Latest developments and characterisation results of the MALTA sensors in TowerJazz 180nm for High Luminosity LHC

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Andrea Gabrielli
CERN

12th International Conference on
POSITION SENSITIVE DETECTORS

Hosted by
UNIVERSITY OF BIRMINGHAM

CMOS motivation

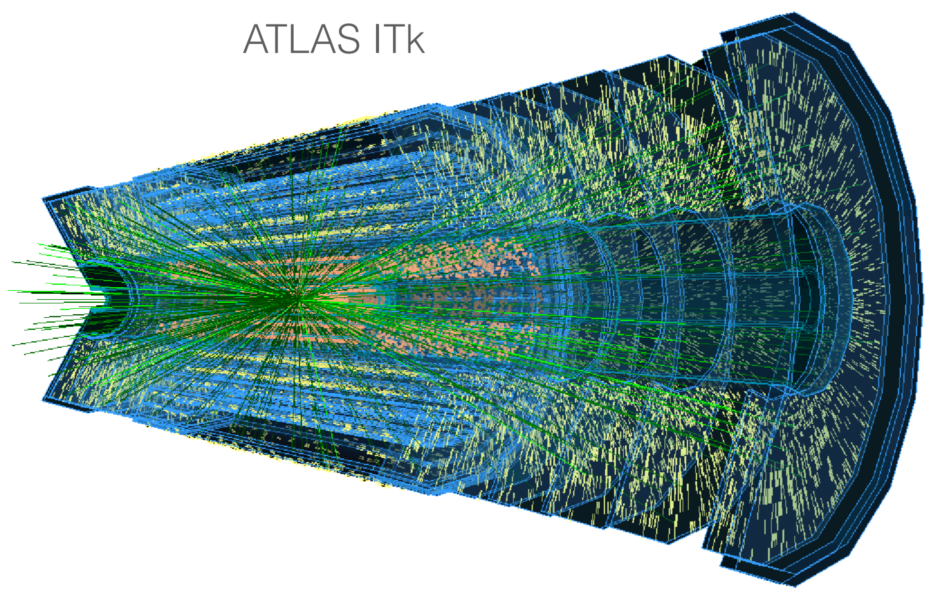
- requirements for future HEP detectors are vey challenging:
  - extreme ration tolerance
  - very fast response
  - very large surface
  - very thin
  - high granularity

CERN-OPEN-2018-006

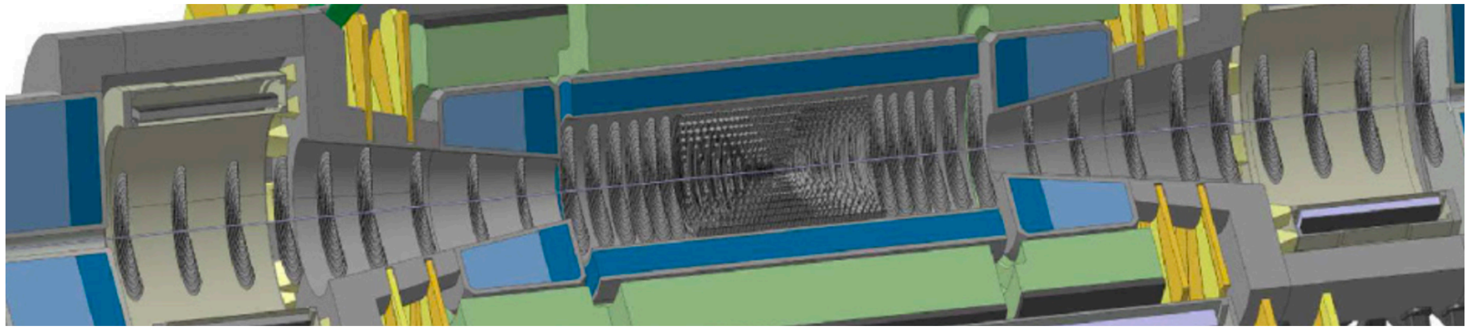
Exp. / Parameter	LHC	HL-LHC	SPS	FCC-hh	FCC-ee	CLIC 3 TeV
Fluence [$n_{eq}/cm^2/y$]	N x 10^{15}	10^{16}	10^{17}	10^{16} - 10^{17}	<10^{10}	<10^{11}
Max. hit rate [$s^{-1}cm^{-2}$]	100 M	2-4 G****)	8 G****)	20 G	20 M ***)	240k
Surface inner tracker [m^2]	2	10	0.2	15	1	1
Surface outer tracker [m^2]	200	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 [μm^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

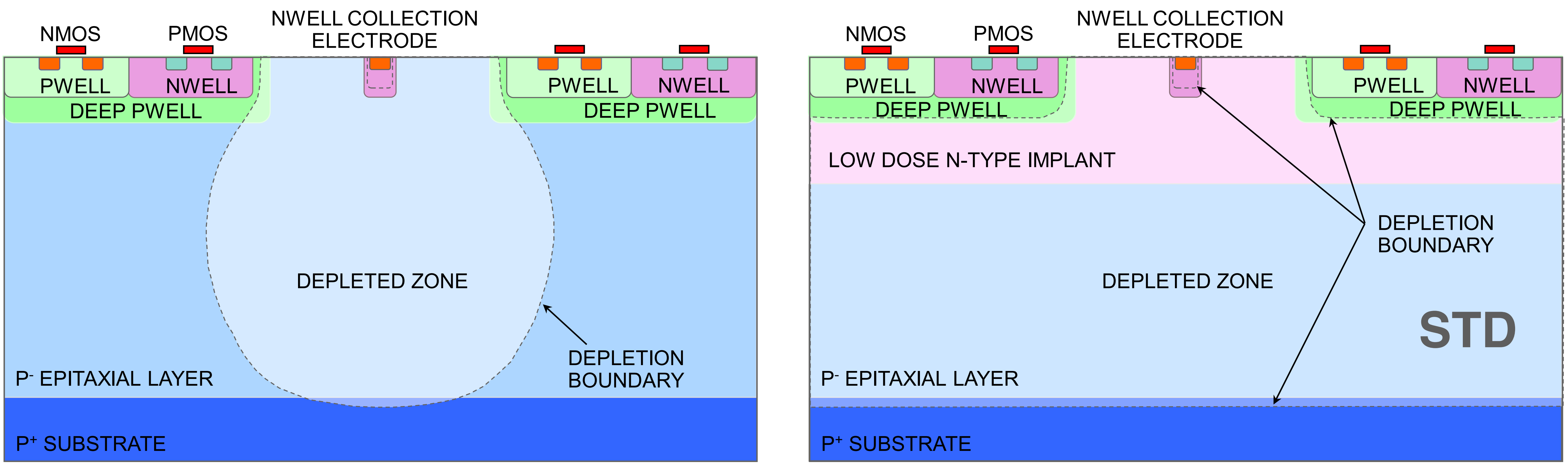


FCC: hh



Tower Semiconductor 180nm CMOS sensors

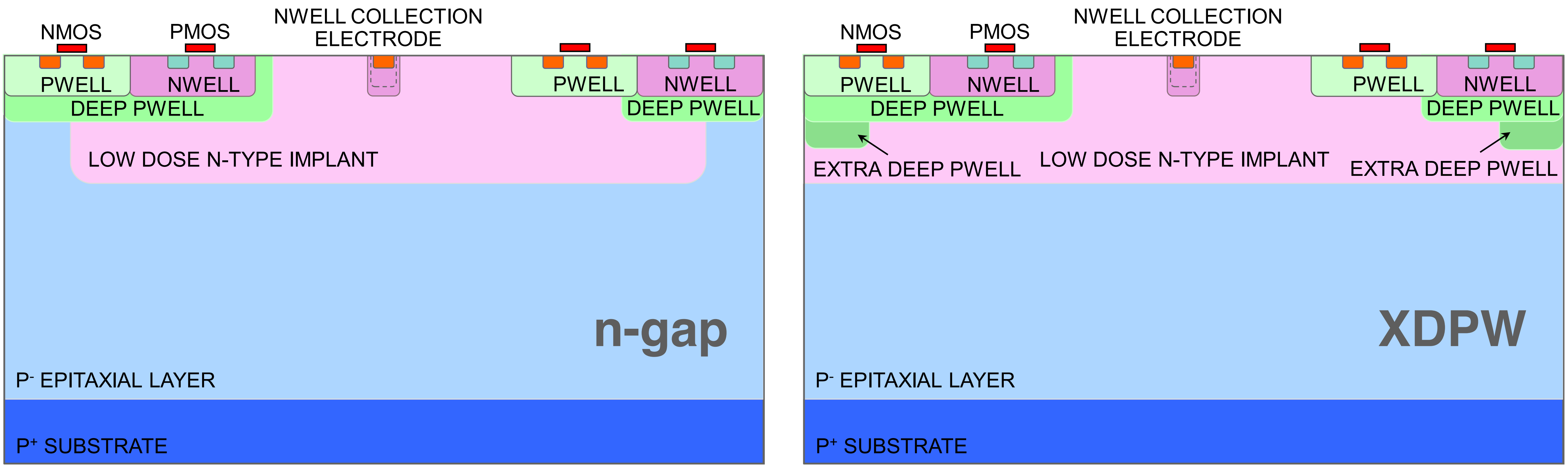
- Towejazz process:
  - high-resistivity Epi layer, 25 μm depletion→ ~1500 e- for MIP, high signal to noise ratio (~20)
- modified process:
  - extra low dose n-type layer to improve depletion under the deep p-well, better radiation tolerance



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

Tower Semiconductor 180nm CMOS sensors

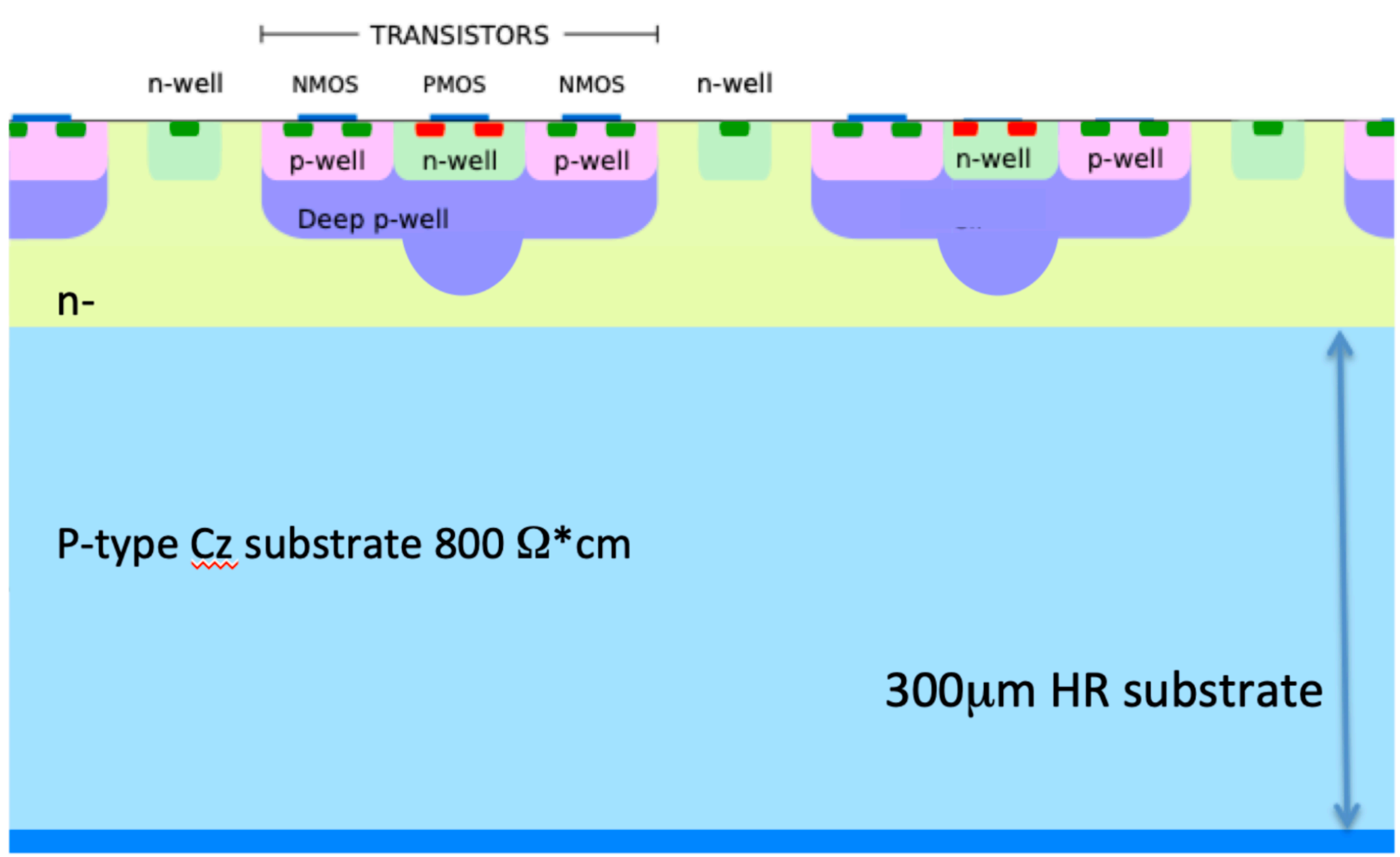
- special layouts for deep p and n wells to optimize field configuration and charge collection: increase lateral field near pixel edge to “focus” charge to electrode:
  - gap in the n-layer: 4 μm gap in the low dose n-layer
  - ‘extra-deep p-well’ layer: 5 μm wide additional p-well implant



H.Pernegger NIM A 986 (2021) 164381
M. Dyndal,JINST 15 (2020) P02005
M. Mironova, NIM A 956 (2020) 163381
Magdalena, M.Munker PIXEL 2018

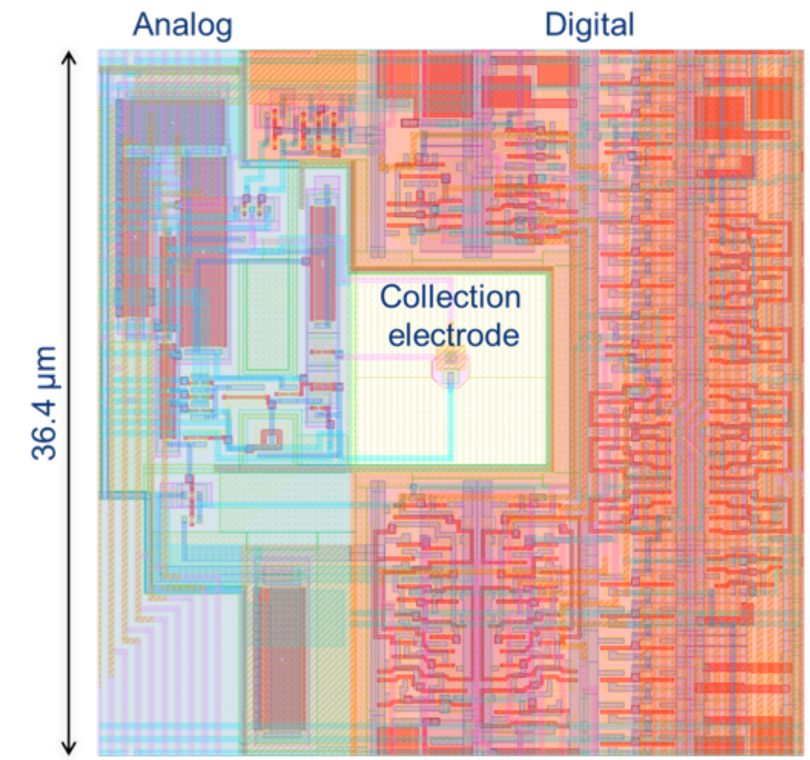
Tower Semiconductor 180nm CMOS sensors

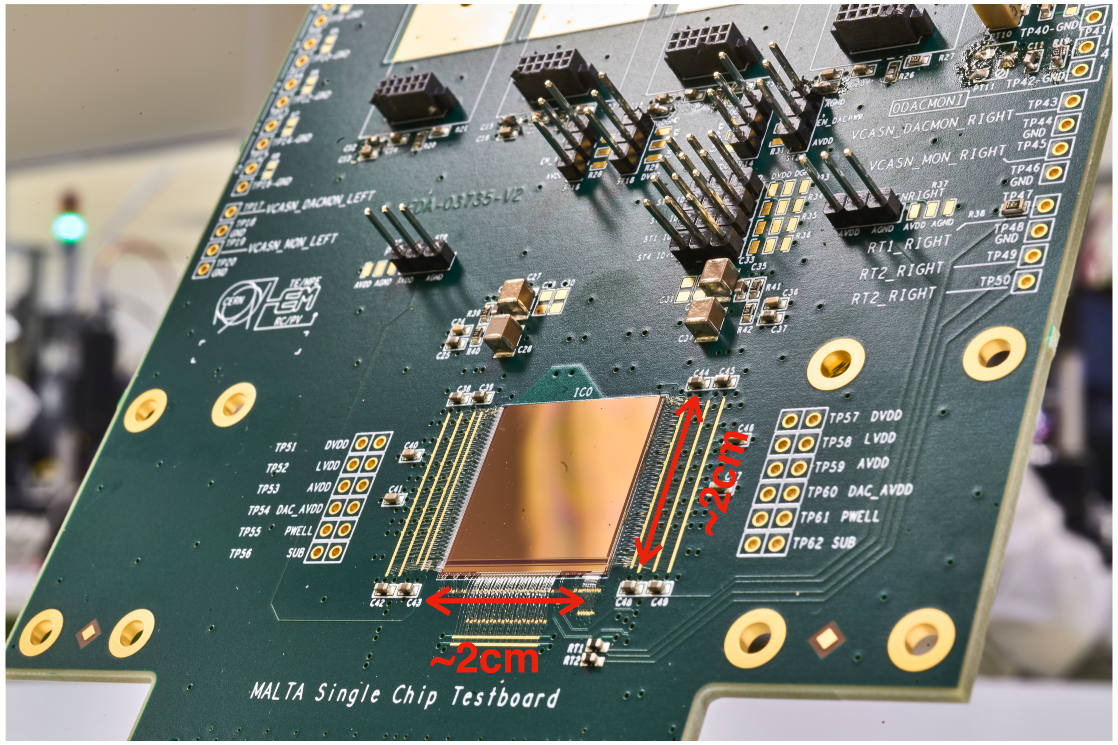
- MALTA with high resistivity Czochralski(Cz) substrate material
- significant larger depletion and signal:
  - higher radiation hardness
  - high operation voltage up to 50V -> high depletion depth



MALTA pixel detector

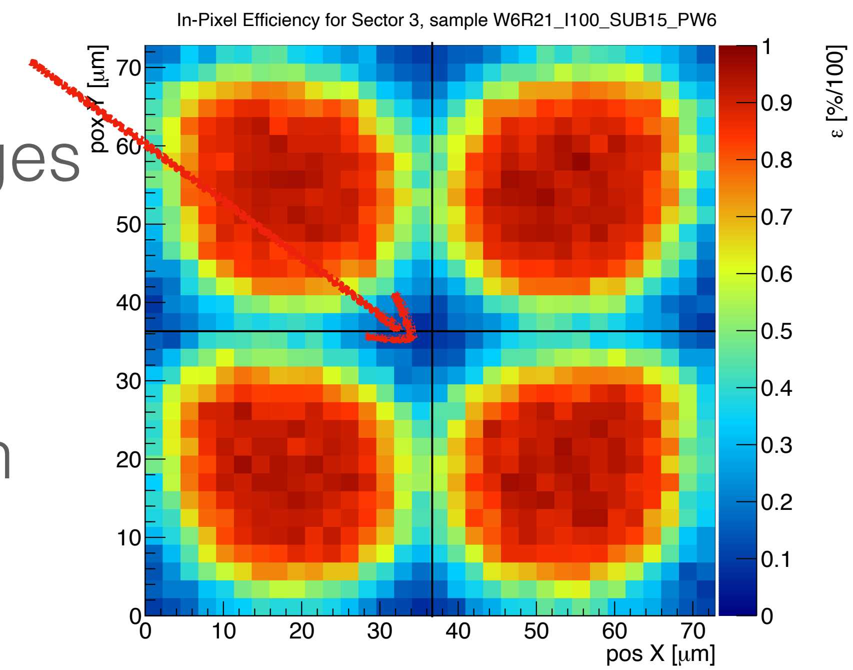
- matrix 512 x 512 pixels of 36.4 x 36.4 μm^2 size
- small collection electrode of 2-3 μm^2 to achieve minimal input capacitance <3fF
- 3.4-4 µm spacing between electrode and electronics: low cross talk
- asynchronous architecture
- very low power consumption:
  - 1 µW/pixel analog power
  - 70 mW/cm^2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



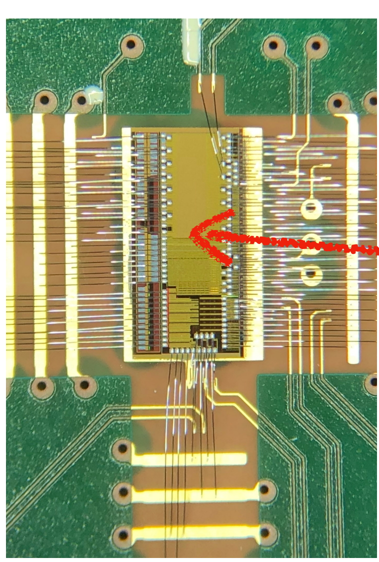


Malta history

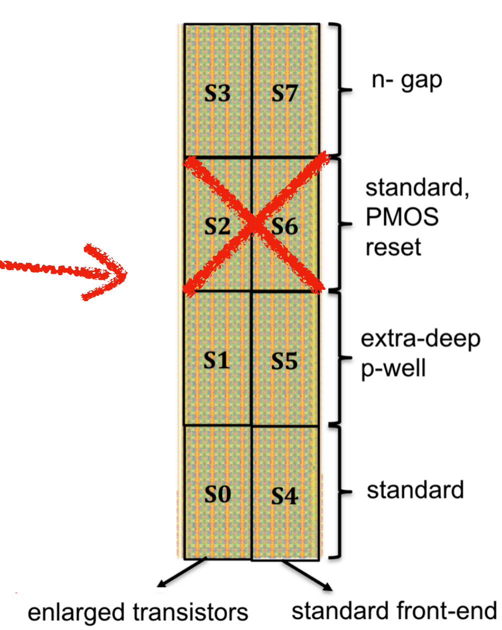
- 2018, first MALTA: after neutron irradiation the collection efficiency is degraded at pixel edges
- Jan 2019, MiniMALTA: smaller matrix version that changes the p-well extension to address the efficiency loss on corners and improved Front-End
- Aug 2019, reprocessed MALTA: large demonstrator with MiniMalta sensor improvements
- Jan 2021: MALTA2 improved Front-End

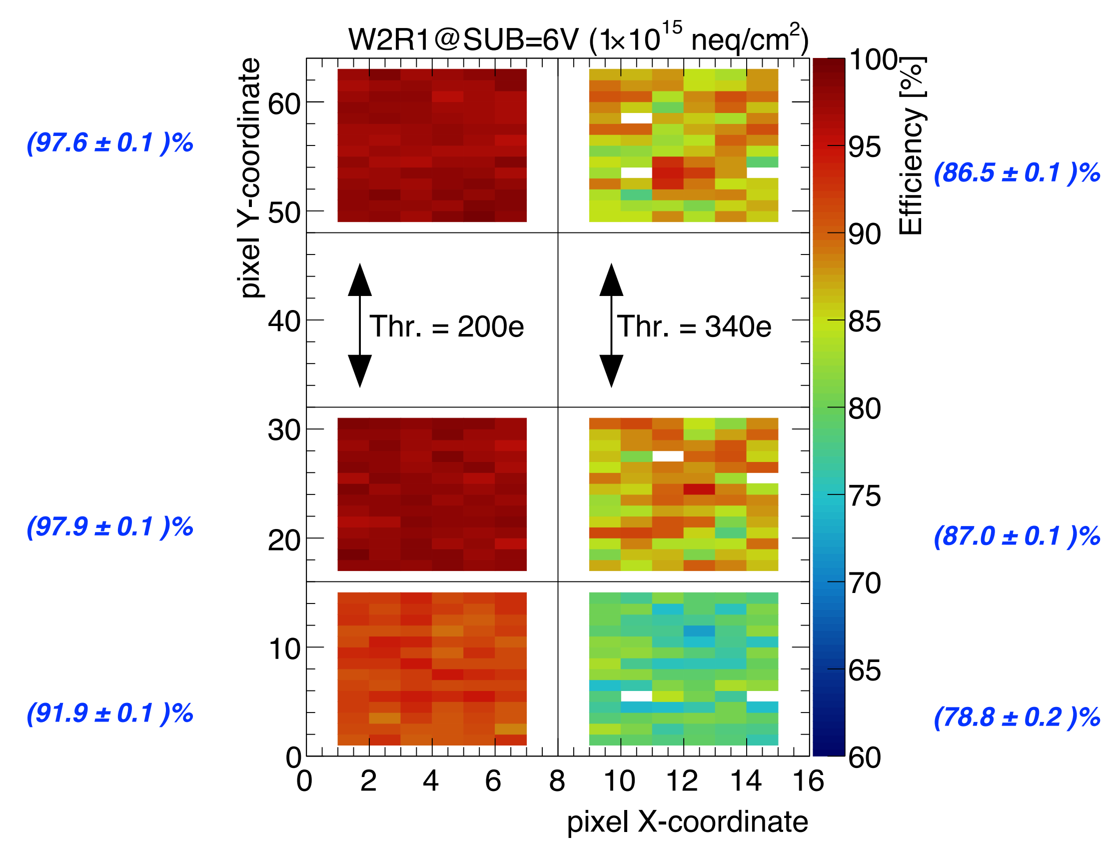


MiniMALTA demonstrator
5 mm x 1.7 mm



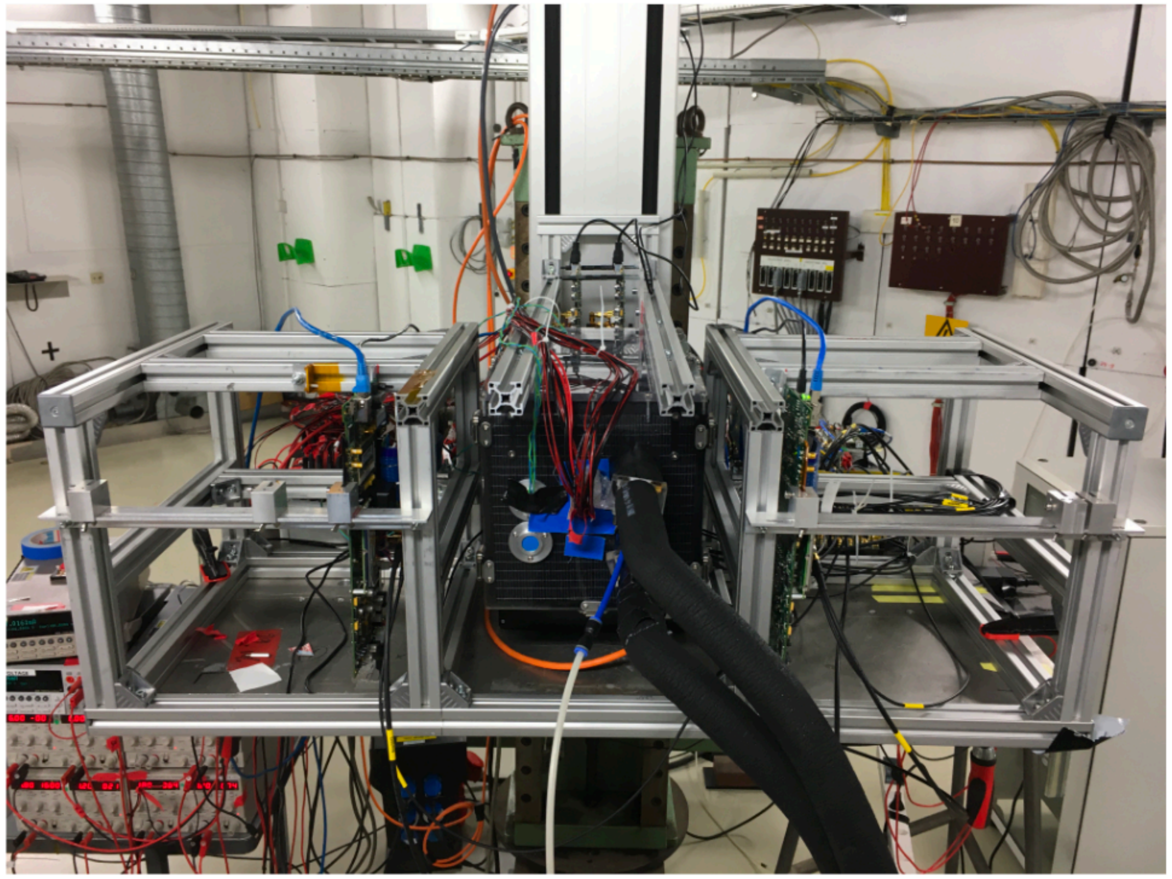
JINST 15 (2020) 02, P02005
I. Asensi VERTEX (2020)

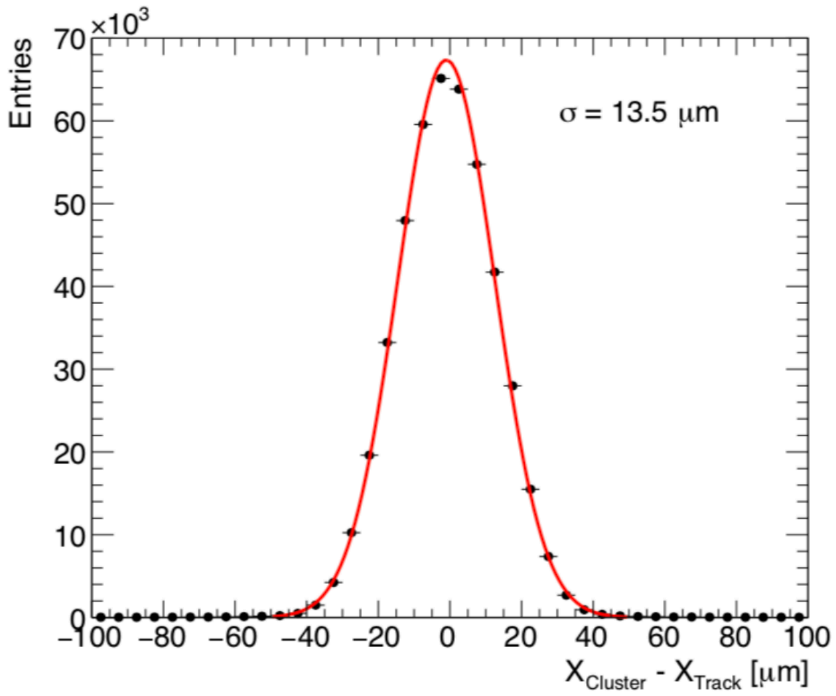


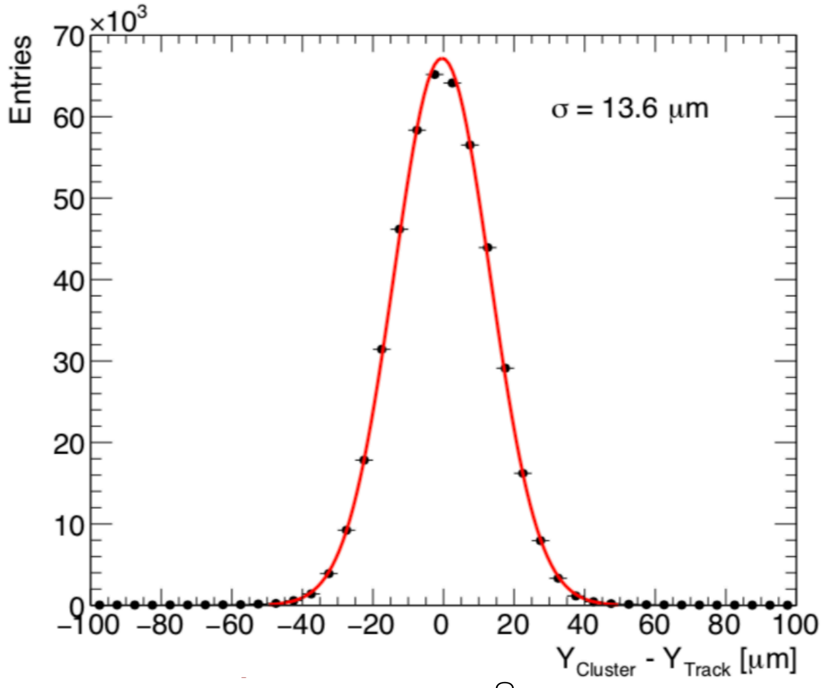


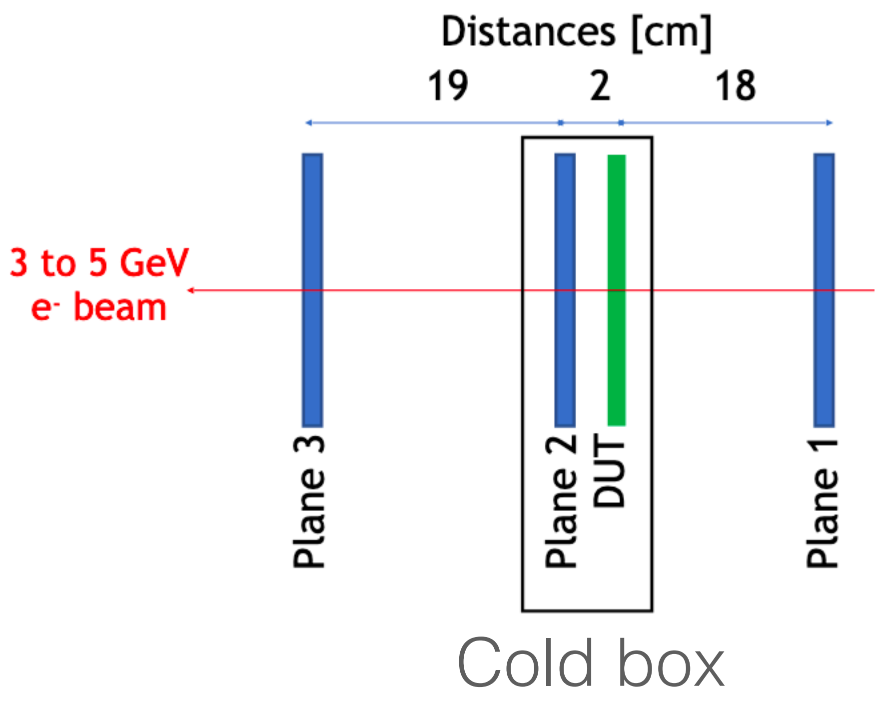
MALTA telescope testbeam

- 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



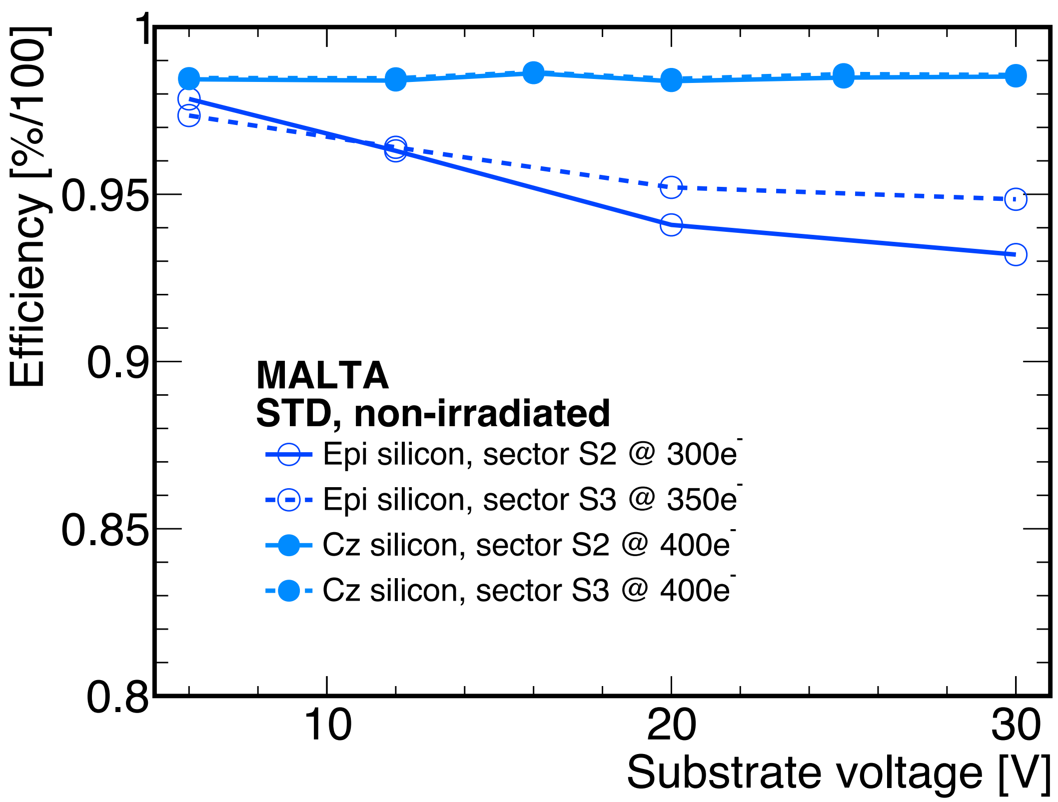


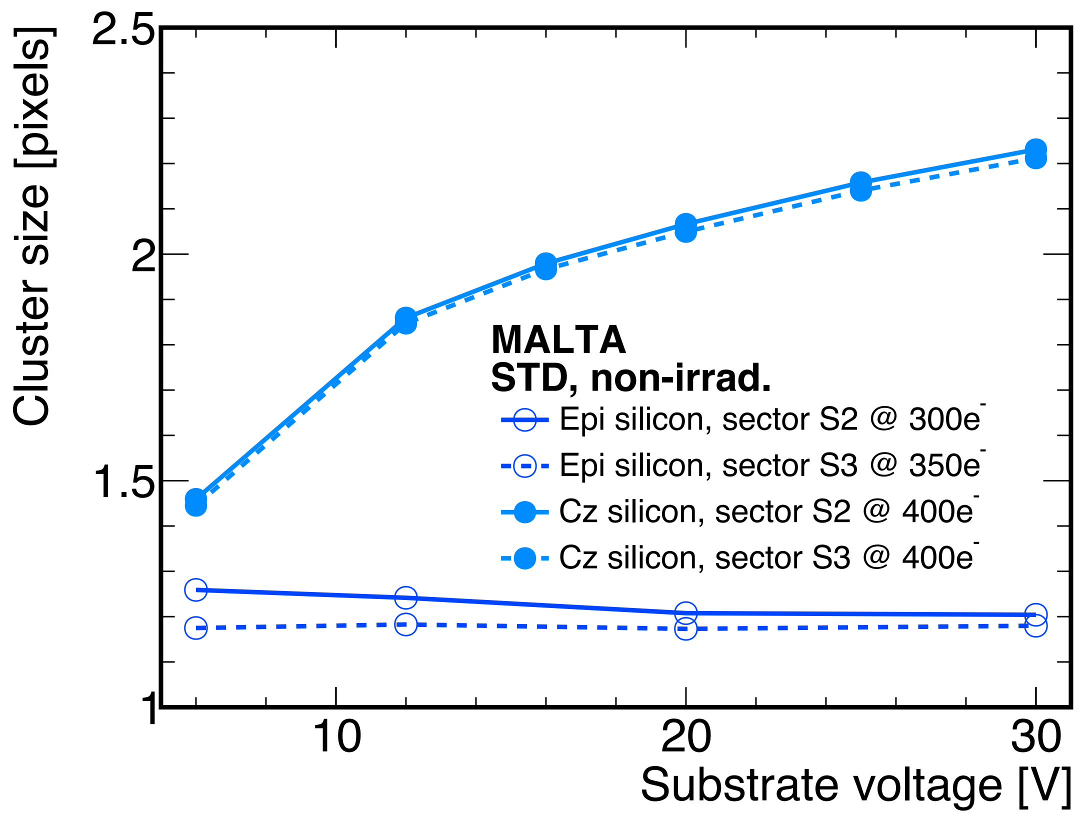




MALTA non-irradiated chip

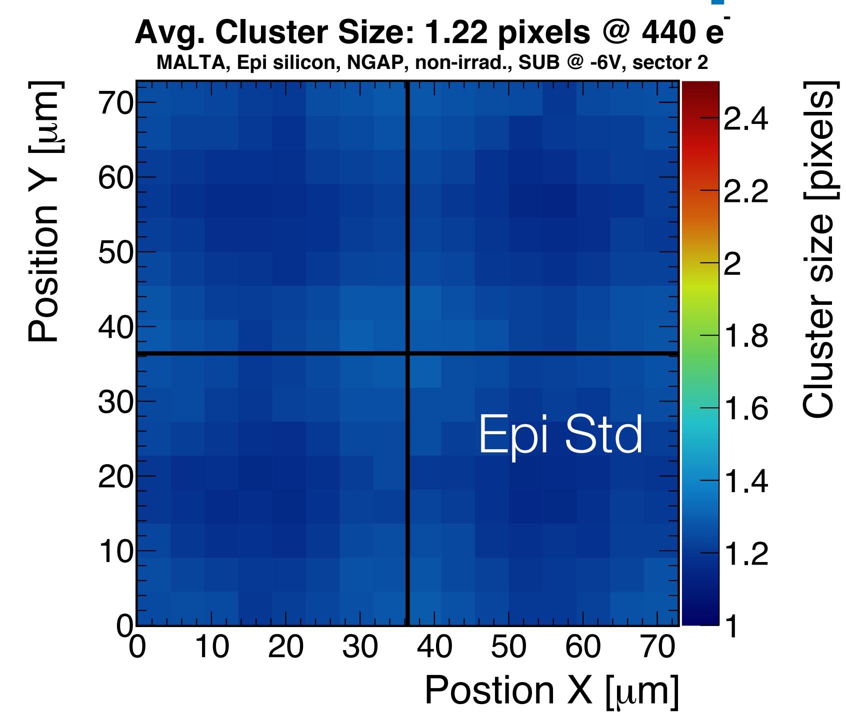
- efficiency vs substrate voltage:
  - Epi: no gain at high voltage (full depletion at 6V)
  - Cz: flat efficiency vs substrate voltage
- cluster size vs substrate voltage:
  - Epi: constant cluster size
  - Cz: smooth increase when increasing substrate voltage (more charge sharing in Cz material)

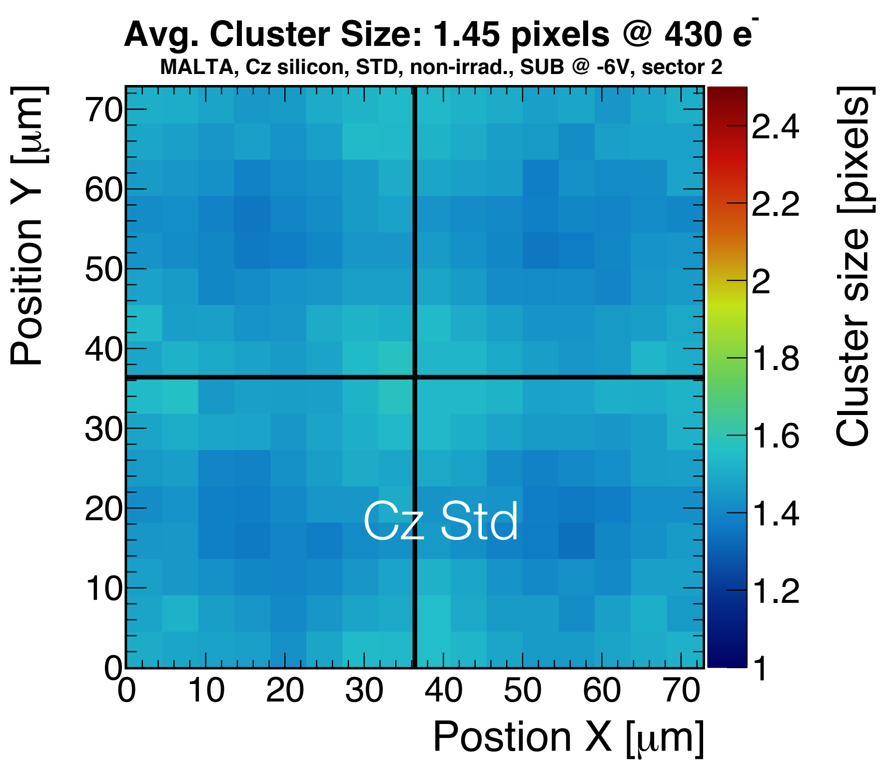


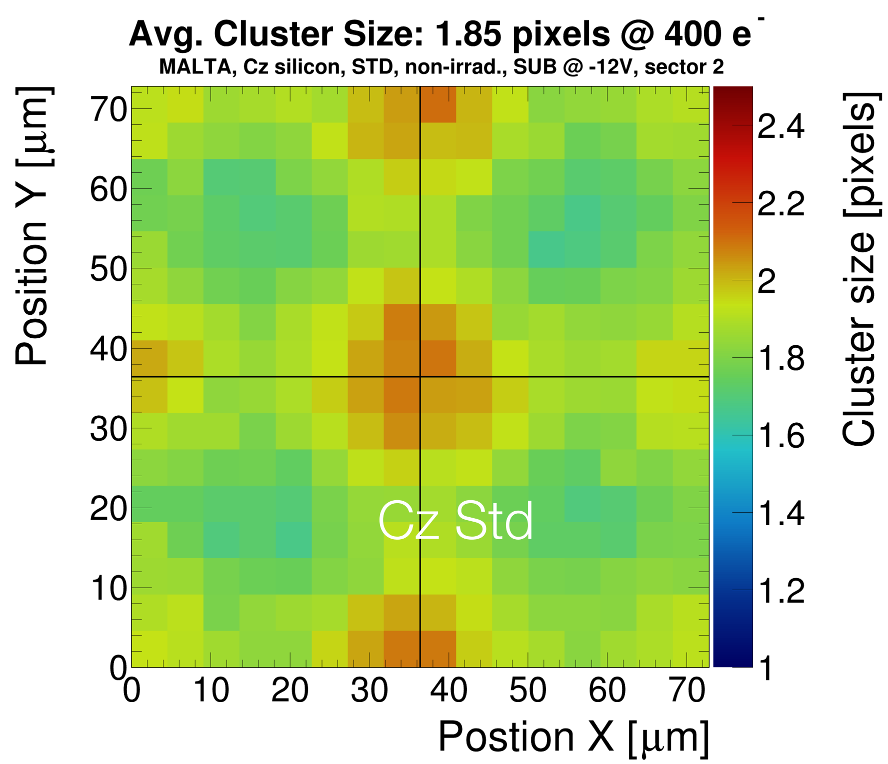


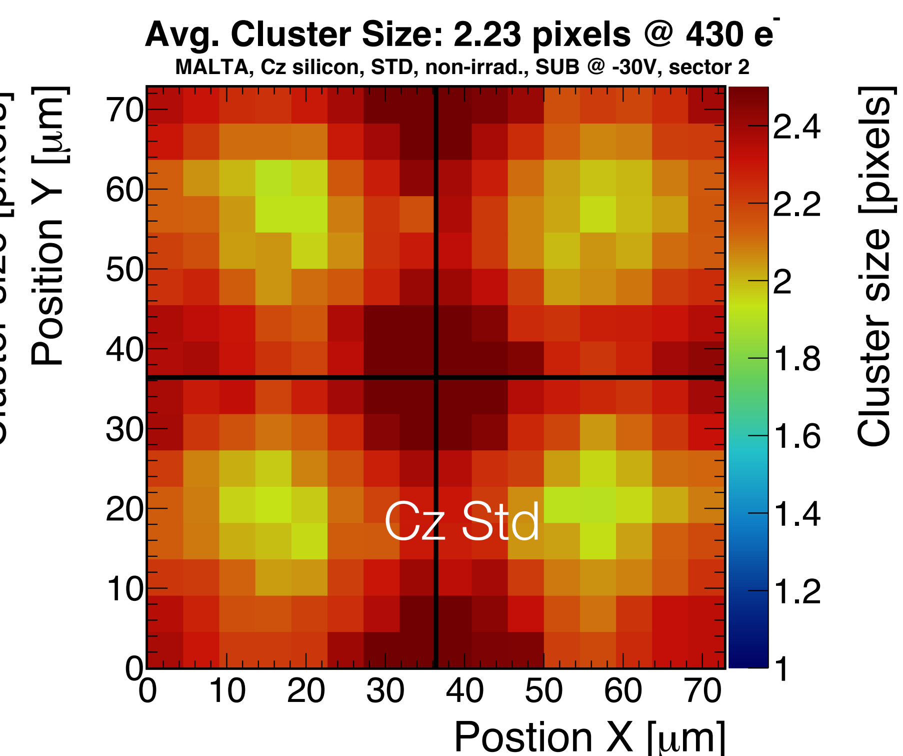
MALTA non-irradiated chip

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





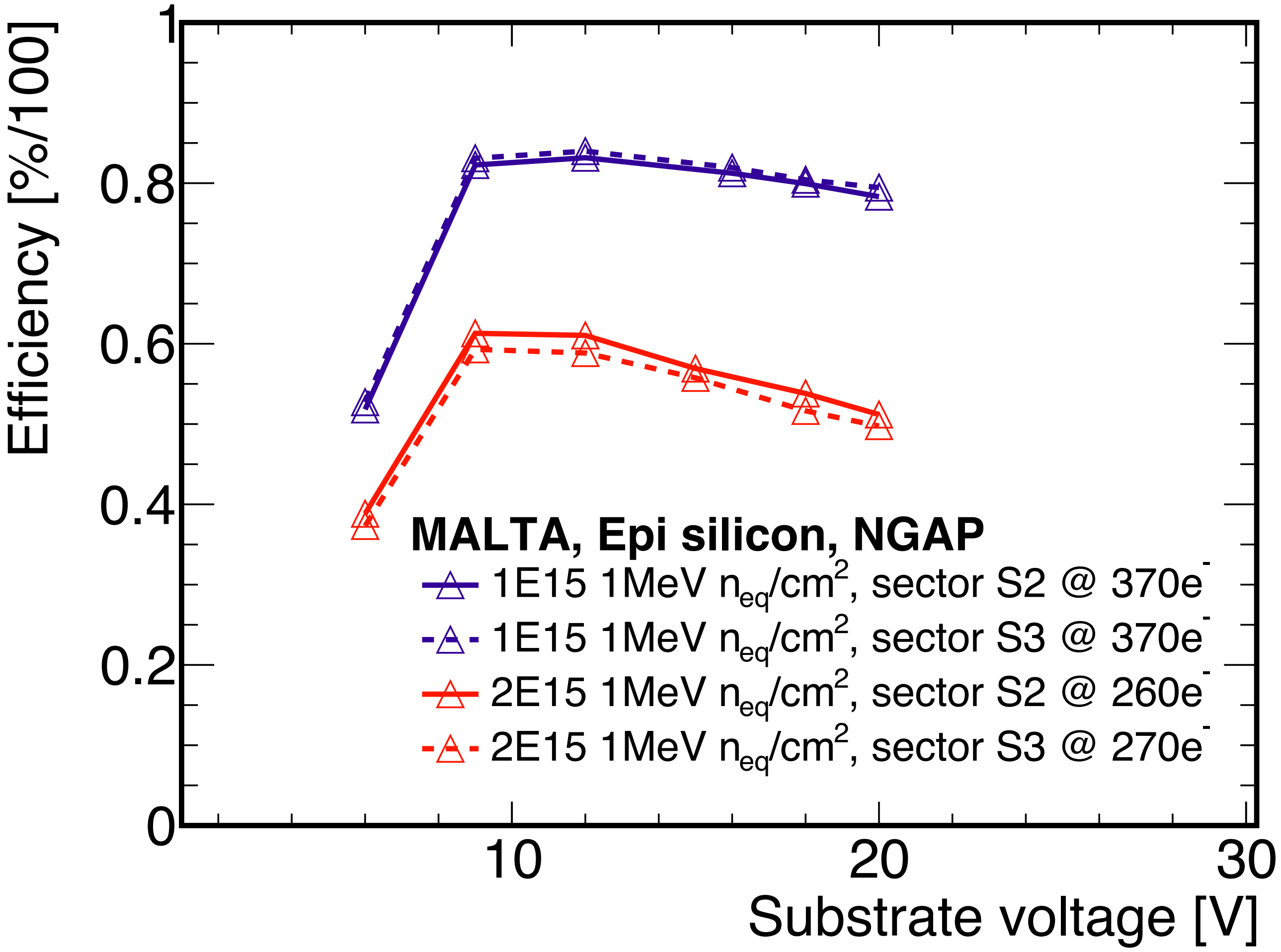


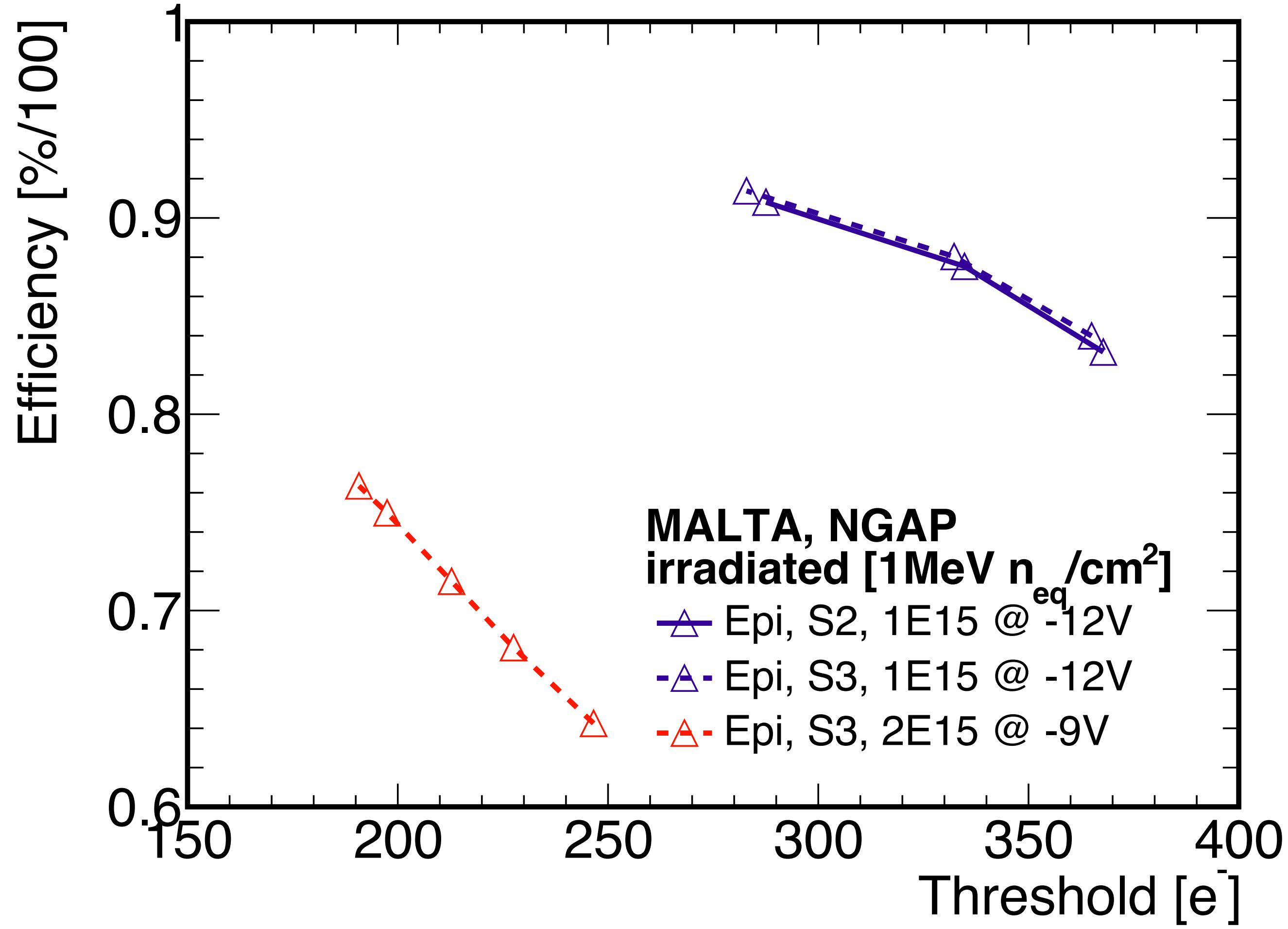


6 V 12 V 30 V SUB V

MALTA irradiated chips

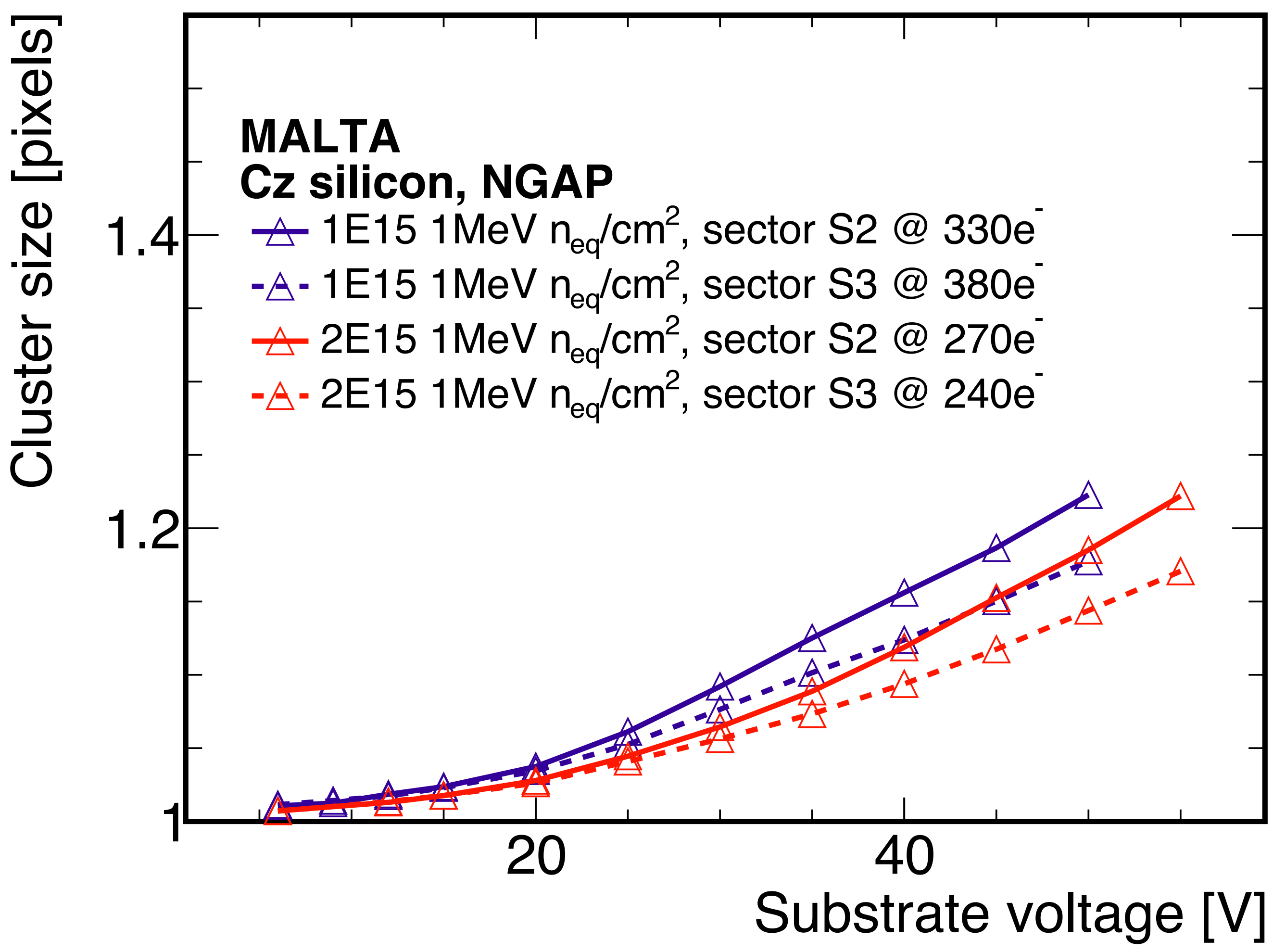
- Epi silicon sensor low efficiency for irradiated chip (1e^{15} n_{eq}/cm^2) ~80% @-10 V @370 e$^-$
- no gain with higher substrate voltage
- results consistent with previous MiniMalta measurements

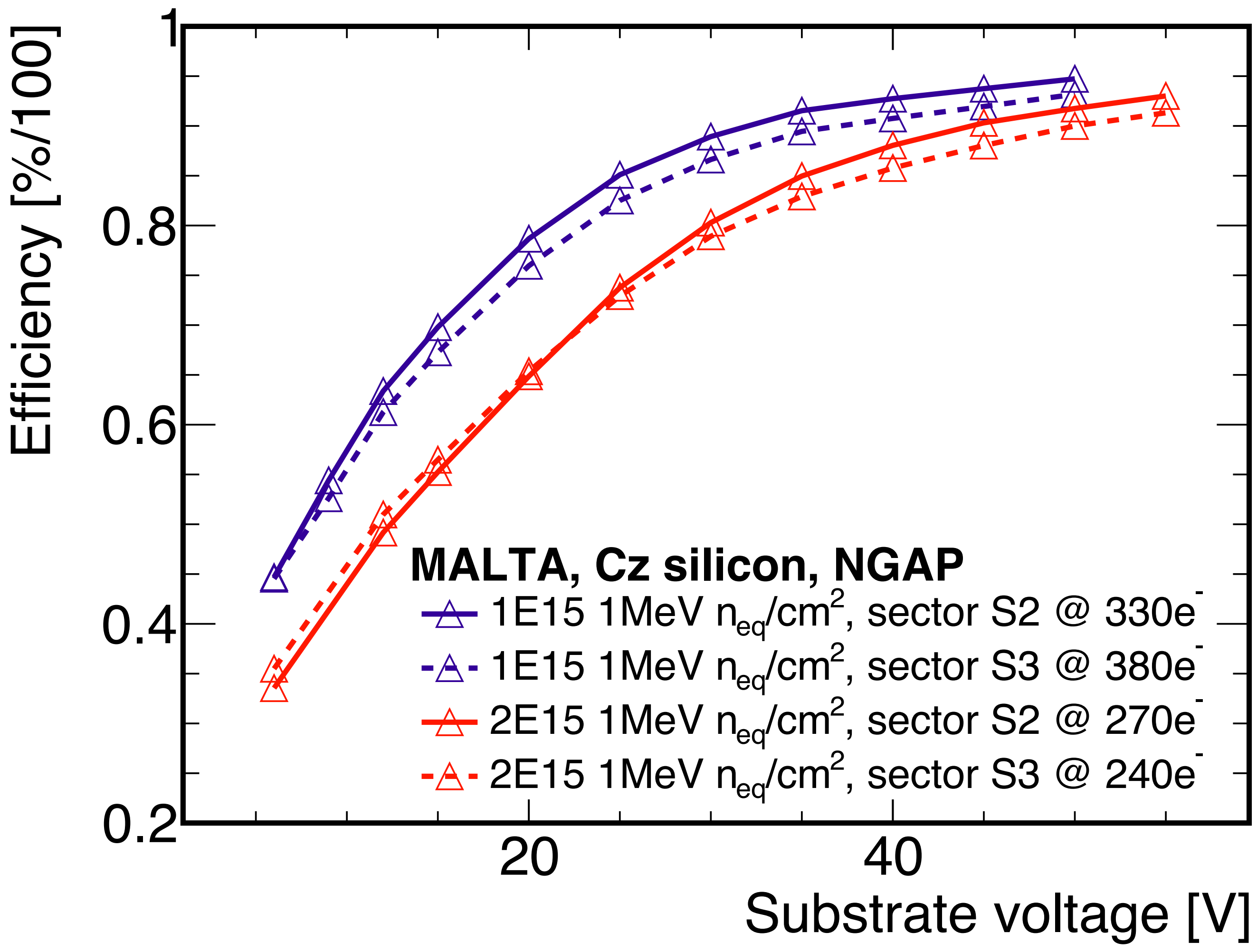




MALTA irradiated chips

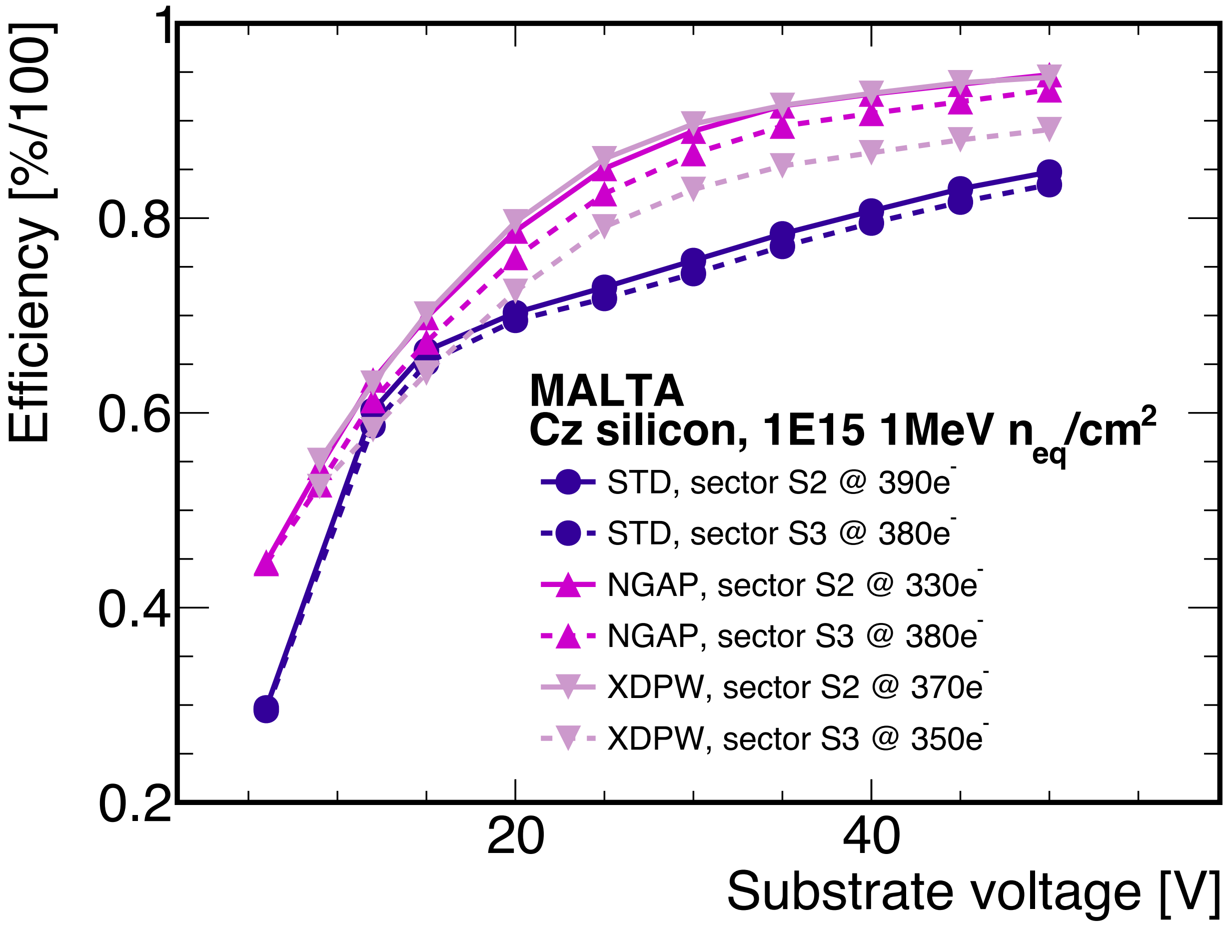
- Cz silicon sensor: higher radiation hardness
- smooth dependency of efficiency (and cluster size) vs substrate voltage
- max efficiency with irradiated chip (n-gap @2e^{15} n_{eq}/cm^2) ~93%

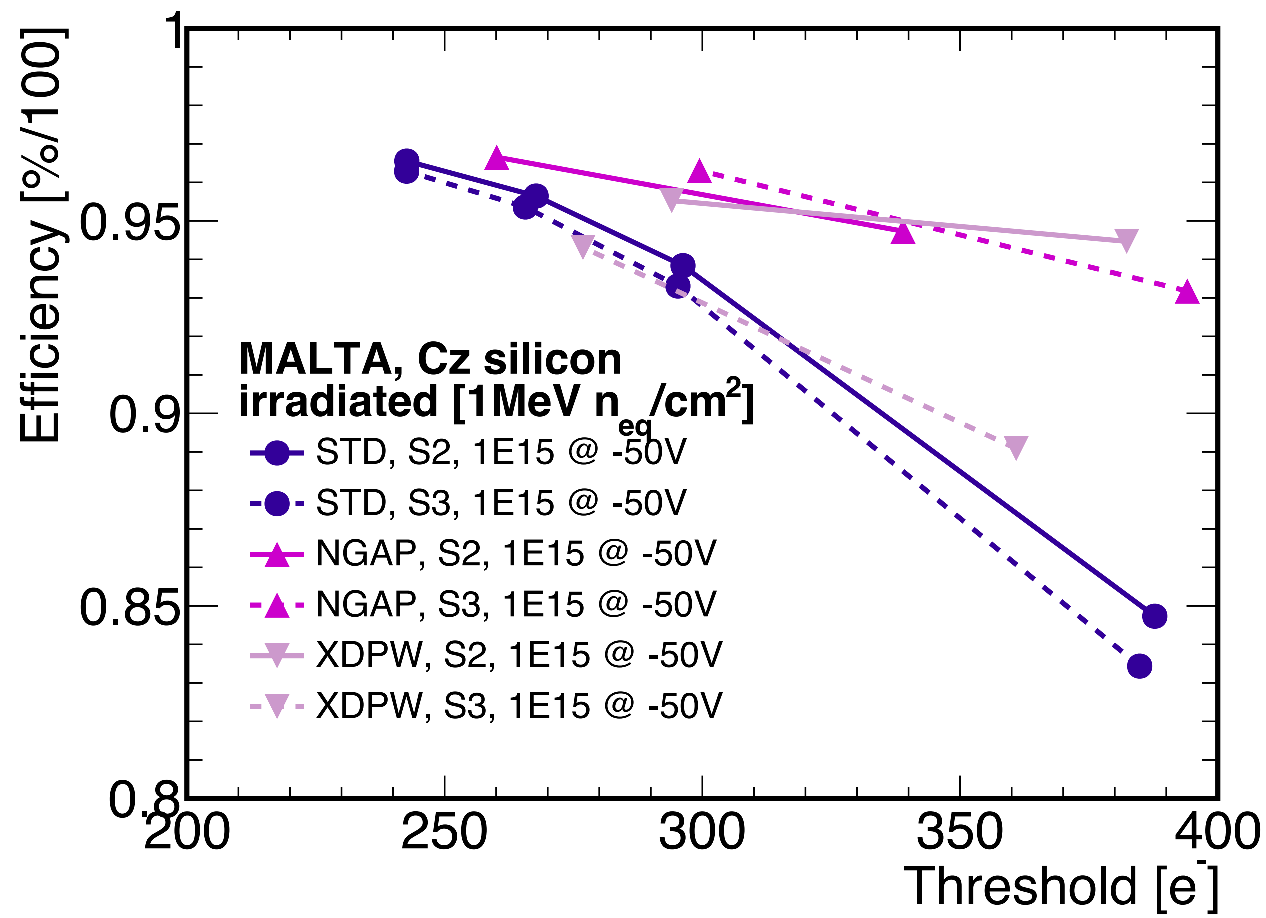




MALTA irradiated chips

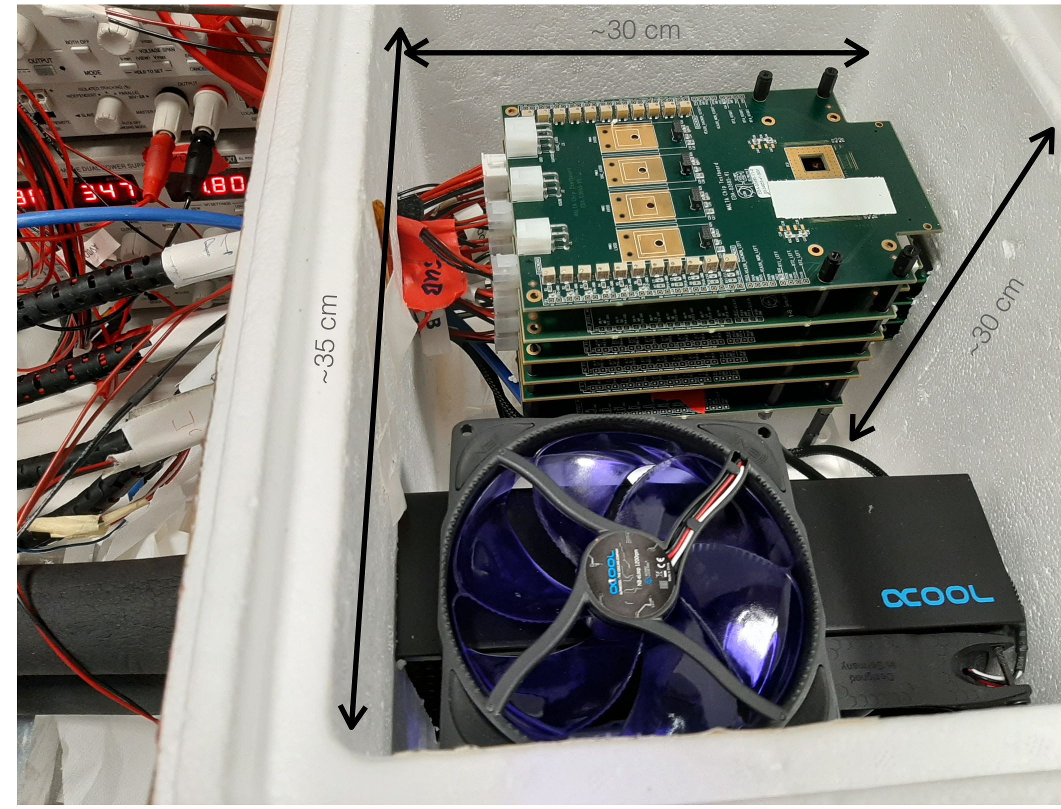
- Cz sensors comparison
- at similar (high value) of threshold:
  - larger efficiency ~95% (n-gap and xdpw) vs 85% (std)

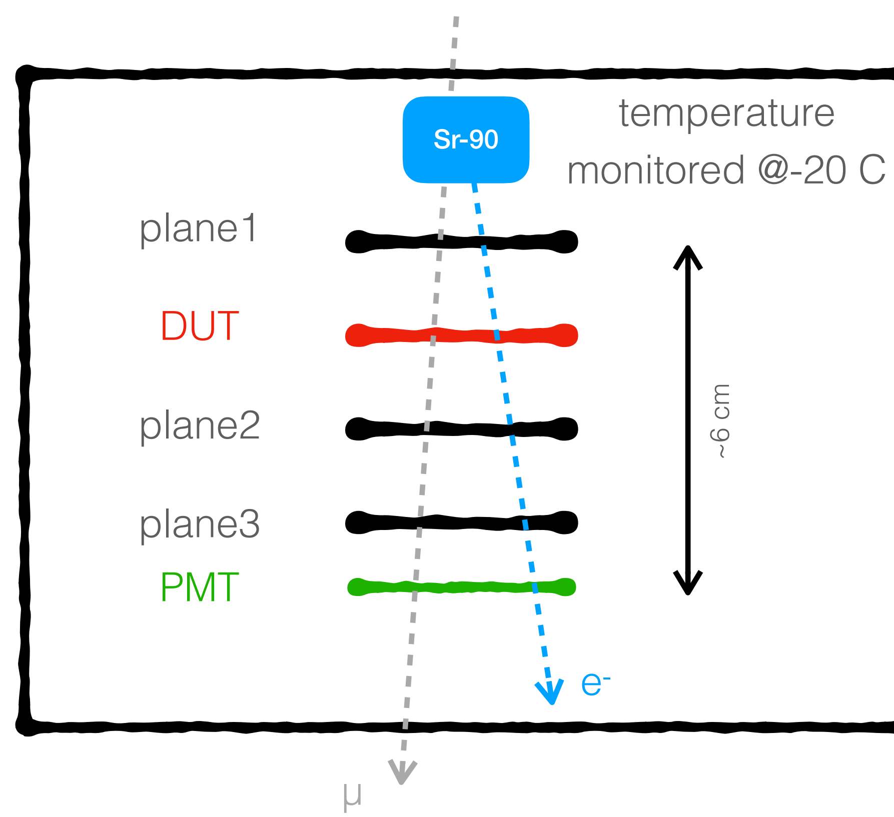




MALTA telescope 2020

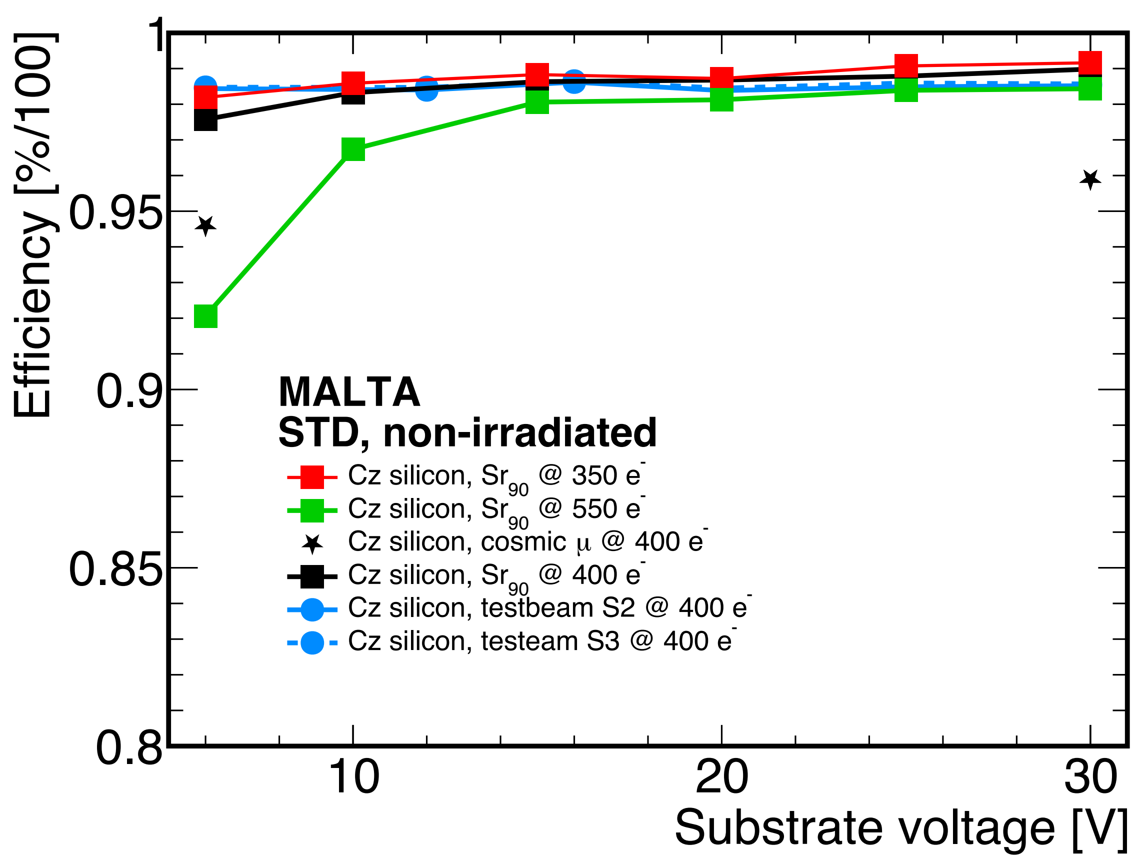
- telescope for lab measurements
- 4 MALTA planes and one PMT
- PicoTDC for timing measurements
- different runs:
  - cosmic muons: high resolution but very low rate 1μ/6’
  - low energy electrons Sr-90: high rate but high multiple scattering
- entire telescope in a cold box
- powerful setup to test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

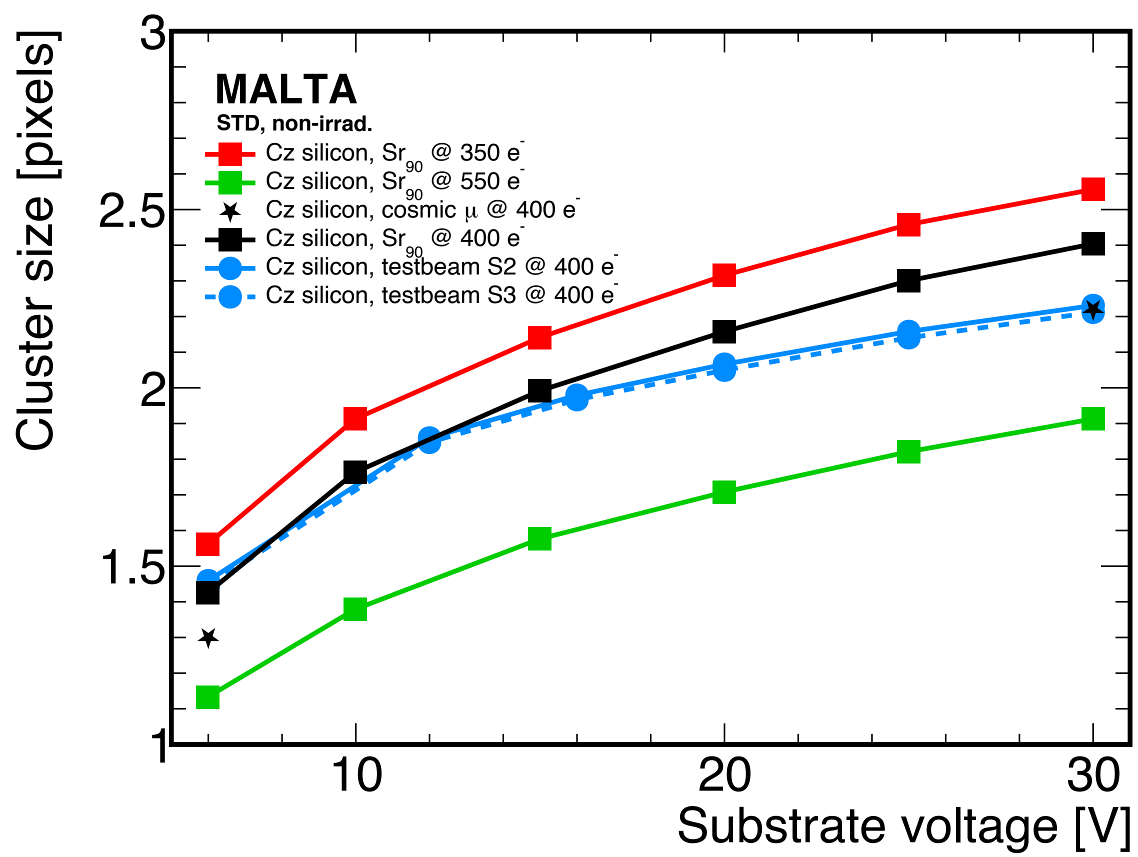




MALTA lab measurements

- 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

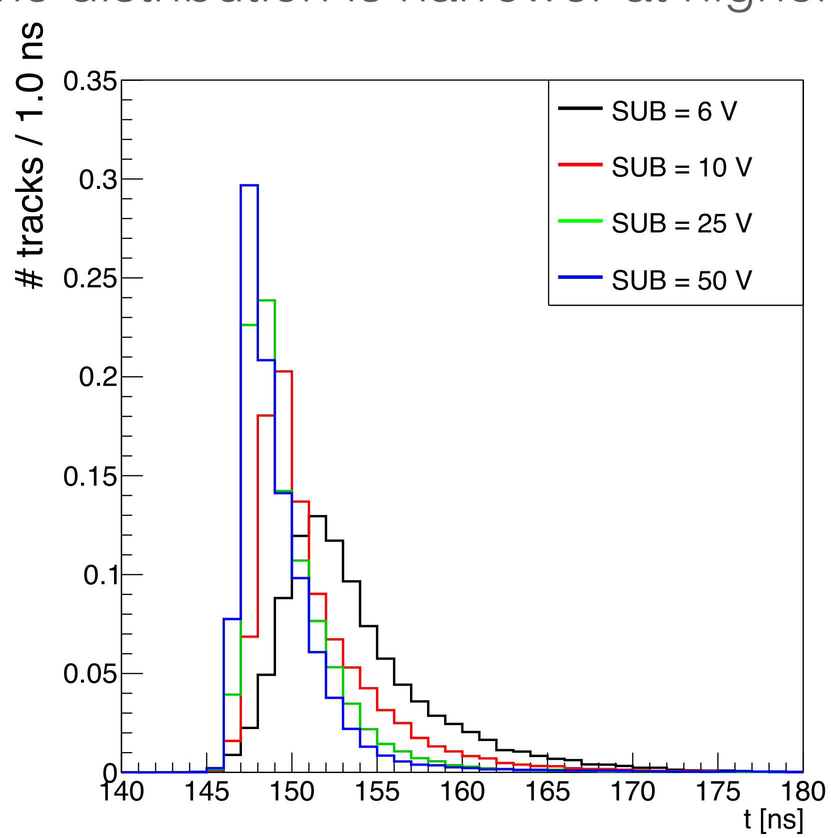




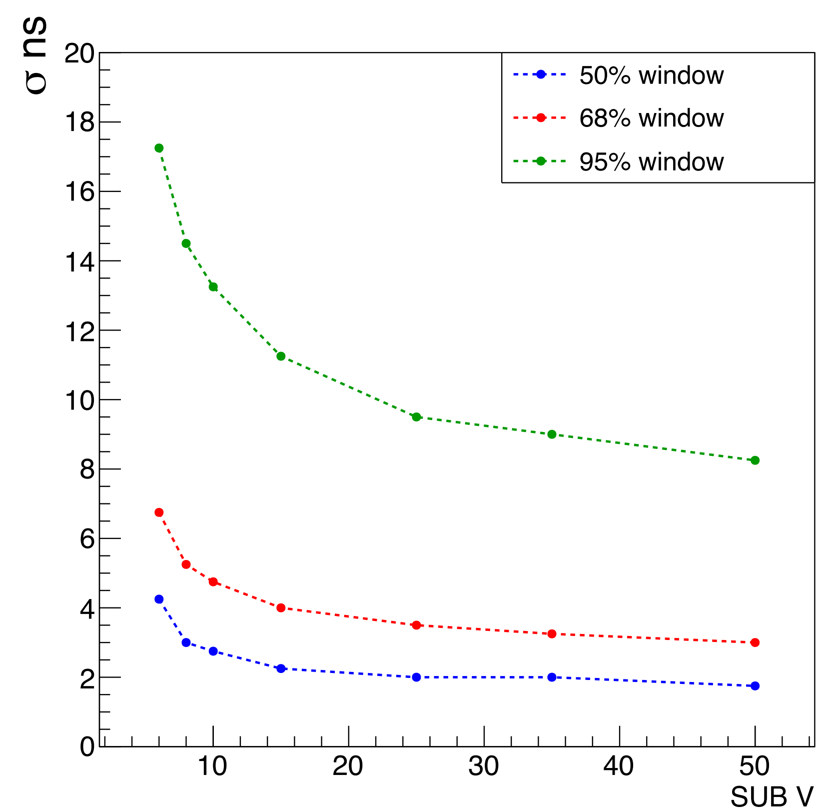
MALTA timing measurements

- 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 σ_{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

time distribution is narrower at higher sub

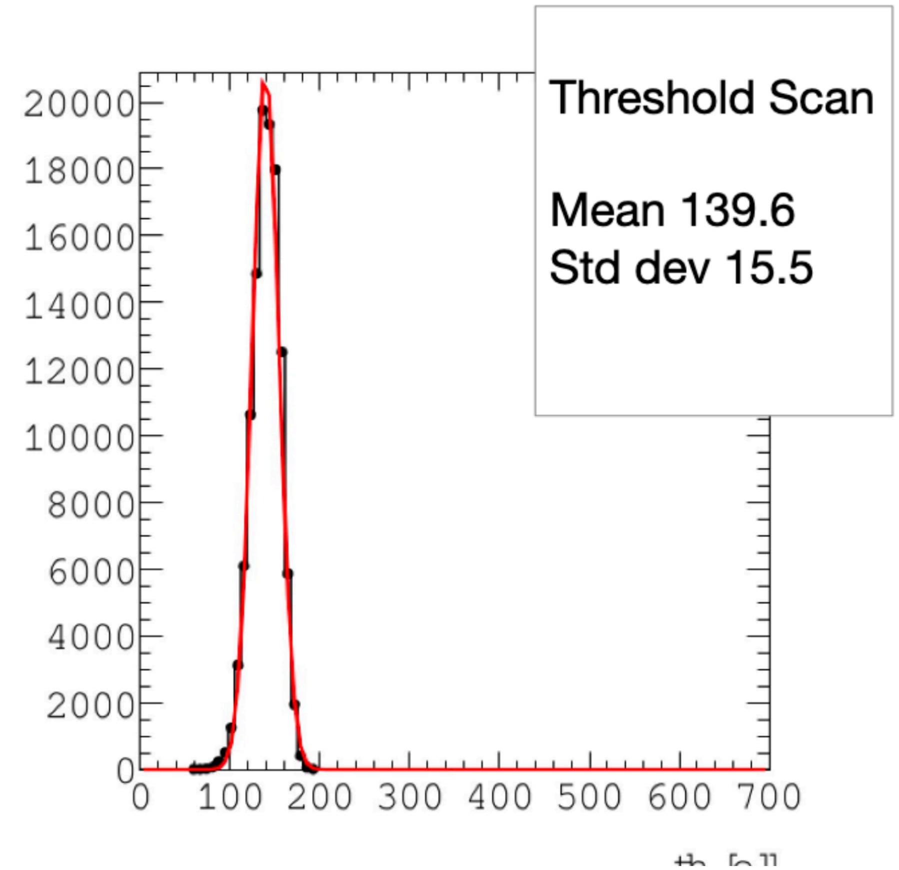


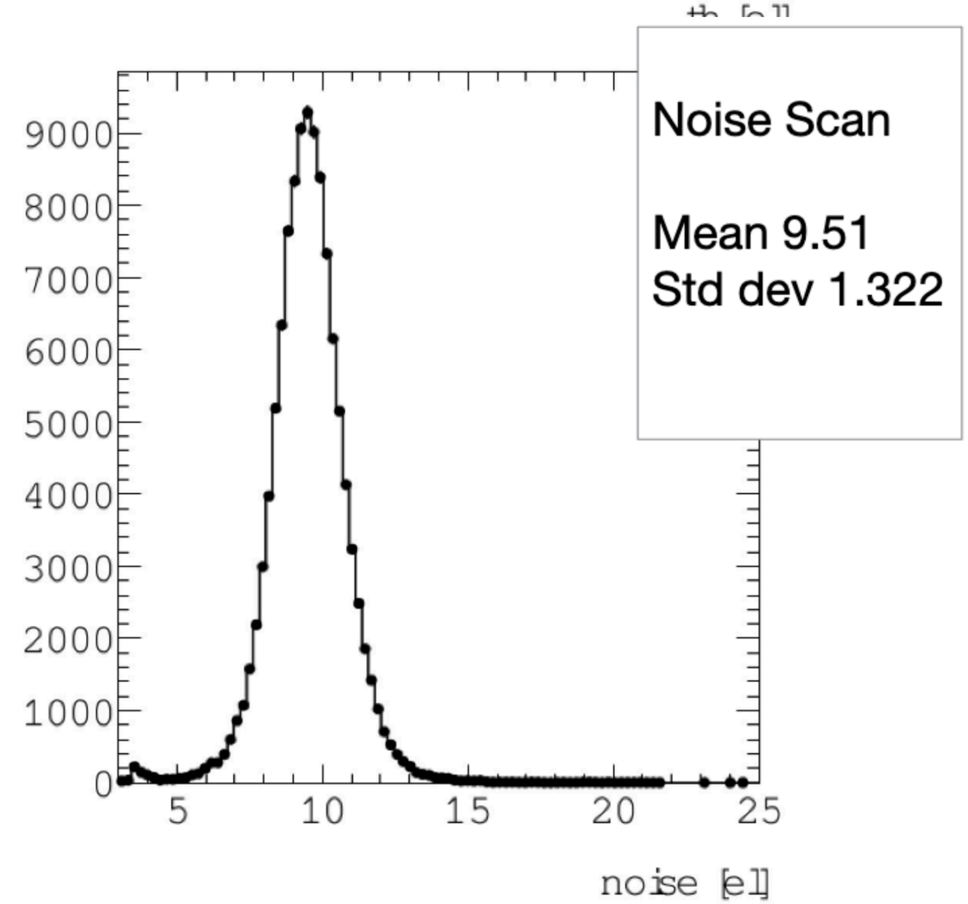
50% of the hits arrive within 2 ns above 15 V

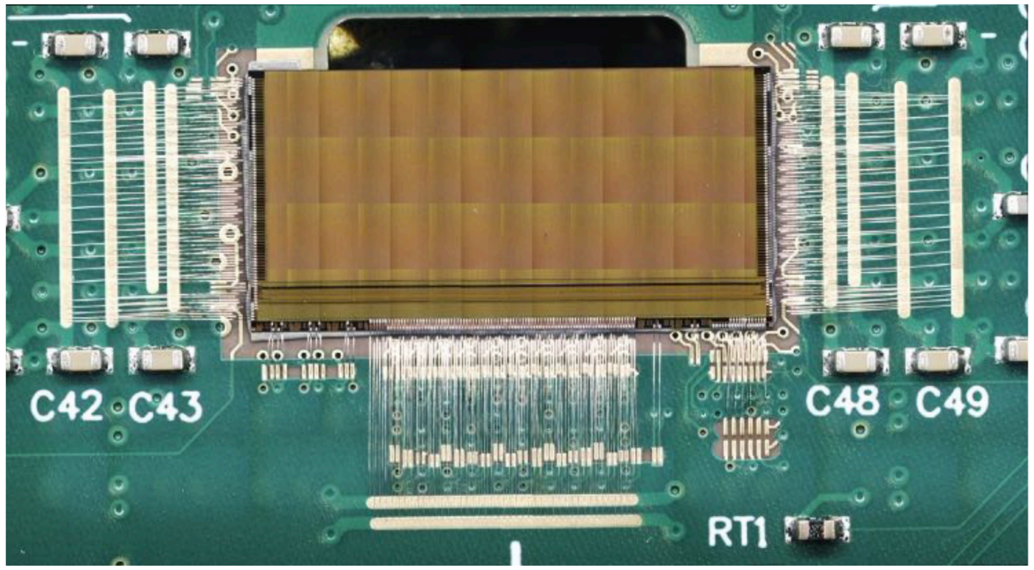


MALTA 2

- returned from foundry in Jan 2021
- 20.2x10.1 mm^2 sensor about half size of MALTA
- matrix of 224x512 pixels of 36.4 um size
- faster analog front-end improves time resolution (larger transistors and the additional cascoded transistor)
- enlarged transistors as implemented in Mini-MALTA
- applying all the knowledge learnt from previous prototypes

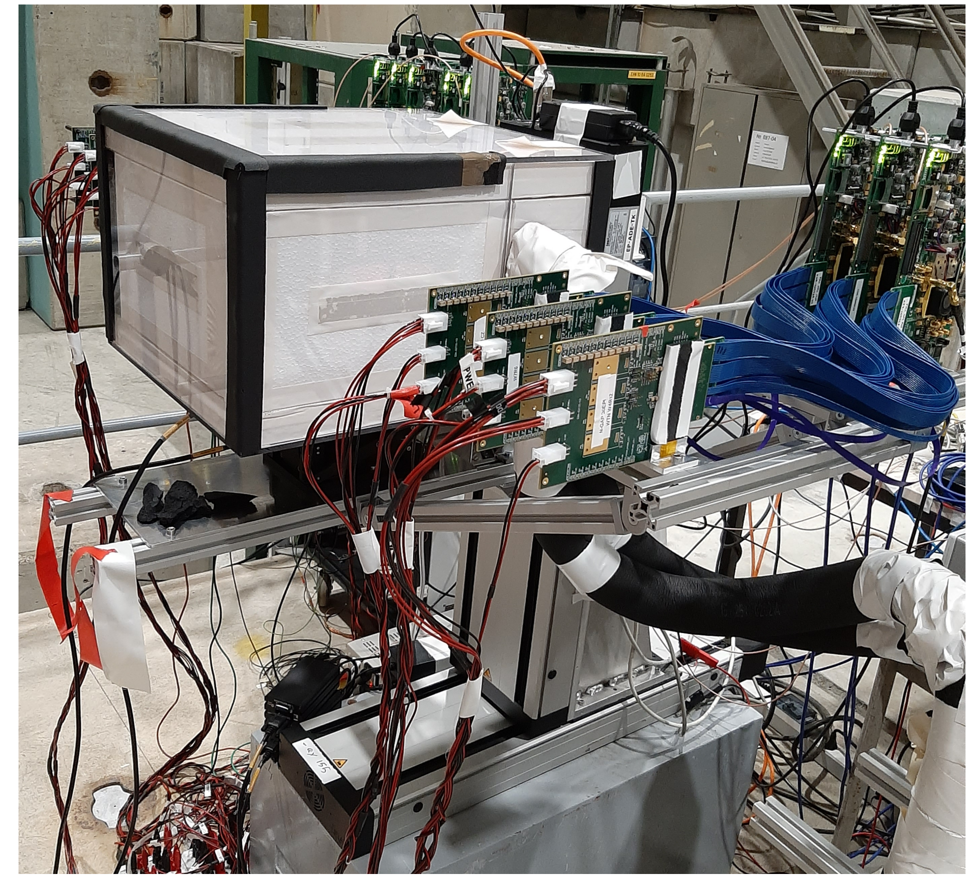




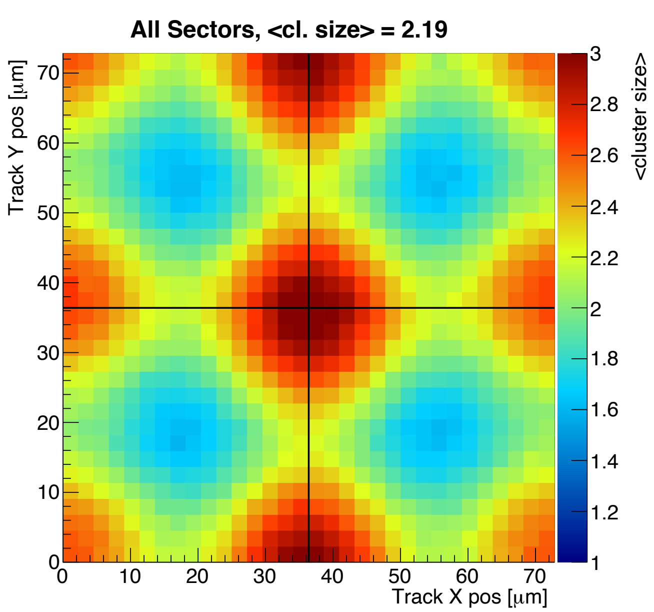


MALTA testbeam 2021

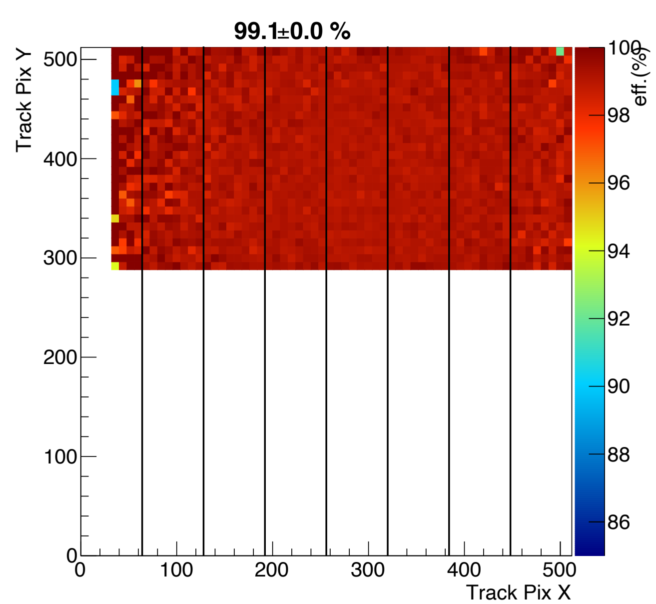
- **test beam efforts at SPS CERN ongoing**
- goal: dedicated to demonstrate MALTA2 performance in terms of radiation hardness (>10^{15} MeV Neq/cm^2) and timing performance

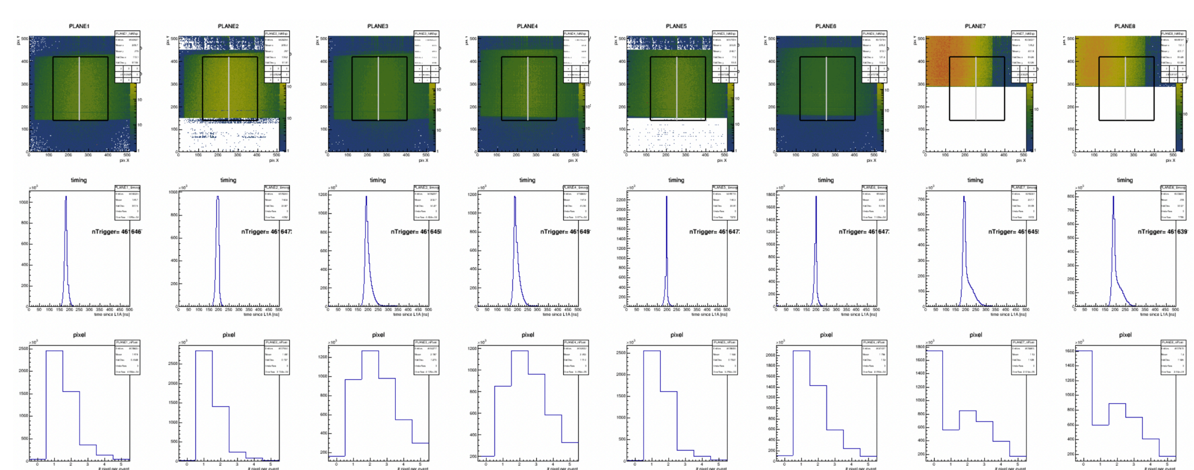


MALTA Cz std -50V unirradiated



MALTA2 -6V unirradiated





conclusions

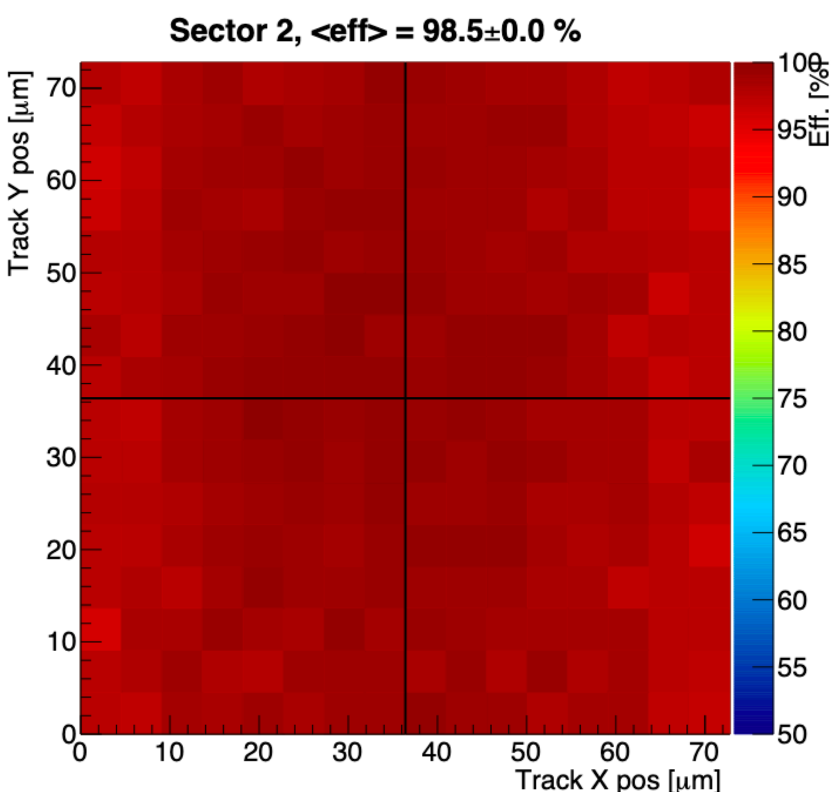
- development of the MALTA CMOS pixel sensors (TowerJazz 180 nm technology)
- MALTA very efficient after neutron irradiation (up to $2x10^{15}$ n_{eq}/cm^2)
- continue integrating MALTA in performing telescope systems
- more results from DESY 2019 test beam still to come
- testbeam @SPS in 2021: taking data results will come out soon

extra slides

In-pixel efficiency

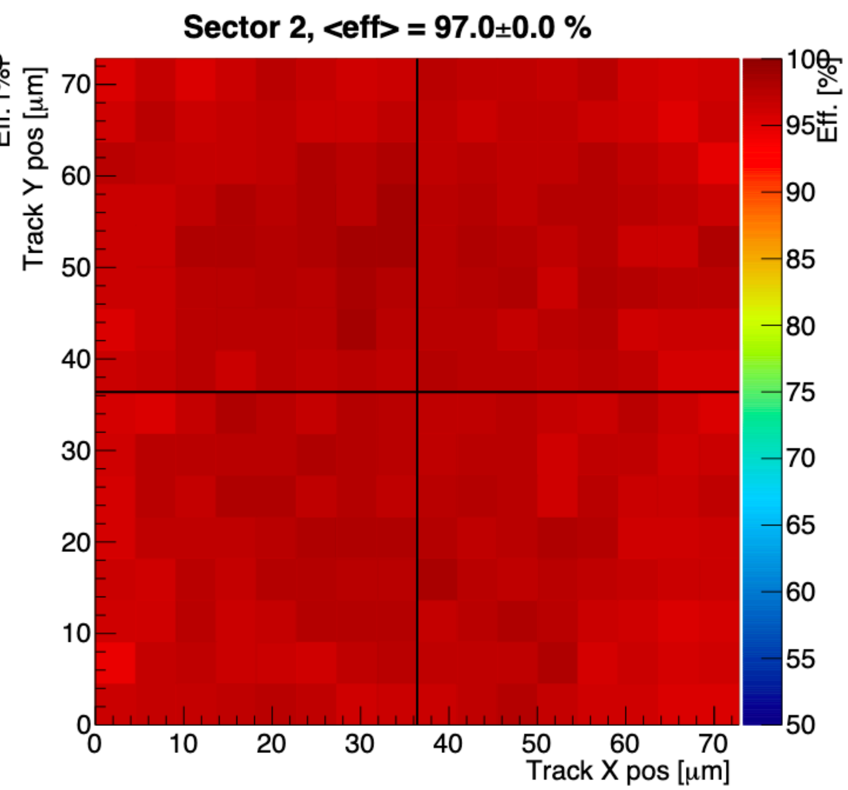
MALTA Cz unirradiated

ε = 98.5%



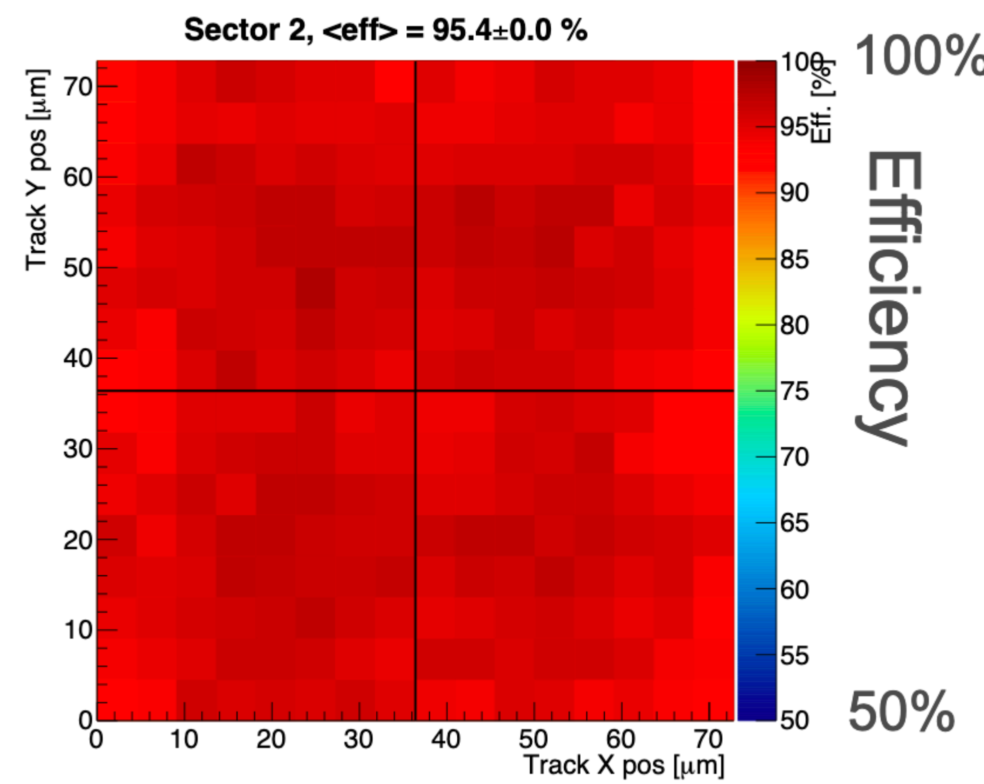
MALTA Cz n-gap $1x10^{15}$ n_{eq}/cm^2

ε = 97.0%



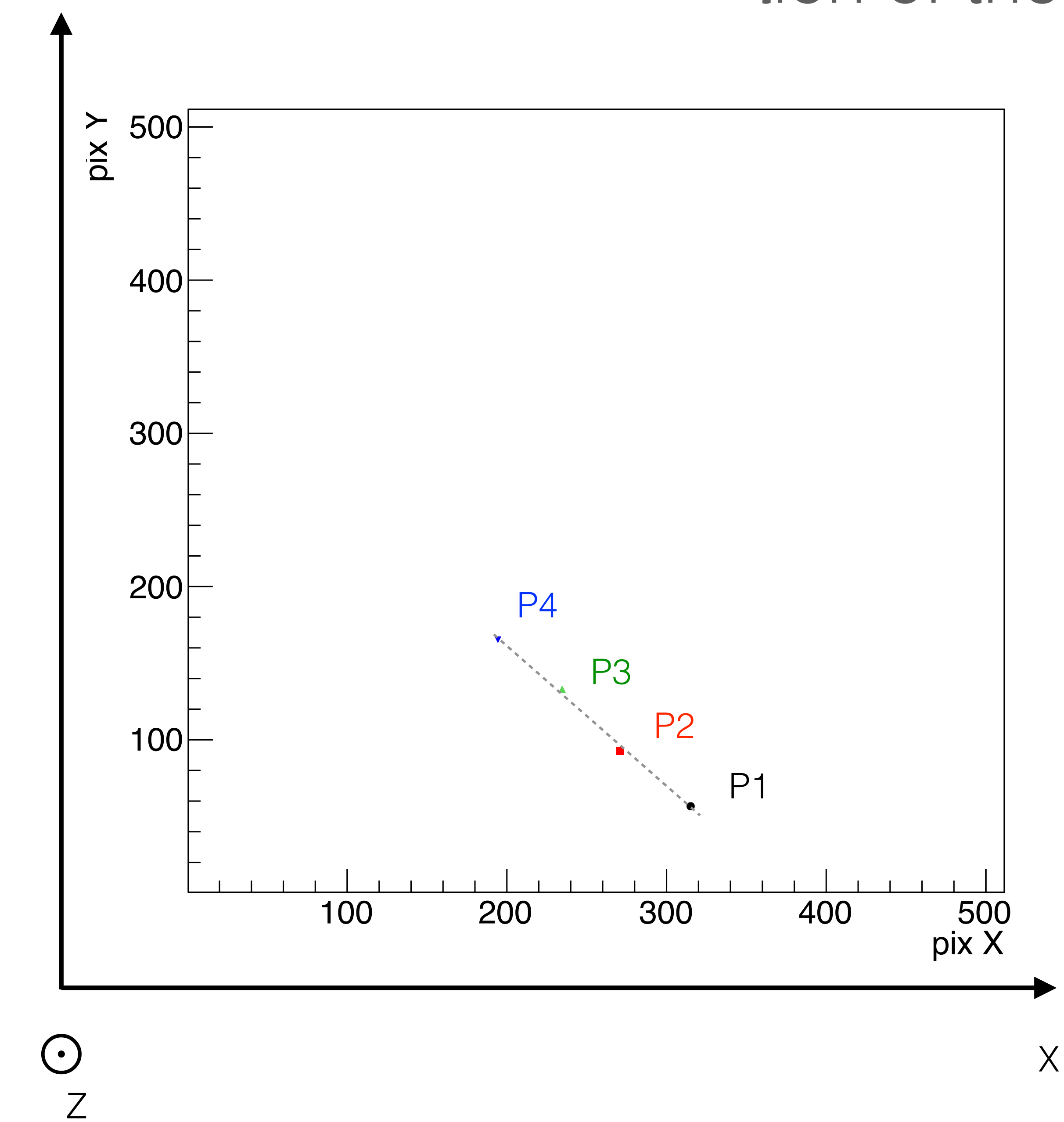
MALTA Cz n-gap $2x10^{15}$ n_{eq}/cm^2

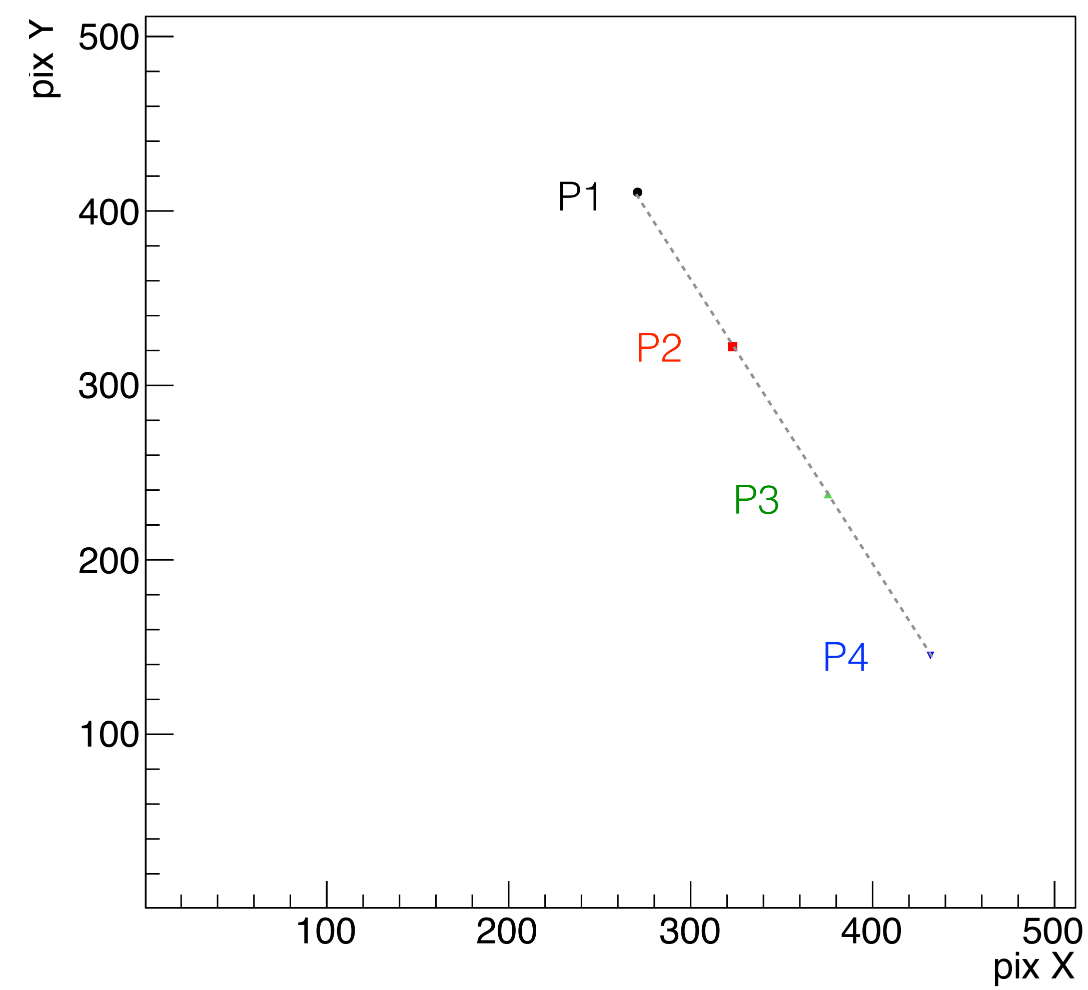
ε = 95.4%



cosmic muon

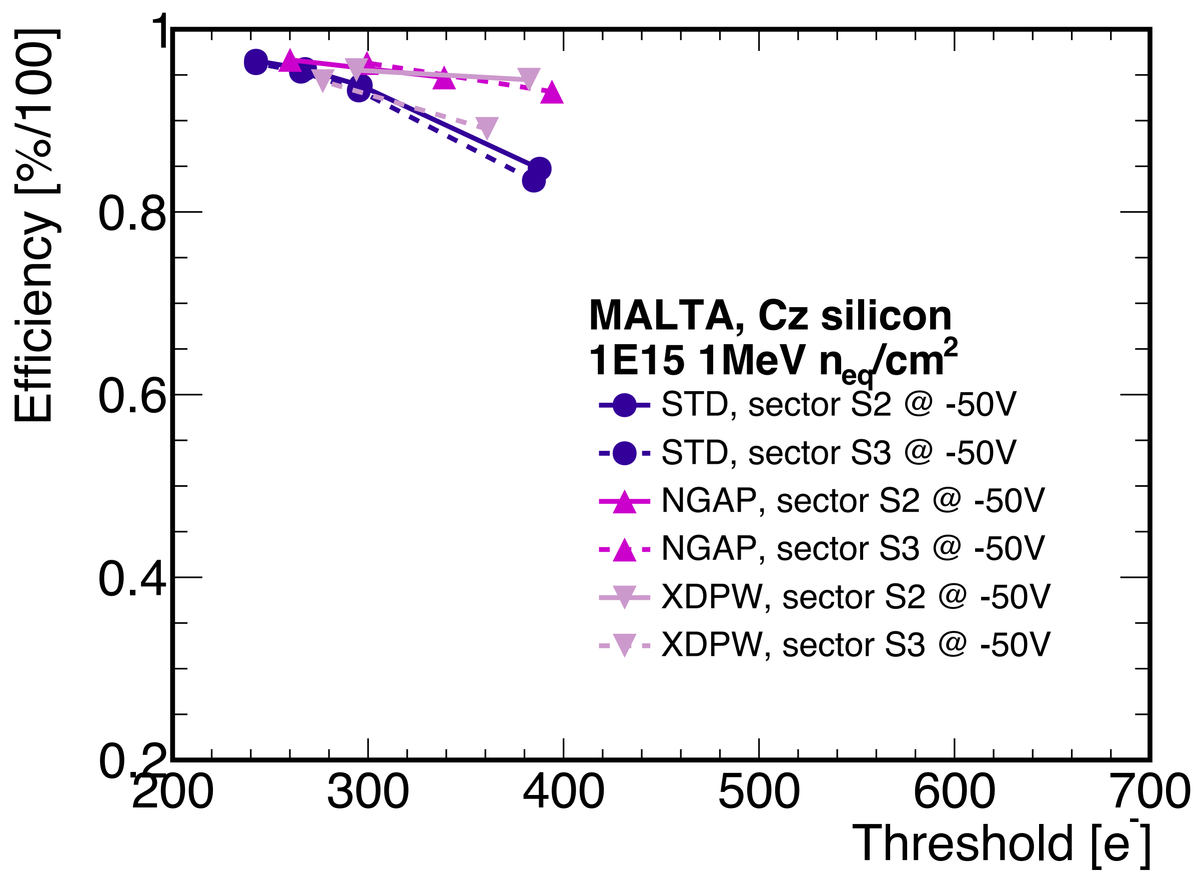
- Z projection of the 4 telescope planes



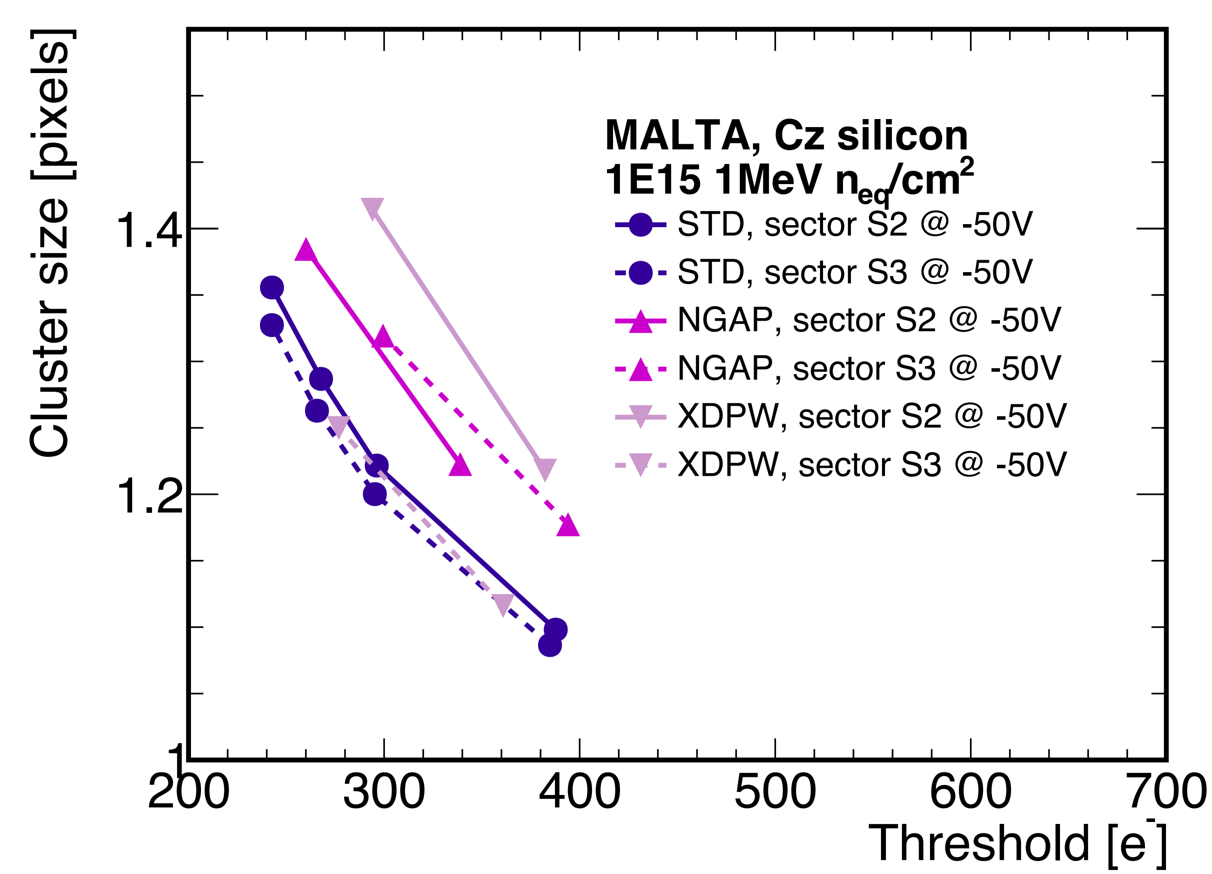


Cz irradiated chips

efficiency vs threshold

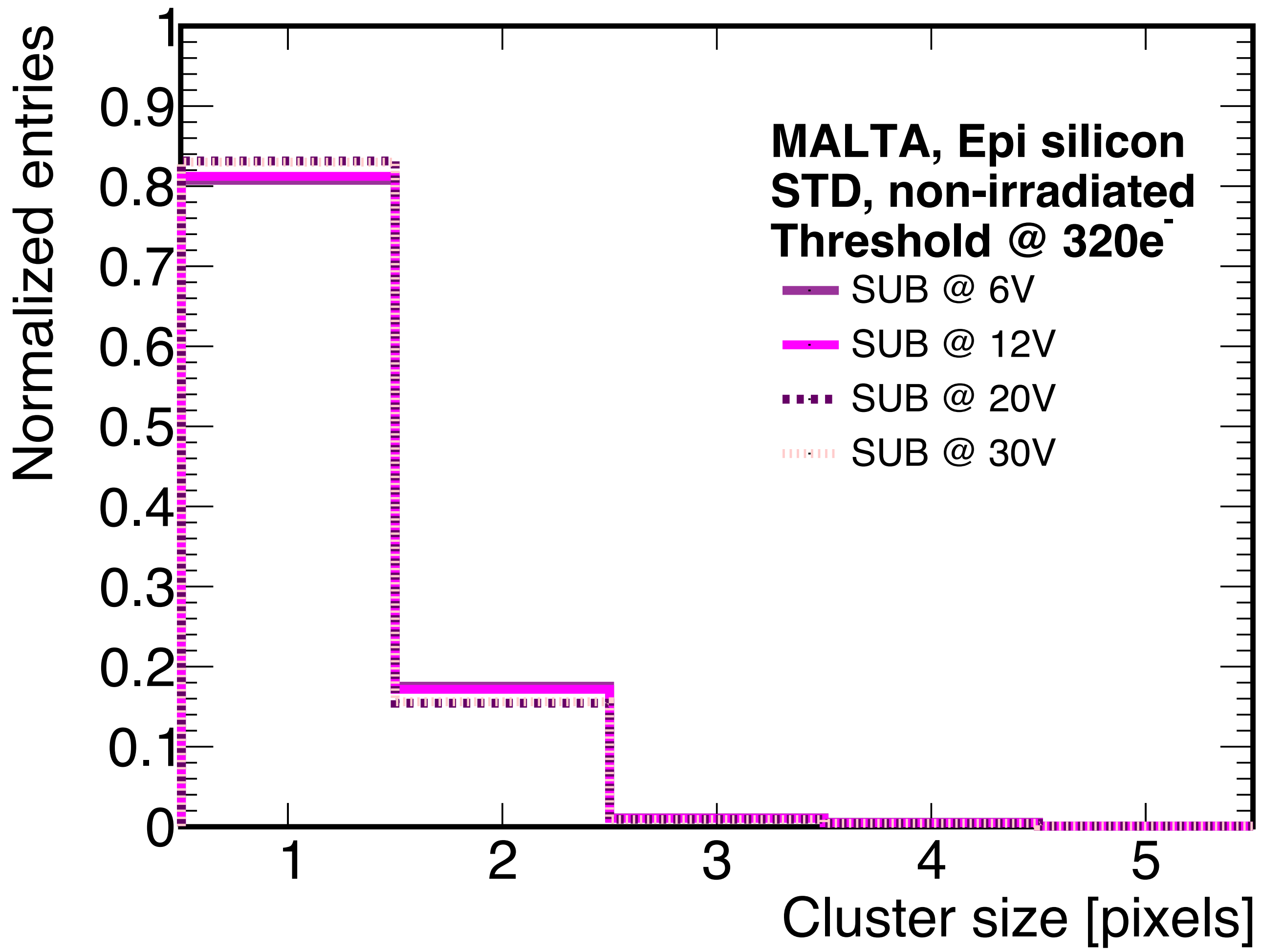


cluster size vs threshold

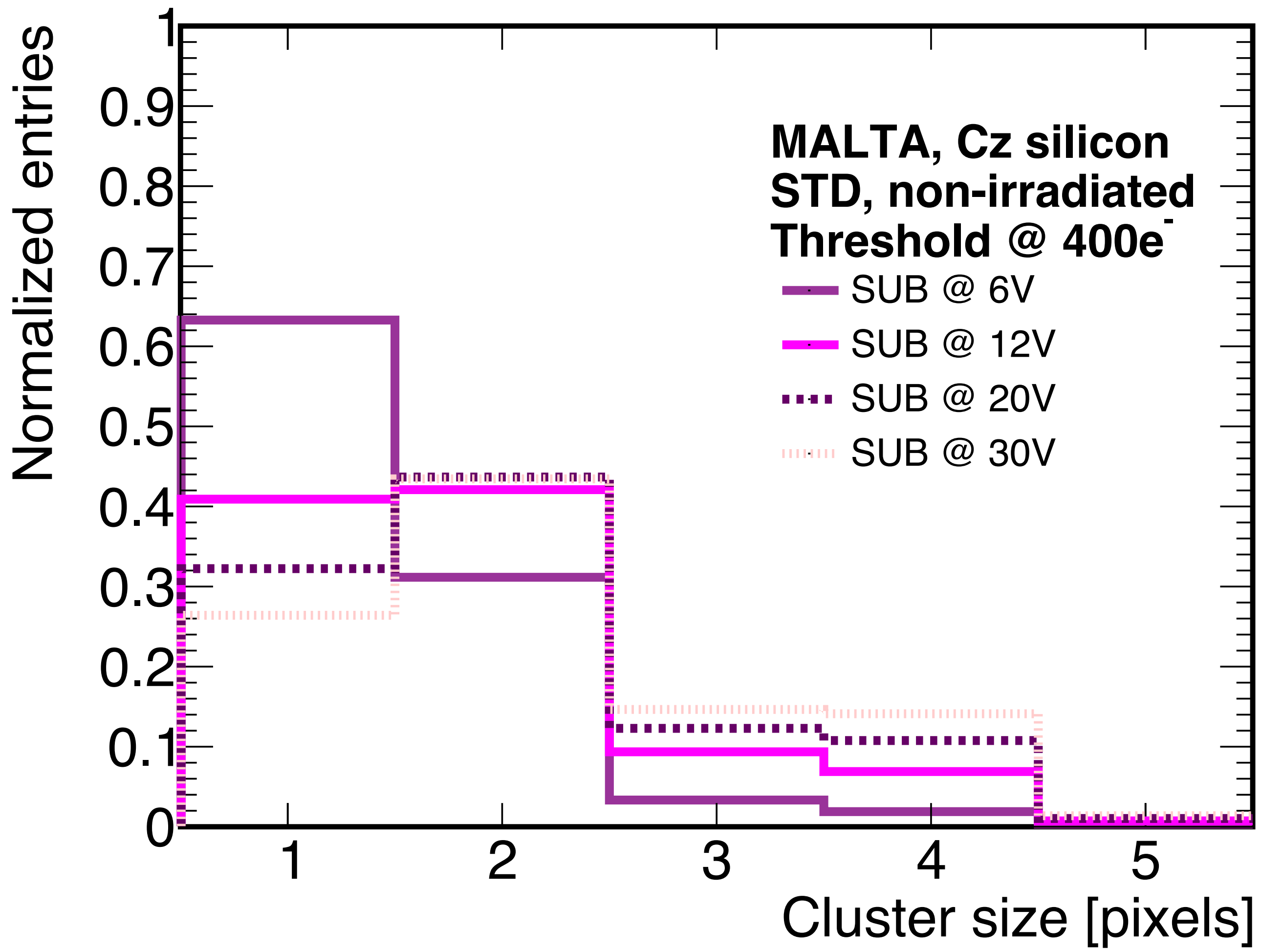


non irradiated chips

std Epi silicon

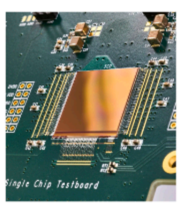


std Cz silicon



MALTA history 2

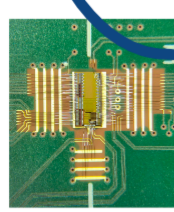
Jan 2018



MALTA1 & MLVL

- Sensor
- Front-end

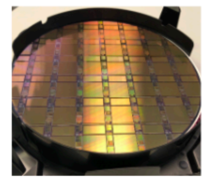
Jan 2019



Mini-MALTA

- Sensors
- Front-end

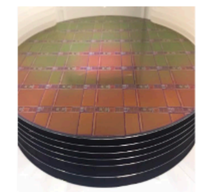
Aug 2019



MALTA C

- SlowControl fix
- Front-end
- Sensors

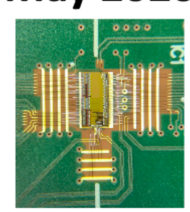
Oct 2019



MALTA Cz

- SlowControl fix
- Front-end
- Sensors

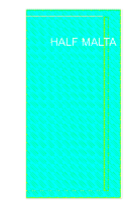
May 2020



Mini-MALTA ATTRACT

- Sensors
- Front-end
- Cascoded

Submission mid Oct 2020



MALTA 2

- Sensors
- Front-end
- New SlowControl
- Cascoded