TowerJazz Investigator measurements: Summary

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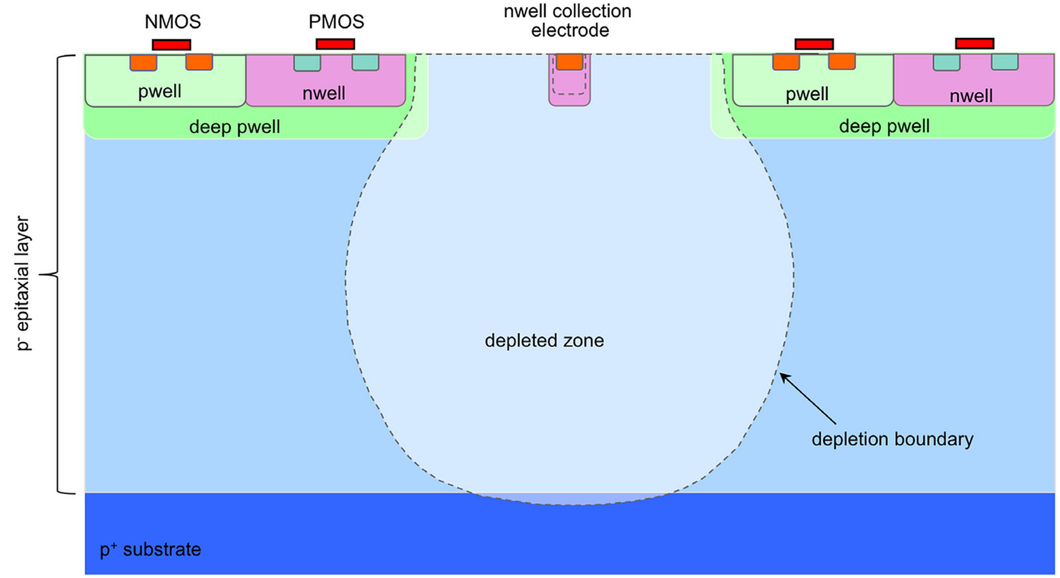
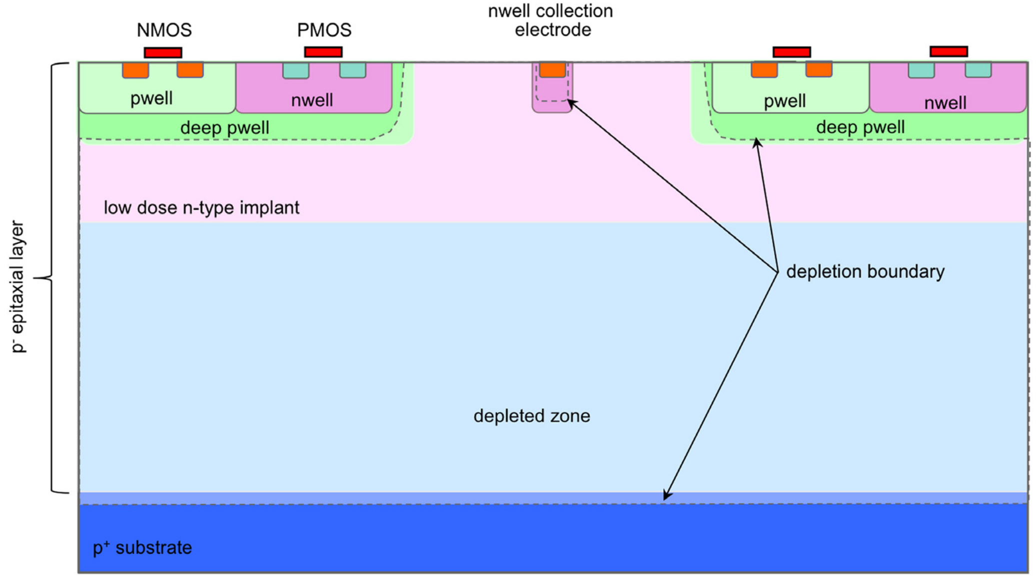
TJ processes cross sections

- Standard



- Modified

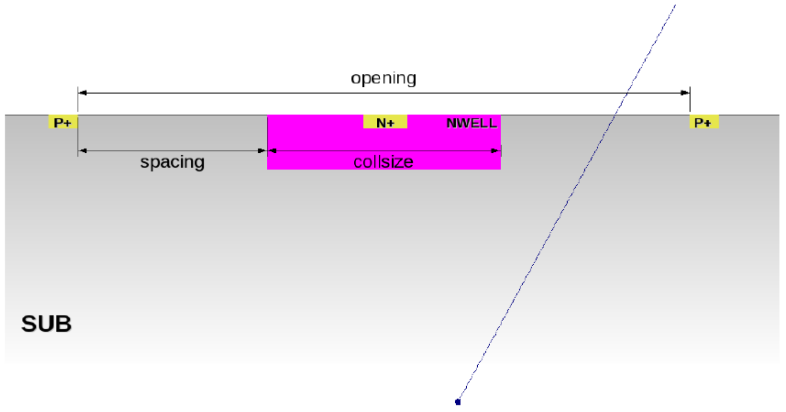


W. Snoeys *et al, A process modification for CMOS monolithic active pixel sensors for enhanced depletion, timing performance and radiation tolerance,* http://dx.doi.org/10.1016/j.nima.2017.07.046

TJ1, TJ1B, TJ2

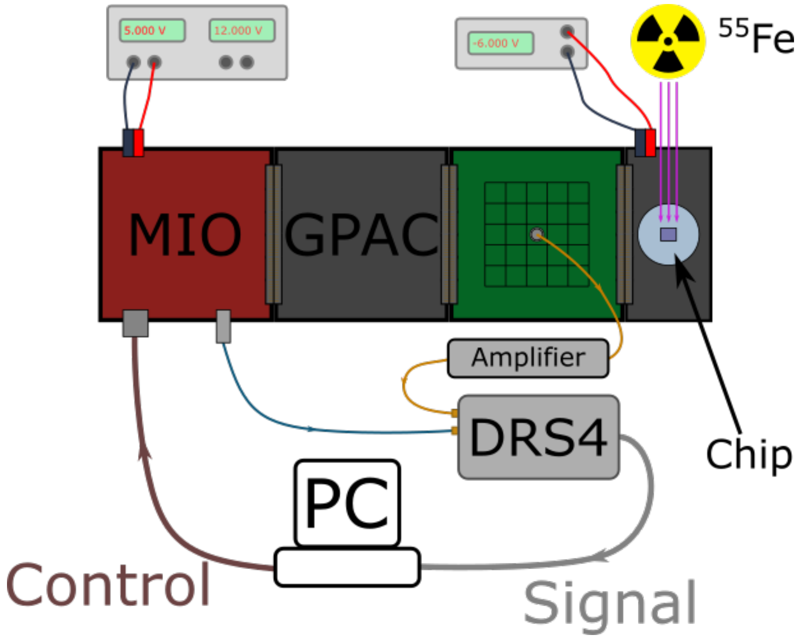
- All have 134 10x10 pixel matrices, with different pitch, collection electrode size, and spacing between collection electrode and PWELL.
- TJ1B same as TJ1, apart from **separate biasing of PWELL voltage and HV (substrate) voltage.**
- TJ2 **faster electronics**, and **smaller spacing** in the larger pixels.

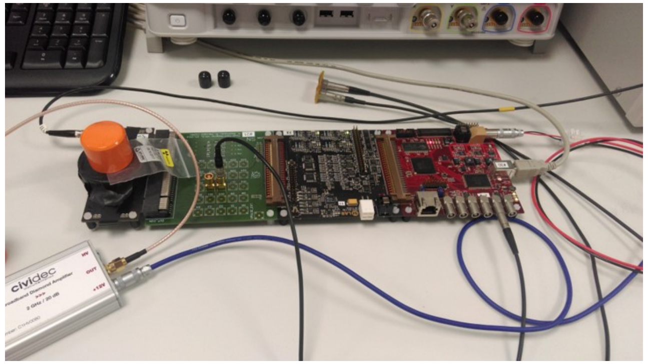
Chip	HV and PWELL bias	Electronics	Layout	Implant dose
TJ1	Common	Standard	Standard	Low or High
TJ1B	Separate	Standard	Standard	High or very high
TJ2	Separate	Faster	Smaller spacing for larger pixels	High or very high



Experimental setup: TJ1

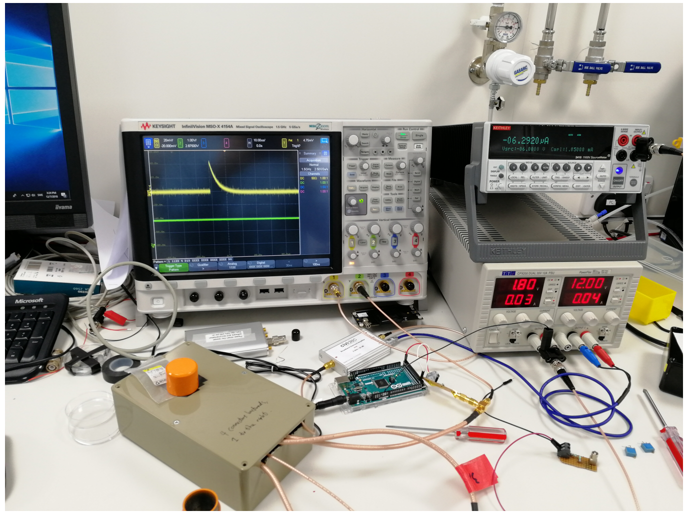
- Source tests with iron-55.
- MIO, GPAC, passive board, chip carrier board.
- Reset signal provided by MIO
  - **25 µs integration time**
- HV provided by Keithley
  - **HV and p-well bias in common by design, at -6 V**
- Output into CIVIDEC amplifier, and then DRS4.

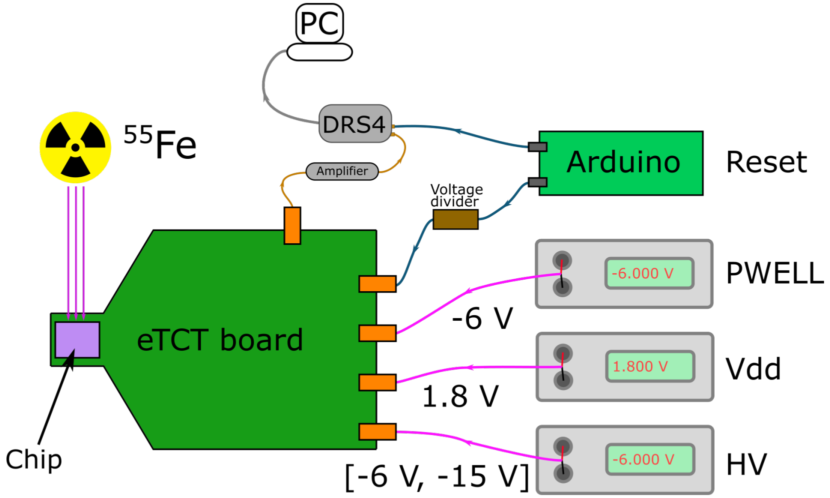




Experimental setup: TJ1B & TJ2

- Source tests with iron-55
- HV and PWELL biased separately.
- Reset signal provided by Arduino
  - **400 μs integration time**
- Output into CIVIDEC amplifier, and then DRS4.
- For the TJ2 chip, resistors had to be trimmed to provide the correct bias voltage
  - Electronics different from previous versions





TowerJazz Investigator 1

TowerJazz Investigator 1

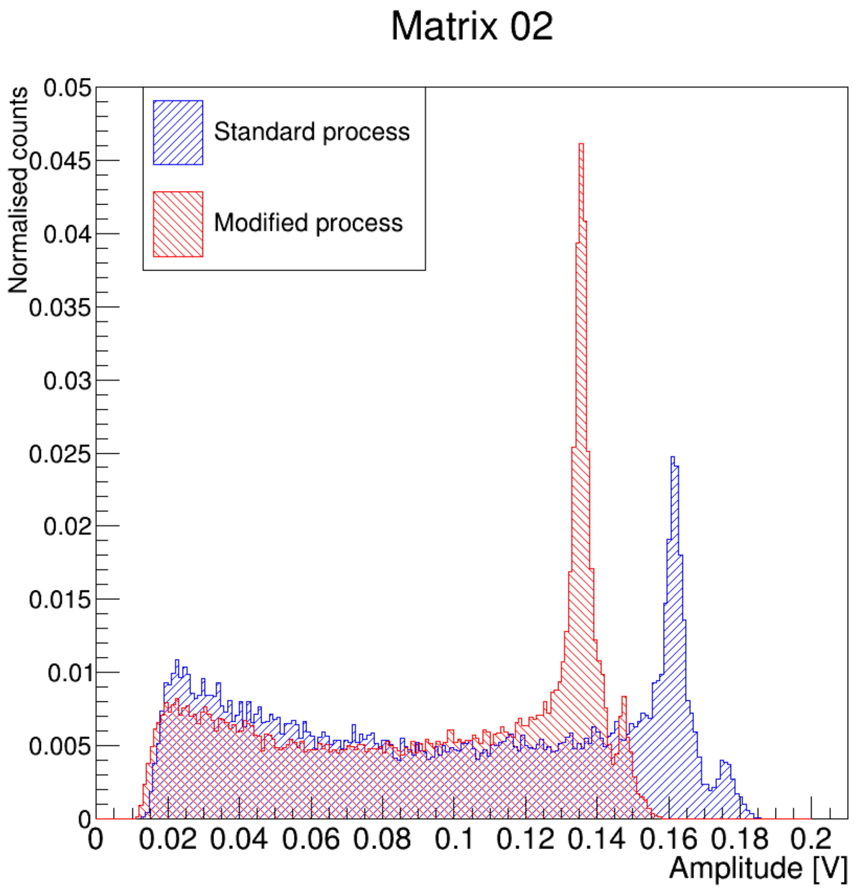
- Tests performed in **standard and modified process**, for the following mini-matrices

Minimatrix	Pixel size [µm²]	Coll.el.size [µm]	Spacing [µm]	Transistor
2	20x20	3x3 oct	3	Standard Outside
75	28x28	2x2 oct	3	Standard Outside
106	30x30	3x3 oct	3	Standard Outside
118	40x40	3x3 oct	13.5	Standard Inside
124	50x50	3x3 oct	13.5	Standard Outside
129	50x50	3x3 oct	18.5	Standard Inside

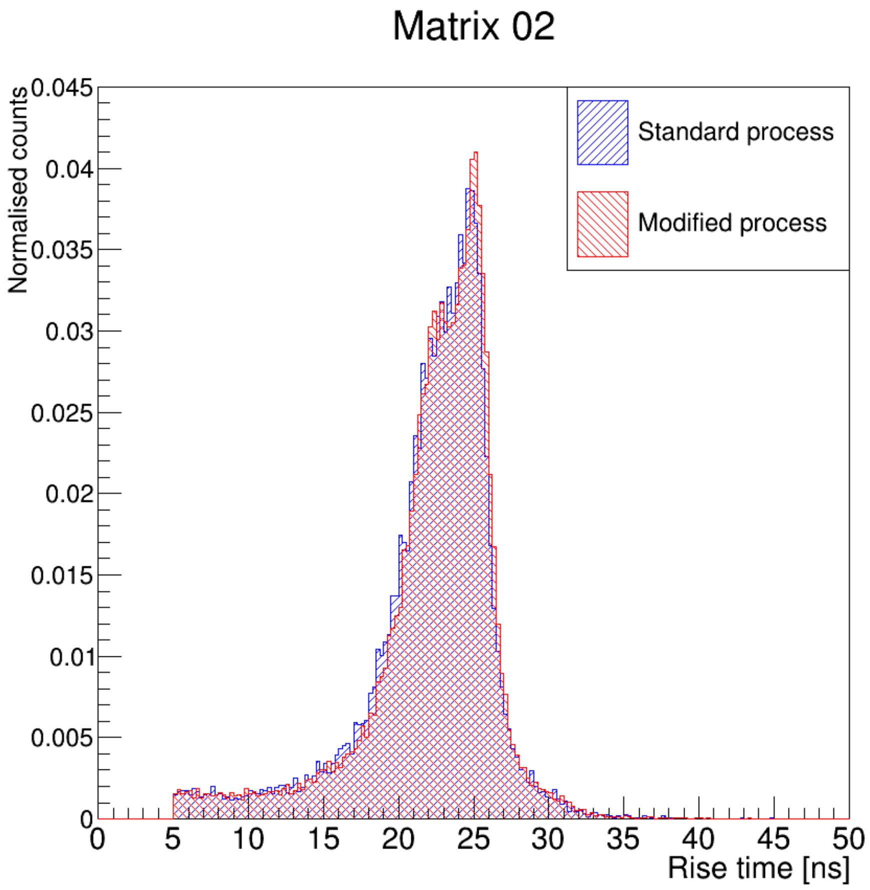
Note larger spacing for pitch $\geq$ 40 µm

- **p-well bias = HV = -6V**
- Chips have 25 µm thick epitaxial layer.

Matrix 2 – 20x20 μm²

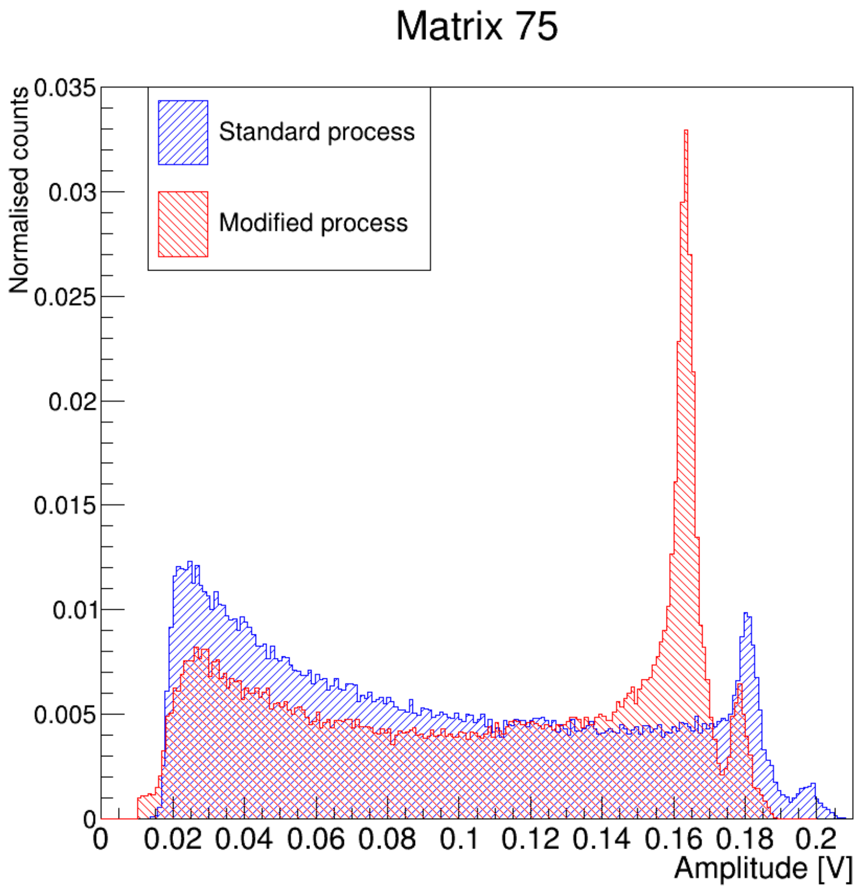


Amplitude

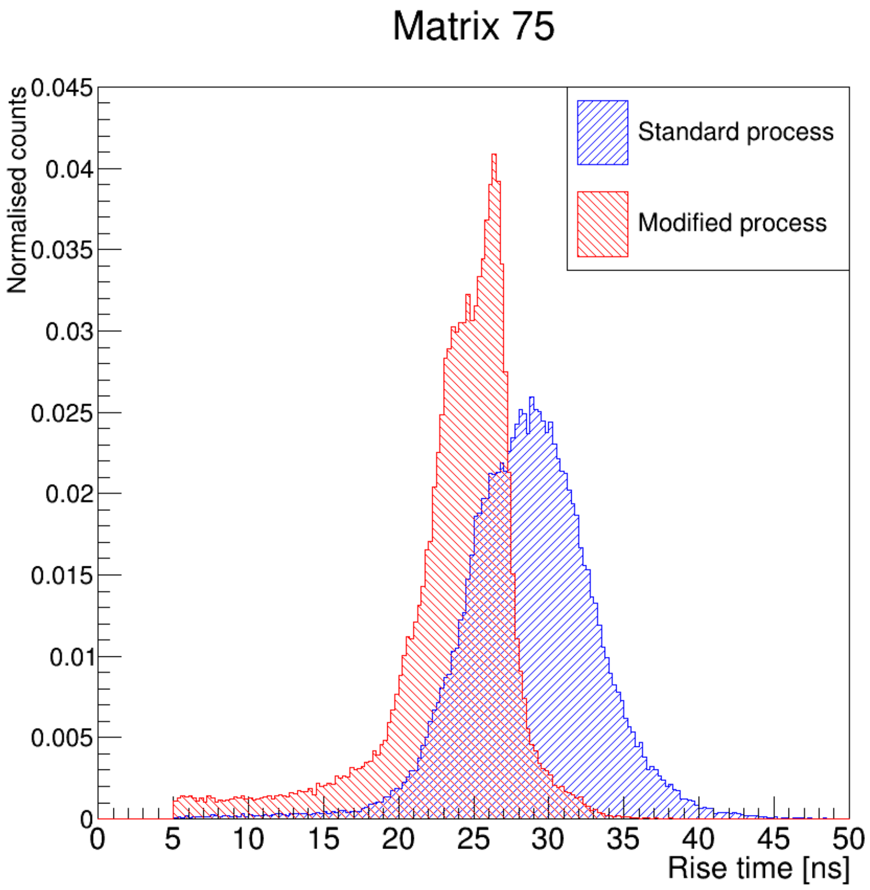


Rise time

Matrix 75 – 28x28 μm^2

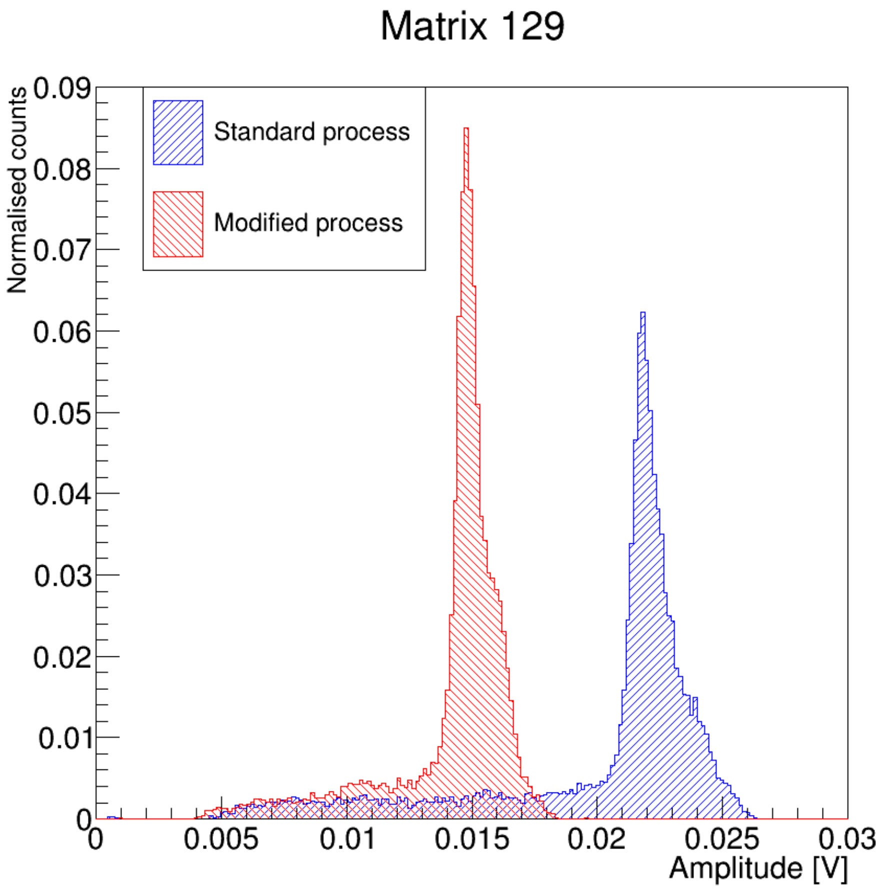


Amplitude

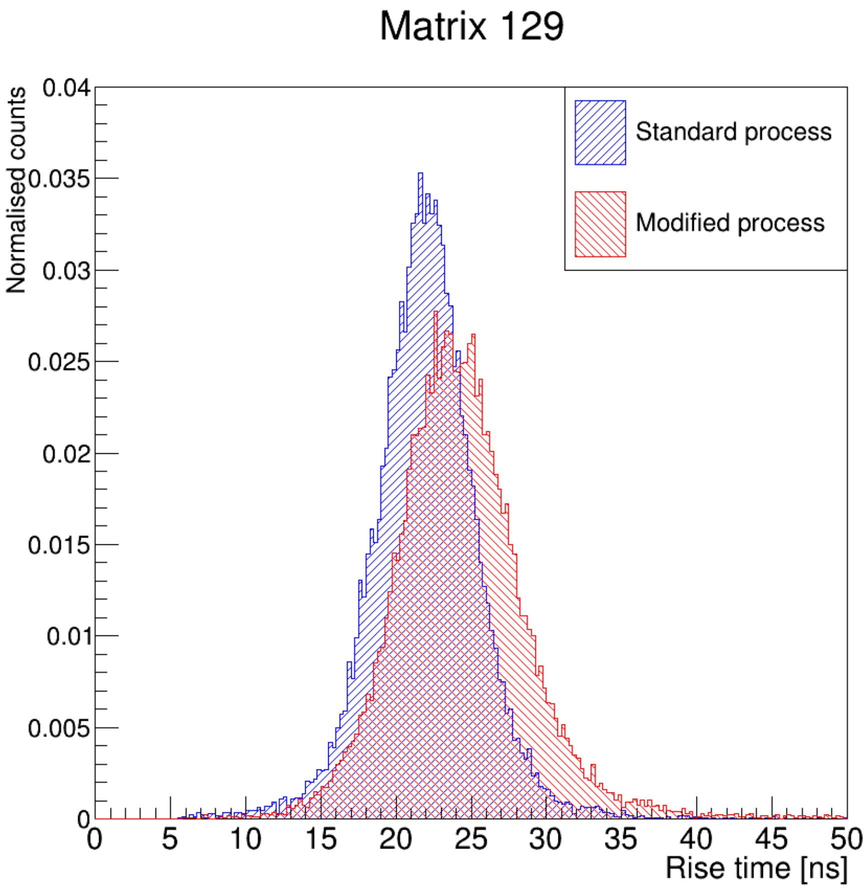


Rise time

Matrix 129 – 50x50 μm^2



Amplitude



Rise time

Rise time

- Faster and more uniform charge collection for pixels with small spacing between collection electrode and p-well in the modified process.
- When spacing becomes larger, charge collection is slower in the modified process. The distribution widens indicating non-uniform charge collection.

Matrix number	Mean rise time [ns]		Distribution width [ns]	
	Standard	Modified	Standard	Modified
2 (20x20 μm^2)	22.78±0.12	22.23±0.11	3.145±0.145	2.960±0.120
75 (28x28 μm^2)	29.72±0.14	23.25±0.11	4.090±0.110	2.810±0.120
106 (30x30 μm^2)	27.71±0.15	23.78±0.10	4.051±0.161	2.642±0.088
118 (40x40 μm^2)	22.29±0.09	23.21±0.11	2.607±0.073	3.322±0.110
124 (50x50 μm^2)	22.58±0.09	24.49±0.10	2.892±0.077	3.462±0.077
129 (50x50 μm^2)	22.87±0.09	24.70±0.10	3.149±0.082	3.871±0.103

Observations

- Indications that charge collection properties can be improved by larger depletion in modified process
  - Charges collected by drift, faster and larger signal
- Signal-to-noise ratio improved for all pixel sizes
- Faster and more uniform charge collection observed for pixels larger than 20x20 μm^2, with small spacing between collection electrode and p-well
  - Slower and less uniform charge collection for pixels with large spacing

→Process performance dependent on sensor layout parameters

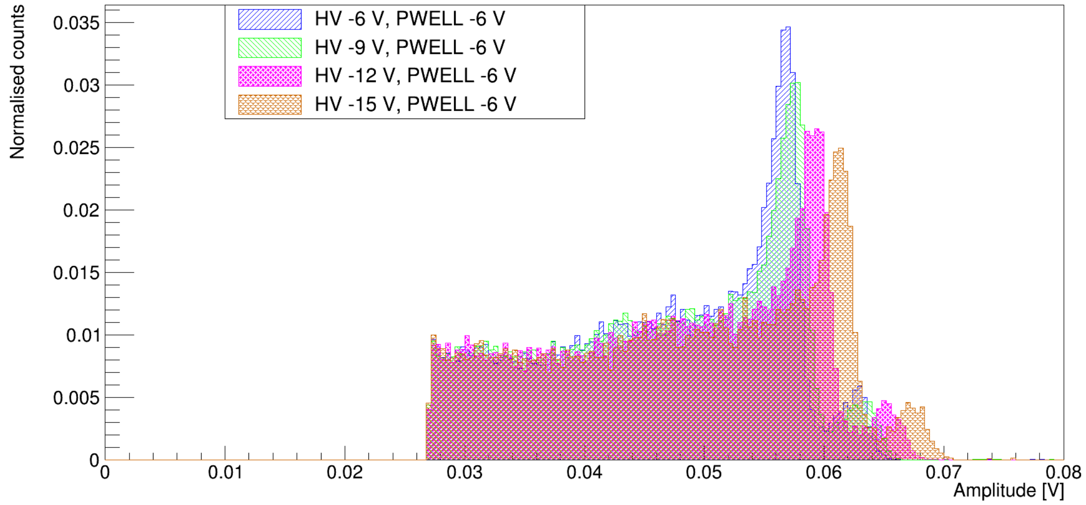
→Sweet spot at 28x28 μm^2 with small spacing and HV=p-well=-6V (improved charge collection speed and larger signal-to-noise ratio)

TowerJazz Investigator 1b

TowerJazz Investigator 1B

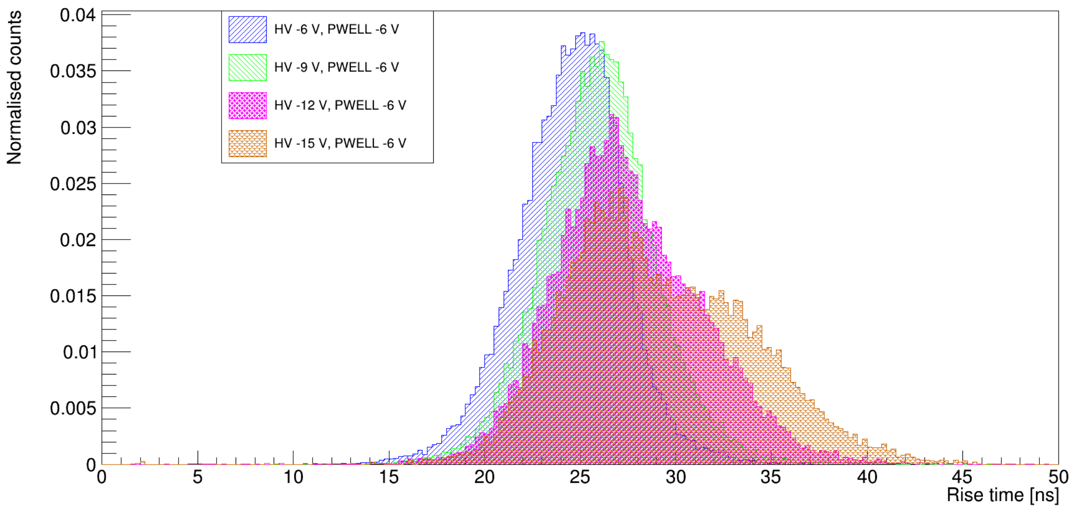
- Available in modified process only.
- Allows **separate biasing** for p-well and substrate high voltage, otherwise identical to the TJ1.
- Study of influence of sensor bias voltage on charge collection properties.

Matrix 75 (28x28 μm^2)



- Histograms normalised by the total number of counts.
- Amplitudes for peaks is higher for higher HV bias → gain change.
- Signal-to-noise ratio decreases with higher HV bias
  - This is not seen by CERN collaborators.
  - Still under investigation.

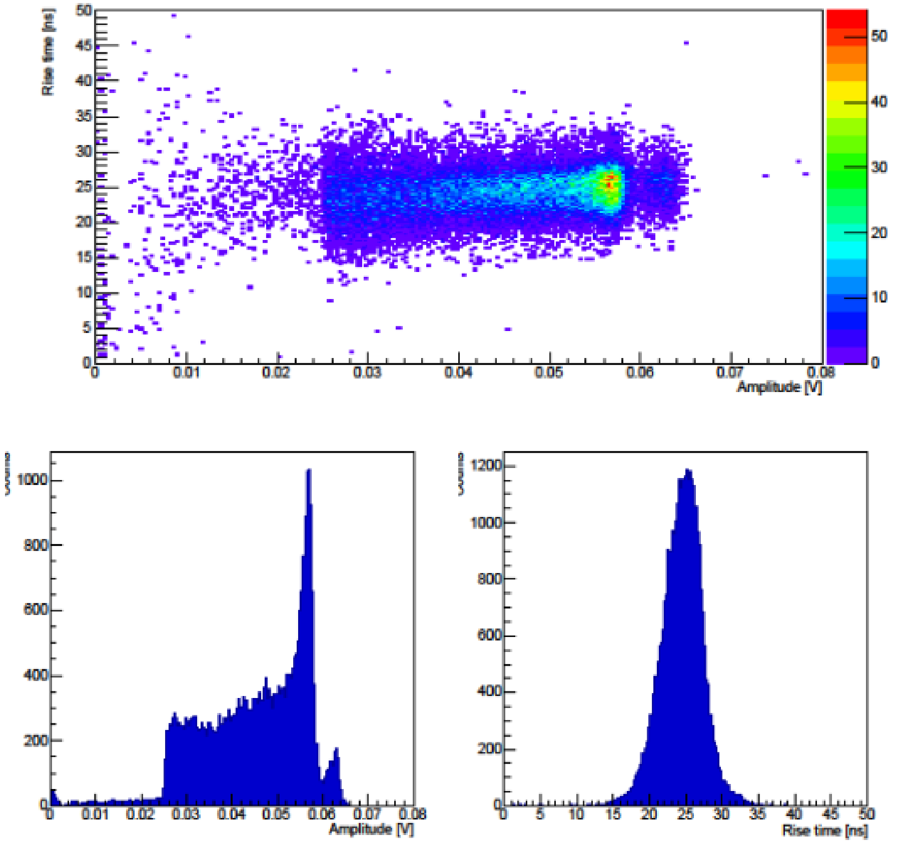
Matrix 75 (28x28 μm^2)



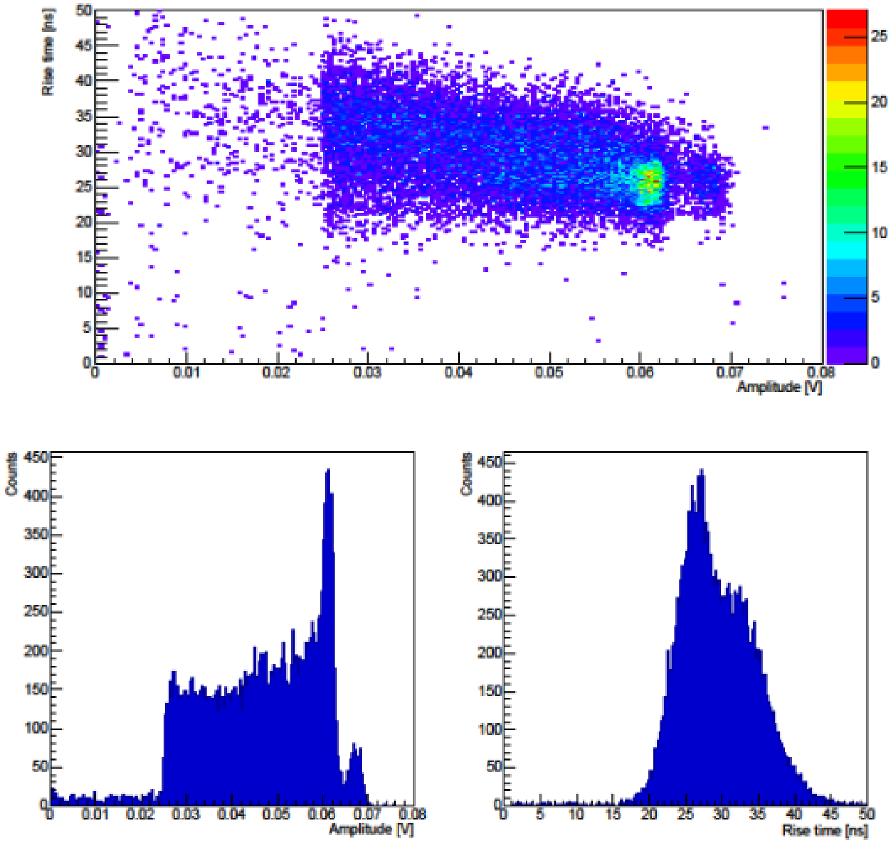
- Histograms normalised by the total number of counts.
- Rise time distribution changes with higher HV.
- Second peak appearing at HV < -12V.

Matrix 75 (28x28 μm^2)

HV -6 V



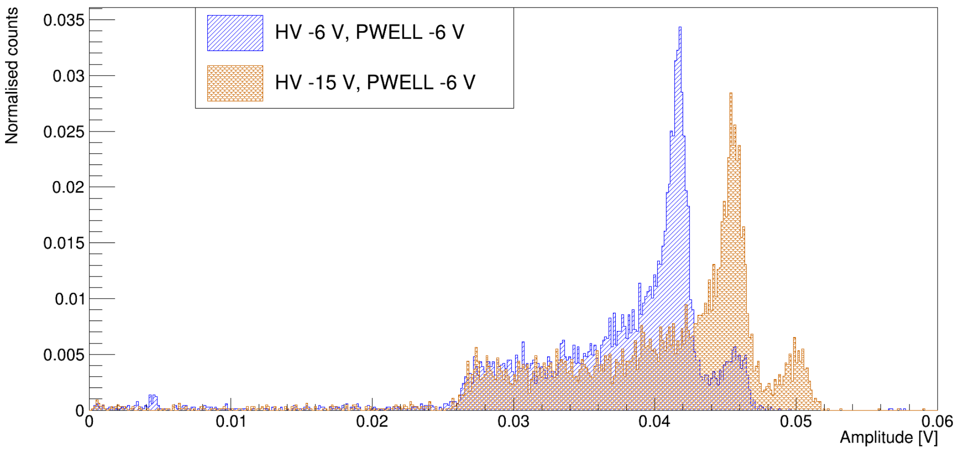
HV -15 V

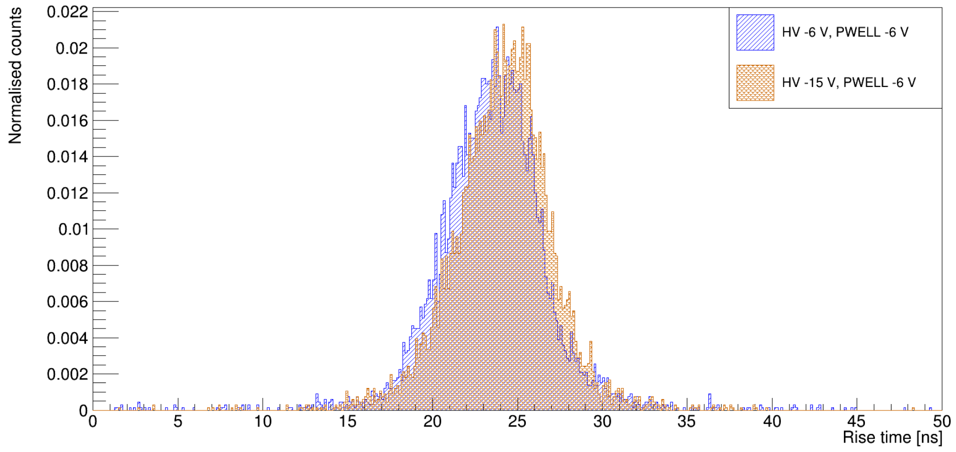


- Small charges collected slower than large charges for higher HV

Matrix 2 (20x20 μm^2)

- Only two measurements done; HV -6 V and HV -15 V, for PWELL -6 V.
- Decrease in signal-to-noise ratio at higher HV bias visible
- Rise-time distribution does not change with increasing HV as for 28x28 μm^2 pixel

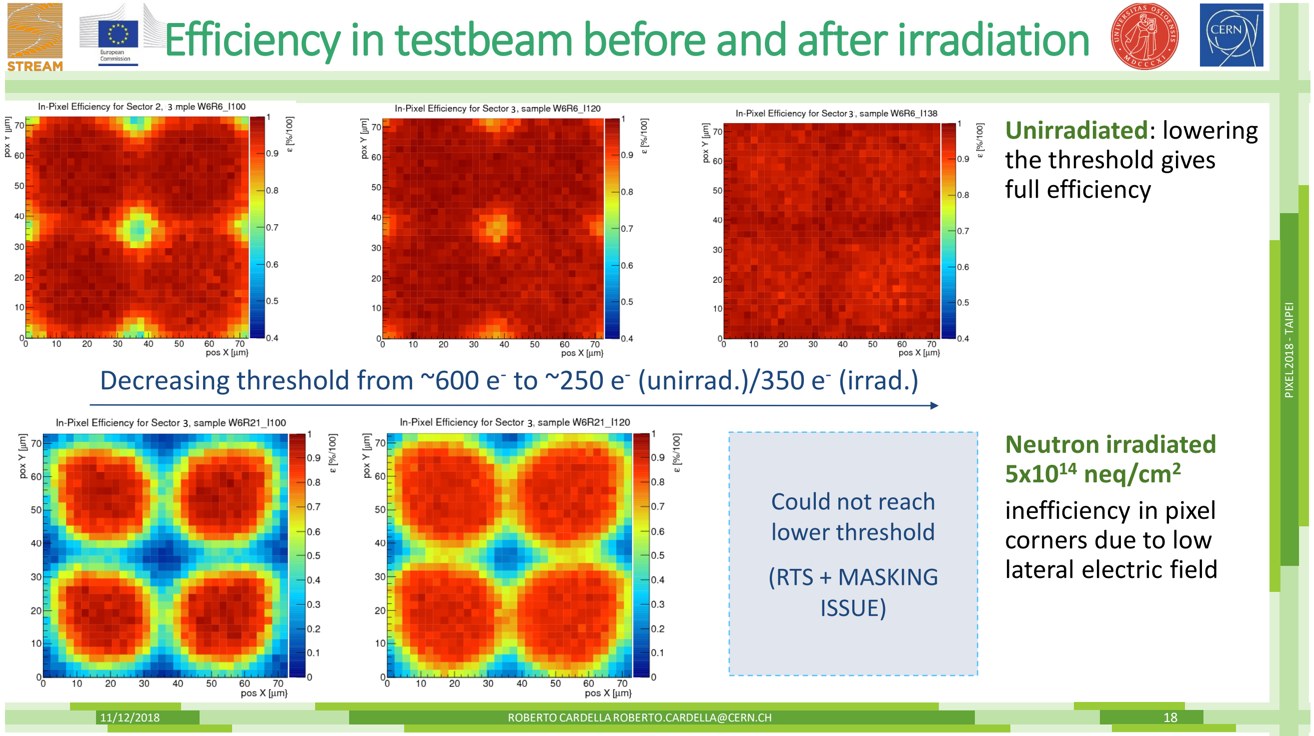




Results from MALTA sensor

- 36.4 x 36.4 μm^2 pixel, 3-4 μm spacing, 25 ns integration time, same submission as TJ1B/TJ2
- Low efficiency at pixel edges already before irradiation

R. Cardella *et al, MALTA: an asynchronous readout CMOS monolithic pixel detector for the ATLAS High-Luminosity upgrade,* 2019 *JINST* **14** C06019



https://indico.cern.ch/event/669866/contributions/3235298/attachments/1768859/2873169/PIXEL2018_MALTA.pdf

TCAD simulations

M. Munker *et al, Simulations of CMOS pixel sensors with a small collection electrode, improved for a faster charge collection and increased radiation tolerance,* 2019 *JINST* **14** C05013

- TCAD simulations based on MALTA design
- Issue with electric field at pixel border
  - Charges pushed to potential minimum between pixels and then slowly drifting to collection electrode
- Critical design factor: extent of the p-well containing the electronics
- Sensor layout modifications (n-gap, deep p-well) bend the electric field lines towards the collection electrode and show faster and larger charge collection from pixel edge
- Increasing the HV above the p-well voltage
  - Modified process: slower charge collection and reduced signal at pixel corner
  - Modified process with modifications: faster charge collection and increased signal at pixel corner

TJ1b rise time results explanation based on TCAD

- Charges collected at the edge of the pixel are small because of charge sharing
- These charges drift along a longer path than charges collected closer to the middle of the pixel
- Increasing the HV above -6V makes the drift from the pixel edge slower
- In a 28 x 28 μm^2 pixel, the rise time distribution widens, and small charges appear as a second slower peak for increasing HV
- For smaller pixel sizes, where the p-well covers a smaller percentage of the pixel size, the charge collection speed is not influenced by the HV

Mini-MALTA

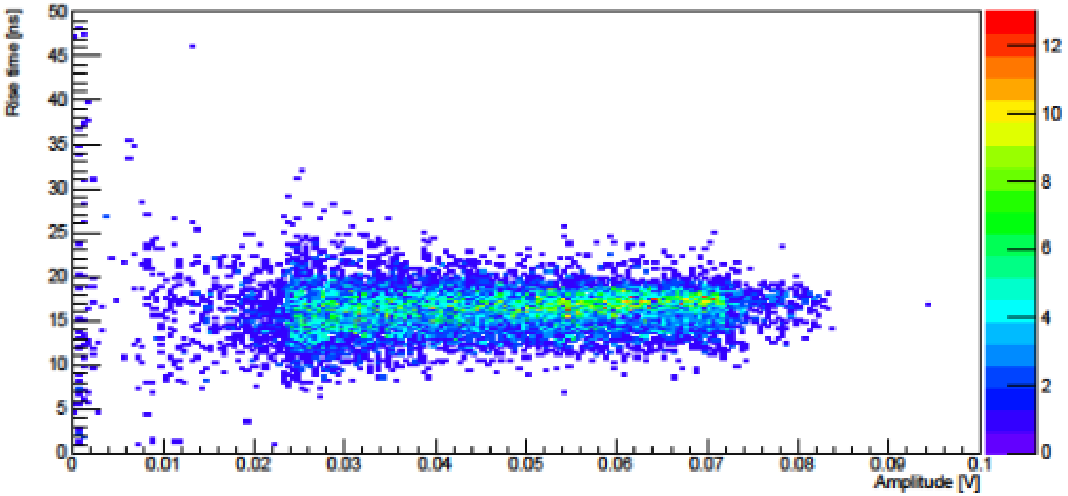
R. Cardella *et al, MALTA: an asynchronous readout CMOS monolithic pixel detector for the ATLAS High-Luminosity upgrade,* 2019 *JINST* **14** C06019

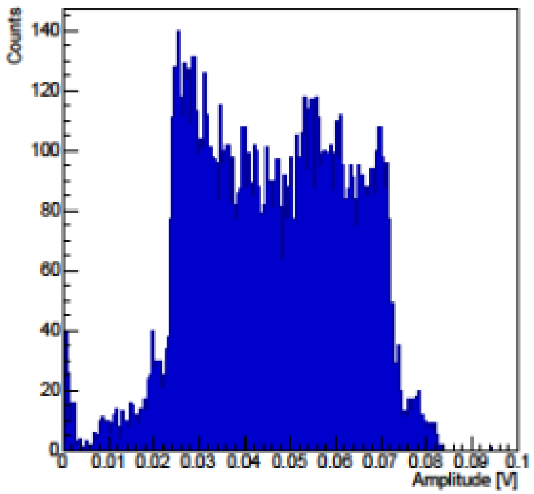
- Pixel size: 36.4 x 36.4 μm^2
- 64x16 pixel matrix includes 8 sectors with splits on analogue front-end design, reset mechanism and **process modifications (n-gap, extra deep p-well)**
- On-going analysis of beam tests at different facilities
- UoB working on Diamond test beam data analysis
  - Preliminary results indicate improved tracking efficiency with sensor modifications
  - Results are being prepared for publication with Oxford and CERN colleagues

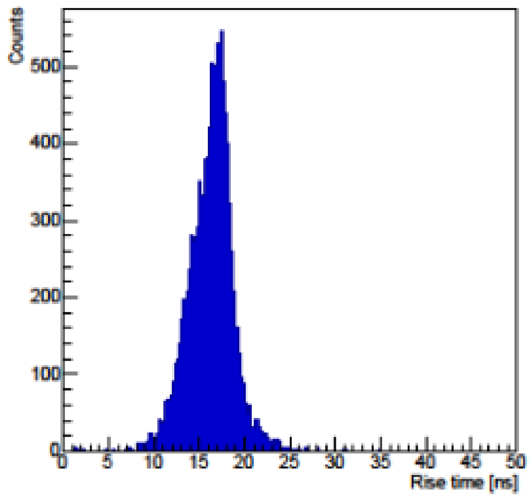
TowerJazz Investigator 2

Matrix 75 (28x28 μm²)

- PWELL -6 V, HV -6 V.
- Amplitude very noisy; x-ray peaks not clearly visible.
  - Possibly still wrong values of bias current.
- Faster rise time than TJ1 and TJ1b, as expected from readout modification.







Conclusion on TJ investigators

- The modified process improves charge collection properties but the sensor layout is crucial
  - Small spacing between collection electrode and p-well
  - n-gap or deep p-well between pixels
- Increasing the substrate bias voltage
  - Worsens charge collection properties of the modified process
  - Maintains improved charge collection properties with the n-gap or extra deep p-well modifications
- Without n-gap or extra deep p-well, sweet spot for 28 x 28 μm^2 and -6V common on p-well and substrate