VERTEX 2020

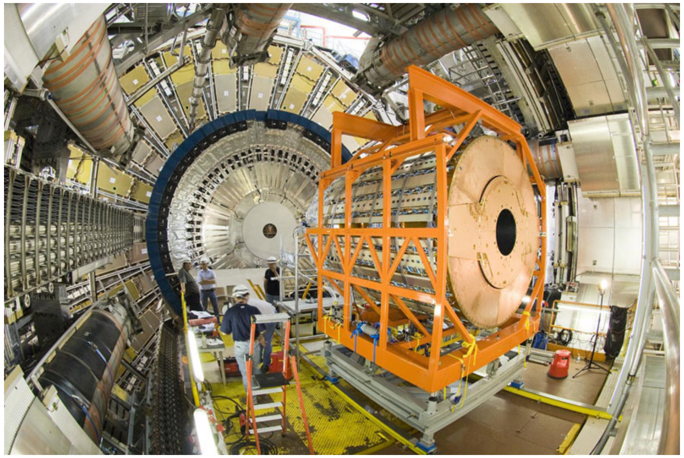
Latest developments and results of radiation tolerance CMOS sensors with small collection electrodes

Ignacio Asensi on behalf of Phil Allport, Tobias Bisanz, Daniela Bortoletto, Valerio Dao, Dominik Dobrijevic, Mateusz Dyndal, Leyre Flores, Patrick Freeman, Andrea Gabrielli, Laura Gonella, Maria Mironova, Kaan Oyulmaz, Heinz Pernegger, Petra Riedler, Jose Torres, Abhishek Sharma, Carlos Solans, Walter Snoeys, Steven Worm…

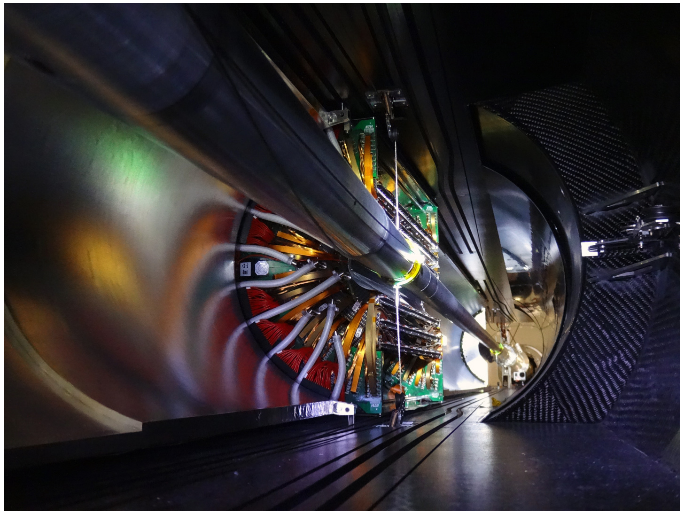
LHC Introduction

- LHC is going through a series of upgrades
- HL-LHC will deliver 3000 fb^{-1} after Phase II
- Luminosities from 7.5 to 30 x 10^{34} cm^{-2} s^{-1}
- And from 200 up to 1000 interactions per bunch crossing
- These upgrades present many challenges for electronics and radiation hardness
- Monolithic pixel detectors could address these challenges for the LHC and beyond

Pixel sensors at the LHC



ATLAS Inner detector



CMS pixel detector

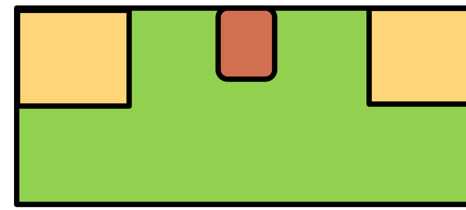
- Higher rates of **~2MHz/mm²** require smaller sensors to separate individual particles
- Pixel detectors have to overcome high radiation requirements of **1e15 to 2e15 n_{eq}/cm^2** NIEL
- Pixel detectors can overcome fast timing of **25ns** bunch crossing
- Interesting for studies beyond HL-LHC
  - FCC recommended by 2020 Update of the European Strategy for Particle Physics
  - Monolithic pixel sensors present a high potential for HEP with low power consumption (**<0.5W/cm²**) and industrial-like production

Depleted Monolithic Active Pixel Sensors

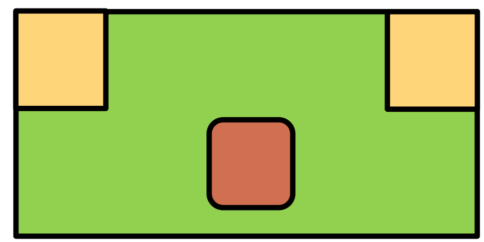
RnD designs for Depleted Monolithic Active Pixel Sensors (MAPS) on the search for best performance and radiation hardness

- Large electrode
  - Large capacitance (~100 fF)
  - Electronics in collection well
  - Higher noise (due to larger sensor capacitance)
  - Potential crosstalk between digital and analog sections
- **Small electrode**
  - Low capacitance (~5 fF)
  - Electronics separated from collection well
  - Lower noise (small capacitance for high SNR)
  - Separate digital and analog electronics
  - Need process modification for radiation hardness
- Buried electrode
  - Separated layers for electronics and sensor
  - To overcome radiation ionization charge trapped in the non depleted part

Large electrode



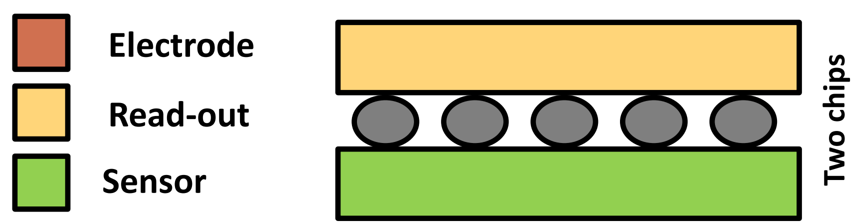
Small electrode



Buried electrode

To be compared with Hybrid sensors

- More expensive and complex
- Two chips: Sensor and a read-out chips
- Large electrodes and large capacitance
- Buried electrodes



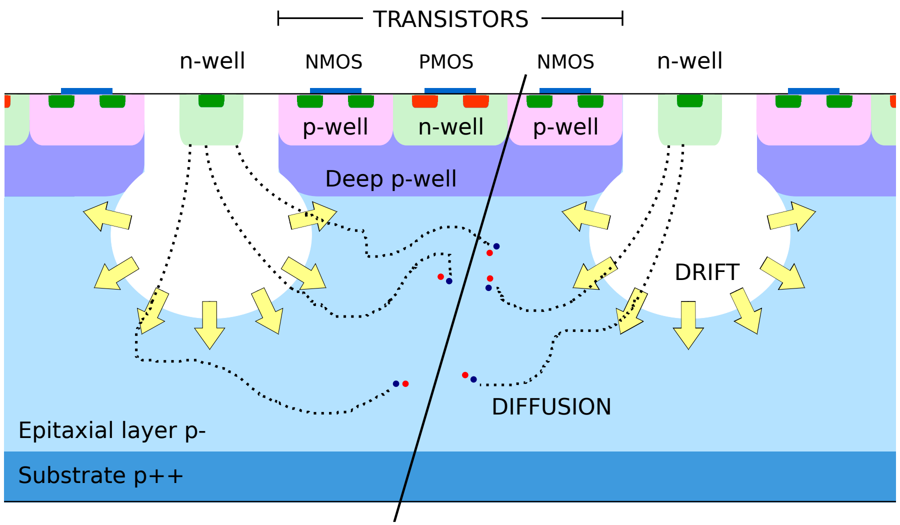
TowerJazz 180 nm CMOS technology

Processes already used in Alice (ALPIDE)

Standard

- **Small collection electrode** (~3 μm²) with high-resistivity Epi layer
- Small input capacitance (< 3 fF)
- Small depletion depth (~20 μm)
- High signal to noise ratio (~20)

Standard process

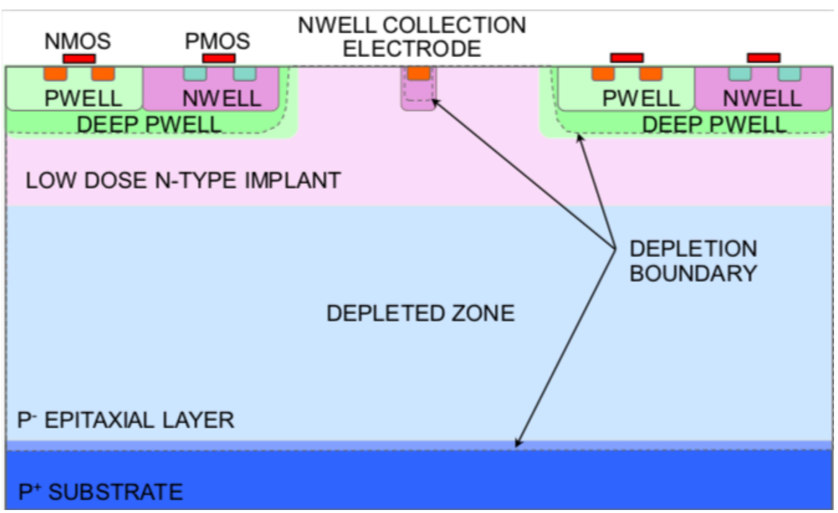


[W. Snoeys, NIM A 871 (2017) 90-96](https://doi.org/10.1016/j.nima.2017.07.046)

Modified with continuous n-layer

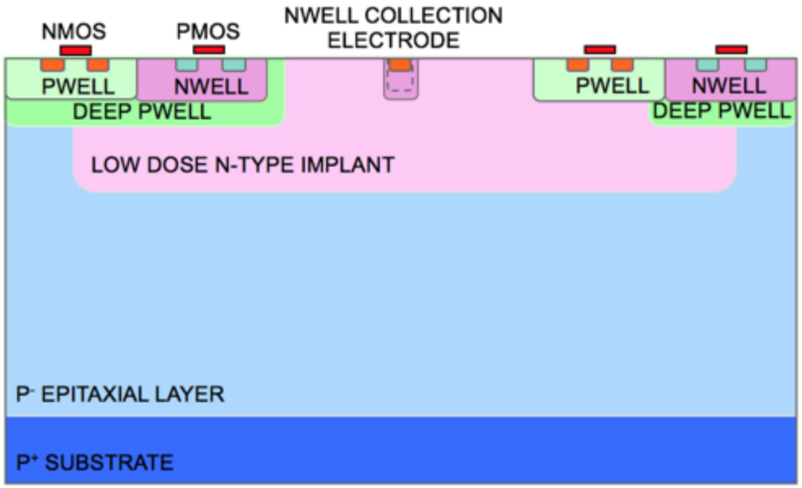
- Extra n-type layer to improve depletion under the deep p-well
- Overcome diffusion which makes collection slower

Continuous N-layer

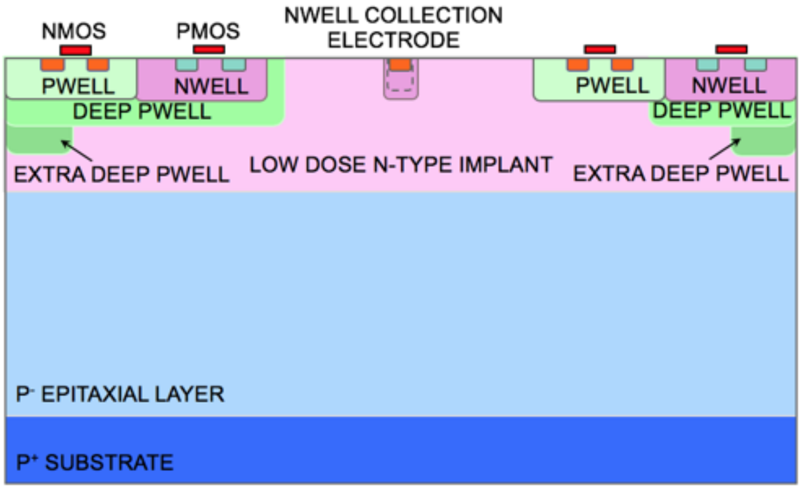


TowerJazz 180 nm CMOS technology

Gap in the n-layer



Extra deep p-well



More details and description of the process modification and summary of results in:

M. Dyndal, JINST 15 (2020) P02005

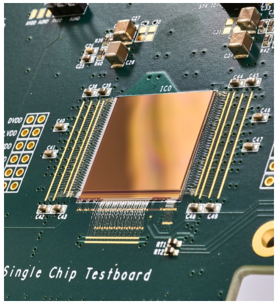
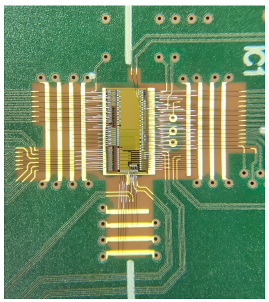
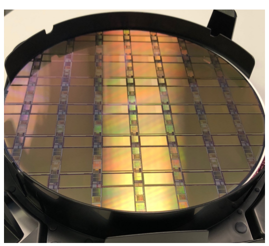
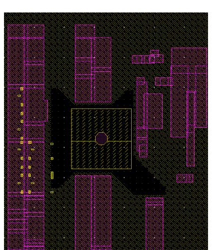
M. Mironova, NIM A 956 (2020) 163381

Magdalena, M. Munker PIXEL 2018

Process **modifications** for radiation hardness

- **Continuous n-layer (Cont.)**: Full lateral depletion. (See prev. slide)
- **Gap in the n-layer (n-gap)**: Modification of the mask
- **Extra deep p-well implant (EDPW)**: Additional mask

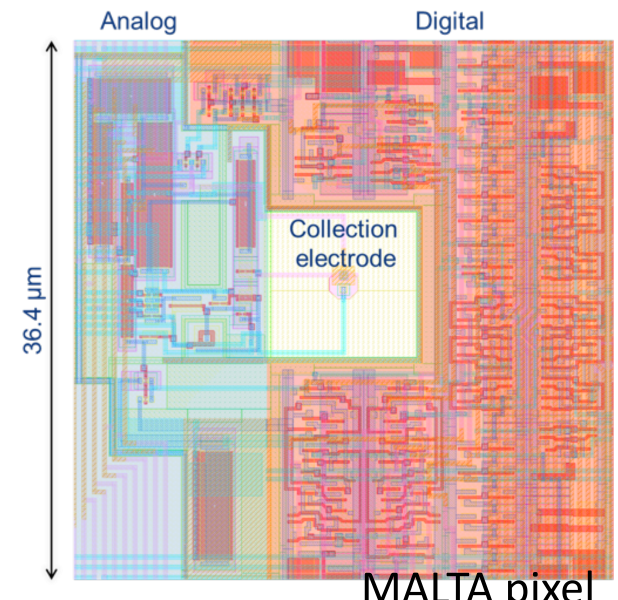
Development

			Sensor modifications	Chip
	Jan 2018 Jun 2018	**MALTA1 & MLVL**	• Continuous n-layer • MLVLC	• Large demonstrator 2x2 • Asynchronous readout • Slowcontrol issues
	From Jan 2019	**Mini-MALTA And Mini-MALTA ATTRACT**	• Cascoded FE • Process modification	• Small demonstrator 1.7x0.5 • Serial output • Full efficiency after 1e15 n/cm^2
	From Aug 2019	**MALTA C and MALTA Cz**	• 3 types of process modification	• Large demonstrator 2x2 • Slow control improvements • Enlarged cluster size and improved time resolution
	Oct 2020	**MALTA 2**	• Mini-MALTA FE • 3 types of process modification • Different doping levels	• Smaller matrix 2x1 • New Slowcontrol • Baseline for CERN EP R&D WP 1.2

stream.web.cern.ch

TJ MALTA sensor

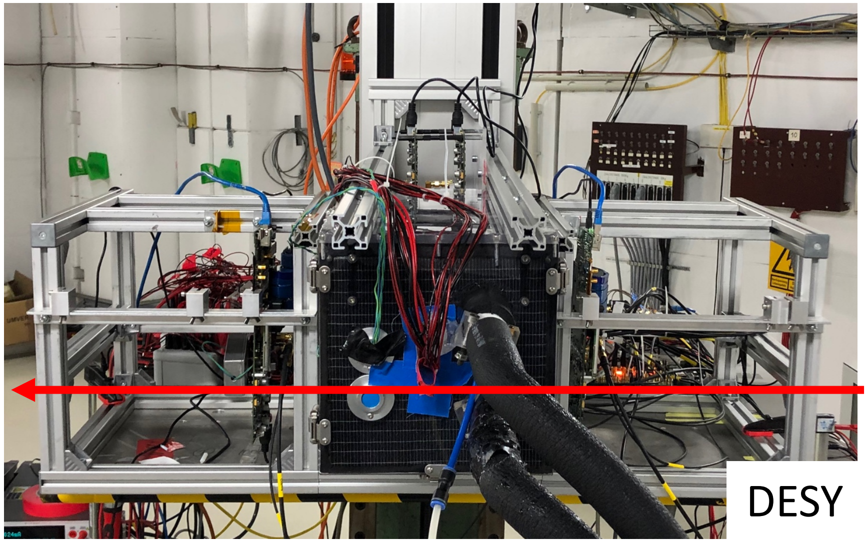
- Matrix **512 x 512** pixels of **36.4 x 36.4 μm²** size
- **8 sectors** with different pixel flavors
- Fully clock-less matrix architecture
- **Asynchronous readout** architecture for high hit rates and fast signal response. Parallel read-out bus 37bit.
- 10 mW/cm² digital power
- Small collection electrode of 2-3 μm to achieve minimal capacitance <3fF
- 3.4 - 4 μm spacing to electronics
- **Very low power consumption:**
  - **1 μW/pixel** analog power
  - **70 mW/cm²** analog power



Possible MALTA application

Using MALTA to trigger telescope

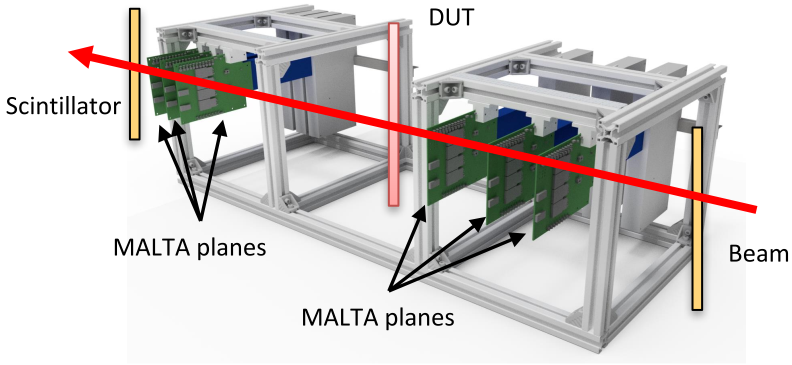
- Xilinx Virtex-7 FPGA VC707 for readout
- Trigger from MALTA planes as combination reference signals and compatible with AIDA telescopes

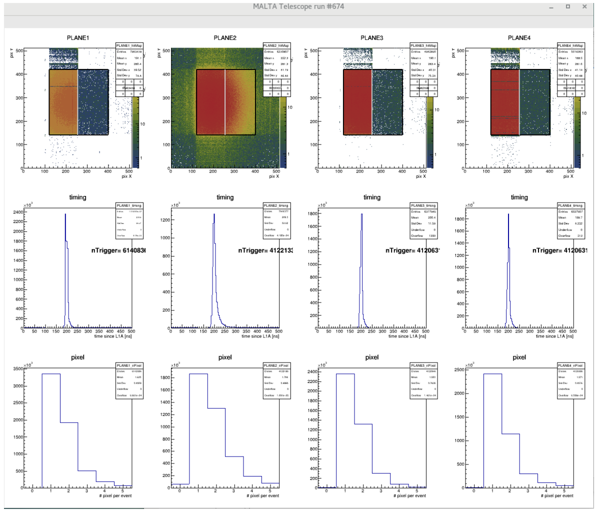


Setup with DUT cold down to -20℃ by Si-oil system

Telescope details:

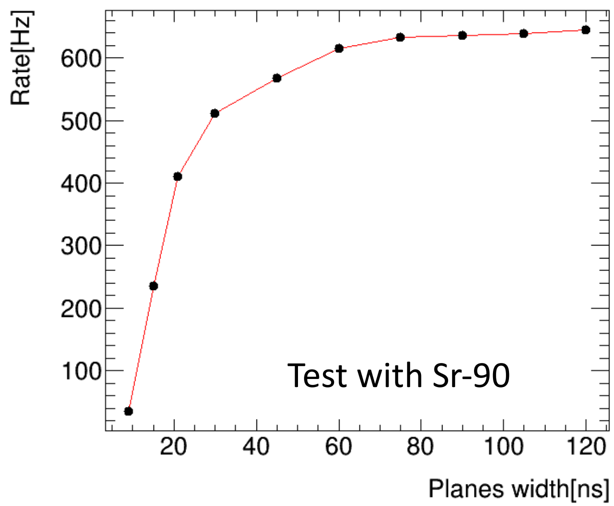
- 4 to 6 MALTA planes (100 µm thick, 36µm pitch size)
- Achieving 14 µm track-hit resolution using only 3 tracking planes and General Broken Line (GBL) algorithm in Proteus with 3 e^- GeV beam in DESY
- Carry-on telescope during LS2 with linear stage for alignment
- Based on custom multi threaded application
- USB based PSU control





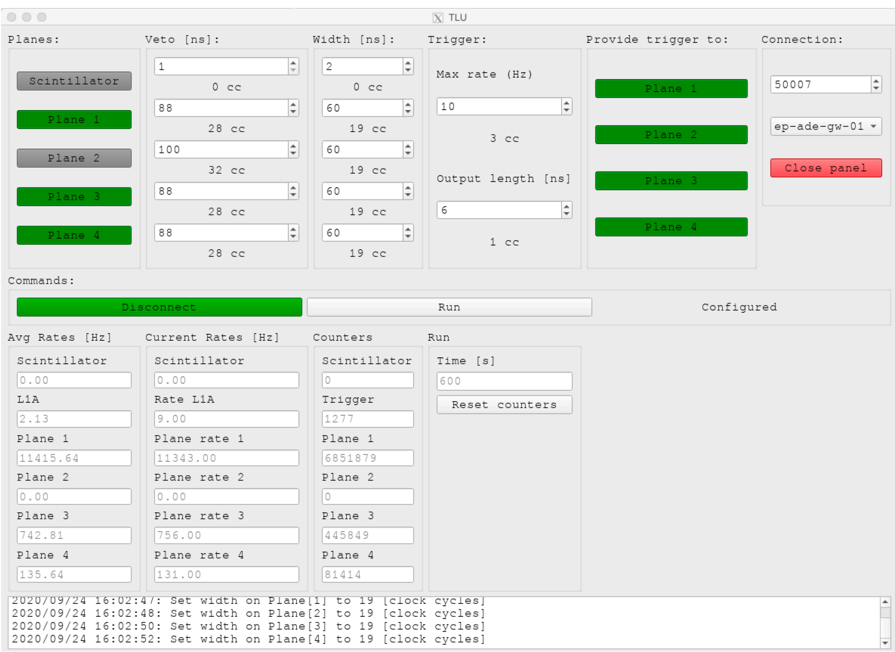
Improved DAQ interface

MALTA telescope TLU

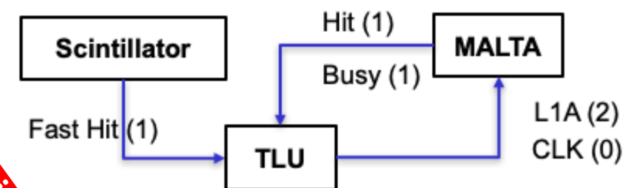


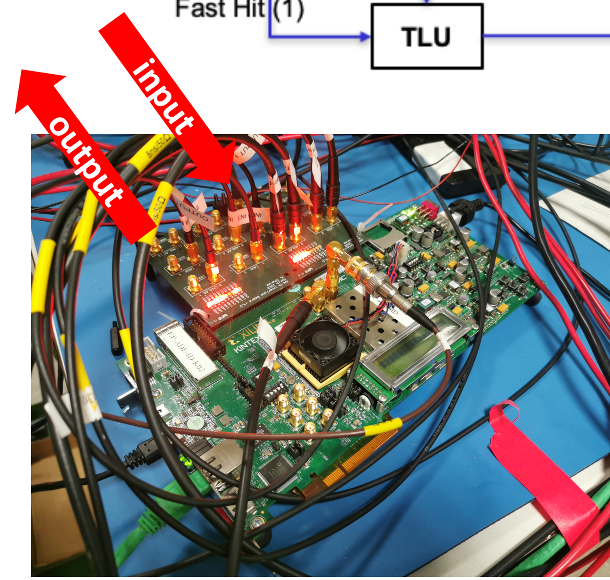
Custom Kintex based Trigger Logic Unit (TLU)

- VHDL FW, CMS IPbus and C++/python driven
- Veto, signals width and combination logic configurable from GUI
- Support for scintillator and up to 6 planes



TLU GUI operating and monitoring telescope

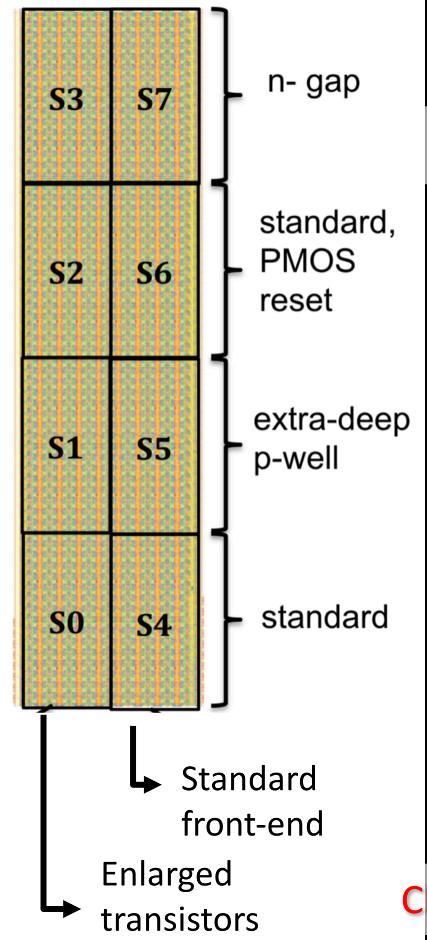


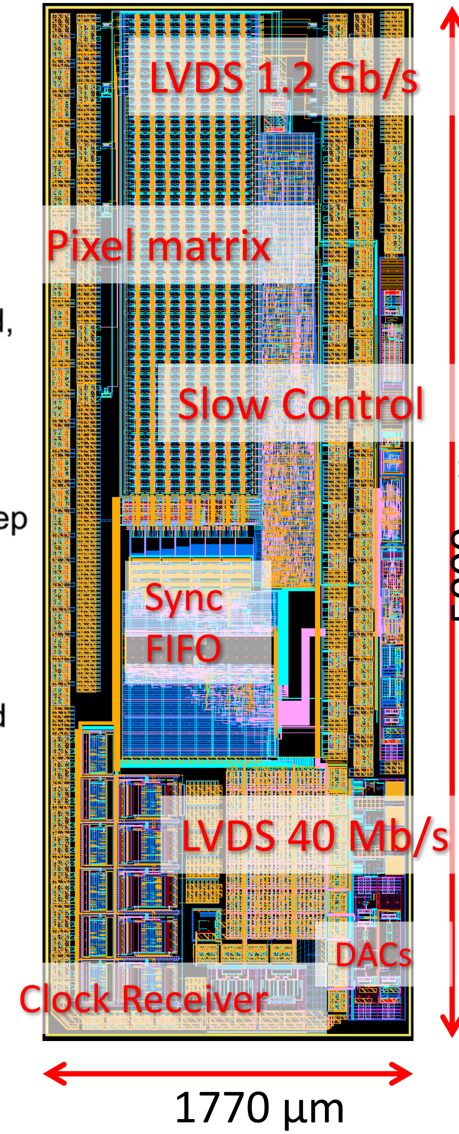


TJ Mini-MALTA sensor

Aim to improve MALTA efficiency loss after irradiation

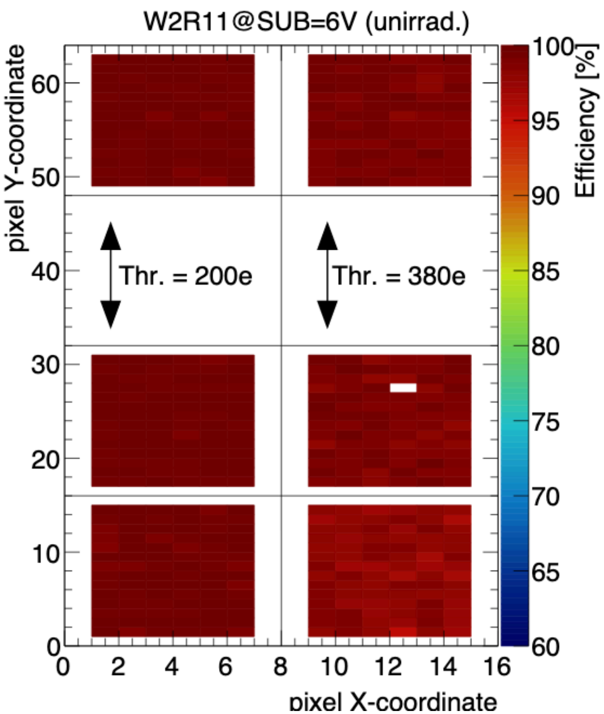
- Matrix **64x16** pixel with **36.4µm** pitch
- **8 sectors** with different analogue front-end design
- Asynchronous read-out
- Improved **SlowControl** implementation
- Single serial data stream: 40Mbs or 1.2 Gpbs with 8b10b encoding
- **Implemented gap in n- layer and extra deep p-well process modifications**
- Periphery data synchronization using a custom RAM memory
- **Larger capacitors** to reduce noise





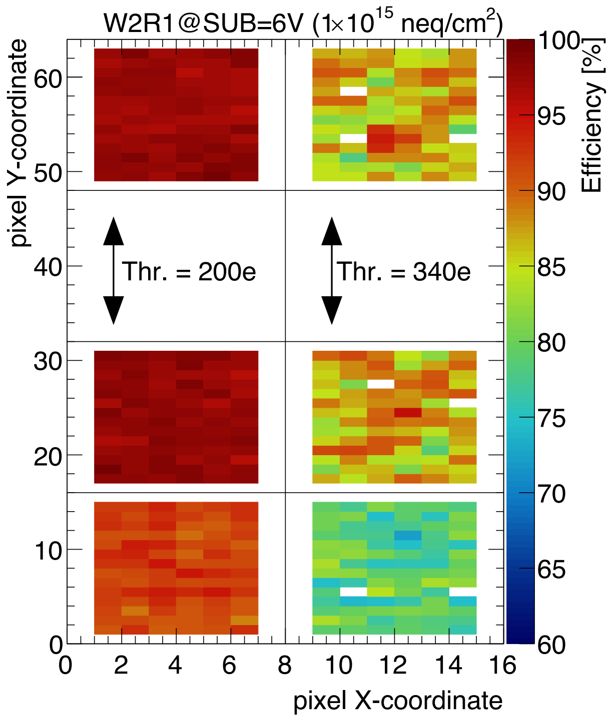
Mini-MALTA efficiency map

Non irradiated



Enlarged transistors | **Std size transistors**

Irradiated*



Enlarged transistors | **Std size transistors**

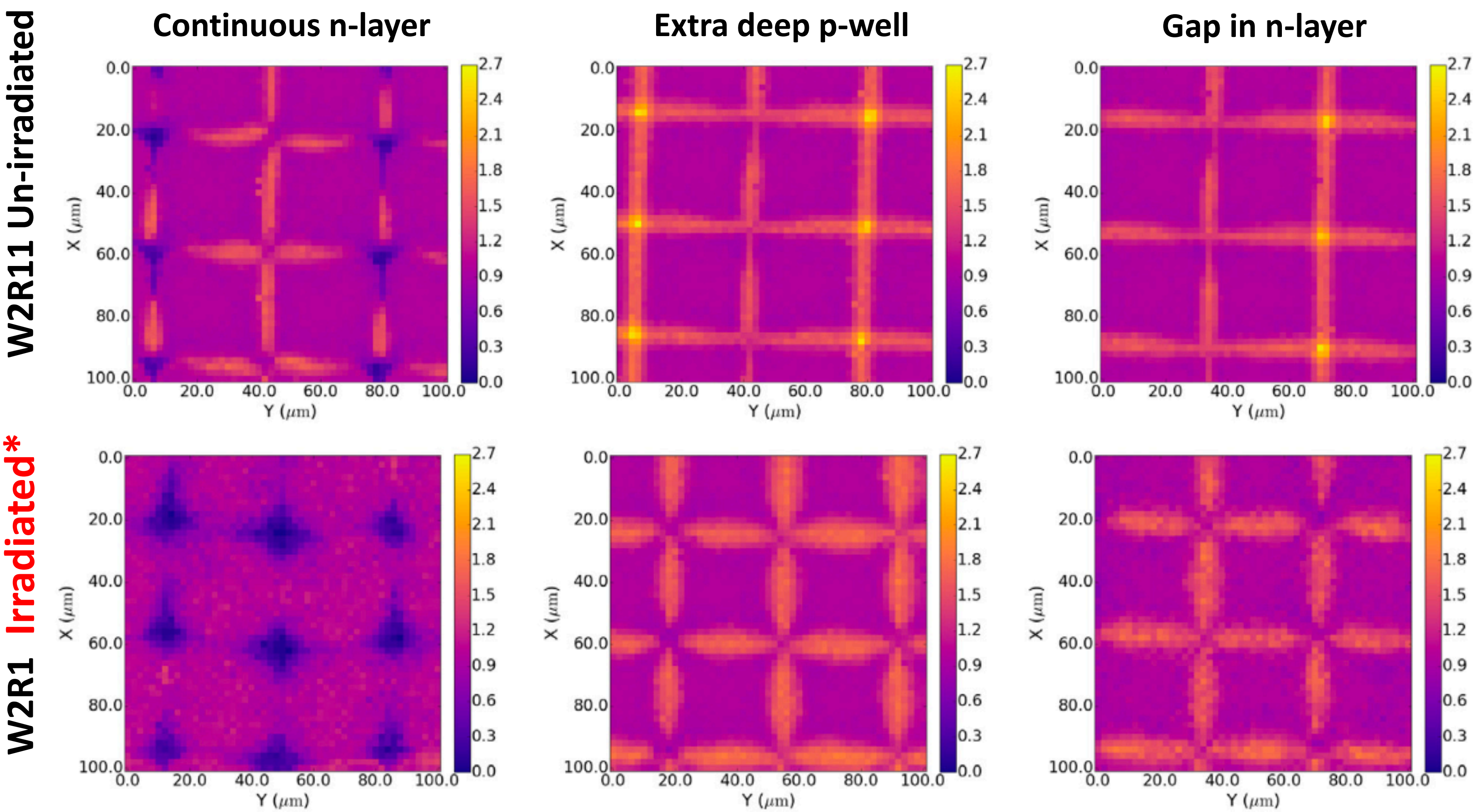
- Full efficiency after irradiation at 200 e- threshold at 6V bias on sectors with enlarged transistors
- Due to improved charge collection in the pixel corners with respect to previous design (MALTA 1)
- Also observed with focused x-ray beam at Diamond Light Source (next slide)

* Irradiated to 1e15 n/cm^2, and measured with 2 GeV electron beam at ELSA, with 6 V bias voltage.

JINST 15 (2020) 02, P02005

Mini-MALTA at Diamond

- **Photon pixel response as function of dose**
  - Reduction of pixel response in continuous n-layer of 10%
  - Almost no reduction on extra deep p-well and n-gap



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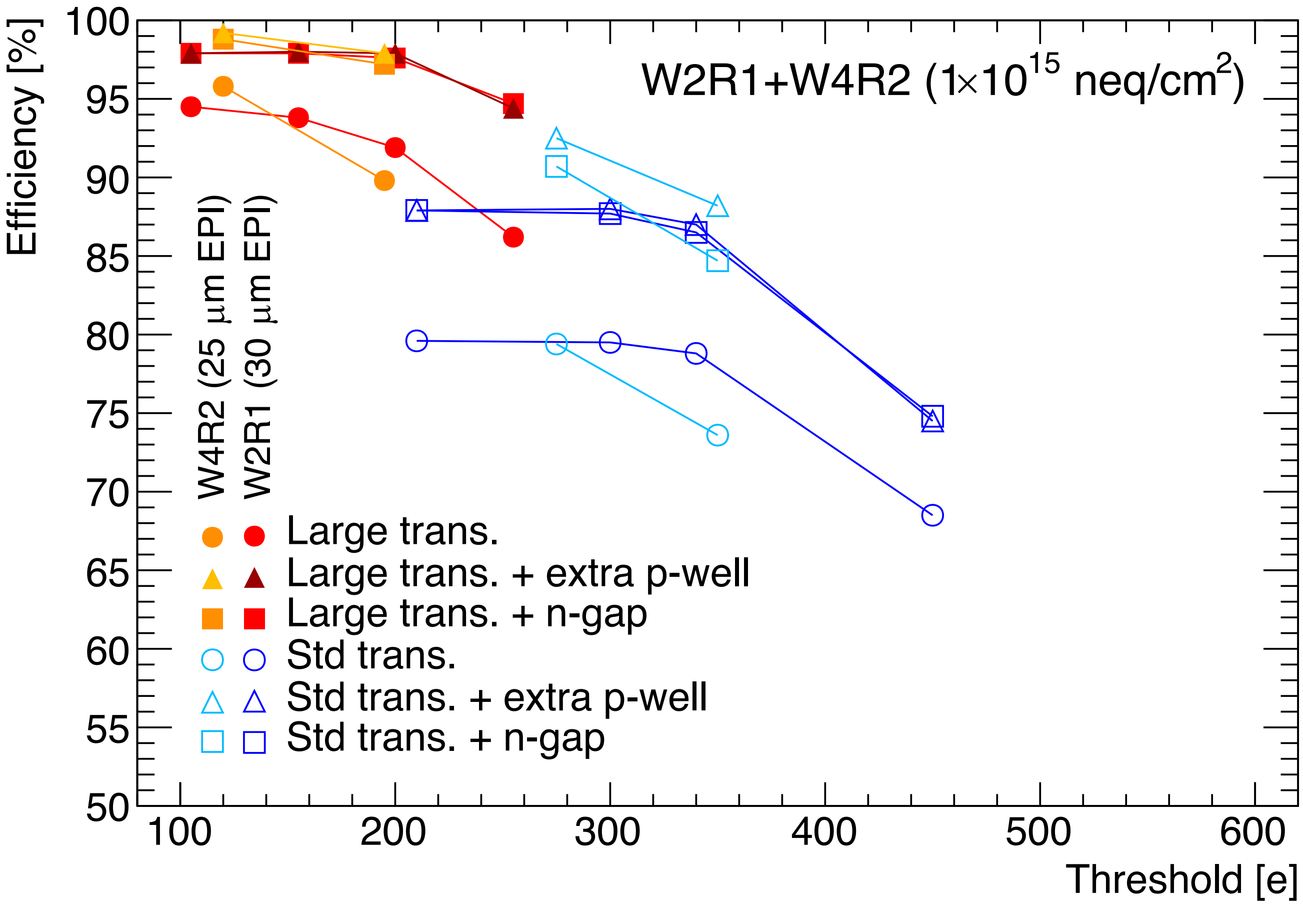
* Neutron-irradiated to 1e15 n/cm^2

Mini-MALTA efficiency vs threshold



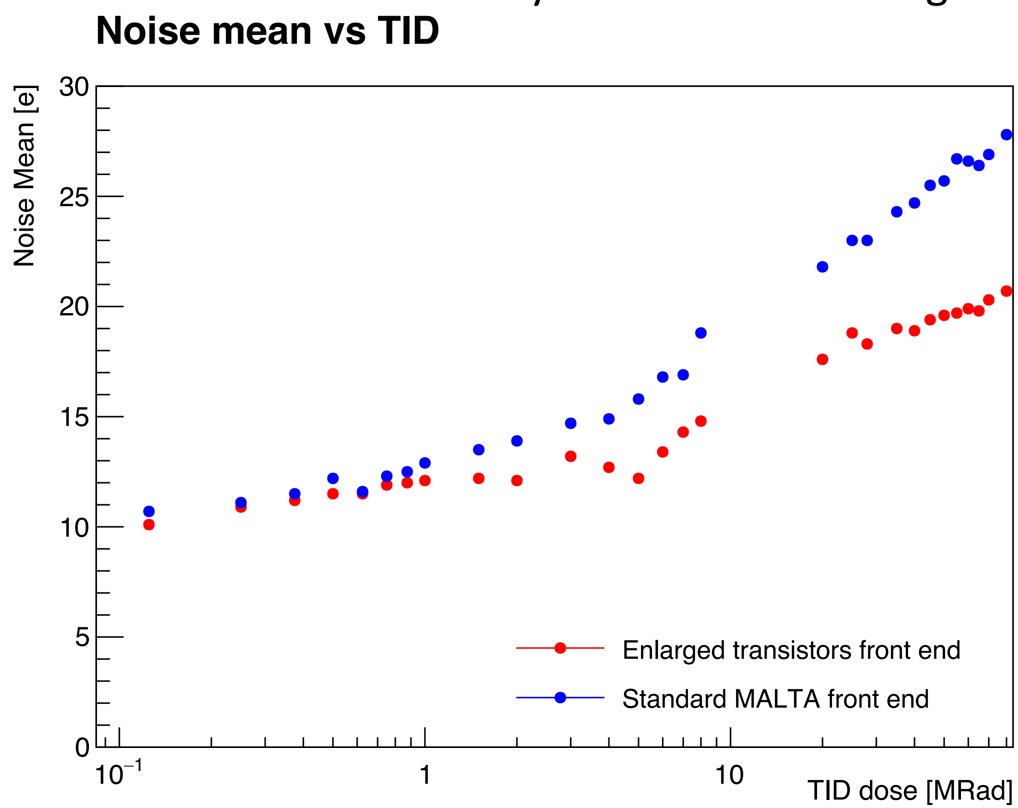
- Efficiency above 97% sensor modification with enlarged transitions
- Higher efficiency for enlarged transistors
- Efficiency above 90% after 2e15 n_{eq}/cm^2 irradiation (see backup slide)

Efficiency versus threshold for two different Mini-MALTA samples, neutron irradiated to 1e15 n_{eq}/cm^2, and measured with 2 GeV electron beam at ELSA, with 6 V bias voltage

Mini-MALTA x-ray irradiated to a TID 100 Mrad Fe fluorescense

- Noise increase $10e^-$ to $20e^-$ during irradiation on enlarged transistors
- $10e^-$ to $30e^-$ on standard front-end

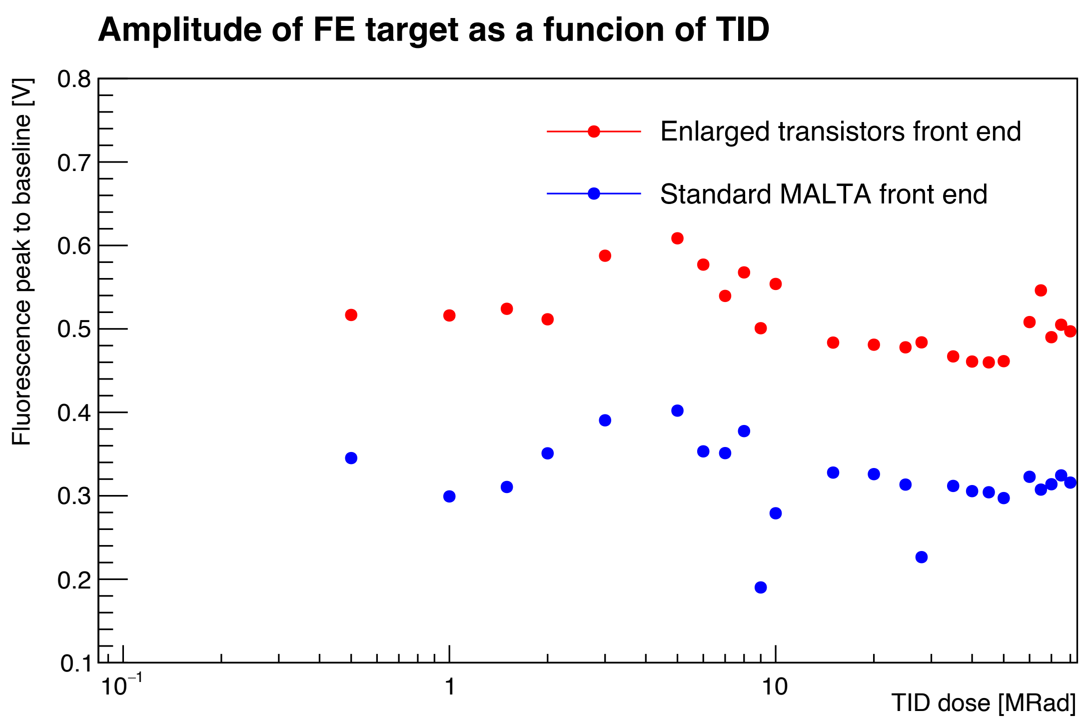
X-ray irradiations at Glasgow



Mini-MALTA γ-irradiated to a TID 100 Mrad Fe fluorescense

X-ray irradiations at Glasgow

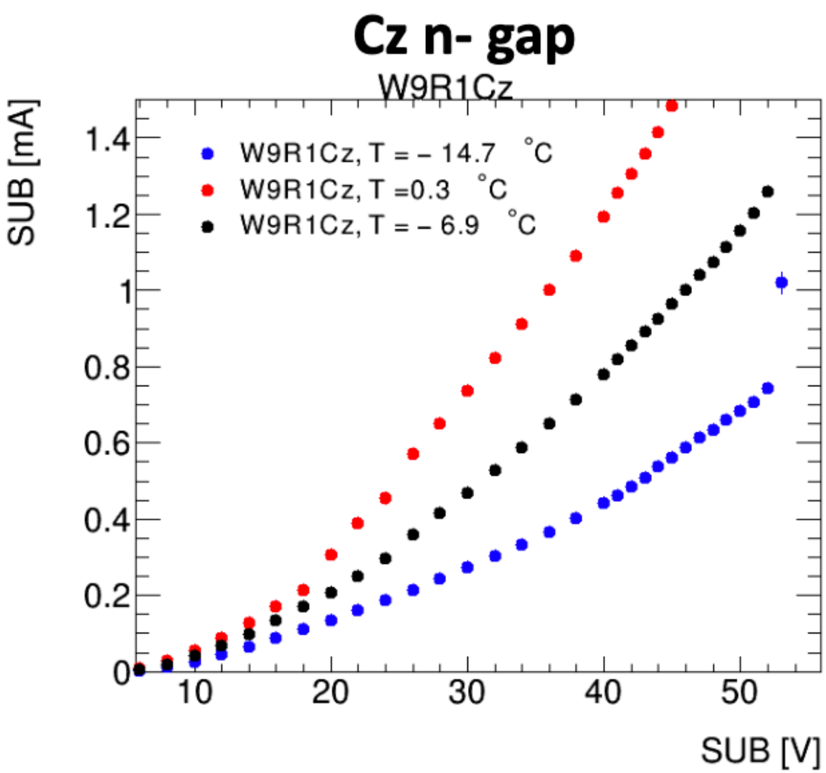
- Analog performance measured during irradiation
- Higher gain for enlarged transistors
- Unchanged after dose but with slight increase and then stabilization

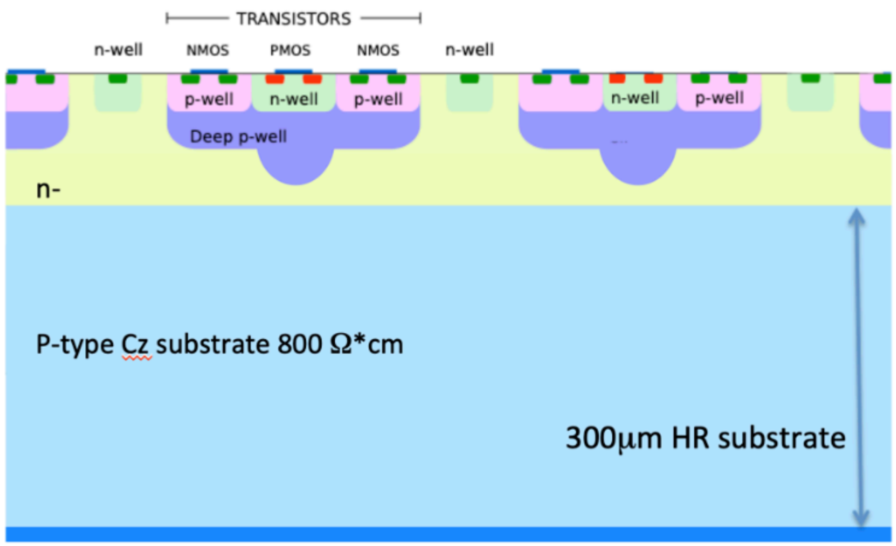


MALTA Czochralski (Cz)

Processed with high resistivity Cz substrate material

- Larger depletion voltage and signal
- Higher radiation hardness
- **High operation voltage** up to 50V
  - High depletion depth

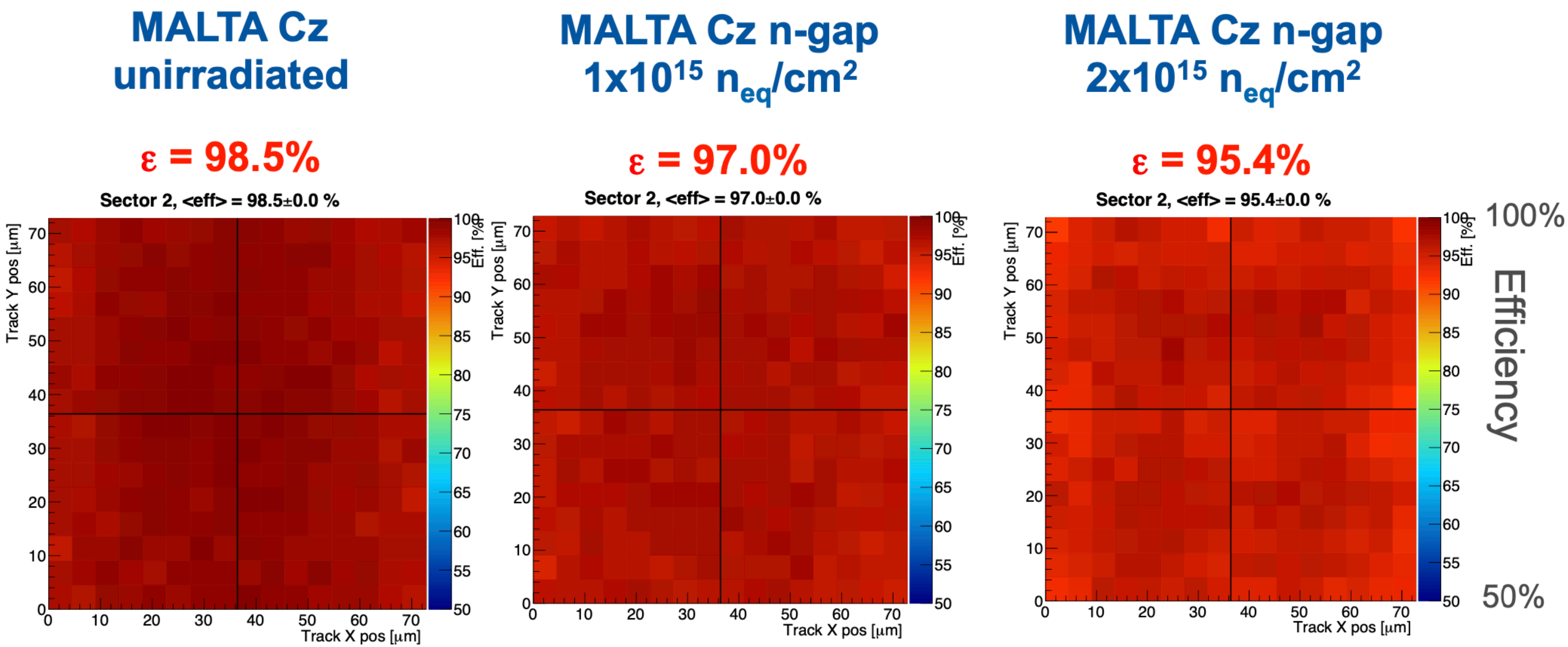




MALTA CZ - Efficiency

- Radiation hardness of full size MALTA with Cz
- From 98.5 (un-irradiated) to 95.4 % efficiency after $2x10^{15}$ n/cm^2

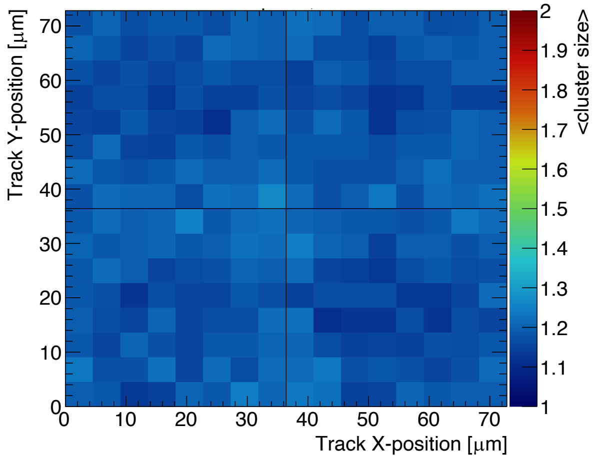
Irradiated at DESY with 4 GeV electron beam



[Check Hiroshima Presentation H.Pernegger HSTD12]

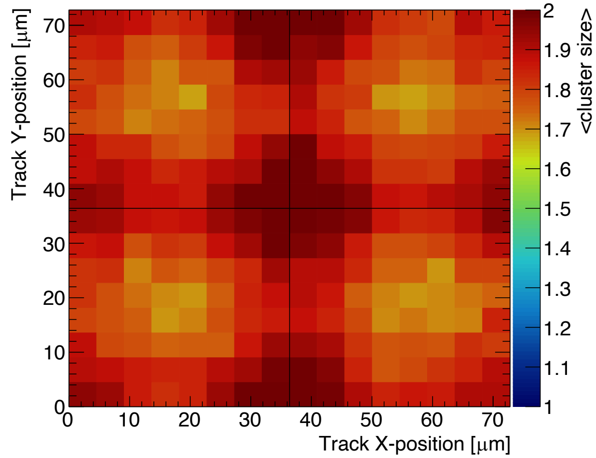
Cluster size - Epi vs Cz std and n-gap

W7R4 Epi std, SUB=-12V
Cluster size 1.2



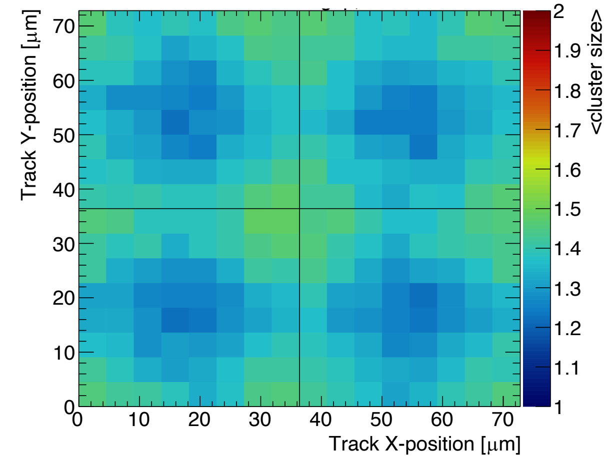
Epi

W7R12 **Cz std**, SUB=-12V
Cluster size 1.8

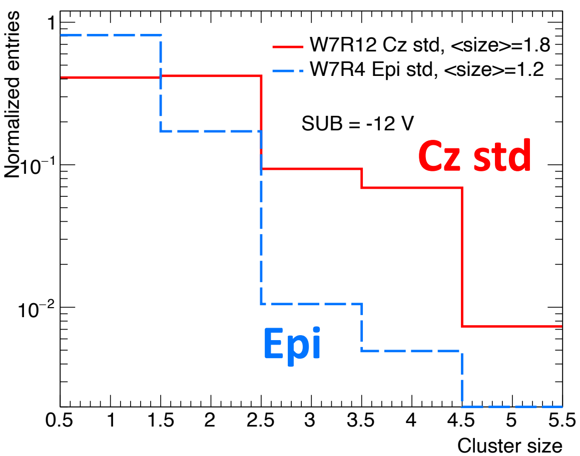


Cz std

W9R11 **Cz n-gap**, SUB=-12V
Cluster size 1.4

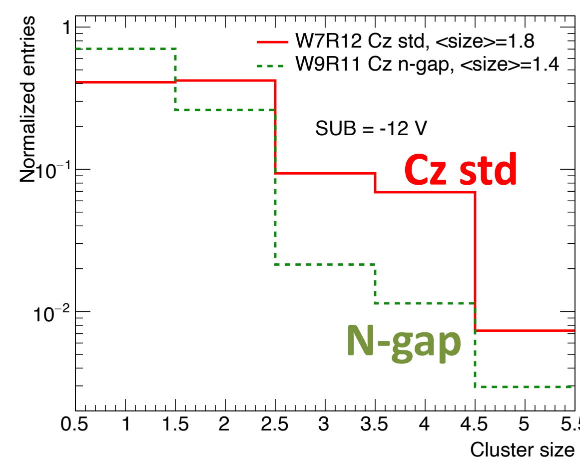


N-gap



Before irradiation

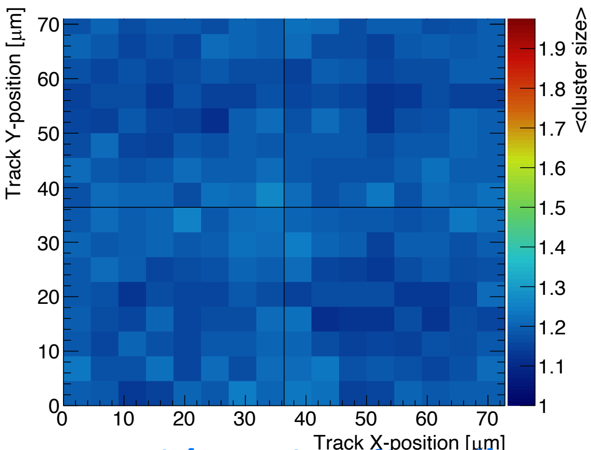
- Cz has higher cluster size (1.8)
- And more charge collection sharing
- N-gap modification has worse performance



Cluster size - Epi vs Cz std and n-gap

W7R4 **Epi** std, SUB=-12V

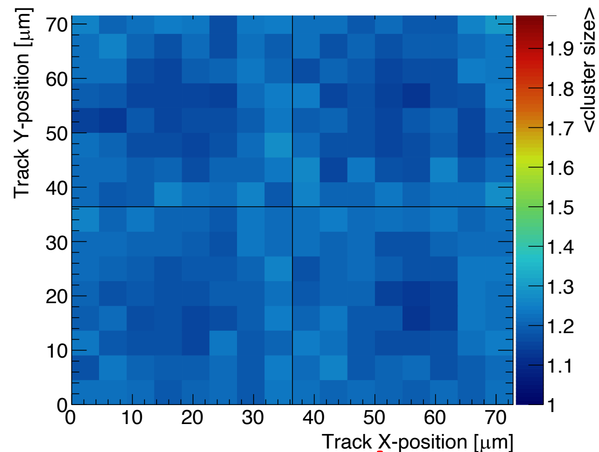
Cluster size 1.2



Epi (Non irradiated)

W7R1 Cz **std**, SUB=-50V

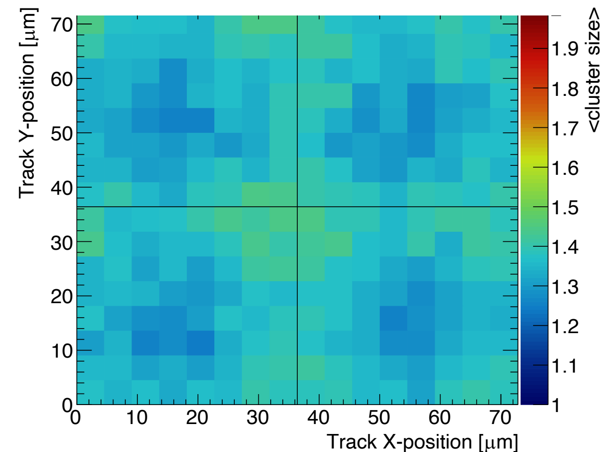
Cluster size 1.2



Cz std

W9R0 Cz **n-gap**, SUB=-50V

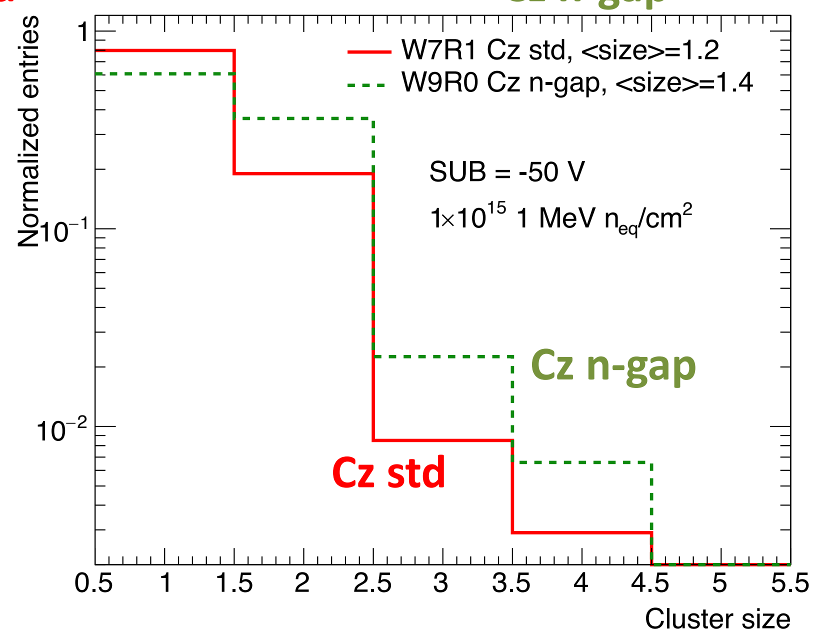
Cluster size 1.4



Cz n-gap

Cluster size after irradiation at -50V

- $1x10^{15}$ MeV n_{eq}/cm^2 at DESY with 3 GeV electron beam
- **Cz standard** more affected by irradiation : From 1.8 to 1.2
- **Cz n-gap** modification less affected: From 1.4 to 1.2



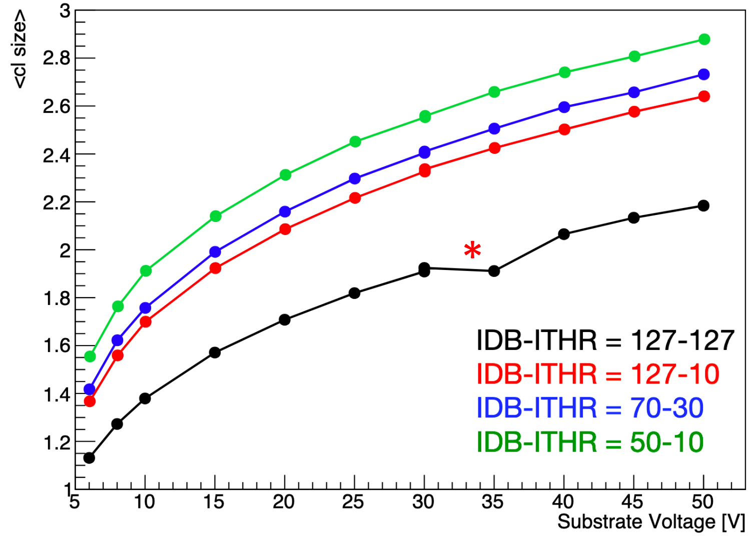
MALTA CZ – Efficiency and Cluster size

Sr-90 measurements in the lab

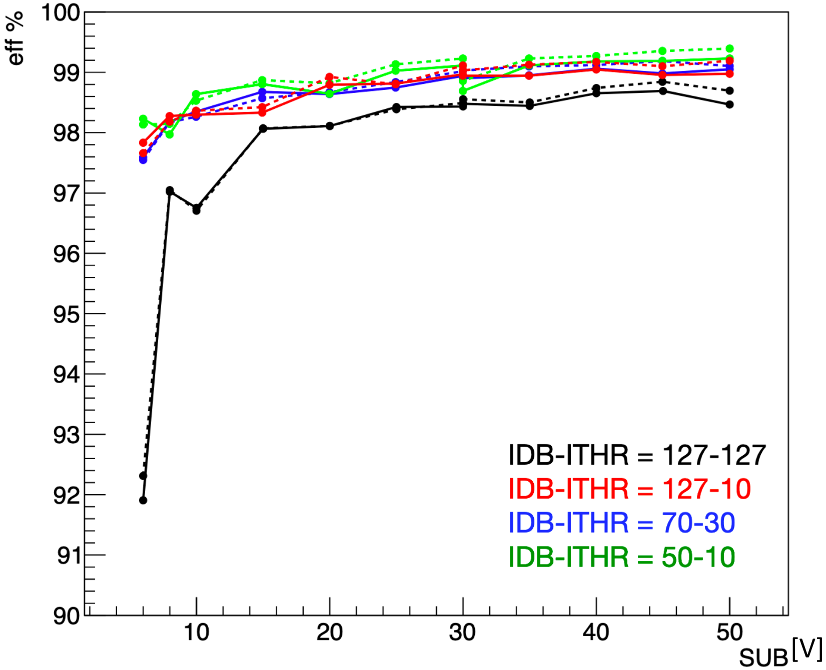
IDB: Threshold for the discriminator

ITHR: Pulse duration of the amplifier output

- Cluster size
  - We observe a smooth increase when increasing the voltage



- Efficiency
  - Large discontinuities observed at 8V to ~12V and slighter over 30V

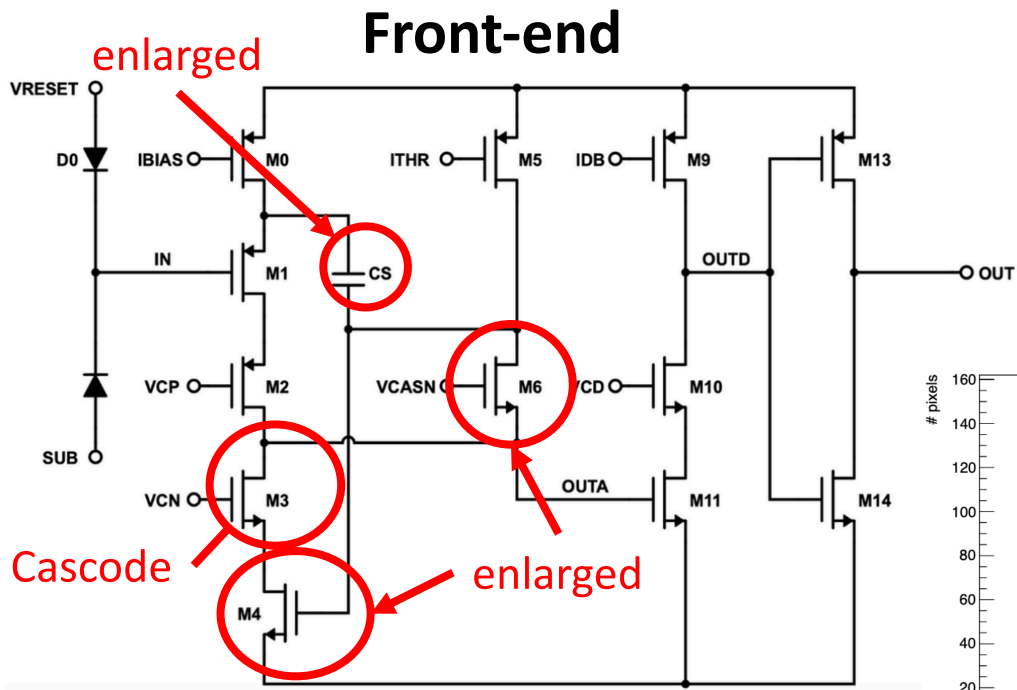


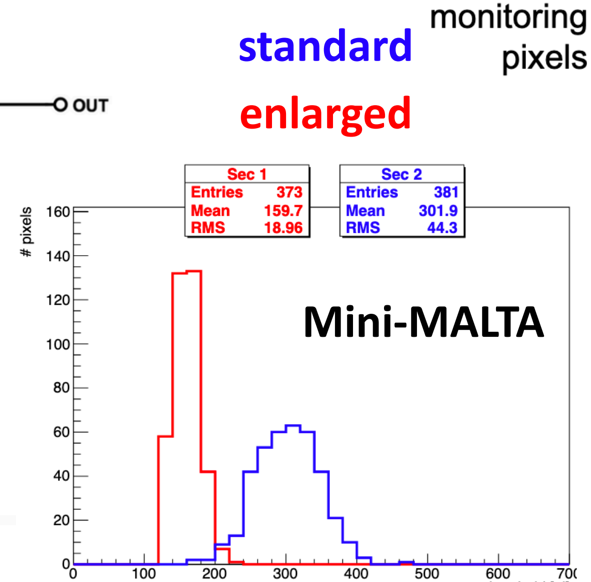
* **Note at 30V**

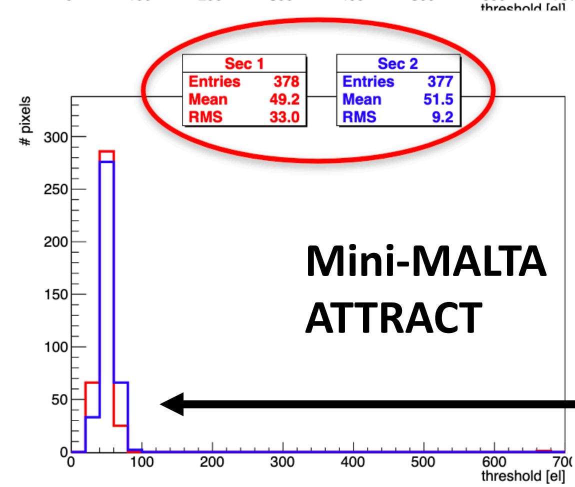
Power supply replacement and higher room temperature

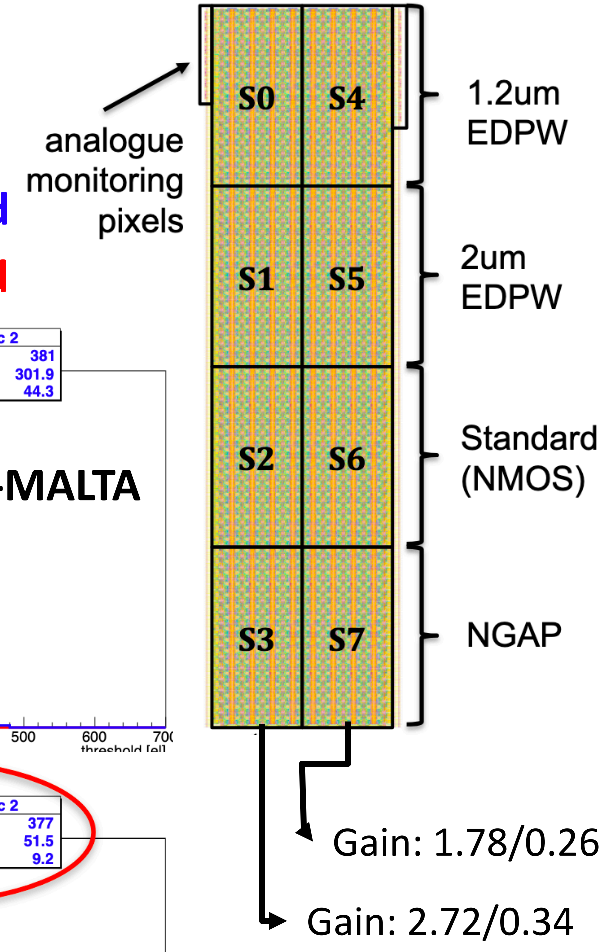
Mini-MALTA ATTRACT

Front-end





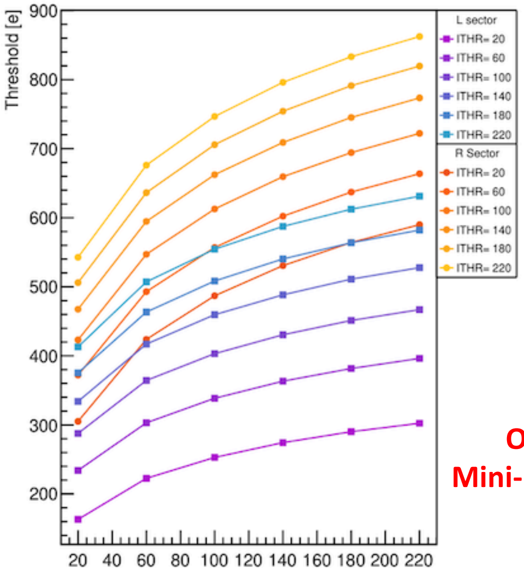




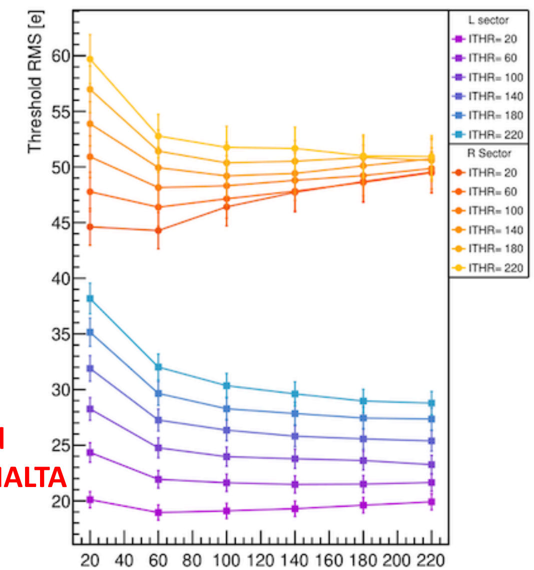
- All sectors have cascode front-end (M3) and enlarged transistors
- Sectors 0 to 3 have higher gain (CS, **M4**, M6)
- Sectors 0 and 4 are 1.2 um EDPW
- Sectors 1 and 5 are 2 um EDPW
- Sectors 2 and 6 are standard n-layer
- Sectors 3 and 7 are NGAP

Mini-MALTA ATTRACT - threshold - IDB

W2MOD - Mean value

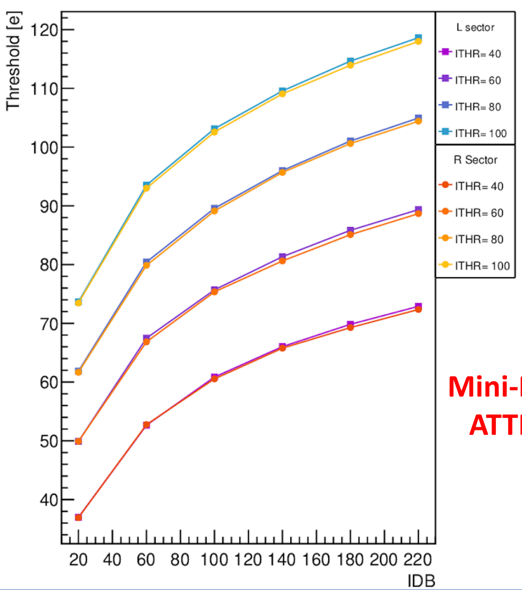


W2MOD - RMS Value

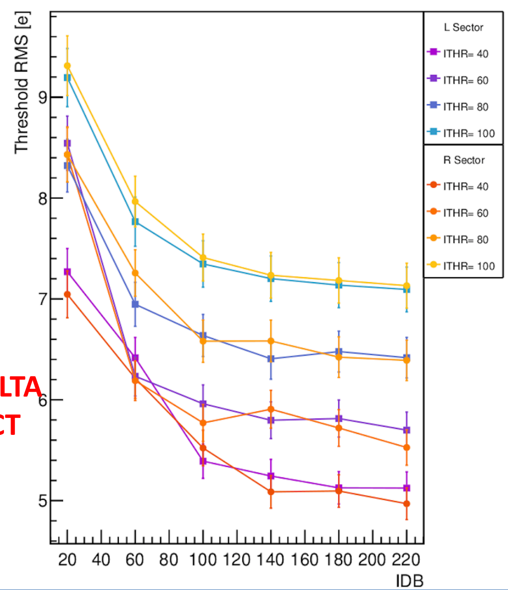


Old Mini-MALTA

W15R3 - Mean value



W15R3 - RMS Value



Mini-MALTA ATTRACT

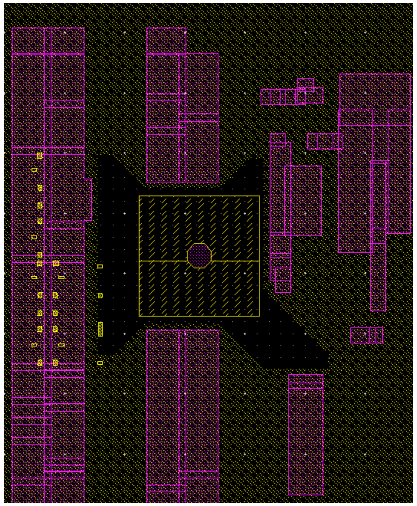
Mini-MALTA ATTRACT with full cascoded front-end

- Preliminary results
- Improvements in Front-end control and threshold
- **Cascoded FE allows to reach thresholds below 100e**
- Also more consistent values between enlarged and standard transistors

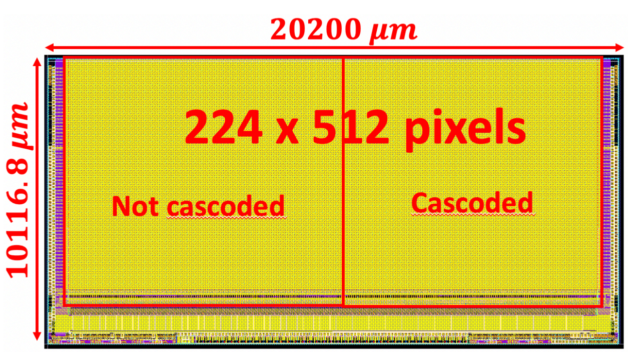
PWELL = -6V

MALTA 2

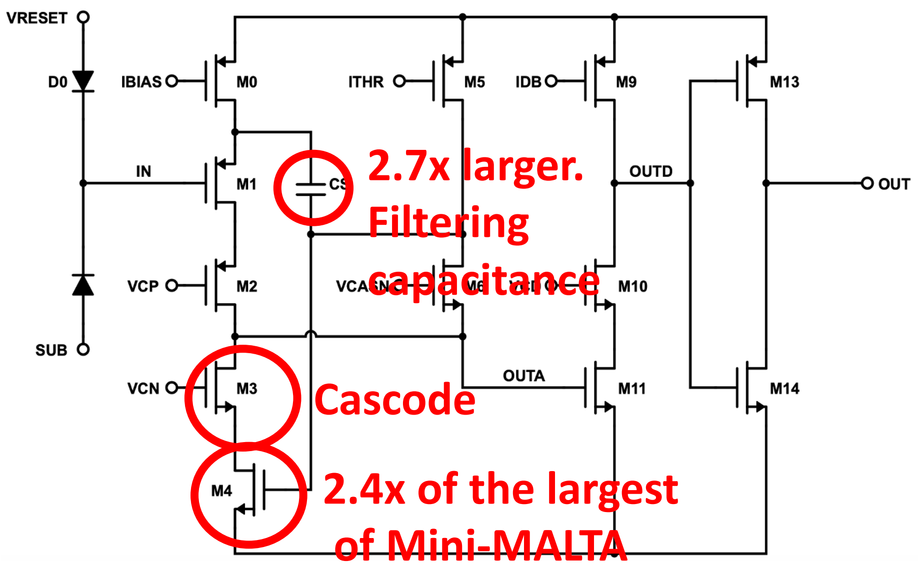
- **Submission on mid October 2020**
- 20.2x10.1mm sensor. Almost half size of MALTA
- Matrix of 224x512 pixels of 36.4 um size
- New sensor with gain optimized to improve time resolution
- 4322 bit shift register as new Slow Control
- Enlarged transistors from Mini-MALTA
- Half sensor cascode front-end for higher gain and reduced RTS noise
- **Applying all the knowledge we learnt from MALTA C, Mini-MALTA, ATTRACT and Czochralski**



MALTA 2 two front-end flavors



Analog front end modifications



Conclusions

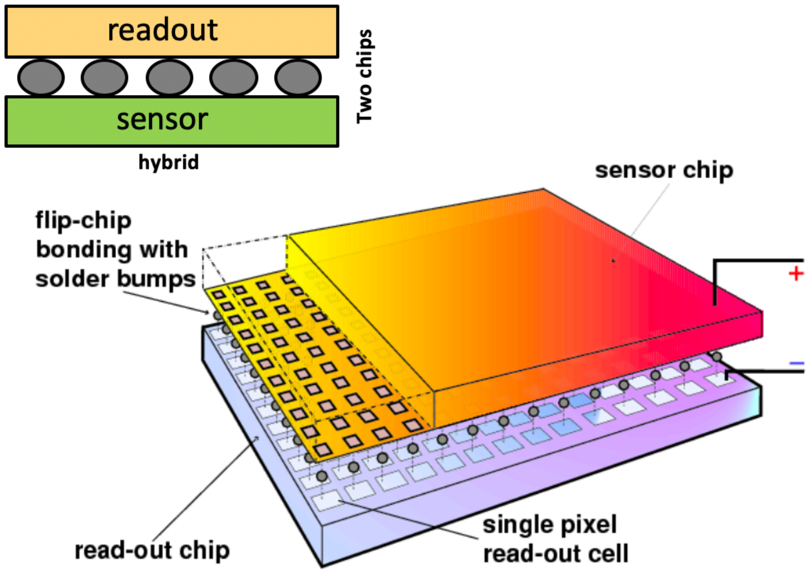
- MALTA monolithic CMOS sensor continues improving performance with Mini-MALTA and Cz versions
- Modifications n-gap and extra deep p-well show full efficiency after 100Mrad and $10^{15} n_{eq}/cm^2$
- Many improvements applied to the design of MALTA 2 which will be submitted mid October

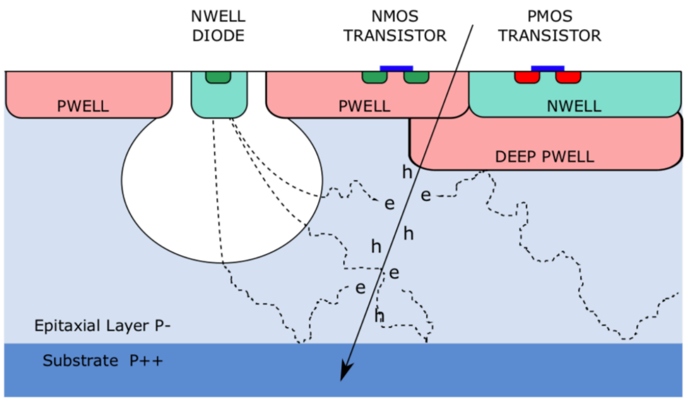
Acknowledgements

- 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)
- Dr. Ben Phoenix, Prof. David Parker and the operators at the MC40 cyclotron in Birmingham (UK).

Backup

Hybrid vs Monolithic sensors





Hybrid

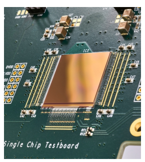
- Popular in current LHC detectors
- Proven radiation hardness
- Dedicated front-end electronics bonded to the sensor
- Thicker modules
- Complex and costly assembly due to fine-pitch bump bonding

Monolithic

- Radiation hardness in research
- Electronics and sensor integrated on a single chip
- Low cost per wafer
- Thinner modules
- Substantial cost reduction and reduced module assembly time

Modifications time line overview

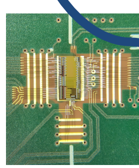
Jan 2018



MALTA1 & MLVL

- Sensor
- Front-end

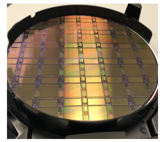
Jan 2019



Mini-MALTA

- Sensors
- Front-end

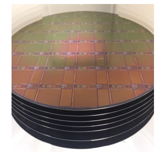
Aug 2019



MALTA C

- SlowControl fix
- Front-end
- Sensors

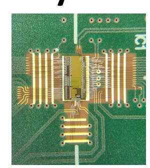
Oct 2019



MALTA Cz

- SlowControl fix
- Front-end
- Sensors

May 2020



Mini-MALTA ATTRACT

- Sensors
- Front-end
- Cascoded

Submission mid Oct 2020

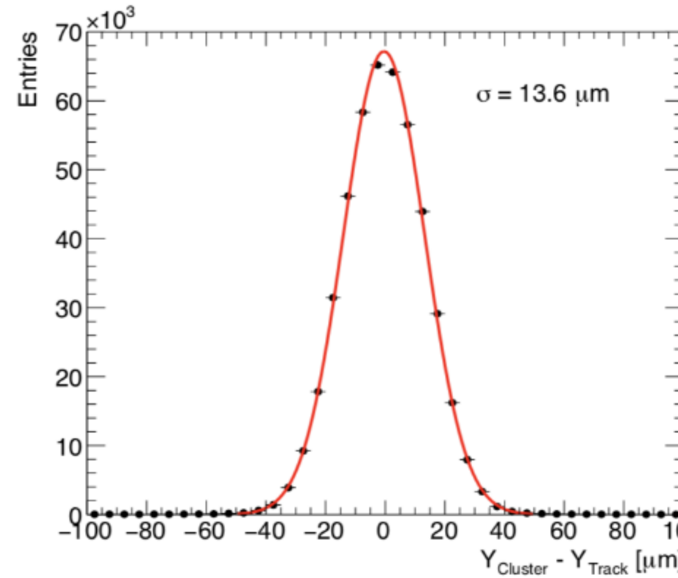
MALTA 2

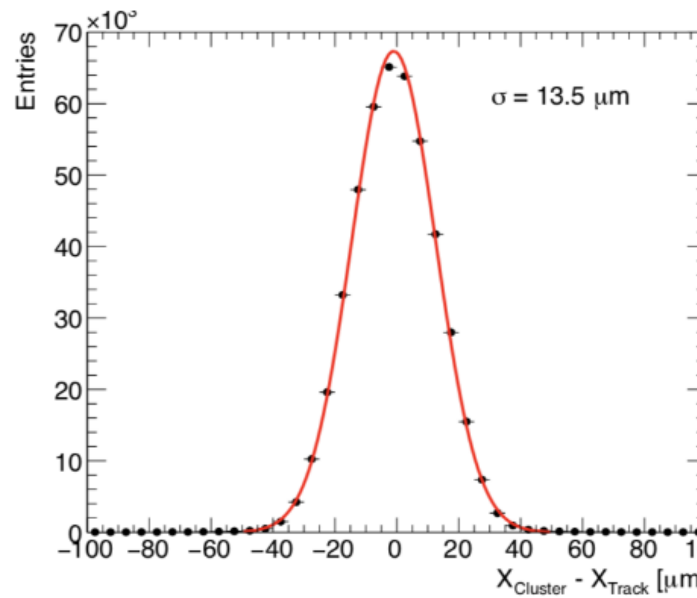
- Sensors
- Front-end
- New SlowControl
- Cascoded

MALTA telescope tracking

Using General Broken Lines (GBL) algorithm to mitigate multiple scattering effects

- Tracking resolution
  - Distance from the cluster barycenter to the track intercept using a clusterizer algorithm
- Embedded in Proteus software
- Using MALTA Cz un-irradiated

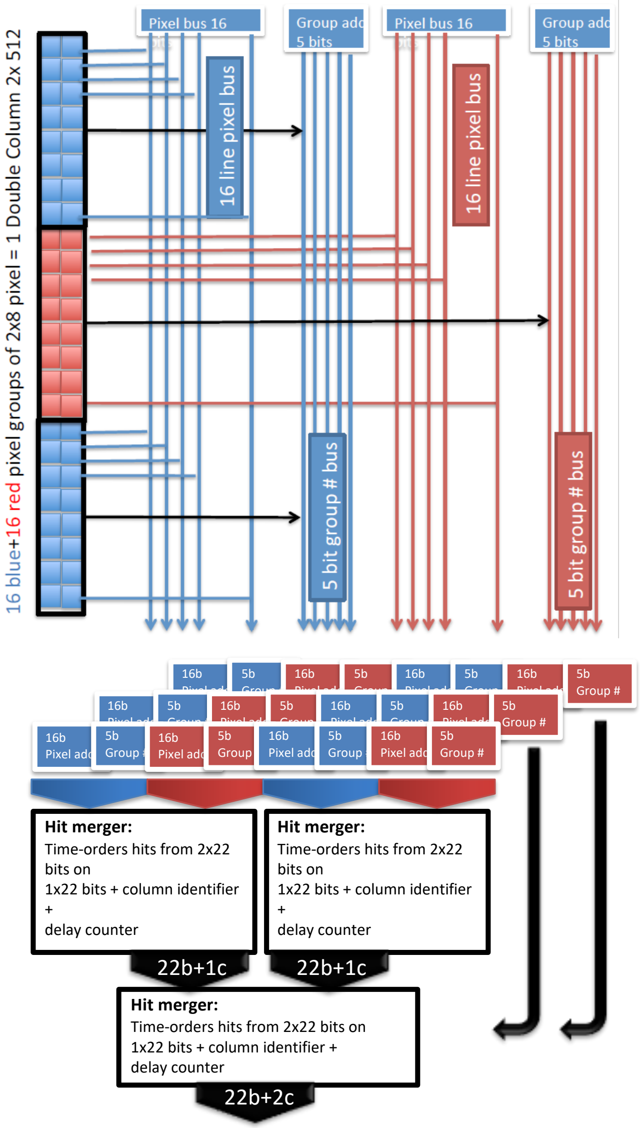




From ELSA test beam Apr 2019

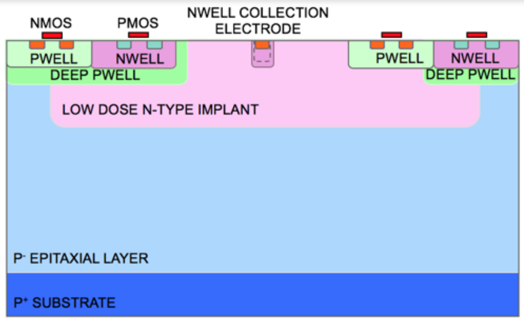
MALTA read-out architecture

- Novel asynchronous readout architecture for high hit rate capability with 40 bit parallel data bus for data streaming
  - Groups of 2x8 pixels with pattern assignment to reduce data size from clusters
  - Front-end discriminator output is processed by a double-column digital logic
  - Pulse width adjustable between 0.5 ns and 2 ns
  - Data transmitted asynchronously over high speed bus to end of column
- At the periphery, arbitration and merging resolves timing conflicts of simultaneous signals
  - Timing information stored in dedicated bits
  - Output signals transmitted by 5 Gbps LVDS driver
- Virtex VC707 implementation
  - 38 asynchronous oversample
  - 400ps hit arrival precision

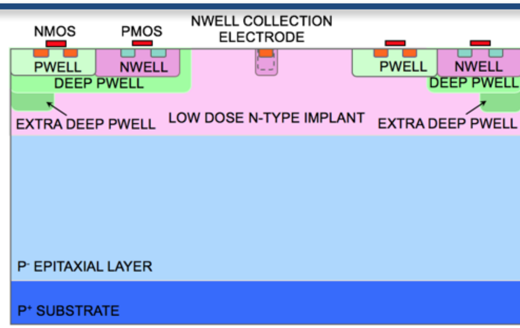


Mini-MALTA

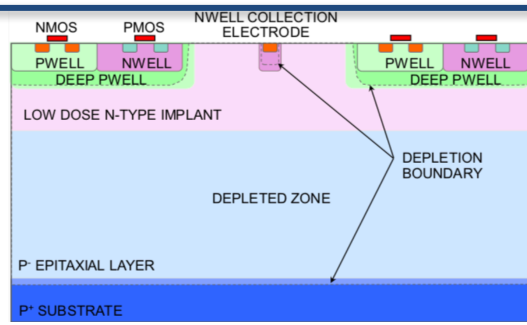
Modified Process with gap in n-



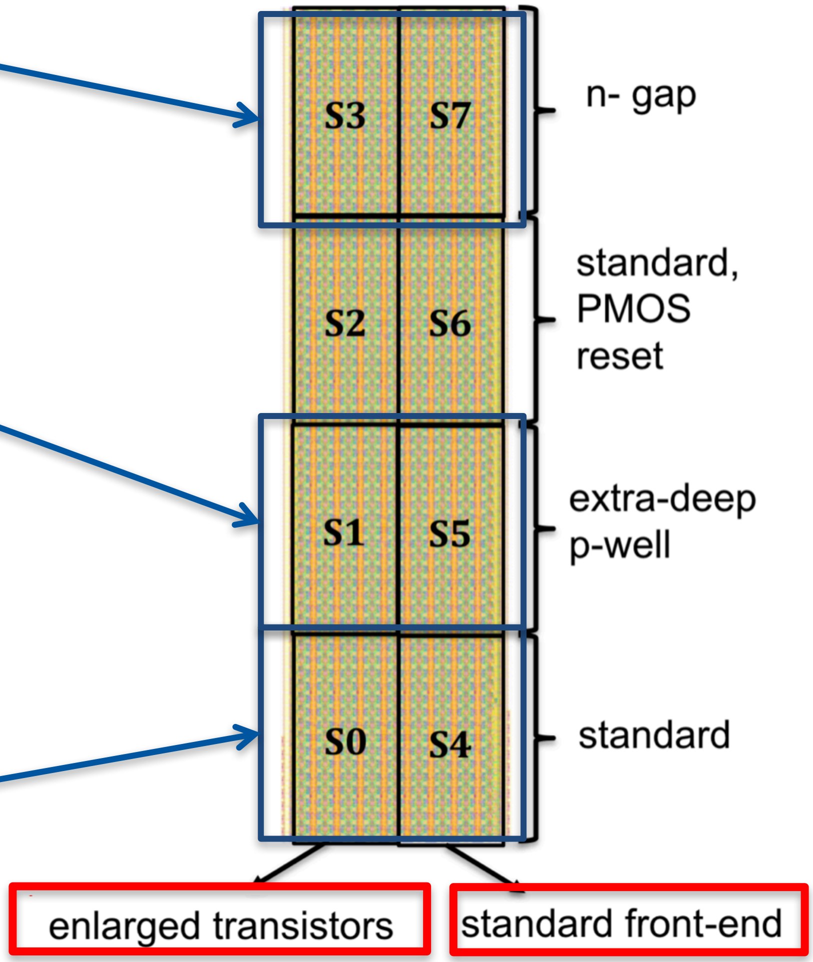
Modified Process plus additional DPW



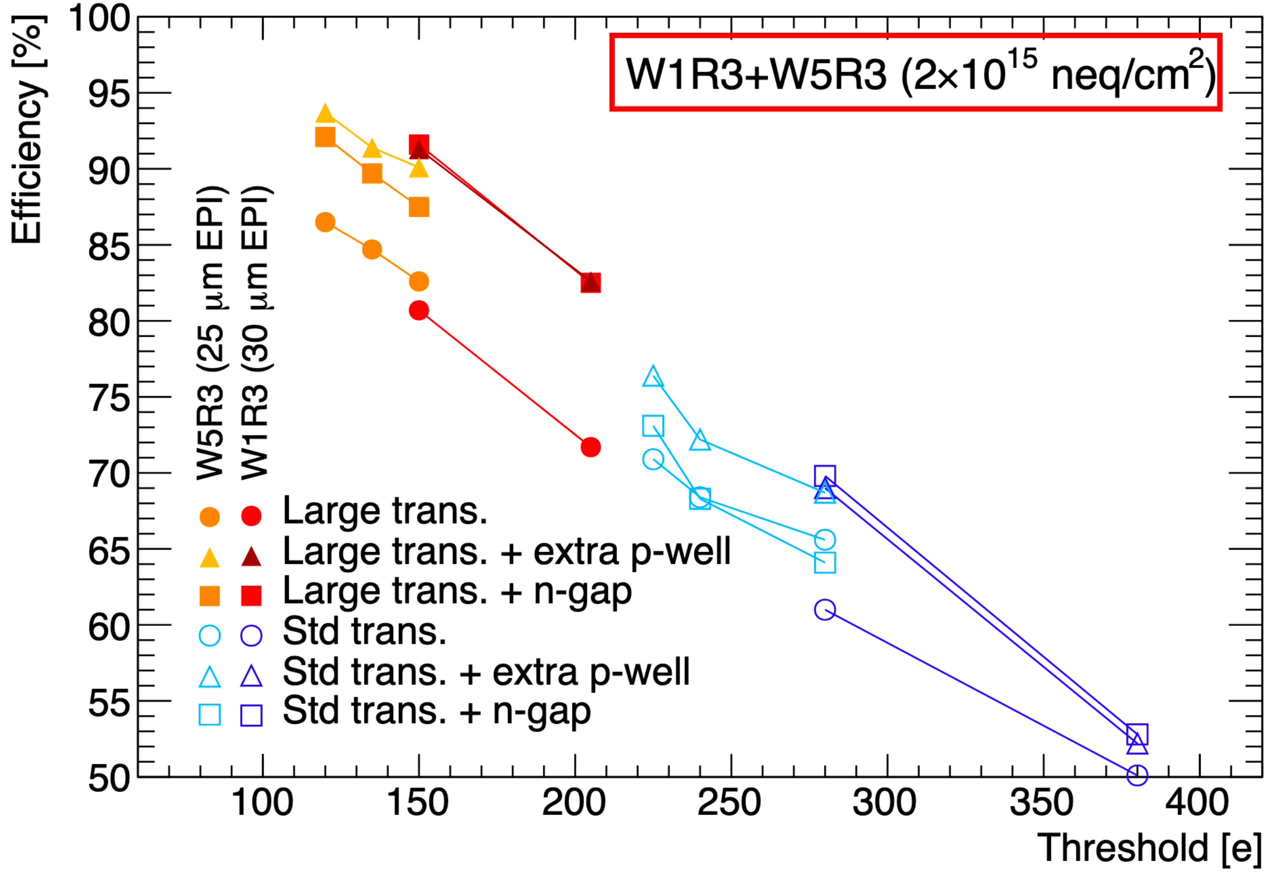
Modified Process



Sectors



Mini-MALTA efficiency vs threshold



Efficiency versus threshold for two different Mini-MALTA samples, neutron irradiated to 2e15 n_{eq}/cm^2, and measured with 2 GeV electron beam at ELSA, with 6 V bias voltage

- Efficiency above 97% sensor modification with enlarged transitions
- Higher efficiency for enlarged transistors
- Efficiency above 90% after **2e15 n_{eq}/cm^2 irradiation** (see backup slide)