MALTA monolithic Pixel sensors in TowerJazz 180 nm technology

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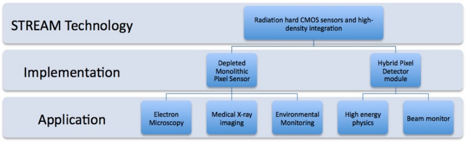
Introduction

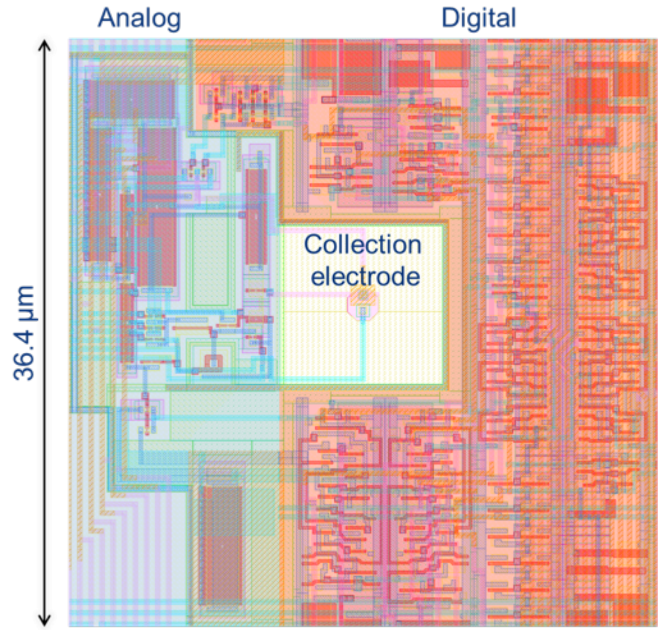
- Following the success from STREAM Innovative Training Network
- CERN EP R&D Programme on Technologies for future Experiments work packages 1.2 and 1.3 on Monolithic Pixel detectors
  - Innermost radii for maximum performance
  - Outer-layers as cost effective pixel trackers
  - High granularity and low material budget
  - Stitching and thinning of sensors
  - Module studies
- AIDA Work package 5 on Depleted Monolithic Active Pixel Sensors
  - Development of radiation hard DMAPS
  - Design and fabrication of test structures
  - Development of readout systems
  - Characterization of devices

STREAM



AIDA innova

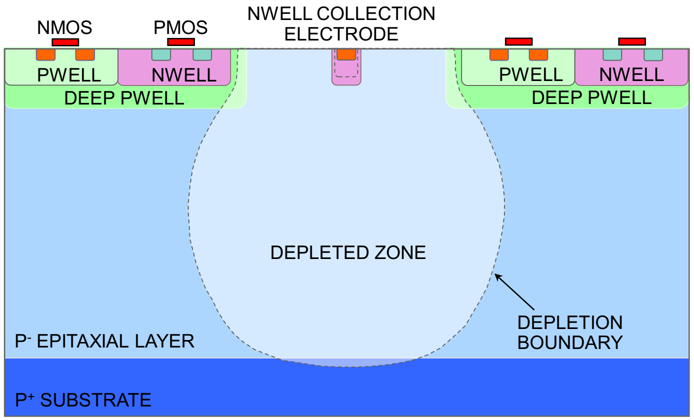
MALTA pixel cell



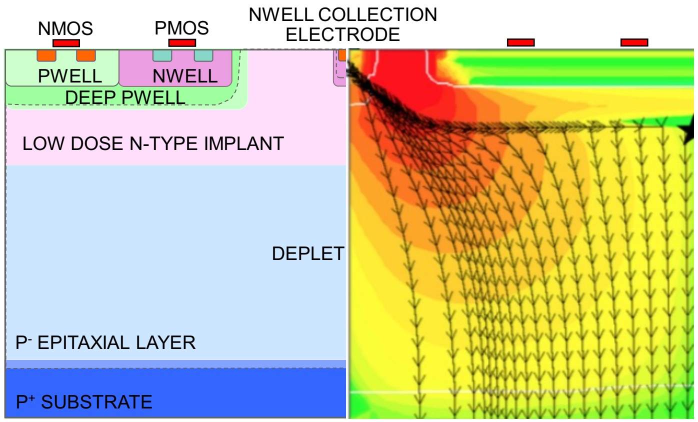
- Pixel size 36.4 x 36.4 μm^2 allows good spatial resolution
- 2-3 µm collection electrode provides minimal capacitance (< 5fF)
- 3.4 - 4 µm spacing to electronics avoids cross-talk
- Asynchronous read-out without clock distributed to the cell
- 1 µW/pixel to minimize power consumption

TowerJazz 180 nm CMOS

- High resistivity Epitaxial process 25 or 30 µm thick
- Reach full depletion around ~10 V
- High signal to noise ratio ~ 20
  - Expected MIP energy deposition (1500 e-) and low noise
- Modified “standard” process
  - Additional low dose n- layer to improve depletion under the deep p-well
  - Radiation tolerance had to be evaluated



TowerJazz process (ALPIDE)

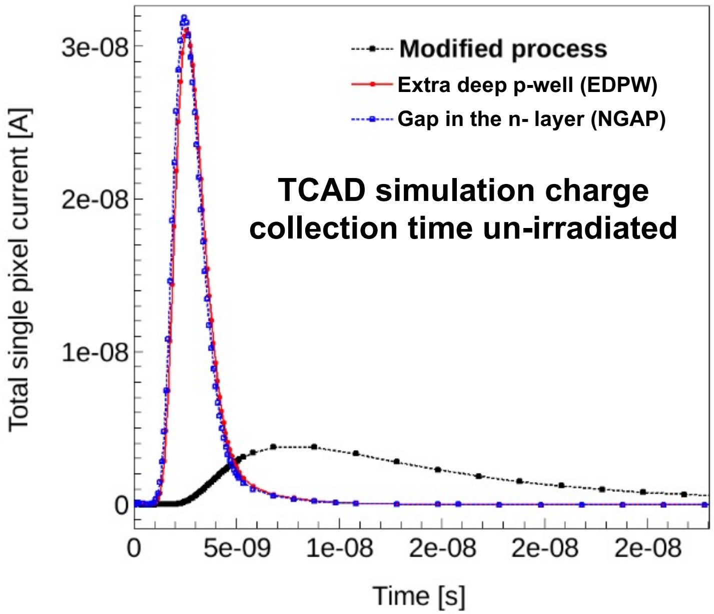


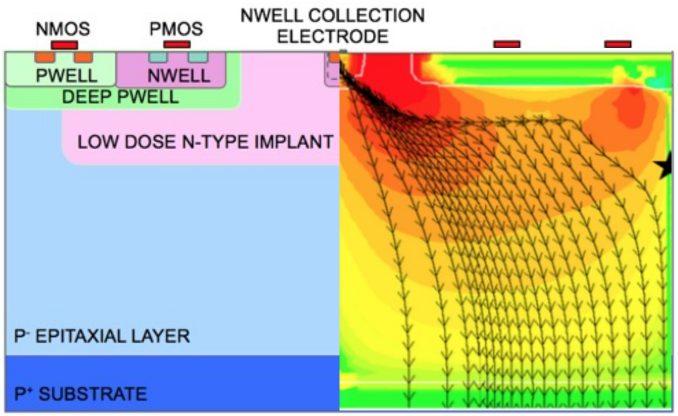
Standard modified process

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

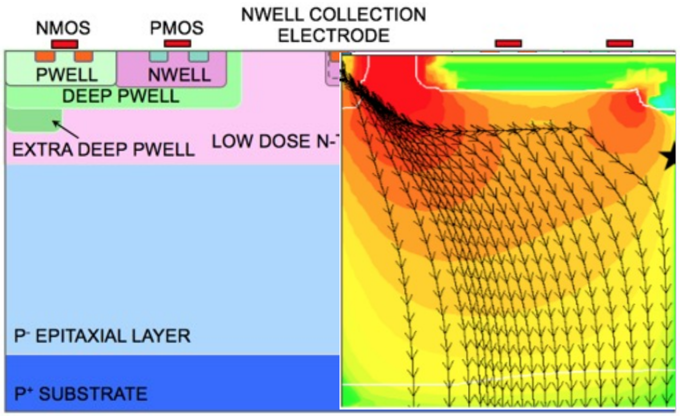
TowerJazz modified processes

- Process modified based on TCAD simulations
  - Increase the lateral field configuration
  - Reduce charge collection time
- Gap in the n-layer
  - 4 μm gap in the low dose n-layer
- Extra-deep p-well
  - 5 μm wide additional p-well implant





Gap in the n- layer (n-gap)

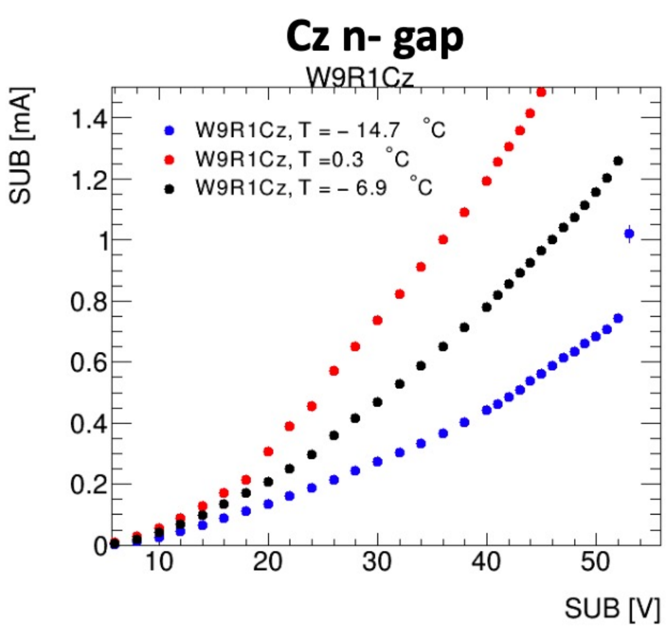


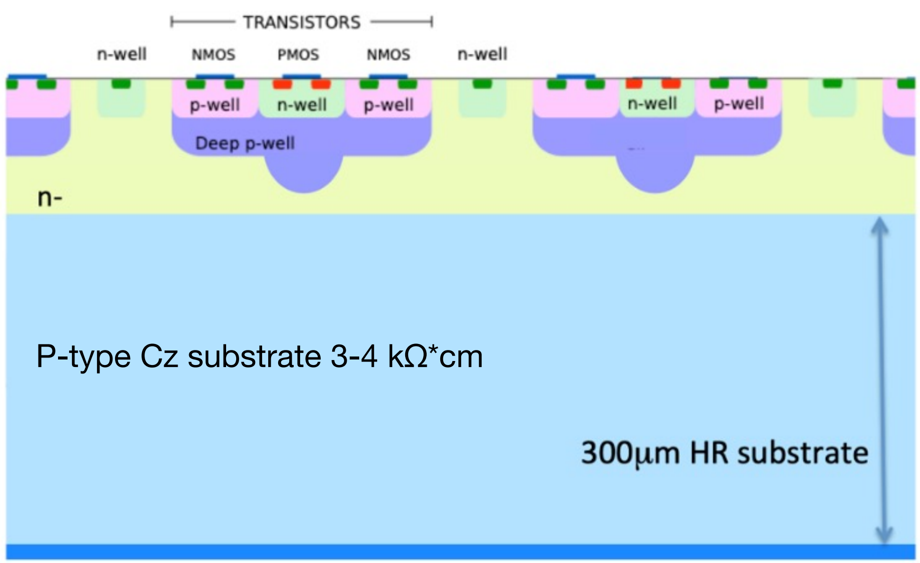
Extra deep p-well (EDPW)

M. Munker, JINST 14 (2019) C05013

Substrate engineering

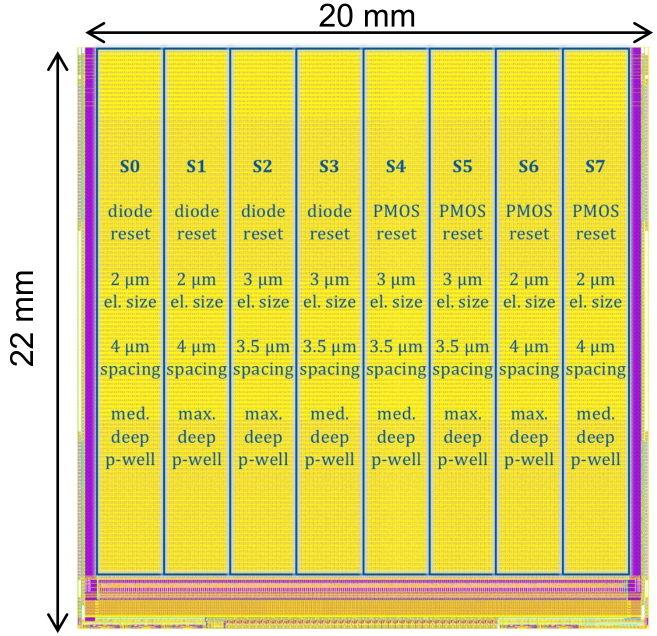
- Possibility of processing on high resistivity Czochralski substrate
  - Resistivity of ~3-4 kΩ·cm
  - Can operate at 50V reverse bias for larger depletion
  - Increased charge collection
  - Aim for better time resolution and higher radiation hardness
- Implement the same process modifications
  - Continuous n-layer (standard), gap in the n-layer (n-gap), extra deep p-well

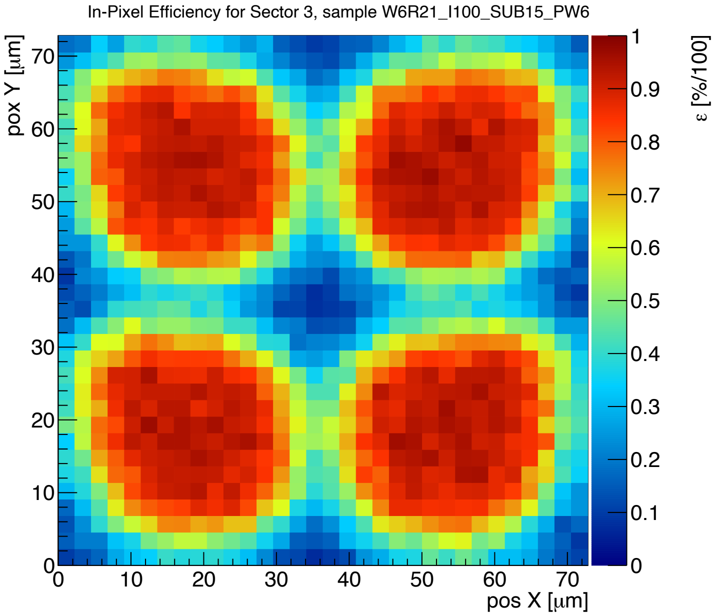




H. Pernegger, NIM A 986 (2021) 164381

TowerJazz MALTA (2018)



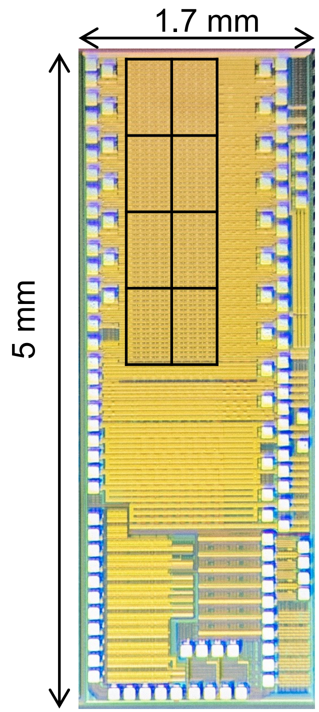


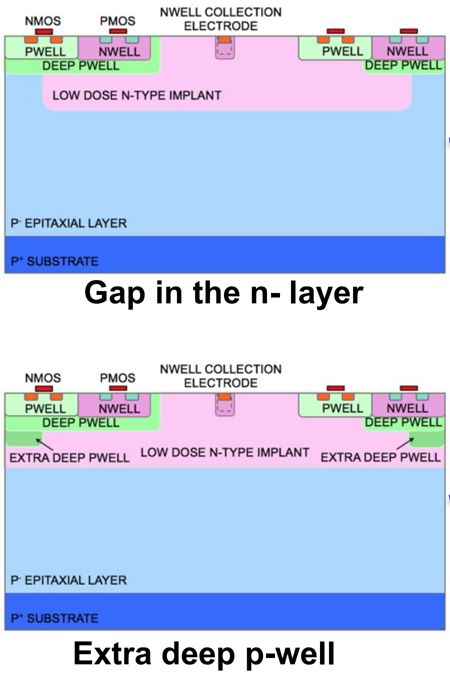
Sector 3 efficiency projected to a 2x2 pixel array of sample irradiated to 10^{14} n_{eq}/cm^2

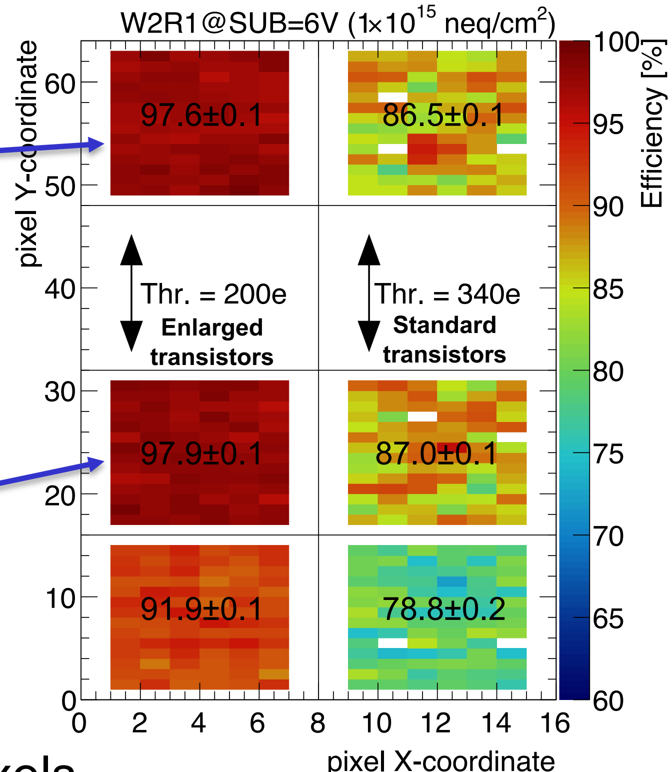
- 22 x 20 mm^2 full size demonstrator
- 512 x 512 pixels (>250k) grouped in 8 sectors
- Fully clock-less matrix architecture with 37-bit bus read-out
- 10 mW/cm^2 digital + 70 mW/cm^2 analog power
- Efficiency degraded at pixel edges after 10^{14} n_{eq}/cm^2

I Berdalovic et al. JINST 13 (2018) C01023 E.J. Schioppa et al. NIM A 958 (2019) 16242

TowerJazz Mini-MALTA (2019)





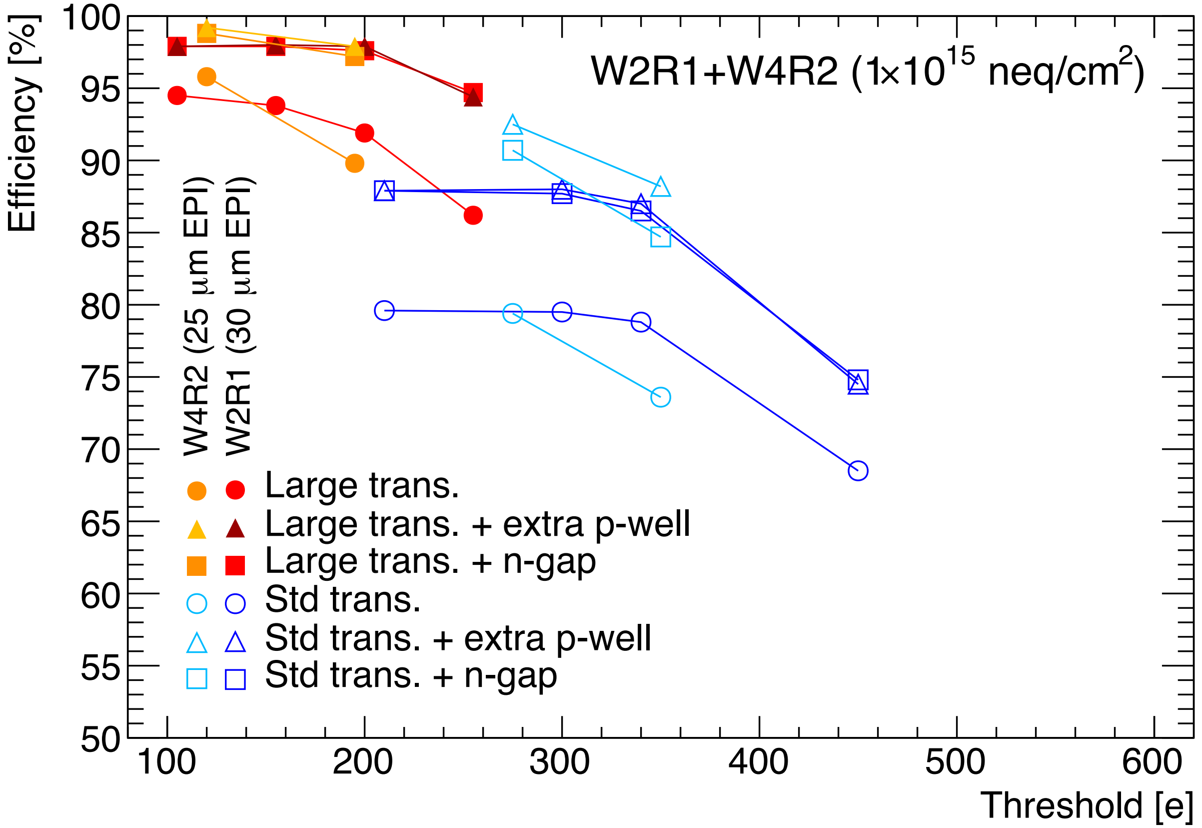


- 5×1.7 mm^2 demonstrator with 64 x 16 MALTA pixels
- 4 different process modifications to address radiation hardness
- 2 capacitor sizes to address RTS noise
- On chip data synchronization using a custom RAM memory
- Modified processes with enlarged transistors radiation hard to 10^{15} n_{eq}/cm^2

M. Dyndal, JINST 15 (2020) P02005

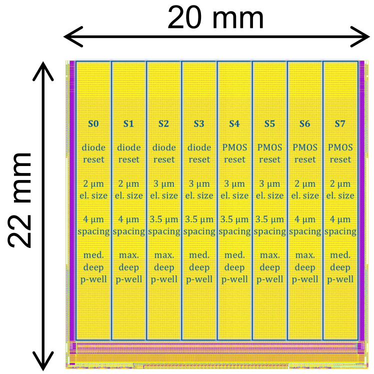
Efficiency vs threshold (10^{15} n/cm^2)

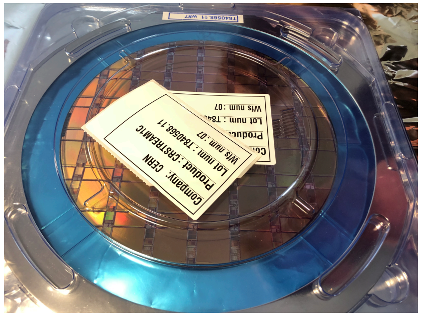
- Two trends: standard size and enlarged size transistors
- Enlarged transistors reach lower thresholds (~150 e-) and higher efficiency (>98%)
- Slightly higher efficiency for additional process modifications
- Similar performance between 25 µm and 30 µm EPI thickness

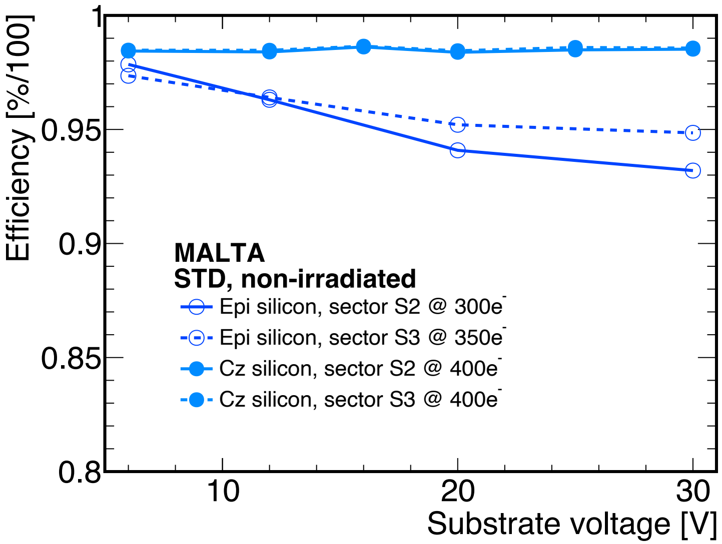


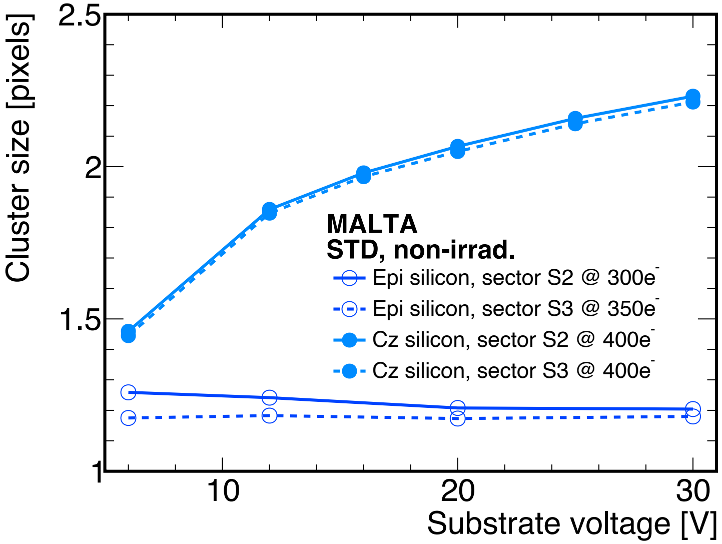
Efficiency versus threshold for two different Mini-MALTA samples 30µm EPI and 25µm EPI neutron irradiated to 10^{15} n/cm^2, and measured with 3 GeV electron beam at ELSA, with 6 V bias voltage

MALTA Czochralski (2019)



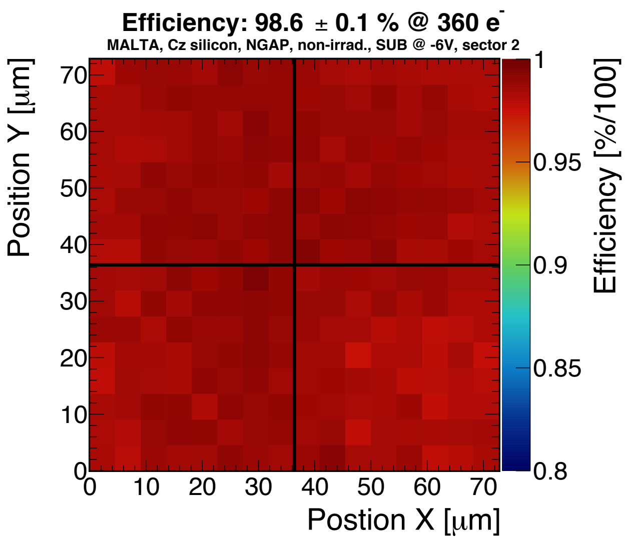




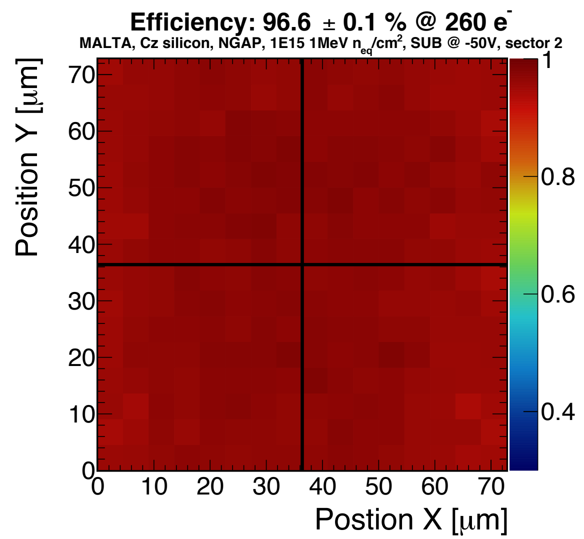


- 22 x 20 mm^2 full size demonstrator with slow control improvements manufactured on Epitaxial and Czochralski substrates
- Efficiency of Epitaxial samples decreases with bias voltage as opposed to Czochralski sensors
- Cluster size on Czochralski samples reaches 2.2 at 30V as opposed to Epi

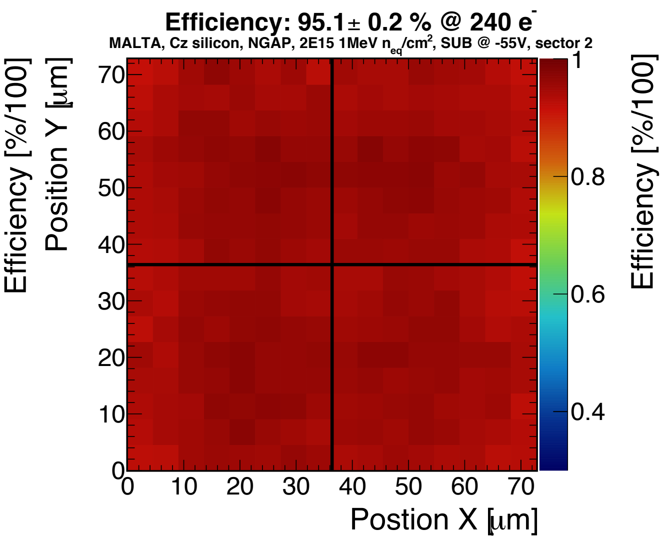
MALTA Czochralski efficiency



MALTA Cz n-gap unirradiated

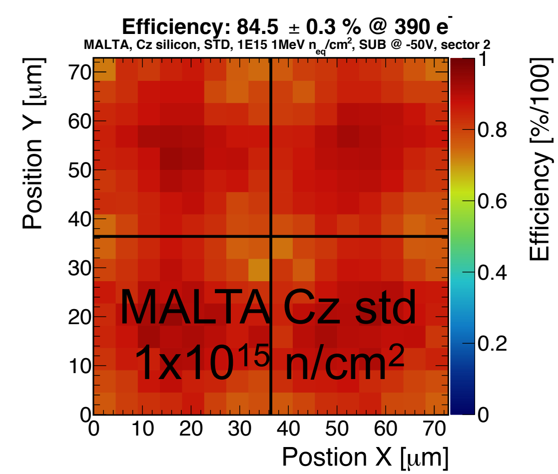


MALTA Cz n-gap $1x10^{15}$ n/cm^2

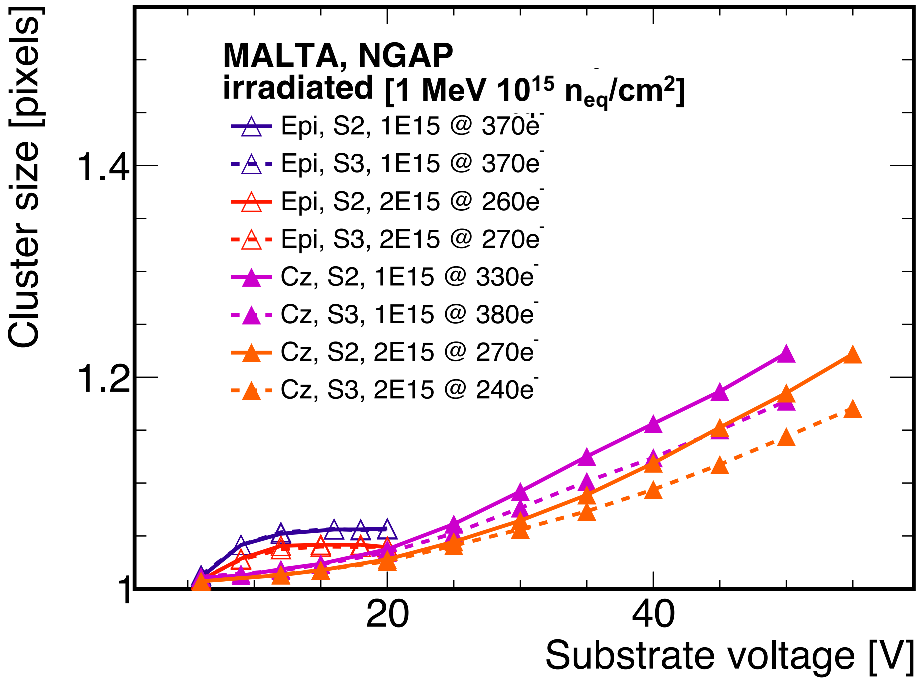


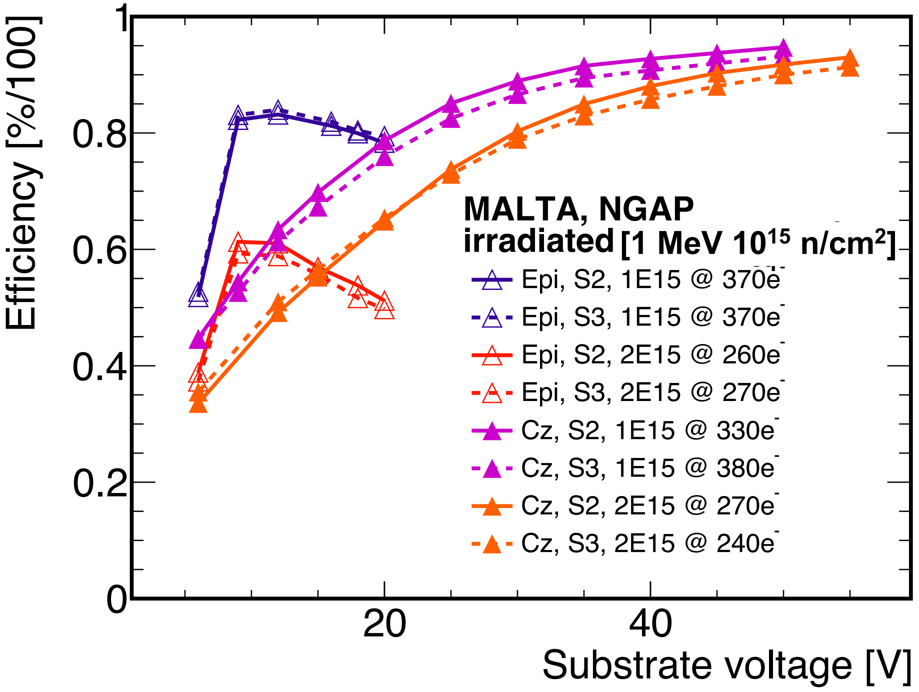
MALTA Cz n-gap $2x10^{15}$ n/cm^2

- MALTA samples produced on HR Czochralski substrates allow further depletion than EPI
- Corner efficiency after 10^{15} n/cm^2 fully recovered with Czochralski samples with extra process modification ~50 V bias and operated at -15 C measured at DESY test beam 4 GeV electron beam



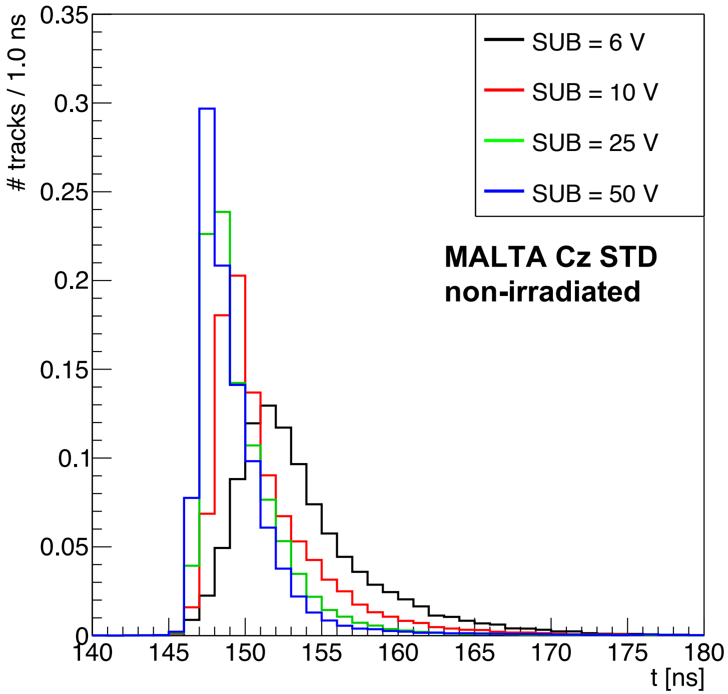
MALTA Czochralski vs bias



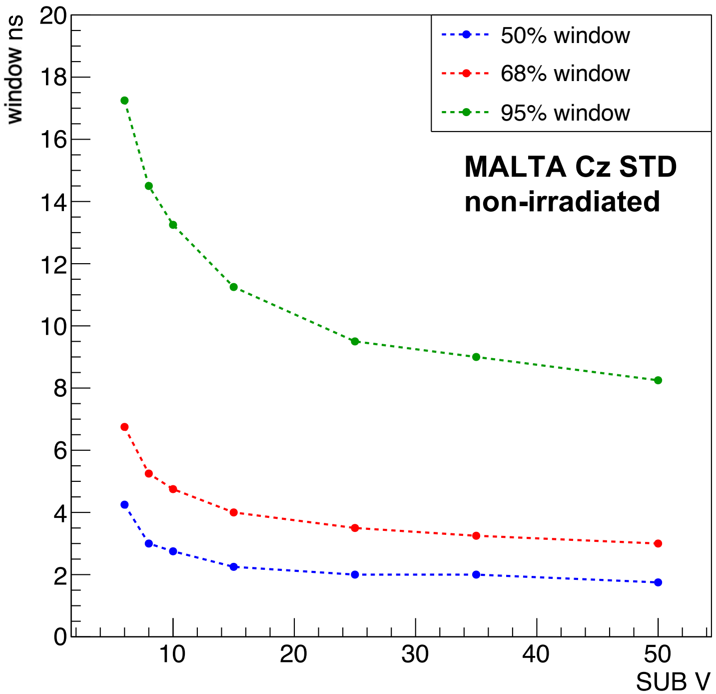


- MALTA epitaxial sensors irradiated at 10^{15} n/cm^2
  - Cluster size remains at ~1.05 and reach maximum efficiency at ~12 V
- MALTA Czochralski sensors irradiated at 10^{15} n/cm^2
  - Cluster size reaches ~1.2 at ~50V and reach full efficiency (>95%) at ~50 V

Timing with MALTA Czochralski



Time difference between MALTA hit and trigger signal at different substrate bias voltages

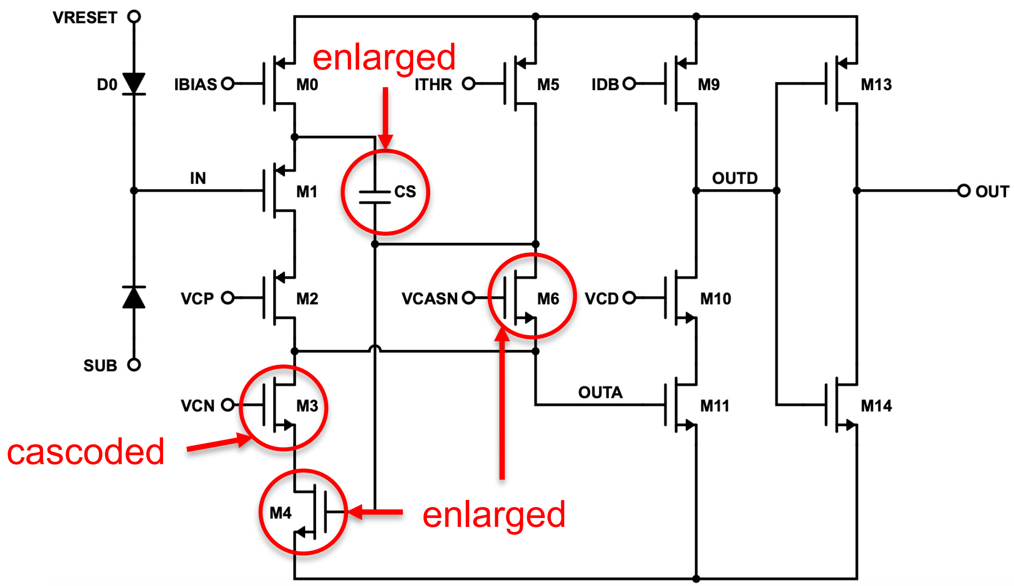


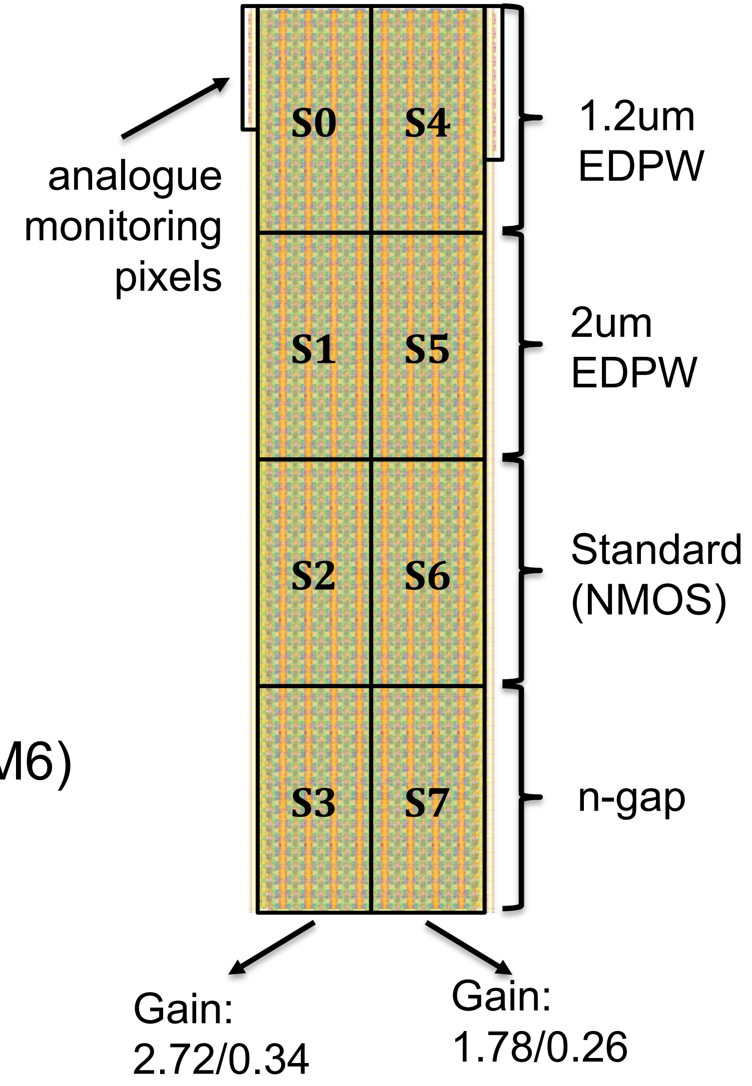
Integral curves of time difference distributions between MALTA hit and trigger signal

- Faster signal and higher amplitude at large substrate voltages reduce time-walk and narrow the time-difference distribution between trigger scintillator and non-irradiated MALTA Cz STD sample (measured with Pico-TDC*)
- 50% of the hits arrive within 2 ns at a substrate voltage above 15V

L Perktold et al. JINST 9 (2014) C01060

TJ Mini-MALTA split 7 (2020)

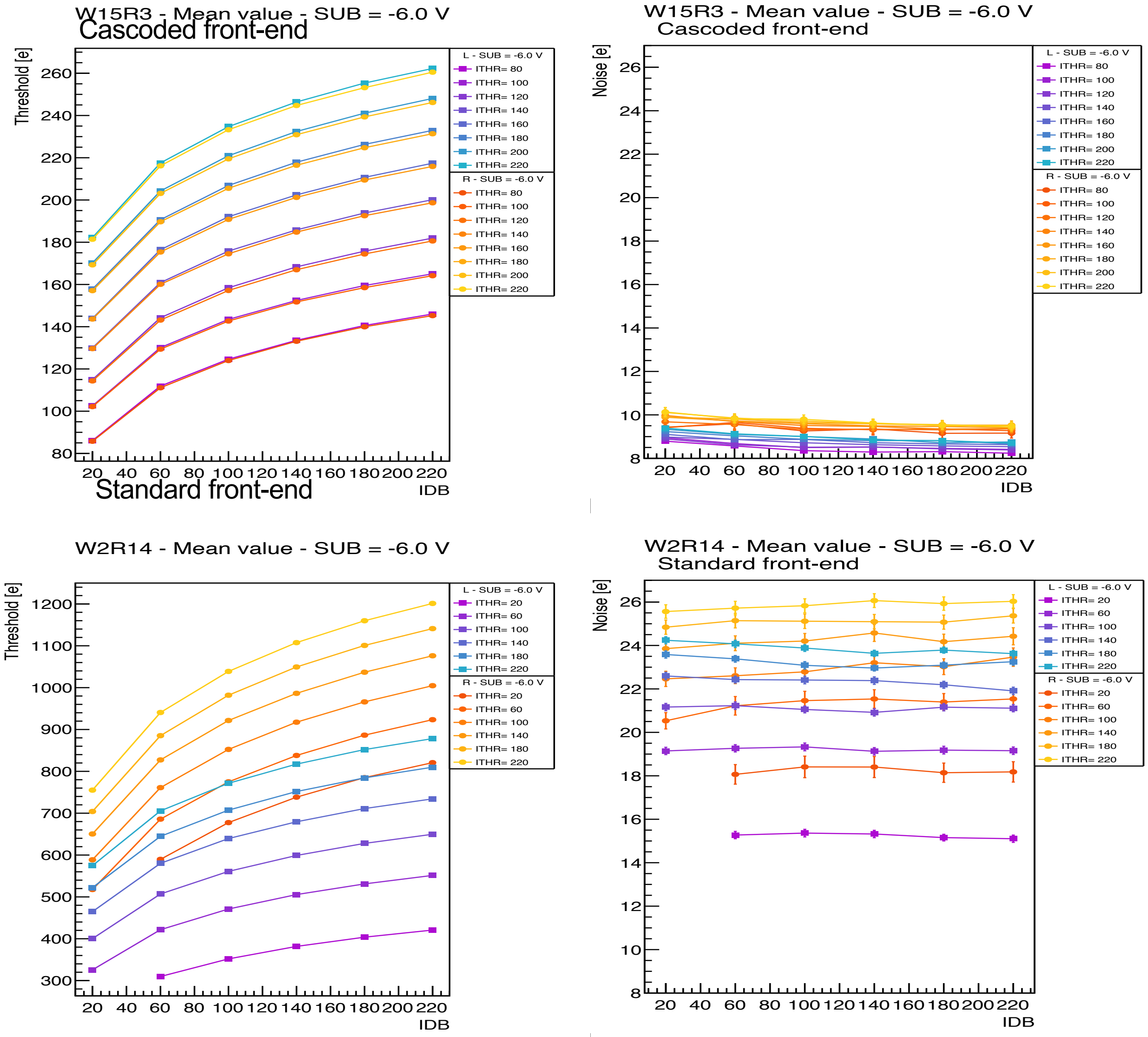




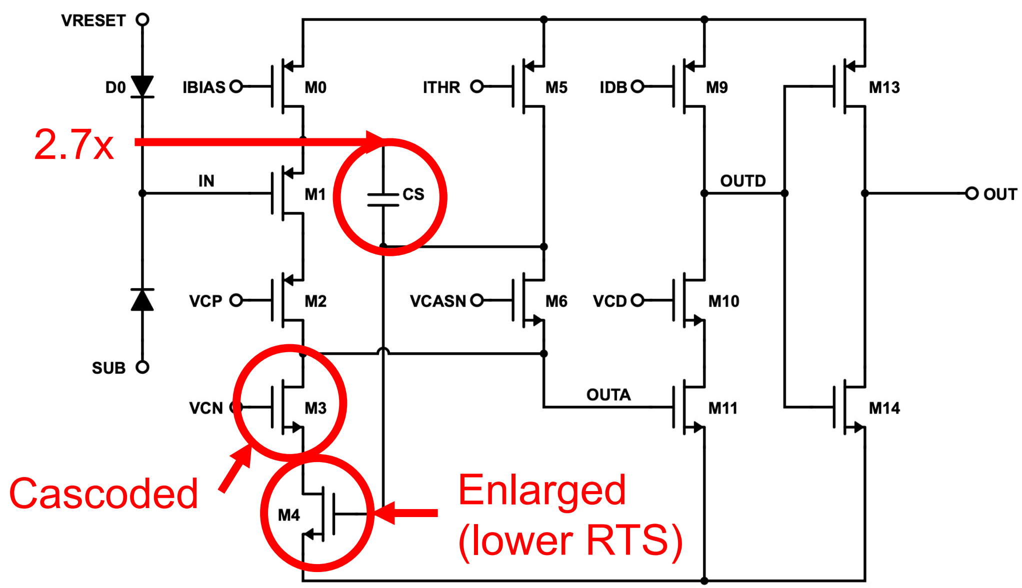
- All sectors have cascoded front-end (M3)
- Sectors 0 to 3 have higher gain (CS, M4, M6)
- Sectors 0 and 4 are 1.2 um EPDW
- Sectors 1 and 5 are 2 um EPDW
- Sectors 2 and 6 are standard n- layer
- Sectors 3 and 7 are n-gap

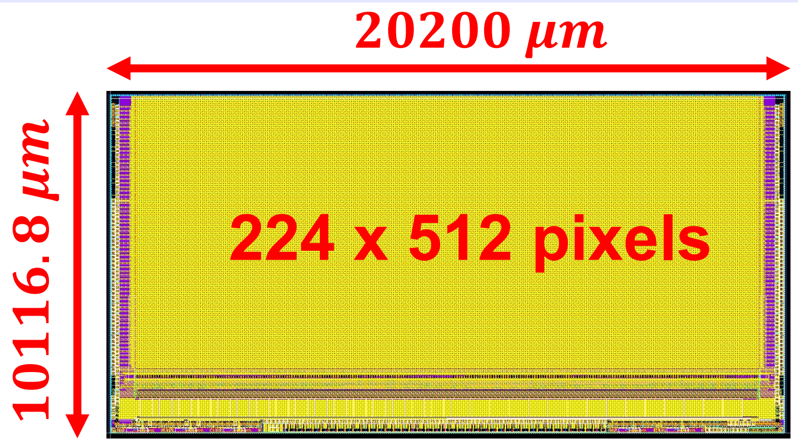
Cascoded front-end

- Cascoded front-end implemented in Mini-MALTA split 7
- Reaches lower threshold values
- Threshold is less affected by the size of the other transistors
- Cascoded front-end has smaller noise
- Selected for the front-end of MALTA2



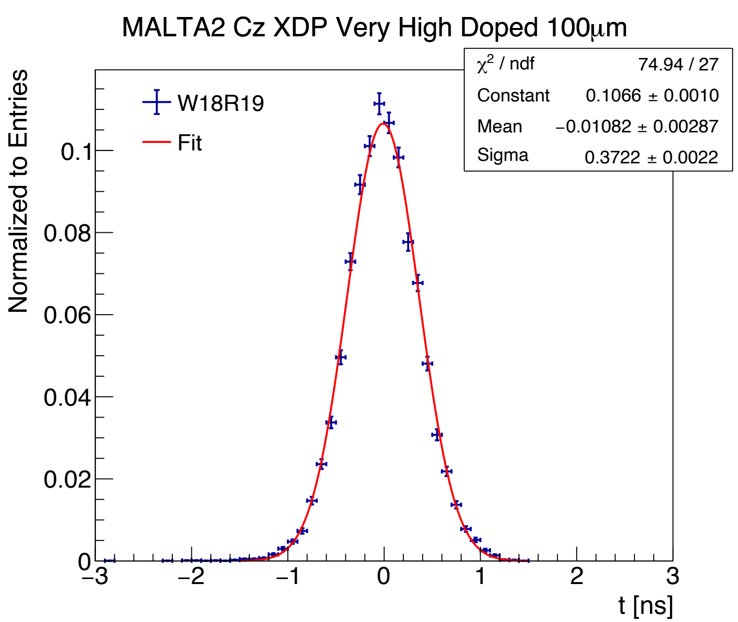
TowerJazz MALTA2 (2021)



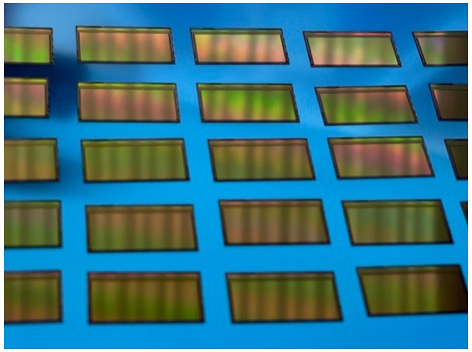


MALTA 2 foot-print

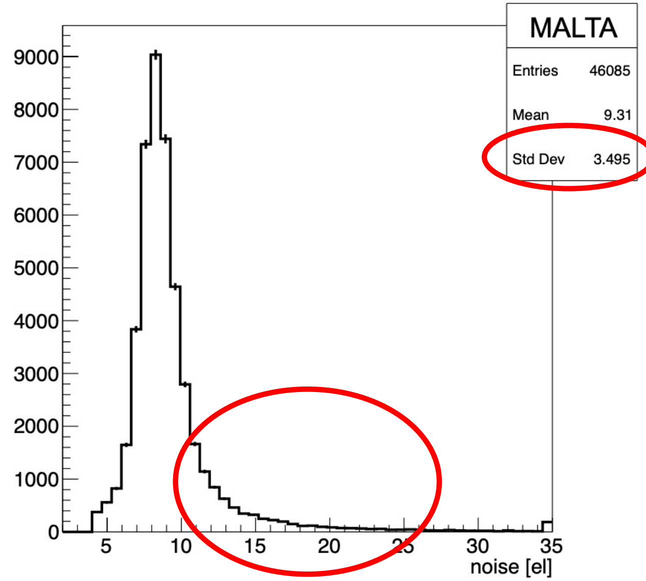
- 20 x 10 mm^2 size demonstrator
- 224 x 512 MALTA pixels
- Single pixel design
  - 2 μm col. el. size and 4 μm spacing
- Cascoded front-end from Mini-MALTA split 7
- Enlarged M4 transistor and CS capacitor
- Improved jitter in time propagation down the column

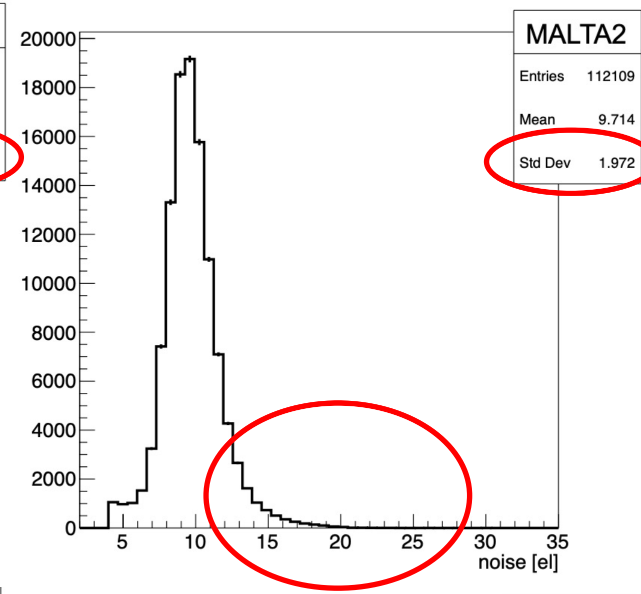


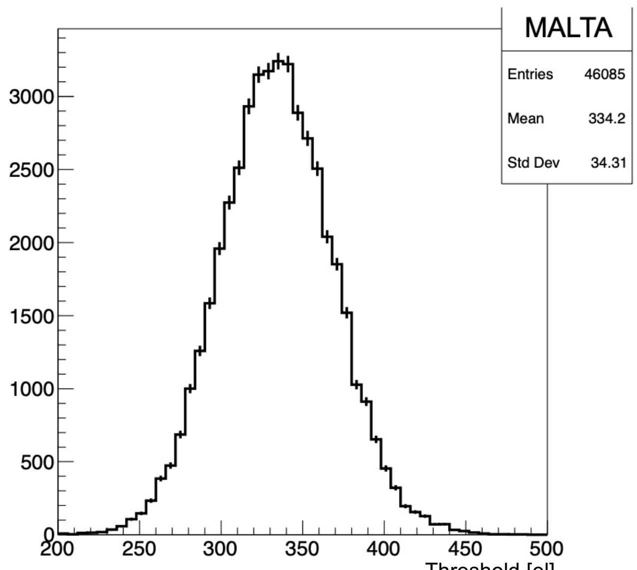
MALTA2 front-end

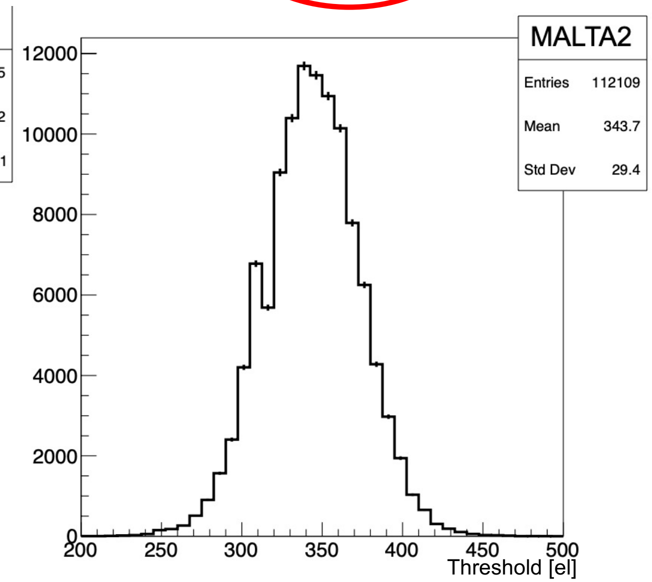


- MALTA2 has less RTS noise (reduced noise tails) compared to MALTA at the same threshold (~350 e-) and 6V bias
- Threshold dispersion similar to MALTA (~10% of the mean)



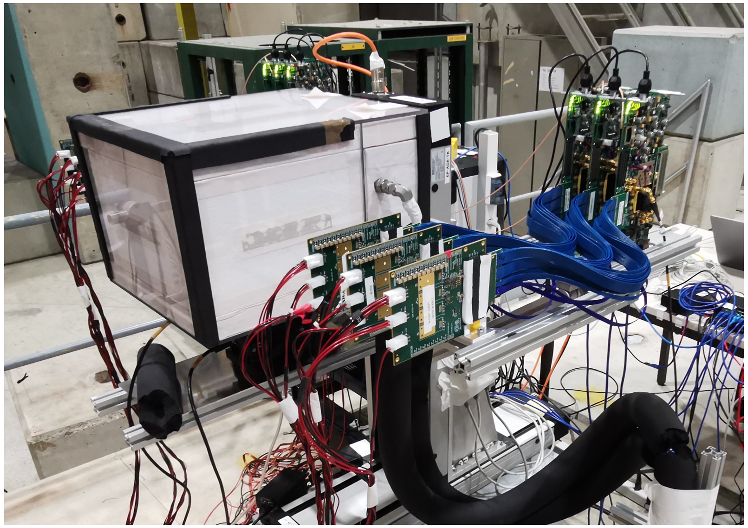






Test-beam telescope

- Custom MALTA telescope with fast read-out, online monitoring, and cold box for or irradiated samples
  - Up to 7 planes + DUT
  - or 6 planes + 2 DUT
- Triggering directly out of MALTA planes through combination of reference signals
  - Scintillator for better time reference
- Interface with pico-TDC for precise characterization of the timing properties of the signal
- Define ROI on tracking planes and check hits on DUT
- Confirmed results with MIMOSA telescope at DESY

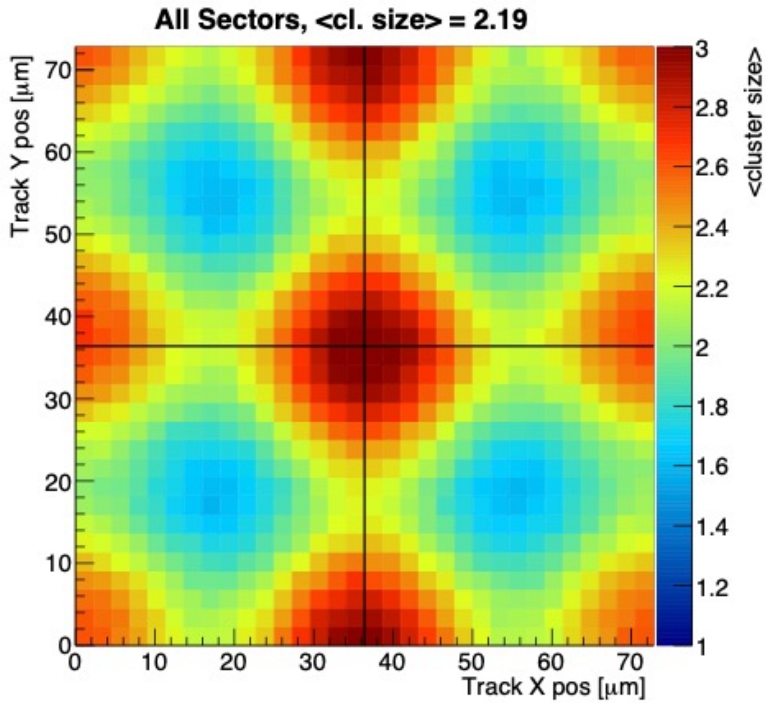


MALTA telescope at SPS

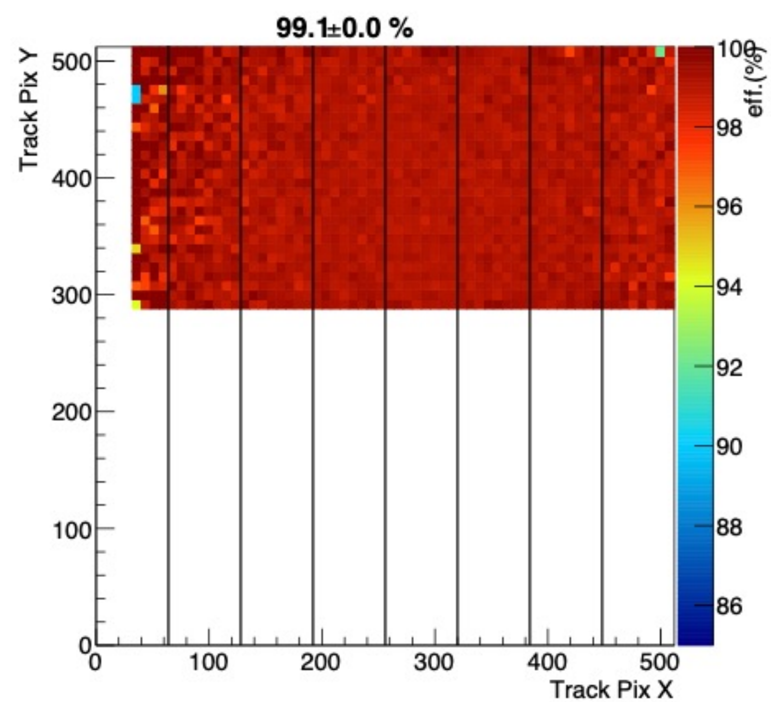
Detail of MALTA and MALTA2 planes

MALTA 2 test-beam results

MALTA Cz std -50V unirradiated

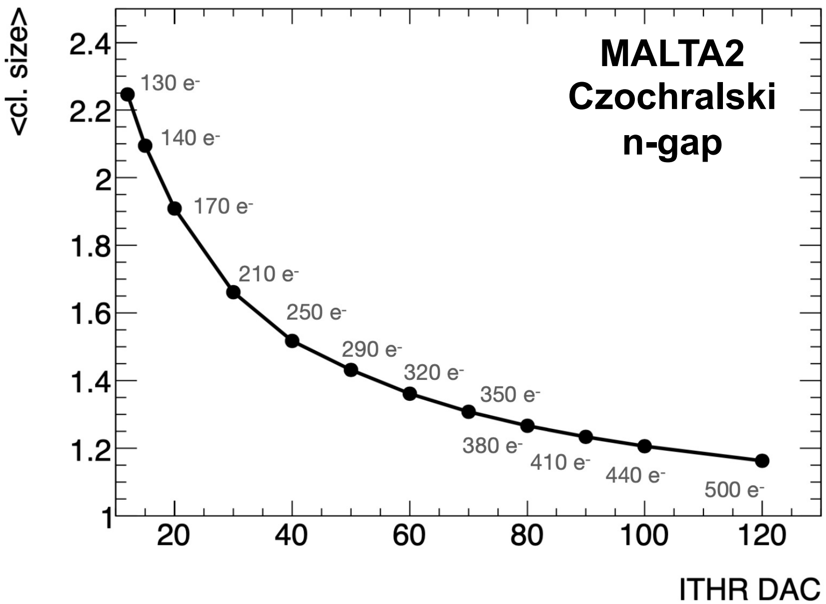


MALTA2 -6V unirradiated

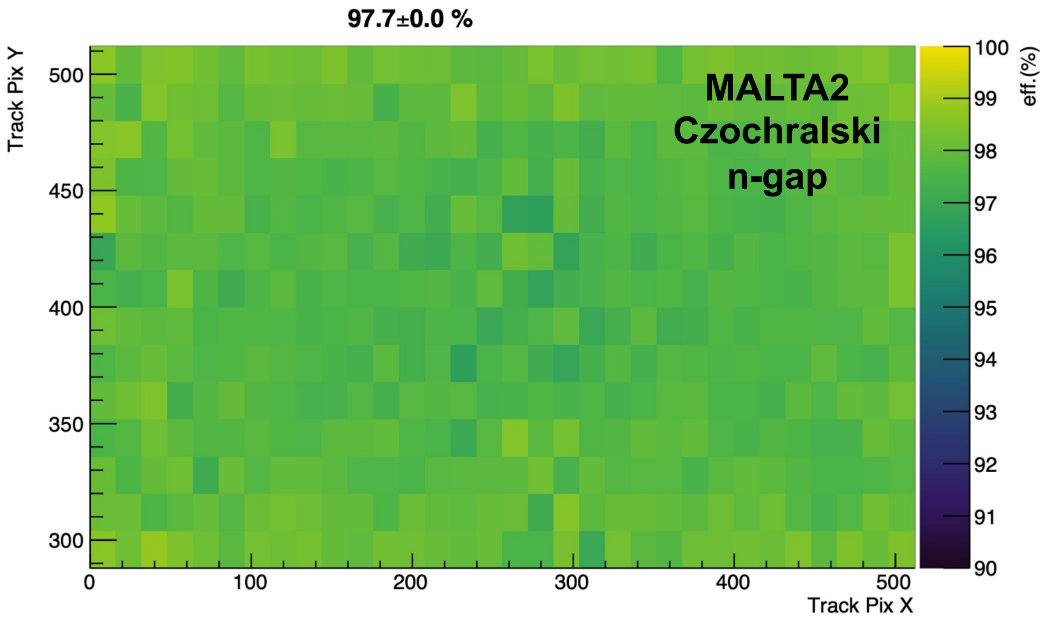


- Ongoing test-beam campaign at SPS from July to November
- Test radiation hardness of MALTA2 above 10^{15} n/cm^2
- Large cluster size from MALTA Cz standard at the pixel corners
- Full efficiency for un-irradiated MALTA2 EPI sensors at -6V

MALTA2 test-beam results



Average cluster size of versus ITHR at fixed IDB 120.
For every data point the corresponding threshold is quoted.

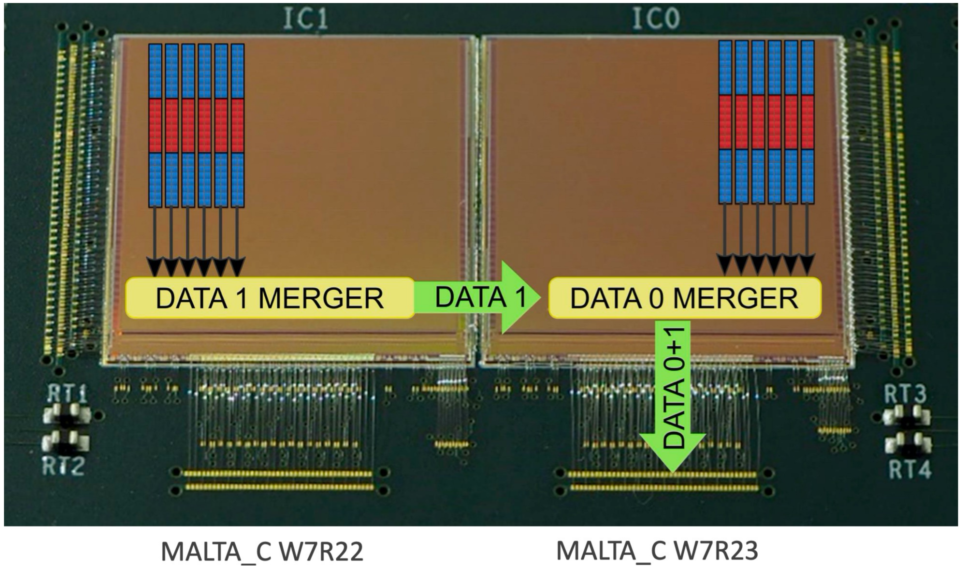


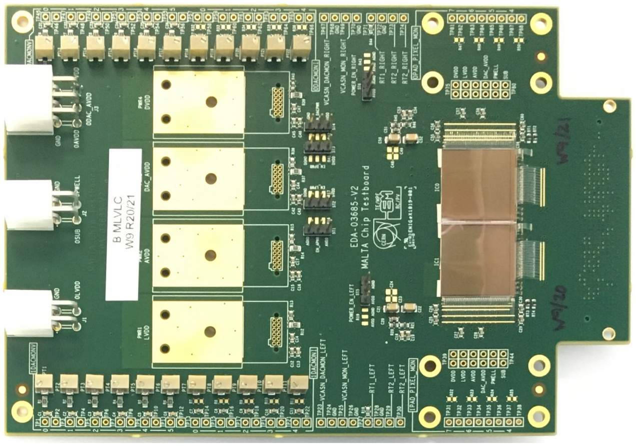
Efficiency map of un-irradiated MALTA 2 Cz n-gap at 320 electrons threshold and 6 V bias

- Full efficiency for un-irradiated MALTA2 Cz n-gap sensors at -6V
- Cluster size reaches 2.2 at 130 electron threshold and -6V bias

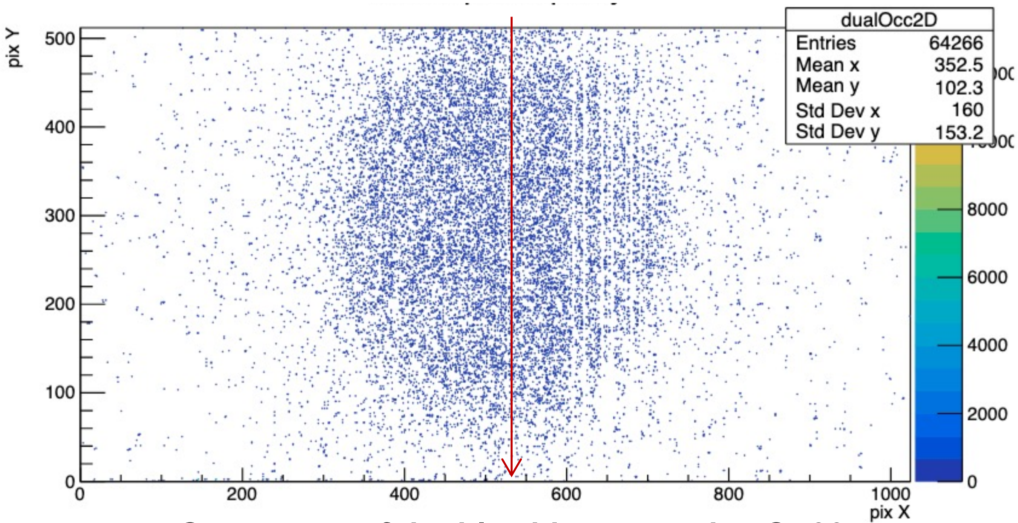
MALTA daisy chain

- Data from MALTA can be routed to another MALTA to the left or to the right through CMOS outputs
- Aim to target larger sensing surfaces and reduce services





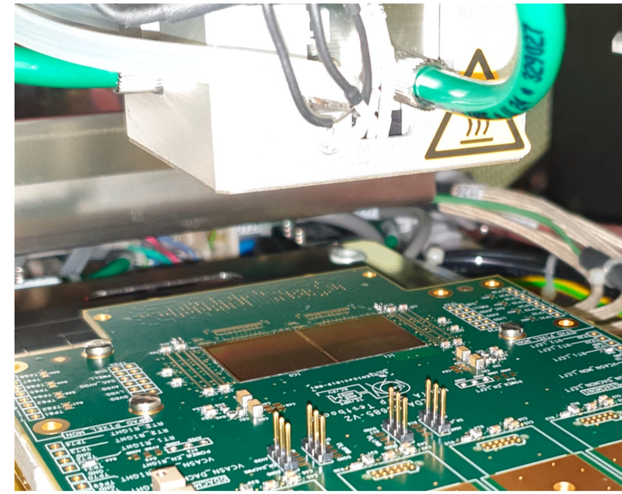
Dual chip carrier board



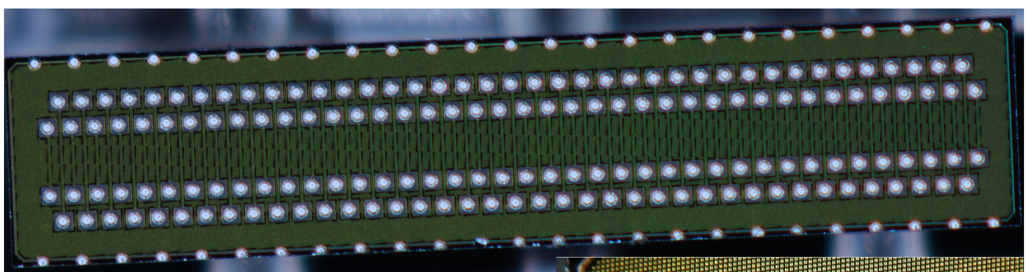
Occupancy of double chip exposed to Sr-90

Towards modules

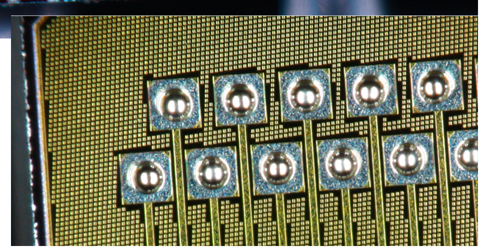
- Silicon bridge can connect two MALTA samples with 10 µm positioning precision
- Bridge is attached to chips with ACF glue, 1 kg of pressure and at 150°C for 10 seconds



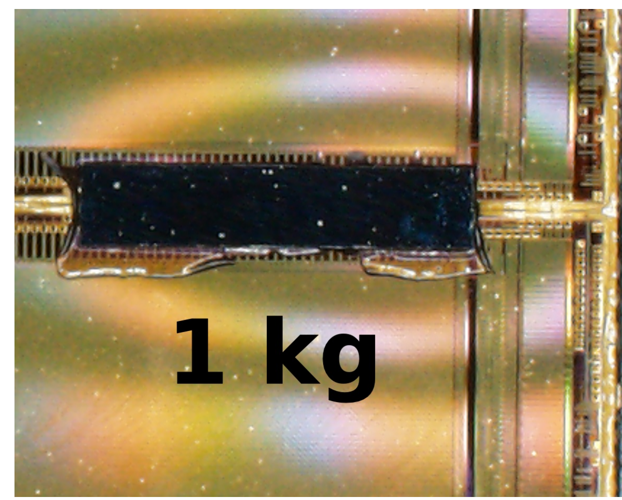
Positioned MALTA 2 chip carrier



Silicon bridge

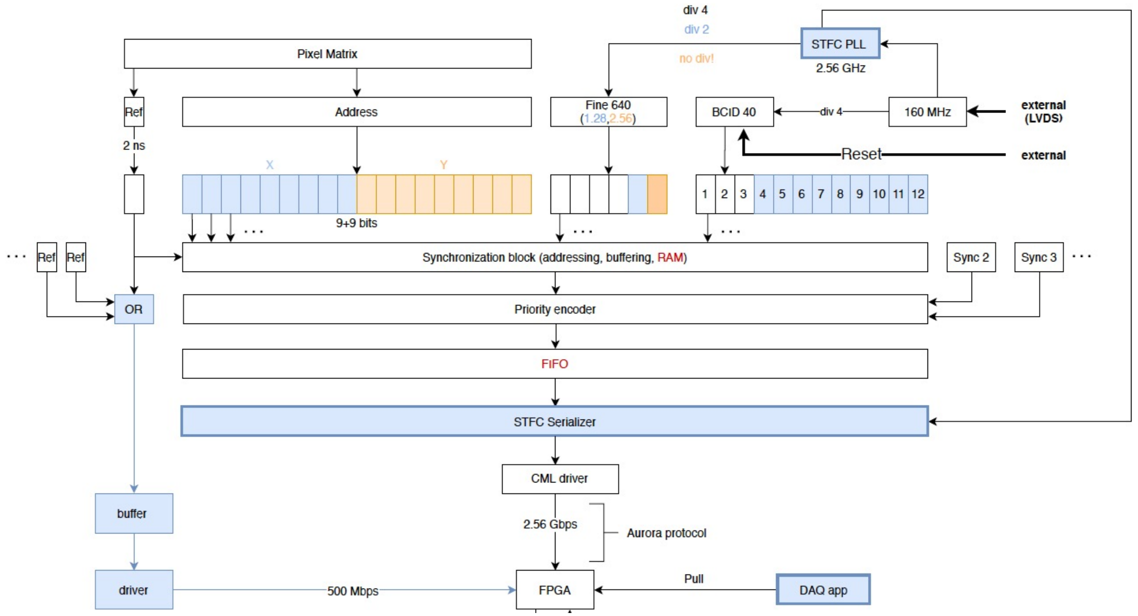


Tin studs on silicon bridge



Silicon bridge between 2 MALTA chips

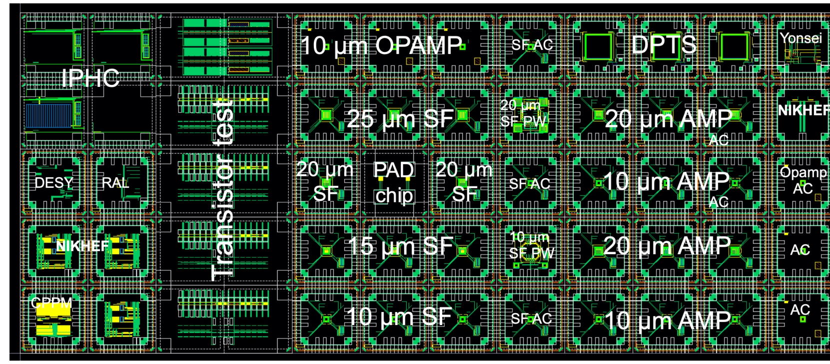
MALTA3

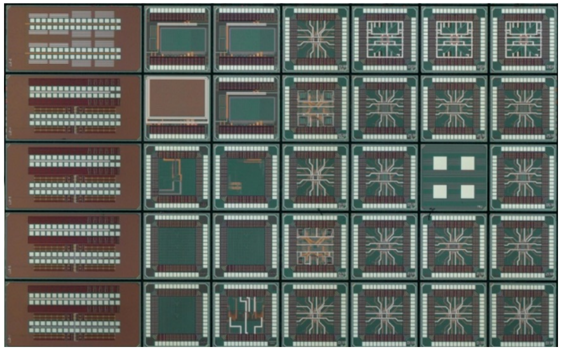


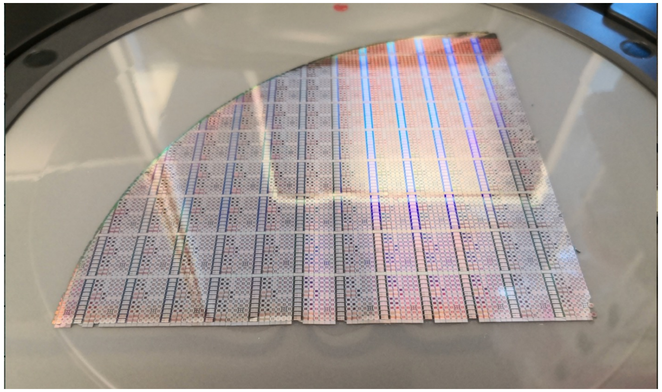
- MALTA 3 will merge latest process modifications, and front-end design with improved time resolution and asynchronous read-out
- Main features: nanosecond time resolution, full reticle size, data streaming, chainable sensor, integration into LPGBT read-out
- Focus on radiation hardness and high granularity
- Ongoing digital design flow, MPW submission expected by Q1 2022

News from TowerJazz 65 nm

- Dedicated chips and test structures on MLR1
  - IPHC: rolling shutter larger matrices
  - DESY: Krummenacher feedback
  - RAL: LVDS/CML receiver/driver
  - NIKHEF: bandgap, T-sensor, VC
  - CPPM: ring-oscillators
  - Yonsei: amplifier structures
- GDS submitted Dec 1, 2020. Wafers delivered first half of June.
  - First chips delivered on blue tape in August, first samples distributed and being mounted on test cards
- Working on the next submission with two stitched chips and some other.







Conclusions

- MALTA sensors produced in TowerJazz 180 nm CMOS technology with small collection electrode are an interesting candidate for future experiments
- 36.4 μm^2 pixel pitch with low power asynchronous read-out make them attractive for high granularity detectors
- Additional process modifications (gap in n- layer and extra deep p-well) showed full efficiency after 10^{15} n/cm^2 neutron irradiation
- Substrate engineering (Czochralski substrates) show increase tracking and timing resolution due to increased depletion depth and charge sharing

Acknowledgements

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- The measurements leading to these results have been performed at the TestBeam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).
- Measurements leading to these results have been performed at the E3 beam-line at the electron accelerator ELSA operated by the university of Bonn in Nordrhein-Westfalen, Germany.
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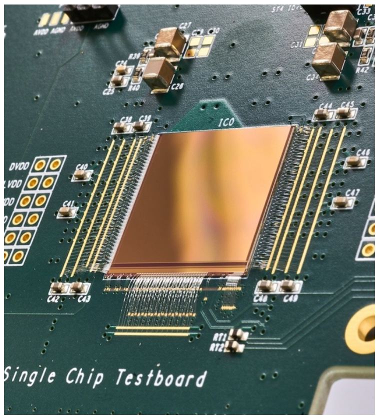
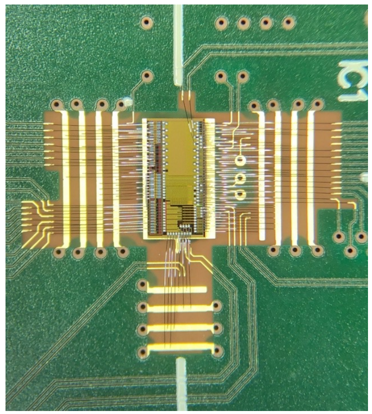
- Dr. Ben Phoenix, Prof. David Parker and the operators at the MC40 cyclotron in Birmingham (UK).

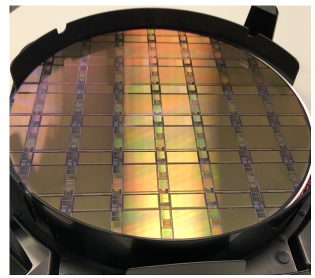
MALTA sensors in TowerJazz 180 nm

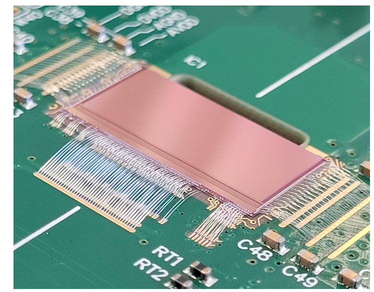
STREAM

AIDA Innova WP5 and CERN EP R&D WP 1.2







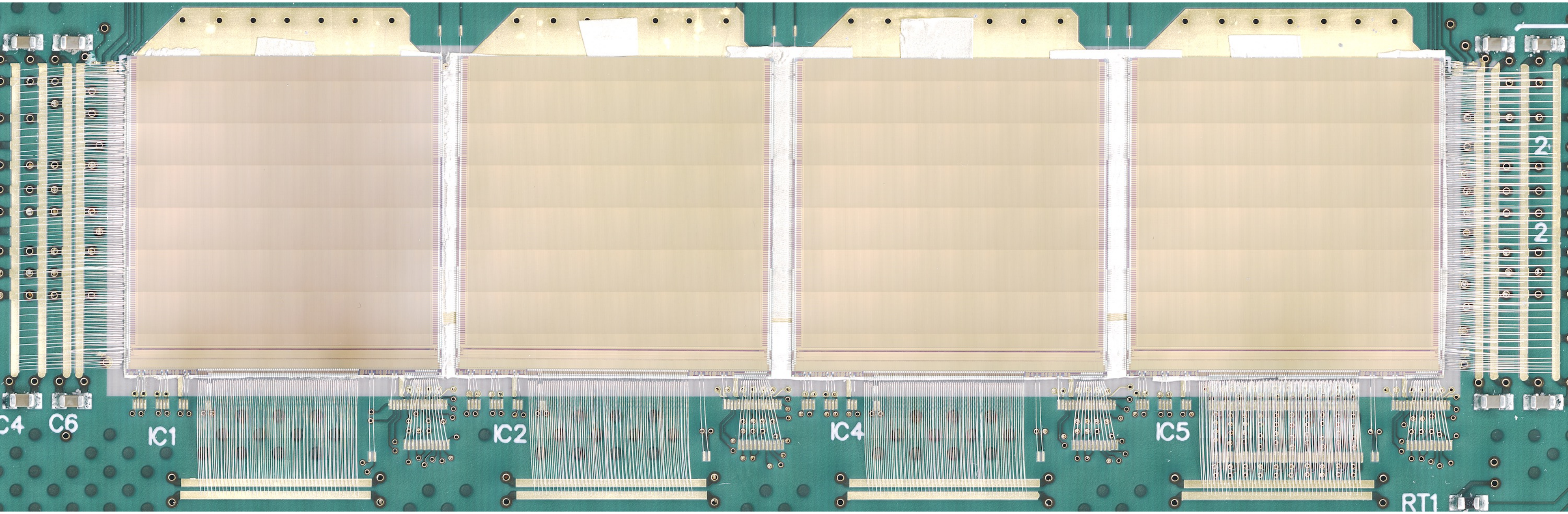


MALTA3
#digital-flow-design

MALTA1 & MLVL	Mini-MALTA	MALTA C	MALTA 2	MALTA 3
Jan 2018	**Jan 2019**	**Aug 2019**	**Jan 2021**	**2023**
Large demonstrator Asynchronous readout Electrode size and reset mechanism evaluation	Small demonstrator Process and mask modification	Slow control improvements on EPI and Czochralski substrates	New front-end Additional process modification	Large matrix Time tagging
Poor lateral field after irradiation	Full efficiency after 1e15 n/cm^2	Enlarged cluster size and improved time resolution on Czochralski	Improved time resolution and on chip synchronization	

Bonus

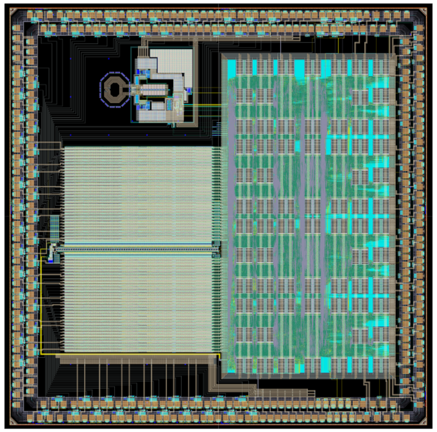
System integration



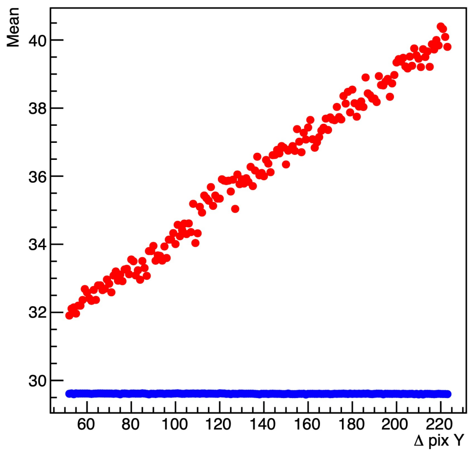
MALTA 4 chip module

- Module with 4 MALTA sensors
- Daisy chain data into single output
- Use a rad-hard ASIC for read-out and control
  - Testing today with pico-TDC
  - Plan to use LPGBT in the future

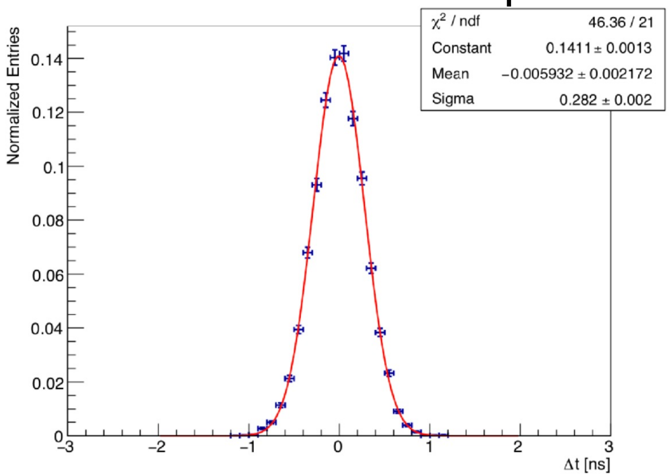
LPGBTX


Pico-TDC

Jitter of MALTA2 front-end

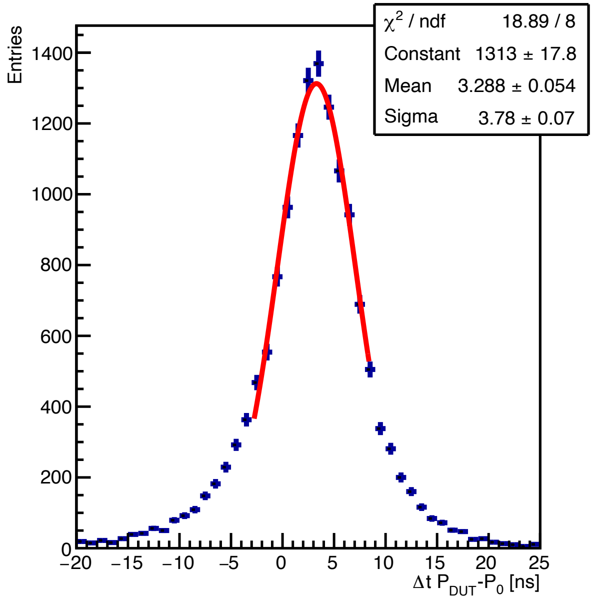


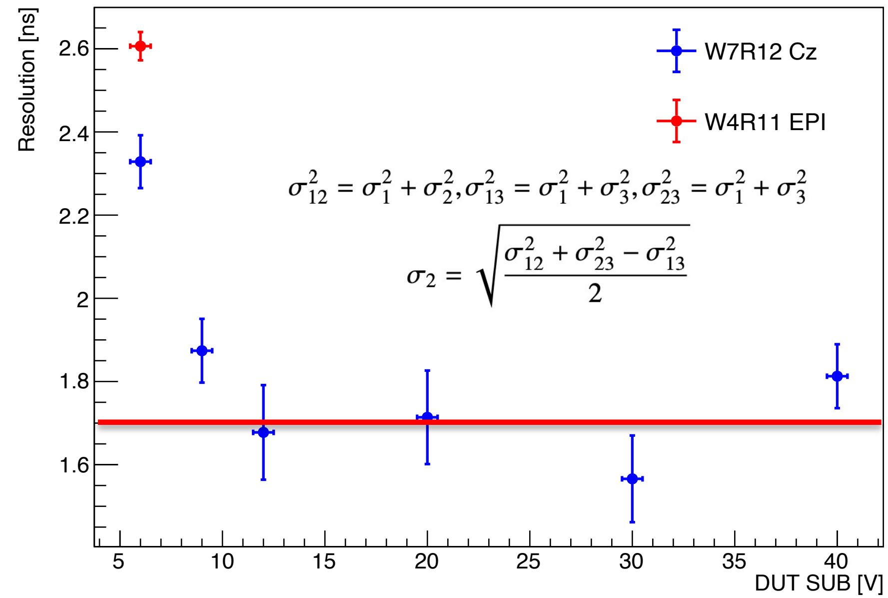
MALTA2 Cz XDPW 100 µm thick



- Jitter of the MALTA2 front-end electronics measured every 5th column on Cz XDPW sensors thinned down to 100 um for two different doping concentrations. Higher doping has 372 ± 2.2 ps jitter while the low doping has 282 ± 2 ps jitter. Timing is obtained by injecting charge to two-pixel on a column at the same time. Time distribution of injections are measured with PicoTDC and the measurement is repeated for all pixels on the columns.

Time resolution on MALTA C



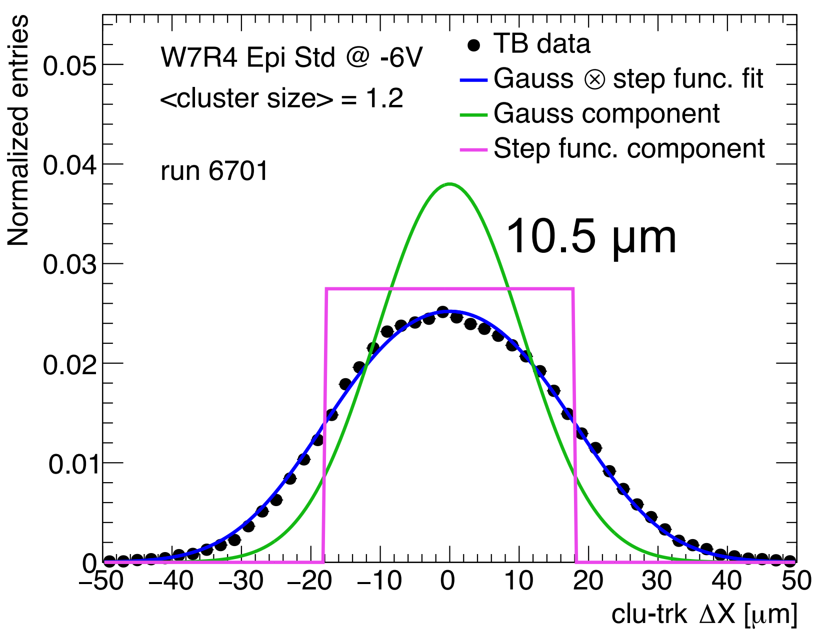


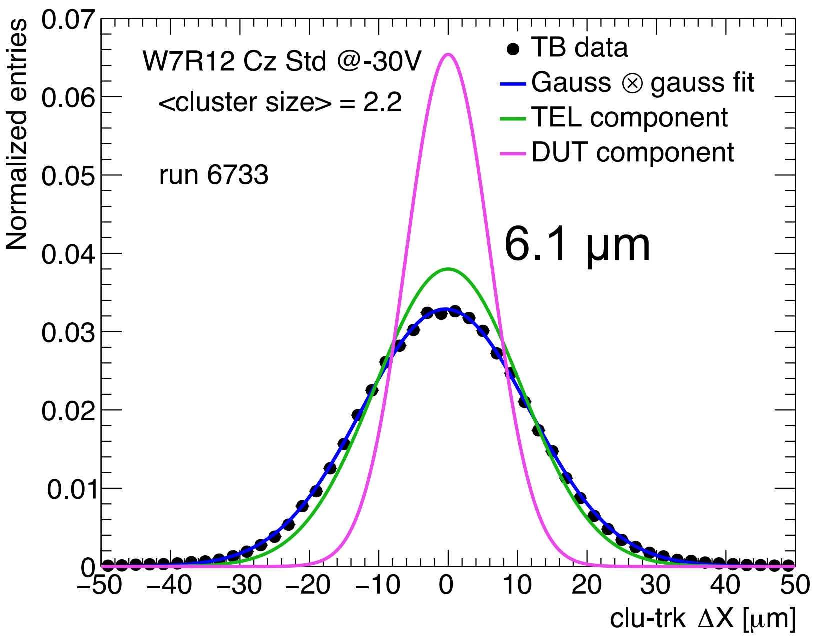
- Resolution is extracted from the linear combination of the time differences of reference MALTA signals between planes from test-beam data
- Measurement of lead time of cluster using Pico-TDC *
- Time resolution on EPI sample is 2.60 ± 0.05 ns at 6 V, while the time resolution on the Czochralski sample is compatible with 1.7 ± 0.1 ns between 10 V and 30 V.

L Perktold et al. JINST 9 (2014) C01060

Tracking resolution

- Using General Broken Lines (GBL) algorithm for track reconstruction to mitigate multiple scattering effects (few GeV electron beam)
  - Embedded in Proteus software [M. Kiehn et al., 0.5281/zenodo.2586736]
- Extracted telescope resolution is 10.5 µm from the convolution of a gaussian distribution with a two-sided step distribution with 36.4 µm width corresponding to the pixel pitch of MALTA
- Can improve tracking resolution of telescope up to 6.1 µm by using Czochralski samples at higher bias (30V) for reference planes (increased charge sharing)





MALTA 4-chip carrier board