Development of the radiation hard MALTA CMOS sensor for tracking applications

Heinz Pernegger (CERN) on behalf of the MALTA development team:

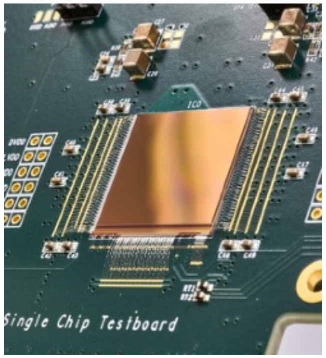
H. Pernegger, P. Allport, I. Asensi Tortajada, D.V. Berlea, D. Bortoletto, C. Buttar, F. Dachs, V. Dao, H. Denizli, D. Dobrijevic, L. Flores Sanz de Acedo, A. Gabrielli, L. Gonella, N. Guerrini, V. Gonzalez, G. Gustavino, H. Larsen, M. LeBlanc, K. Oyulmaz, F. Piro, P. Riedler, H. Sandaker, C. Solans, W. Snoeys, T. Suligoj, M. van Rijnbach, I. Sedgwick, A. Sharma, M. Vazque Nunez, J. Weick, S. Worm, A. Zoubir

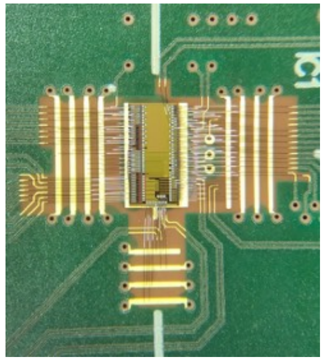
Vertex 2022, October 24-28, 2022, Tateyama, Japan

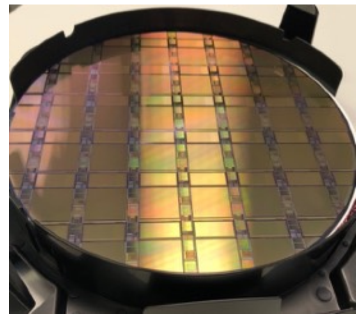
The timeline of MALTA developments

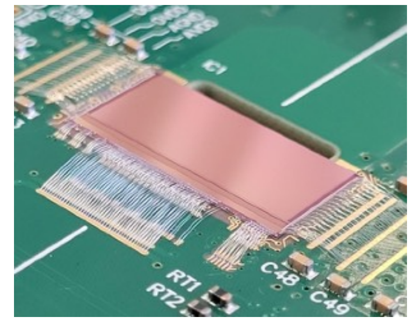
H2020 MSCA ITN "STREAM"

AIDA Innova and CERN EP R&D



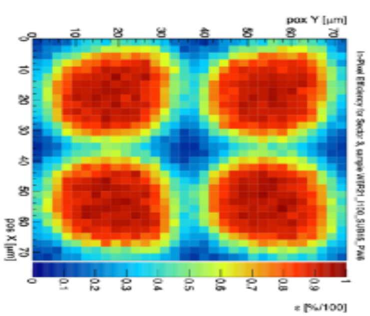




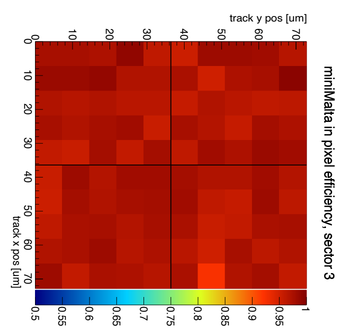


MALTA3
#digital-flow-design

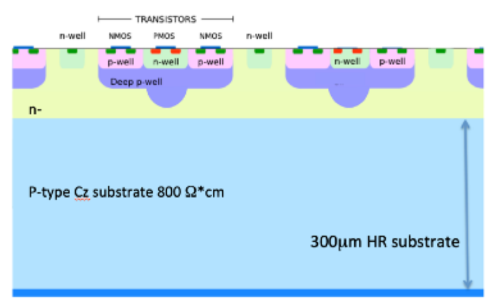
MALTA1 & MLVL	Mini-MALTA	MALTA C	Split 7	MALTA 2	Mini-MALTA 3
Jan 2018	Jan 2019	Aug 2019	Oct 2020	Jan 2021	Oct 2022
Asynchronous readout	Process and mask modification	Czochralski substrates	Reduced noise and increased gain		Data serialization and time tagging



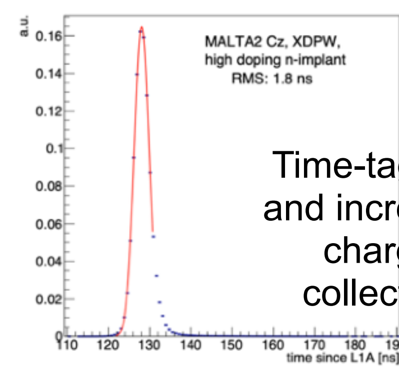
Design optimisation for better lateral field



Full efficiency after 1e15 n/cm²



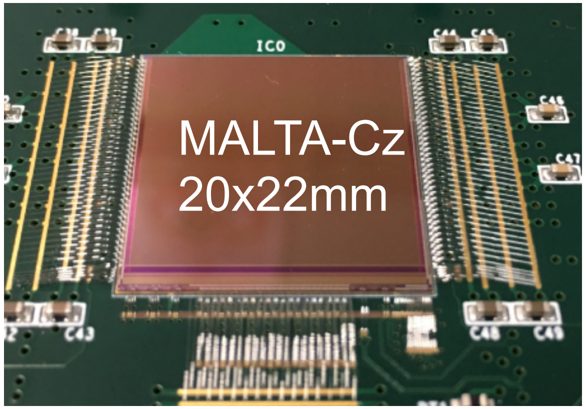
Substrate and process optimisation



Time-tagging and increased charge collection

The MALTA Sensor and basic specifications

- **The "MALTA" Sensor**
  - **Asynchronous readout** architecture for **high hit rate** capability with 40bit parallel data bus for hit address and timing readout
  - **Data streaming** for trigger less operation
  - **Sensor-to-Sensor high-speed signal** transmission (no-Flex system integration for minimal X_0)

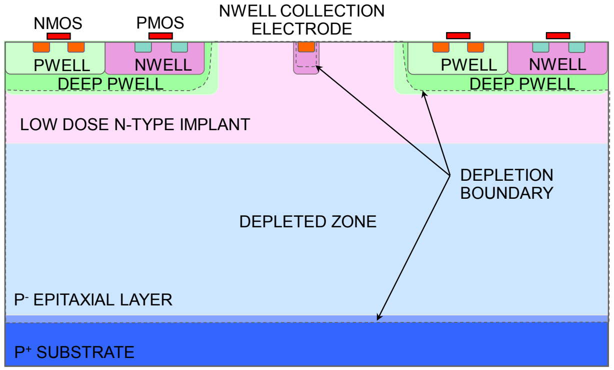


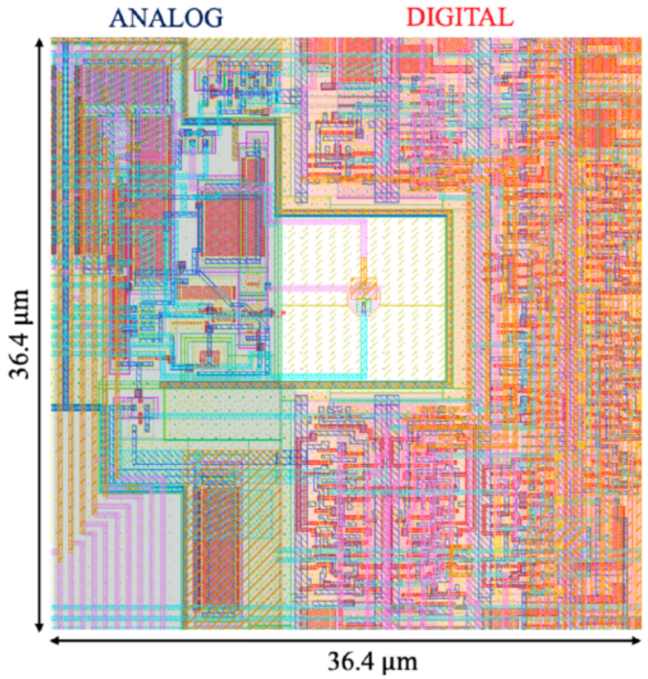
MALTA-Cz main features	
Pixel Pitch	36.4x36.4 μm^2
Matrix size / active area	512x512 /18.3x18mm^2
Hit rate capability	>> 100MHz/cm^2
Time resolution	~2ns
TID radiation hardness	>100Mrad
NIEL radiation hardness	>10^{15} n_{eq}/cm^2

- Developed as radiation hard tracker for HL-LHC application
  - originally developed with specifications for ATLAS ITK Outer layer
  - Radiation hardness for a low noise CMOS sensor is key development goal

The MALTA Pixel design

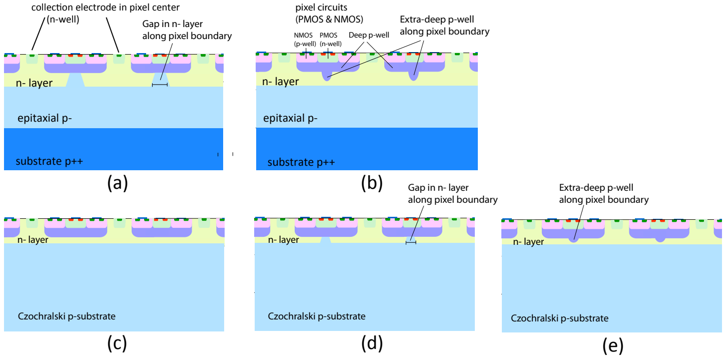
- Small electrode design 3x3um collection electrode in depleted pixel
  - minimal capacitance (<5fF)
  - Threshold ~100e- and ENC noise < 10e-
- Sensor thickness can be optimised for application
  - epitaxial 30um active in 50um thick sensors for minimal material
  - thicker Cz substrate for larger signal or soft X-ray sensitivity (100 to 300um)
- Sensor Matrix power consumption
  - 1uW/pixel analog
  - 70mW/cm² analog
  - ~10mW/cm² @ 100MHz hit rate (digital power minimised as no clock in matrix)





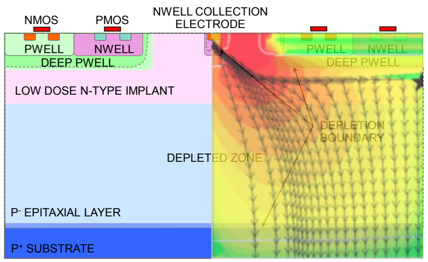
MALTA sensor process (TJ180nm CIS)

- produced in Tower 180nm CIS process
  - optimisation of implantations with foundry
  - produced on epitaxial and Czochralski substrates

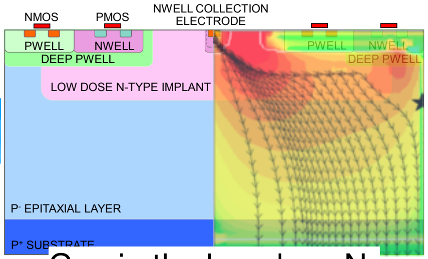


Additional process modifications can increase E-field in pixel corners, further reducing charge collection tails.

STD

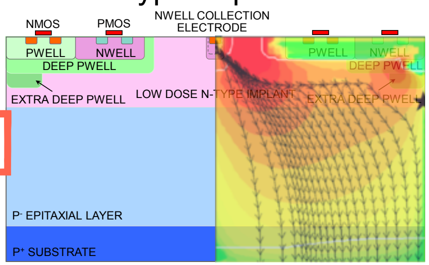


NGAP

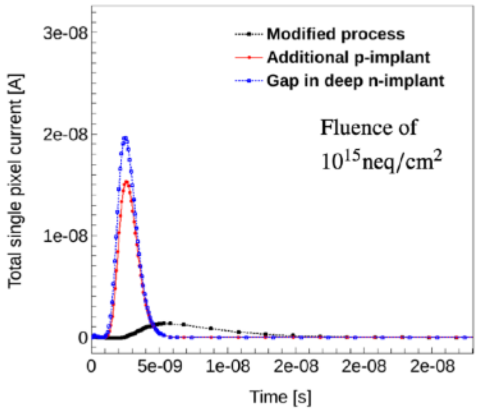


Gap in the low dose N-type implant

XDPW



Extra Deep P-Well



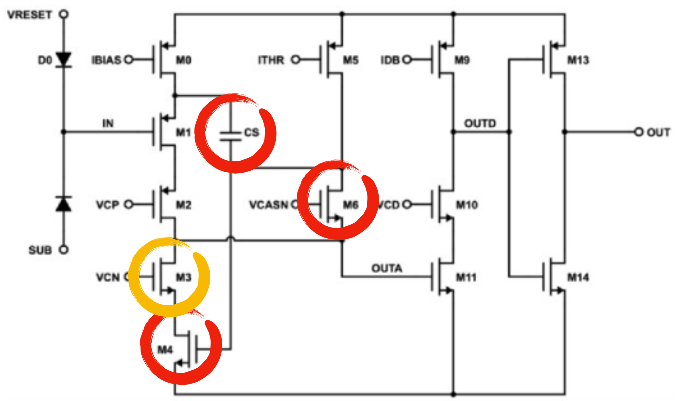
* faster charge collection

* substantial improvement in radiation hardness due to better charge collection

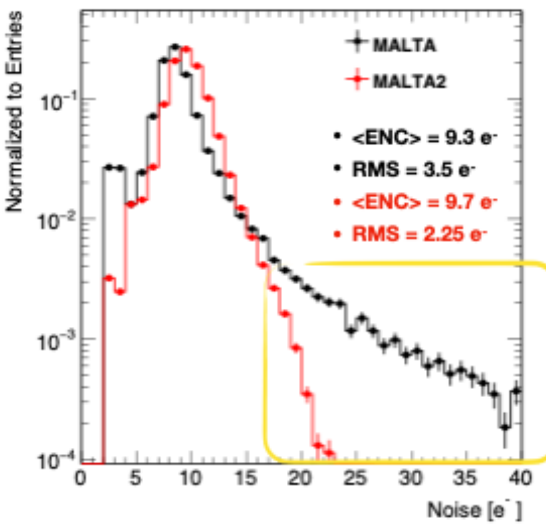
[M. Munker, JINST 14 (2019) C05013](https://doi.org/10.1088/1748-0221/14/05/C05013)

Improved Front-End - MALTA2 sensor

* Same matrix design with asynchronous hit transmission and improved FE:
  - lower noise & higher gain by enlarged transistors & cascode stage
  - ☑ enables operating the chip at lower threshold (down to O(100) e-) by significantly reducing noise tail (RTS noise)
  - ☑ increases sensitivity to small signal
    - higher radiation tolerance (Ref. *JINST 15 (2020) 02*) : with same configuration MALTA1 FE threshold = 340 el. c.f. MALTA2 FE = 200 el.
    - substantially improves efficiency @ $1x10^{15}$ n_{eq}/cm^2: MALTA1 FE=87%, MALTA2 FE =98%
  - ☑ improve speed of analog FE



IEEE Trans. Nucl. Sci. , vol. 69, no. 6, pp. 1299-1309, June 2022

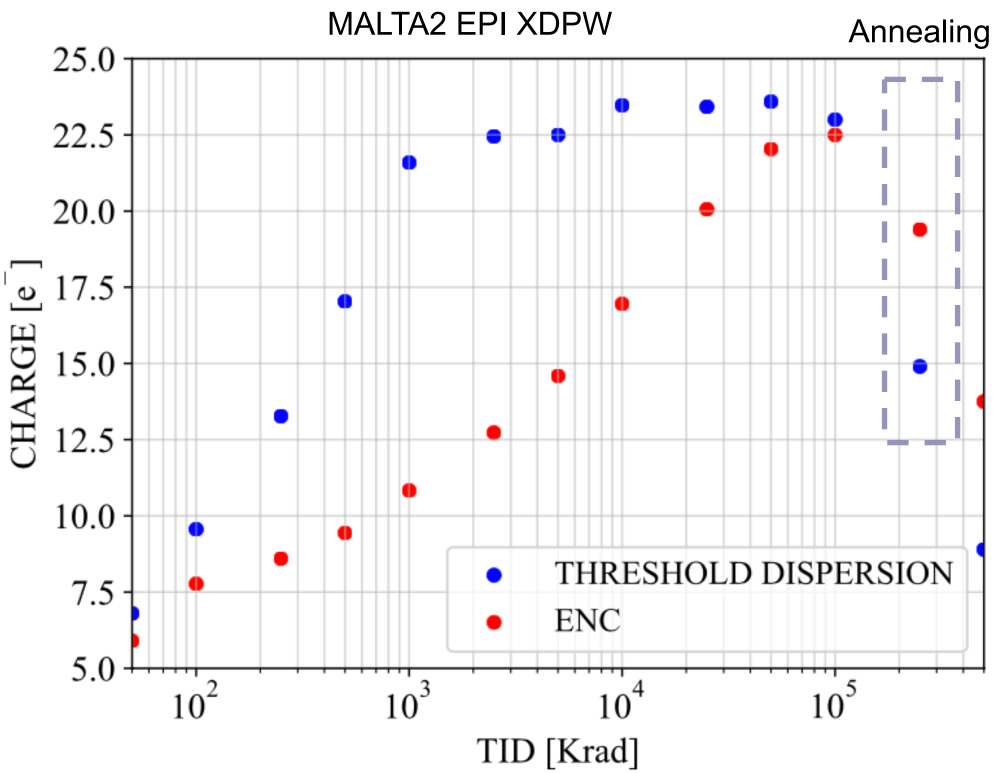


Comparison of MALTA & MALTA2 at compatible threshold (~340 e-)

Front-end performance before/after TID 100Mrad

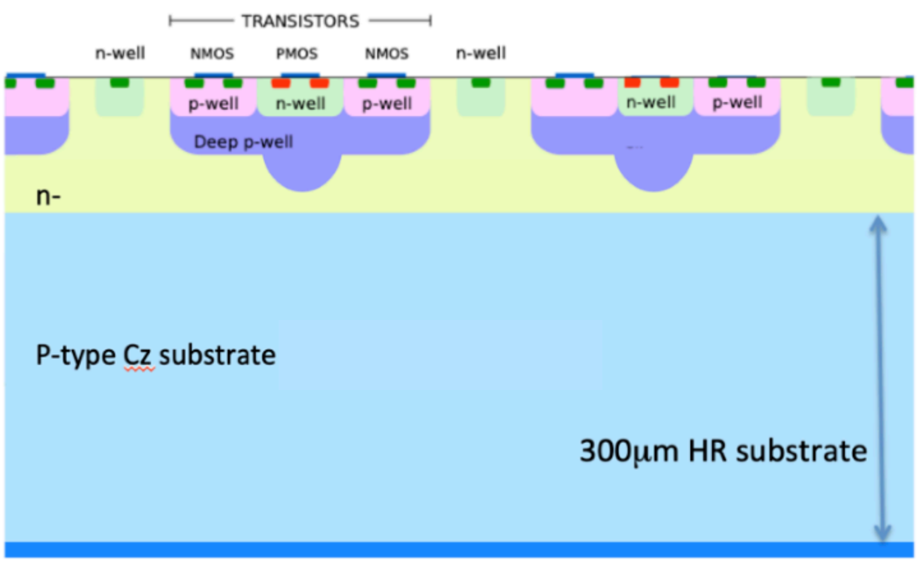
- MALTA 2 sensor irradiated with X-ray to 100Mrad
  - characterise FE threshold and noise through threshold scans

- threshold dispersion
  - starts at ~ 7e- and increases until 10Mrad, then saturates ~22e-
- ENC
  - starts at ~ 6e- and increases to ~22e-
- 24h@R/T Annealing reduces threshold dispersion and ENC



Substrate choice: MALTA sensor on Czochralski p-type

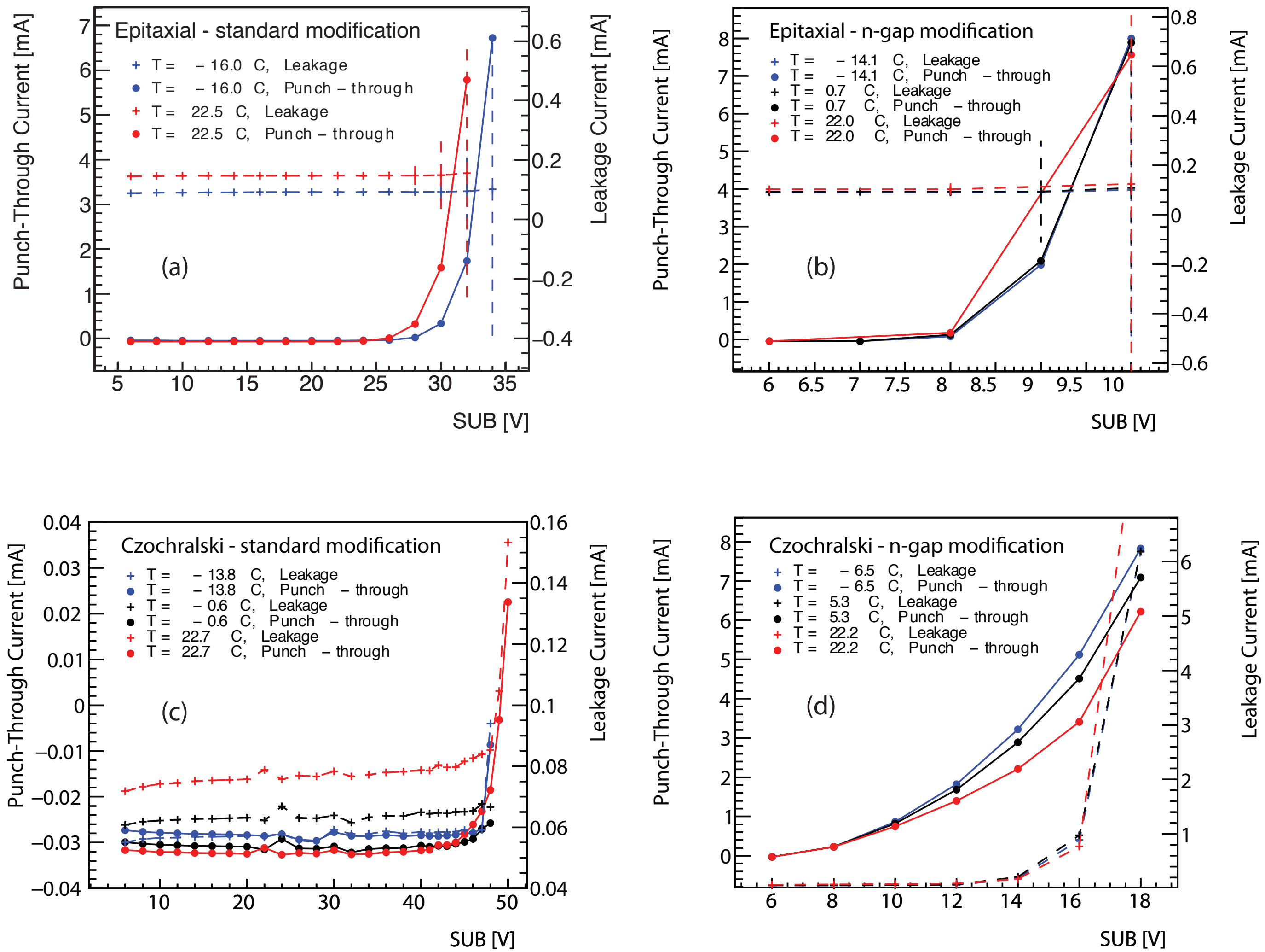
- Possibility of processing on high resistivity Czochralski substrate
  - p-type Cz substrates with resistivity of >4 kΩ·cm
  - Can operate at 50V reverse bias for larger depletion (~100um)
  - Aim for higher radiation hardness
- Implement the same design and process modifications
  - Continuous n-layer (standard), gap in the n-layer (n-gap), extra deep p-well
- To deplete large fraction of HR substrate: need to separate p-well from p-type substrate
  - influenced by n-layer doping as well as details of NGAP width of XDPW implant width & doping depth
  - Have optimised in TCAD and with foundry process experts



H. Pernegger, NIM A 986 (2021) 164381

Substrate bias voltage: Epitaxial & Czochralski

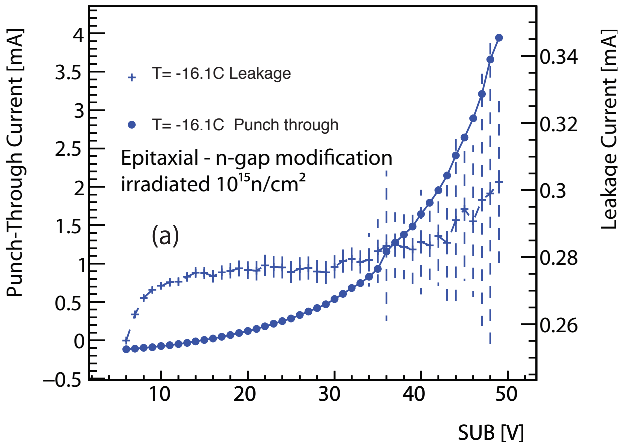
- Measured punch-through on MALTA1 on HR Cz substrate
- before irradiation
- continuous n-layer well separates the p-well from p-substrate
- NGAP/XDPW reduce possible substrate voltage



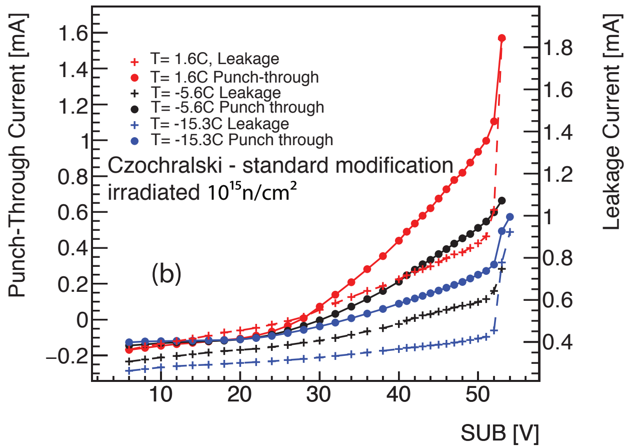
Substrate bias voltage: Epitaxial & Czochralski

- After irradiation (1e15 neutrons/cm2)
- Separation between p-well and substrate improves
- Large operation voltages (~50V) are also possible with NGAP/ XDPW which improves depletion and charge collection after irradiation

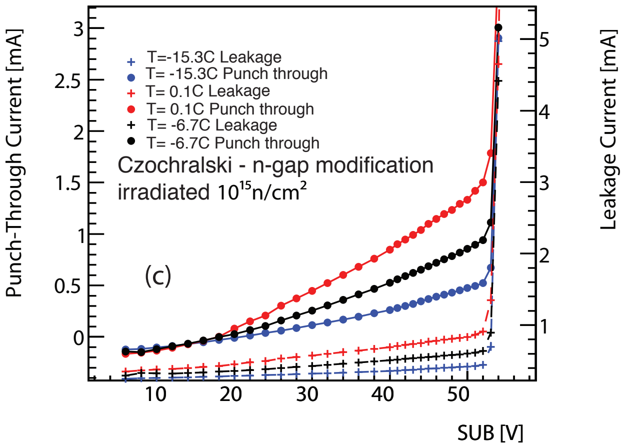
epitaxial N-gap n-layer



Cz continuous n-layer

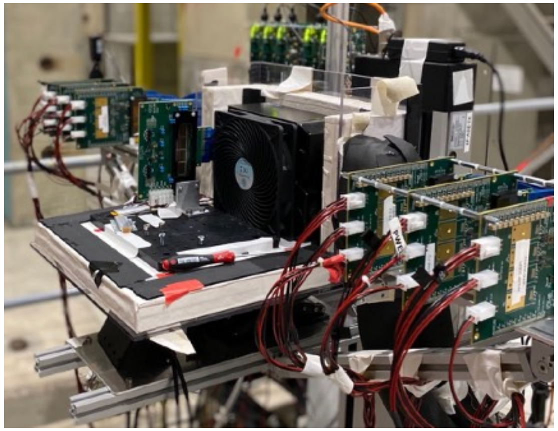


Cz N-gap



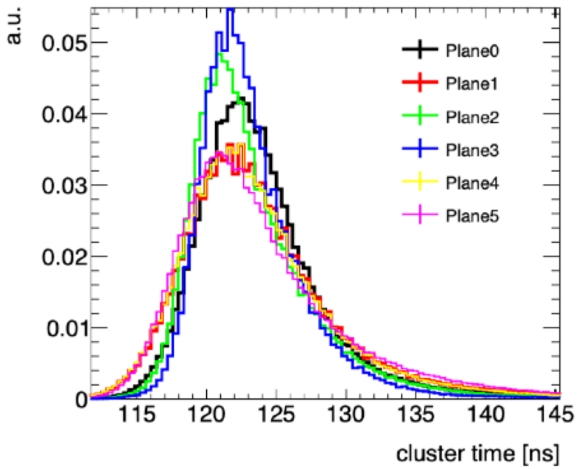
MALTA Testbeam Telescopes & Beam tests

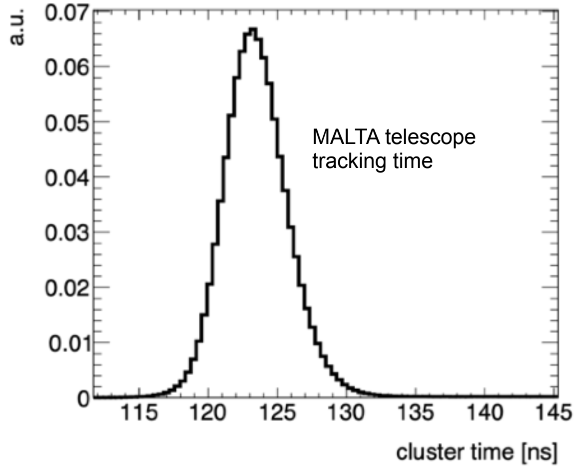
- Custom MALTA telescope with fast read-out, online monitoring, and cold box for irradiated samples
  - Up to 7 planes + DUT or 6 planes + 2 DUT
  - Triggering directly out of MALTA planes
  - Scintillator for better time reference
  - Continuous operation in 2021 and 2022
- Track reconstruction better than 6 um position and ~2 ns timing



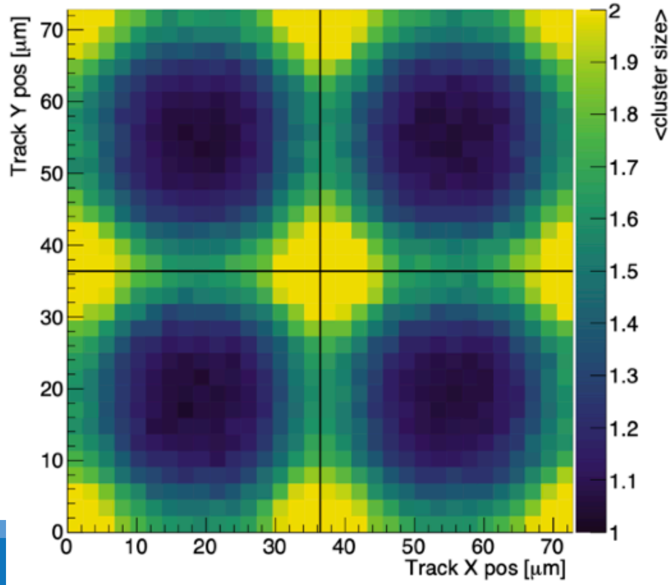
MALTA telescope at SPS

Cluster arrival time in different planes:





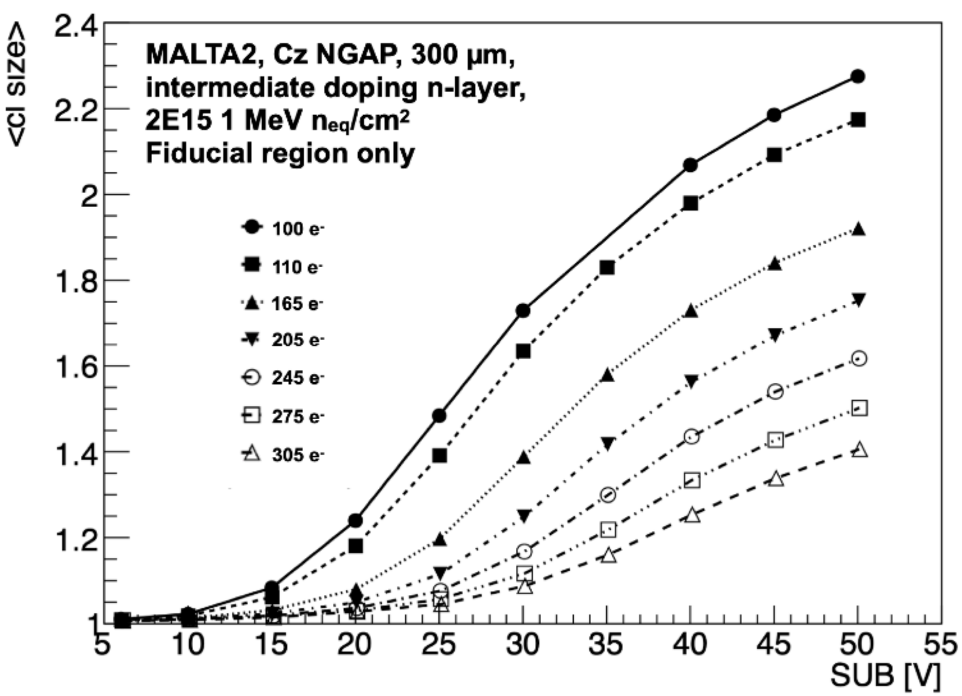
Cluster size versus hit position (Cz)

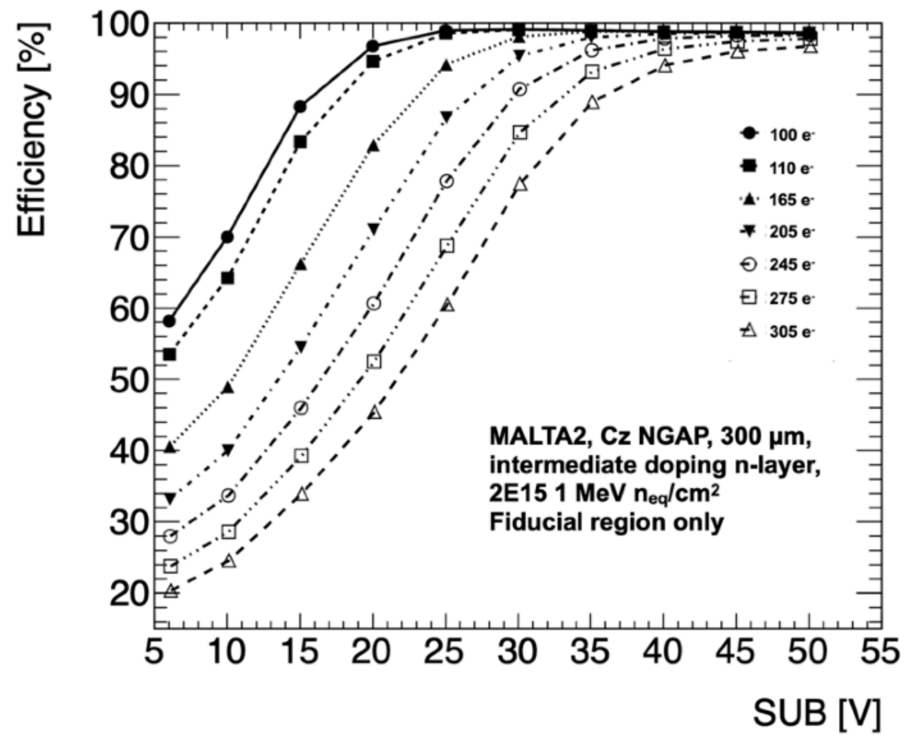


M. Van Rijnbach BTTB 2022

NIEL Irradiated MALTA2 sensors

- Good performance of Cz samples at $2x10^{15}$ n/cm^2
- Sensor back with conductive glue to PCB for more uniform substrate biasing
- Cluster size increases with substrate voltage
  - Maximum at ~2.2 at 50 V at 100 e-
- After $2x10^{15}$ n/cm^2 efficiency better than 98% at 50 V bias at threshold = 100 e-

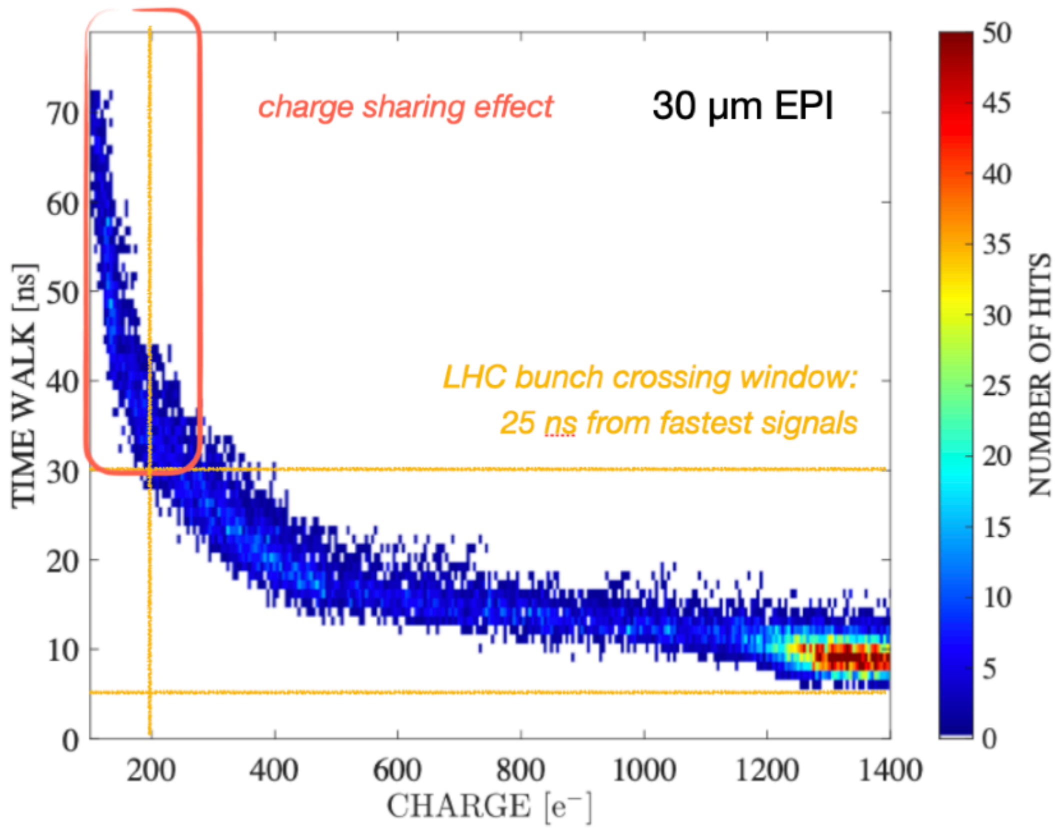




Timing properties of MALTA2 sensor FE

- FE time-walk measured on special pixels with analog output

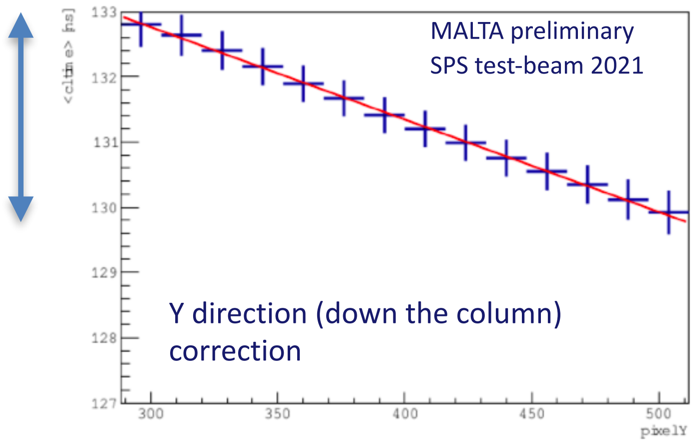
- Sensor measured with 90Sr source
- 90% of hits (not clusters !) arrive within 25ns
  - late hits are small hits from shared clusters
- In-time threshold ~ 200e-

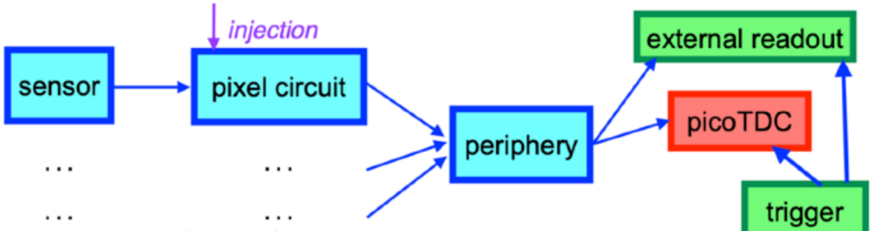


IEEE Trans. Nucl. Sci. , vol. 69, no. 6, pp. 1299-1309, June 2022

Timing properties of MALTA2 matrix

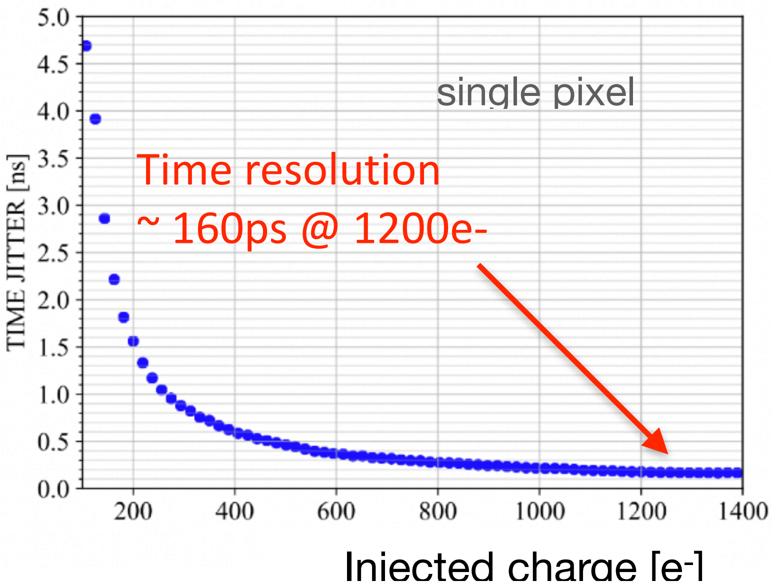
- Signals discriminated in pixel and transmitted through pixel logic down column to periphery





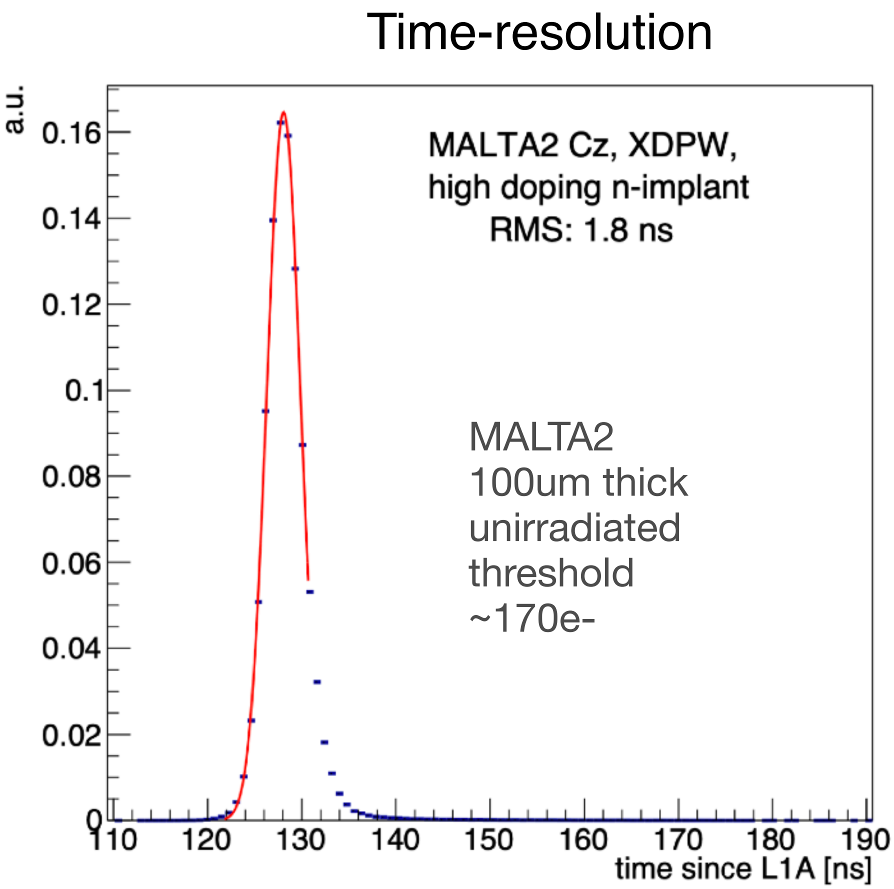
Column propagation time ~3ns for 224 rows

- Measure Time resolution with injected pulses
  - Total jitter from FE to DAQ is dominated by FE
  - Jitter varies from 4.7ns @ 100e- to 160ps @>1200e-
  - Uniform across the chips

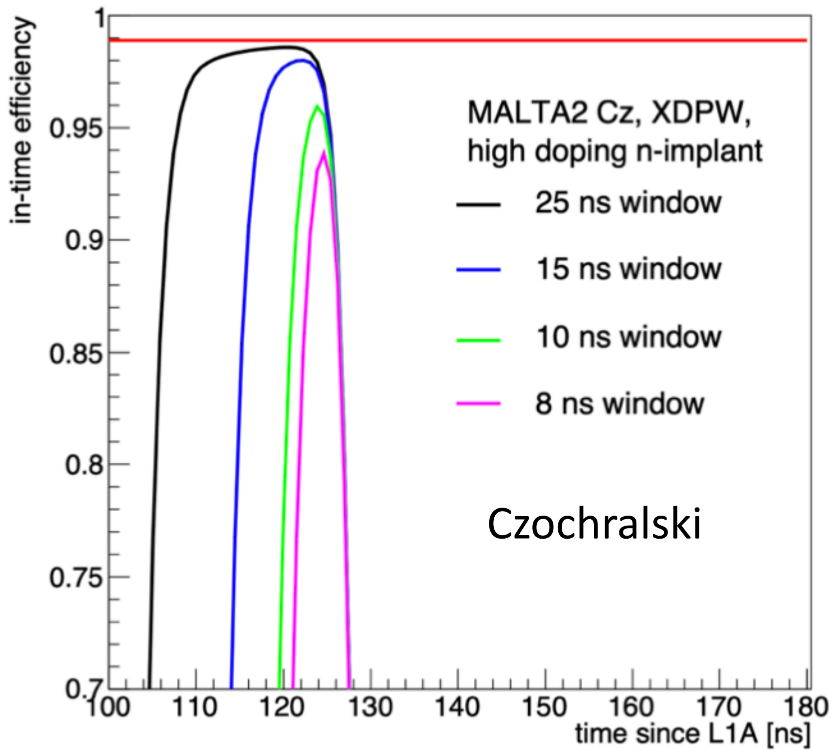


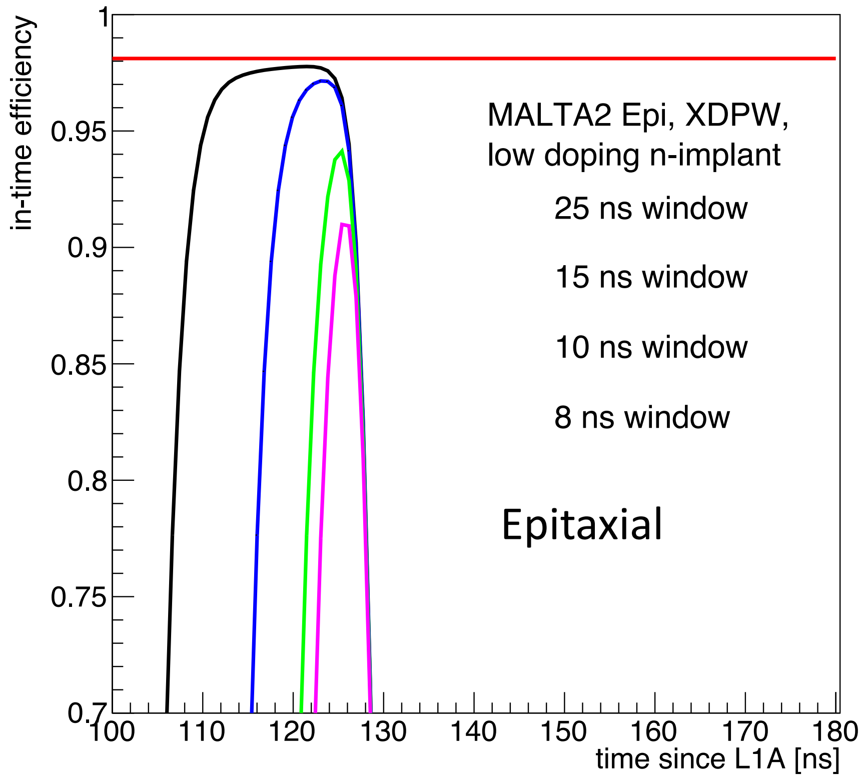
MALTA2 Time resolution in beam tests

- Time of arrival of leading hit in the cluster w.r.t. scintillator reference
  - Included scintillator jitter : 0.5 ns
  - Signal latching at FPGA: 3.125/sqrt(12) = 0.9 ns
- Timing resolution integrated on full chip 1.8 ns r.m.s. including above system contribution
- Time resolution unfolded ~ 1.45 ns
  - propagation along column corrected



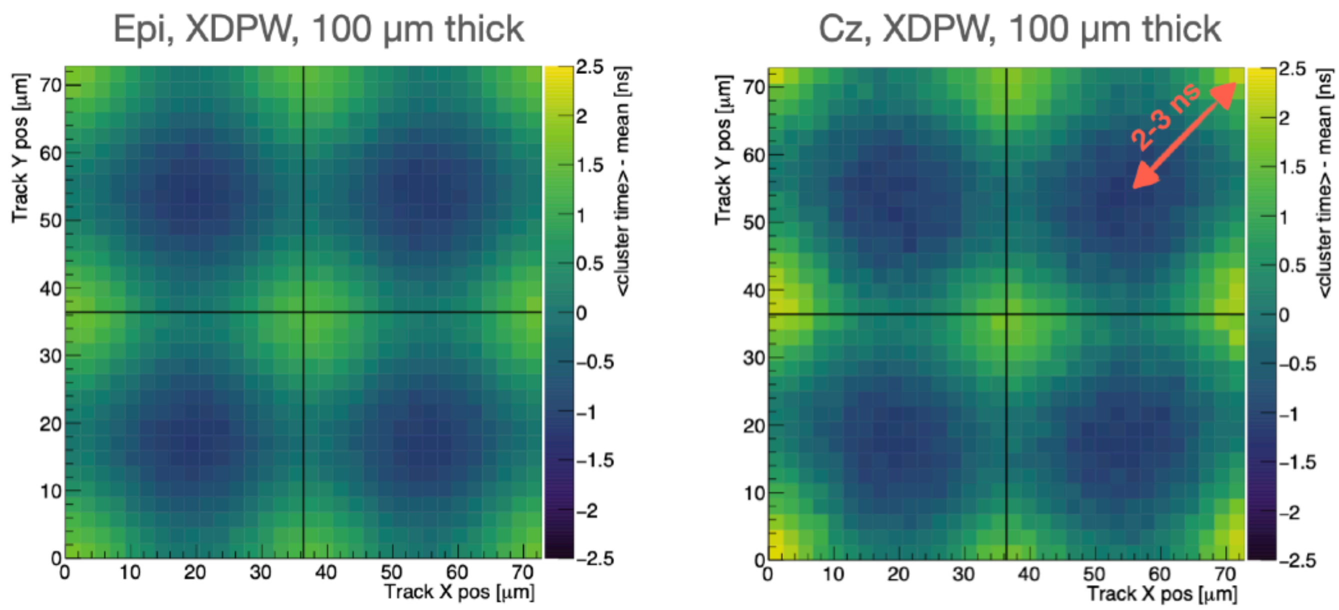
MALTA2 In-time efficiency in beam tests





- In-time efficiency 98% in 25ns (LHC) time window & 95% in 10ns time window
- Better in-time efficiency on Cz substrates (higher signal amplitude)

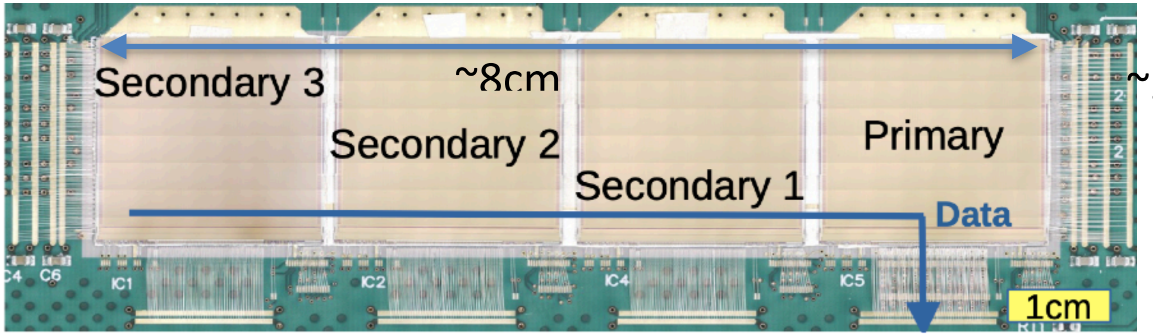
MALTA2 Timing versus hit position in pixel



- Induced current signal from hits under deep-p-well in pixel corner is delayed by ~2ns wrt hits close to the electrode
  - this is due to the very non-uniform weighting field in small electrode pixel designs and their drift field & velocity
  - This has been confirmed by simulation (TCAD, Weightfield2 with MALTA doping profiles)
- FE Time-walk adds to this due to smaller signals in pixel corners due to charge sharing

MALTA Modules with multiple sensors

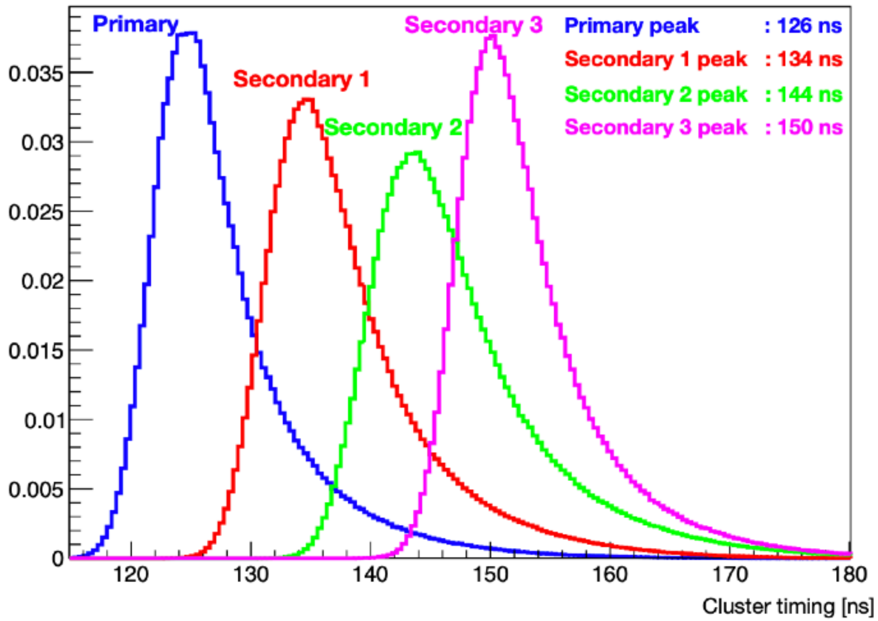
- Develop module concepts for the MALTA sensor as part of EP RD WP 1.3
  - low material budget assemblies
  - direct signal transmission from sensor to sensor



F. Dachs / Elba 2022

Testbeam with 4-chip module:

Cluster time for hits in chips



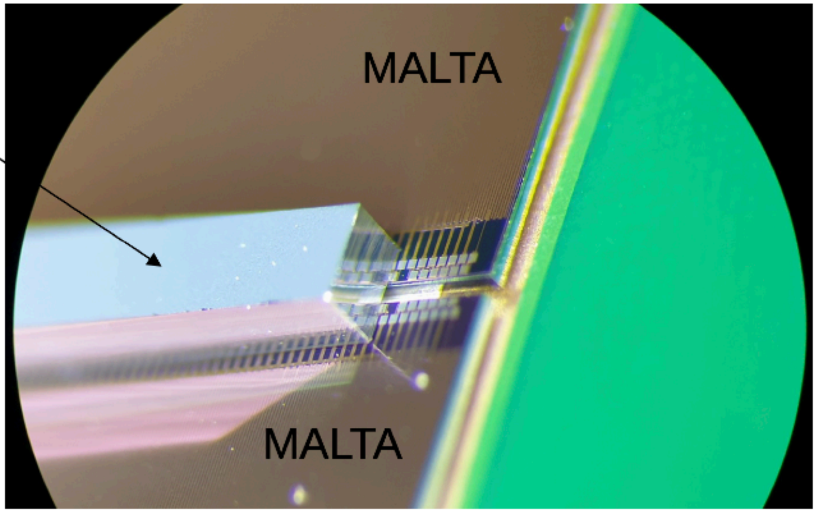
- Built modules with up to 4 sensors, tested in Lab and beam tests
- Daisy chain data of several sensors into single output
- Chip to chip readout works: hit address & timing information transmits well to primary and DAQ

MALTA Module assemblies with silicon bridges

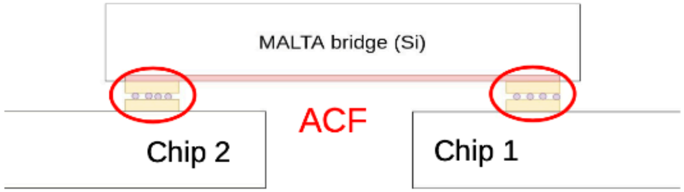
- No wire bonds - use silicon bridges to interconnect signal and power
- Bridges are produced in same TJ180nm process and can include active components like regulators (sensor powering) or amplifiers/ buffers (signal transmission)

- A flip chip process is used to place a **silicon interposer (silicon bridge)** between adjacent MALTA chips for data and power transfer
- Silicon bridge processed as part of the engineering run
    - Potential to adapt design to use silicon bridge for:
        - **Logic**
        - **Additional Power** delivery
- Interconnection is realized using **Anisotropic conductive film (ACF)**

J. Weick / TWEPP 2022



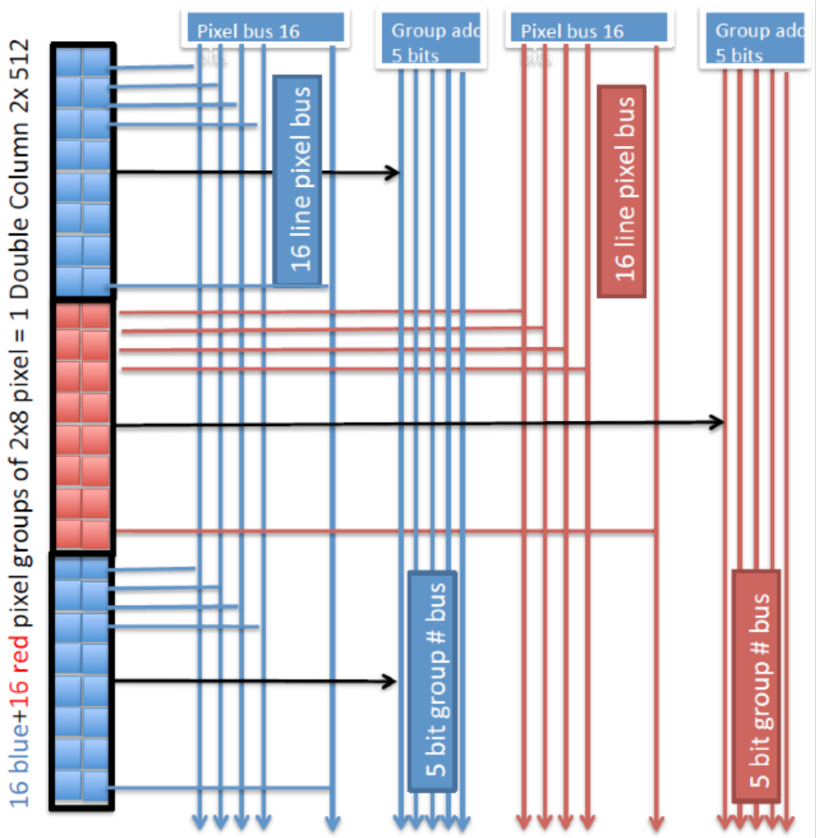
Silicon bridge connection two MALTA 1 chips



Outlook: MALTA3 with integrated hit time tagging

- MALTA matrix is based on asynchronous signal transmission

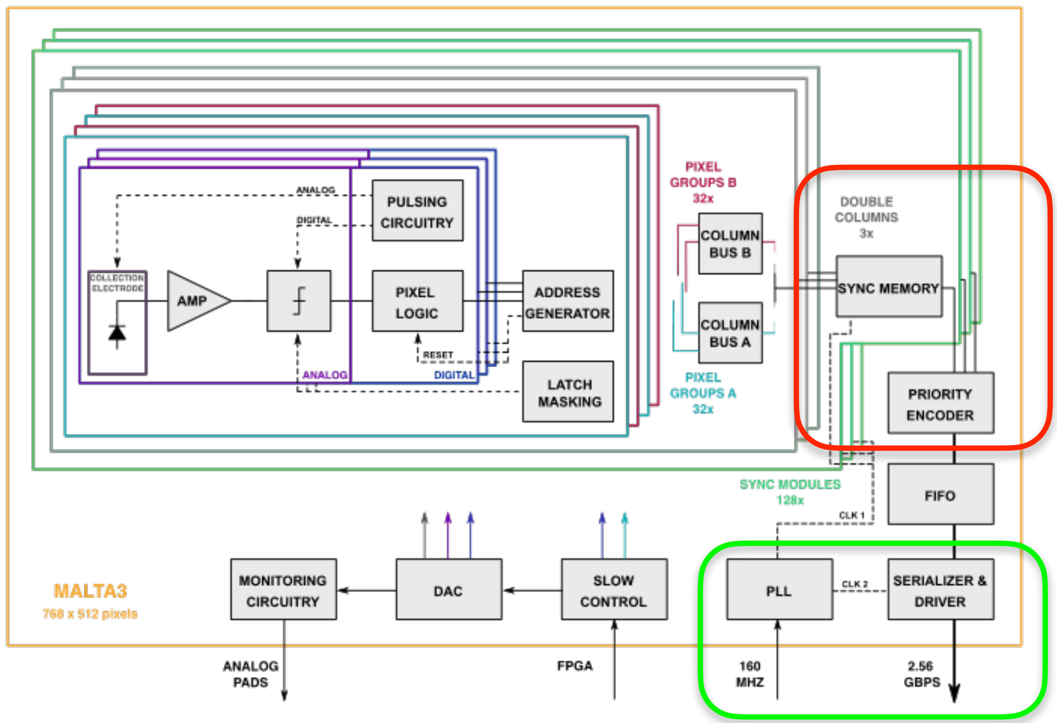
- Hits are stored using in-pixel flip-flops and **transmitted asynchronously over high-speed buses to the end-of-column logic** (digital periphery)
- **No clock distribution** over the active matrix to reduce power consumption and maintain hit-time information
- For MALTA1 and MALTA2 the signals are aggregated on 40bit parallel bus
- Time stamping is currently done in FPGA



Outlook: MALTA3 with integrated hit time tagging

- Integrate time-stamping and data serialiser directly on sensor in periphery
- Developed in same TJ180 process as MPW chip (submission 2023)

- Modular 24-column block design to scale to desired sensors matrix size up to full-reticle size (2x3 cm)
- Improved timing reference pulse and masking
- Time-stamping of signals on-chip
- Time-stamping logic @ 1.28GHz
- Serialized high-speed output



Block diagram of MALTA3

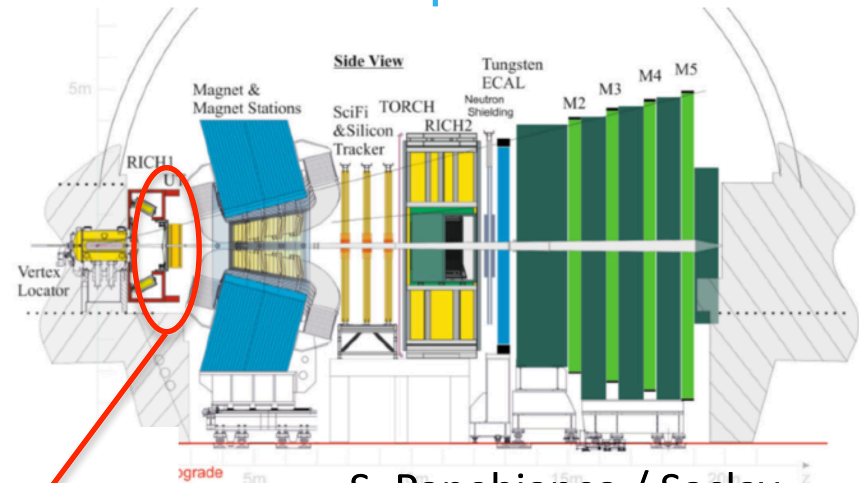
New for MALTA3 5-bit fine time synchronisation memory & readout logic

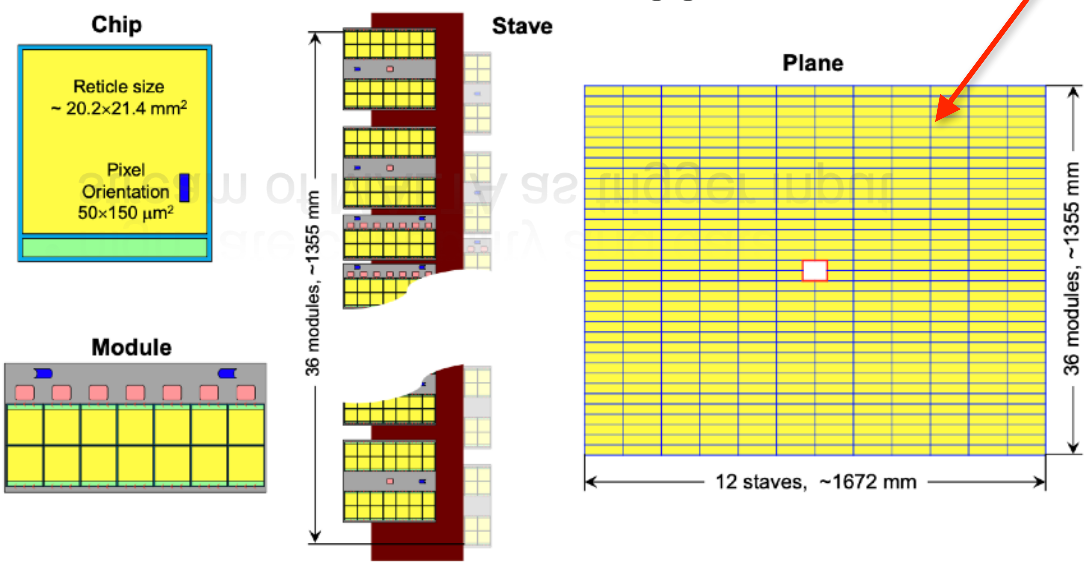
STFC "Precise" chip (PLL & serialiser already demonstrated on silicon)

D. Dobrijevic TWEPP 2022

LHCb UPGRADE 2 - Upstream Tracker upgrade

- LHCb plans to upgrade its Upstream Tracker and Mighty Tracker with MAPS (LV-CMOS and HV-CMOS)
- MALTA is consider as LV-CMOS candidate for the Upstream Tracker given the UT requirements:
  - NIEL 0.5 to 3 x10^{15} n/cm^2
  - desired time resolution < 3 ns
  - required pixel size < 50x150um
  - high rate capability and data stream of MALTA as trigger input





S. Panebianco / Saclay
J. Wang / Syracuse

CERN/LHCC 2021-012

Summary

- The MALTA sensor is being developed as radiation hard monolithic CMOS sensors for future trackers
  - The MALTA sensor is based on small electrode pixels and a trigger less asynchronous readout architecture
  - We have achieved 98% efficiency after $2x10^{15}$ n/cm^2 NIEL irradiation and good FE performance after 100Mrad
  - The MALTA sensors allows time-tagging of clusters with a time resolution of 1.8 ns for trackers in 40MHz to 100MHz bunch crossing experiments
- Develop multi-sensor MALTA Modules with new assembly techniques aiming at low-mass implementation and high data rate
- For MALTA3 implement on-sensor time-tagging and data serialisation to enable system integration for asynchronous matrix readout in future experiments