Testing pixel detectors with X-Rays

Measurements of the mini-MALTA prototype

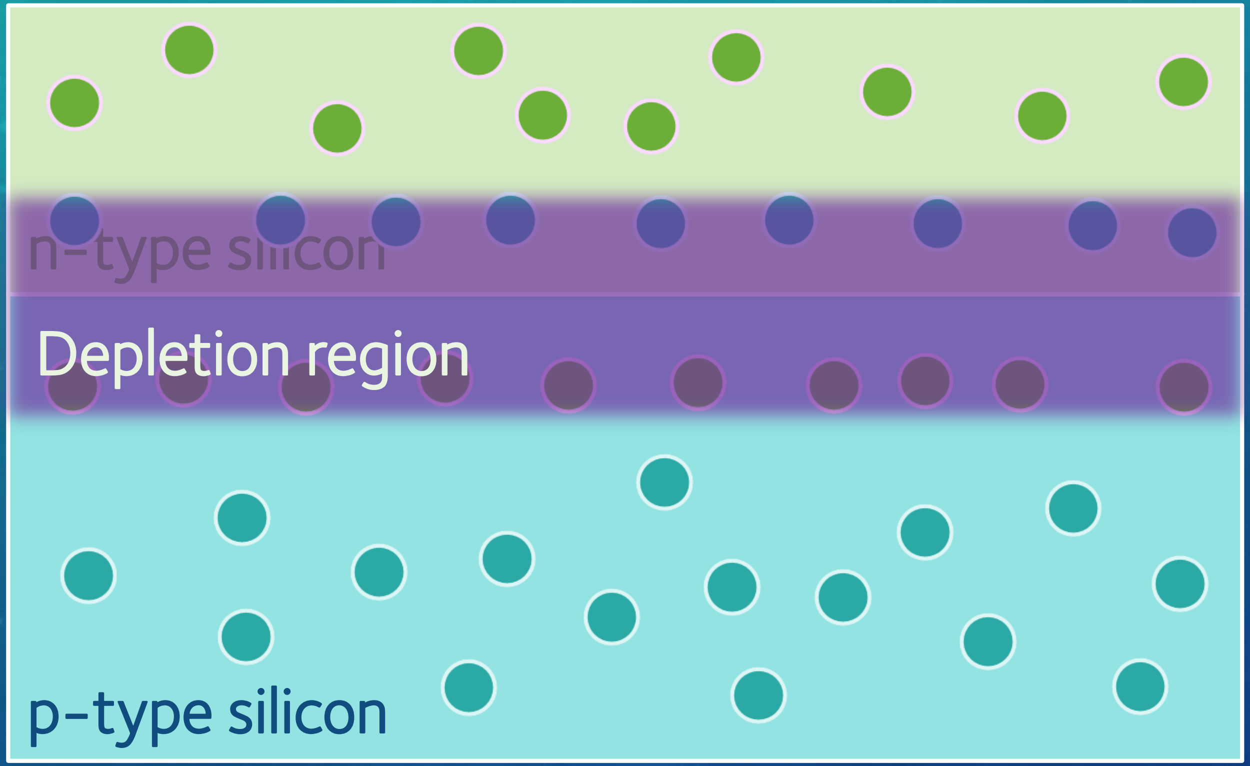
Kaloyan Metodiev

12/09/2019

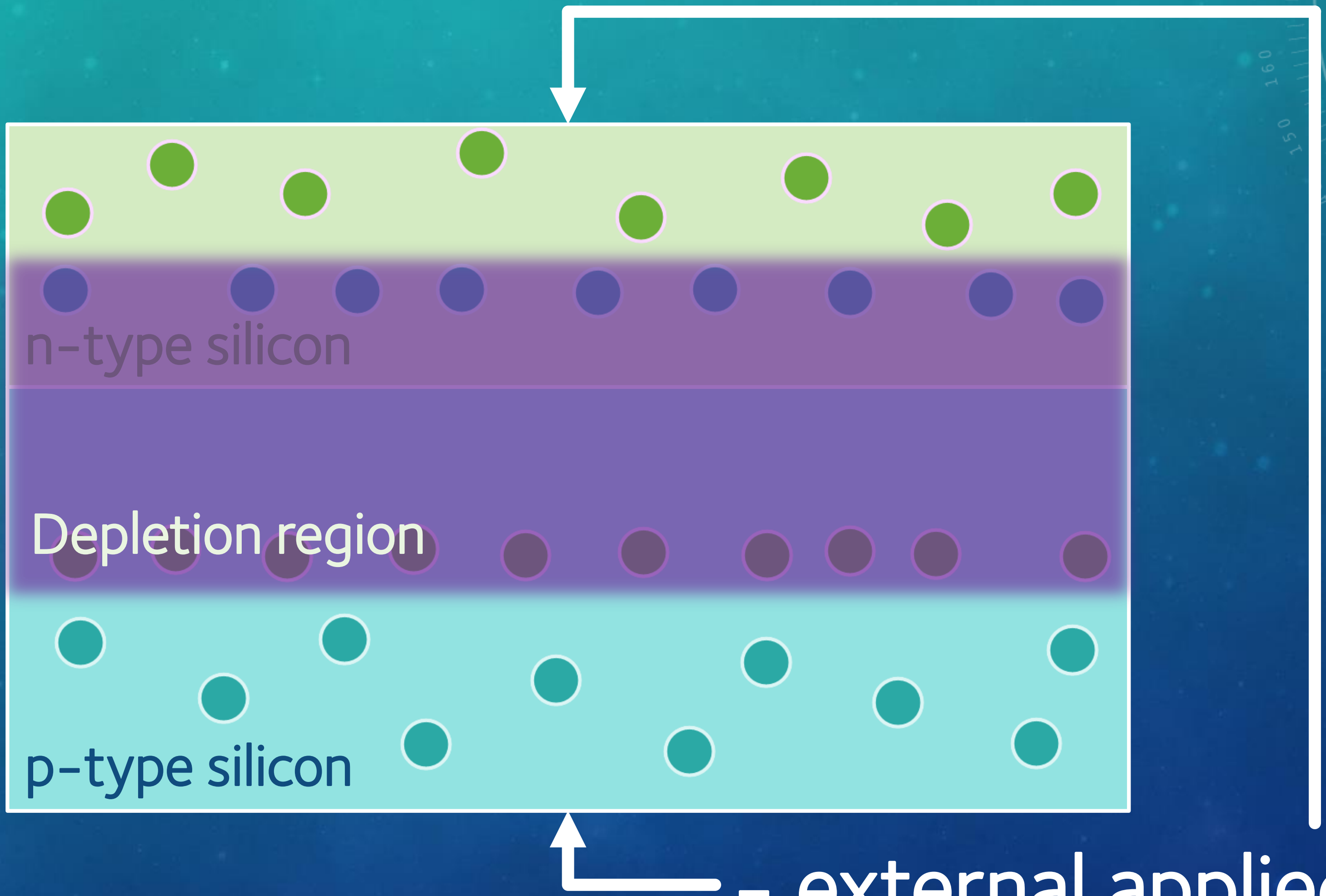
OUTLINE

- Overview of CMOS technology for ATLAS
- Part I: X-Ray testbeam at Diamond Light source
- Part II: New method for estimating detector efficiency for MIPs using Diamond Light Source

SILICON DETECTORS

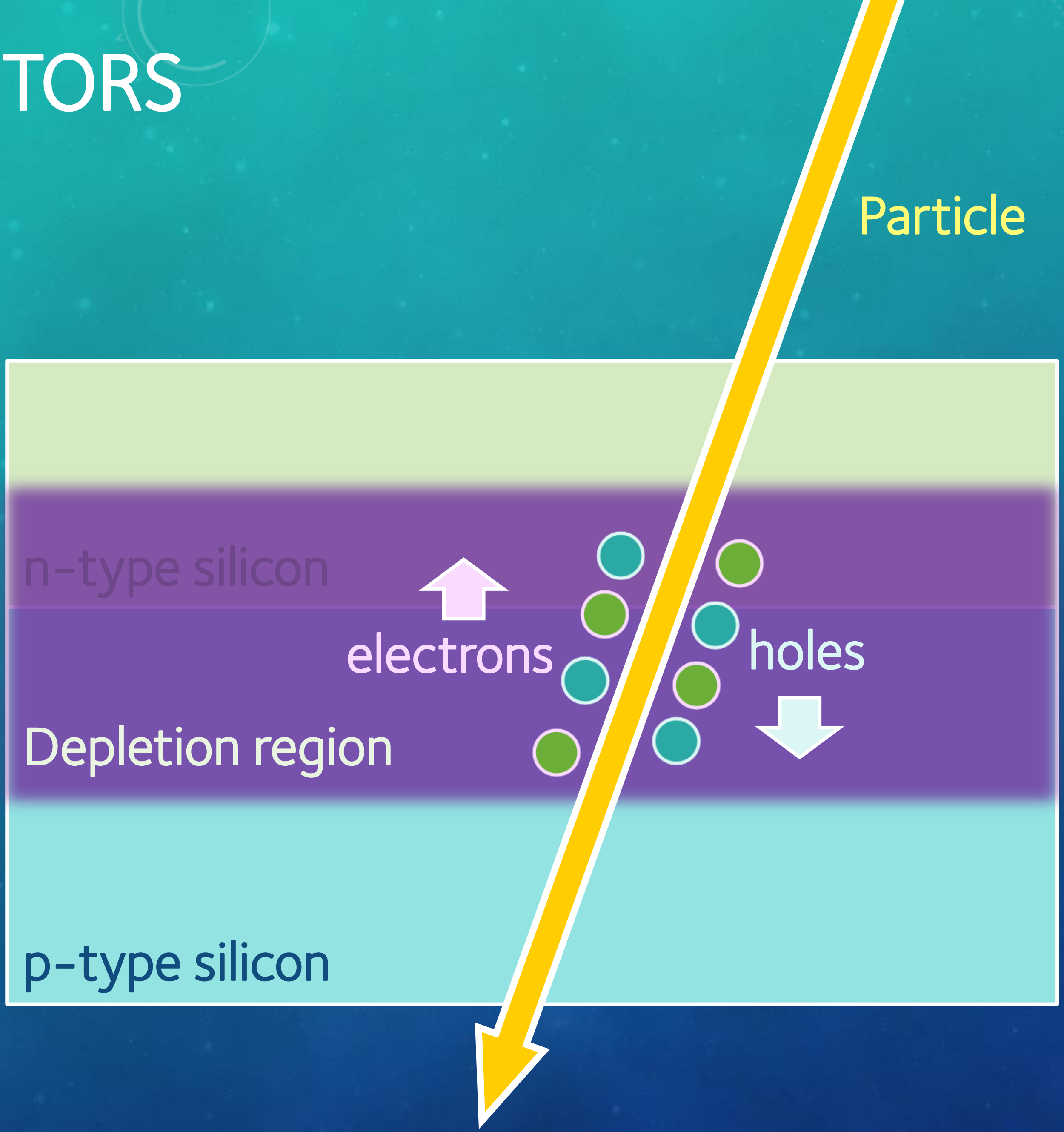


SILICON DETECTORS

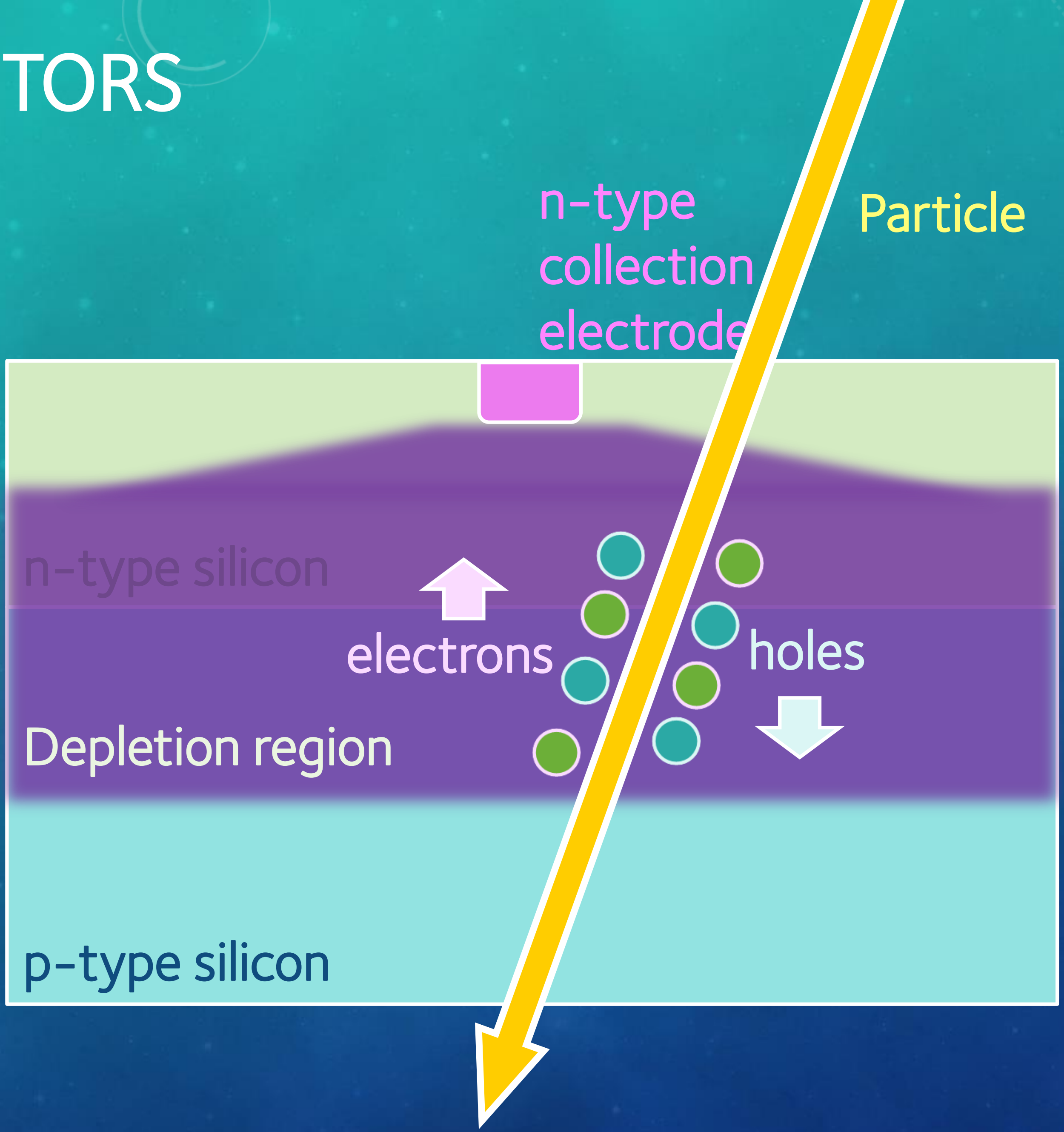


– external applied voltage

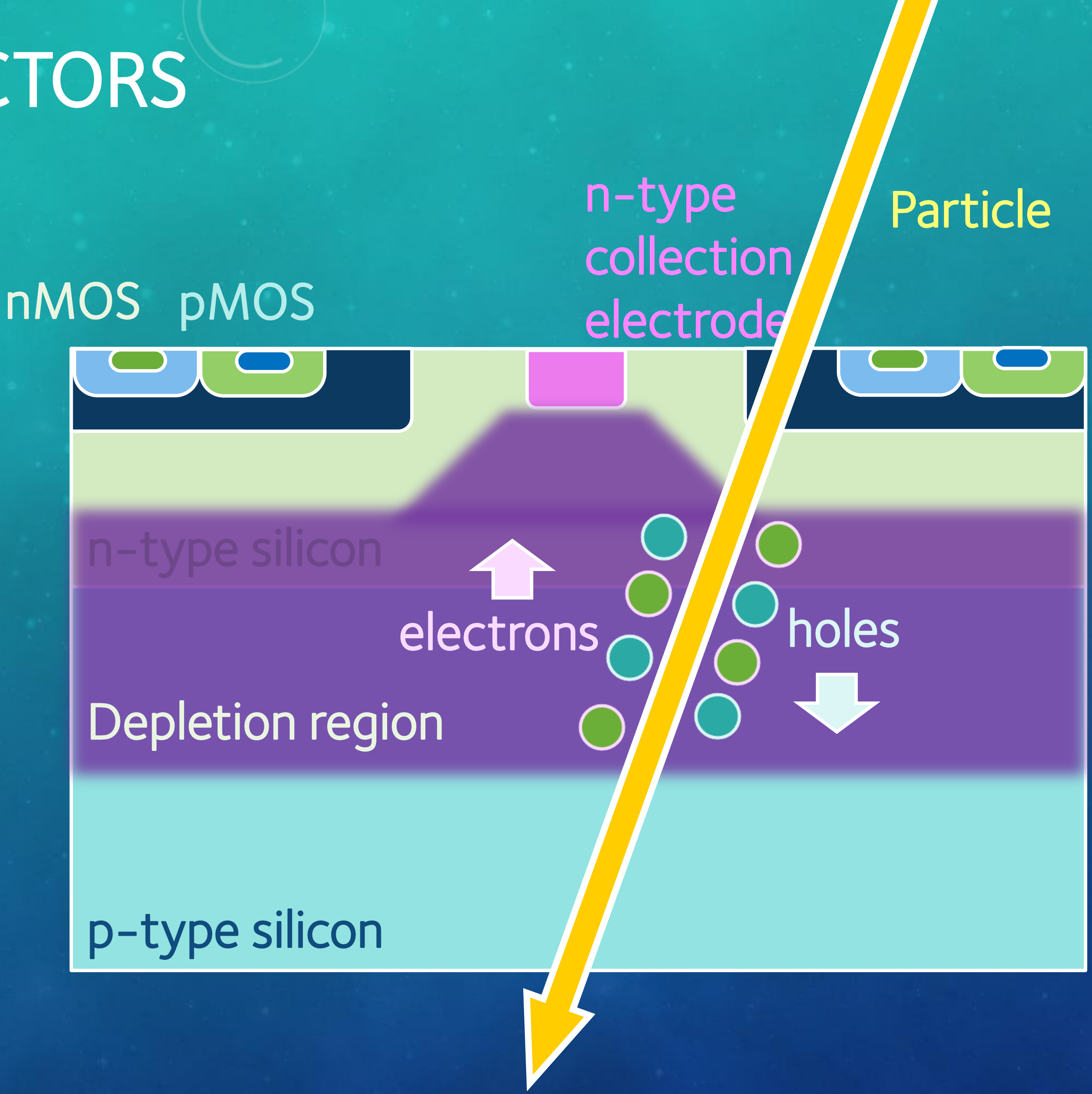
SILICON DETECTORS



SILICON DETECTORS

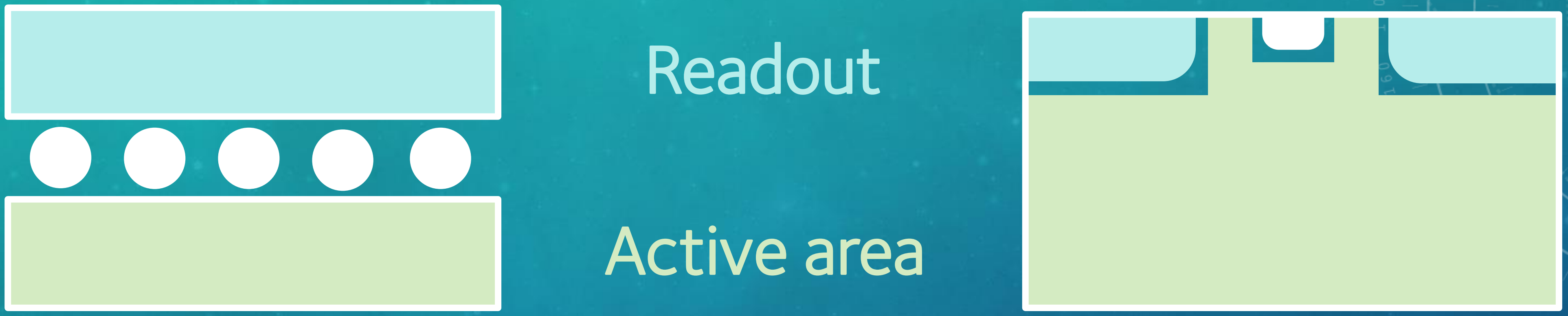


CMOS DETECTORS



Hybrid

CMOS



👍 Known technology (e.g in ATLAS)

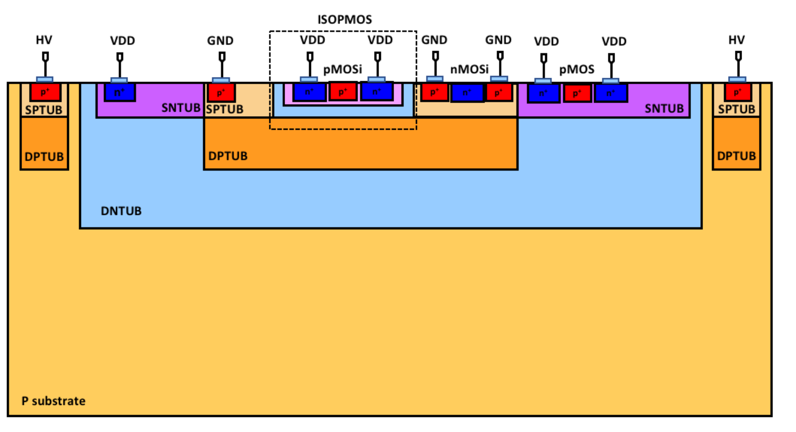
👎 Bump bonding is expensive

👍 Cheaper process

👎 Novel technology in HEP → R&D

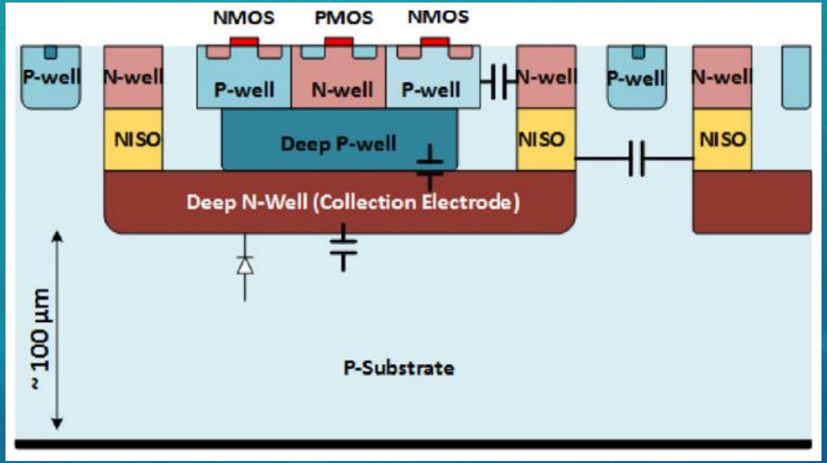
CMOS EFFORT FOR ATLAS

AMS



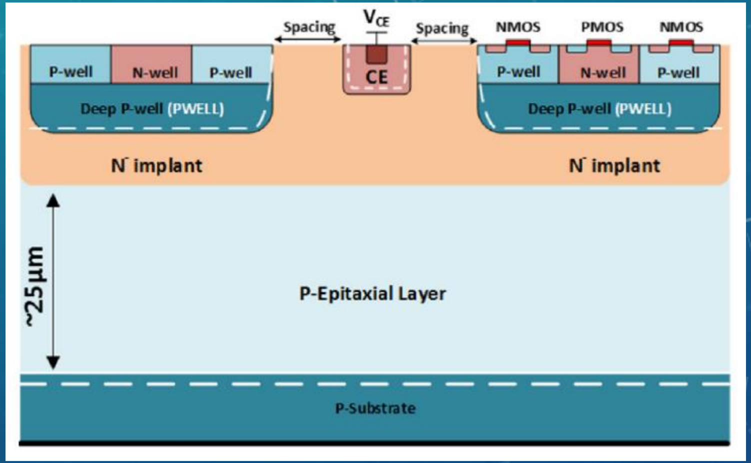
- AtlasPix
- H35Demo
- H18
- CCPDv(1-4)

LFoundry



- LF Monopix
- CPIX
- CCPD_LF

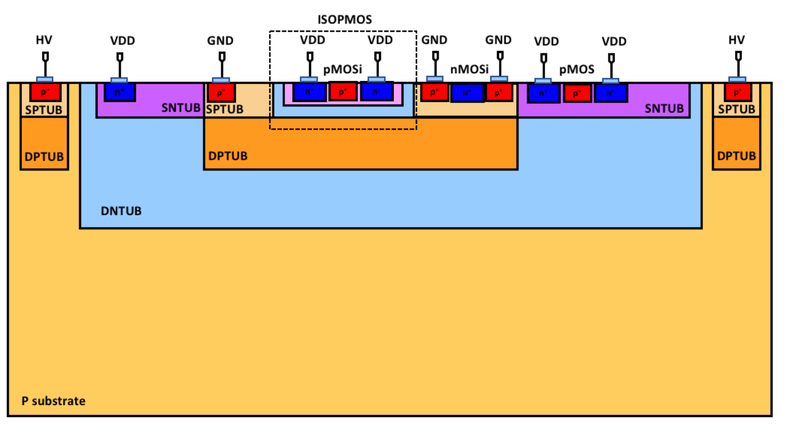
TowerJazz



- Mini-MALTA
- MALTA
- TJ Monopix
- Investigator (1-2)

CMOS EFFORT FOR ATLAS

AMS



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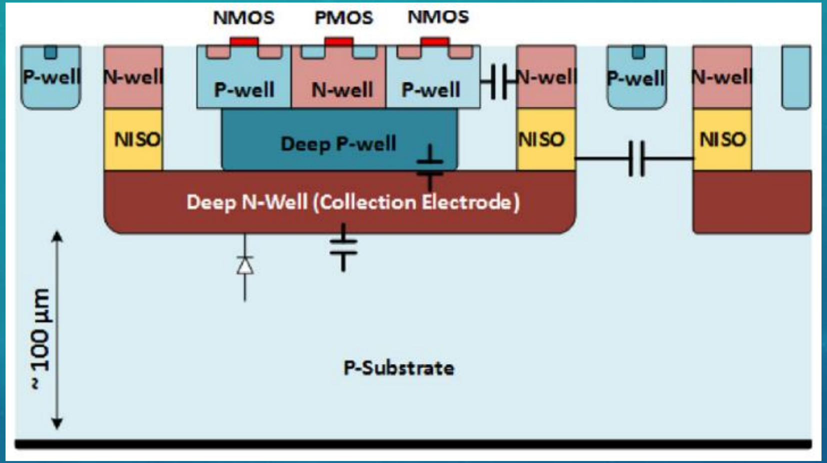
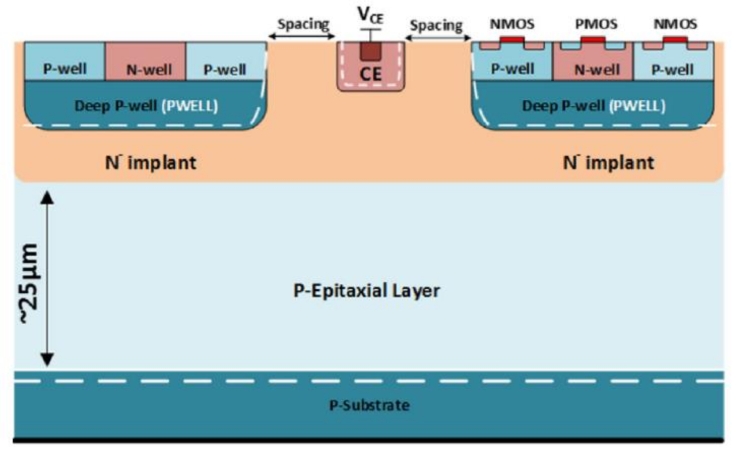


- LF Monopix
- CPIX
- CCPD_LF

TowerJazz

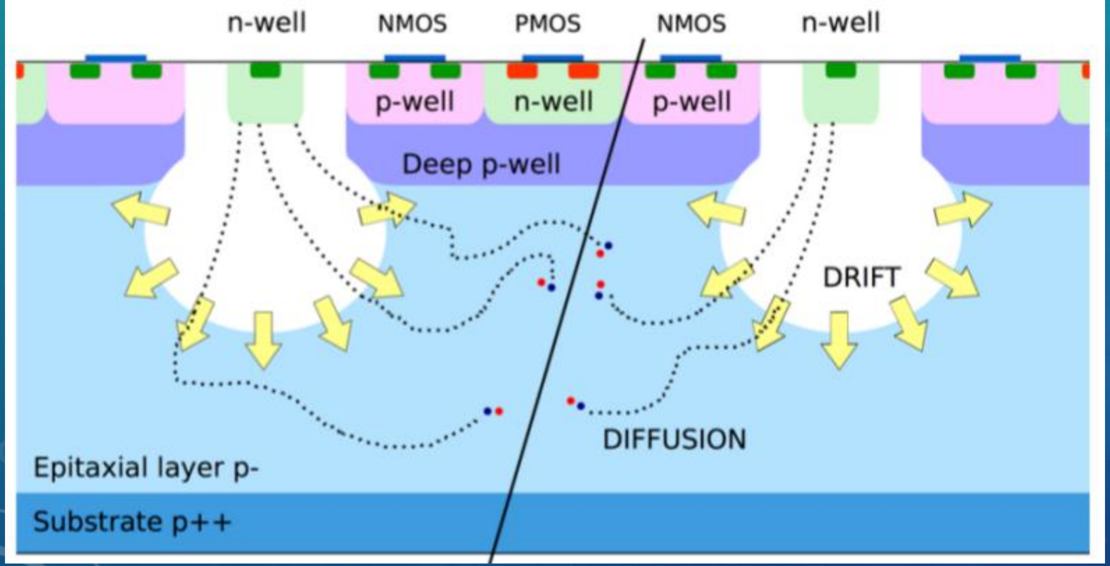


- Mini-MALTA
- MALTA
- TJ Monopix
- Investigator (1-2)

HISTORY

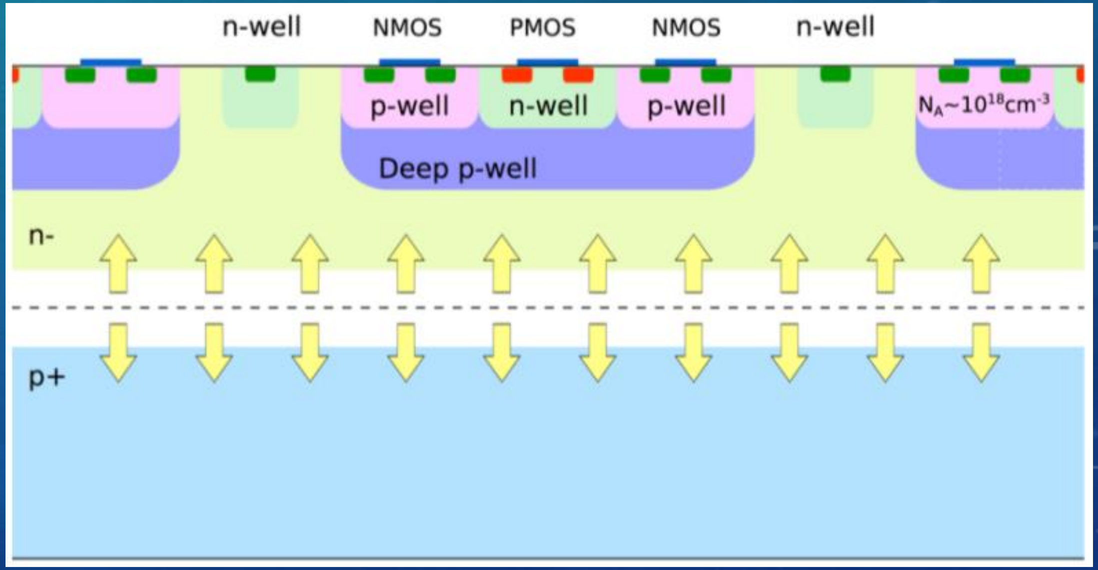
INVESTIGATOR 0

- Radiation hardness: 10^{13} 1 MeV n_{eq} /cm^2
- Using standard TowerJazz 180nm process
- Evolved into ALPIDE for ALICE ITS



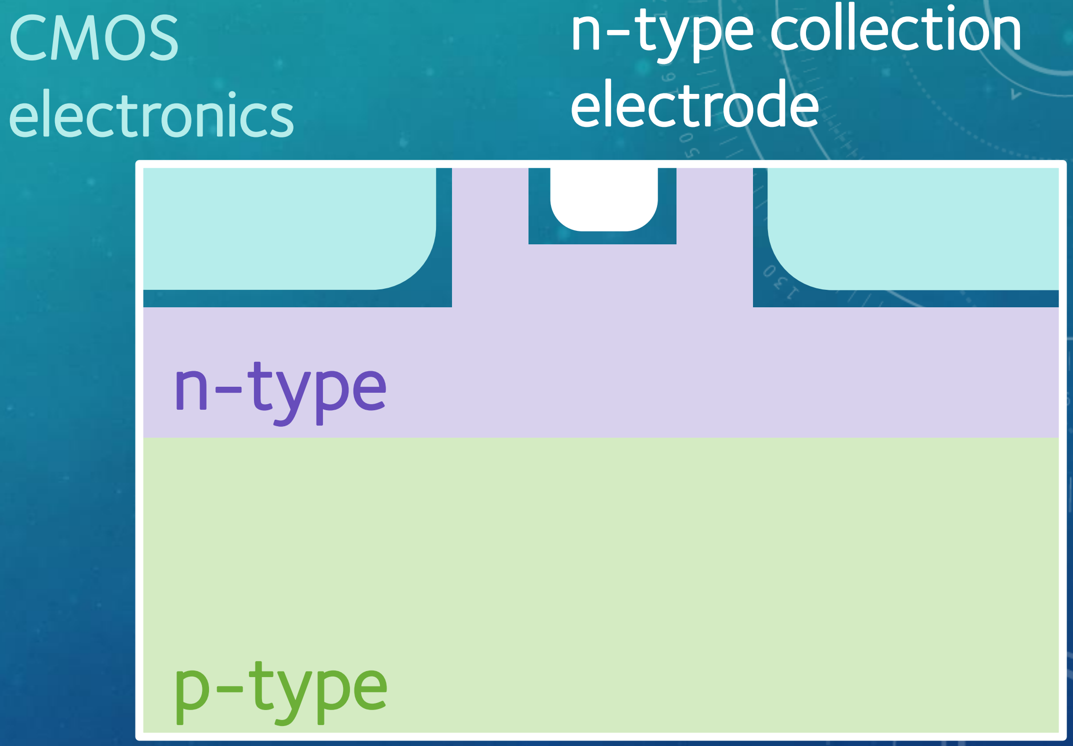
INVESTIGATOR 1

- Radiation hardness: 10^{15} 1 MeV n_{eq} /cm^2
- Using modified TowerJazz 180nm process
- Modified design allows full depletion of the epitaxial layer



HISTORY

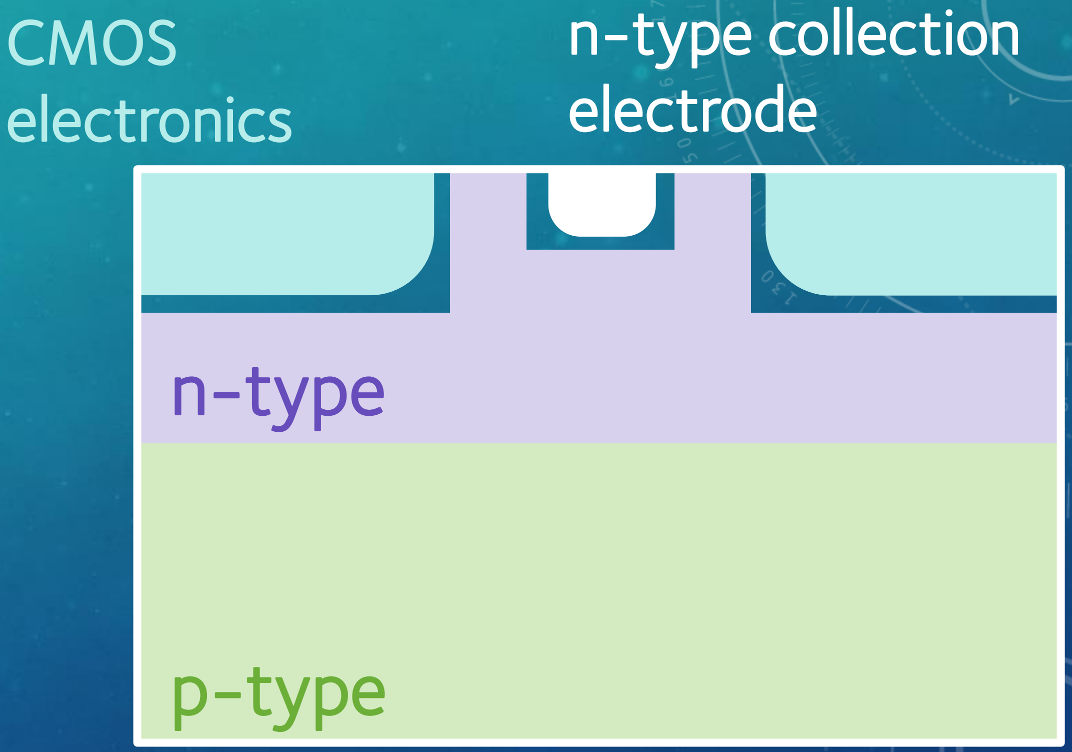
- Minimal readout electronics on chip
- Many different combinations of chip parameters, such as:
  - Pixel pitch
  - Collection diode size
  - Transistor size and position
  - Reset circuit type
- Evolved to MALTA / TJ-Monopix (different front-ends)



Investigator Series

HISTORY

- *MALTA* chip
  - Full sized demonstrator
  - 2x2 cm^2
  - 36.4 x 36.4 μm^2 pixel pitch
  - Asynchronous readout for high hit rates

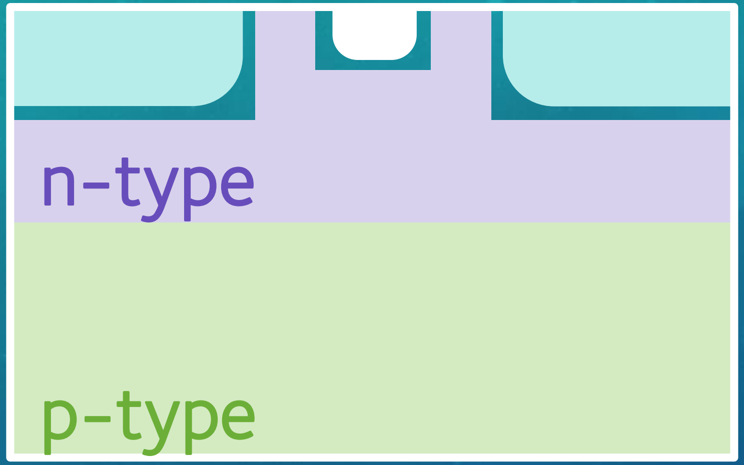


Standard MALTA design

HISTORY

Mini-MALTA: 3 regions

MALTA



P-WELL

Extra-deep p-well

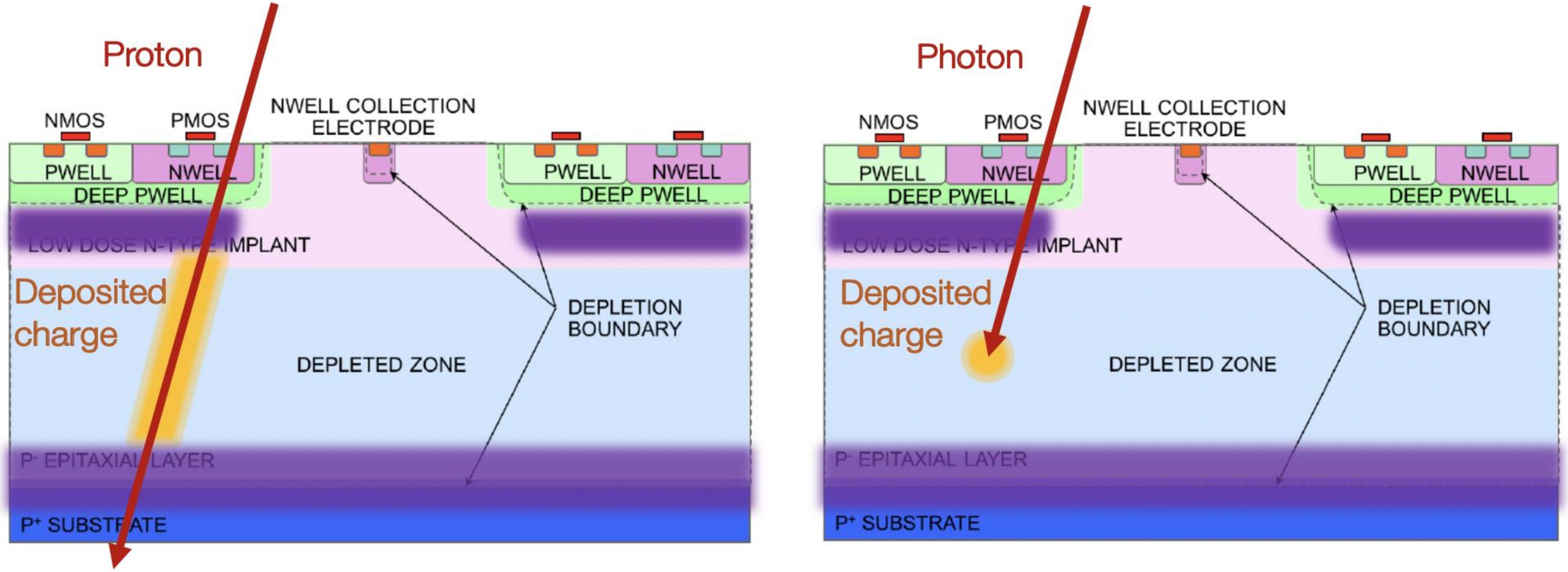
N-GAP

Gap in n-layer

Part I: X-Ray Testbeam at Diamond Light Source

MIP TESTBEAM VS X-RAY TESTBEAM

	MIP testbeam	X-ray testbeam
Energy deposition	MIP leaves track of e/h pairs	e/h pairs produced in one location



MIP TESTBEAM VS X-RAY TESTBEAM

	MIP testbeam	X-ray testbeam
Energy deposition	MIP leaves track of e/h pairs	e/h pairs produced in one location
Beam	Can see single particle tracks in telescope planes	Only approx. 30% of photons stop in the active silicon (for our setup)

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Position reconstruction	Reconstructed form clustering & tracks	Move device wrt small beam spot (2 μm)

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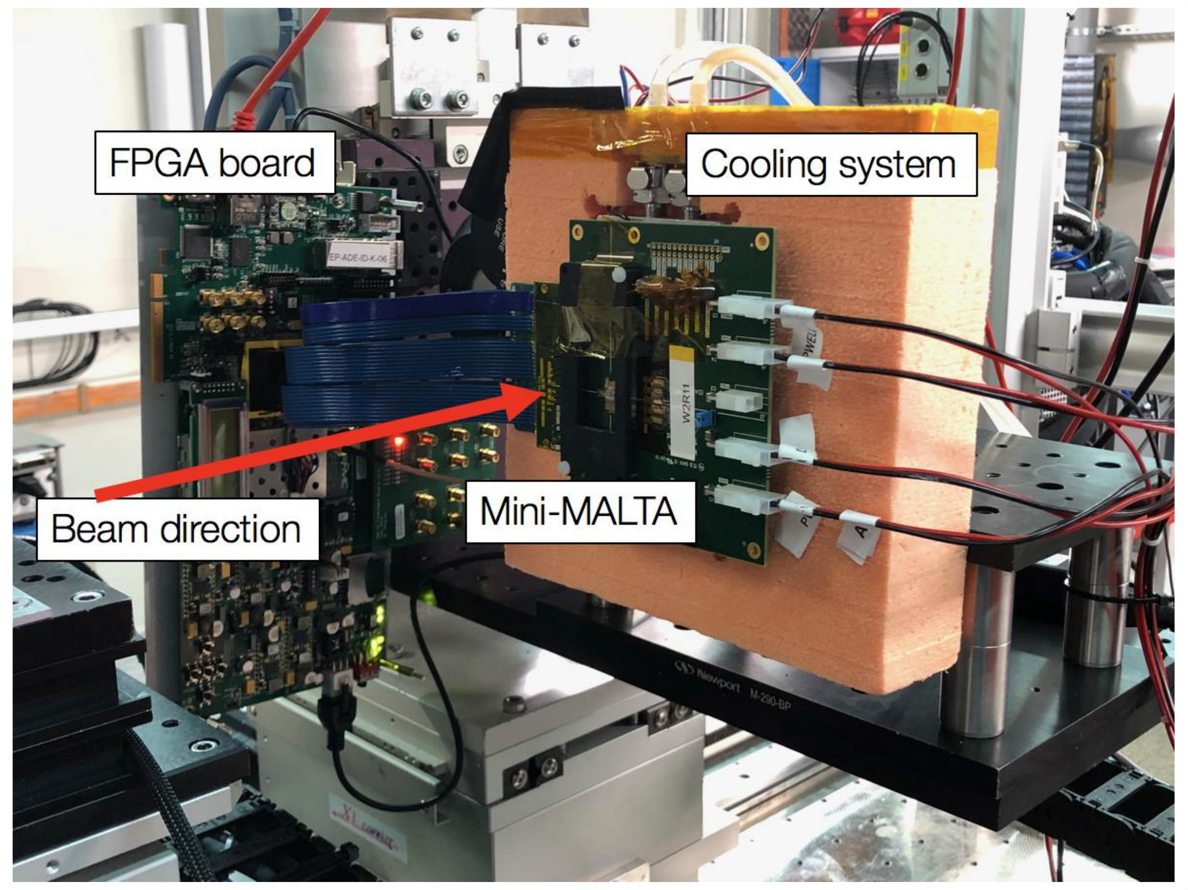
Beam	Can see single particle tracks in telescope planes	Only approx. 30% of photons stop in silicon
Position reconstruction	Reconstructed form clustering & tracks	Move device wrt small beam spot (2 μm)
Sensitivity	Absolute efficiency wrt telescope planes	High resolution images of pixels → response to photons

SETUP

- B16 beamline at Diamond Light Source
- X-ray beam:
  - Energy: 8 keV
  - Beam spot: 2 µm
- Setup on motion stage:
  - Raster scan
  - Step size: 2 µm



QUESTION 1:
HOW DOES RESPONSE CHANGE WITH IRRADIATION?

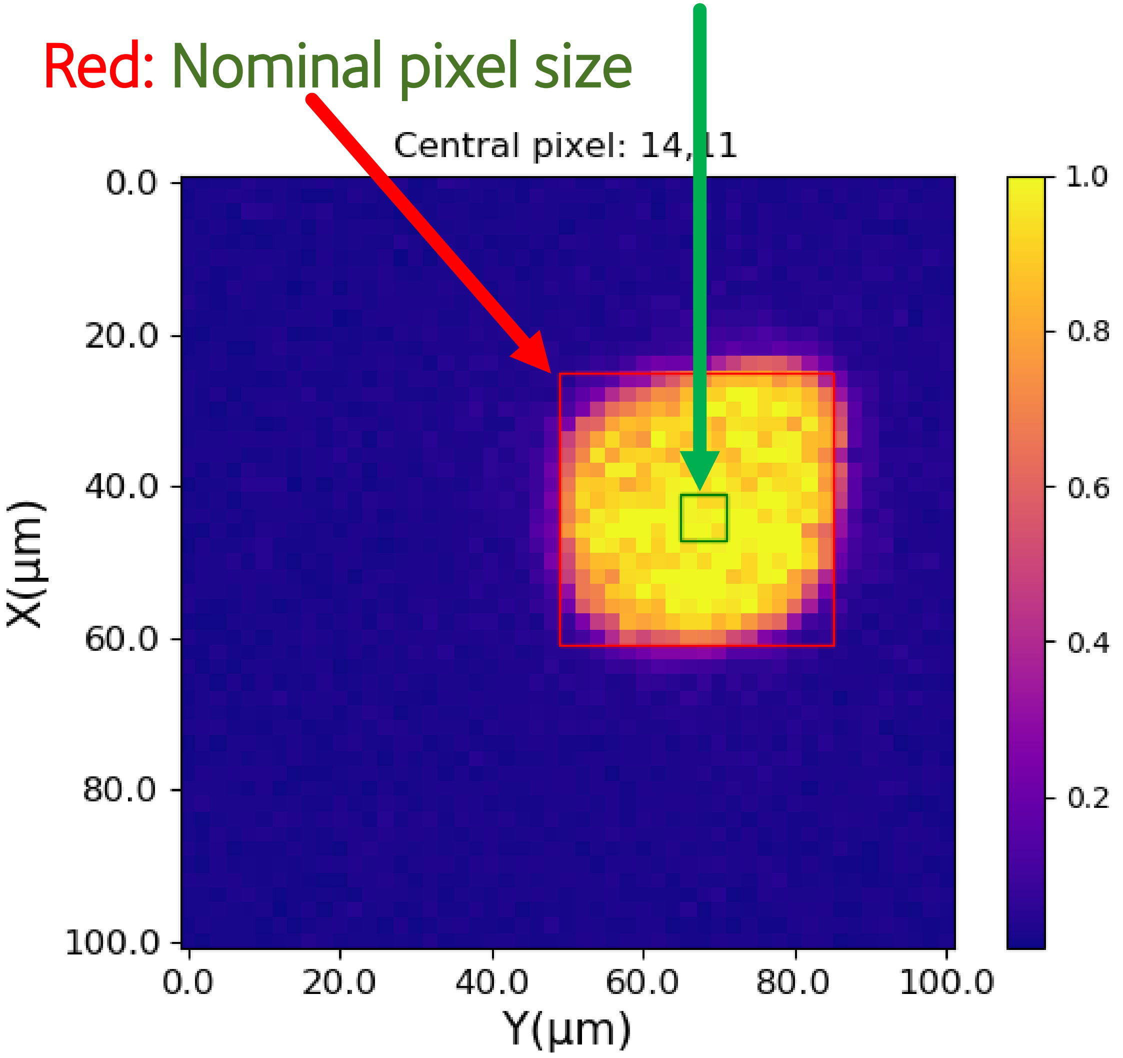
ANALYSIS

- Plot hits for one pixel
- Find pixel centre
- Normalisation
- Error estimation
- Average over pixel area

→ Relative photon response

Green: Normalisation area

Red: Nominal pixel size



Hit map for single pixel

PIXEL RESPONSE

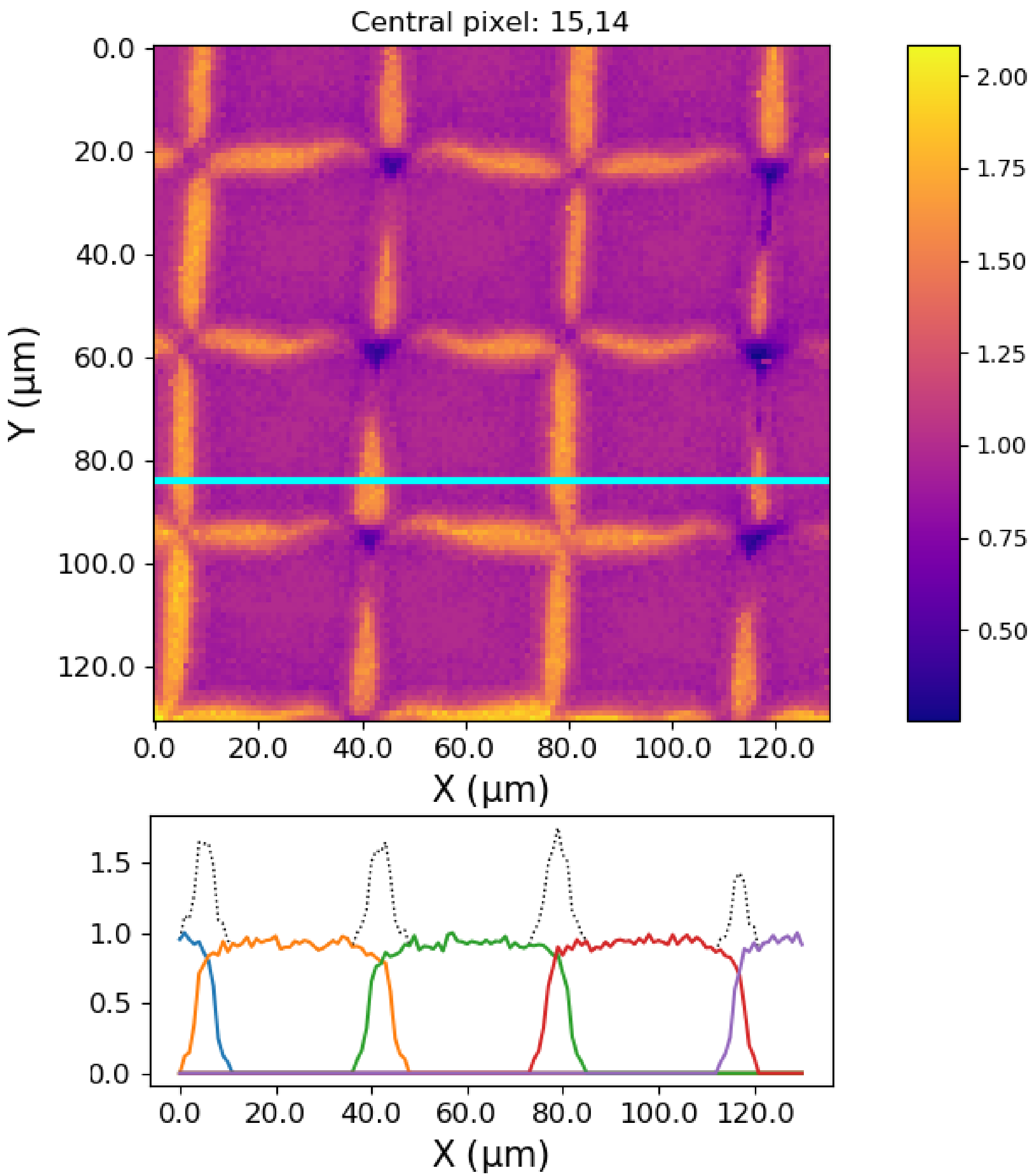
Sample	Radiation	MALTA response (%)	P-well response (%)	N-gap response (%)
W2R11	0	89.3 ± 2.4	91.2 ± 2.2	91.6 ± 2.2
W2R9	5e14 (p)	82.8 ± 2.8	87.6 ± 4.2	89.0 ± 3.8
W2R1	1e15 (n)	76.7 ± 3.8	91.1 ± 2.8	90.0 ± 3.1
W5R9	5e14 (p)	81.5 ± 2.8	89.8 ± 2.5	89.9 ± 2.2
W4R9	7e13 (p)	79.6 ± 2.6	90.5 ± 2.3	90.8 ± 2.3

Decrease with irradiation for MALTA

Increase in response for new designs

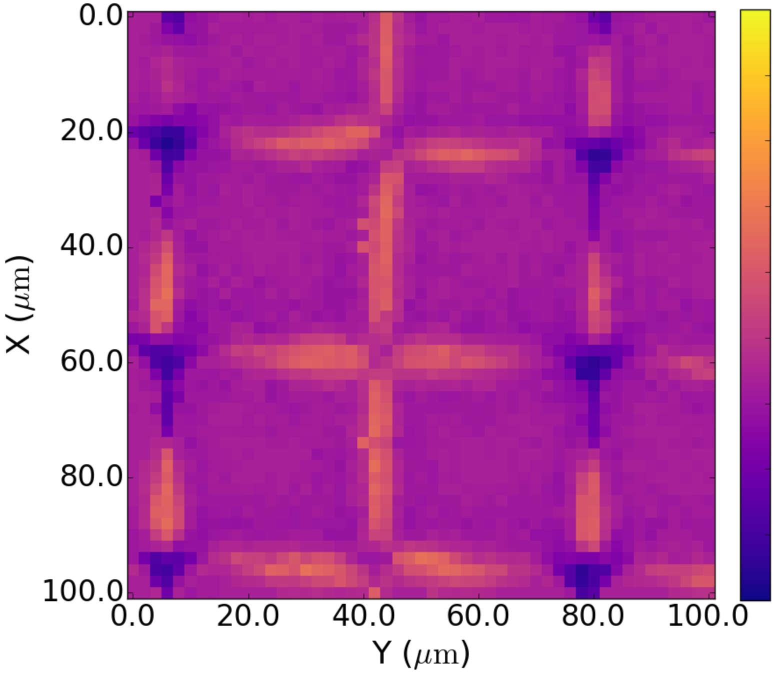
PIXEL MAPS

- Plotting results for multiple pixels
- Sum efficiency maps
- Pixel profile
- Charge sharing
    - Charge collected by two pixels
    - >100% response



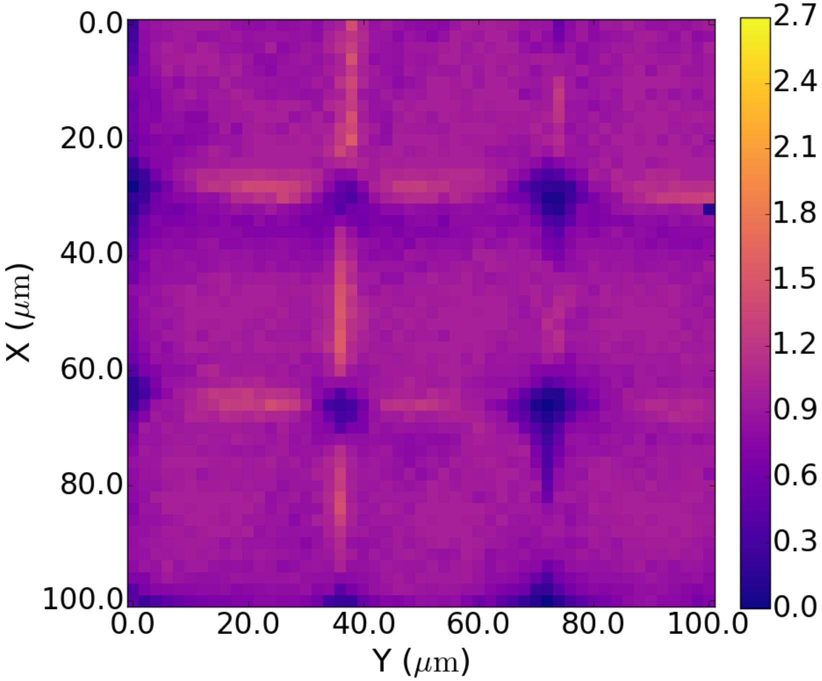
RESULTS: MALTA

unirradiated



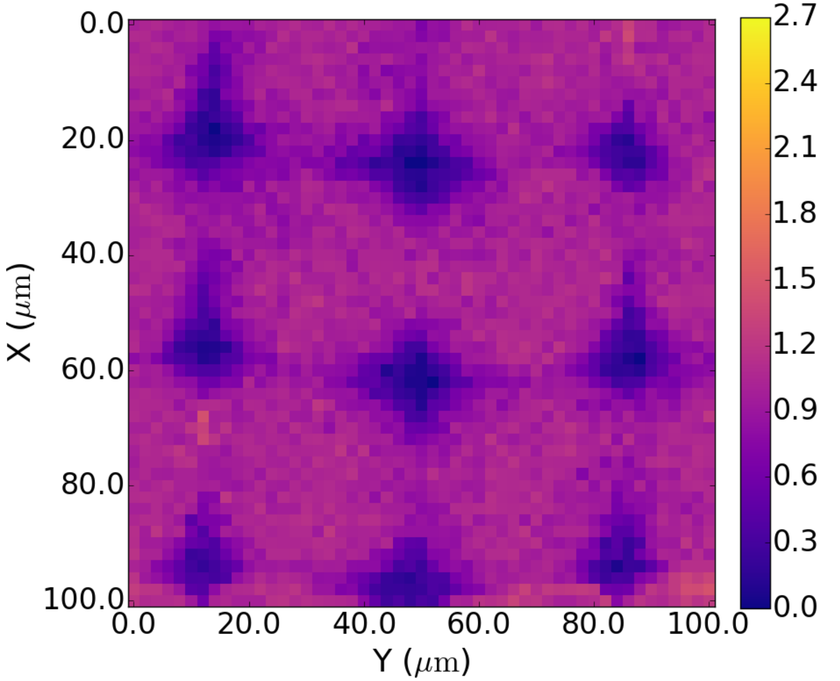
(89 ± 3) %

$5x10^{14}$ n/cm^2



(82 ± 3) %

$1x10^{15}$ n/cm^2

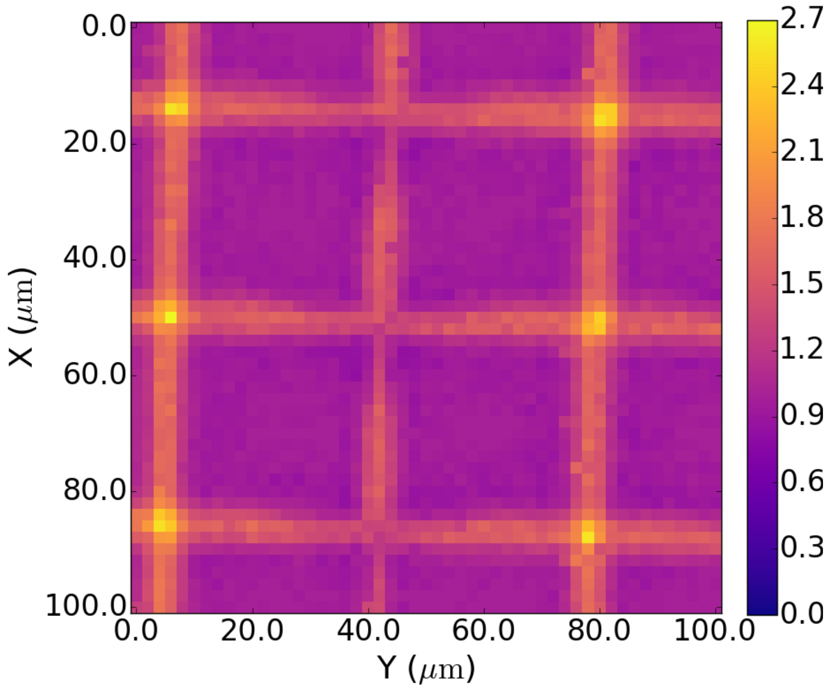


(77 ± 4) %

Decrease in response

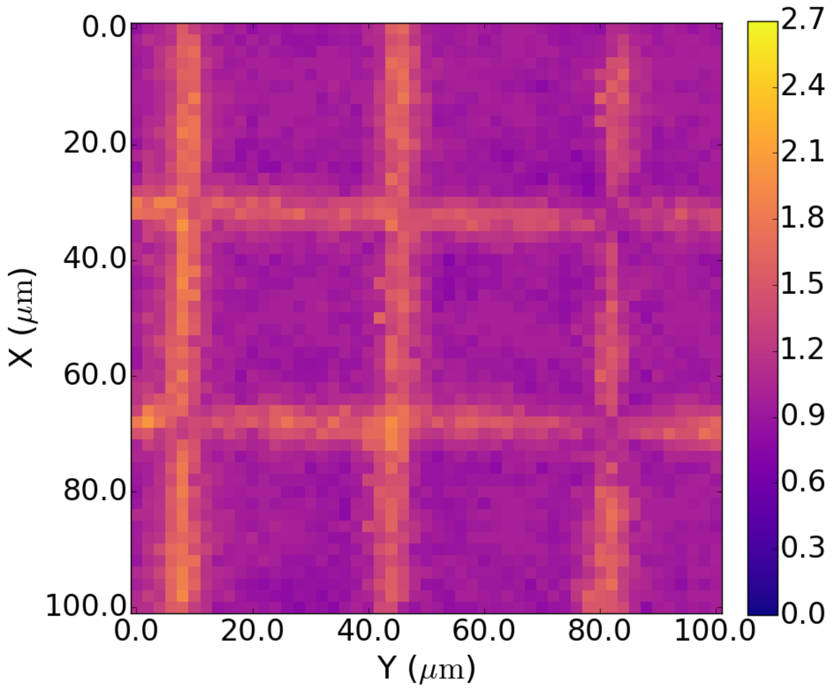
RESULTS: P-WELL

unirradiated



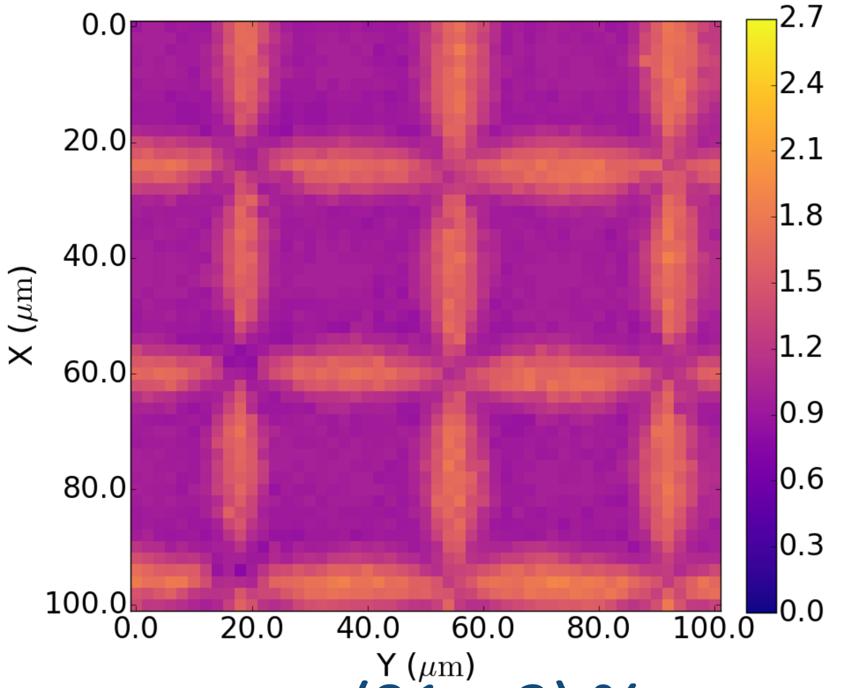
(91 ± 2) %

$5x10^{14}$ n/cm^2



(88 ± 4) %

$1x10^{15}$ n/cm^2

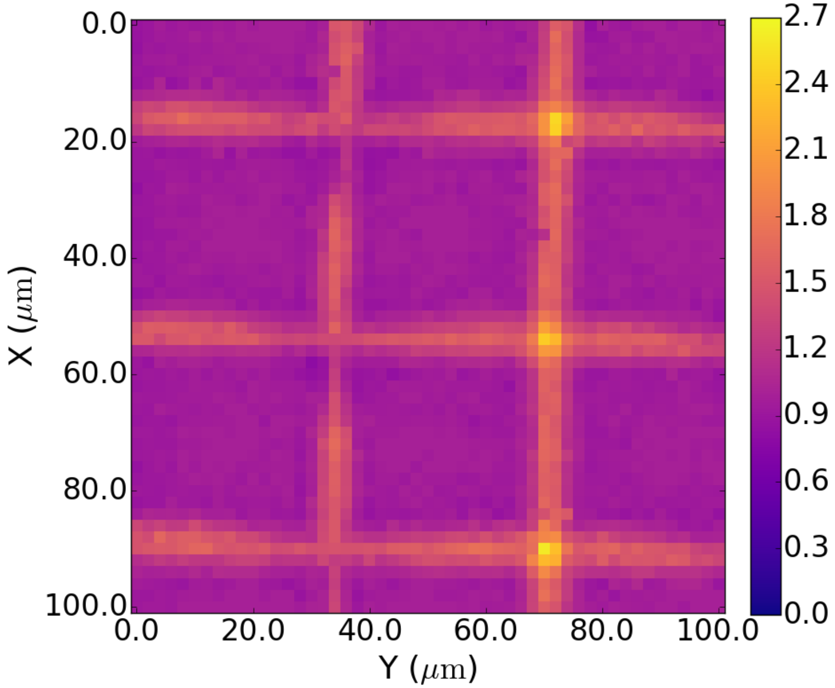


(91 ± 3) %

No change in response

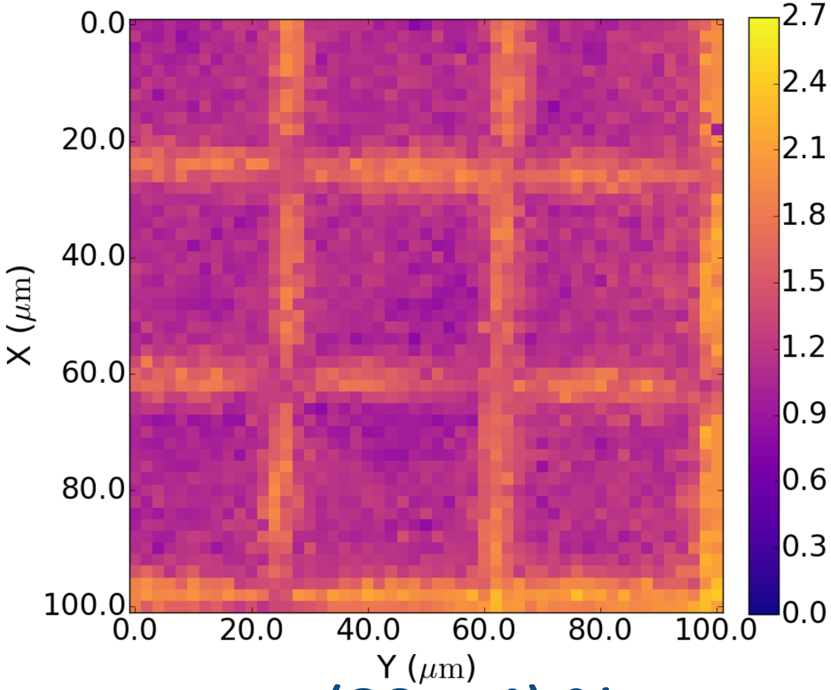
RESULTS: N-GAP

unirradiated



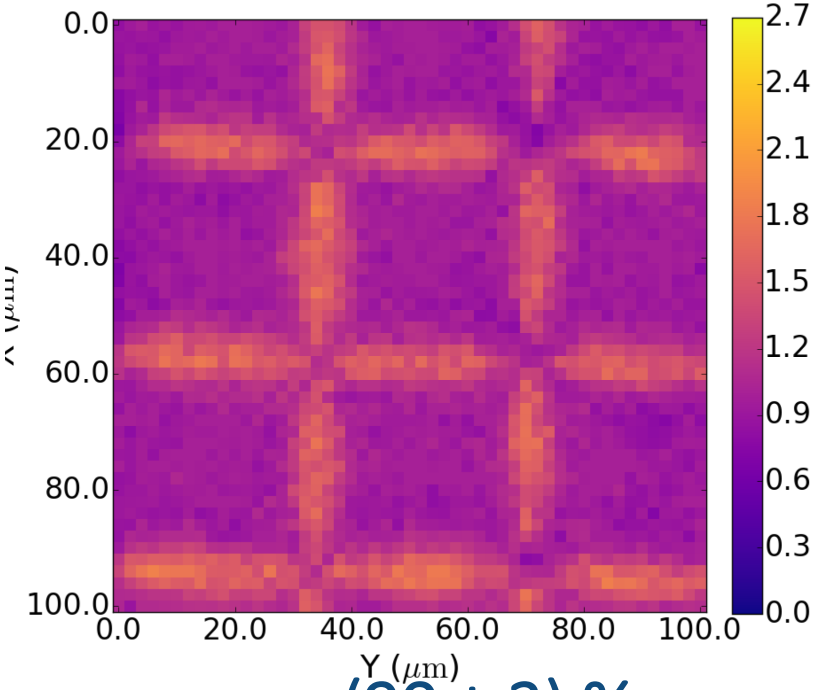
(92 ± 2) %

$5x10^{14}$ n/cm^{2}



(89 ± 4) %

$1x10^{15}$ n/cm^{2}



(90 ± 3) %

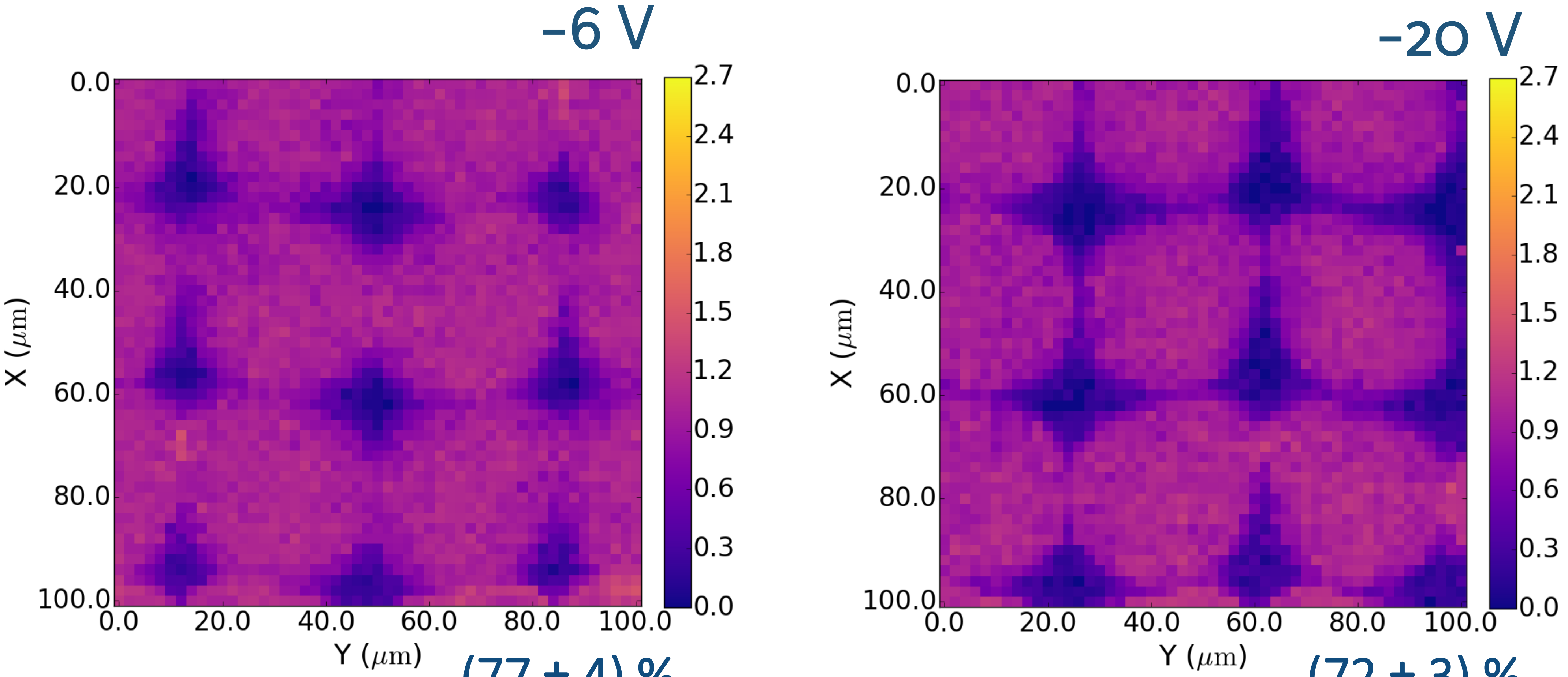
No change in response

QUESTION 1:
HOW DOES RESPONSE CHANGE WITH IRRADIATION?

- Decrease in response with irradiation on MALTA
- P-well and n-gap designs perform better
- No decrease in response with irradiation for p-well and n-gap

QUESTION 2:
HOW DOES RESPONSE CHANGE WITH BIASING VOLTAGE?

DIFFERENT VOLTAGE – MALTA



(77 ± 4) %

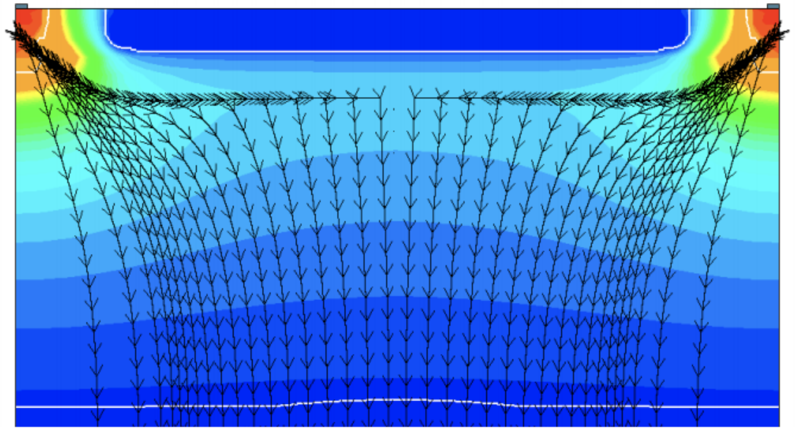
(72 ± 3) %

Higher backside voltage - modified process

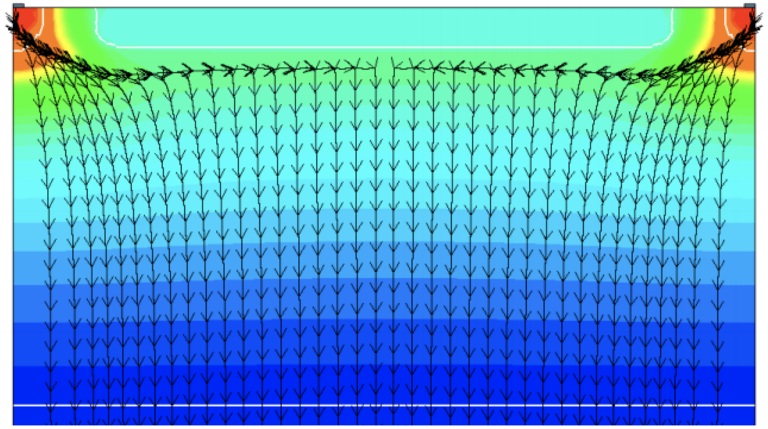
Magdalena Munker, Pixel 2018

Electrostatic potential:

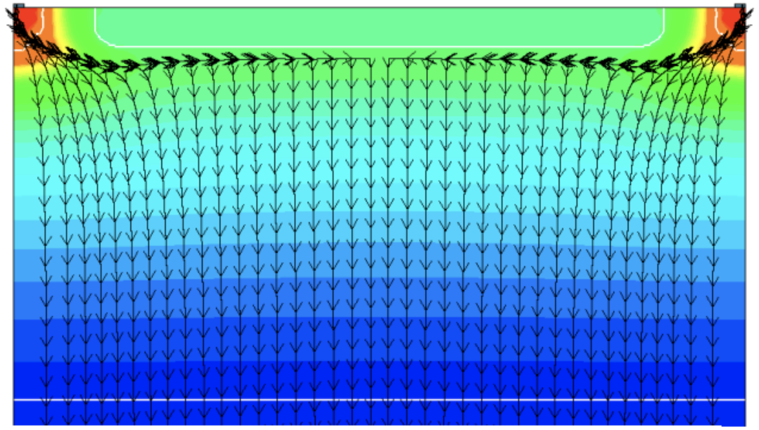
Backside voltage - 6 V:



Backside voltage - 15 V:



Backside voltage - 20 V:



Two different effects:

1. Higher backside voltage results in smaller potential variations along lateral pixel dimension:

—> Electric field lines less bend towards collection electrode —> longer drift path

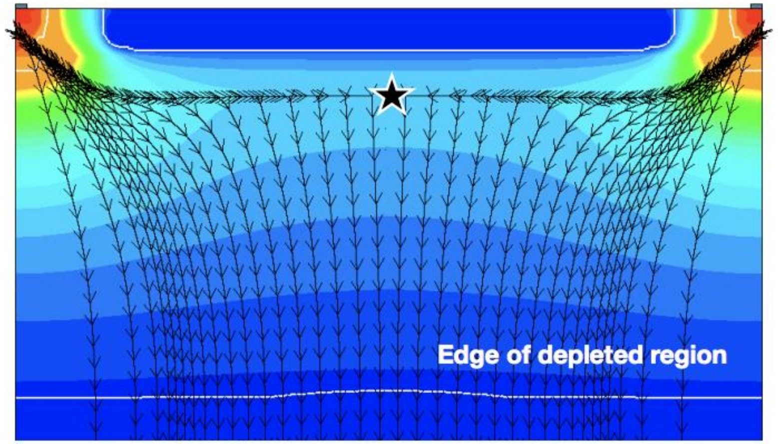
2. Higher backside voltage results in larger potential variations along sensor depth:

—> Enhanced electric field and faster drift along sensor depth

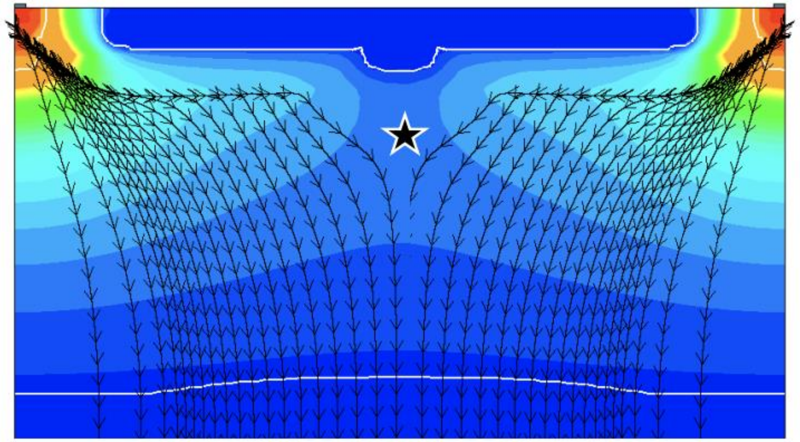
Electrostatic potential and drift path

Magdalena Munker, Pixel 2018

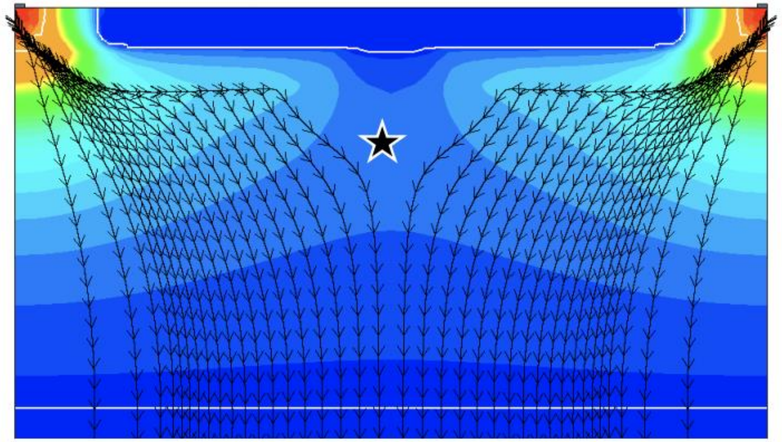
Modified process:



Modified process with additional p-implant:



Modified process with gap in n-layer:

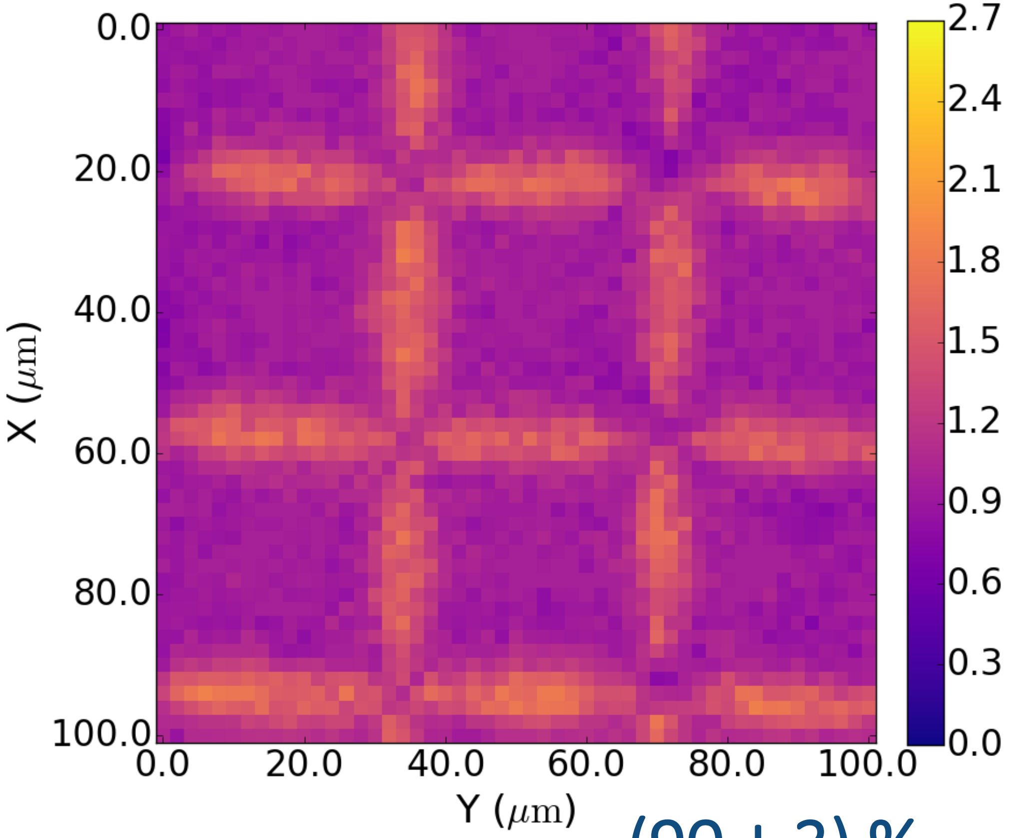


—> Constant potential at pixel border results in electric field minimum (★)

—> Additional implant & gap in n-layer create larger potential difference in lateral pixel dimension

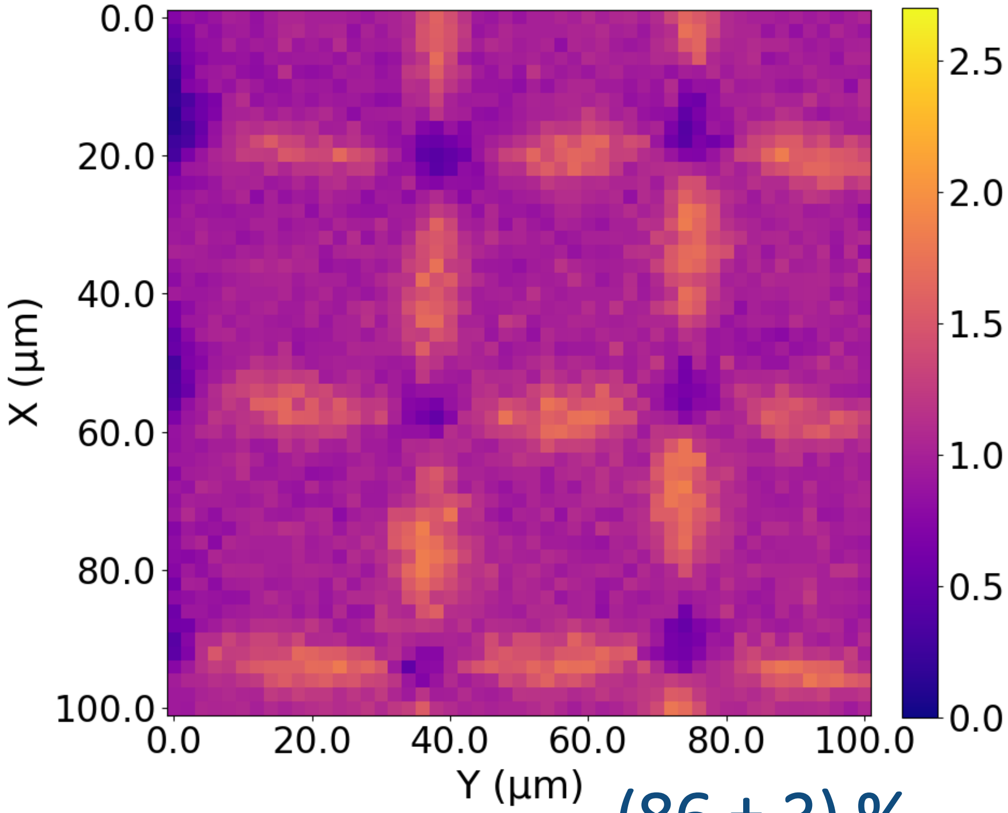
DIFFERENT VOLTAGE – NGAP

–6 V



(90 ± 3) %

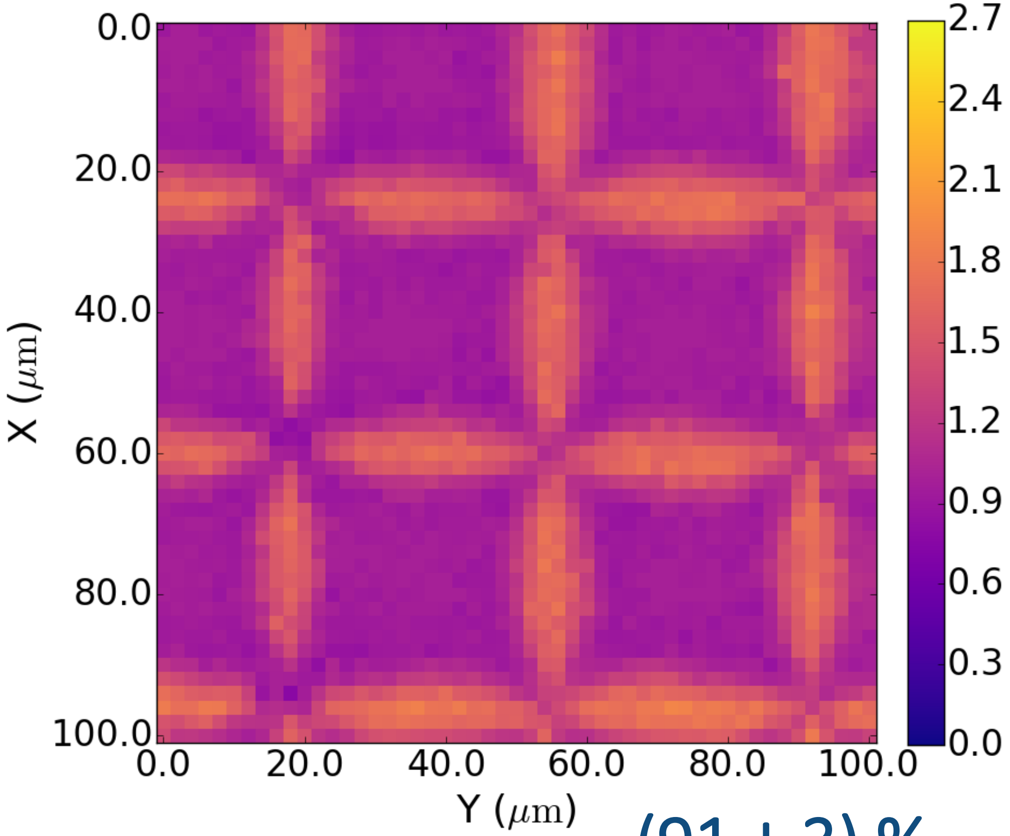
–20 V



(86 ± 3) %

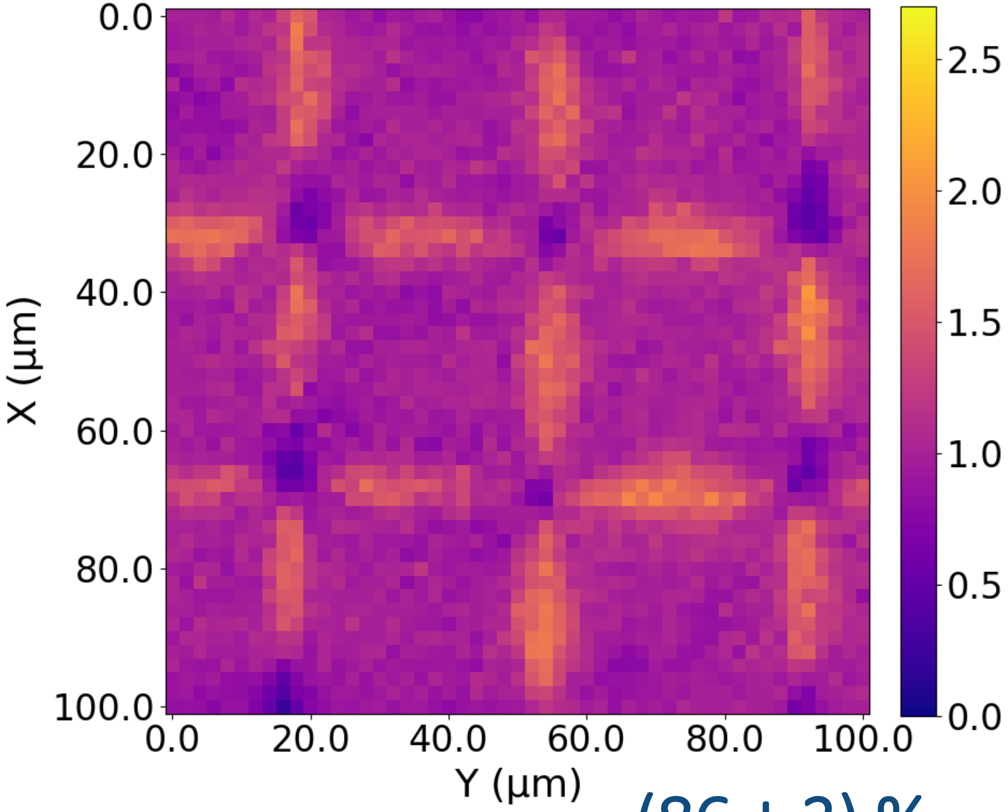
DIFFERENT VOLTAGE – PWELL

−6 V



(91 ± 3) %

−20 V



(86 ± 3) %

QUESTION 2:
HOW DOES RESPONSE CHANGE WITH BIASING VOLTAGE?

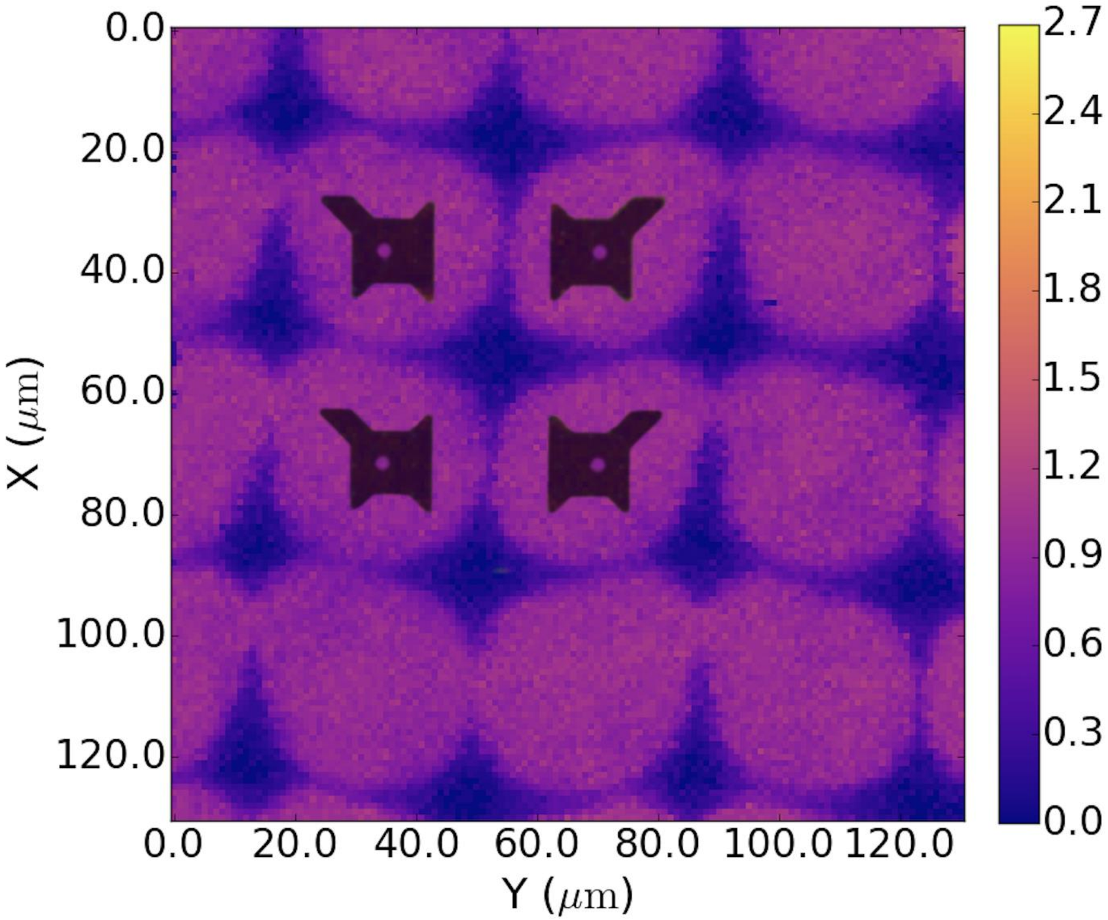
- Decrease in response with increased biasing voltage
- For all three designs
- Pixel edges seem sharper

QUESTION 3:

WHAT IS THE PIXEL SHAPE?

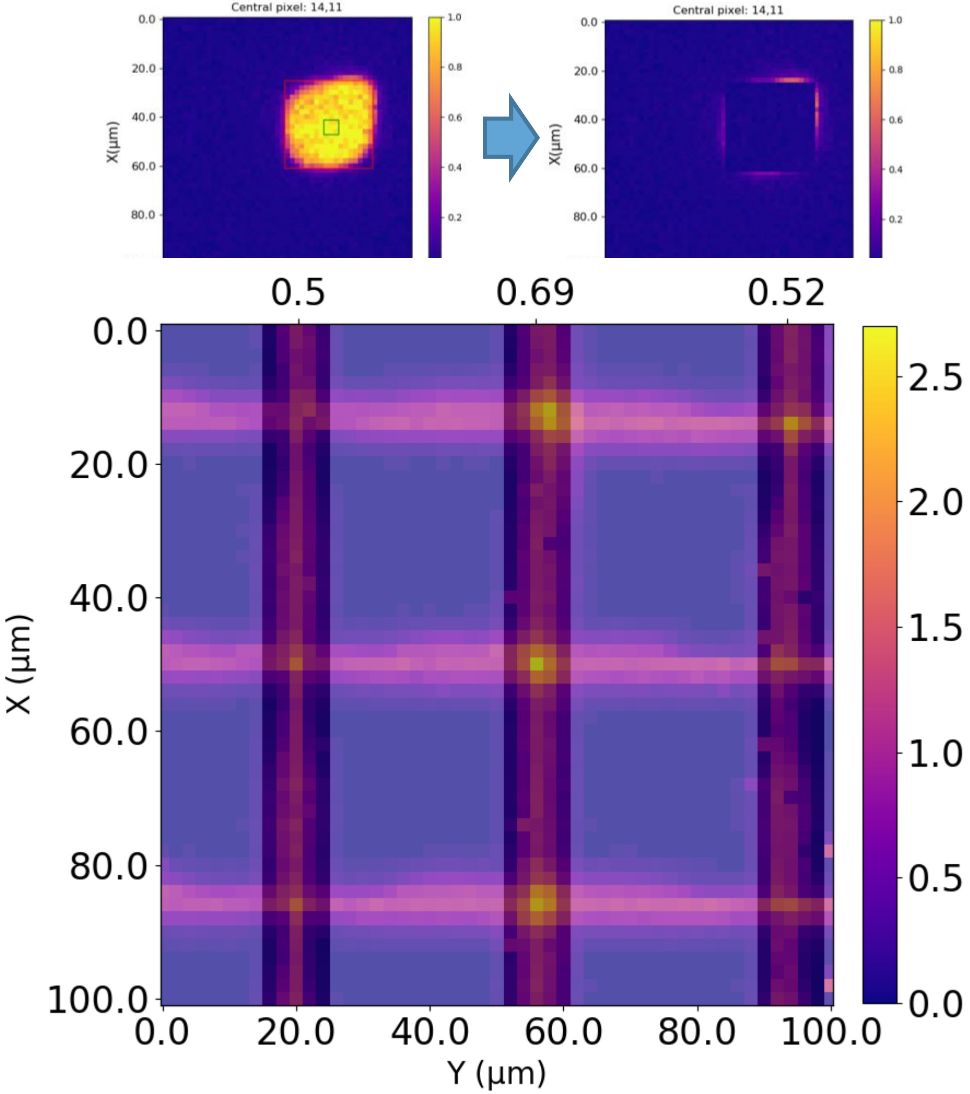
PIXEL SHAPE

- Irradiated (1e15 n/cm^2) MALTA sector
- Asymmetric pixel shape
- Double-column structure
- Due to p-well cutout



Overlay of raster scan and p-well shape

QUANTIFYING THE PIXEL ASYMMETRY



- Pixel asymmetry
- Double column structure
- Calculate average response due to charge sharing
- Asymmetry as a ratio:

$$\frac{Response_{high}}{Response_{low}} = \frac{0.69}{0.51} = 1.32$$

PIXEL ASYMMETRY

Sample	Dose	Asymmetry		
		MALTA	P-well	N-gap
W2R11	none	1.89 ± 0.10	1.49 ± 0.05	1.43 ± 0.04
W2R9	5e14	1.49 ± 0.08	1.11 ± 0.15	0.96 ± 0.14
W2R1	1e15	1.16 ± 0.09	1.07 ± 0.13	1.15 ± 0.08
W5R9	5e14	1.39 ± 0.08	1.02 ± 0.07	1.12 ± 0.06
W4R9	7e13	1.22 ± 0.09	1.02 ± 0.08	1.09 ± 0.10

↓ Decrease with irradiation

→ Decrease for new designs

QUESTION 3:
WHAT IS THE PIXEL SHAPE?

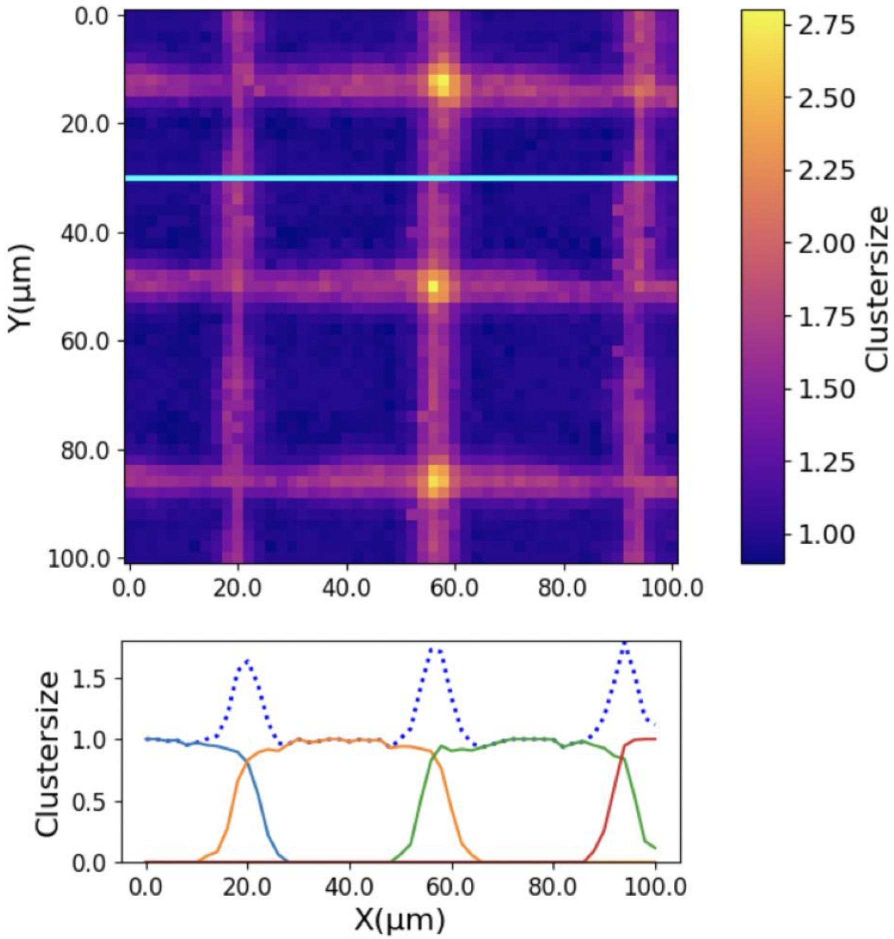
- Asymmetric pixel shape due to p-well cutout
- Asymmetry smaller for new designs
- Asymmetry decreases with irradiation

QUESTION 4:
DOES THE CHARGE SHARING CHANGE WITH IRRADIATION?

CHARGE SHARING – BASIC ANALYSIS

- Summed single pixel response
- Get the shape of the charge sharing regions

+ single pixel information



CHARGE SHARING – CLUSTERING ANALYSIS

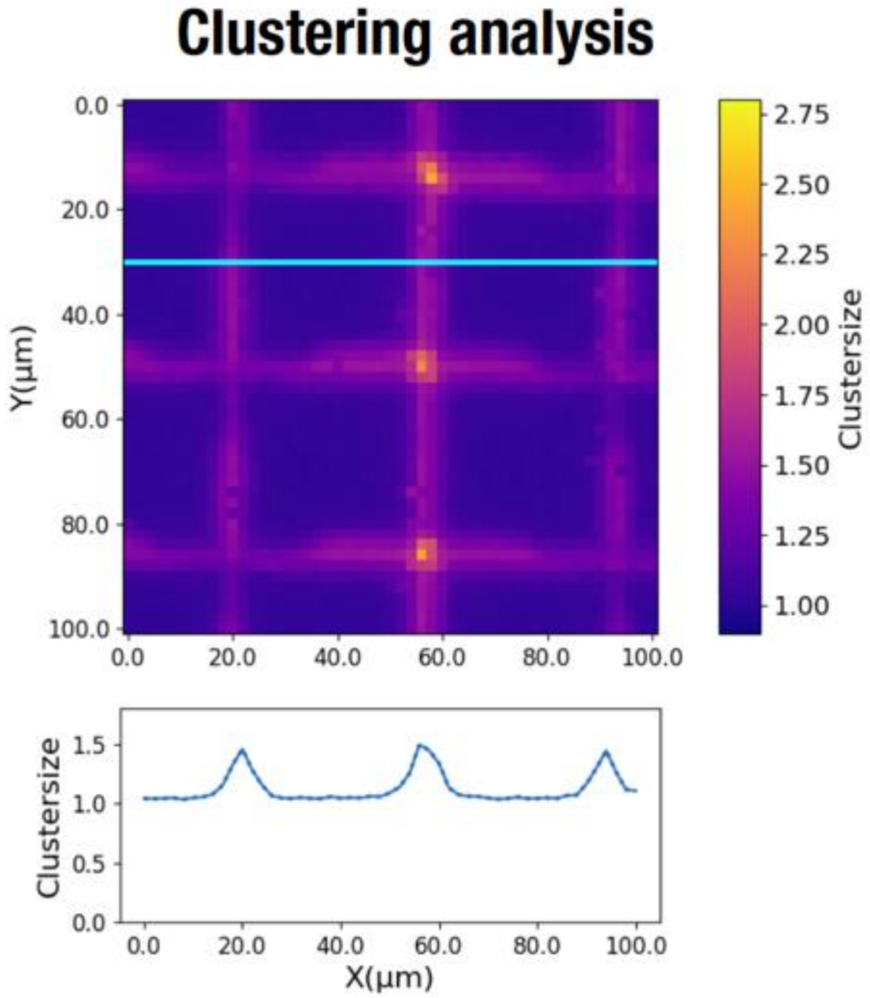
- Consider 25 ns events
- Check for hits in neighbouring pixels
- Consider only visible pixels in scan

→ Remove halo hits and noisy pixels

- Threshold on number of hits

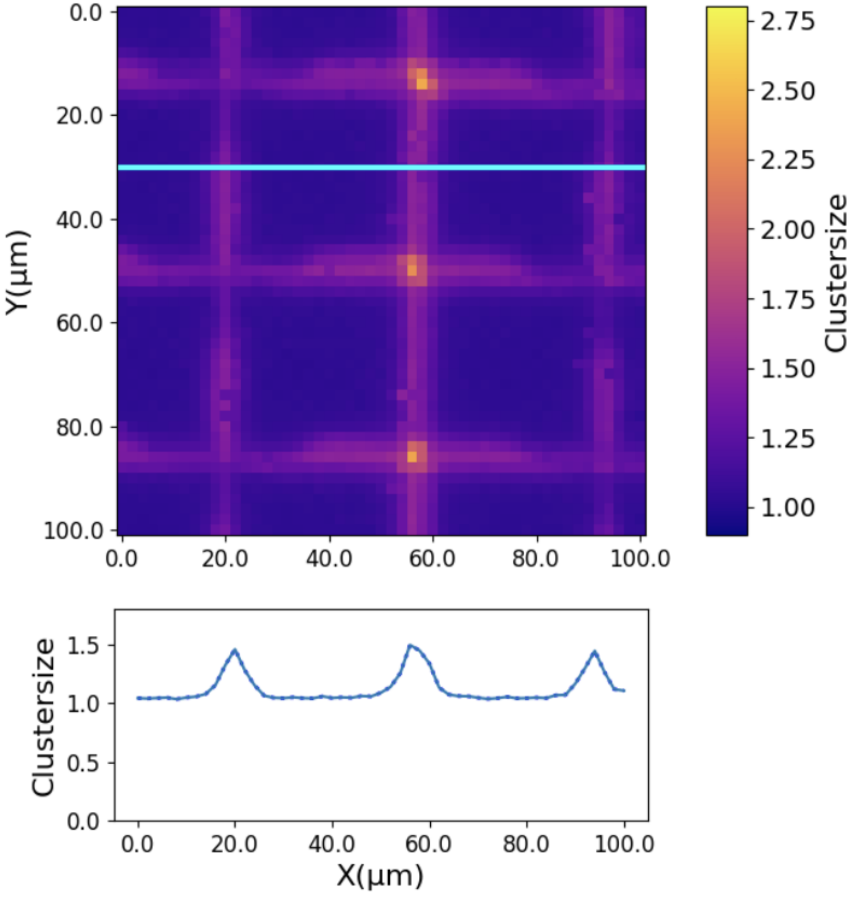
→ Remove halo hits in visible pixels

- Just cluster size (no effect of depletion depth or response loss in corners)

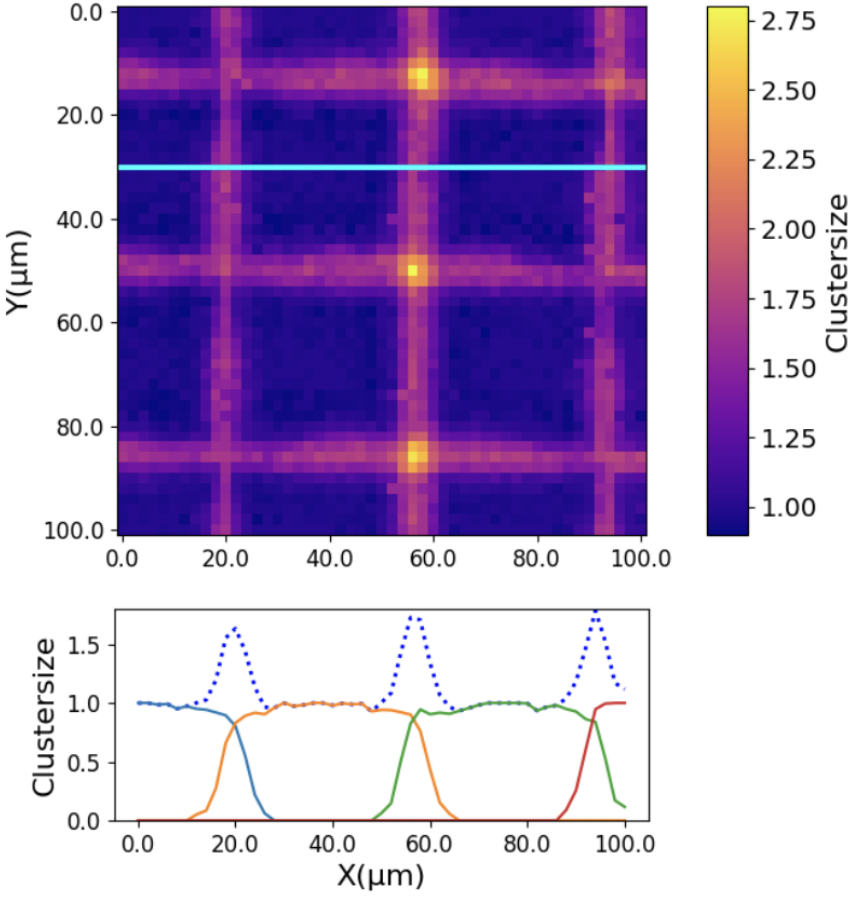


COMPARISON

Clustering analysis



Our previous analysis



CHARGE SHARING EXTENTS

Sample	Radiation	MALTA charge sharing (μm)	P-well charge sharing (μm)	N-gap charge sharing (μm)
W2R11	0	4.5 ± 1.5	5.4 ± 1.3	4.5 ± 1.8
W2R9	5e14 (p)	2.6 ± 1.8	5.4 ± 2.2	5.5 ± 2.0
W2R1	1e15 (n)	3.2 ± 2.0	6.1 ± 2.0	6.5 ± 2.6
W5R9	5e14 (p)	2.4 ± 2.0	4.5 ± 1.8	3.7 ± 2.7
W4R9	7e13 (p)	2.4 ± 1.9	4.1 ± 1.9	4.6 ± 1.0

↓ Decrease with irradiation for MALTA

No decrease for new designs

QUESTION 4:
DOES THE CHARGE SHARING CHANGE WITH IRRADIATION?

- Two methods:
  - I. Pixel response analysis
  - II. Clustering analysis
- Charge sharing decreases with irradiation for MALTA
- No decrease with irradiation for p-well and n-gap

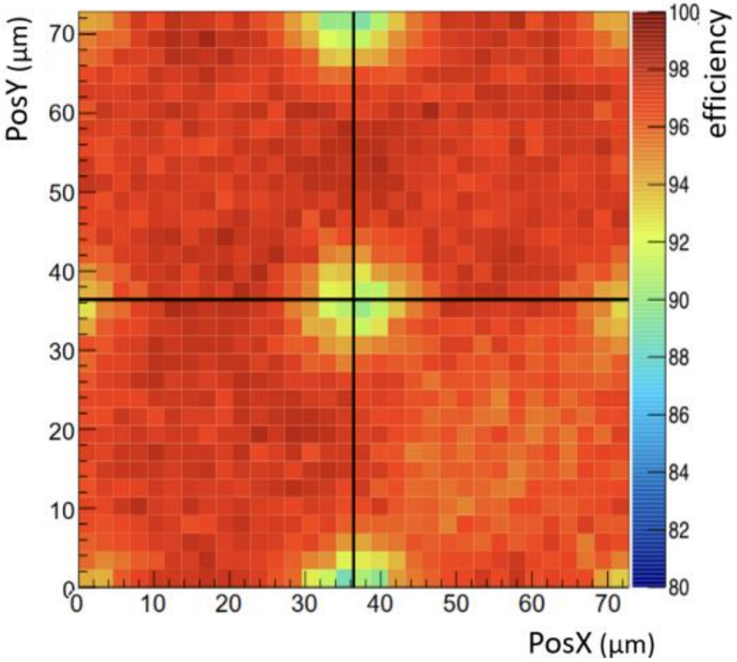
Part II: New method for estimating detector efficiency for MIPS using Diamond Light Source

PHOTON VS PROTON TESTBEAM RESULTS

- MALTA SPS testbeam

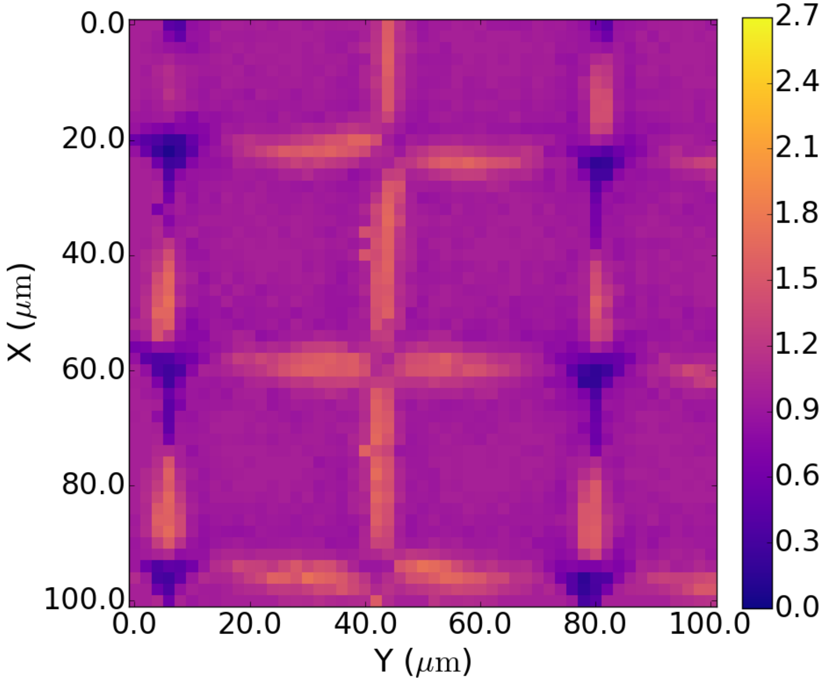
→ Higher efficiencies

Protons



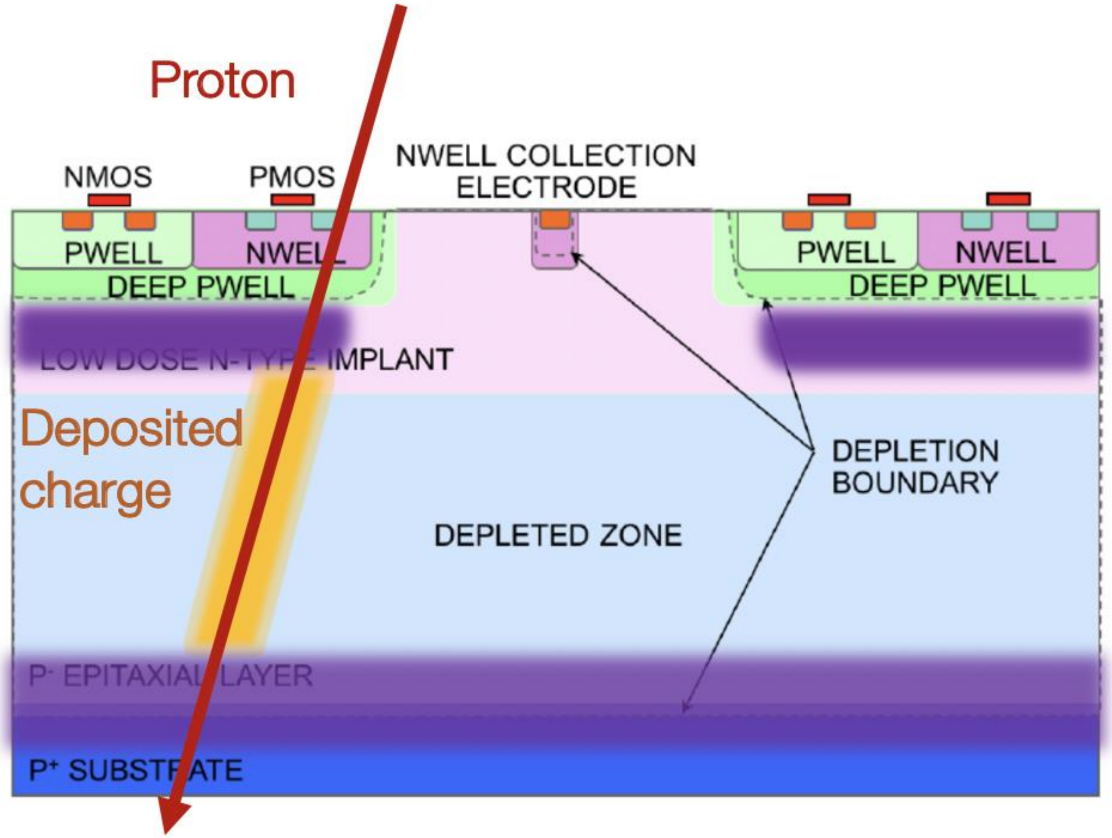
Average: 96%
Minimum: 90%

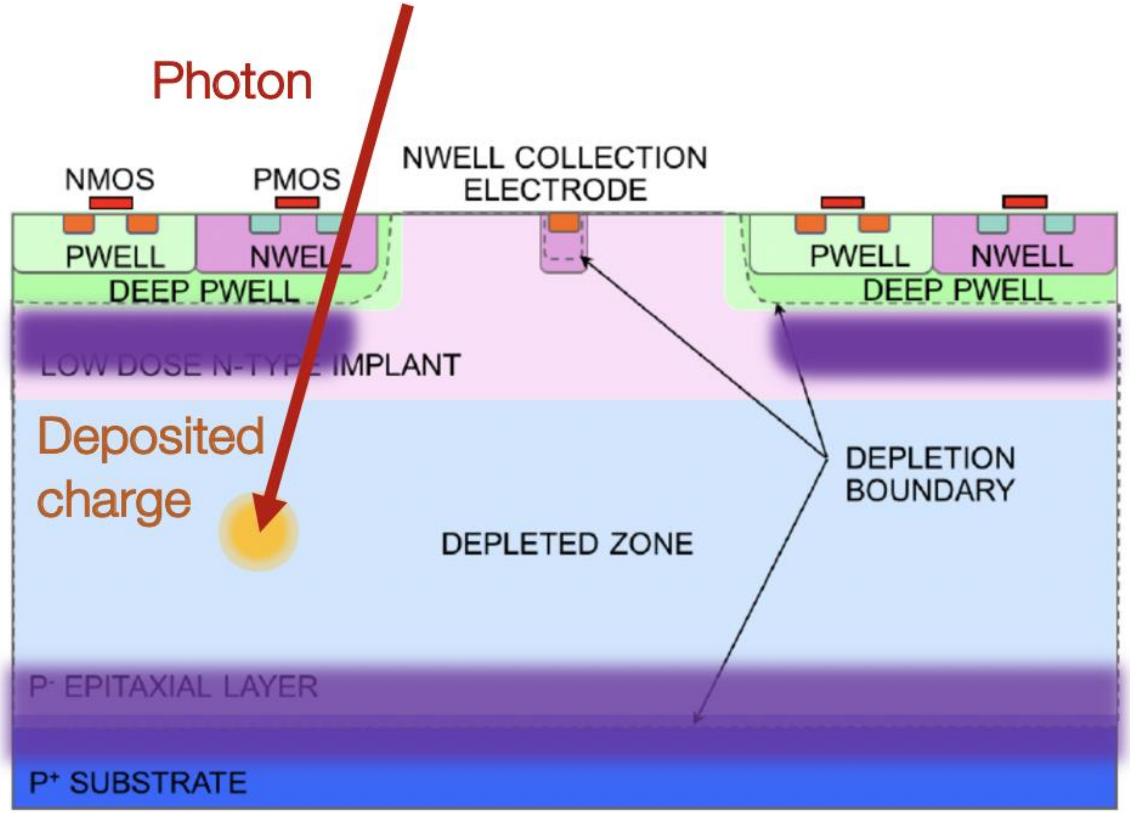
Photons



Average: 89%
Minimum: 20%

PHOTON VS PROTON ENERGY DEPOSITION





PHOTON VS PROTON TESTBEAM RESULTS

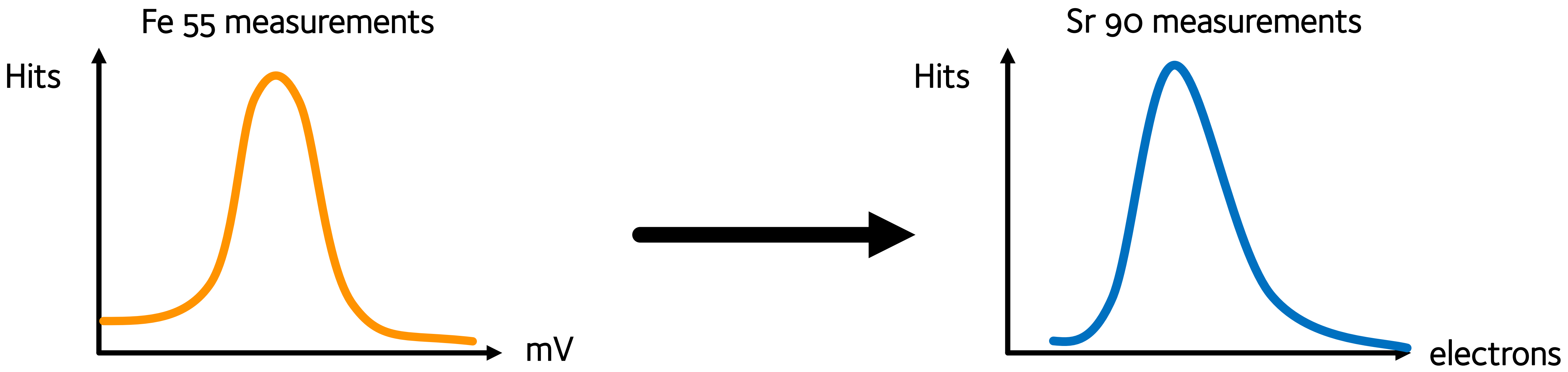
- Assumption: Low response in the corners with X-rays due to depletion depth

→ X-ray map effectively gives us map of depletion depth

- Would a MIP still deposit enough energy to be seen?

→Idea: Get analogue MIP response in centre and scale it to corners

ANALYSIS – ON A SINGLE ANALOGUE PIXEL



Fe 55 measurements

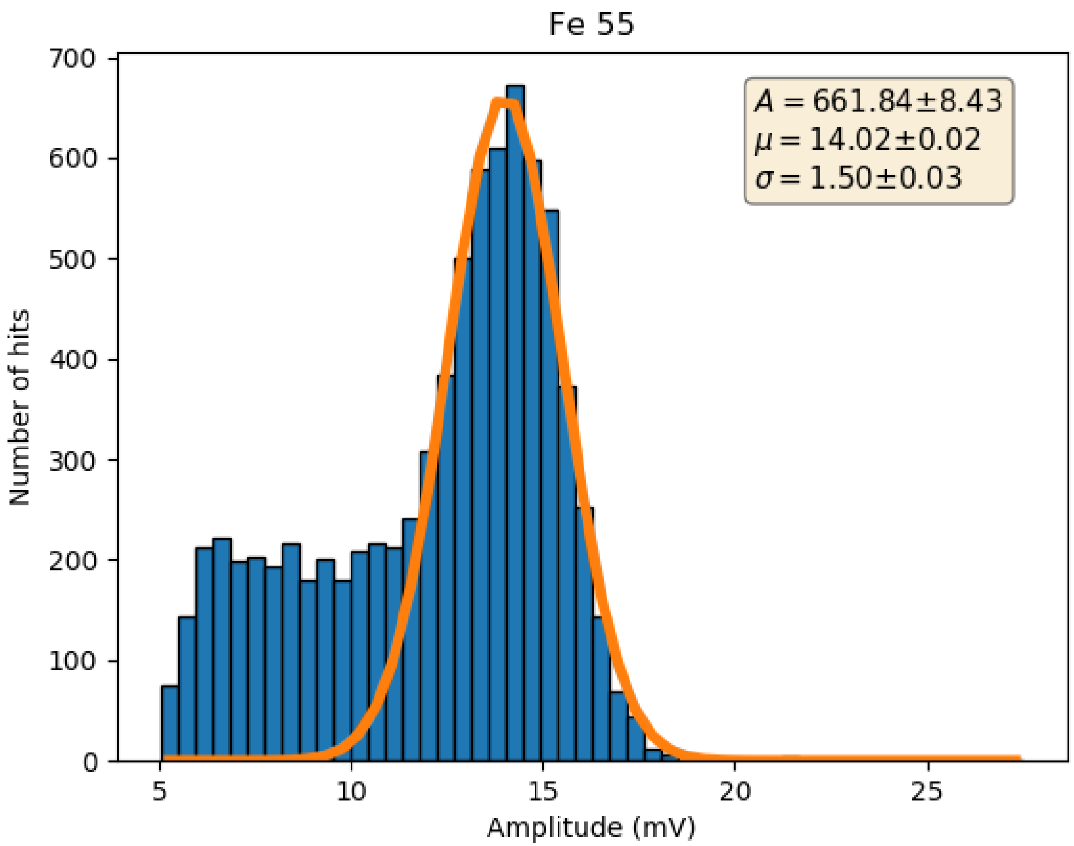
Sr 90 measurements

- Source measurements an analogue MALTA pixel
- Fe55: Convert mV scale to electrons
- Sr90: Get Landau

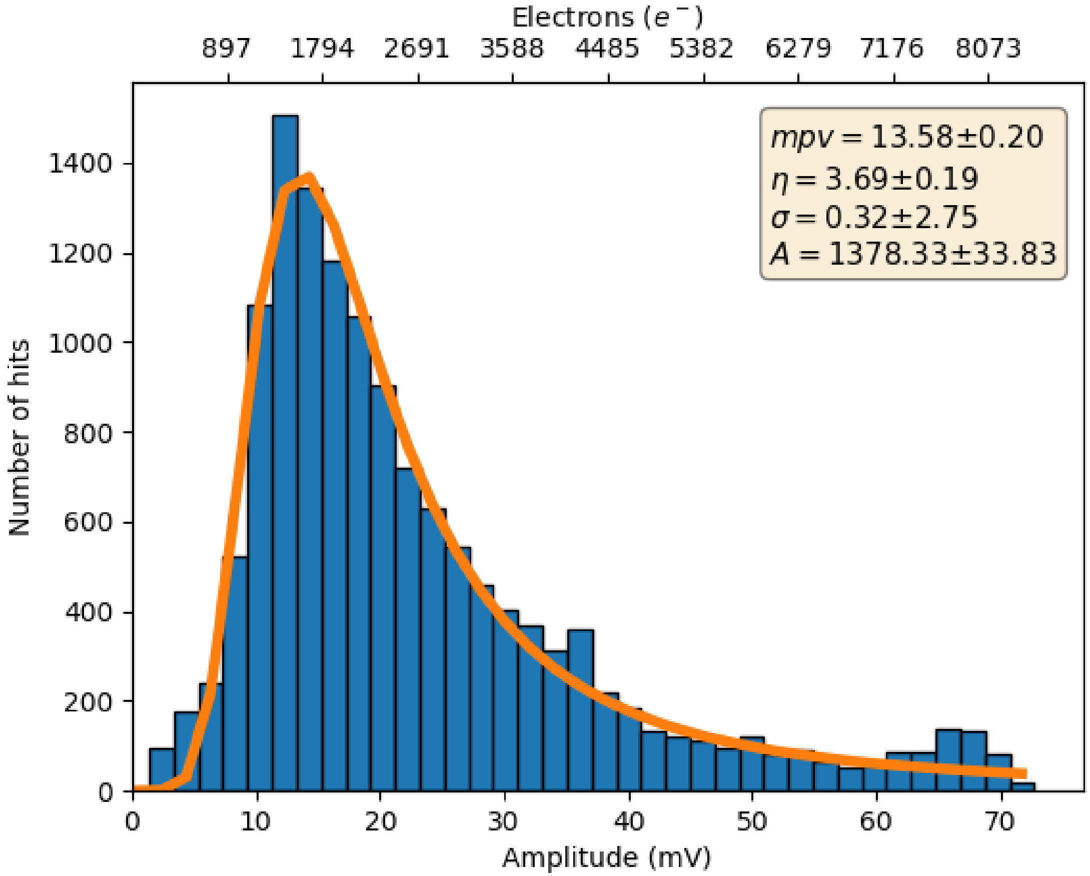
→ peak: what a MIP would deposit at full depletion

RESULTS

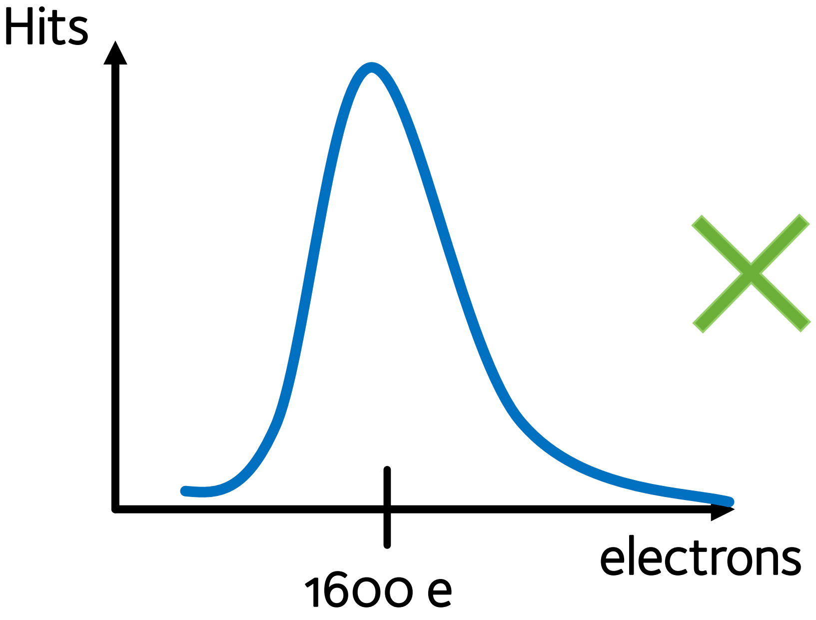
Fe 55 measurement:



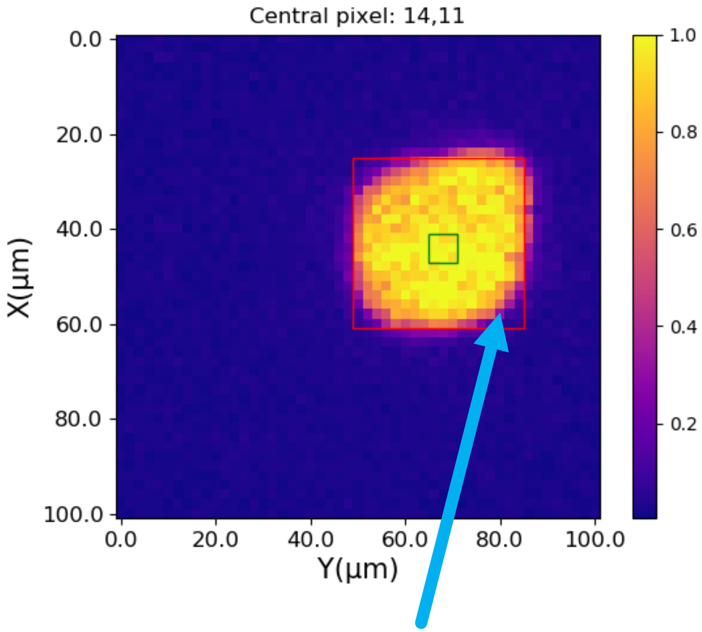
Sr 90 measurement:



ANALYSIS

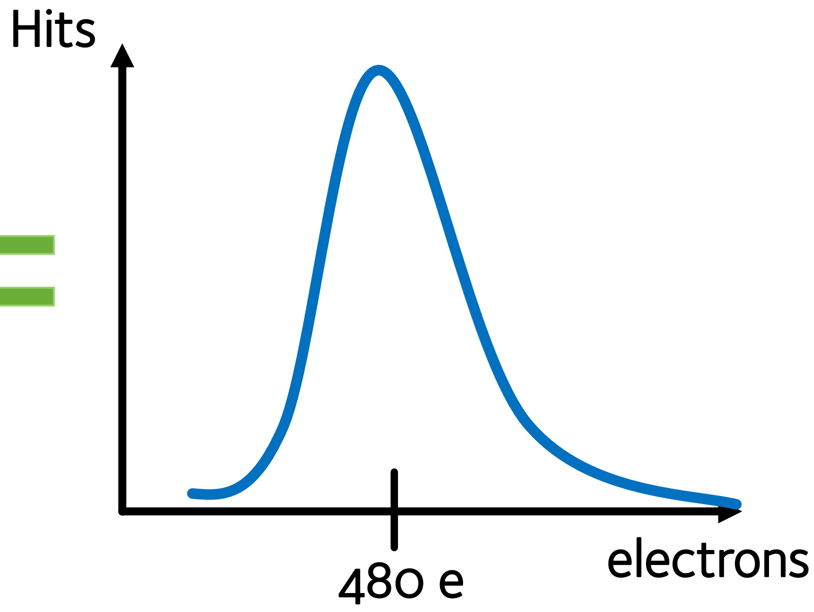


×

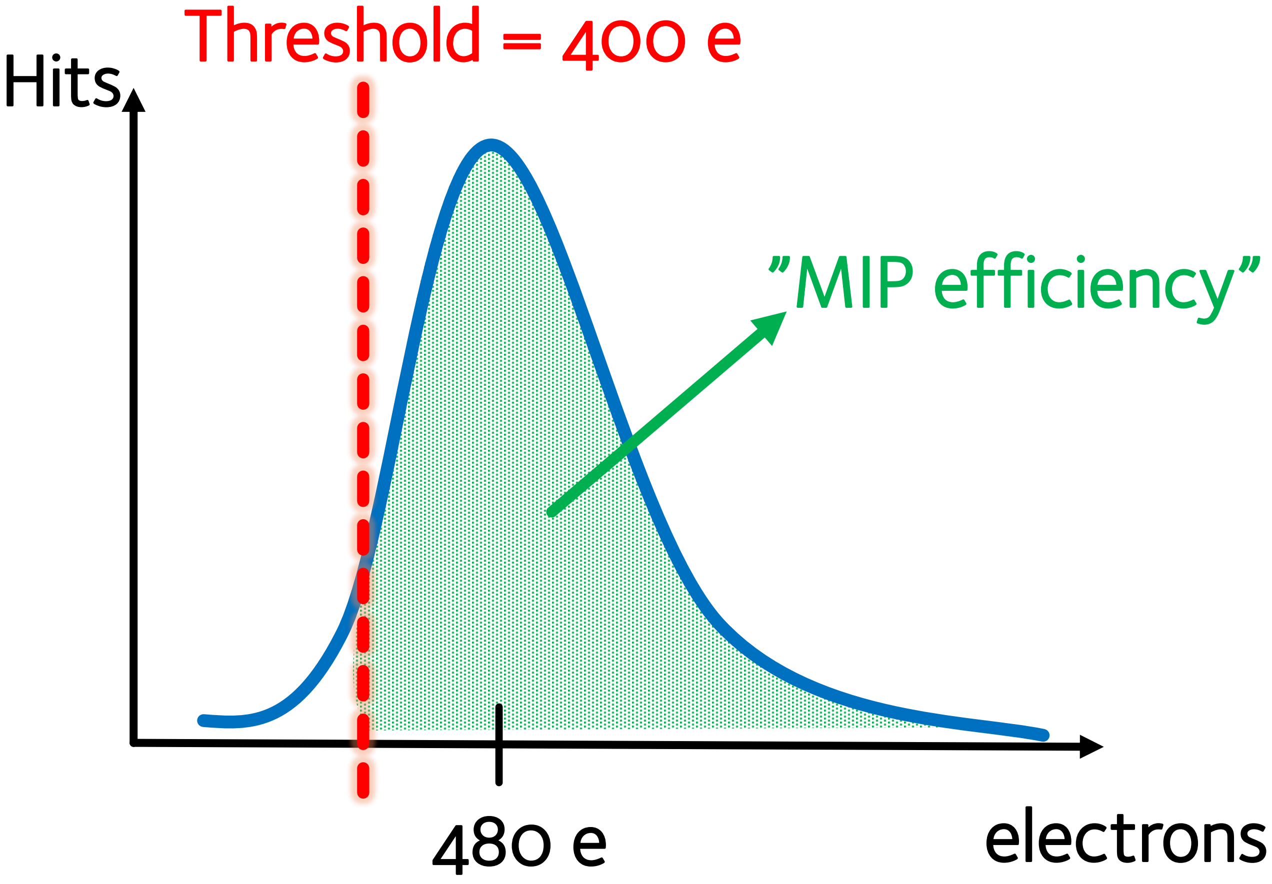


i.e. 0.3 here

=



ANALYSIS



- Scale Landau to expected depletion depth
- Check what percentage is above threshold

→ MIP efficiency

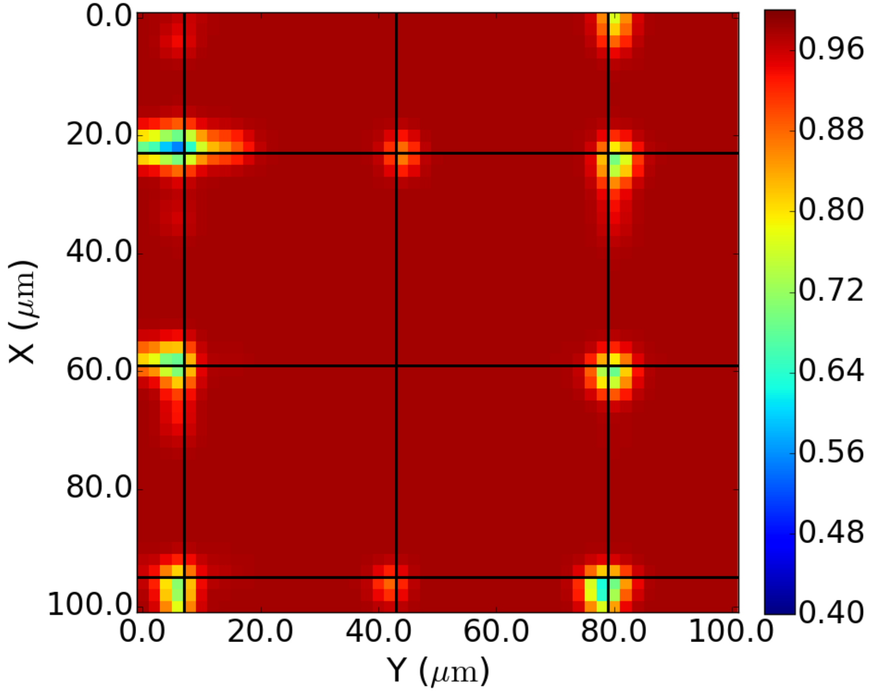
ERROR ANALYSIS

- Propagate errors from:
  - Fitting the Landau
  - Pixel threshold
  - Normalisation

MIP DETECTION PERFORMANCE

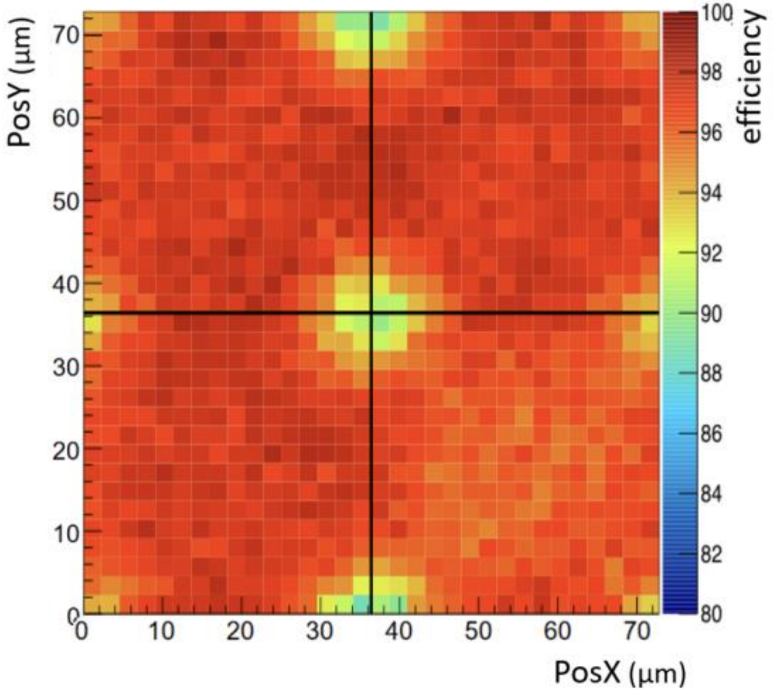
MALTA sector before irradiation – threshold 250 e

Diamond



(97.6 ± 1.0) %

SPS

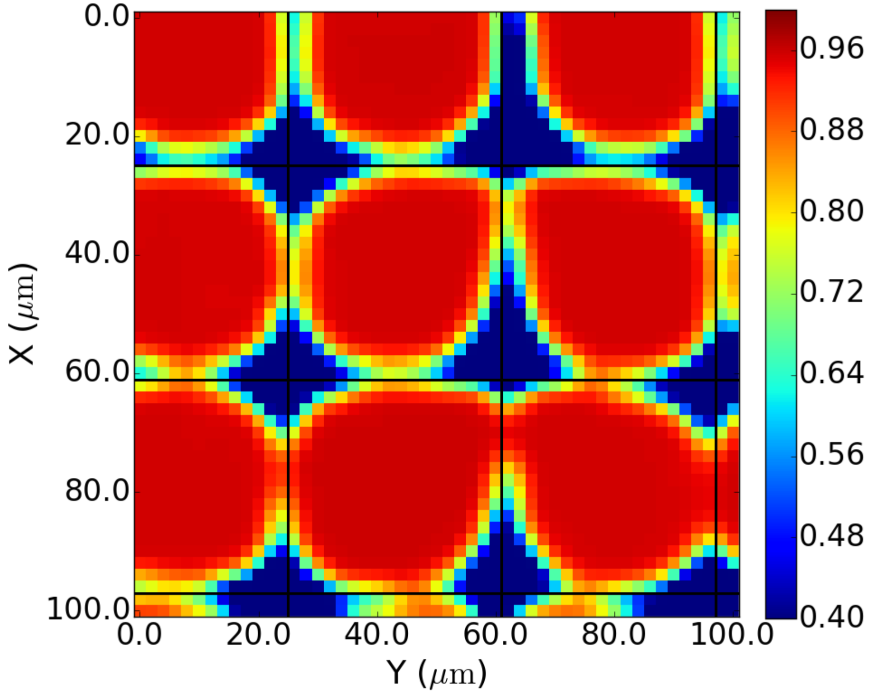


Average: 96%

MIP DETECTION PERFORMANCE

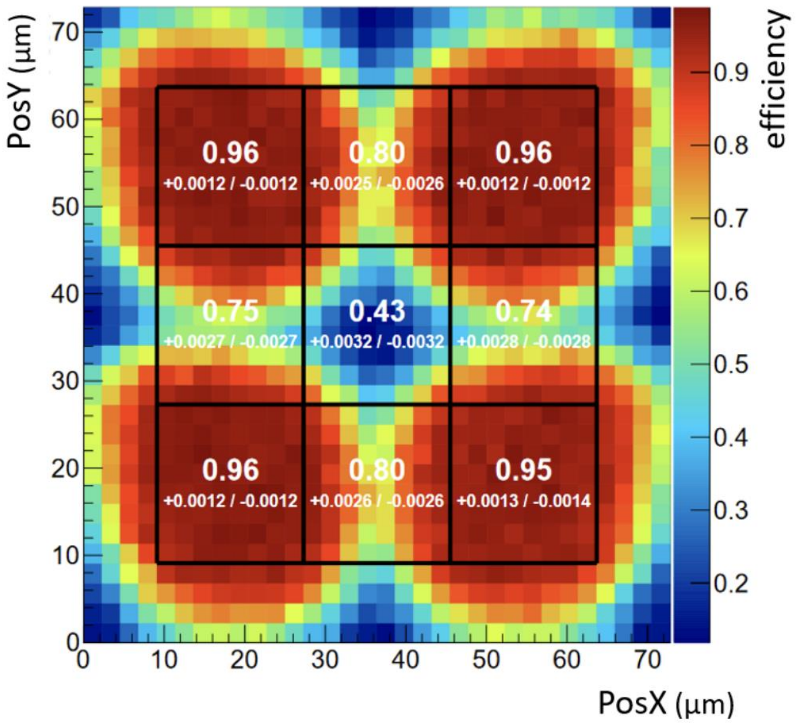
MALTA sector after irradiation (1e15 n/cm²) – threshold 450e

Diamond



(82.2 ± 8.3) %

SPS

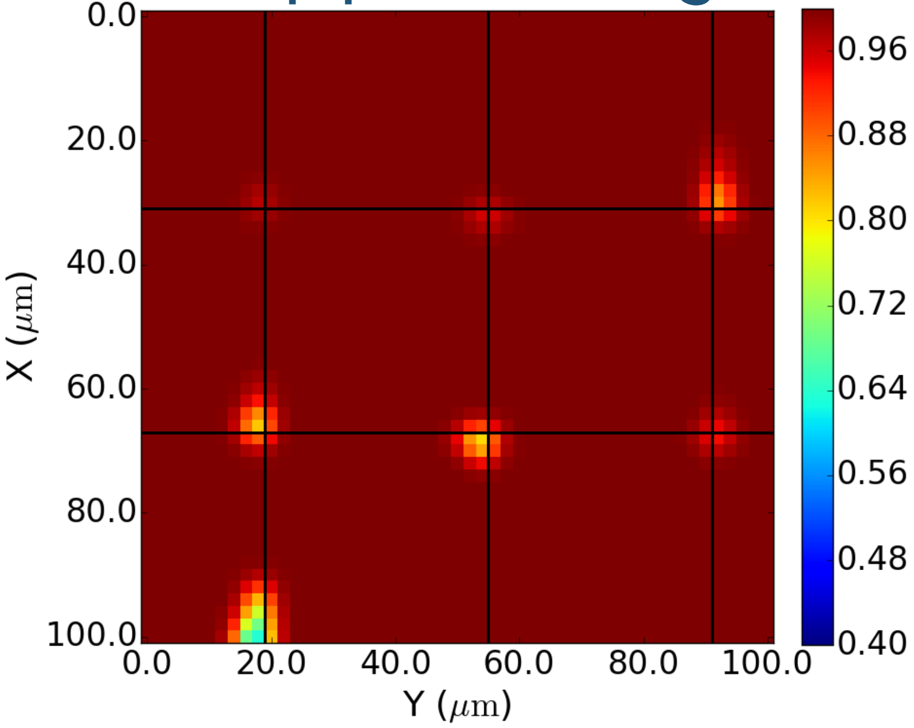


Average: 72%

NEW DESIGNS

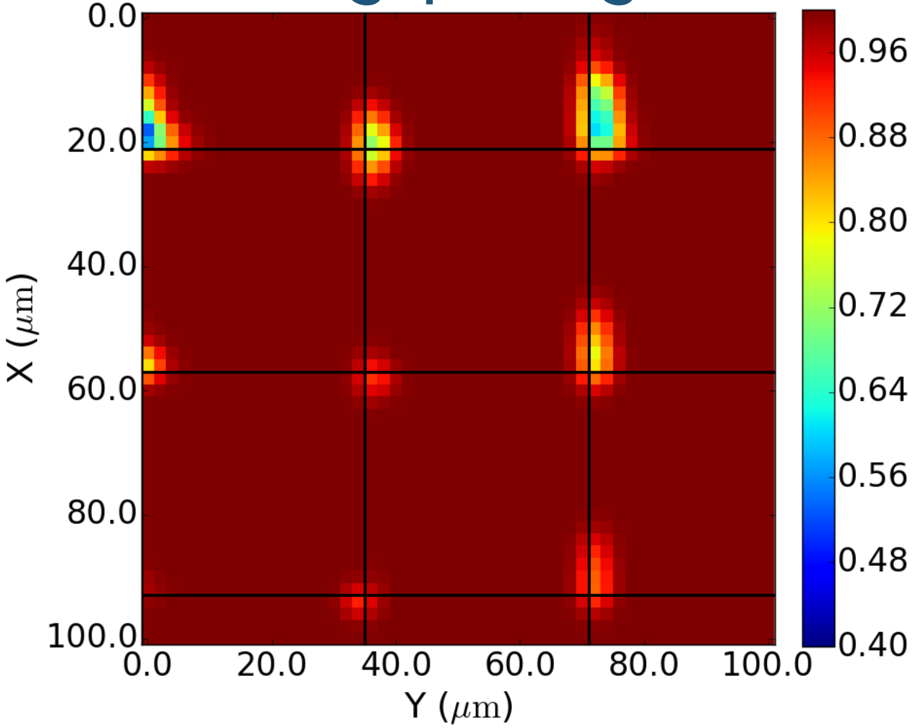
Extrapolate MIP efficiencies for new designs after irradiation (1e15 n/cm^2) – threshold 200e

deep p-well design



(99.8 ± 0.9) %

n-gap design



(99.6 ± 0.9) %

CONCLUSIONS

- X-Ray testbeam provides high resolution information about charge collection shape
- New designs perform better than standard MALTA
  - MALTA response decrease by >10% for $1\text{x}10^{15}$ n/cm^2
  - P-well and n-gap response do not decrease

CONCLUSIONS

- Response decreases as a function of biasing voltage
- Quantified pixel asymmetry for different designs
- Charge sharing with clustering analysis
- Could qualitatively reproduce results from MIP testbeams

Thank you!

Questions?

Additional Slides

CHARGE SHARING PERCENTAGES

Sample	Radiation	MALTA charge sharing (%)	P-well charge sharing (%)	N-gap charge sharing
W2R11	0	15.8	20.3	16.9
W2R9	5e14 (p)	7.7	17.9	21.18
W2R1	1e15 (n)	7.1	23.6	21.3
W1R9	7e14 (p)	17.8	23.7	25.6
W5R9	5e14 (p)	7.3	14.1	15.4
W4R9	7e13 (p)	8.4	14.9	15.7

Decrease with radiation for MALTA

CHARGE SHARING EXTENTS

Sample	Radiation	MALTA charge sharing (µm)	P-well charge sharing (µm)	N-gap charge sharing (µm)
W2R11	0	4.5 ± 1.5	5.4 ± 1.3	4.5 ± 1.8
W2R9	5e14 (p)	2.6 ± 1.8	5.4 ± 2.2	5.5 ± 2.0
W2R1	1e15 (n)	3.2 ± 2.0	6.1 ± 2.0	6.5 ± 2.6
W1R9	7e14 (p)	4.8 ± 1.4	6.1 ± 1.3	6.0 ± 3.1
W5R9	5e14 (p)	2.4 ± 2.0	4.5 ± 1.8	3.7 ± 2.7
W4R9	7e13 (p)	2.4 ± 1.9	4.1 ± 1.9	4.6 ± 1.0

Decrease with radiation for MALTA

DIFFERENT BIASING VOLTAGES

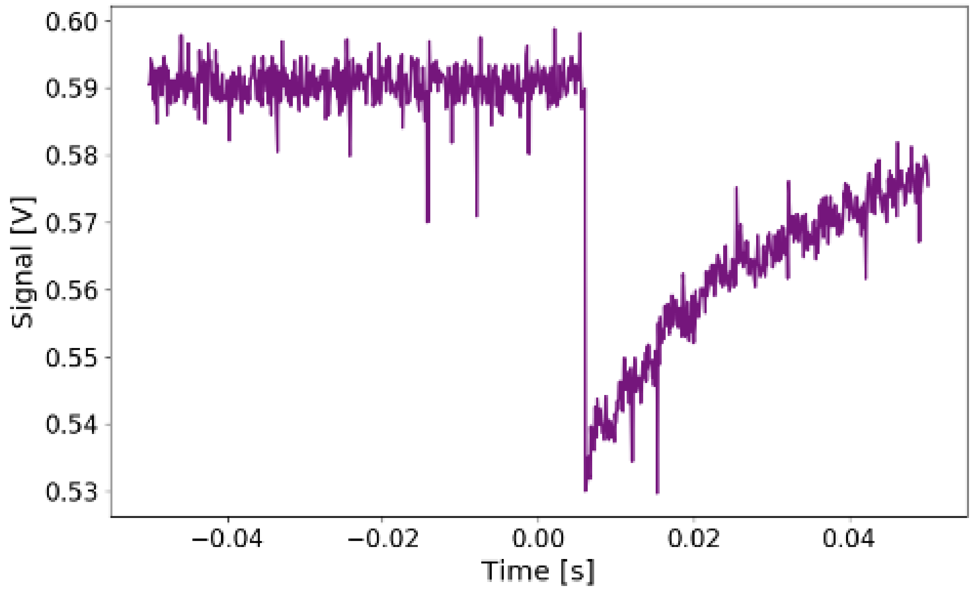
Sample	Voltage	MALTA efficiency (%)	P-well efficiency (%)	N-gap efficiency (%)
W2R1	-1.5V	76.7 ± 6.1	91.1 ± 3.8	90.0 ± 4.9
	-20V	72.2 ± 6.5	86.6 ± 8.2	86.4 ± 4.8

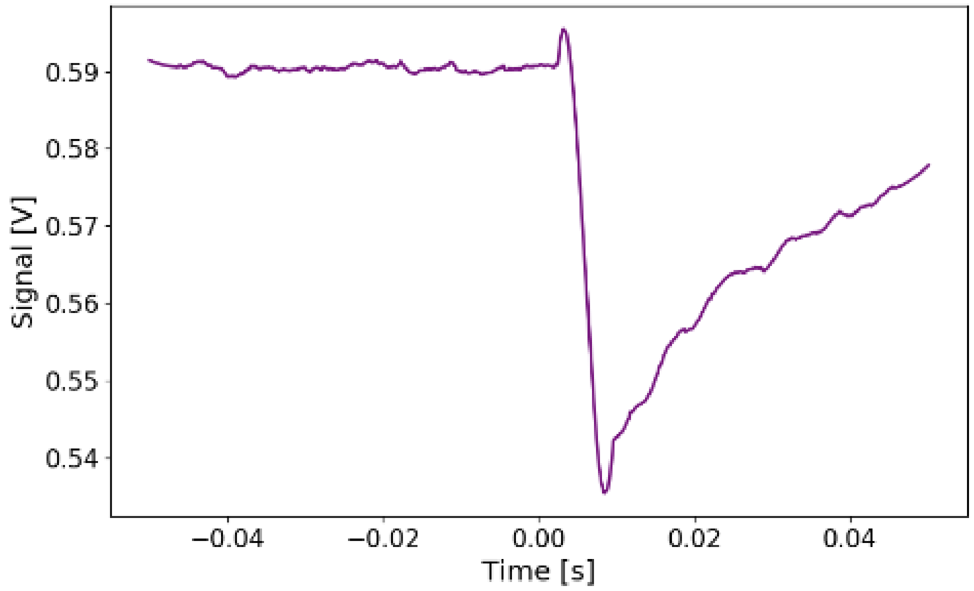
Decrease with bias voltage

Sample	Voltage	MALTA efficiency (%)	P-well efficiency (%)	N-gap efficiency (%)
W1R9	-1.5V	90.8 ± 3.6	93.0 ± 2.8	92.6 ± 3.6
	-8V	91.1 ± 3.2	92.9 ± 2.7	93.1 ± 3.1

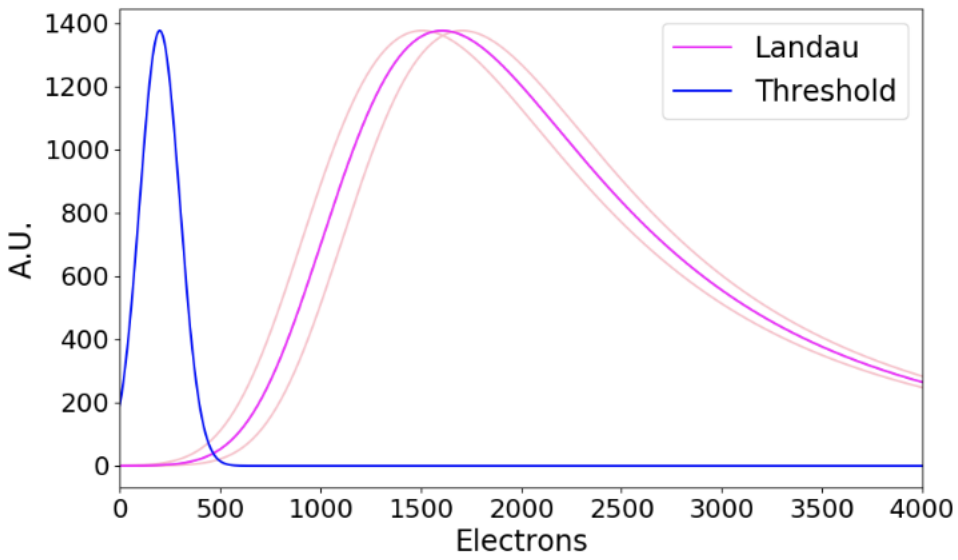
No change

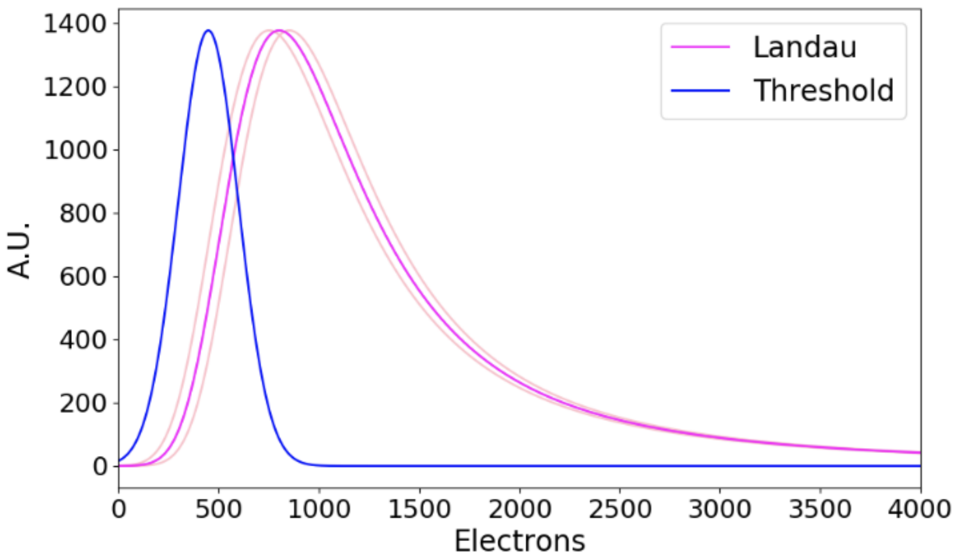
SR-90 WAVEFORMS





ERROR ANALYSIS





RADIATION DAMAGE

- Surface damage:
  - Total ionising dose (TID) effects
  - In units of X-ray equivalent Rad
  - Affects electronics in CMOS

- Bulk damage
  - Non-ionising energy dose (NIEL) effects
  - In units of 1MeV neutron equivalent does (n/cm^2)
  - E.g. causes crystal defects (displaced atom and vacancy)

MINIMALTA

- CMOS prototype with 36.4 x 36.4 μm^2 pixel size
- New designs to improve charge collection in pixel edges