Advancement and Innovation for Detectors at Accelerators

TJ-MALTA developments

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WP5 DMAPS - AIDAinnova 2nd annual meeting

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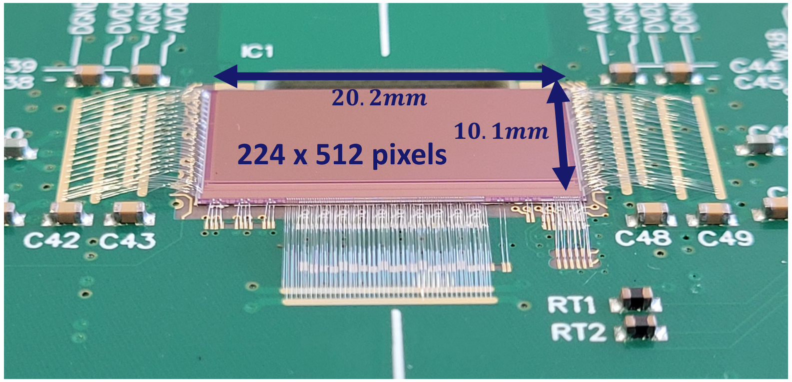
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101004761.

Task objectives

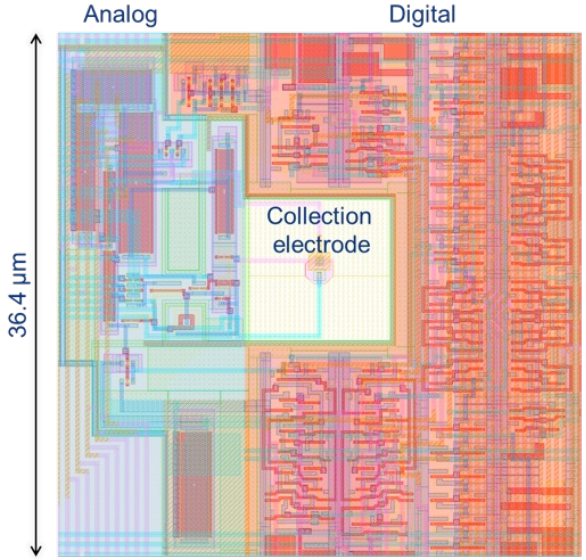
- Design of test structures and DMAPS for fluences > 10^{15} n/cm^2
  - Validation of designs using simulation (functional, TCAD)
- Fabrication of test structures and prototype in MPW
  - Careful interaction with foundry, 180nm TOWER.
- Development of readout and test system for devices
  - Build on 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 2 flavors (n-gap and 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



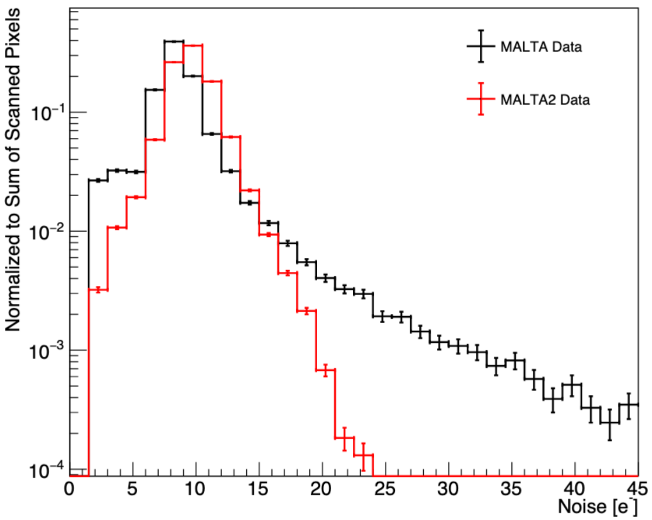
MALTA 2 on carrier board

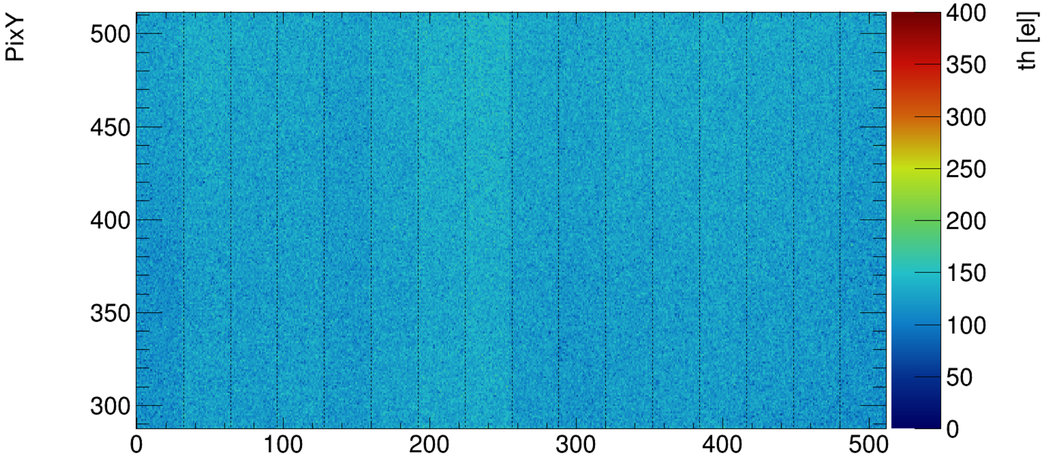


MALTA pixel

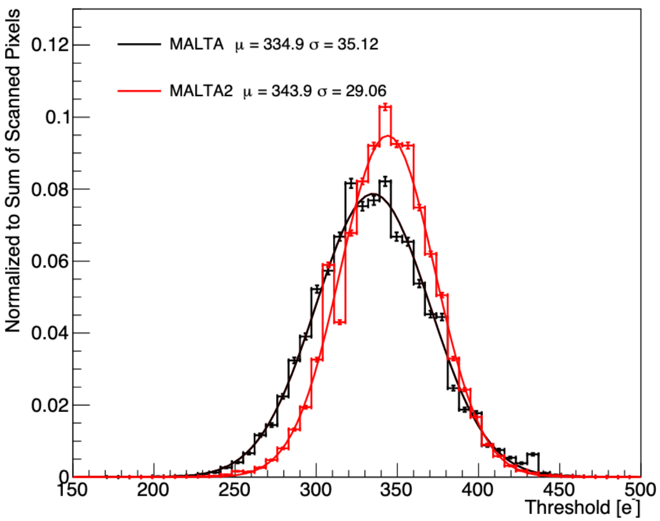
MALTA2 front-end noise

- 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



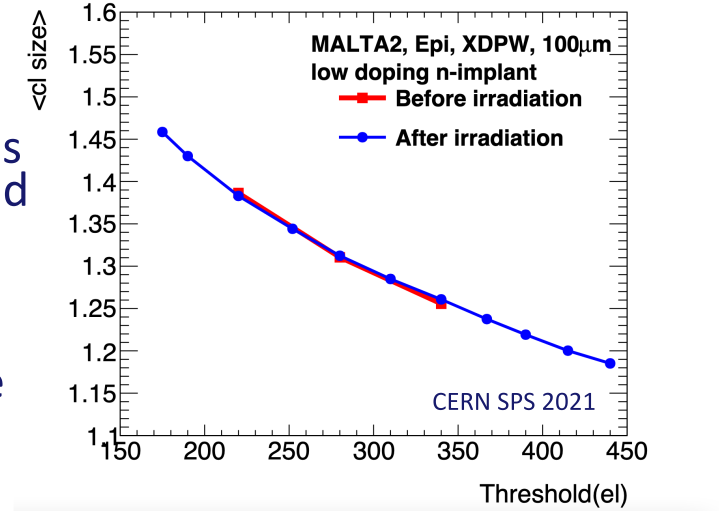


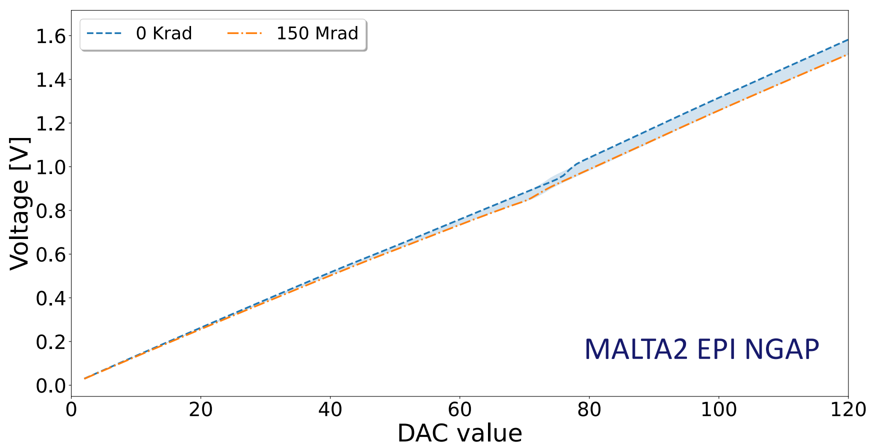
2D Threshold map, MALTA2 Cz NGAP intermediate doping
300 um thick 2x10^{15} n/cm^2 IDB: 120, ITHR=20



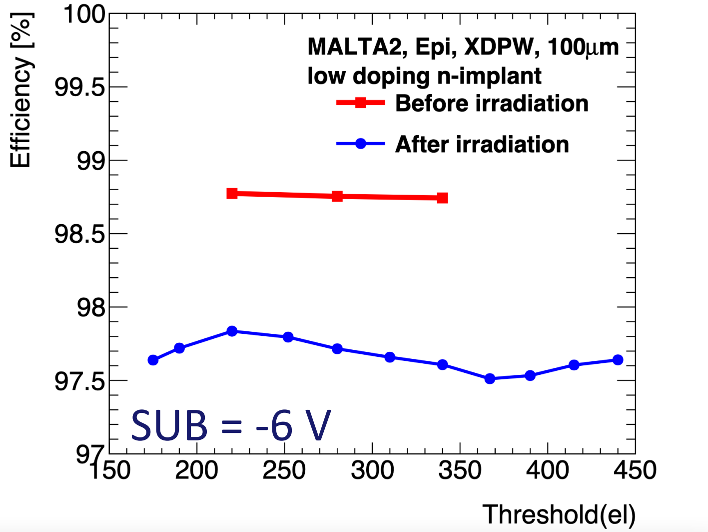
MALTA2 front-end vs TID

- 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



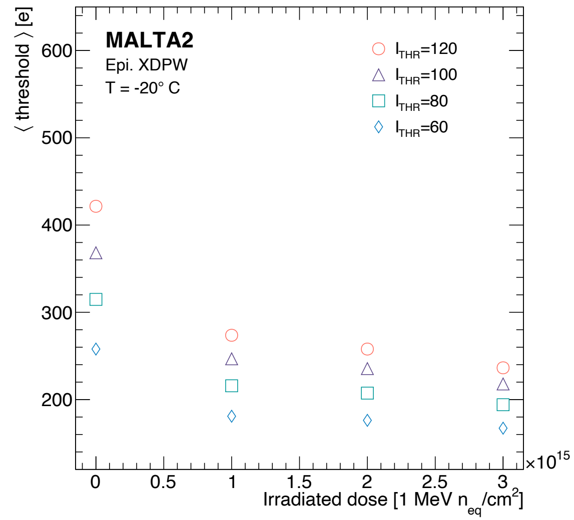


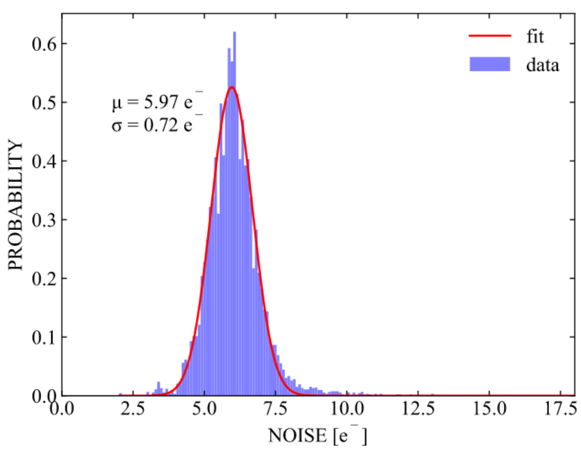
Deviation of the voltage settings with TID



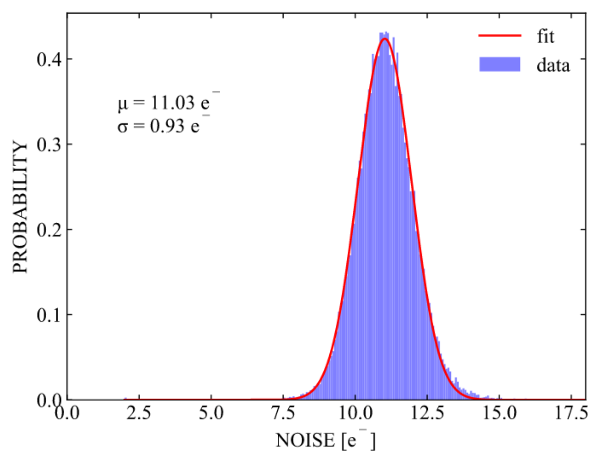
MALTA2 vs NIEL

- MALTA2 is radiation hard up to 3×10^{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

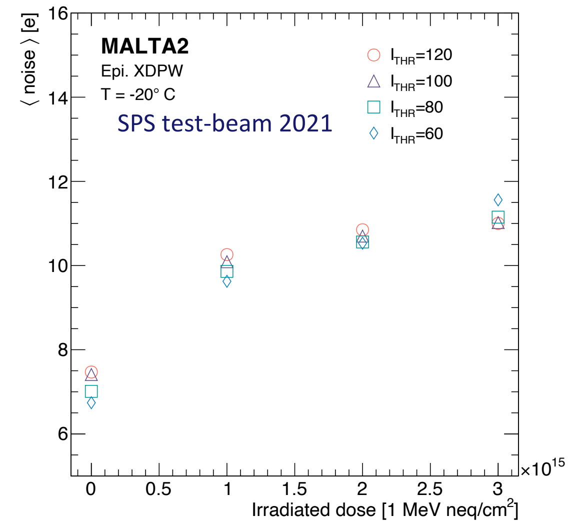




Unirradiated sample

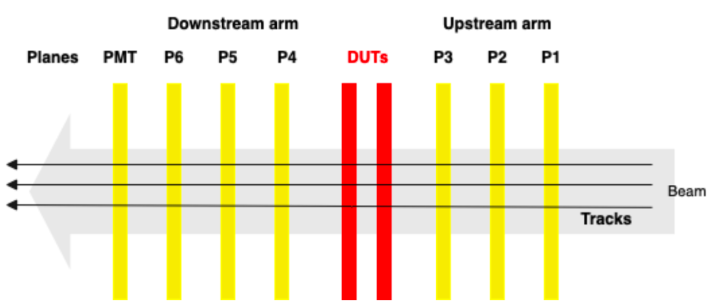


Sample irradiated at 3×10^{15} n/ 1-MeV neq/cm2

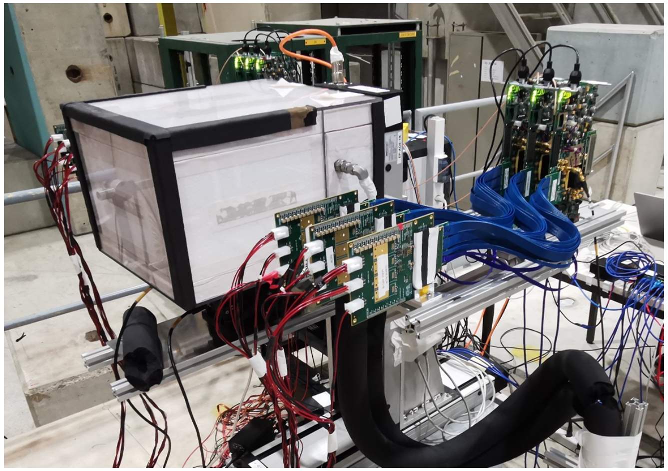


MALTA telescope at SPS

- Continuous operation in SPS from July to Nov 2021 and 2022
  - 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



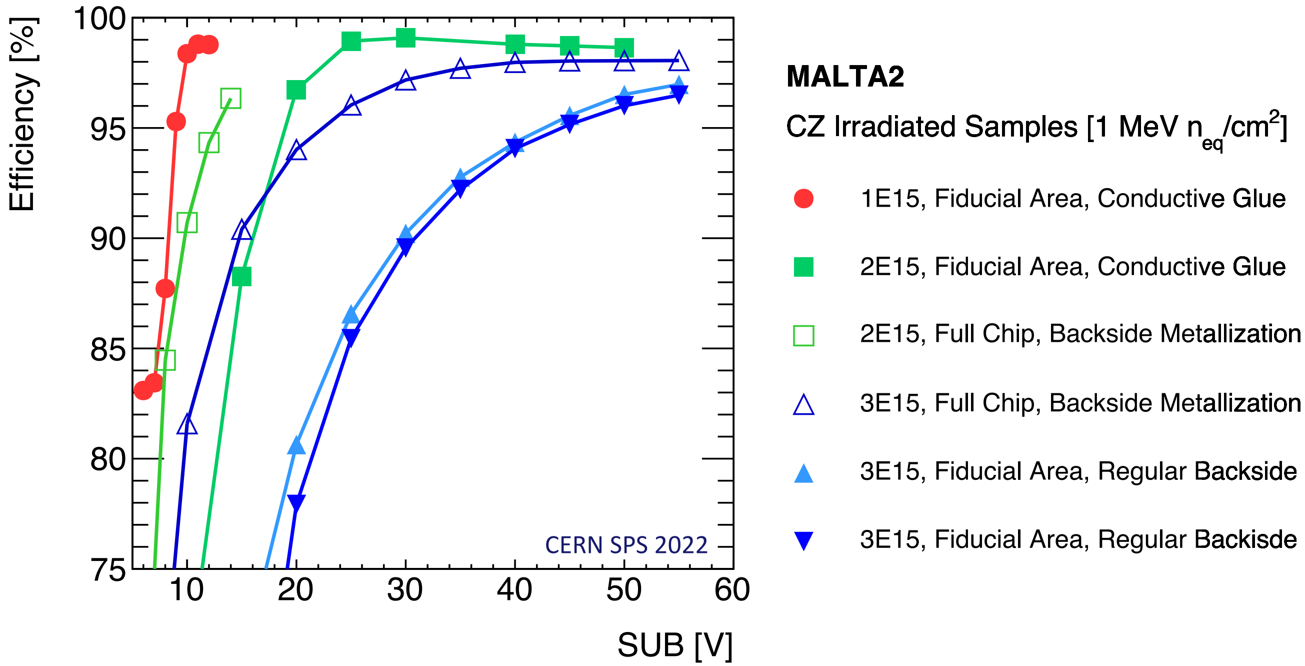
Schematic sketch of the MALTA beam telescope where the six tracking planes (P1-P6), the device under tests (DUTs), and the scintillator (PMT) are indicated



MALTA telescope at SPS

Detail of MALTA and MALTA2 planes

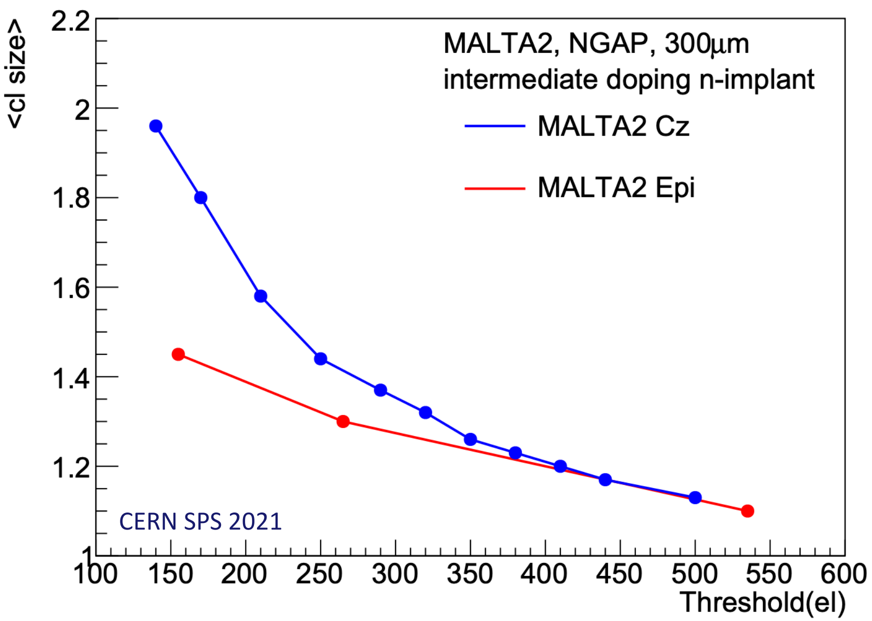
MALTA2 on Cz efficiency



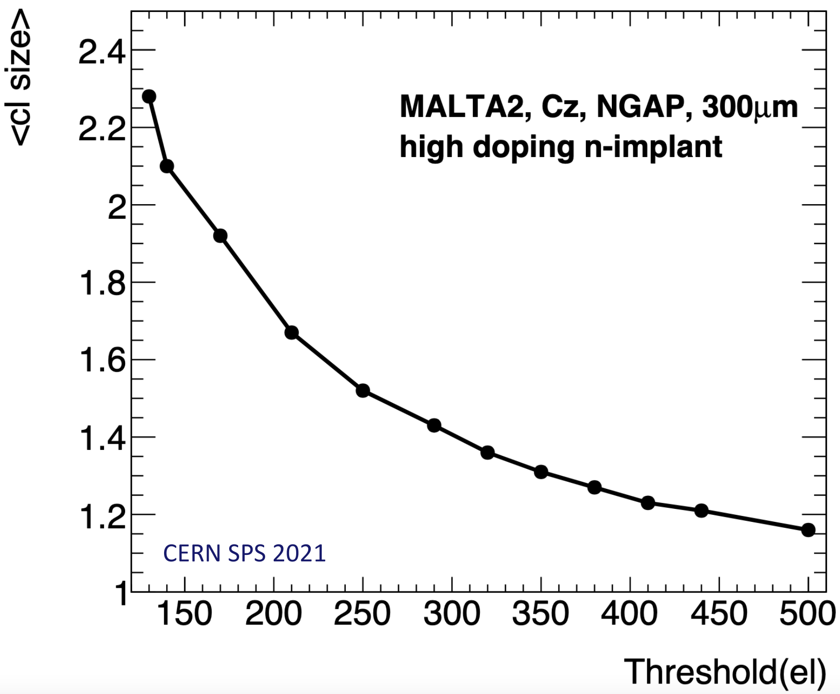
Average efficiency of irradiated MALTA2 on Czochralski substrate versus SUB voltage

- For the samples with backside metallisation, the quoted efficiency corresponds to the performance of the full chip
- Full wafer back metallization really improves the per chip charge collection
- Fiducial regions chosen manually as best performing show “better results”
- Almost full efficiency after 3e15 n/cm2 for back-metallized samples (98.5%)

MALTA2 Cz cluster size



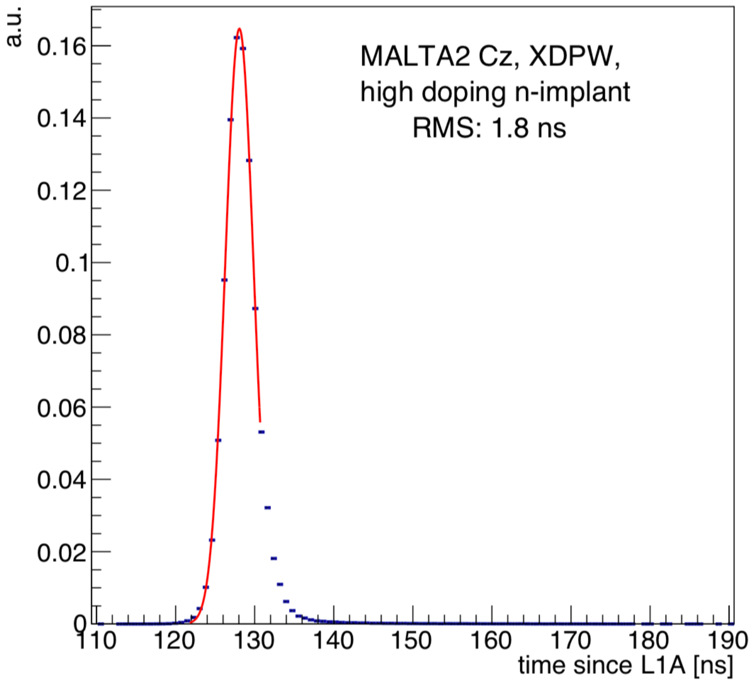
Cluster: sum of contiguous pixels fired in the same event and received within 500 ns



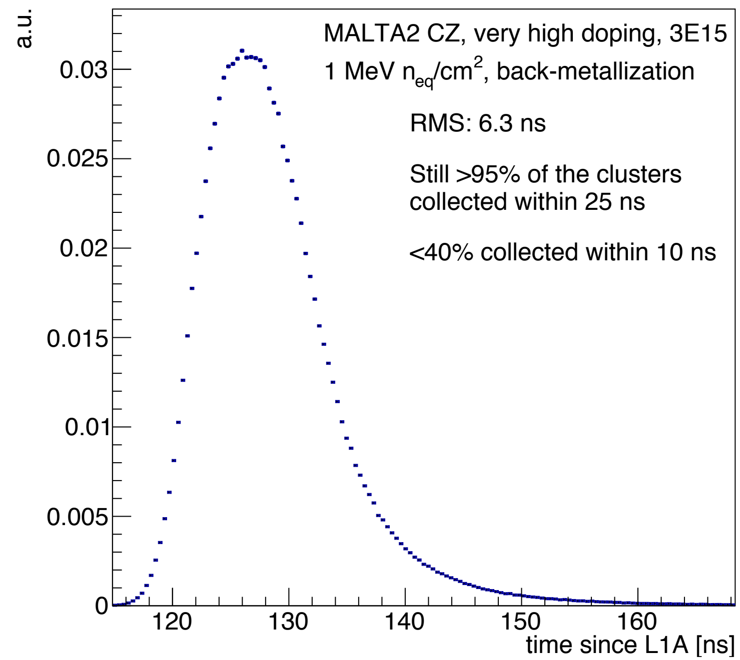
Average cluster size of non-irradiated MALTA2 versus the threshold in electrons at -6V SUB

- Cz sample reaches a cluster size of 2.25 ± 1 for 130 el, while EPI sample reaches 1.45 ± 0.01 for the same threshold

MALTA2 on Cz time resolution



Unirradiated sample

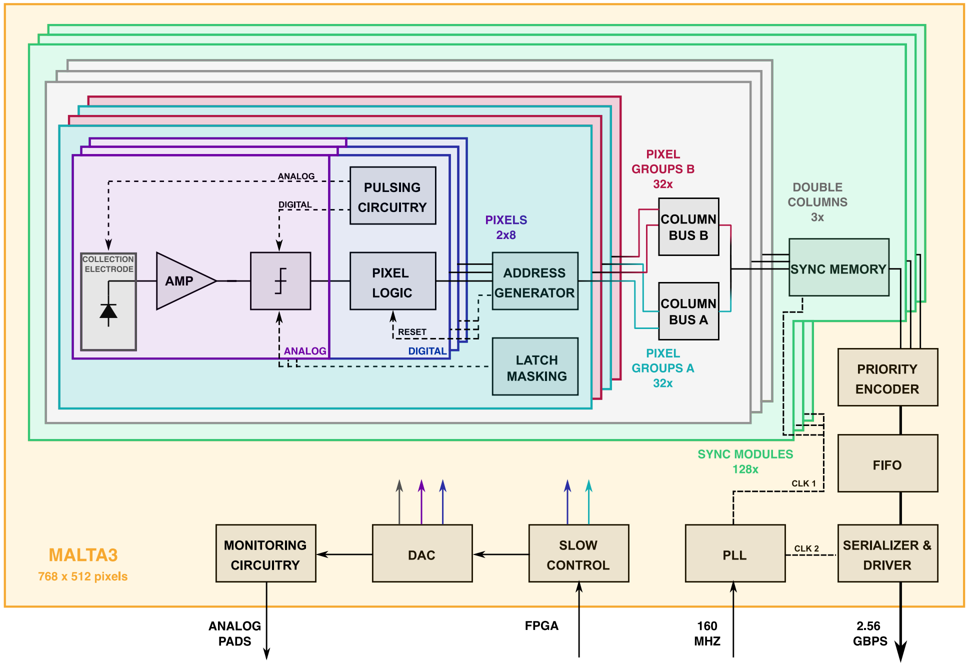


Sample irradiated at 3×10^{15} n/ 1-MeV neq/cm2

- 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)

MALTA3

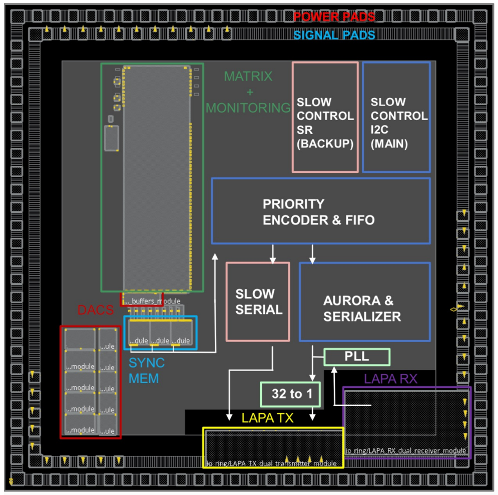
- Next step in asynchronous read-out architecture
  - Full reticle size 3x2 cm^2
  - Re-use front-end from MALTA2
  - Asynchronous hit propagation
  - Time tagging at end of column
  - Fast read-out with standard protocol
- Following top-down approach
  - Using digital flow design tools
- Push the technology to the limit
  - Add a 1.28 GHz local clock generated from a PLL for time tagging
- Standard 64b/66 Aurora protocol will be used to transmit data of the chip
- Pseudo-LVDS sends data to the LPGBT or FPGA at 1.28GHz.
- Slow control will be based on the I2C protocol.



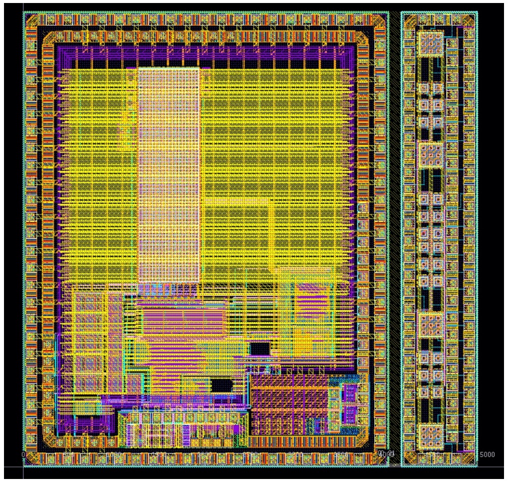
Flow diagram of MALTA3

Fabrication-Mini-MALTA3 MPW

- 5x4 mm2 demonstrator
- 48x64 matrix size of 36.4 um^2 pixels
- New digital on top flow
- PLL from STFC (2.56GHz) ready for fast timing (780 ps) and serialization (1.28 GHz)
- Pseudo-LVDS sends data to the LPGBT or FPGA at 1.28GHz.
- Synchronization and timing block ready
- Aim for submission in May 2023



Top-level implementation design



Top-level layout

Summary

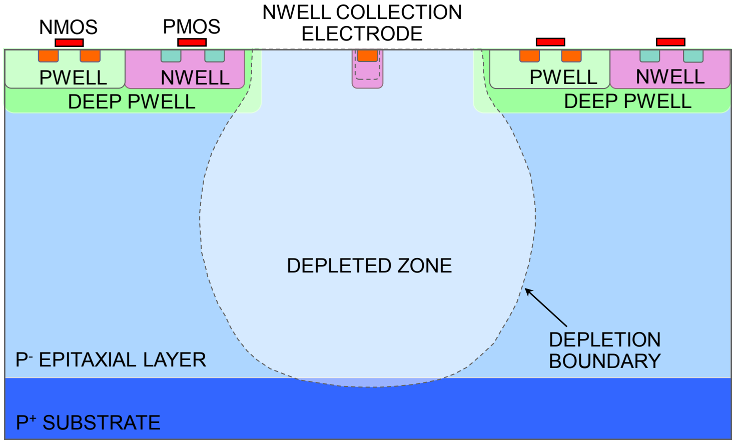
- Characterization and design activities progressing well
  - Proceedings from TWEPP 2021 and 2022
    - https://doi.org/10.1088/1748-0221/17/04/C04034
  - Proceedings from VERTEX 2021 submitted to NIM A
  - Proceedings from VCI 2022 (2):
    - MALTA2:
      - https://doi.org/10.1016/j.nima.2022.167390
    - MALTA3:
      - https://doi.org/10.1016/j.nima.2022.167226
  - IEEE MALTA2-FE:
    - https://doi.org/10.1109/TNS.2022.3170729
  - Synergy between AIDA innova activities and EP R&D WP 1.2 and 1.3 on Monolithic Pixel detectors
    - https://doi.org/10.1016/j.nima.2022.167809
  - Fabrication of MPW -> being submitted in May

Acknowledgements

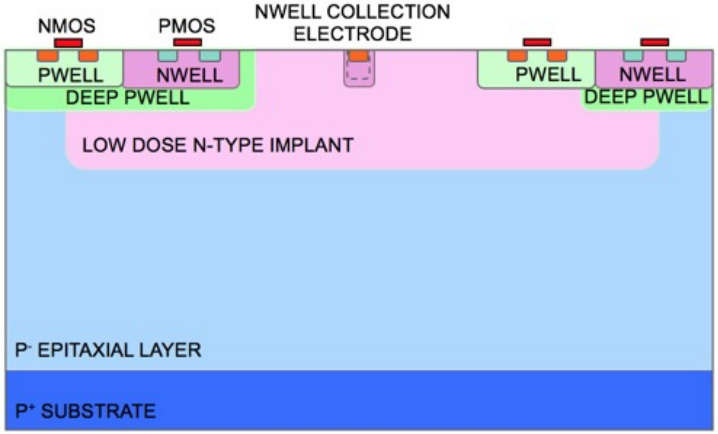
- European Union's Horizon 2020 Research and Innovation programme under grant agreement No 101004761.
- Supported by the Marie Sklodowska-Curie Innovative Training Network of the European Commission Horizon 2020 Programme under contract number 675587 (STREAM).
- The measurements leading to these results 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.
- 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

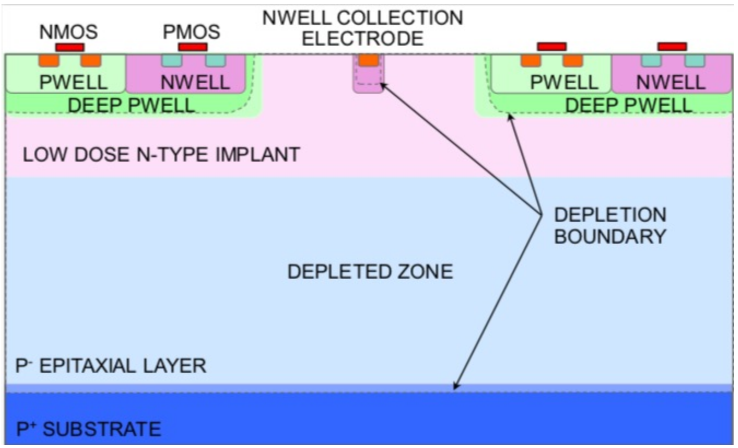
TJ 180 nm Modified Processes



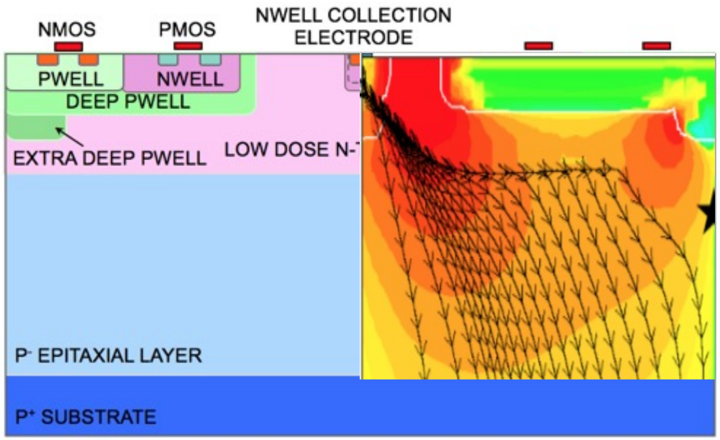
Unmodified process. Large collection time via diffusion



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



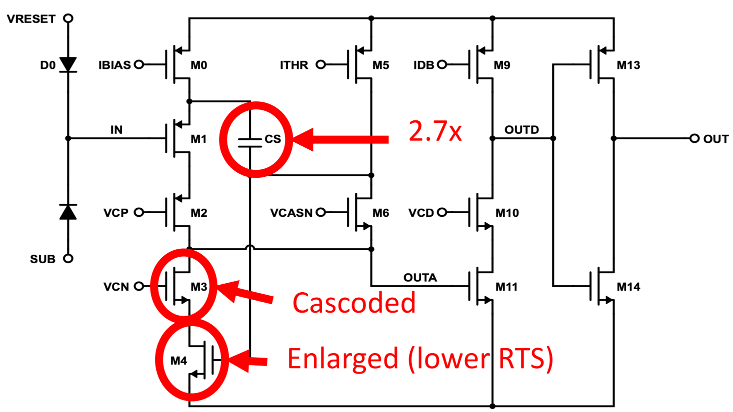
Modified process. Low dose n- implant under the p-well. Low charge collection in pixel edges.



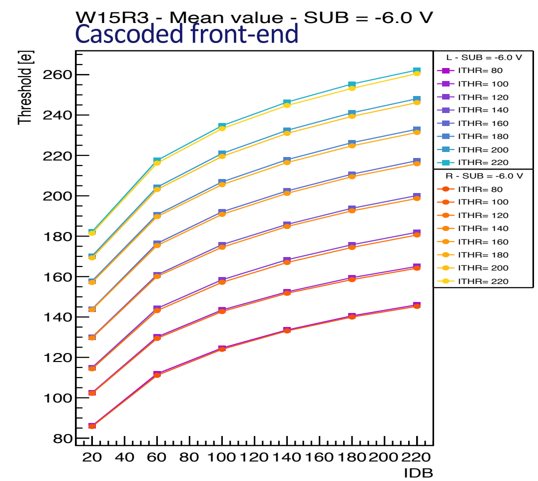
Modified process with extra deep p-well (XDPW). Improved charge collection in the pixel edges.

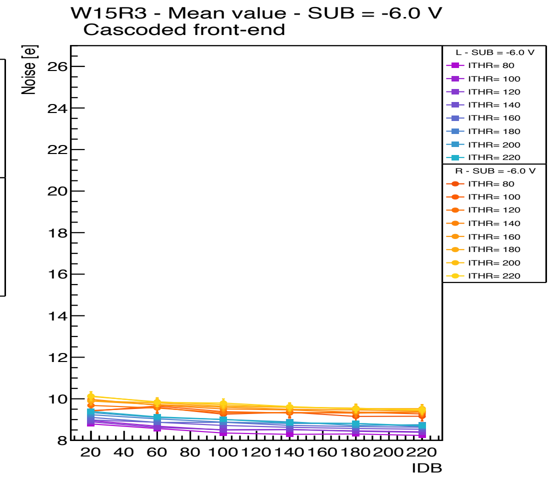
MALTA2 Cascoded front-end

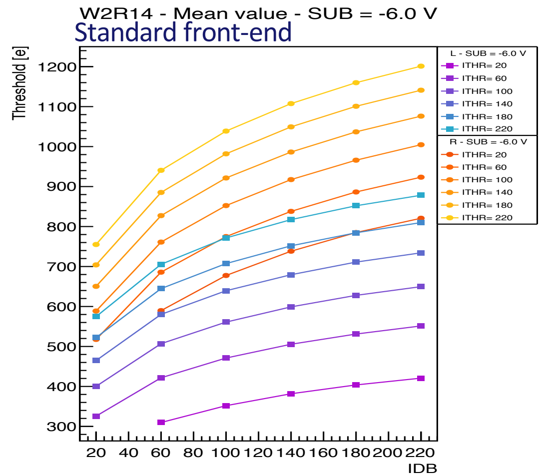
- Cascoded front-end introduces a new transistor in series with the input node
  - Increases the gain of the front-end
  - Reducing the threshold reach
- Standard front-end with larger size feedback NMOS transistor (L) have lower threshold than the ones with smaller size (R)
  - IDB DAC proportional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

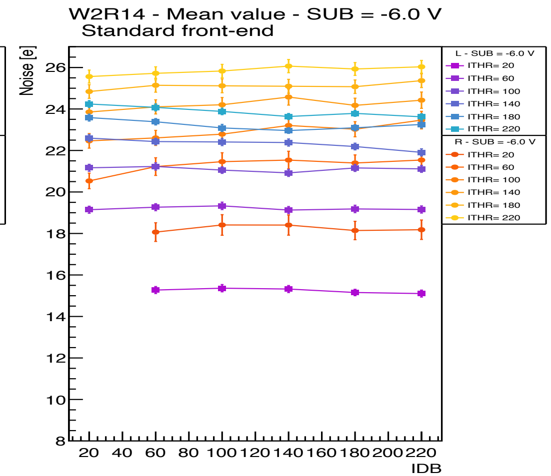


MALTA2 front-end



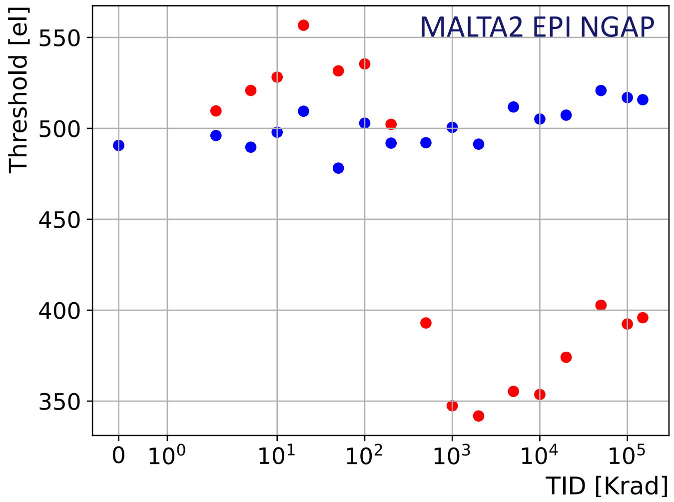


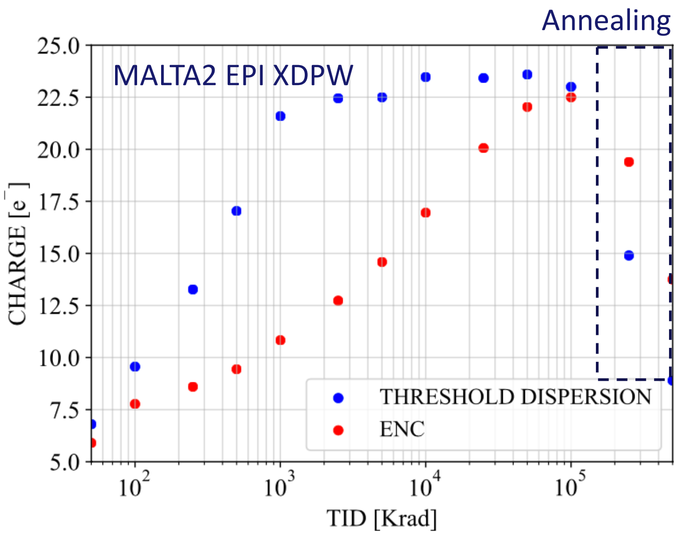




MALTA2 front-end vs TID

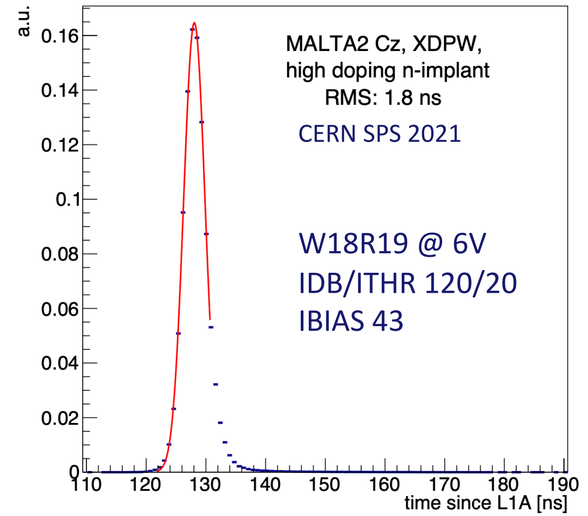
- MALTA2 is radiation hard up to 150 Mrad TID
- Both XDPW and NGAP modifications tested
- Threshold can be kept stable at given value by changing front-end settings
- Threshold dispersion ~2x after 10 Mrad and stabilizes after that
- Noise increases monotonically
- Noise and threshold dispersion recover after 24 hours annealing at 80 C

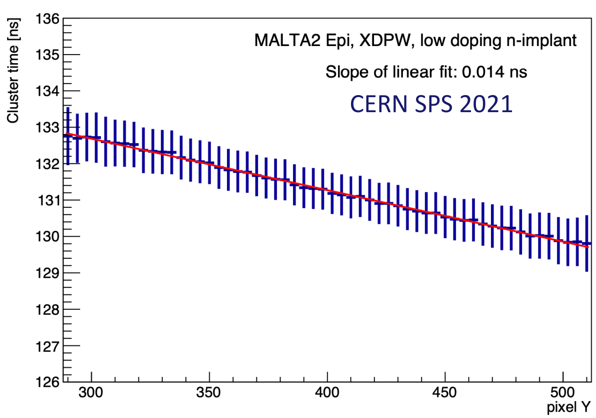




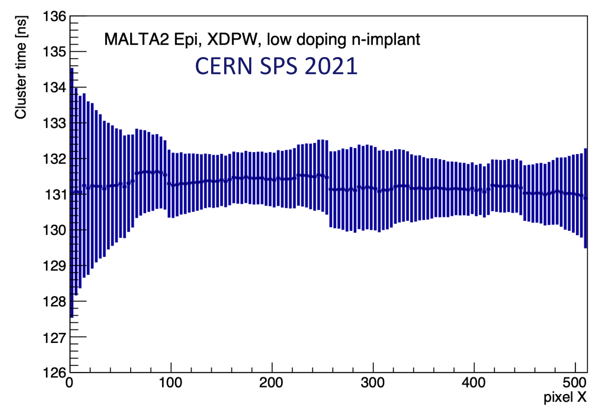
Timing performance of MALTA2

- 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

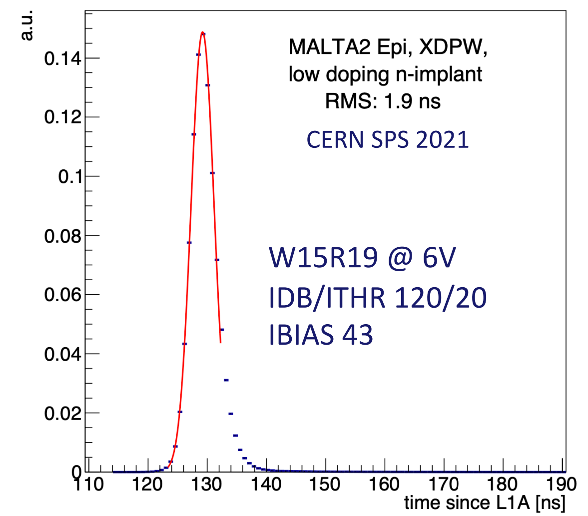




Y direction (down the column) correction

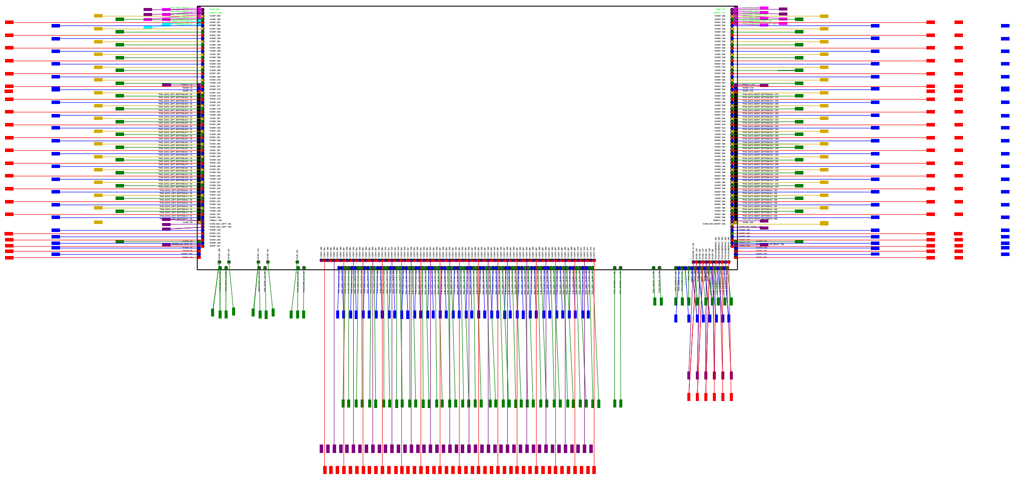


X direction (across the row) correction

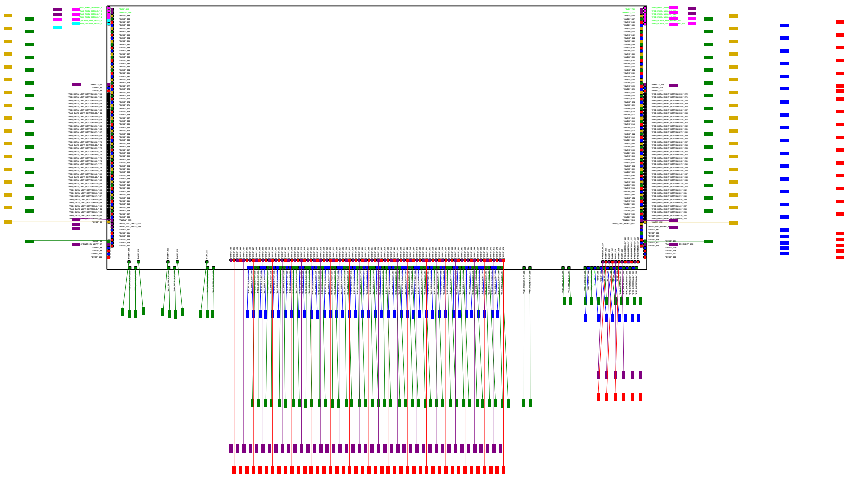


Exploring powering options

- 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



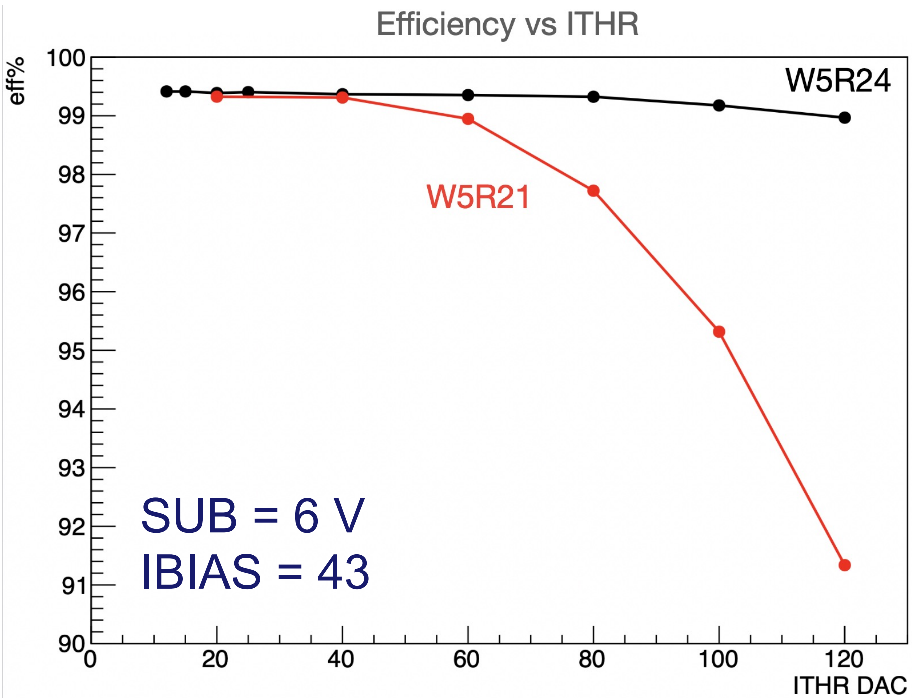
Default wire bonding diagram for MALTA2
Power is provided from the sides and the bottom of the chip

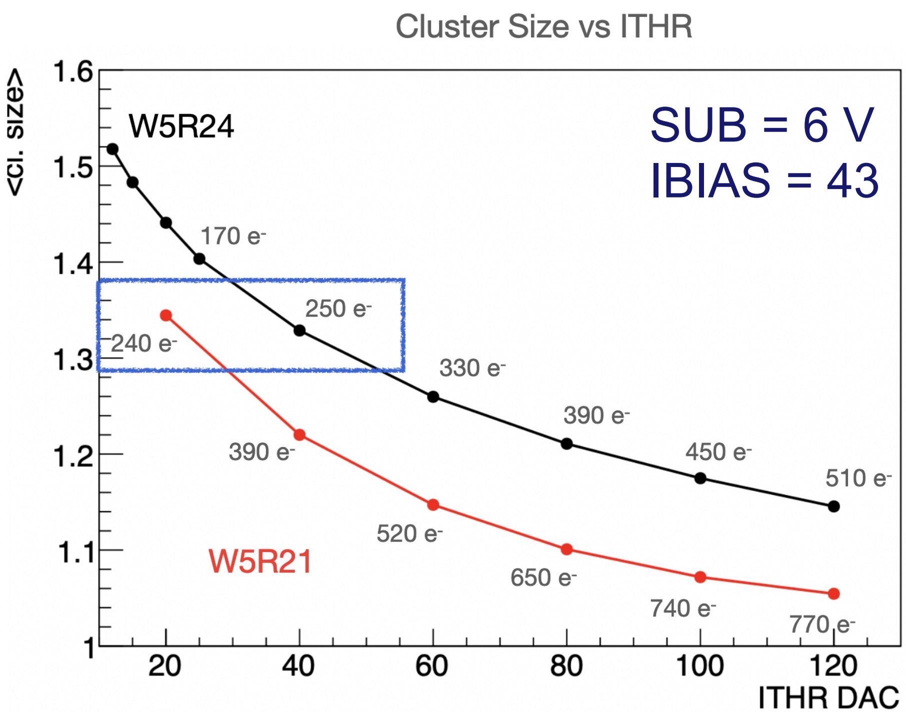


Minimal wire bonding diagram for MALTA2
Power is provided from the bottom of the chip

Bonding effects on EPI NGAP

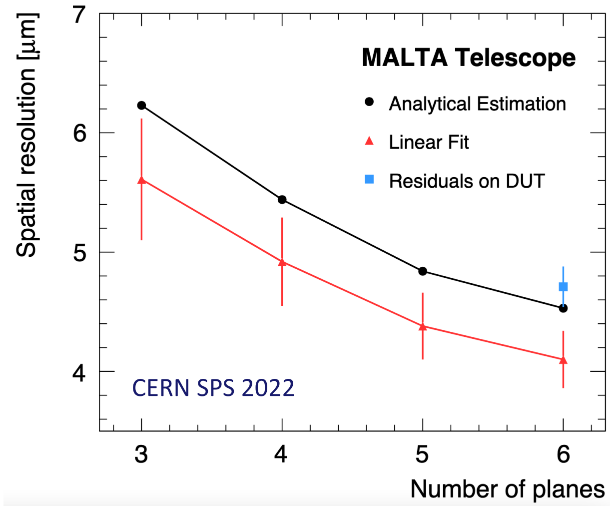
- Measured the effects on un-irradiated MALTA2 EPI 30 um NGAP high doping
- Observed drop in efficiency and and cluster size wrt to regular bonding
- Threshold for minimally bonded chip much higher
- Trends follow those of regular bonded sample

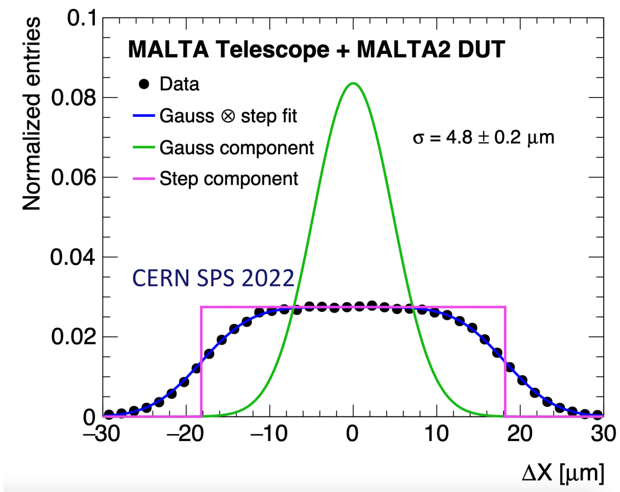




Telescope results

- 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





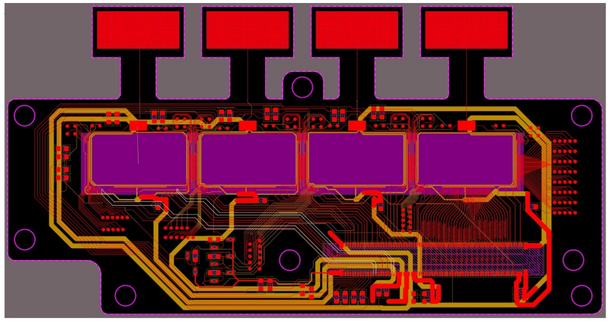
SPS-TESTBEAM 2022

- MALTA was parasitic user from April to November 2022
  - In 2023 we will also take data for 8 months of the year
- A lot of data has been taken:
  - Performance of irradiated and unirradiated MALTA2 CZ & EPI samples
  - Cluster analysis
  - Different backside processing of samples
  - Timing resolution

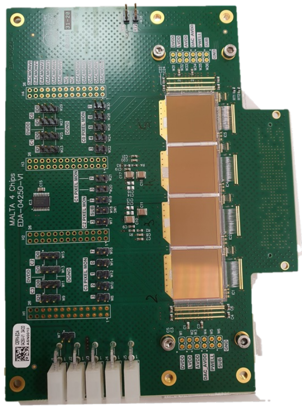
MALTA2 Sample	Subs	Flavour	Doping [n- layer]	Thickness [um]	Dose [10^{15} n/cm^2]
W5R5	EPI	NGAP	High	300	2
W5R6	EPI	NGAP	High	300	2
W5R9	EPI	NGAP	High	300	p
W5R10	EPI	NGAP	High	300	0
W5R21	EPI	NGAP	High	300	0
W5R23	EPI	NGAP	High	300	0
W5R24	EPI	NGAP	High	300	0
W8R19	EPI	XDPW	Low	100	0
W8R20	EPI	XDPW	Low	100	0
W8R24	EPI	XDPW	Low	100	0
W11R0	Cz	XDPW	High	100	0
W12R0	Cz	XDPW	High	100	0
W12R1	Cz	XDPW	High	100	0
W12R8	Cz	XDPW	High	100	0
W14R11	Cz	NGAP	High	300	0
W14R12	Cz	NGAP	High	300	0
W14R3	Cz	NGAP	High	300	2
W15R0	Cz	NGAP	High	100	1
W15R4	Cz	NGAP	High	100	2
W15R5	Cz	NGAP	High	100	2
W15R9	Cz	NGAP	High	100	3
W15R10	Cz	NGAP	High	100	3
W15R11	Cz	NGAP	High	100	3
W15R19	Cz	NGAP	High	100	0
W18R9	Cz	NGAP	High	100	3
W18R10	Cz	XDPW	Very high	100	3
W18R17	Cz	XDPW	Very high	100	0
W18R19	Cz	XDPW	Very high	100	0
W18R21	Cz	XDPW	Very high	100	3

Quad chip module operation

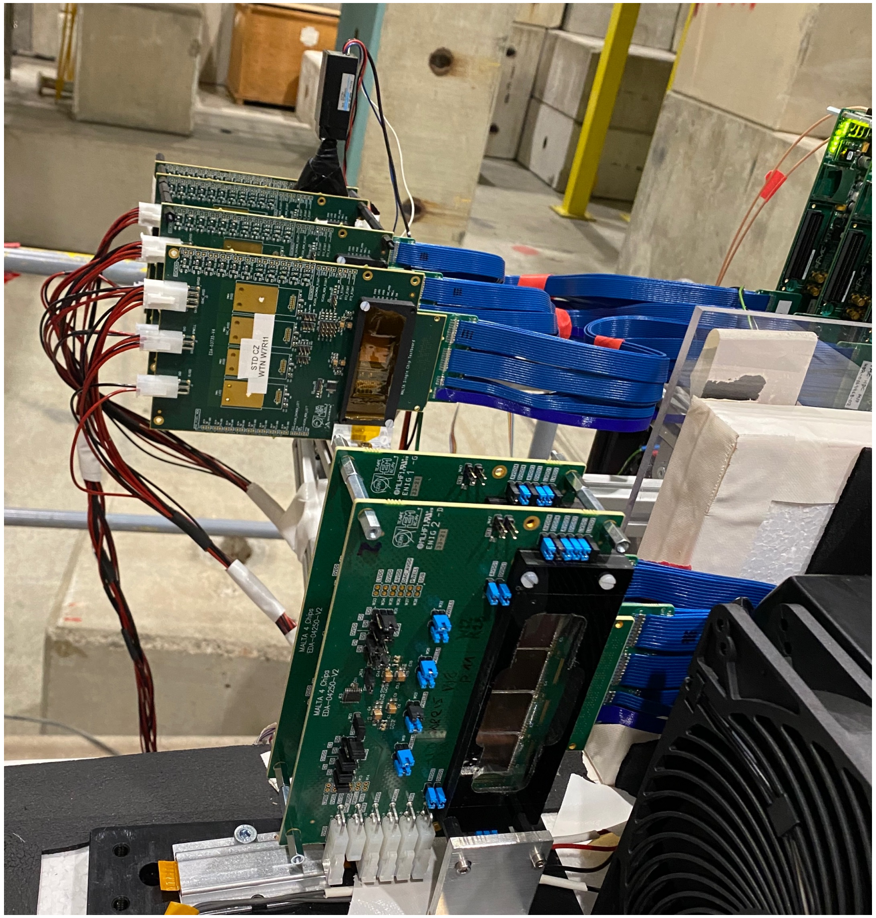
- Data from MALTA can be routed to the left or right through CMOS output
- Quad modules for MALTA extensively tested in the laboratory
- Installed quad-module on telescope this week for measurements with beam particles
- MALTA2 module still in production



MALTA2 module layout



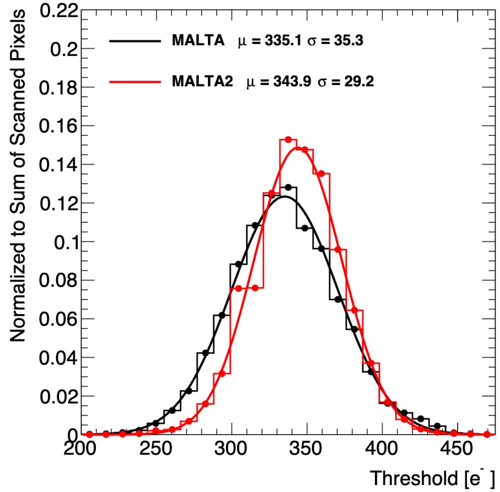
MALTA quad-module

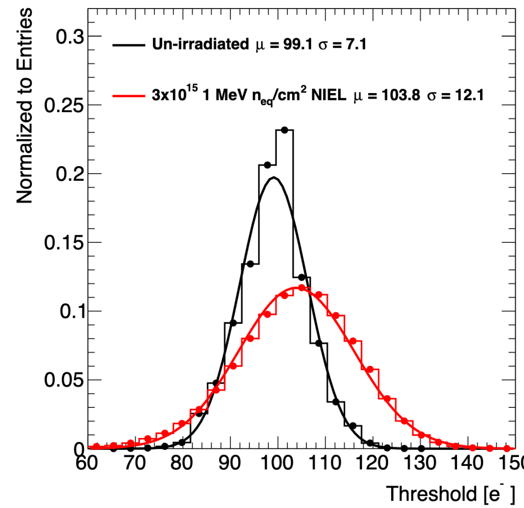


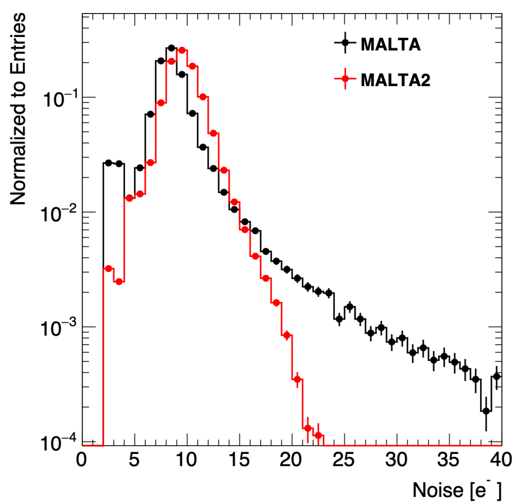
MALTA quad-module in MALTA telescope at SPS

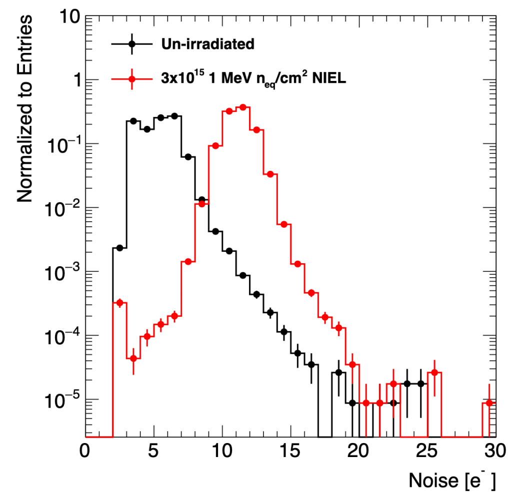
MALTA2 vs NIEL

- MALTA2 is radiation hard up to 3x10^{15} n/cm^2 NIEL
- Threshold reduces and noise increases vs NIEL

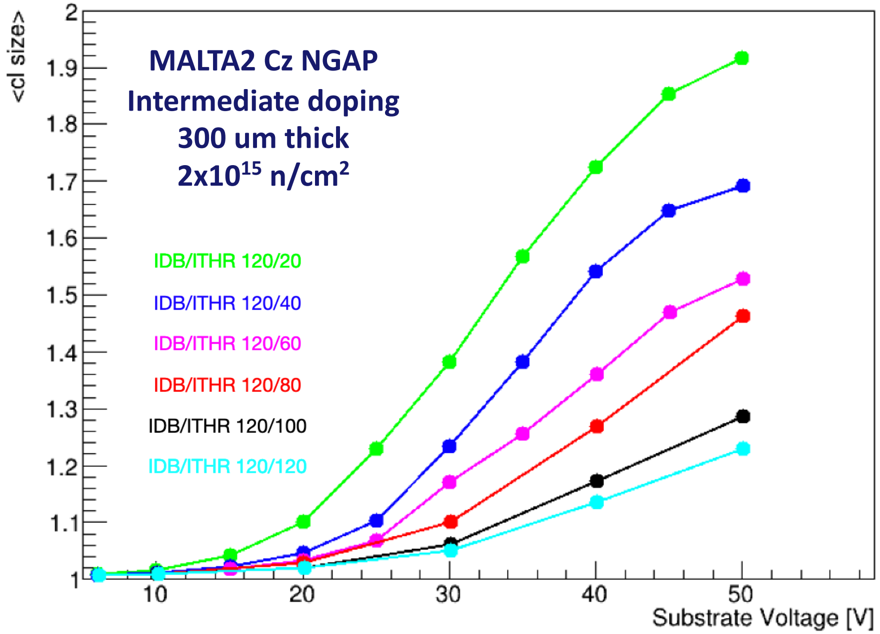


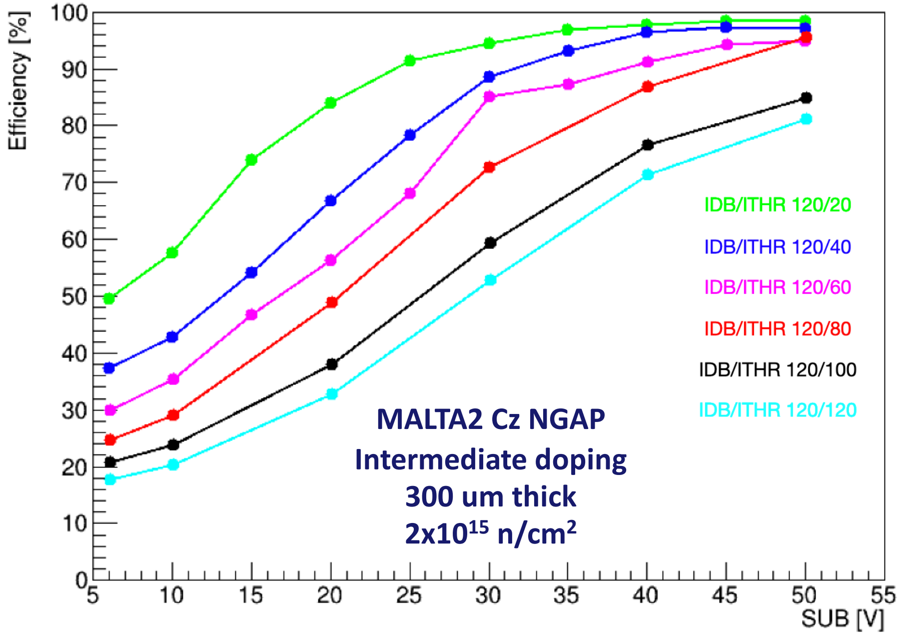






MALTA2 efficiency

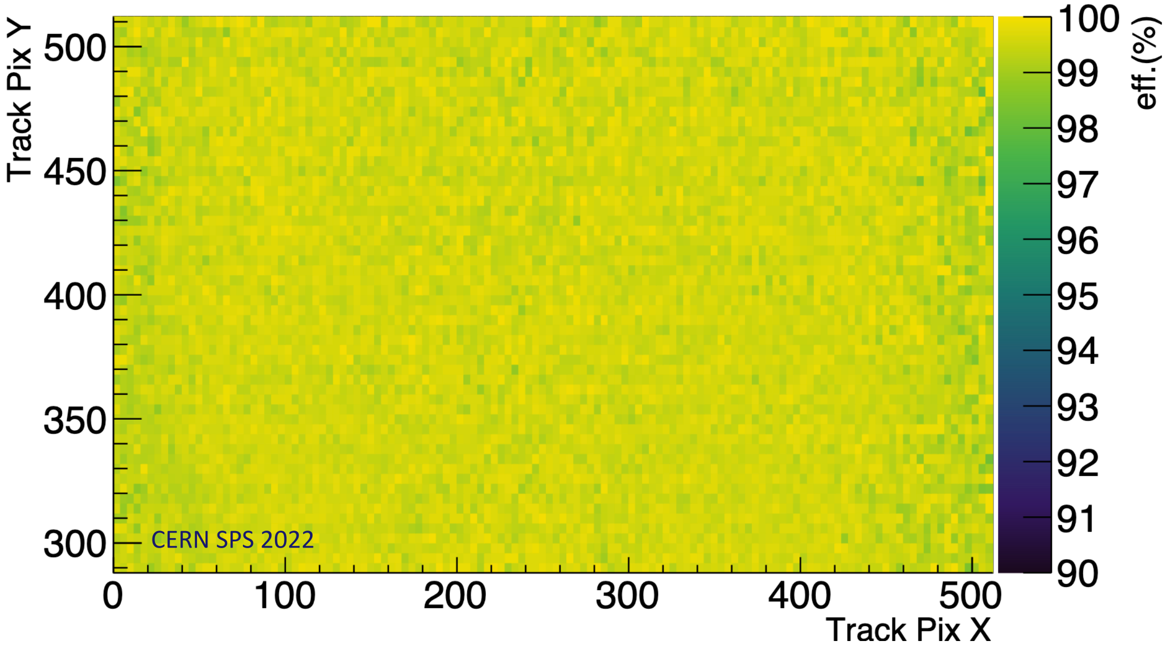




Cluster: sum of contiguous pixels fired in the same event and received within 500 ns

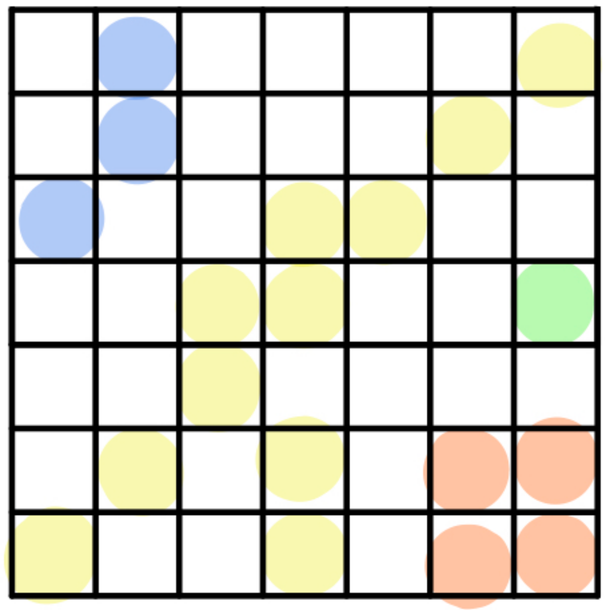
- Good performance of Cz samples at 2×10^{15} n/cm^2
  - Modulo the distribution of the substrate voltage
- Expected uniformity at lowest threshold setting
- Cluster size increases with substrate voltage
  - Maximum at ~1.9 at 50 V at 120 e-
- Efficiency better than 98% at 50 V bias at 120 e-

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

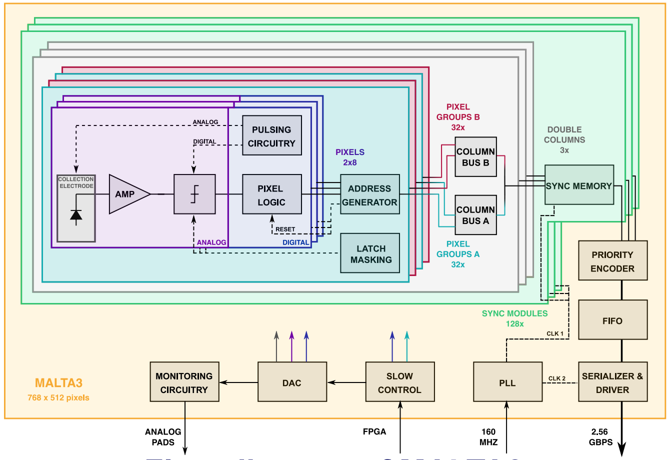
Cluster explanation



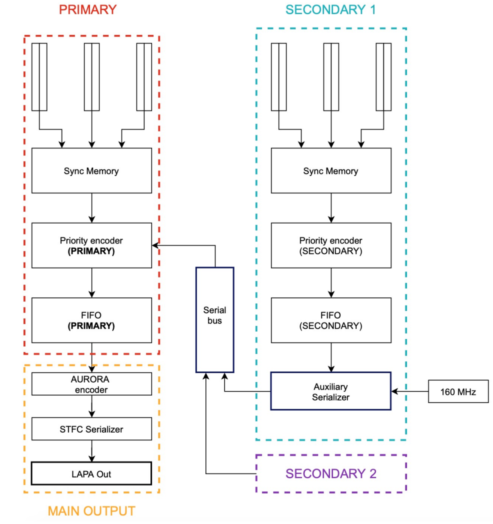
- A Cluster is a set or group of adjacent pixels that have a hit
- The red dots would be a cluster of size 2
- The green one a cluster of size 1
- Yellow is impossible, a single particle cannot leave the track of the yellow signal

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

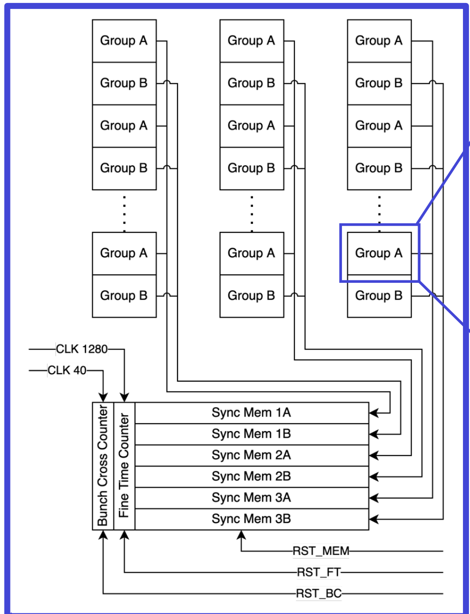


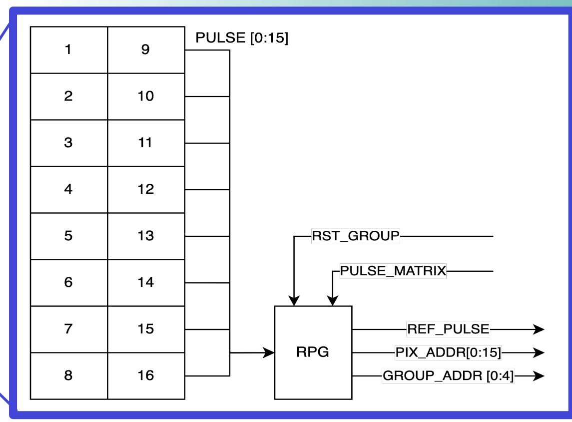
Flow diagram of MALTA3

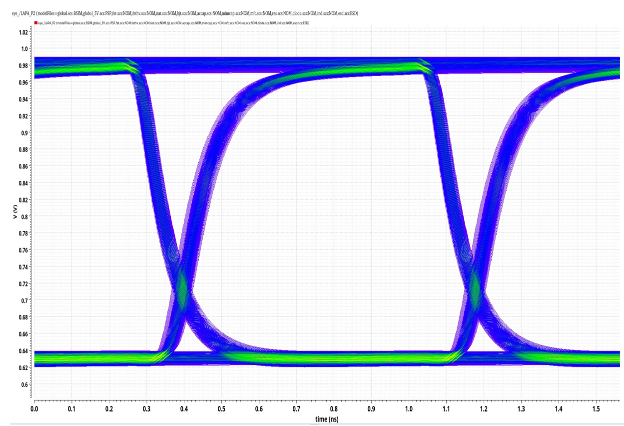


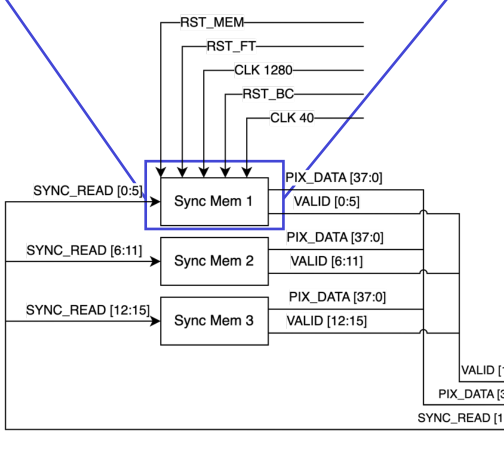
Concept for serial communication

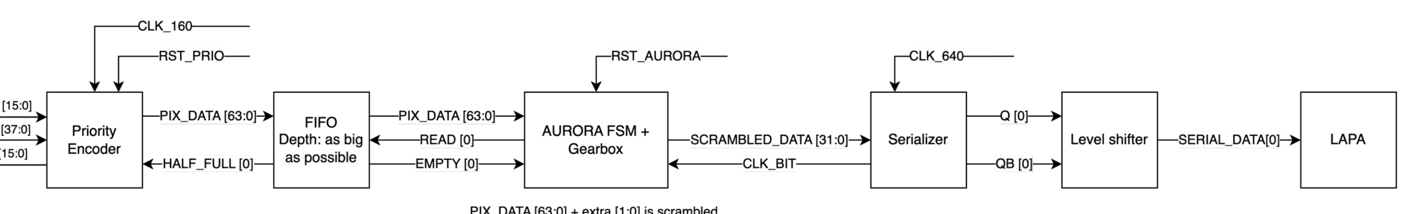
Mini-MALTA3 data path











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