University of Glasgow | Department of Physics & Astronomy

STREAM

A study of the effects of ionizing radiation on CMOS pixel sensors

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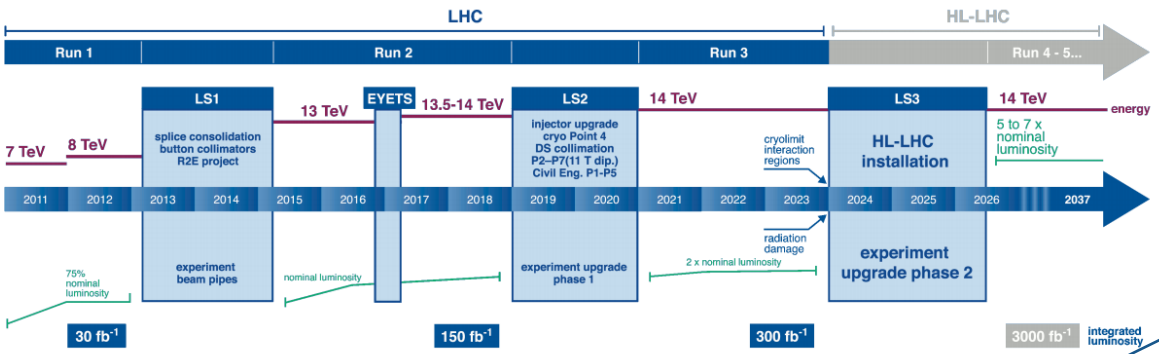
17/09/2019, STREAM Final conference

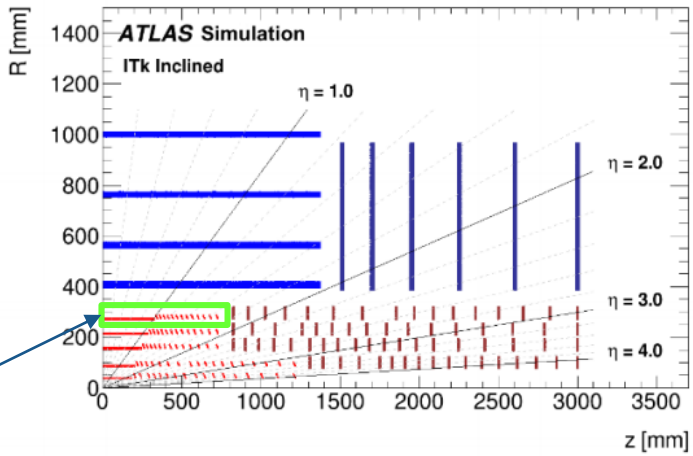
OUTLINE

- **ATLAS Inner Detector upgrade**
- **Introduction to Ionizing radiation damage**
- **X-ray irradiation facility at the University of Glasgow**
- **TowerJazz CMOS sensor development for the ATLAS ITk**
- **MALTA sensor irradiation campaign**
- **Mini-MALTA sensor irradiation campaign**
  - Analog signal results
  - Threshold calibration results
  - Fluorescence measurements
- **Conclusions**

HL-LHC requirements

LHC upgrade on 2024 to increase luminosity (HL-LHC)

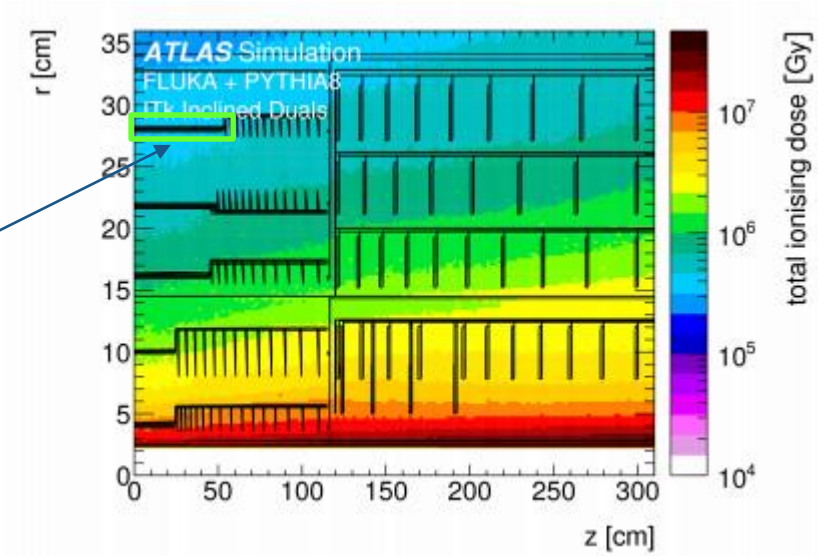




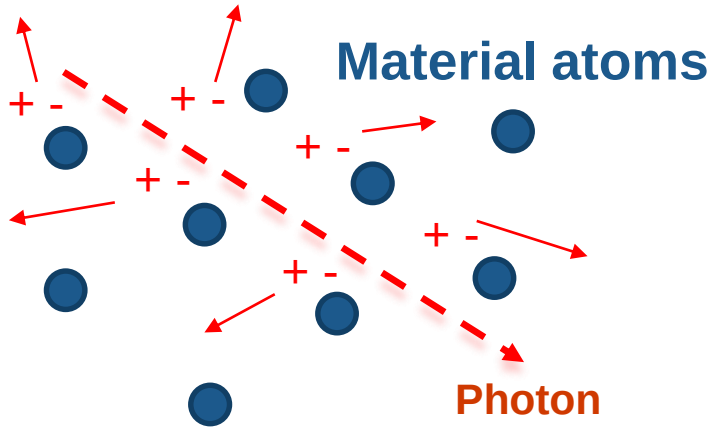
- Proposed option for the outermost Layer 4: Depleted Monolithic Active CMOS sensors (DMAPS)
- 45% of the outer barrel!

Radiation tolerance requirements:

- NIEL 1e15 neq/cm2
- **TID 80 Mrad**
- Hit rate 100 – 200 MHz/cm^2
- Timing resolution 25 ns



Ionizing radiation damage

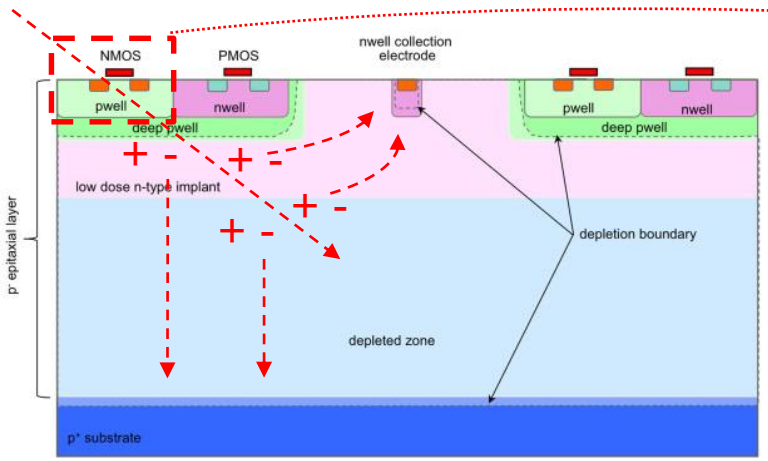


Units: Radiation Absorbed Dose (RAD)

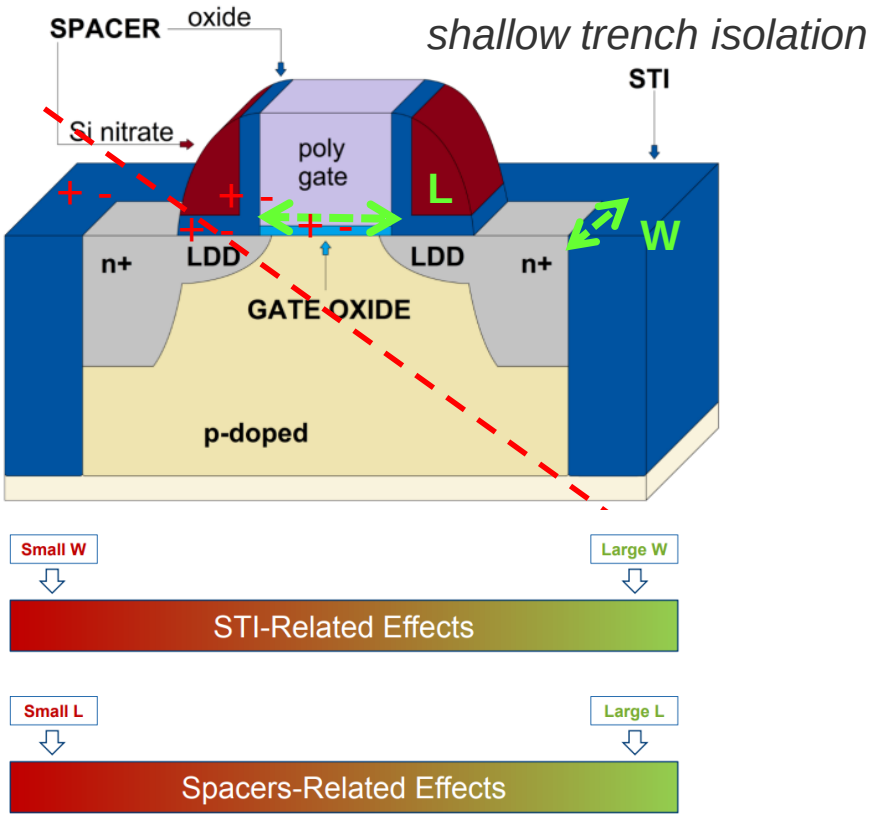
1 rad = 0.01 J/kg = 8.1 x 10^{12} e-h/ cm^3 (SiO_2)

Lasting damage done on SiO_2:

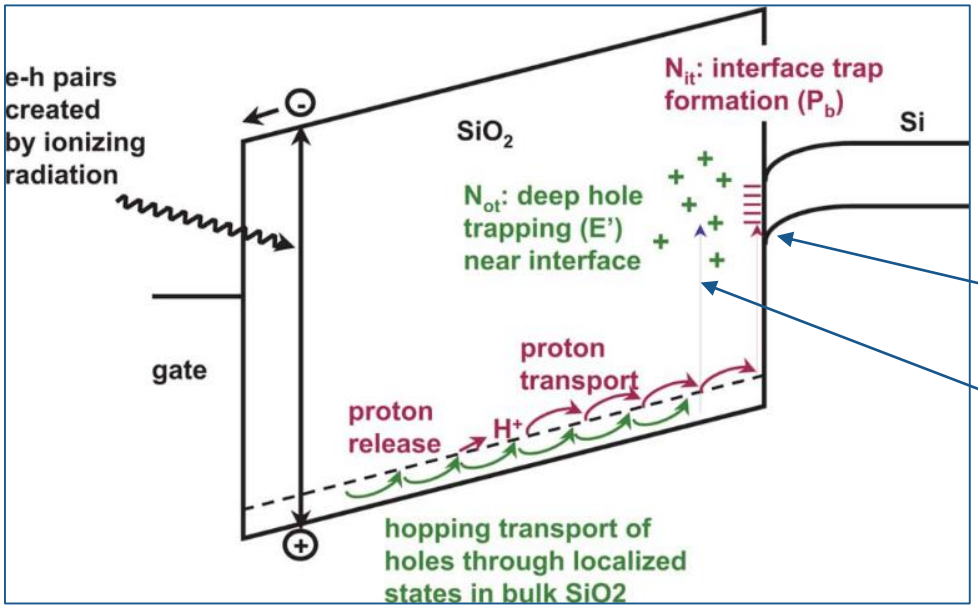
Radiation damage in Si bulk is reversible:



W. Snoeys et al., NIM A871 (2017) 90 – 96.



Effects of TID on MOS devices



Schwank, James R., et al. IEEE Trans. Nucl. Sci. 55.4 (2008): 1833-1853.

	nMOS	pMOS
Oxide traps	+	+
Interface traps	-	+

Threshold voltage shift:

- Negative for pMOS
- From negative to positive for nMOS

→ Expect degradation of front-end functionality

Anneal from 400 ºC

Anneal at room temperature

→ Time between measurements has to be consistent

Number of traps increase linearly up to 1 MRad

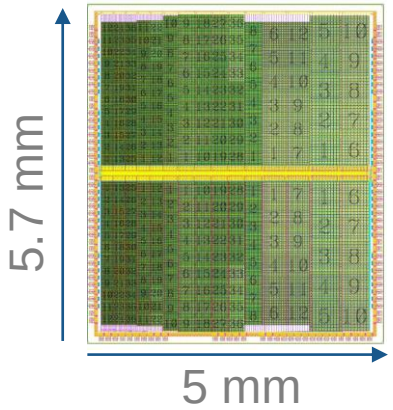
→ Fine steps to observe evolution

TJ CMOS DMAPS development

2015/2016 → **2017/2018** → **2019/Present**

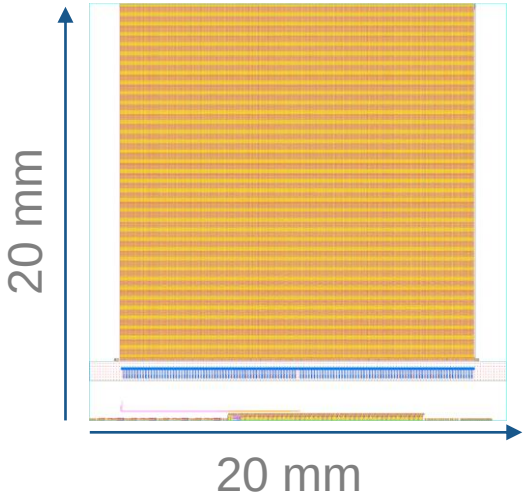
TJ Investigator1

Multiple pixel designs to determine optimal pixel performance



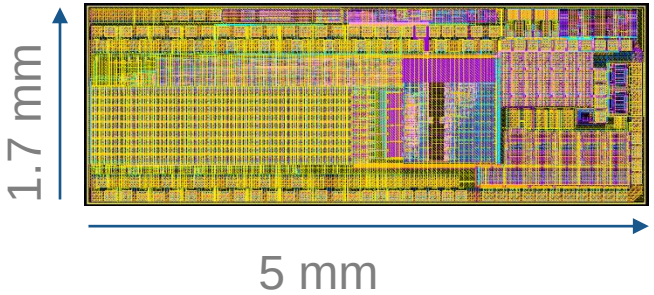
MALTA

Full ATLAS size demonstrator with a novel asynchronous readout



Mini-MALTA

Following the MALTA characterisation results, this chip implements features to improve radiation hardness



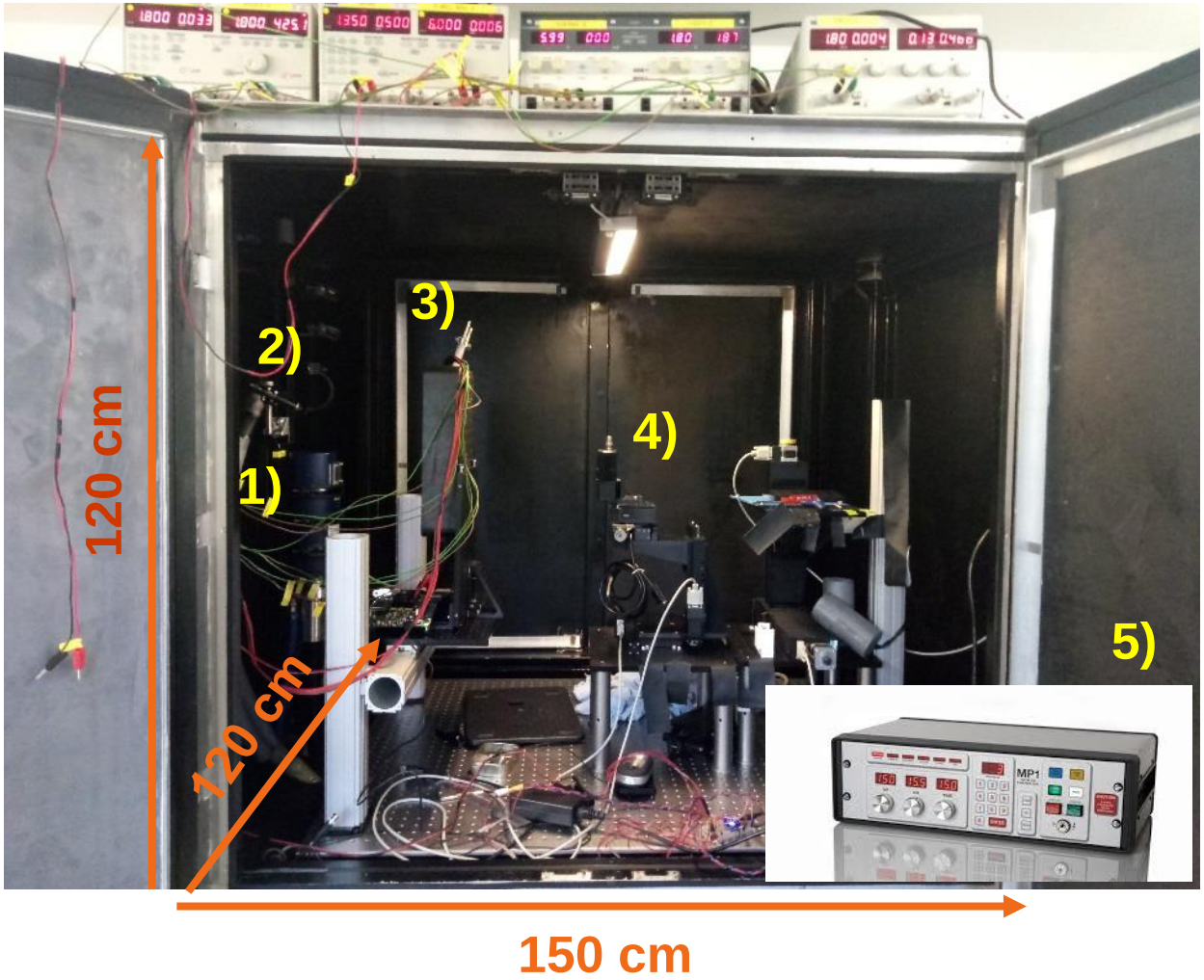
TowerJazz 180 nm technology with process modification

Small electrode with high resistivity (>1kΩ cm) p-type epitaxial layer

Allow for reverse bias to improve charge collection and radiation hardness

X-ray chamber overview

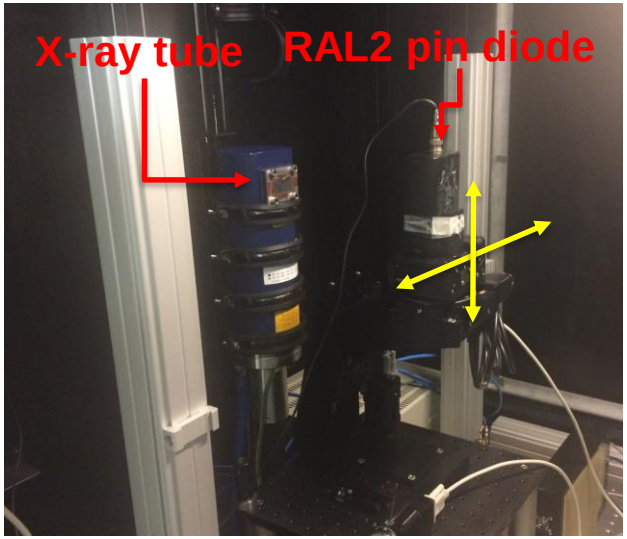
1) X-ray tube operated at 50 kVp (6.3 mA)
2) Laser sample alignment system
3) 35x25x6 cm^3 cold sample box (down to 0 °C with Silicone oil circulation)*
4) X-ray dosimetry done using a calibrated pin diode from RAL**
5) Gulmay MP1 integrated controller



** Lower temperatures are achieved with Peltier cooling based system*

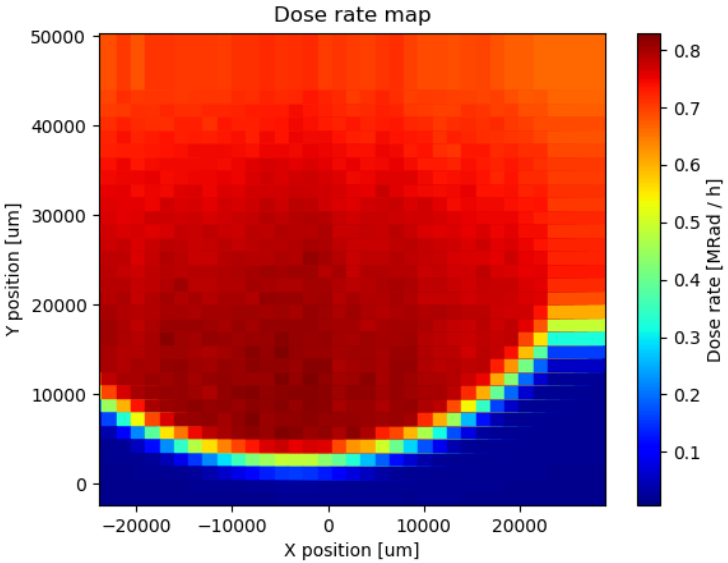
** Rutherford Appleton Laboratory, Oxfordshire (UK)

X-ray metrology

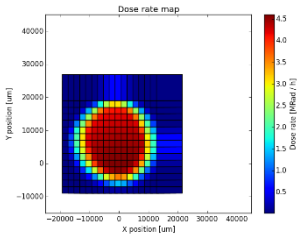


- RAL diode mounted in X-Y stages
- Biased at -5V and current consumption read back
- **Current ∝ intensity ∝ dose**

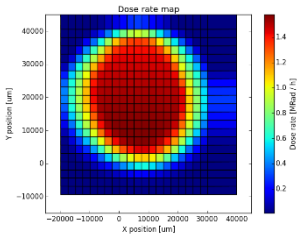
1) Dose rate measured at different positions by moving X-Y stages



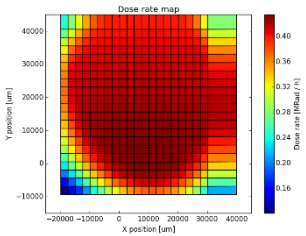
Z = 10 cm
3.1 Mrad/h
10x10 mm



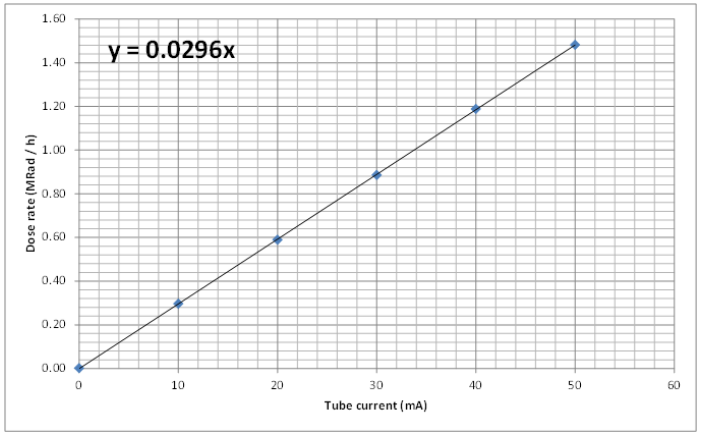
Z = 20 cm
1.3 Mrad/h
20x20 mm



Z = 40 cm
0.45 Mrad/h
30x30 mm



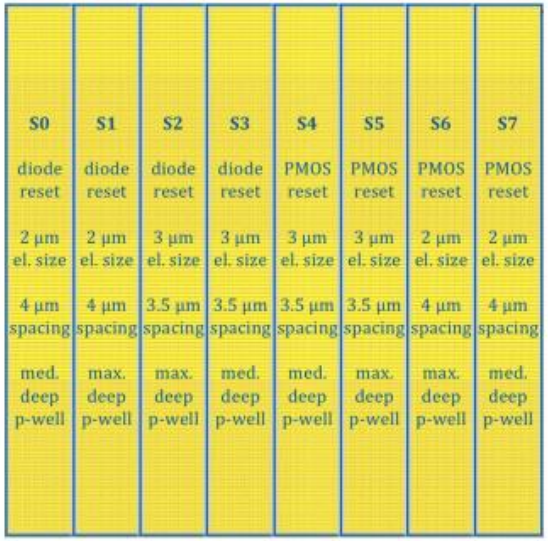
2) At the beam position, vary the potential applied by Gulmay controller to tune the dose rate



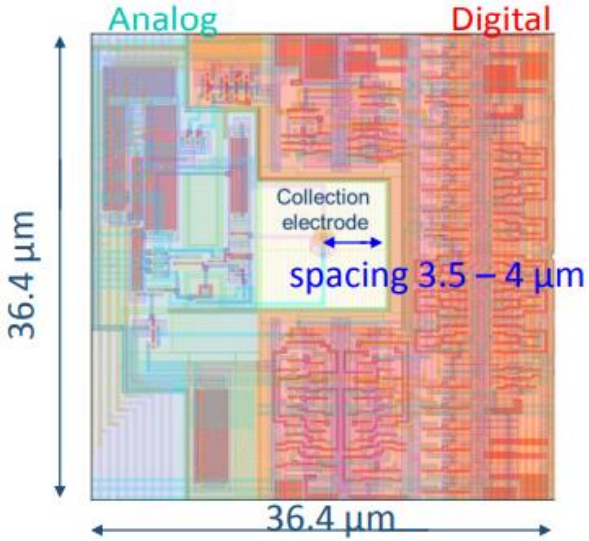
The MALTA sensor

Chip characteristics:

- Full ATLAS size demonstrator
- Size: 20 x 20 mm^2
- Pixel size: 36 x 36 um^2
- 512 x 512 pixels (8 flavours)



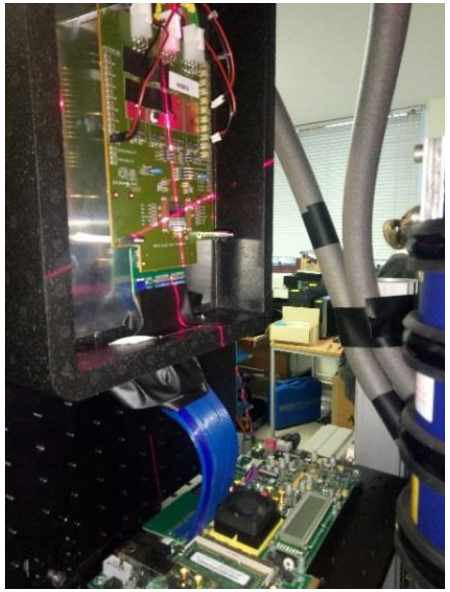
- Asynchronous readout -> low power:
  - Analog power ≈ 1 µW per pixel (75 mW/cm2)
  - Digital power (Layer 4) ≈ 10 mW/cm2

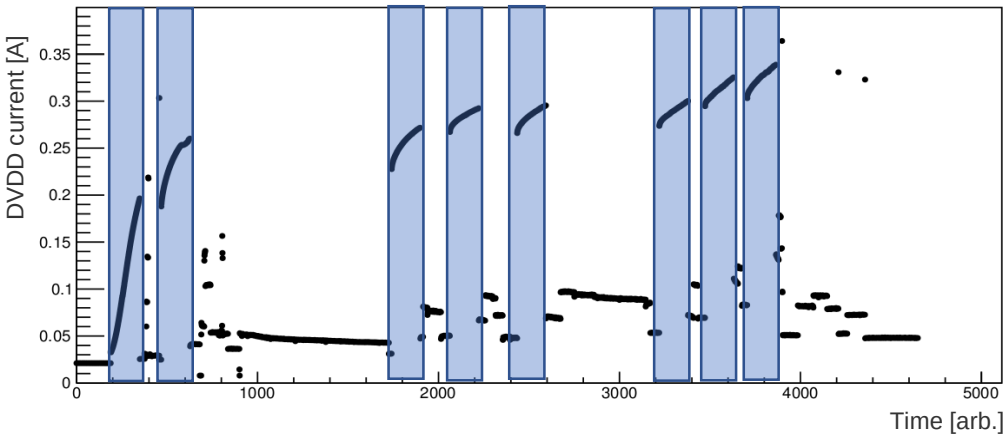


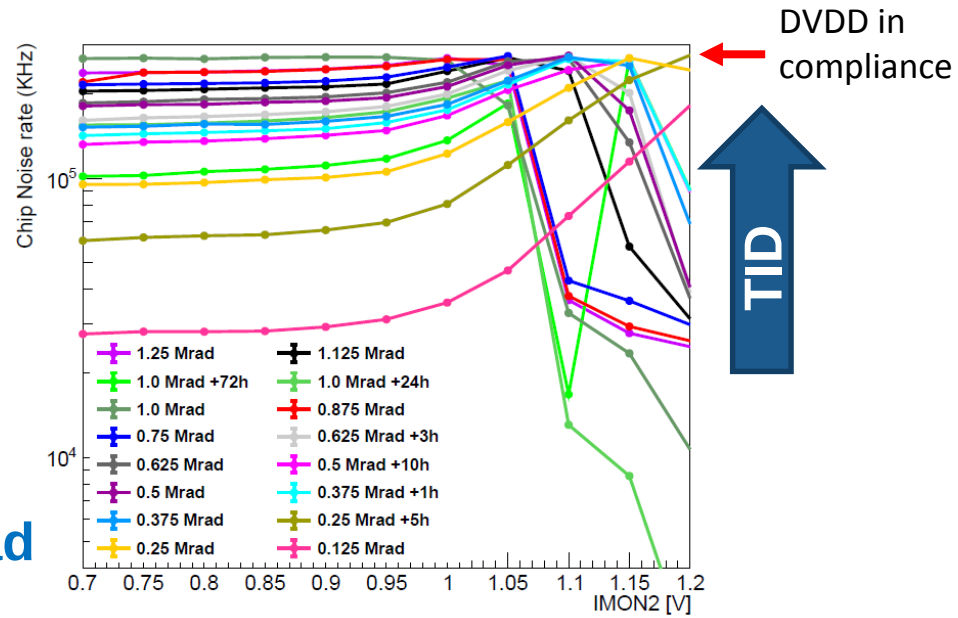
Malta TID irradiation campaign

IRRADIATION SUMMARY:

- 2.5 Mrad
- 0.25 Mrad/h
- Monitored Noise, Threshold, Gain, analog waveforms and current consumption
- Chip powered during irradiation
- Cooled down to 0 ºC



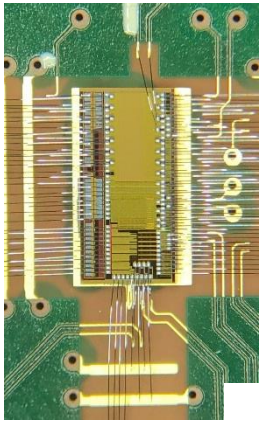




High noise in few pixels + no masking

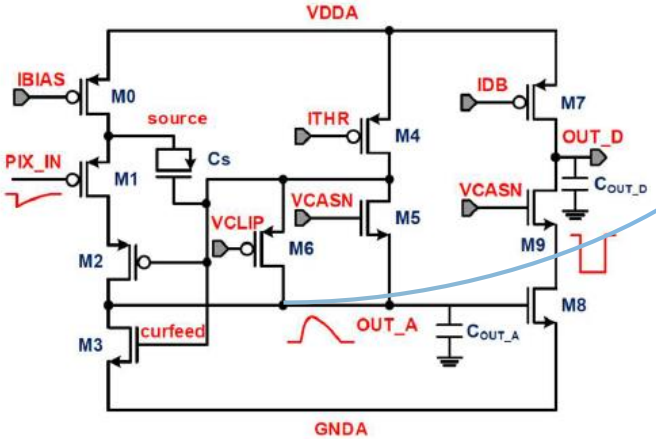
Not able to operate the chip after 2.5 MRad

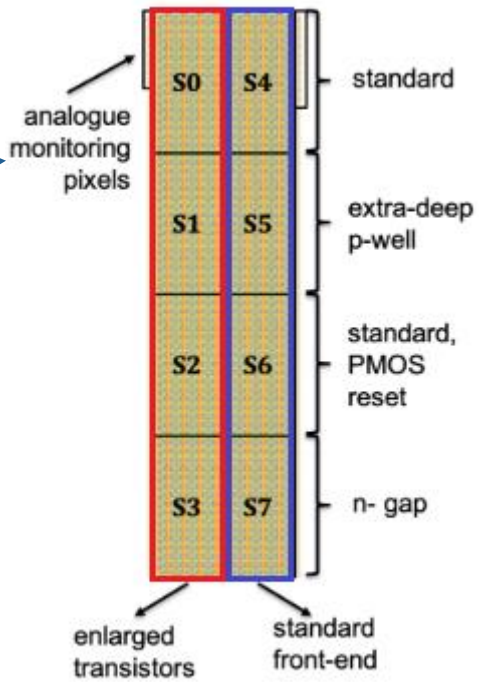
The mini-MALTA sensor



Chip characteristics:

- Size: 1.7 x 5 mm^2
- Pixel size: 36.4 x 36.4 um^2
- 16 x 64 pixels (8 flavours)





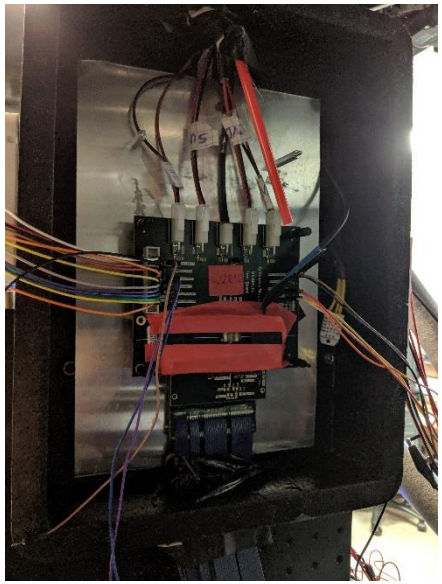
Transistor	Standard	Enlarged
M3	W = 1 μm L = 0.18 μm	W = 1.22 μm L = 0.38 μm
M6	W = 0.44 μm L = 0.18 μm	W = 0.88 μm L = 0.18 μm

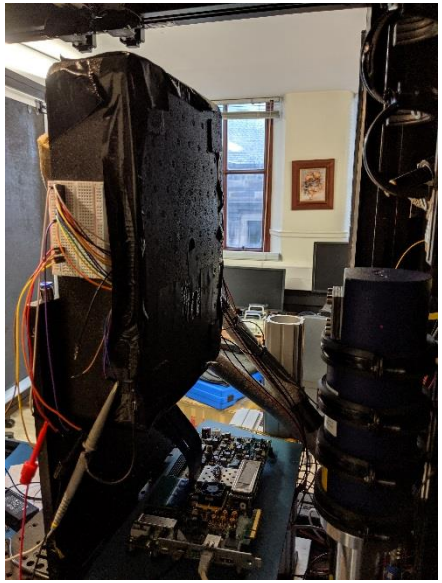
Improvements:

- Larger transistors to reduce RTS noise
- Extra-deep p-well implant and n-gap sectors to improve collection efficiency

See R. Cardella presentation

Mini-MALTA irradiation





Cold environment:

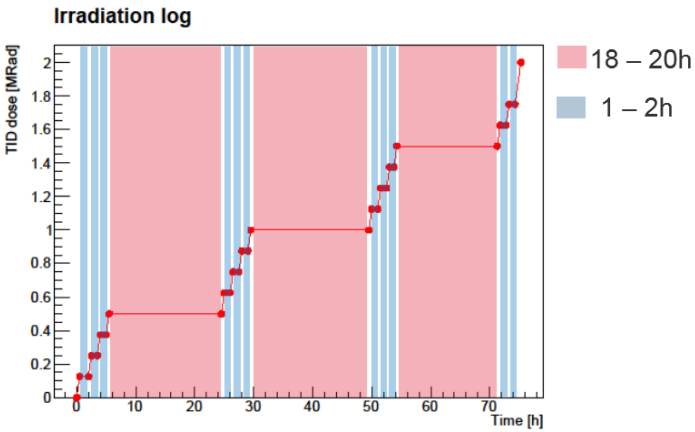
- Silicone oil flow: -40ºC
- Dry air pump
- Humidity monitor
- PCB temperature monitored: 0ºC

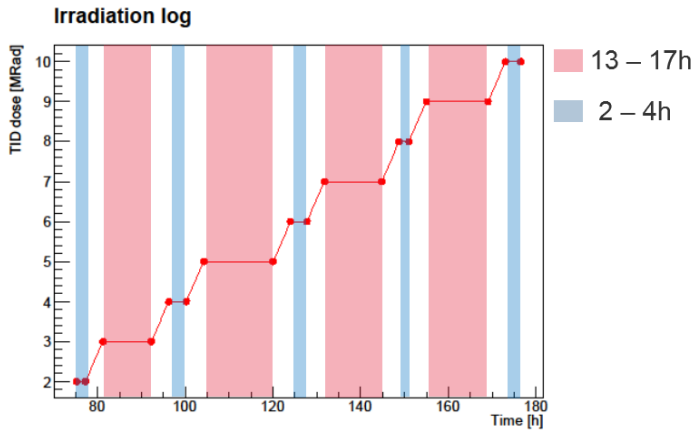
Electrical functionality tests:

- 0 – 2 Mrad: 0.125 Mrad step
- 2 – 10 Mrad:1 Mrad step
- 10 – 80 Mrad: 5 Mrad step

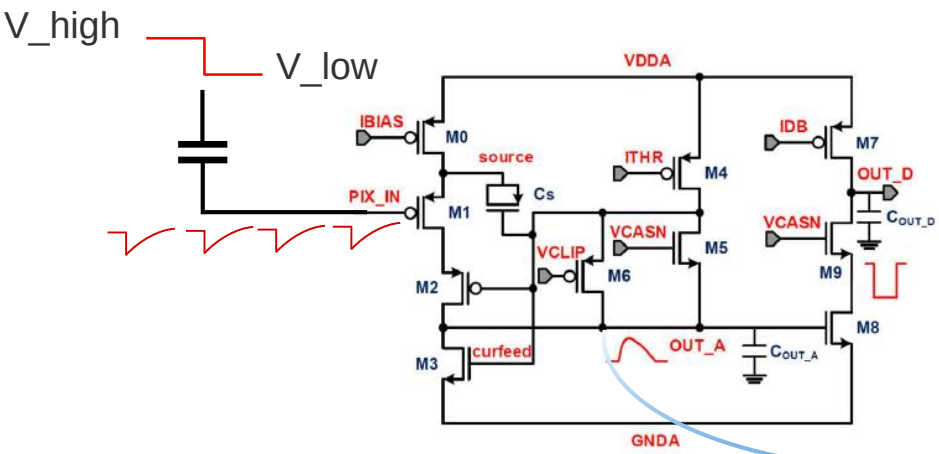
Irradiation parameters:

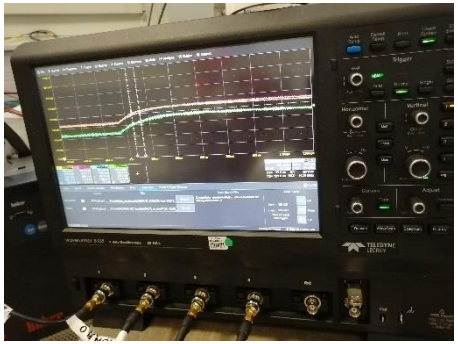
- 50 kVp X-rays
- 0.25 MRad/h
- Delivered 80 MRad



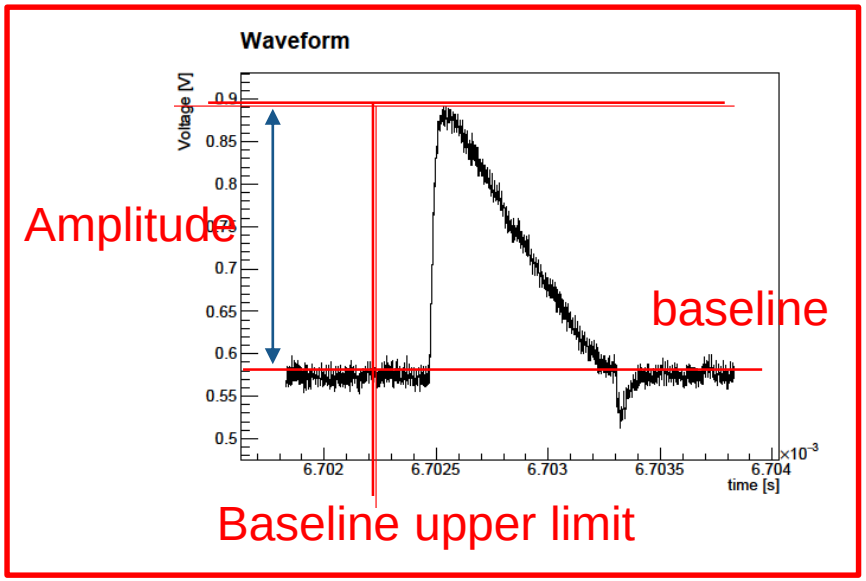


Analog waveform output

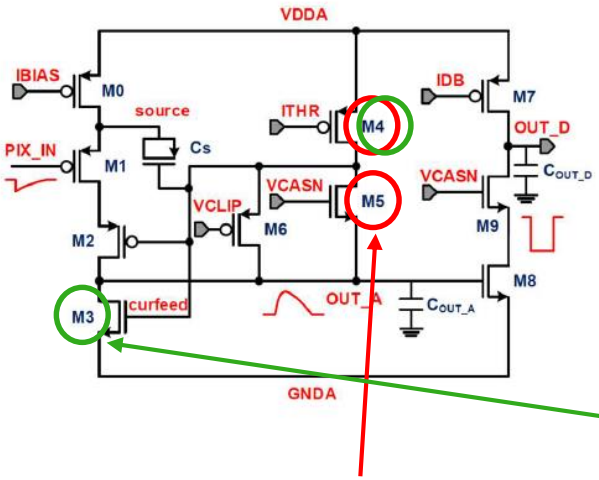




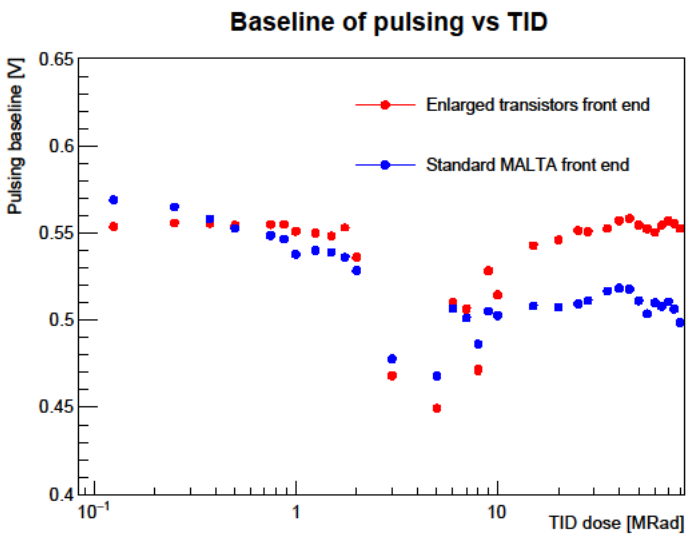
- Send pulses of the same amplitude
- Record 128 waveforms on the analog output
- Compute parameters offline

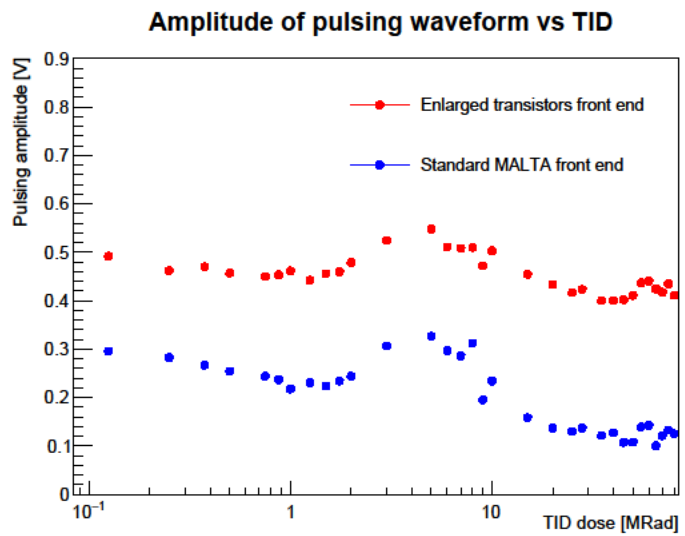


Analog waveform output

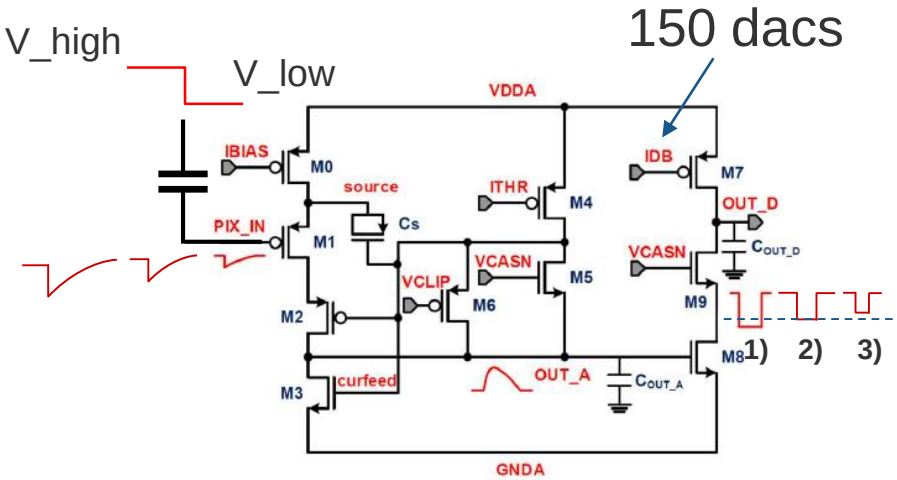


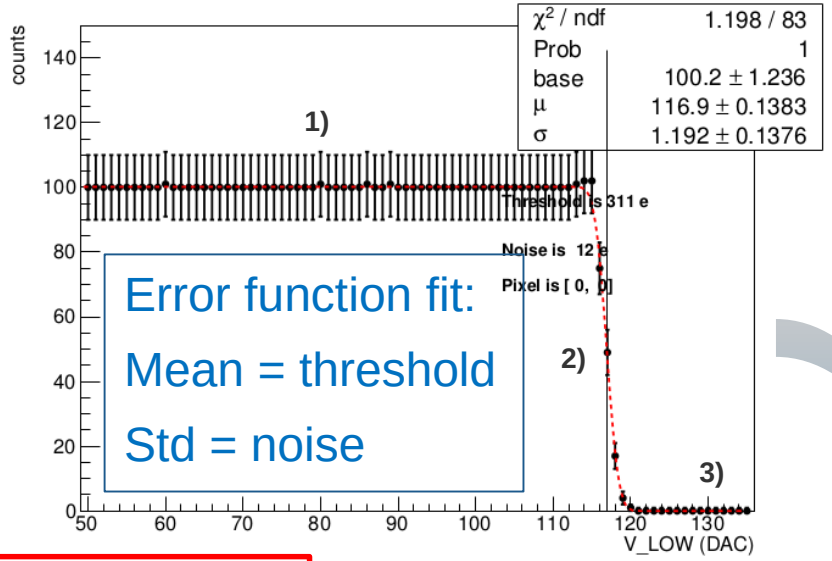
	Baseline	Amplitude
Std/ET (0 MRad)	0.96	0.6
Std/ET (80 MRad)	0.90	0.41
ET 80 / ET 0	0.996	0.93
Std 80 / Std 0	0.87	0.63





Threshold Scans

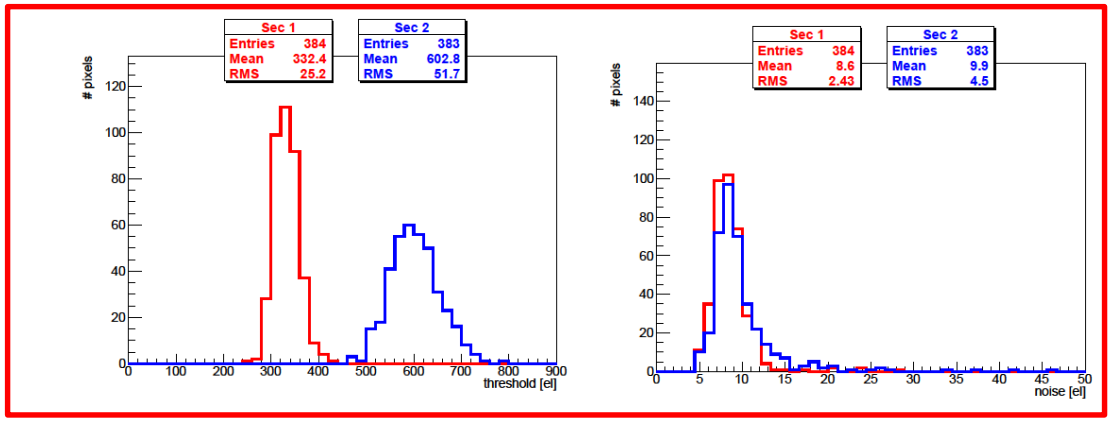


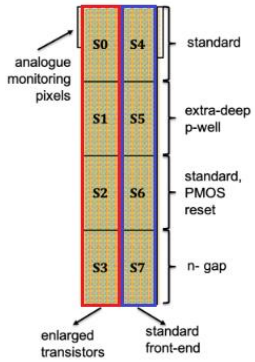


Error function fit:

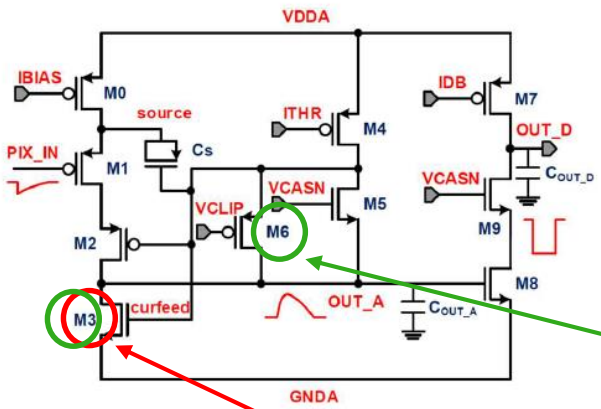
Mean = threshold

Std = noise

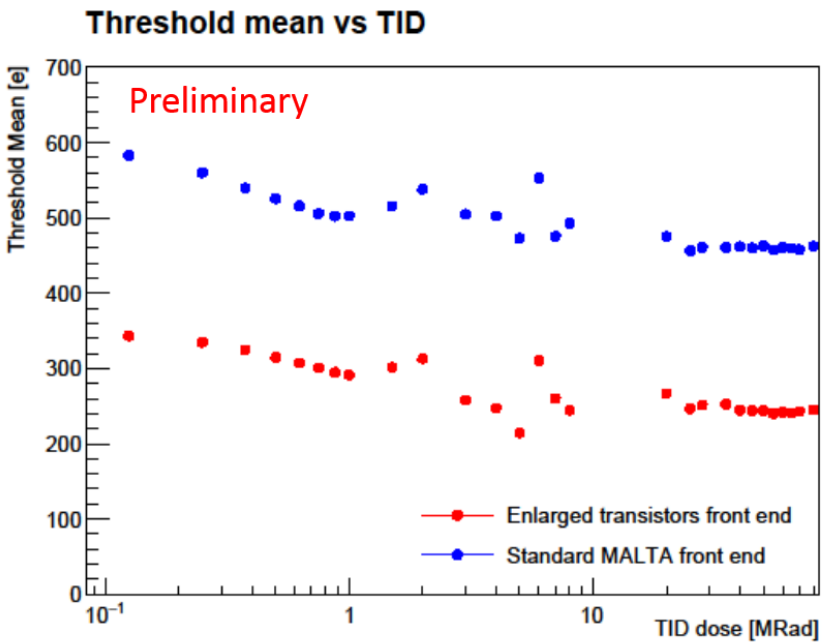


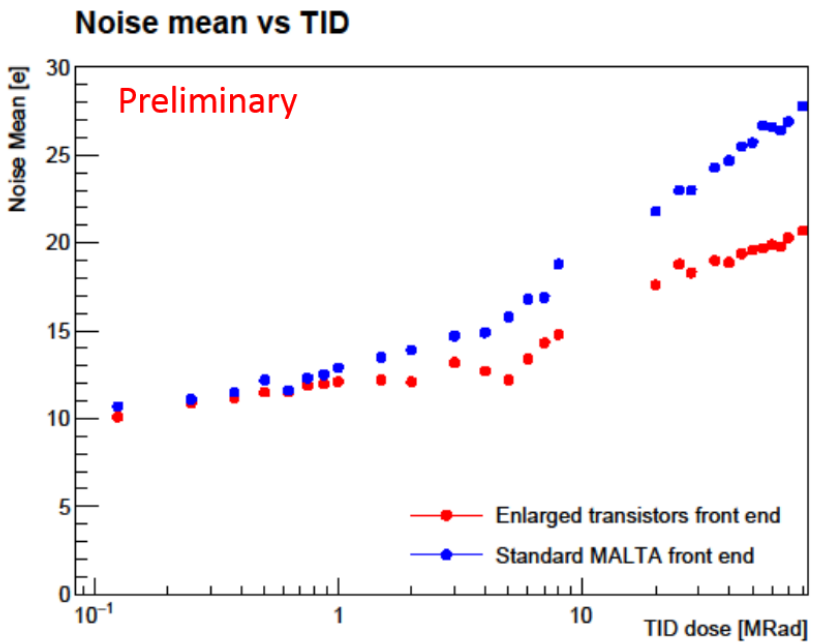


Threshold scans - Mean

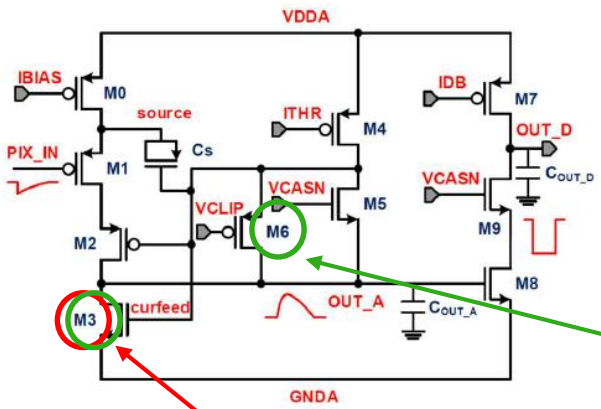


	Threshold	Noise
Std/ET (0 MRad)	1.81	0.87
Std/ET (80 MRad)	1.88	0.74
ET 80 / ET 0	0.74	2.4
Std 80 / Std 0	0.76	2.8

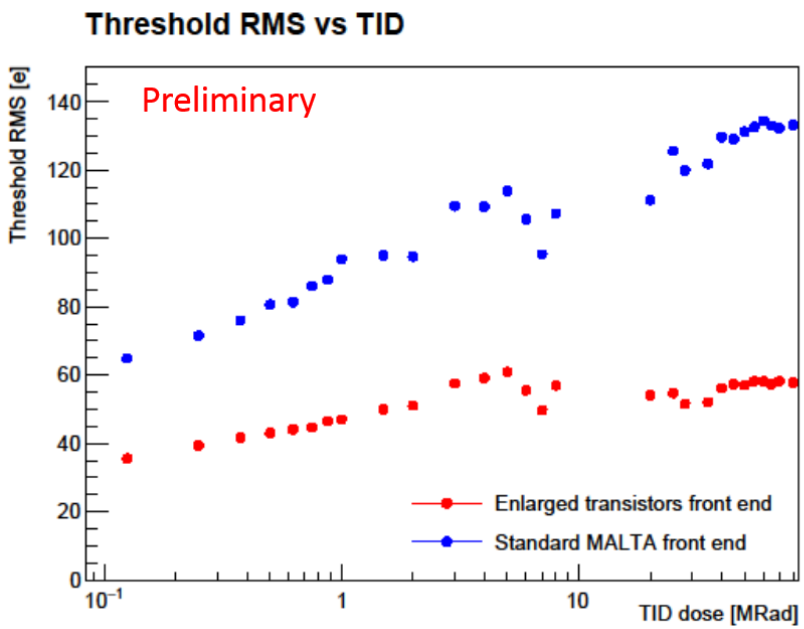


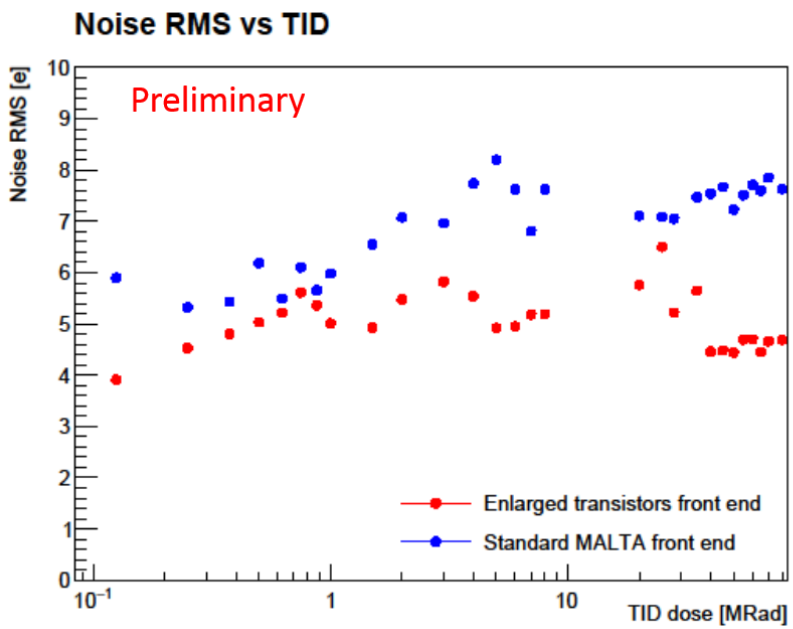


Threshold Scans - RMS



	Threshold	Noise
Std/ET (0 MRad)	2.05	1.88
Std/ET (80 MRad)	2.3	1.62
ET 80 / ET 0	2.29	1.68
Std 80 / Std 0	2.6	1.93

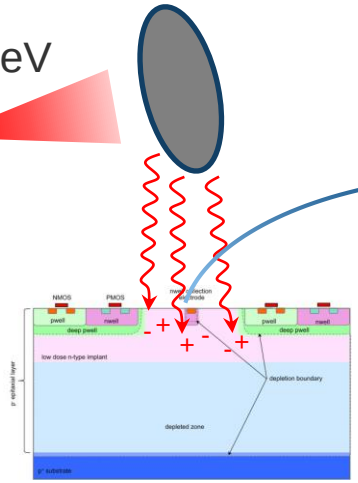


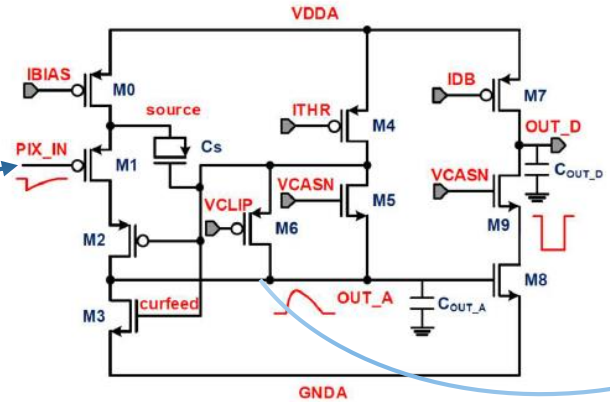


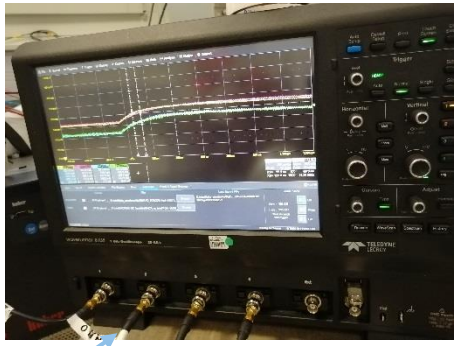
Fluorescence measurements

Fe (6.4 keV) / Ti (4.5 keV)

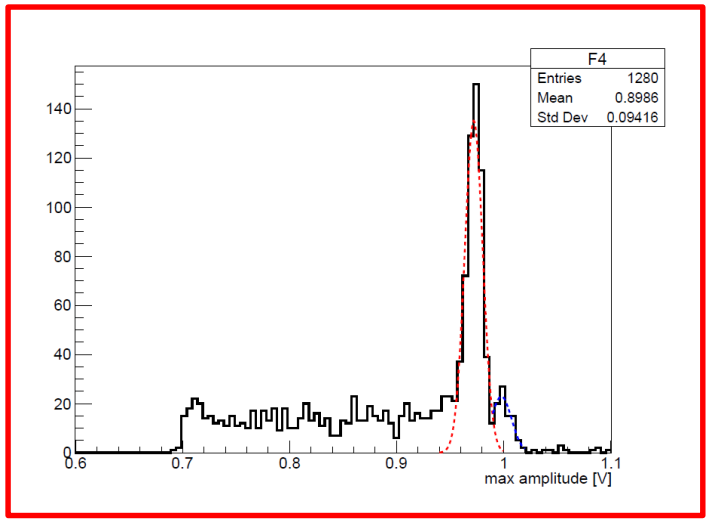
30 keV



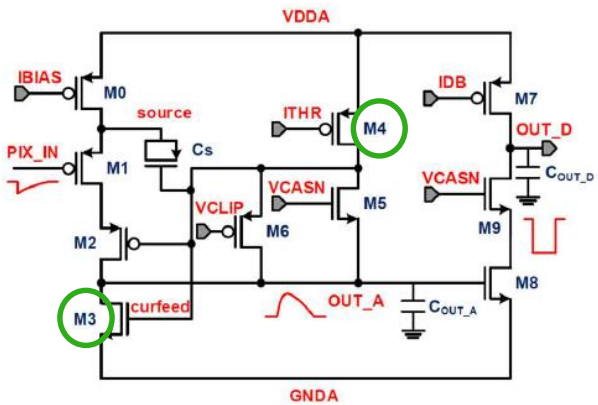




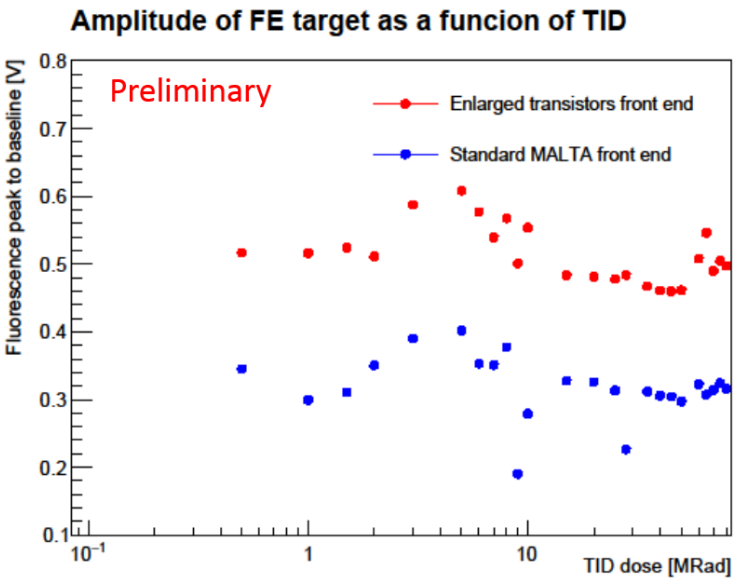
- Induce signal in the detector using a monochromatic x-ray beam from fluorescence
- Record amplitude on the analog output

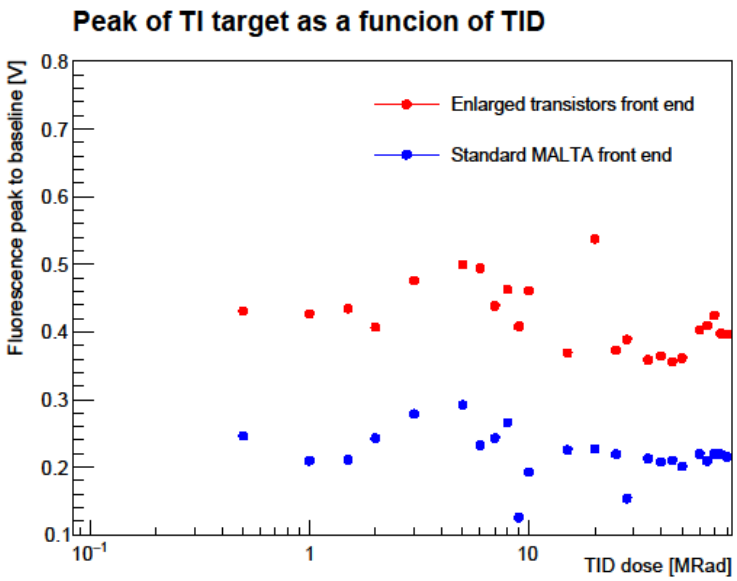


Fluorescence measurements



	Fe (6.4 keV)	Ti (4.5 keV)
Std/ET (0 MRad)	0.71	0.61
Std/ET (80 MRad)	0.38	0.30
ET 80 / ET 0	0.92	0.86
Std 80 / Std 0	0.49	0.43





Conclusions

- CMOS DMAPS aiming the ATLAS ITk requirements are being developed in the TJ 180 nm technology
- A mini-MALTA chip has been successfully irradiated to 80 Mrad
- Threshold, noise, analog waveform and fluorescence has been measured at different stages of the irradiation
- Sectors with enlarged transistors show a better performance after irradiation:
- Baseline drops ~0% after 80 Mrad vs ~15% in standard transistors
- Amplitude of analog waveform drops ~10% after 80 Mrad vs ~45% in standard transistors
- Gain 1.5x higher than in standard transistors
- Noise 30% lower than in sector with standard transistors after 80 Mrad
- Noise dispersion ~30% lower at 0 Mrad and ~40% at 80 Mrad
- Threshold value 55% lower before and after 80 Mrad
- Threshold dispersion 2.3x smaller after 80 Mrads

Thank you!

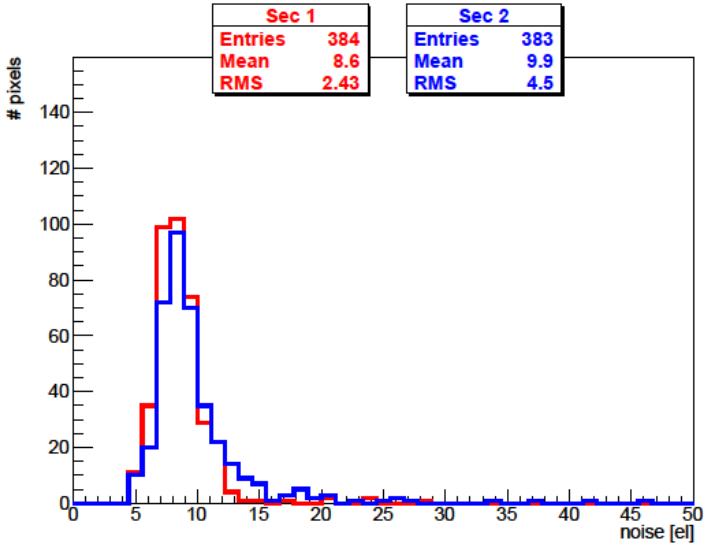
Backup

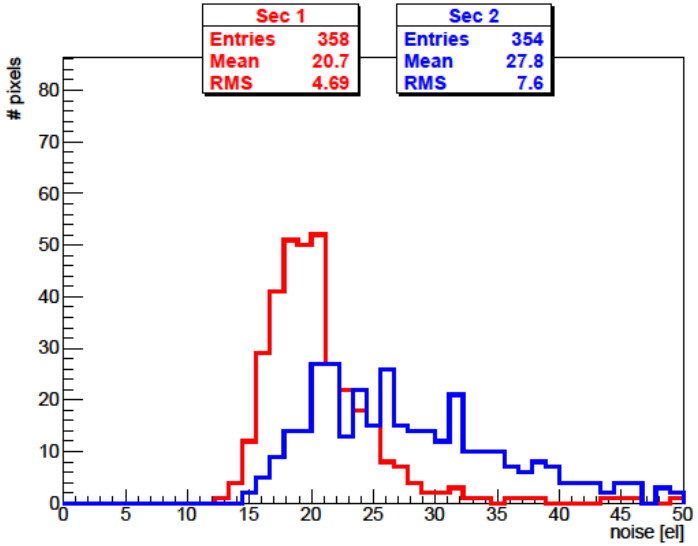
Threshold Scans distribution

0 MRad

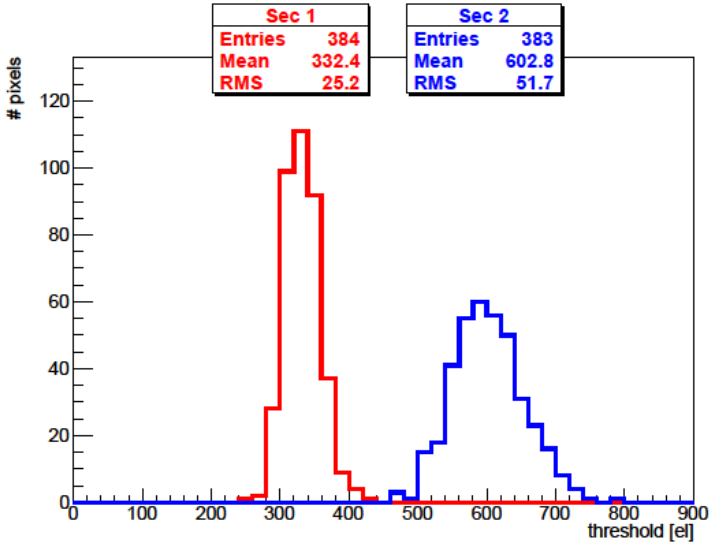
80 MRad

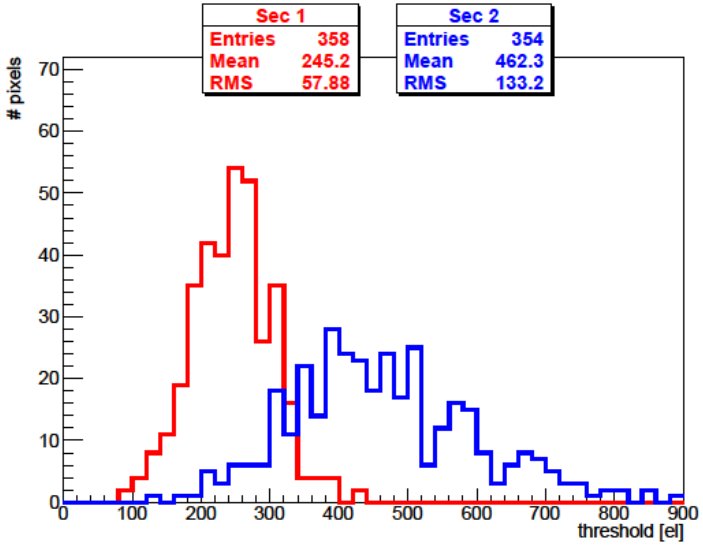
Noise distribution





Threshold distribution





Threshold RMS over Mean