Development of MALTA, a radiation hard high-speed monolithic CMOS sensor for the ATLAS experiment at the HL-LHC

Patrick Freeman

On behalf of

The MALTA team

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Outline

- Introduction to MAPS in HEP
- MALTA
  - Tower Jazz 180 nm Modified Process
  - One of 2 chips based on Investigator targeting ATLAS
  - 2018 SPS test beam results
  - Motivation for miniMALTA
- MiniMALTA
  - Re-designed substrate, front-end
  - 2019 test beam results
  - TID measurements
- MALTA SC, MALTA V2 and the future

Introduction

- Why Monolithic Active Pixel Sensors (MAPS):
  - Easier detector assembly
  - Low material budget
  - Potentially smaller feature sizes, capacitances
  - CMOS is industry standard – large firms, high throughput, low cost
- MAPS in HEP:
  - Main challenge is designing radiation tolerant devices
    - Typically collect charge via diffusion, but need depletion to go above 1e13 n_{eq}/cm^2
    - For ATLAS ITk L4: **1.5e15 n_{eq}/cm^2, 100 MRad**
    - Solution: reverse biased, thin epitaxial depletion region
    - Called "DMAPS" for "depleted MAPS"
  - ALPIDE chip from TJ 180 nm to be installed during ALICE tracker upgrade
  - Prototypes from LFoundry 150 nm, AMS 180 nm, and Tower Jazz 180 nm (TJ) designed for ATLAS radiation specifications
  - **This talk focuses on one of two TJ 180 nm chips for ATLAS, the MALTA**

DMAPS in HEP

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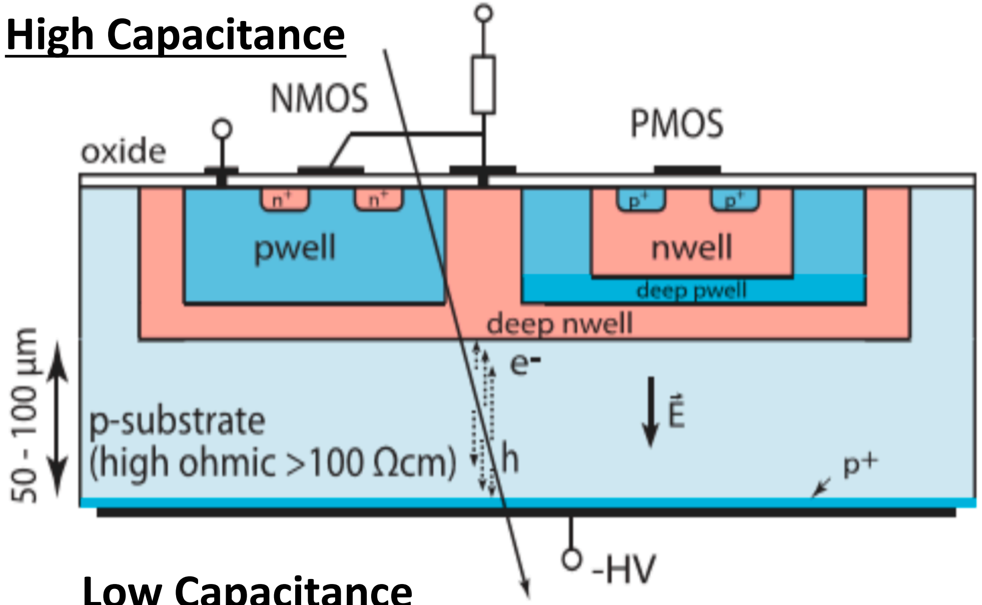
2 types of design proposed for implementing DMAPS in HEP:

Large Fill-factor
- Electronics in collection n-well
- High resistivity substrate
- Large signal
- Larger fill factor
- **High capacitance (~100 fF)**

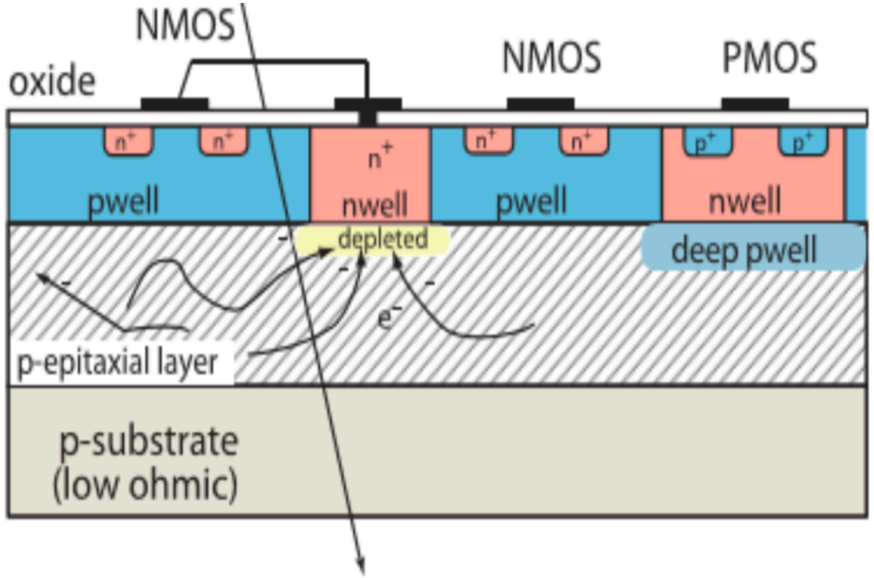
Depletion depth ~ $\sqrt{V\rho}$

Small Fill-factor
- Electronics next to electrodes
- Low resistivity substrate
- Epitaxial layer for collection
- Smaller fill factor
- Weak field long collection times away from the electrode
- **Low capacitance (~5 fF)**
- Design of ALPIDE, MALTA

High Capacitance



Low Capacitance



M. Garcia-Sciveres and N. Wermes. Reports on Progress in Physics, vol 81, 6, 066101, 2018.

Modified TJ 180 nm Process

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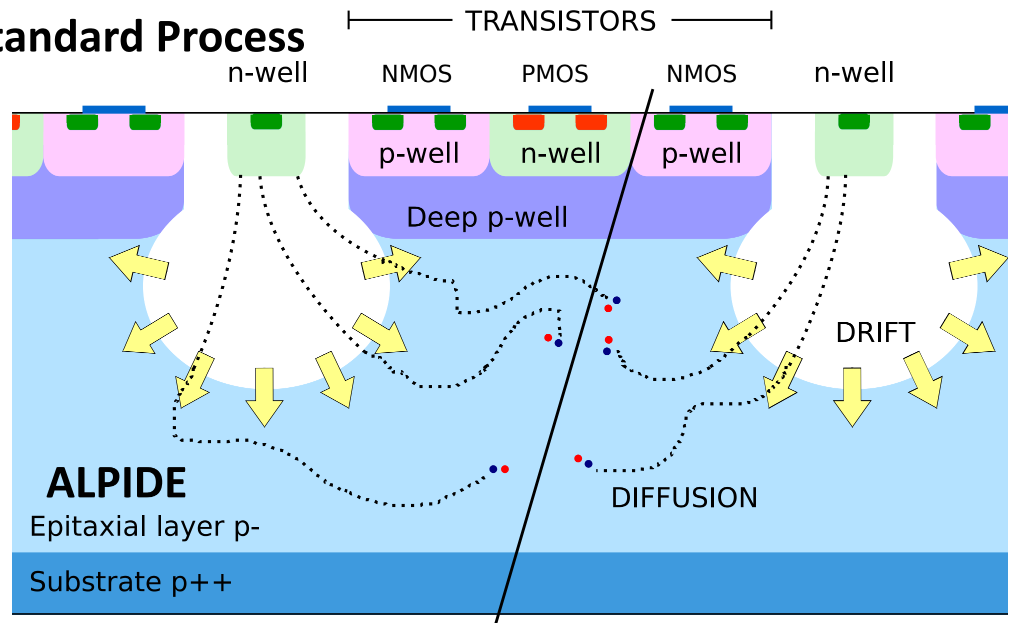
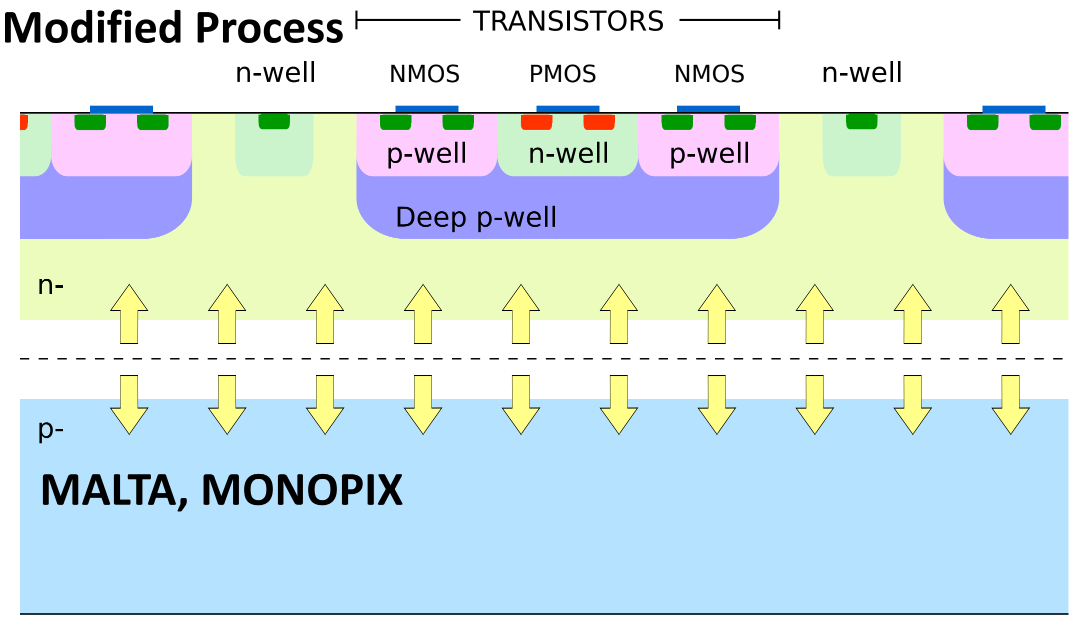
Standard Process



Modified Process



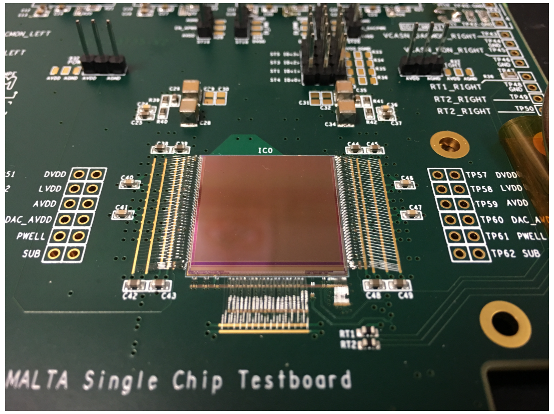
W. Snoeys et al. DOI 10.1016/j.nima.2017.07.046
H. Pernegger et al 2017 JINST 12 P06008

- 25 -30 µm epitaxial layer
- Small collection electrode, ~5 fF input capacitance
- Modified process with uniform n-implant to improve lateral depletion
  - Periphery efficiency, time walk
- 2 chips: MALTA (asynchronous) and MONOPIX (synchronous)
- MALTA based on the ALPIDE chip in ALICE
- Produced Jan 2018

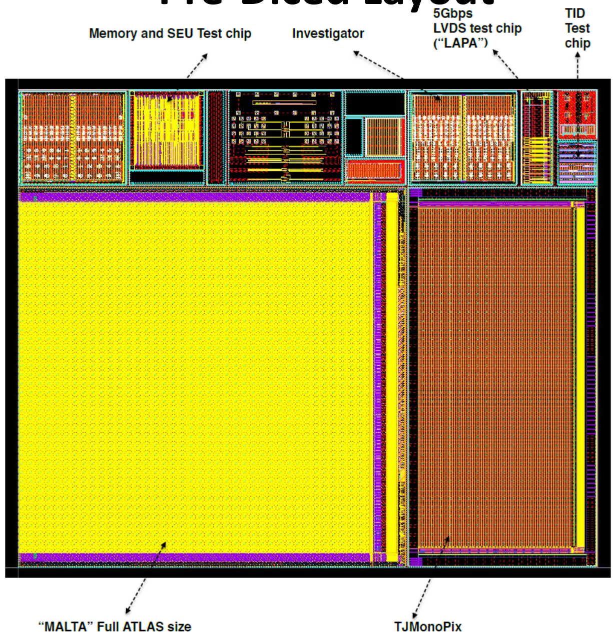
TJ 180 nm MALTA for ATLAS

- 20 x 22 mm
- 512 x 512 pixel matrix
- 36.4 μm pixels with CSA + discriminator + flip-flop
- 3 μm electrode with capacitance < 5 fF
- Novel asynchronous readout architecture for high hit rate capability with 40bit parallel data bus for streaming
- 5 Gbit/s readout
- Low analog power (< 70 mW/cm2)

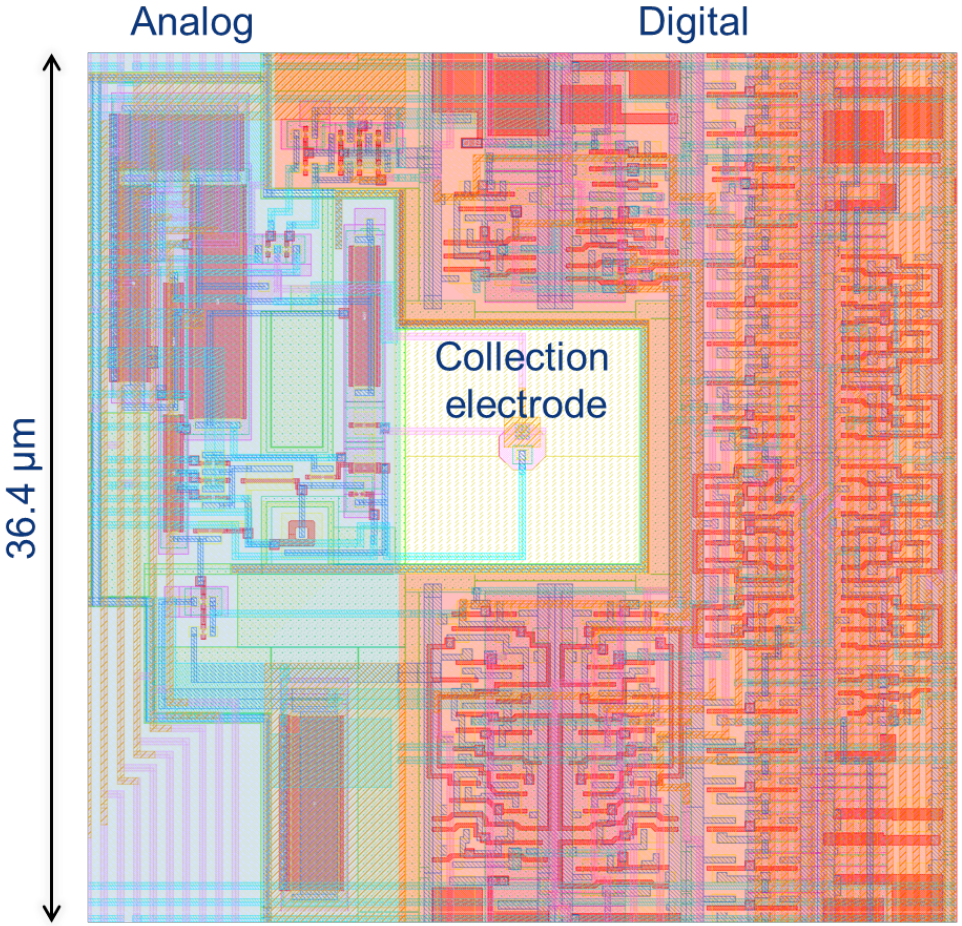
Chip bonded on Testboard



Pre-Diced Layout



Pixel Schematic



MALTA Readout architecture

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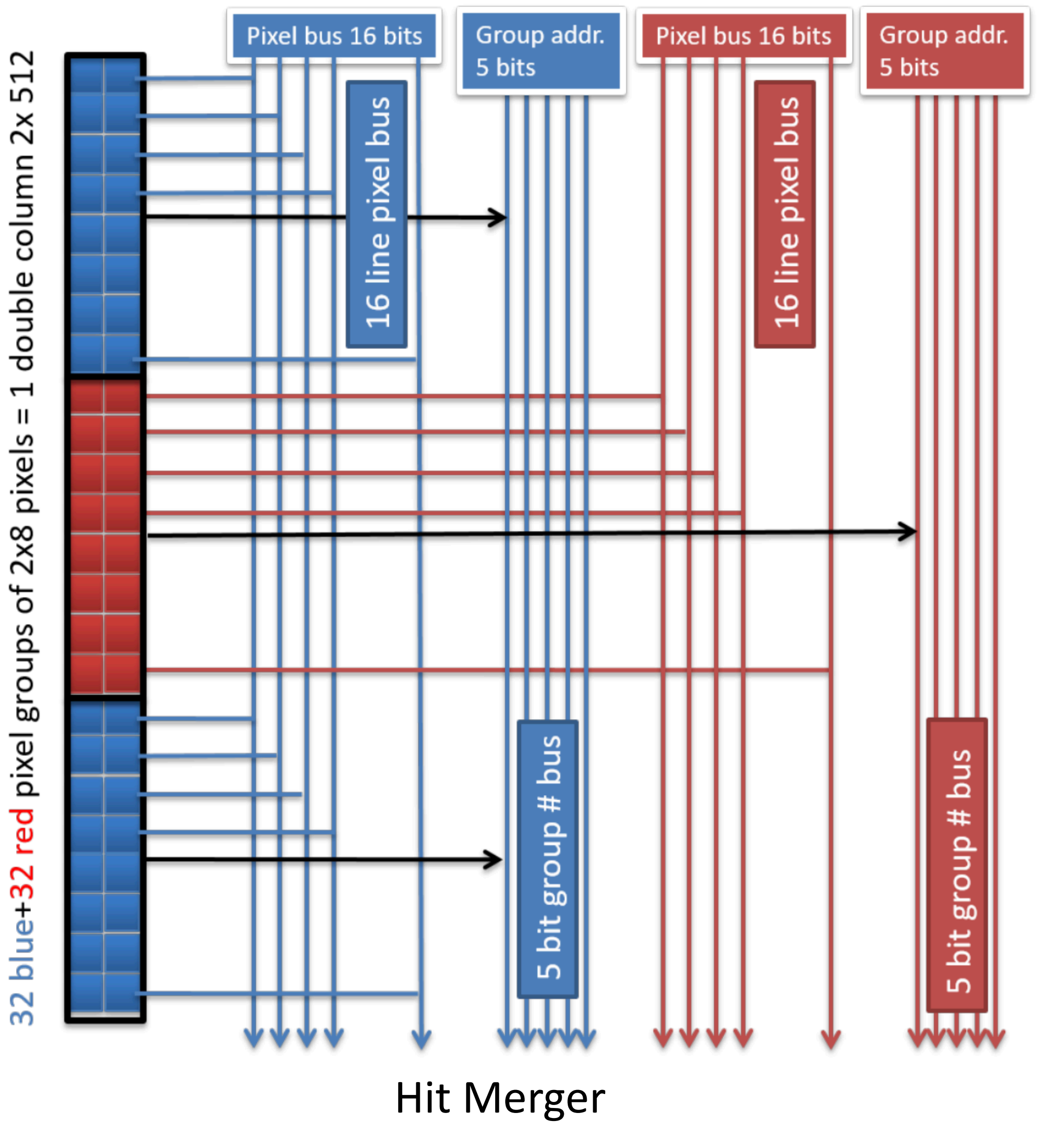


I. Berdalovicet al. JINST 13 C01023 (2018)

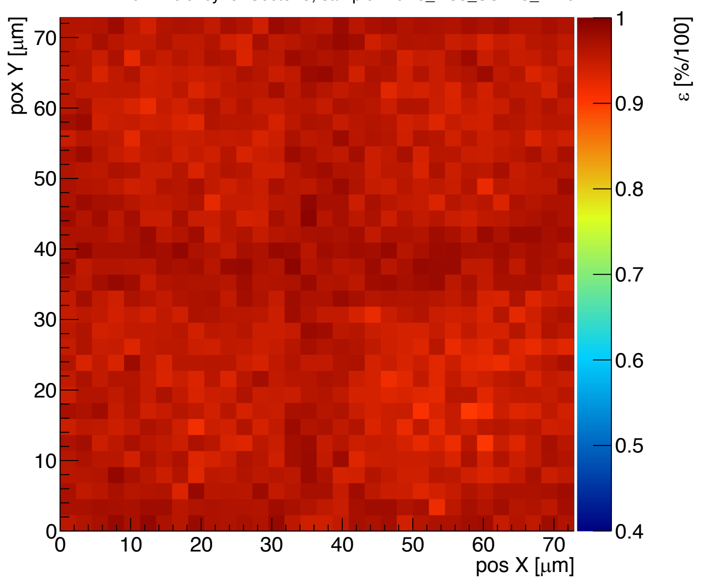
- Asynchronous readout
- No clock distributed to matrix (low power)
- Hit readout from discriminator immediately (fast)
- Double column structure
- Alternating "red" & "blue" groups of 2 x 8 pixels
- 16-bit bus shared groups of same color
- 5 bits for group ID
- Hits merged at periphery, timing information included
- Each hit is written as 40-bit word w/ timing (BCID), double column, color, group, and pixel encoded

Efficiency Results (2018)

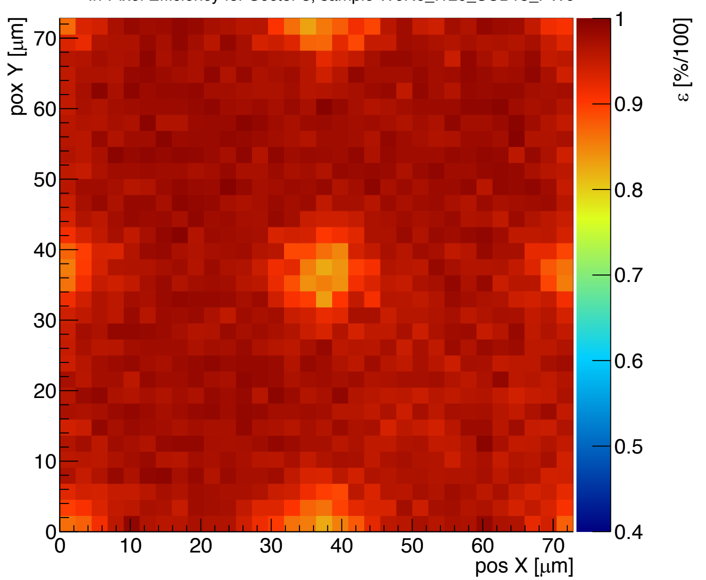
- 180 GeV pions at SPS at CERN, Summer 2018
- Results show decrease in efficiency after irradiation to 5e14 n_{eq}/cm^2
- Inefficiency in pixel periphery
- Too noisy to operate at low threshold after irradiation
- 4 pixels per plot

Unirradiated

Threshold ~250 e-

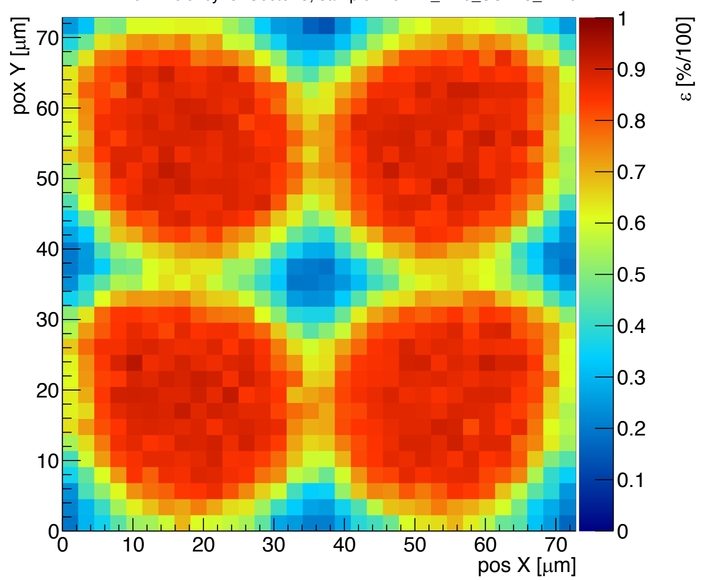


Threshold ~400 e-



5e14 n_{eq}/cm^2

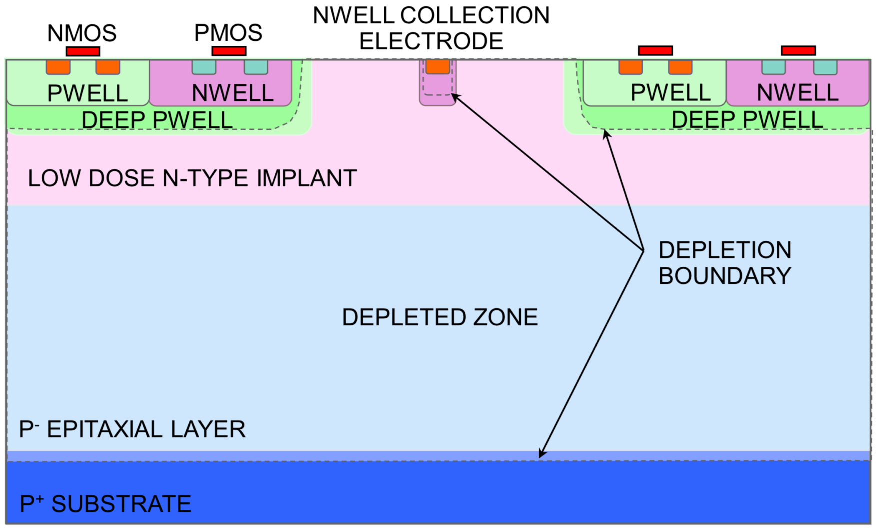
Threshold ~400e-

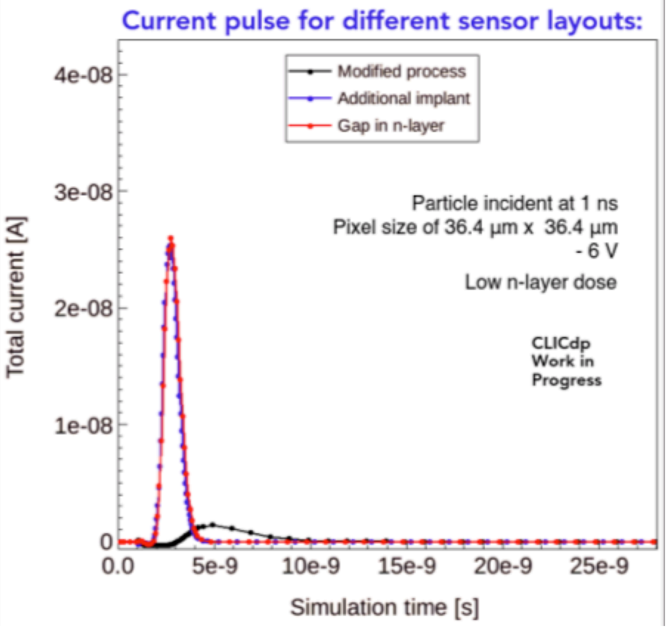


Redesign: MiniMALTA Substrate

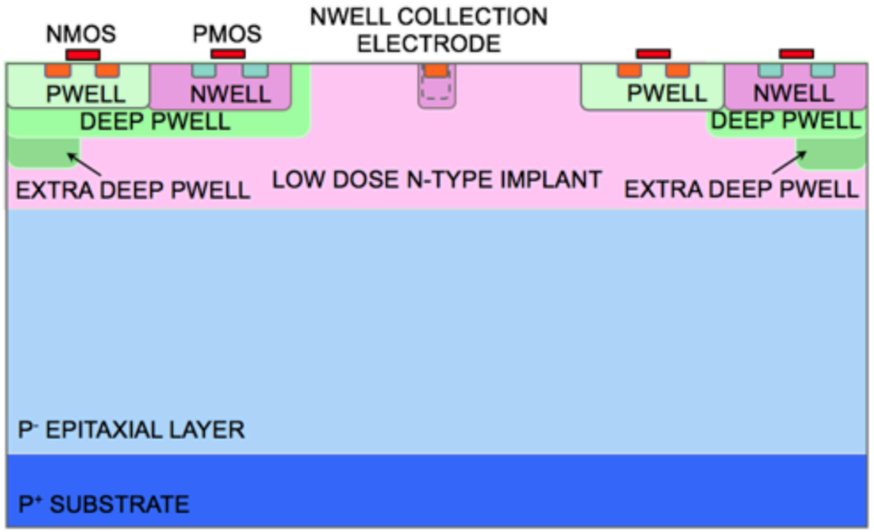
- 2 changes to sensor substrate to increase lateral field near electrode:
  - Extra deep p-well
  - Gap in n- layer
- Simulation predicts a faster, higher amplitude signal for hits in periphery
  - Before & after irrad

Continuous n- layer (old design)

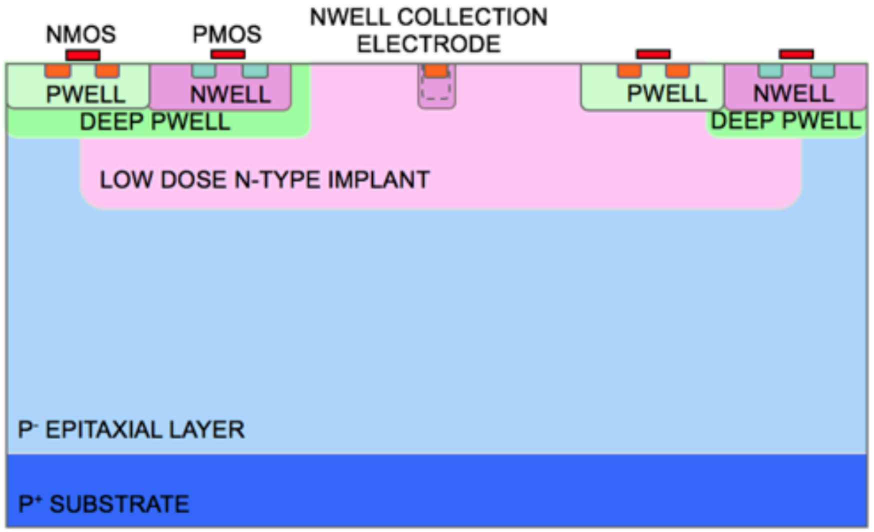




Extra deep p-well



n- gap



M. Munker et al. 9th Workshop on Semiconductor Pixel Detectors for Particles and Imaging (PIXEL), December 2018.

Redesign: MiniMALTA Front End

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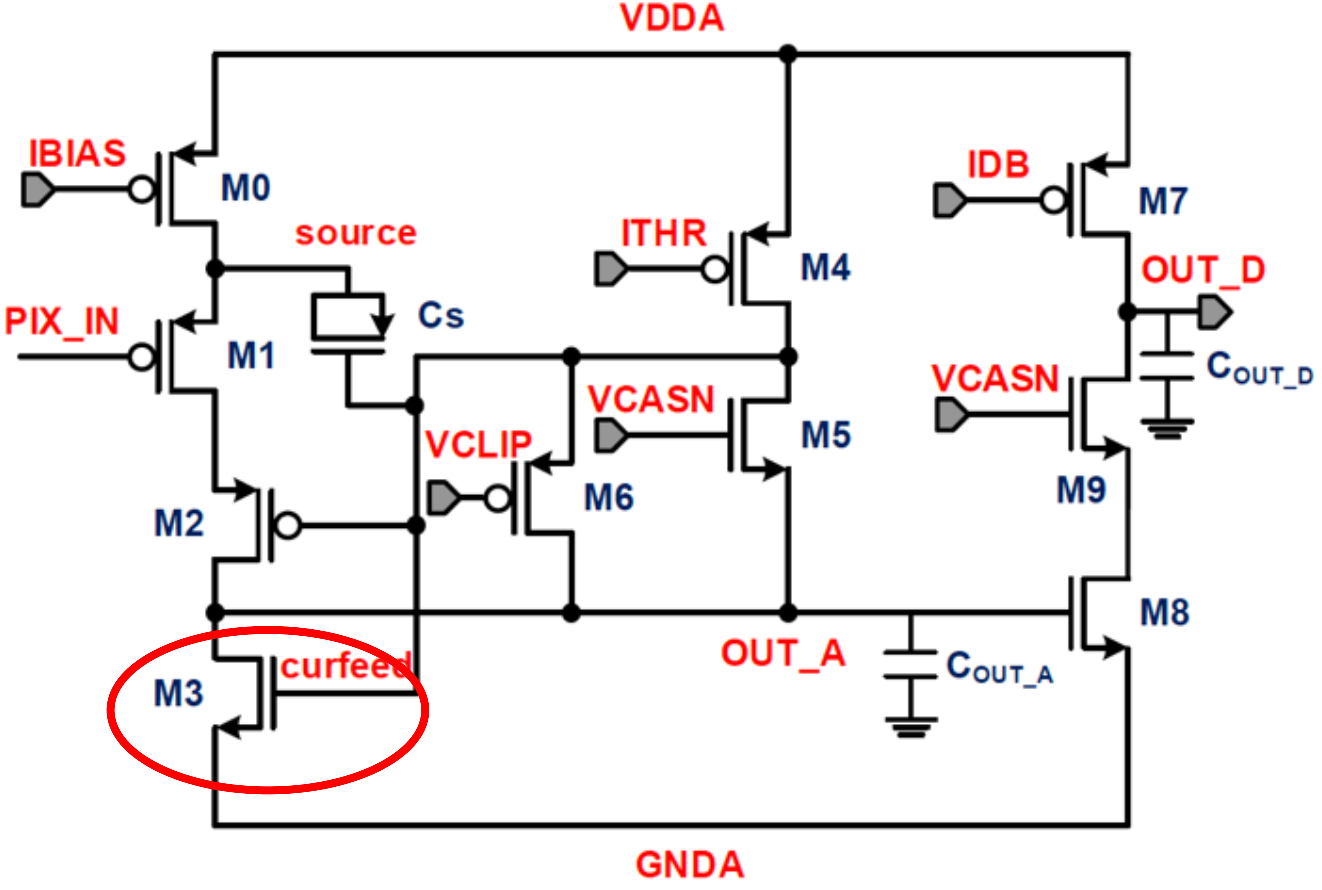
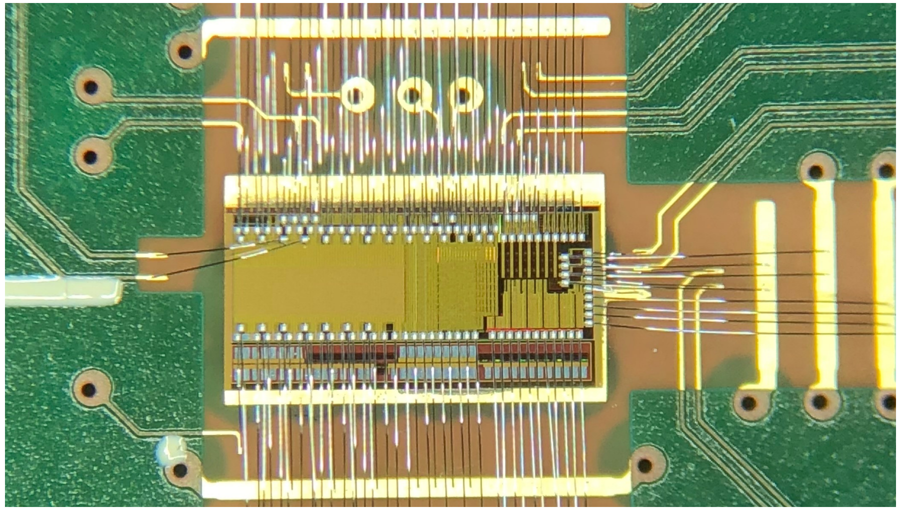
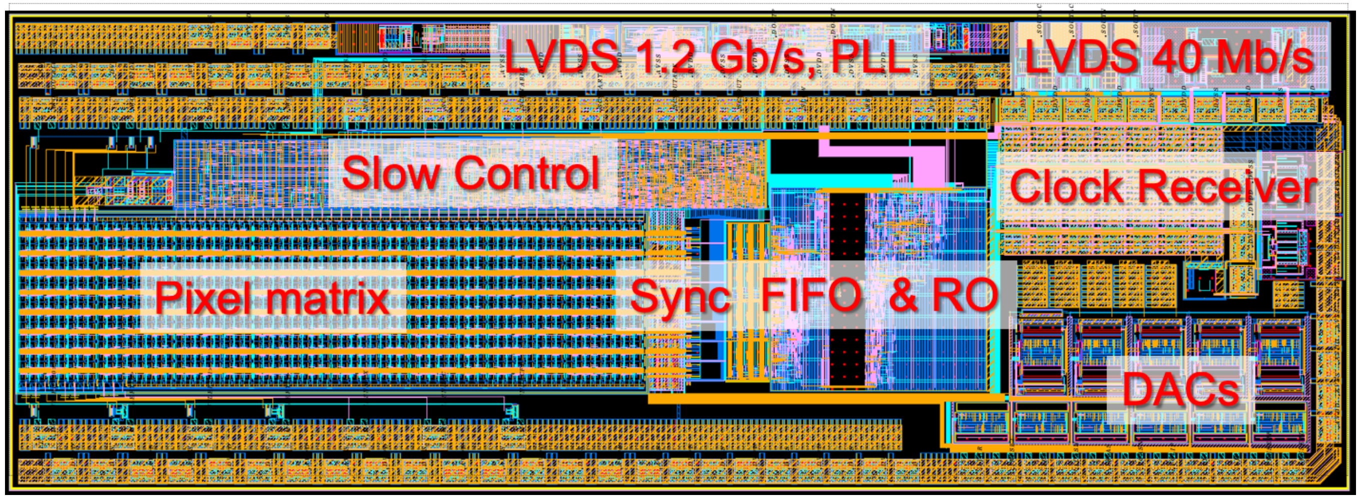
- Random Telegraph ('popcorn') noise prevented low thresholds in MALTA
- M3 NMOS transistor enlarged
- Gain increase
- Lower thresholds
- Better threshold dispersion
- Fewer noisy pixels



MiniMALTA Chip

- Chip produced in Jan 2019
- 64 x 16 pixel matrix
- 36.4 µm pitch
- 8 redesigned sectors
- 0.5 x 0.1 mm
- Lab measurements show front-end is improved w/ addition of large transistor





MiniMALTA Threshold Scans

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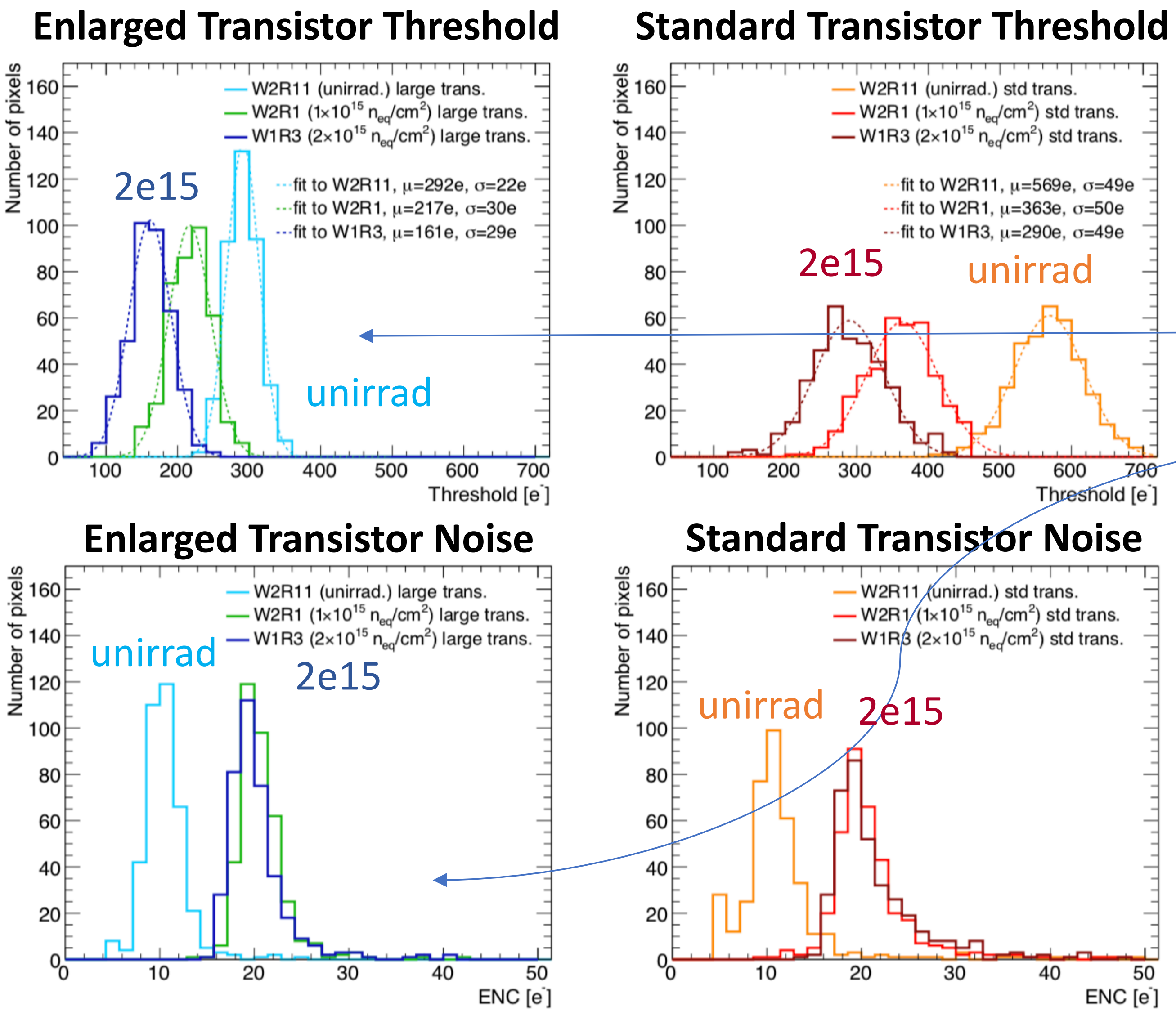


Submitted to arXiv:1909.11987v1

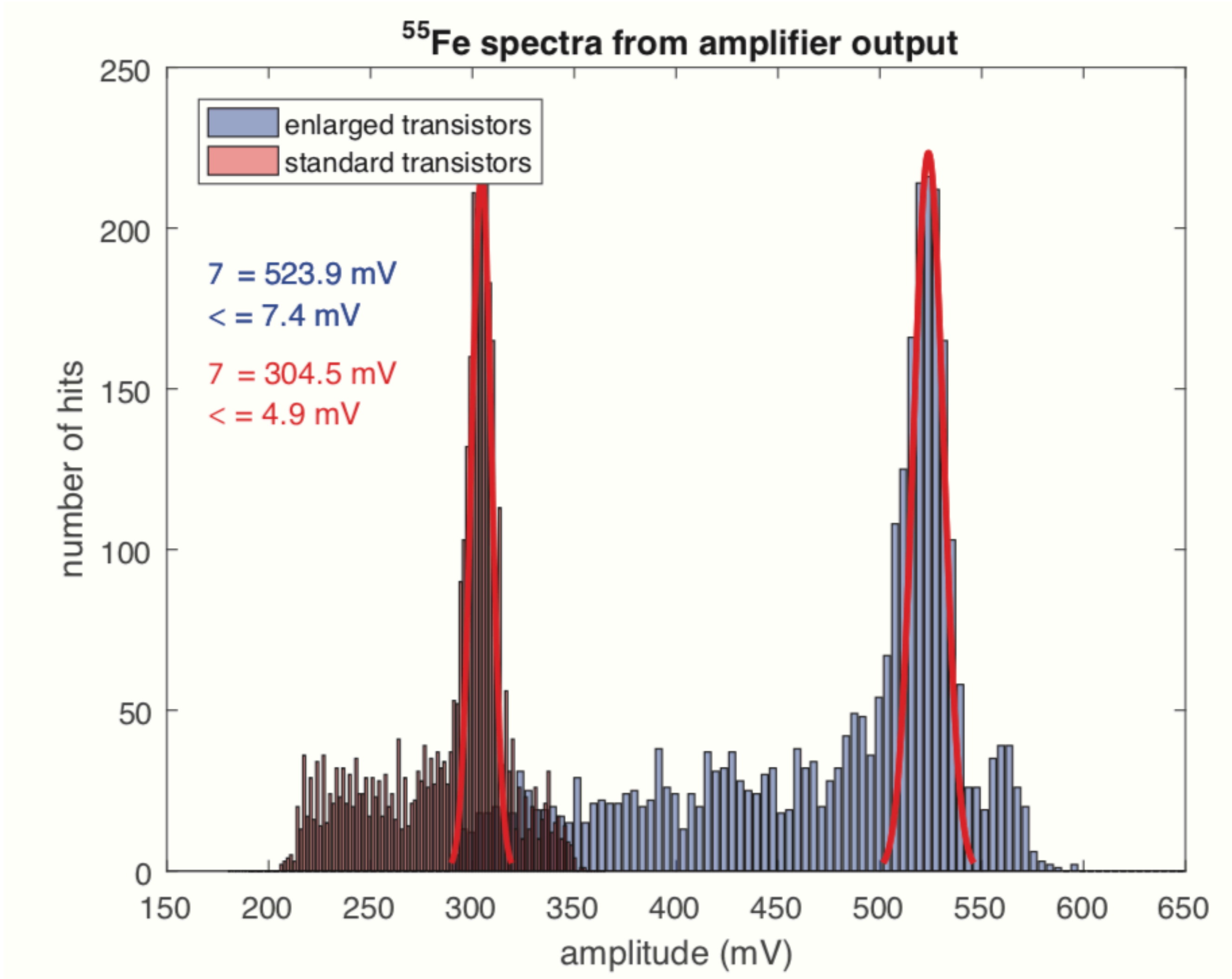
Threshold scans show:

- Improvement of front end with enlarged transistor
  - Lower thresholds
  - Lower noise
  - **Fewer high-noise pixels**

Irradiation dependence

- Lower thresholds
- Noise increases with irradiation, though plateaus at 2e15 n_{eq}/cm^2

MiniMALTA X-ray measurements



Submitted to arXiv:1909.11987v1

- Fe-55 gamma source
  - 5.9 keV X-rays => ~1600 e-
- Increased gain w/ enlarged transistor

MiniMALTA X-ray measurements

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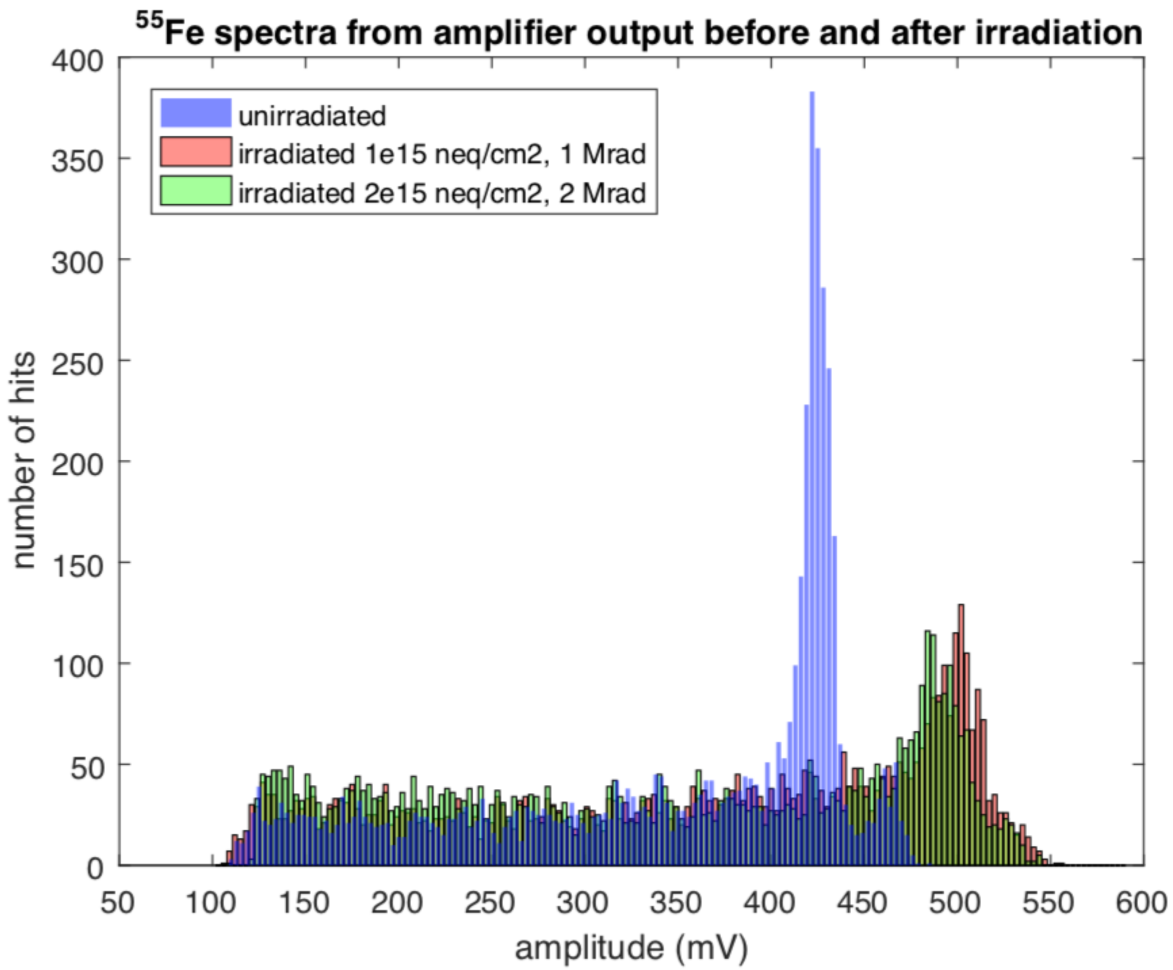
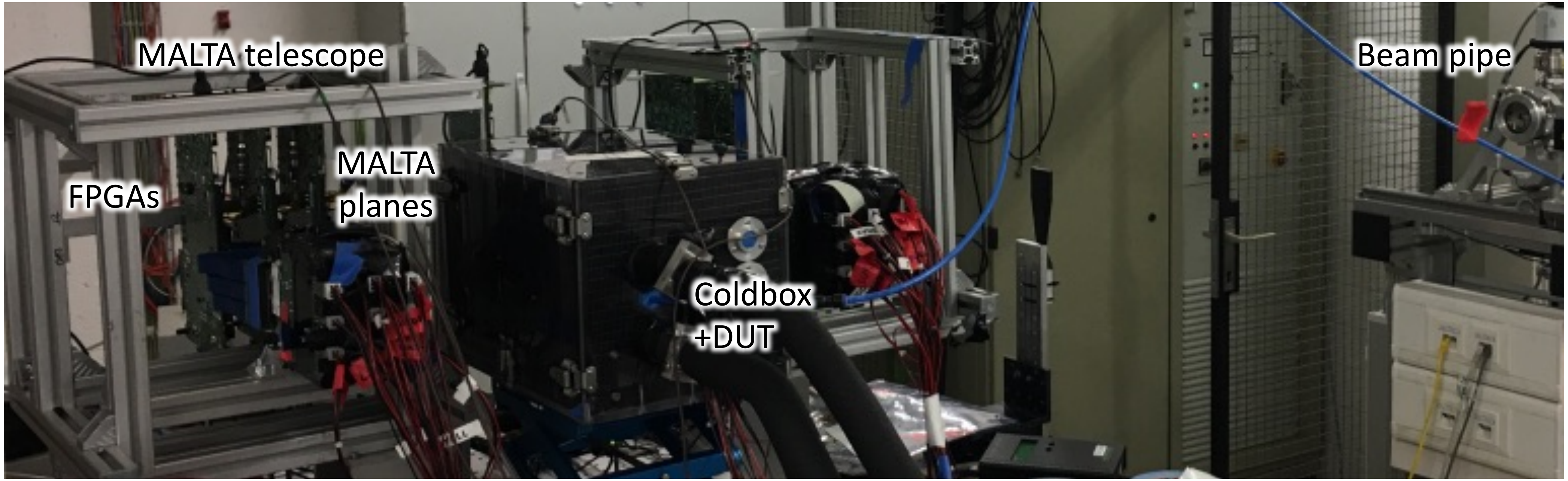


Submitted to arXiv:1909.11987v1

- Fe-55 gamma source
  - 5.9 keV X-rays
- Measurement of unirradiated, 1e15 n_{eq}/cm^2, and 2e15 n_{eq}/cm^2 samples
- Increase in gain after irrad?
  - Front-end changes?
  - No: Measurements => Change in pixel capacitance
- Does improved performance lead to higher efficiency?

MiniMALTA Efficiency



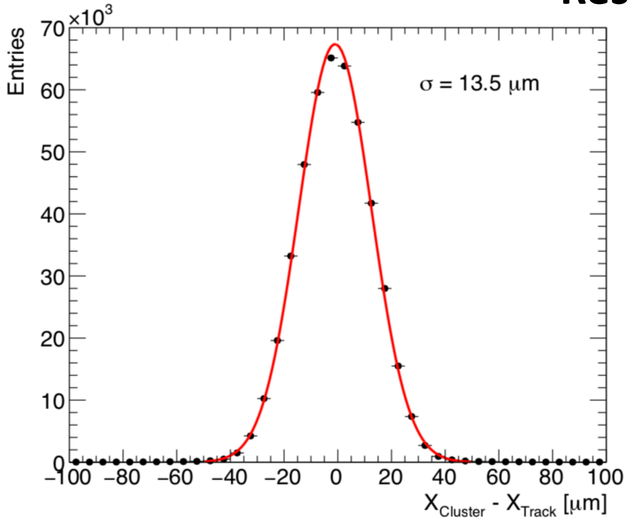
- April 2019 test beams at DESY and ELSA
- 2.5 - 5 GeV electron beams
- Beam telescopes to reconstruct tracks, measure efficiencies
  - MIMOSA at DESY, MALTA at ELSA
- Tested neutron irradiated MiniMALTA samples at 1e15 n_{eq}/cm^2

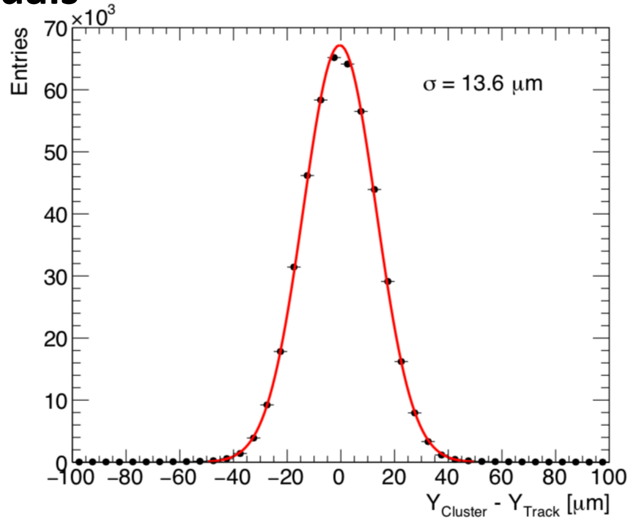
MALTA Beam Telescope

- Telescope constructed from 6 MALTA planes
- Xilinx Virtex-7 FPGA VC707 for readout
- Developed during SPS test beam, 2018
- Used at ELSA test beam in 2019, currently at DESY
- 13 μm residuals with 3 GeV electrons at DESY
  - GBL in Proteus for tracking
  - Predict 6 μm with 180 GeV pions
- Time resolution ~10 ns
- Now includes custom TLU

MALTA Beam Telescope at SPS

Residuals





MiniMALTA Efficiency 1e15 n_{eq}/cm^2

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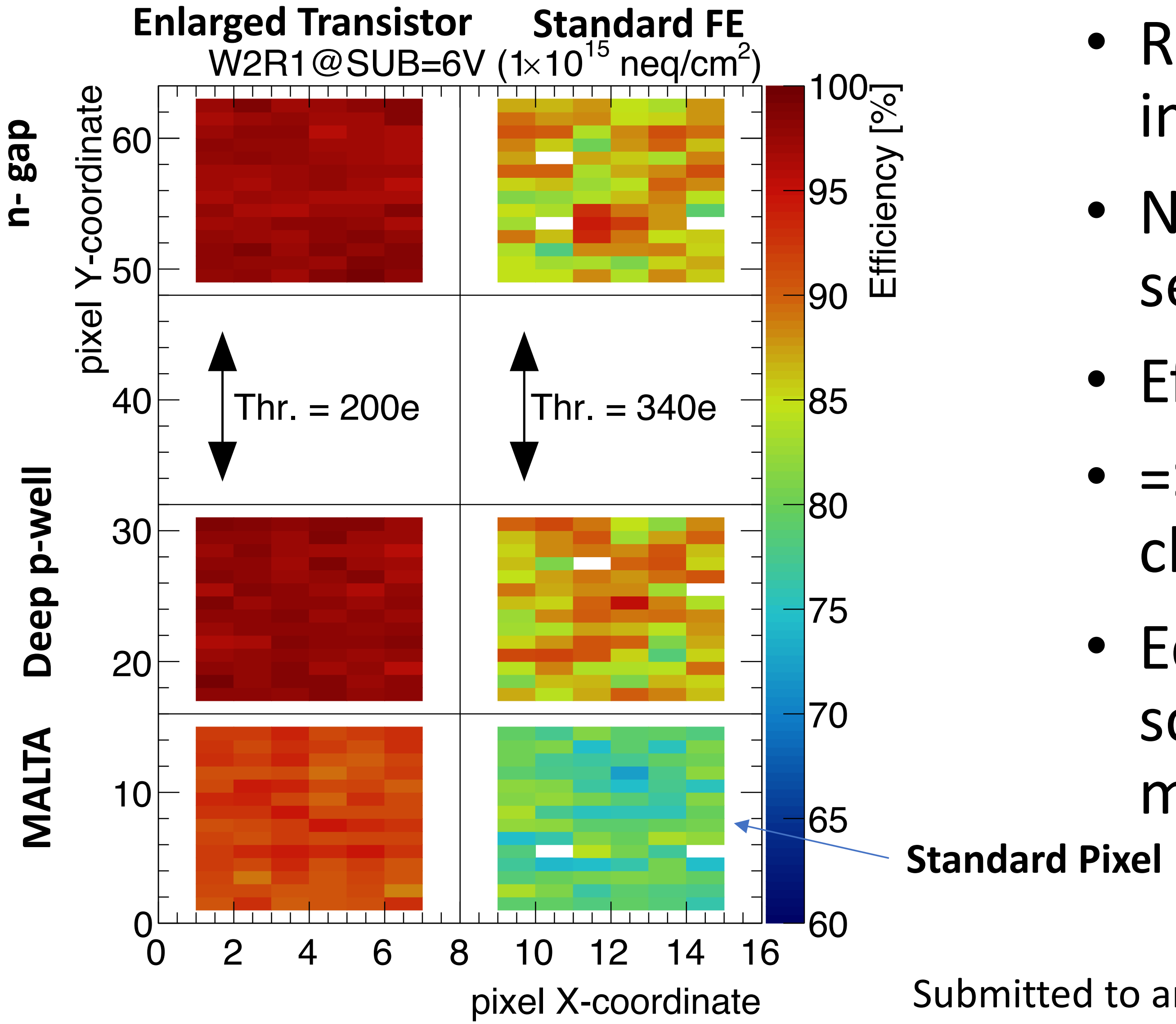
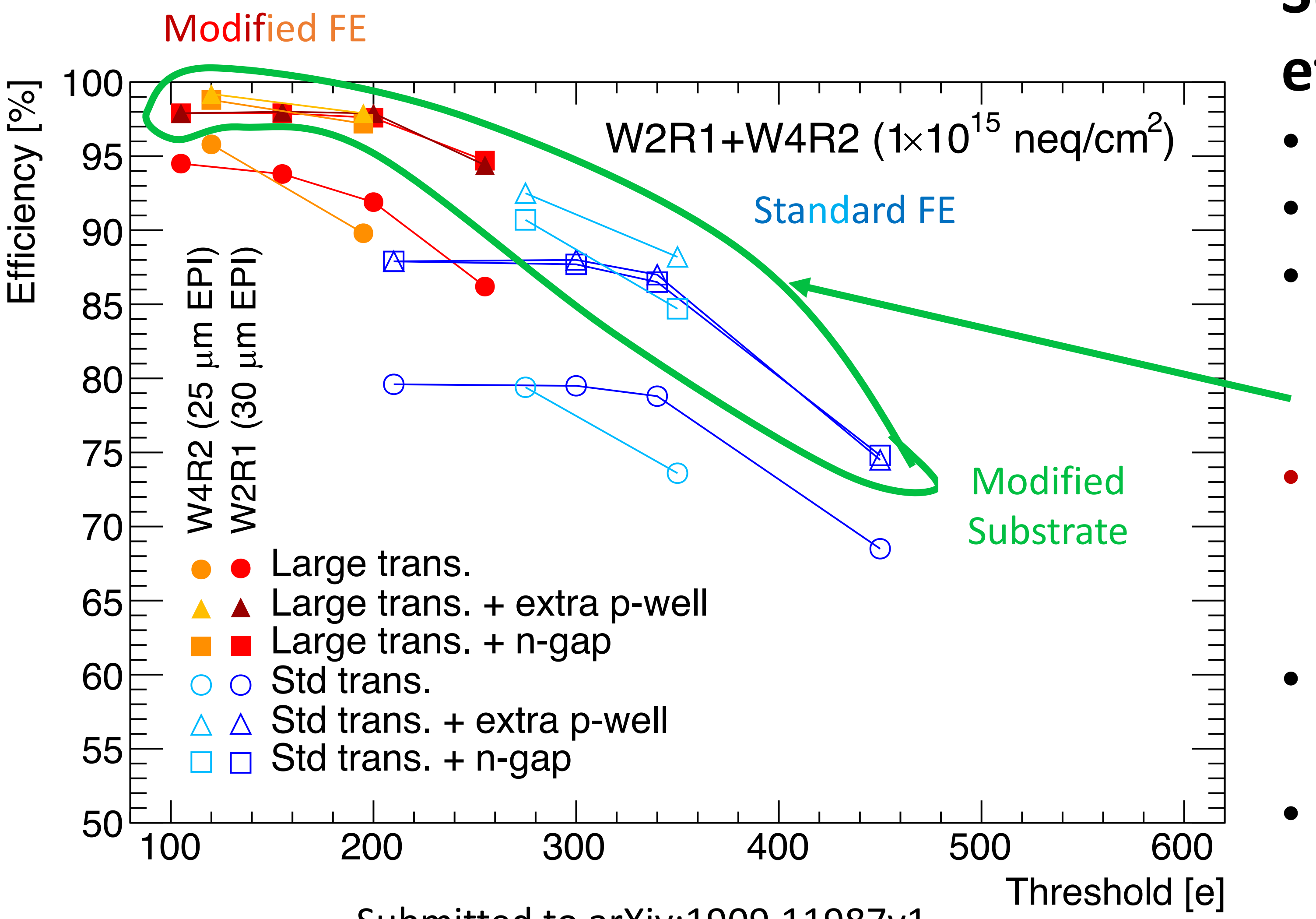


- Re-designed sectors show much improvement
- No signal from PMOS reset sector
- Efficient to 1e15 n_{eq}/cm^2
- => Substrate **and** front-end changes are necessary
- Edges of regions limited by scattering, edge effects b/w matrices

Submitted to arXiv:1909.11987v1

MiniMALTA Efficiency Results



Submitted to arXiv:1909.11987v1

Summary of 1e15 n_{eq}/cm^2 efficiencies

- One 25 µm & one 30 µm
- [compare at const. threshold]
- Extra deep p-well and n- gap at higher efficiency than standard substrate
- Modified front-end, more efficient, lower thresholds than Standard
- Threshold lower for 30 µm than 25 µm epitaxial
- **Is loss of efficiency still in periphery?**
- **TID?**

Diamond Test Beam

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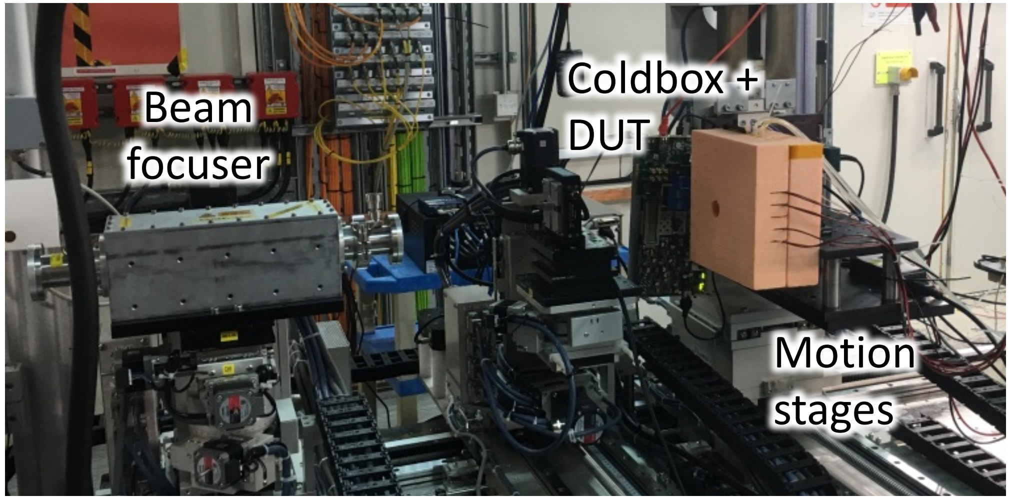
X-Ray test beam measurements at Diamond Light Source in April 2019

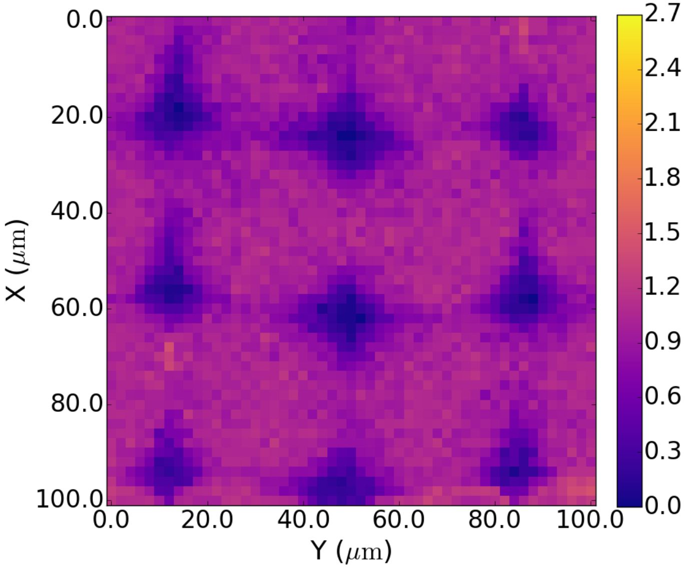
- 2 µm beam spot scanned across pixels
- Pixel performance decreases with irradiation in MALTA sector
- New p-well and n- gap designs + enlarged transistor improve pixel performance
- Proton irradiated samples w/ TID +NIEL



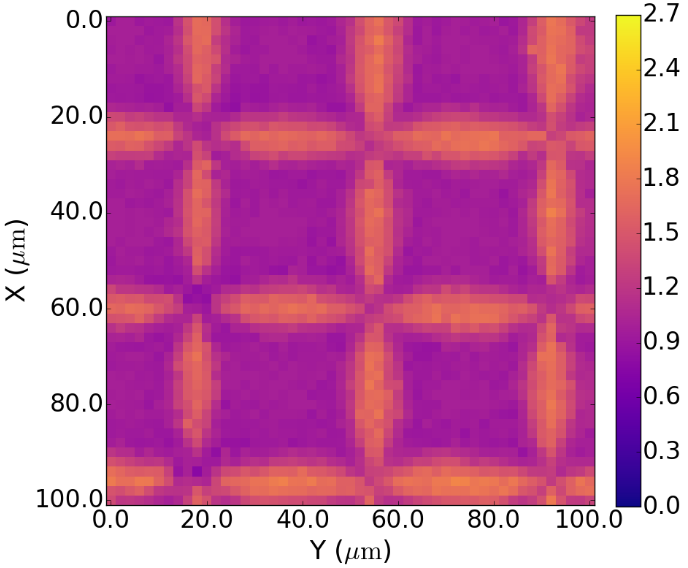
Scaled Hit Maps ≠ efficiency

W2R1
1e15 n_{eq}/cm^2
(neutron irrad)

Standard MALTA + standard transistor



Deep p-well + enlarged transistor



See M. Mironova's Poster

Submitted to arXiv:1909.08392

MiniMALTA X-ray Irradiations

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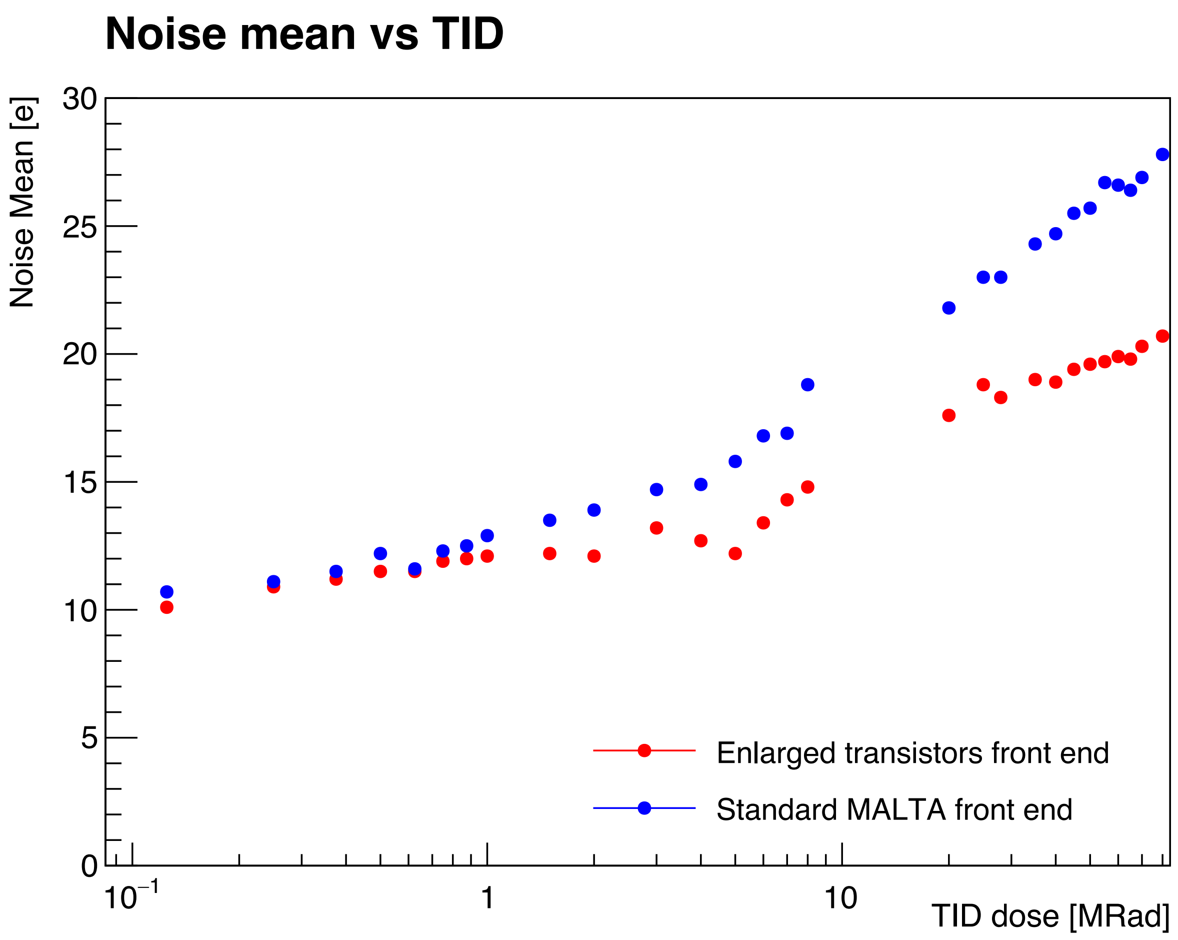

X-ray irradiations at Glasgow for measurement of effect of TID, esp. on front-end

- Threshold scan results
- Noise increases with TID
  - More so w/ enlarged transistors than standard

Presented at TWEPP 2019 by L. Simon
https://indico.cern.ch/event/785806/

MiniMALTA X-ray Irradiations

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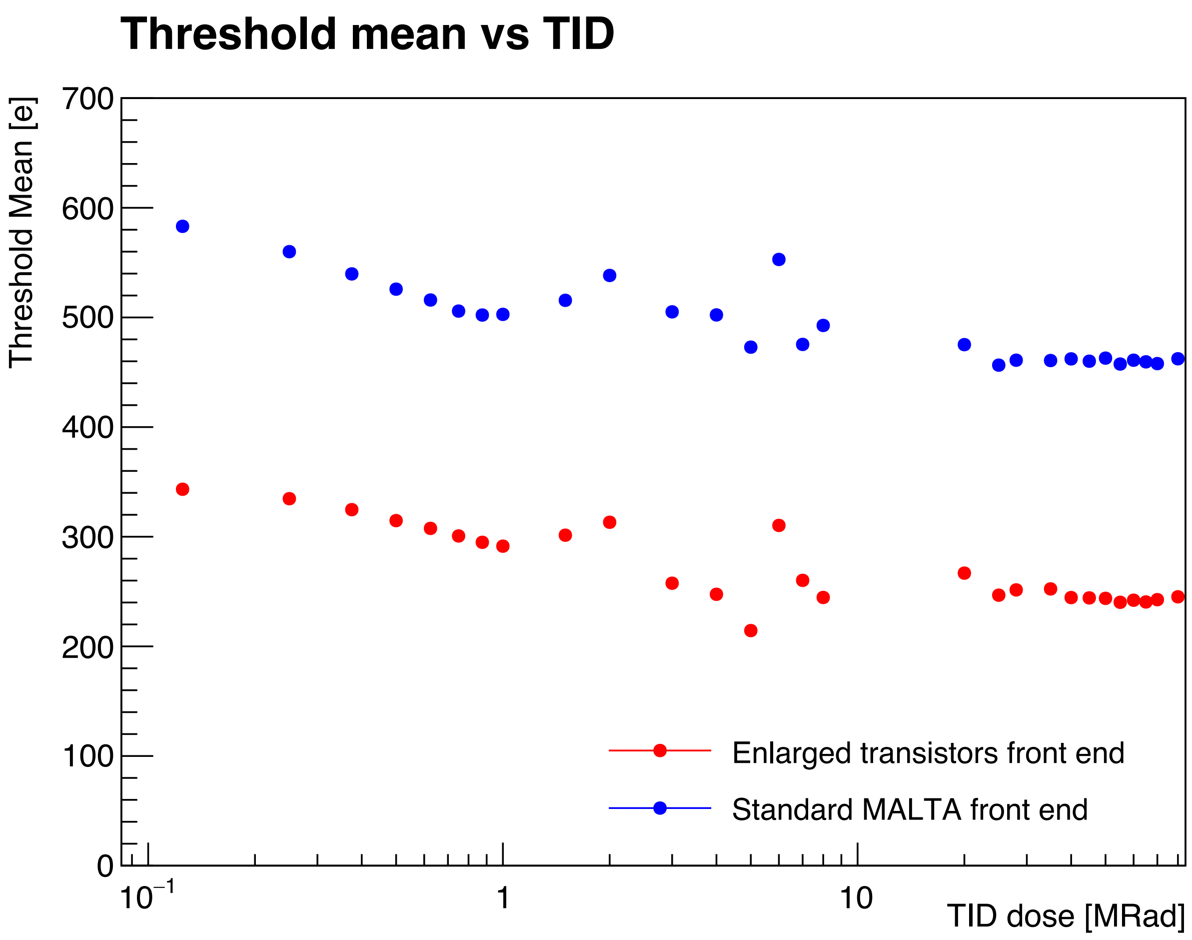
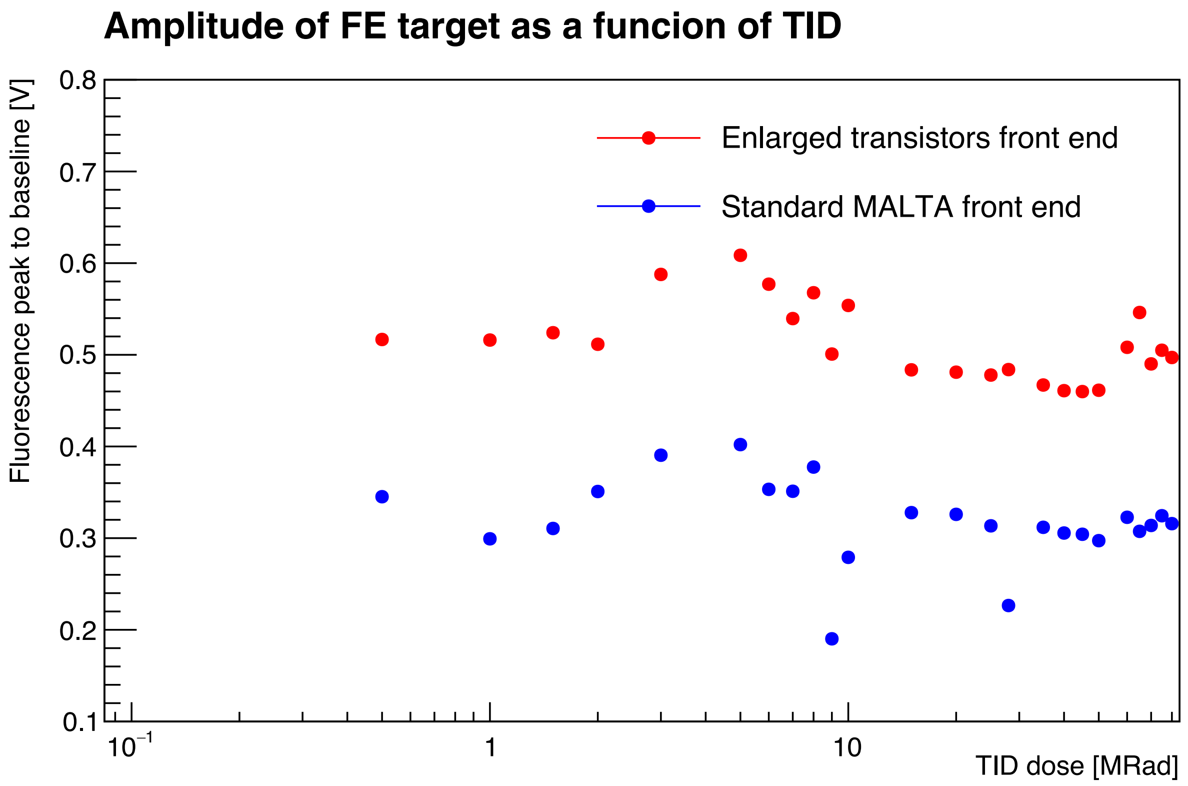


X-ray irradiations at Glasgow for measurement of effect of TID, esp. on front-end

- Threshold scan
- Threshold decreases after bump at 2-10 Mrad, then stabilizes
- Pixels w/ enlarged transistors have lower thresholds than standard

Presented at TWEPP 2019 by L. Simon
https://indico.cern.ch/event/785806/

MiniMALTA X-ray Irradiations



X-ray irradiations at Glasgow for measurement of effect of TID, esp. on front-end

- Measurements of analog pixel waveforms
- Gain increases slightly then stabilizes
- Pixels w/ enlarged transistors have higher gain lower thresholds than standard

Overall results correlate well with Diamond test beam on proton irradiated samples with TID = 70 MRad

- Additional measurements at CERN in September currently being summarized

Presented at TWEPP 2019 by L. Simon
https://indico.cern.ch/event/785806/

New Sensors: MALTA SC

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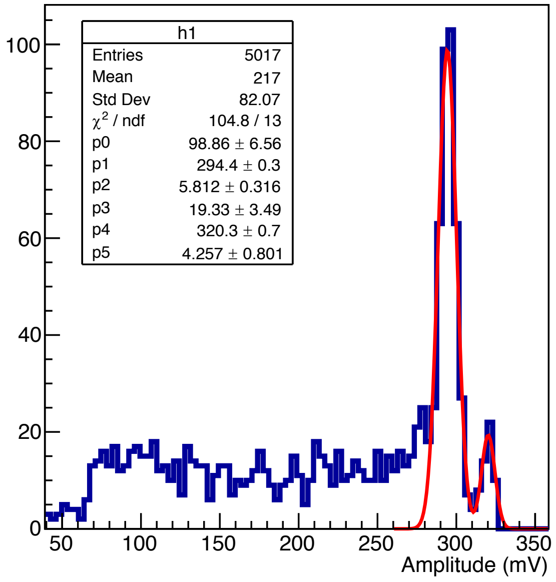
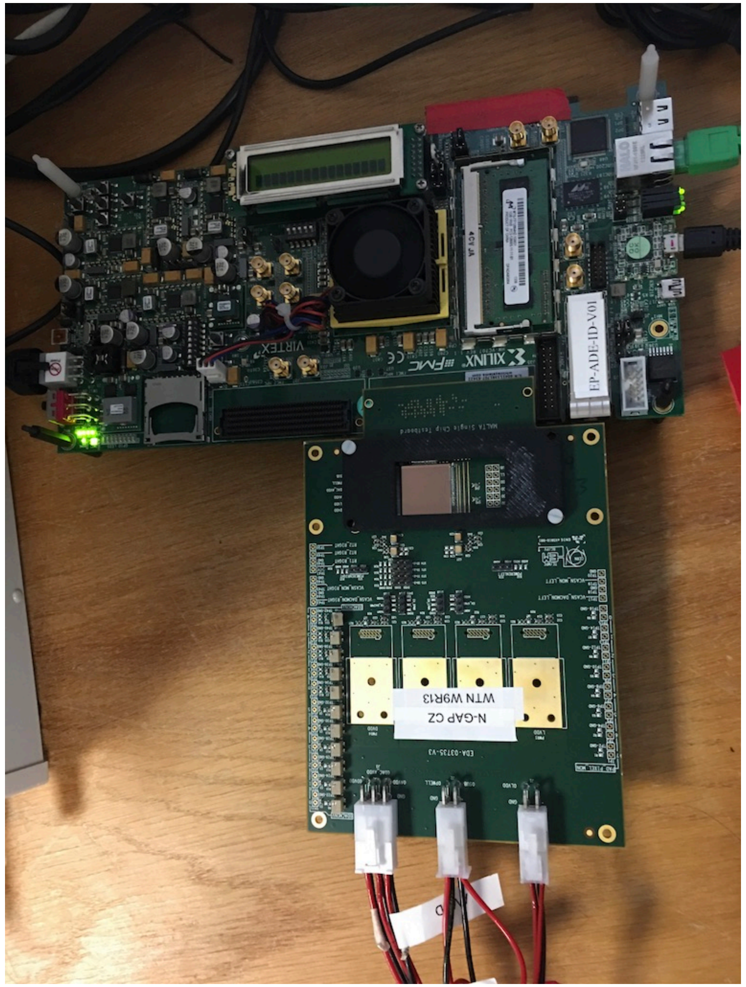
MALTA_SC: Full size 2x2cm with focus on time-resolutions and radiation hardness

- Features entire wafers with substrate redesigns
- No enlarged transistor
- Also implemented on Cz Silicon
  - Lower resistivity
  - High oxygen content
  - 300 µm substrate
  - may be able to deplete ~60 µm or more => more signal
- Measurements: threshold scans, Fe55, currently testing at DESY test beam
- Neutron irradiated chips up to 5e15, proton irradiations next week in Birmingham

Fe55 Spectrum





New Sensors: MALTA V2

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MALTA V2: new sensor with gain optimized FE for best time-resolution (~ns)

- Currently in design with focus on new FE – maximizes gain for best time-resolution (goal ~1ns) in small pixel matrix
- Will include all implant fixes of MiniMALTA and be produced on EPI and HR Cz material
- Submission Q4 2019

Summary

- MALTA prototype for outer pixel layers ATLAS experiment
- TowerJazz 180 nm modified process based on ALPIDE design
- Prototype to improve radiation hardness: MiniMALTA
  - Fully efficient at 1e15 n_{eq}/cm^2
  - Good indications of performance at 80 Mrad
  - Design changes have intended effects
- New Cz prototypes being tested (up to 5e15 n_{eq}/cm^2)
- MALTA V2 to be produced in ~Spring 2020 in epi & Cz
- A lot of work measuring new sensors to look forward to! :)

Thank you!

References

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H. Pernegger et al. *First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors.* JINST 12 P06008 (2017)

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Backup

timeline

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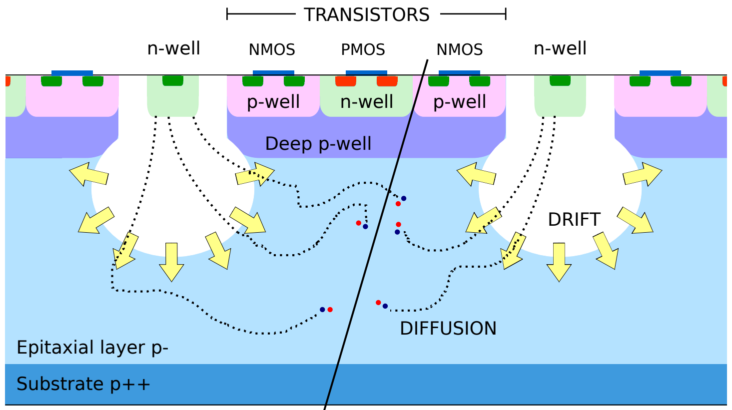
Timeline

2017	TJ Investigator studies
Jan2018	MALTA production
May 2018	MALTA SPS test beams
	MiniMALTA design submission
Nov. 2018	
January 2019	MiniMALTA production
	MiniMALTA irradiations & measurements
April 2019	MiniMALTA test beams
August 2019	MALTA_SC produced
	MALTA_SC irrad & measurer
Now	DESY test beam for MALTA_S &MiniMALTA

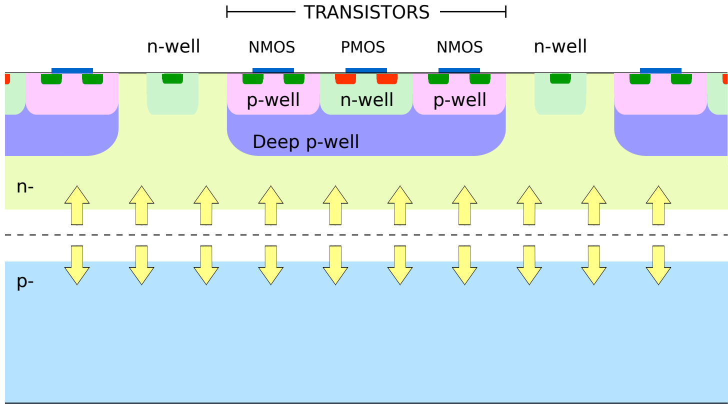
Tower Jazz Investigator 1 & 2

- 180 nm TJ
- Analog sensor for design optimization
- 25 -30 µm epitaxial layer
- Small collection electrode for small (~5fF) input capacitance
- Modified process in Investigator 2 features uniform n-implant to improve lateral depletion
    - For periphery efficiency
    - Improves time walk
- Many matrices with different pixel size, electrode size, shape, etc.
- Good radiation tolerance up to 1e15 n_{eq}/cm^2 (Sr90 measurements)
- 2 chips based off Investigator: MALTA (asynchronous readout for faster data rates) and MONOPIX (synchronous readout)



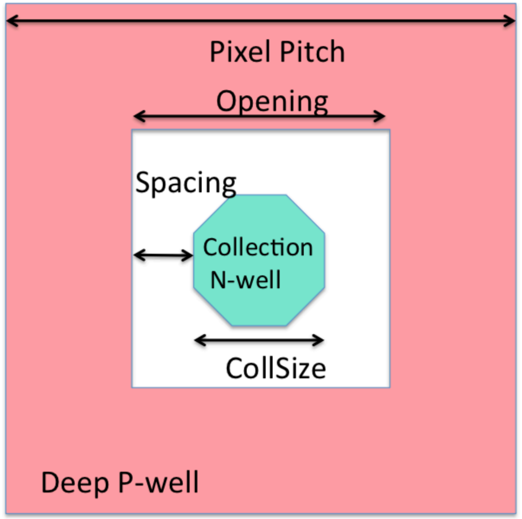
Standard Process

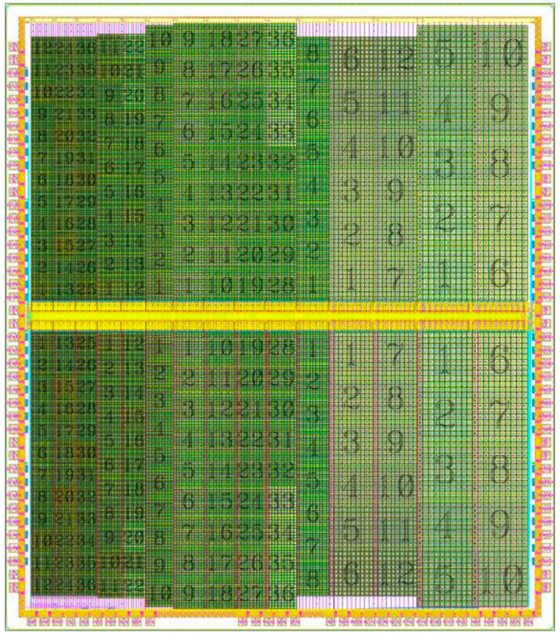
W. Snoeys et al. DOI 10.1016/j.nima.2017.07.046



Modified Process

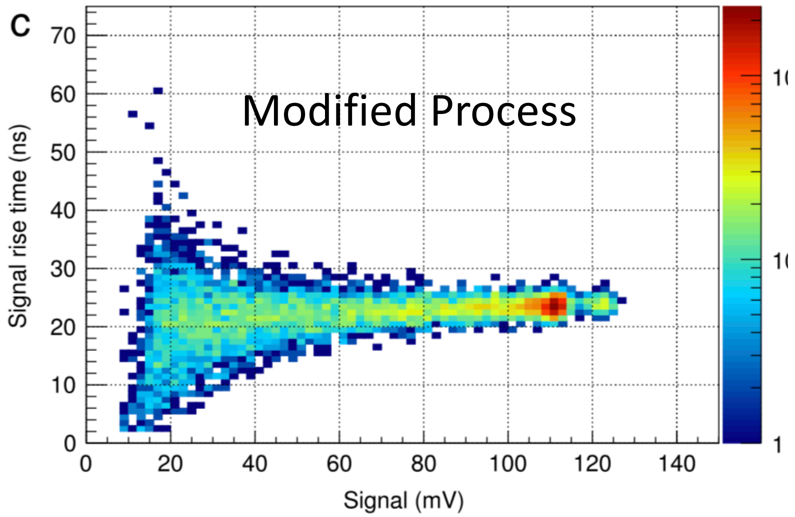
H. Pernegger et al 2017 JINST 12 P06008

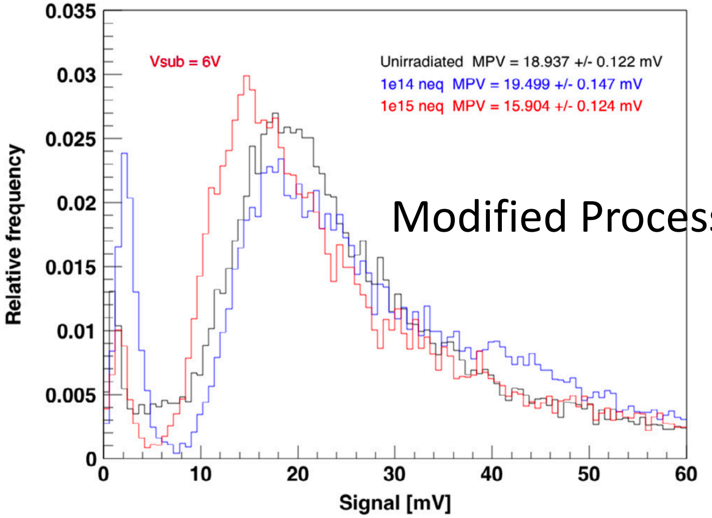


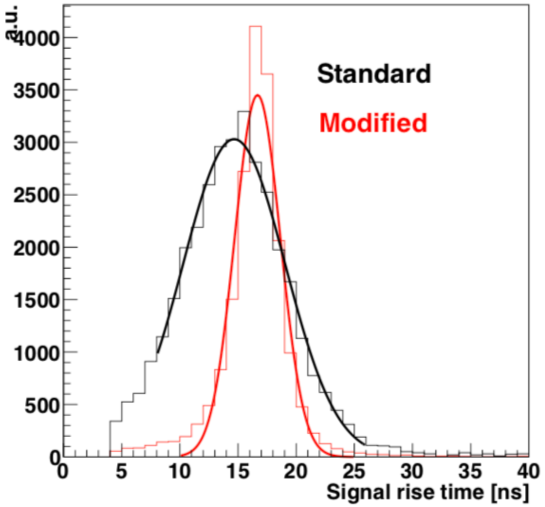


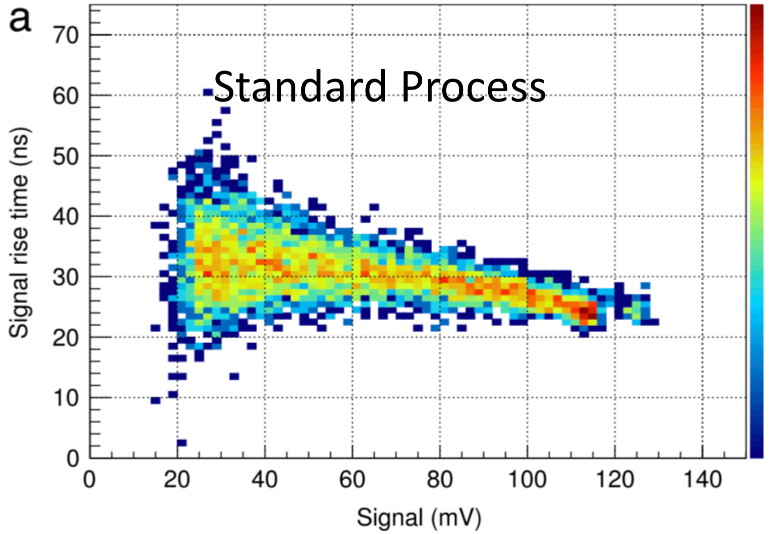
Tower Jazz Investigator

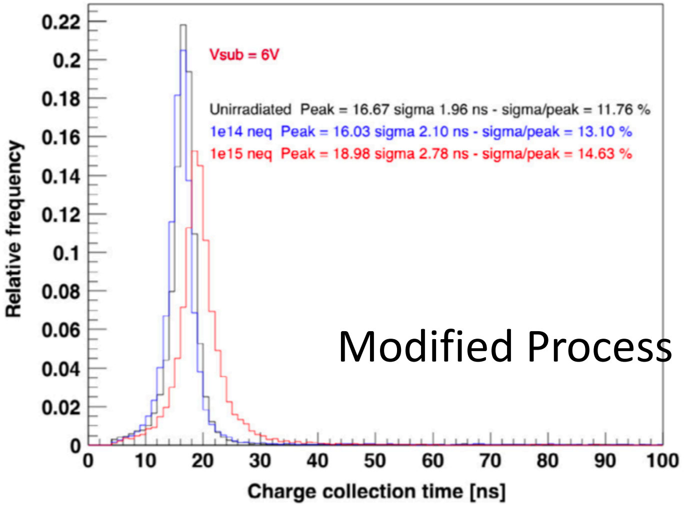
- Modified process results in faster, more uniform pulses
  - => improved time walk
- Good radiation tolerance
- Modified pixels efficient in periphery











W. Snoeys et al. DOI 10.1016/j.nima.2017.07.046 H. Pernegger et al 2017 JINST 12 P06008

Tower Jazz Investigator Efficiency

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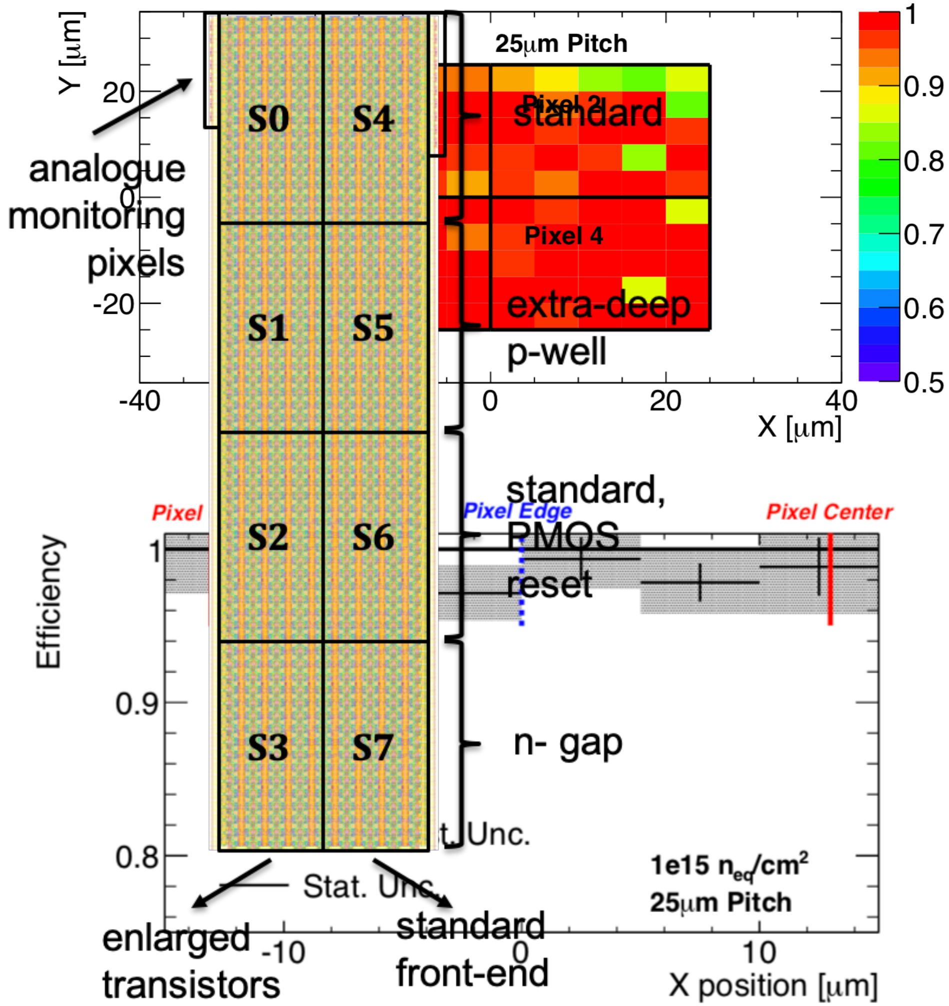
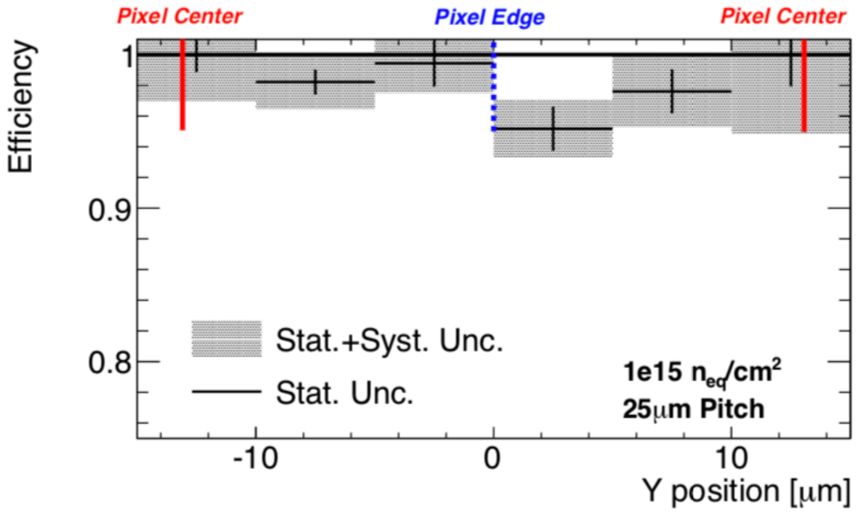


- Modified pixels efficient in periphery
- 25 um pixel w/ 1e15 n_{eq}/cm^2
- => create chip based on modified process



Modified Process

W. Snoeys et al. DOI 10.1016/j.nima.2017.07.046 H. Pernegger et al 2017 JINST 12 P06008

MALTA analog after irradiation

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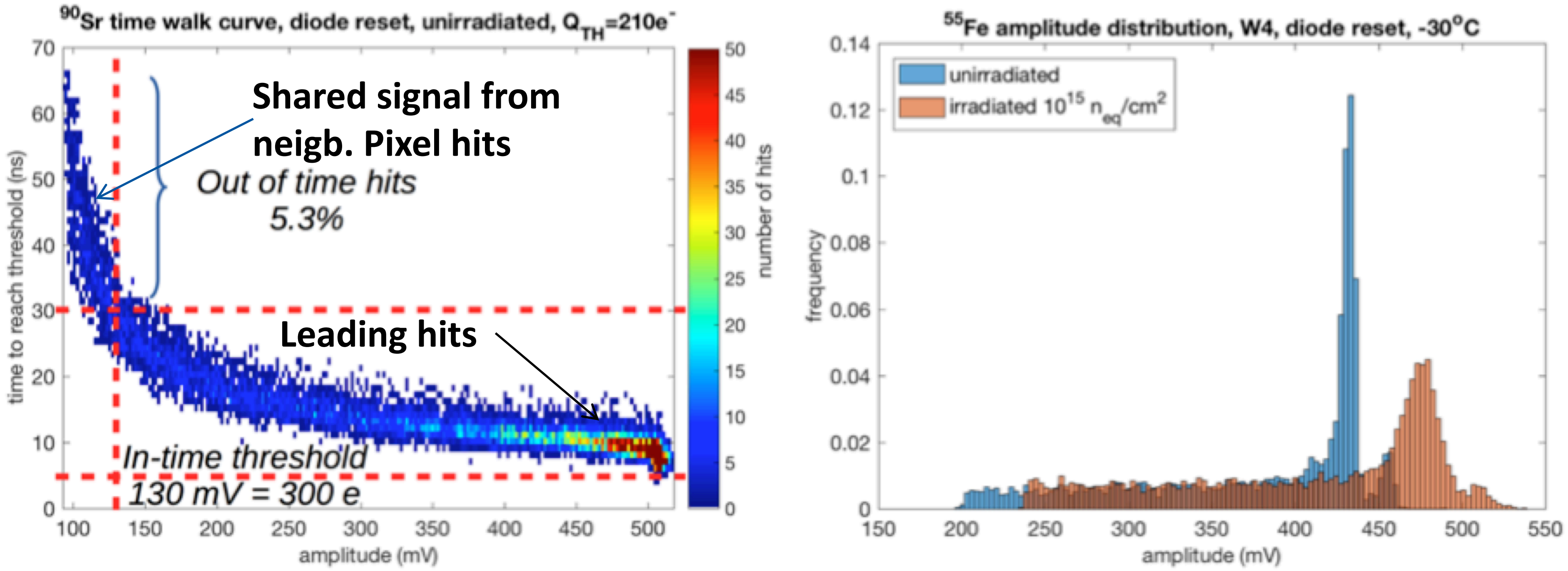
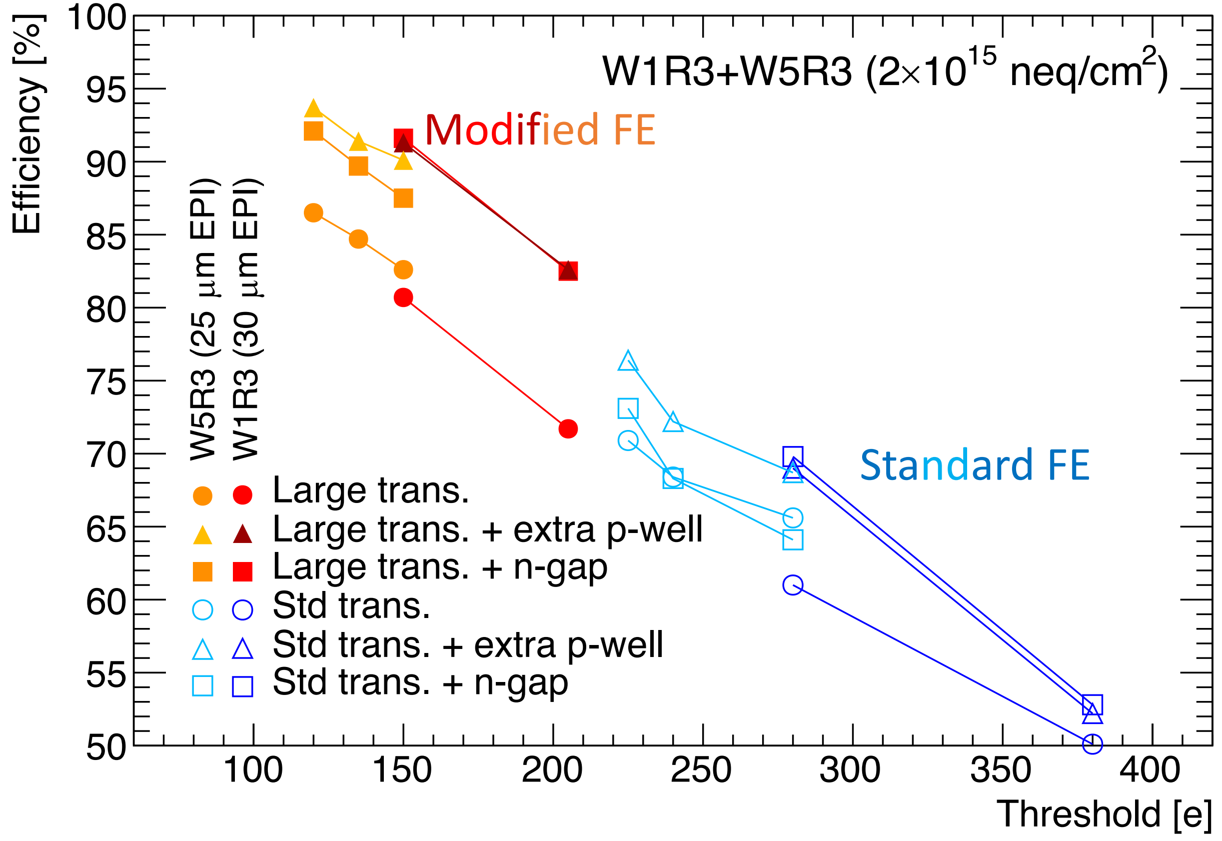
- Neutron irradiated n_{eq}/cm^2
- Good analog performance for ENC and timing
- Need improvement on threshold dispersion



Copied from Heinz…

MiniMALTA Efficiency Results



Submitted to arXiv:1909.11987v1

Summary of 2e15 n_{eq}/cm^2 efficiencies

- Efficiency < 95 %
- One 25 μm & one 30 μm
- Threshold lower & efficiency higher for 30 μm than 25 μm epitaxial
- Efficiency seems linear w/ threshold

Chip loses efficiency, is it still in the periphery?

MiniMALTA Diamond Test Beam

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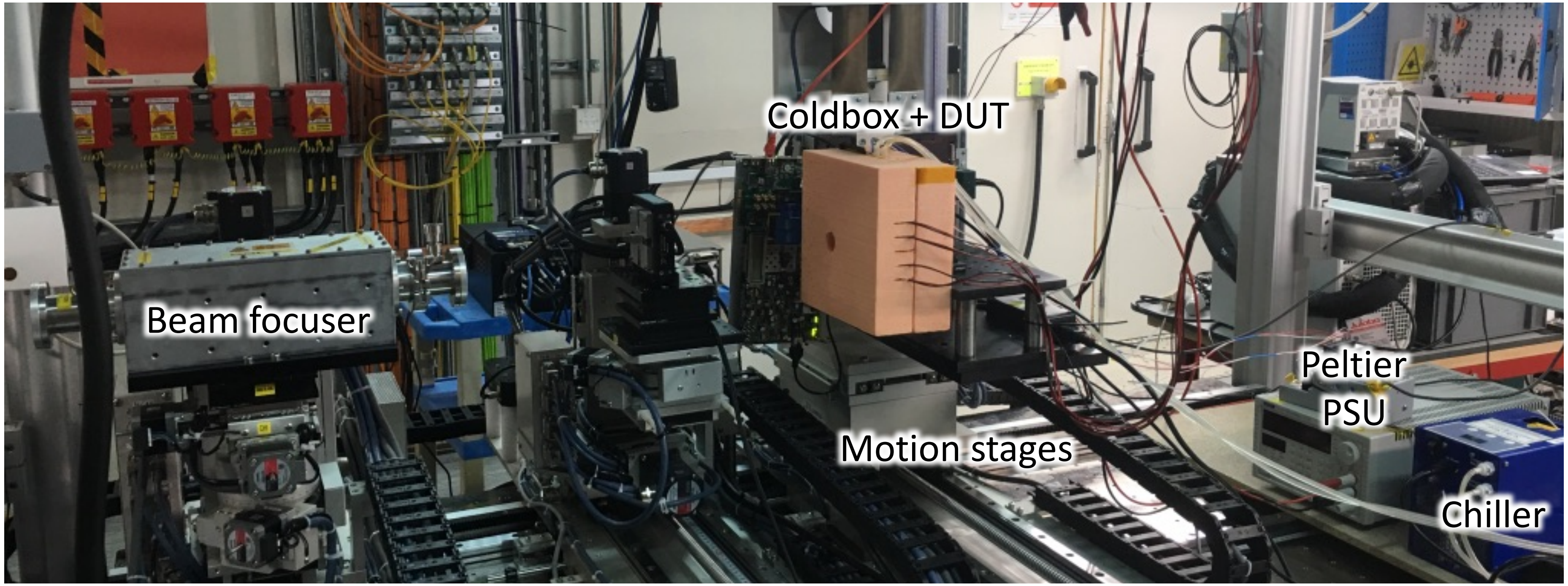

- April 2019 at Diamond Light Source
- Measurement of **proton** and **neutron** irradiated chips
- Focus on 3 sectors:
  - n- gap w/ enlarged transistors
  - Deep p-well w/ enlarged transistors
  - Standard MALTA (for comparison)

- Precision focused X-ray beam
  - 2 μm spot size
  - 8 keV photons
    - ~2200 e-/hole pairs
    - Slightly below mean energy deposited by MIP close to MPV
- Precision motion stages for scanning (400 nm)
- => Can make high-resolution relative response maps (basically **high precision TCT**)

MiniMALTA Diamond Results

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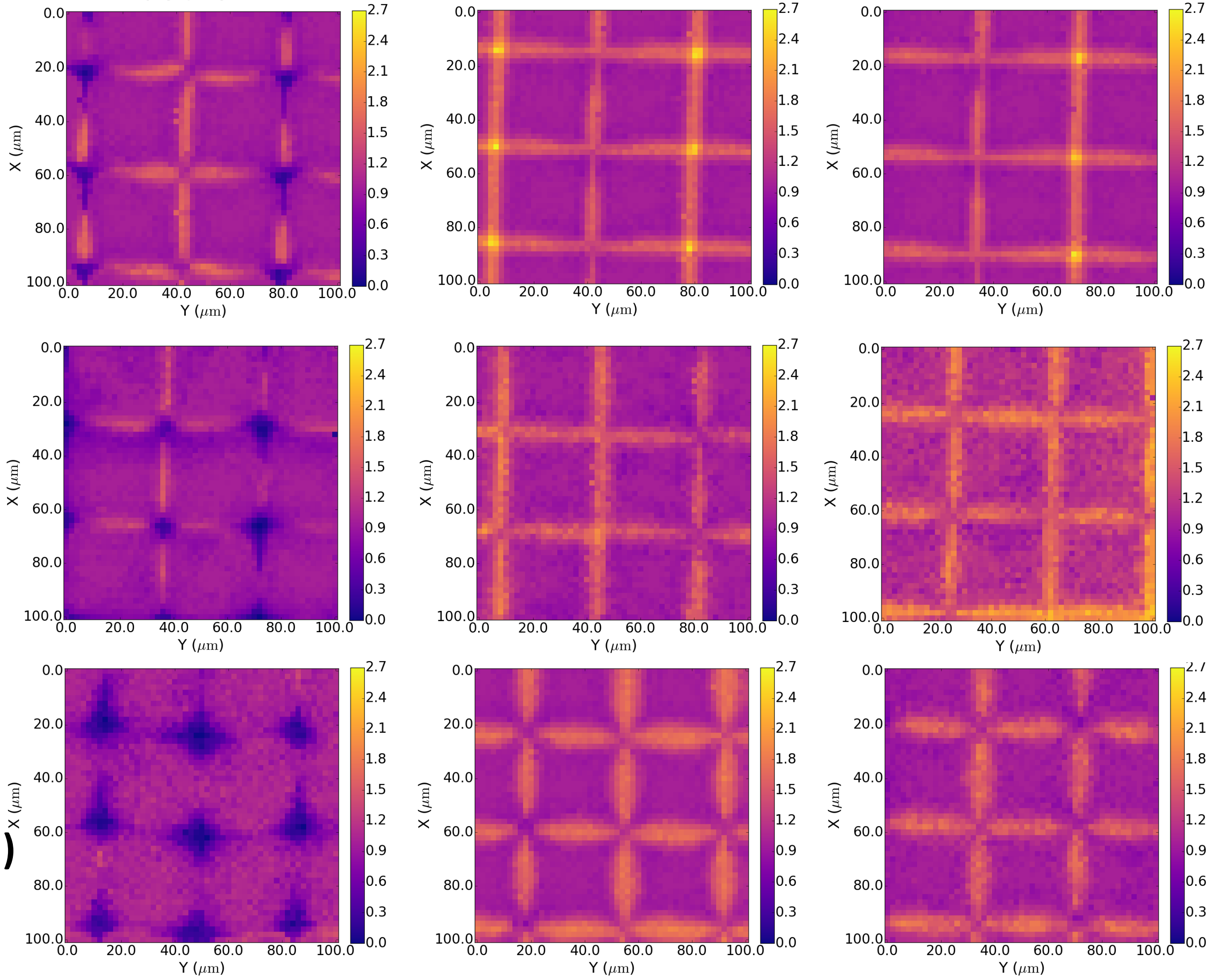
	MALTA sector	Deep p-well + enlarged transistor	n- gap + enlarged transistor
W2R11 unirradiated			
W2R9 5e14 n_{eq}/cm^2 66 Mrad (proton irrad)			
W2R1 1e15 n_{eq}/cm^2 (neutron irrad)			



- Occupancy plots from 8 keV photons
- Response in the periphery decreases w/ irradiation in the MALTA sector
- Re-designed sectors show improvement
- Charge sharing evolves with irradiation: pixels become “wider”
- Trends in integrated response match efficiency trends in ELSA
- Proton irradiated chips up to 5e14 neq/cm^2 and 70 Mrad have comparable response to 1e15 neq/cm^2 sensors
- More detailed results in Maria Mironova’s poster
- Can estimate MIP efficiency from results (see Maria Mironova’s poster)

photos

power adapter
Setup NIM crate
Hits per pixel : 1k
Fixed time
500 µs
stage Y
SPS