Advancement and Innovation for Detectors at Accelerators

TJ-MALTA developments

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WP5 DMAPS - AIDAinnova 3rd annual meeting

19 March 2024

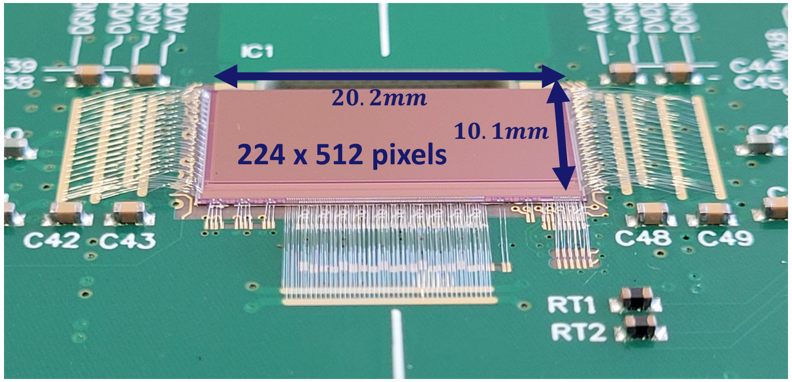
This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101004761.

Task objectives

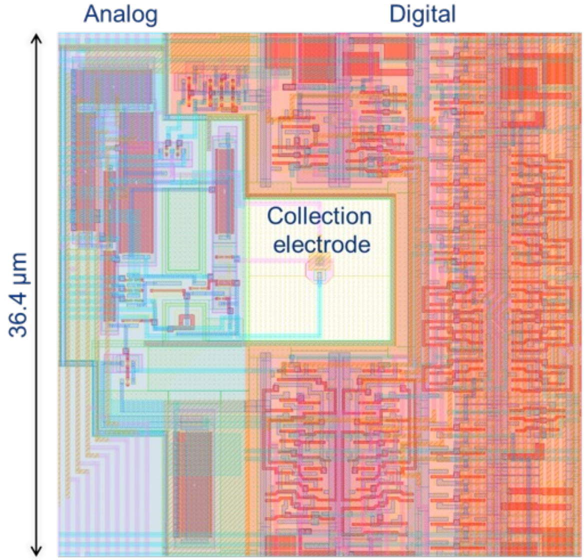
- Design of test structures and DMAPS for fluences > 10^{15} 1 MeV n/cm^2
  Validation of designs using simulation (functional, TCAD)
- Fabrication of test structures and prototype in MPW
  - Careful interaction with foundry, 180nm TOWER.
- Development of readout and test system for devices
  - Build on existing infrastructure
- Characterization of prototypes including particle beams before and after irradiation
  - Irradiation of samples at different target doses

MALTA2

- First large-scale prototype to implement the cascoded front-end from Mini-MALTA split 7
  - 20 x 10 mm^2 size demonstrator
  - 224 x 512 MALTA pixels 36.4 µm^2
  - Single pixel design: 2 µm collection electrode size, 4 µm spacing to electronics, and maximum cut-out of the p-well
  - Enlarged M4 transistor and CS capacitor
- Produced in 3 flavors (standard, n-gap, extra deep p-well) and 2 substrates (EPI, Czochralski)
  - 10 mW/cm^2 digital power
  - 70 mW/cm2 analog power
- Submitted in October 2020
- Received in January 2021
  - Under extensive tests since then



MALTA 2 on carrier board



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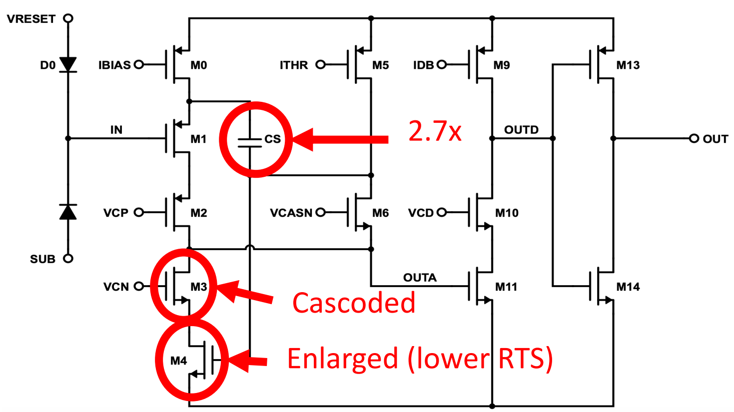
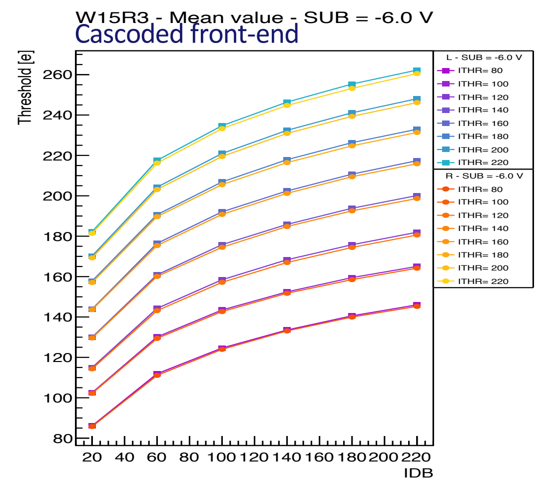
MALTA pixel

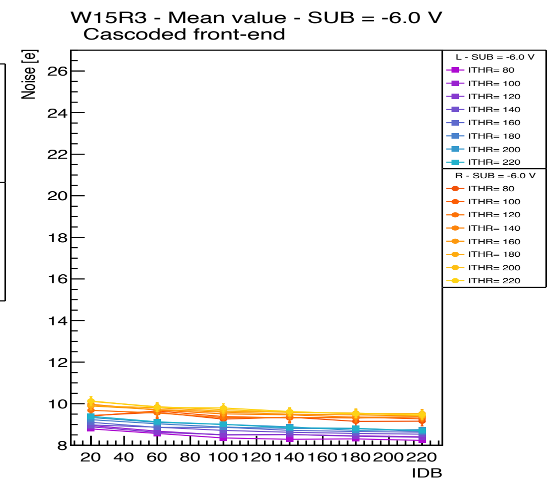
MALTA2 Cascoded front-end

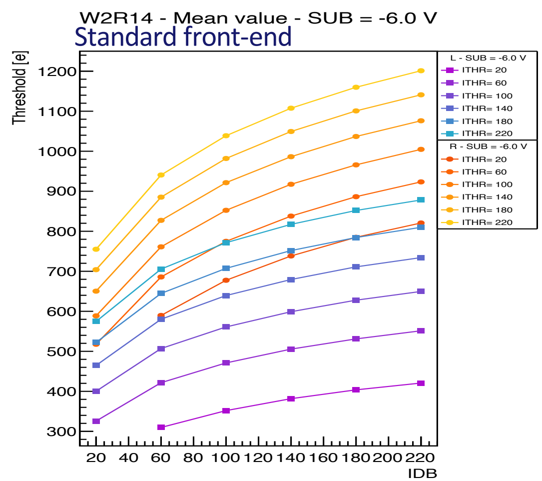
- Cascoded front-end introduces a new transistor in series with the input node
  - Increases the gain of the front-end
  - Reducing the threshold reach
- Standard front-end with larger size feedback NMOS transistor (L) have lower threshold than the ones with smaller size (R)
  - IDB DAC proportional to threshold
  - ITHR DAC proportional to return to baseline speed
- Noise is significantly reduced

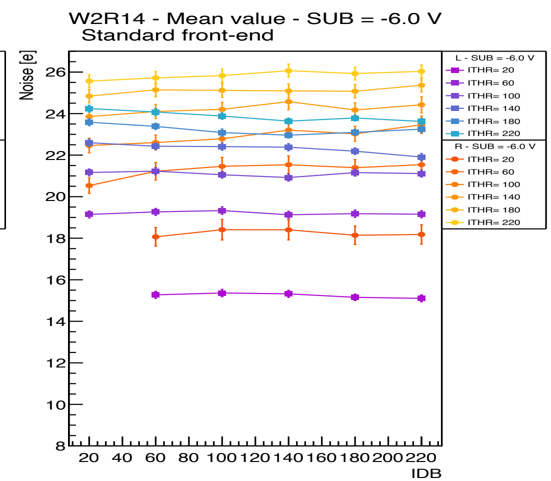


MALTA2 front-end



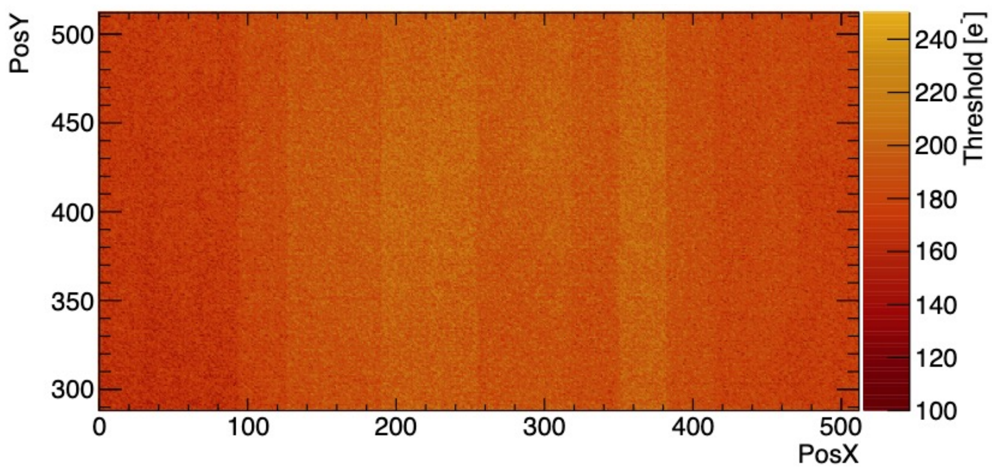




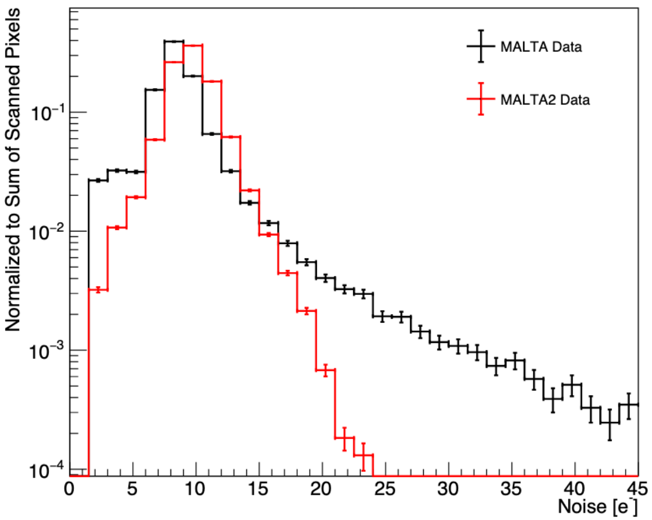


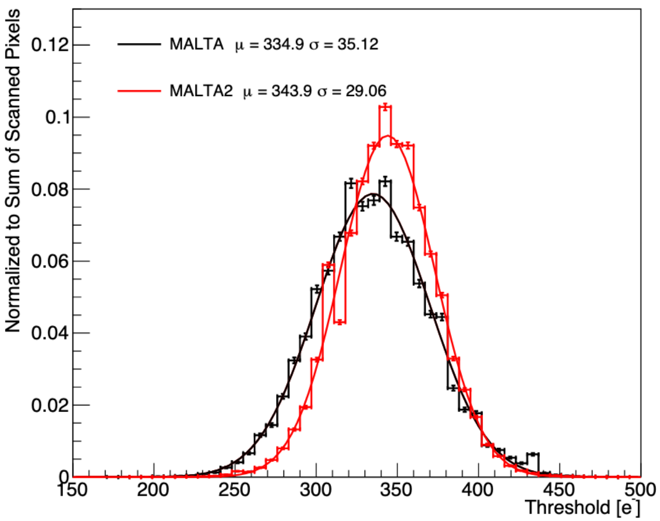
MALTA2 front-end noise

- MALTA2 has less RTS noise (reduced noise tails) compared to MALTA at the same threshold (~350 e-) and 6V bias
- Threshold dispersion same as previous designs (~10% of the mean)
  - No in-pixel threshold tuning
- Noise standard deviation of MALTA2 is half of MALTA
- Good uniformity across the matrix



2D Threshold map, MALTA2 Cz NGAP high doping
100 µm thick, Vsub = -6 V

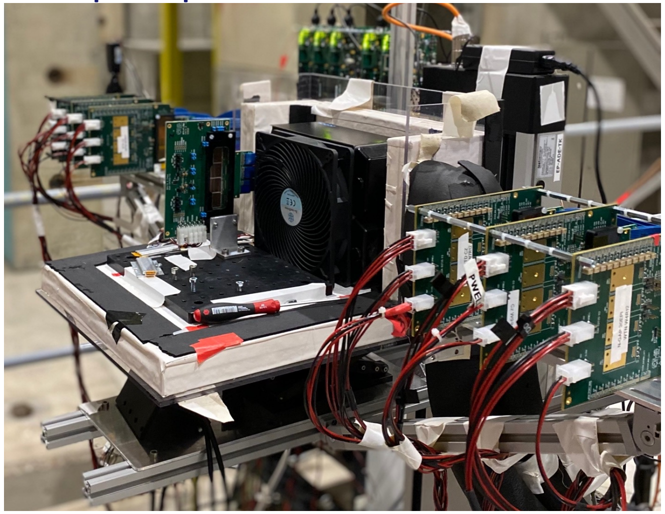




SPS test-beam 2023

- MALTA telescope installed at CERN SPS H6
  - Parasitic users since 2021. More than 60 samples tested, with 4 different fluences, 3 process modifications, and 2 substrates.Large range of MALTA2 samples tested throughout 2023 + external users
- Improved telescope stability to cope with 5e6 particles/spill at 50 kHz readout
  - Trigger directly on MALTA planes
  - Use scintillator for time reference
  - 6 tracking planes + 2 DUTs
  - ~2 ns time resolution
  - ~5 µm spatial resolution

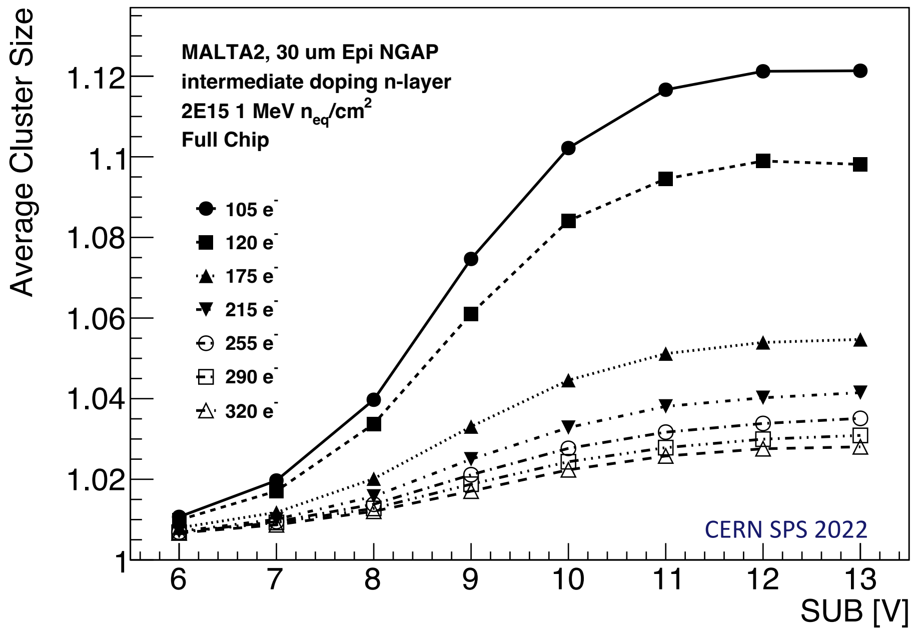
https://link.springer.com/article/10.1140/epjc/s10052-023-11760-z

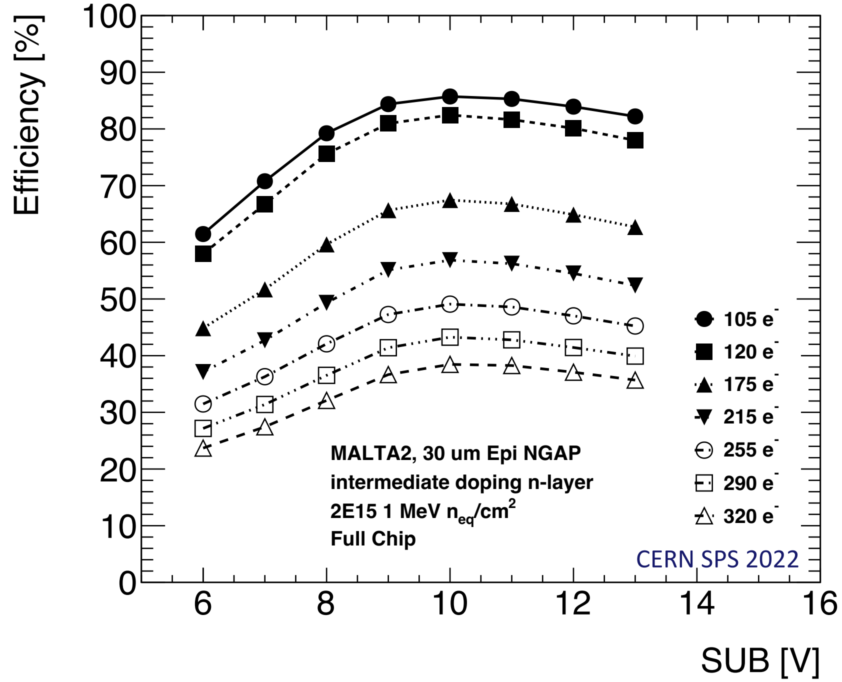

MALTA telescope at SPS

Year	2021	2022	2023
#Samples	24	29	16
#Events	1M	2M	1M
# Runs	2000	3300	3000
# Months	4	8	7

Testbeam planning

MALTA2 EPI results



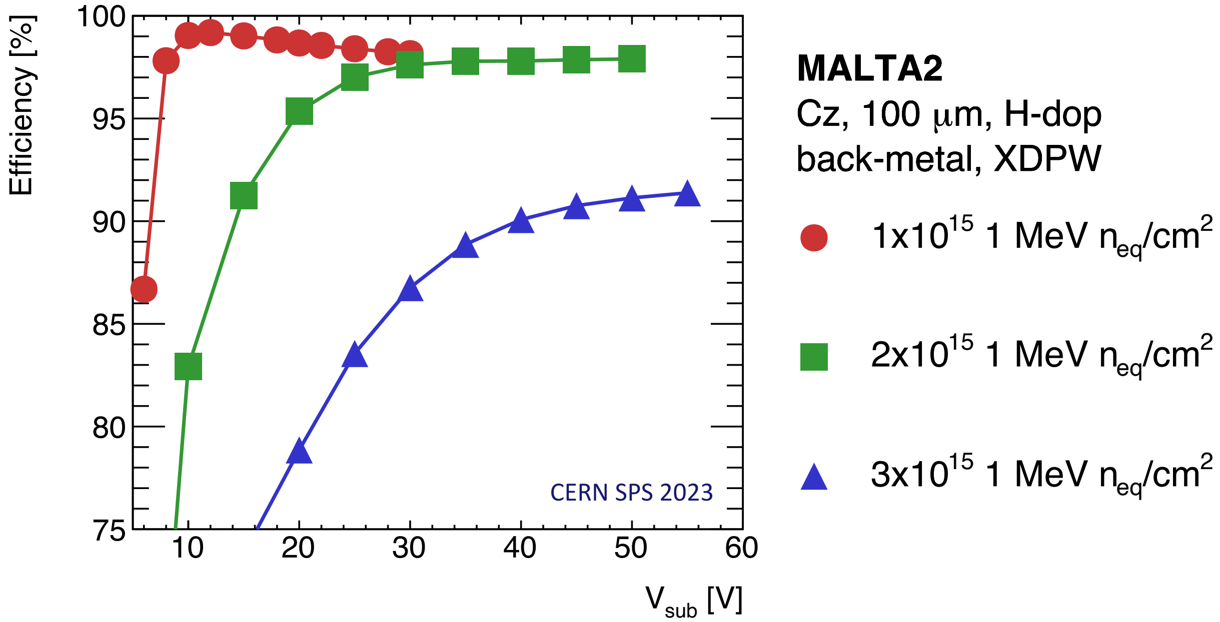


Cluster: sum of contiguous pixels fired in the same event and received within 500 ns

Average cluster size of non-irradiated MALTA2 versus the threshold in electrons at -6V SUB

- Almost 90% efficiency after $2x10^{15}$ 1 MeV n/cm^2
- Average cluster size increases as the operating threshold is lowered
- EPI sample reaches a cluster size of 1.12 ± 0.1 for Vsub = 13 V

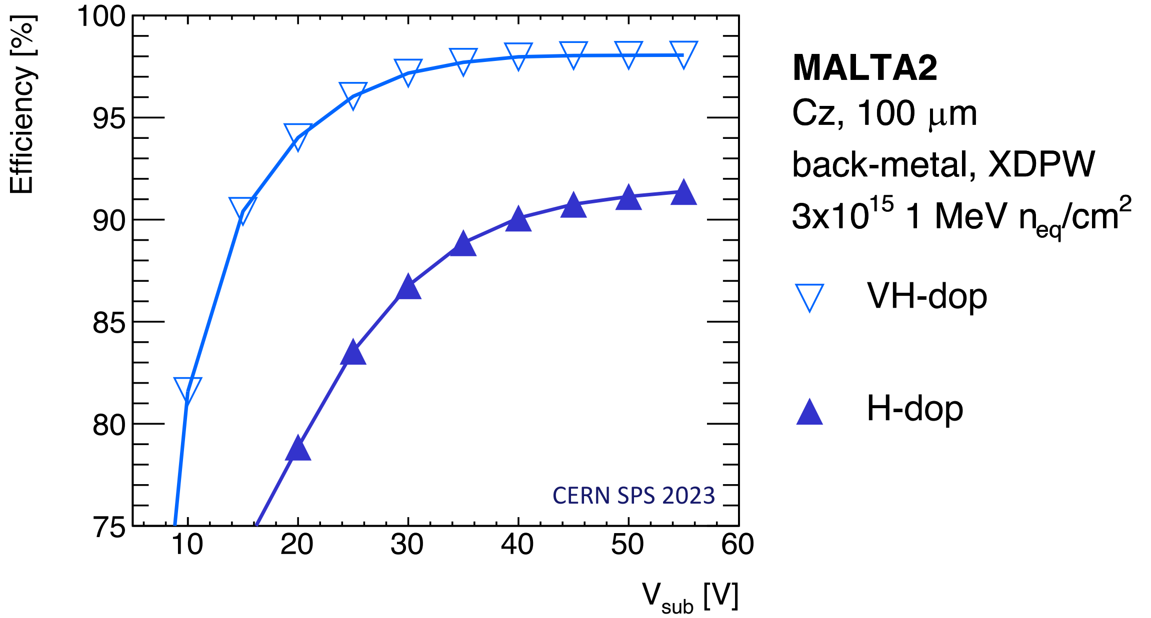
Efficiency after irradiation in CZ



Average efficiency of irradiated MALTA2 on Czochralski substrate versus SUB voltage

- This plot shows 1,2,3x10^{15} 1 MeV n/cm^2 of a sample with high doping of the n- layer.
- Almost full efficiency after 1x10^{15} 1 MeV n/cm^2 for back-metallized samples (>99%)
- At higher fluence levels, a higher substrate voltage is required to obtain high efficiency

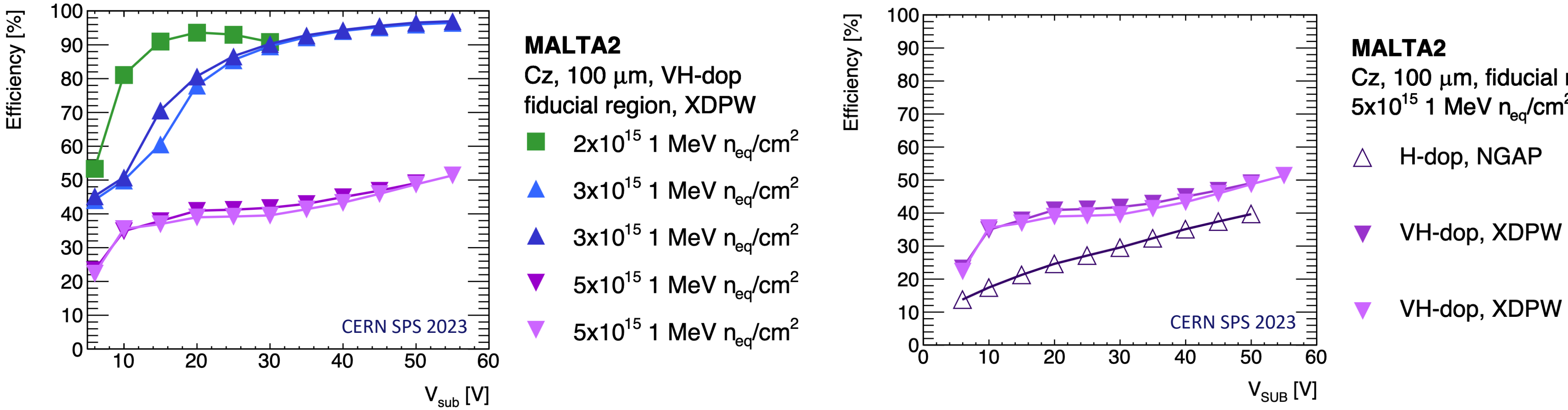
Effect of doping



Average efficiency of irradiated MALTA2 on Czochralski substrate versus SUB voltage

- Test samples with higher doping level of n- layer to compensate for radiation damage: high doping and very high doping
- Difference in doping level refers to relative difference in implantation dose
- >97 % efficient at ~30V for sample with very high doping of n- layer at fluence level of $3x10^{15}$ 1 MeV

Effect of doping in 5E15



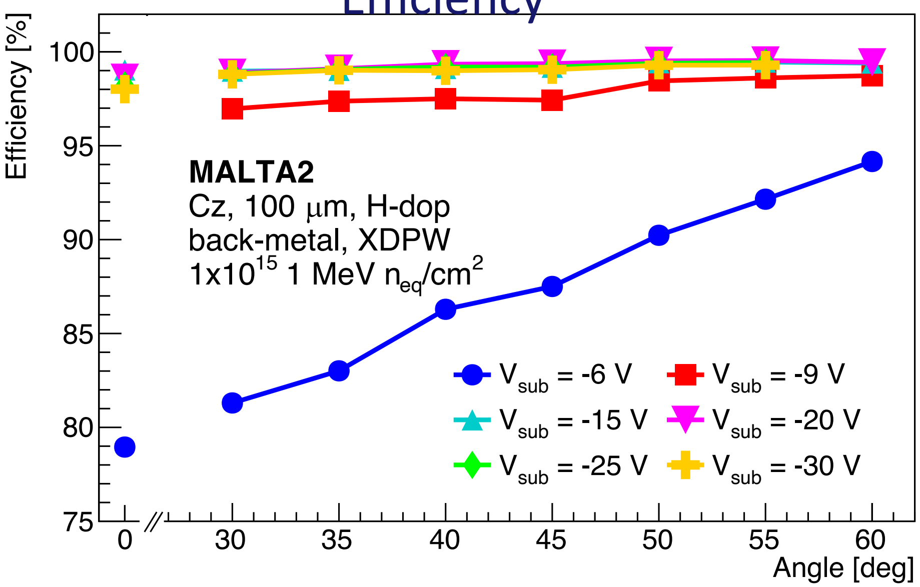
Average efficiency of irradiated MALTA2 on Czochralski substrate versus SUB voltage

- Efficiency after 5×10^{15} 1 MeV n/cm^2 for VH doping and no back-metallized samples above 50%
- Different doping concentrations of the n-layer in the pixel were done (high and very high)
- All samples have substrate thickness of 100 µm
- All samples were operated at ~100 electrons at -15°C
- Very high doping increases efficiency by 10-15%

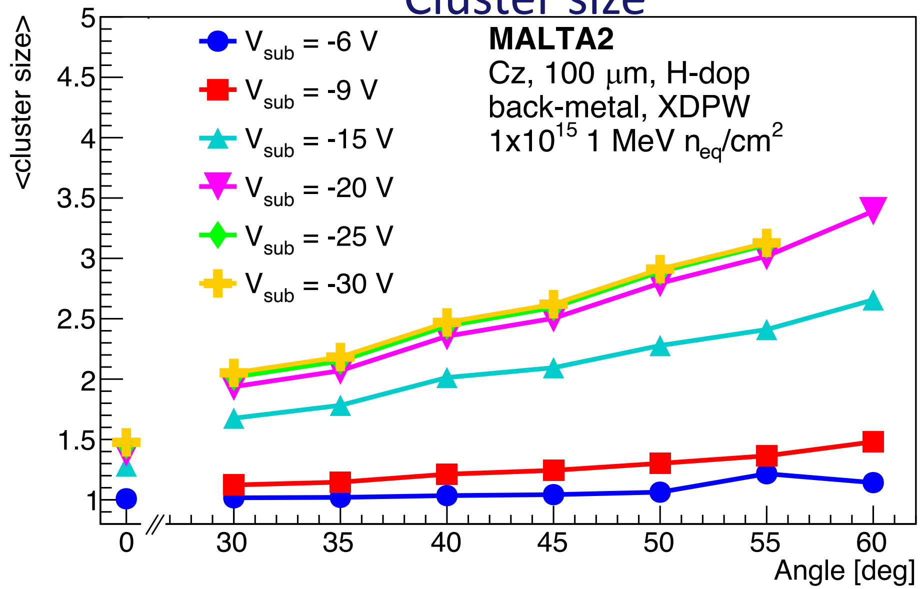
MALTA2 Inclined angle studies

- Studies with inclined MALTA2 sensors at the SPS
- Demonstrated increased efficiency and cluster size for inclined 1×10^{15} 1 MeV n/cm^2 irradiated MALTA2 Czochralski sample

Efficiency

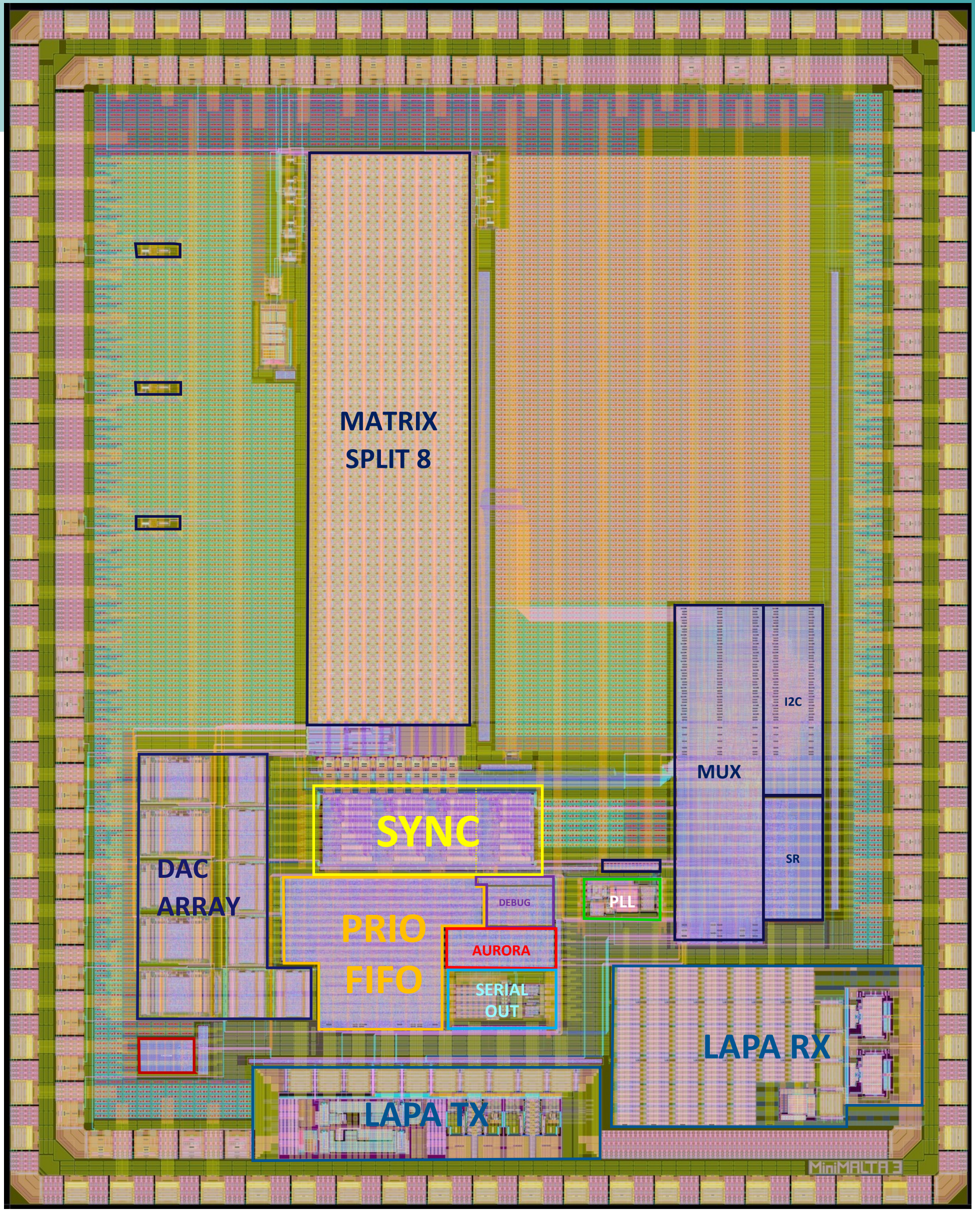


Cluster size



Mini-MALTA3

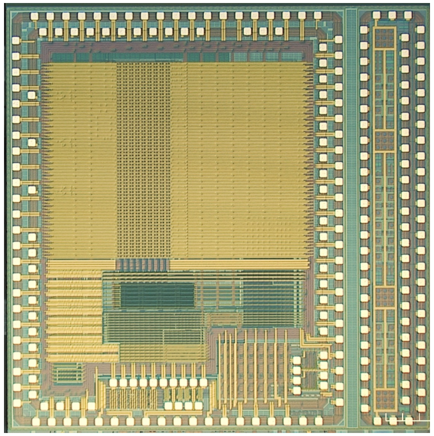
- 5x4 mm2 demonstrator
- 48x64 matrix size of 36.4 um^2
- Same front-end as MALTA2
- No clock over the matrix
- Synchronization memory with 0.78 ns time resolution
- Fast clock generation with STFC PLL from 80 MHz clock input to 1.28 GHz at the output
- Slow control implemented in I2C and shift register protocols
- LAPA used for receiver and transmitter
- Reset and pulsing implemented via fast command input
- Output data scrambled using Aurora
- Data serialization at the output



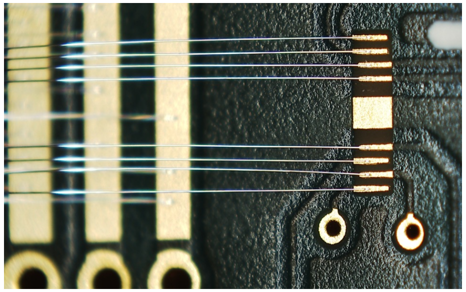
Mini-MALTA3 results

- Samples arrived in late 2023
- Improved wire bonding with respect to previous samples
- Power consumption within expected values
- Shift register slow control seems to be working fine
- DAC scans look good, results within expected values
- Ongoing test with the PLL

Chip is alive and we are at the very beginning of systematic tests of all new digital blocks

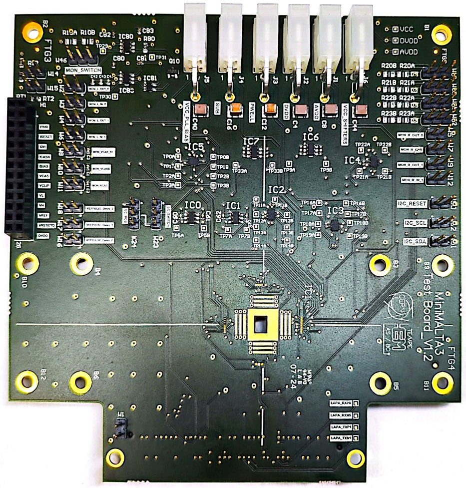


MiniMALTA3 chip



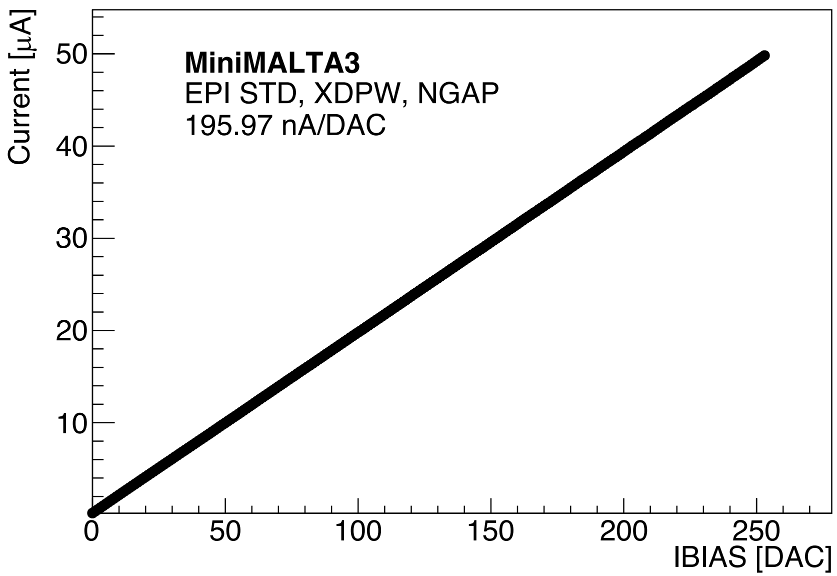
MiniMALTA3 wire-bonding view

MiniMALTA3 testing setup

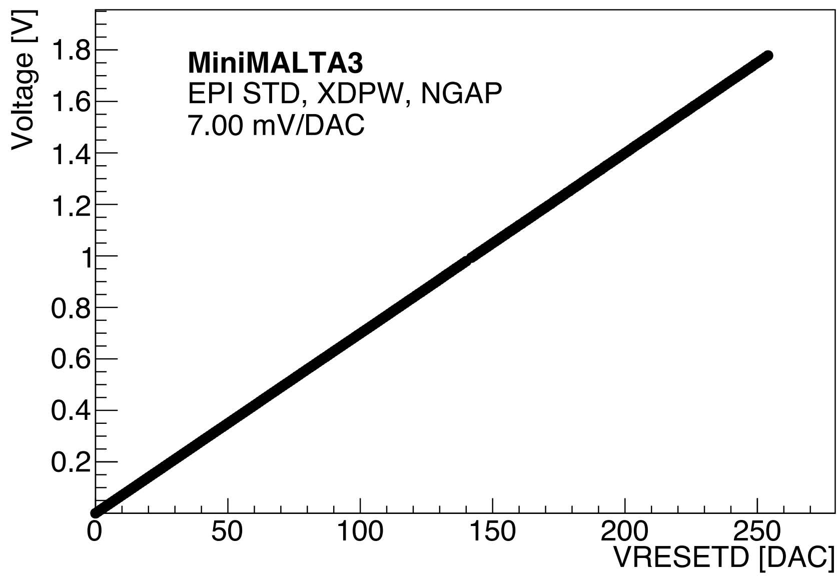


MiniMALTA3 carrier board

Mini-MALTA3 DAC scans



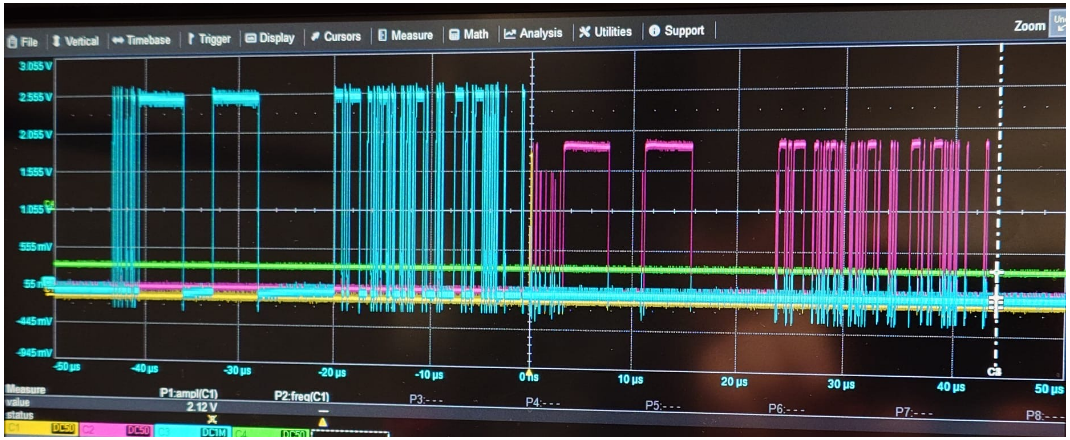
IBIAS current characteristic curve generated at the respective DAC value

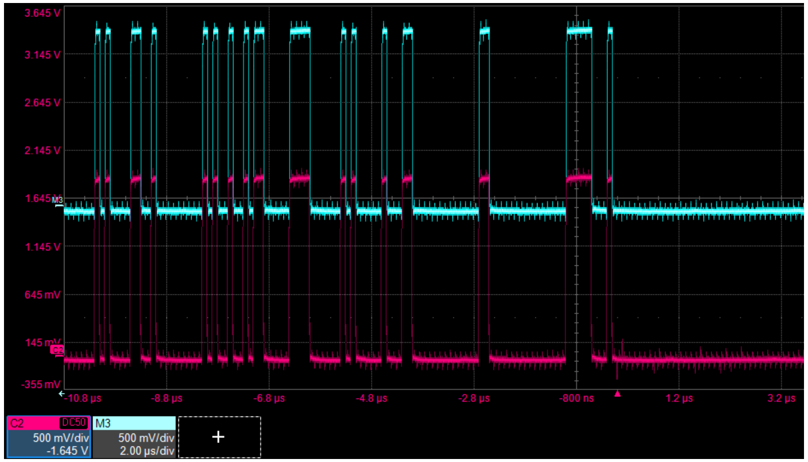


VRESETD voltage characteristic curve generated at the respective DAC value

- DAC scans on MiniMALTA3 sample were carried out with good linearity
- Measurements were performed on MiniMALTA3 sample (25 µm thick EPI, high doping of n-blanket) with a thickness of 700 µm
- Measurements performed with a Keithley 2400 at the monitoring pins

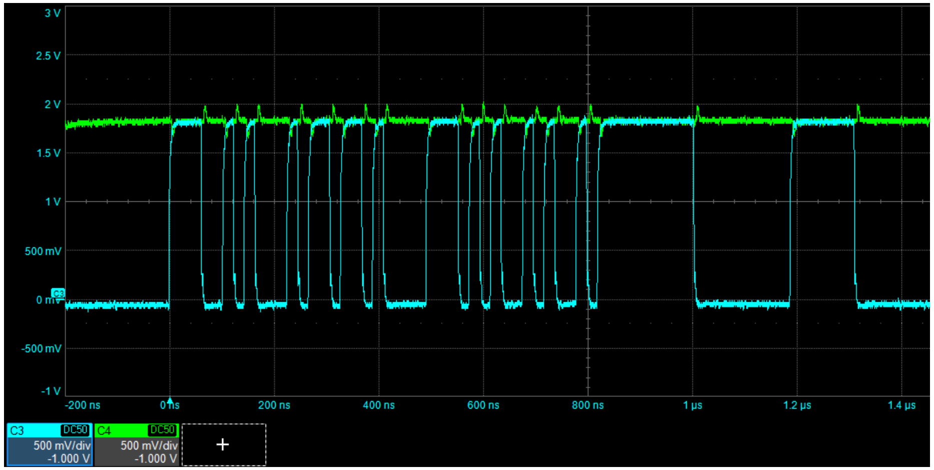
Mini-MALTA3 slow control





Slow control analysis operated with shift register

- MiniMALTA3 can be operated with the shift register (436 bits)
- The chip responds to the shift register
- Above plot shows digital communication between FPGA and Mini-MALTA3
- The debug signal, which provides data at 21 ns, come generated from the PLL divided by 32, suggesting an operational frequency of 1.5 GHz for the PLL.



PLL analysis by debug output signal

Summary

- Characterization and design activities progressing
  - MALTA2 on Czochralski substrate fully characterized in beam tests
  - A study on the energy loss in silicon is ongoing by modifying the front-end parameters
  - MALTA2 samples with considering option of increasing the doping concentration to increase radiation hardness. Would need to evaluate the impact of the increased capacitance
  - Mini-MALTA3 small demonstrator samples received, still testing
  - MiniMALTA3 could be included in test-beam 2024
  - MALTA3 design

- Publications
  - New: Rad-hard MALTA2 Cz in EPJ-C https://arxiv.org/abs/2308.13231 (pre-print)
  - New: Proceedings from Hiroshima Symposium (HSTD13) in preparation
  - MALTA telescope in EPJ-C: https://doi.org/10.1140/epjc/s10052-023-11760-z
  - Proceedings from TWEPP 2022:
    - MALTA2: https://doi.org/10.1088/1748-0221/18/03/C03011
    - MALTA3: https://doi.org/10.1088/1748-0221/18/03/C03013
  - MALTA2 front-end in TNS: https://doi.org/10.1109/TNS.2022.3170729
  - Proceedings from VCI 2022 (2):
    - MALTA2: https://doi.org/10.1016/j.nima.2022.167390
    - MALTA3: https://doi.org/10.1016/j.nima.2022.167226
  - Radiation hardness of MALTA2: TNS 70 (2023) 10: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=10246423

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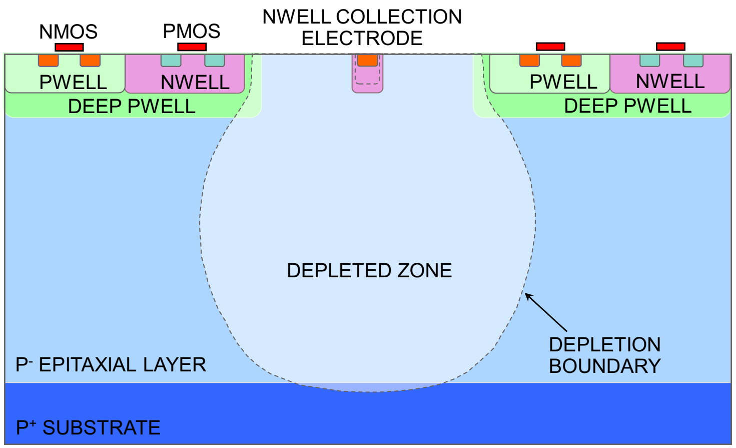
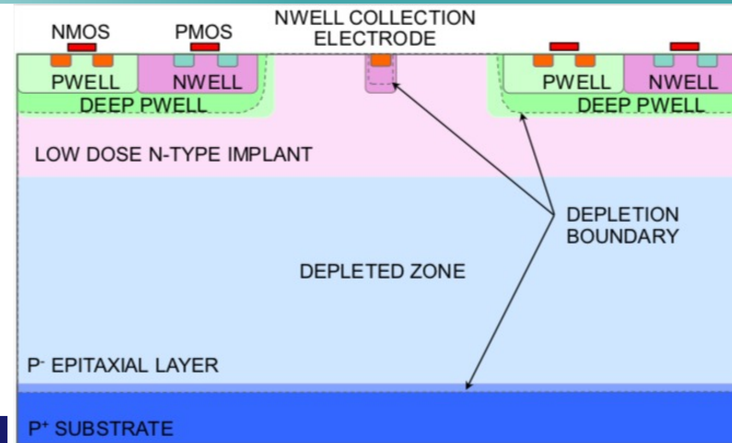
- Supported by the Marie Sklodowska-Curie Innovative Training Network of the European Commission Horizon 2020 Programme under contract number 675587 (STREAM).
- The measurements leading to these results have been performed at the TestBeam Facility at DESY Hamburg (Germany), a member of the Helmholtz 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.
- This project has received funding from the European Union’s Horizon 2020 Research and Innovation programme under Grant Agreement no. 654168 (IJS, Ljubljana, Slovenia).
- Dr. Ben Phoenix, Prof. David Parker and the operators at the MC40 cyclotron in Birmingham (UK).

Back-up

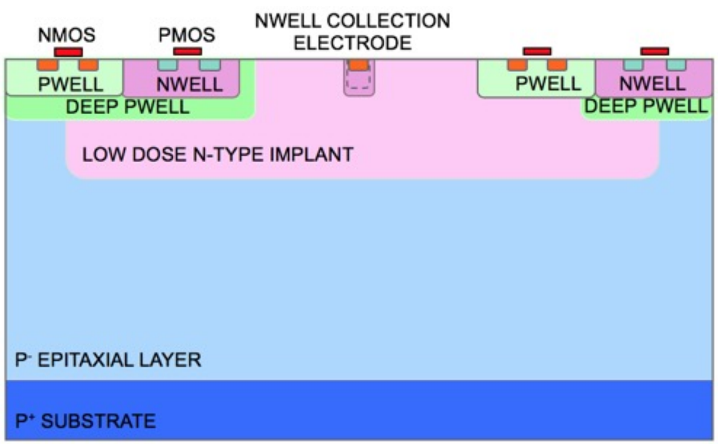
TJ 180 nm Modified Processes



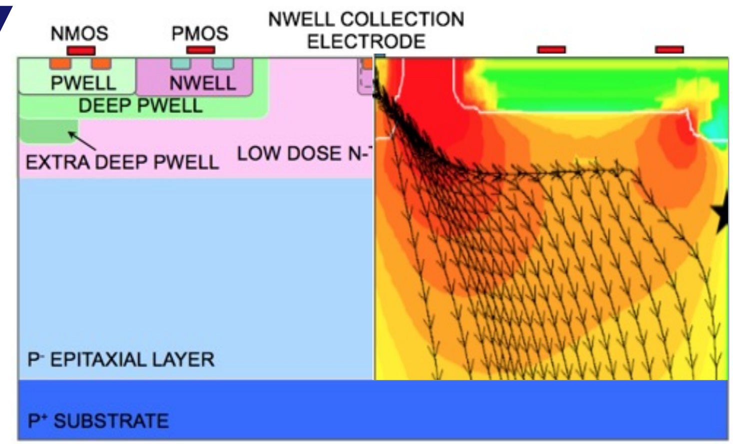
Unmodified process. Large collection time via diffusion



Modified process. Low dose n- implant under the p-well (Standard). Low charge collection in pixel edges.

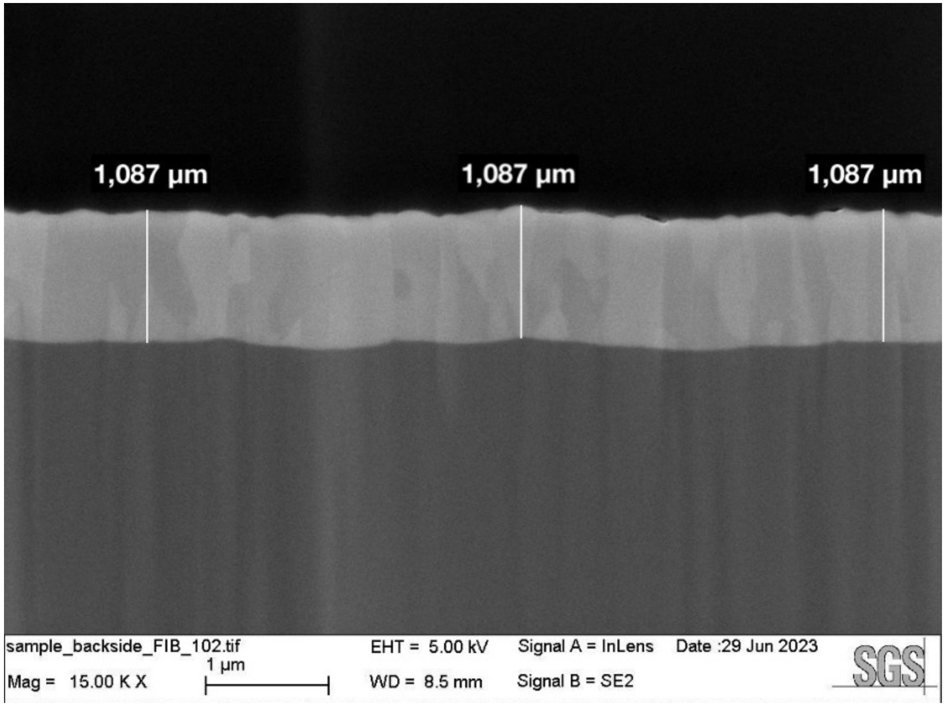


Modified process with gap in the n- blanket (NGAP). Improved charge collection in the pixel edges.



Modified process with extra deep p-well (XDPW). Improved charge collection in the pixel edges.

BACK side metallisation

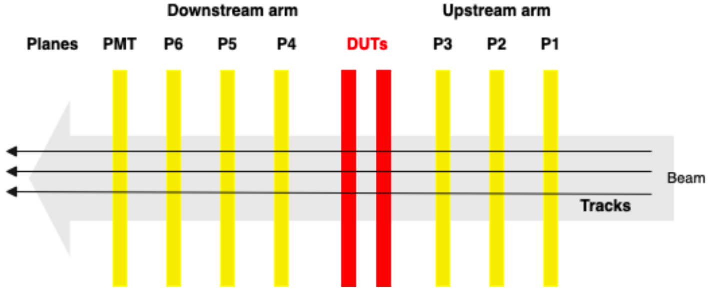


- Cross-sectional SEM image of a MALTA2 sample with backside metallisation. The light grey area indicates the 1 µm thick Aluminium layer

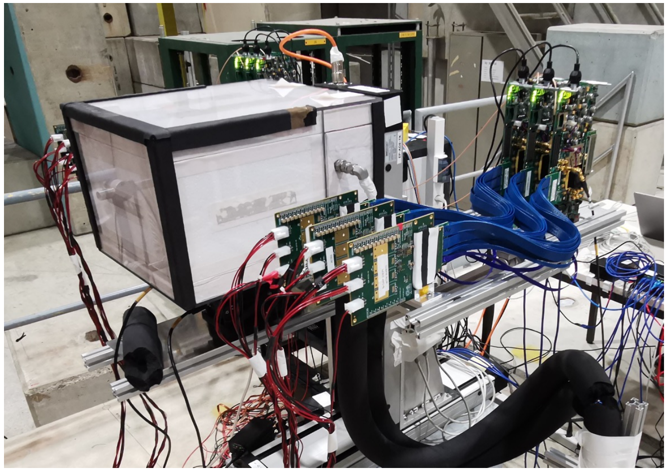
https://arxiv.org/pdf/2308.13231.pdf

MALTA telescope at SPS

- Continuous operation in SPS from July to Nov 2021, 2022 and 2023
  - Stable data-taking even at >50k particles per spill
  - Max DAQ rate limited to 50KHz by external readout
- Fabricated with fast read-out, online monitoring, and cold box for irradiated samples
  - Up to 7 planes + DUT
  - or 6 planes + 2 DUT
- Triggering directly out of MALTA planes
  - Scintillator for precise timing reference
  - Define ROI on tracking planes and check hits on DUT
- Confirmed results with MIMOSA at DESY in 2019



Schematic sketch of the MALTA beam telescope where the six tracking planes (P1-P6), the device under tests (DUTs), and the scintillator (PMT) are indicated

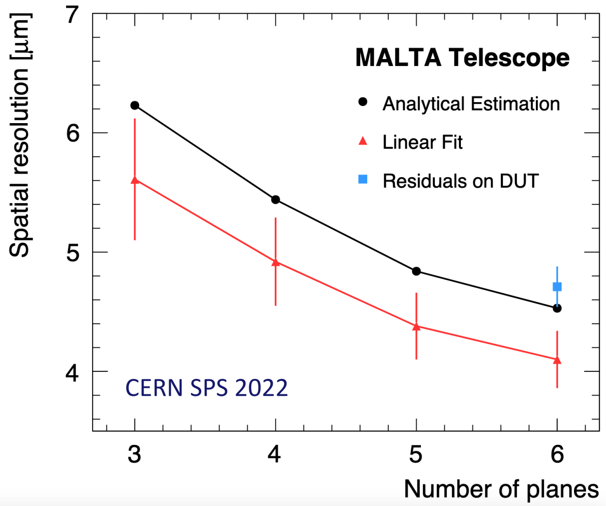


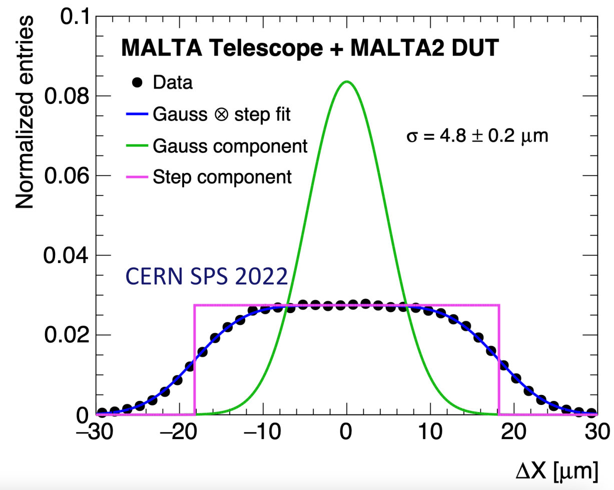
MALTA telescope at SPS

Detail of MALTA and MALTA2 planes

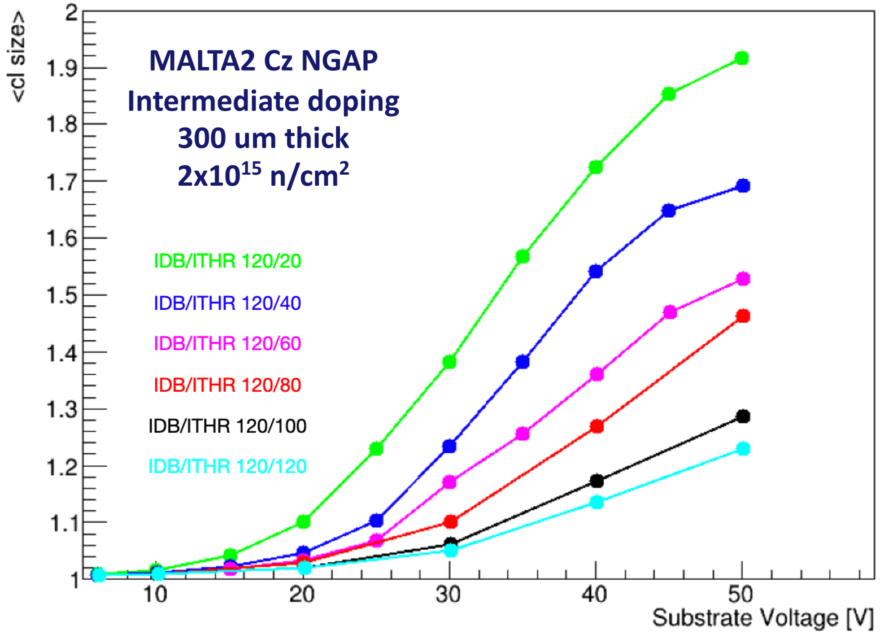
Telescope results

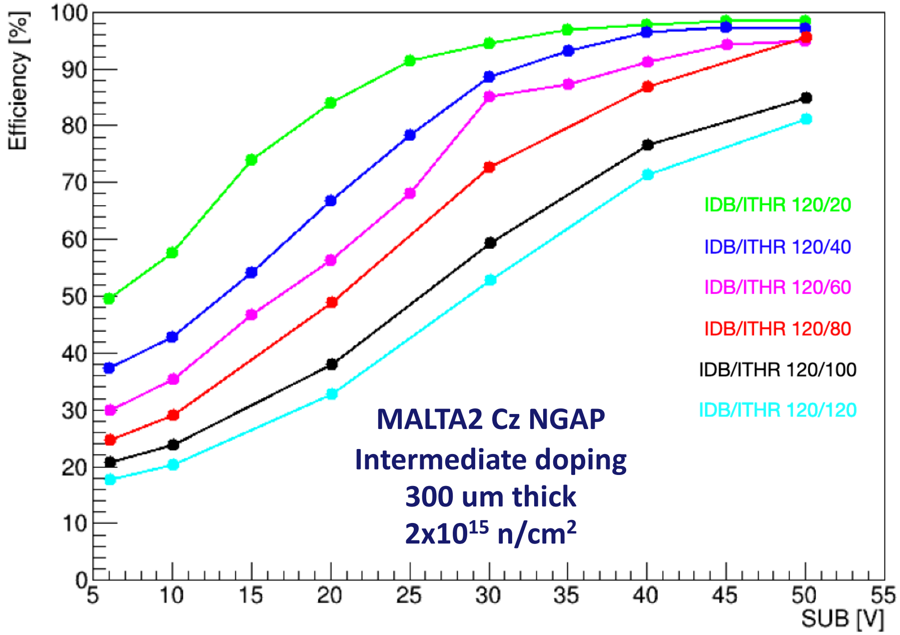
- The results obtained from the straight line fit (red) using the position of the cluster barycenters on the telescope planes are shown.
  - The full telescope spatial resolution is also estimated from the fit of the distance between the first-in-time hits of a MALTA-2 un-irradiated chip used as a DUT and the track intercepts.
  - A gaussian function convoluted with a two-sided step distribution, with the width corresponding to the MALTA pixel pitch, is adopted (blue).
- The extracted telescope resolution from the fit is 4.8 ± 0.2 µm
  - Overlay to the data is the fit of a gaussian distribution convoluted with a two-sided step distribution with 36.4 µm width corresponding to the pixel pitch of MALTA2





MALTA2 efficiency

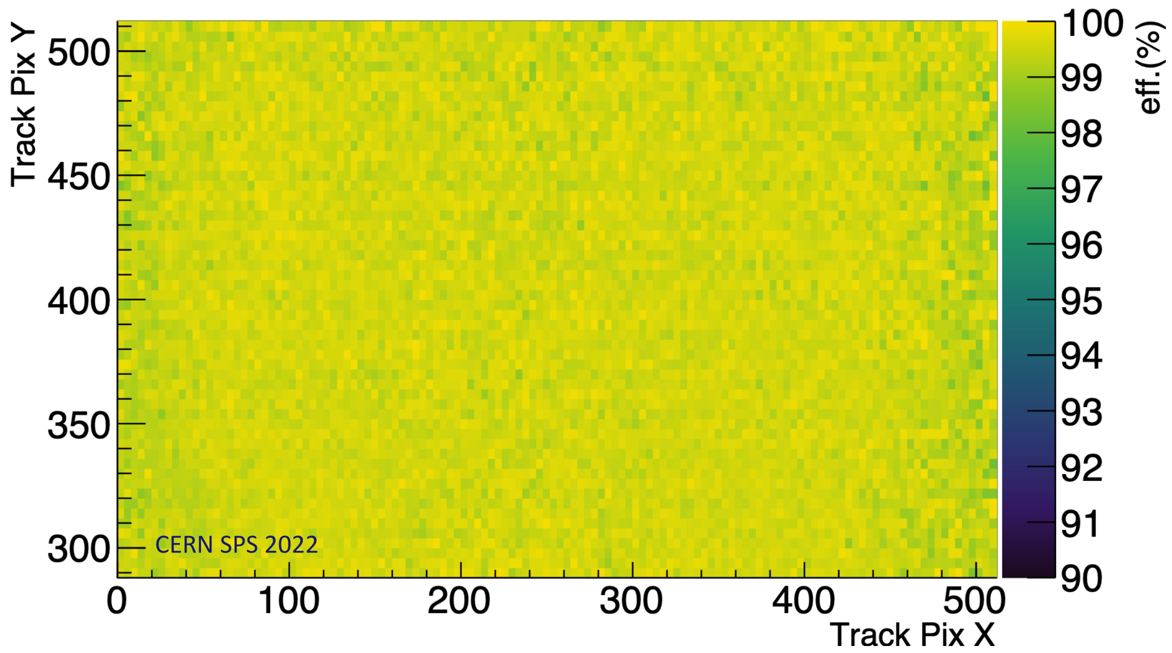




Cluster: sum of contiguous pixels fired in the same event and received within 500 ns

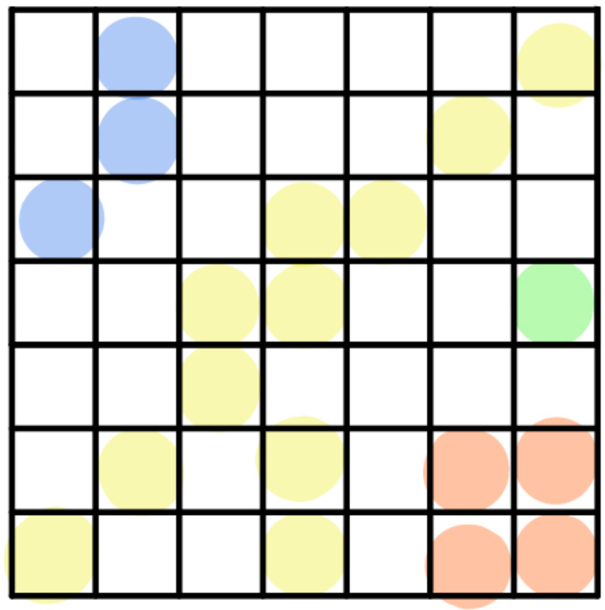
- Good performance of Cz samples at $2x10^{15}$ n/cm^2
  - Modulo the distribution of the substrate voltage
- Expected uniformity at lowest threshold setting
- Cluster size increases with substrate voltage
  - Maximum at ~1.9 at 50 V at 120 e-
- Efficiency better than 98% at 50 V bias at 120 e-

MALTA2 Cz efficiency



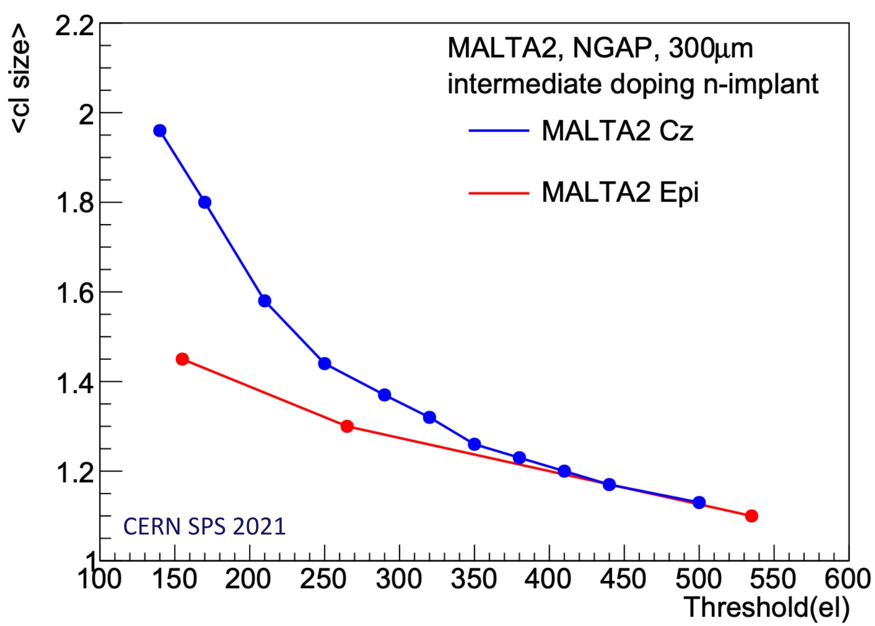
- 2D efficiency map of the entire matrix of non-irradiated MALTA2 (Cz, NGAP, 300µm thick) at -6V SUB.
- Threshold corresponds to 150el.
- Uniform efficiency of 99.6% is achieved for the entire matrix

Cluster explanation

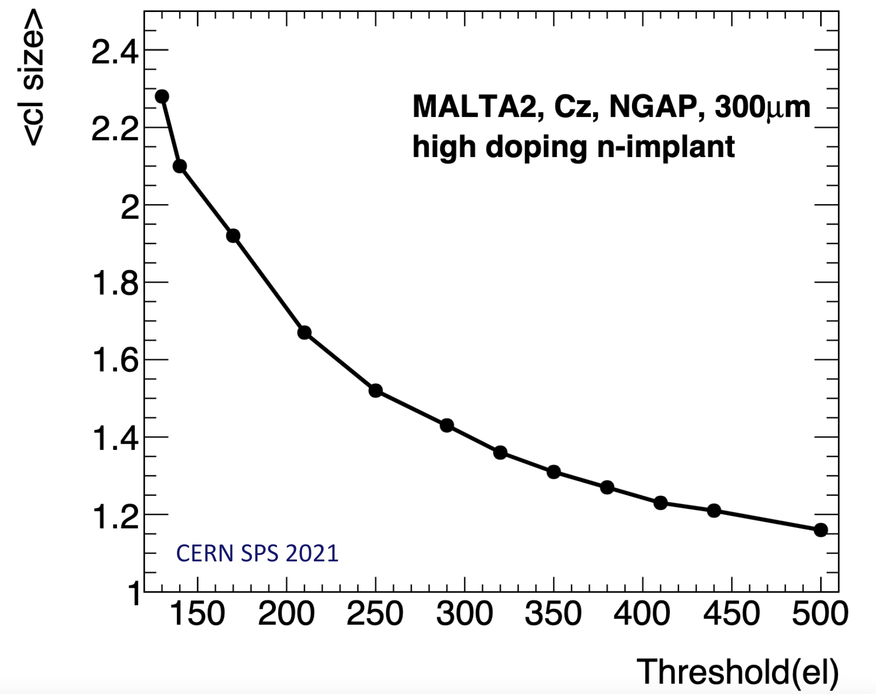


- A Cluster is a set or group of adjacent pixels that have a hit
- The red dots would be a cluster of size 2
- The green one a cluster of size 1
- Yellow is impossible, a single particle cannot leave the track of the yellow signal

MALTA2 Cz cluster size



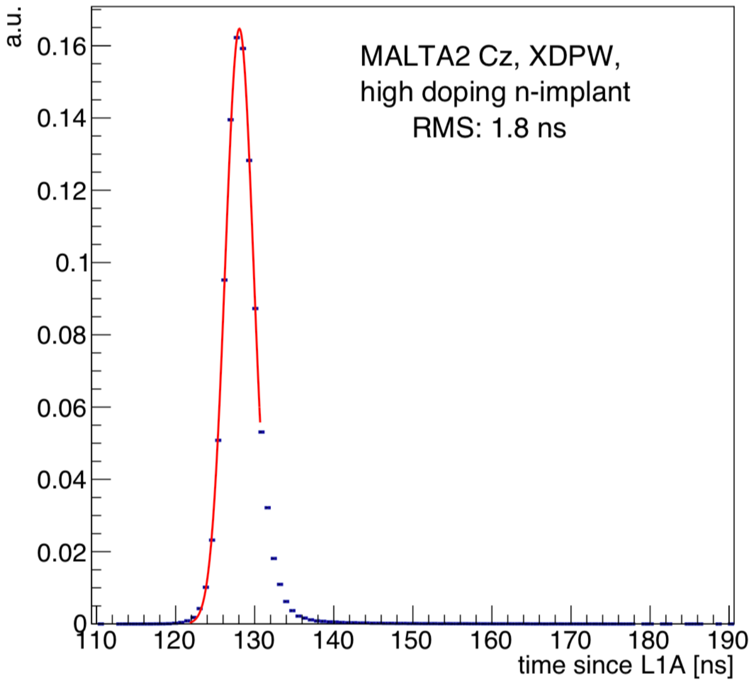
Cluster: sum of contiguous pixels fired in the same event and received within 500 ns



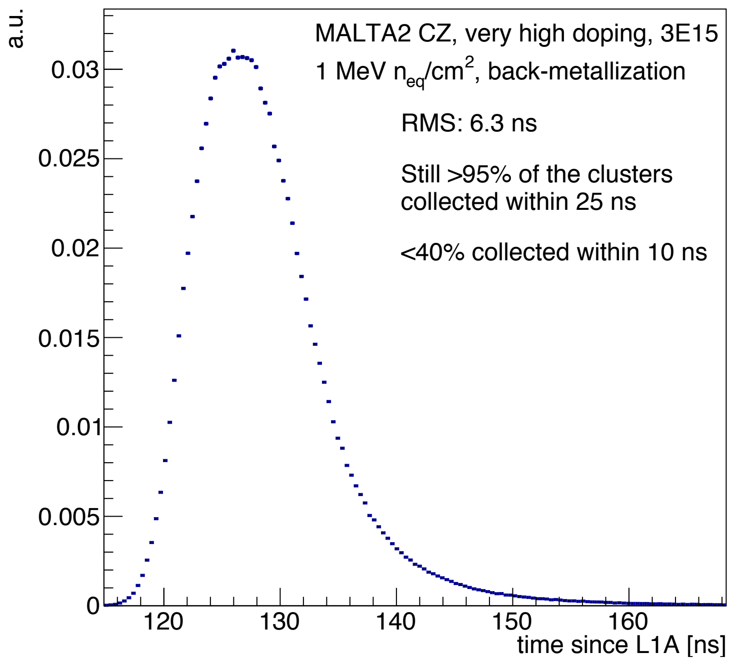
Average cluster size of non-irradiated MALTA2 versus the threshold in electrons at -6V SUB

- Cz sample reaches a cluster size of 1.97 ± 1 for 130 e-, while EPI sample reaches 1.45 ± 0.01 for the same threshold
- Very high doping in Cz sample increases cluster size up to 2.25 ± 1 for 130 e-

MALTA2 on Cz time resolution



Unirradiated sample

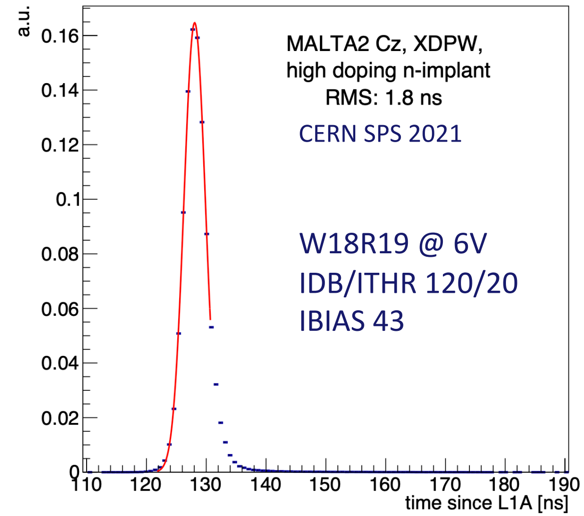


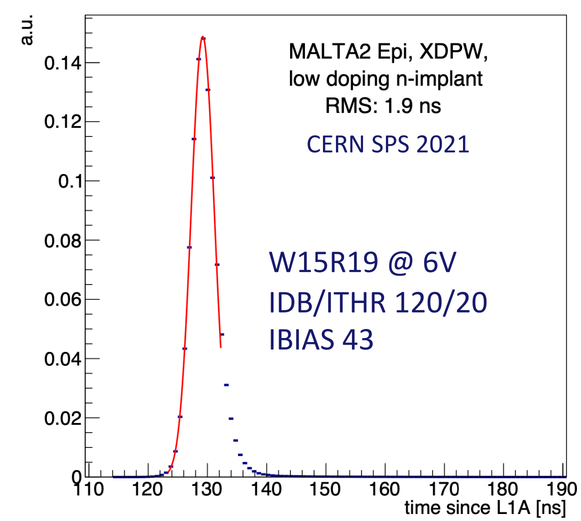
Sample irradiated at $3x10^{15}$ n/ 1-MeV neq/cm2

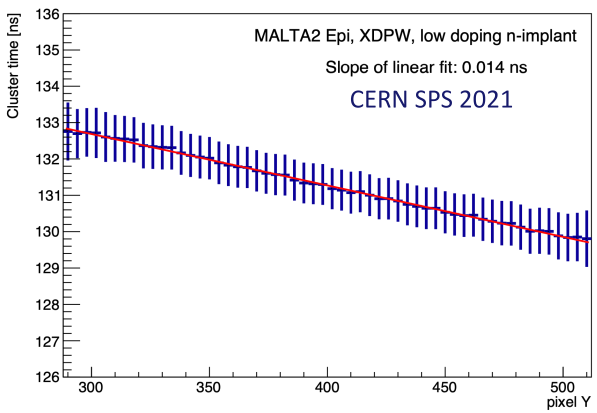
- Time of arrival of leading hit in the cluster with respect to a scintillator reference, in-time efficiency
- Unirradiated sensor (left plot) : >>95% of the hits in 25ns (>90% in 8ns)
- Irradiated to 3e15 n/cm^2 > 95% in 25ns (<40% in 10ns)

Timing performance of MALTA2

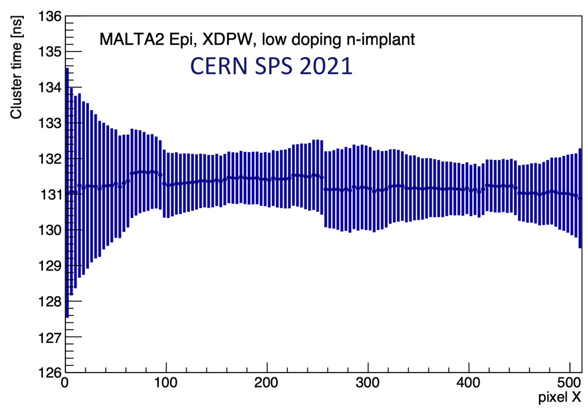
- Time of arrival of leading hit in the cluster w.r.t. scintillator reference has RMS smaller than 2 ns
  - Included scintillator jitter : 0.5 ns
  - And sampling error : 0.9 ns
- Includes corrections for signal propagation in X and Y direction of the chip
  - Y correction due to time propagation across the column (linear behaviour)
  - X correction compensates for non-uniformities in chip response





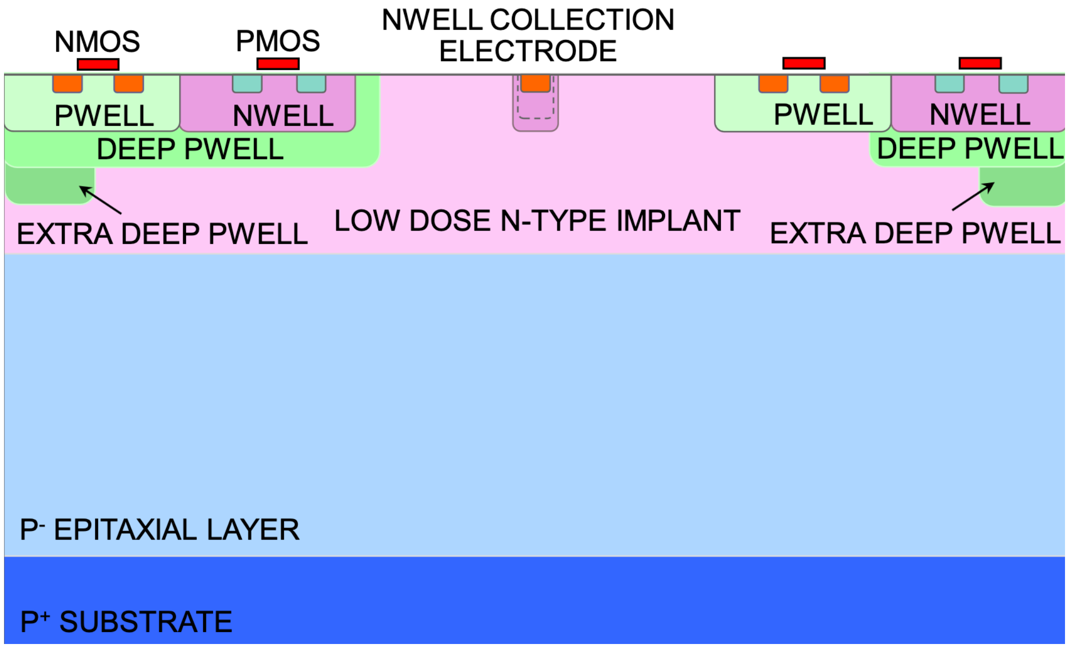


Y direction (down the column) correction



X direction (across the row) correction

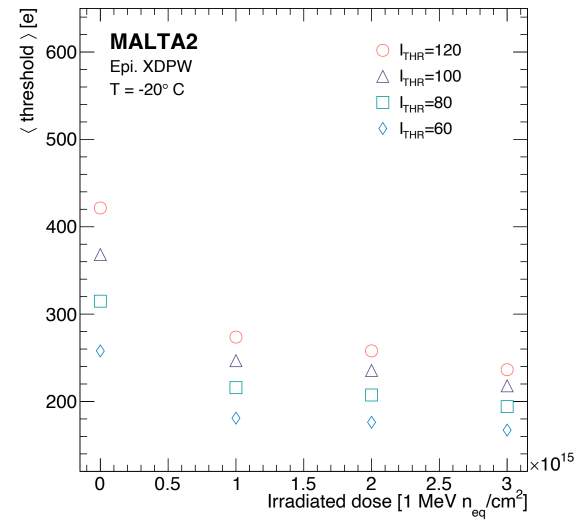
MALTA2 on Cz efficiency after irradiation

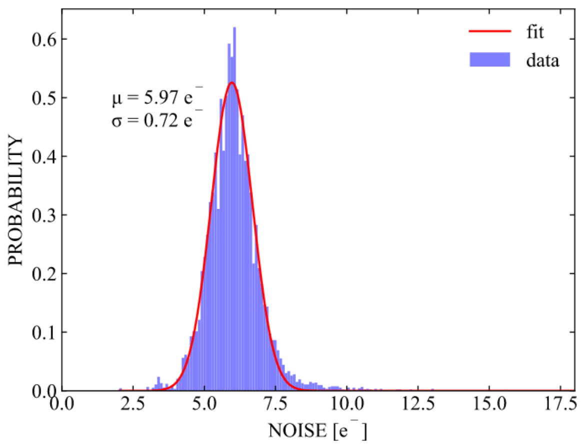


- Cross section of the modified process where an extra deep p-well is added at the edge of the pixel (XDPW) implemented in the MALTA and MiniMALTA chips.

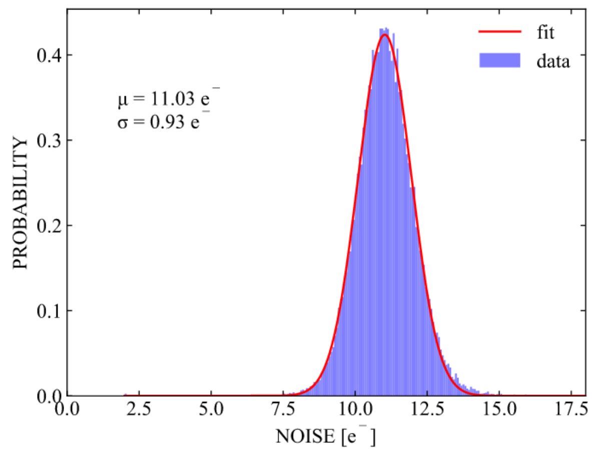
MALTA2 vs NIEL

- MALTA2 is radiation hard up to $3x10^{15}$ n/cm^2 NIEL
- Front-end gain increase with NIEL (same as previous designs)
  - Decrease of the effective doping of the n- layer
  - Lower capacitance of the collection electrode
  - Higher voltage for the same collected charge
- Threshold reduces and noise increases vs NIEL

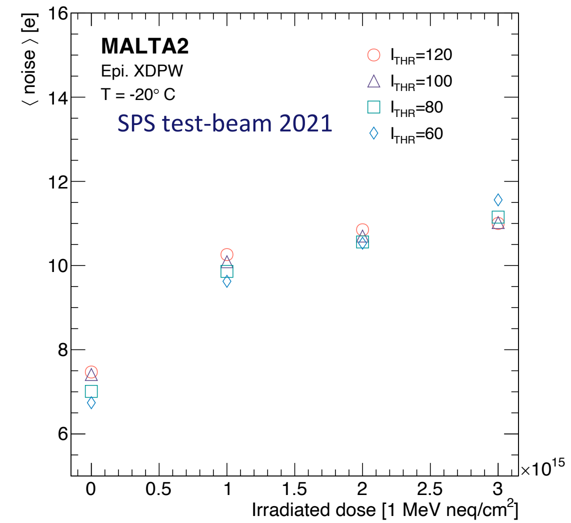




Unirradiated sample

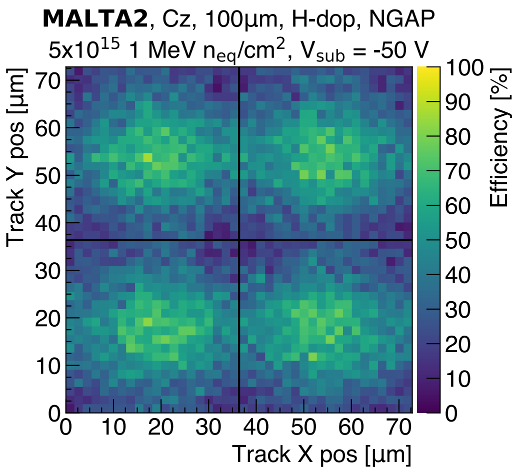


Sample irradiated at $3x10^{15}$ n/ 1-MeV neq/cm2

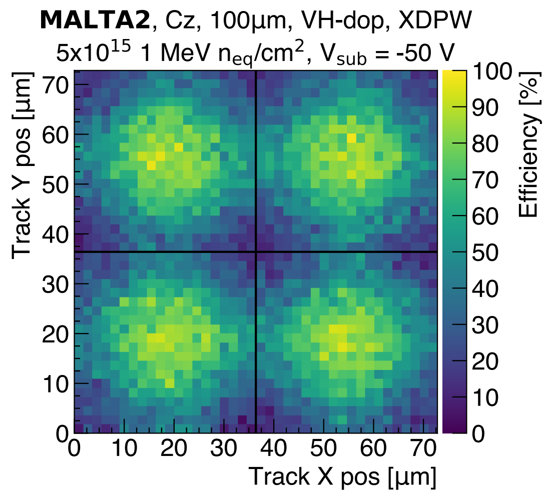


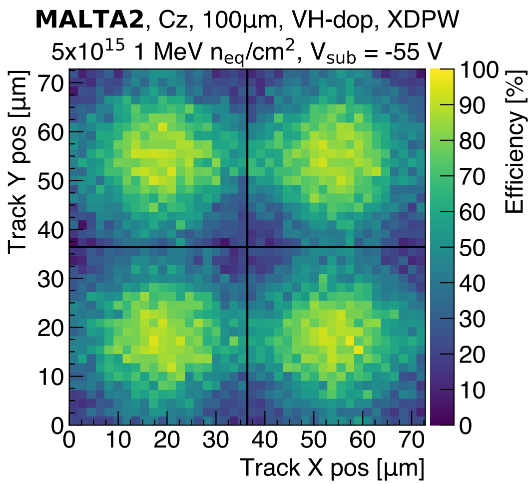
Effect of doping

H-dop



VH-dop



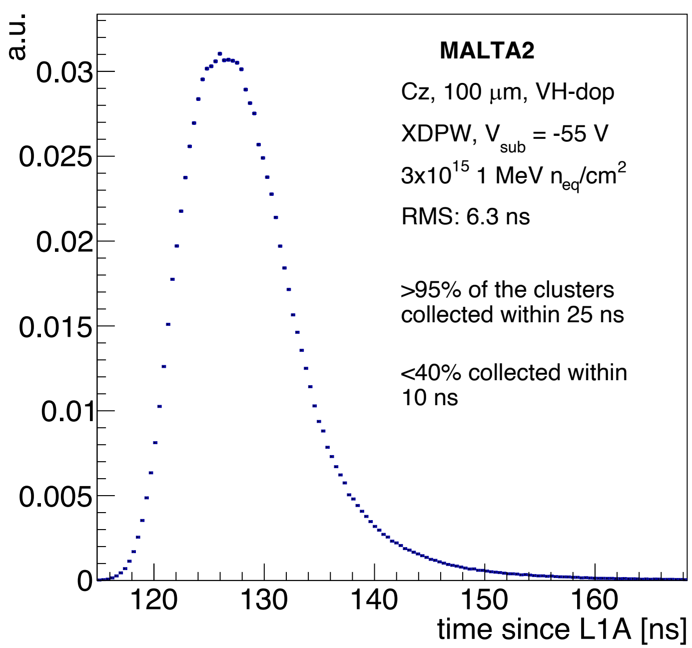


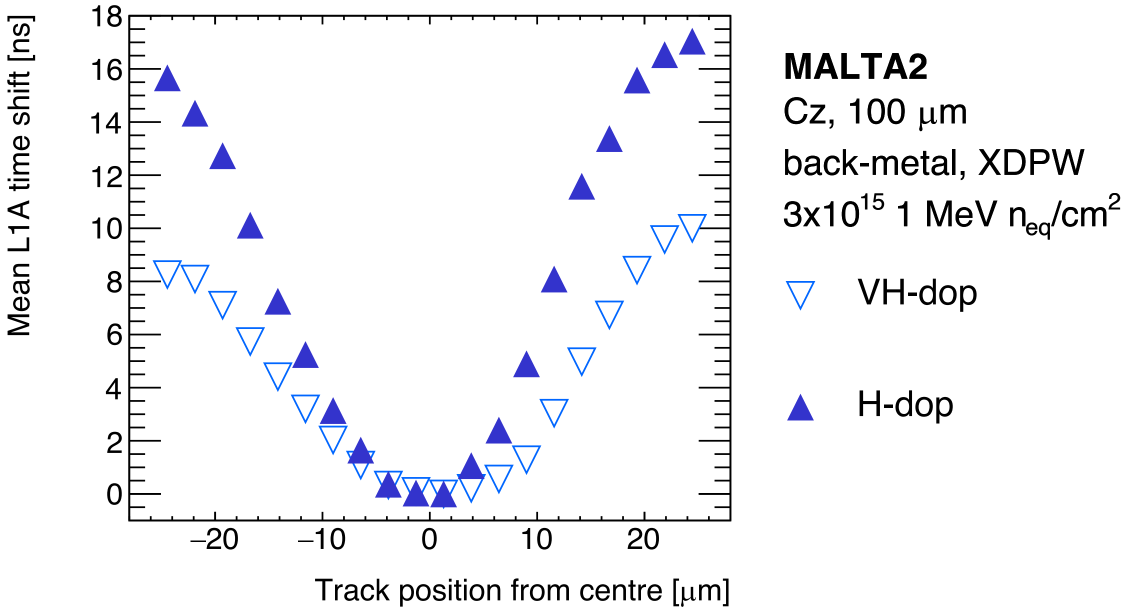
2D sample efficiency projected onto a 2x2 pixel matrix on Czochralski substrate

- Central efficiency after 5×10^{15} 1 MeV n/cm^2 for VH doping, Vsub = 55V and no back-metallized samples above 84%
- All samples have substrate thickness of 100 µm
- All samples were operated at ~100 electrons at -15°C

MALTA2 Czochralski Irradiated

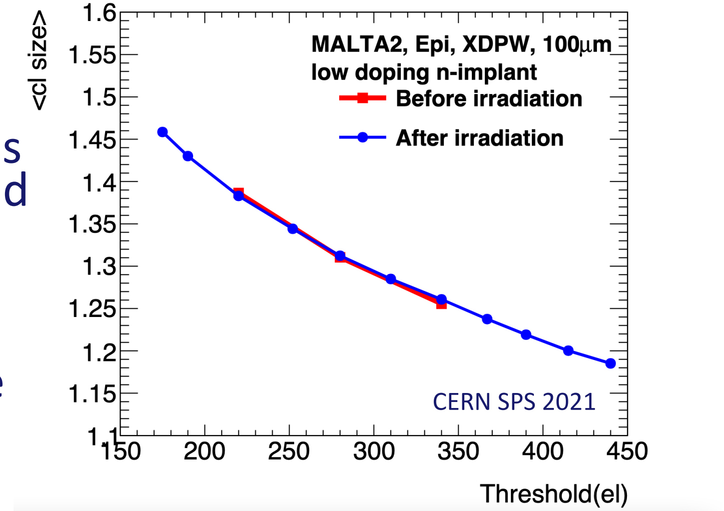
- Radiation hardness - neutron irradiated MALTA2 up to 3×10^{15} 1 MeV n_{eq}/cm^2
- Sample with very high n-layer doping shows less degradation of signal timing
  - Timing resolution ~6 ns
  - More uniform response across the pixel
- Publication accepted: arXiv:2308.13231 (pre-print)

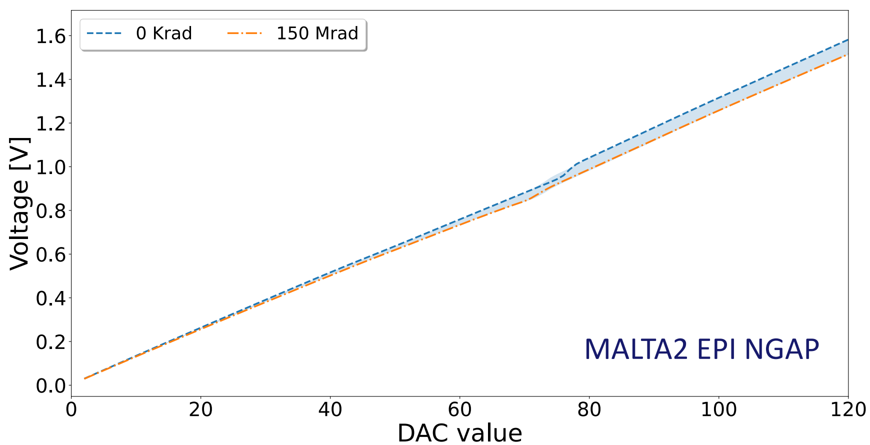




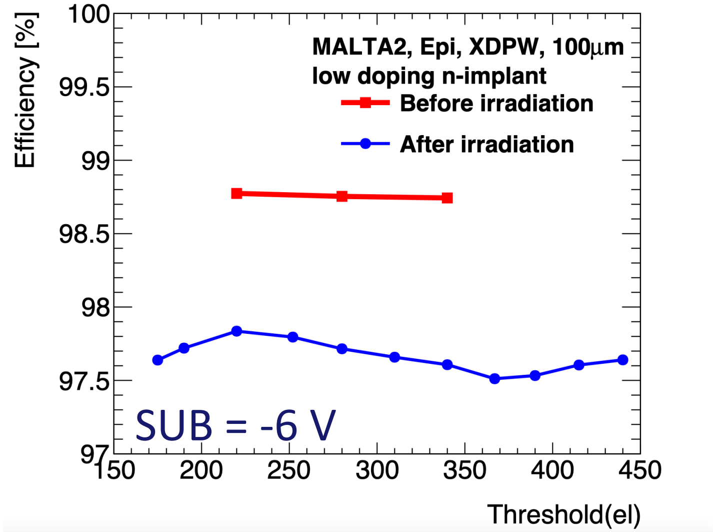
MALTA2 front-end vs TID

- MALTA2 is radiation hard up to 150 Mrad TID
- Both XDPW and NGAP modifications tested
- Same cluster size is measured in particle test-beams (180 GeV beam at SPS CERN) for the same threshold settings before and after TID
  - Cluster: sum of contiguous pixels fired in the same event and received within 500 ns
- Slight efficiency reduction (~2%) measured in same conditions should be recovered by increasing bias voltage





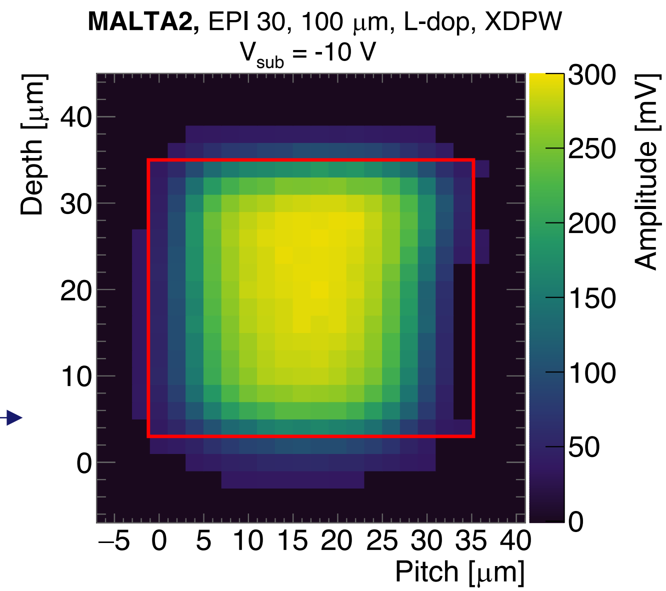
Deviation of the voltage settings with TID

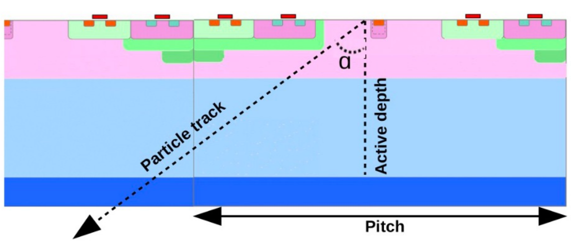


Active depth measurements

- Measured the active depth of EPI with TCT: 30 µm at 200 e- threshold
  - Plot shows amplitude measured in analog pixels as a function of the laser focal point
  - Surface of the cup is at bottom, the laser scans into the chip, and from one side to the other of the pixel (pitch)

To be published in proceedings of HSTD13





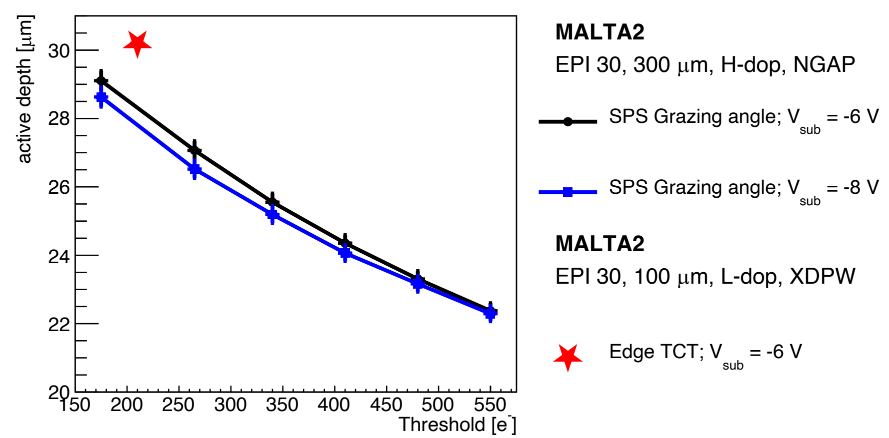
$Cl.size_{\perp}(\tan\alpha) = (d/p)^{*}\tan\alpha + Cl.size_{\perp}(0)$

Geometrical model:

- $Cl.size_{\perp}$ – perpendicular to axis of rotation
- α – track angle
- p – pixel pitch
- d – measured active depth

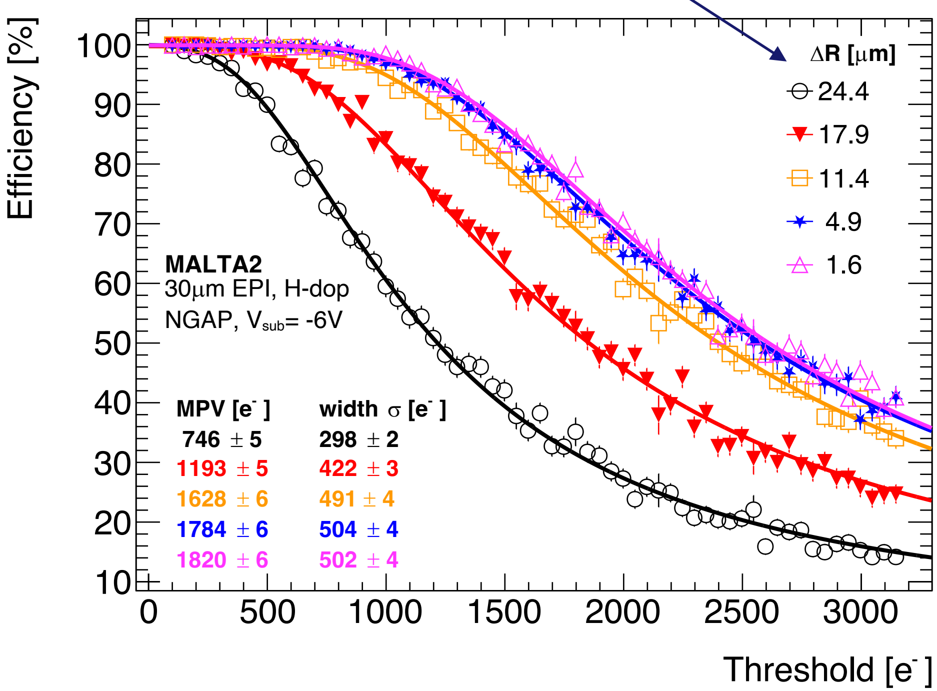
- Measurement from grazing angle technique in SPS yields 28 µm active depth

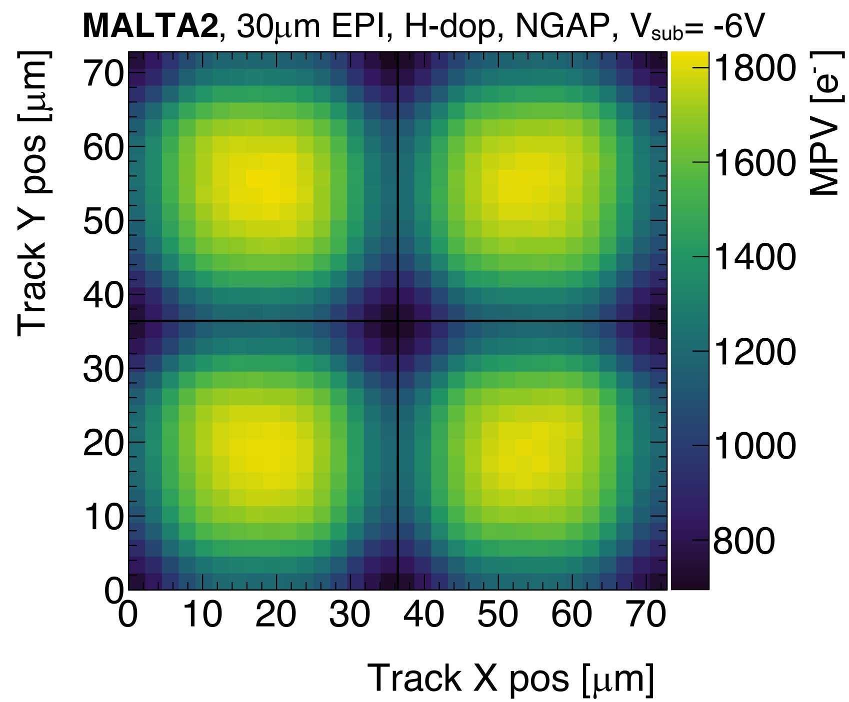
[K. Dort et al. NIM A (2022) 167413](#)



- Using efficiency-threshold relation to determine the MPV of the energy loss
- EPI pixel centre shows >1800 e- most probable value of energy loss

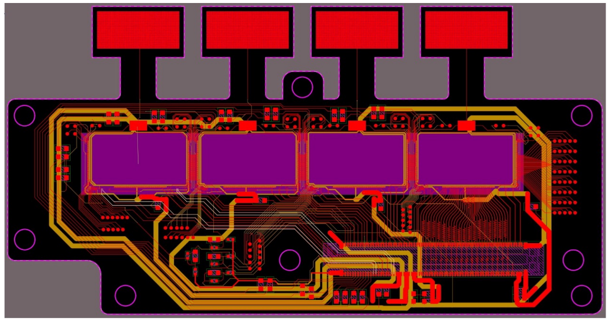
distance from pixel centre



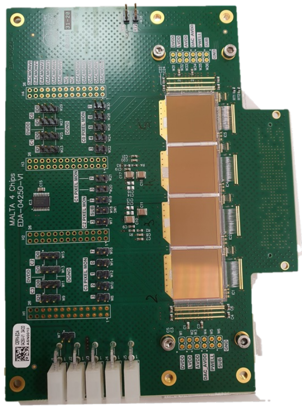


Quad chip module operation

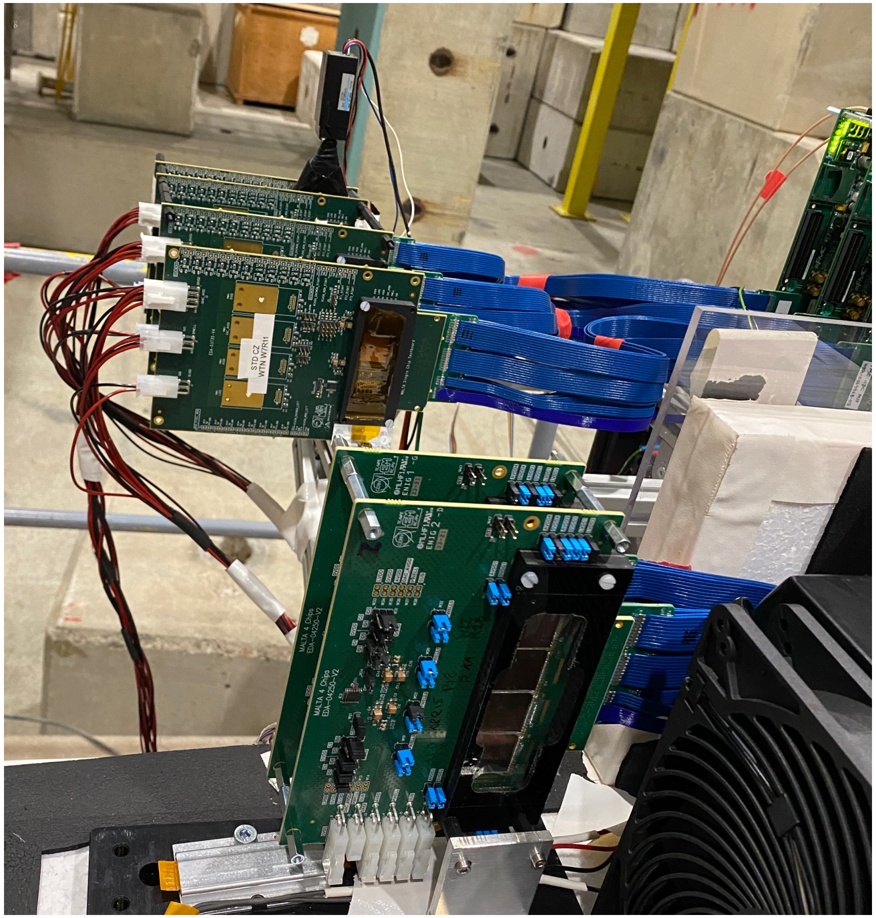
- Data from MALTA can be routed to the left or right through CMOS output
- Quad modules for MALTA extensively tested in the laboratory
- Installed quad-module on telescope this week for measurements with beam particles
- MALTA2 module still in production



MALTA2 module layout



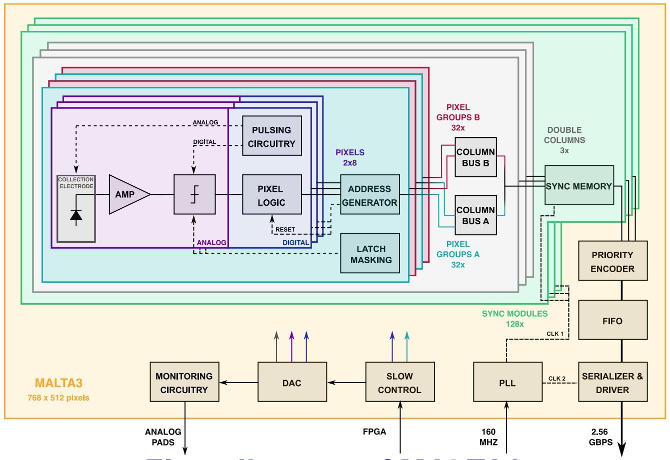
MALTA quad-module



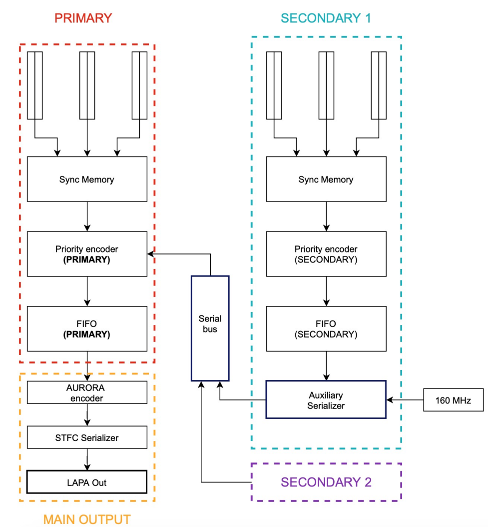
MALTA quad-module in MALTA telescope at SPS

MALTA3

- Next step in the asynchronous read-out architecture development
  - Full reticle size 3x2 cm^2
  - Re-use front-end from MALTA2
  - Improve the 2x8 pixel group operation through additional masking and more resilient reference pulse generation
  - Asynchronously propagated hits are time-tagged (synchronized) at the end of the column
  - Fast read-out with standard protocol
- Digital-on-top approach followed for design and assembly
  - New features and improvements are in the digital periphery
- 180nm technology will be pushed to the limit
  - Sub 1ns timing possible due to 1.28 GHz encoded twisted-ring counter
  - The fast clock will be locally generated with a PLL, used for output serializer as well
- Planned MPW submission by Q3 2022

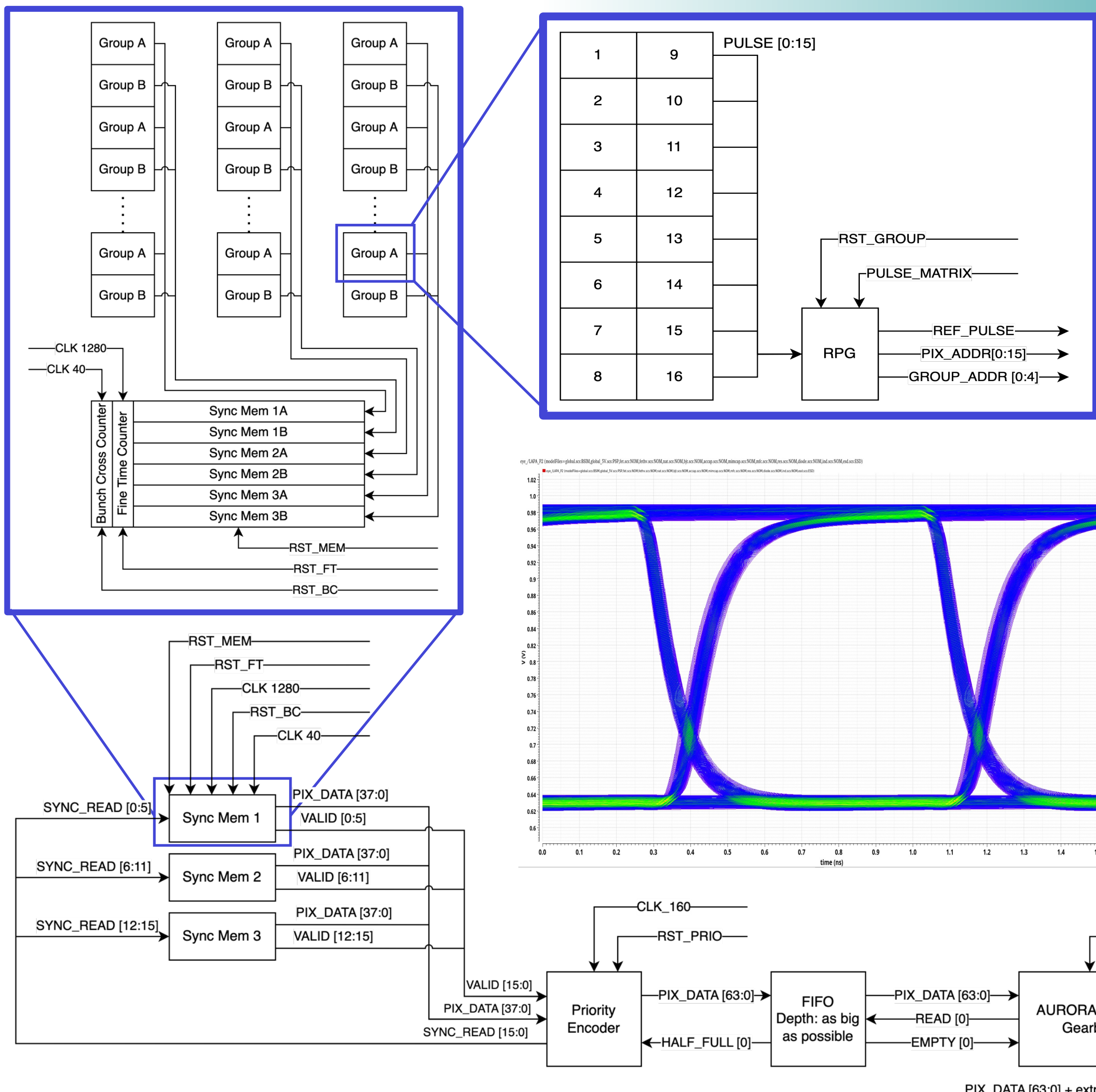


Flow diagram of MALTA3

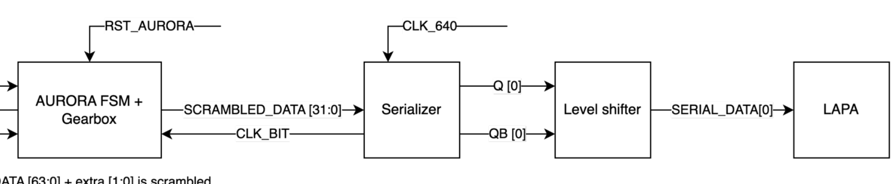


Concept for serial communication

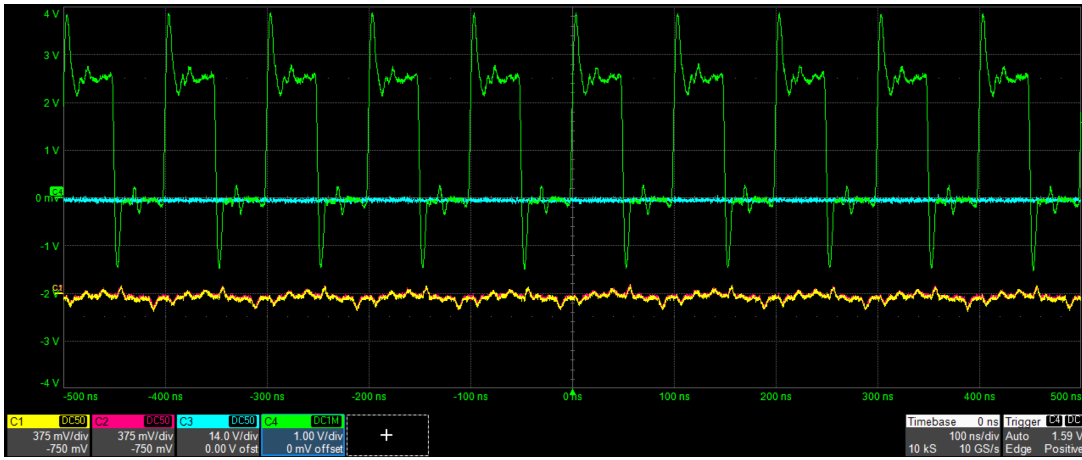
Mini-MALTA3 data path



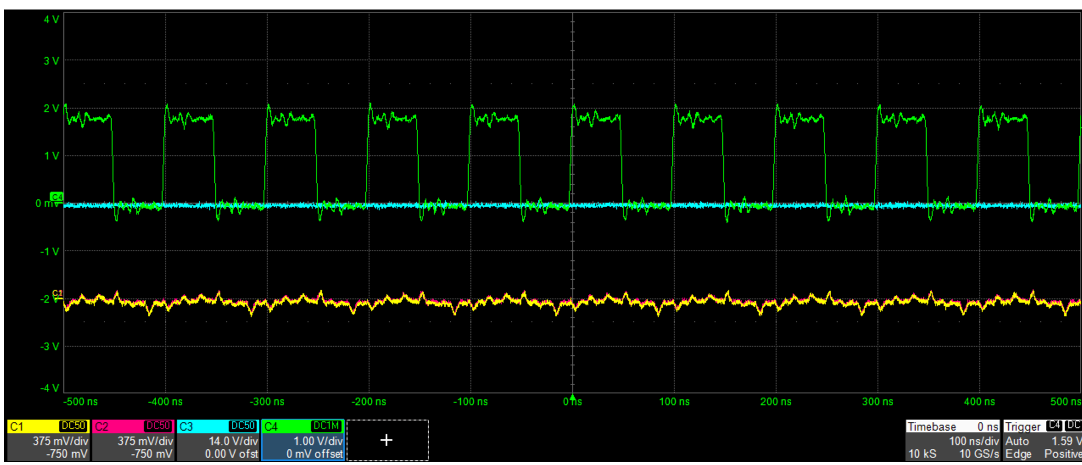
- Analog pixel
- Group + RPG
- Sync memory + counters
- Priority encoder
- FIFO
- Aurora FSM
- PLL
- Serializer
- Level Shifter
- LAPA
- Slow control (2 versions)
- Command decoder



SC_CLK, shift register clock



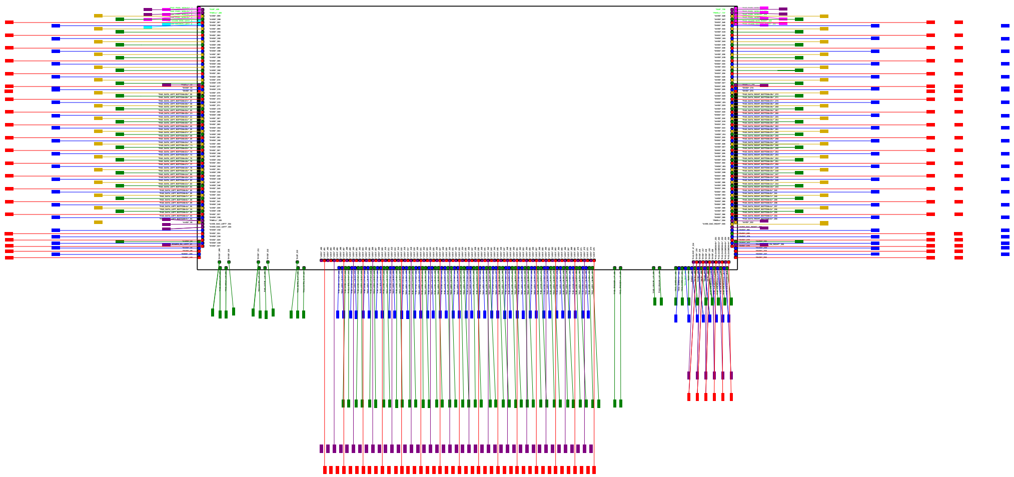
- Shift register was tested in the PCB version 2
- Clock at 10 Mhz was delivered to the chip from FPGA through level shifters.
  - Signal comes from FPGA at 2.5 V



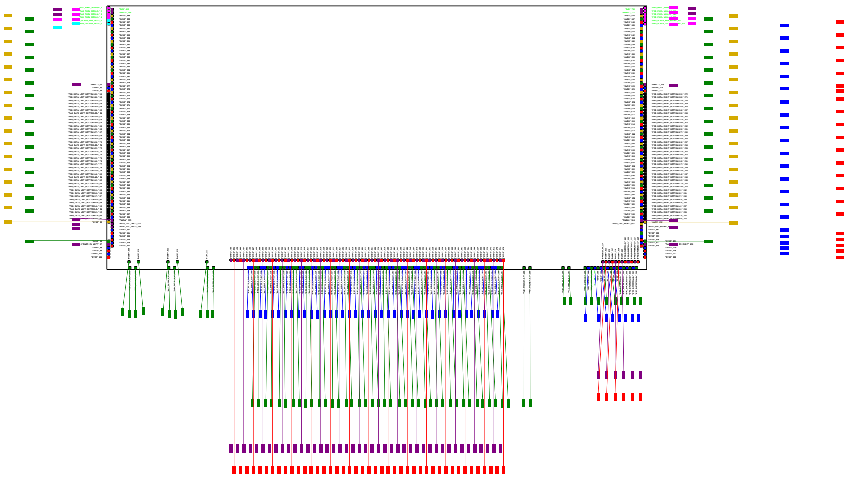
- Level shifters clean the clock signal from FPGA, sending a suitable signal to the chip at 1.8V
  - Output signal of level shifter to the chip at 1.8 V

Exploring powering options

- Bonded MALTA2 samples with minimal number of wire-bonds
- Power is provided only from the chip bottom (alike RD53 prototypes)
- Understand the effects of the powering in the matrix
- Potentially ease the bonding procedure
- Important to understand the power requirements for MALTA3



Default wire bonding diagram for MALTA2
Power is provided from the sides and the bottom of the chip



Minimal wire bonding diagram for MALTA2
Power is provided from the bottom of the chip

Bonding effects on EPI NGAP

- Measured the effects on un-irradiated MALTA2 EPI 30 um NGAP high doping
- Observed drop in efficiency and and cluster size wrt to regular bonding
- Threshold for minimally bonded chip much higher
- Trends follow those of regular bonded sample