IR Detector characterization at CEA LETI

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Agenda

1. **II VI process line at LETI**
2. **Characterization means**
3. **Focus on some figures of merit**
    - QE
    - Pixel PSF & MTF
    - Persistence
    - Irradiation testing
4. **Conclusion**

1.

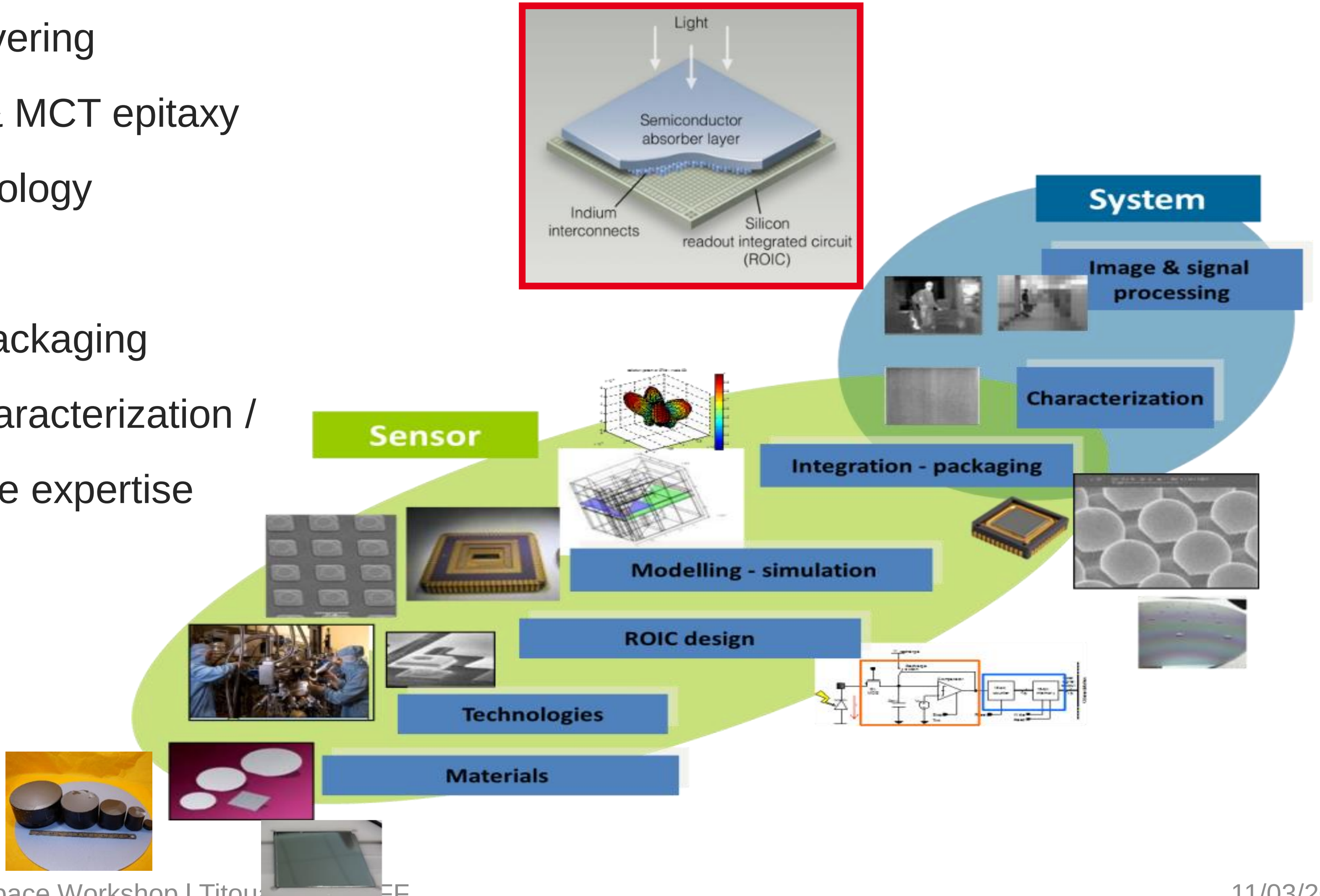
II VI process line at LETI

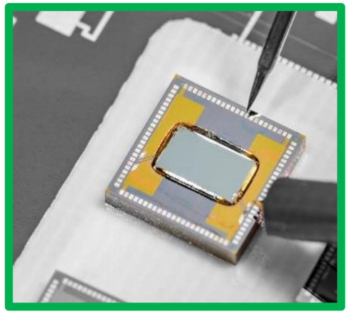
General presentation

What do we do: developing technologies for high performance **cooled IR imagers** and **APD**.

Full process flow covering

- Substrat growth & MCT epitaxy
- Photodiode technology
- ROIC design
- Hybridization & packaging
- Electro-optical characterization / simulation / device expertise





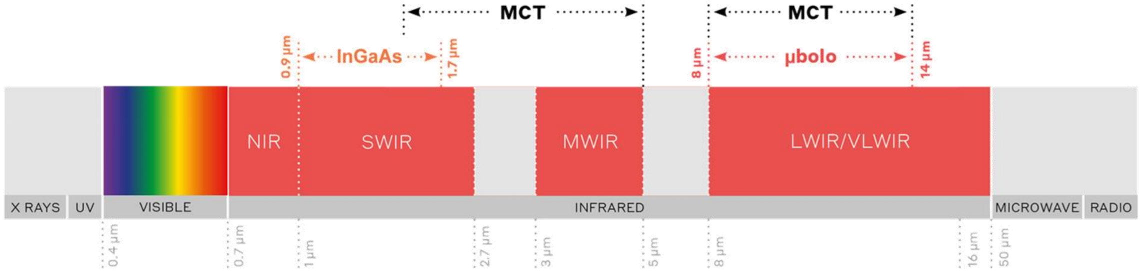
General presentation

A wide electro-optical characterization range covered:

- From material quality, photodiodes or test chips to full hybridized array

- ROIC types :
  - SFD, DI, CTIA, APD
  - Analog or digital

- Spectral bands:



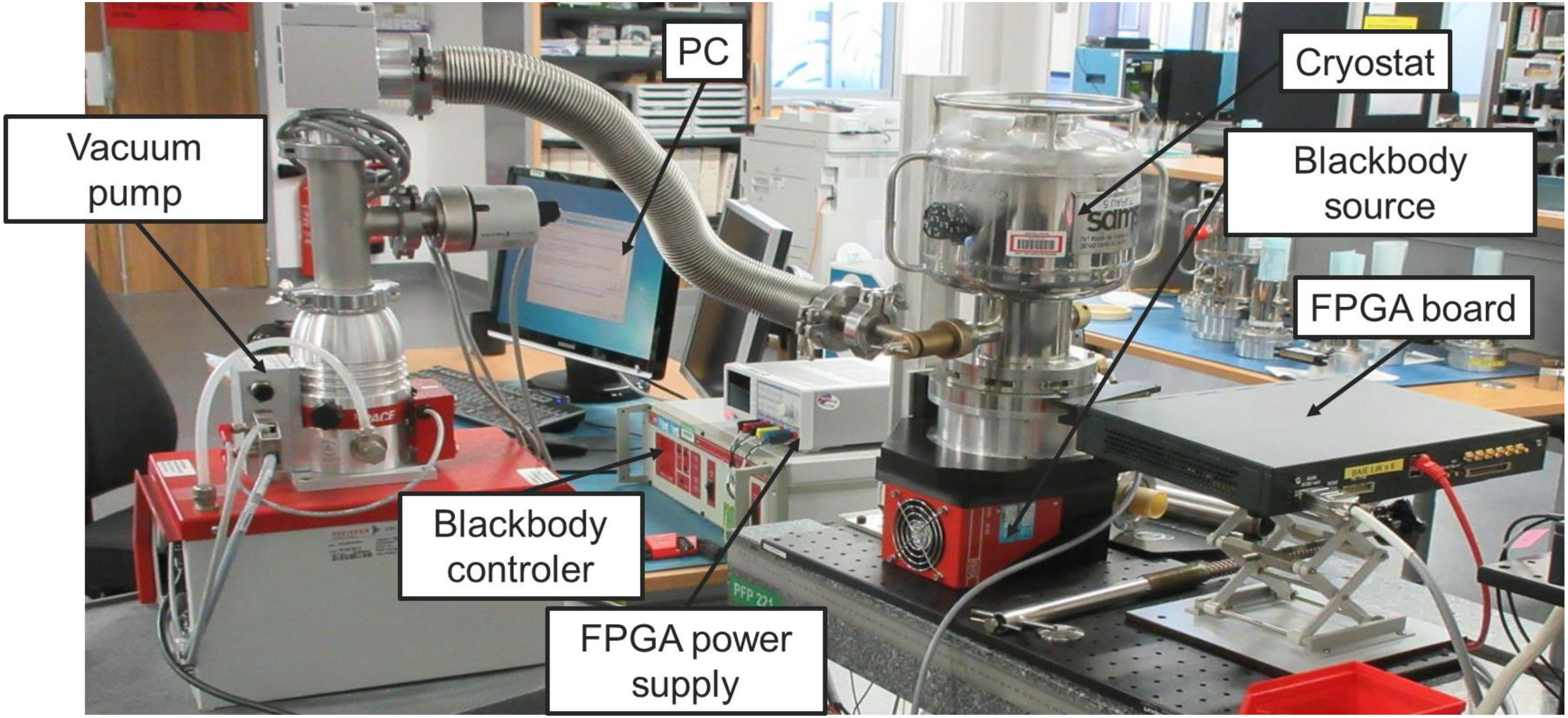
- Applications:
  - Defense
  - Earth observation from space
  - Science and astronomy
  - Telecom FSO, LIDAR, quantum optics with mono-element APD

CEA Saclay Irfu

MOON PHOTONICS

2. Characterization means

Characterization means

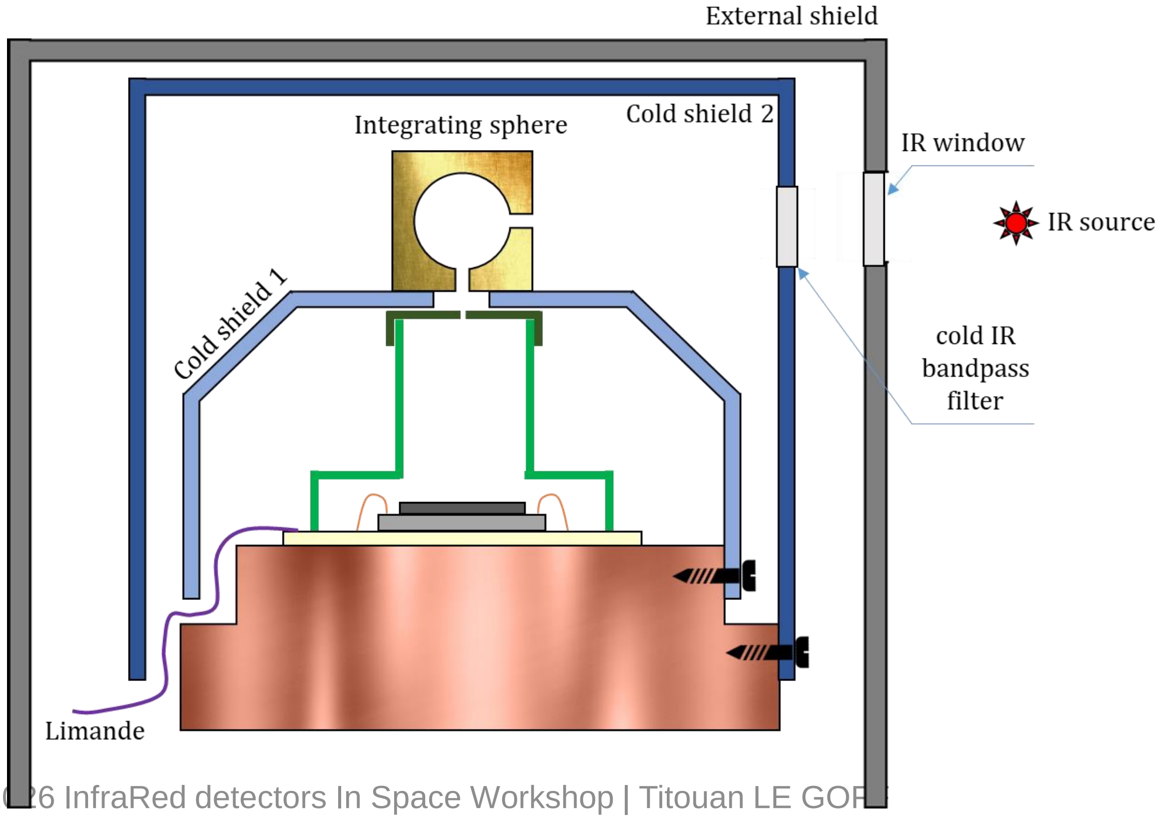


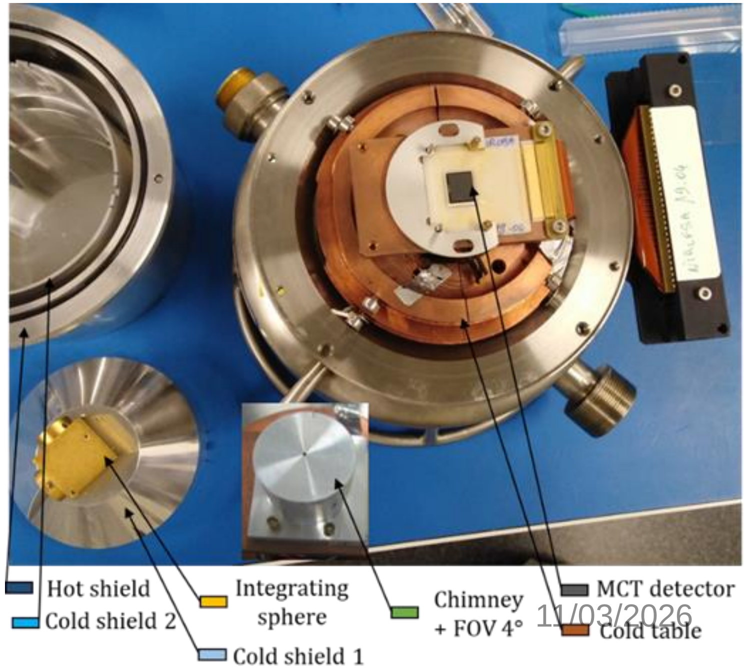
Fits in a car and can be transported at an irradiation facility for instance !

Characterization means

Liquid N_2 cooled Cryostat with integrating sphere

- <u>Classical blackbody illumination</u>
  - Hot output window
  - Optionnal cold bandpass filter
  - Cold integrating sphere

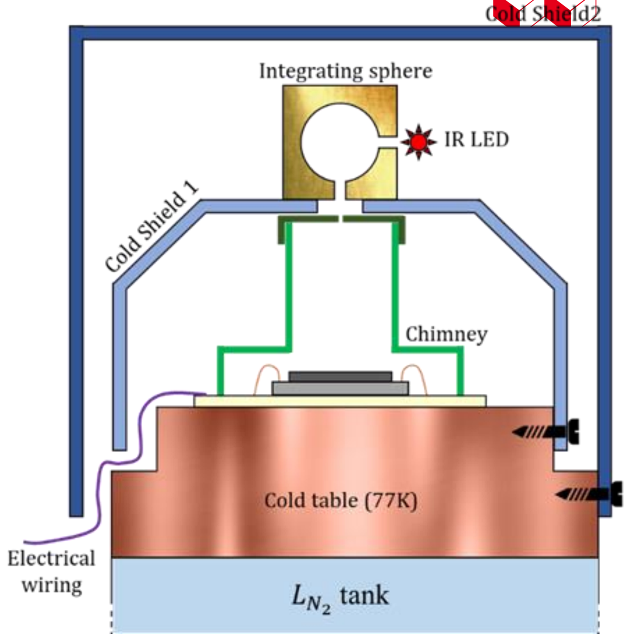


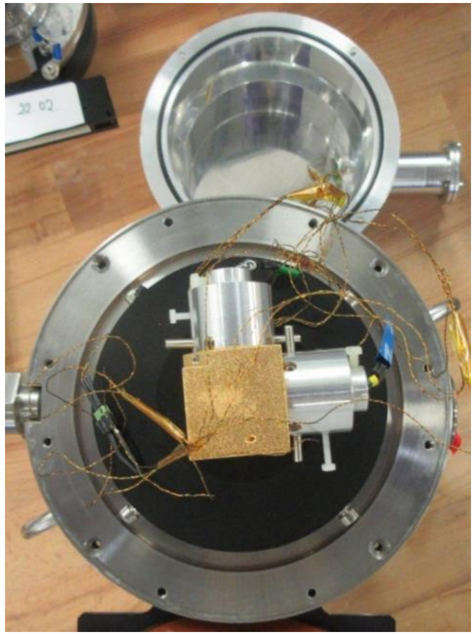


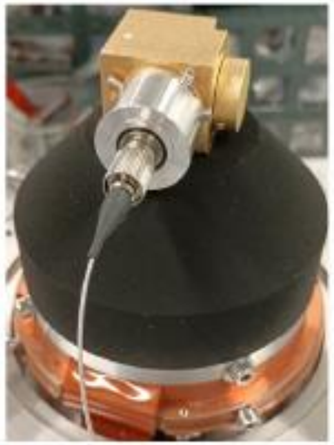
Characterization means

Liquid N_2 cooled Cryostat with integrating sphere

- LED configuration
  - Light leak < $0{,}001\ ph/s$
  - Pulsed mode : 4 ph/pix/puls
  - Continuous mode: > 100pA/pixel
- Optical fiber configuration
  - Degraded dark condition
  - Fibered LED or laser input
  - Blackbody illumination still possible







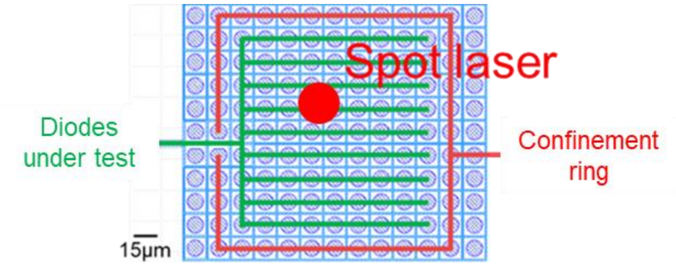
3.

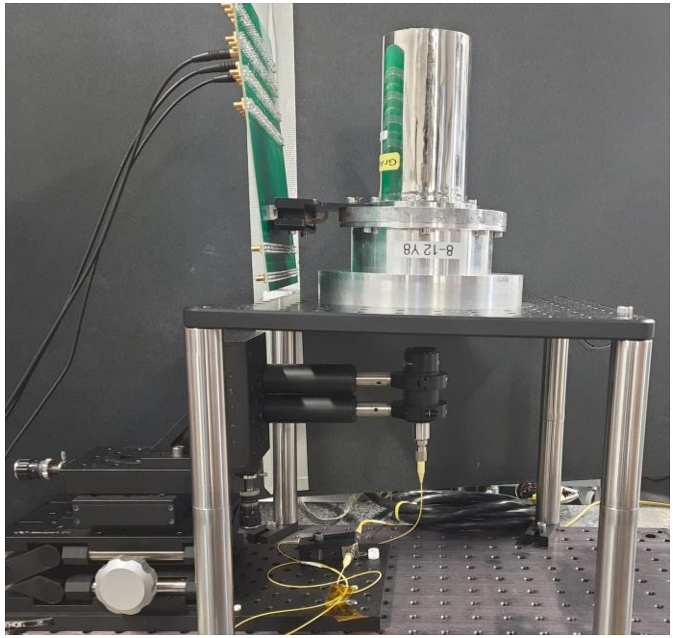
Focus on some figures of merit

3. 1 QE on test chip

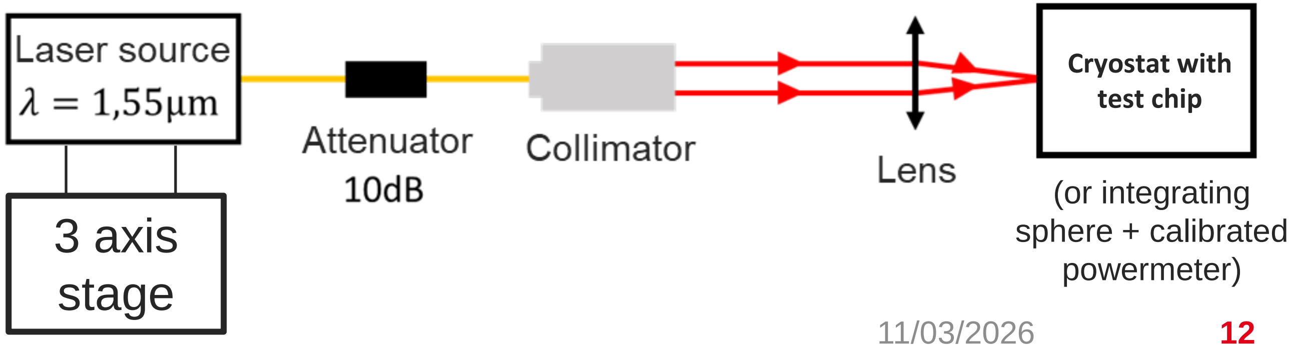
QE on test chip

- Principle:
  - Focusing a laser (1.55µm) spot
  - Calibrating laser source with powermeter
  - Test chip: **cluster of interconnected photodiodes**





- Challenges:
  - Laser spot must be narrower than the diode cluster (theoretical $\Phi_{spot} < 10\mu m$)
  - Collection surface must be known -> confinement ring
  - The cluster must be homogenious
  - Tolerance to small position variation



Laser source $\lambda = 1{,}55\mu m$

3 axis stage

Attenuator 10dB

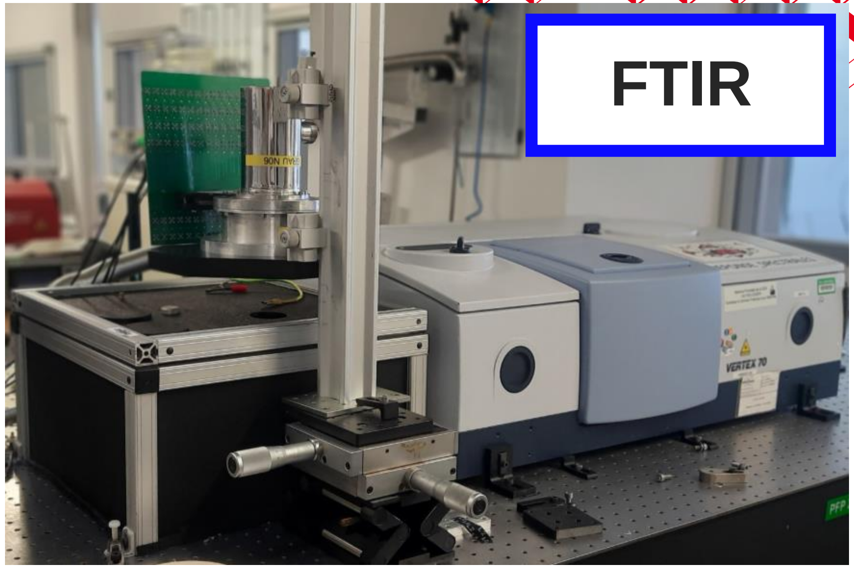
Collimator

Lens

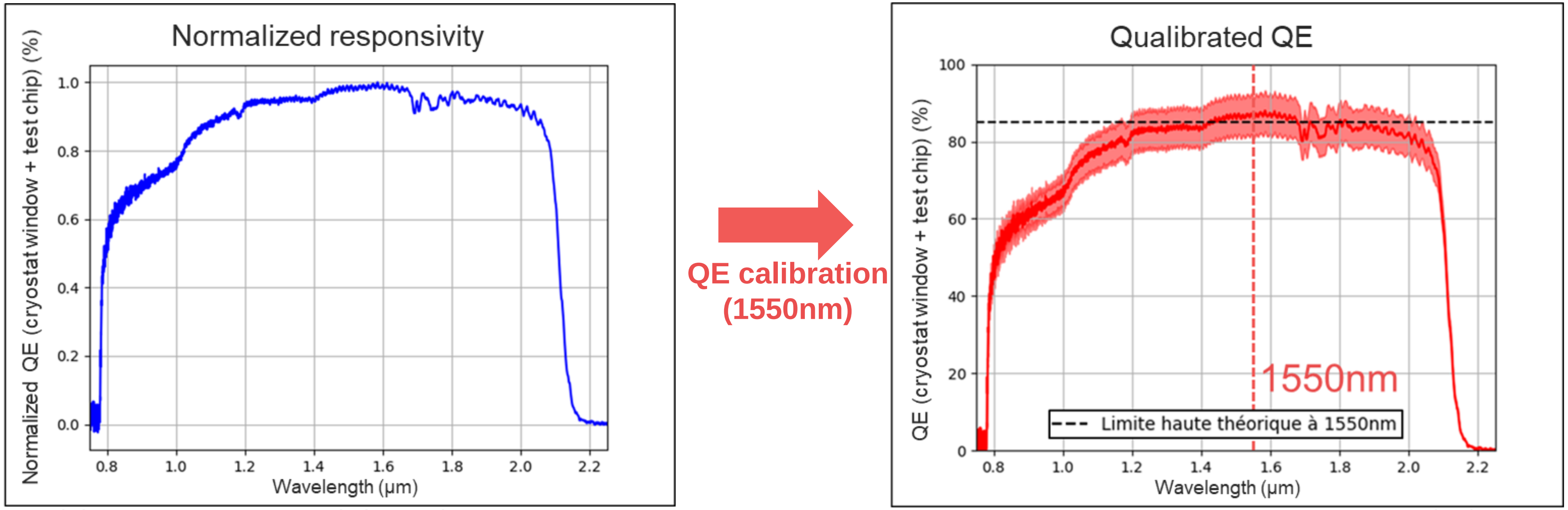
Cryostat with test chip

(or integrating sphere + calibrated powermeter)

QE on test chip



- ☐ **QE obtained : 85% at 1.55µm** (including cryostat window)
  - **ALFA P/N technology** (2.1µm cutoff)
  - 9x9 or 6x6 15µm pitch test chips
  - Independant on P_{laser}
  - ~6% total uncertainty
- ☐ Can be combined with normalized responsivity to get **spectral QE**

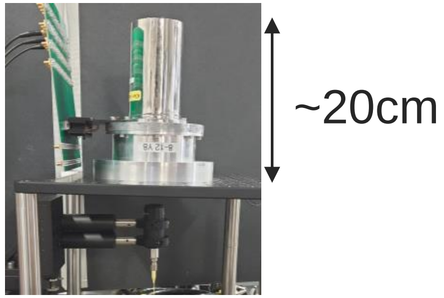


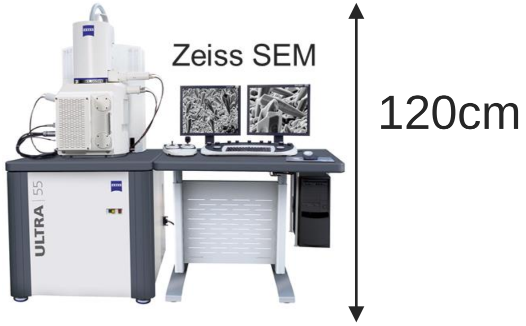
3. 2 Pixel PSF & MTF

PSF characterization

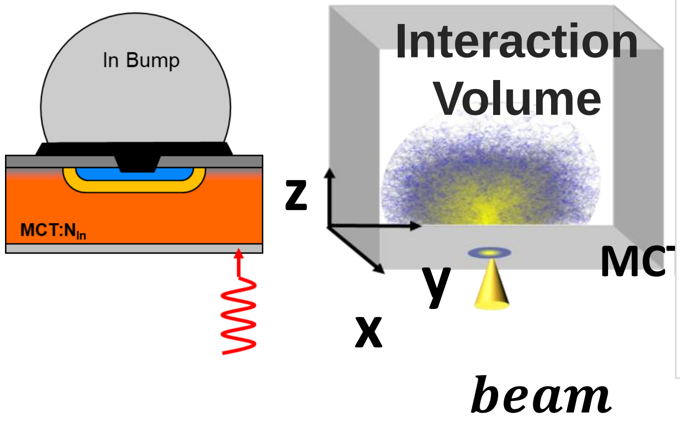
- ☐ **Objective** : MTF on **MWIR (λ_c 5μm)** & small pixel pitch [15 -> **5µm**].
- ☐ **2 technics developed at LETI:**

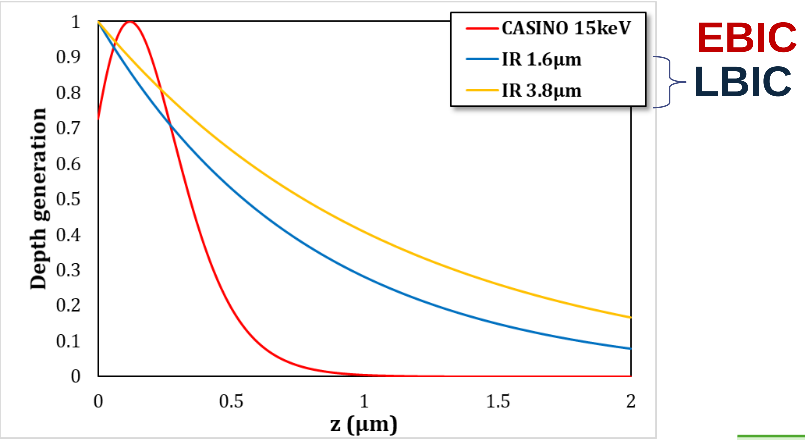
- Laser beam induced current (LBIC) @1.55µm
- Electron beam induced current (EBIC)



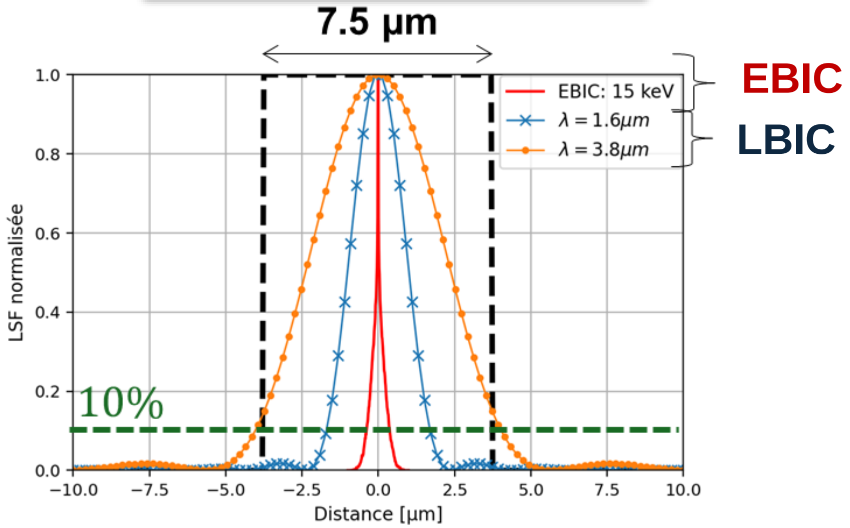


Volume extention





Beam lateral extention



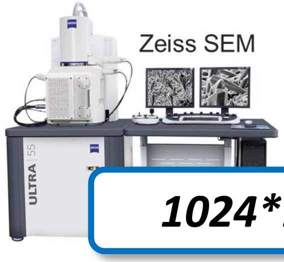
Direct PSF measurement, no deconvolution →

No substrate removal requiered
Volume generation of e$^-$/h$^+$ pairs →

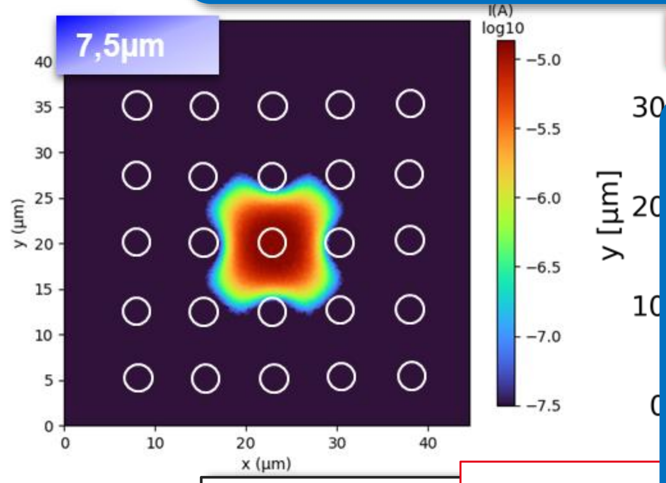
	$\Delta^{10\%}_{horizontal}$	$MTF(f_{Ny} = 67)$
EBIC (15 keV)	**0.75 µm**	**>99%**
$\lambda = 1.6$ µm	**3.5 µm**	**83%**
$\lambda = 3.8$ µm	**7.9 µm**	**61%**

PSF with EBIC probe

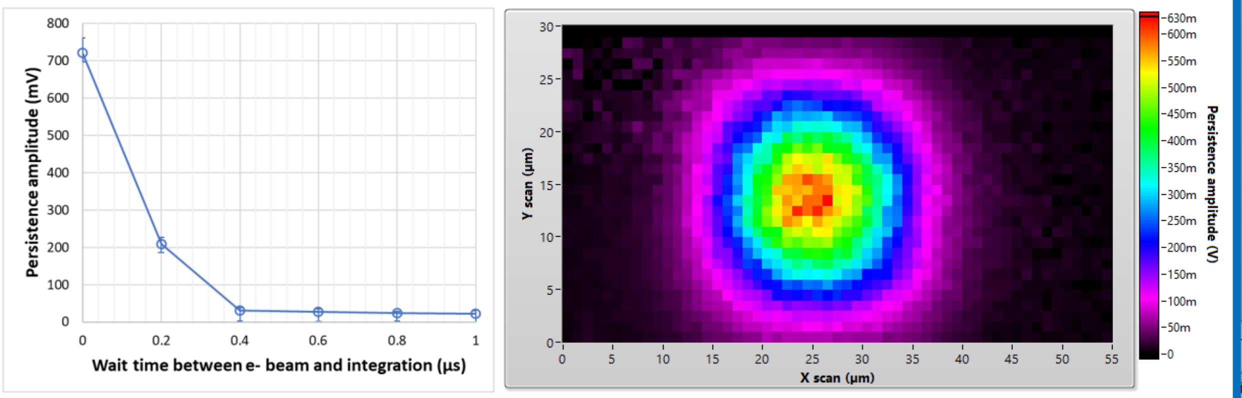
***MWIR diodes** in an array configuration*
Backside charge injection

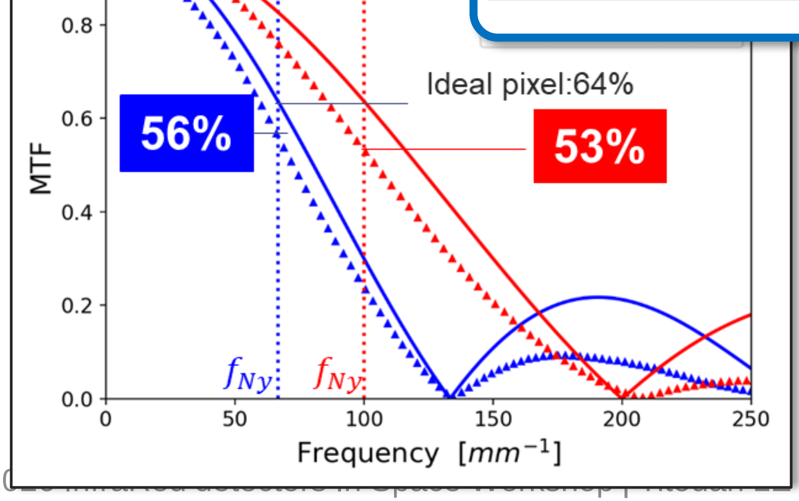


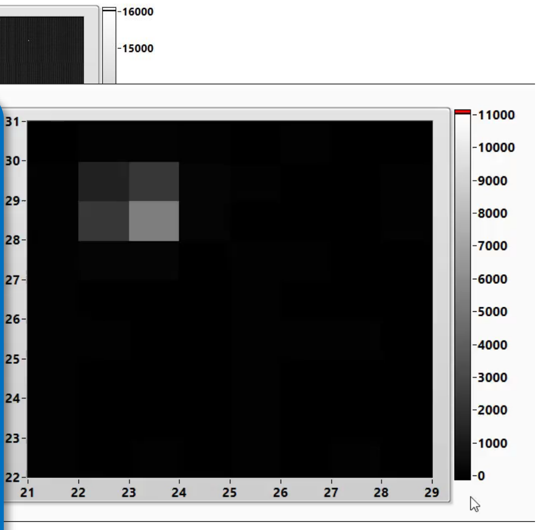
1024*1280 7.5µm pix MWIR FPA (direct injection)

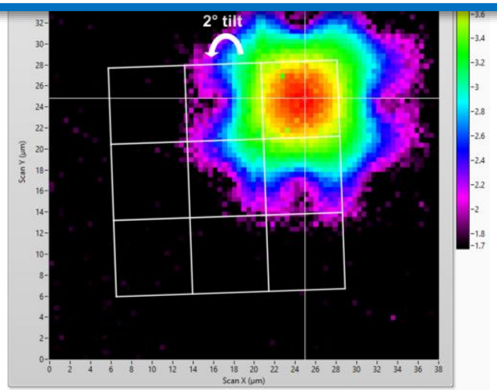


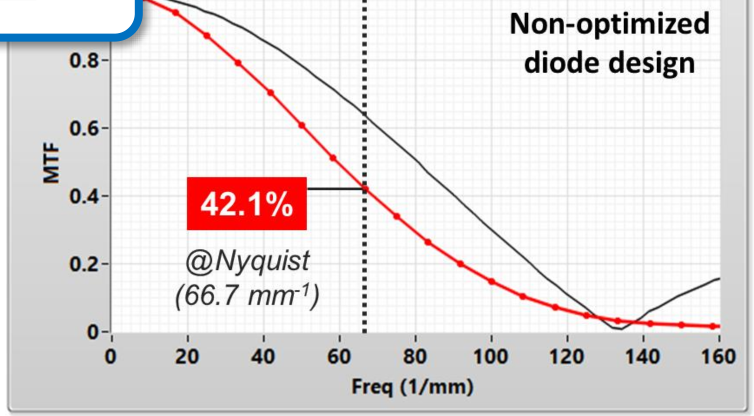
Toward intra-pixel persistence mapping with EBIC ?











Pixel PSF → FFT → Pixel MFT

S. Bustillos Vasco & al, *Journal of Electronic Materials, 2023*

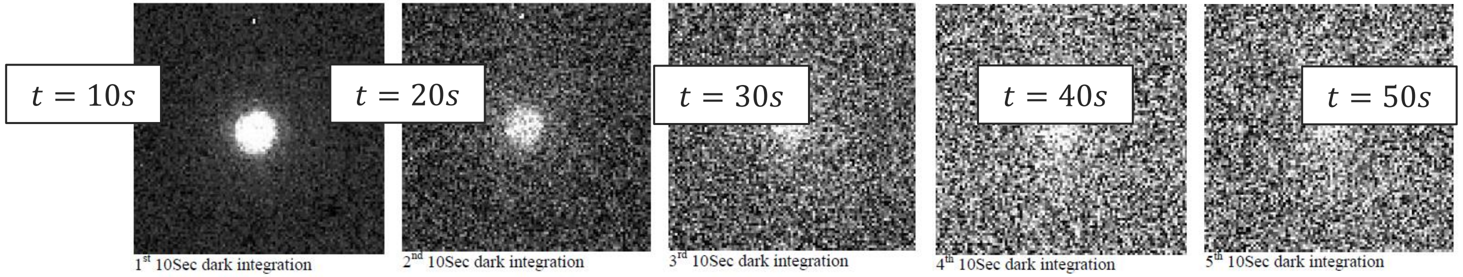
N. Baier & al, *Scientific Detector Workshop, 2025*

3. 3 Persistence

Persistence definition

Persistence

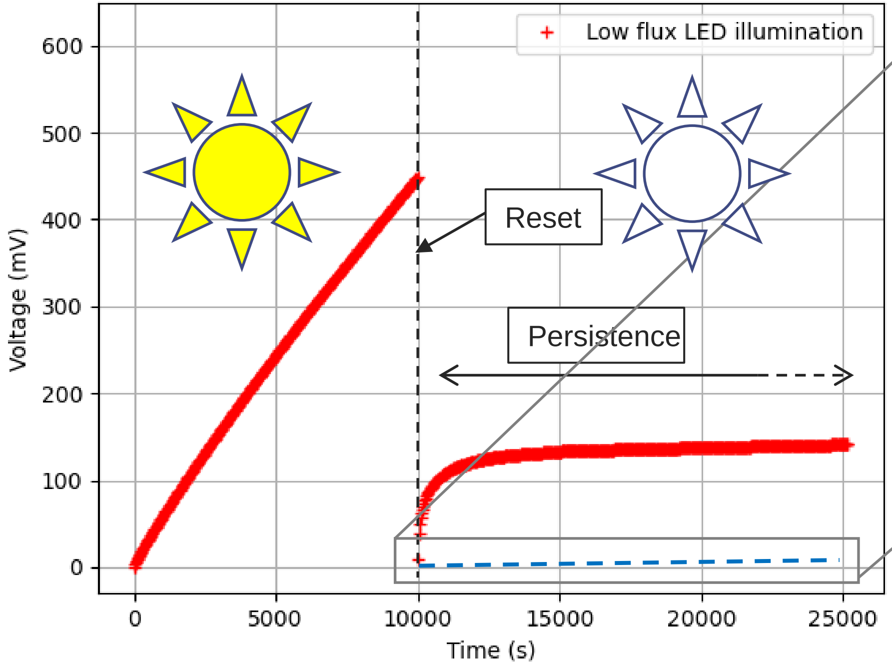
= Transitory after any previous stimulation (photon flux, voltage change, particle impact …)



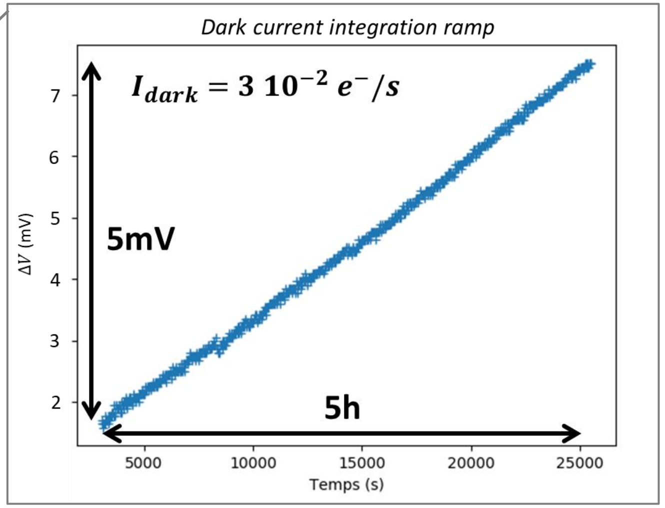
1st 10Sec dark integration
2nd 10Sec dark integration
3rd 10Sec dark integration
4th 10Sec dark integration
5th 10Sec dark integration

N. Besawada (2004)

Persistance : excessive and non-linear signal



Expected linear dark current



Persistence : How to measure it ?

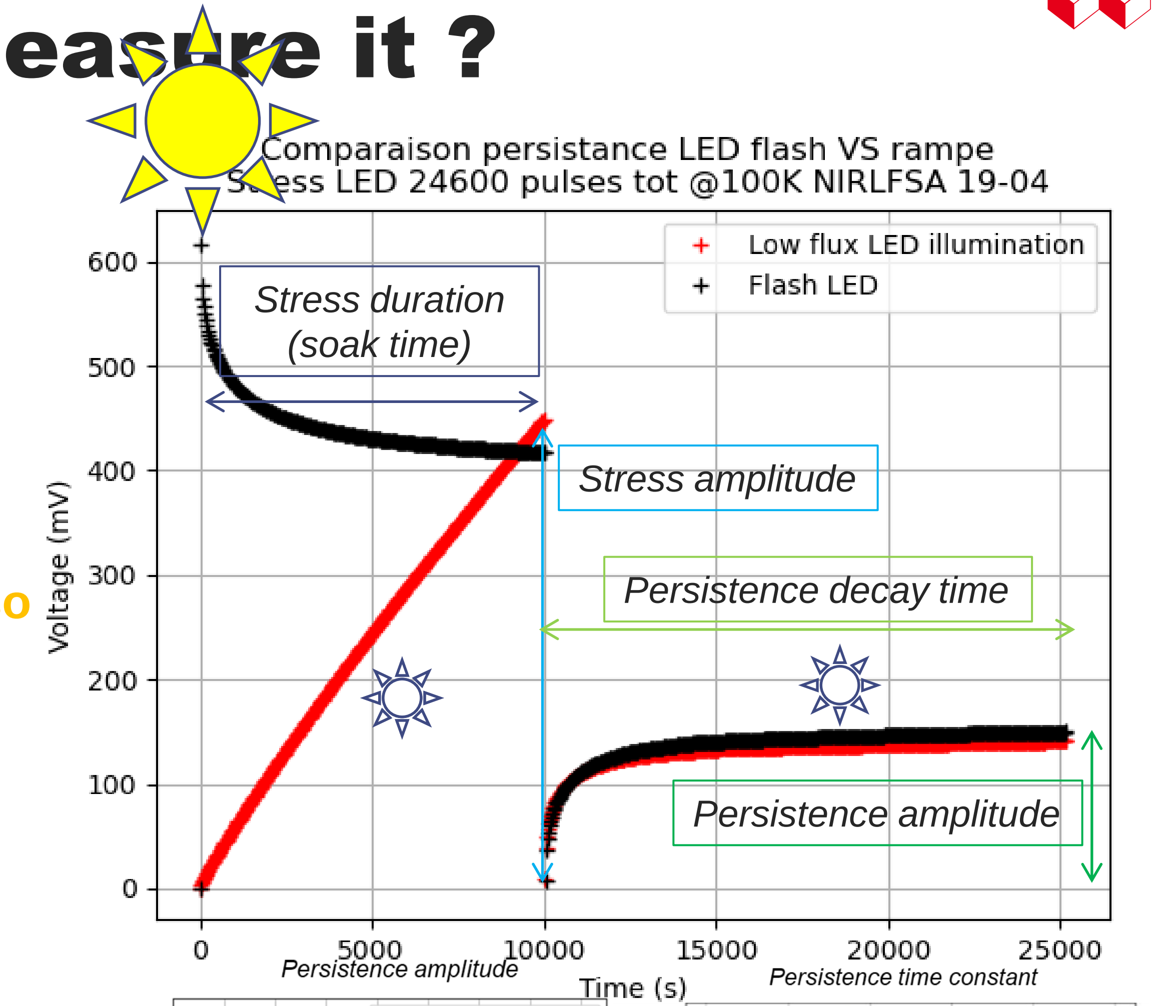
<u>Type of measurement</u>:

- Detector conditioning before any measurement
- Long and diffuse **illumination ramp**
- **Optical flash + soak time**
  - LED flash / ramp difference : **persistence also has impact on photometry !**

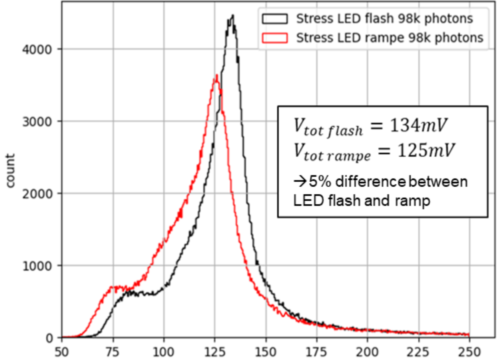
-> effect related to the charge time of persistence

<u>Parameters of interest</u>

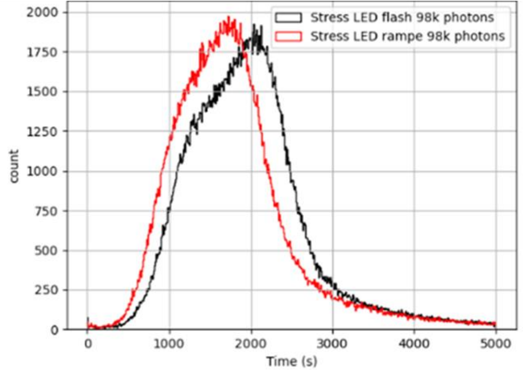
- Amplitude : photon fluence or ΔV
- Soak time
- Operating temperature



Persistence amplitude



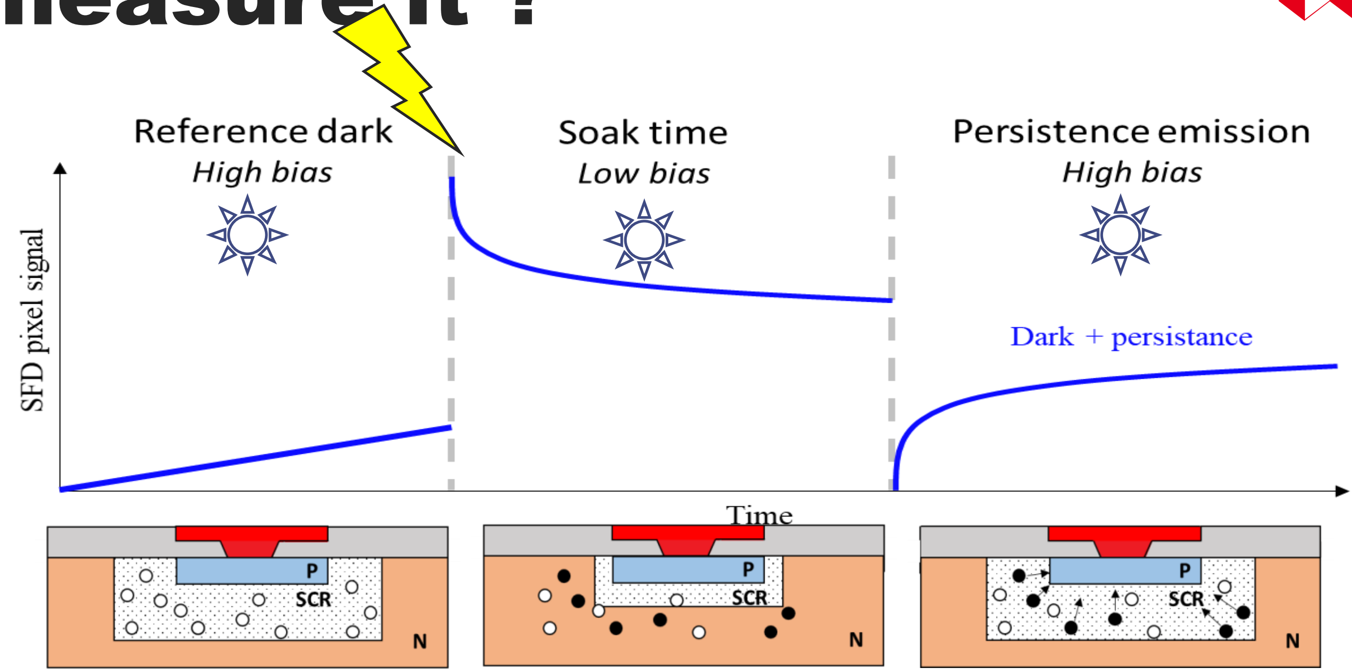
Persistence time constant

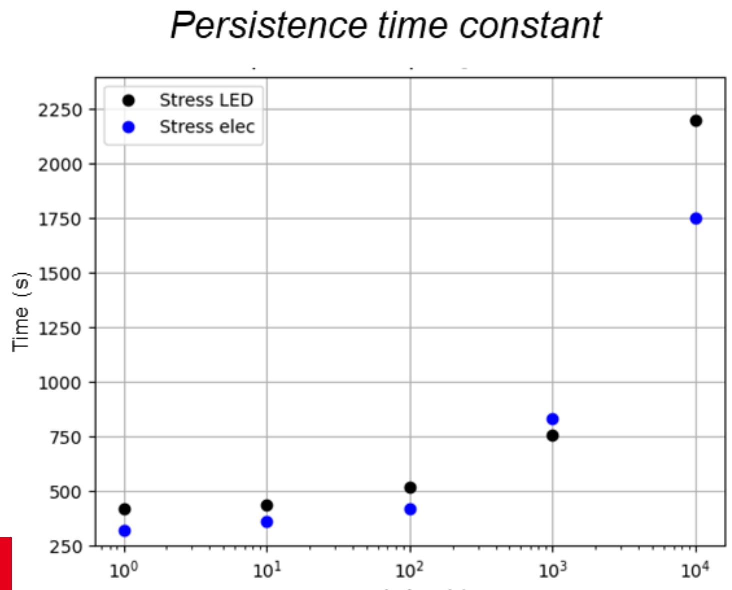


Persistence : How to measure it ?

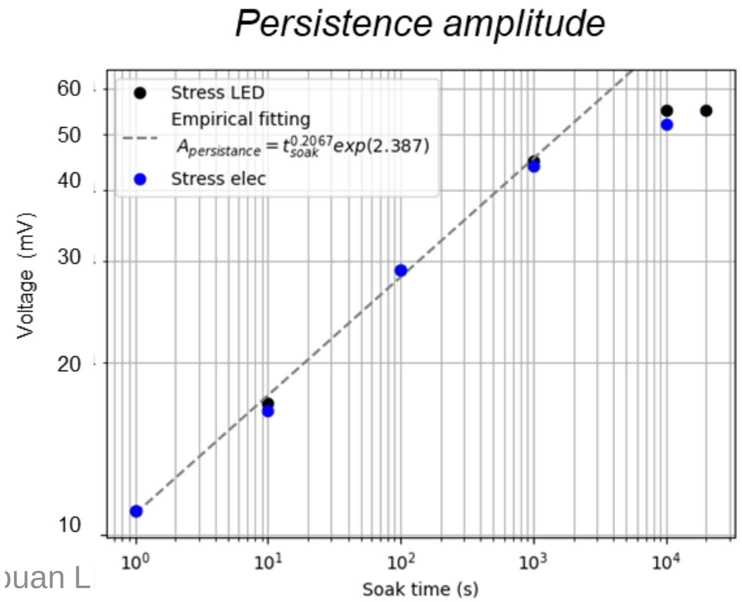
Electrical stimulation : an analog to LED flash

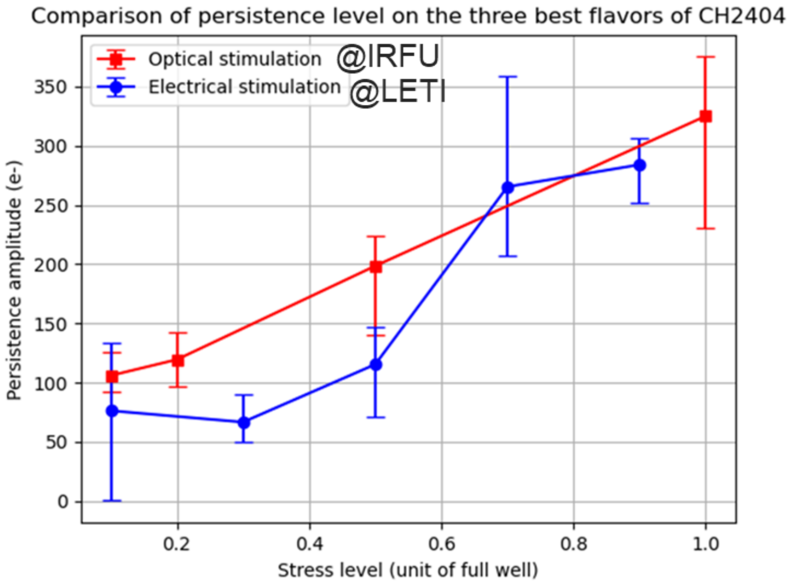
- Abrupt voltage change with soak time
- Accounts well for stress **below saturation**





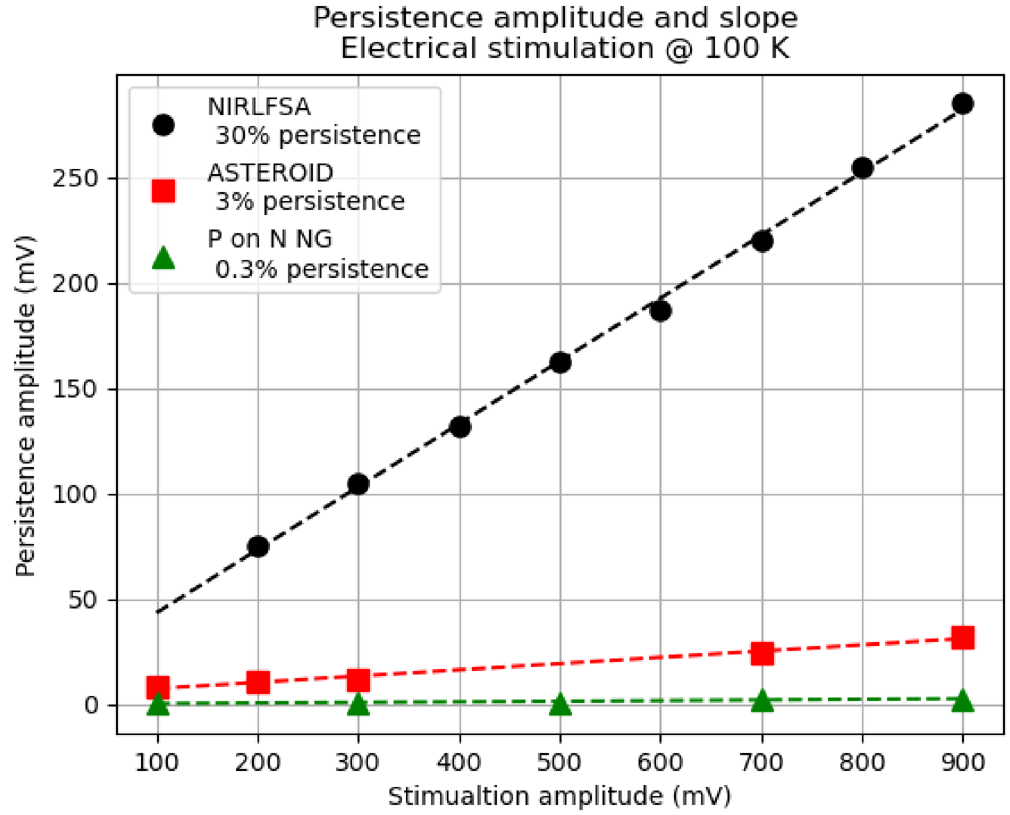
T. Le Goff & al, SPIE Proc., 2022

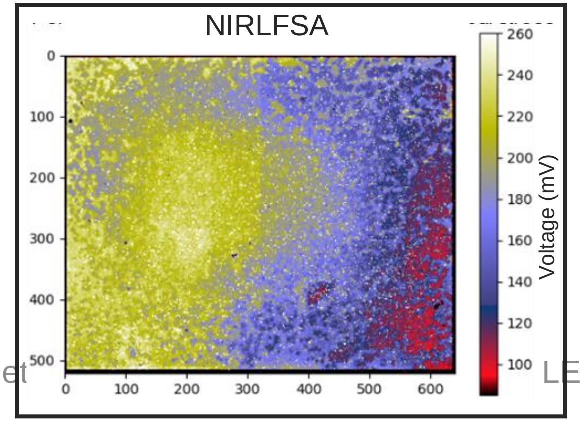


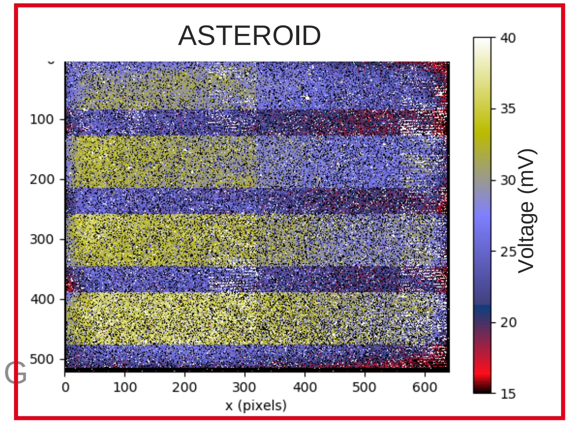


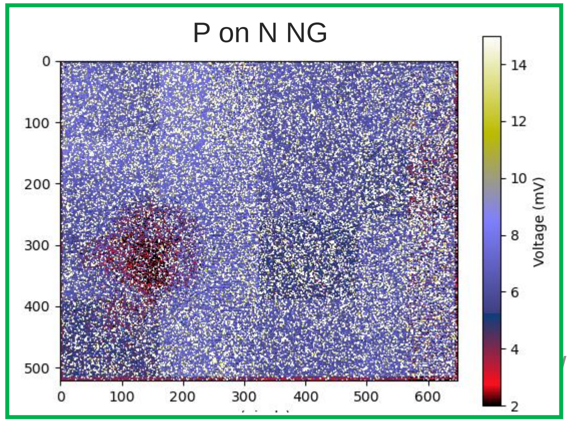
Persistence as a tool to evaluate a technology performance

- **Electrical stress persistence**:
  - Easier to carry out
  - ‘Infinite’ soak time maximizes persistence emission
- **Comparison on successing in-house technologies**
  - Similar equipment and test protocol
  - Persistence can be mitigated with material quality & diode fabrication improvement

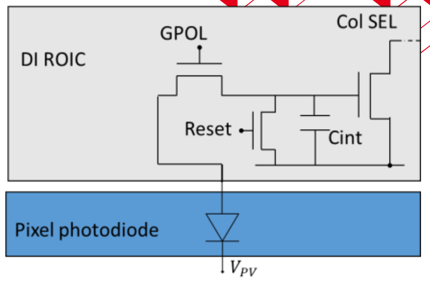








Persistence as trap analysis tool

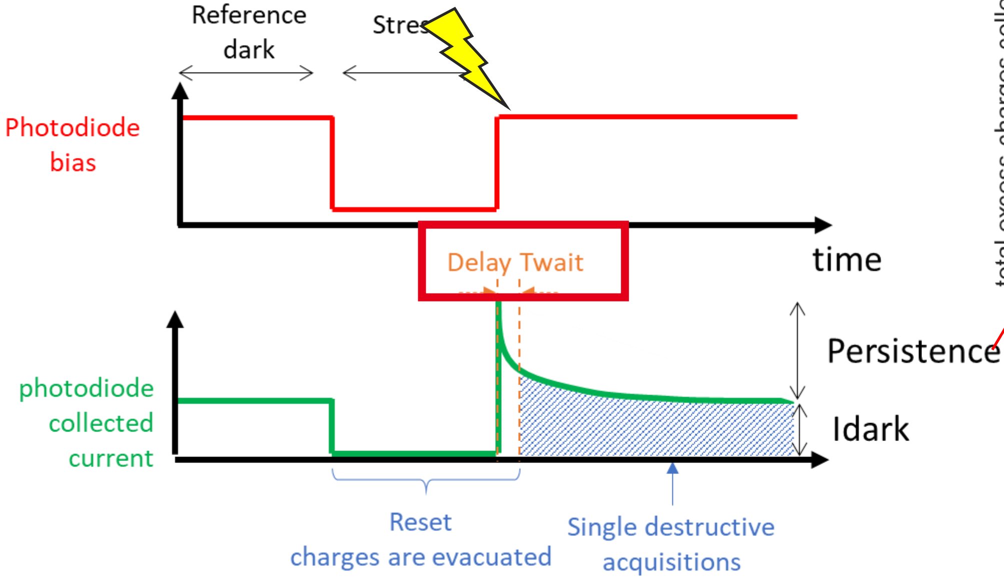


- ❑ Electrical persistence adapted on Direct Injection (defense application oriented ROIC)

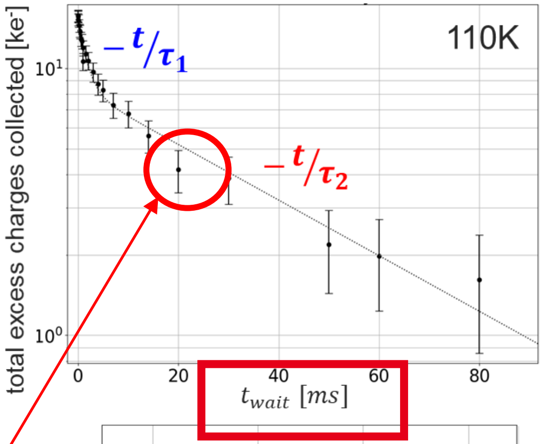
-> Current transient integrated on a fixed Cint

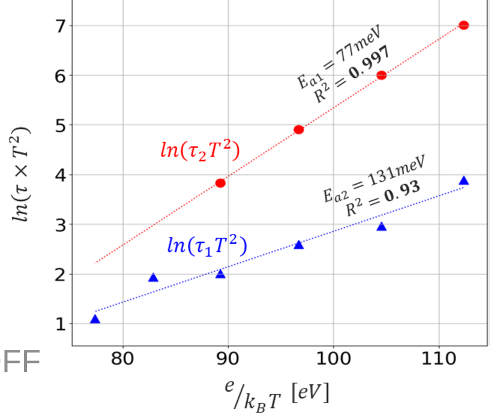
-> Destructive readout mode : A **delay twait** inserted after the stress to reconstruct trap decay dynamic.

Performed on MCT SWIR, MWIR, P/N, N/P and T2SL arrays… Should also work on CTIA ROIC



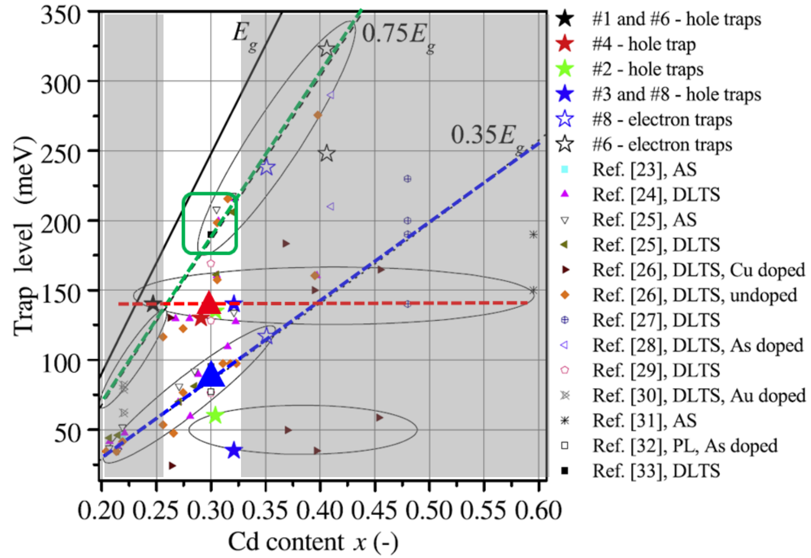
H. Rousset & al, Journal of Electronic Materials, 2025





Coherent trap properties estimation with littérature on MCT MWIR !

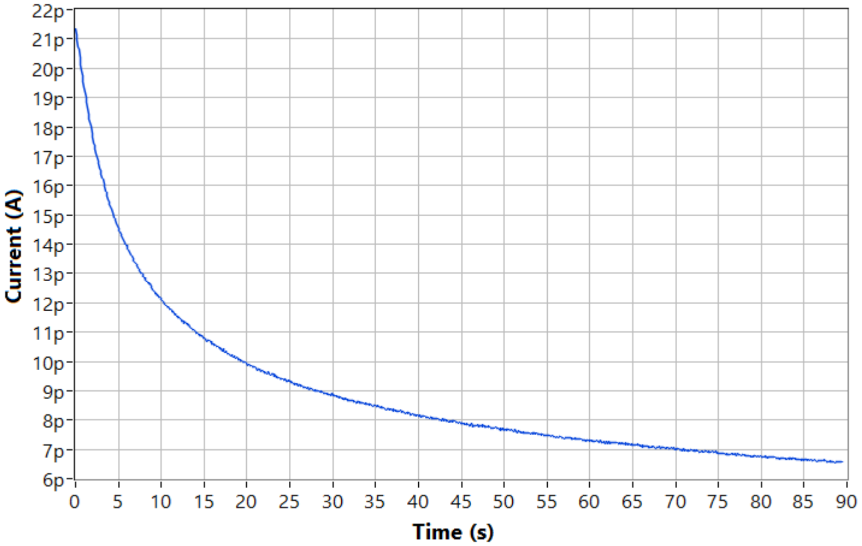
(Ciura 2016)



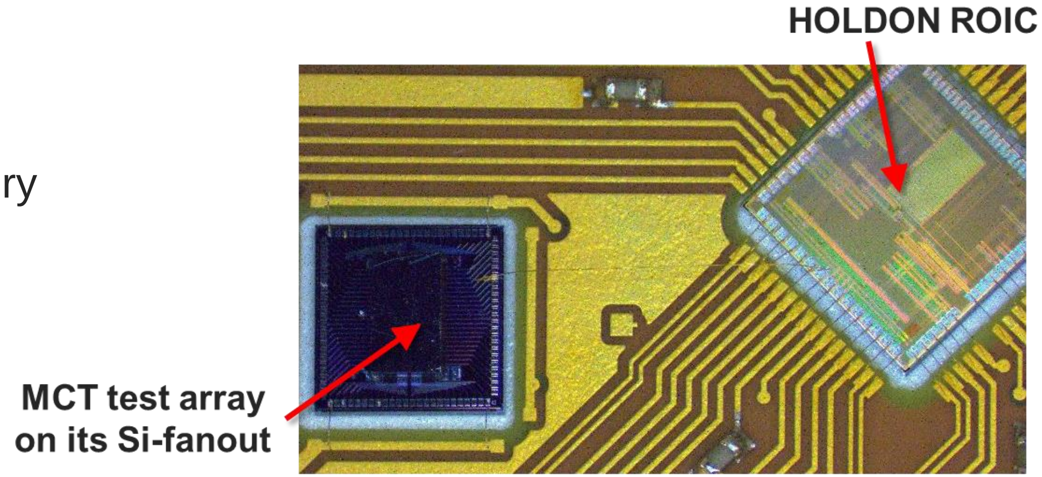
Persistence on test chip

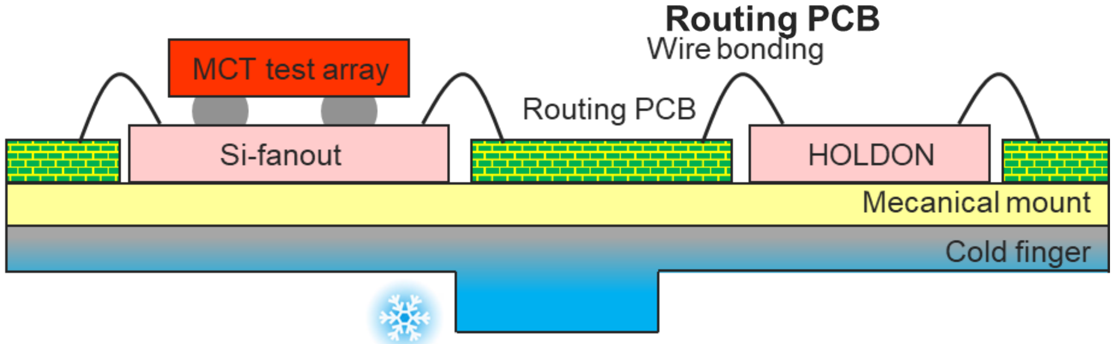
- **A setup for persitance diagnostic with test chips**
  - On FPA → final product but **costly** and reluctance to perform **post process treatments**
  - On test arrays → how to measure **low currents** with on-the-self amplifiers?

- **First results: electrical remanence test on SWIR test array ($\lambda_c = 2.1 \mu m$)**
  - Both electrical & optical stimulus possible
  - Large memory depth : adaptable sampling for fast & very long acquisition



- **Solution: coupling test array to CTIA ROIC**
  - Single diode **CTIA input ROIC**
  - High operating frequency (up to 300MHz)
  - Non destructive readout (fast sampling & observation up to several hours)
  - Fully reconfigurable (during acquisition) 4 gains CTIA





E. De Borniol & al, ICSO, 2022

3. 4 Irradiation testing

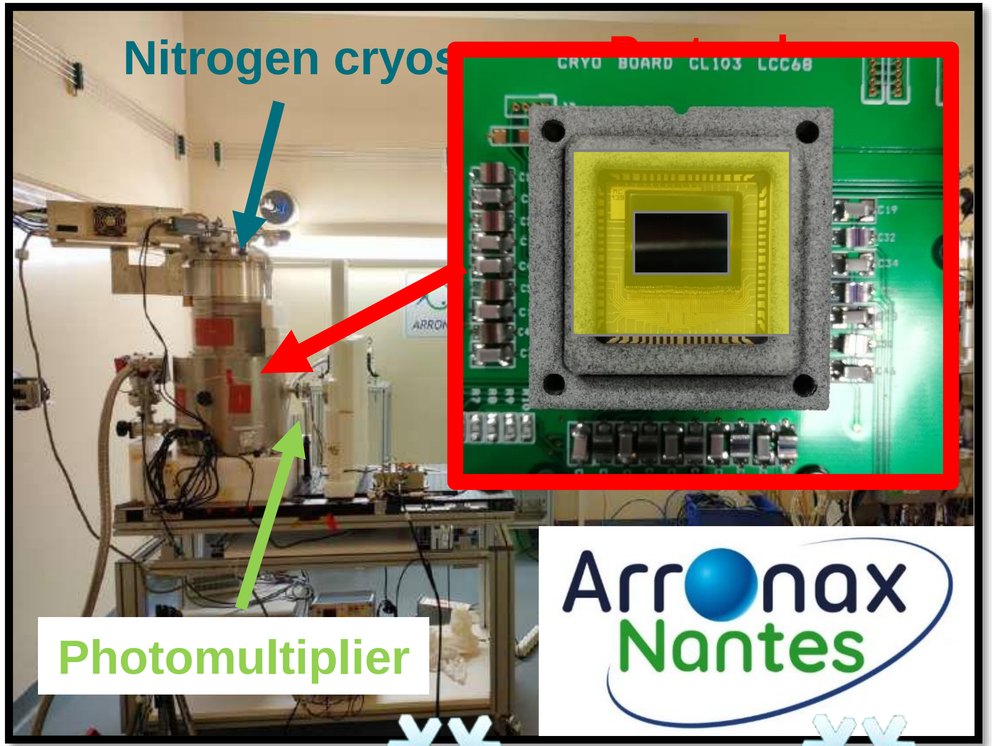
Irradiation testing

Why ? Technology evaluation, defect formation after irradiation stressing

→ Irrad are performed at much higher dose than EOL !

- Proton/neutron/γ_{ray} irrad on tactical MWIR N/P (S. Dinand)
- Dark current & RTS on LWIR & VLWIR P/N (T. Friess & A. Claret)
- **Dark current degradation on SWIR P/N Source-Folower detector** (T. Friess & T. Pichon)

	Cumulative fluence ($proton/cm^2$)	TNID MeV/g (HgCdTe)	TID krad (Si)
Step 1	1.6×10^{10}	3.03×10^{7}	2.12
Step 2	1.5×10^{11}	2.84×10^{8}	19,91
Step 3	4.7×10^{11}	8.89×10^{8}	62,41




1 week before irradiation

Step 1

Step 2

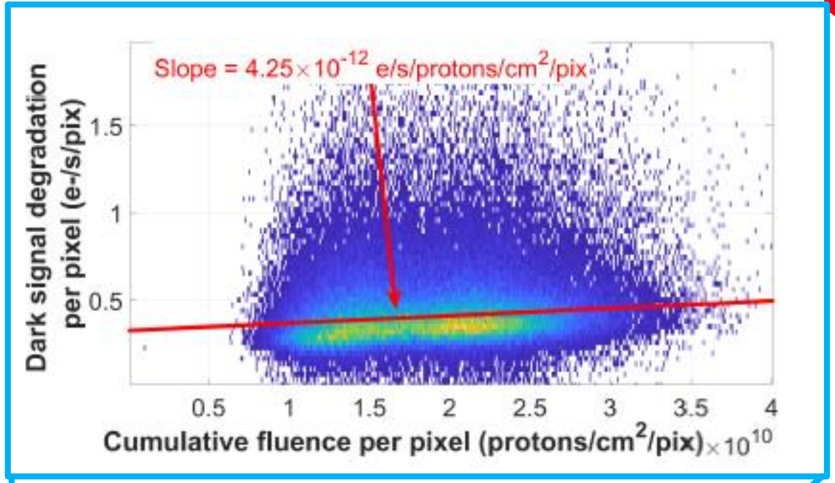
Step 3

One month after

One year after

T. Friess & al, *IEEE Transactions on Nuclear Science, 2025*

Irradiation testing

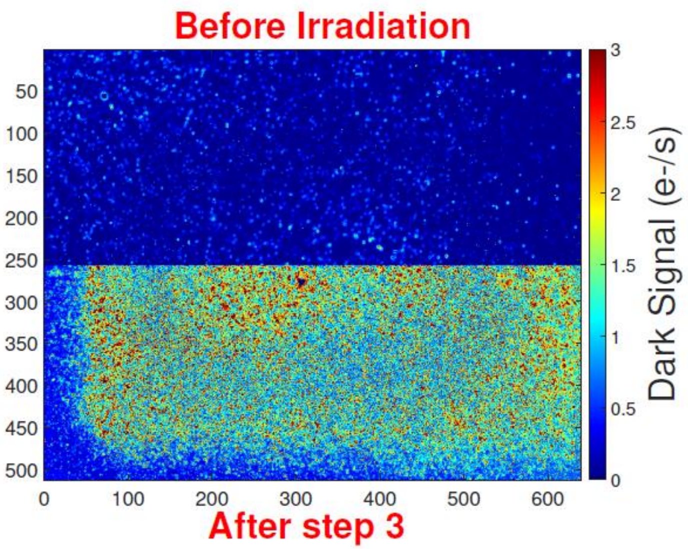


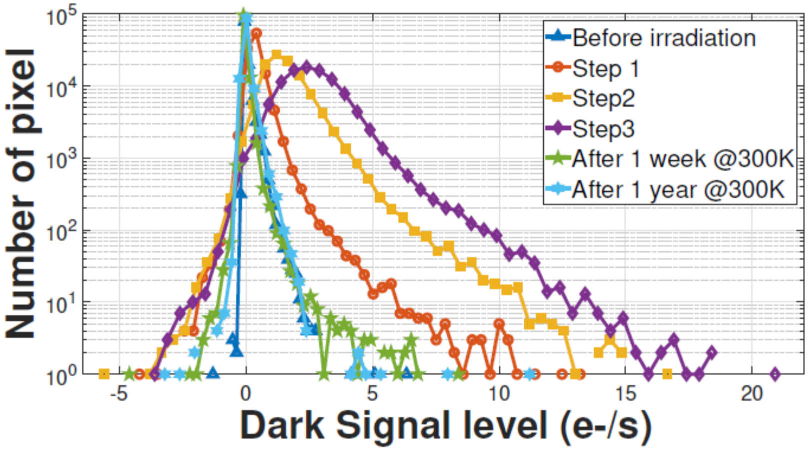
- Dark current increase after irradiation from 0,05 e-/s to > 2e-/s
- Linear dark current degradation = additive defect formation
  - → Also valid for low dose irradiation

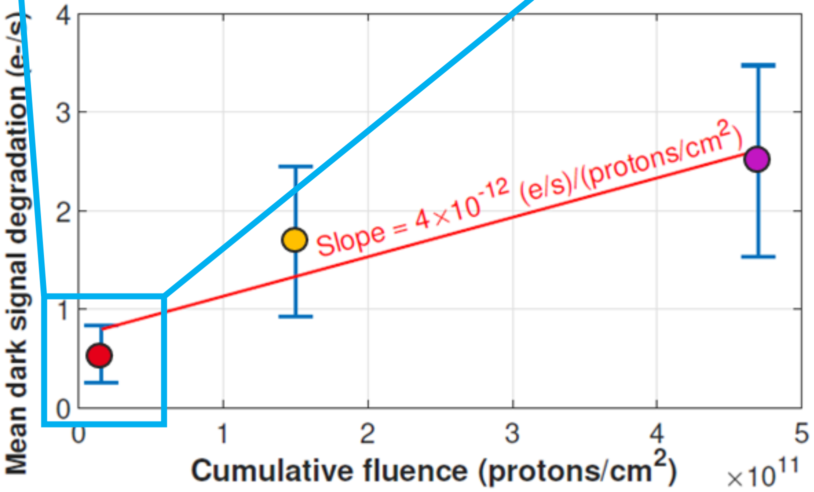
$$1,8\times10^{-6}e-/s/pix/proton$$

$$3\times10^{-10}fA/pix/proton$$

- Recovery of the initial performance after a thermal cycle at ambient temperature
  - → Thermal reconfiguration of defects ?







Thank you

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