Tower Jazz 180 nm MALTA monolithic active pixel sensor Test Beam results

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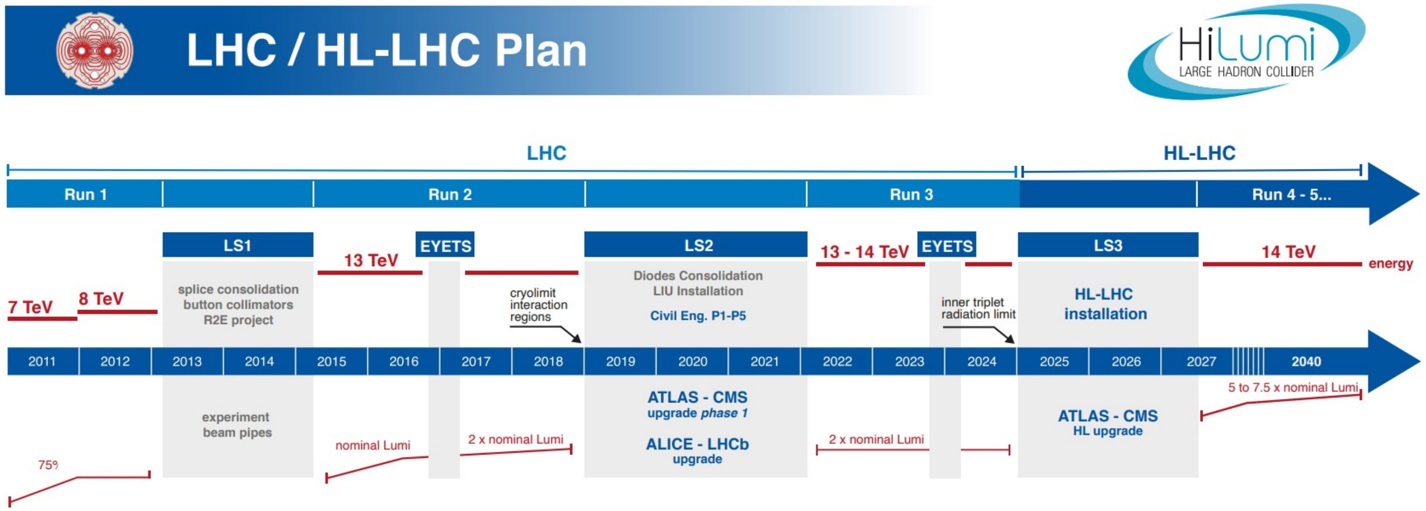
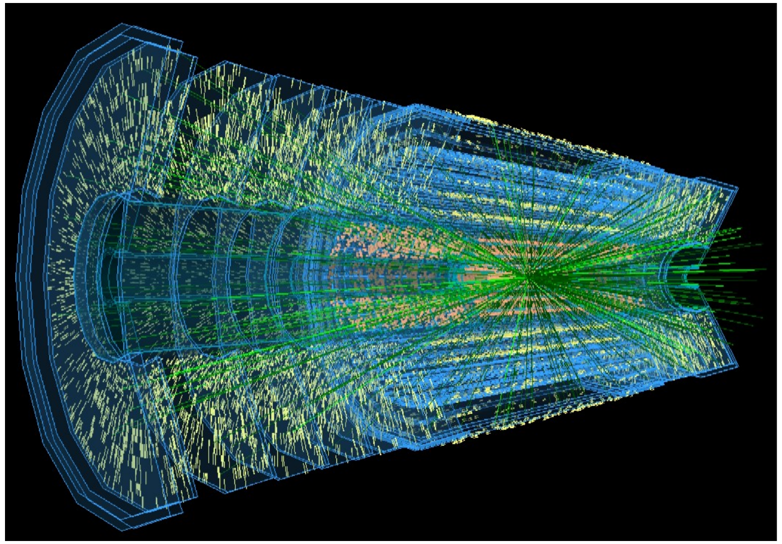
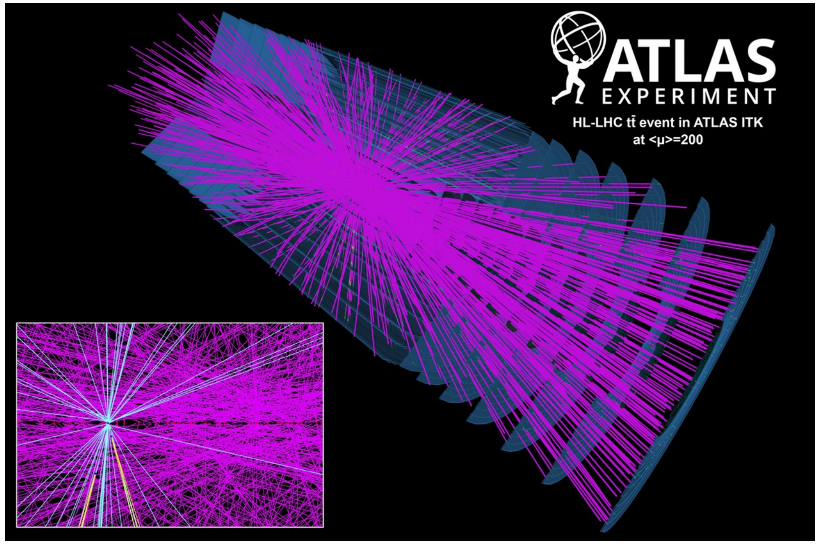
HELMHOLTZ

Future-proofing design

- Very high radiation tolerance
  (1 – 2E15 neq/cm²; 80 Mrad TID)
- High granularity (2MHz/mm² hit rates)
- Good timing response (<25 ns)
- Low material budget
  (cooling, power consumption)
- Large surface area
- Very thin



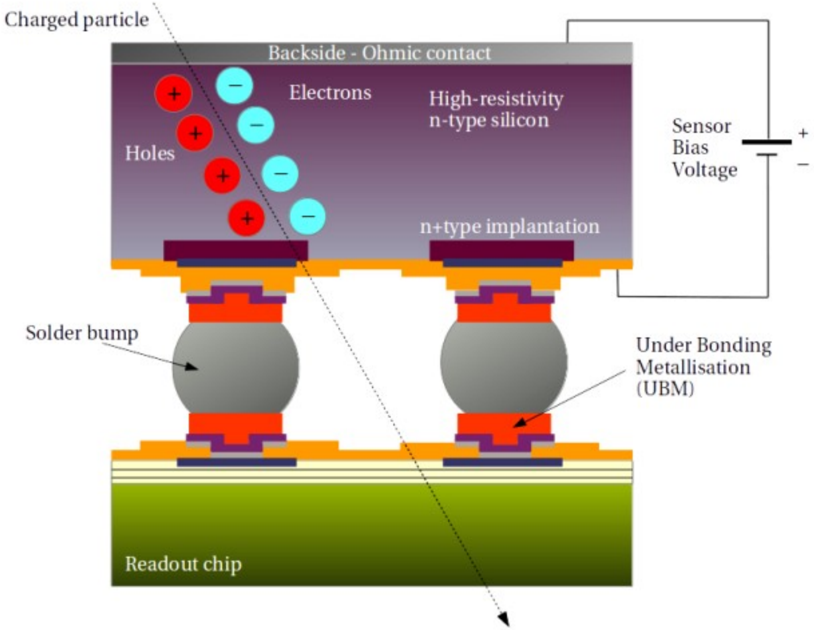


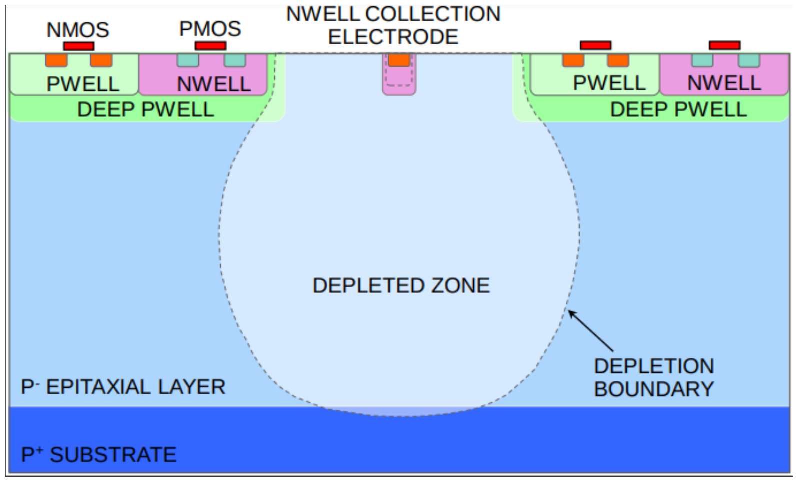


MAPS

Monolithic **A**ctive **P**ixel **S**ensors advantages:

- **Integration** of RO electronics and sensor in one die
- **Smaller pixel pitch**
- **Small sensor capacitance** (< 5 fF)
    - higher voltage signal
    - better power/performance
    - reduced material budget for powering and cooling





Hybrid sensors

- Two chips (sensor, ROC)
- Large electrodes, capacitance
- Expensive bump bonding
- Well understood radiation hardness

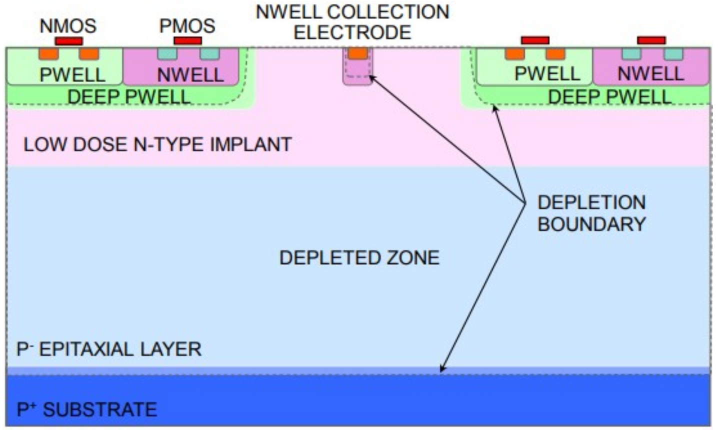
Monolithic sensors

- One chip = (Sensor + ROC)
- Smaller electrodes, capacitance
- Less material; lower power needs
- Radiation effects still being studied

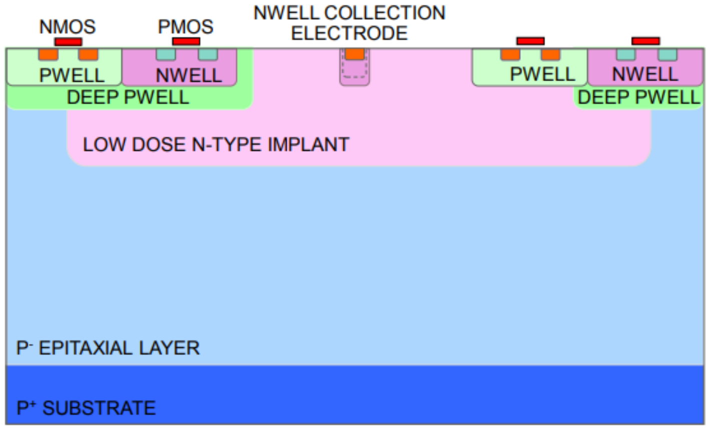
Panati S. "MATISSE: A Versatile Readout Electronics for Monolithic Active Pixel Sensors Characterization" (2017)

TJ 180nm CMOS MALTA Process

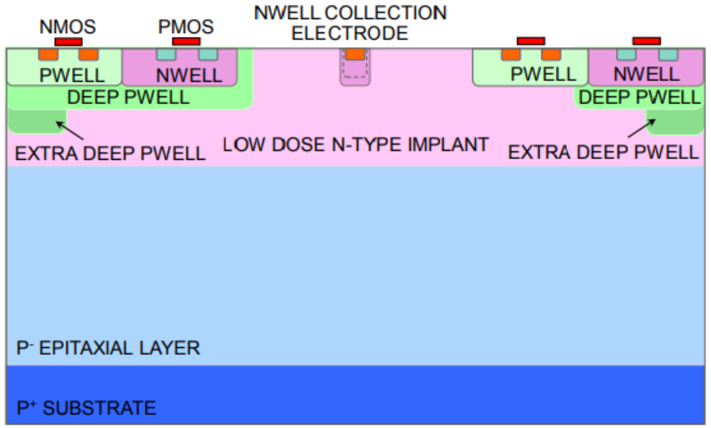
STD



NGAP



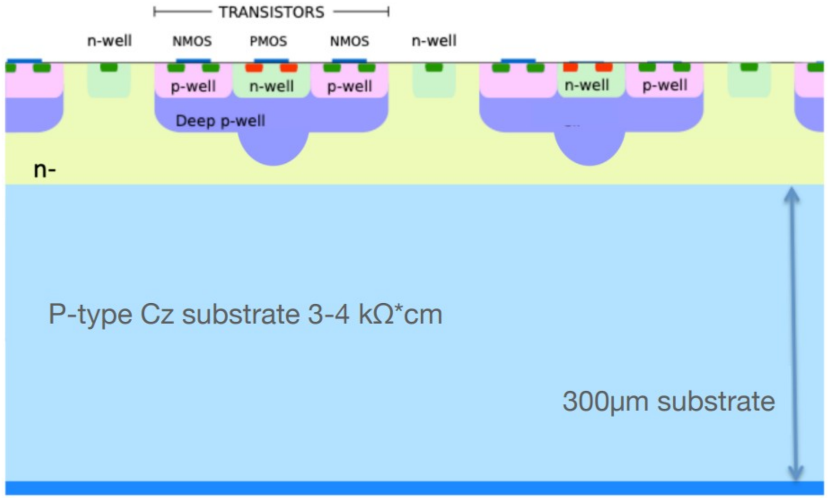
XDPW



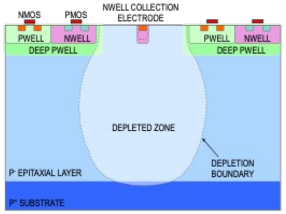
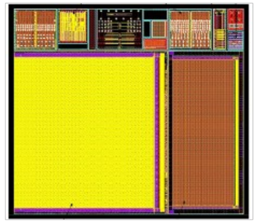
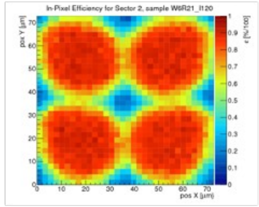
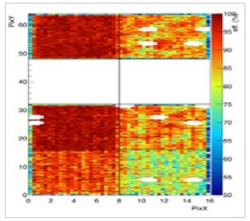
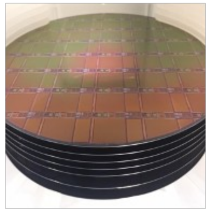
3 CMOS flavours:
- **STD** Extra N-type implant for improved depletion zone
- **NGAP** Gap in the low dose N-type implant
- **XDPW** Extra Deep P-Well

2 different substrates:
- High Resistivity Epitaxial layer (**Epi**)
- Czochralski (**Cz**)

Cz substrate



R&D MALTA Timeline

Standard Modified process		First promising measurements	2014
MALTA and Monopix designs		First engineering run with large designs	07/2017
Sensor characterization		Efficiency/charge loss at the corner of pixels	01/2018
Further improvements miniMALTA		Pixel modifications and RTS improvements	09/2018
MALTA-C		Epi and CZ starting material	09/2019
MALTA2		New cascoded front-end and slow control	01/2021
MALTA3		Time resolution, full reticle size	2023

MALTA

- First large demonstrator (**2x2 cm²**)
- 8 sectors with different pixel flavors
- **Asynchronous readout**
- Sensor functional. Slow control issues

miniMALTA

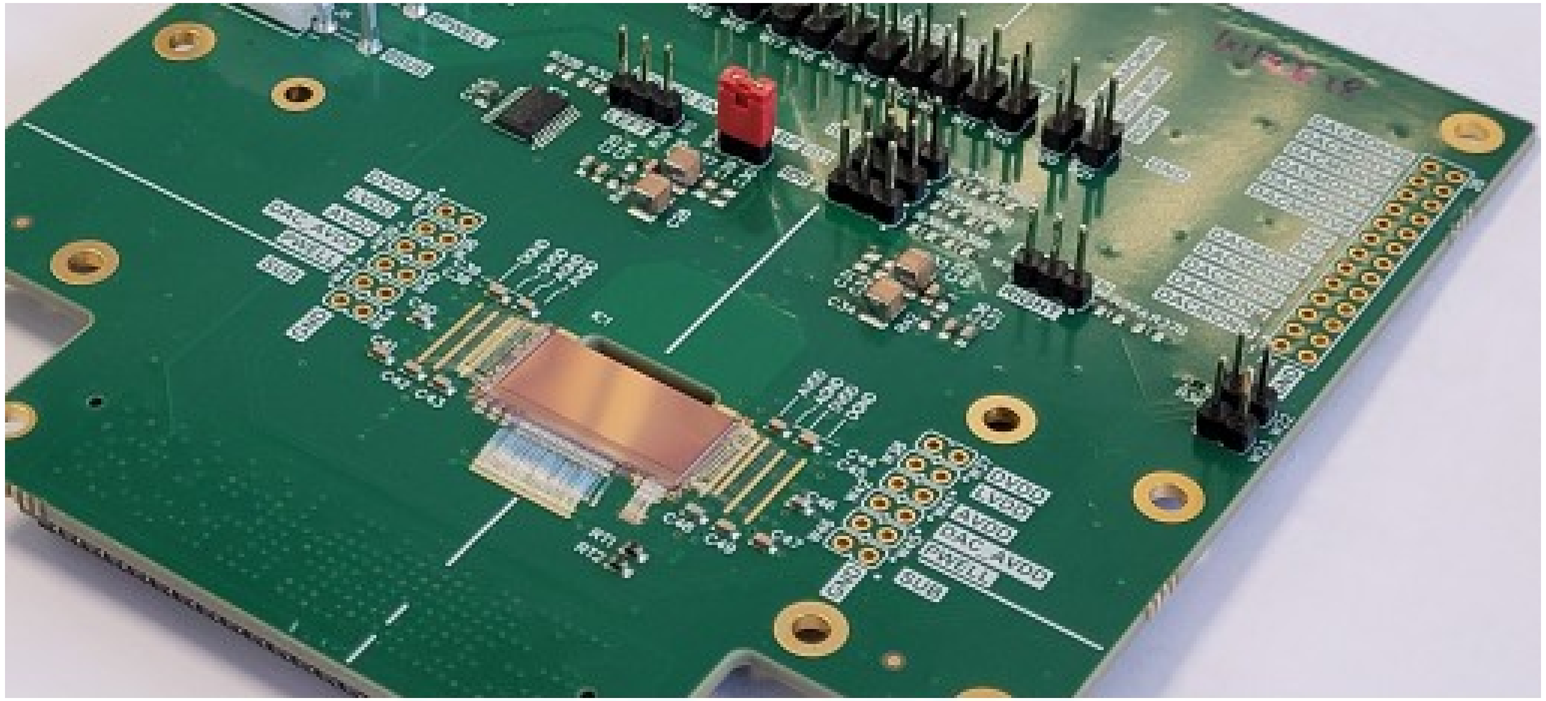
- Small demonstrator (**1.7x0.5 mm²**)
- Serial output
- **Cascoded FE**
- Rad hard, RTS improvements

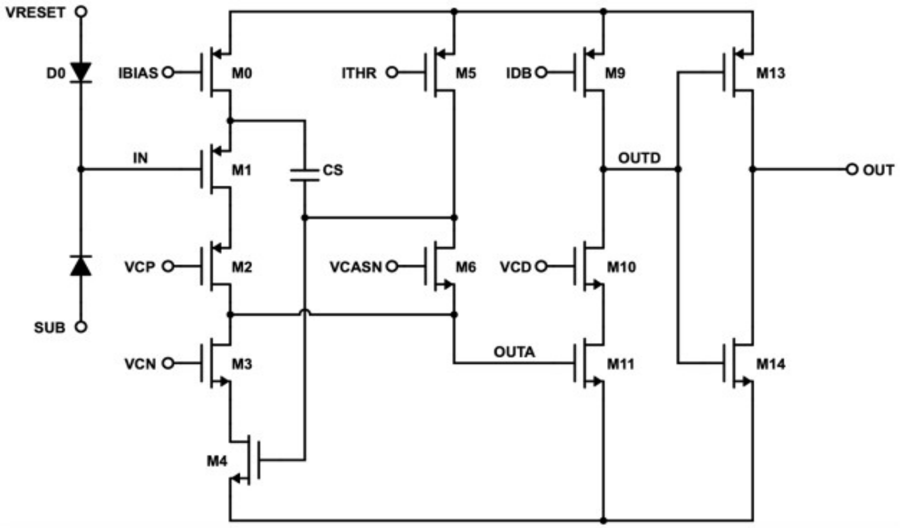
MALTA2

- Smaller matrix (**2x1 cm²**)
- **New Slow control**
- Mini-MALTA FE
- Under test!

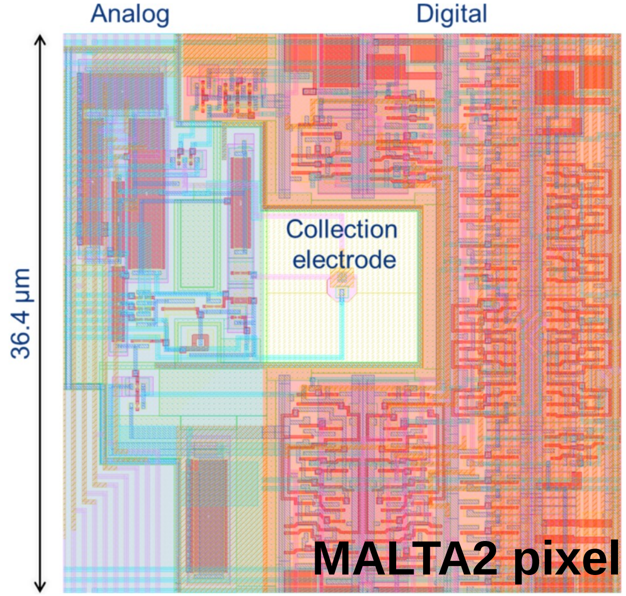
TowerJazz MALTA2

- **224 x 512** pixels (36.4 μm pitch)
- **Small** collection electrode (2-3 μm^2)
- **Low** power consumption:
  - 1 μW/pixel analog power
  - 70 mW/cm^2 analog power
  - 10 mW/cm^2 digital power
- **Asynchronous readout**
  (No distributed clock across matrix)
- New **cascoded** FE (M3) &
  enlarged M4





MALTA2 cascoded FE

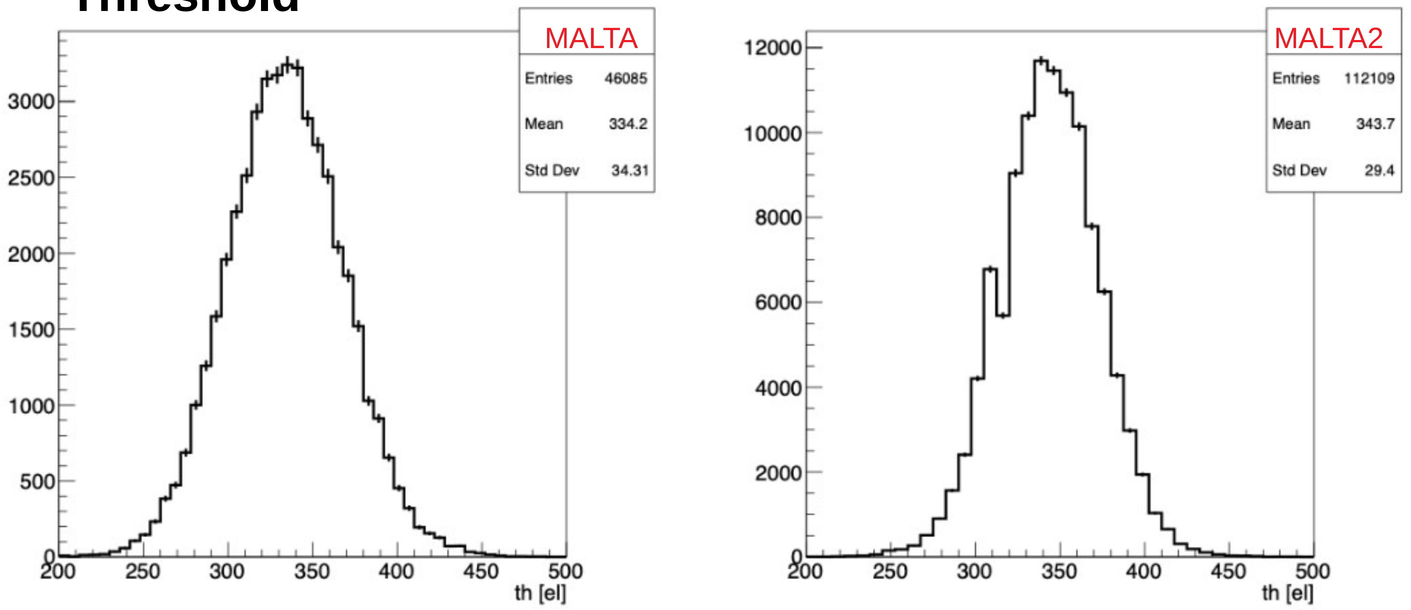


MALTA2 pixel

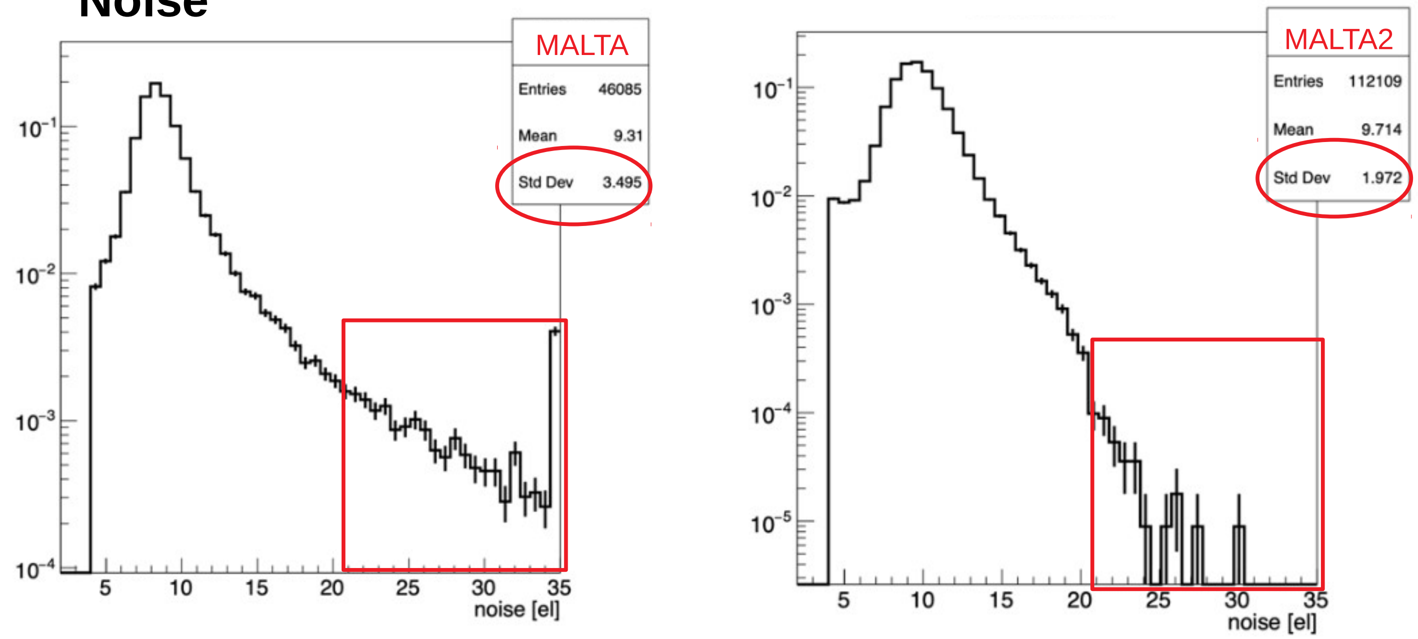
Threshold & noise

- **Threshold** & **noise** scans for MALTA, MALTA2 (Epi, NGAP, high doping of the n-blanket at -6V substrate voltage)
- **Similar threshold dispersion** (10%) around 340 electrons for both MALTA & MALTA2
- MALTA2 (cascoded FE) has **much lower non-gaussian tail** (RTS), compared to MALTA

Threshold



Noise

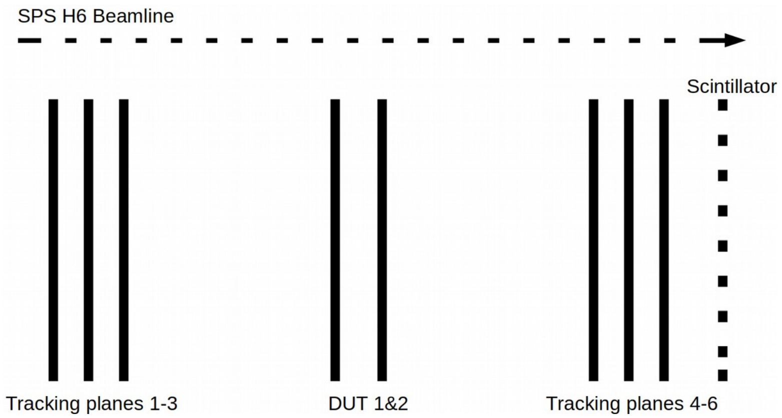


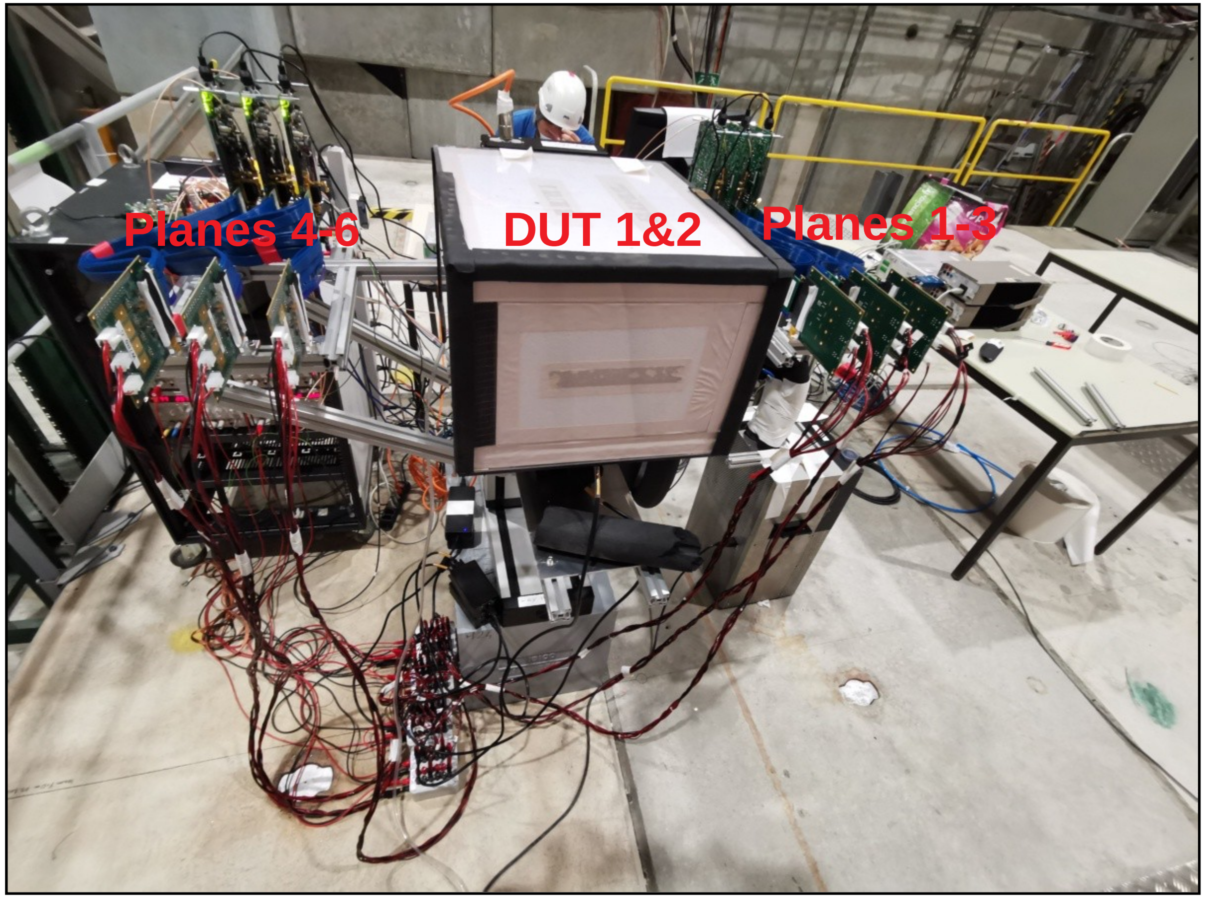
MALTA SPS Telescope

- **Malta Telescope** operated the whole of 2021 at CERN SPS H6 beamline. Aiming for the same for 2022!

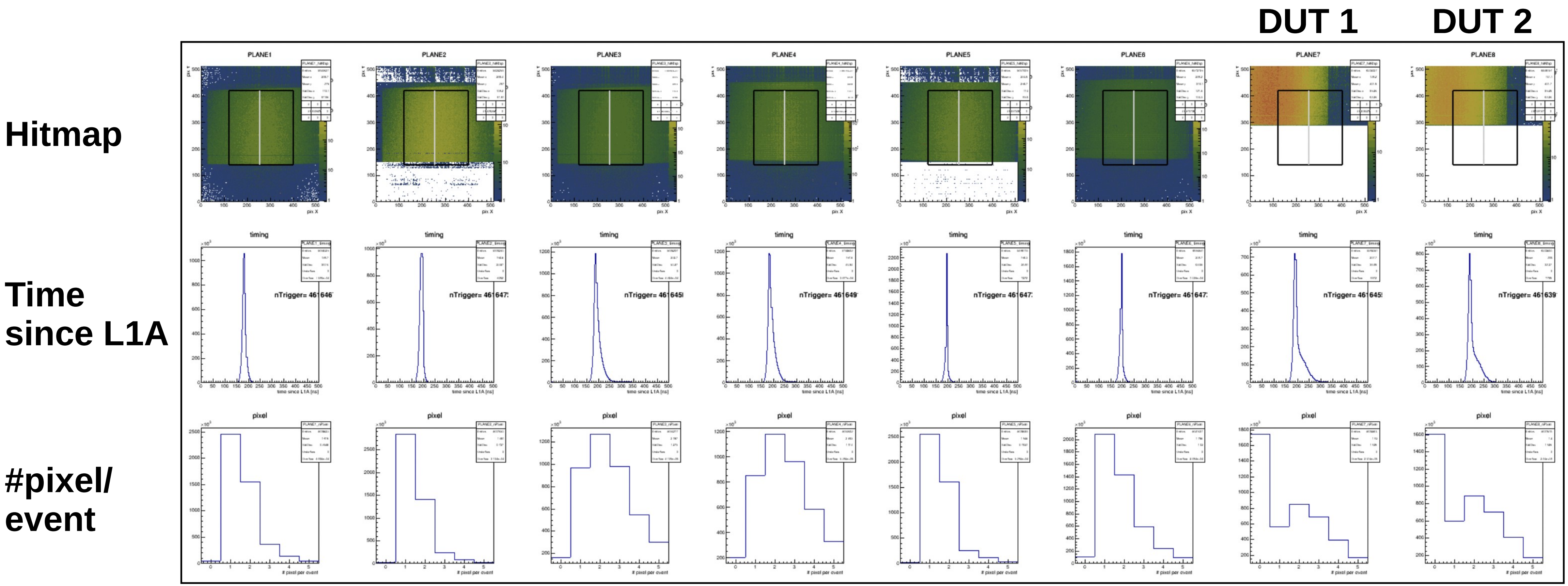
- **2021 SPS Test beam** Testing of MALTA2:
    - MALTA 2 performance
    - Radiation tolerance
    - Timing performance

- **Six MALTA tracking planes** (2x Cz, 4 Epi), Scintillator and Cold Box with capacity for up to 2 DUTs





SPS Testbeam Monitoring plots



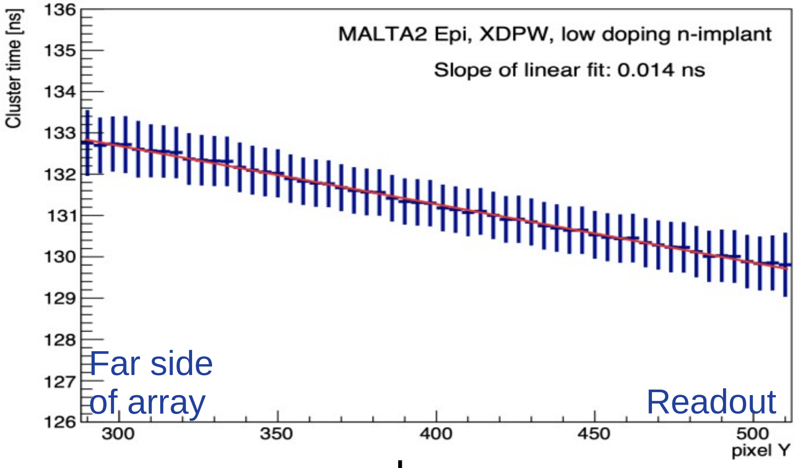
- **DAQ** with **online monitoring** (hit map, time distribution, number of hits per-event)
- **Fast track reconstruction** due to low noise/ occupancy (~1.2 hits/plane/event)

MALTA2 Timing

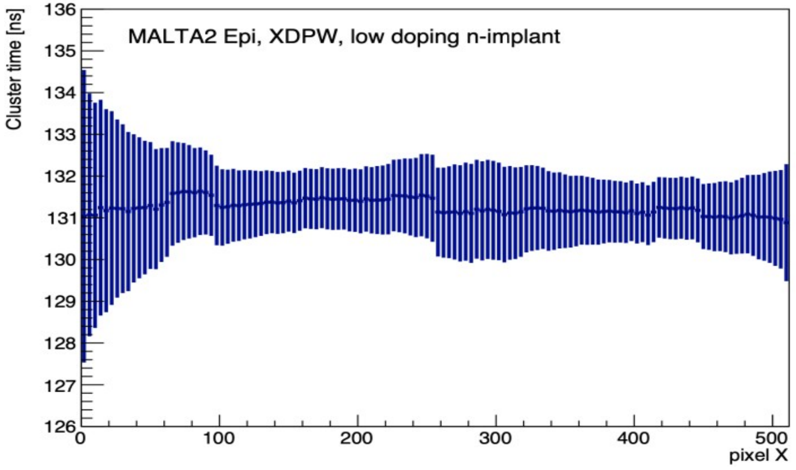
Time of arrival of the fastest hit in a matched cluster w.r.t scintillator reference, as a function of the matrix X/Y coordinate

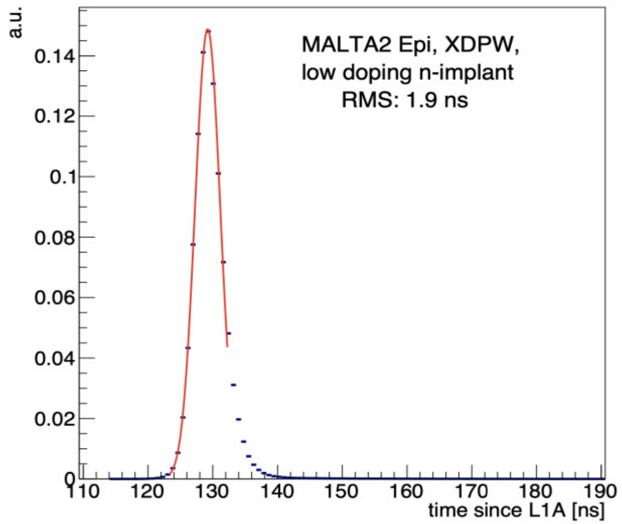
- **Timing corrections**:
  - **(Y)** Linear due to column time propagation (**top**)
  - **(X)** Non-uniform chip response in the row direction (**bottom**)

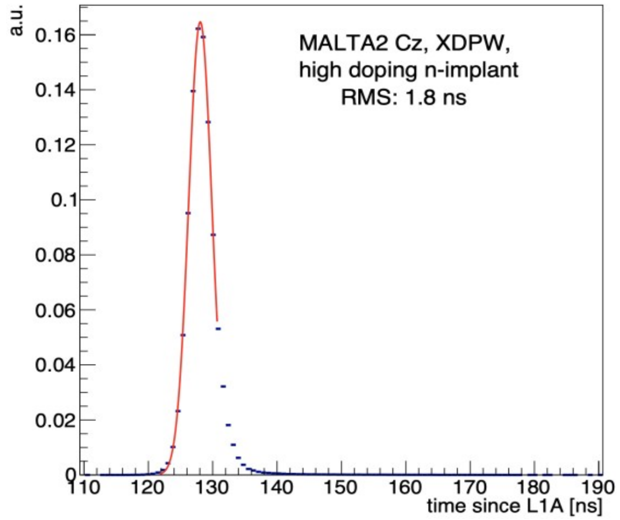
- The **timing plots** are a convolution of:
  - Electronics jitter
  - Time-walk
  - Charge collection effects
  - Scintillator jitter (500ps)
  - FPGA readout jitter (900ps)



Apply corrections

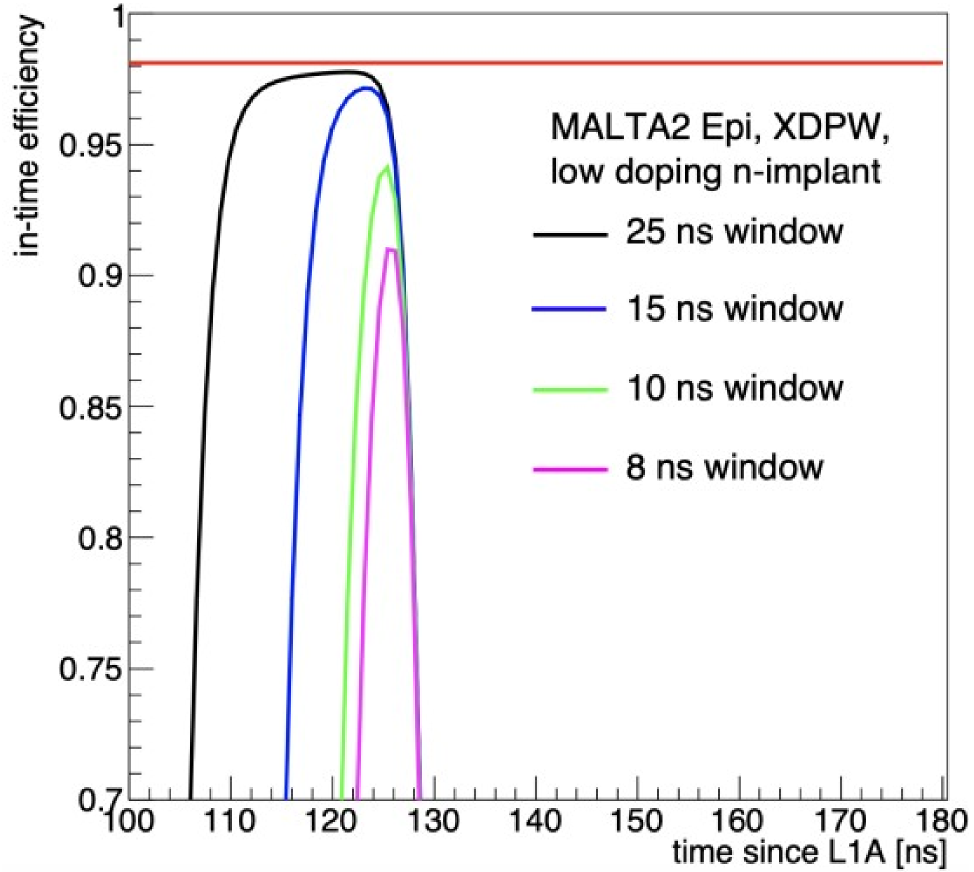


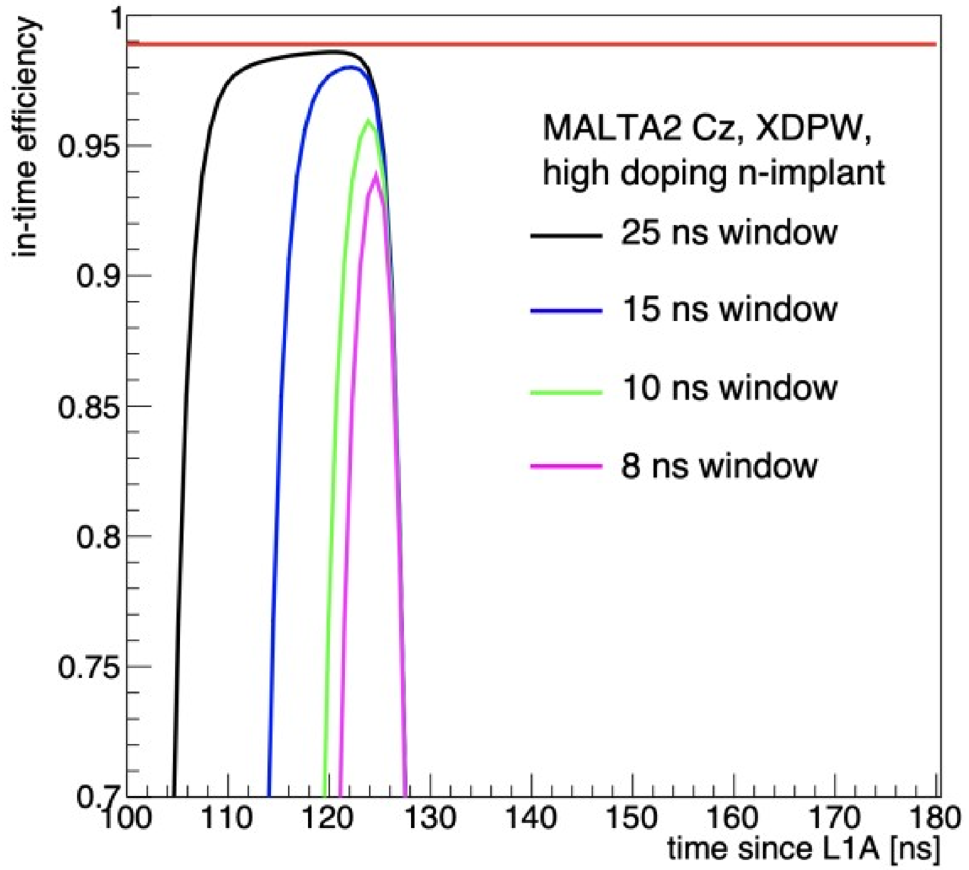




MALTA2 Timing

In-time efficiency for a sliding window of 25,15,10,8 ns w.r.t a scintillator



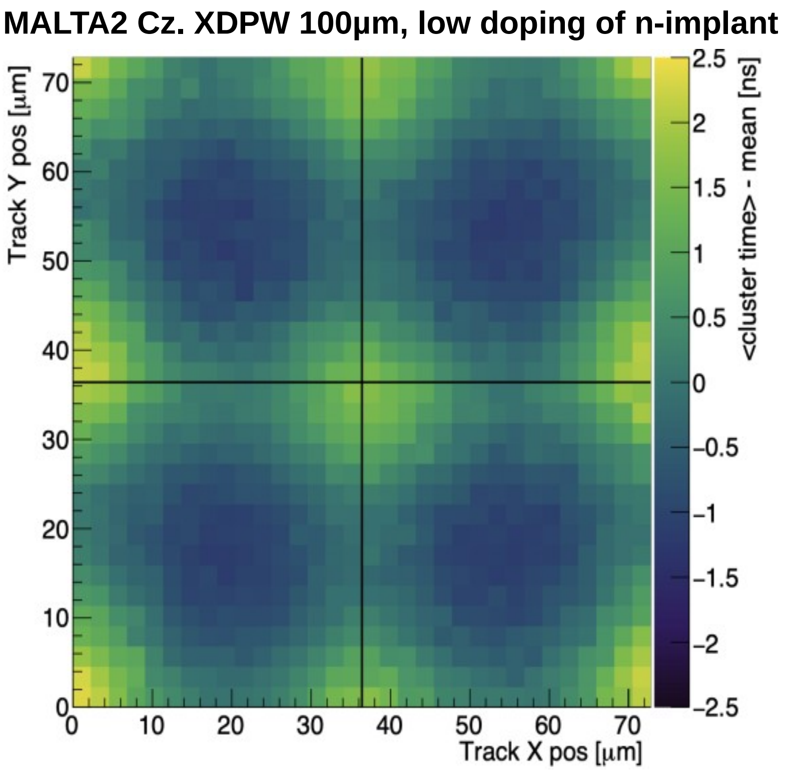


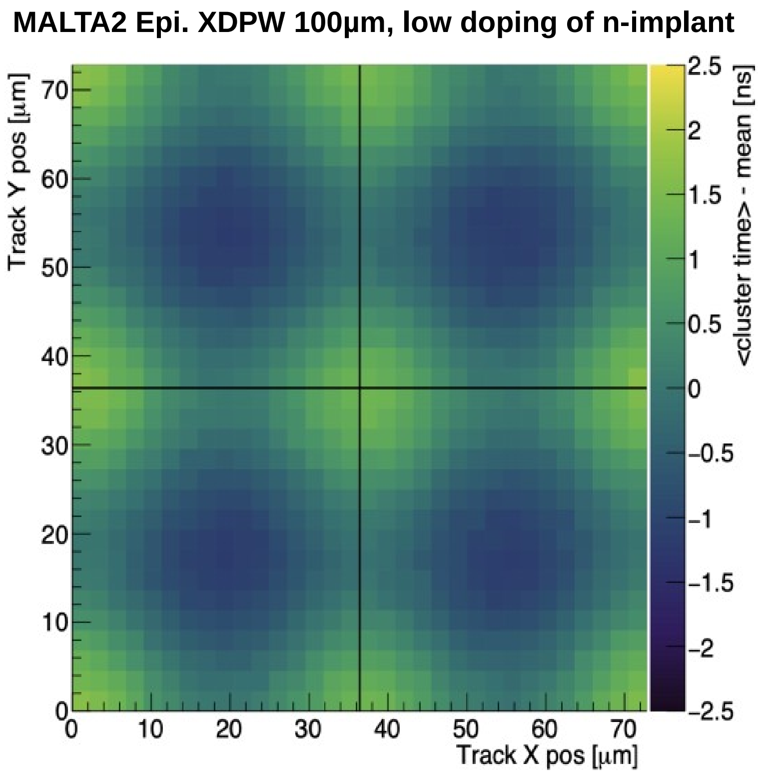
- **LHC 25 ns** bunch spacing: **>98%** of MALTA2 signals arrive; **FCC-ee <15 ns** bunch spacing: **>95%** of MALTA2 signal arrive;**> 90%** in-time efficiency for **8 ns window**

- **Cz** has **5% better** collection for a 8 ns window

MALTA2 Timing

In pixel cluster timing, projected over 2x2 pixel matrix for a Cz and for an Epi MALTA2 sample (XDPW, 100 micron, low doping of the n-implant)



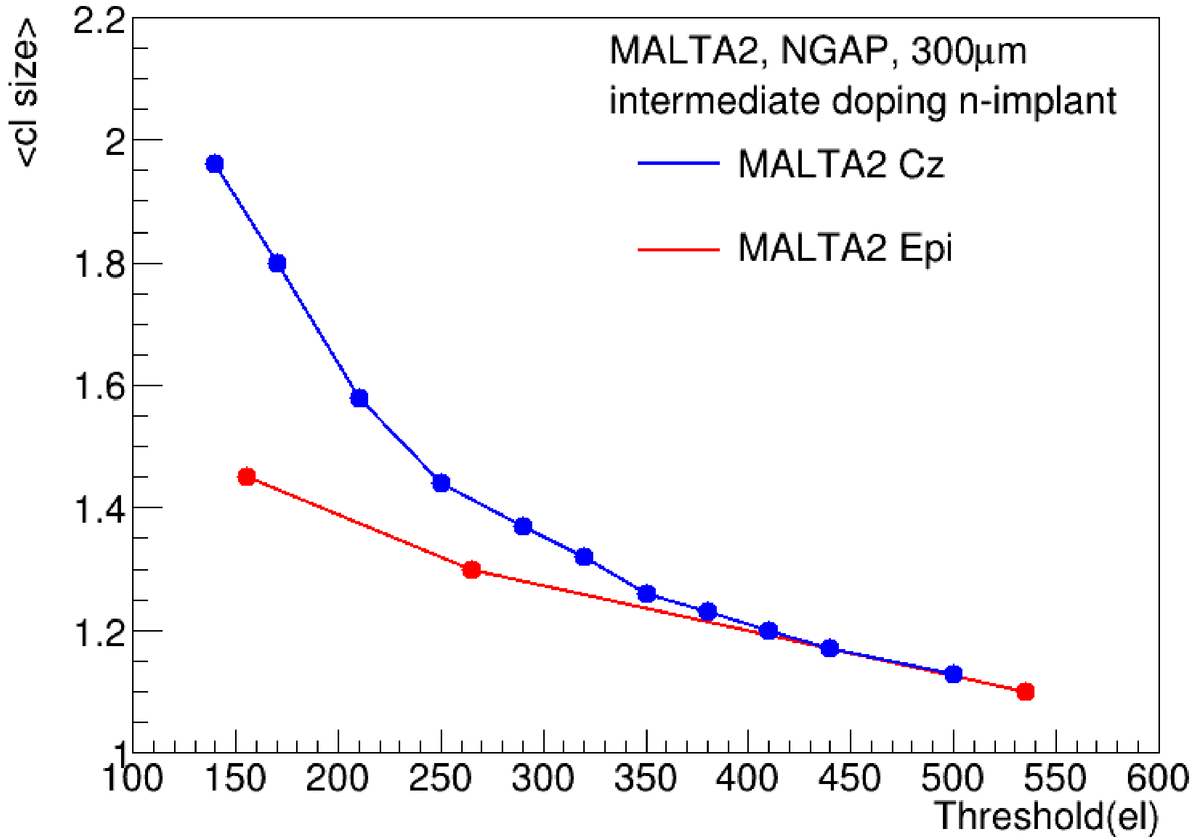


Threshold: 170 e^- @ -6V SUB voltage

- Pixel corners generate late-arriving signals
- Non-irradiated **Cz** and **Epi** sample have **similar** in pixel cluster timing

Cz vs EPI

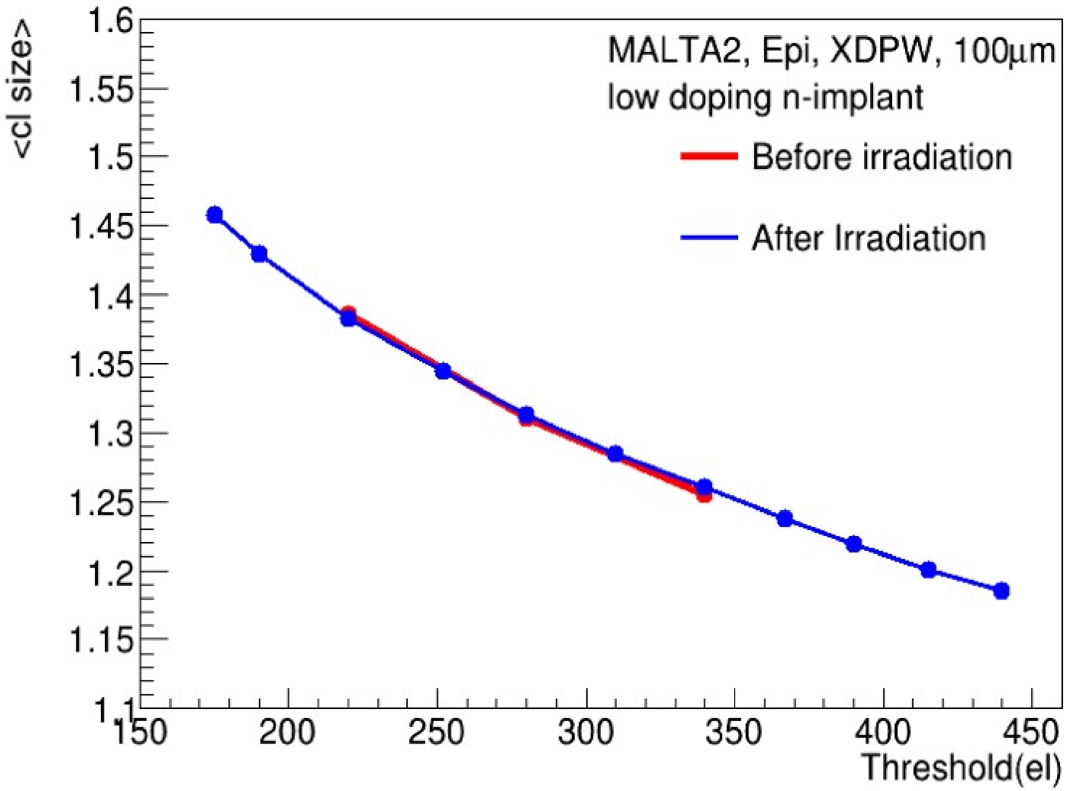
Average cluster size vs threshold in electrons for a MALTA2 Epi and a MALTA2 Cz sample

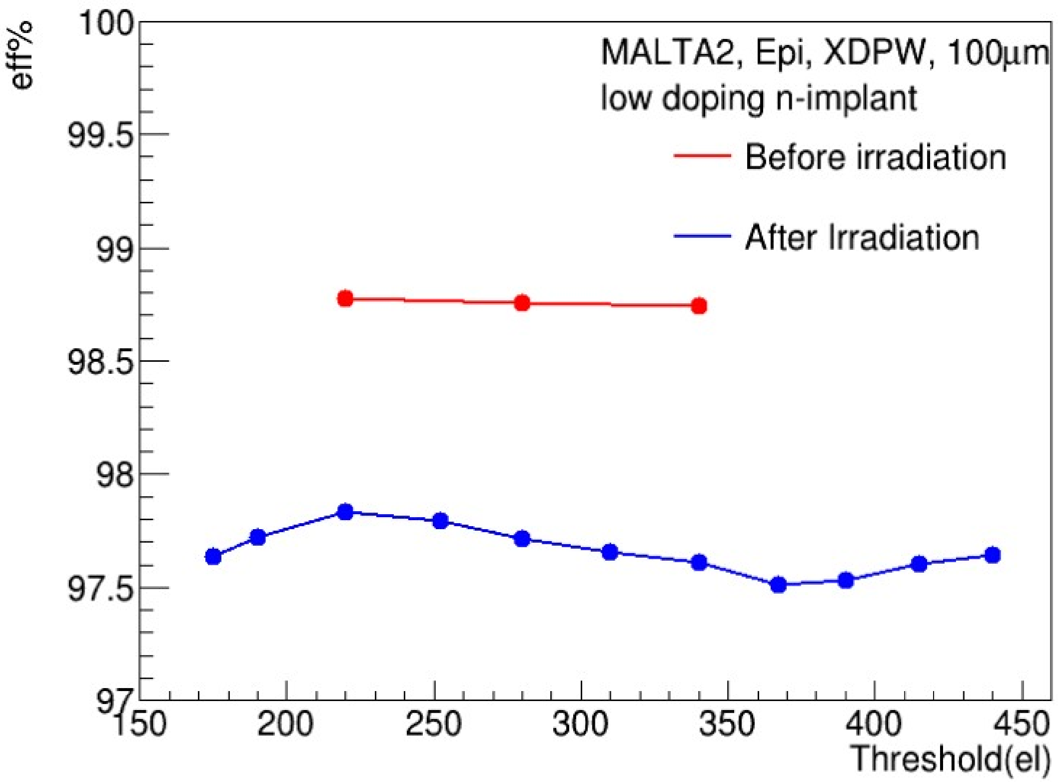


- **Strong dependence** of cluster size on threshold for both Epi and Cz samples at -6V substrate voltage
- Larger depletion voltage & signal of the high resistivity Cz substrate → **higher cl size at lower thresholds**

100 Mrad xray

Average cl size (left) and efficiency (right) in terms of threshold in electrons before and after 100 Mrad Xray irradiation of the same MALTA2 Epi

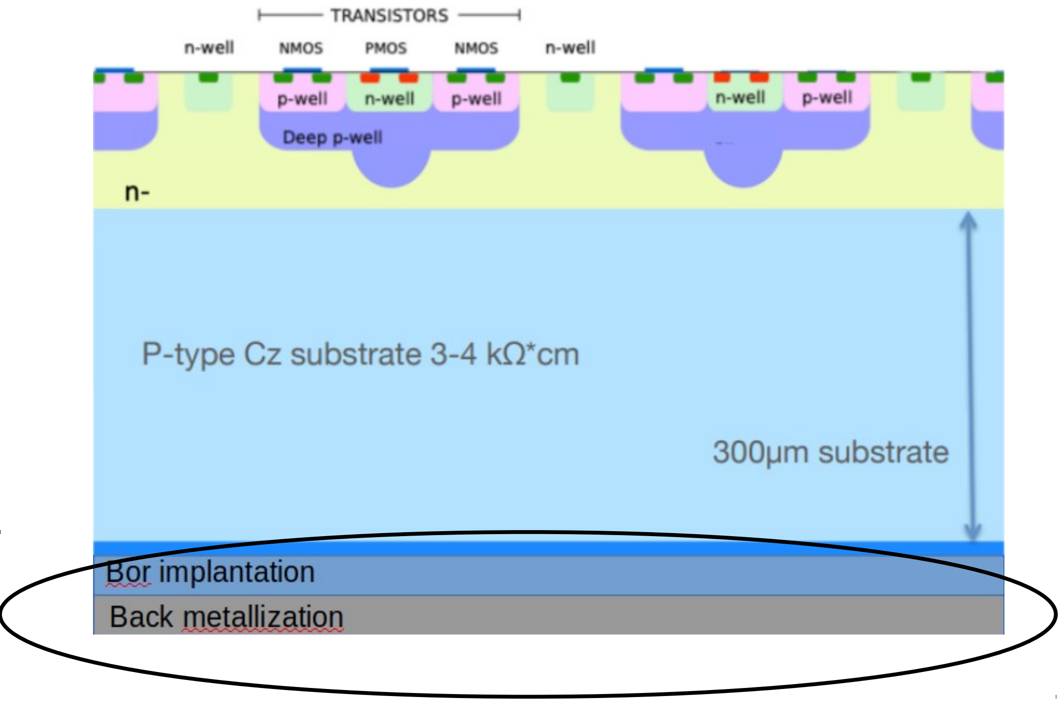


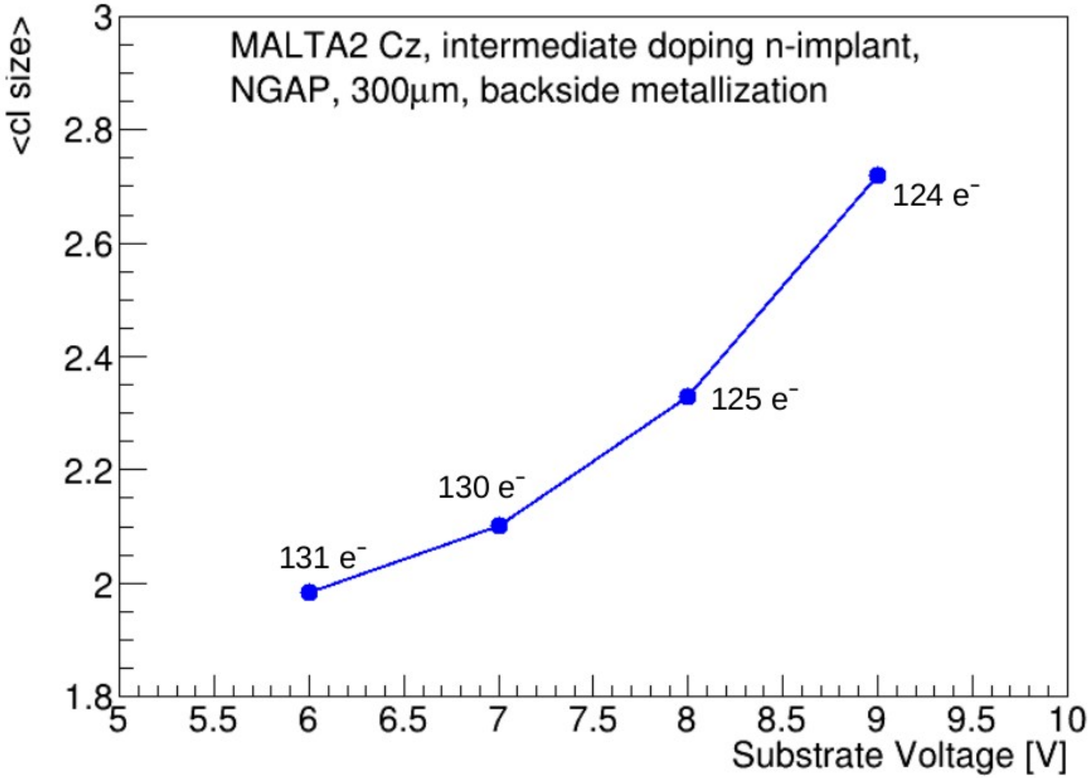


- **Strong dependence** of **cluster size** on threshold; relatively **flat dependence** of **efficiency** on threshold for -6V substrate voltage
- **After 100 Mrad** Xray, MALTA2 **performance is similar**: cluster size and efficiency (>97%) **within 2%**

Backside metallization

Average cluster size vs SUB voltage of a MALTA2 Cz, back metallized

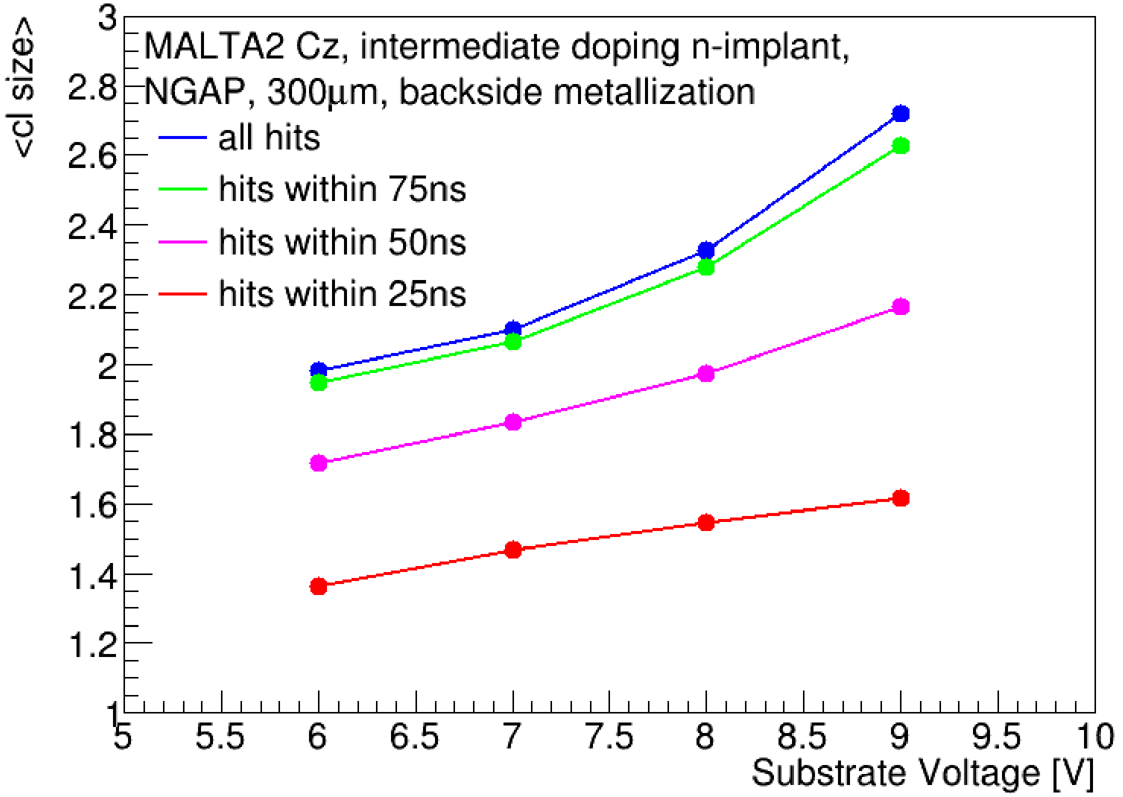




- No P+ substrate → non-homogeneous depletion regions. Back metallization leads to **better propagation of the substrate voltage** → homogeneous electric field
- Very strong increase in cluster size with SUB voltage. A cl size of **2.7±0.1** was achieved for -9V SUB voltage

Backside metallization

The cluster size is computed only for hits arriving in a time window (75,50,25 ns) relative to the median hit arrival time



- **Full cluster** collection needs **3 bunch crossings** (75ns). (for ITK outerlayer occupancy - acceptable)
- To be improved with **MALTA3**

Conclusion and outlook

- Significant improvements in terms of noise for MALTA2, due to its cascoded FE and also improved slow control and radiation hardness.
- SPS 2021 Measurement Campaign:
  - MALTA 2 performance
  - Radiation tolerance
  - Timing performance
- Further analysis is planned on neutron and proton irradiated MALTA 2 samples during the 2022 SPS Testbeam!
- MALTA3 expected for 2023!

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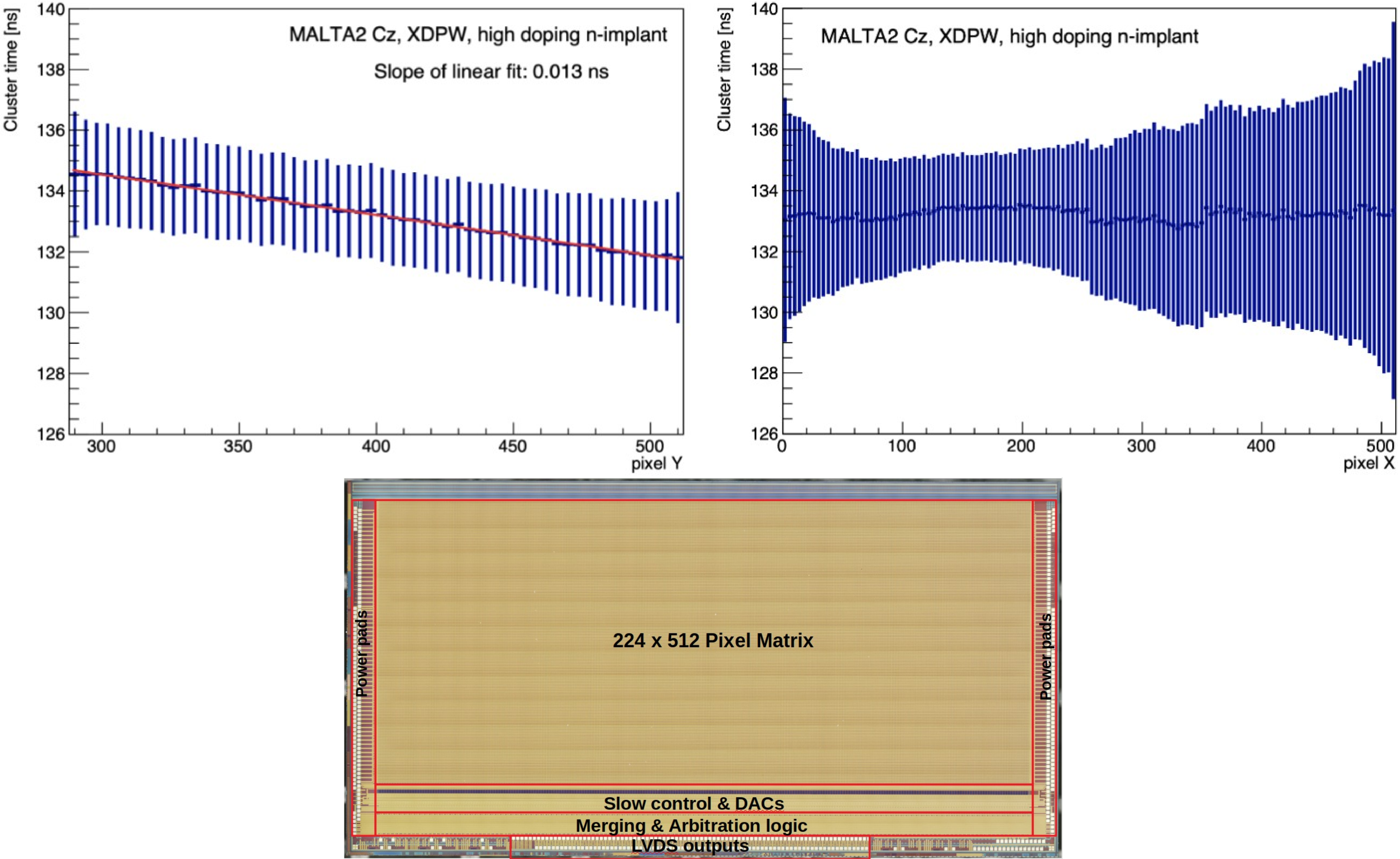
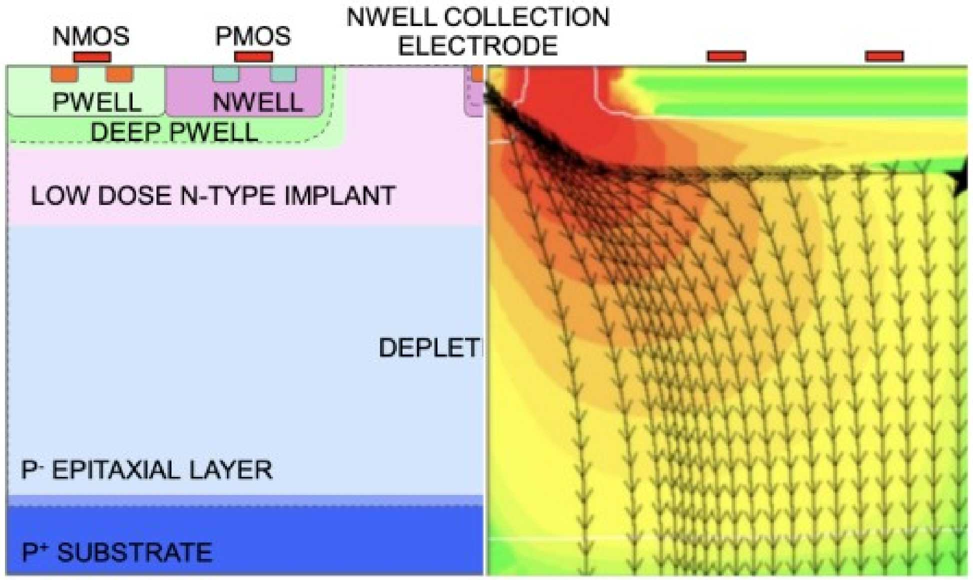
Thank you

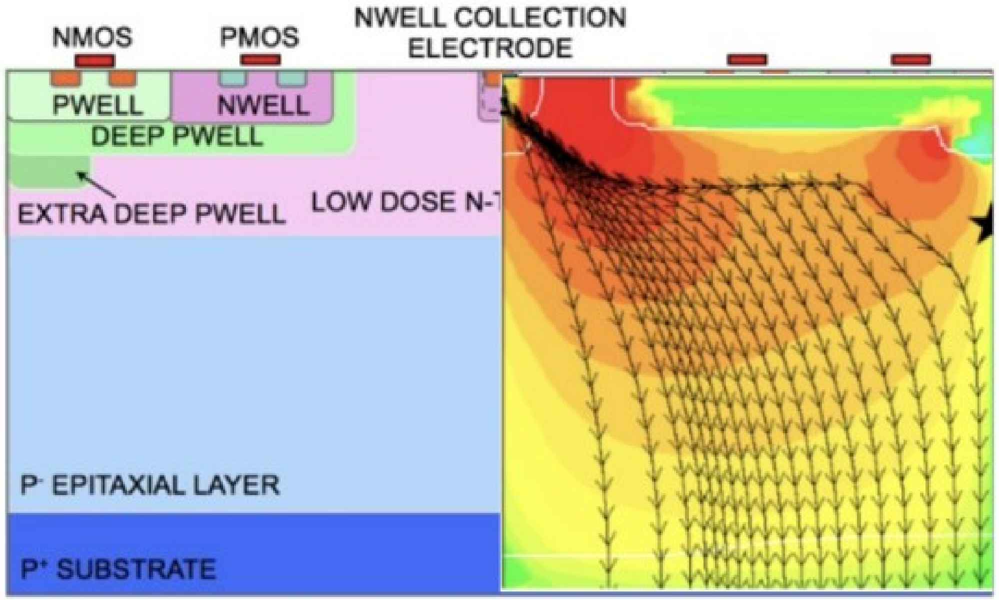
Bonus



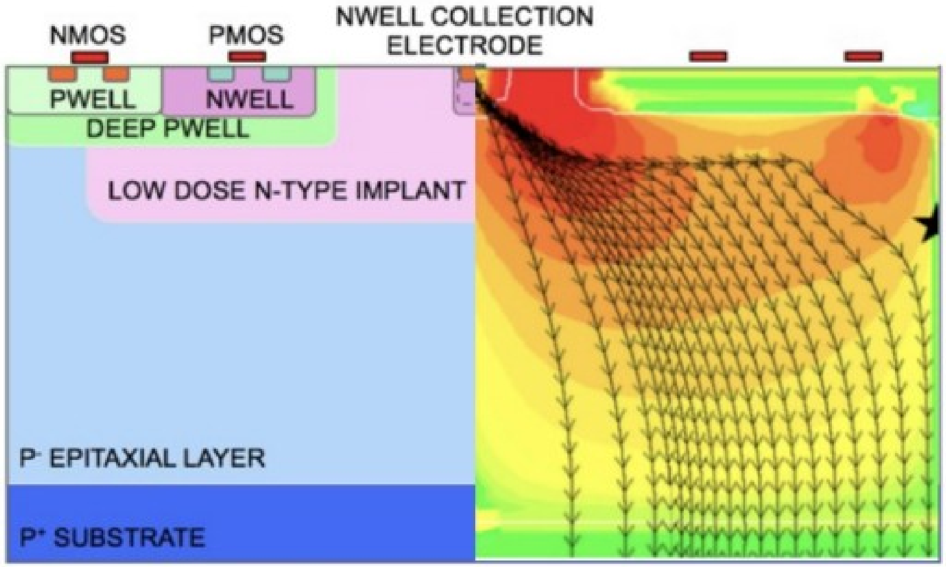
MALTA2 Cz, XDPW, high doping n-implant
Slope of linear fit: 0.013 ns
Cluster time [ns]
pixel Y
MALTA2 Cz, XDPW, high doping n-implant
Cluster time [ns]
pixel X
224 x 512 Pixel Matrix
Power pads
Power pads
Slow control & DACs
Merging & Arbitration logic
LVDS outputs



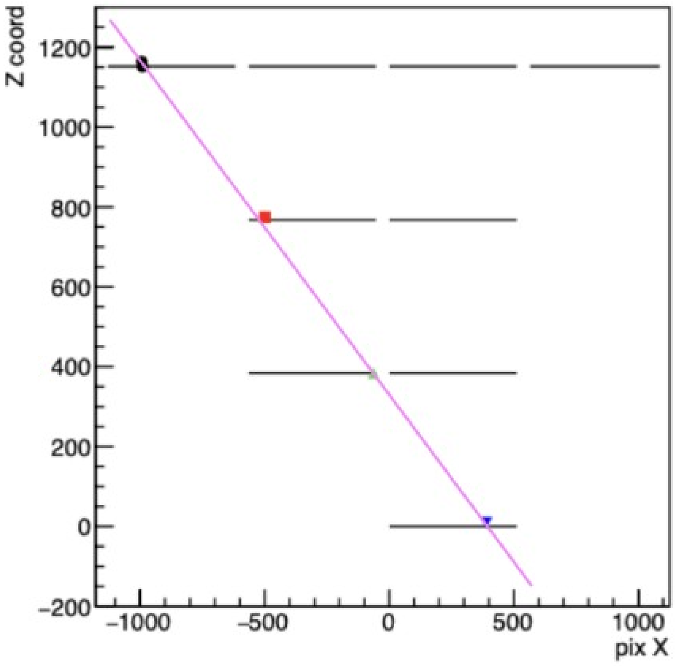
Standard modified process



Extra deep p-well (EDPW)



Gap in the n- layer (NGAP)

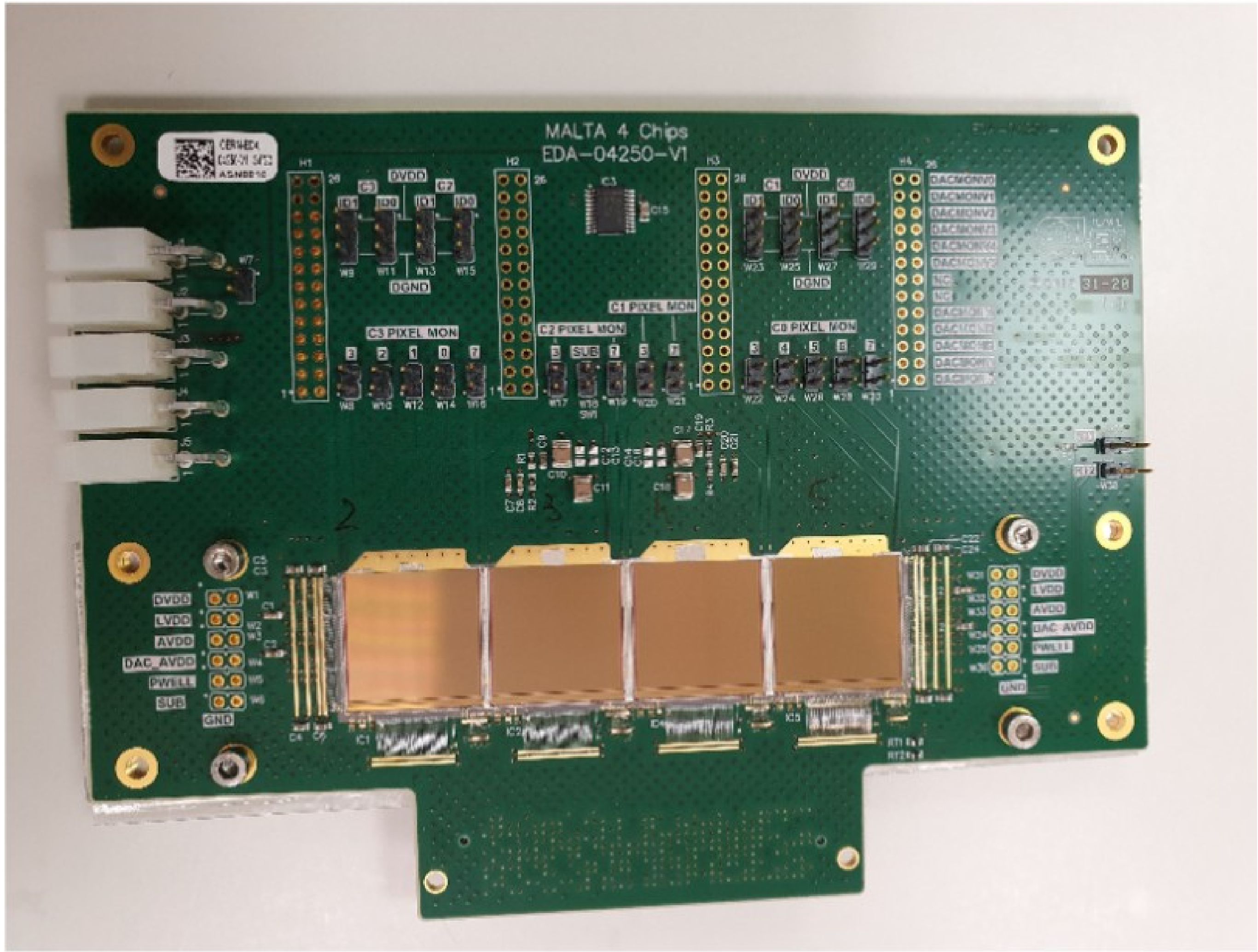


P0: Quad Chip

P1: Dual Chip

P2:Dual Chip

P3: Single chip



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