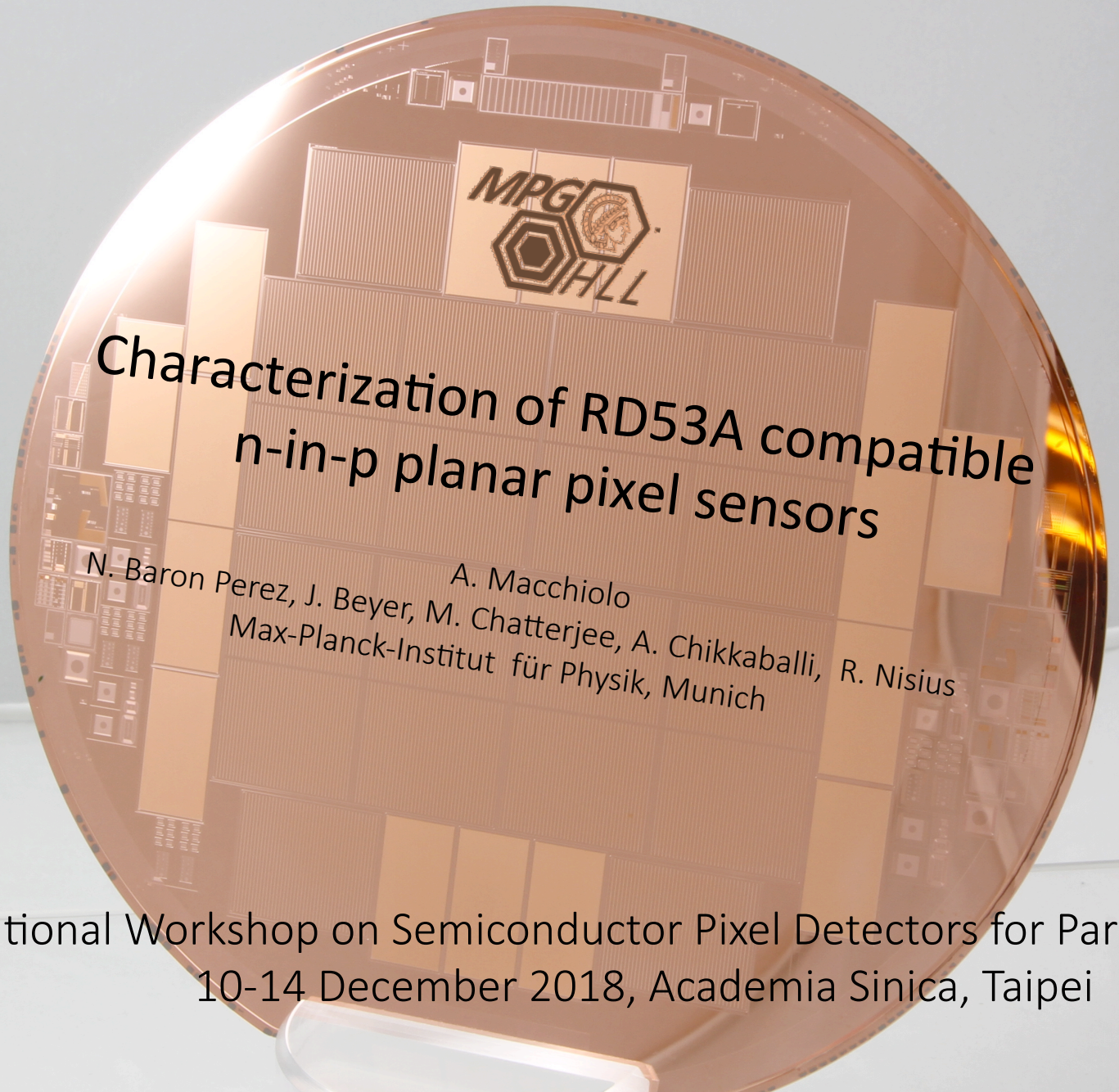
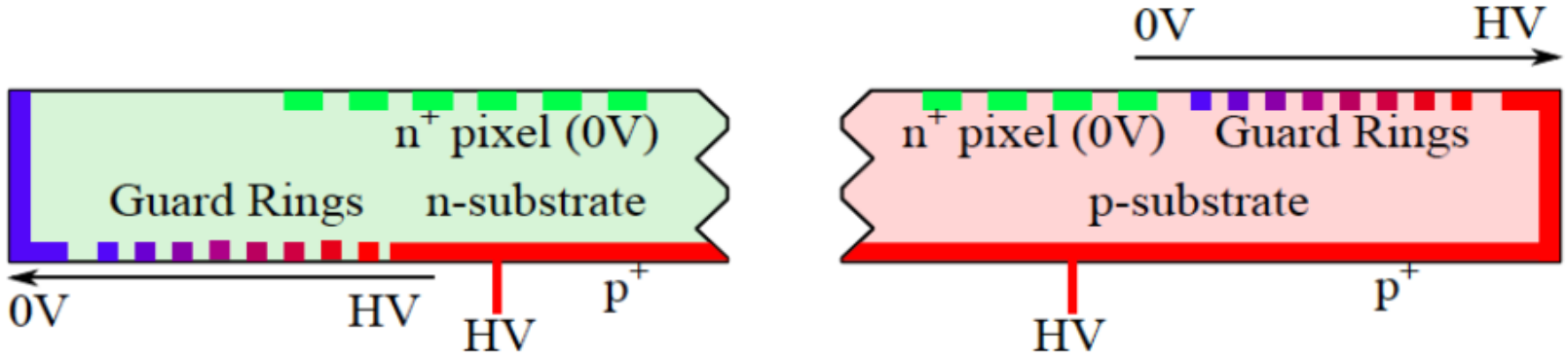


Characterization of RD53A compatible n-in-p planar pixel sensors

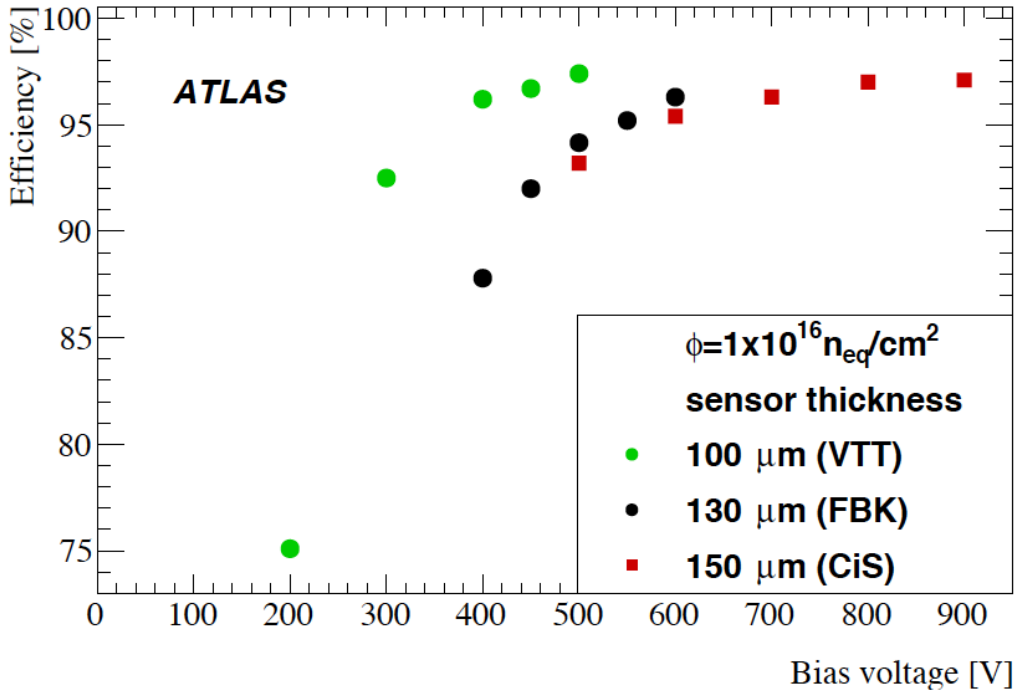
A. Macchiolo
N. Baron Perez, J. Beyer, M. Chatterjee, A. Chikkaballi, R. Nisius
Max-Planck-Institut für Physik, Munich

9th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging
10-14 December 2018, Academia Sinica, Taipei

Planar Sensors for the HL-LHC Pixel Upgrades

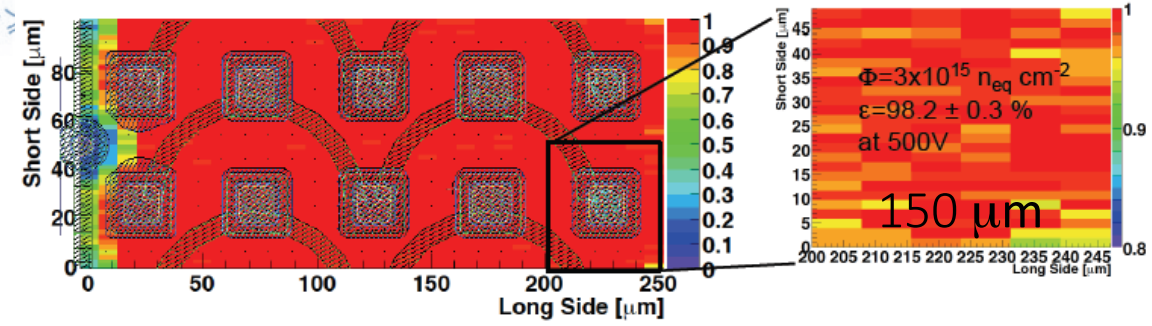


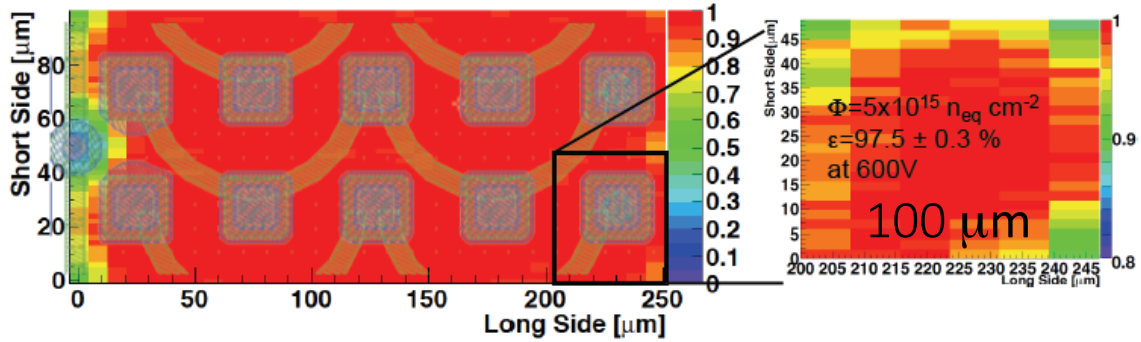
- N-in-p technology chosen for cost reduction and easier handling: baseline from second to fifth layer in ATLAS ITk pixel system
- Thinner sensors reach charge and hit efficiency saturation at lower bias voltages → reduced power dissipation
  - 100 μm thin sensors baseline in the second layer
  - 150 μm thin sensors in the outermost layers
- Localized charge loss due to biasing structures after irradiation → effect in here evaluated with the lower thresholds obtained with the RD53A chip



From the FE-I4 to the RD53A chip

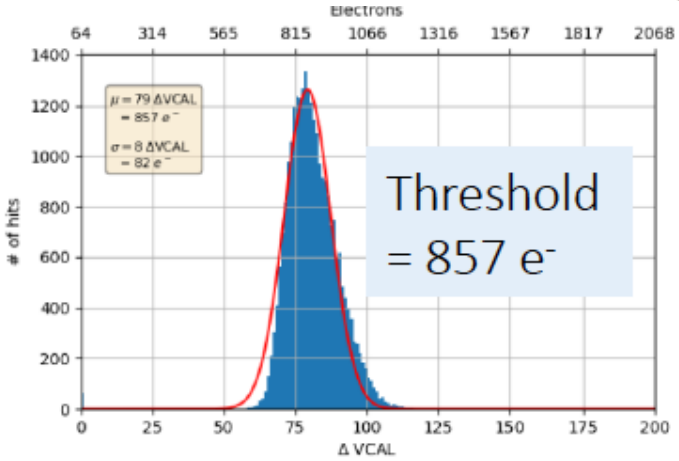
N. Savic, PhD thesis, LMU Munich, 2017





- Estimation of 50x50 μm² performance obtained with FE-I4 modules (**50x250 μm²**) mimicking small pixel cells:
  - FE-I4 chip is affected from a shift between nominal tuned values (1.0-1.5ke in our previous studies) and real threshold (2-2.5 ke)

R. Taibah, Master thesis, LMU Munich, 2018



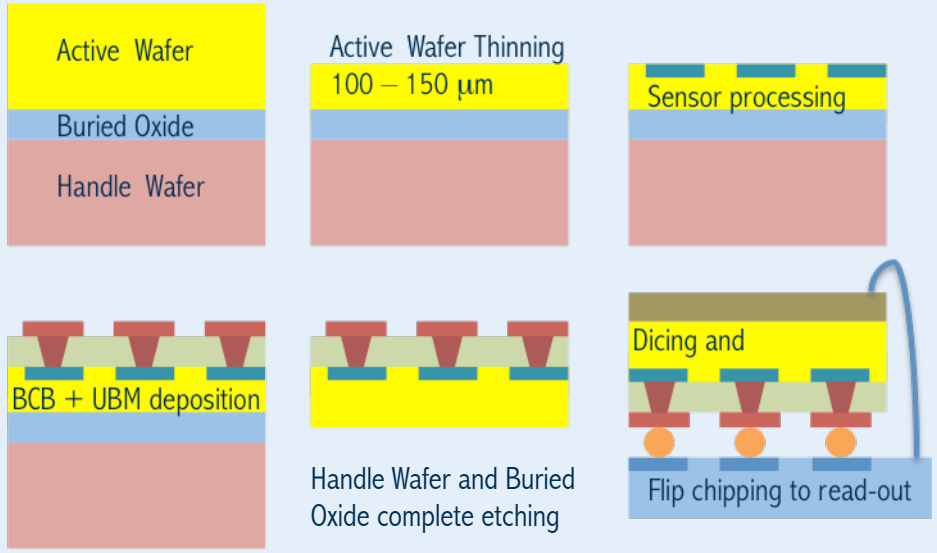
Results obtained with RD53A modules:
- Lower thresholds achievable

DISCLAIMER: the chip tuning has not been optimized →
the following studies are only focused on sensor performance!

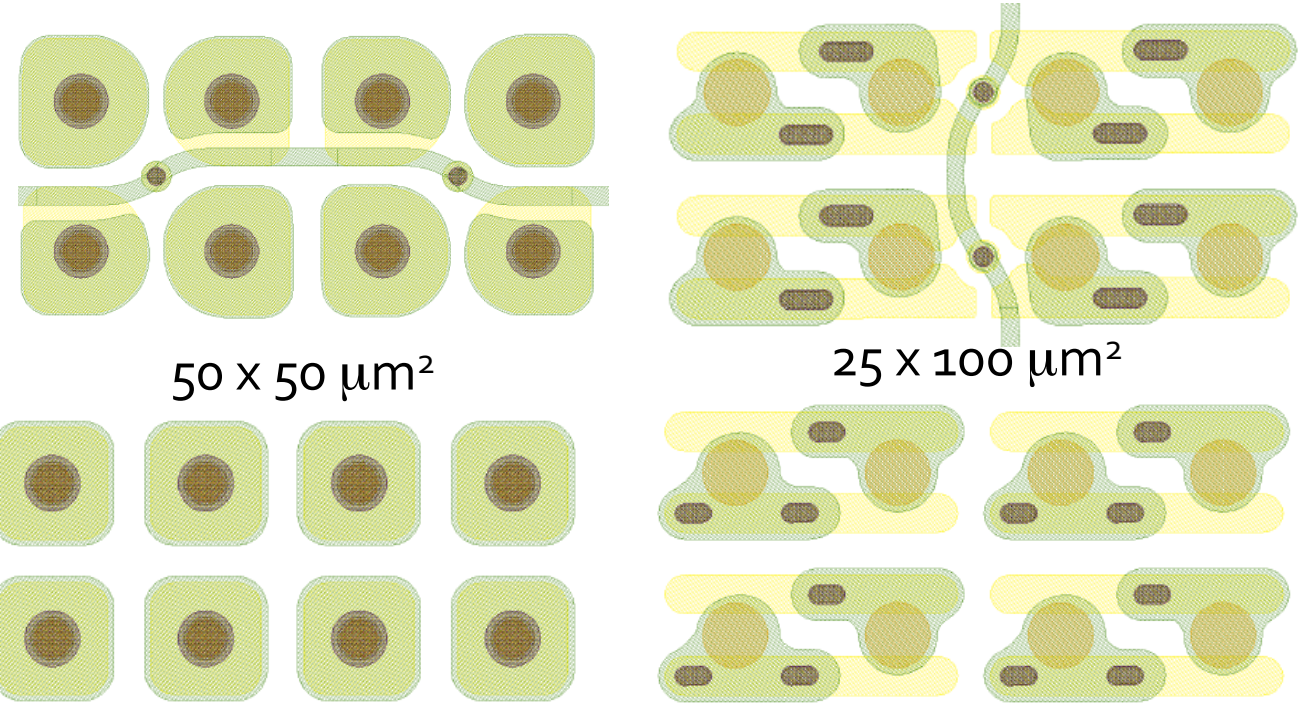
A. Macchiolo, Characterization of RD53A compatible n-in-p planar sensors, PIXEL 2018, 12 December 2018

Production technology and sensor design

- HLL SOI4 production: 8 wafers produced with 100 and 150 µm active thickness
- Cu UBM and BCB passivation deposited at HLL
- Many single chip RD53A sensors: 50x50 and 25x100 µm^2
- Thinning and Aluminum on the backside deposition performed at IZM



With biasing structures

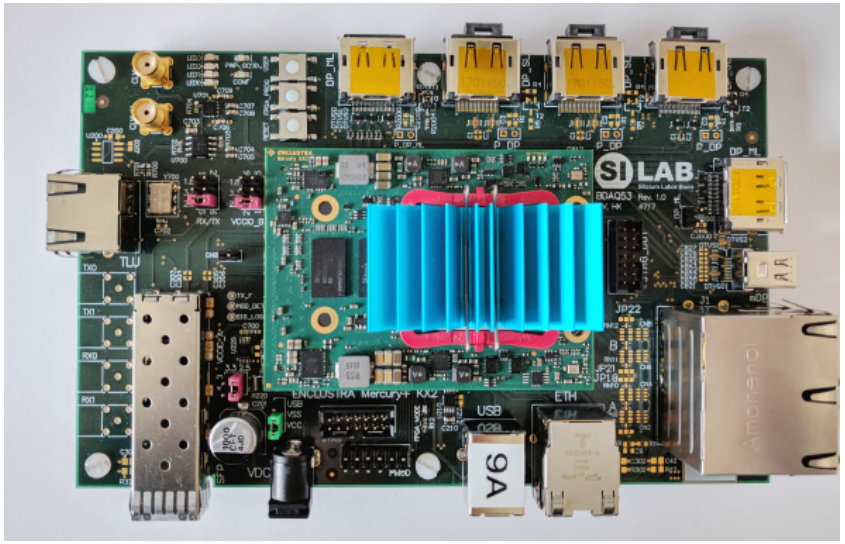


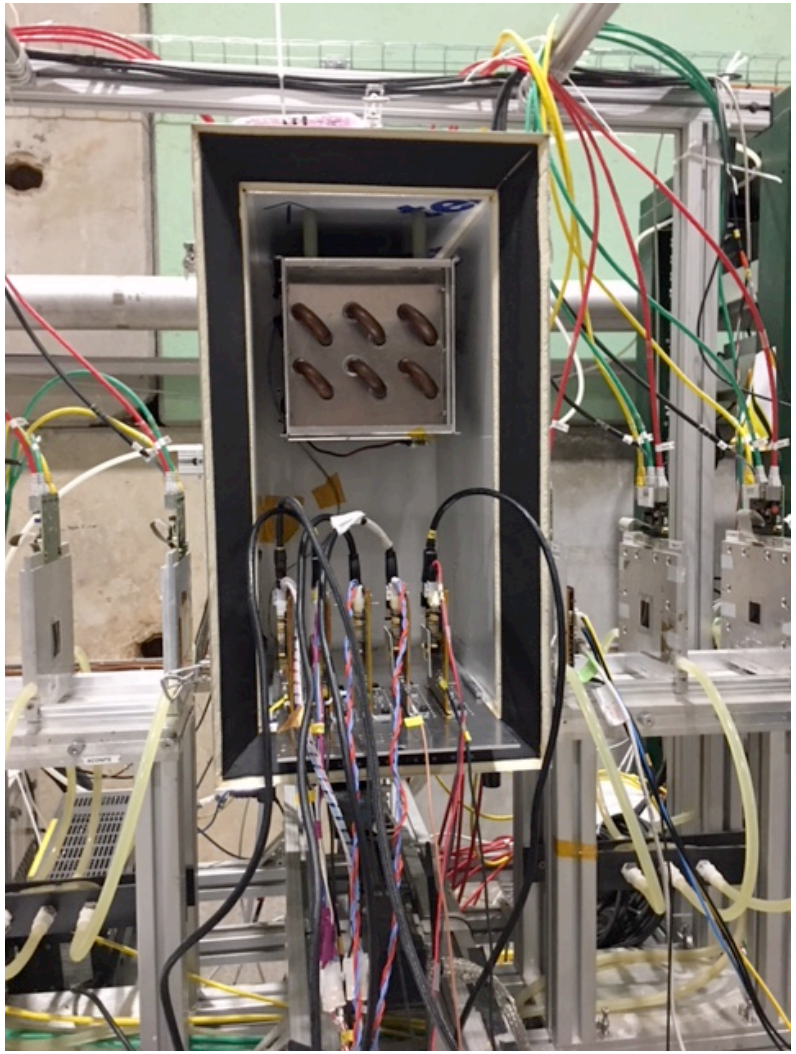
Without biasing structures

- Both geometries compatible with 50x50 µm^2 grid of the RD53A chip

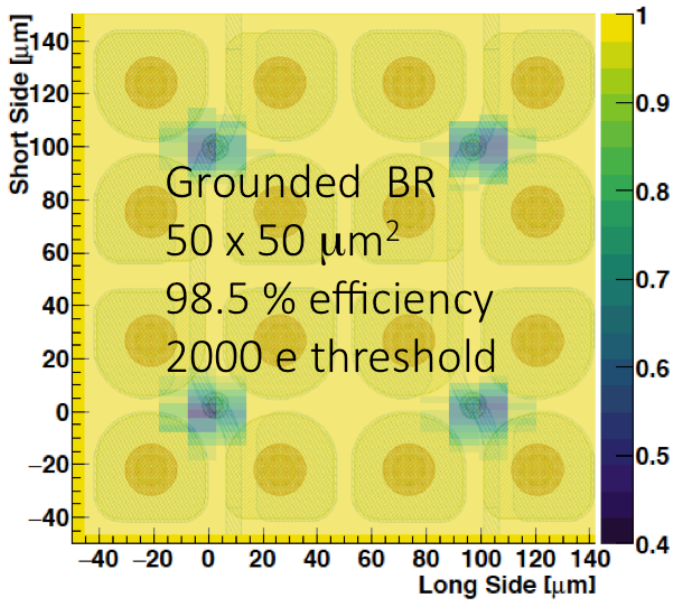
Test-beam analysis of RD53A planar pixel modules

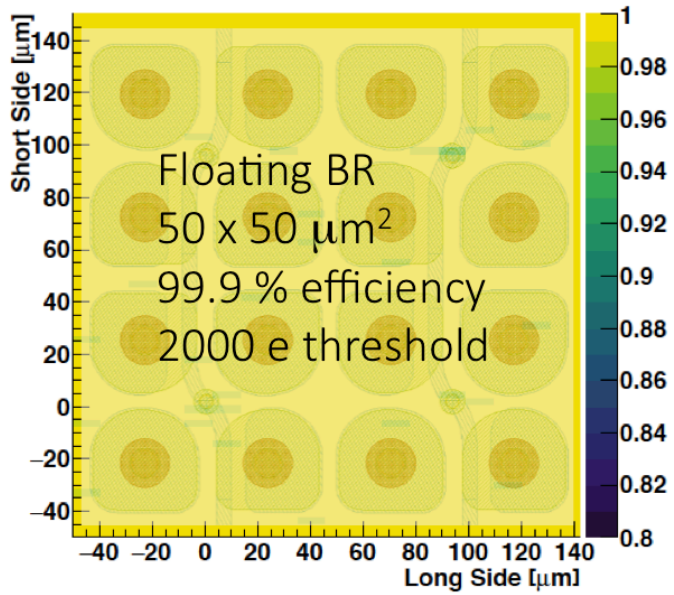
- RD53A modules mainly from the SOI4 HLL production
- Test before and after irradiation at PS at 5e15 and KIT at 3e15 and 5e15 n_{eq}/cm^2
- Measured during May –October 2018 at CERN SPS and in December at DESY with the BDAQ53 read-out
  - Thanks to Bonn colleagues for lending us the read-out boards and support in the learning phase!





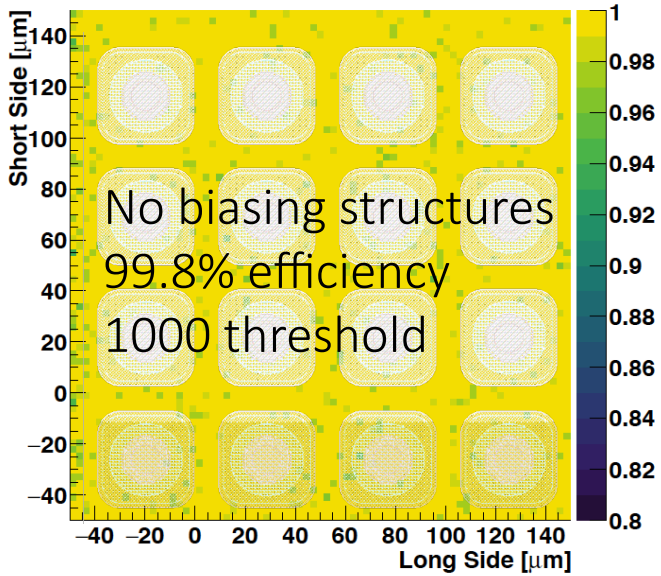
RD53A assemblies: biasing structure effects in 50x50 cells





J. Beyer, RD53A Testing Meeting

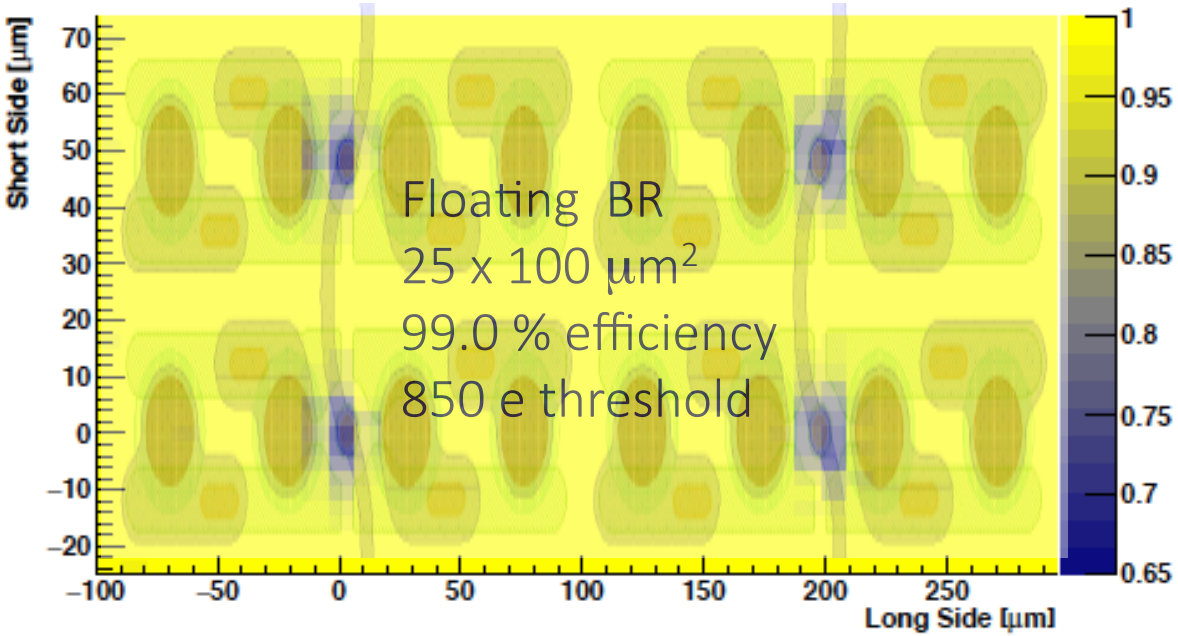
- The RD53A boards allow to ground or leave the BR floating
- 150 μm thick sensors, 50 V bias
  - With PT and floating BR
- 100 μm thick sensors, 50 V bias
  - Without biasing structures

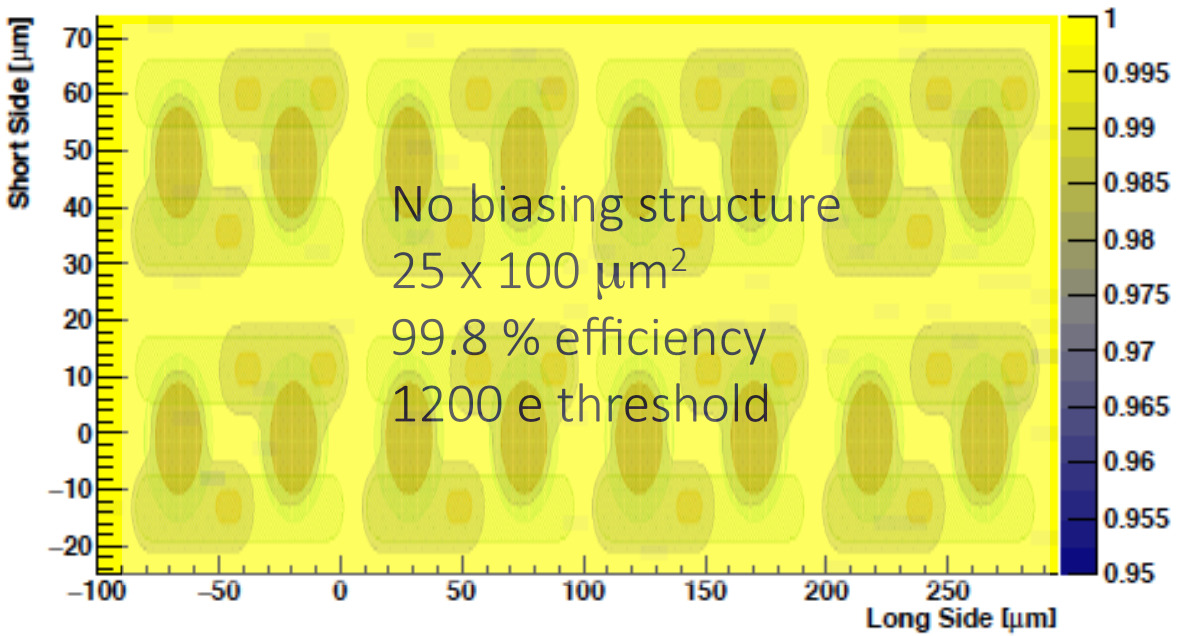


All measurements performed with the linear analog section if not otherwise stated

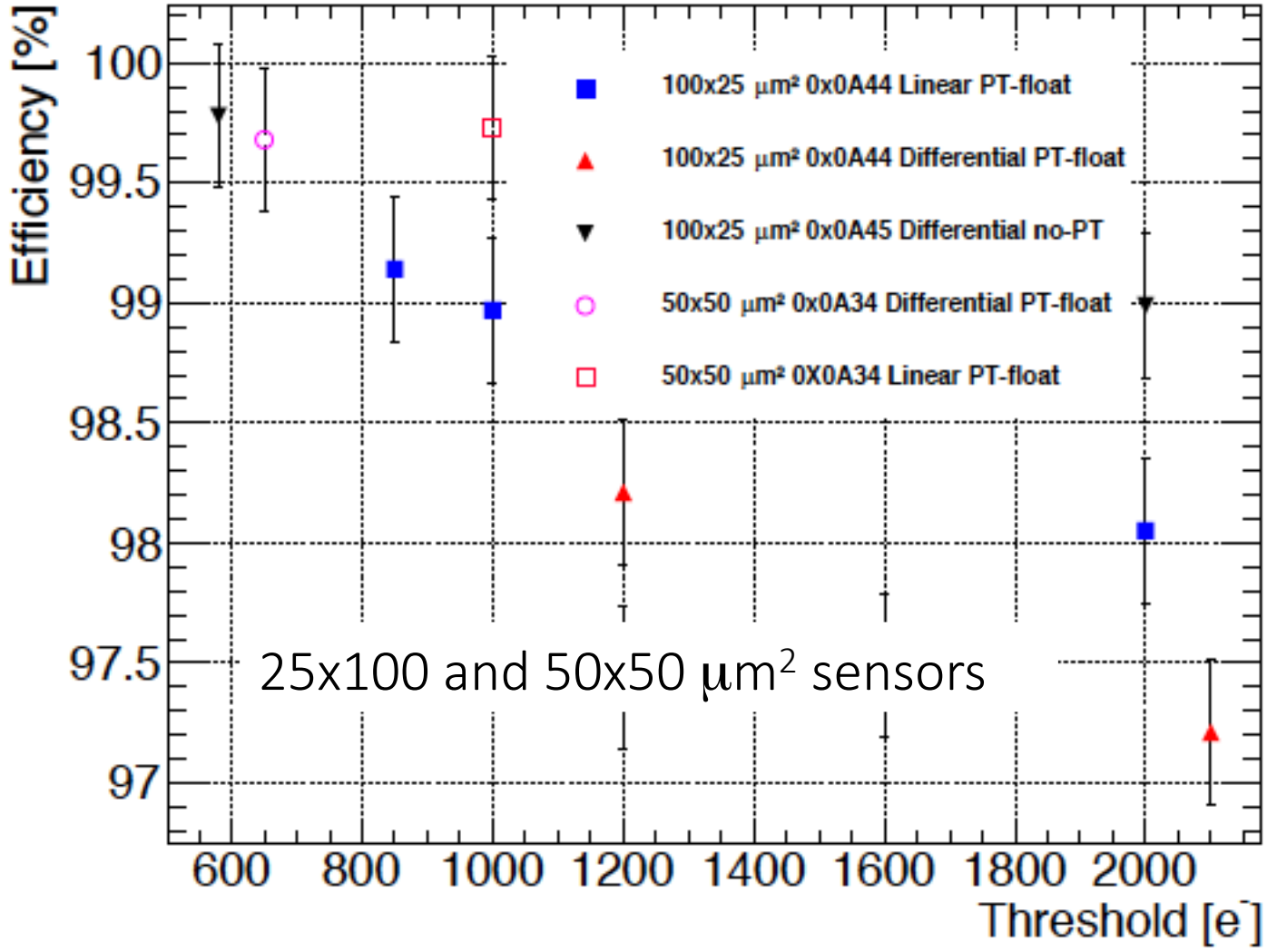
RD53A assemblies: biasing structure effect in 25x100 cells

J. Beyer, RD53A Testing Meeting





RD53A assemblies: threshold dependence

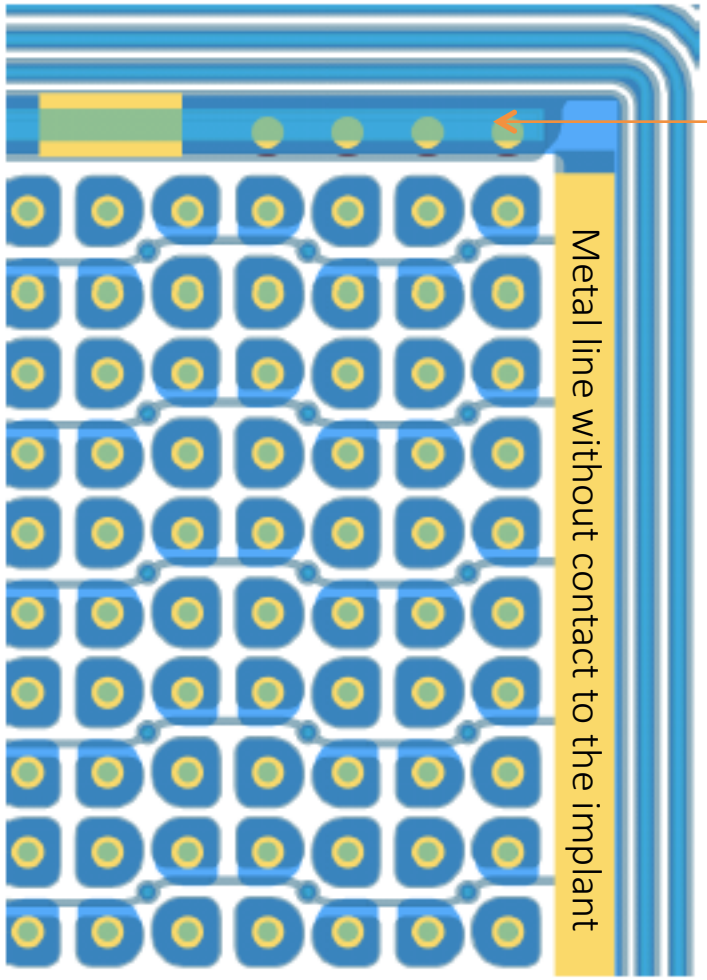


- Hit efficiency increasing with decreasing threshold
- Consistent results between Linear and Differential analog sections
- Sensors without biasing structures deliver higher efficiency

J. Beyer, RD53A Testing Meeting

The "Split" Design

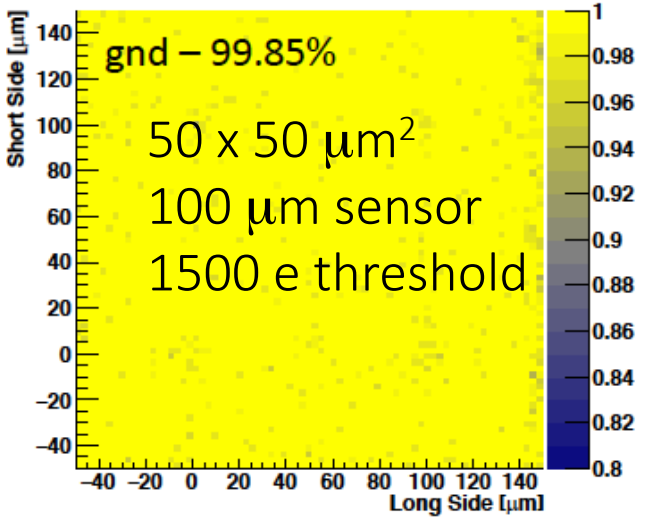
- Developed new design where the implant of the innermost ring can be grounded while the grid for testing is left floating after chip interconnection

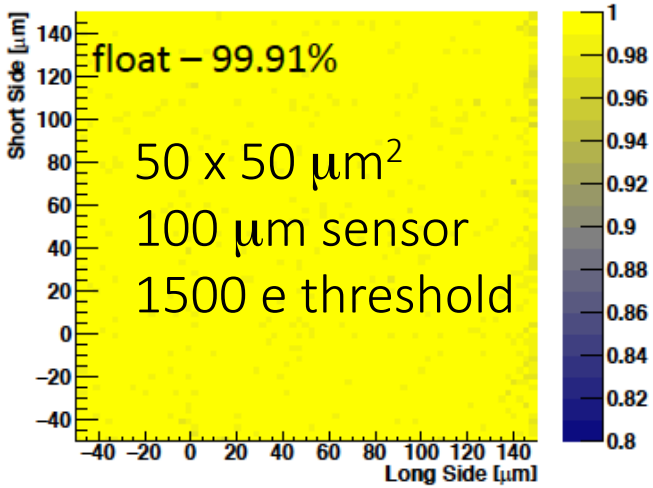


UBM pads on a metal line connected to the implant ring

- The ring implant intercept the sensor currents from the sensor edge avoiding the last columns and rows to become noisy
- Implant can be grounded or floating but PT is always floating

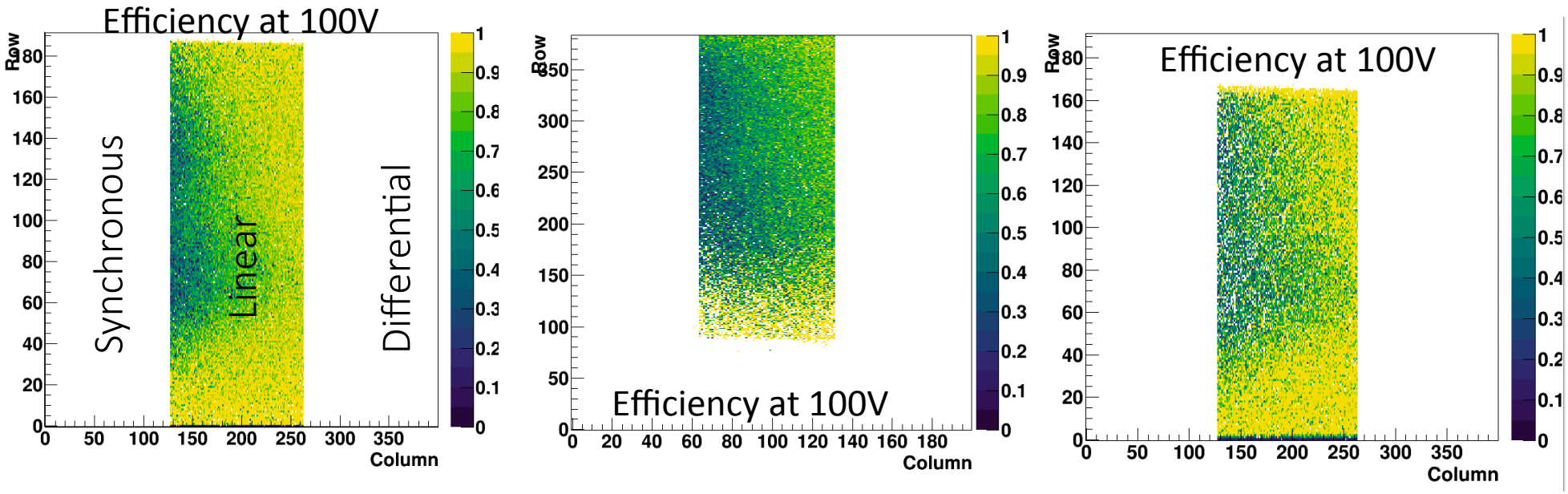
Same efficiency with grounded and floating BR

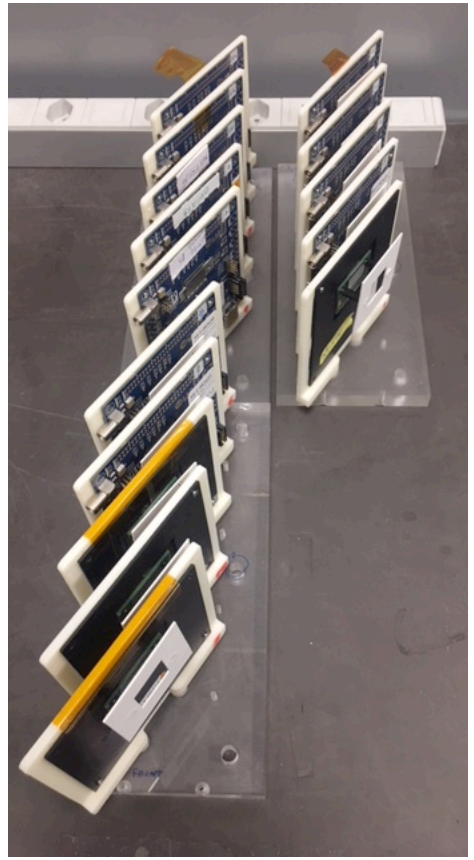




Irradiation at CERN PS

- Inclined irradiation at 55° in x to have more homogeneous irradiation
  - Nominal average fluence of $5x10^{15}$ n_{eq} cm^{-2} → slightly larger than the maximum fluence expected for planar sensors in ITk of $4x10^{15}$ n_{eq} cm^{-2}
  - The beam seems to be not centered on the module
  - Fluence decreases from synchronous -> linear -> differential
- Fluence for the linear section estimated to be $(5\pm1)x10^{15}$ n_{eq} cm^{-2}

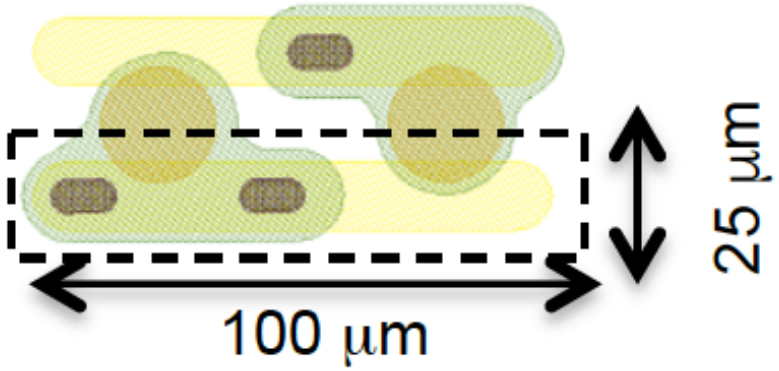


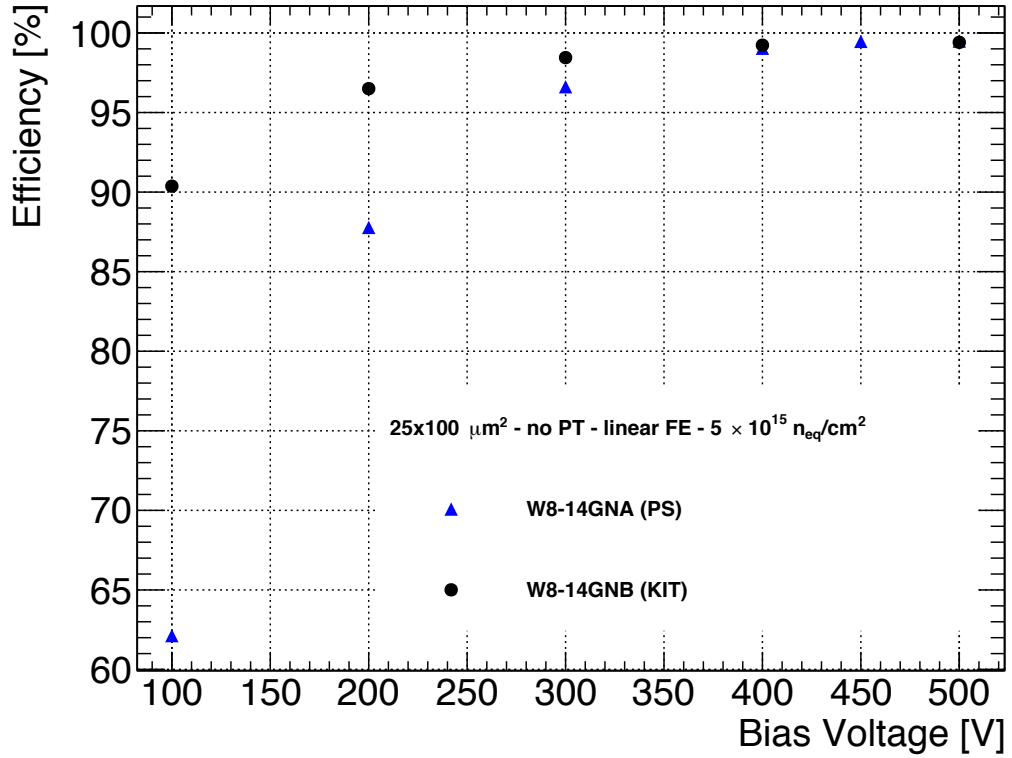


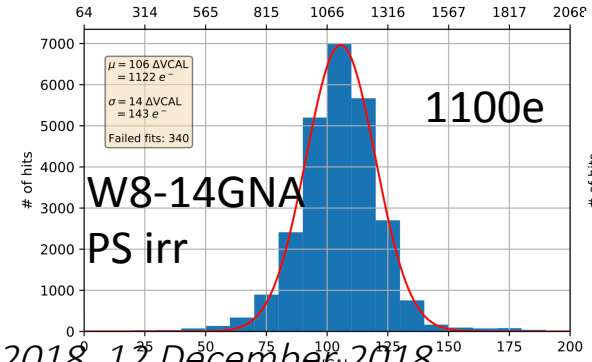
Many thanks to the CERN IRRAD and KIT teams for their support!

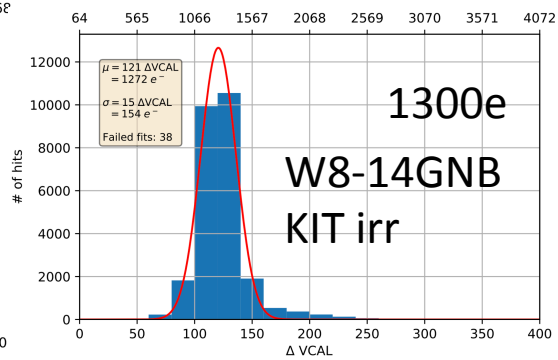
CERN PS- KIT Irradiation Comparison

- Two modules irradiated at CERN PS and KIT to a nominal fluence of $5x10^{15}n_{eq}/cm^2$
  - PS dose is average, KIT is homogeneous
- Same sensor design: 25x100 pixel cell, 150 μm thick sensors without PT
- Analysis performed with the Linear section of the RD53A chip
- Plateau efficiency: 99.0% (PS) - 99.4% (KIT)
- Looking to the evolution of the efficiency with the Bias Voltage it looks like the fluence received by the Linear part is higher than $5x10^{15}n_{eq}/cm^2$



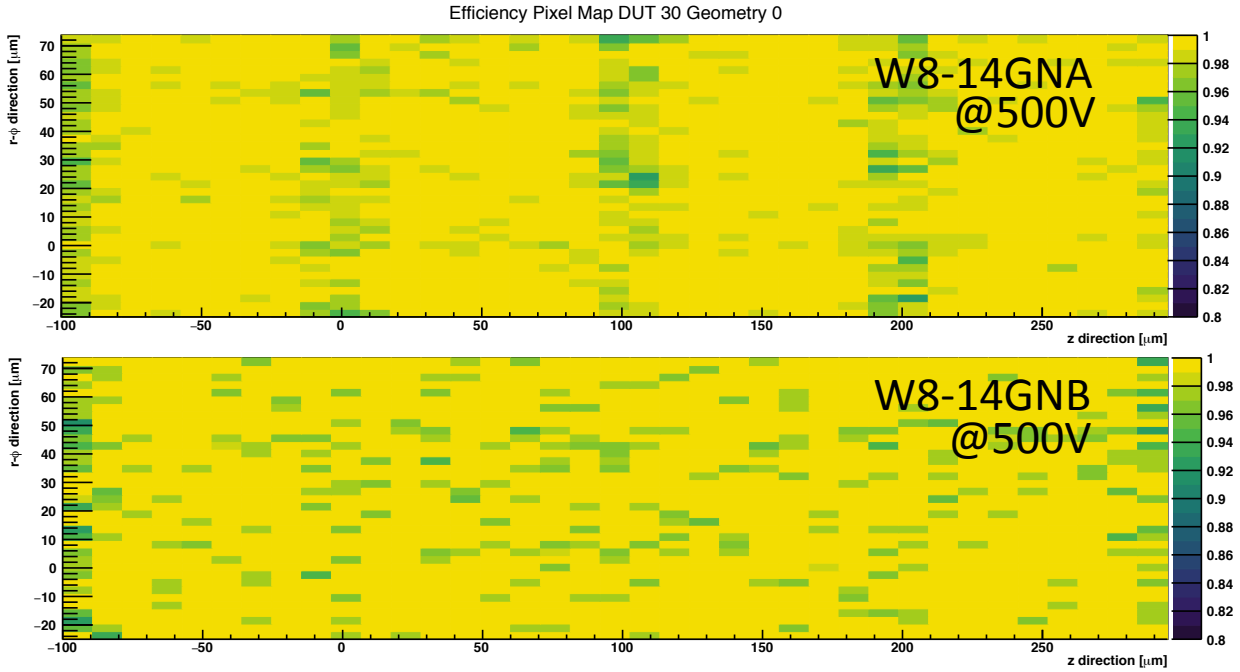


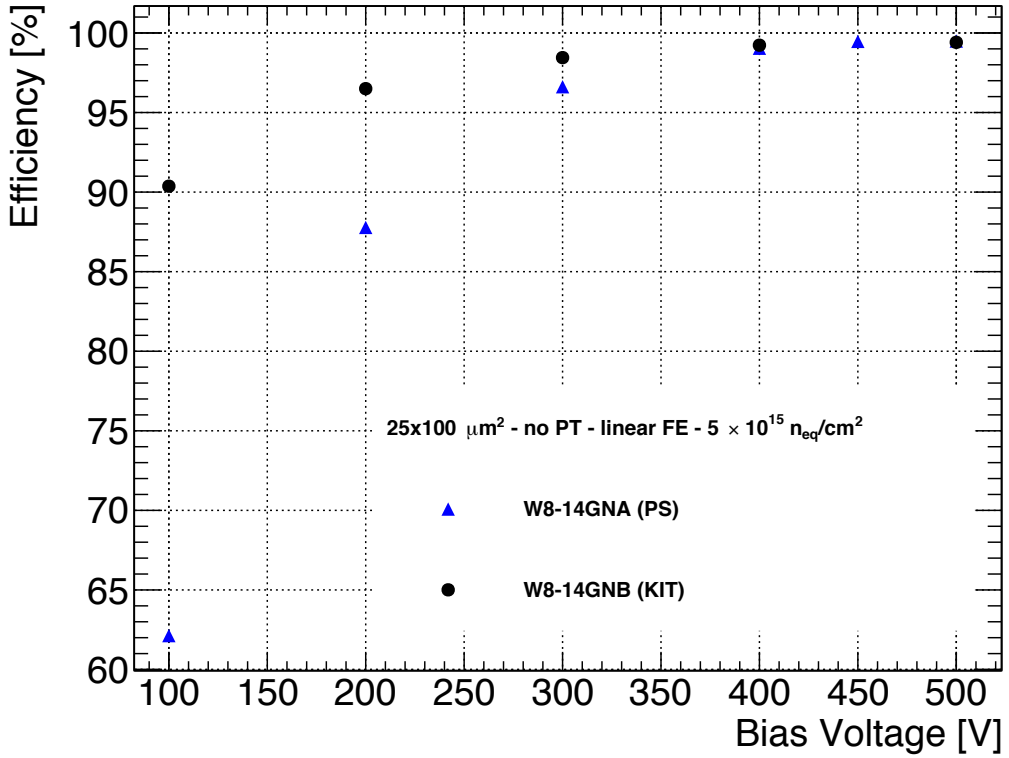


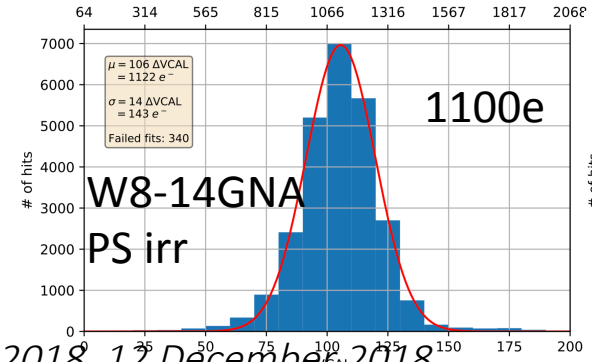


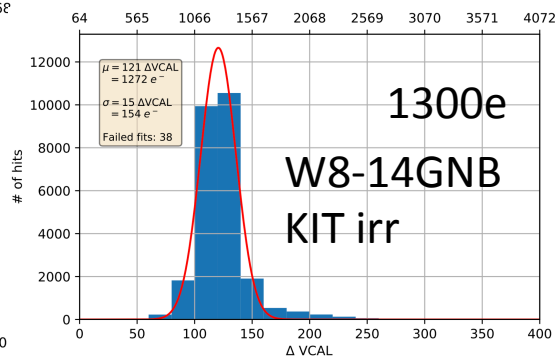
CERN PS- KIT Irradiation Comparison

- Two modules irradiated at CERN PS and KIT to a nominal fluence of $5x10^{15}n_{eq}/cm^2$
  - PS dose is average (will be higher in central region of linear FE), KIT is homogeneous
- Same sensor design: 25x100 pixel cell, 150 μm thick sensors without PT
- Analysis performed with the Linear section of the RD53A chip





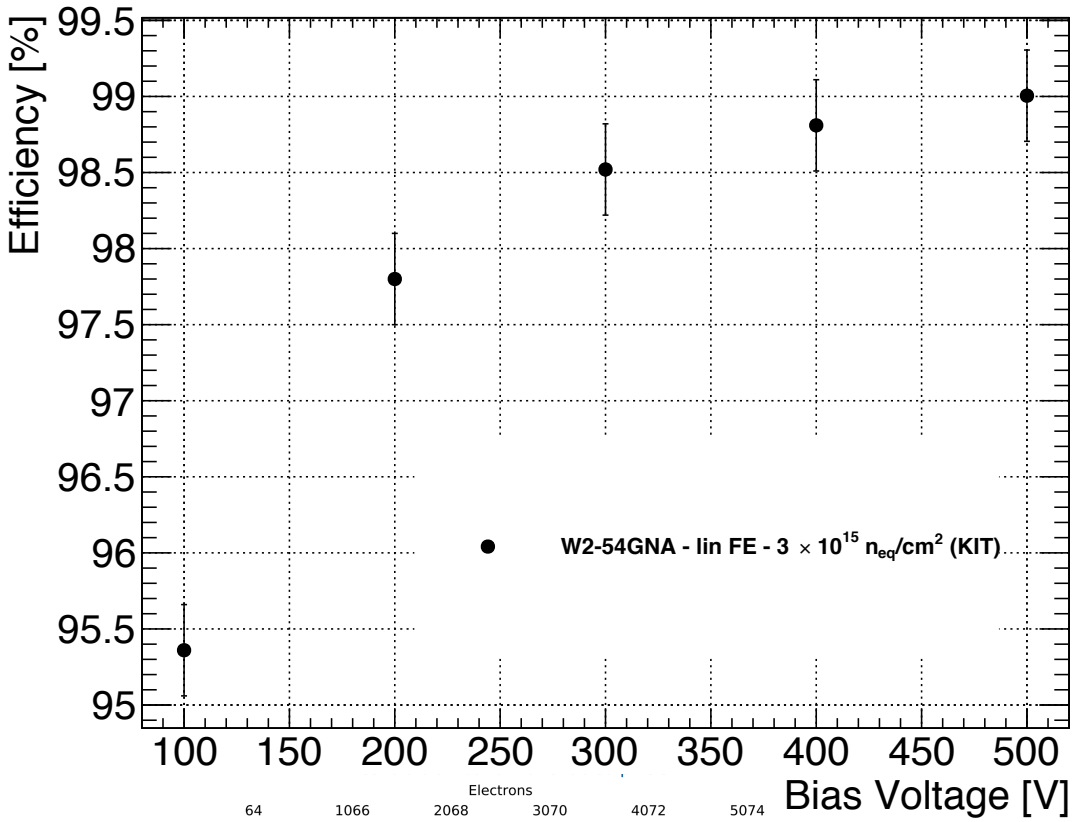


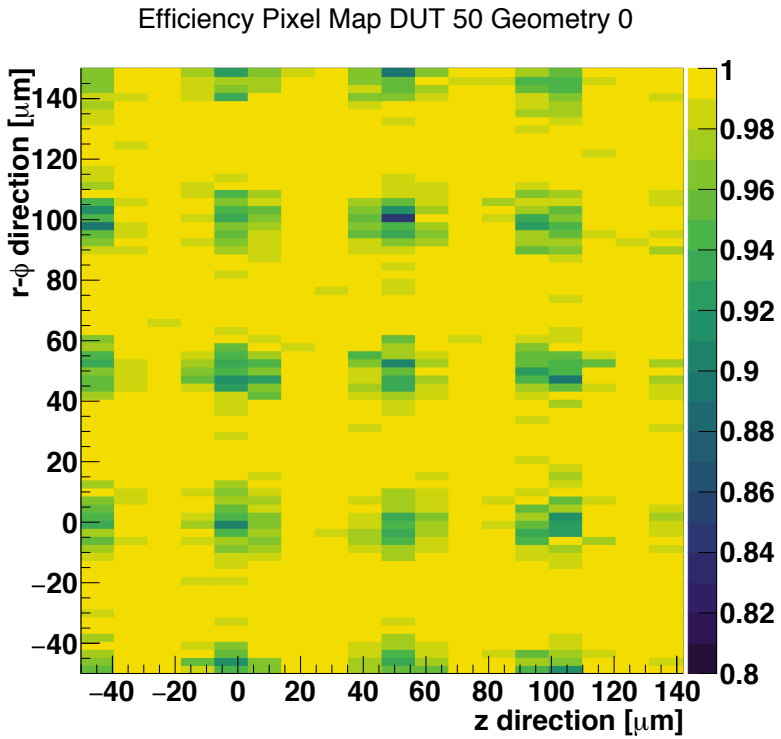


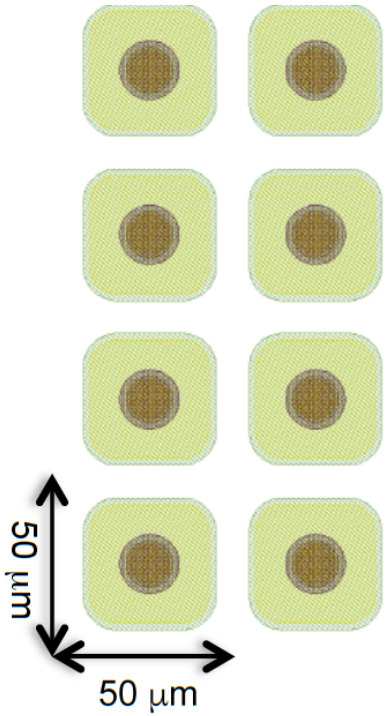
Again no biasing structures, but 50x50

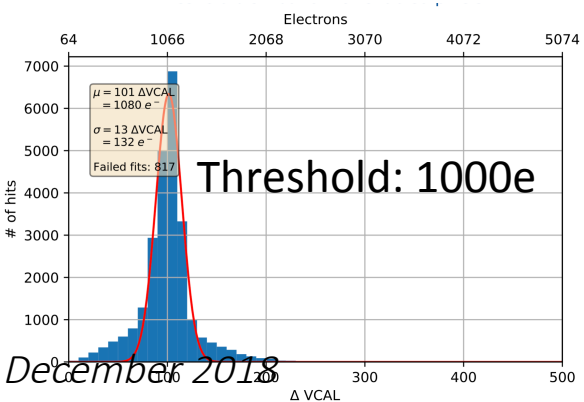
- Irradiated at KIT to $3x10^{15} n_{eq}/cm^2$
- Saturation of efficiency around 400V-500V
- Plateau efficiency: 99.0%
  - but even at 200V already >97% efficiency

100 μm thick sensor, Threshold ~1000 e-







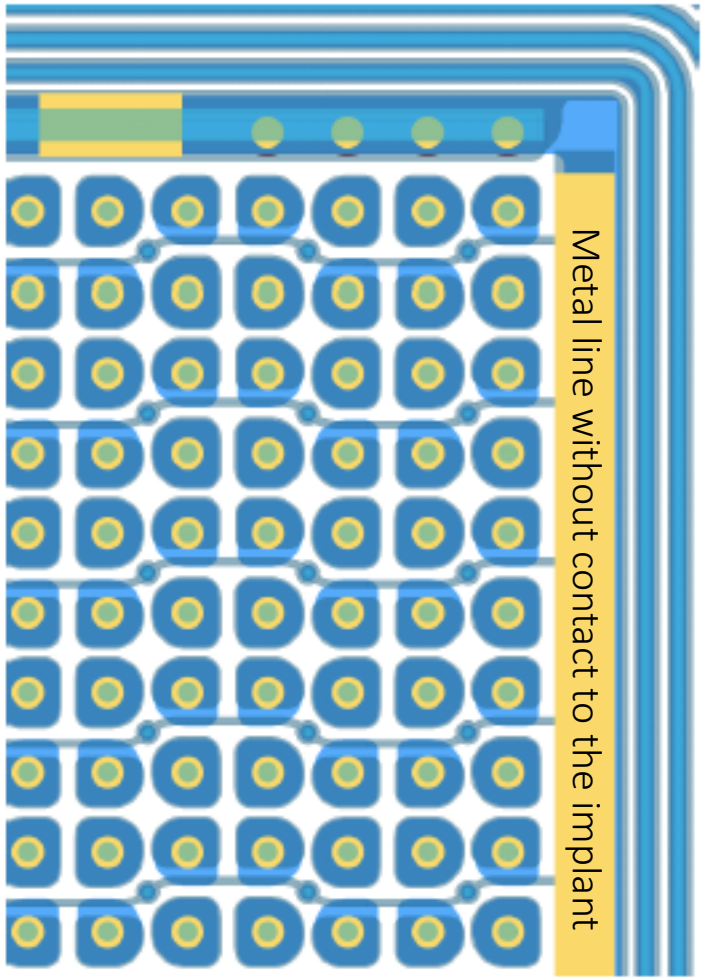


- Inefficiency only due to charge sharing at the four corners of the pixel cell

A. Macchiolo, Characterization of RD53A compatible n-in-p planar sensors, PIXEL 2018, 12 December 2018

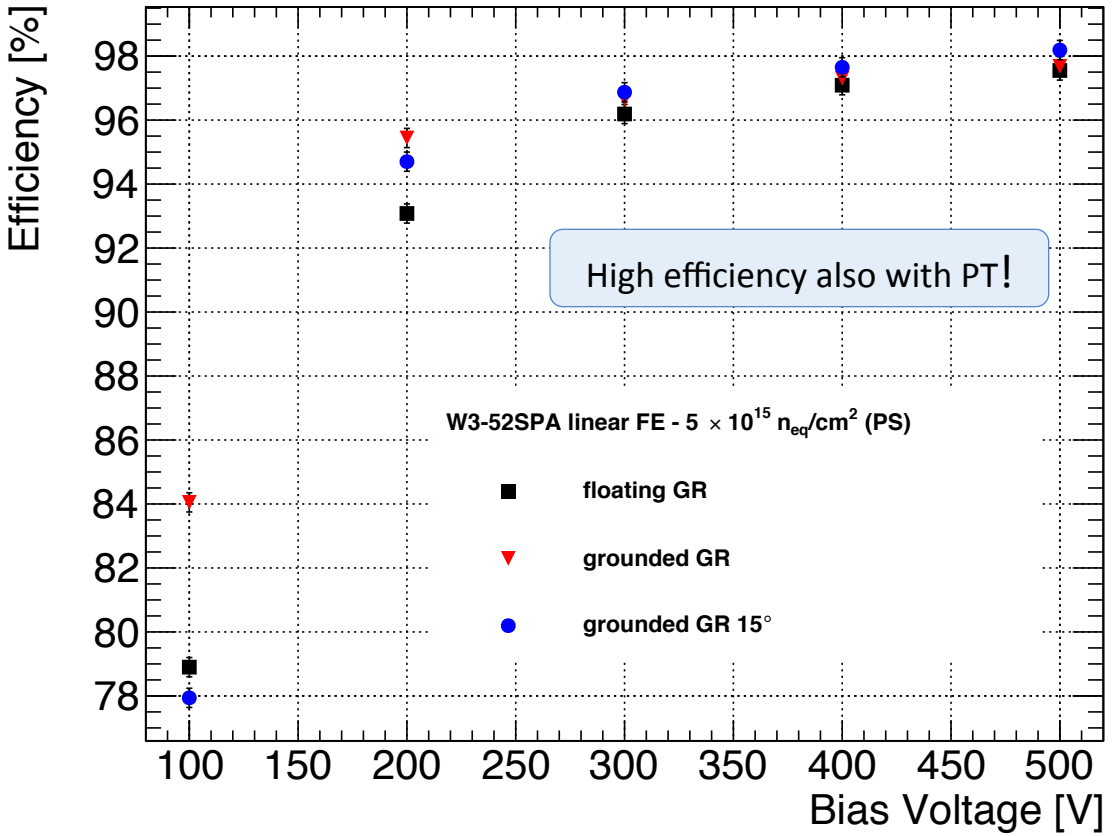
The "Split" Design

- Split design tested in various configuration after irradiation



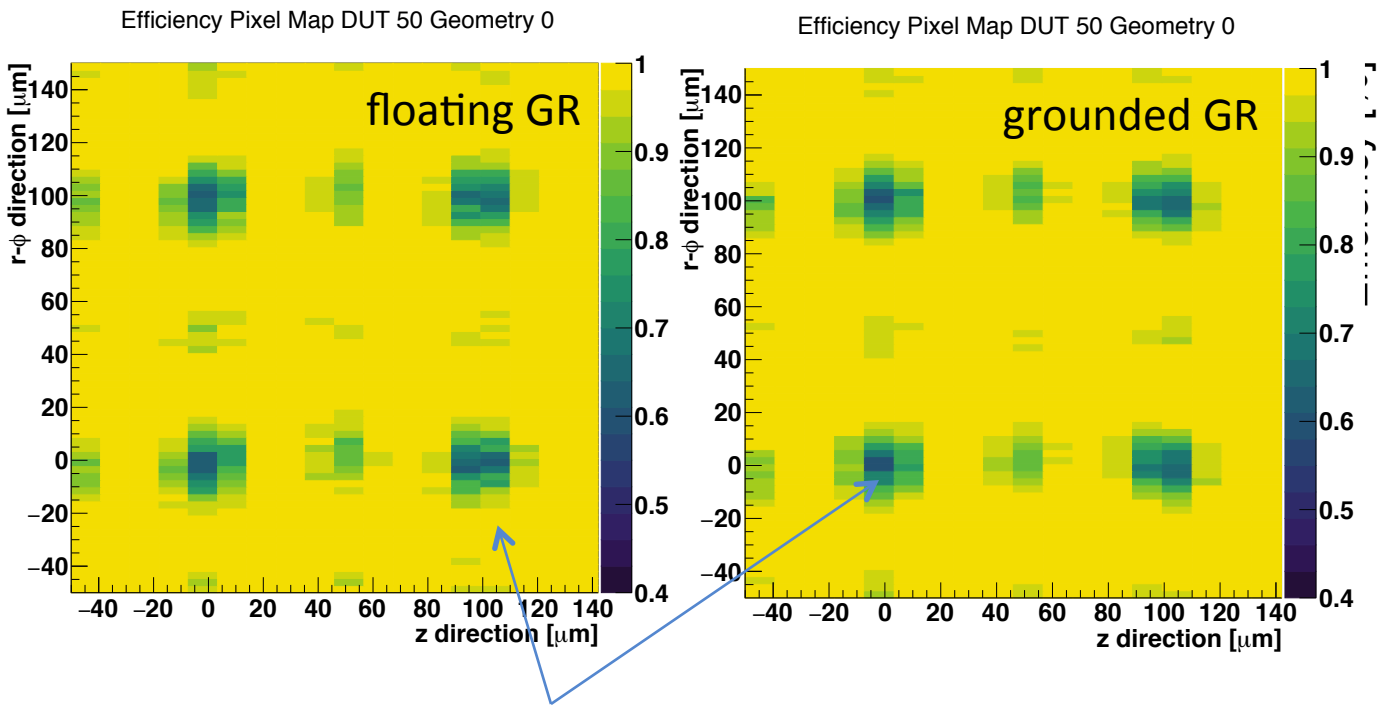
- Plateau efficiency: 97.6% (floating) vs 98.2% (grounded) → probably different area illuminated with slightly different fluence
- Also the test with 15 degrees inclination probably focused on higher fluence area

100 μm thick sensor, Threshold ~1100 e-



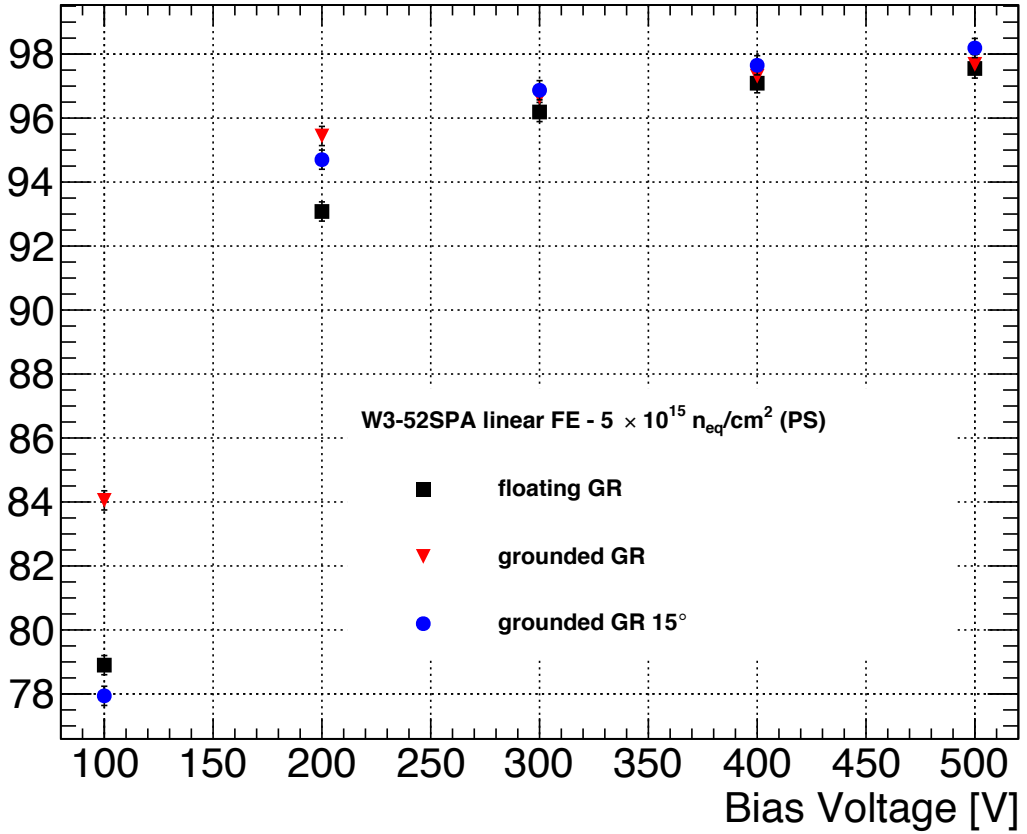
The "Split" Design

- Developed new design where the implant of the innermost ring can be grounded while the grid for testing is left floating after chip interconnection



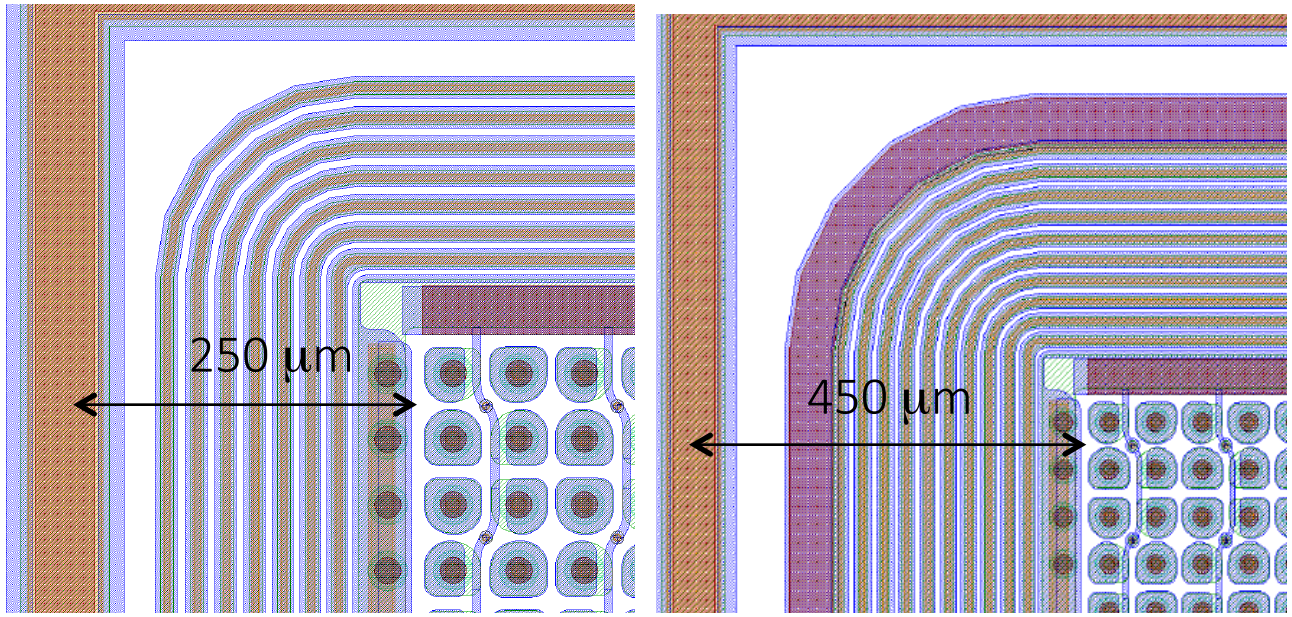
Very similar effect of PT dots with the two different configuration of the ring implant potential

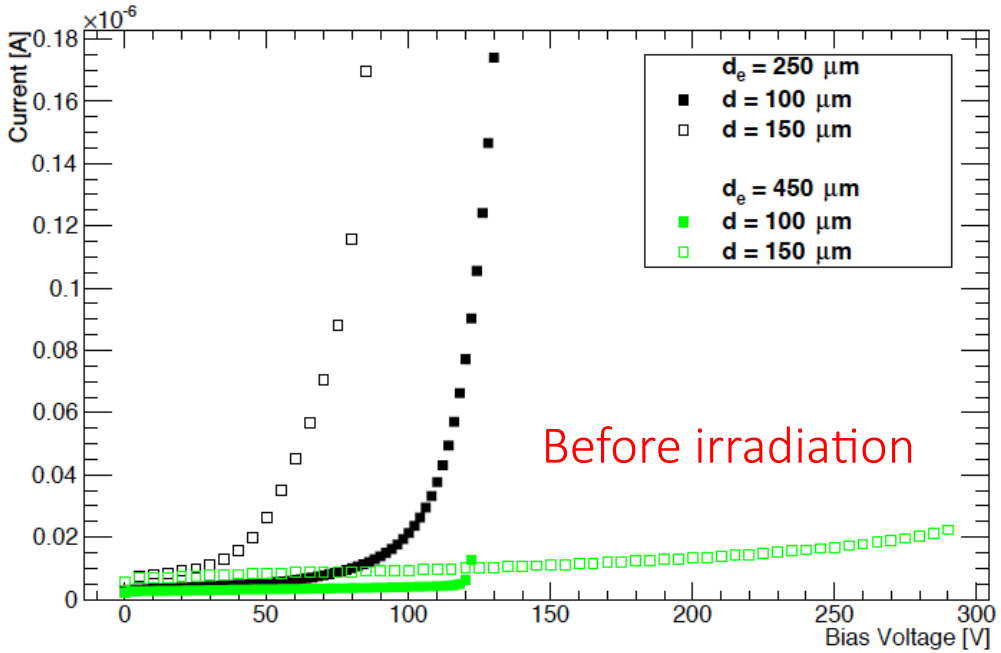
100 μm thick sensor, Threshold ~1100 e-



Reduced sensor edge

- Smaller inactive edges needed for the innermost layers of ATLAS ITk pixel detector
  - Worse performance for **Vbreak** before irradiation with respect to an inactive edge of 450 μm
  - Vbreak high enough after radiation to reach good tracking efficiency

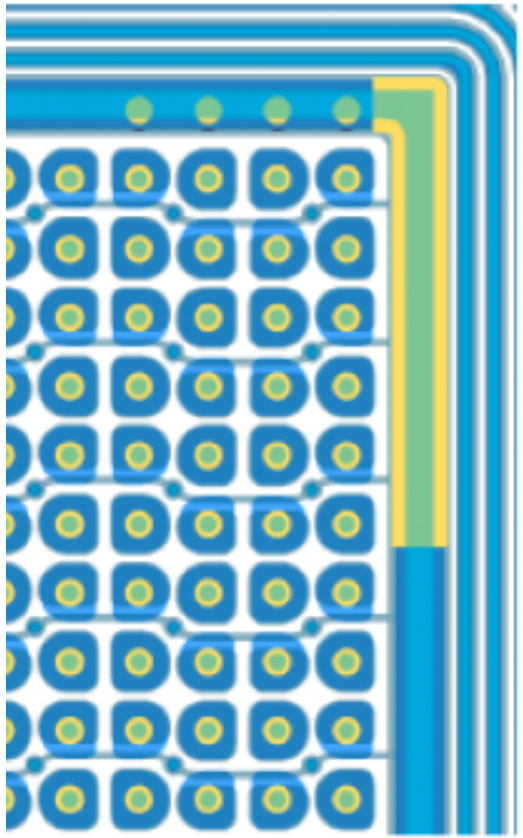




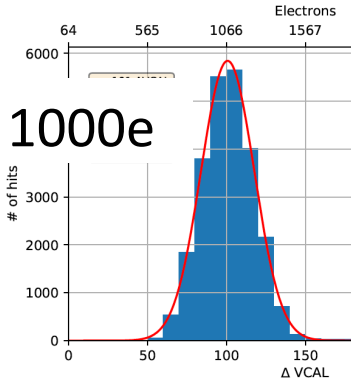
Performance of the Standard Bias Ring Structure after irradiation

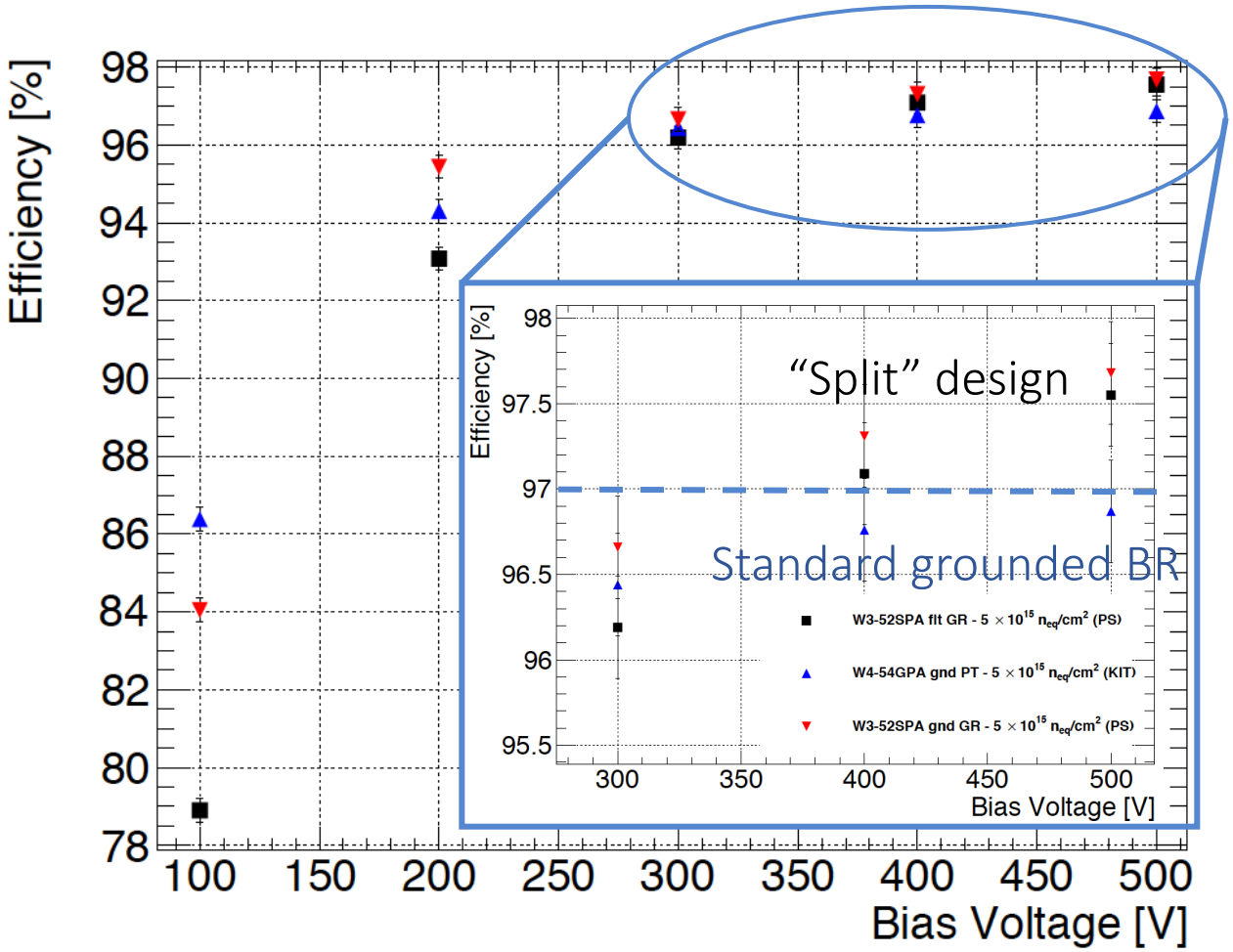
- Standard grounded Bias Ring compared to the “Split” Design

100 μm thick sensor, Threshold ~1000 e-



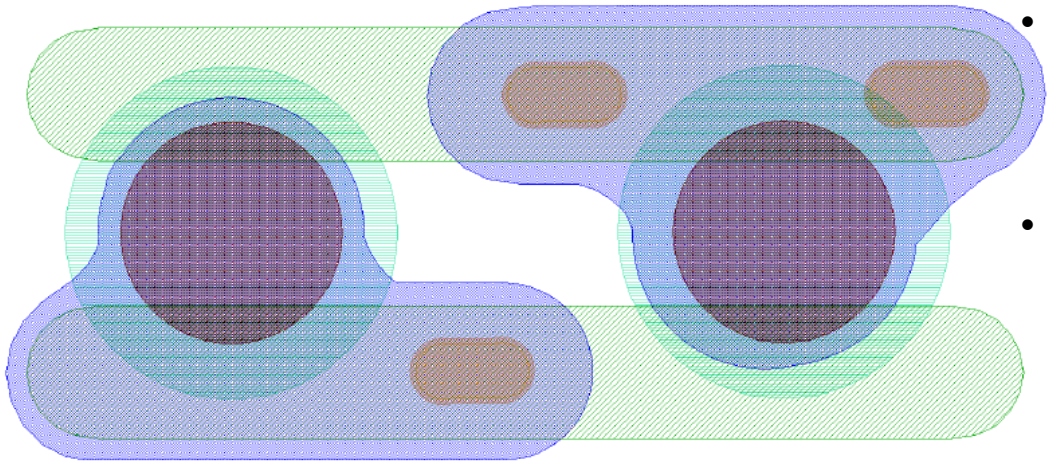
- 50x50 μm² pixel cell
- Irradiation at KIT at 5e15
- 97% efficiency target not reached up to 500V (but close)
- Operation in floating configuration for the BR needs careful investigation of possible effects on noise for the edge pixels



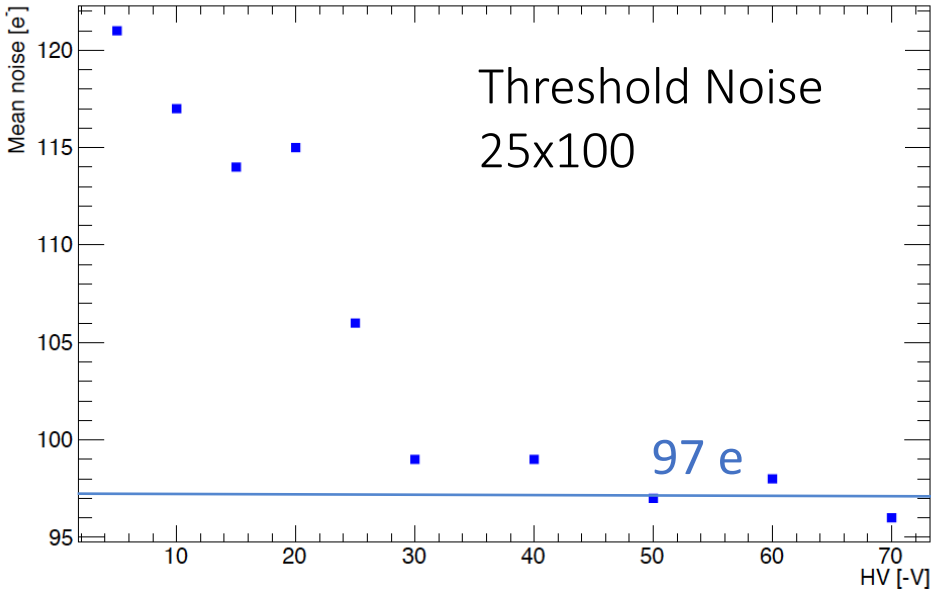


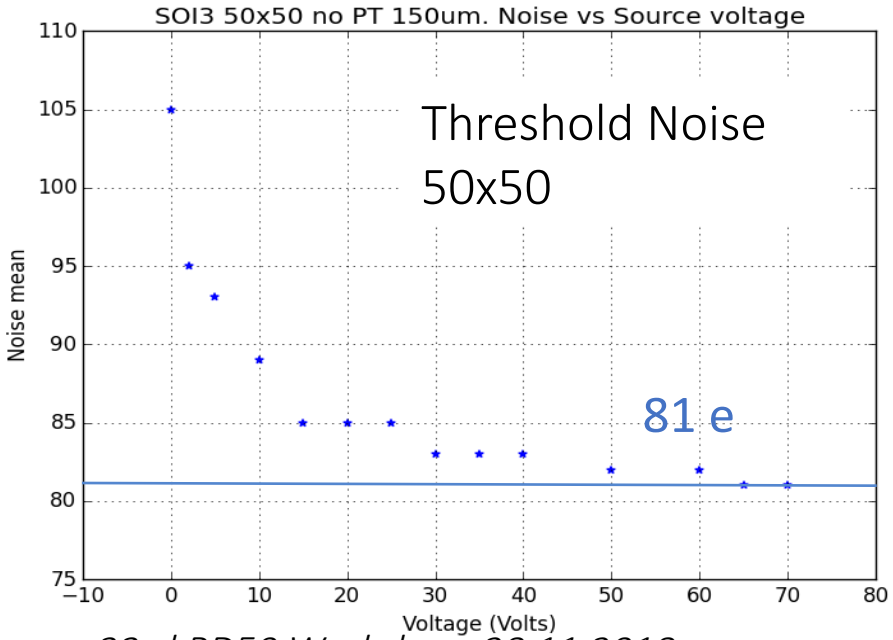
Investigation of cross talk in 25x100 pixel cells

Additional capacitance contribution for 25x100 geometry

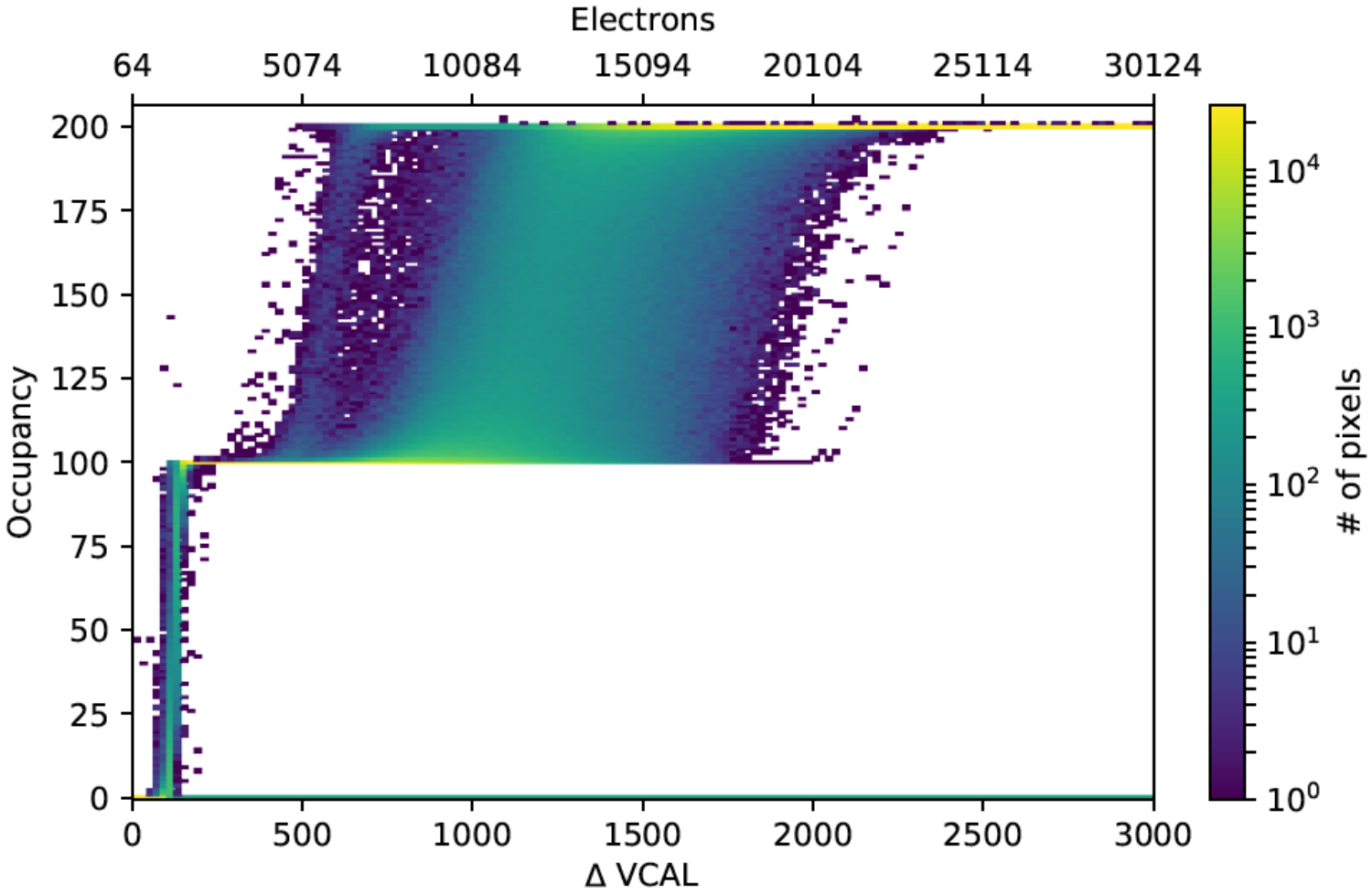


- Capacitance contribution of the overlap of the metal of one pixel with implant of the neighbouring one:
- This capacitance is due mainly to the thin oxide and nitride layers between metal and implant, the capacitance due to the UBM pad is small, thanks to the 3 μm BCB layer in-between metal and UBM pad





Cross-talk appearing in self-injection

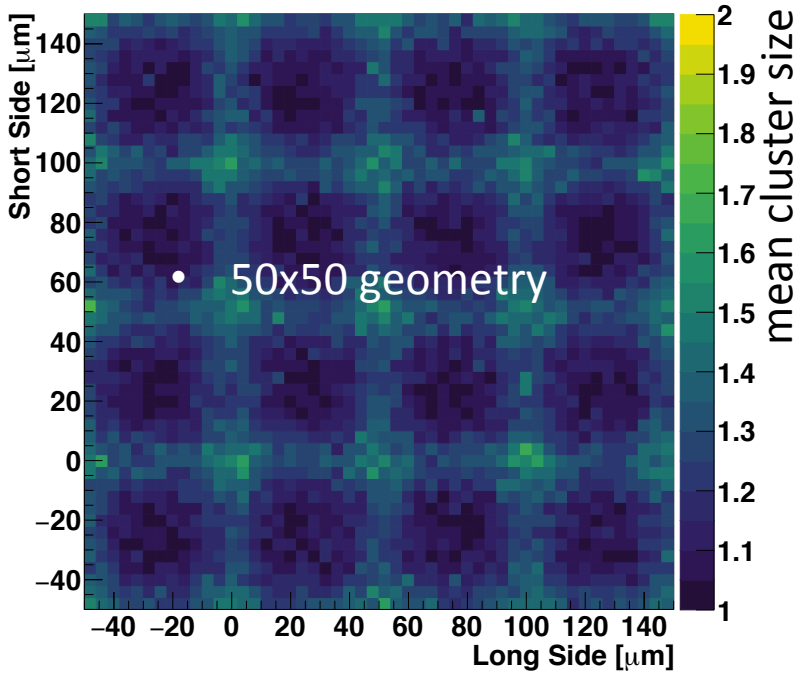


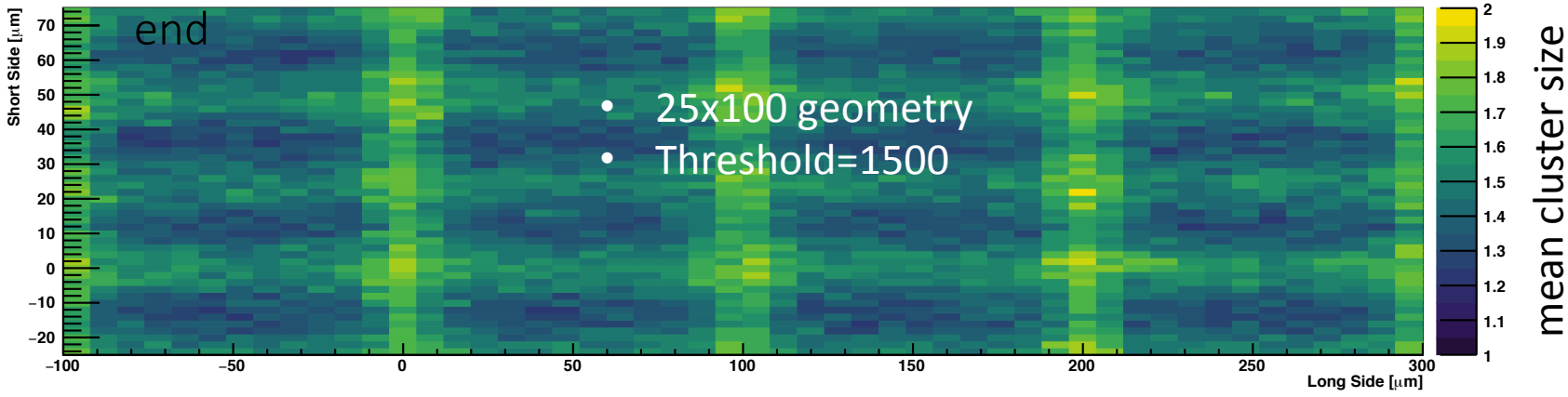
25x100 module show a sign of cross-talk for high injected charge → doubling of number of hits when injecting charge > 6ke

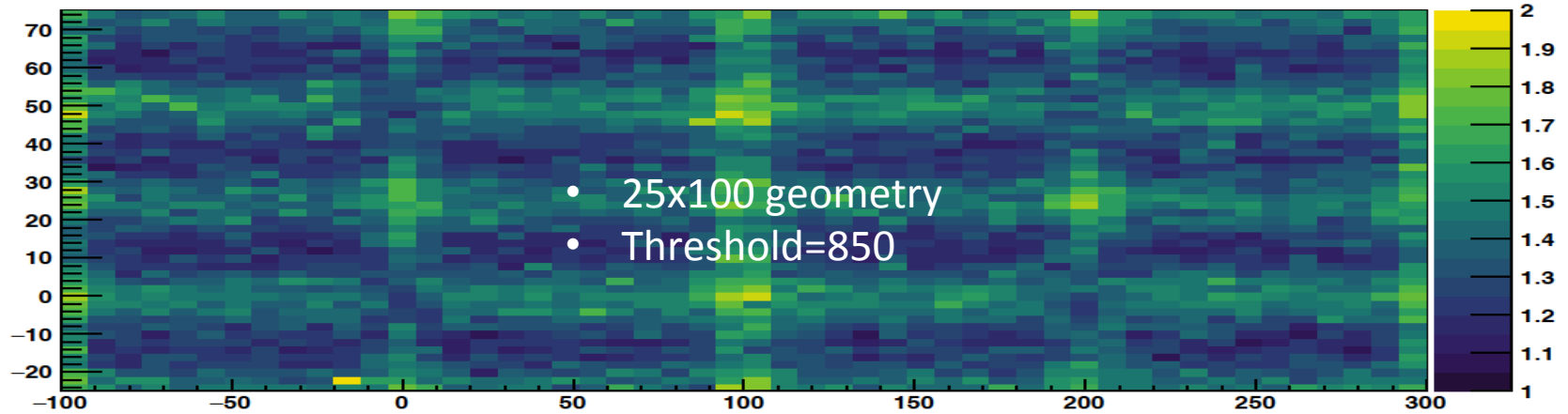
The effect has been seen on multiple modules 25x100 built with SOI3 and SOI4 sensors

Mean cluster size in test-beam data

- Measurements before irradiation at V_{bias}=50V, 150 μm thickness front-end



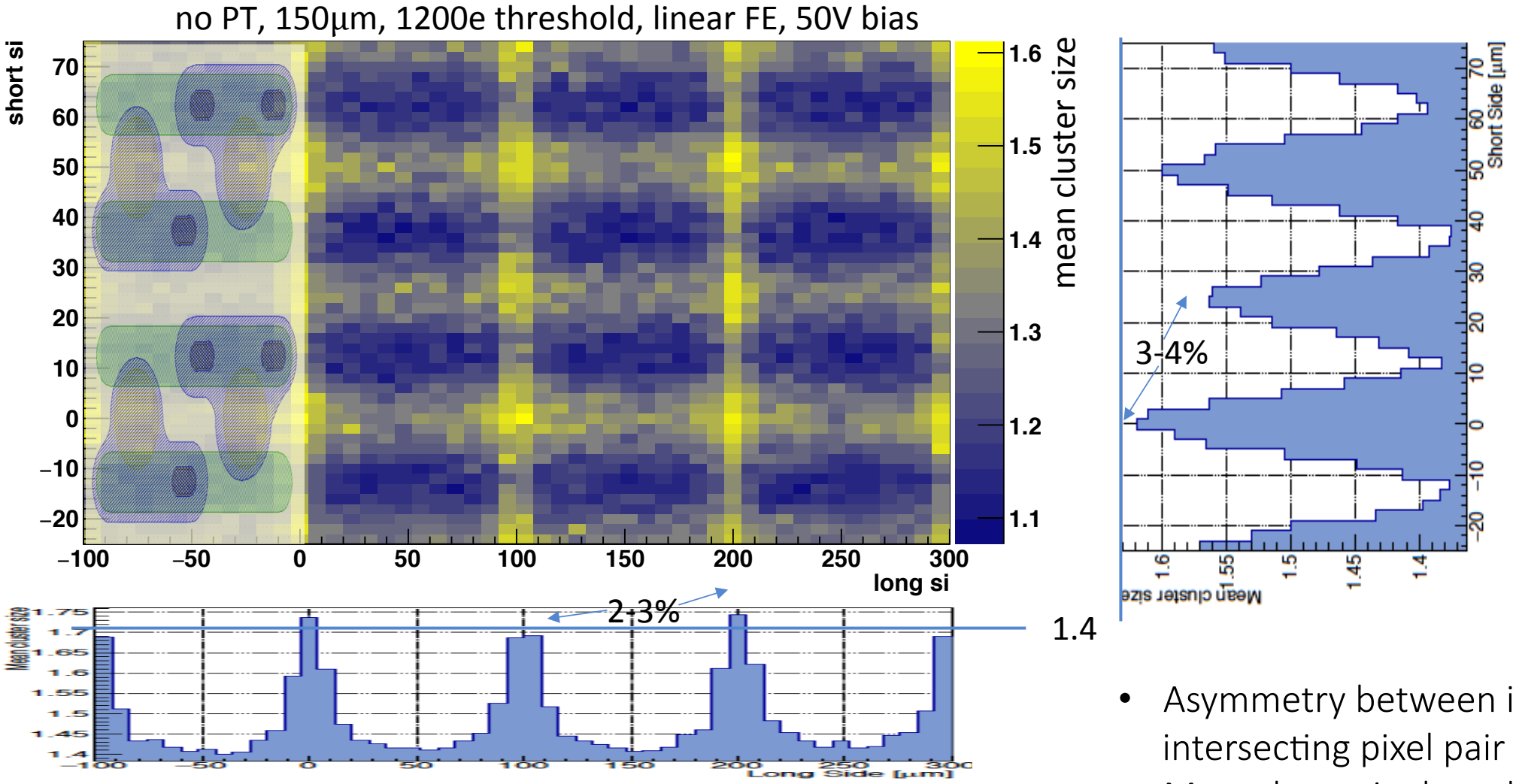




- Strange effects instead seen from threshold ~ 600 e

Cross-talk in data?

Cluster size in 25x100 module before irradiation



- Asymmetry between intersecting and not intersecting pixel pair is only 3-4%
- Most charge is shared along the short side

Conclusions and Outlook

- Good results obtained with the RD53A compatible sensors of 100 and 150 mm thick sensors up to the maximum fluence foreseen for planar assemblies in ATLAS ITk

- Several sensor design compared, with the “Split” design particularly encouraging thanks to good hit efficiency performance together with the feasibility of characterizing the sensor at each step of the production process

- Investigation of 25x100 possible cross-talk:

    - No evidence in test-beam data at “medium” thresholds
    - More studies needed at lower thresholds
    - Need to understand the difference between injection in the chip and in the sensor

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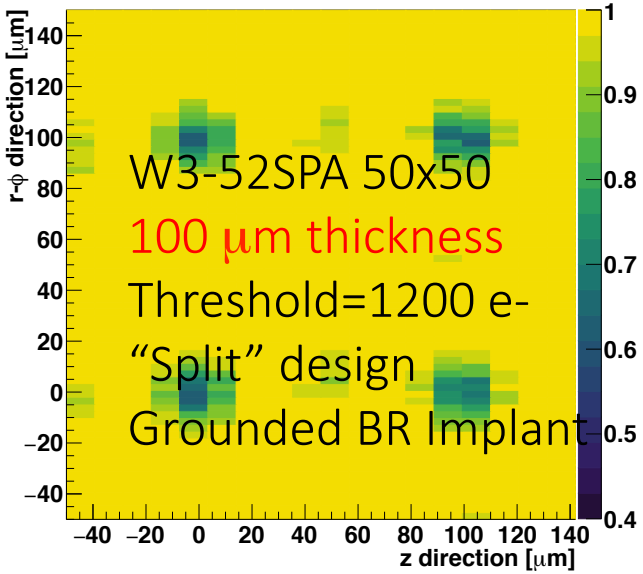
AIDA 2020

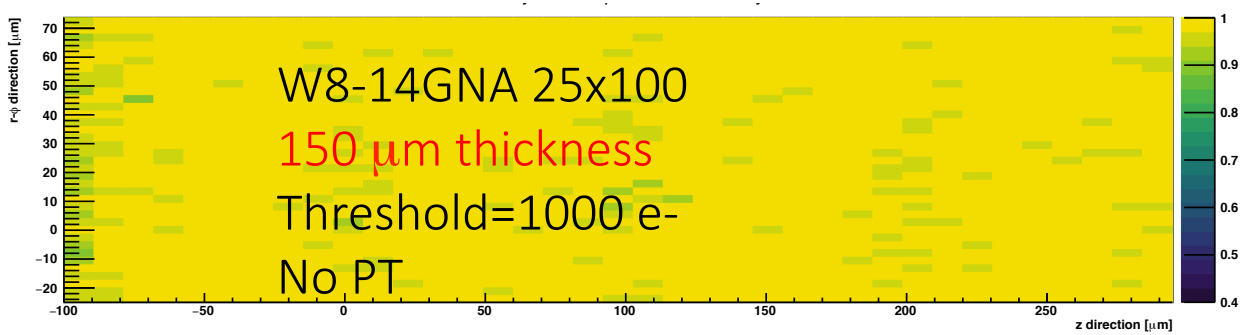
Additional slides

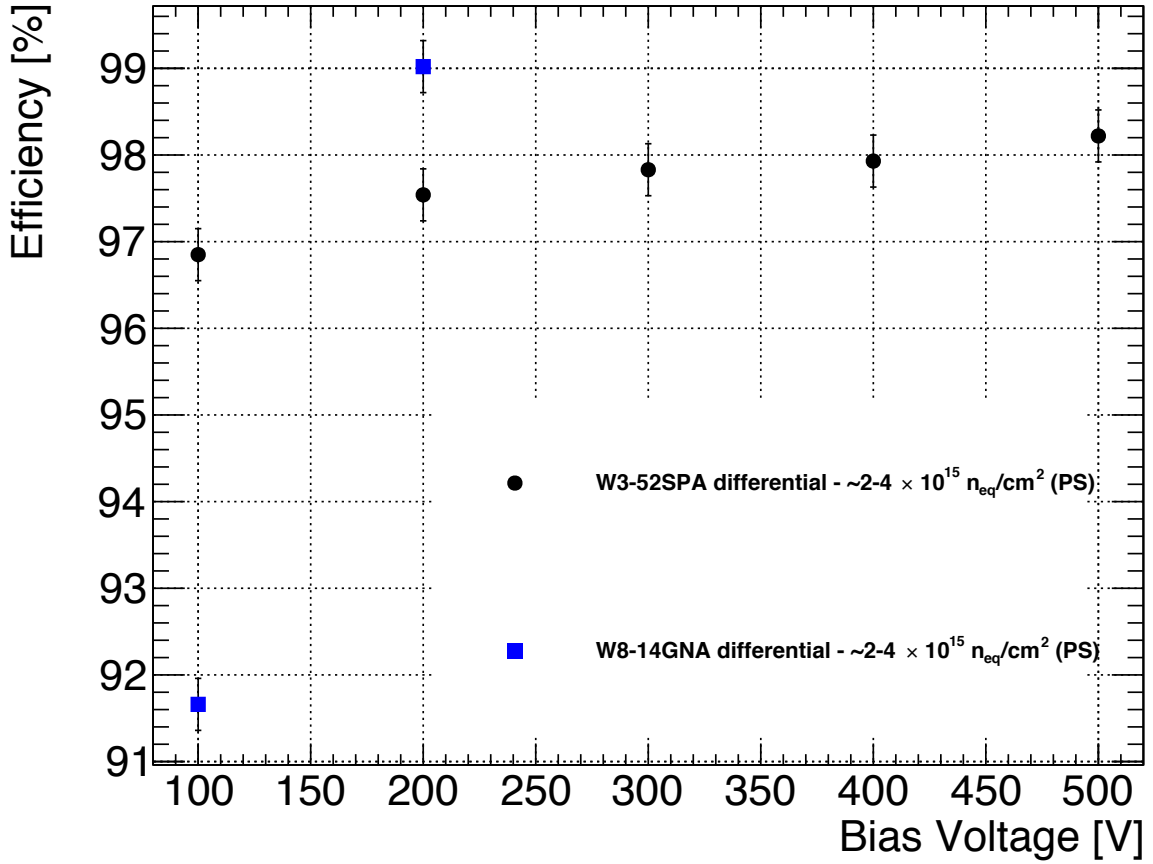
Differential FE flavour

Due to inhomogeneous irradiation, the fluence in the differential section is lower than the average one

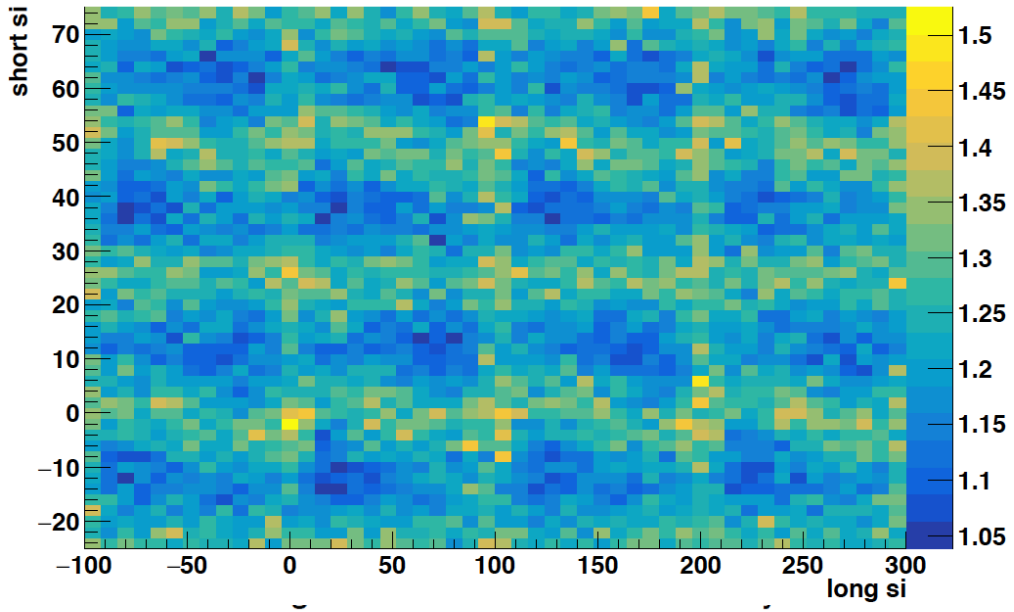
- Probable range 2-4x10^{15} n_{eq}/cm^2 → earlier efficiency saturation than for the Linear section

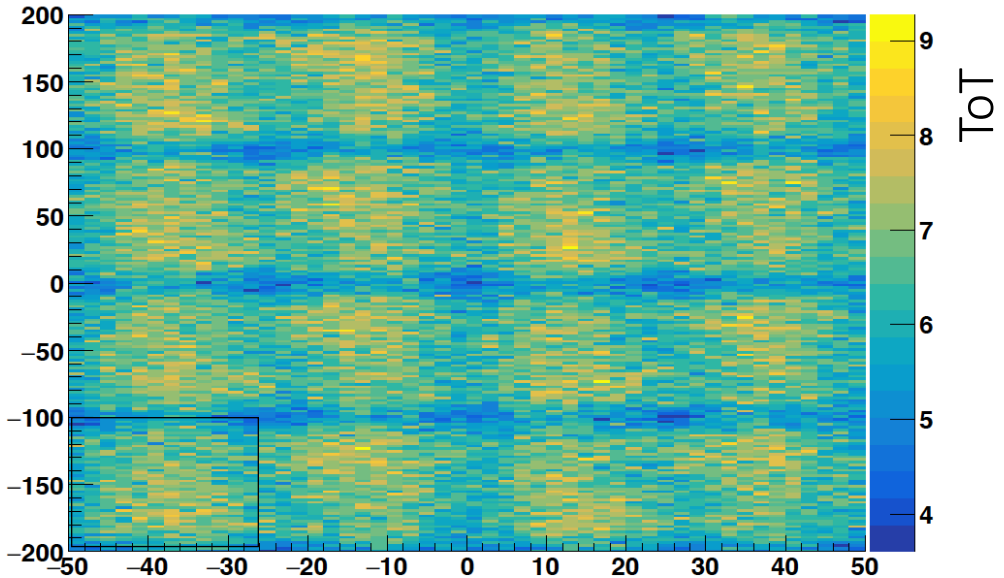


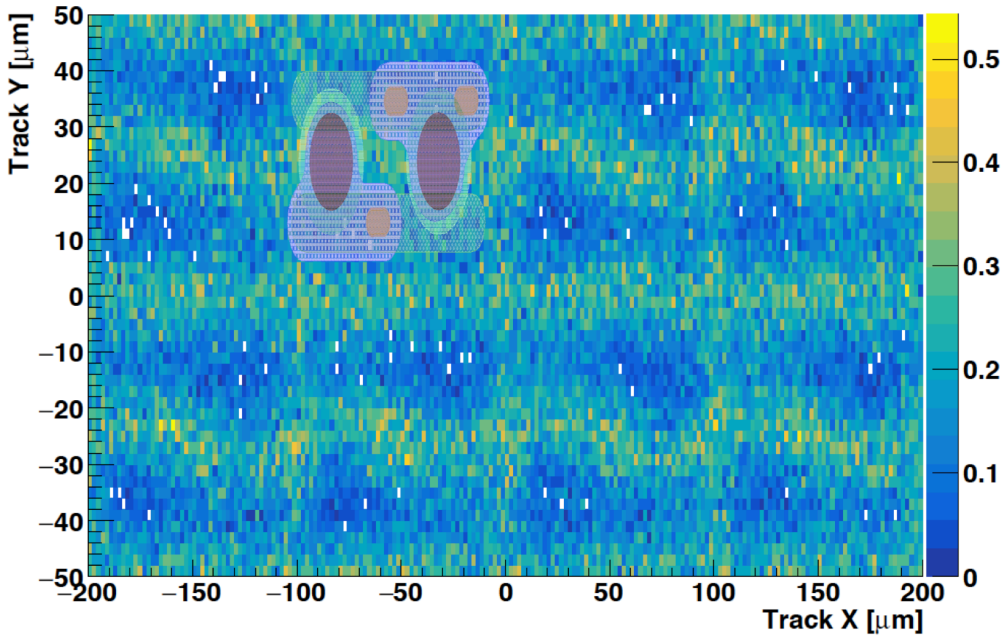




Shared charge fraction for 25x100 pixel sensors at 5e15 and 400V

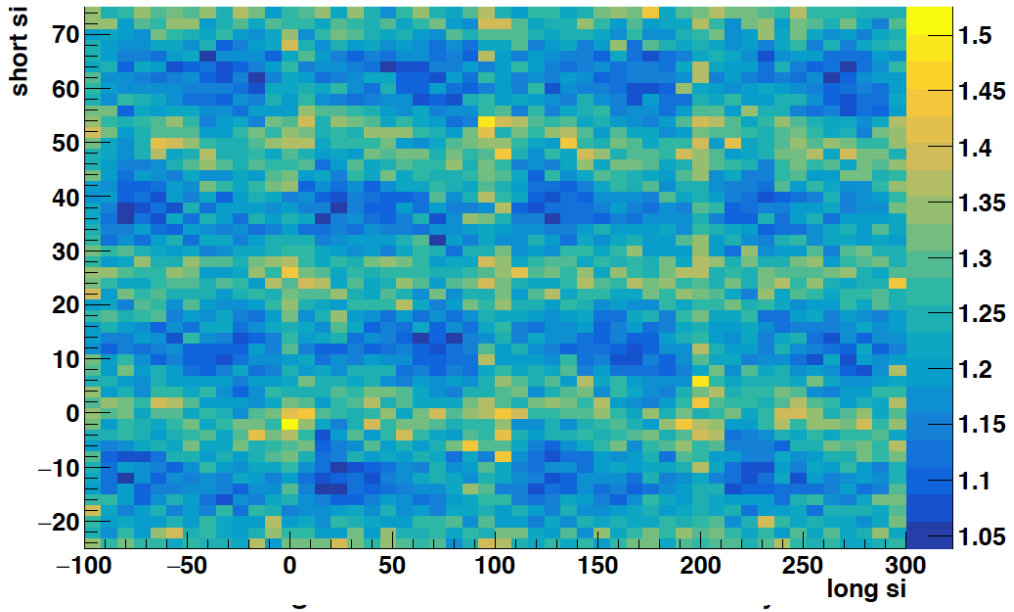




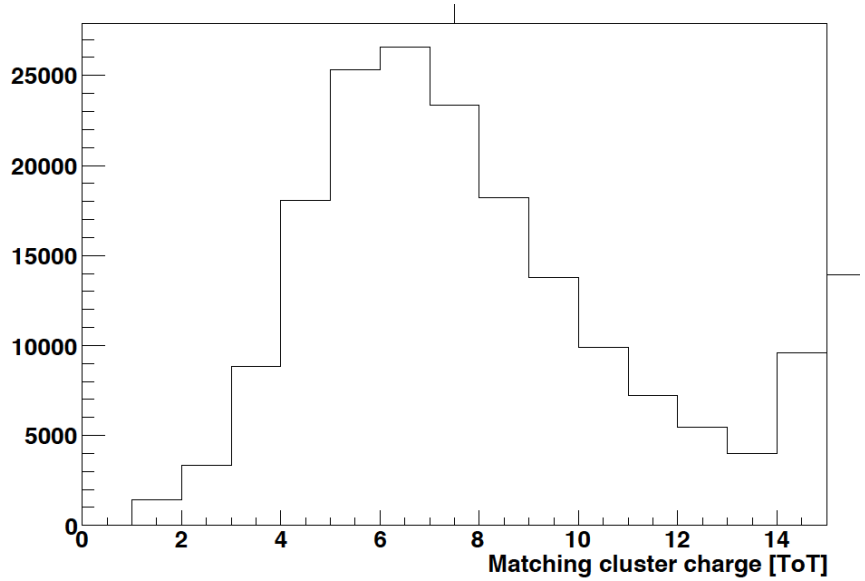


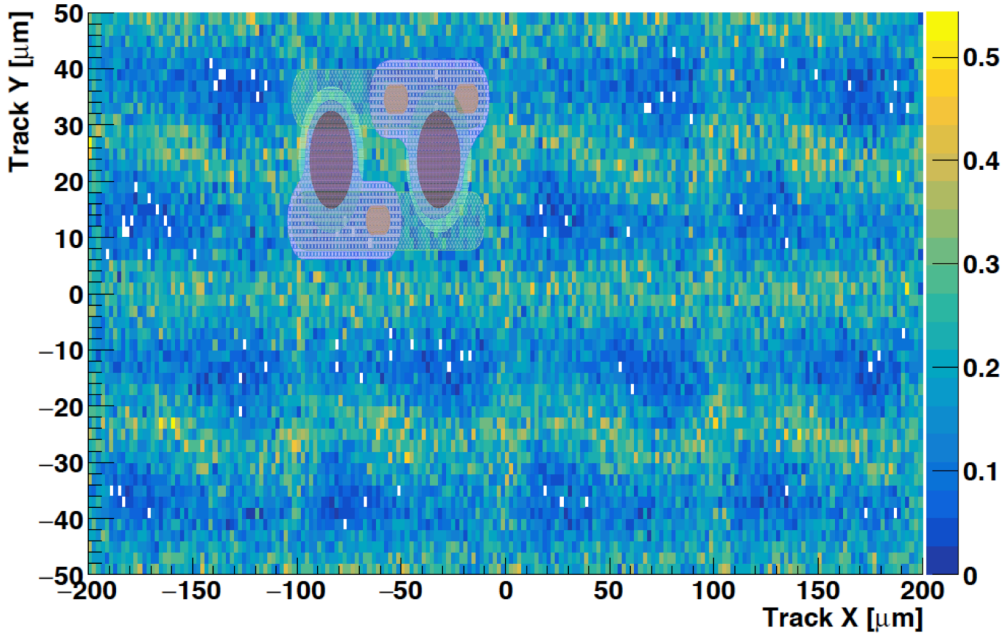
- The fraction of shared charge does not change significantly in the case of intersecting pairs or not intersecting pairs
- The borders of the shared charge follow the metal shape

Shared charge fraction for 25x100 pixel sensors at 5e15 and 400V



Cluster size





Fraction of shared charge

- The fraction of shared charge does not change significantly in the case of intersecting pairs or not intersecting pairs
- The borders of the shared charge follow the metal shape