# MALTA CMOS sensor telescope: new developments and recent measurements

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*CERN*

# CMOS motivation

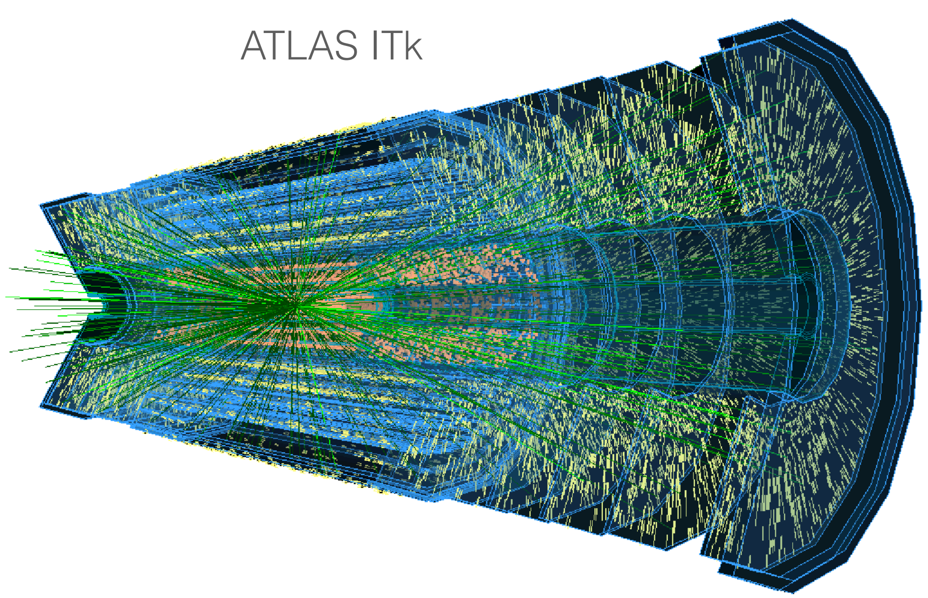
- requirements for future HEP detectors are vey challenging:
  - extreme ration tolerance
  - very fast response
  - very large surface
  - very thin
  - high granularity

*CERN-OPEN-2018-006*

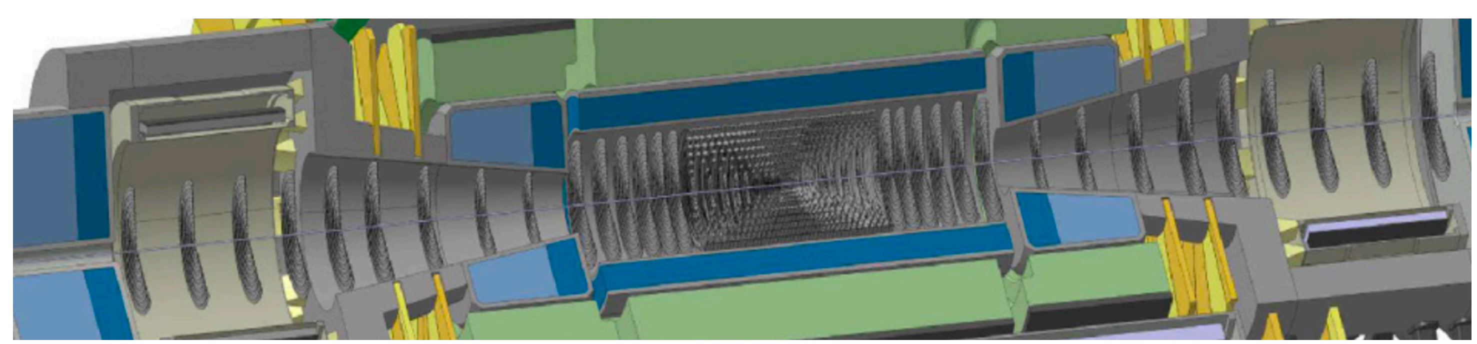
| Parameter \ Exp. | LHC | HL-LHC | SPS | FCC-hh | FCC-ee | CLIC 3 TeV |
|---|---|---|---|---|---|---|
| Fluence [$n_{eq}/cm^2/y$] | N x $10^{15}$ | $10^{16}$ | $10^{17}$ | $10^{16}$ - $10^{17}$ | <$10^{10}$ | <$10^{11}$ |
| Max. hit rate [$s^{-1}cm^{-2}$] | 100 M | 2-4 G****) | 8 G****) | 20 G | 20 M ***) | 240k |
| Surface inner tracker [$m^2$] | 2 | 10 | 0.2 | 15 | 1 | 1 |
| Surface outer tracker [$m^2$] | 200 | 200 | - | 400 | 200 | 140 |
| Material budget per detection layer [$X_0$] | 0.3%*) - 2% | 0.1%*) - 2% | 2% | 1% | 0.3% | 0.2% |
| Pixel size inner layers [$\mu m^2$] | 100x150-50x400 | ~50x50 | ~50x50 | 25x50 | 25x25 | <~25x25 |
| BC spacing [ns] | 25 | 25 | >$10^9$ | 25 | 20-3400 | 0.5 |
| Hit time resolution [ns] | <~25–1k*) | 0.2**)–1k*) | 0.04 | ~$10^{-2}$ | ~1k ***) | ~5 |

*) ALICE requirement **) LHCb requirement ***) At Z-pole running ****) max. output rate for LHCb/high intensity flavour experiments: 300-400 Gbit/s/$cm^2$

ATLAS ITk

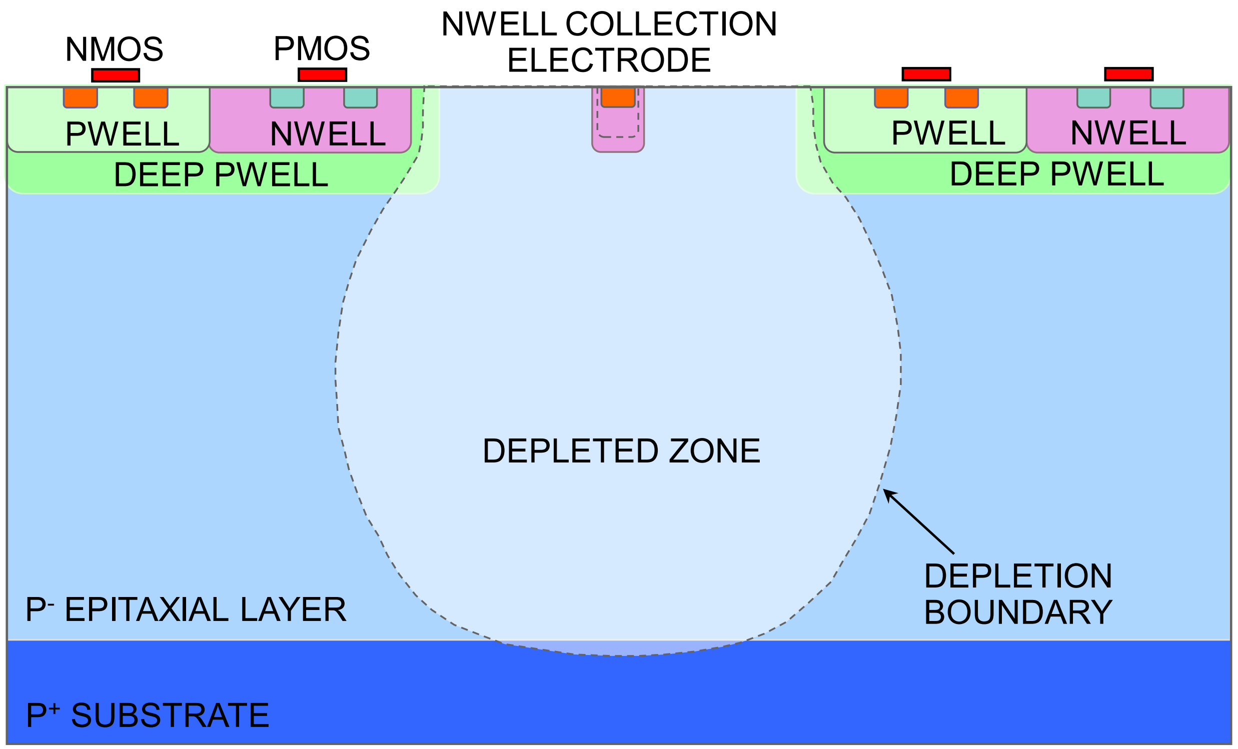


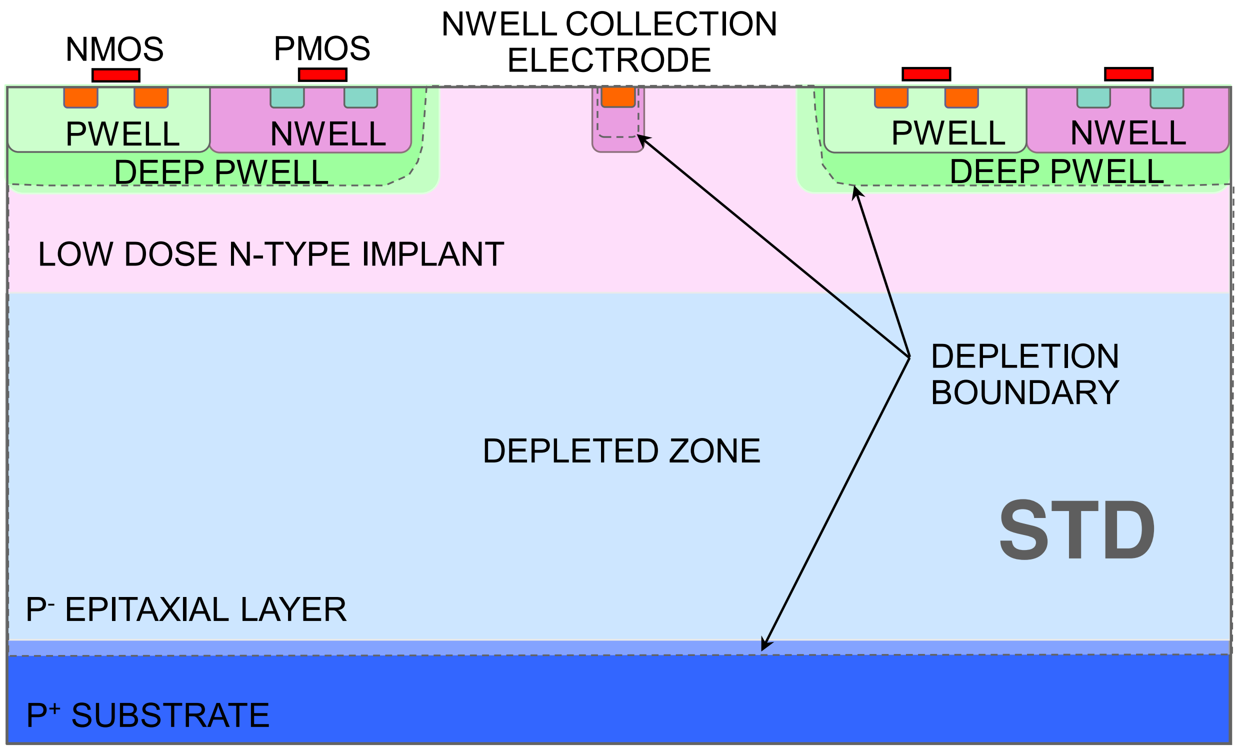
FCC: hh



# Tower Semiconductor 180nm CMOS sensors

- Towejazz process:
  - high-resistivity Epi layer, 25 µm depletion → ~1500 e- for MIP, high signal to noise ratio (~20)
- modified process:
  - extra low dose n-type layer to improve depletion under the deep p-well, better radiation tolerance

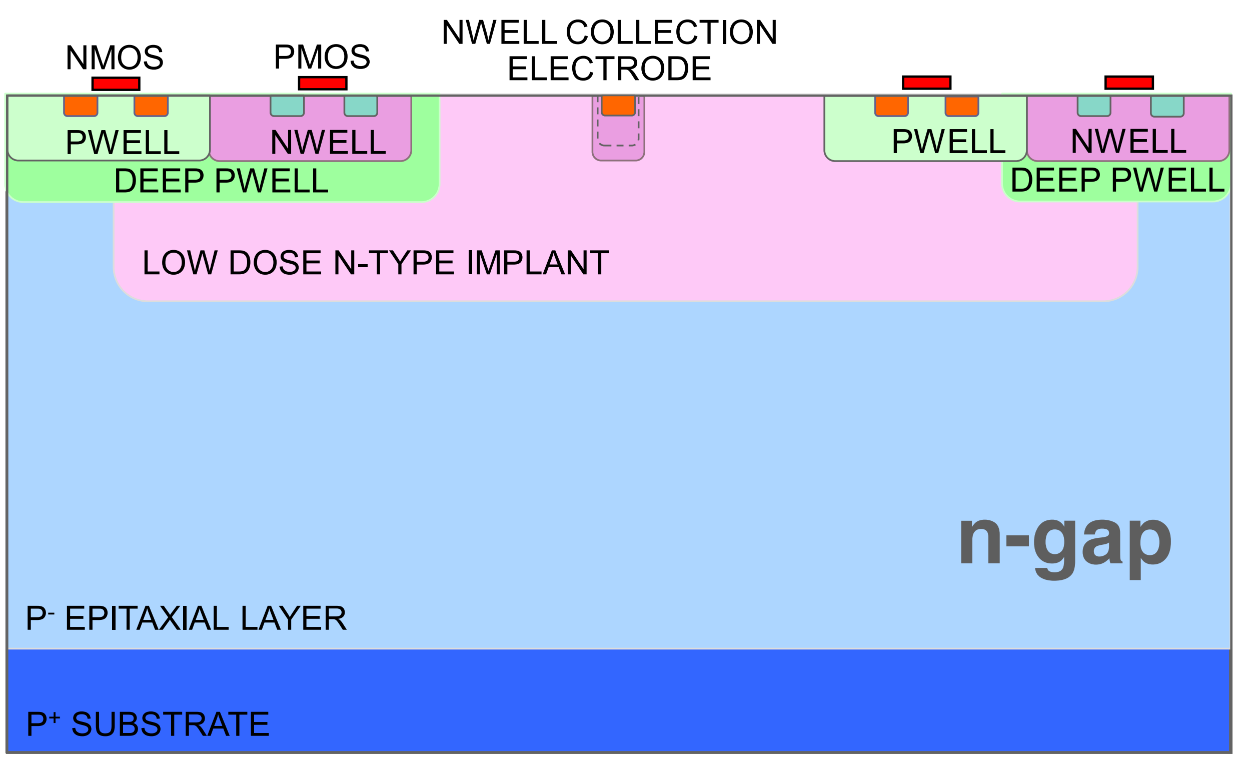


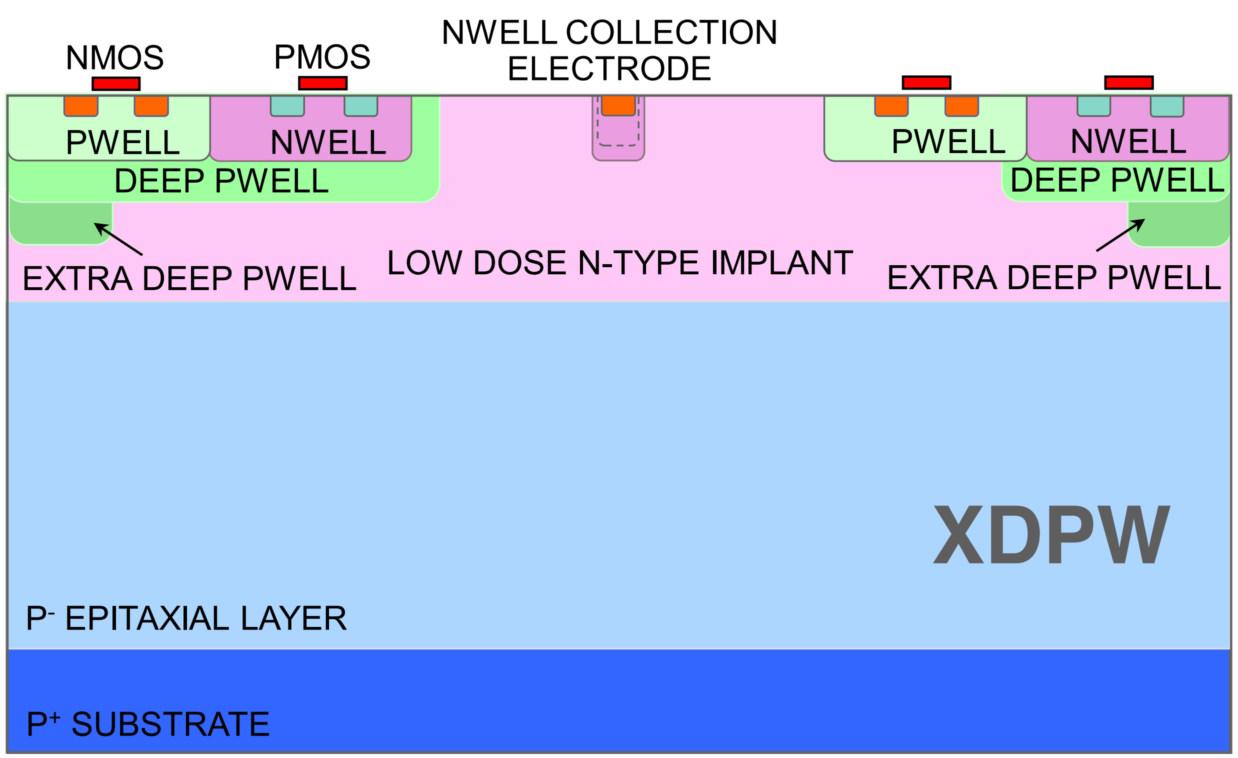




W. Snoeys, NIM A 871 (2017) 90-96

# Tower Semiconductor 180nm CMOS sensors

- special layouts for deep p and n wells to optimize field configuration and charge collection: increase lateral field near pixel edge to “focus” charge to electrode:
  - gap in the n-layer: 4 μm gap in the low dose n-layer
  - ‘extra-deep p-well’ layer: 5 μm wide additional p-well implant

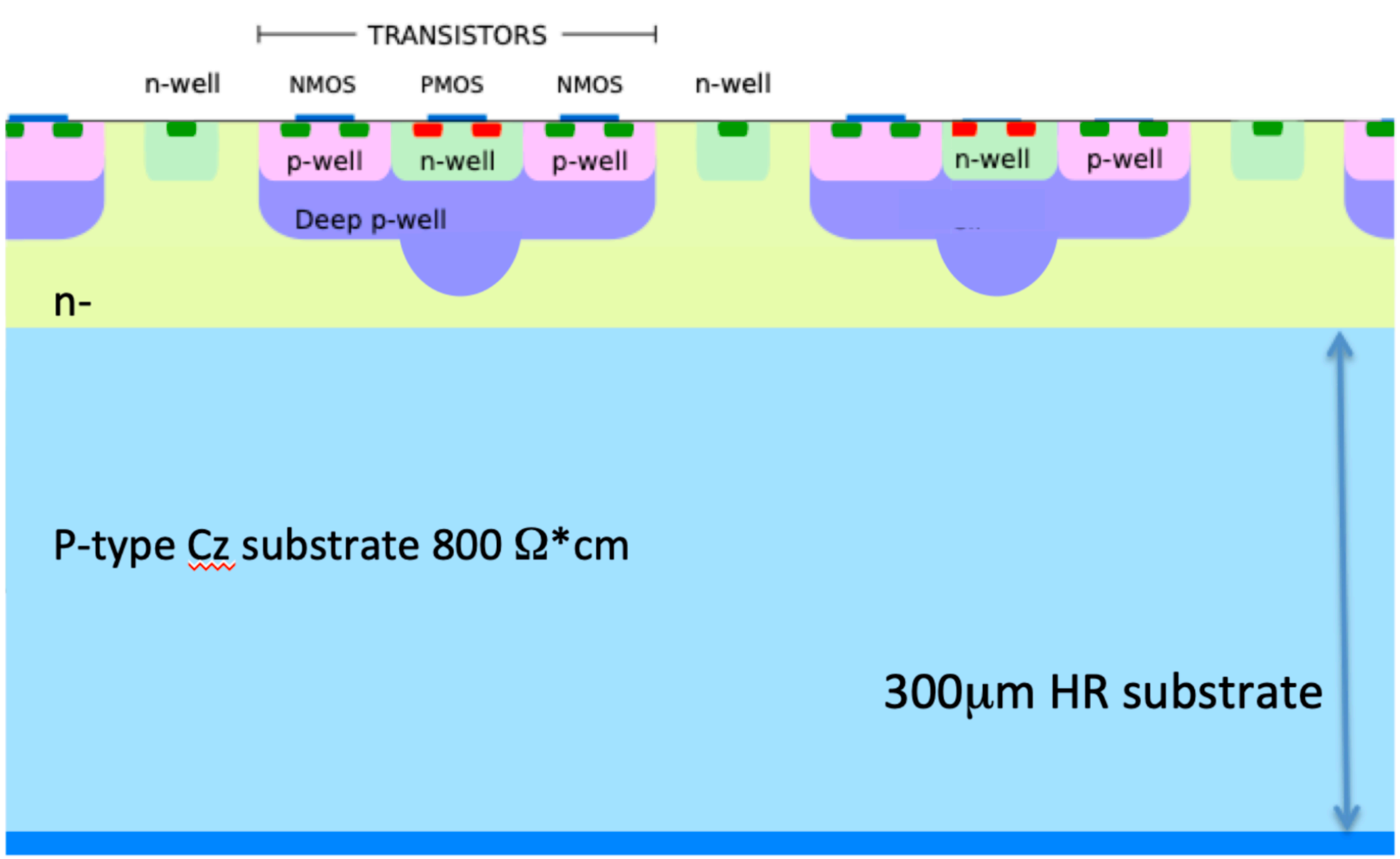



H.Pernegger HSTD12
M. Dyndal,JINST 15 (2020) P02005
M. Mironova, NIM A 956 (2020) 163381
Magdalena, M.Munker PIXEL 2018

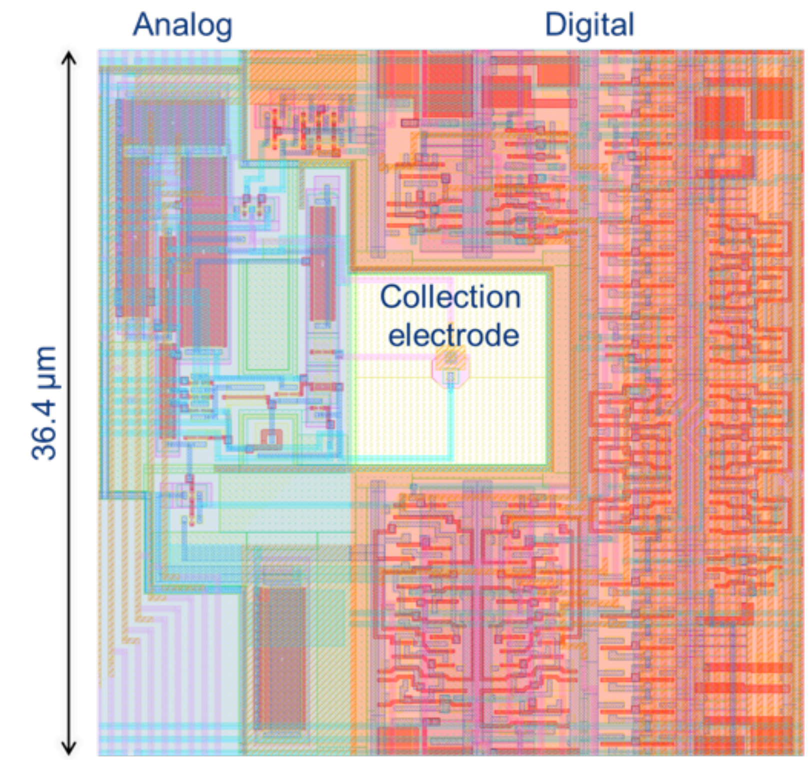
# Tower Semiconductor 180nm CMOS sensors

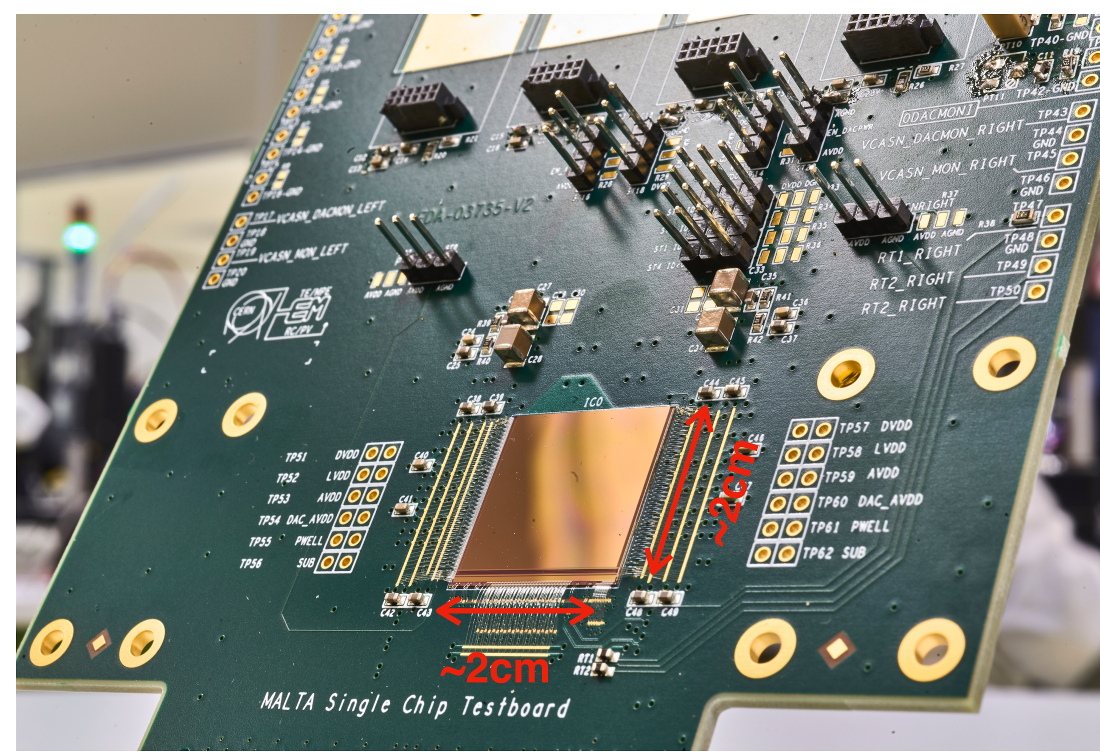
- MALTA with high resistivity Czochralski(Cz) substrate material
- significant larger depletion and signal:
  - higher radiation hardness
  - high operation voltage up to 50V -> high depletion depth



# MALTA pixel detector

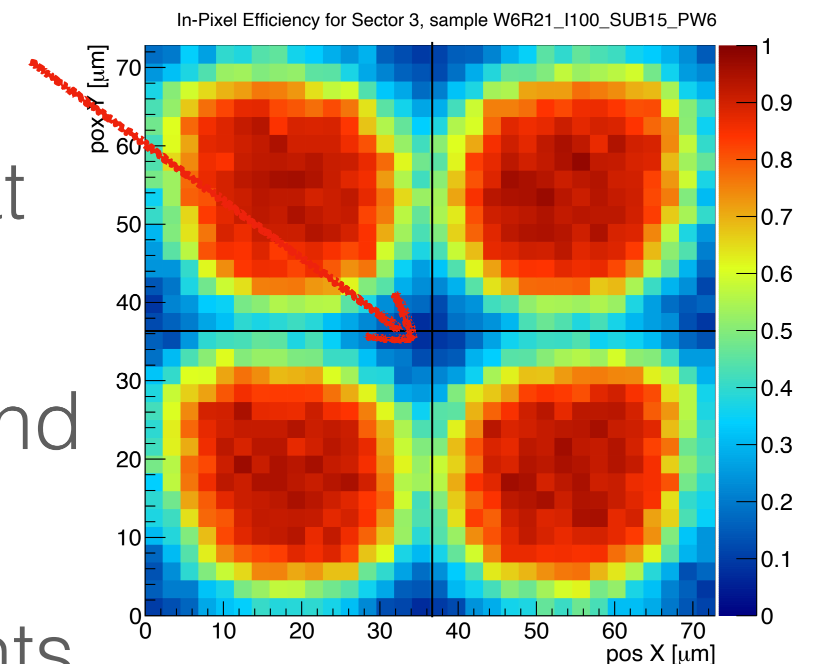
- matrix 512 x 512 pixels of 36.4 x 36.4 $\mu m^2$ size
- small collection electrode of 2-3 $\mu m^2$ to achieve minimal input capacitance <3fF
- 3.4-4 µm spacing between electrode and electronics: low cross talk
- asynchronous architecture
- very low power consumption:
  - 1 µW/pixel analog power
  - 70 $mW/cm^2$ analog power
  - 10 $mW/cm^2$ digital power
- parallel read-out bus 37bit
- Xilinx Virtex/Kintex FPGA for readout



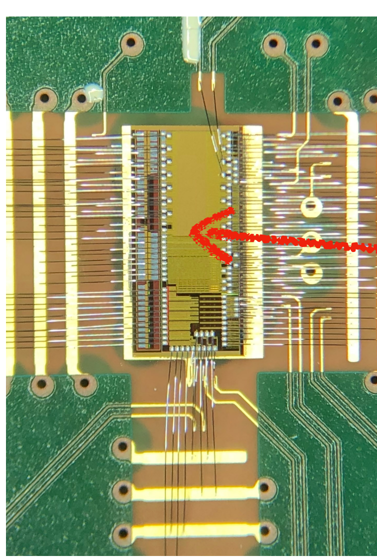



# Malta history

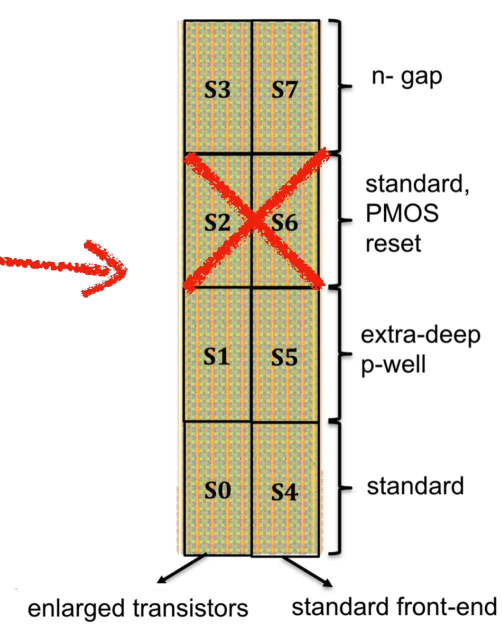
- 2018, first MALTA: after neutron irradiation the collection efficiency is degraded at pixel edges
- Jan 2019, MiniMALTA: smaller matrix version that changes the p-well extension to address the efficiency loss on corners and improved Front-End
- Aug 2019, reprocessed MALTA: large demonstrator with MiniMalta sensor improvements

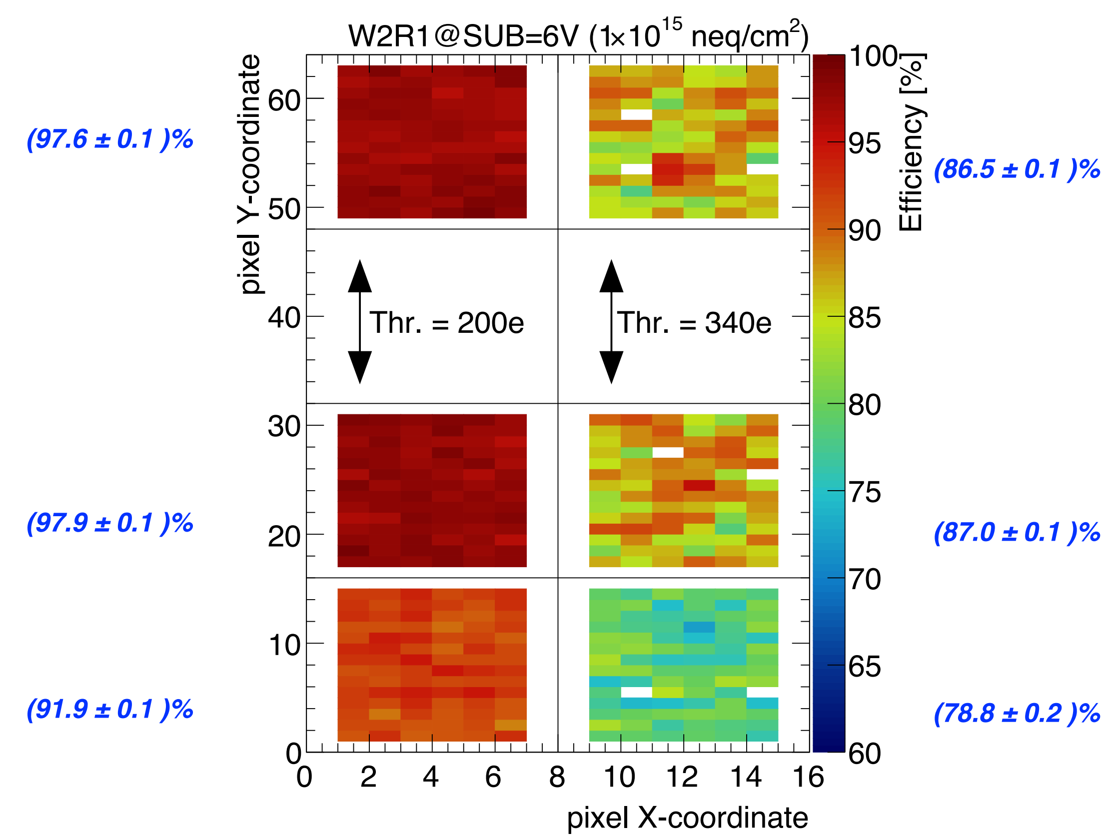



MiniMALTA demonstrator
5 mm x 1.7 mm



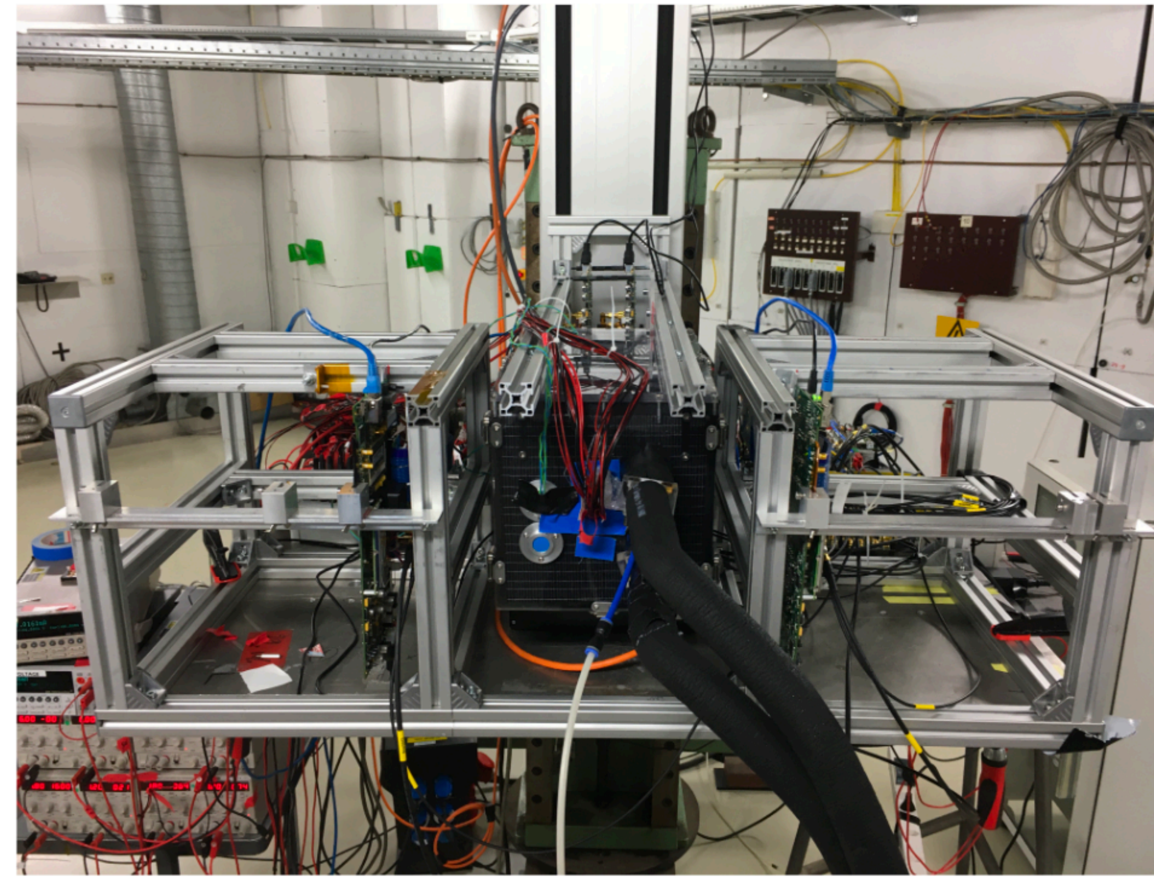
JINST 15 (2020) 02, P02005
I. Asensi VERTEX (2020)

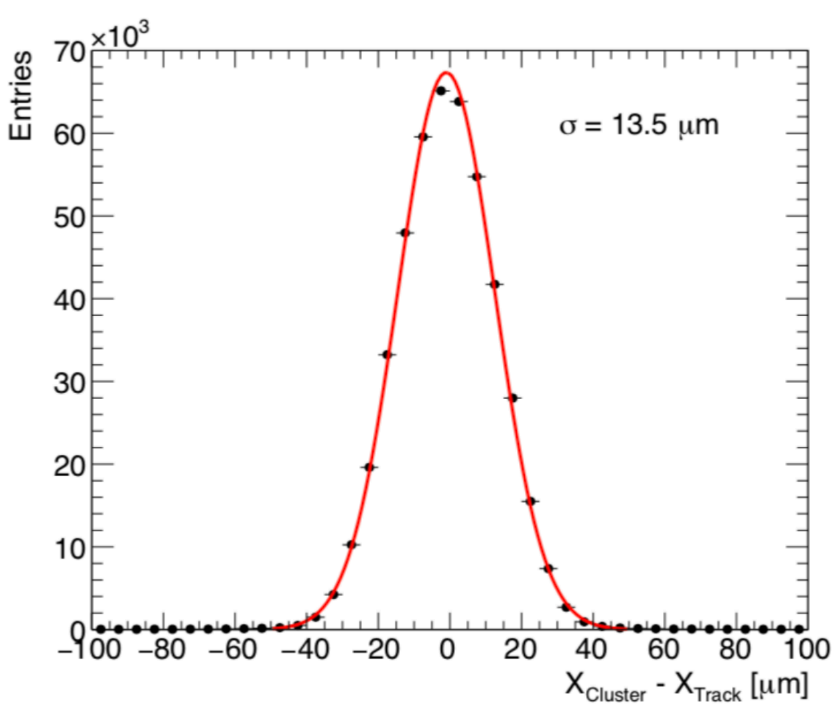


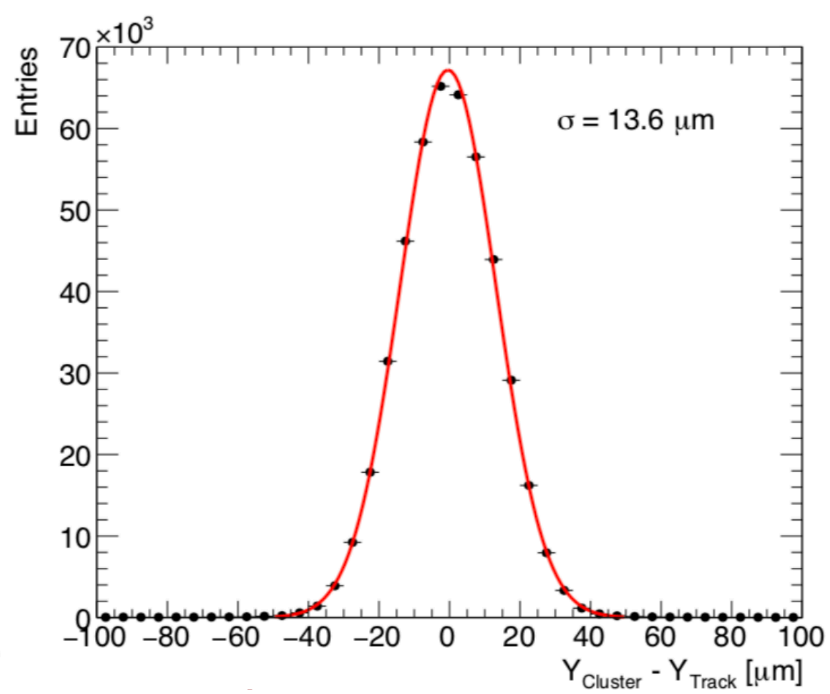



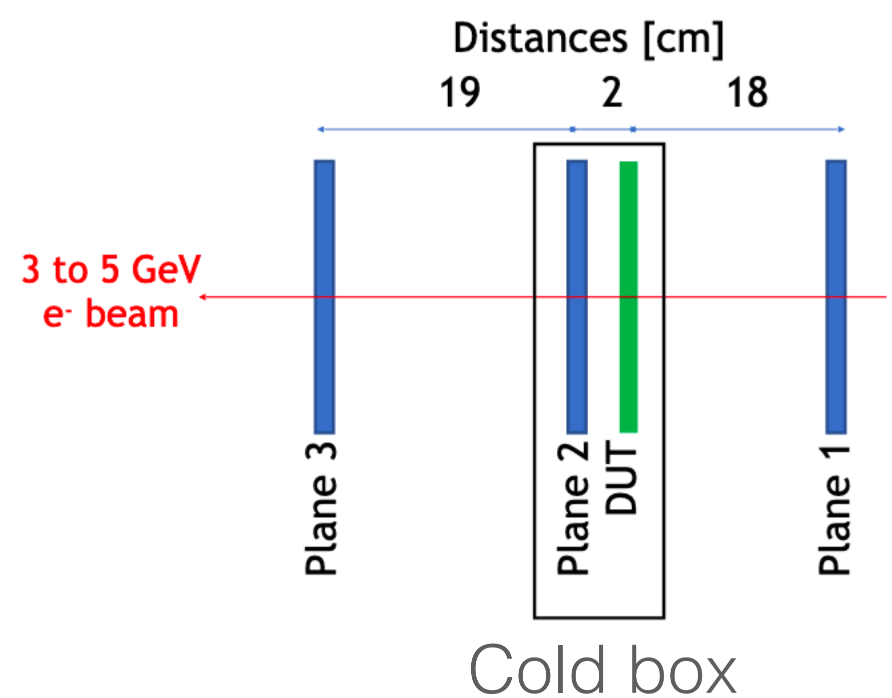
# MALTA telescope testbeam

- DESY testbeam energy = 3-4 GeV
- custom MALTA-based telescope
  - up to 7 MALTA tracking planes (100 µm thick, 36 µm pitch size)
  - triggering on planes with custom TLU with high flexibility
  - tracking performance ~13 µm residual width



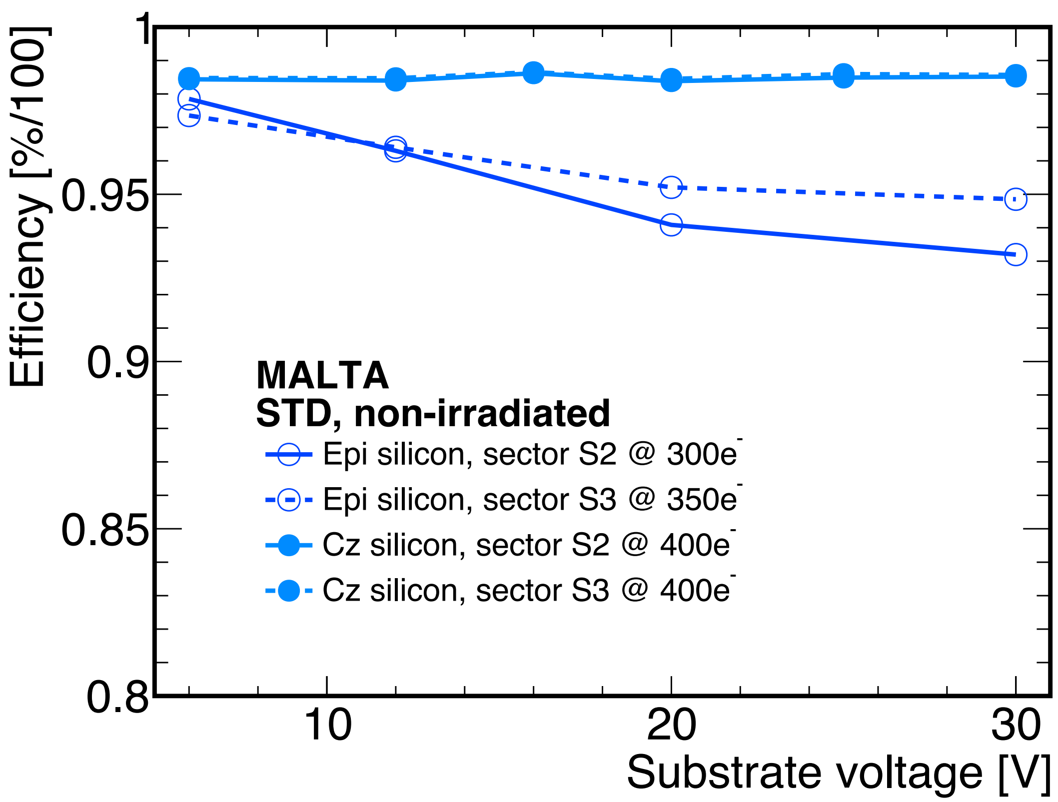


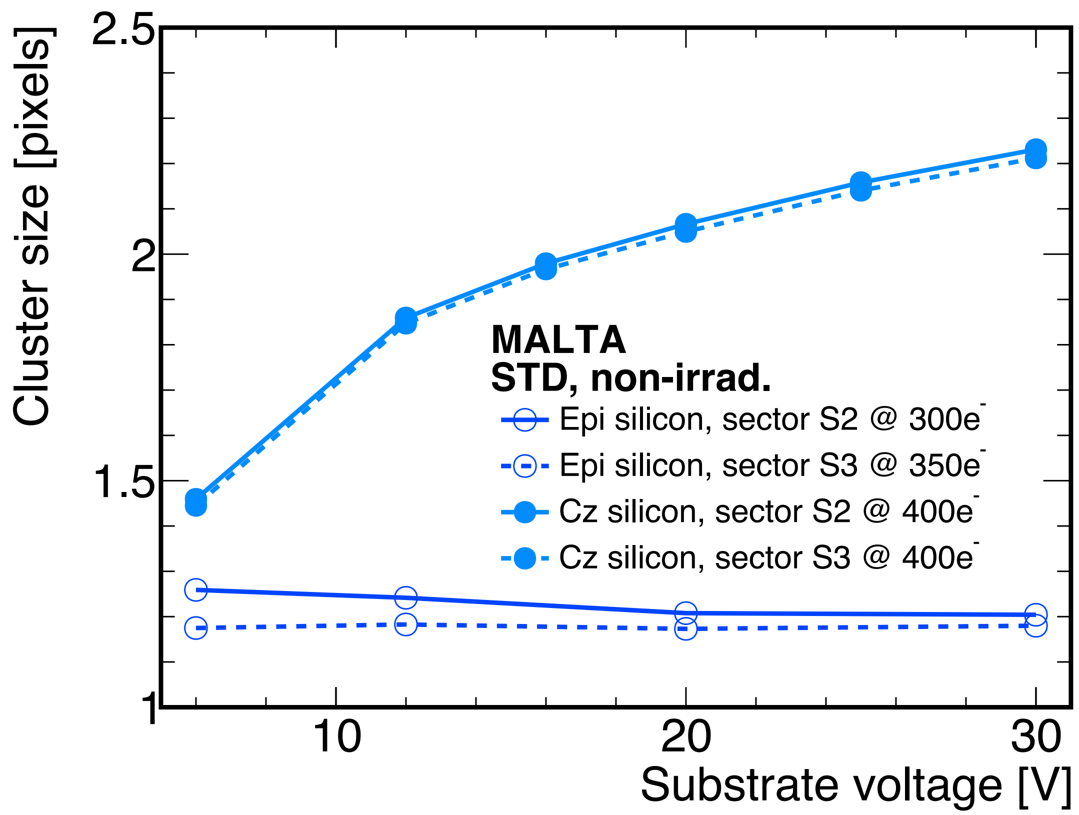



# MALTA non-irradiated chip

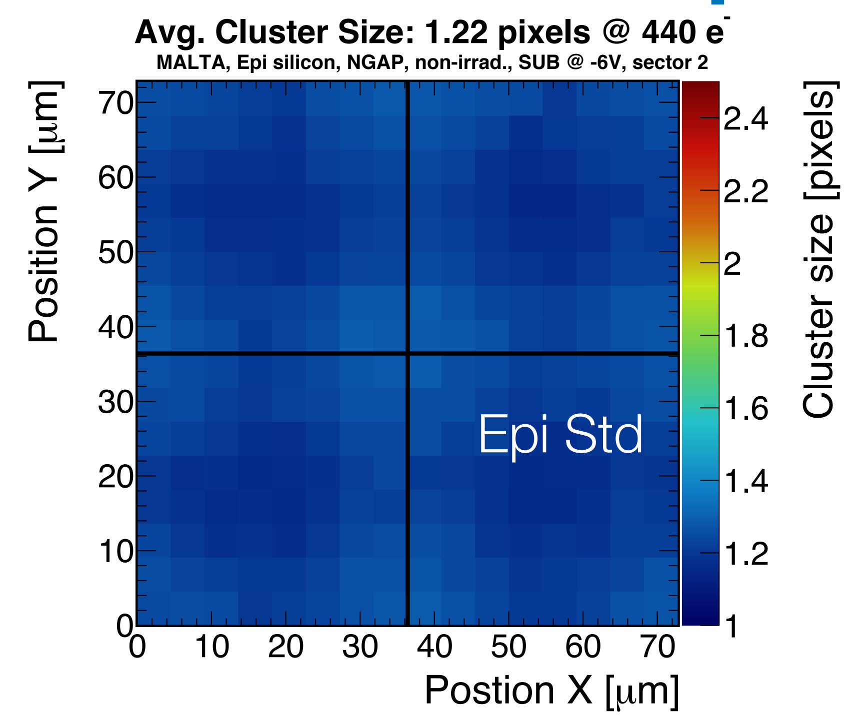
- efficiency vs substrate voltage:
  - Epi: no gain at high voltage (full depletion at 6V)
  - Cz: flat efficiency vs substrate voltage
- cluster size vs substrate voltage:
  - Epi: constant cluster size
  - Cz: smooth increase when increasing substrate voltage (more charge sharing in Cz material)

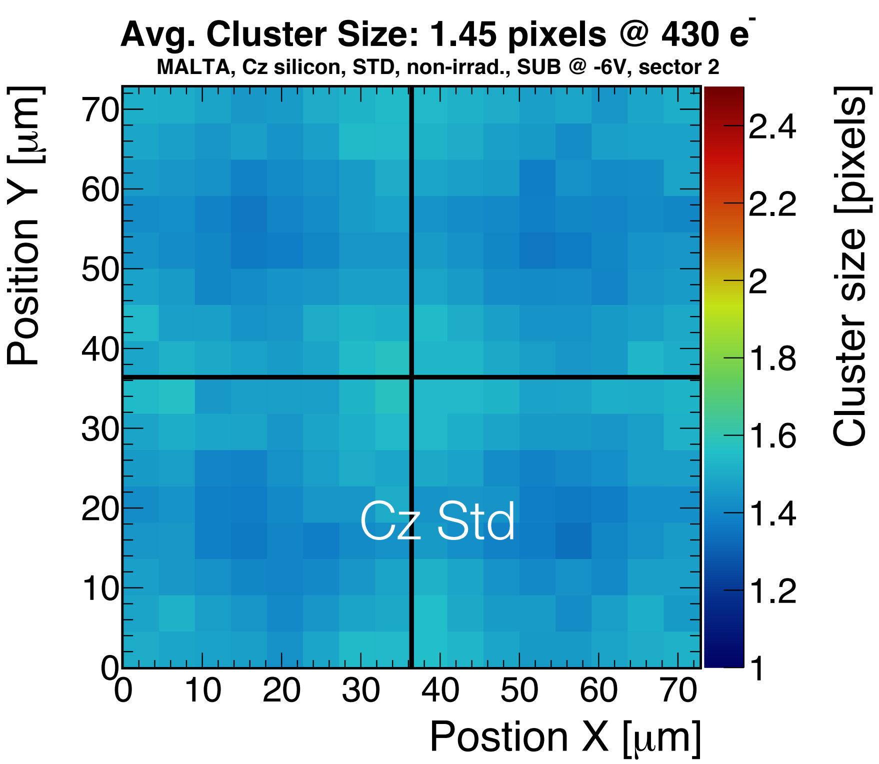


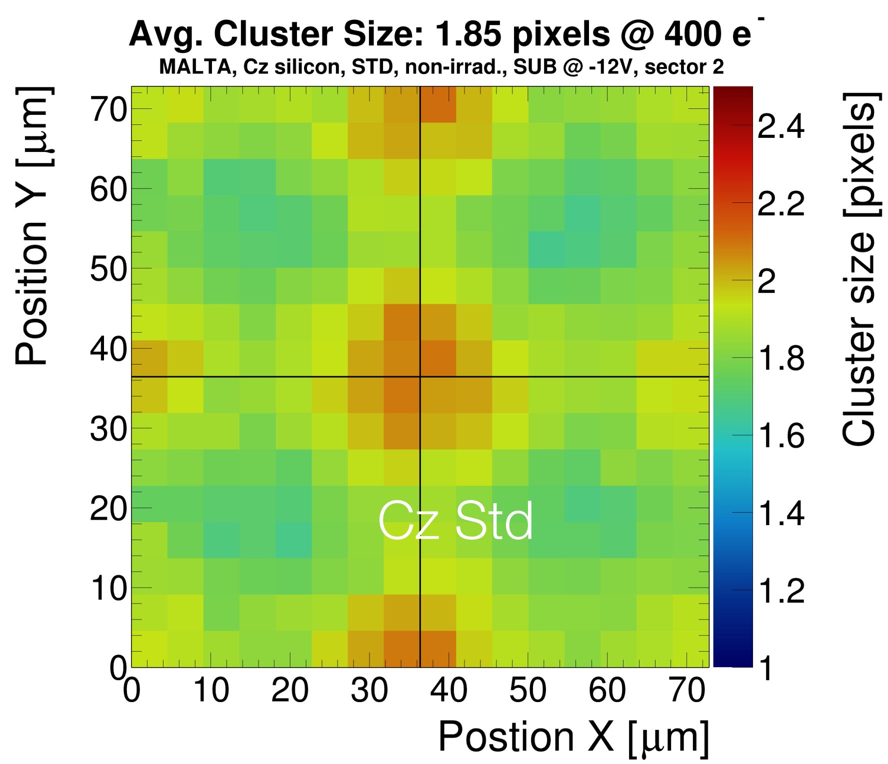



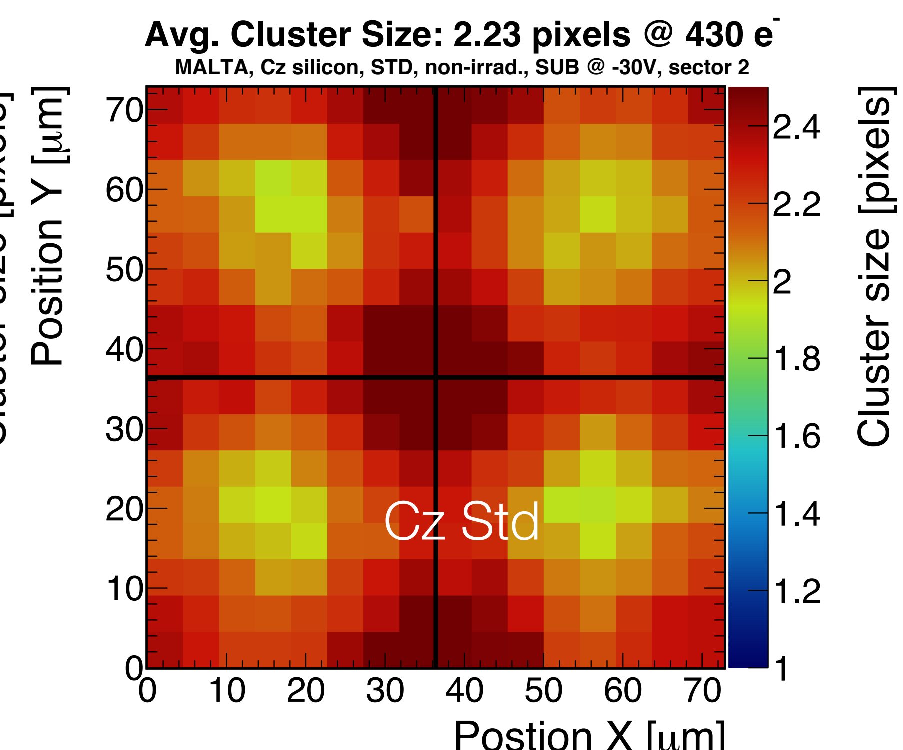
# MALTA non-irradiated chip

- in-pixel cluster size vs substrate voltage (shown as 2x2 pixel x-y dependency)
- Cz has larger cluster size and more charge collection sharing



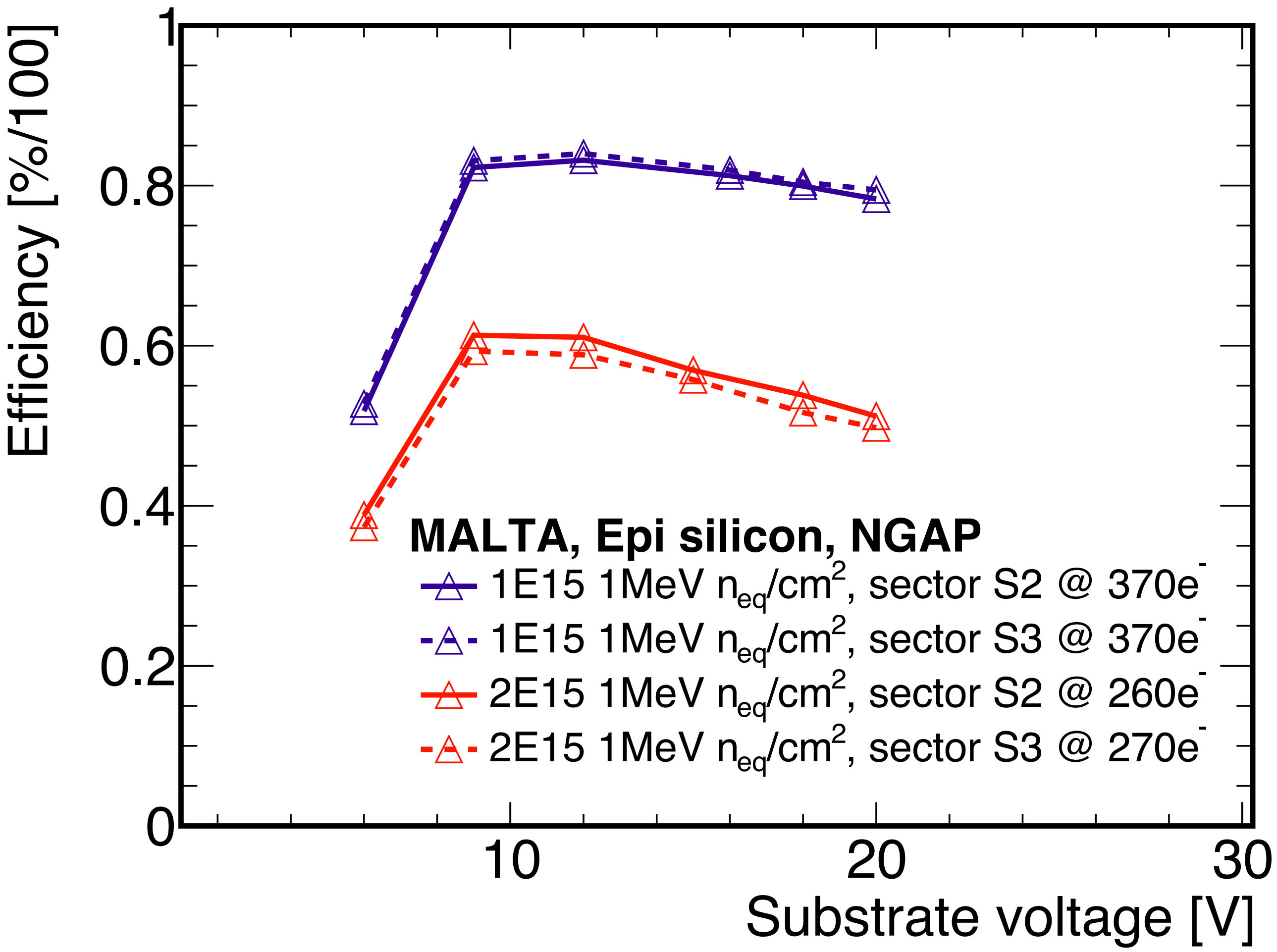



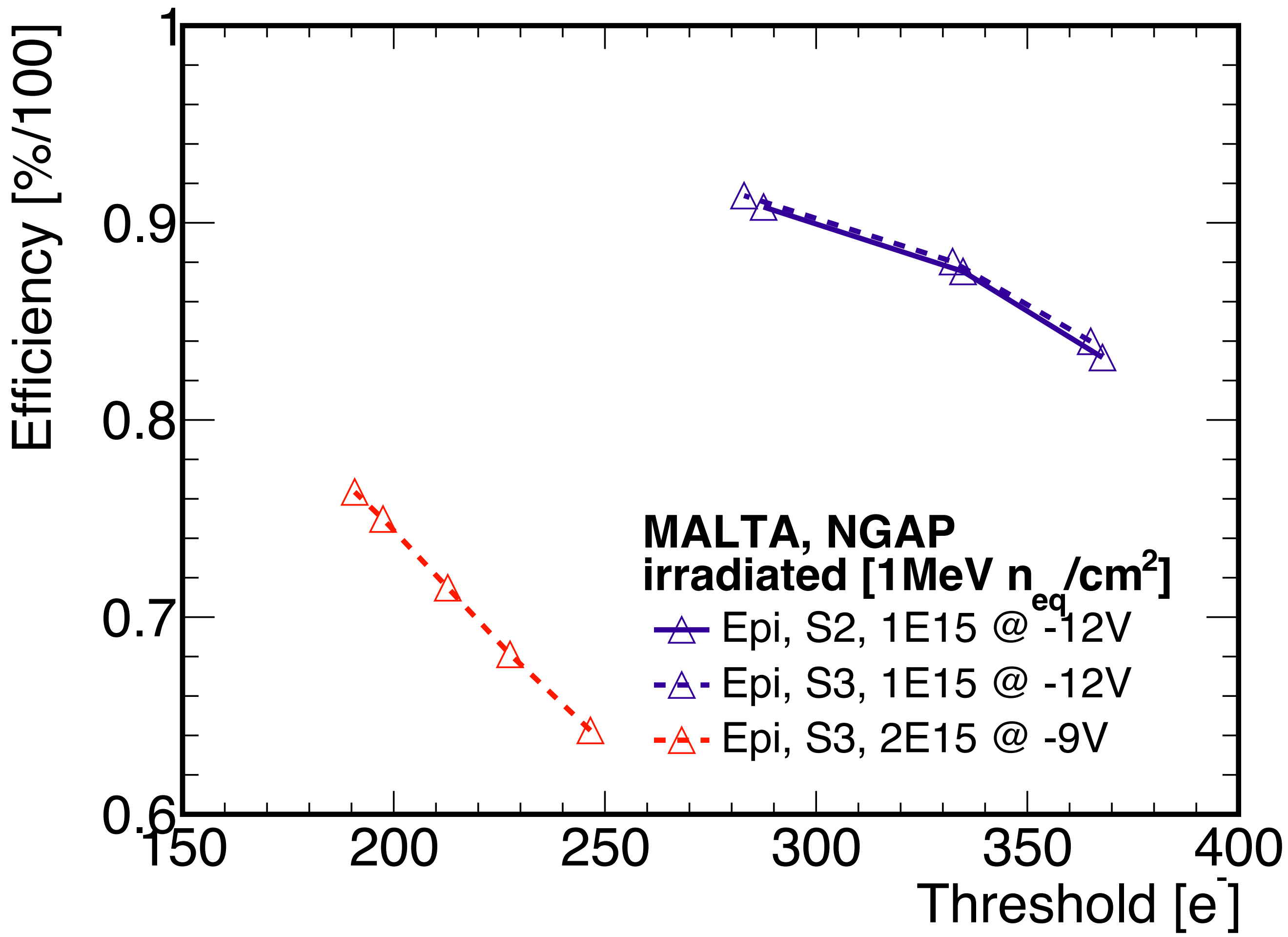




6 V 12 V 30 V SUB V

# MALTA irradiated chips

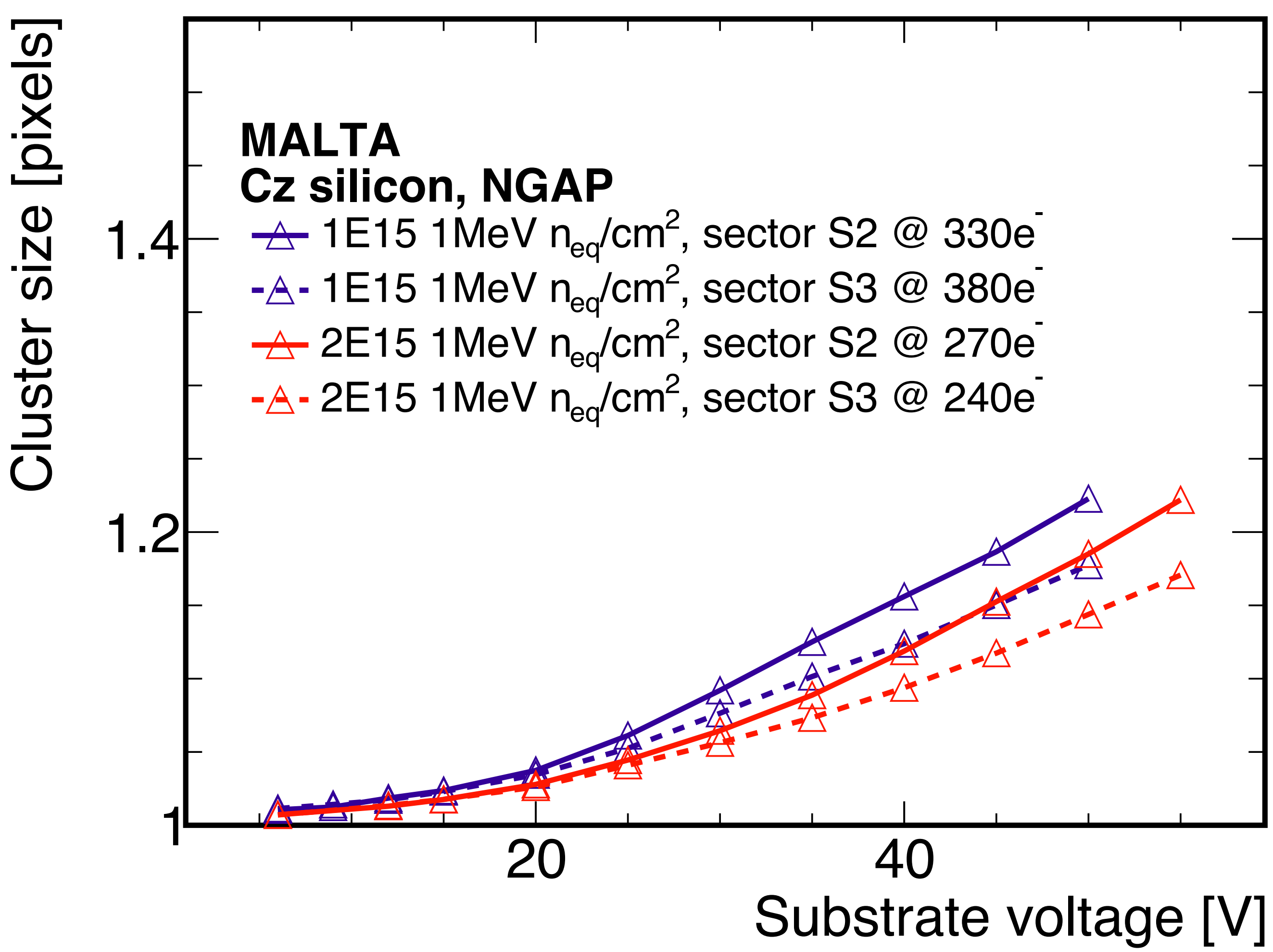
- Epi silicon sensor low efficiency for irradiated chip (1e$^{15}$ $n_{eq}$/cm$^2$) ~80% @-10 V @370 e$^-$
- no gain with higher substrate voltage
- results consistent with previous MiniMalta measurements

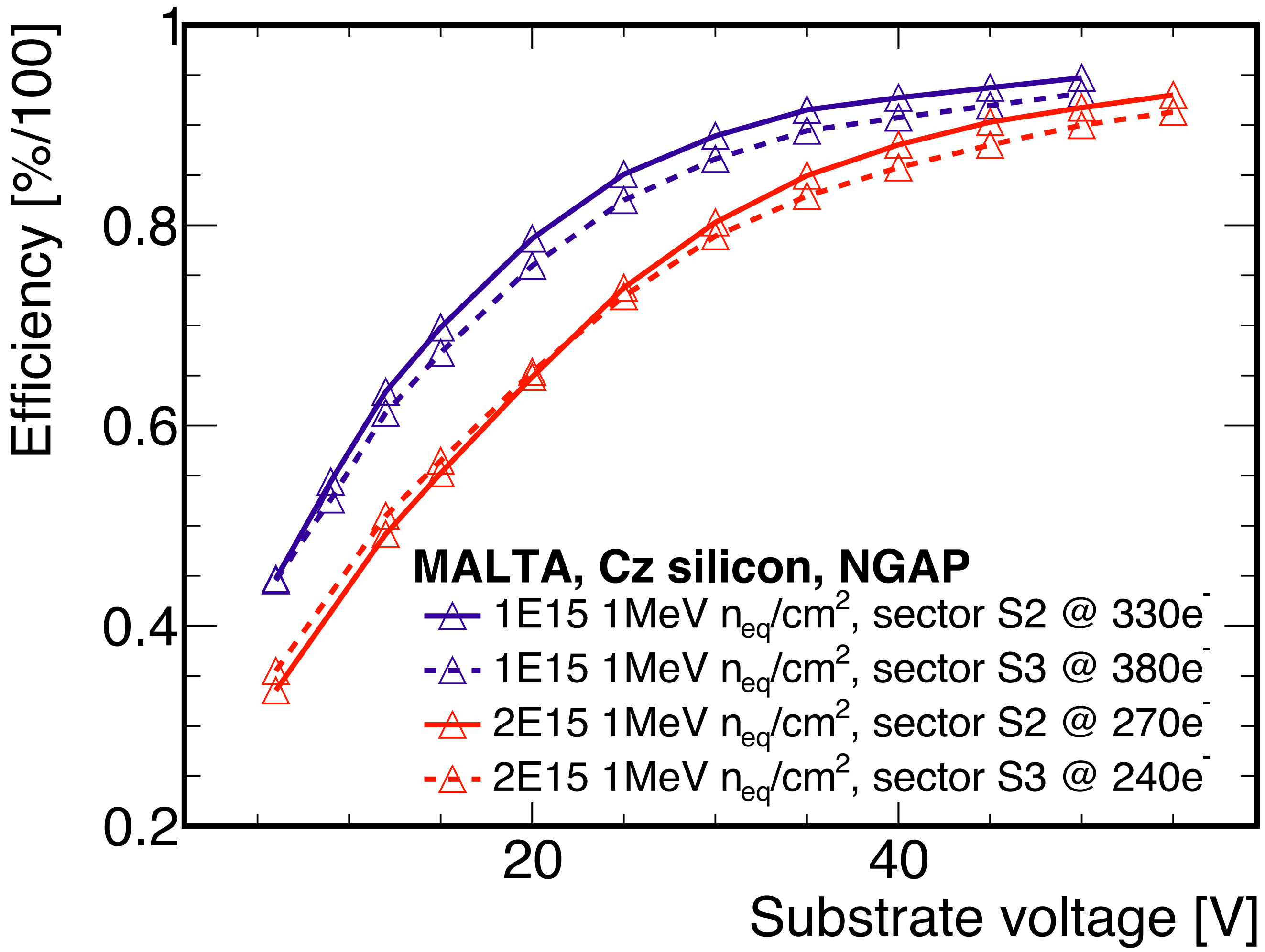


# MALTA irradiated chips

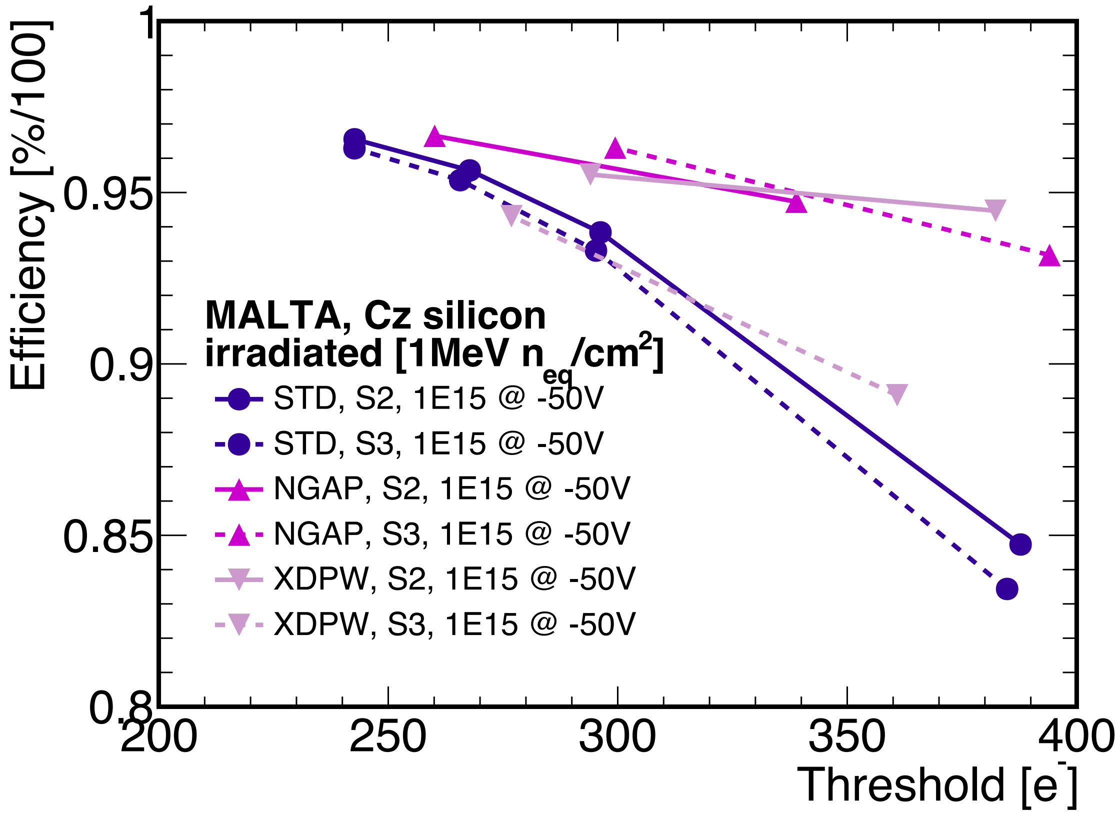
- Cz silicon sensor: higher radiation hardness
- smooth dependency of efficiency (and cluster size) vs substrate voltage
- max efficiency with irradiated chip (n-gap @2e$^{15}$ $n_{eq}$/cm$^2$) ~93%

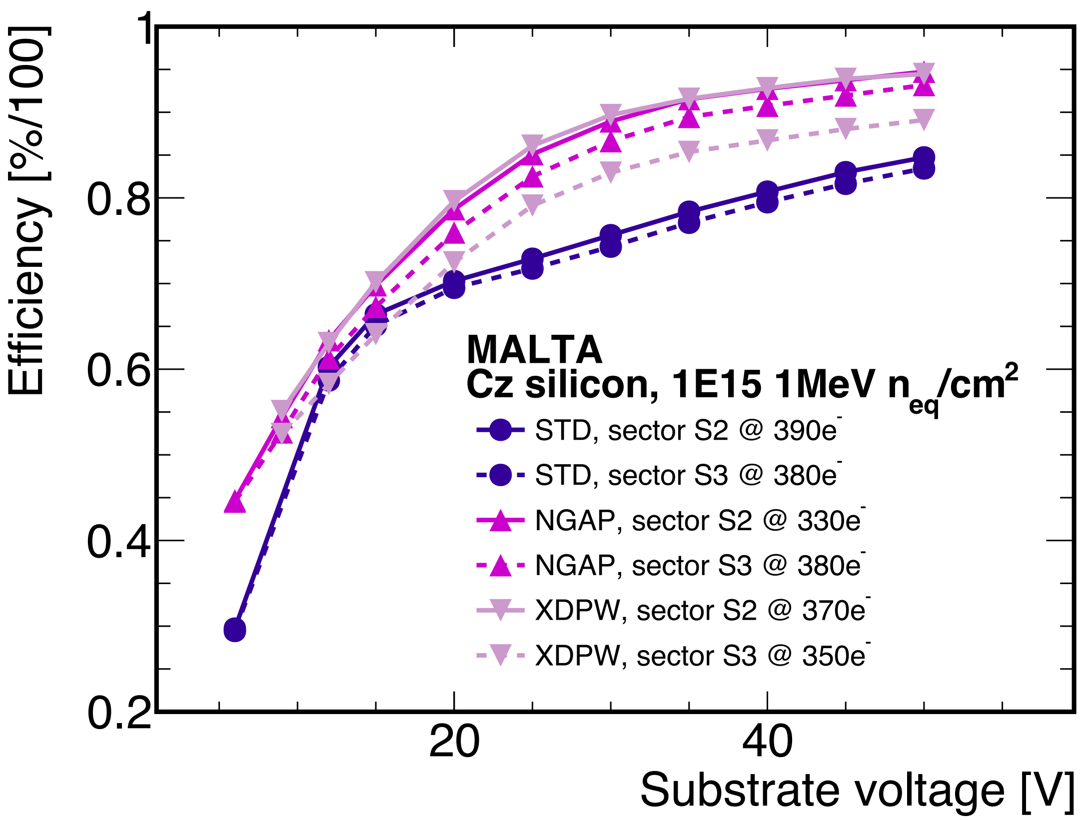


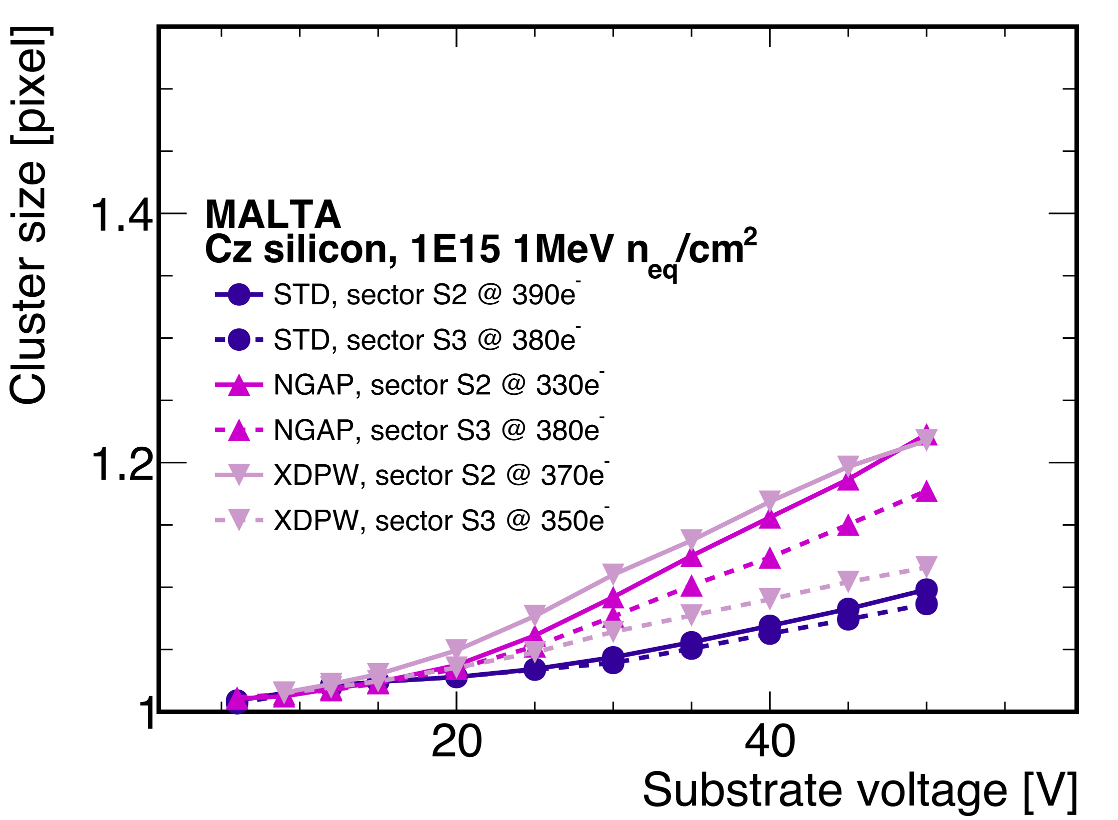



# MALTA irradiated chips

- Cz sensors comparison
- at similar (high value) of threshold:
  - larger efficiency ~95% (n-gap and xdpw) vs 85% (std)
  - larger cluster size

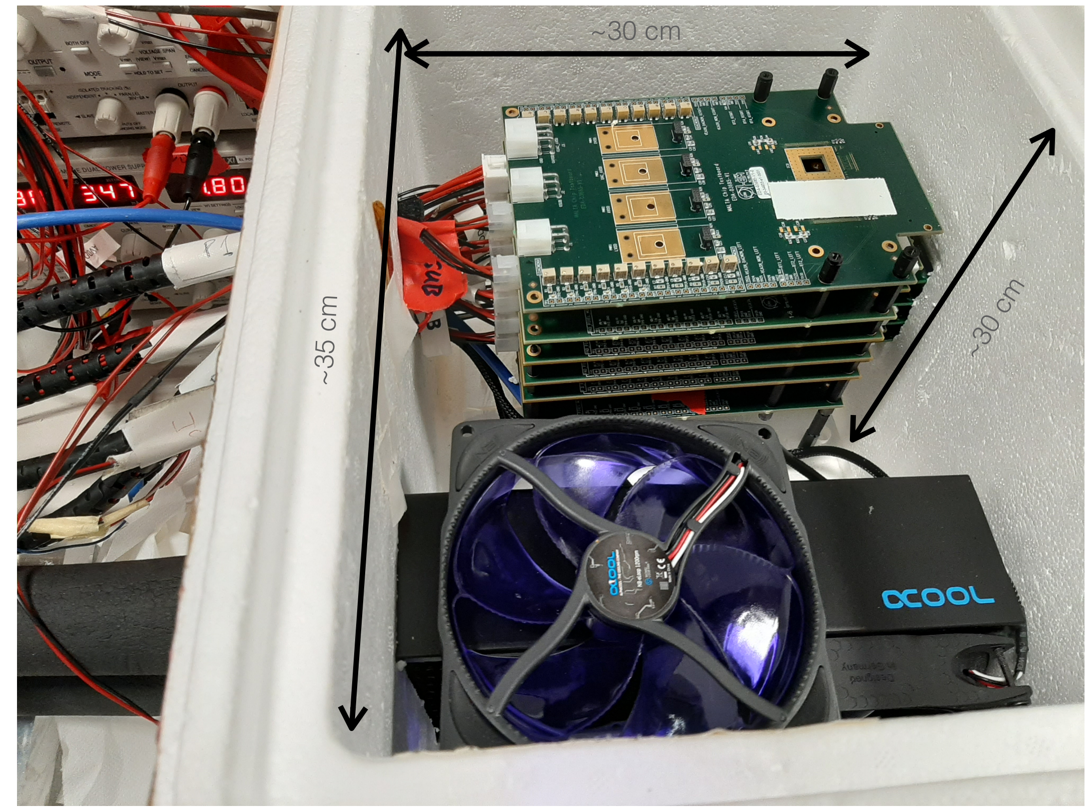


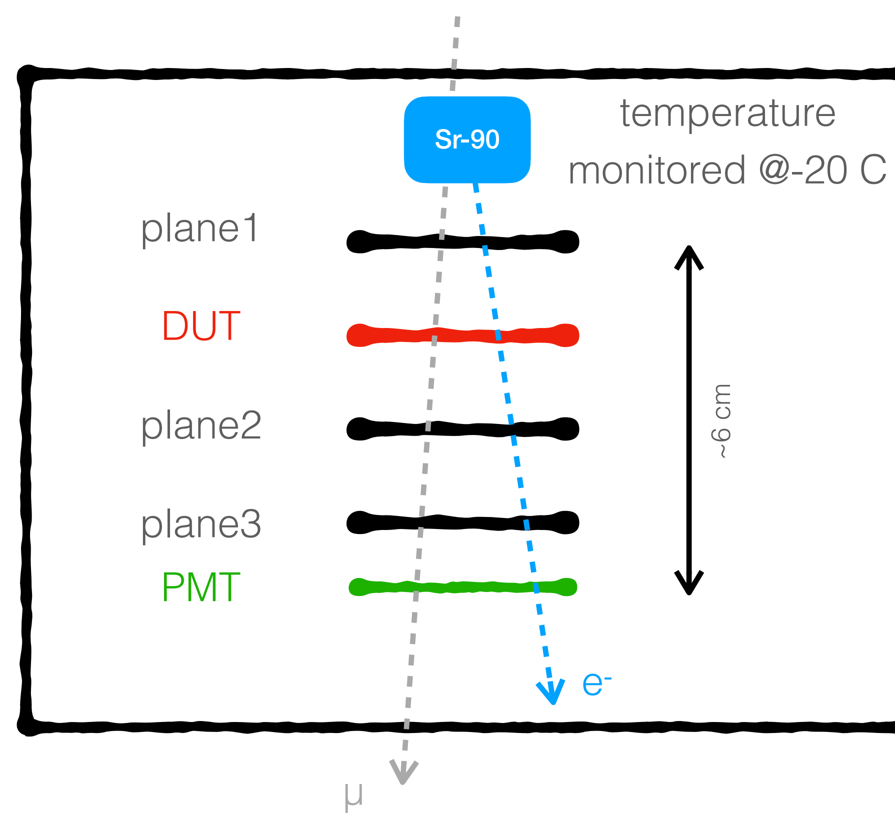



# MALTA telescope 2020

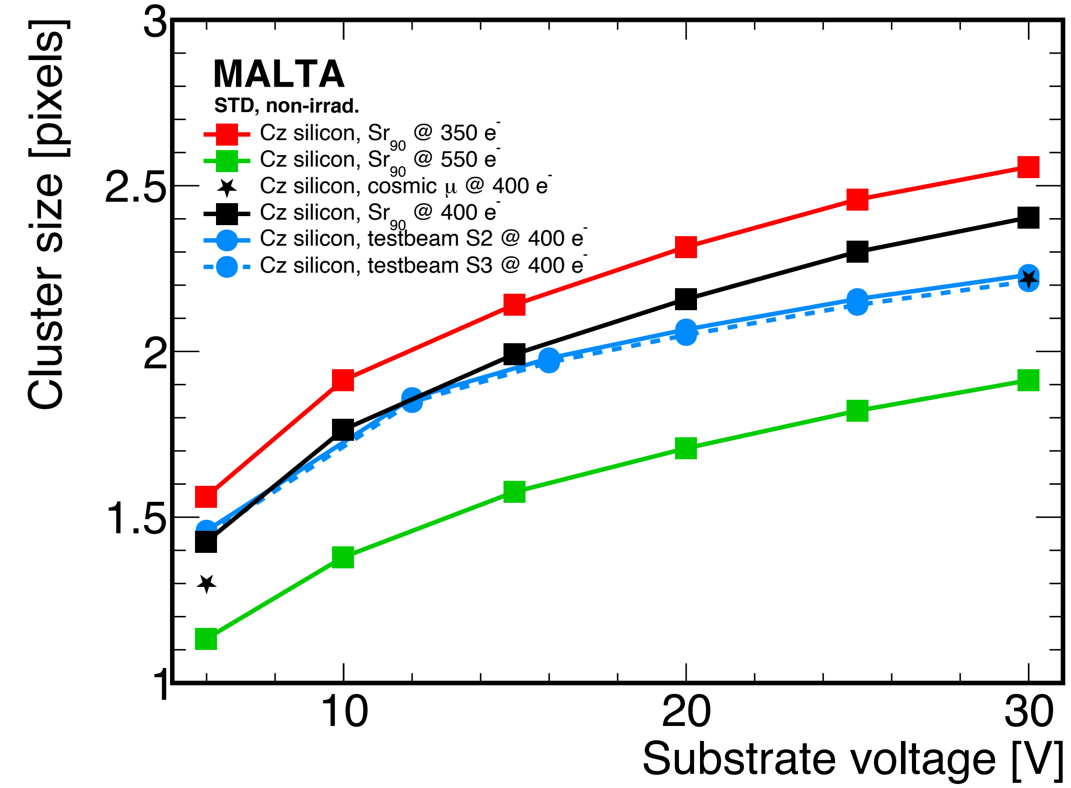
- telescope for lab measurements
- 4 MALTA planes and one PMT
- PicoTDC for timing measurements
- different runs:
  - cosmic muons: high resolution but very low rate 1μ/6’
  - low energy electrons Sr-90: high rate but high multiple scattering
- entire telescope in a cold box
- powerful setup to test new chips
- development of DAQ, DQ and trigger logic for future testbeam

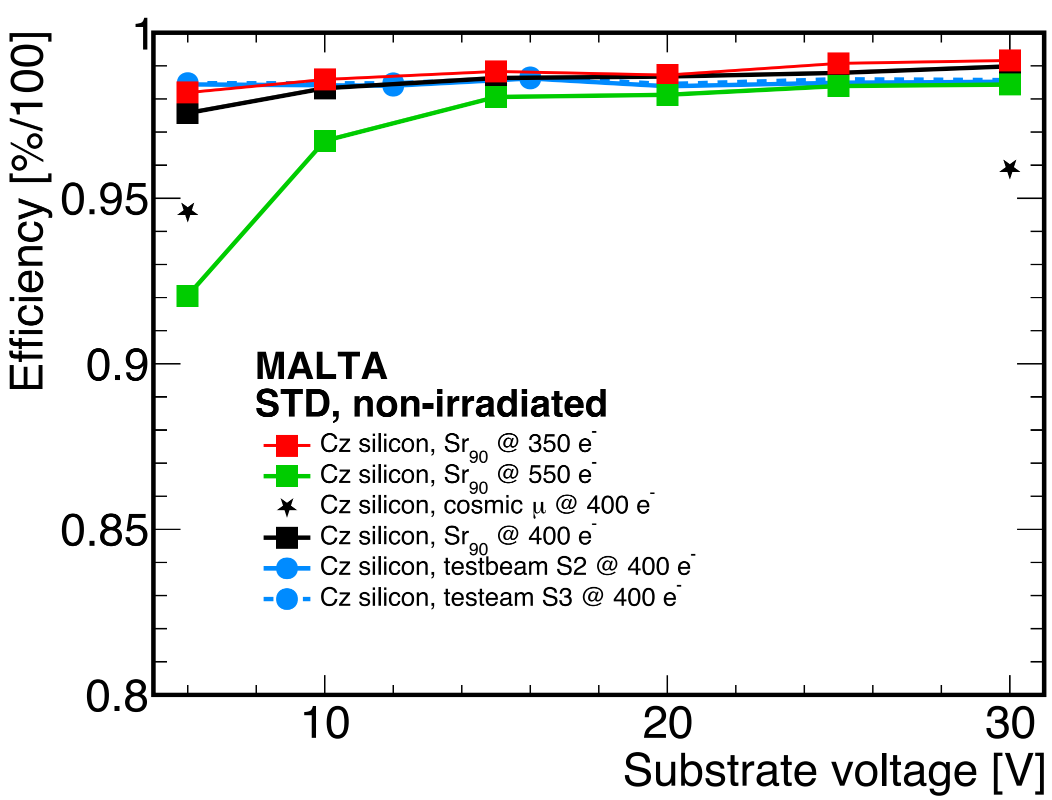


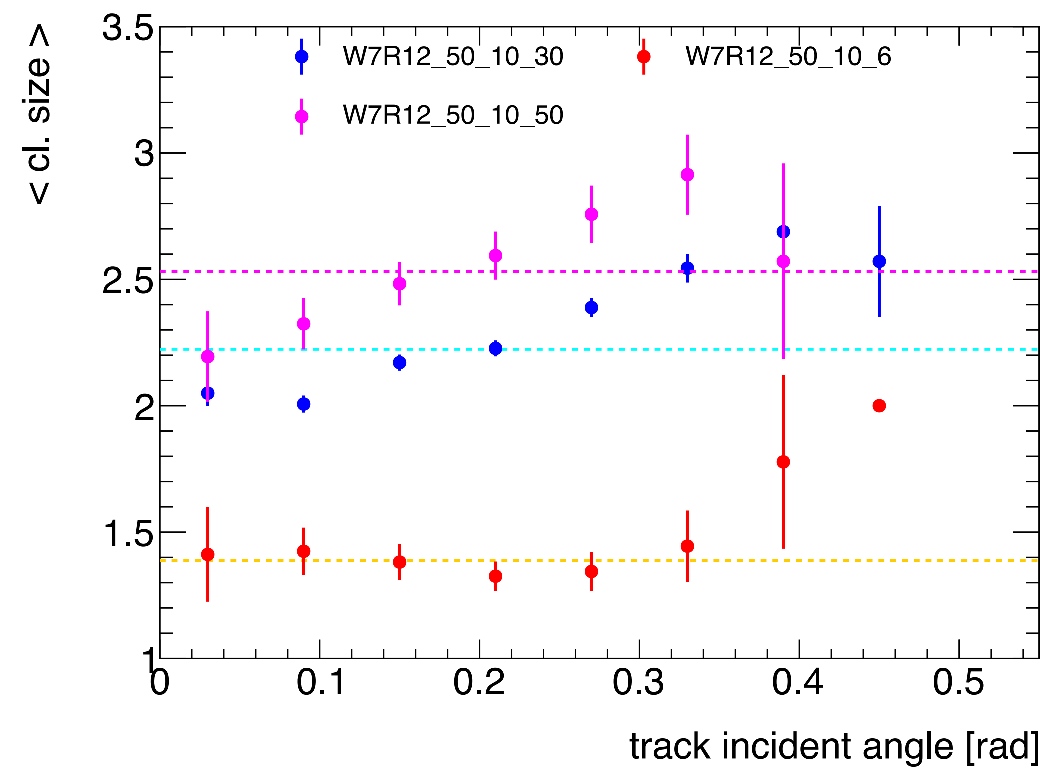



# MALTA lab measurements

- measurement of efficiency and cluster size with cosmic muons and Sr-90
- good behavioural agreement with the testbeam, difference due to:
  - “beam” condition (testbeam ~ 3GeV $e^-$ vs Sr-90 ~2-3 MeV $e^-$)
  - not perfect alignment for μ

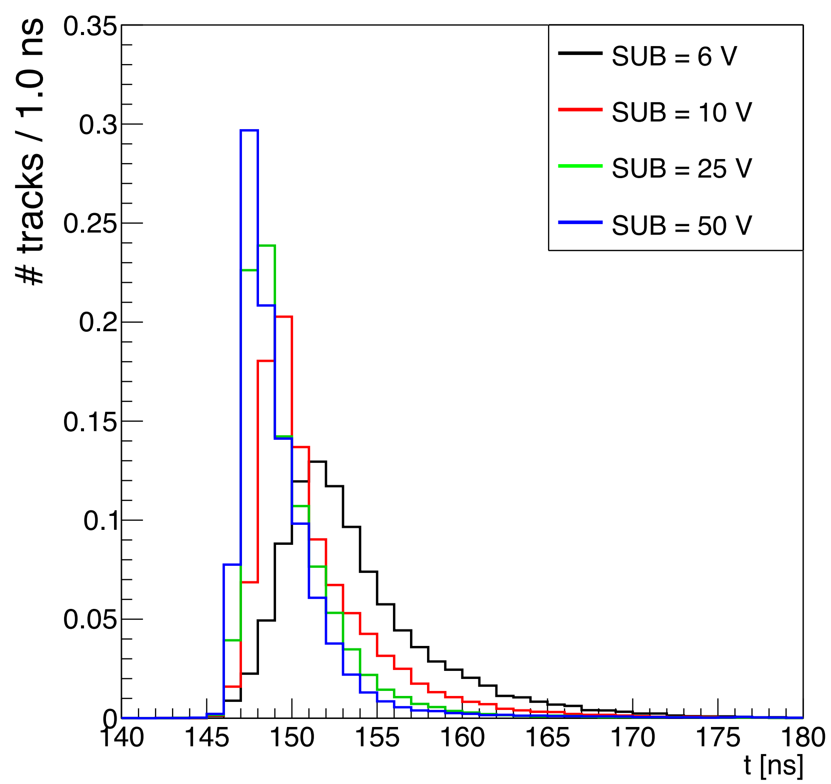


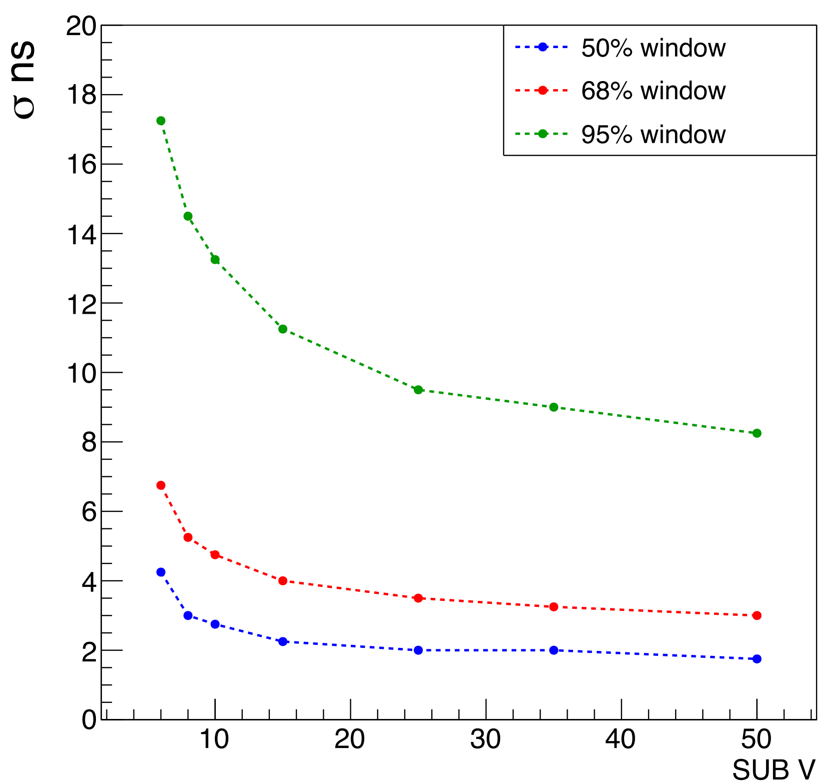



# MALTA timing measurements

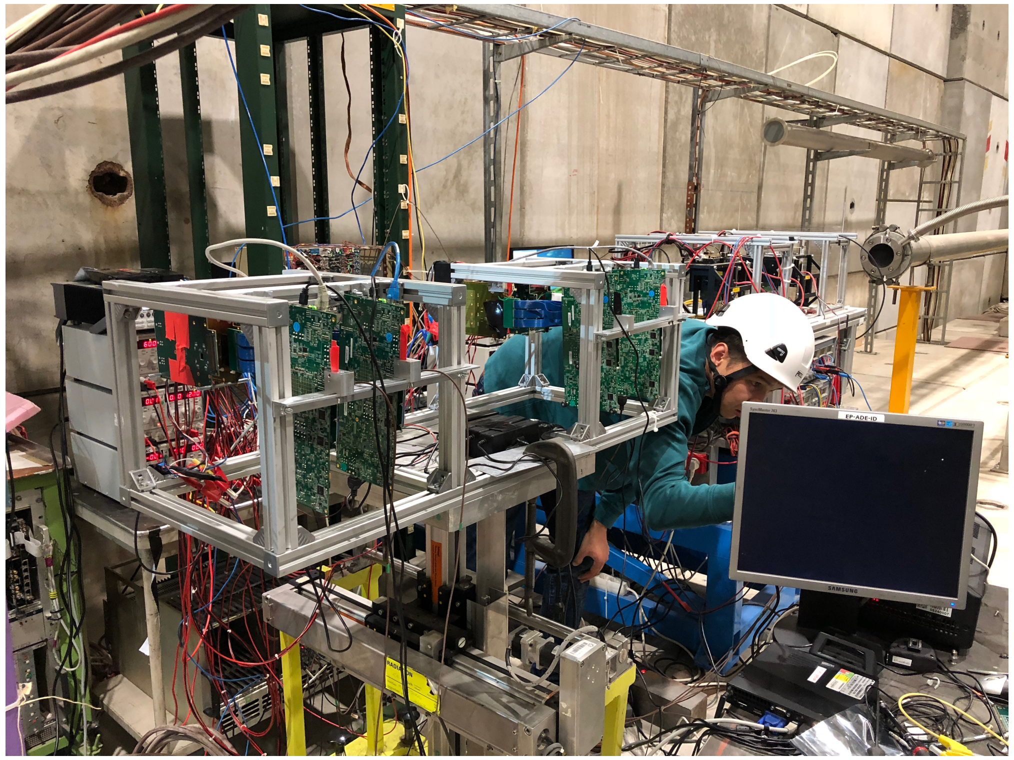
- PicoTDC used to measure Δt ($t_{MALTA}$ - $t_{PMT}$): time of the fastest hit of the cluster (matched with the track in the DUT) - time of the hit in the scintillator $\sigma_{PMT}$~1 ns (not subtracted)
- study the dependency of Δt as a function of substrate voltage and threshold
- define 3 integral windows which contain the 50%-68%-95% of the Δt distribution

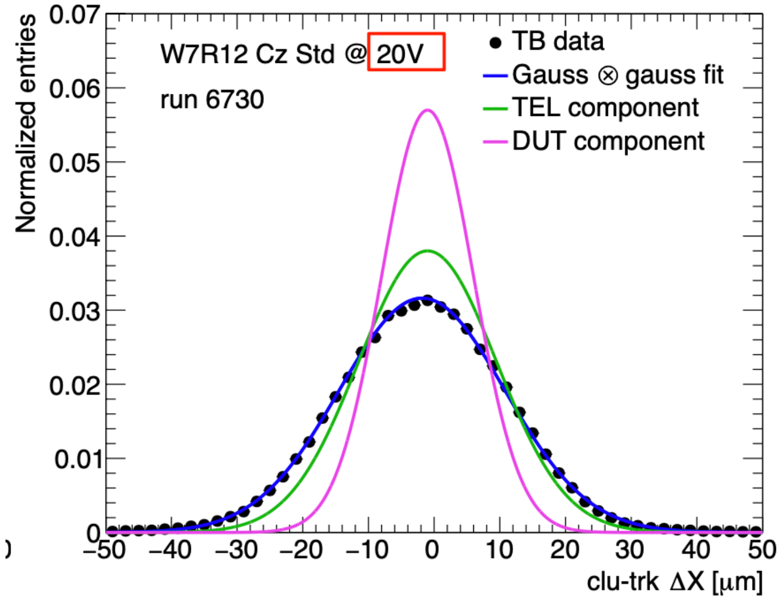


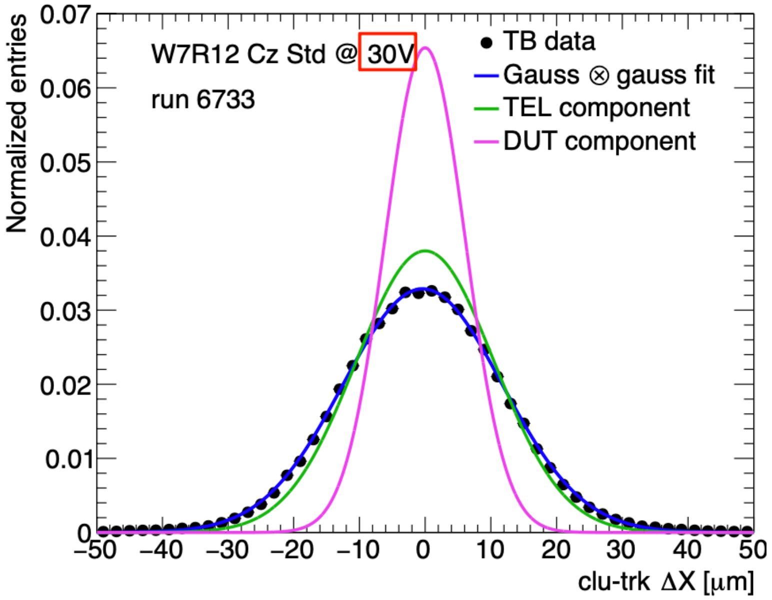



# MALTA testbeam 2021

- **waiting for approval @ SPS**
- standalone MALTA based telescope:
  - cooling, trigger logic, software, etc..
- possible improvement, use Cz samples as tracking planes:
  - better spatial resolution at -30 V due to larger cluster size






| | Epi Std | Cz Std | Cz std | Cz std |
|---|---|---|---|---|
| **SUB V** | -6 | -6 | -20 | -30 |
| **X-res µm** | ~10.5 | ~9.3 | ~7.0 | ~6.1 |

*back*-of-the-*envelope* calculation

# conclusions

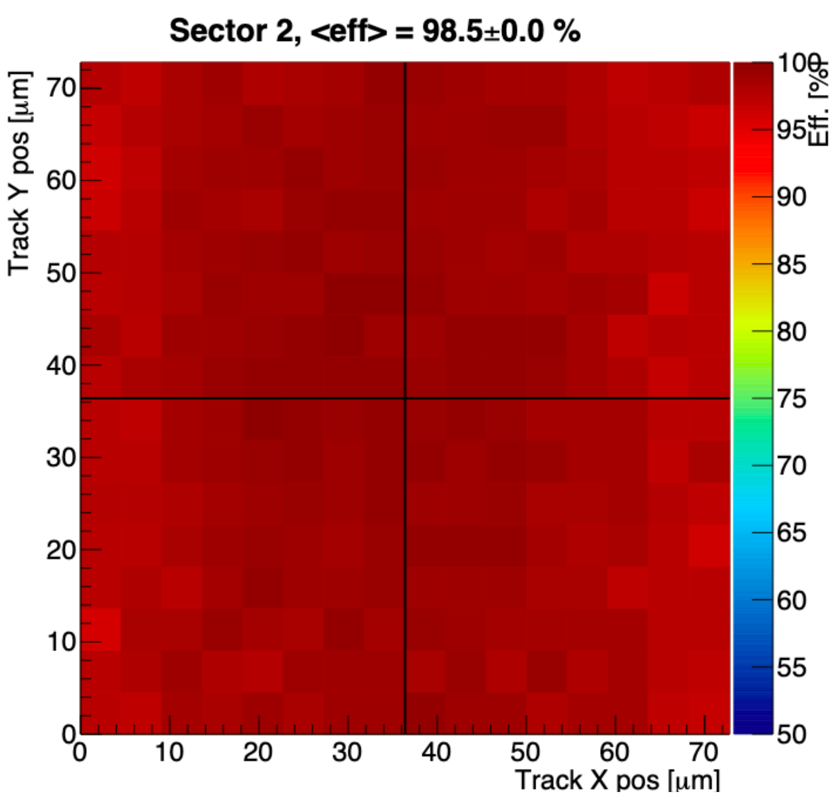
- development of the MALTA CMOS pixel sensors (TowerJazz 180 nm technology)
- MALTA very efficient after neutron irradiation (up to $2x10^{15}$ $n_{eq}/cm^2$)
- continue integrating MALTA in performing telescope systems
- more results from DESY 2019 test beam still to come
- testbeam @SPS in 2021
- MALTA2 (wafer arrived at CERN) with better front-end: larger transistors and cascode frontend --> larger gain and improved noise performance

# extra slides

# In-pixel efficiency

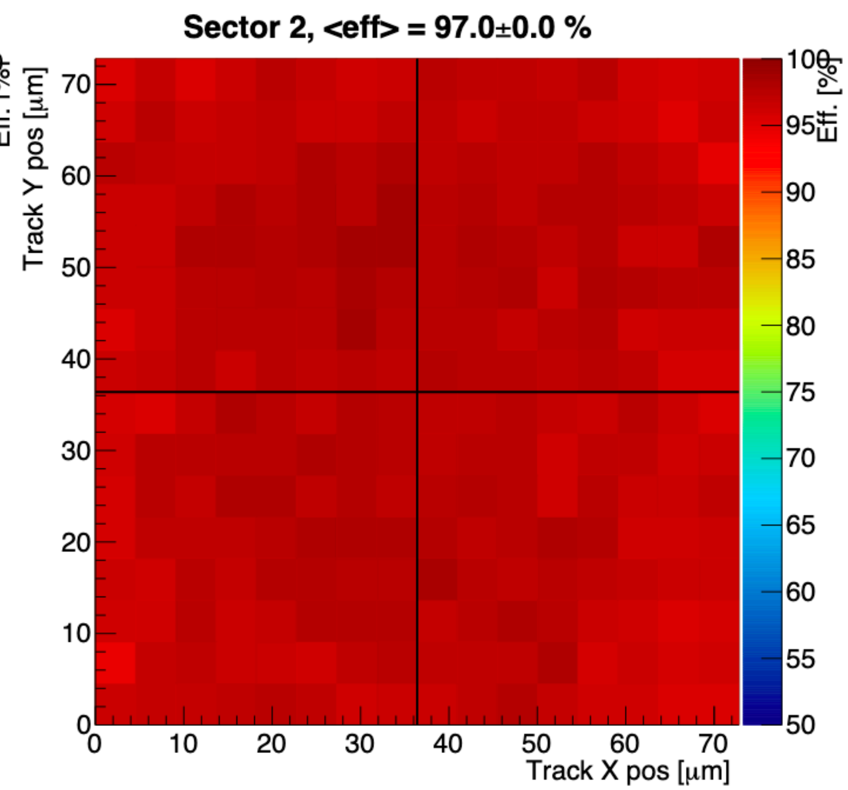
**MALTA Cz unirradiated**

**ε = 98.5%**



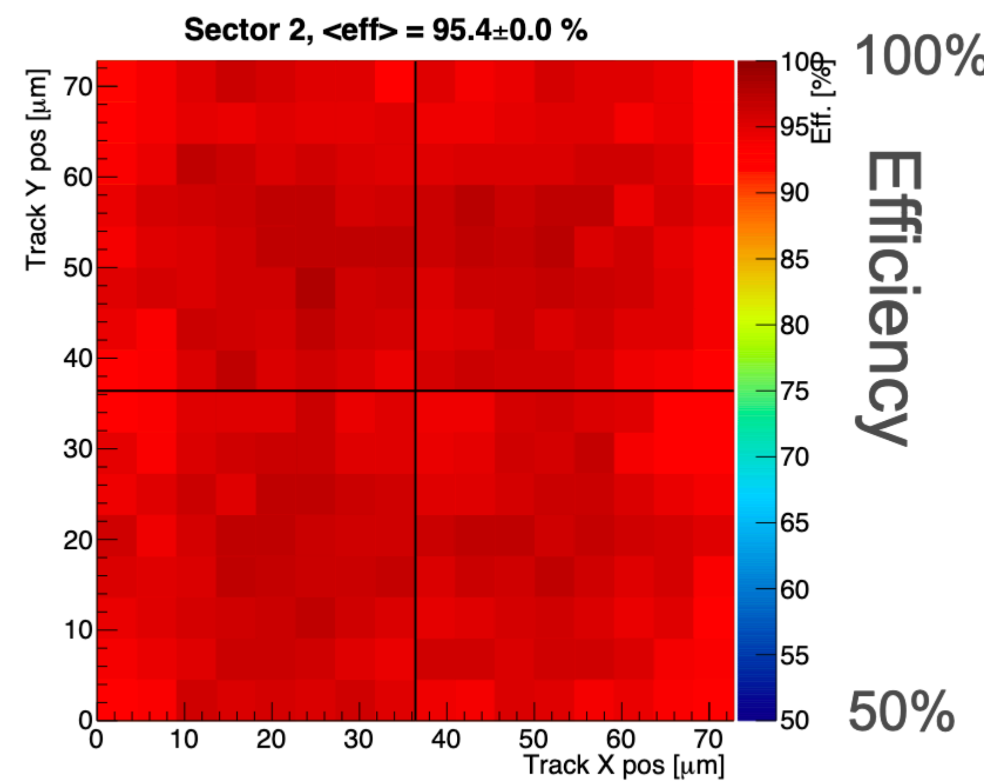

**MALTA Cz n-gap $1x10^{15}$ $n_{eq}/cm^2$**

**ε = 97.0%**



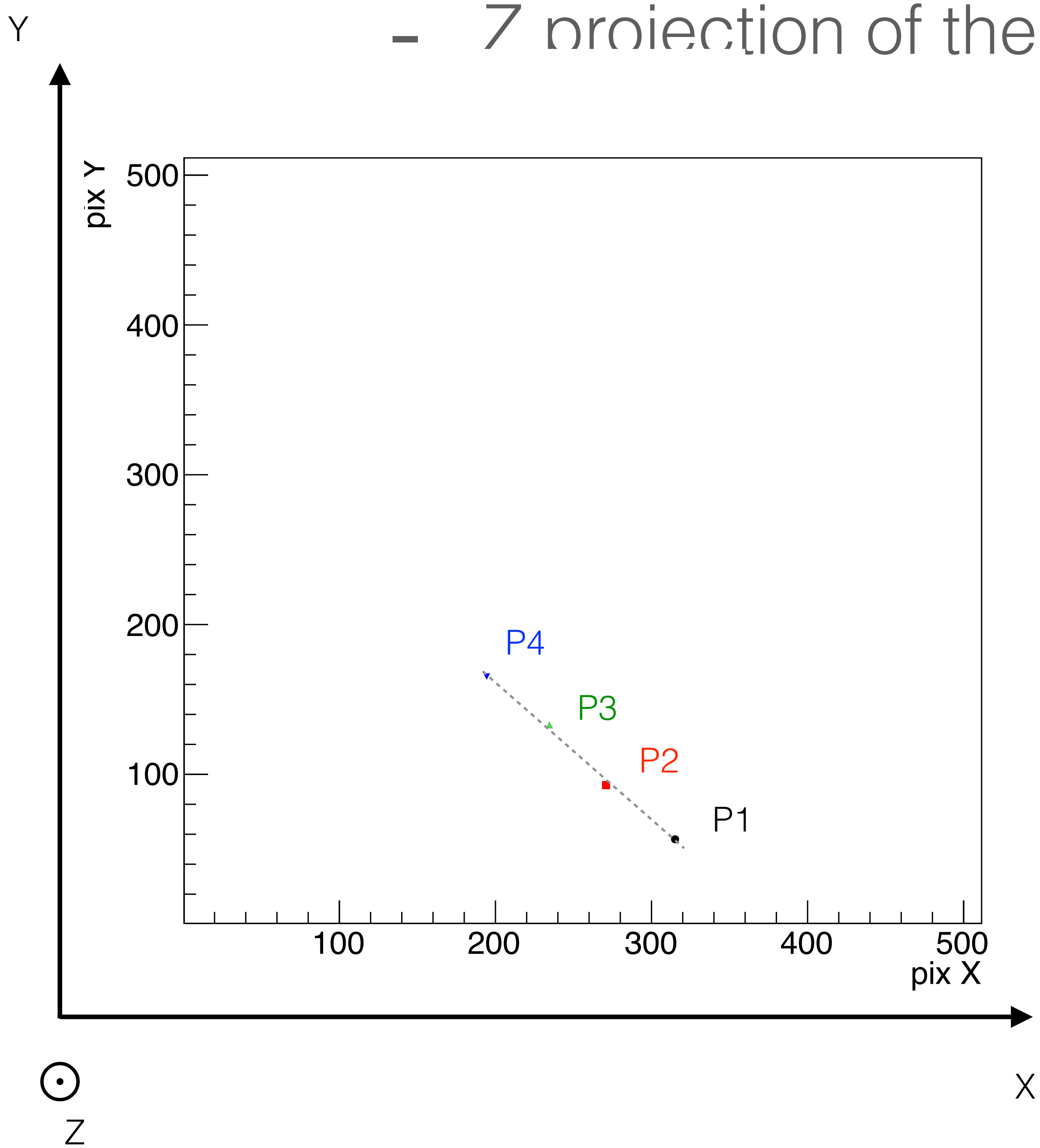

**MALTA Cz n-gap $2x10^{15}$ $n_{eq}/cm^2$**

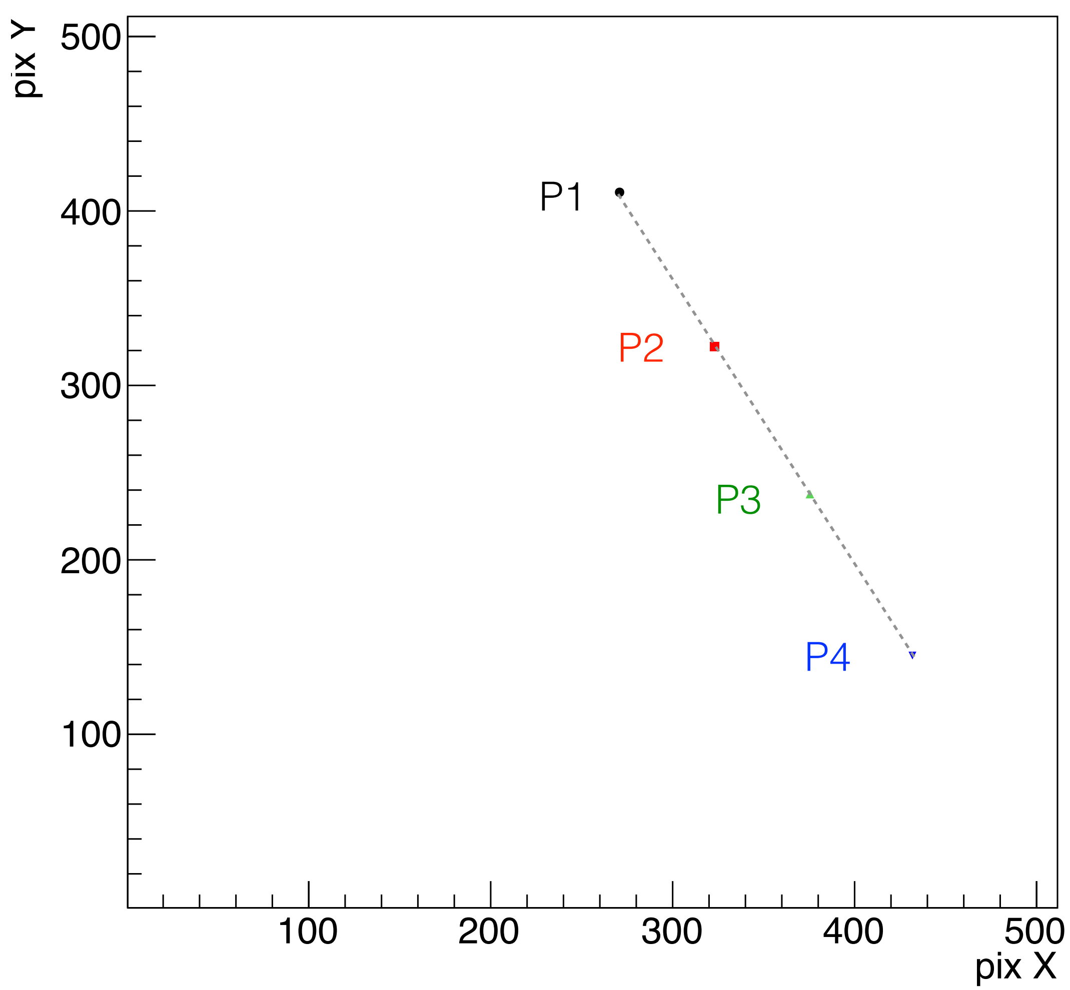
**ε = 95.4%**



# cosmic muon

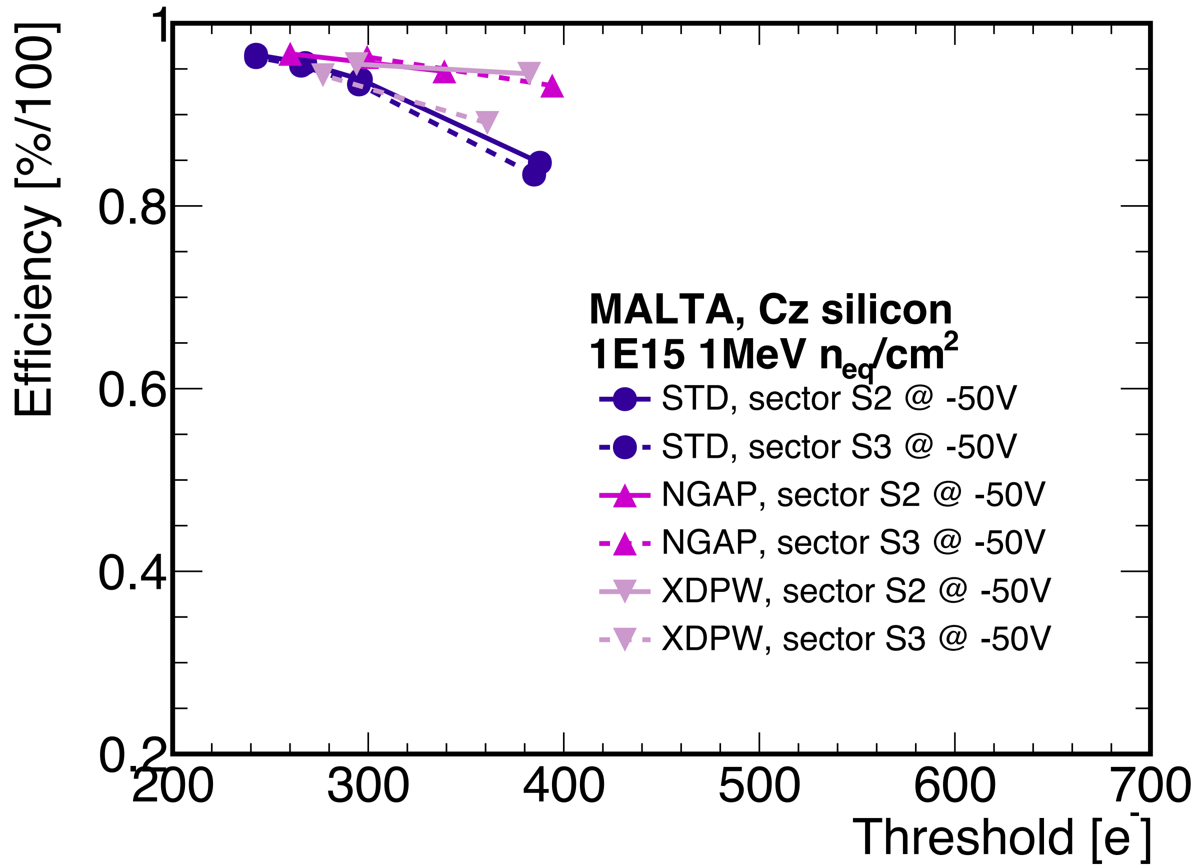
- Z projection of the 4 telescope planes



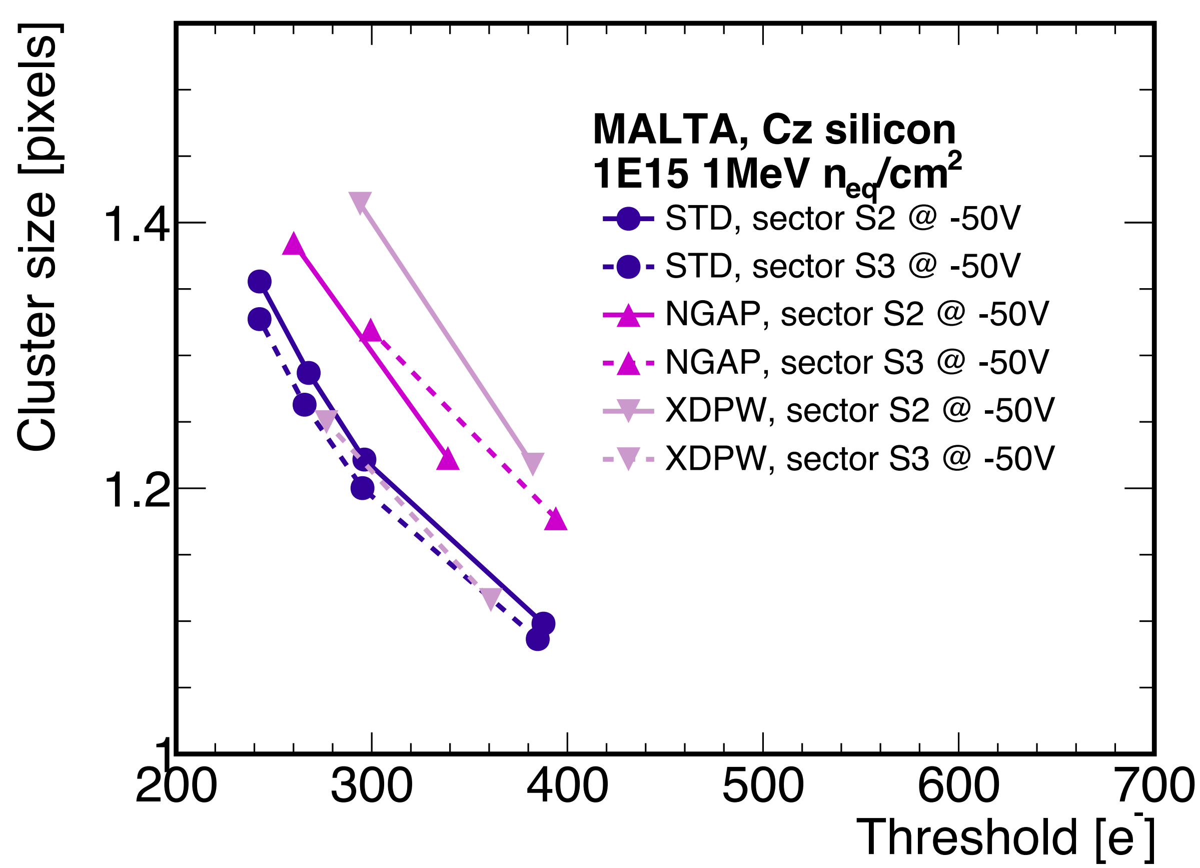



# Cz irradiated chips

efficiency vs threshold

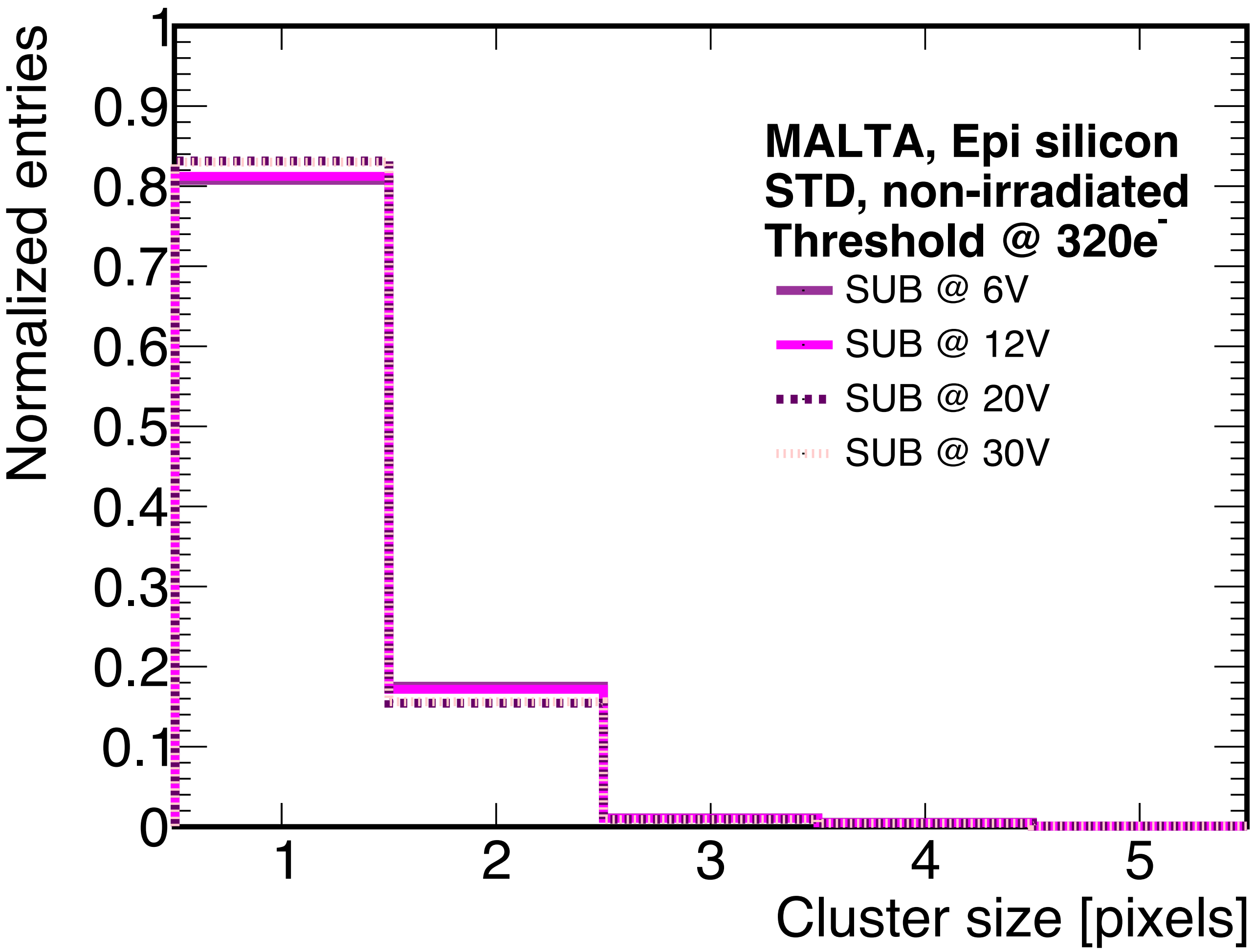



cluster size vs threshold

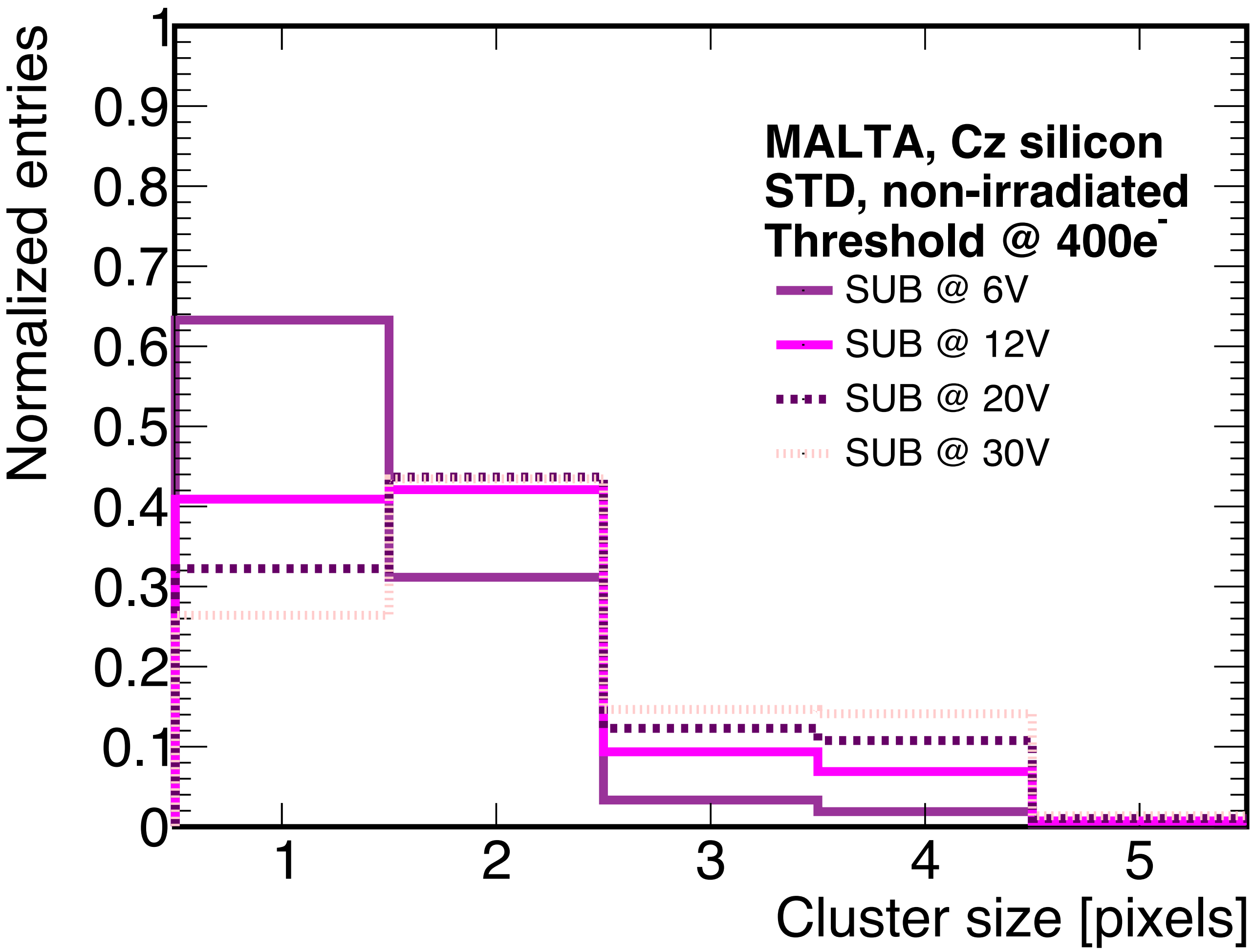


# non irradiated chips

std Epi silicon

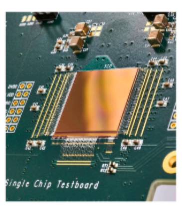



std Cz silicon



# MALTA history 2

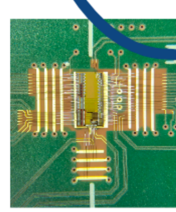
**Jan 2018**



**MALTA1 & MLVL**

- Sensor
- Front-end

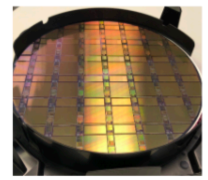
**Jan 2019**



**Mini-MALTA**

- Sensors
- Front-end

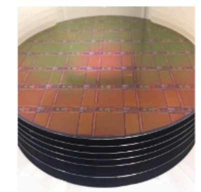
**Aug 2019**



**MALTA C**

- SlowControl fix
- Front-end
- Sensors

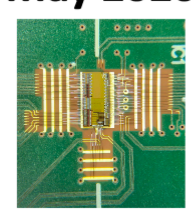
**Oct 2019**



**MALTA Cz**

- SlowControl fix
- Front-end
- Sensors

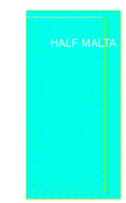
**May 2020**



**Mini-MALTA ATTRACT**

- Sensors
- Front-end
- Cascoded

**Submission mid Oct 2020**



**MALTA 2**

- Sensors
- Front-end
- New SlowControl
- Cascoded