DE LA RECHERCHE À L'INDUSTRIE

Development at Lynred and CEA of very low flux SWIR detectors for astrophysics and space applications : final results for the ALFA detectors

Pichon T., Badano G., Bounab A., Delisle C., Fieque . B, Gravrand O., Horeau B., Lamoure A., Lobre C., Lortholary M., Moreau V., Mulet P., Orduna T., Provost L., Sam-Giao D., Tellier O., and Boulade O.

FOCUS IR detector workhsop

What future for European large format IR detectors ?

www.cea.fr

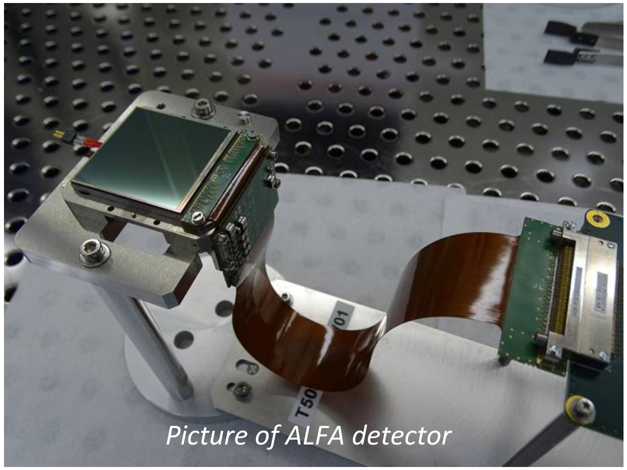
PLAN

1. Introduction
    1. General context
    2. ALFA requirements
    3. Test bench description
2. What works well
    1. Detector gain
    2. Crosstalk
    3. Dark current
    4. Detector cosmetics
    5. Linearity
3. What does not work so well
    1. Quantum efficiency
    2. Excess noise
    3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

Goal: equip Europe with high performance large format IR detectors for space applications and astrophysics

ALFA program

- 2010 — 1st Phase:
  - MCT material performance demonstration
- 2013 — 2nd Phase
  - TV format detector manufacture, test and characterization
- 2016 — 3rd phase:
  - Prototype NIR/SWIR large format array detector 2K² (now)

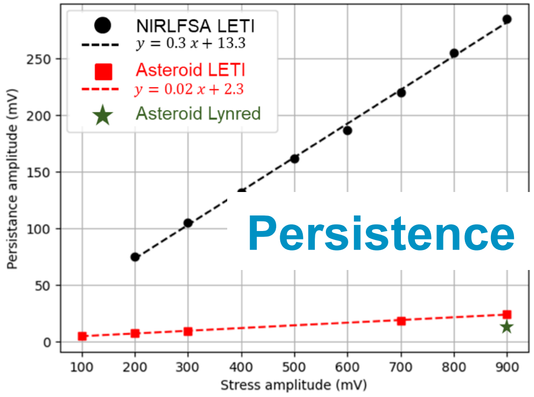


Picture of ALFA detector

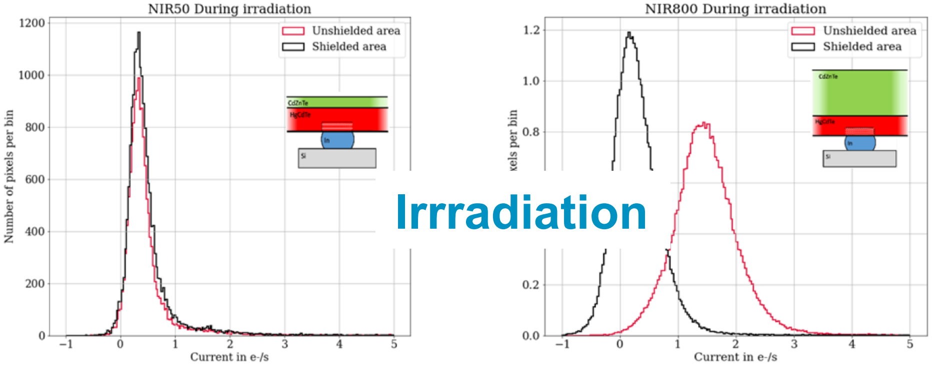
- **ALFA Development:** Lynred (ROIC + Hybridization) + CEA-Leti (PV)
- **Characterisation:** Astrophysics Department, CEA
- **Funding:** ESA, FOCUS

➔ TV format detectors of phase 2 have been extensively studied.

Persistence:
Persistence amplitude as a function of electrical stress amplitude measured on detector from different phases.



Irradiation: effect of the remaining substrate on the response of IR detector under irrradiation



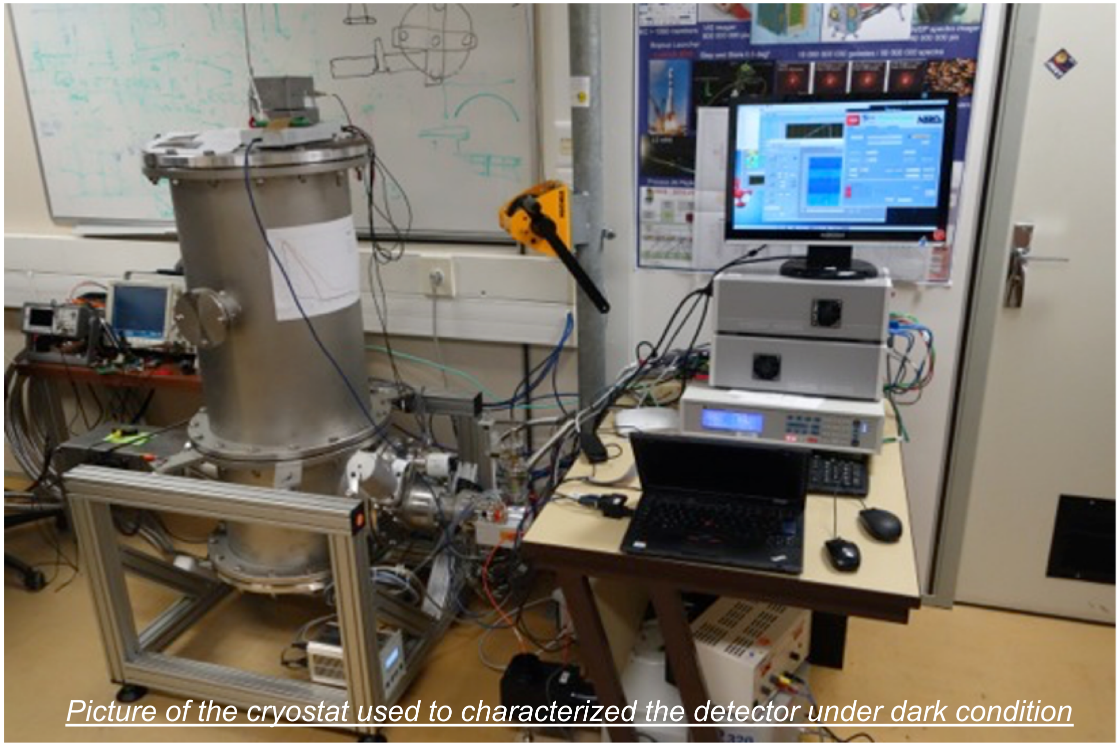
| PAGE 3

ALFA detector specifications: very similar to H2RG.

Parameter	Value
Dimension	
Number of pixels	*2048x2048*
Pixel pitch	*15x15 µm*
Number of outputs	*32 (Readout available through 1, 2, 4, 8, 16, 32)*
Reference Output	*1*
Performance	
Charge handling capacity	*≥ 60ke-*
Cutoff wavelength	*2.1 ± 0.05 µm*
QE	*> 70%*
Dark Current	*< 0.1 e-/s/pix at 100 K*
Operation	
Reset	*Line by line, pixel by pixel, global reset, single pixel reset*
Readout rate	*Science: 100 kHz (pixel readout per channel)* *Fast mode: 5 MHz (pixel readout per channel)*

In total **4 detectors** were fabricated:

- 4 are operable
- 2 have good PV layer → The best one will be used inside the CAGIRE instrument.
  → Presentation will focus on this detector.


Picture of the cryostat used to characterized the detector under dark condition

Test bench description

- Light-tight cryostat with no entrance window.
- Optional LED and Blackbody can be installed inside the cryosat for specific measurement (linearity, persistence, ….)
- Detector temperature can vary between 30 K and 220 K.
- Extremely good temperature control over hours (1.6 mK rms over hours, required for long dark measurements)

Acquisition chain:

- Home developed cold pre-amplifier electronic, based on OPA350 (based on ESO design) , to amplify the detector output signal. Pre amplifier operates at 80 K.
- New Generation Controller (from ESO) used to control the detector

PLAN

1. Introduction
    1. General context
    2. ALFA requirements
    3. Test bench description
2. What works well
    1. Detector gain
    2. Crosstalk
    3. Dark current
    4. Detector cosmetics
    5. Linearity
3. What does not work so well
    1. Quantum efficiency
    2. Excess noise
    3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

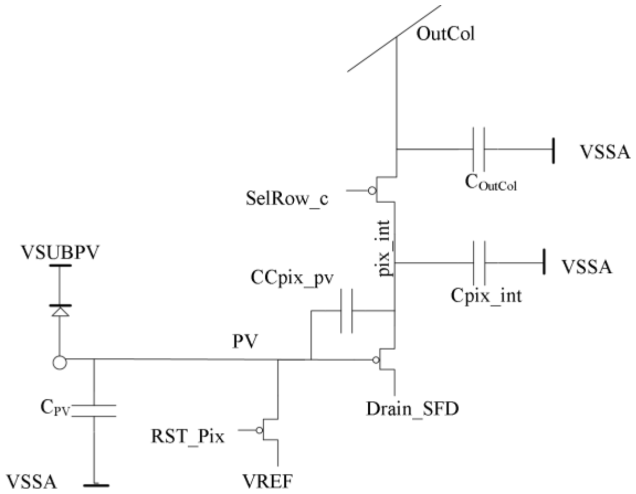
Conversion gain

Expectation:

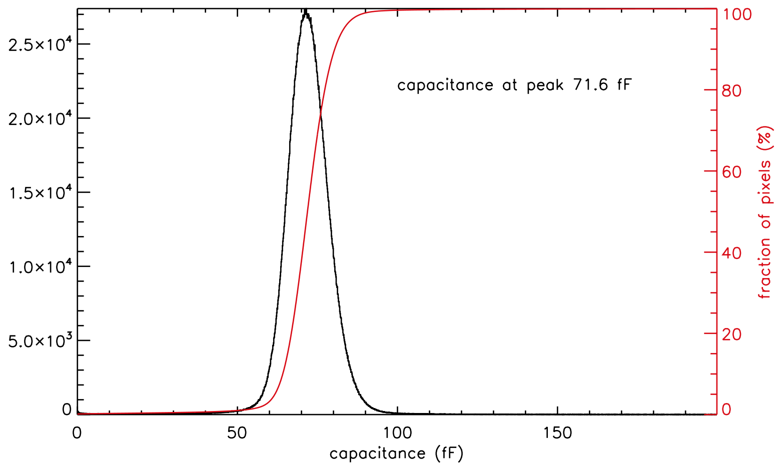
- Status of capacitances of ALFA devices (after discussion with Lynred 31/05/22)
- Estimated total capacitance of integration is composed of:

fixed capacitance + diode capacitance + parasitic capacitance.

- Estimated total capacitance is equal to (worst case) ~**70 fF.**



Schematic view of ROIC architecture



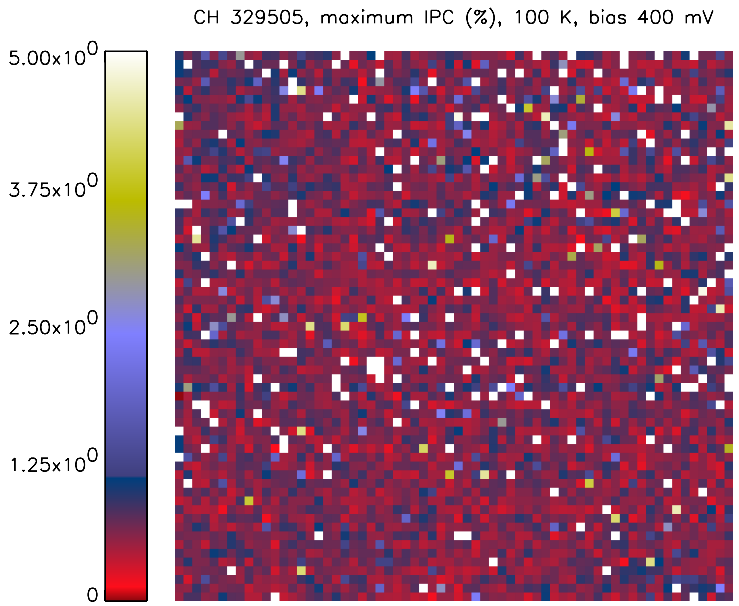
Mesurement:

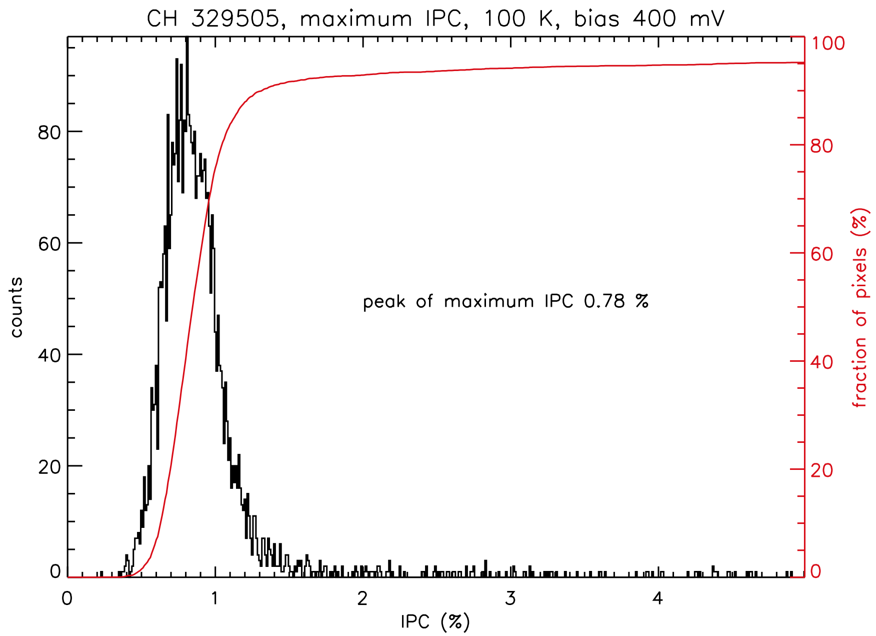
- The conversion gain has been measured with standard Photon Transfert Curve (PTC) technique. The mean capacitance is equal to **71.6 fF** in good agreement with estimation. But this capacitance value has to be corrected for IPC.

Crosstalk

- Capacitances derived from PTC must be corrected from inter pixel capacitance
  - IPC measured for ALFA device, using 4096 IPC pixels (using of a dedicated mode the ROIC)
  - 0.8% for CH329505

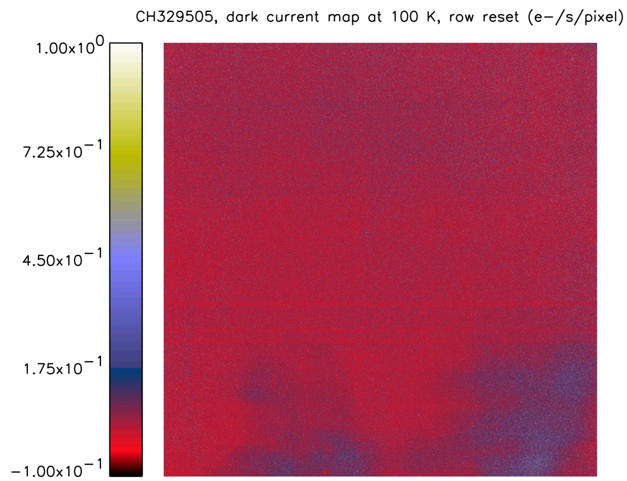
⇒**Average corrected total capacitances is 67.1 fF for CAGIRE detector.**

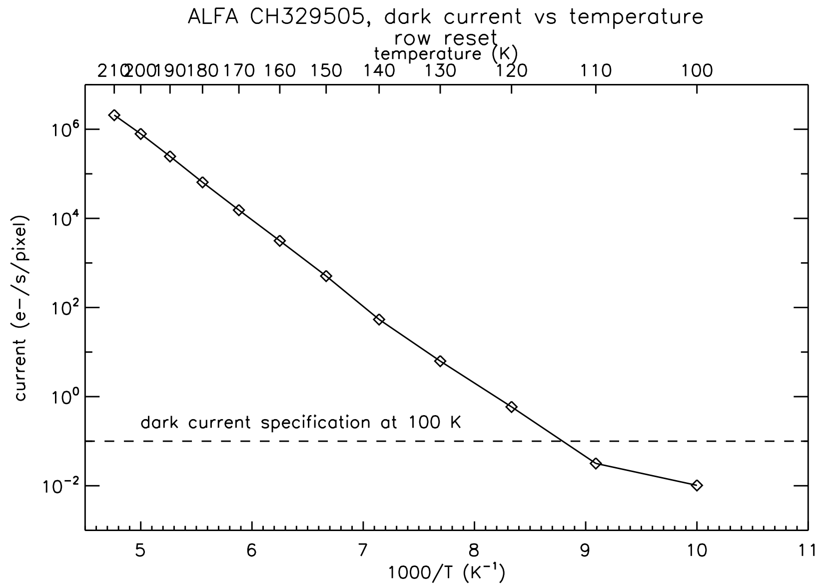


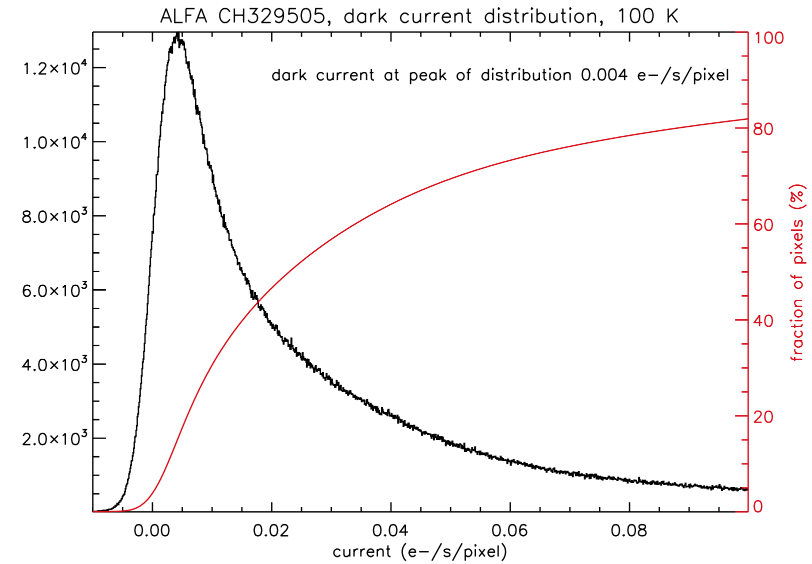


Dark current measurement:

- Dark current measurement at 100K is 20h long
- Peak of the distribution is equal to **0.004 e-/s/pix**
- Operability at dark at 100 K: 95%

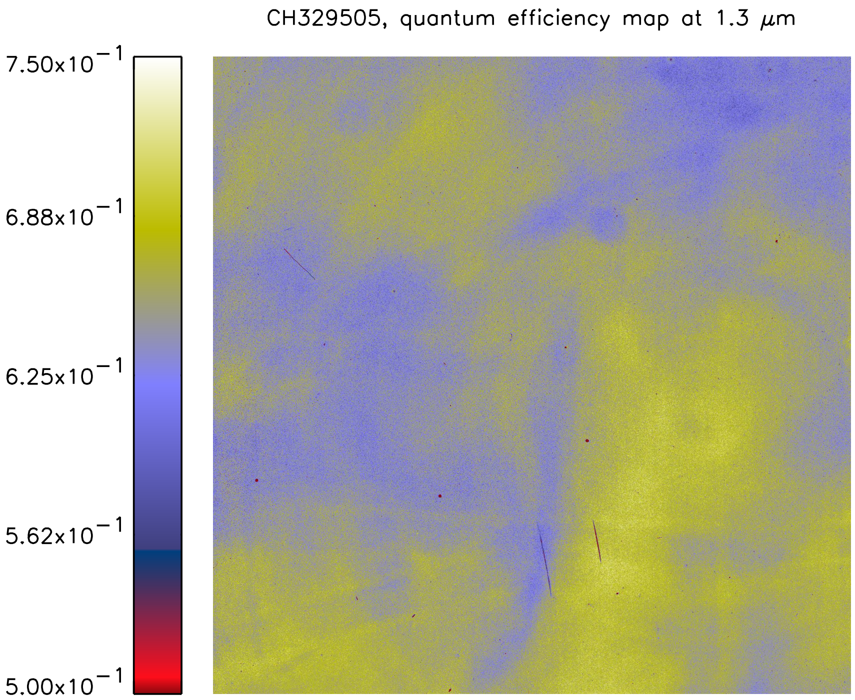






Pixel response non uniformity:

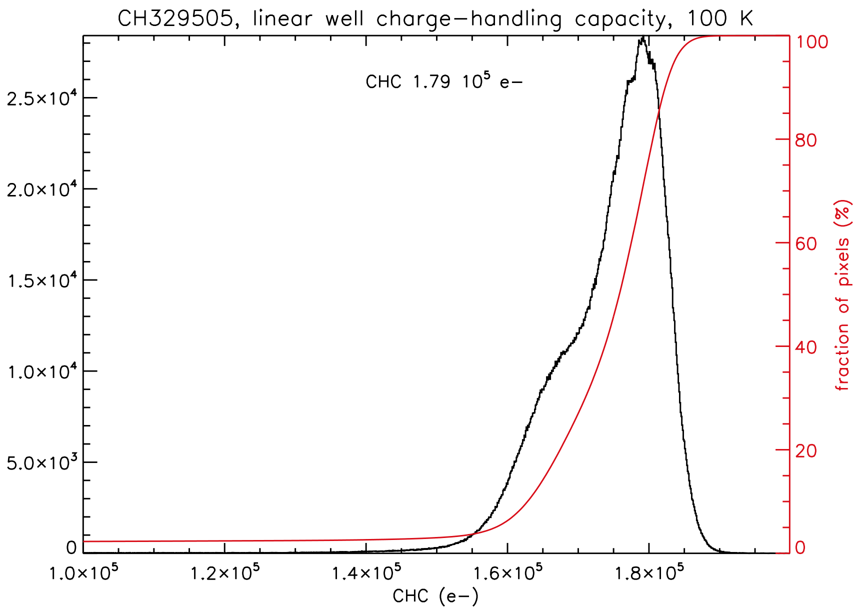
- At 1.3 µm, the PRNU is 5.3%.
- Close to the cutoff wavelength, the QE map changes. The PRNU at 2.05 µm is 6.7%.
- Operability under flux is 99%

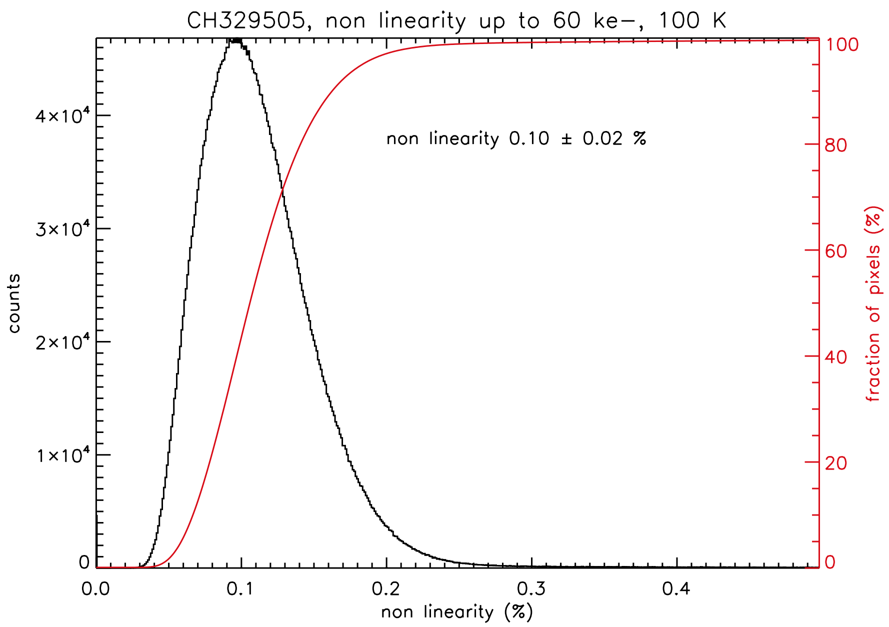


Detector demonstrates very good linearity:

- Charge handling capacity is equal to **179 000 e-**. Defined as the signal level where non linearity exceeds 3%.
- Non linearity is equal to 0.1% at 60 ke-.

Full well requirement

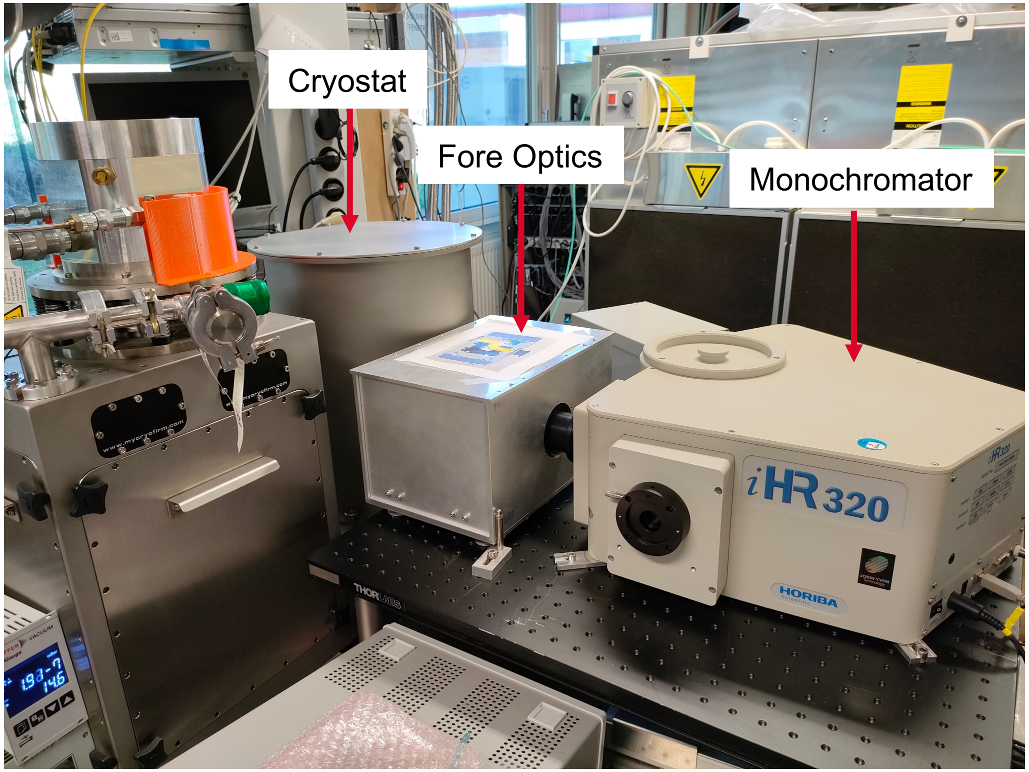




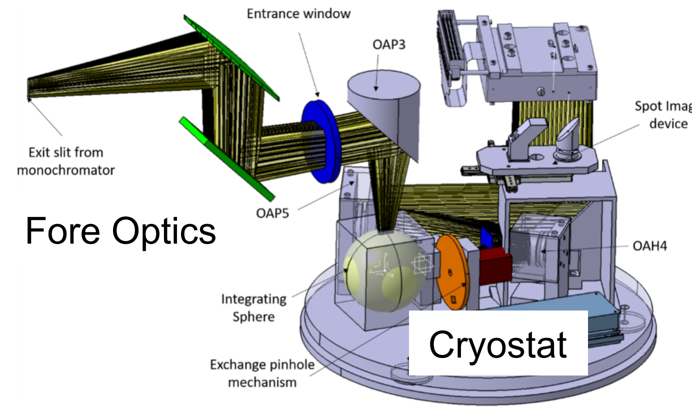
PLAN

1. Introduction
   1. General context
   2. ALFA requirements
   3. Test bench description
2. What works well
   1. Detector gain
   2. Crosstalk
   3. Dark current
   4. Detector cosmetics
   5. Linearity
3. What does not work so well
   1. Quantum efficiency
   2. Excess noise
   3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

3. WHAT DOES NOT WORK SO WELL
1. QUANTUM EFFICIENCY



- Bench funded by FOCUS Labex
- Three components:
  - monochromator,
  - fore-optics
  - cryostat
- Collimated beam to illuminate calibrated photodiode and detector simultaneously

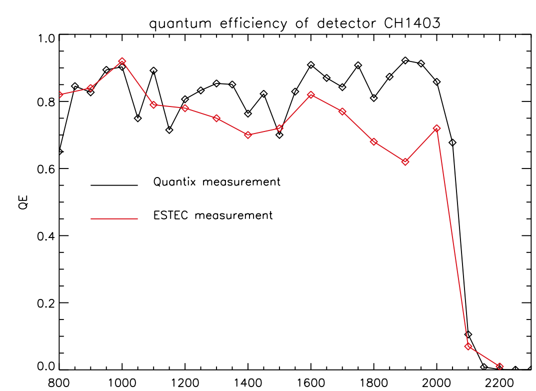


- **Basic principle of the measurement:**

$$QE(\lambda) = \frac{I_{det}}{I_{calib\ phd}} \times \frac{Irr_{calib\_phd}(\lambda)}{Irr_{det}(\lambda)} \times QE_{PHD}(\lambda)$$

Ratio of measured currents | Ratio of illumination | QE of the calibrated photodiode

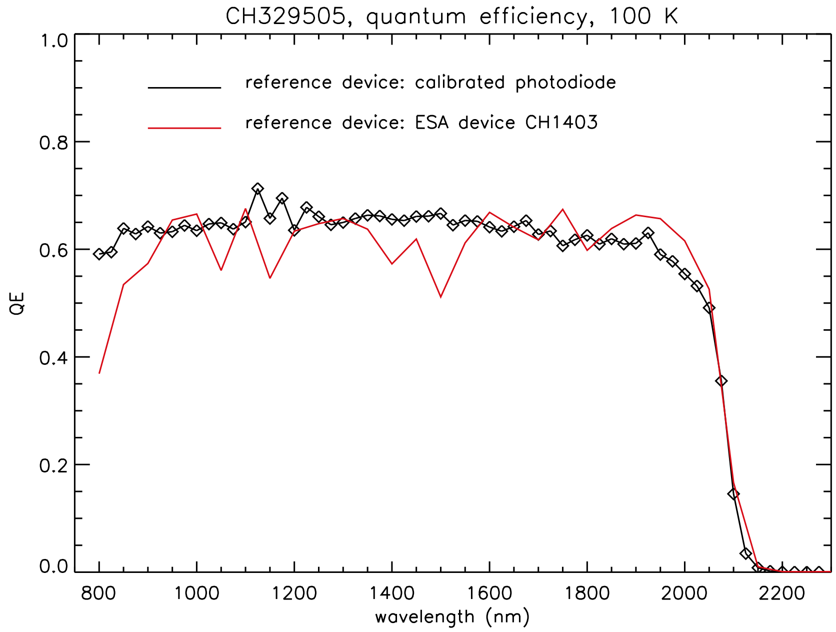
- Test bench validation



3. WHAT DOES NOT WORK SO WELL
1. QUANTUM EFFICIENCY

The **Quantum Efficiency (QE)** of the detector has been measured on Quantix test bench, with two methods:

1. With the calibrated photodiode (FOCUS, CEA/LETI)
2. With the ESA reference device 1403 (manufactured by CEA/LETI)



<u>QE measurement results:</u>

- QE is flat around 60%
- Cut off wavelength: **2.075 µm**
- 12 % uncertaintity on QE measurements (dominated by measurements of the photodiode current)

QE out of requirement (QE ≥ 70%). Measurement validation is pending additionnal test:

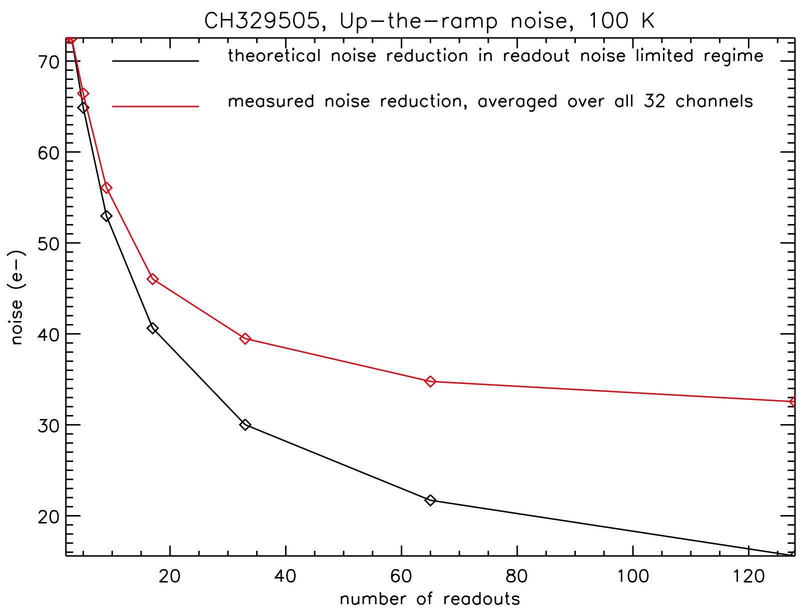
- ➢ Radiometric QE measurements are undergoing.
- ➢ CEA-Leti is also performing measurement on test chip.

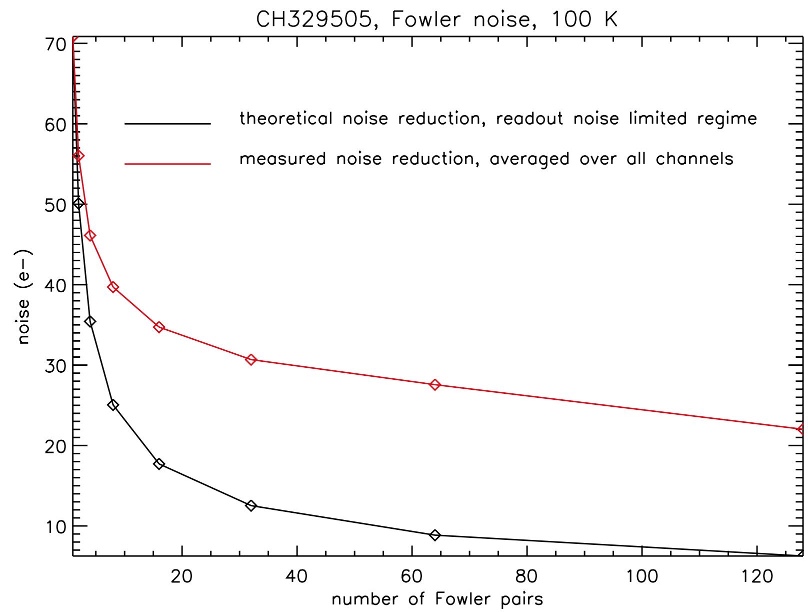
Readout noise

- 100 CDS images acquired
- CDS noise of the detector alone is equal of 60 electrons
- Total CDS noise (detector + acquisition chain) is equal to 72 electrons

FUR noise reduction and Fowler reduction.

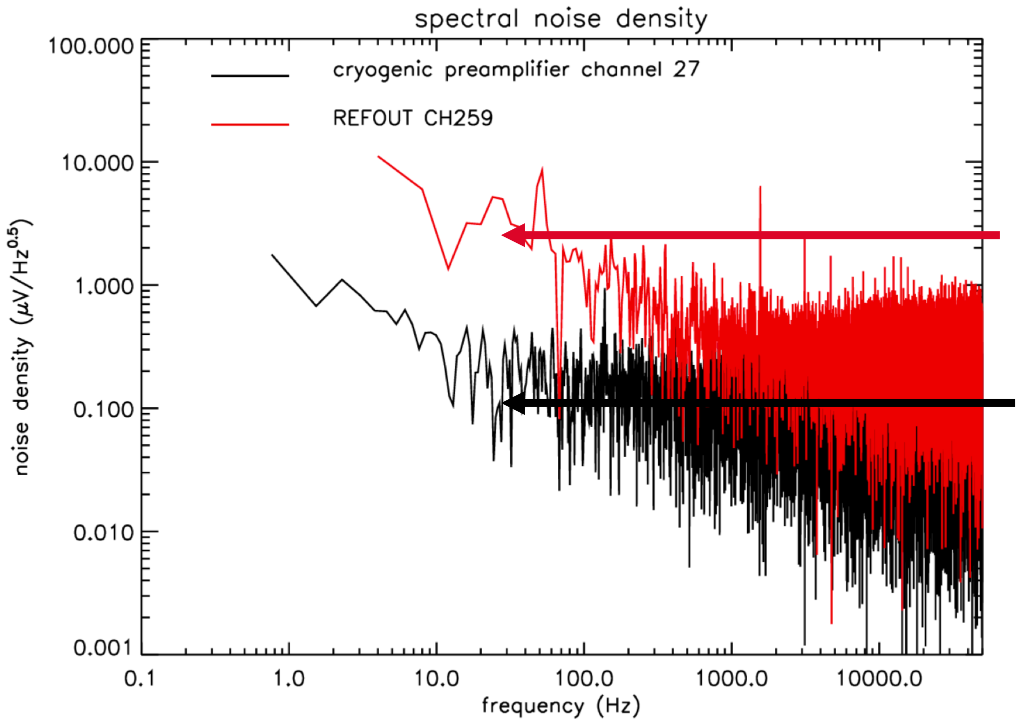
- 100 ramps acquired with 256 images under dark conditions (readout noise limited regime)





Noise spectral density

- Strong 1/f noise is visible
- Different tests have been performed with no effect such as: use external current source, use of very low noise power supply instead of NGC ones, improve grounding, filtering biases.
- The noise has been studied as a function of the two bias voltages used to drive the two stages of source followers. No drastic variation has been observed.



Integral of noise spectral density:
98µV for the reference output

Integral of noise spectral density:
28µV for acquisition chain (lowest value).
The mean acquisition chain is equal to 58.4µV (calculated over 32 channels).

List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).

List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels

Two sets of pixels can be used to check the health of the device. These are schematically shown below

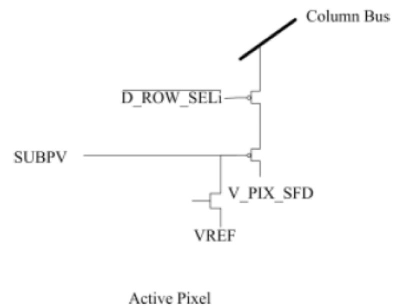


Figure 42: VSUBPD_BR

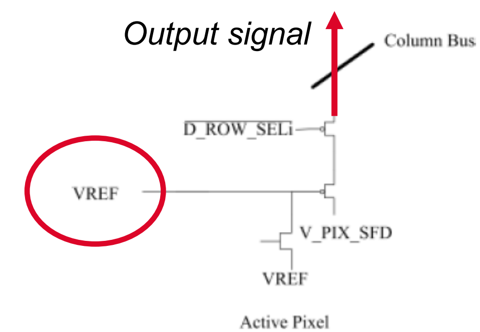
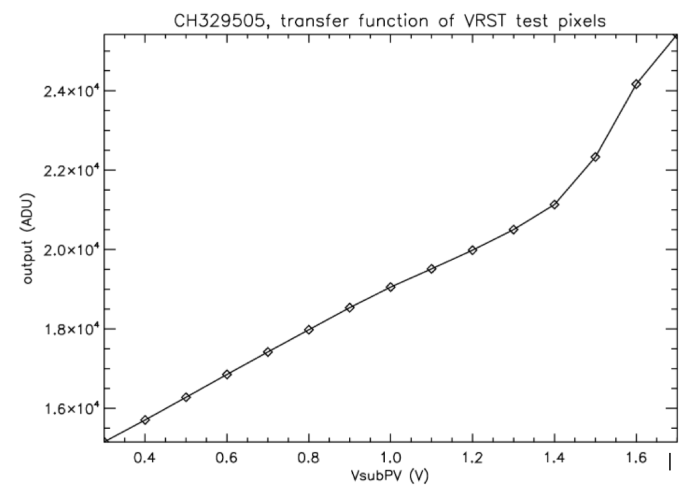


Figure 43: VRST_BR

Signal of VRST test pixel should be independent of VSUBPV voltage. However:



List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels
6. In 1 output and 4 outputs readout modes, the unused outputs are not powered off.
7. In 4 output mode the current in the SF is 8 times to high. In 1 output mode the current in the pixel SF is 32 times too high

List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels
6. In 1 output and 4 outputs readout modes, the unused outputs are not powered off.
7. In 4 output mode the current in the SF is 8 times to high. In 1 output mode the current in the pixel SF is 32 times too high
8. Gradient of offsets

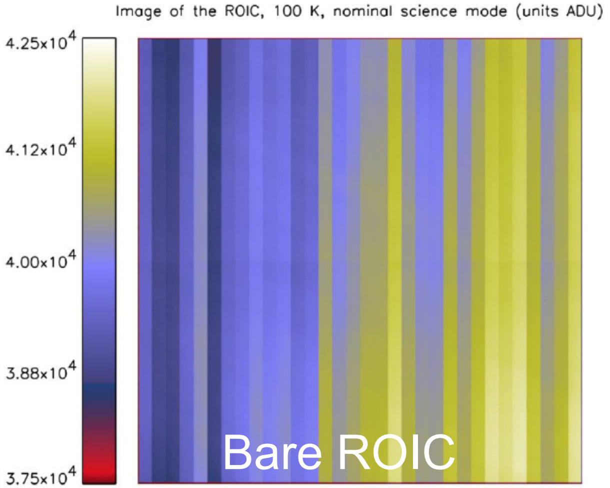
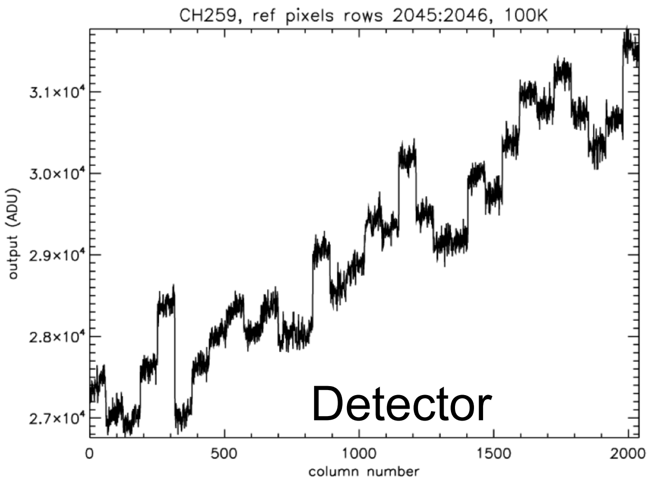


Figure 7 Raw image with the bare ROIC, showing the gradient across channels



→ These offsets are not visible in the acquisition chain alone (pre-amplifier + NGC)

3. WHAT DOES NOT WORK SO WELL
3. GENERAL COMMENTS ON ROIC PROBLEMS

List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels
6. In 1 output and 4 outputs readout modes, the unused outputs are not powered off.
7. In 4 output mode the current in the SF is 8 times to high. In 1 output mode the current in the pixel SF is 32 times too high
8. Gradient of offsets
9. Reference pixel coupling with active pixel

ALFA detector is populated with reference pixels non-sensitive to light. BUT this is not what was measured.

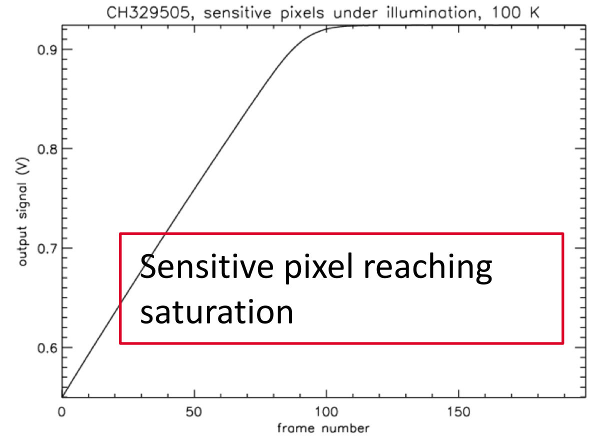


Figure 10 Signal level of the sensitive pixels under illumination, device CH329505

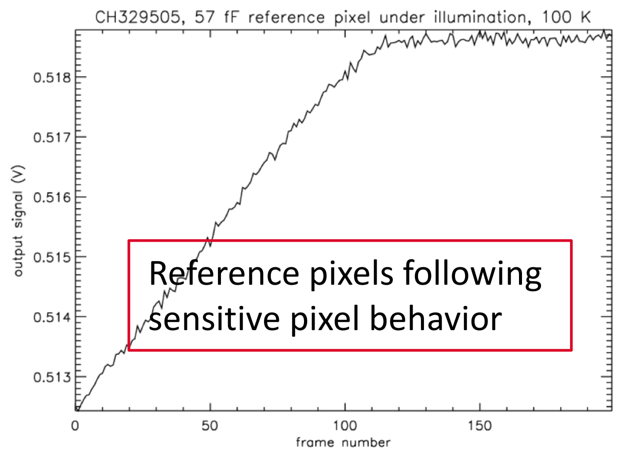


Figure 12 Signal level of the 57 fF fixed capacitance reference pixels under illumination, device CH329505

List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels
6. In 1 output and 4 outputs readout modes, the unused outputs are not powered off.
7. In 4 output mode the current in the SF is 8 times to high. In 1 output mode the current in the pixel SF is 32 times too high
8. Gradient of offsets
9. Reference pixel coupling with active pixel
10. Row reset

Dark current map depending on the reset pattern.

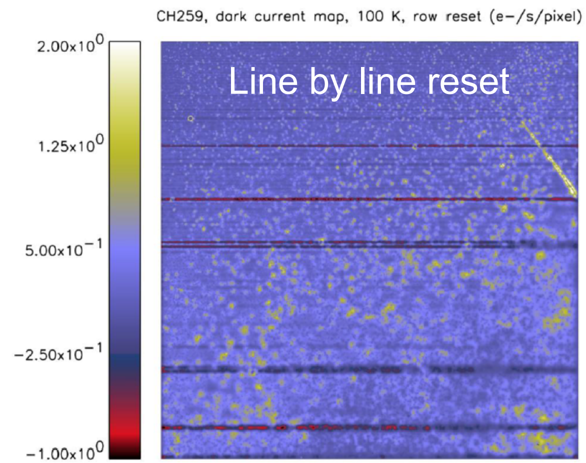


Figure 21 Dark current map of device CH259 at 100 K, row reset

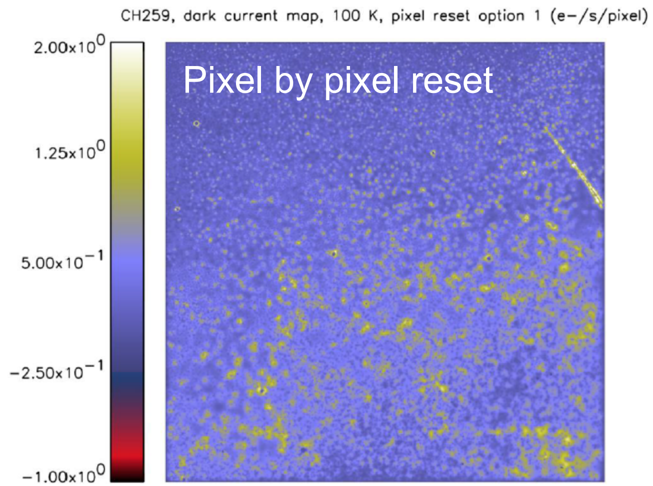


Figure 22 Dark current map of device CH259 at 100 K, pixel reset option 1

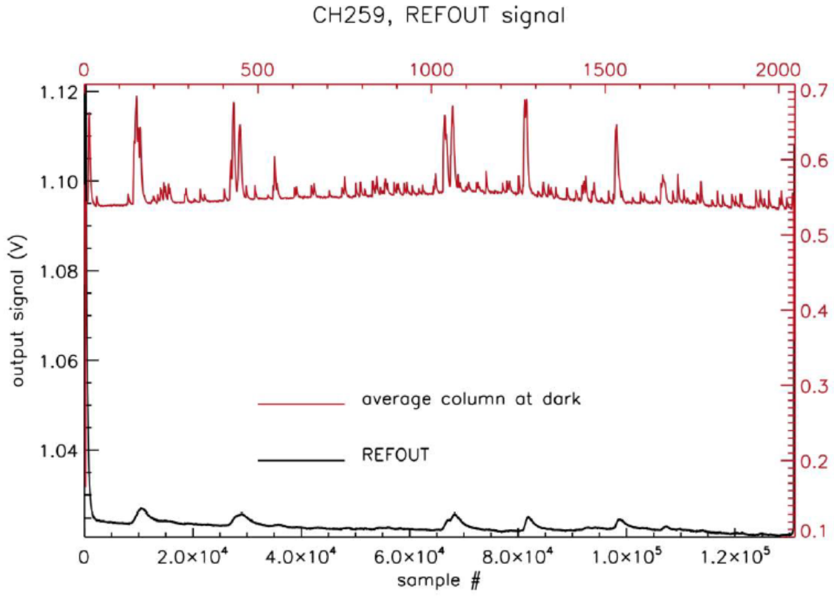
List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels
6. In 1 output and 4 outputs readout modes, the unused outputs are not powered off.
7. In 4 output mode the current in the SF is 8 times to high. In 1 output mode the current in the pixel SF is 32 times too high
8. Gradient of offsets
9. Reference pixel coupling with active pixel
10. Row reset
11. IPC mode (due to reset problems)

List of issues

1. Global reset cannot be programmed
2. REFOUT output signal sees only output follower and not the pixel source follower → Offset difference.
3. Output signal of active pixels is lowered by 1V during reset
4. Short circuit between bias voltage SUBPV and VREF during RESET (via test pixels).
5. Health check, coupling between test pixels
6. In 1 output and 4 outputs readout modes, the unused outputs are not powered off.
7. In 4 output mode the current in the SF is 8 times to high. In 1 output mode the current in the pixel SF is 32 times too high
8. Gradient of offsets
9. Reference pixel coupling with active pixel
10. Row reset
11. IPC mode (due to reset problems)
12. Reference output correlation with sensitive pixel

Separate reference output signal is correlated with sensitive pixel signal.



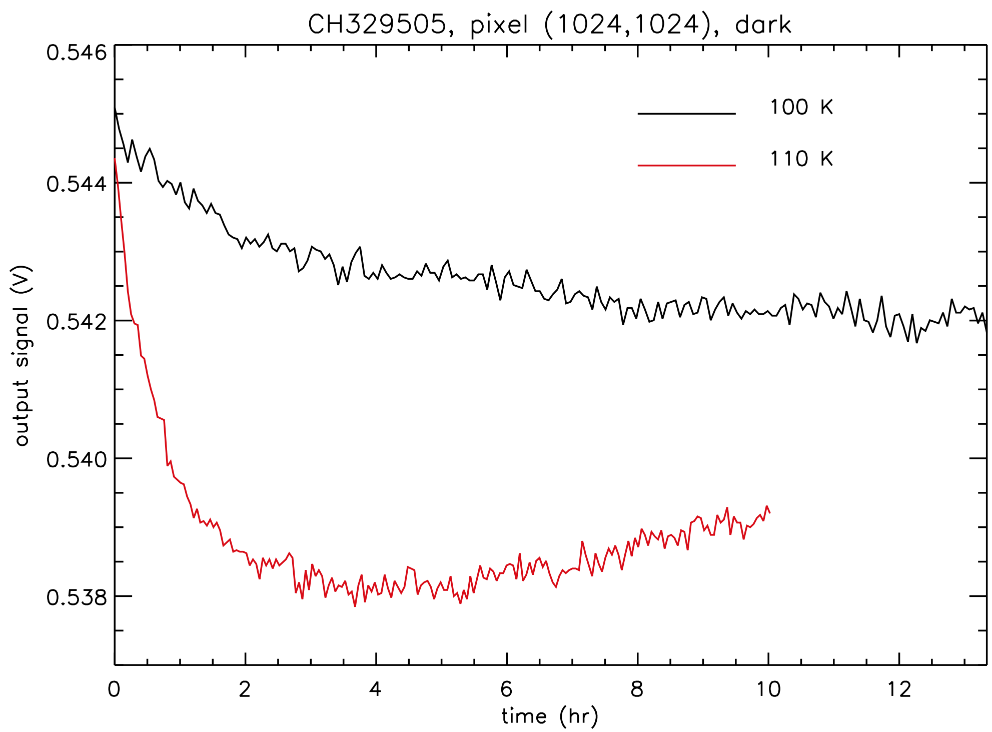
PLAN

1. Introduction
   1. General context
   2. ALFA requirements
   3. Test bench description
2. What works well
   1. Detector gain
   2. Crosstalk
   3. Dark current
   4. Detector cosmetics
   5. Linearity
3. What does not work so well
   1. Quantum efficiency
   2. Excess noise
   3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

Electrically stimulated persistence induced by reset

- Very long settling time at dark at Tdet ≤ 110K

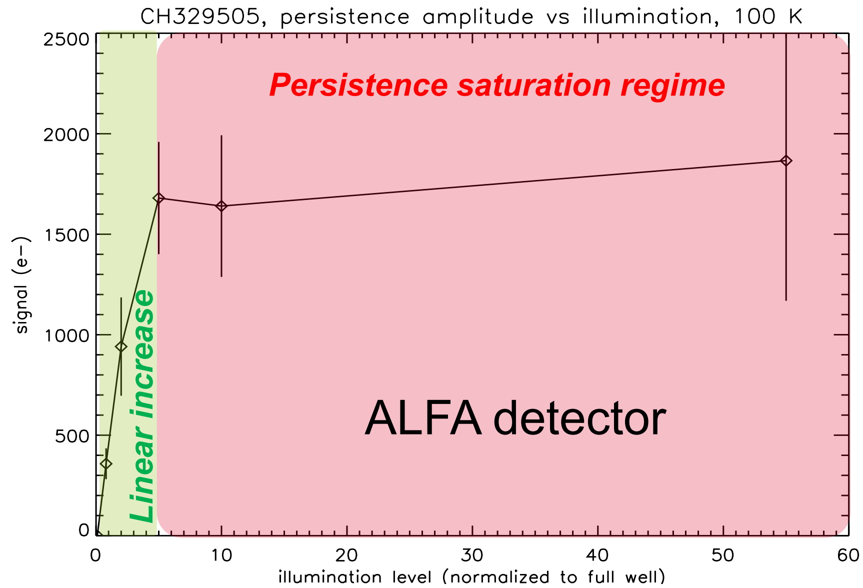
⇒ Duration of dark current measurement at 110 K > 10h, at 100 K > 20 h...



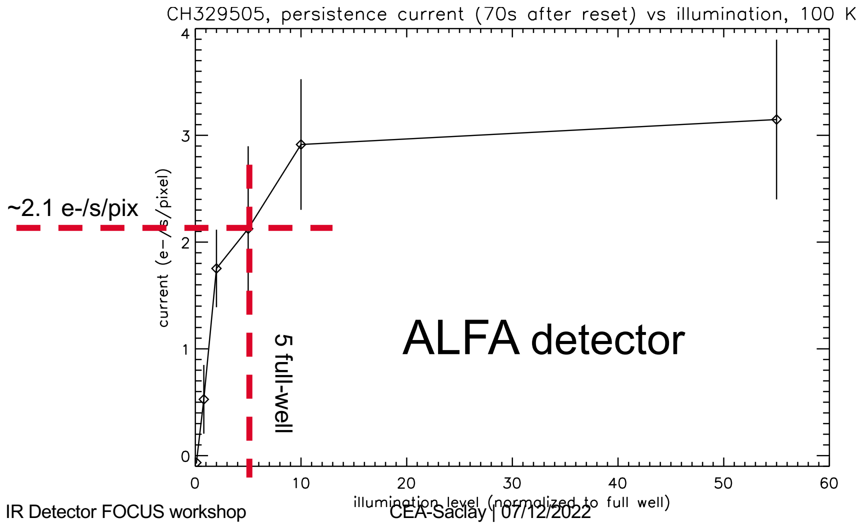
➔ The reset seems to be highly disturbing. It induces very long perturbations of the detector

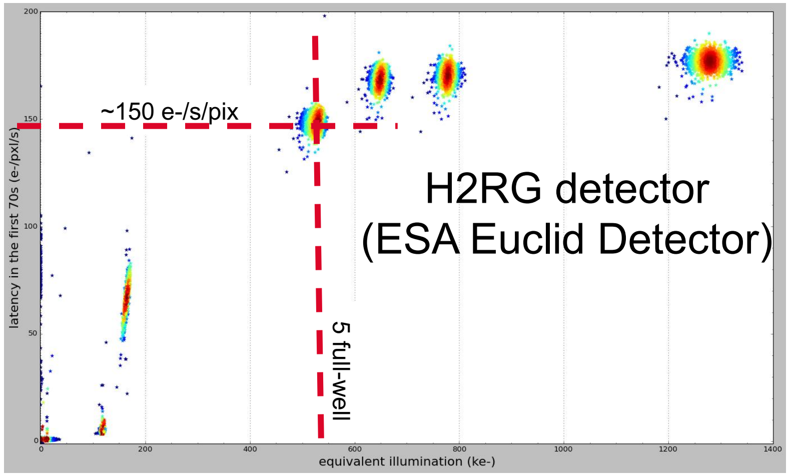
Optically stimulated persistence

- Persistence has been measured as a function of illumination level.
- Measurement protocol:
  1. Conditionning of the detector
  2. Dark reference
  3. Optical flash
  4. Persistence measurement
- Analysis protocol
  - Fit with 3 exponentials with a dark current contribution



Persistence current 70s after reset





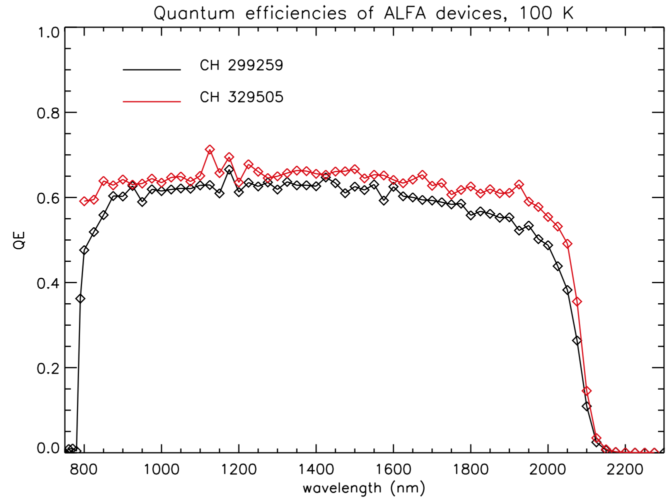
PLAN

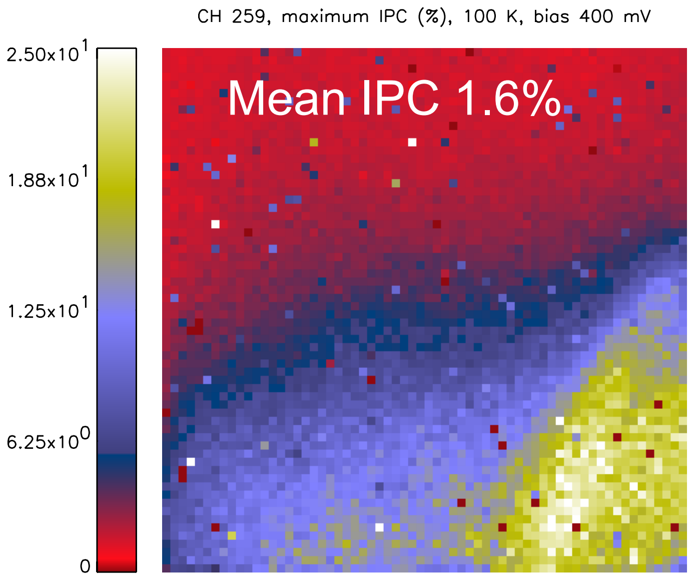
1. Introduction
    1. General context
    2. ALFA requirements
    3. Test bench description
2. What works well
    1. Detector gain
    2. Crosstalk
    3. Dark current
    4. Detector cosmetics
    5. Linearity
3. What does not work so well
    1. Quantum efficiency
    2. Excess noise
    3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

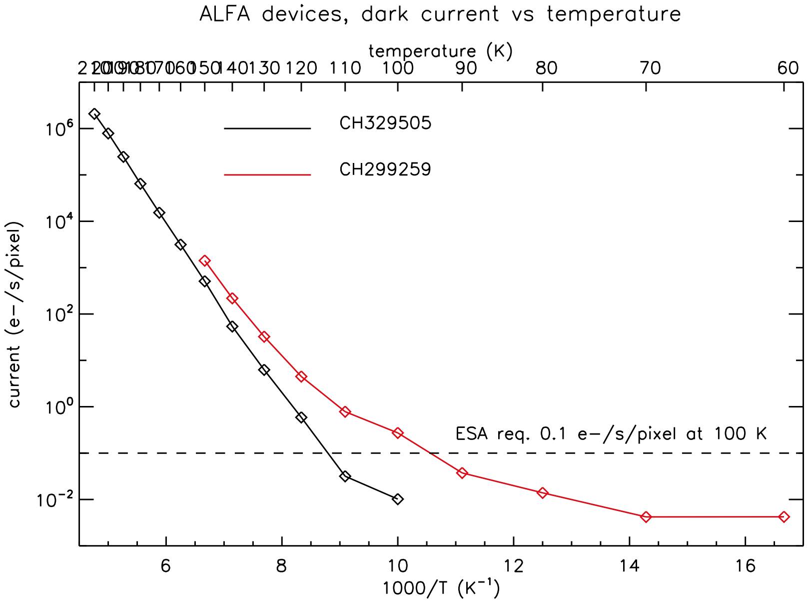
5. FEW WORDS ABOUT OTHER ALFA DETECTORS

Regarding the other good detector

- Same QE (about 60 %) ✗
- Same noise, and same ROIC problems ✗
- Dark current very low ✓
- Cross talk problem on the right left corner ✗







PLAN

1. Introduction
   1. General context
   2. ALFA requirements
   3. Test bench description
2. What works well
   1. Detector gain
   2. Crosstalk
   3. Dark current
   4. Detector cosmetics
   5. Linearity
3. What does not work so well
   1. Quantum efficiency
   2. Excess noise
   3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

ASTEROID: **AST**ronomy **E**u**RO**pean **I**nfrared **D**etection

- **Funding** :
  - European Commission
- **Development**:
  - Lynred (PV, 1st SWIR PV layer dedicated to very low flux applications) and CEA-Leti (ROIC)
- **Characterisation :**
  - Astrophysics Department, CEA
- **ASTEROID Specifications:**
  - ALFA like technology, HgCdTe-based IR detectors
  - 640x512 with a pixel pitch of 15µm.
  - **Spectral domain 0.8µm to 2.1µm.**
  - **Dark <0.1 e-/s/pix at 100 K**

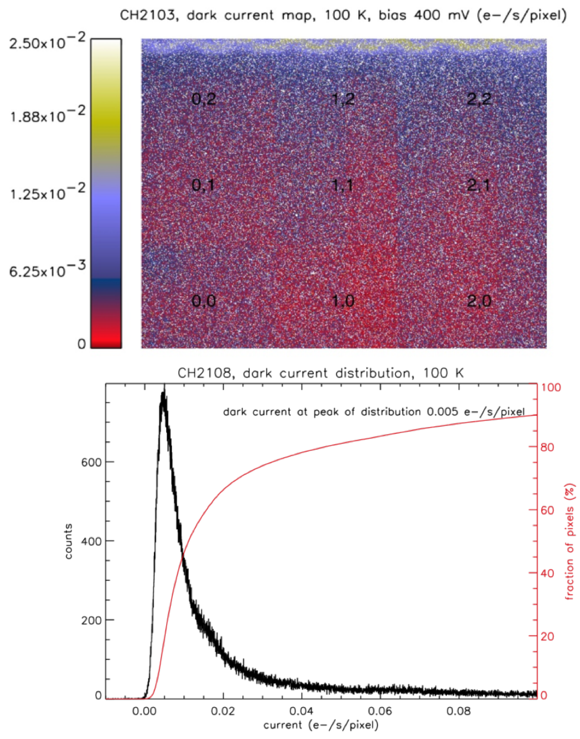
9 detectors manufactured
→ 7 delivered at CEA-Dap
→ 6 characterized

ref. LETI	Type	Characterized at DAP
21-07	étude I	Not delievred to DAp
21-09	Monovariante	

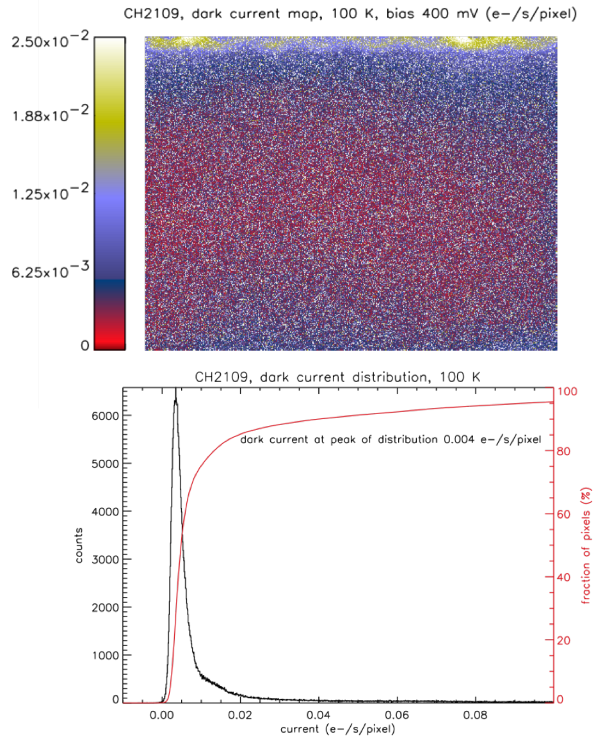
ref. LETI	General performance
21-03	Very good
21-08	Very good
21-09	Very good
21-02	Polluted by glow
21-04	Polluted by glow
21-06	Bad

- Detector bias: 400 mV
- Detector temperature: 100 K
- Detector operated in Following Up the Ramp: 10 hours long measurement, 1200 images

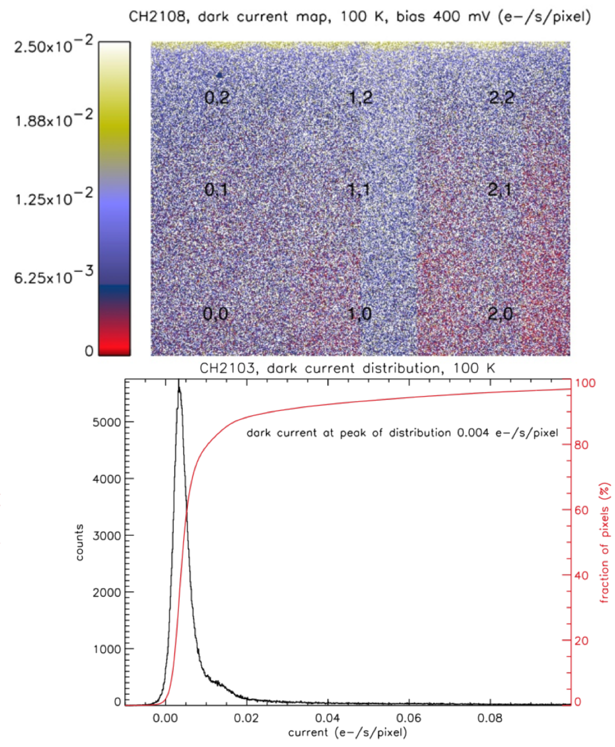
2108



2109



2103



Median dark current < 0.005 e-/s/pix

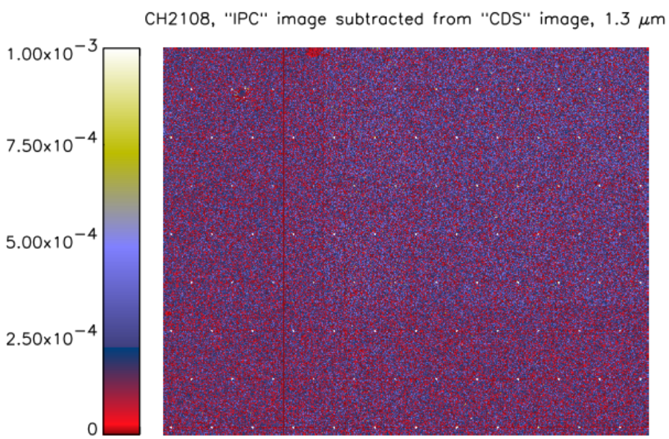
Despite glow mitigation protocol, glow of the output amplifier is still visible.

6. ASTEROID PROGRAM: LYNRED SWIR PV LAYERS
3. INTERPIXEL CAPACITANCE

A number of predefined pixels are keep under reset while the others integrate.

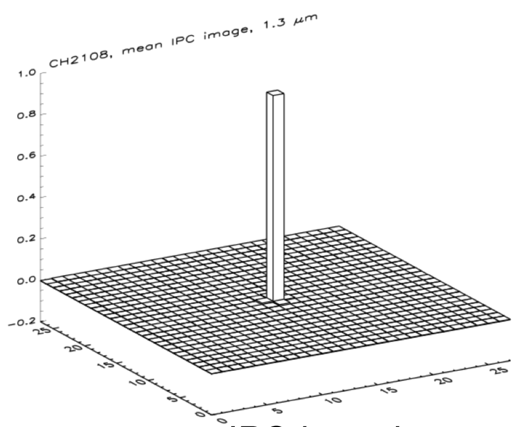
Two images are aquired:
1. One standard CDS image
2. One also in CDS with IPC pixels are kept under reset.

Difference of the two images give the « IPC image ». Image is then normalized to retrieve IPC.

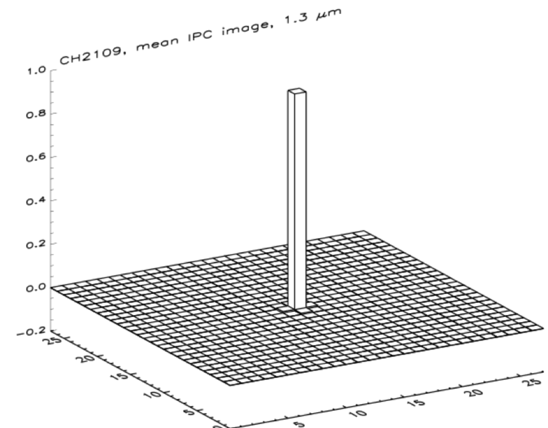


Results

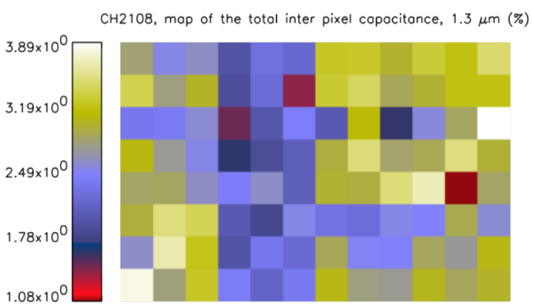
2108

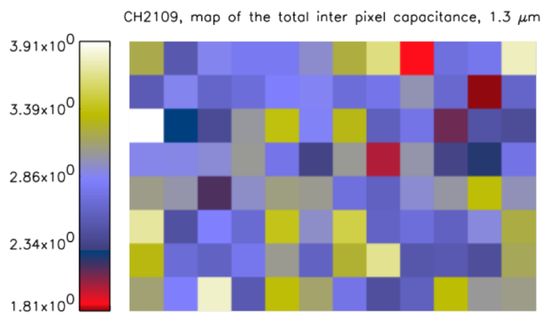


2109



IPC kernel measured on both detector



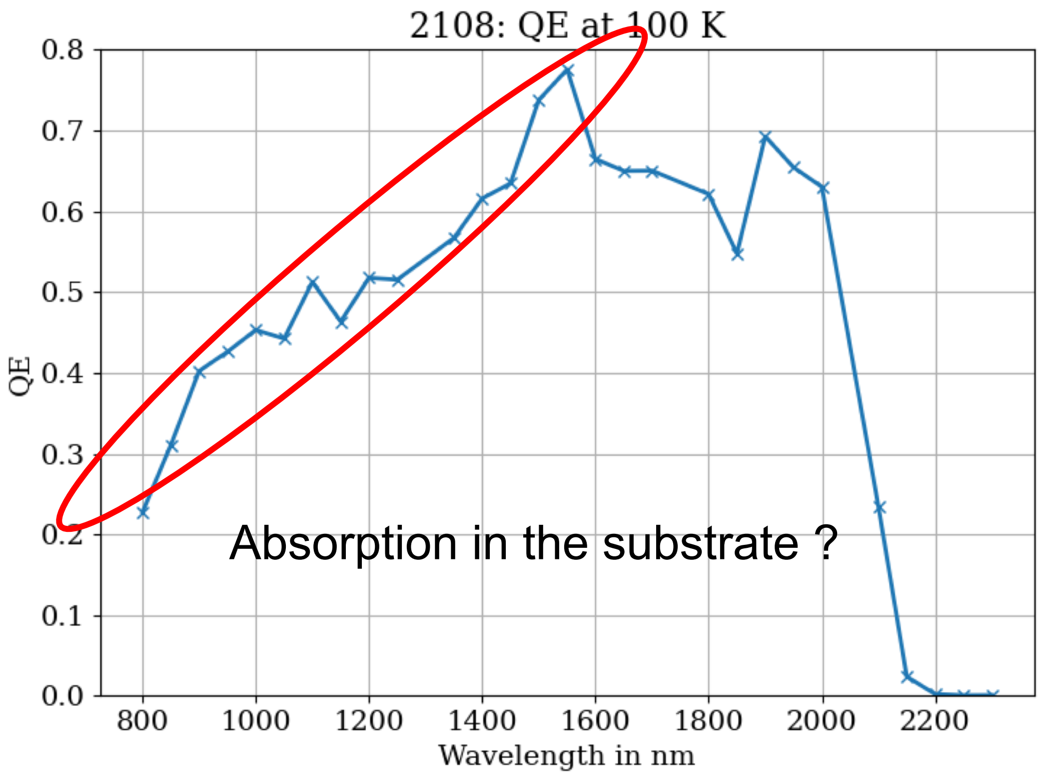


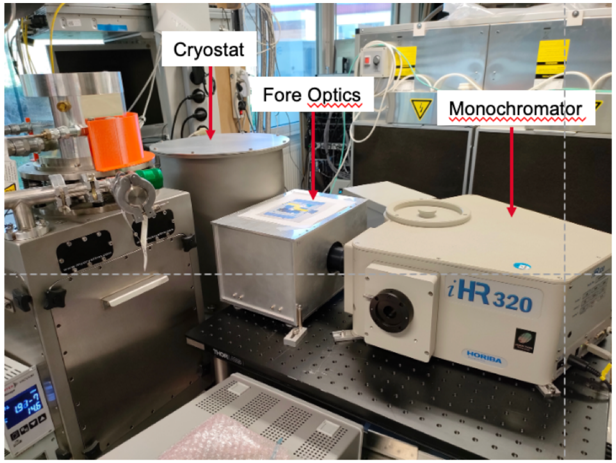
IPC map measured on both detector

The total mean IPC is lower than 2.6 % (sum of 8 pixels around central pixel)

6. ASTEROID PROGRAM: LYNRED SWIR PV LAYERS
4. QUANTUM EFFICIENCY MEASUREMENT

The **Quantum Efficiency (QE)** of the detector has been measured on Quantix test bench.





Picture of the Quantix test bench

- Cut off wavelength: **2.05 µm**
- 12 % uncertaintity on QE measurements (dominated by measurement of the photodiode current)

The **Pixel Response Non Uniformity (PRNU)** at 1.3 µm is very good, **around 2% for all diode technologies**: for each diode technology, the photonic current in each corresponding subarea of the array was normalized to its mean value)

PLAN

1. Introduction
    1. General context
    2. ALFA requirements
    3. Test bench description
2. What works well
    1. Detector gain
    2. Crosstalk
    3. Dark current
    4. Detector cosmetics
    5. Linearity
3. What does not work so well
    1. Quantum efficiency
    2. Excess noise
    3. General comments on ROIC problems
4. Persistence
5. Few words about other ALFA detectors
6. ASTEROID program: Lynred SWIR PV layers
7. Final conclusions

7. IN A NUTSHELL

Lynred and CEA-Leti demonstrate rather good PV layer manufacturing capability
...but lots of ROIC problems

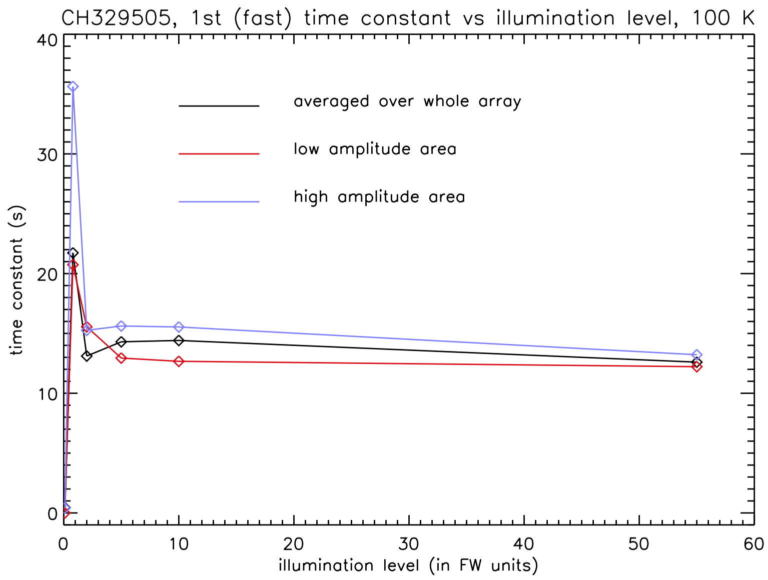
Detector	EUCLID H2RG detector, 2.3 µm cutoff	CEA/LETI CH1403 (ESA ref for Quantix, 1st phase of ALFA program)	ASTEROID: Lynred CH2109	ASTEROID: Lynred CH2108 Detector with different diode geometries	ASTEROID: Lynred CH2103 Detector with different diode geometries	ALFA: CEA/LETI CH329505 (Detector CAGIRE)
IPC (%)	2.1-2.6	2.4	2.5	2.3	To be measured	2.3
QE	~80 %	~80 %	To be measured	max 75 %	To be measured	60 %
Dark current at 100 K in e-/s/pix	0.0052 (Phd Serra B.)	~1 (polluted by glow, to be remeasured)	0.004	0.003-0.006	0.002-0.005	0.004

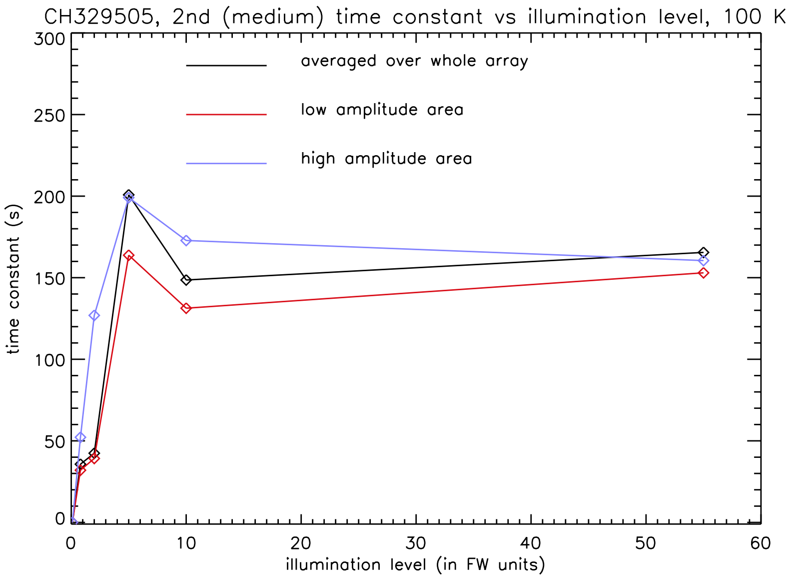
The results are highly encouraging, but further improvement would require:

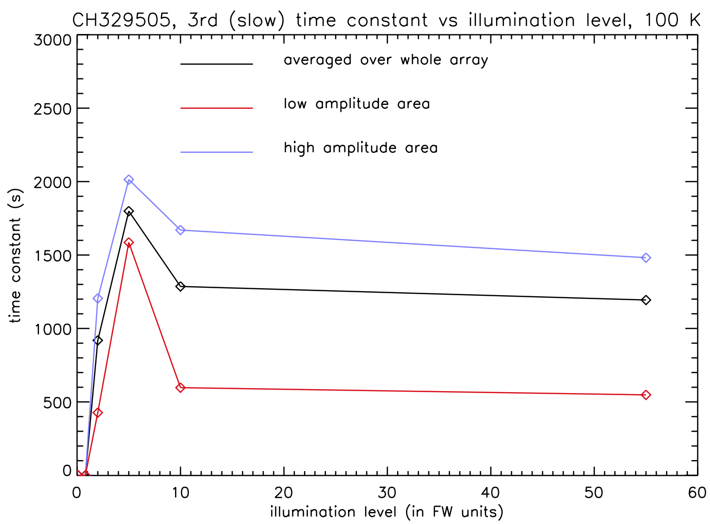
1. 2nd version of ROIC
2. Additionnal manufacturing of ALFA detectors to improve statistics

BACK UP

BACK UP


CH329505, 1st (fast) time constant vs illumination level, 100 K
averaged over whole array
low amplitude area
high amplitude area
time constant (s)
illumination level (in FW units)
0
10
20
30
40
0
10
20
30
40
50
60


CH329505, 2nd (medium) time constant vs illumination level, 100 K
averaged over whole array
low amplitude area
high amplitude area
time constant (s)
illumination level (in FW units)
0
50
100
150
200
250
300
0
10
20
30
40
50
60


CH329505, 3rd (slow) time constant vs illumination level, 100 K
averaged over whole array
low amplitude area
high amplitude area
time constant (s)
illumination level (in FW units)
0
500
1000
1500
2000
2500
3000
0
10
20
30
40
50
60