UiO : University of Oslo

MALTA Monolithic Pixel Sensor Telescope: New Developments and Recent Measurements

Milou van Rijnbach

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, V. Gonzalez, G. Gustavino, M. LeBlanc, K. Oyulmaz, H. Pernegger, F. Piro, P. Riedler, H. Sandaker, A. Sharma, C. Solans, W. Snoeys, T. Suligoj, M. Vazque Nunez, J. Weick, S. Worm, A. Zoubir

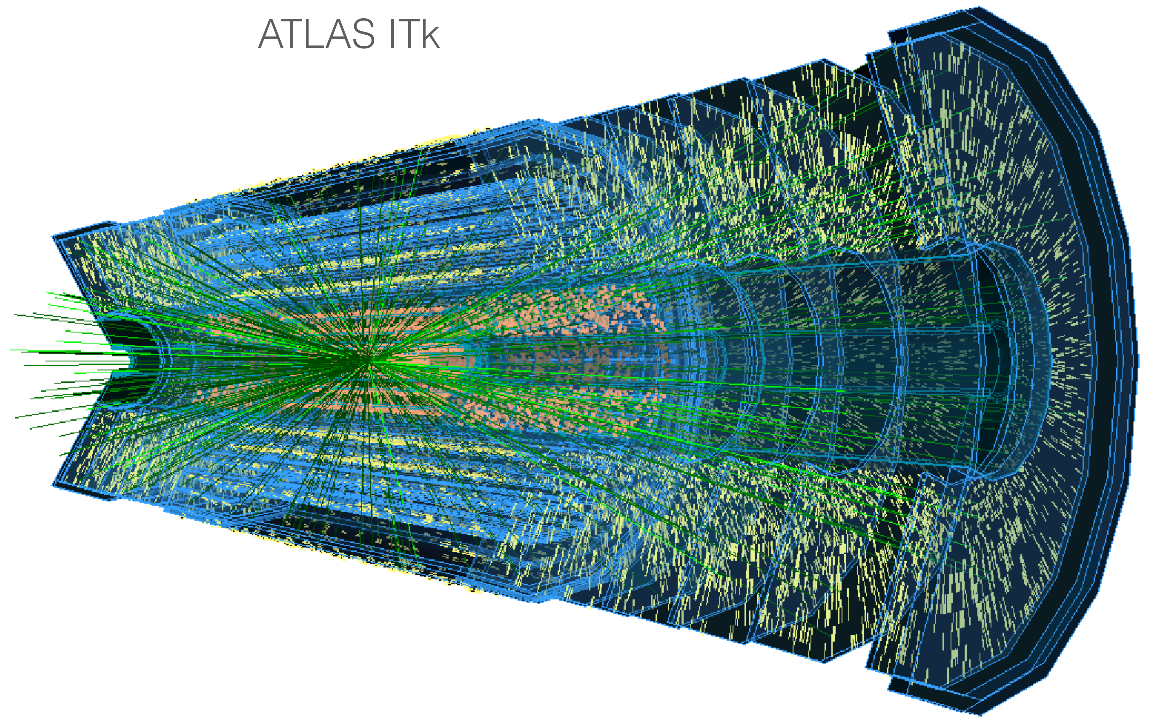
10th Beam Telescopes and Test Beams (BTTB) Workshop / 20.06.2022

Motivation for Monolithic Pixel Sensors

Challenging requirements for future collider experiments:

- Extreme radiation tolerance
- Large hit rate
- High granularity
- Fast response time
- Large surface
- Very thin

ATLAS ITk



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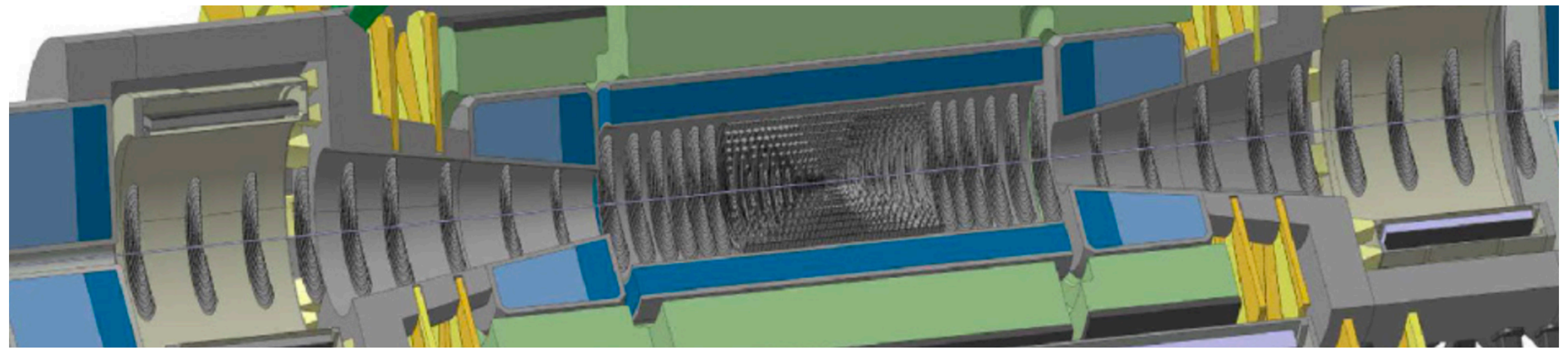
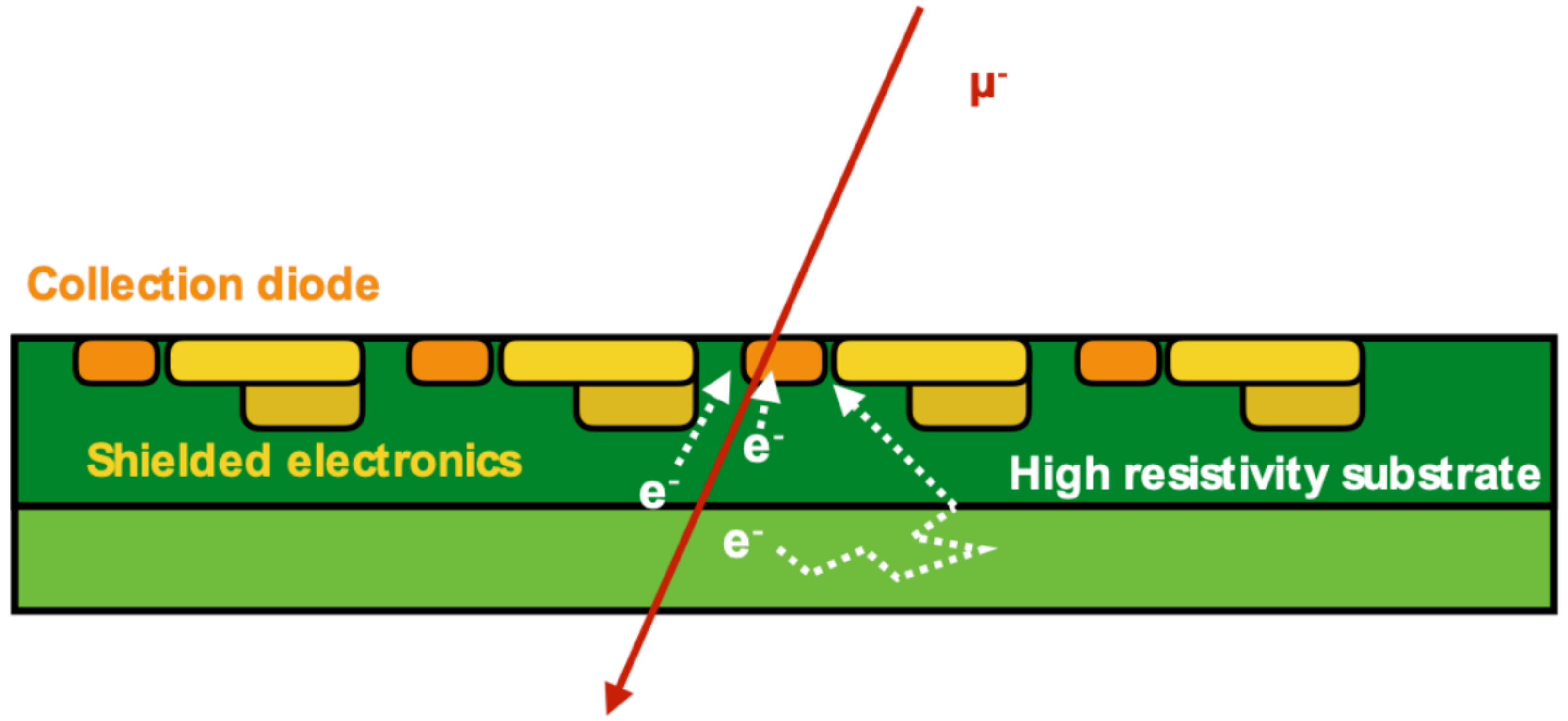


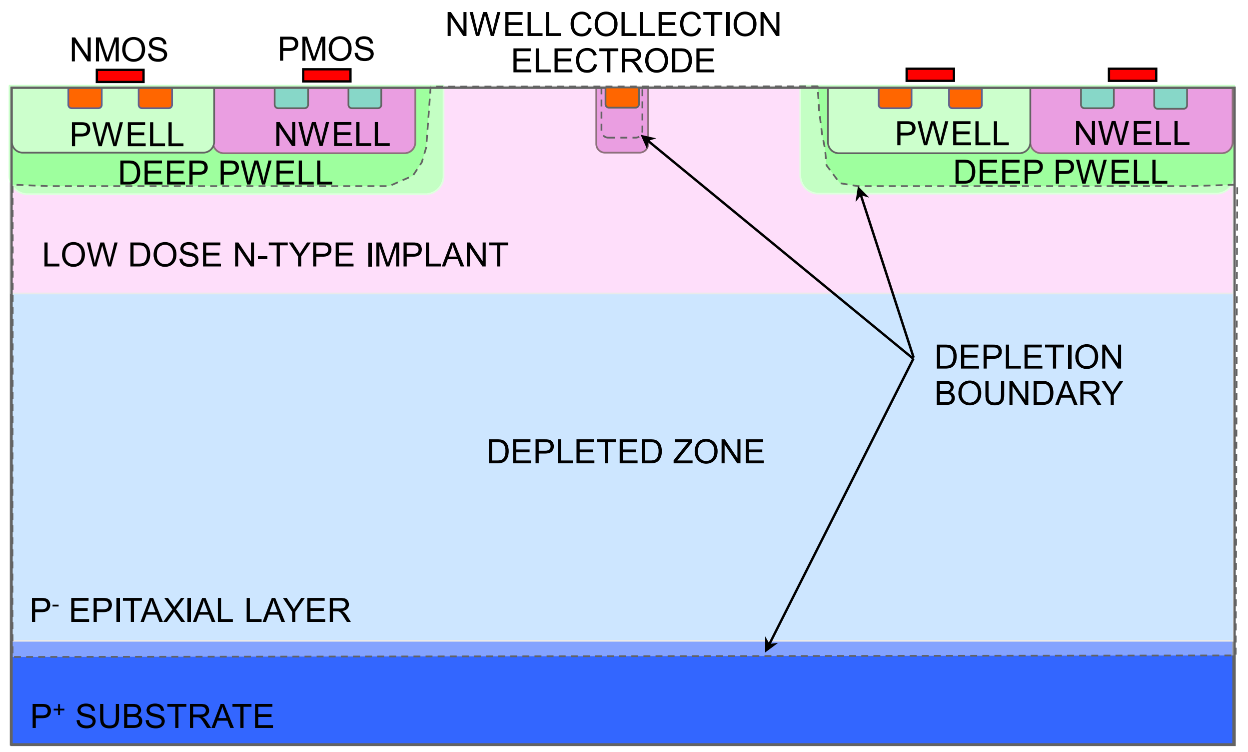
Monolithic Pixel Sensors with Small Collection Electrode:

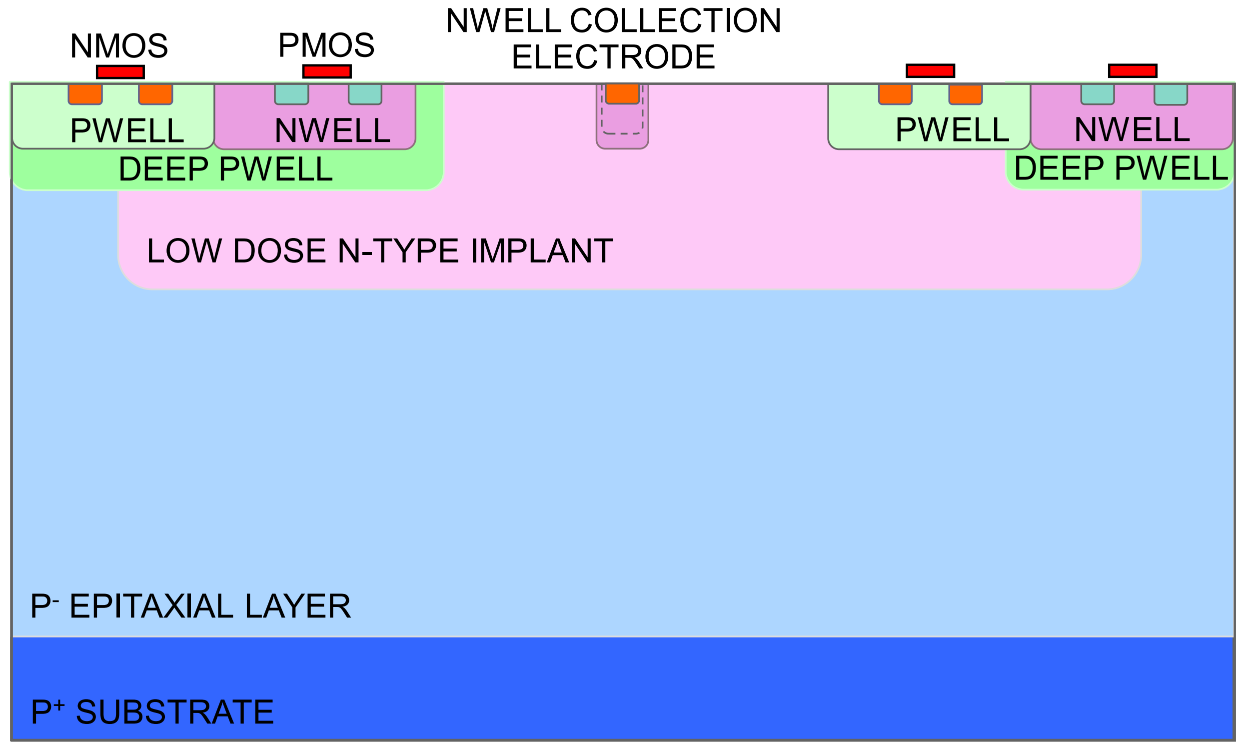
- Reduced production effort
- Reduced costs
- Reduced material
- Large signal/noise ratio

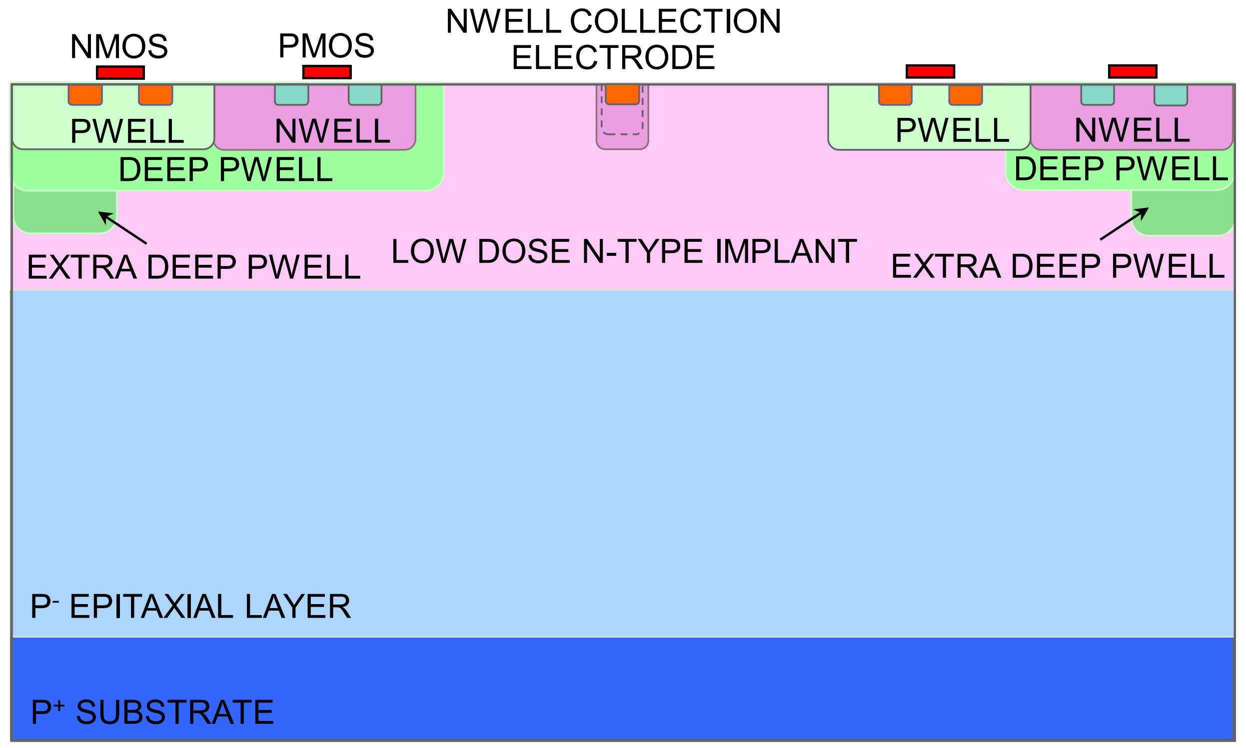


Munker, M. "Fast Charge Collection in Small Collection Electrode Monolithic CMOS Pixel Sensor" CERN Detector Seminar (2021)

TowerJazz 180 nm CMOS Technology







Three Different Flavours:

"STD"
Standard Modified Process

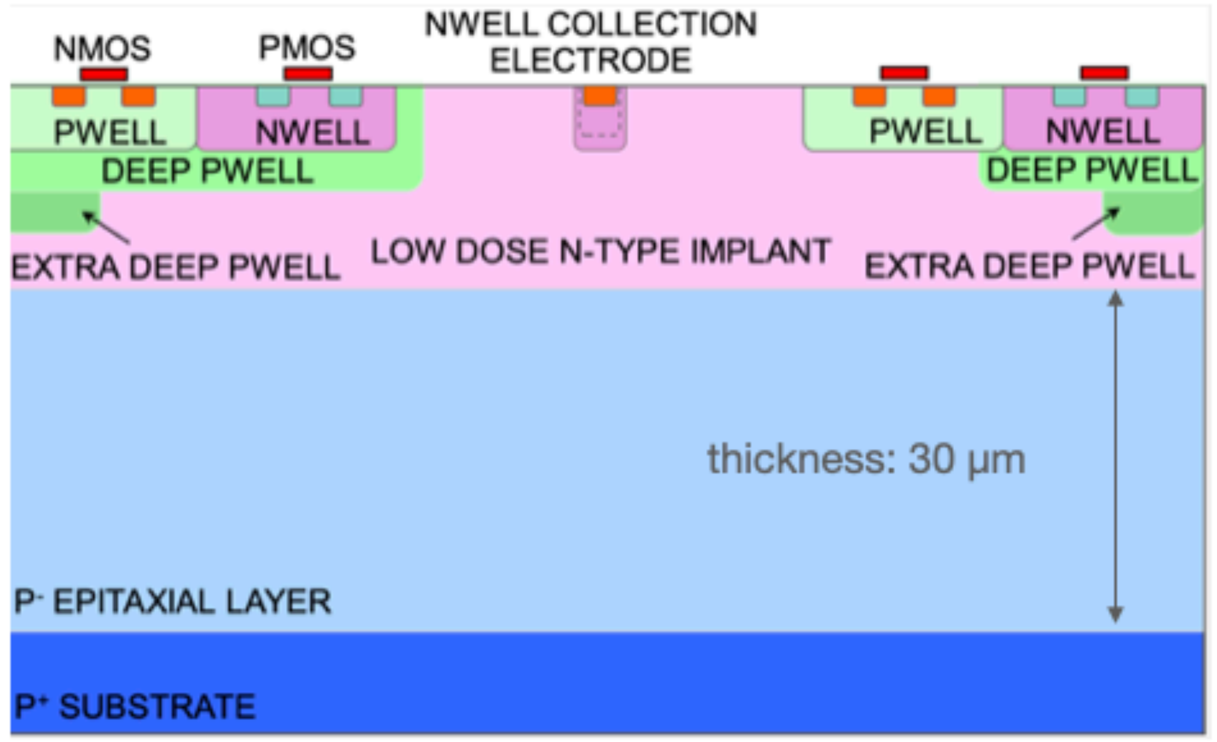
"N-GAP"
Gap Low Dose N-Type Implant

"XDPW"
Extra Deep P-Well

- 180 nm standard imaging technology process
- Three different flavours : Standard modified process, gap in low dose n-type implant and extra deep p-well
- Different flavours to optimise field configuration and charge collection
- Two different substrates: High resistivity epitaxially grown and Czochralski (Cz)

Two Different Substrates :

"Epitaxial layer on p-type substrate" (EPI)



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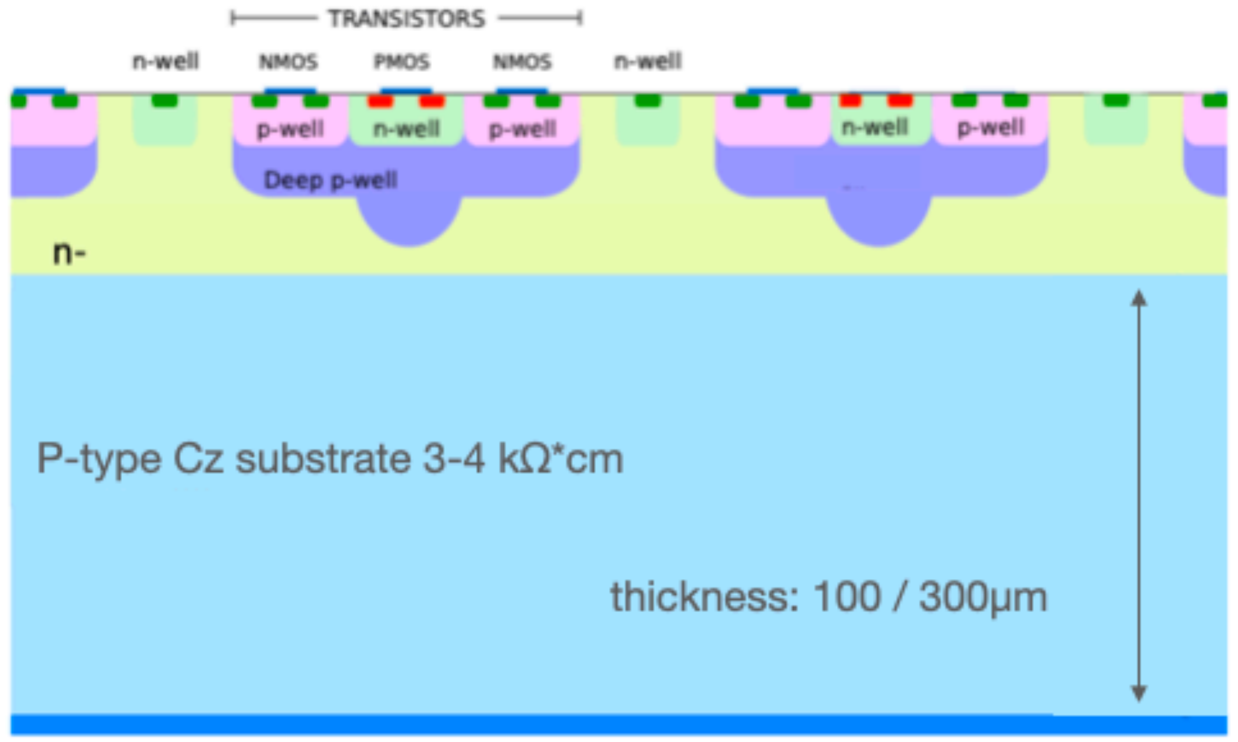
"High resistivity thick Czochralski substrate" (Cz)



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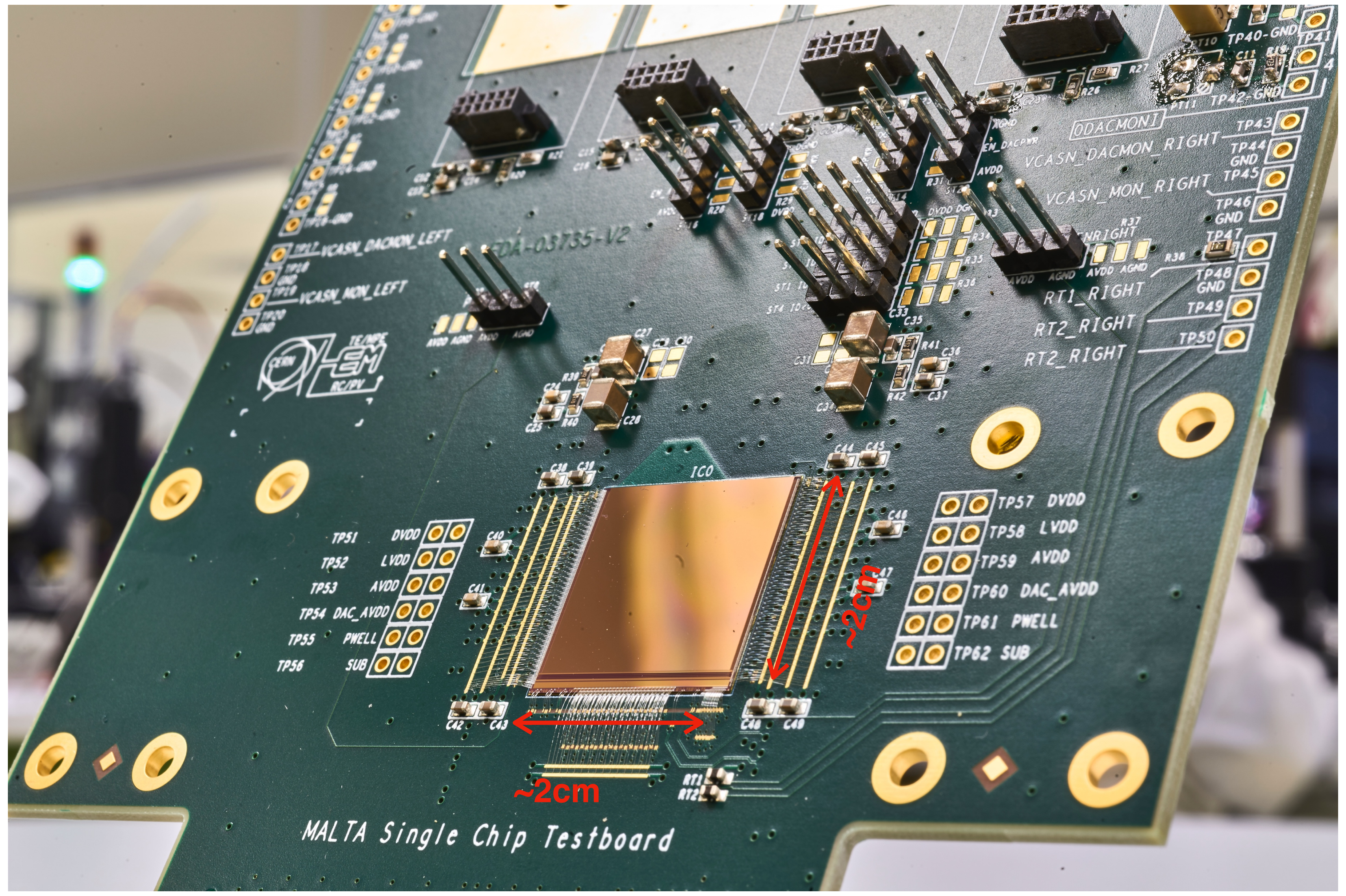
H.Pernegger NIM A 986 (2021) 164381
M. Dyndal,JINST 15 (2020) P02005
M. Mironova, NIM A 956 (2020) 163381
M.Munker PIXEL 2018

TowerJazz MALTA

MALTA: Depleted monolithic active pixel sensor with small collection electrode



- Matrix: 512x512 pixels (pixel pitch 36.4 μm)
- Electrode size: 2-3 μm^2
- Asynchronous readout
- Low power consumption
    - 1 μW/pixel analog power
    - 70 mW/cm^2 analog power
    - 10 mW/cm^2 digital power
- Xilinx Virtex / Kintex FPGA for readout

MALTA2: Second prototype of MALTA family

- Using the knowledge of previous prototypes and Mini-MALTA to improve performance
- Matrix : 224 x 512 pixels (pixel pitch 36.4 μm)
- FE improvements to reduce RTS noise (increase size specific NMOS transistors and introduced cascode transistor)
    - Opens the possibility to operate at lower thresholds and therefore reach higher efficiencies
- Fabricated in Epi / Cz substrate material with 3 process modifications

Francesco Piro et al. (2022). A 1 μW radiation-hard front-end in a 0.18 μm CMOS process for the MALTA2 monolithic sensor. *IEEE Transactions on Nuclear Science.*
Vlad Berlea, "Tower Jazz 180 nm MALTA monolithic active pixel sensor Test Beam results", TREDI, 2022, https://indico.cern.ch/event/1096847/contributions/4742327/attachments/2400093/4104325/TREDI2022_final.pdf

TowerJazz MALTA

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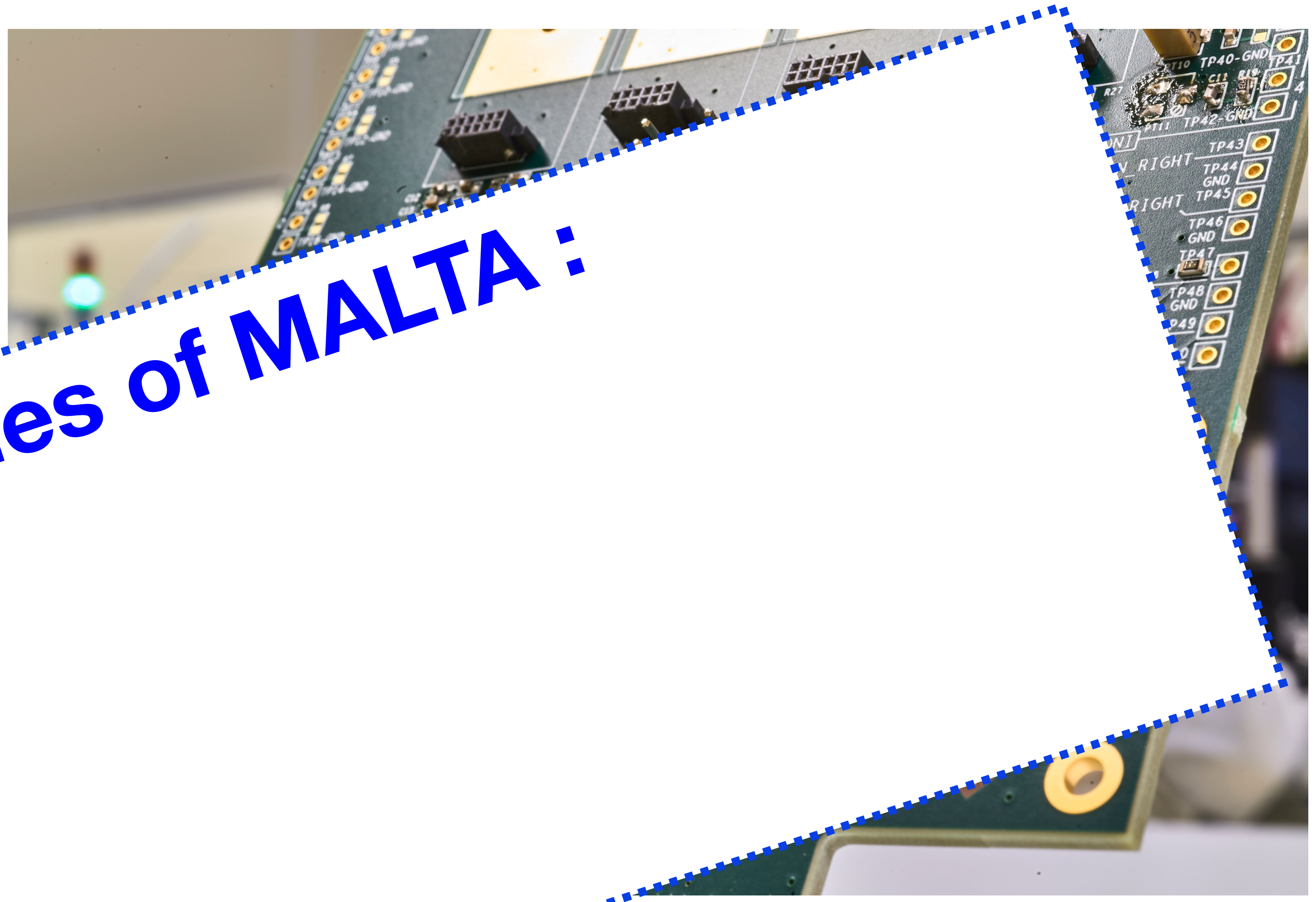
- Electrode size: 2-3 μm^2
- Asynchronous readout
- Low power consumption
    - 1 μW/pixel analog
    - 70 mW/cm
    - 10
- Xilinx

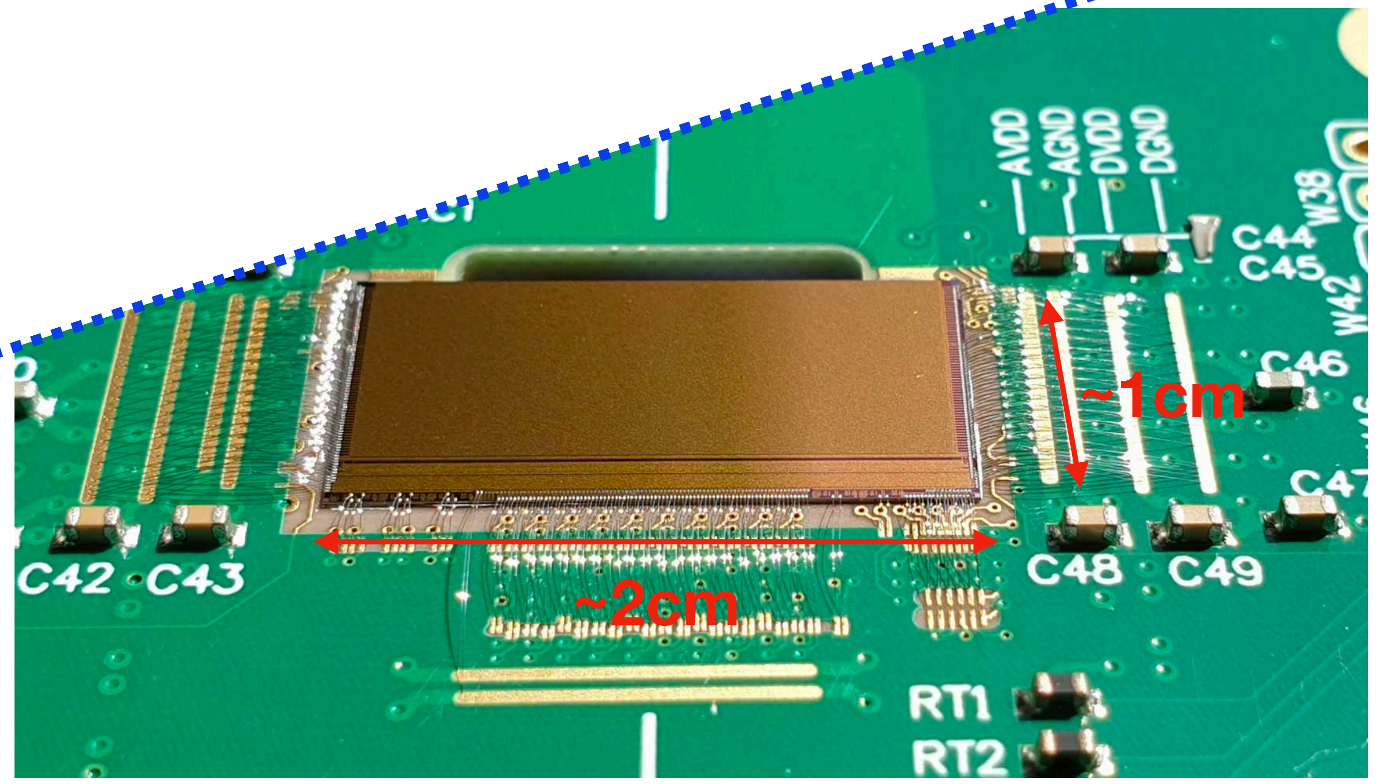


MALTA-based telescope exploits the best qualities of MALTA :

+Large area (full prototype)
+High granularity
+Self-triggering
+Good timing resolution

MALTA2:

- Using the ... prototypes and Mini-M... performance
- Matrix : 224 ... pixels (36.4 μm)
- Larger transistors in the amplifier feedback loop to reduce RTS noise. Additional cascaded transistor in input branch to increase the gain.
    - Opens the possibility to operate at lower thresholds and therefore reach higher efficiencies
- Fabricated in Epi / Cz substrate material with 3 process modifications



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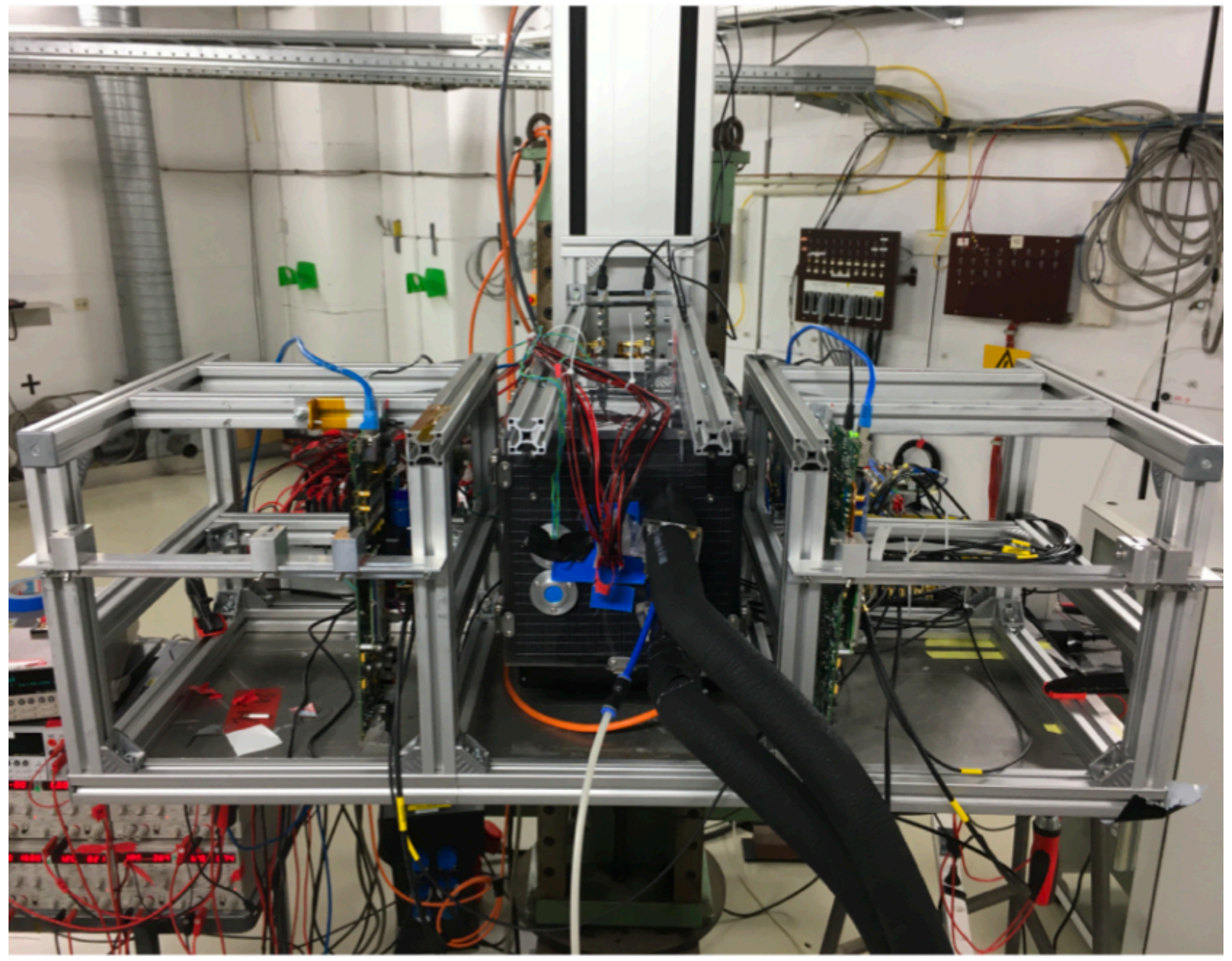
MALTA Telescope Timeline

2019 2020 2021 2022

MALTA Telescope @ DESY

- Custom based MALTA Telescope
- Up to 7 MALTA tracking planes
- 3-4 GeV electron beam



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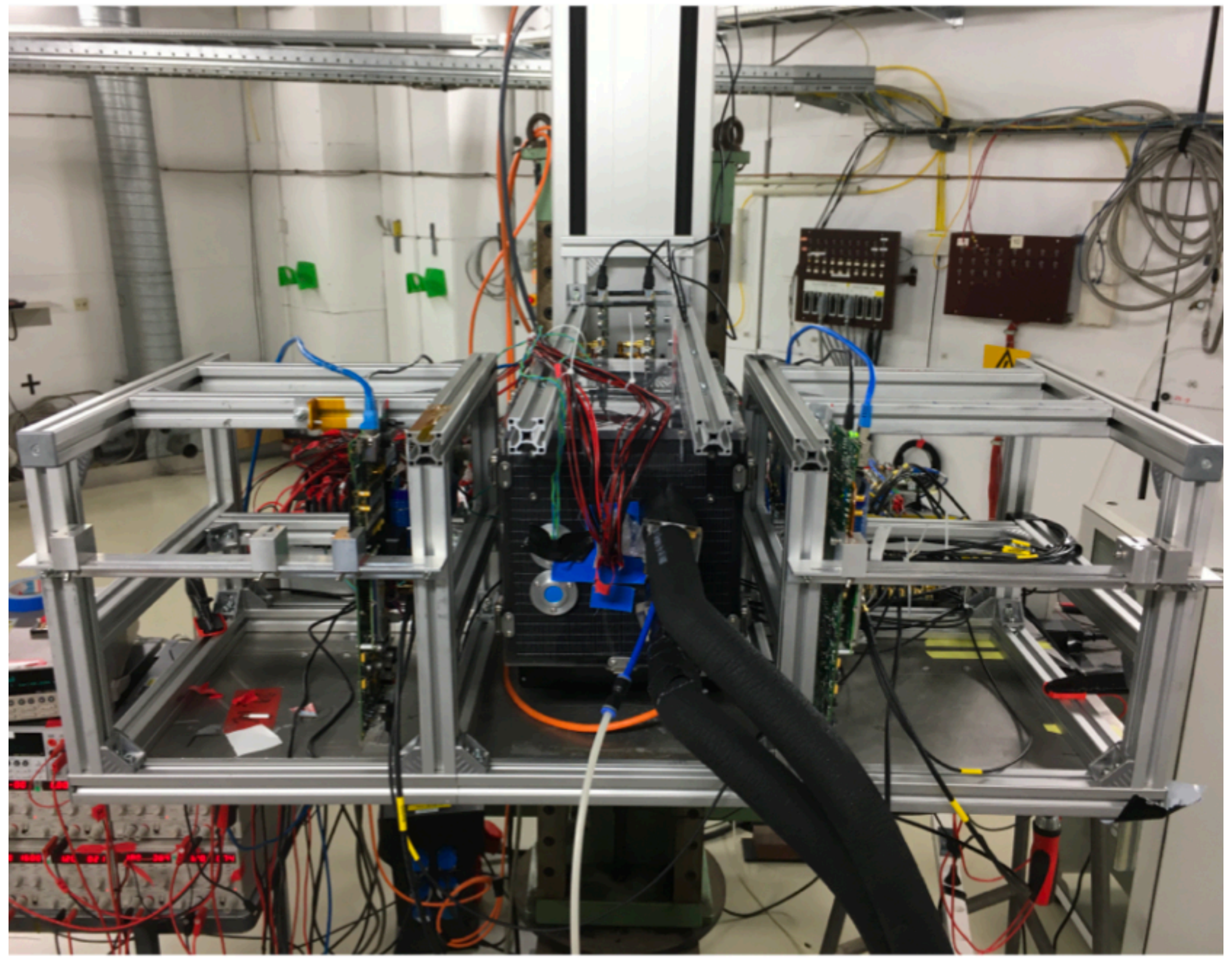
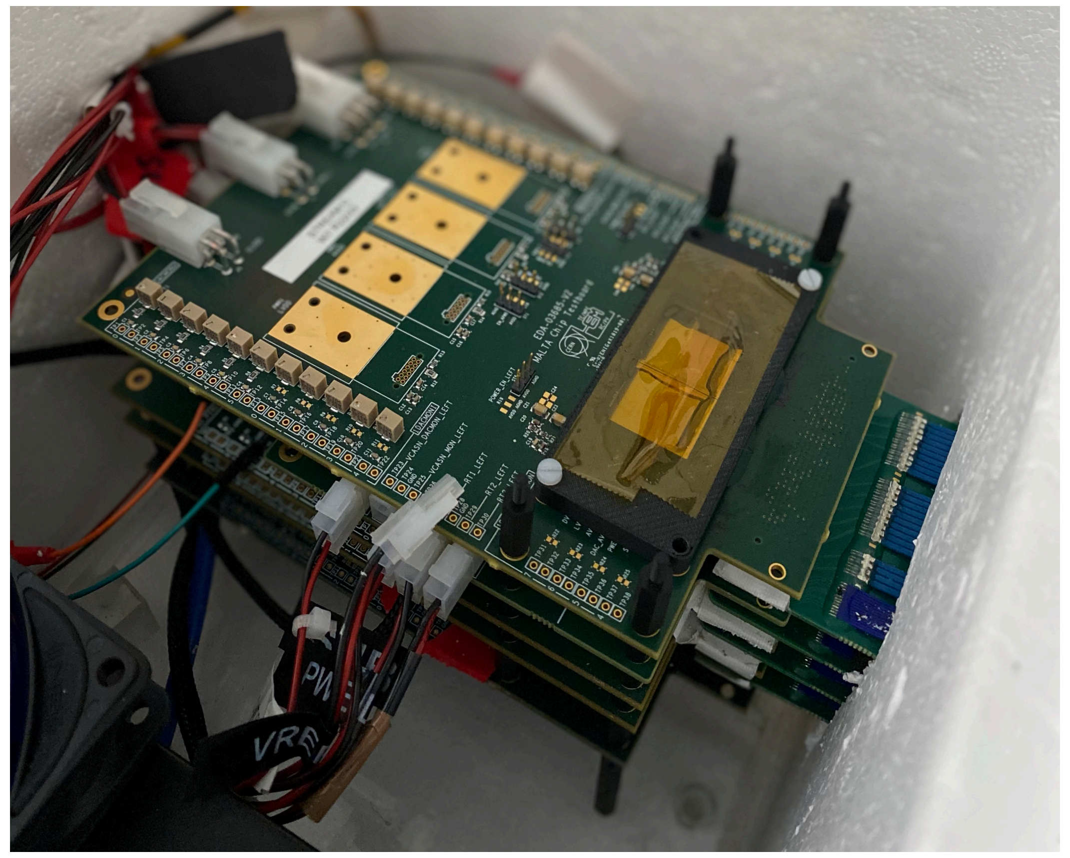


MALTA mini-telescope @ CERN

- Small scale mini telescope (lab scale)
- Up to 4 MALTA planes + scintillator
- PicoTDC for timing measurements
- Sr90 electrons or cosmic muons



Focus point of BTTB 2021 talk by Andrea Gabrielli:
DESY test beam campaign 2019 and
mini telescope set-up in lab 2020

Gabrielli, A. “MALTA CMOS sensor telescope: new developments and recent measurements” *Talk at BTTB2019* (2019)

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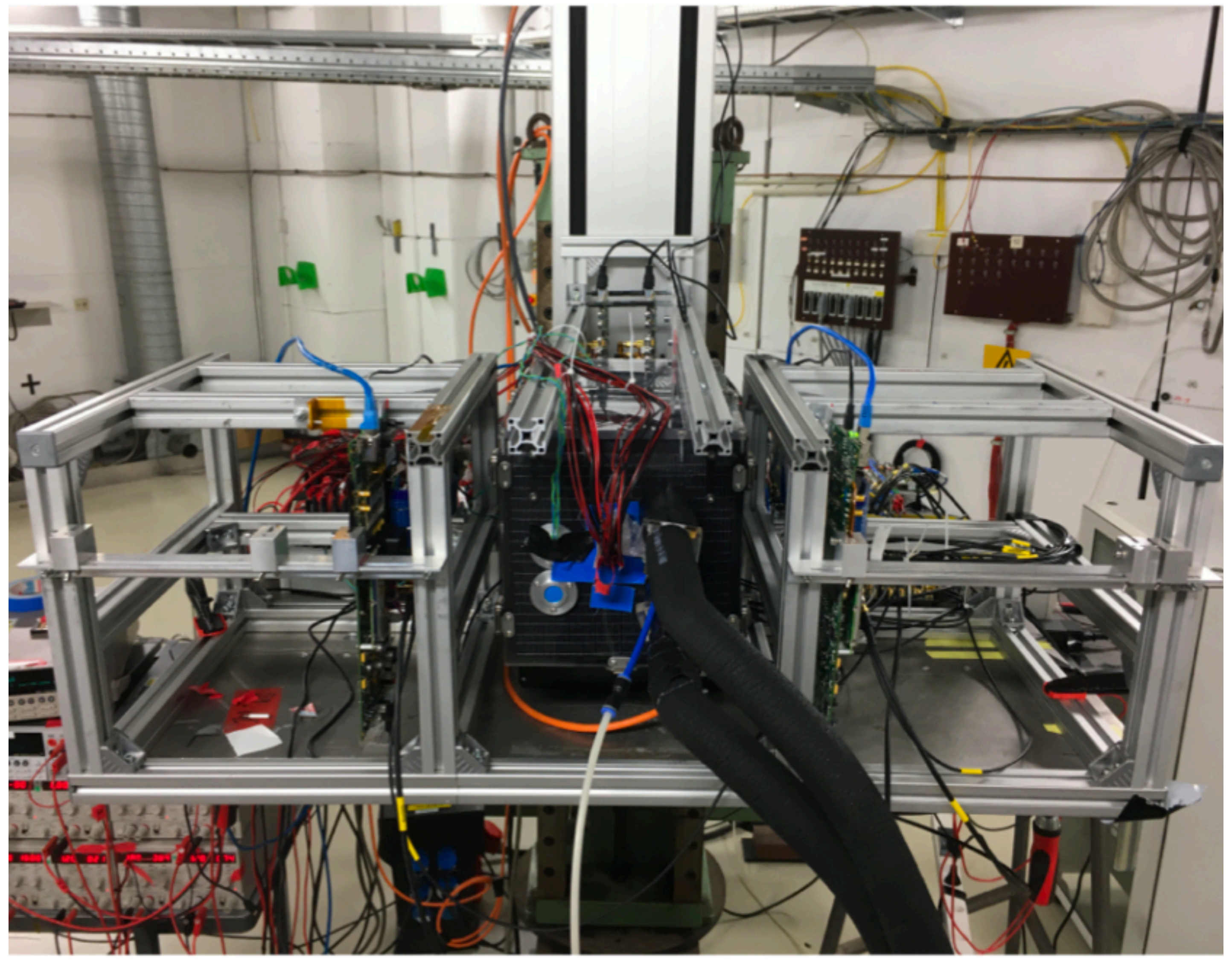

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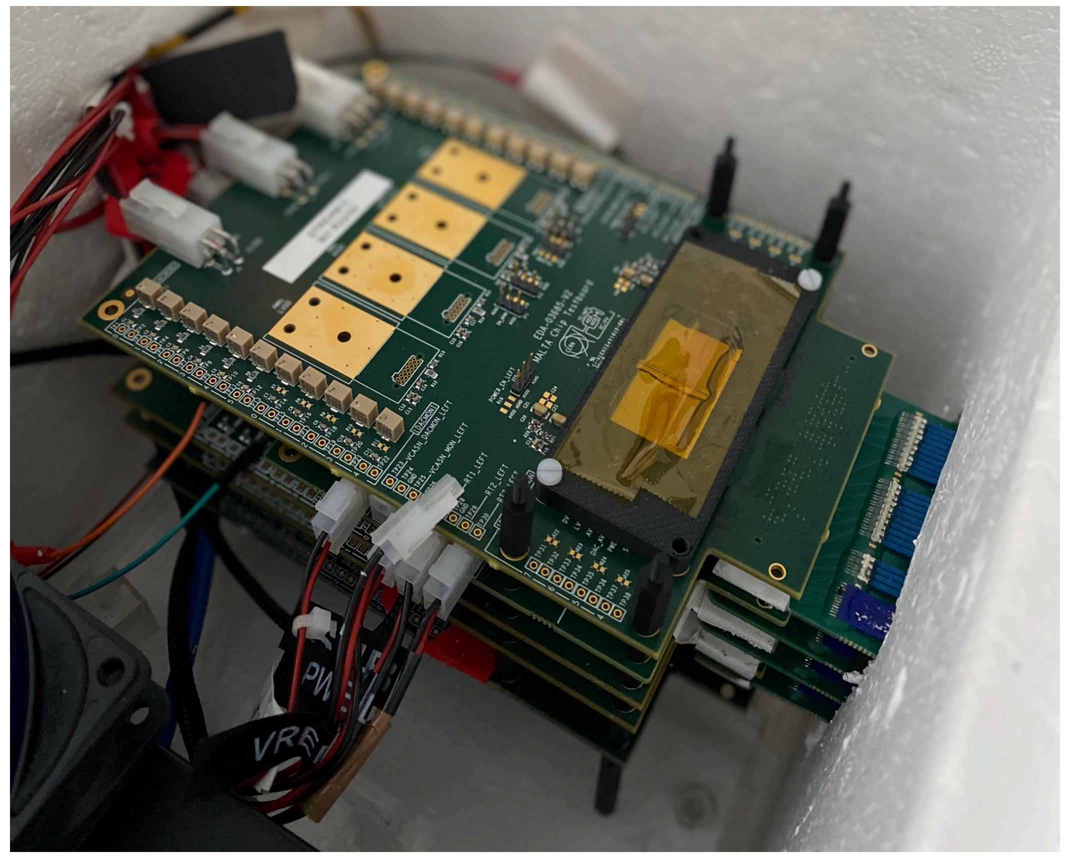
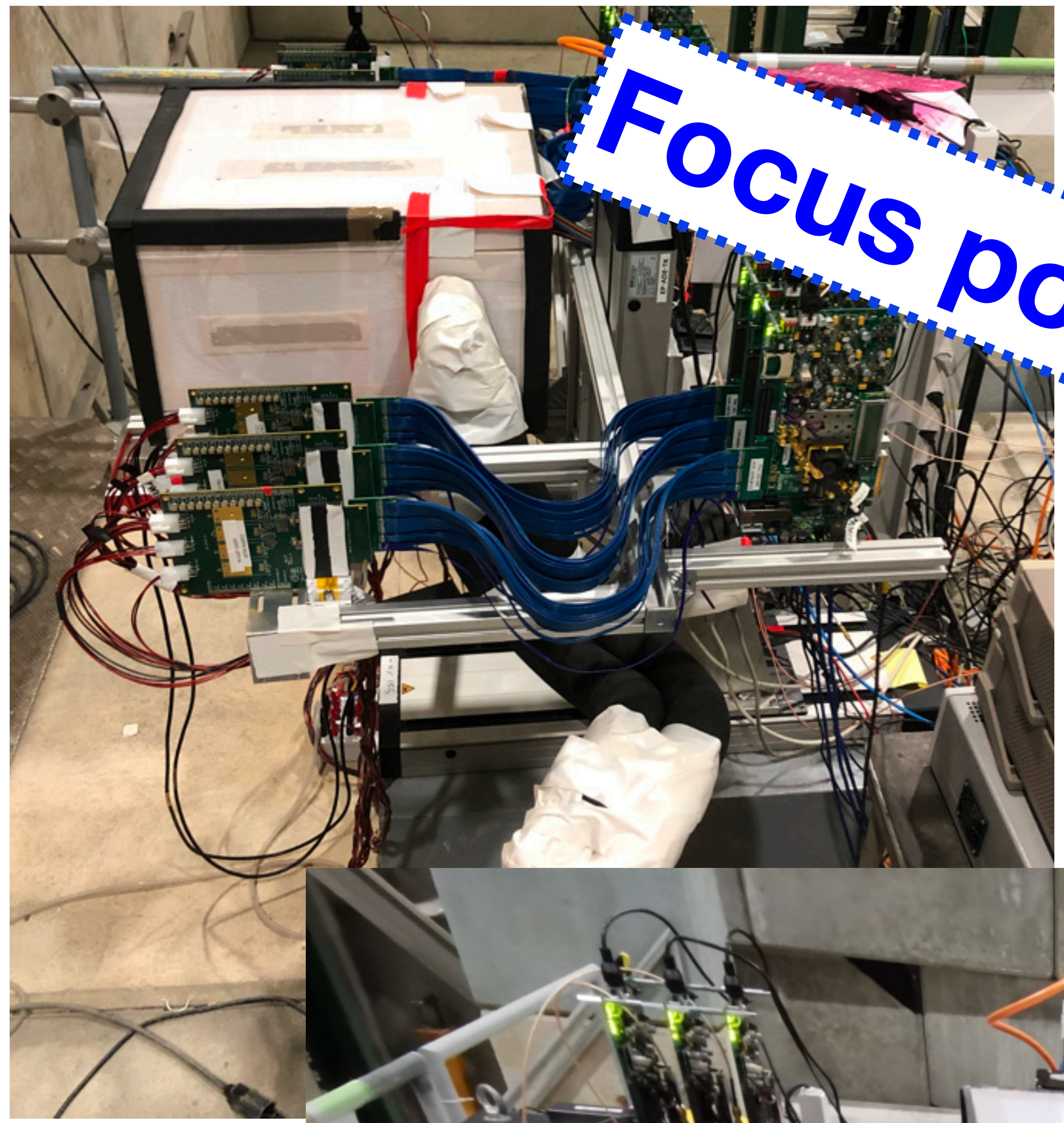
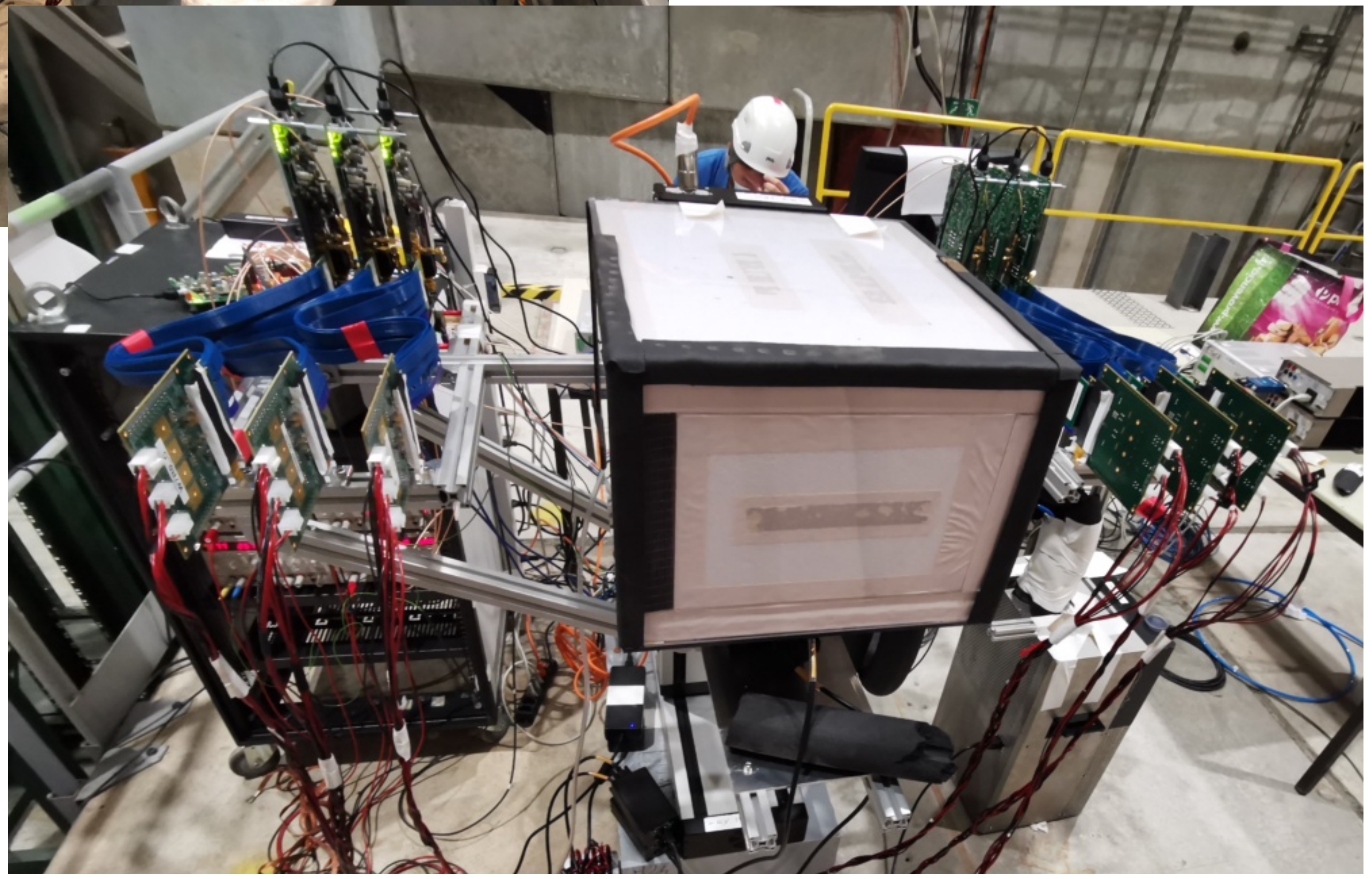


MALTA Telescope @ SPS

Focus point of this talk!

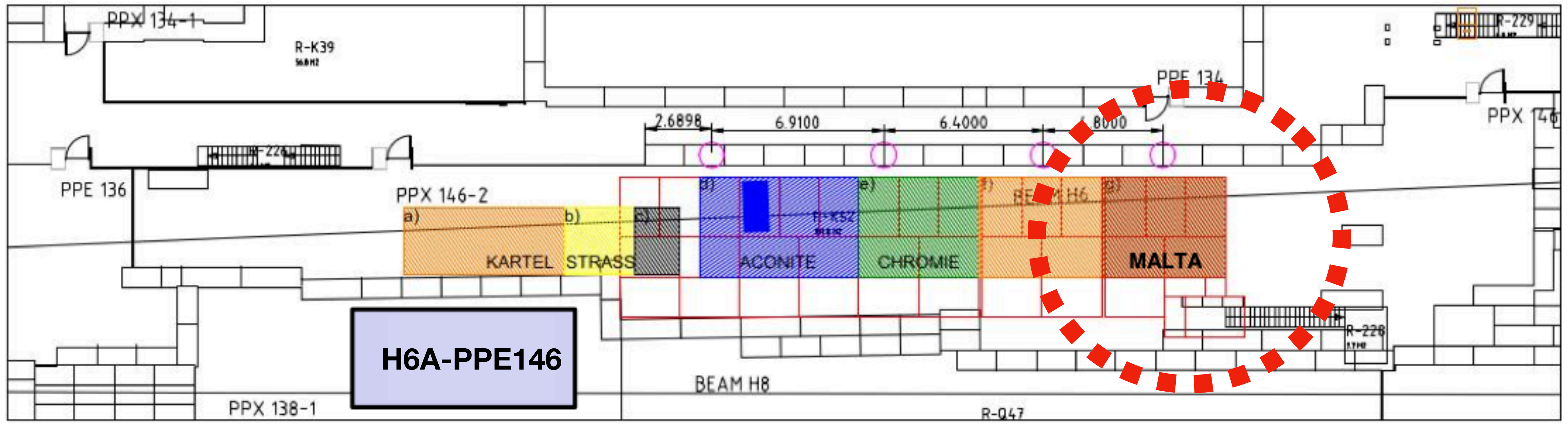


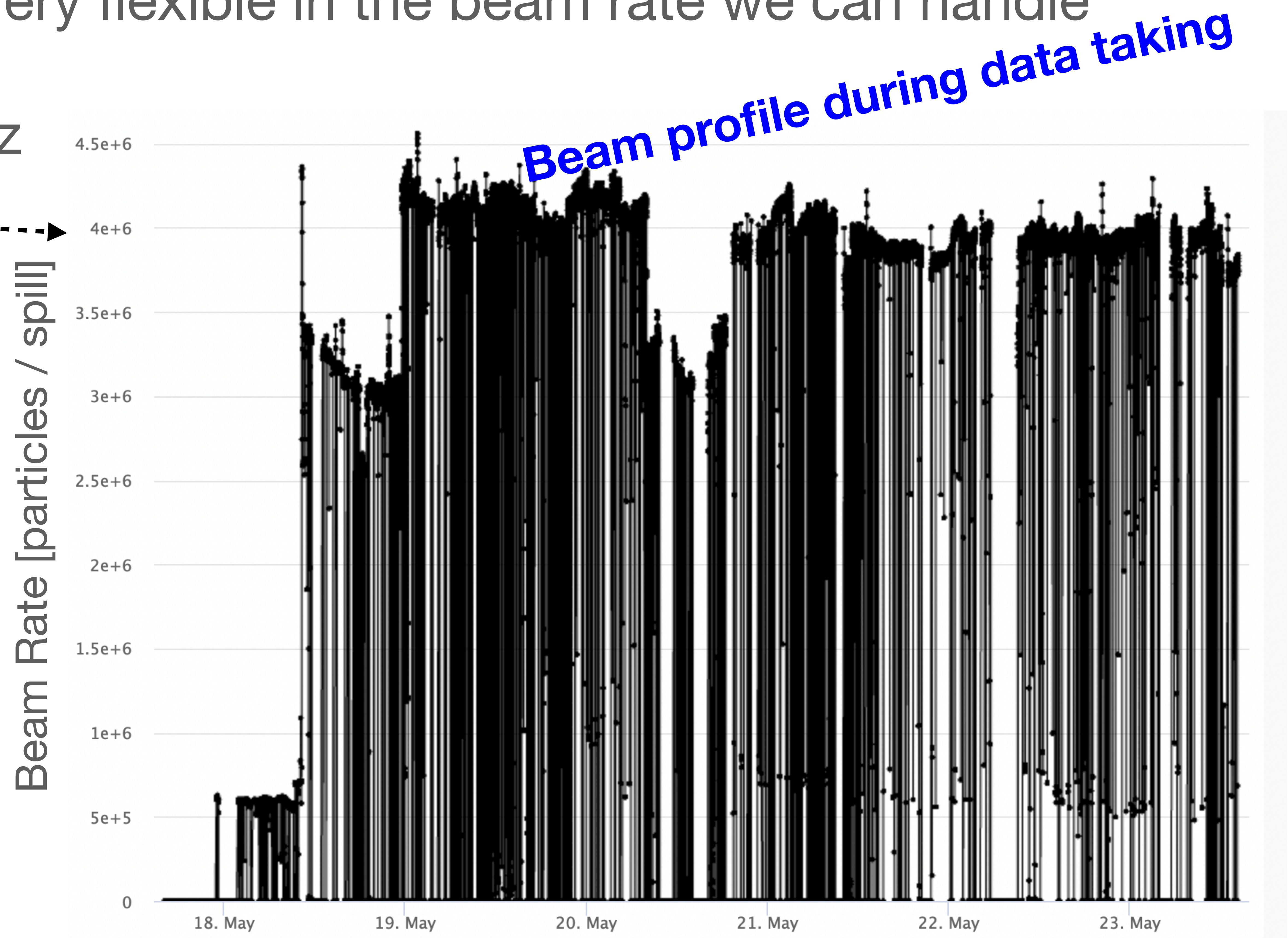


Gabrielli, A. "MALTA CMOS sensor telescope: new developments and recent measurements" *Talk at BTTB2019* (2019)

SPS Testbeam 2021 and 2022

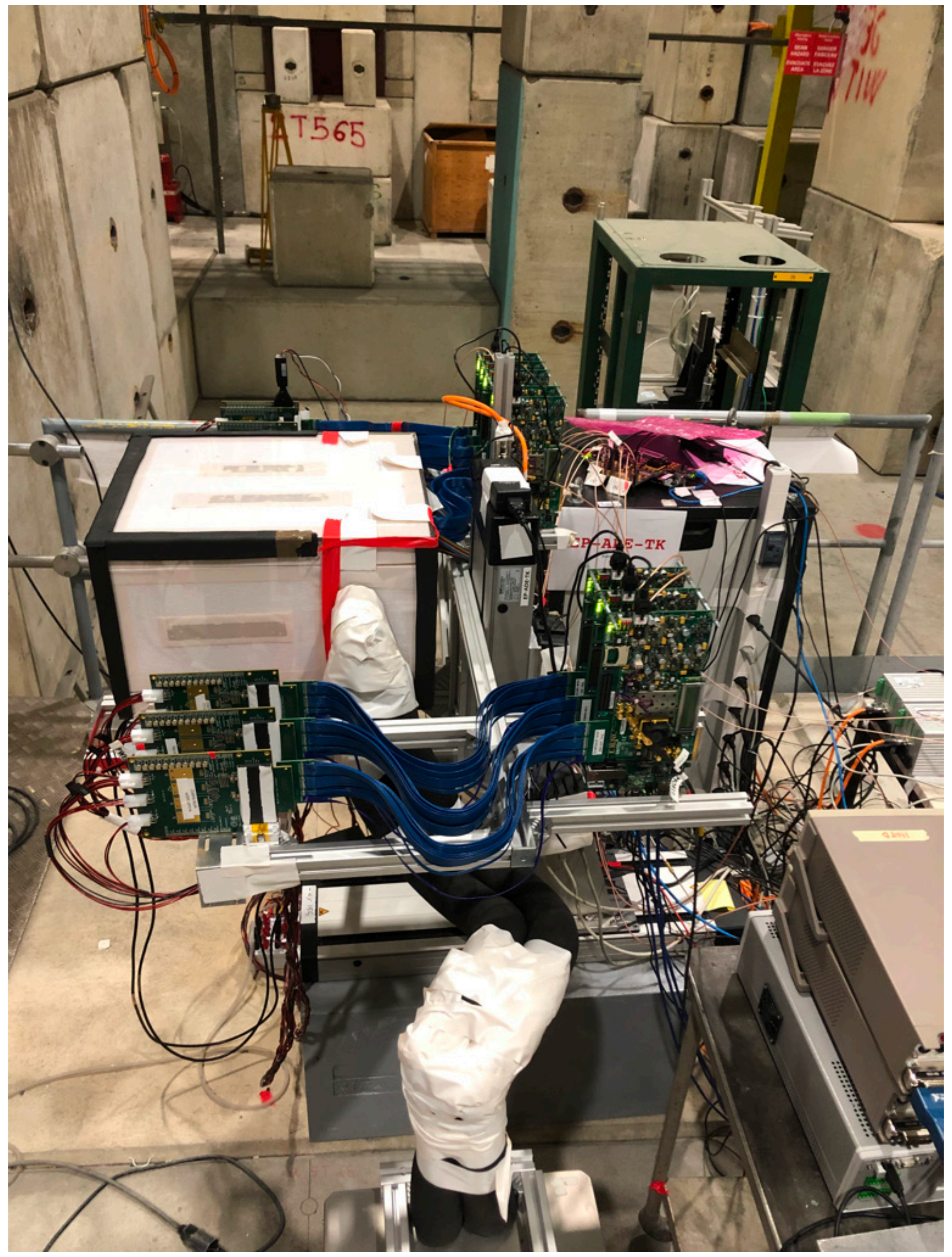
- Test beam at SPS CERN ongoing with the goal to demonstrate next generation MALTA (MALTA2) performance in terms of radiation hardness (> 10^{15} 1 MeV neq/cm^2) and timing performance.
- Experimental user located in the North Area (H6A)
- Selected weeks of main user and parallel user, remaining as parasitic user.
- Subject to beam type and intensity from other users -> very flexible in the beam rate we can handle
- Able to sustain 4E6 particles per spill at L1 rate of 50 kHz



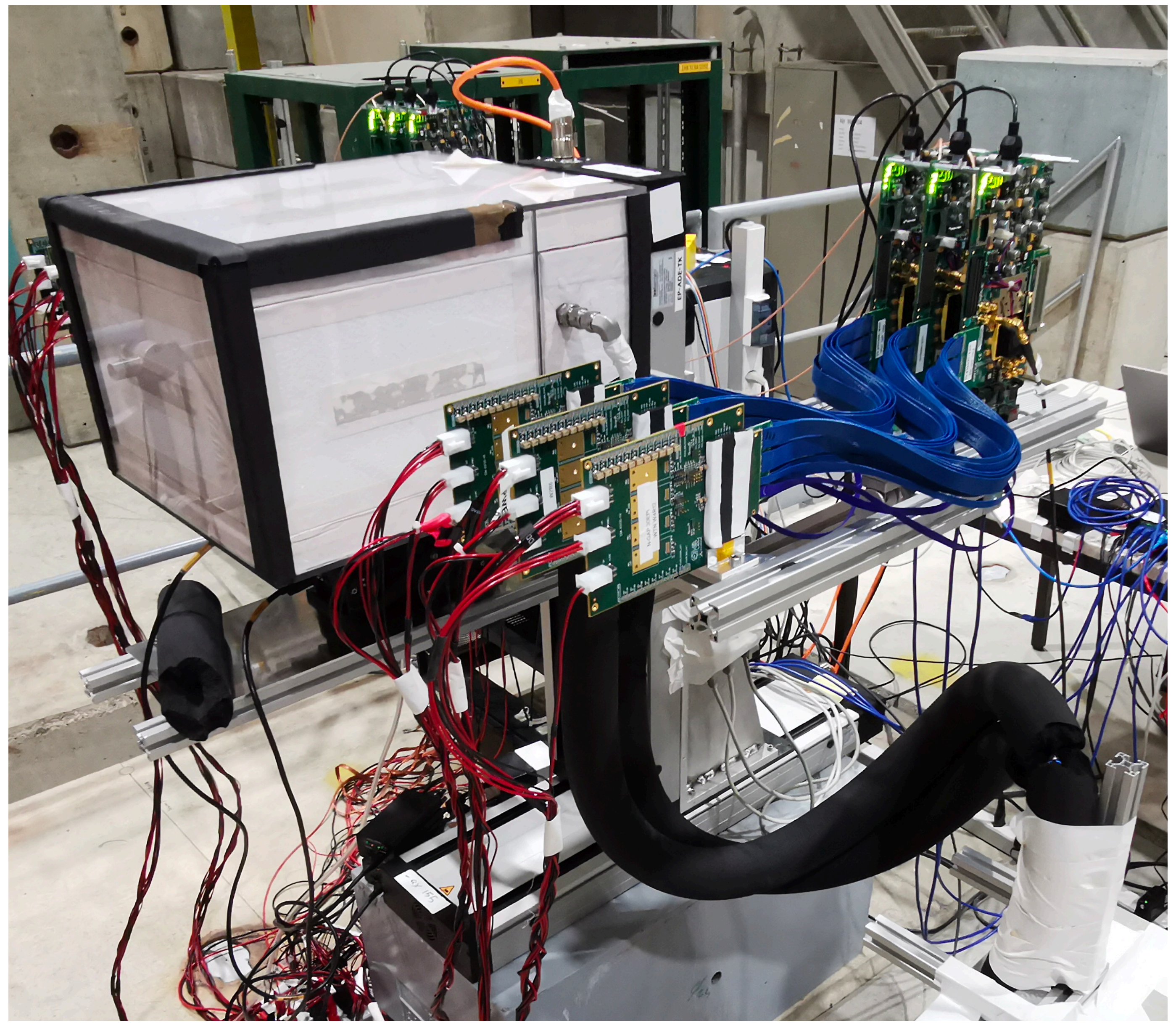


MALTA Telescope @ SPS Overview

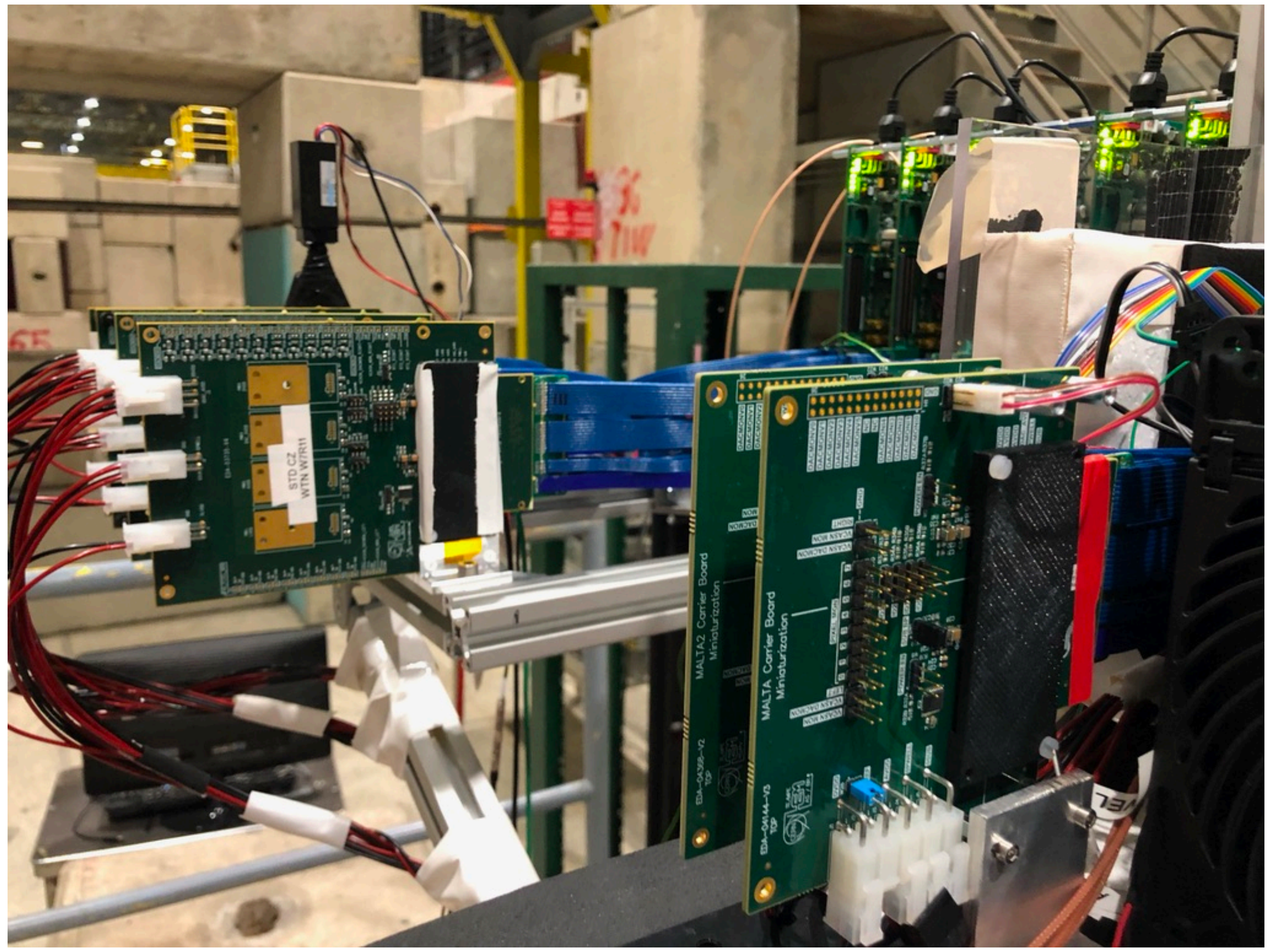
- Telescope consists of 6 MALTA tracking planes
- Custom MALTA telescope with fast read-out and online monitoring
- Custom Trigger Logic Unit (TLU) which allows to trigger on both individual planes and scintillator for timing reference
- Independent DUT support with cold box (possibility for 2 MALTA DUTs and room for others…)



MALTA Telescope at SPS



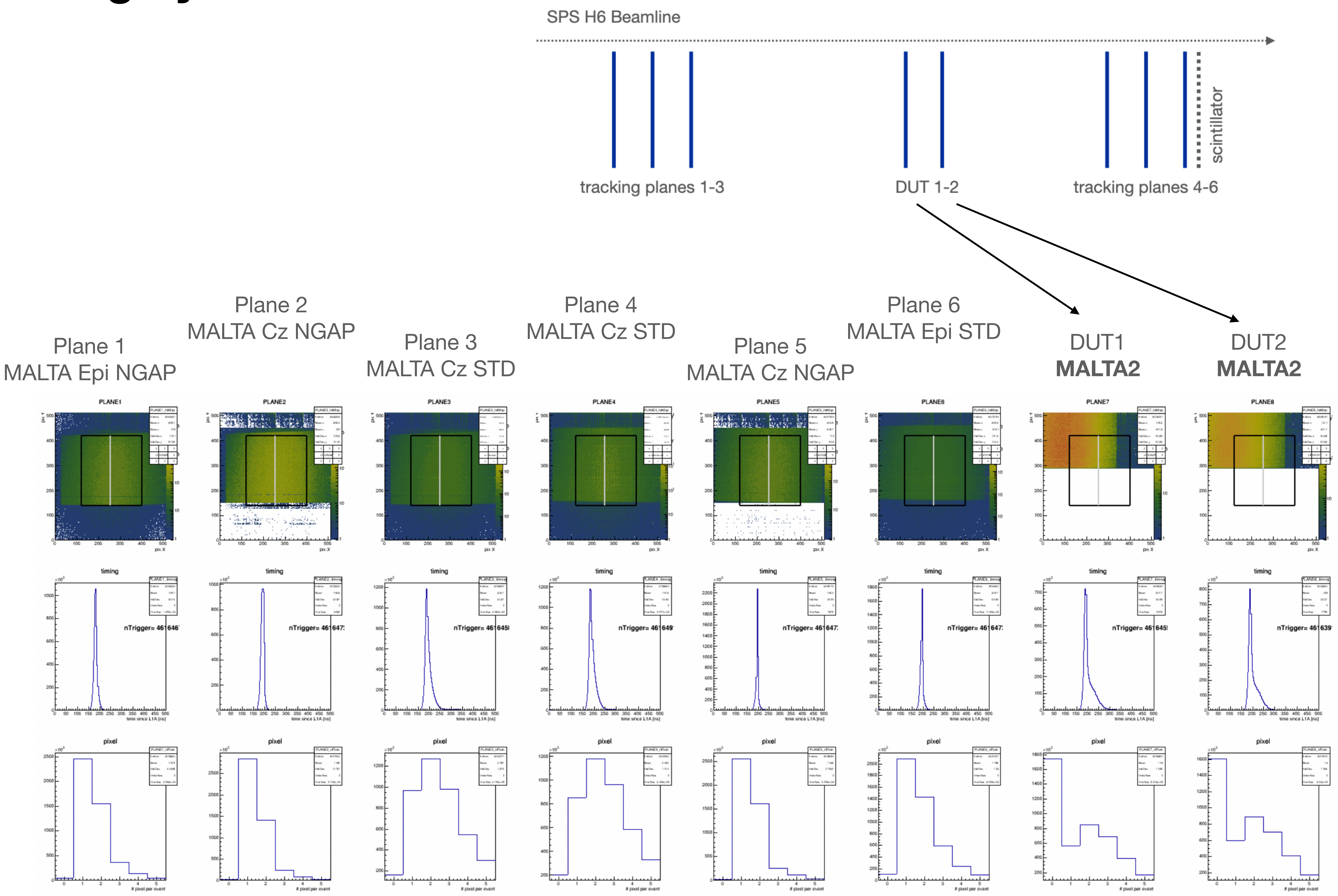
First three MALTA tracking planes and cold box



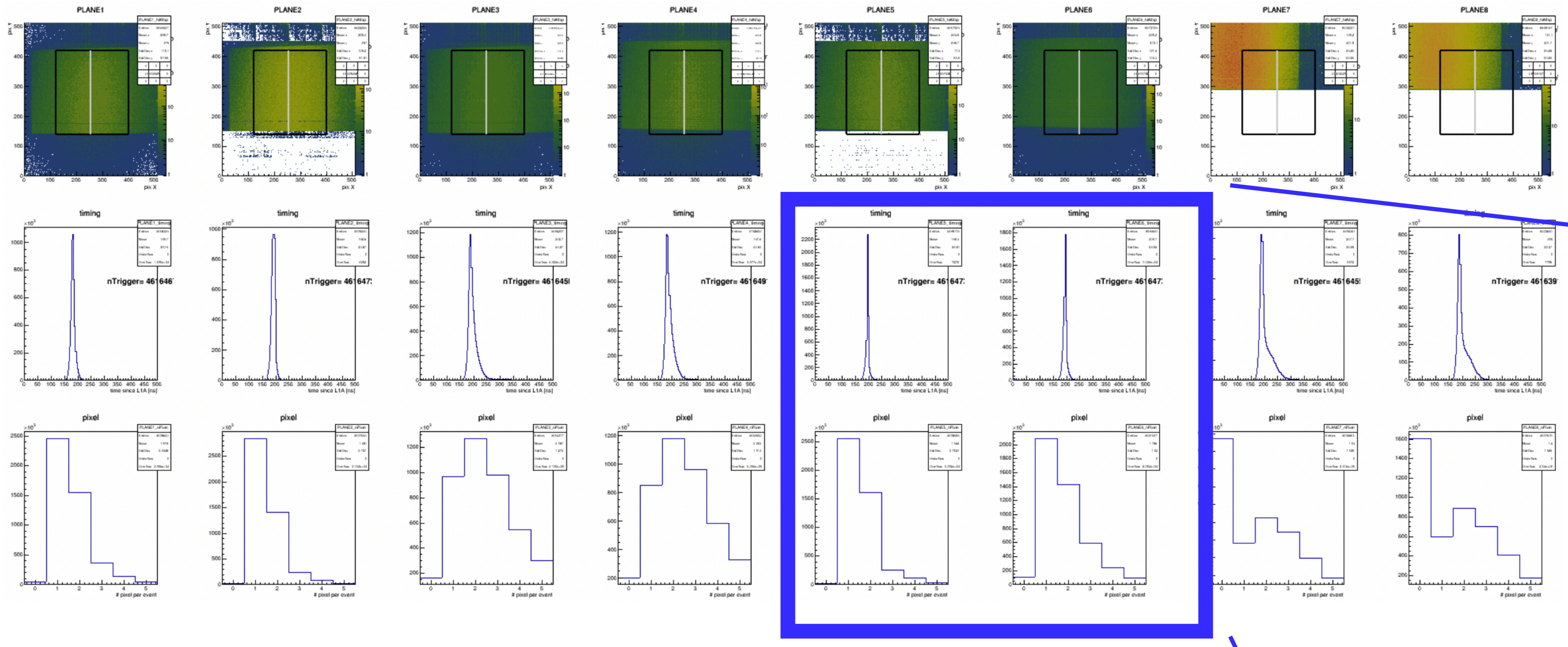
Details of MALTA planes and MALTA2 (DUT) planes

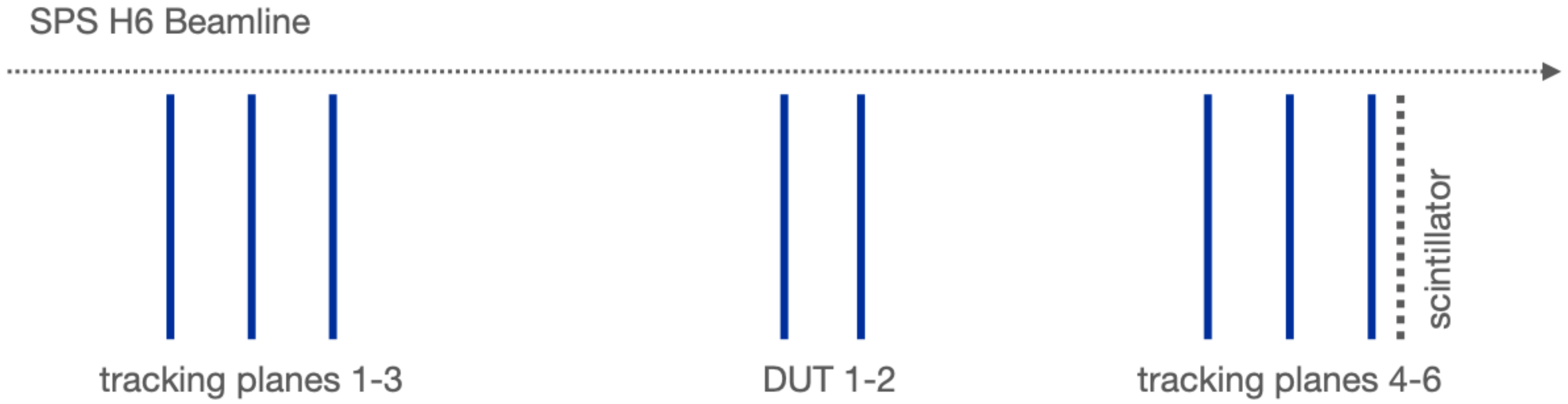
MALTA Online Monitoring System

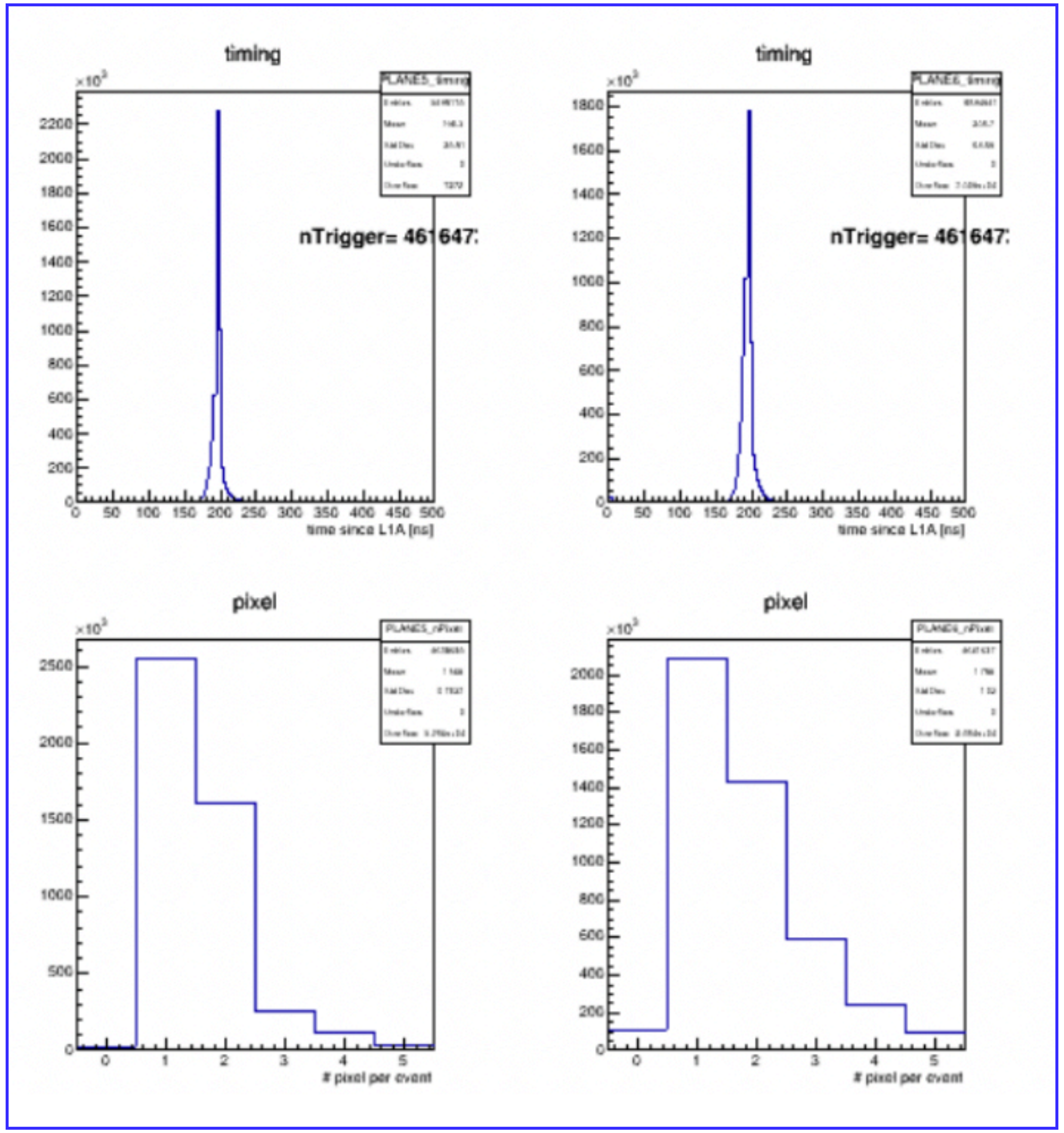
- Monitoring plots showing hit map, time of arrival w.r.t. trigger, and hit multiplicity.
- Fast analysis fully automised and ability to give feedback on DUT performance in a run within minutes.
- Ability to introduce ROI on the tracking planes.
- MALTA Cz. tracking planes (#3 and 4) @ 30V to improve tracking resolution.



MALTA Online Monitoring System







Time of arrival w.r.t trigger signal

Hit multiplicity

- Ability to handle high beam rate.
- Readout window after each trigger : 500 ns
- Alignment and tracking routines with Proteus.

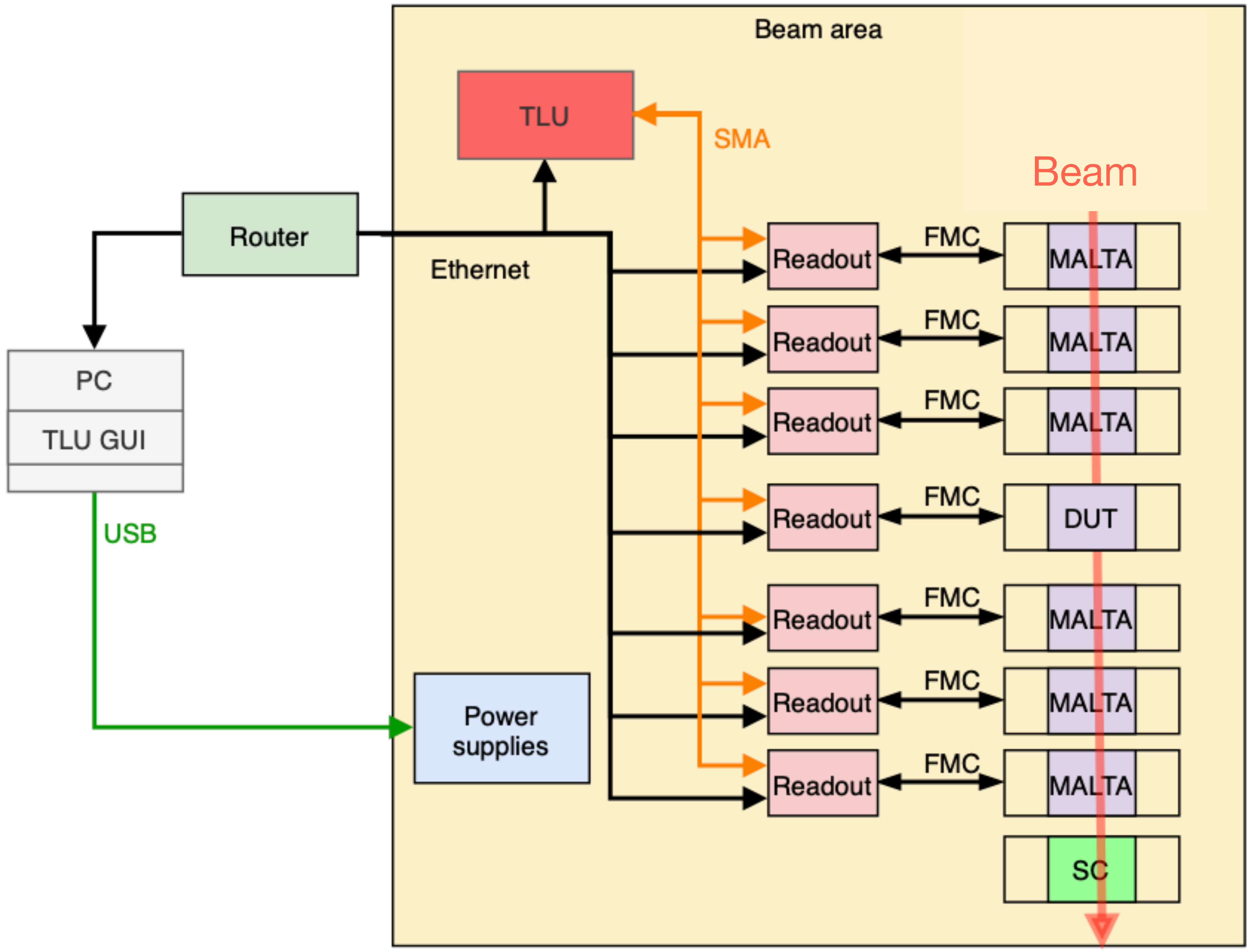
L Perktold et al. JINST 9 (2014) C01060

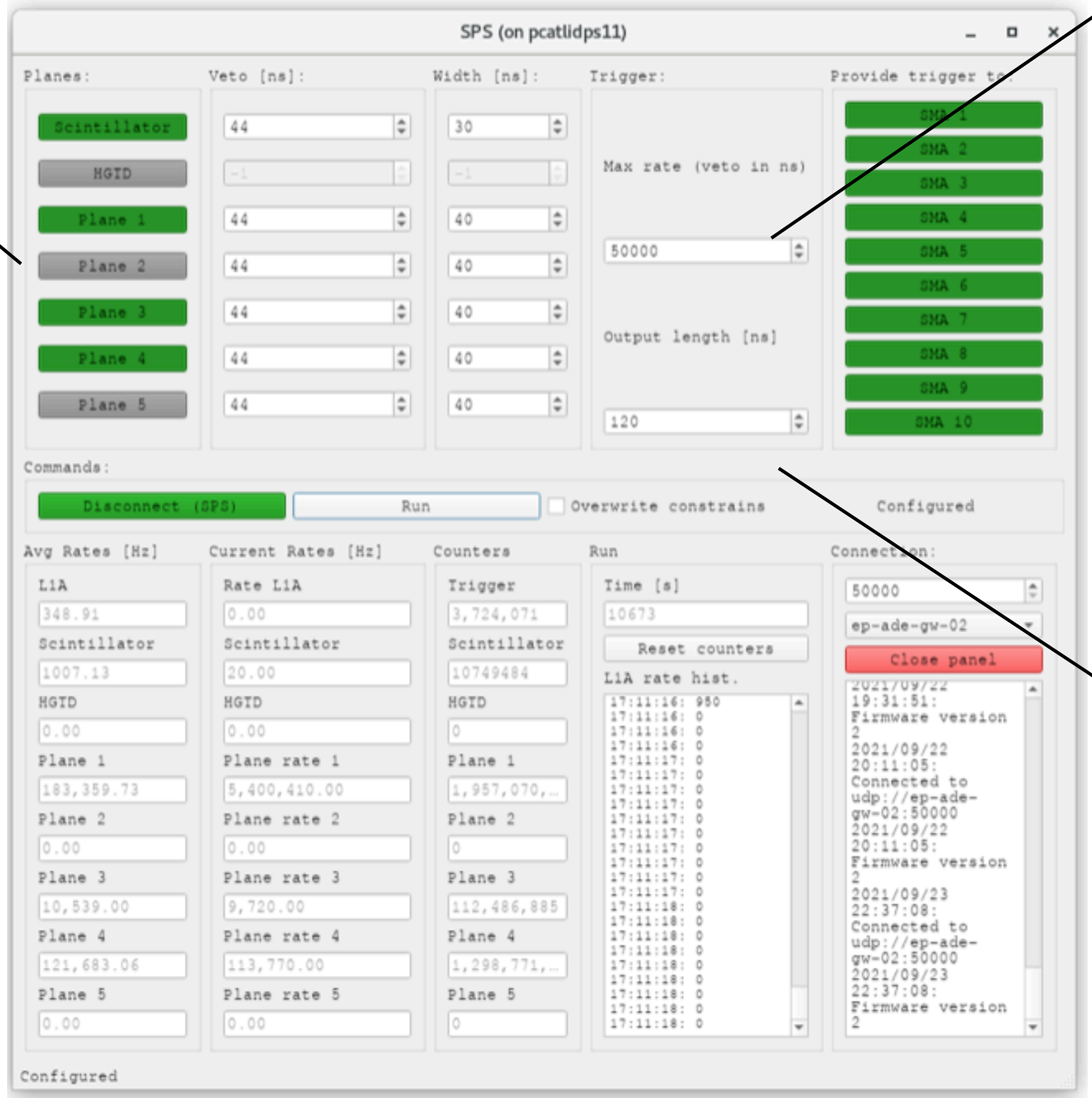
MALTA Trigger Logic Unit (TLU)

- MALTA TLU based on Kintex-7 evaluation board @ 320 MHz, offering flexible triggering possibilities.
- TLU is interfaced using SMA connectors to the planes and scintillator.
- Coincidence among MALTA planes is used to gate the signal of the scintillator.
- TLU GUI allows for the configuration and monitors rate of each plane and total rate (counters in real time).

Which planes do I want to trigger on?

What is the maximum rate I allow?

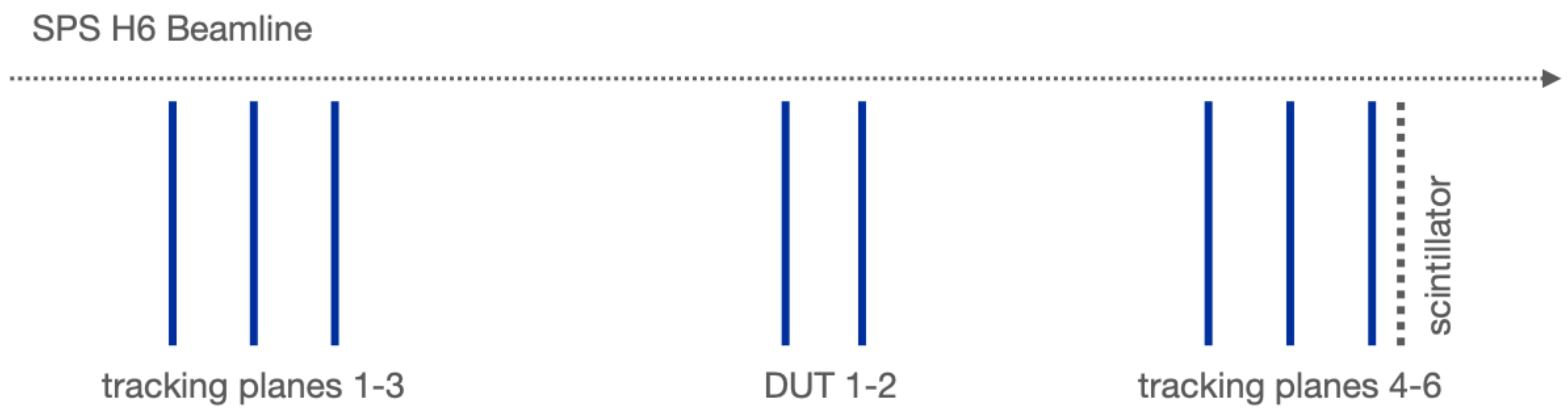


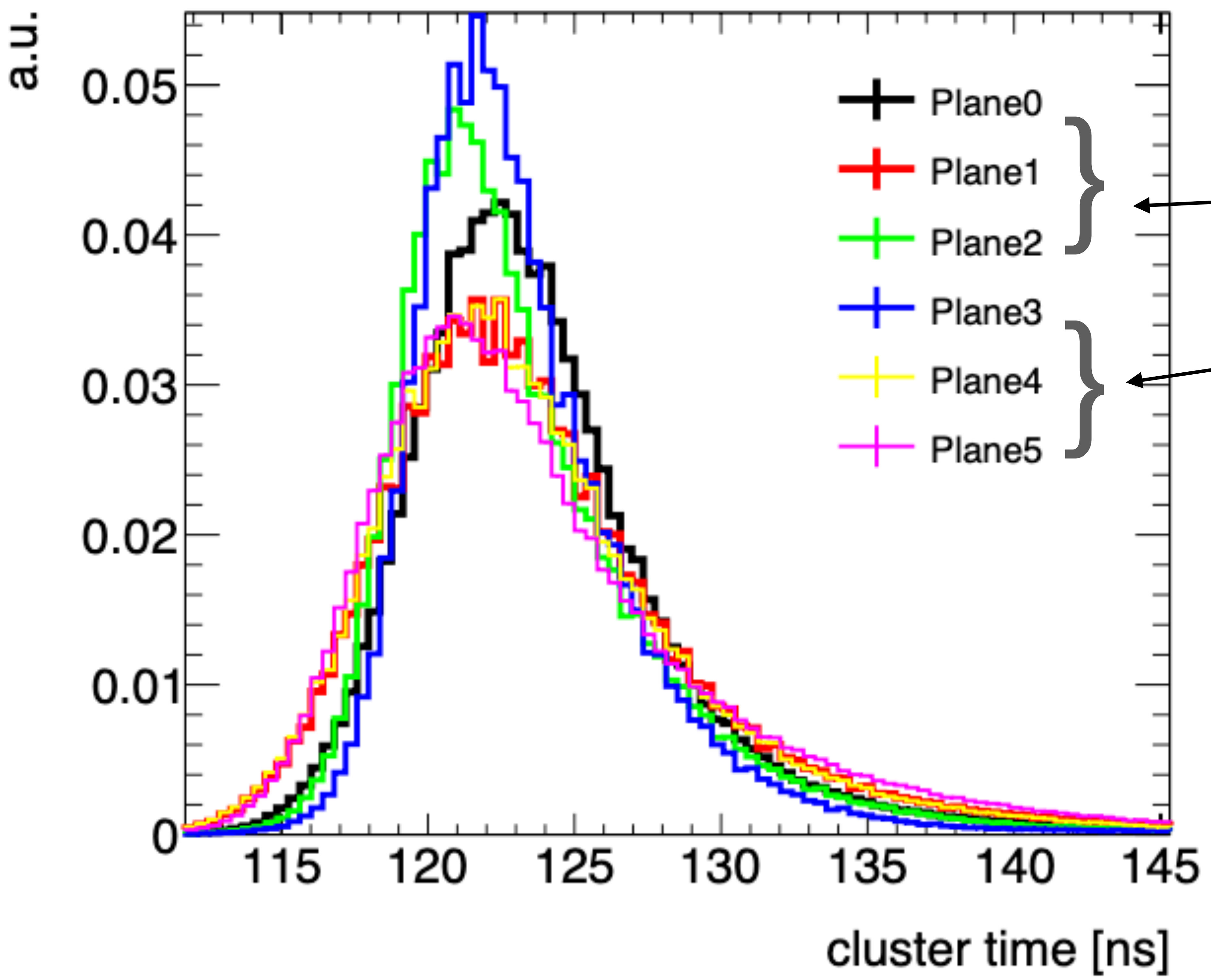


What is the output length of my trigger signal?

Ignacio Asensi Tortajada, Design and Development of Safety and Control Systems in ATLAS, Sep 2021, https://cds.cern.ch/record/2791748, Presented 09 Nov 2021

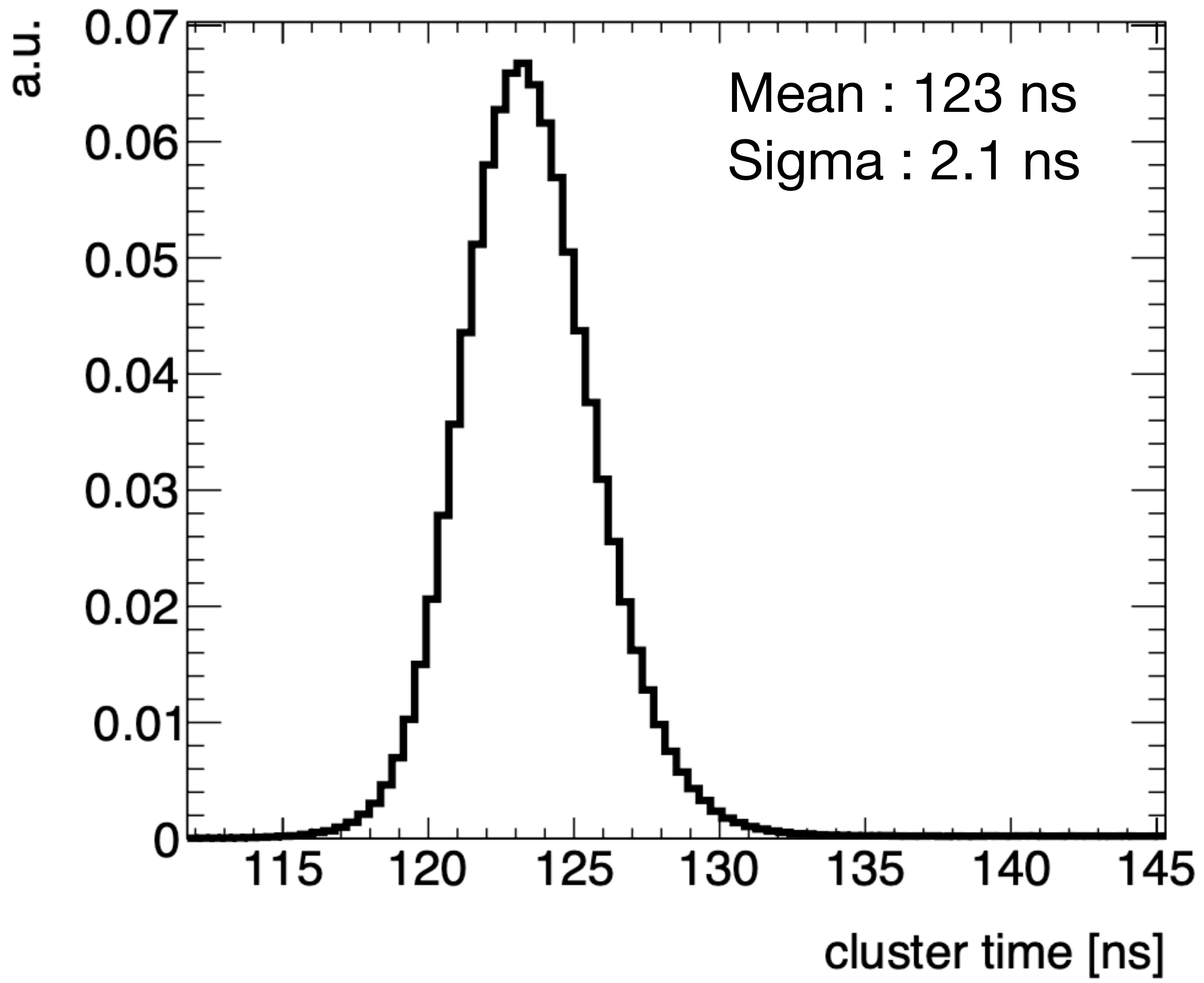
MALTA Telescope Time Resolution





Averaging of timing of Telescope Planes

Track timing

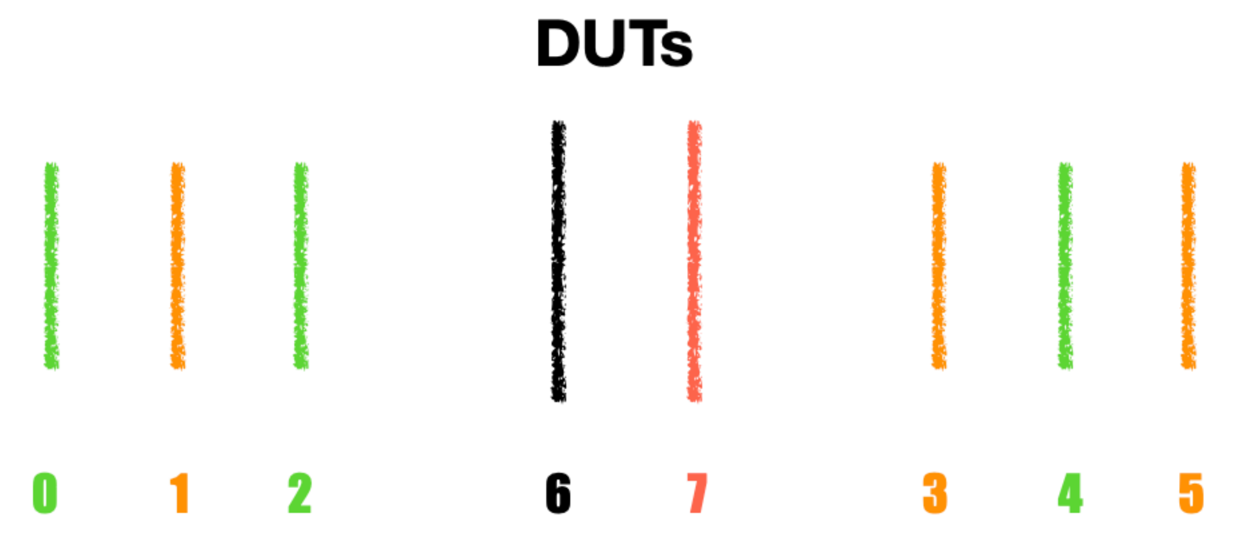


- Very precise hit timing for DUT’s and tracking (MALTA) planes.
- Trigger propagated asynchronously from TLU to each of the readout planes (0.9 ns jitter).
- Timing distribution still includes scintillator jitter (~0.5 ns).
- Timing resolution of MALTA2 has even better resolution (~1.9 ns).

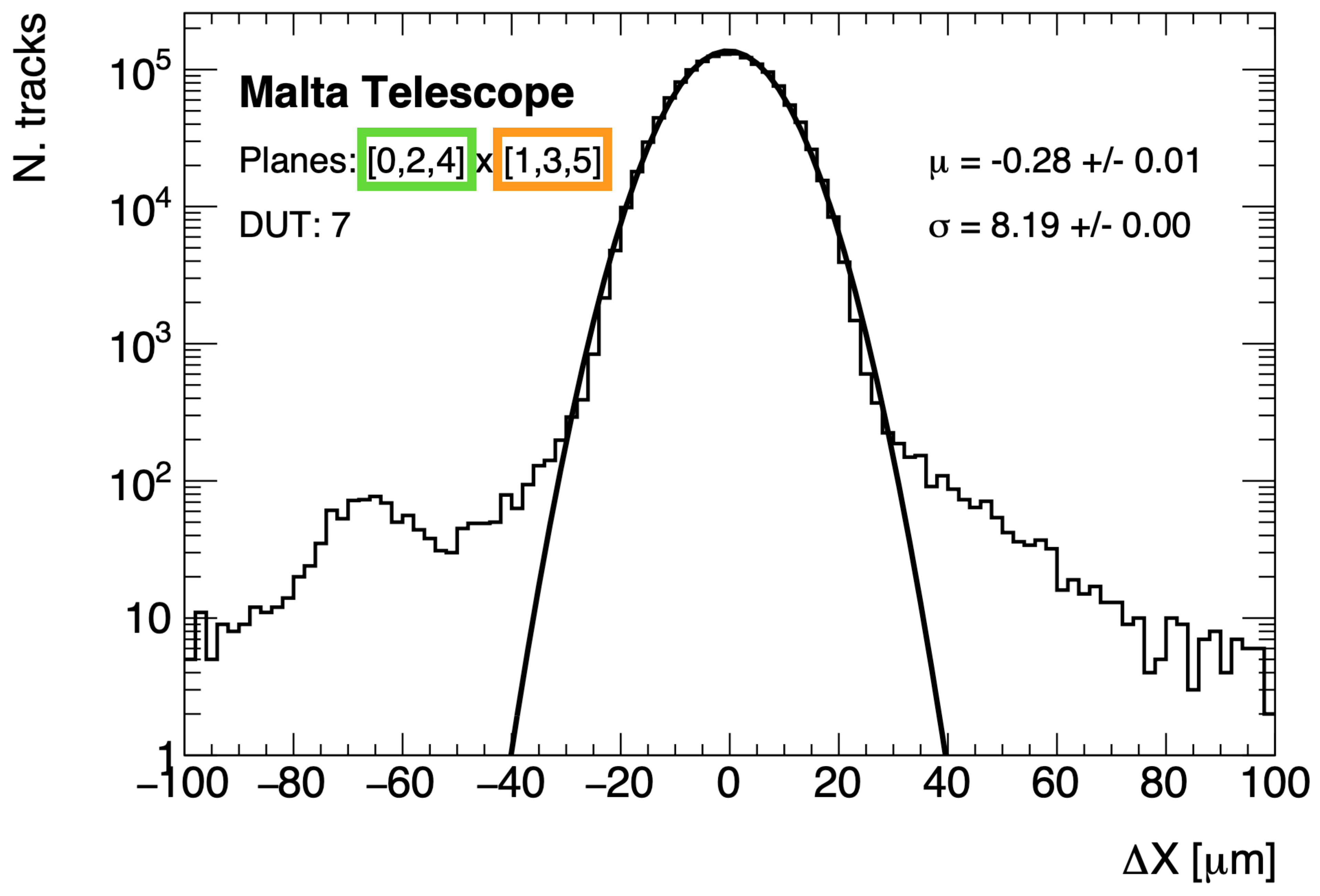
Vlad Berlea, "Tower Jazz 180 nm MALTA monolithic active pixel sensor Test Beam results", TREDI, 2022, https://indico.cern.ch/event/1096847/contributions/4742327/attachments/2400093/4104325/TREDI2022_final.pdf

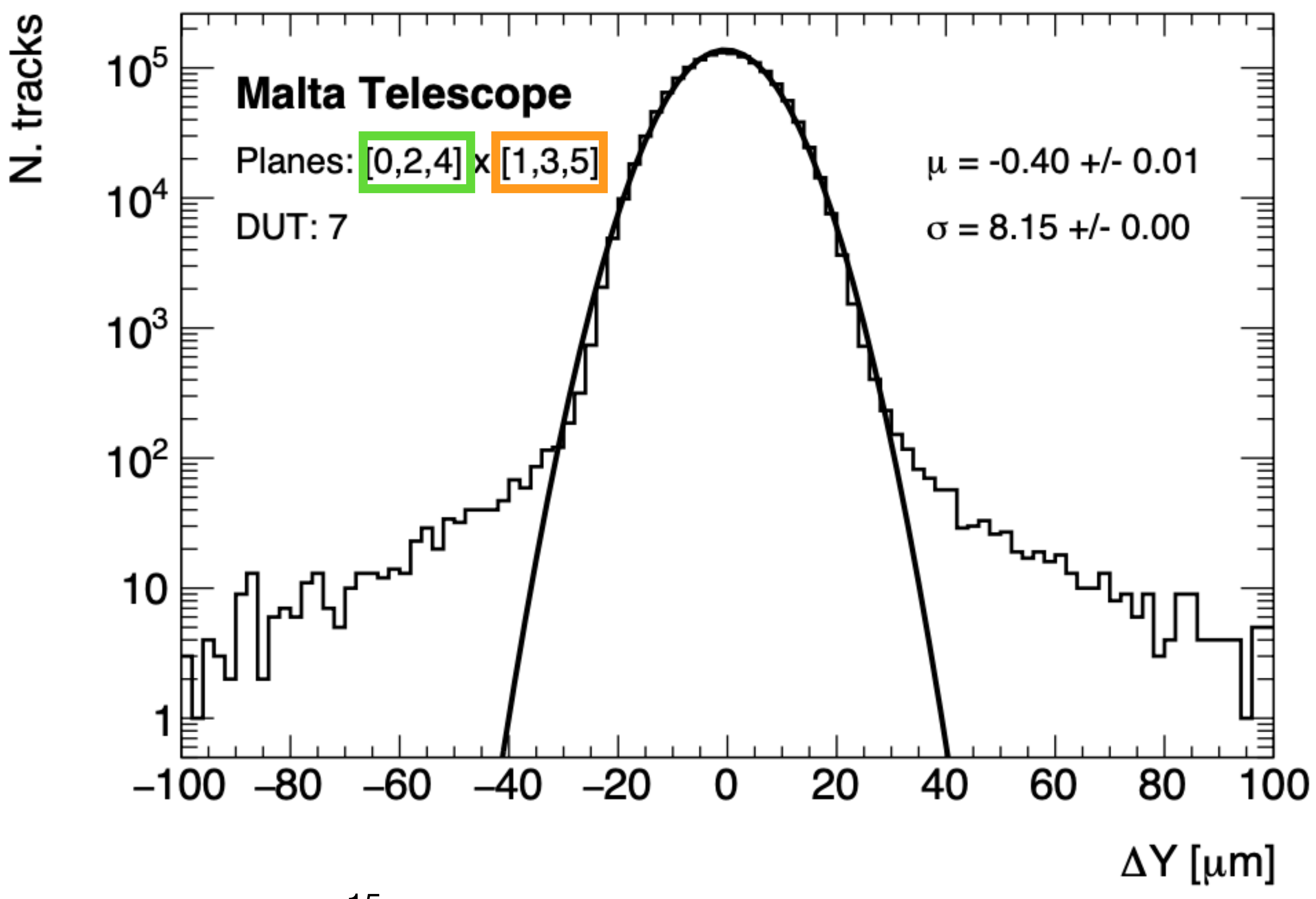
MALTA Telescope Resolution

- Telescope resolution estimated with double reconstruction of tracks with subset of telescope planes, e.g. comparing tracks reconstructed with 3 planes with 'same' configuration.
- Select subset of events with only 1 track reconstructed in both configuration, apply chi2/dof cut for track quality, difference of extracted position on DUT position divided by √2 (if the 2 setup configurations are symmetric). Exercise performed on 2 planes, 3 planes and four planes.



Telescope resolution based on three planes : 5.8 μm



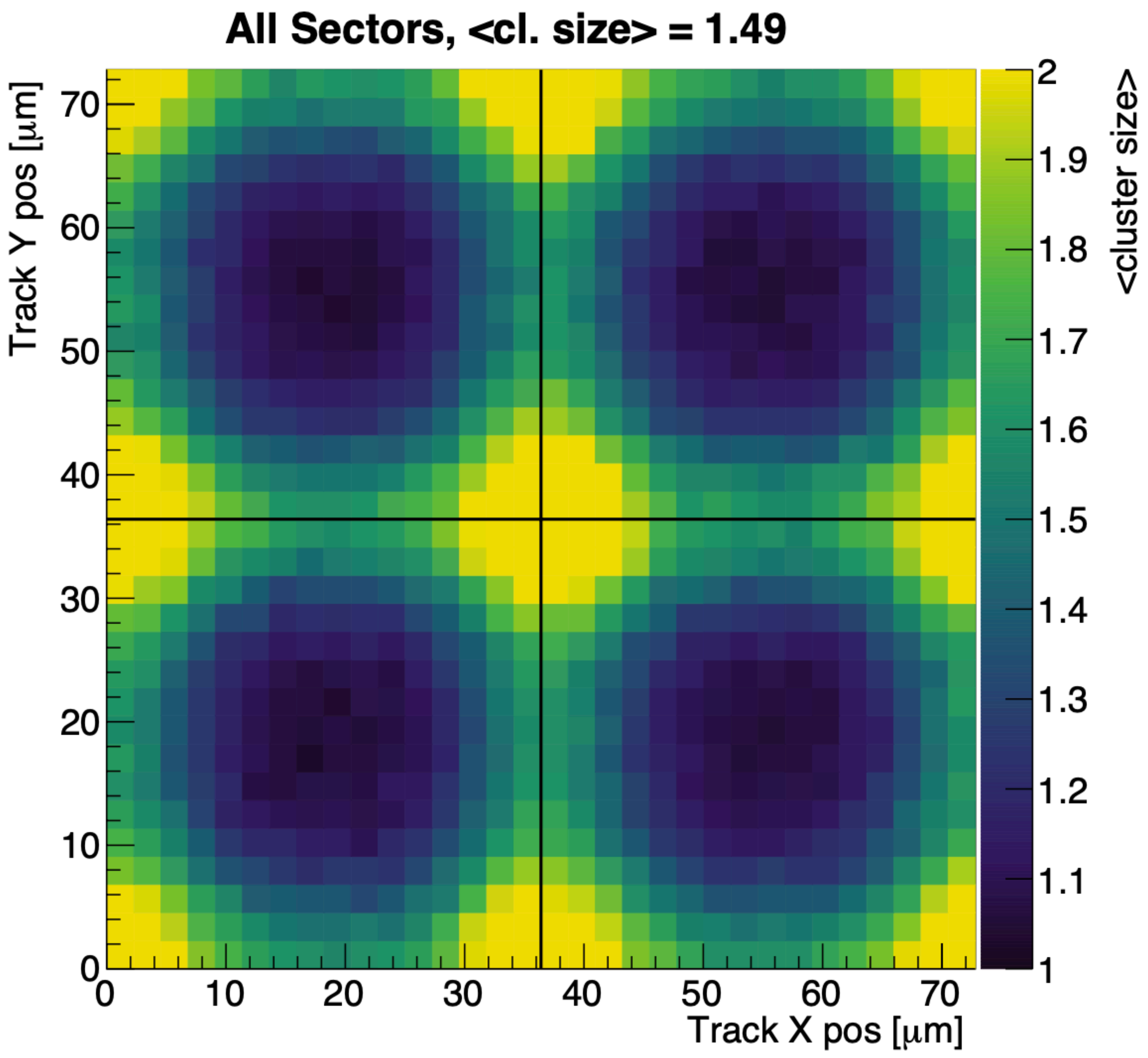


- Track requirement : Chi2/dof < 2
- Small dependence of chosen DUT (for this example DUT Plane 7)

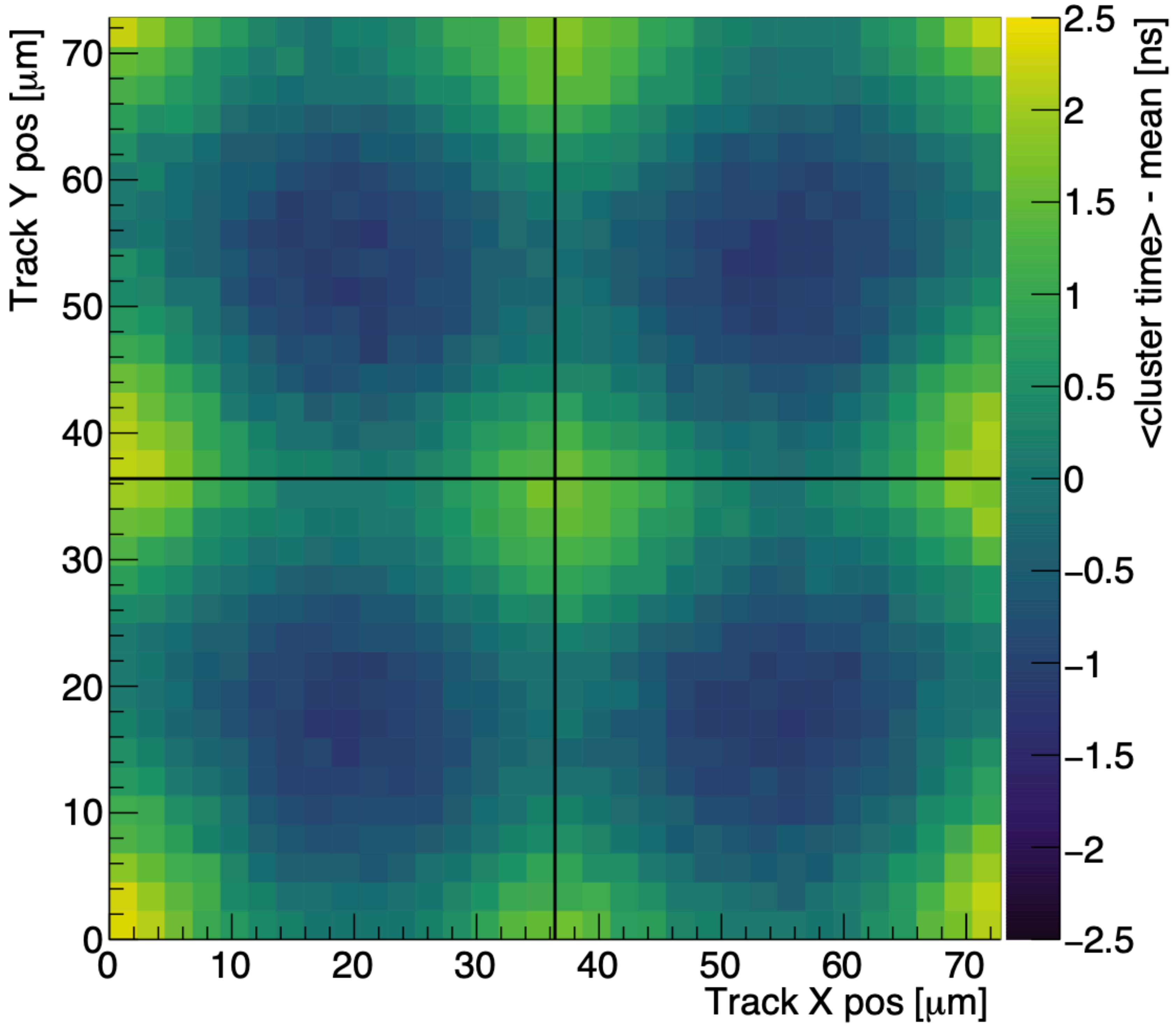
MALTA Telescope Resolution Applications

Why is the spatial resolution of importance ?

- Good resolution allows us to observe the effects between pixels more finely
  - Effects of cluster size and cluster timing are studied more precisely inside the pixels.
- Observations of charge collection effects (i.e. charge sharing) are useful for simulation work.



InPixel Cluster Size of Epi MALTA2 projected on 2x2 matrix
(threshold ~ 150 electrons)
SPS 2022



InPixel Cluster Timing of Cz MALTA2 projected on 2x2 matrix
(threshold ~ 170 electrons)
SPS 2021

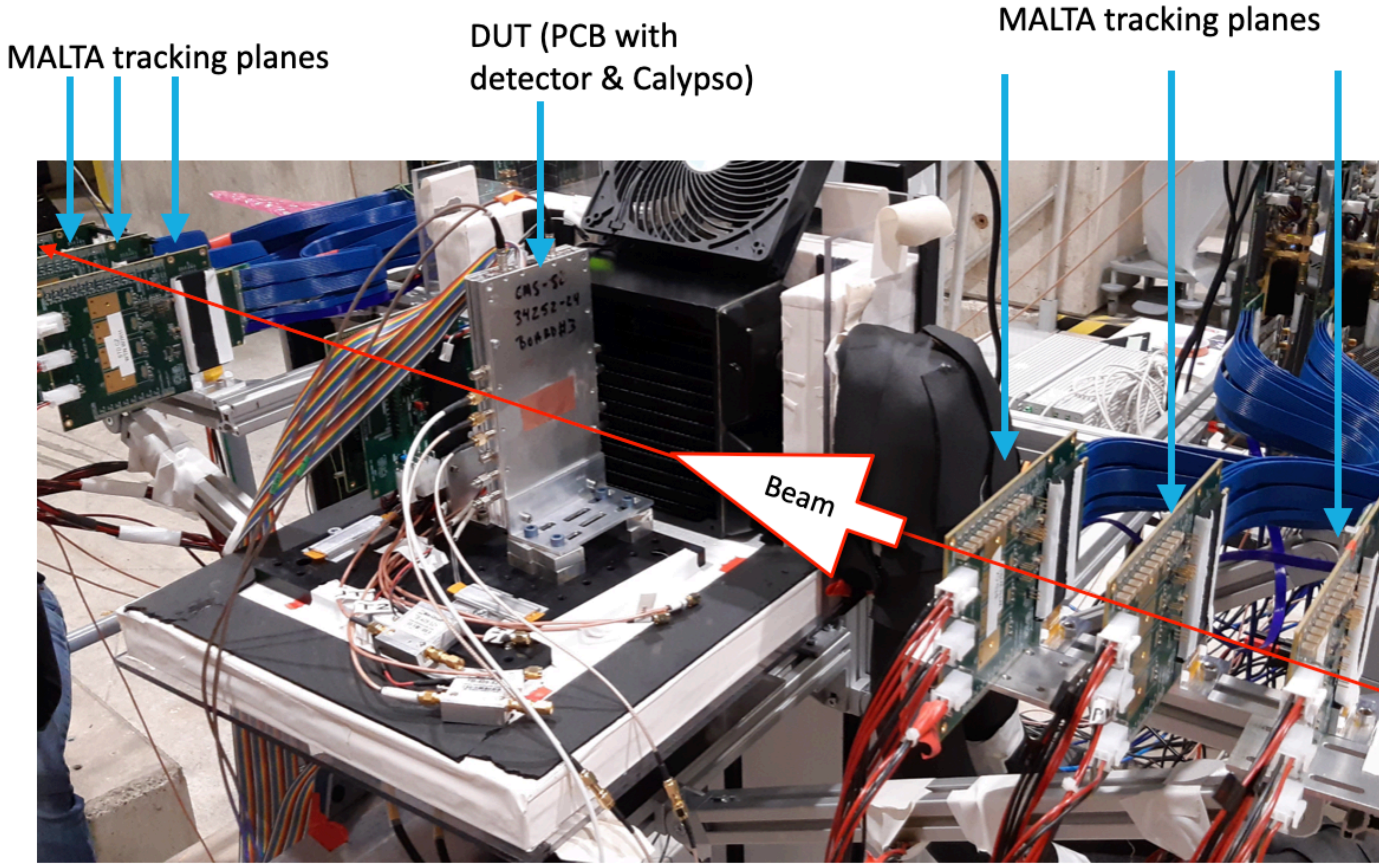
S

ATLAS HGTD

See talk by Louie Dartmoor Corpe 23/06

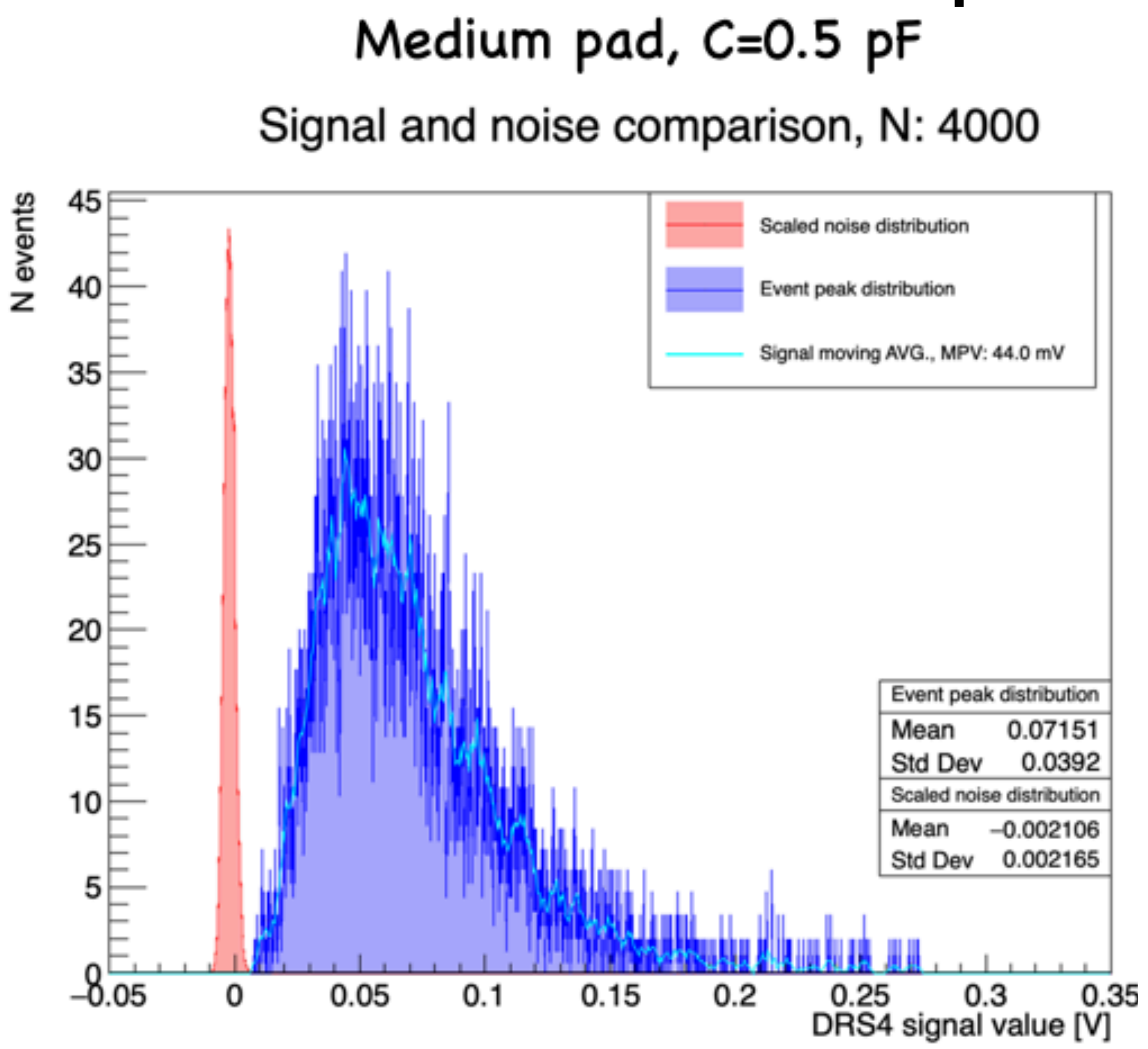
- MALTA tracking for efficiency calculation
- Reference LGAD (known 35ps resolution): extract time resolution
- Oscilloscope to measure waveforms/collected charge

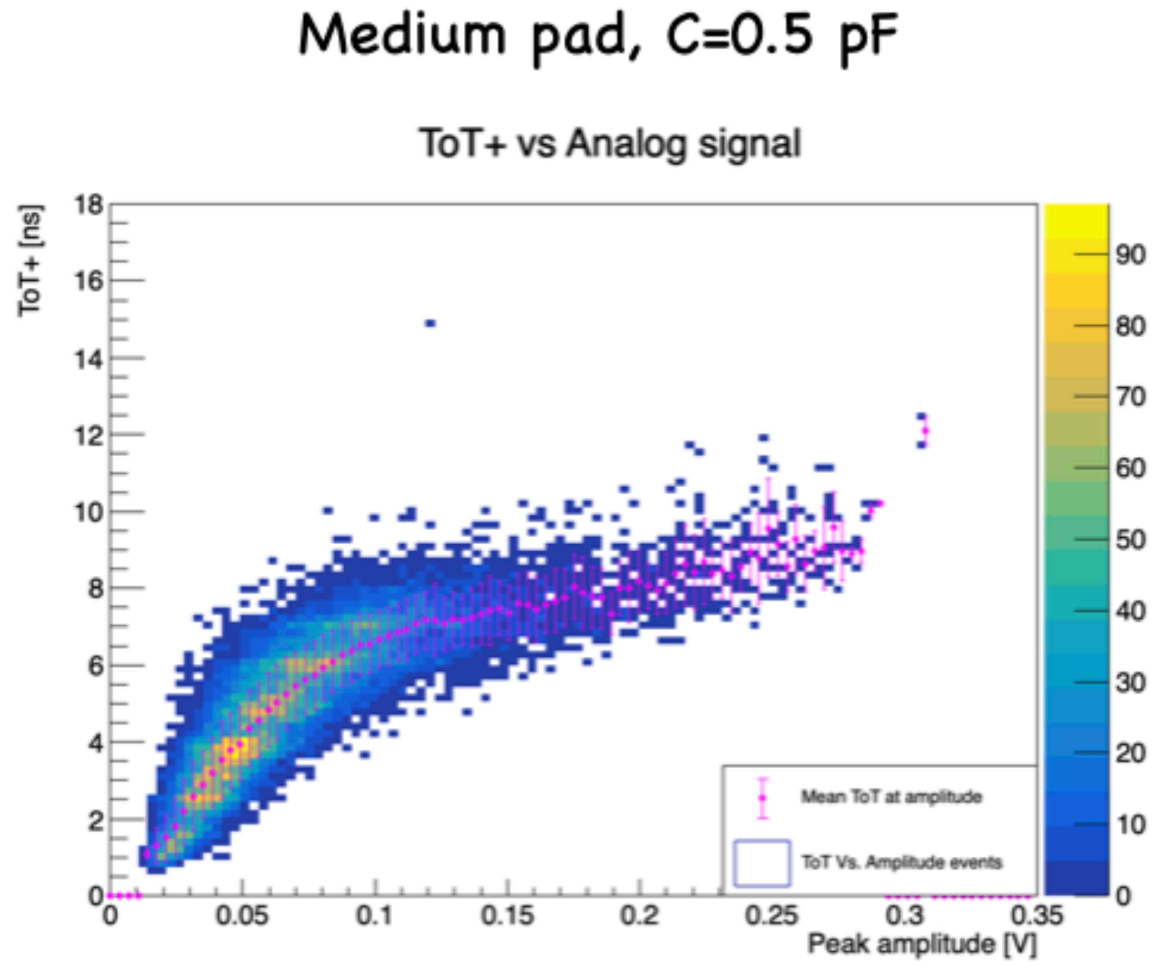
ATLAS BCM'



- MALTA Telescope used for tracking and timing information for reconstruction.
- Samples : Single Crystal diamond, 3D diamond, different pCVD diamonds..
- DRS4 used for readout (2 or 4 GHz).

pCVD Diamonds:





Conclusions and Outlook

- MALTA : Depleted Monolithic Active Pixel sensors designed in TowerJazz 180nm imaging technology. The MALTA sensor has been produced on Cz substrates in view of optimising the signal for efficiency and time resolution.

- A custom telescope with MALTA planes has been developed for a testbeam campaign at SPS (CERN) using up to six MALTA tracking planes and the ability to host several devices under test (DUT).

- The telescope system has a dedicated custom readout, online monitoring integrated into DAQ with realtime hit map, time distribution and event hit multiplicity. It furthermore hosts a dedicated fully configurable trigger system giving the possibility to trigger on coincidence between telescope planes and reference from scintillators.

- The excellent time resolution performance allows for fast track reconstruction, due to the possibility to retain a low hit multiplicity per event which reduces the combinatorics.

- Ongoing test beam at SPS with the MALTA Telescope will demonstrate efficiency and timing performance of next generation, post-processed MALTA2 samples.

Acknowledgements

- Part of the measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).
- Part of the 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 Nordhrein-Westfalen, Germany.
- This project has received funding from the European Union's Horizon 2020 Research and Innovation program under Grant Agreement no. 654168.(IJS, Ljubljana, Slovenia).
- This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement No 101004761.
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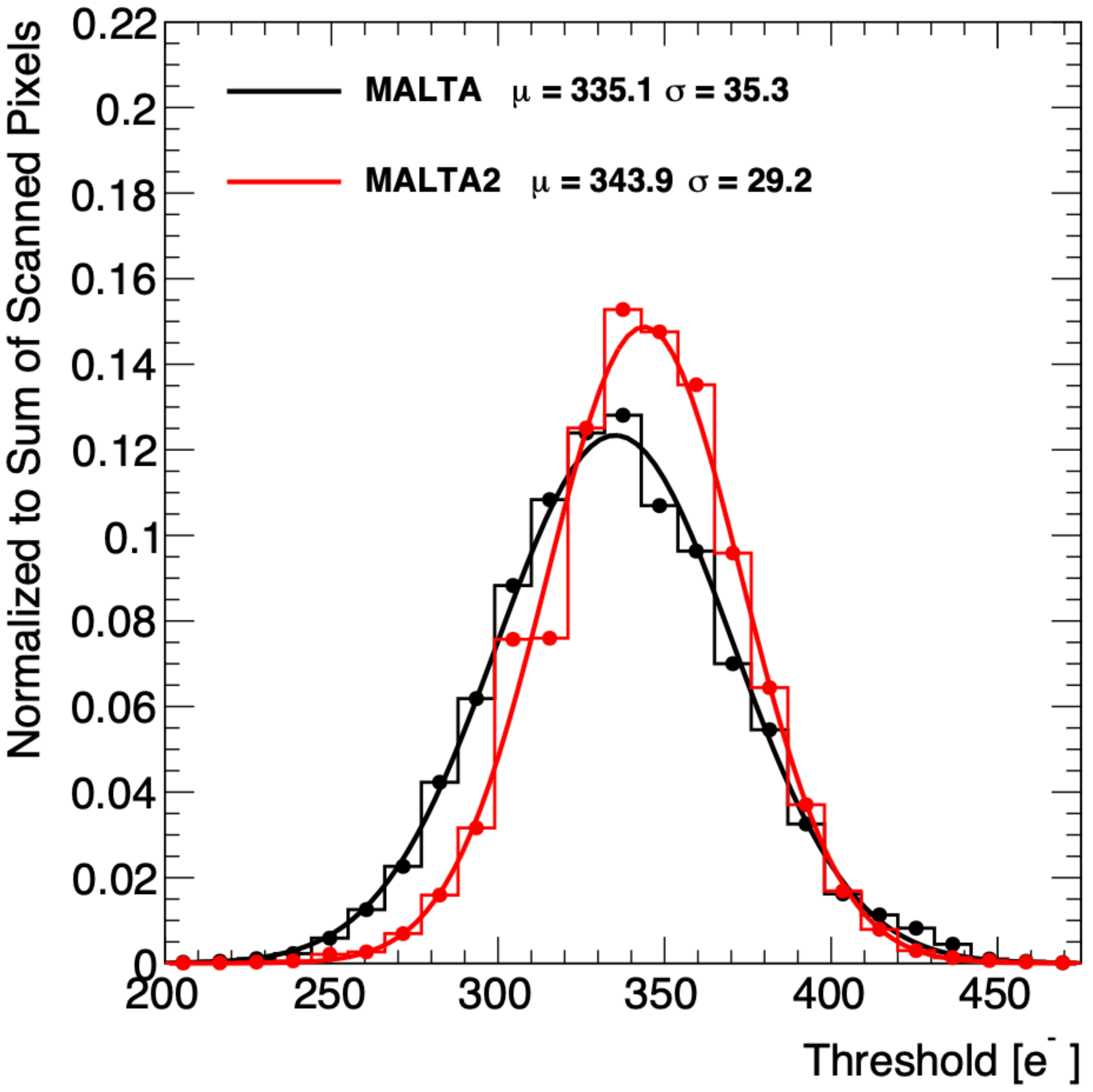
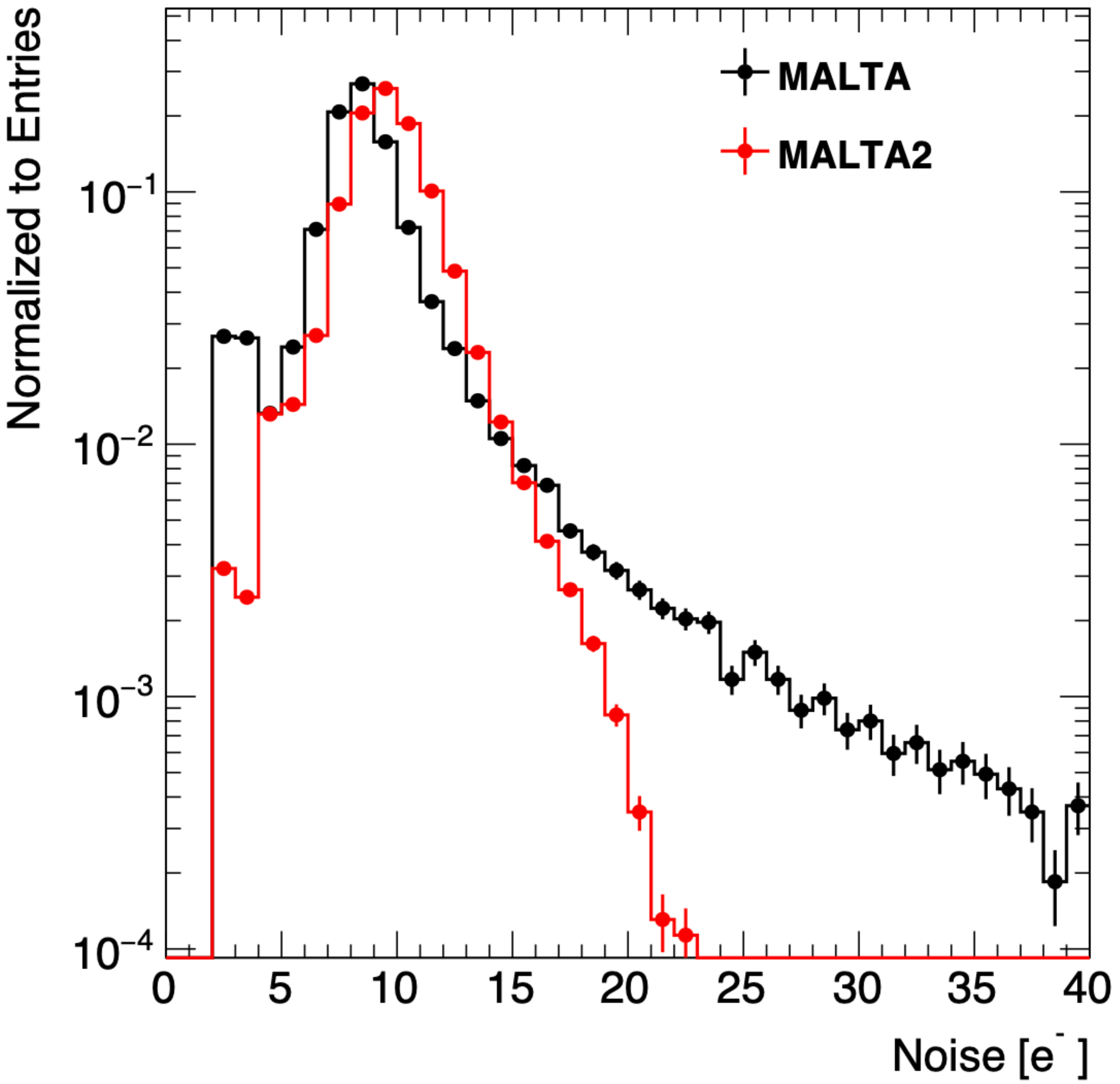
- Dr. Ben Phoenix, Prof. David Parker and the operators at the MC40 cyclotron in Birmingham (UK).

Back-up // Threshold and Noise MALTA vs MALTA2



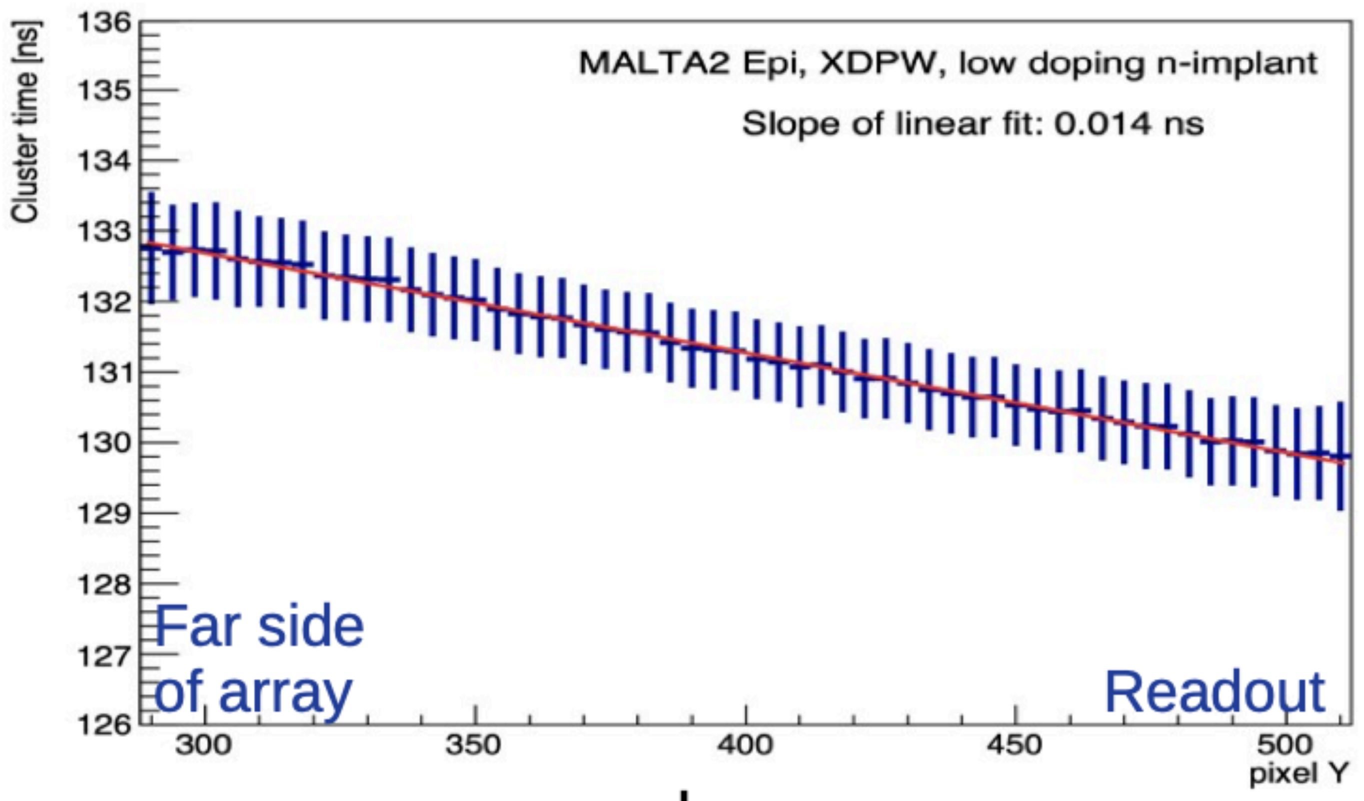


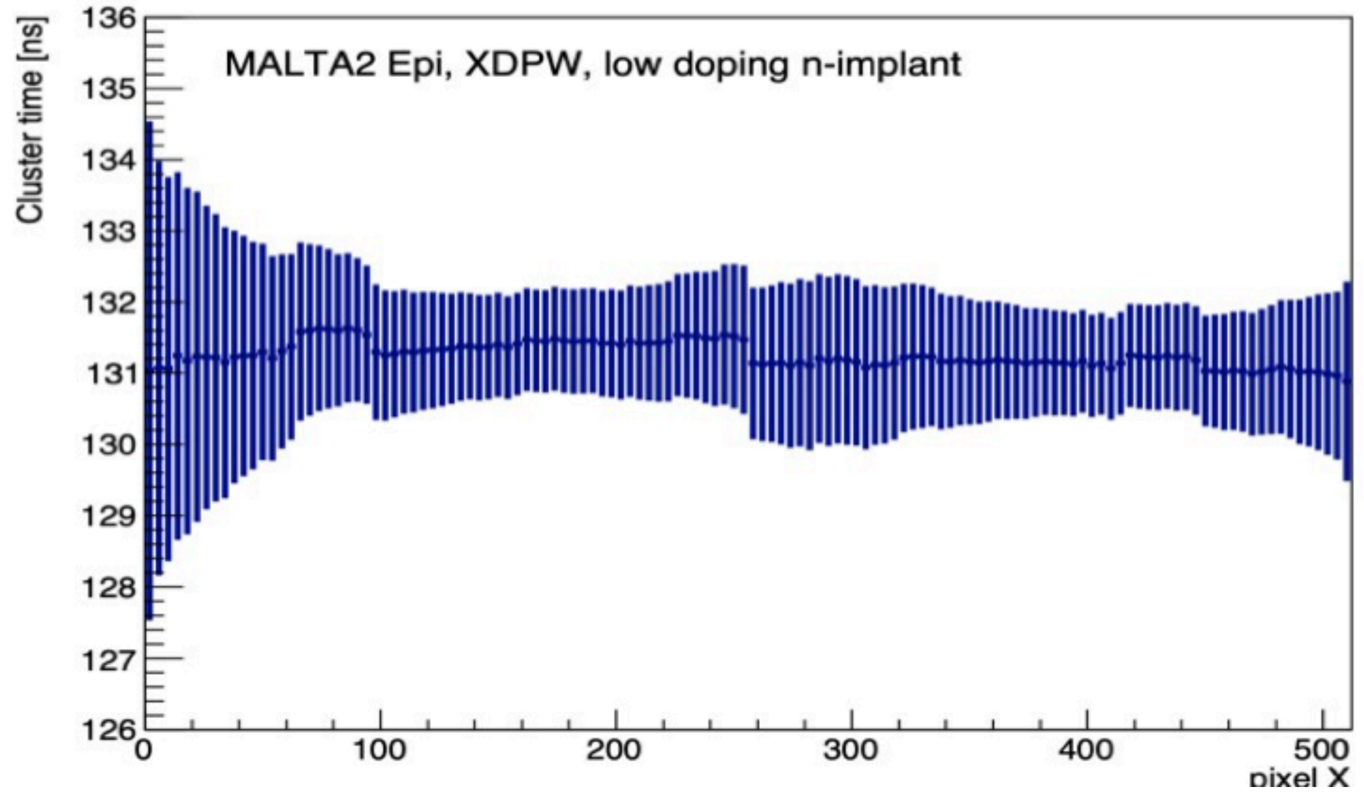
- Threshold (left) and Noise (right) scan for MALTA (black) and MALTA2 (red), both flavour Epi NGAP
- MALTA2 has less RTS noise (reduced noise tails) compared to MALTA at the same threshold at -6 V SUB bias and similar threshold level (~350 electrons)
- Threshold dispersion of MALTA2 similar to MALTA (~10% of the mean)

Back-up // Timing MALTA2

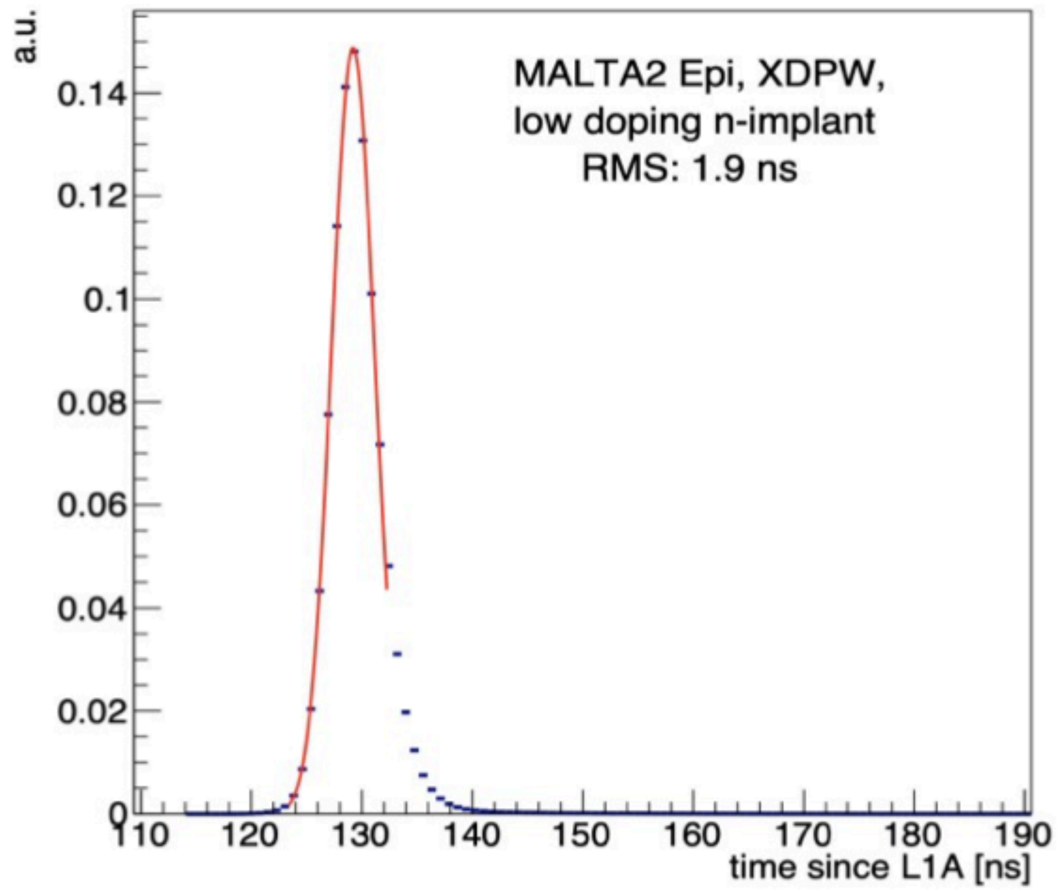
Time of arrival of the fastest hit in a matched cluster w.r.t scintillator reference, as a function of the matrix X/Y coordinate

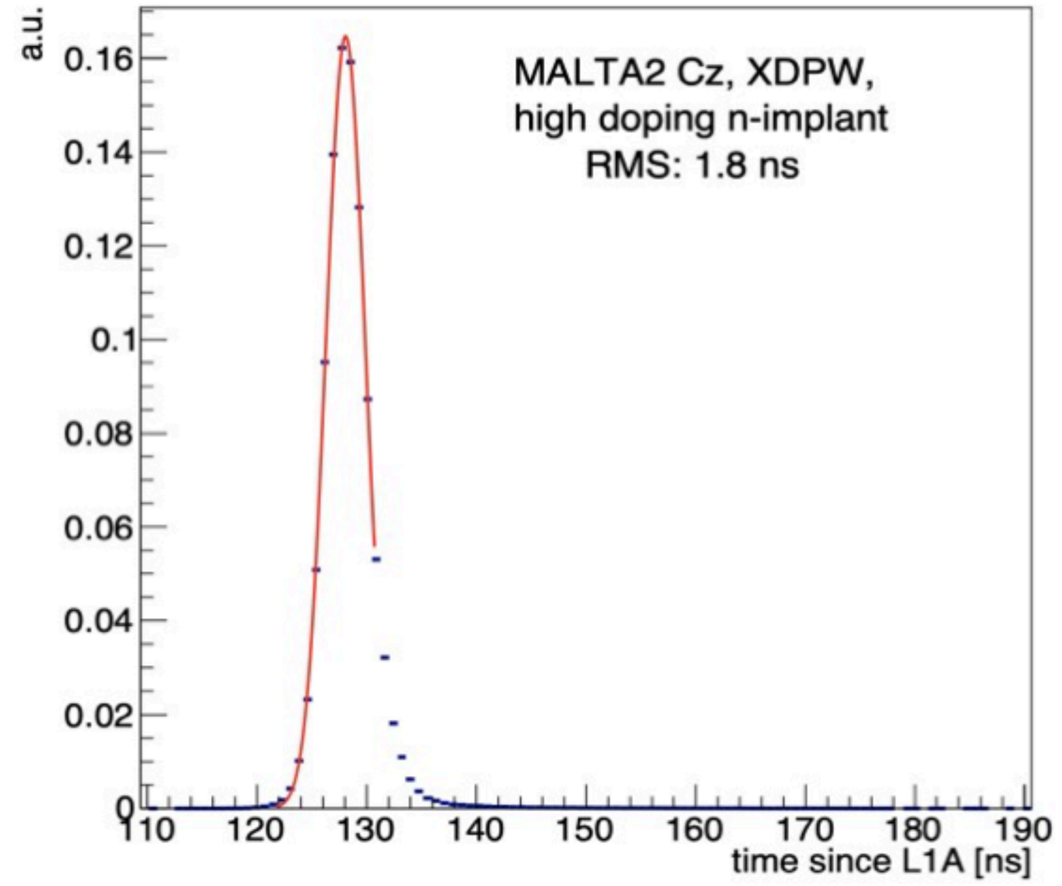
- **Timing corrections**:
    - **(Y)** Linear due to column time propagation (**top**)
    - **(X)** Non-uniform chip response in the row direction (**bottom**)
- The **timing plots** are a convolution of:
    - Electronics jitter
    - Time-walk
    - Charge collection effects
    - Scintillator jitter (500ps)
    - FPGA readout jitter (900ps)





Apply corrections





Vlad Berlea, "Tower Jazz 180 nm MALTA monolithic active pixel sensor Test Beam results", TREDI, 2022, https://indico.cern.ch/event/1096847/contributions/4742327/attachments/2400093/4104325/TREDI2022_final.pdf

Back-up // MALTA Telescope Resolution

Work in progress..

- Resolution estimate based on Telescope Optimiser (estimated on DUT 7)
- Tested for 2, 3, and 4 planes
- Same trend is observed (values closer as soon # planes increases)
- Measured resolution looks better than analytical solution
    - Cluster Size not taken into account
    - Telescope Optimiser results shown for average value instead of envelope

Layout		Sensor			Tracking	MC track position		
Plane #	Position (cm)	Thickness (% X/X_0)	Resolution (µm)	Tracking used	Resolution (µm)	real (µm)	measured (µm)	reconstructed (µm)
	-10.0				8.89	0.0		0.0
0	0.0	0.00	10.5	☑	8.02	0.0	0.0	0.0
1	8.0	0.00	10.5	☐	7.38	0.0	0.0	0.0
2	16.0	0.00	10.5	☑	6.79	0.0	0.0	0.0
6	64.2	0.00	10.5	☐	5.35	0.0	0.0	0.0
7	66.6	0.00	10.5	☐	5.41	0.0	0.0	0.0
3	94.0	0.00	10.5	☑	6.79	0.0	0.0	0.0
4	102.0	0.00	10.5	☐	7.38	0.0	0.0	0.0
5	110.0	0.00	10.5	☑	8.02	0.0	0.0	0.0
	120.0				8.89	0.0		0.0