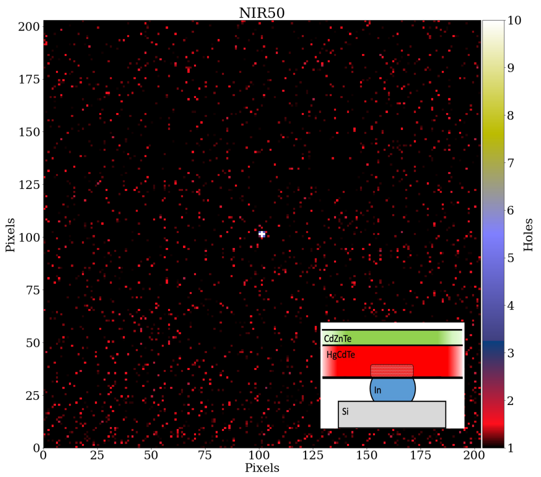


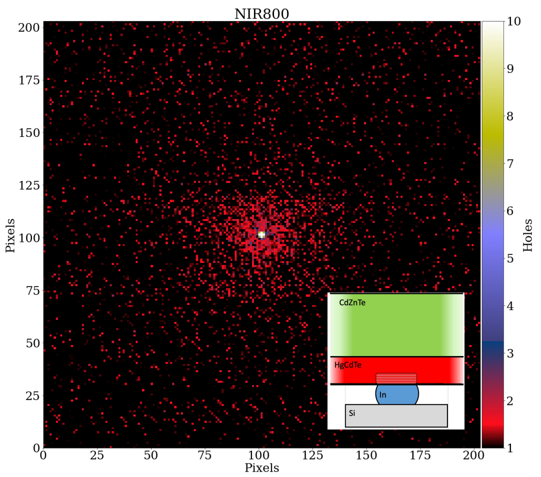
Associated with the emission of low energy photons in the CdZnTe substrate

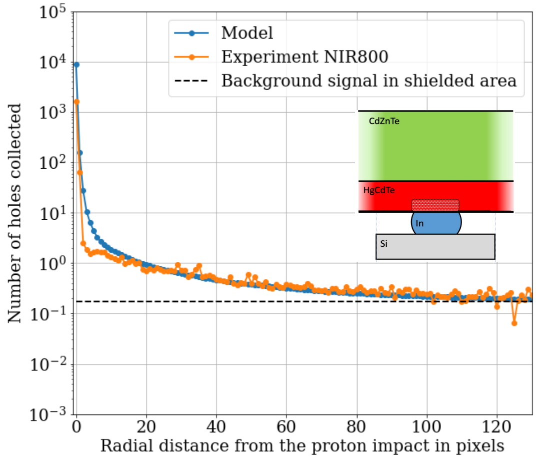


- No detector background elevation under irradiation in detector NIR50
- Background signal elevation under irradiation observed in detector NIR800 is attributed to the large extension of each transient event.
- According to the model this large extension of the radial profile is associated with the emission of low energy photons in the substrate.

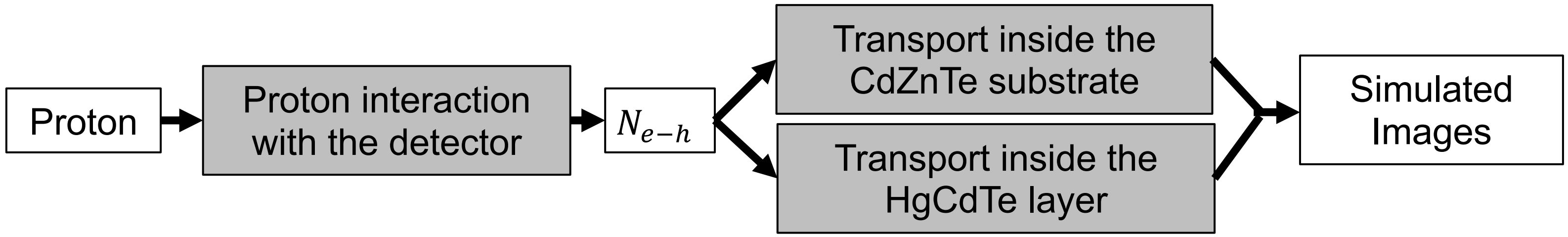
Complete removal of the CdZnTe substrate is not mandatory regarding the influence of protons irradiation on the performances of IR detectors.



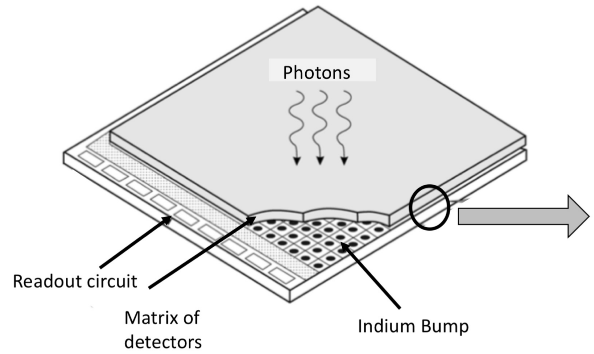


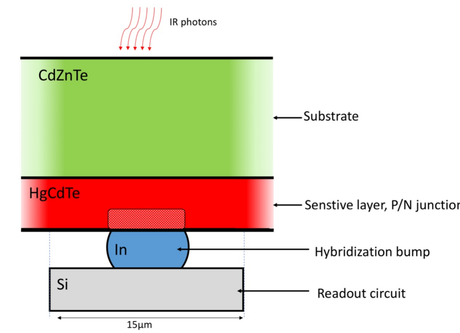


Regarding detector simulation



- A model has been developped to model the response of IR HgCdTe detectors under irradiation when the substrate is not removed.
- This model is fed with material properties measurements
- This model has been validated experimentally.
- For now it considers only normally incident protons but it can be extended to ionizing particles with different incident angles.





Two instruments

FGS (Fine Guidance System) et NIR photometer

Spectral domain: 0.5 – 1.95 µm.

AIRS (ARIEL InfraRed Spectrometer)

Spectrometer with two channels:

- 1.95 – 3.9 µm (CH0)
- 3.9 – 7.8 µm (CH1)