Test beam results of irradiated RD53A 3D modules for ATLAS ITk pixel detector

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25 years 1991-2016
Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
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"la Caixa" Foundation

HL-LHC Upgrade

- LHC is headed towards **High Luminosity upgrade** to improve physics reach by increasing the luminosity
  - Average of **200 simultaneous interactions**

Challenges:

- Large pile-up → Better resolution -> **smaller pixel size**
- Higher particle fluence → **Radiation hard**: develop novel sensor concepts that can survive very high radiation exposure

Need for new detectors!

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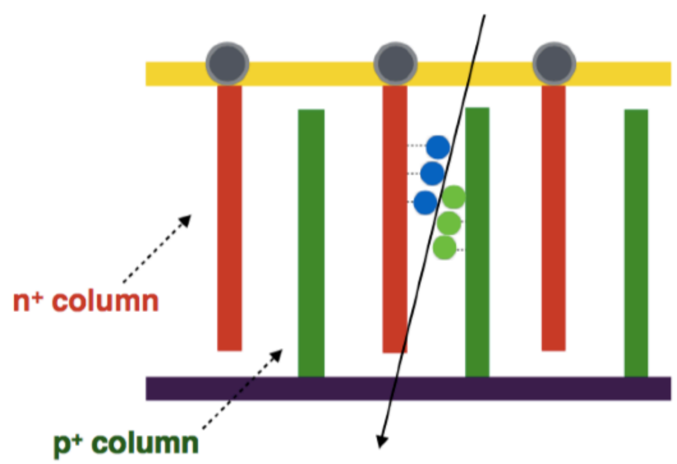
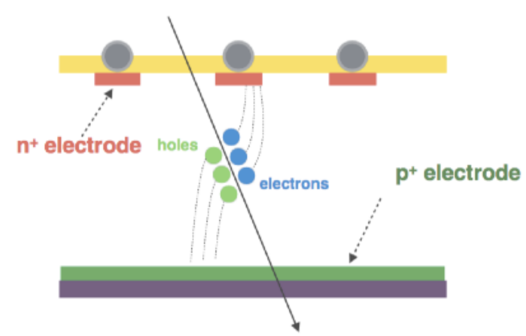
3D silicon sensors





Planar

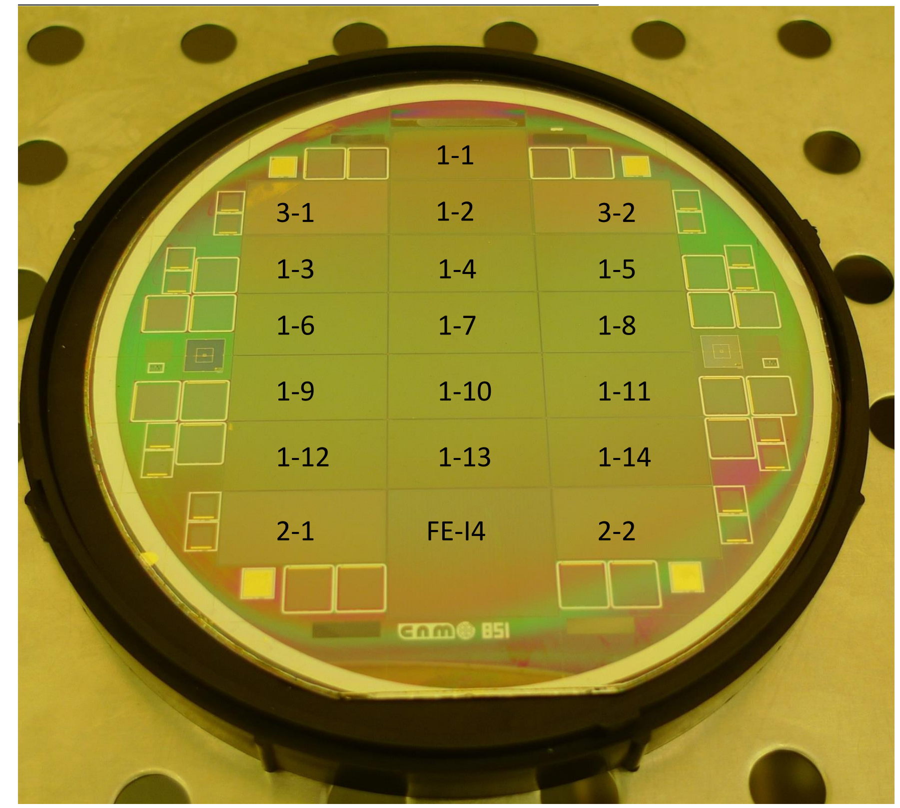
- Electrodes not placed on the surface but columns inserted in the bulk
- Short drift path for electrons-holes pairs towards columns
- Drift path decoupled from active thickness

Radiation hardness!!

Baseline for the innermost layer of ATLAS ITk pixel detector

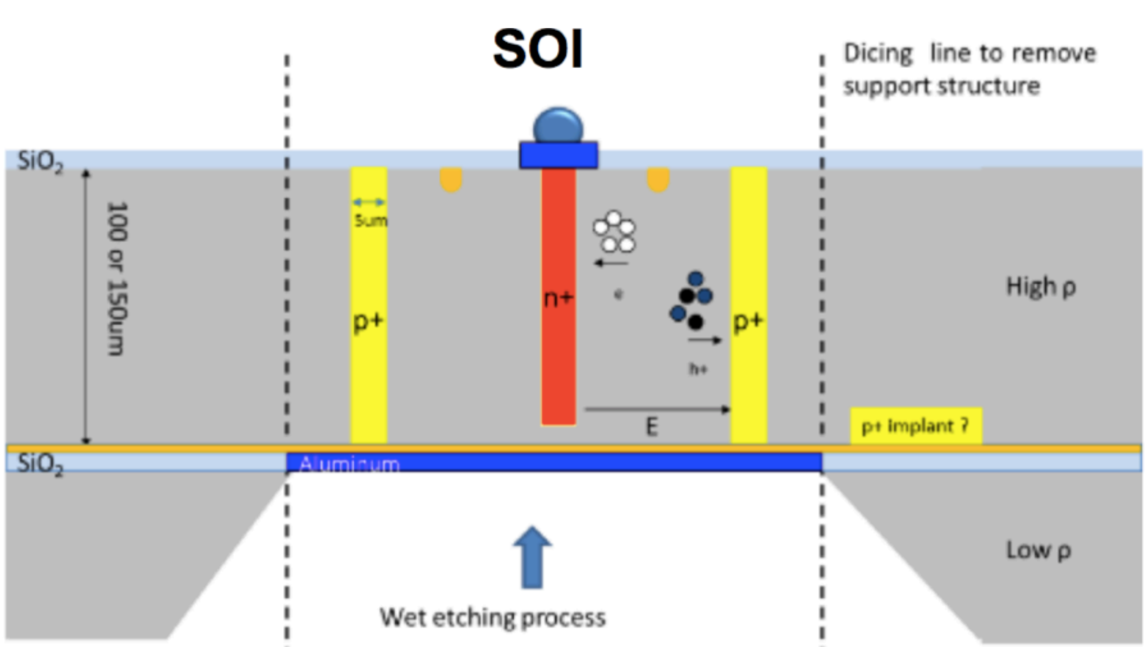
RD53A modules

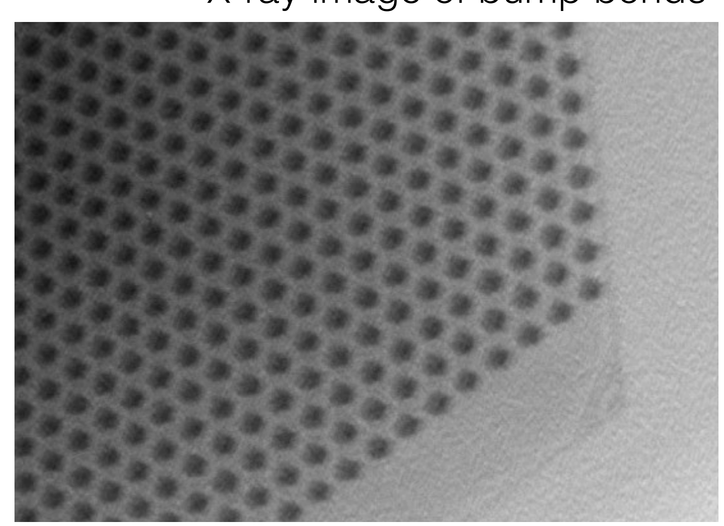
- **RD53A** chip first prototype of HL-LHC pixel ASIC
- CNM -> 3D sensor production **compatible with RD53A chip**
  - Single sided process
  - SOI wafers
  - 150 μm active thickness, 300 μm support wafer
  - 50x50 μm^2 and 25x100 μm^2 1E
  - Electroless UBM at CNM (not always perfect but not going to be used in final production)
- Flip chip and assembly at IFAE
- Characterisation with YARR system

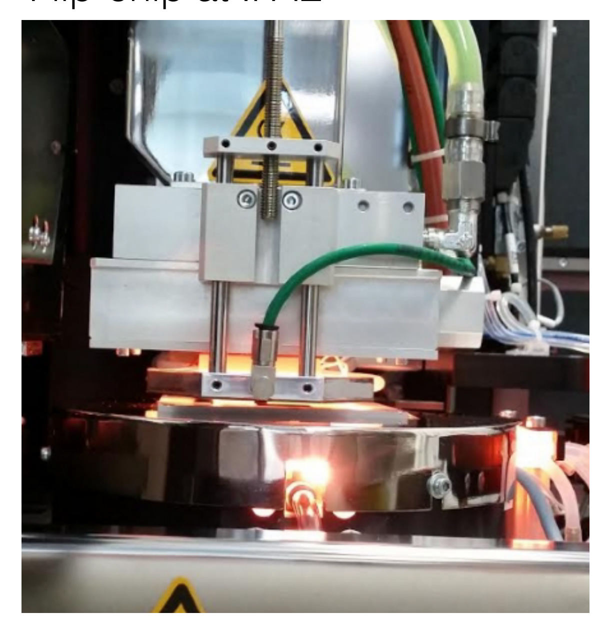


Wafer 3

Overall good yield especially for 50x50 μm^2



X-ray image of bump bonds


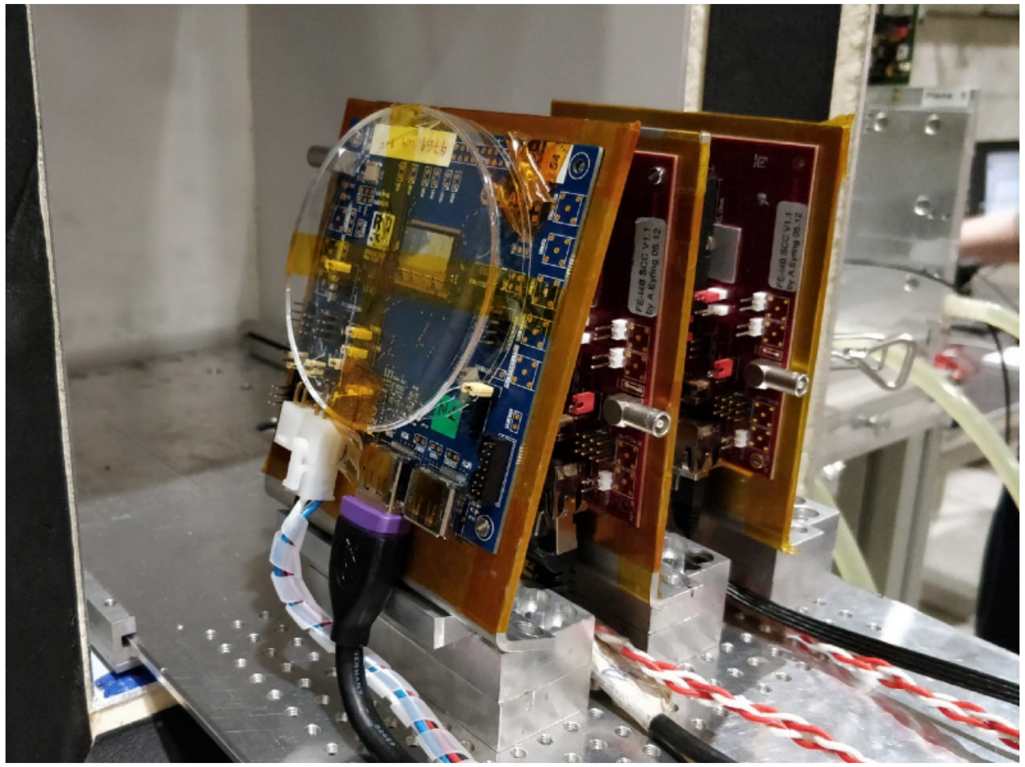
Flip-chip at IFAE


Produced RD53A modules

	Wafer	Sensor	RD53A Chip (GP1 W1 3AS180701#11)	Bump Bonding	Geometry (μm^2)	
1	No sensor		3-3	-	-	-
2	W4	1-5	3-10	Good	50x50	**IRRADIATED AT KIT TO 5E15** **Measured at August tb**
3	W3	3-1	6-5	Good	25x100 1E	**Measured at July tb** **BUT died when moving to another PCB**
4	W3	1-9	4-12	Good	50x50	**IRRADIATED AT PS 1E16** **Measured at October tb**
5	W3	1-7	4-11	Good	50x50	**Measured at July tb** **BEING IRRADIATED AT CYRIC TO 1E16**
6	W3	3-2	3-11	Failed	50x50	**Flip-chip failed due to bad UBM**
7	W1	1-4	3-11 (reused!)	Bad	50x50	**IRRADIATED AT PS 1E16** **Mostly disconnected**
8	W1	1-6	6-4	Good	50x50	**IRRADIATED AT PS 1E16** **Measured at October tb**
9	W1	3-2	6-3	Good	25x100 1E	**Shorted (problematic wire bonding)**
10	W1	3-1	7-3	Edge off	25x100 1E	**IRRADIATED AT KIT 5E15** **Measured at October tb**
11	W1	1-11	7-4	Good	50x50	**Fell apart disconnect. now in reworking**

SPS test beams

- **BDAQ** system to readout RD53As
- Cooling box available in H6A for irradiated devices

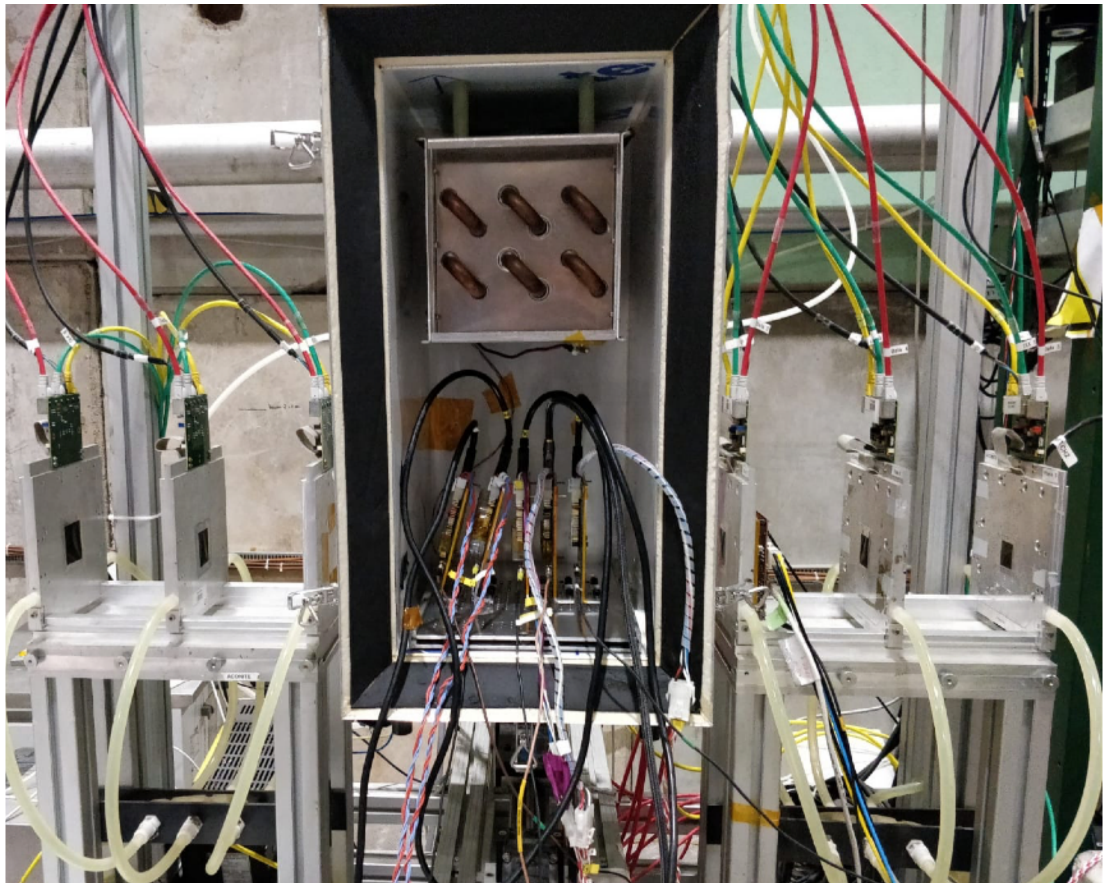


July

- RD53A unirradiated modules, 50x50 μm^2 and 25x100 μm^2 1E

August

- First irradiated RD53A to **5e15 n_{eq}/cm^2**
  - **50x50 μm^2**
  - Uniformly irradiated at KIT with protons to 5e15 n_{eq}/cm^2
  - Both 0° and 15° measured



October

- Irradiated RD53A to **5e15 n_{eq}/cm^2**
  - **25x100 μm^2 1E**
  - Uniformly irradiated at KIT with protons to 5e15 n_{eq}/cm^2
  - Both 0° and 15° measured
- 3 irradiated RD53As to **1e16 n_{eq}/cm^2**
  - **50x50 μm^2**
  - Non-uniformly irradiated at PS with protons to 1e16 n_{eq}/cm^2

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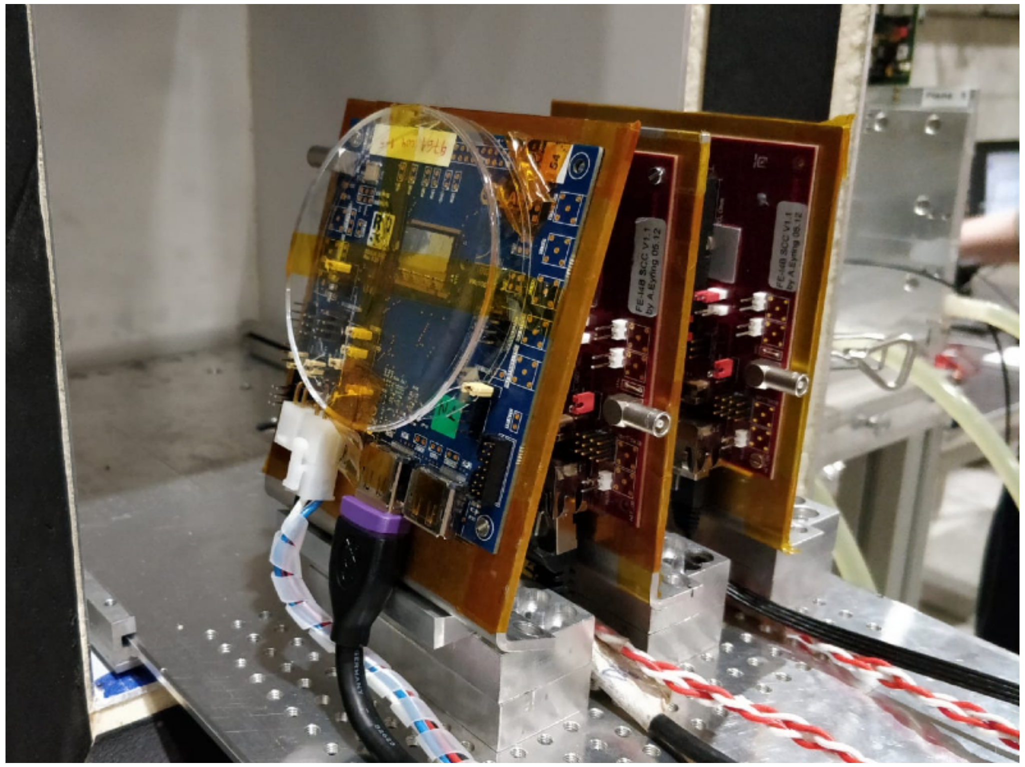
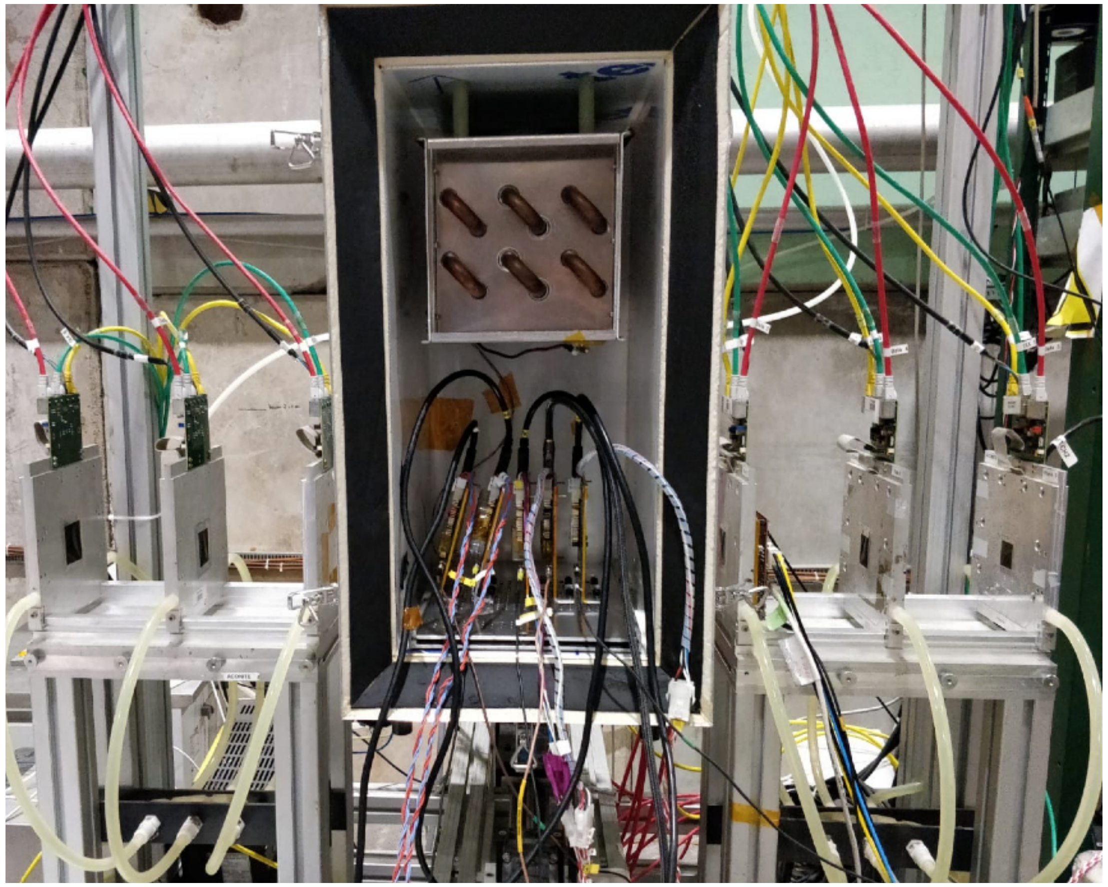
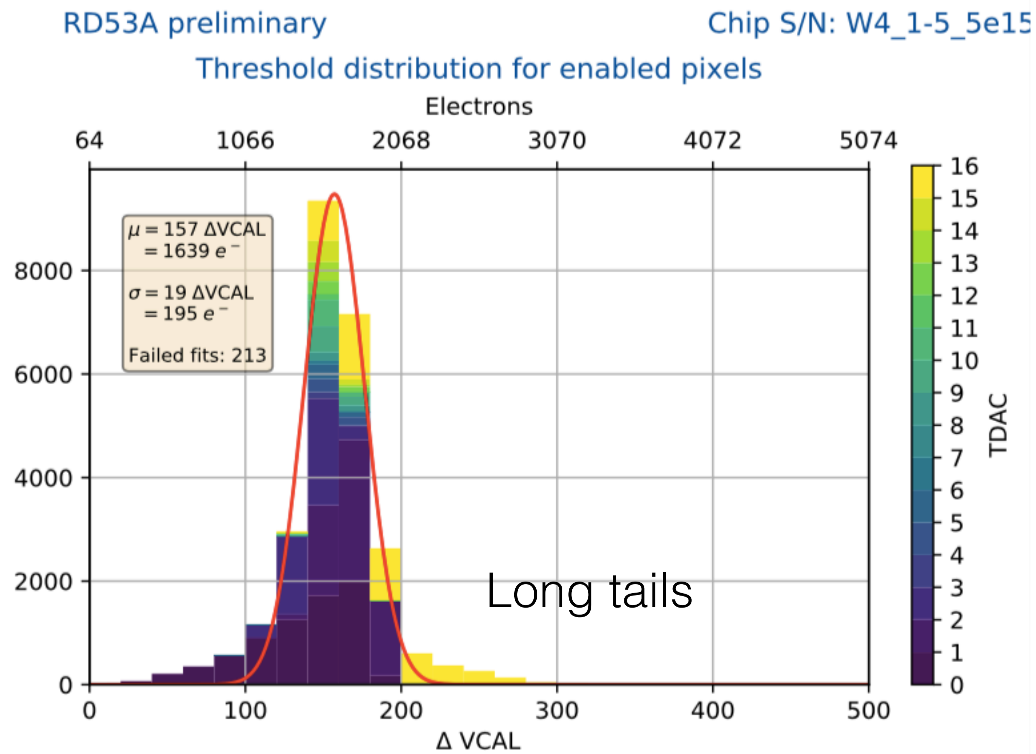
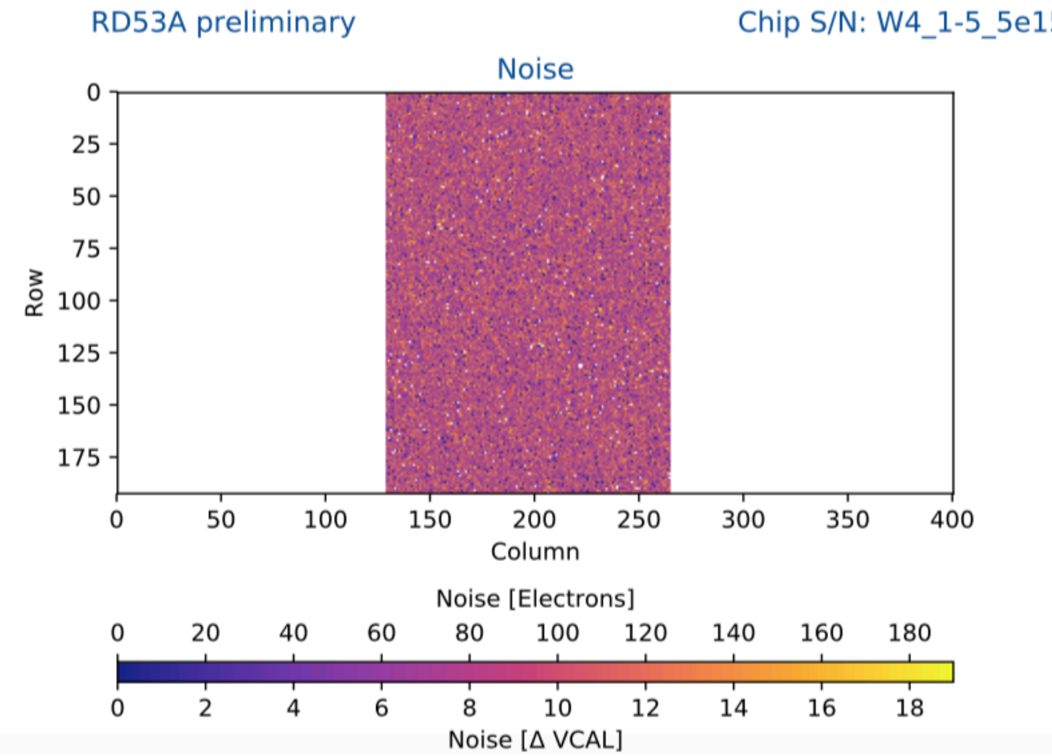
Analysis on going

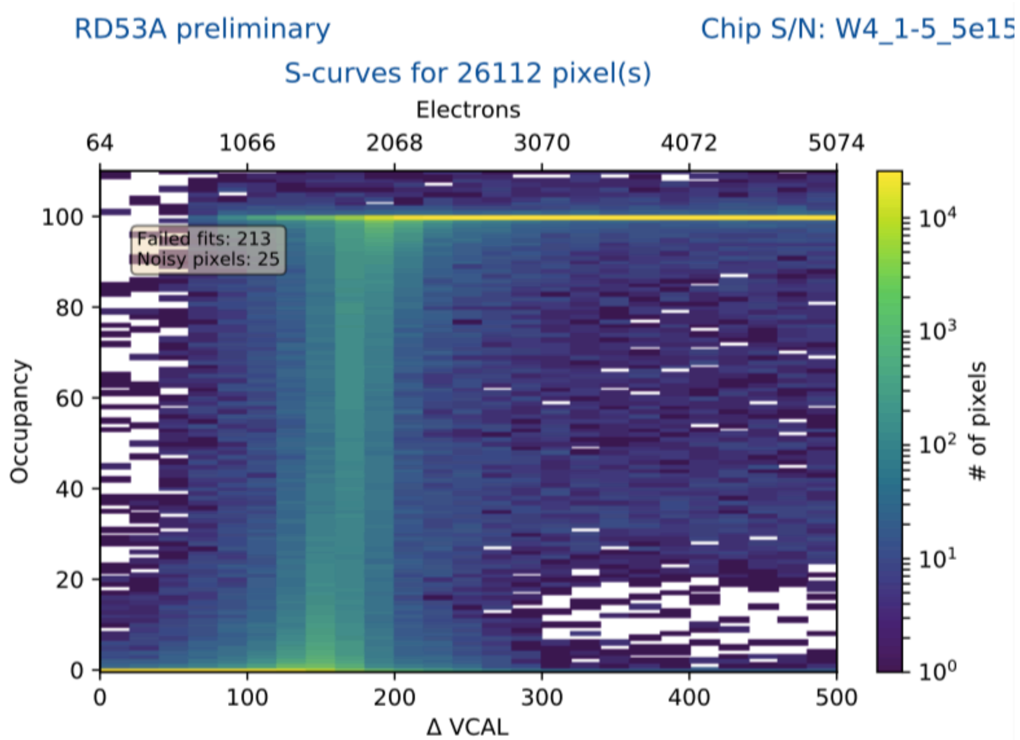


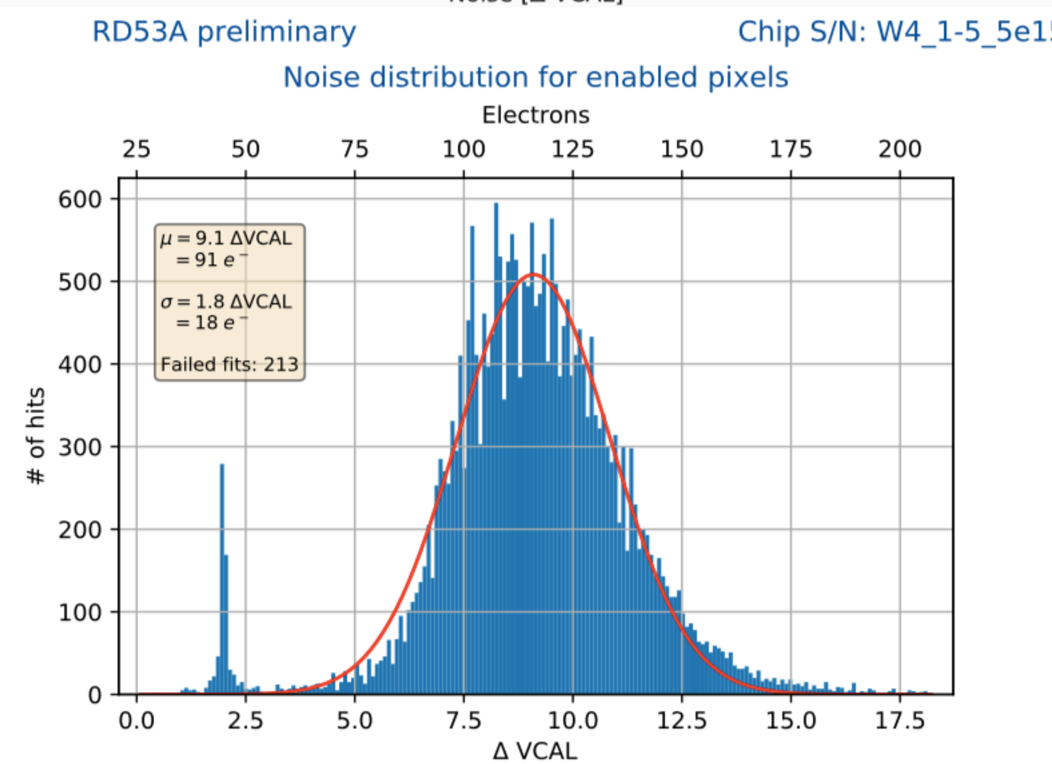


50x50µm² - 5e15 n_{eq}/cm^2 KIT - Tuning linear FE



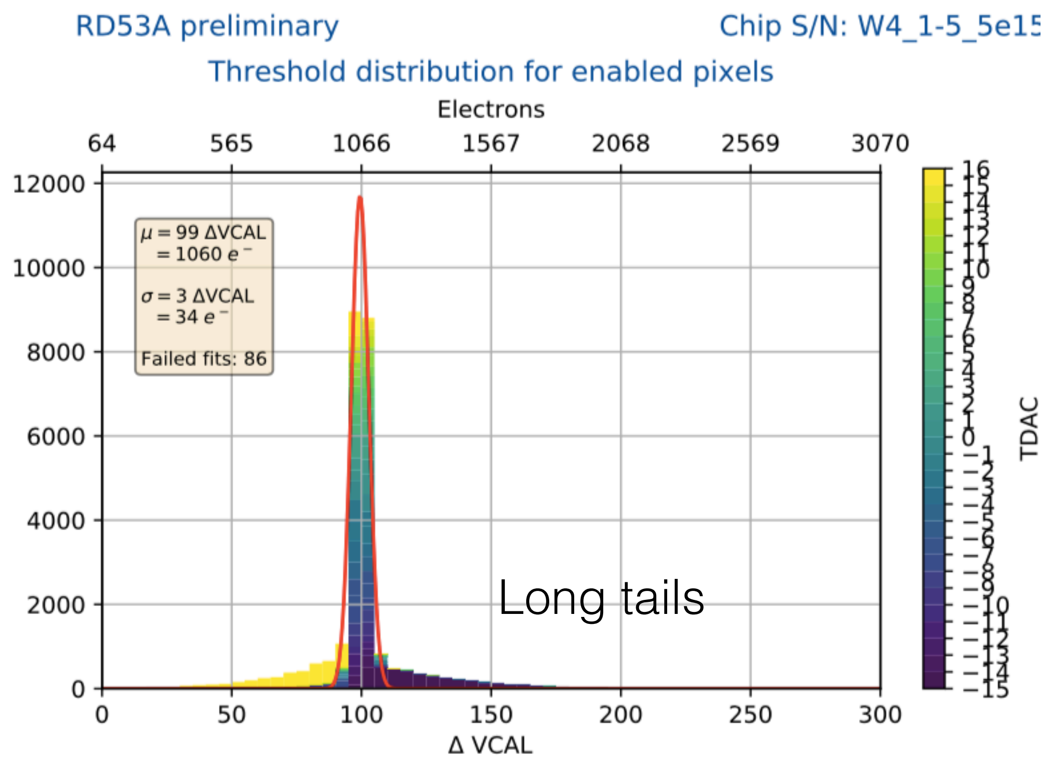


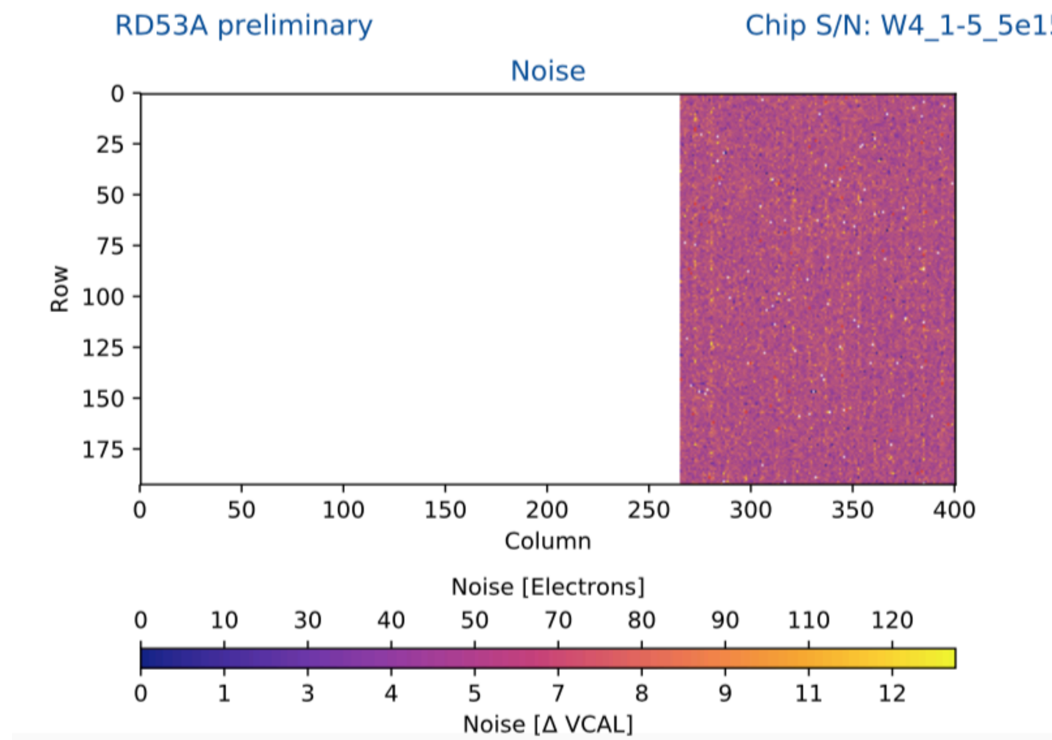


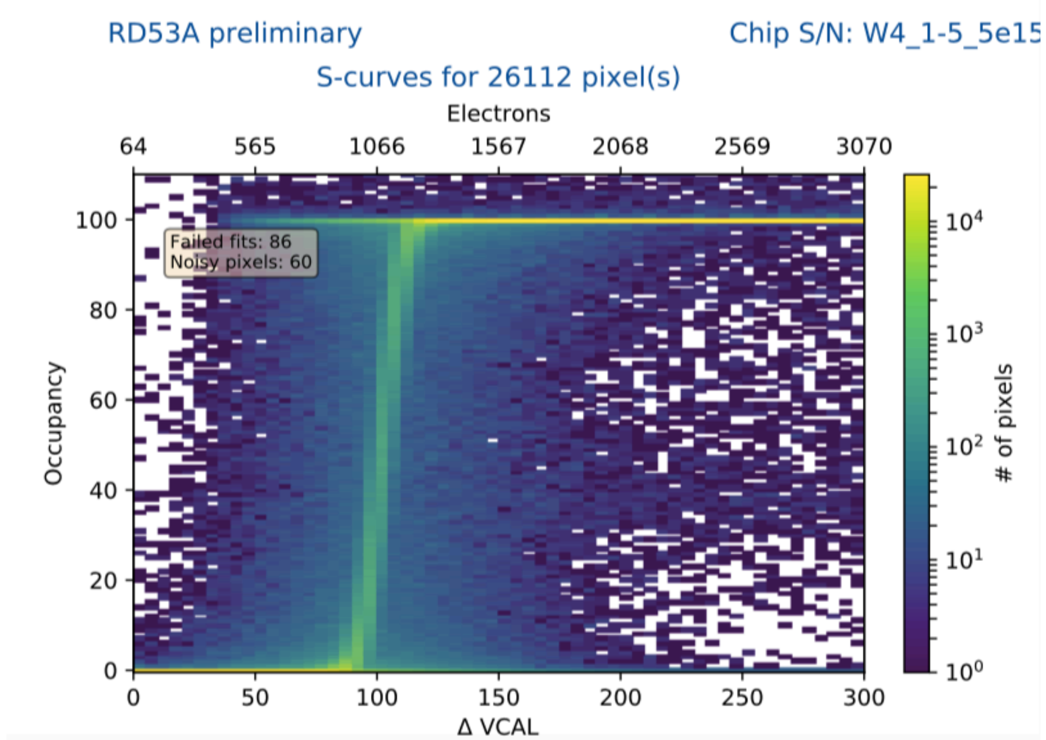


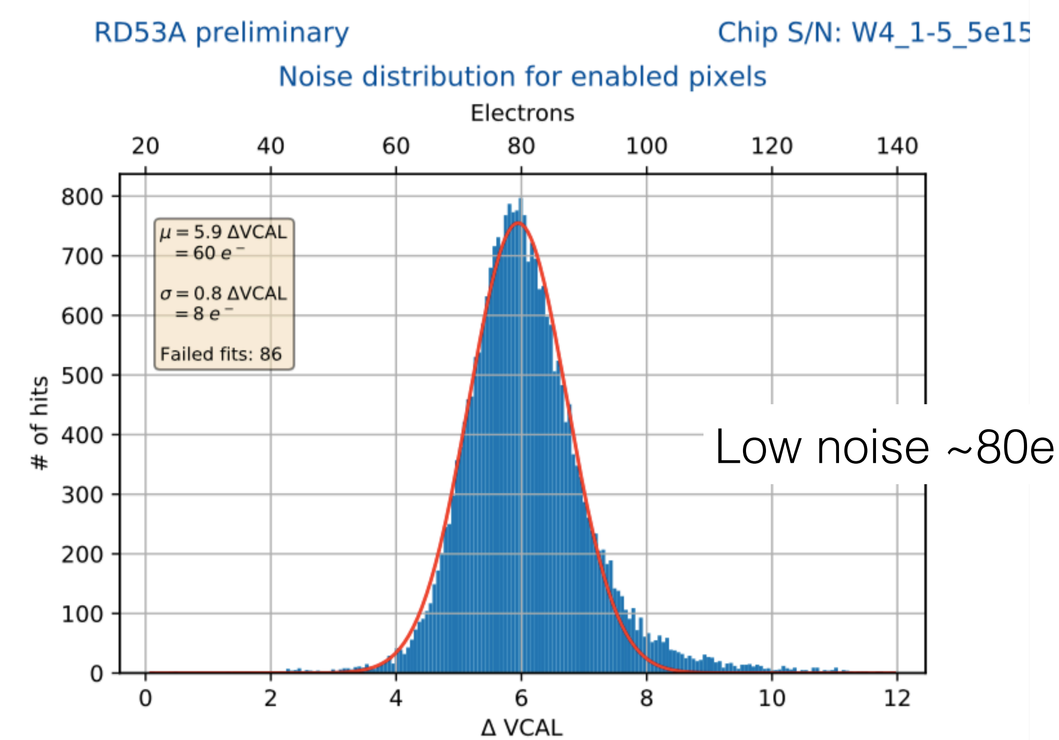
Linear FE calibrated to threshold of ~1600e with a noise dispersion of ~110e

50x50μm² - 5e15 n_{eq}/cm^2 KIT - Tuning diff. FE



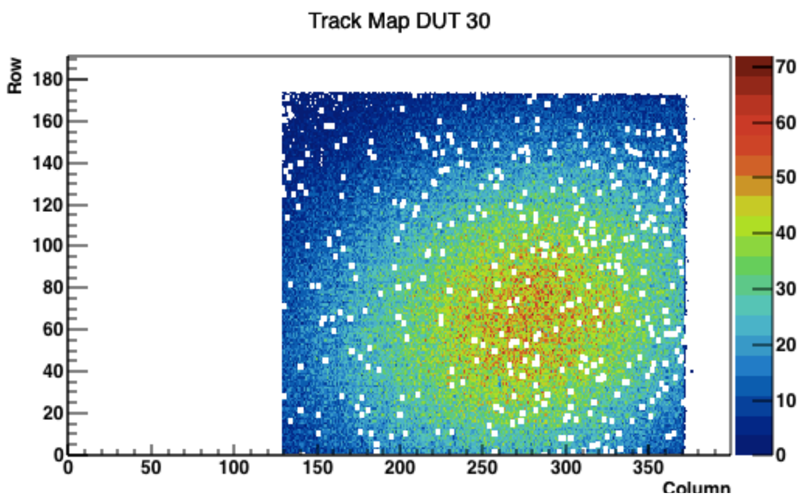


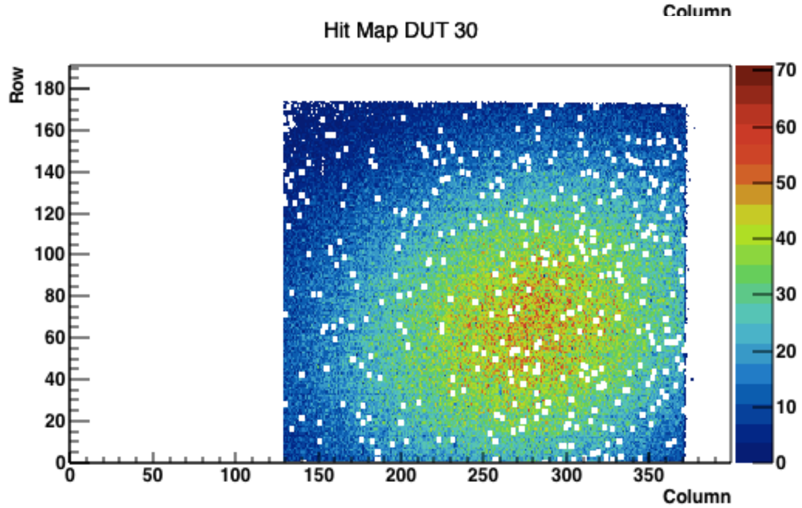


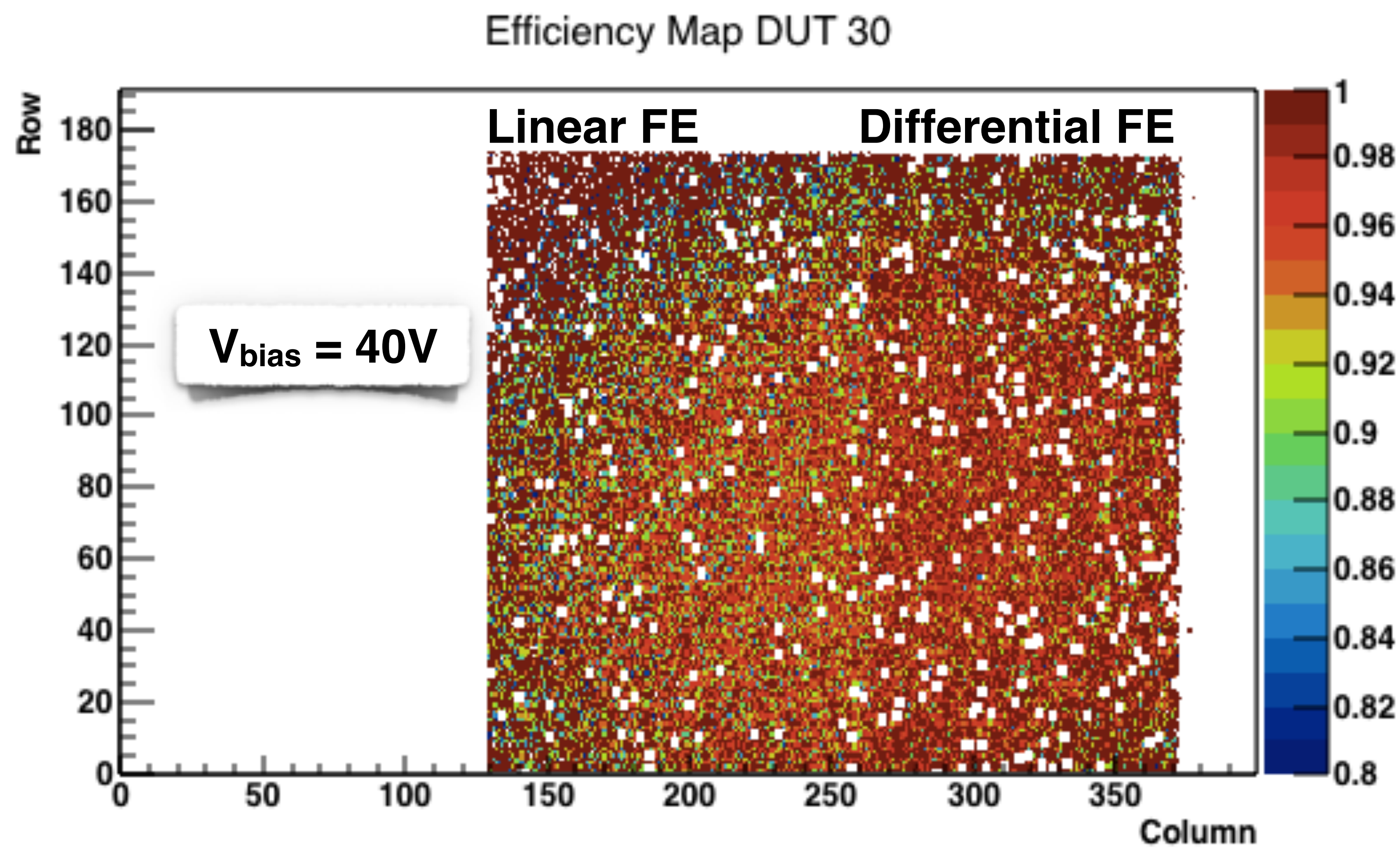


Differential FE calibrated to threshold of ~1000e with a noise dispersion of ~80e

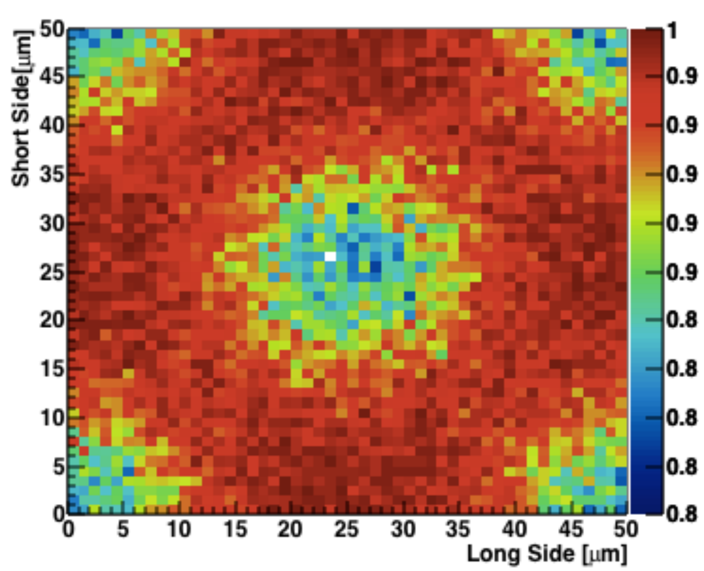
50x50μm² - 5e15 n_{eq}/cm^2 KIT - 0°



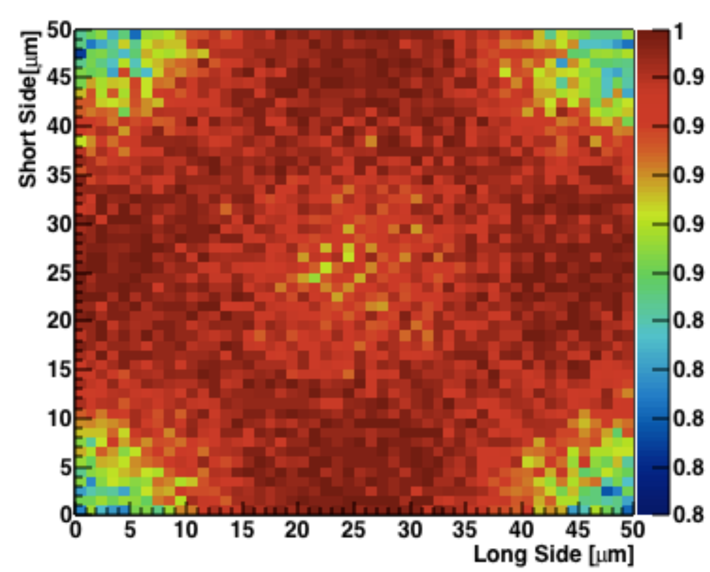




Linear FE

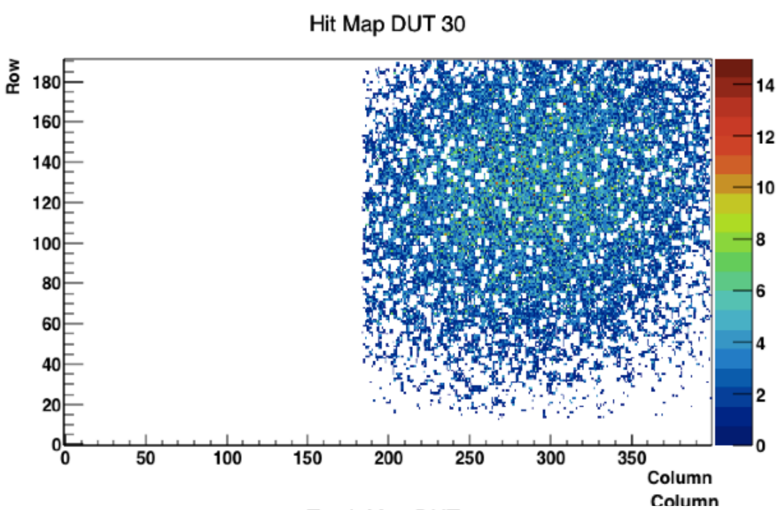


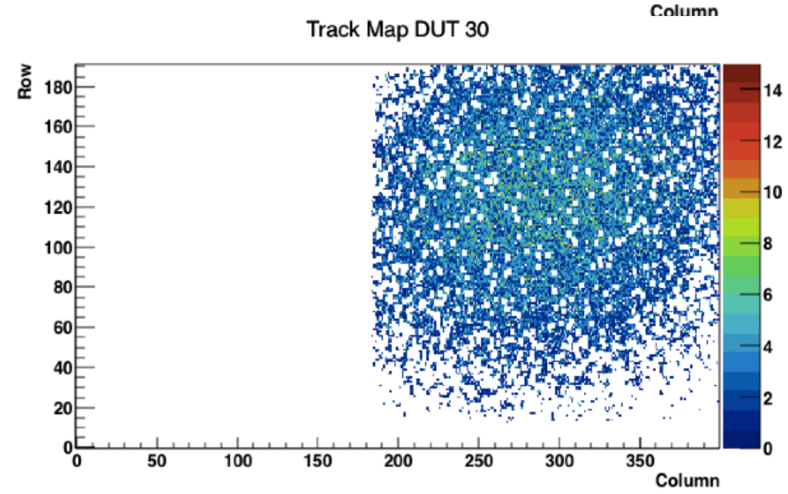
Differential FE

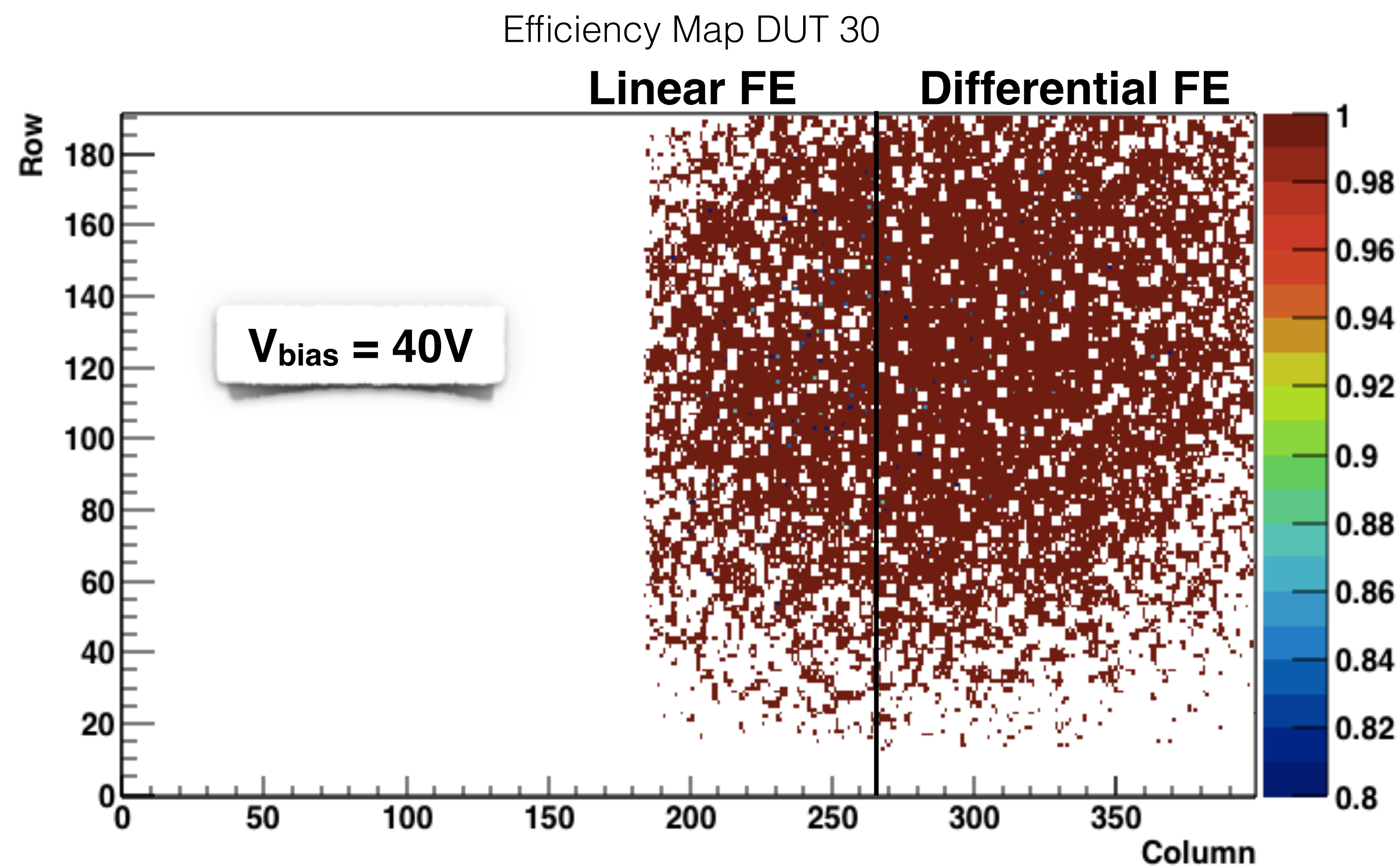


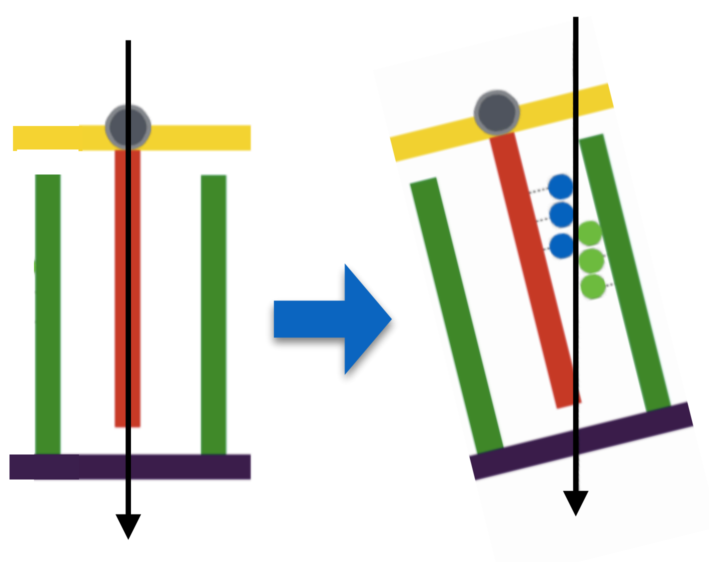
- Efficiency map:
  - Differential FE more uniform and slightly more efficient (lower threshold: 1ke vs 1.6ke linear)
- In pixel map:
  - Inefficiency due to columns very visible
  - Differential FE shows higher efficiency

50x50μm² - 5e15 n_{eq}/cm² KIT - 15°

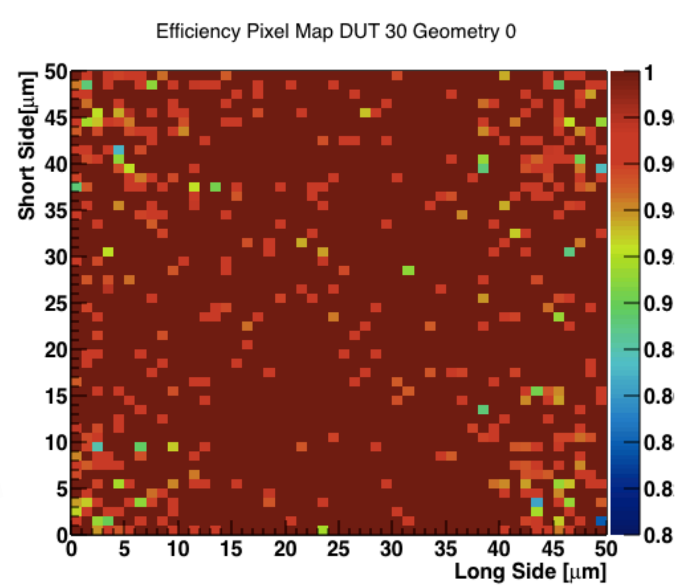








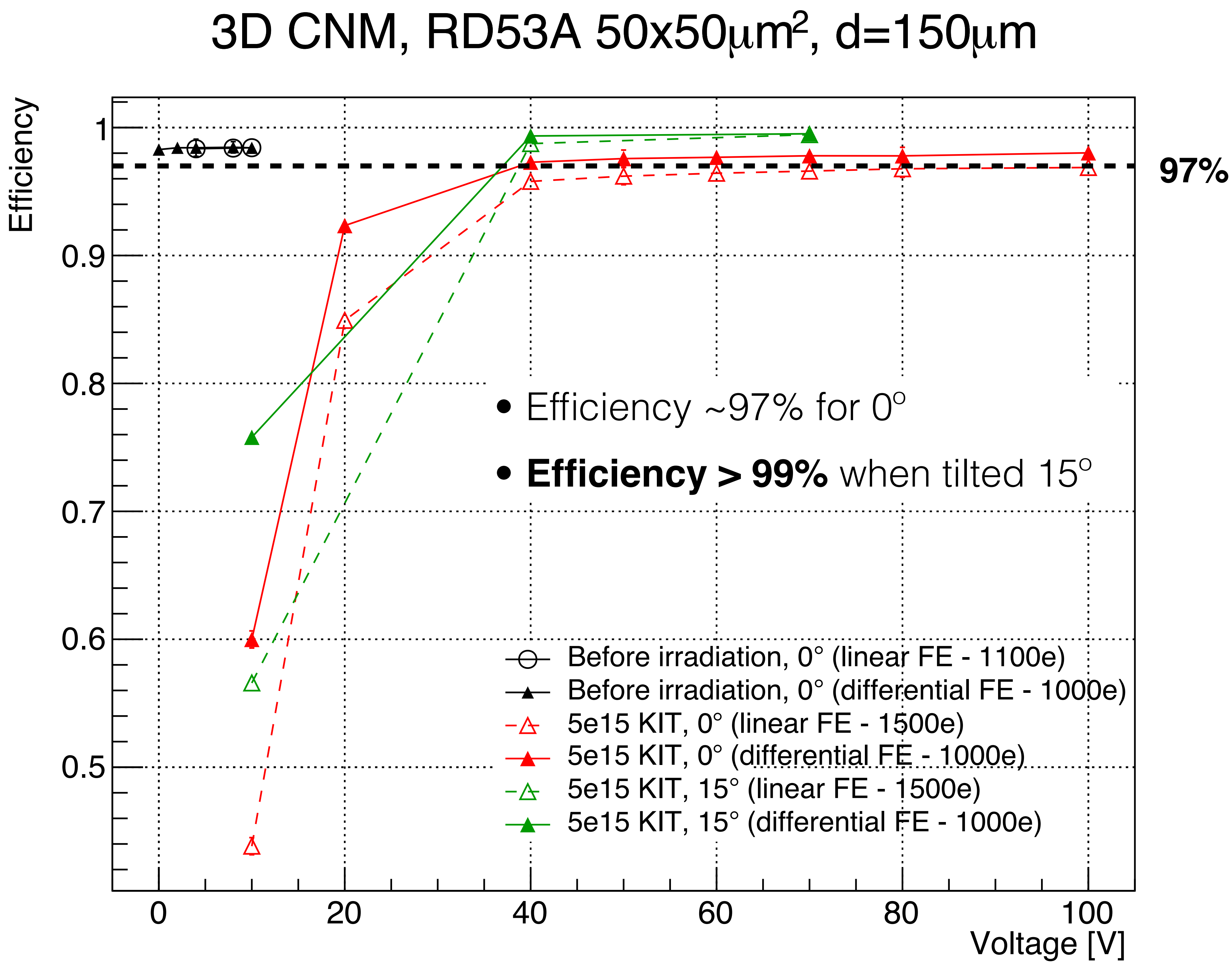
Linear & Differential FE



Measuring the module tilted (incidence angle 15°) increases the efficiency by recovering most events where the hit is lost because of the track passing through a column

- Efficiency map:
    - Uniform response of linear and differential FEs
- In pixel map:
    - In both FEs columns inefficiency is less visible

50x50μm² - 5e15 n_{eq}/cm² KIT - Efficiency



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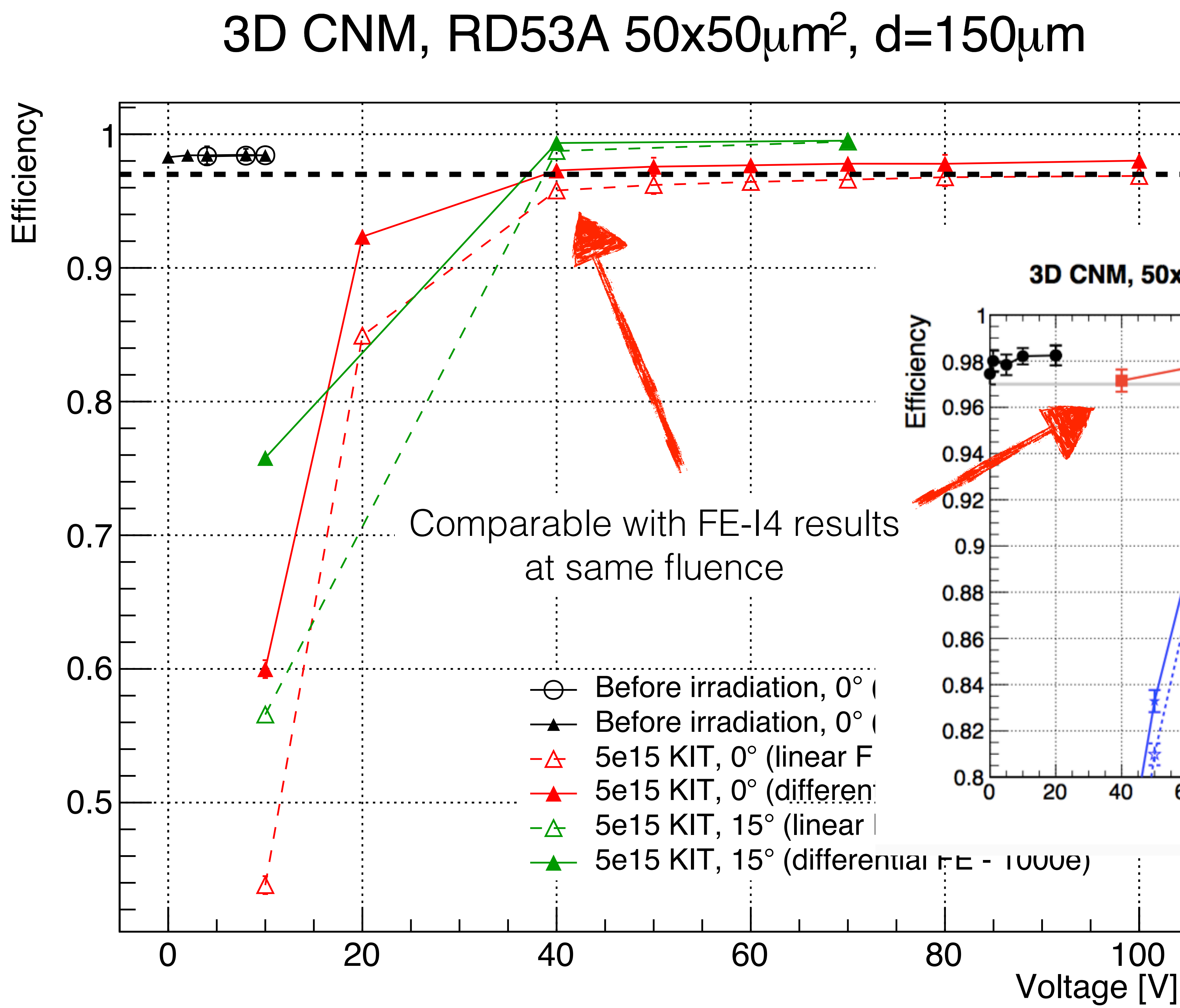
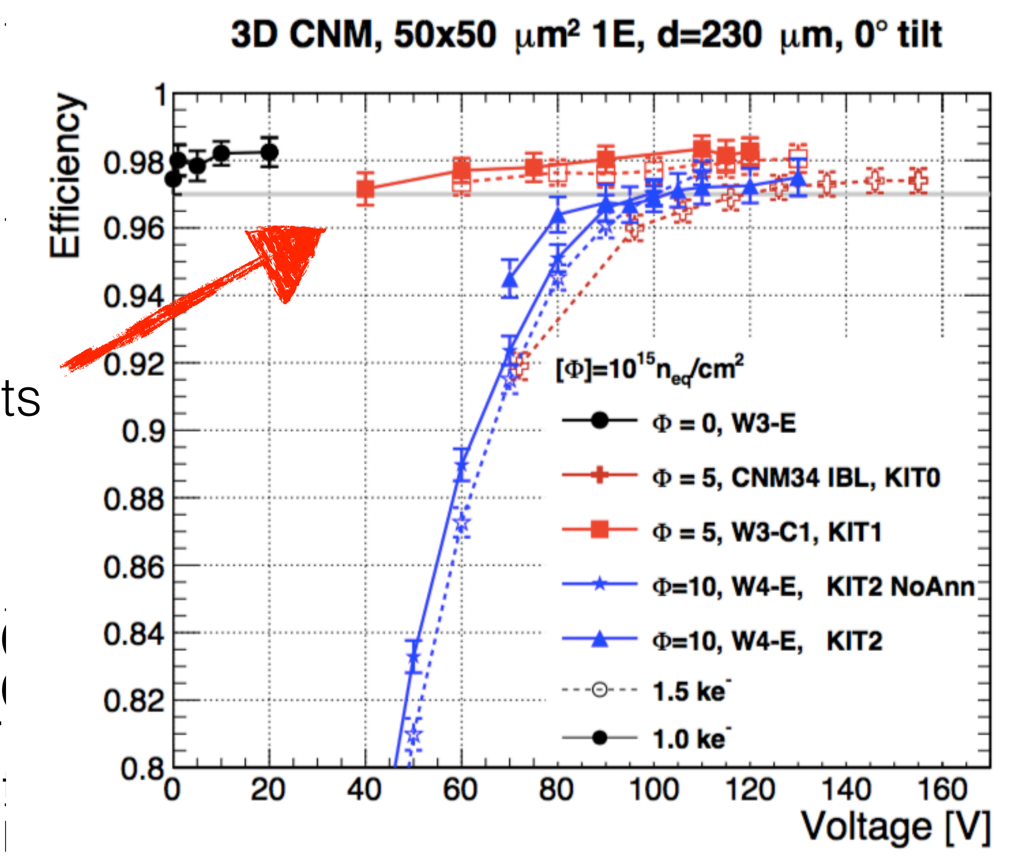


J. Lange et Al., Radiation hardness of small-pitch 3D pixel sensors up to a fluence of 3x10^16 neq/cm2, 2018, JINST



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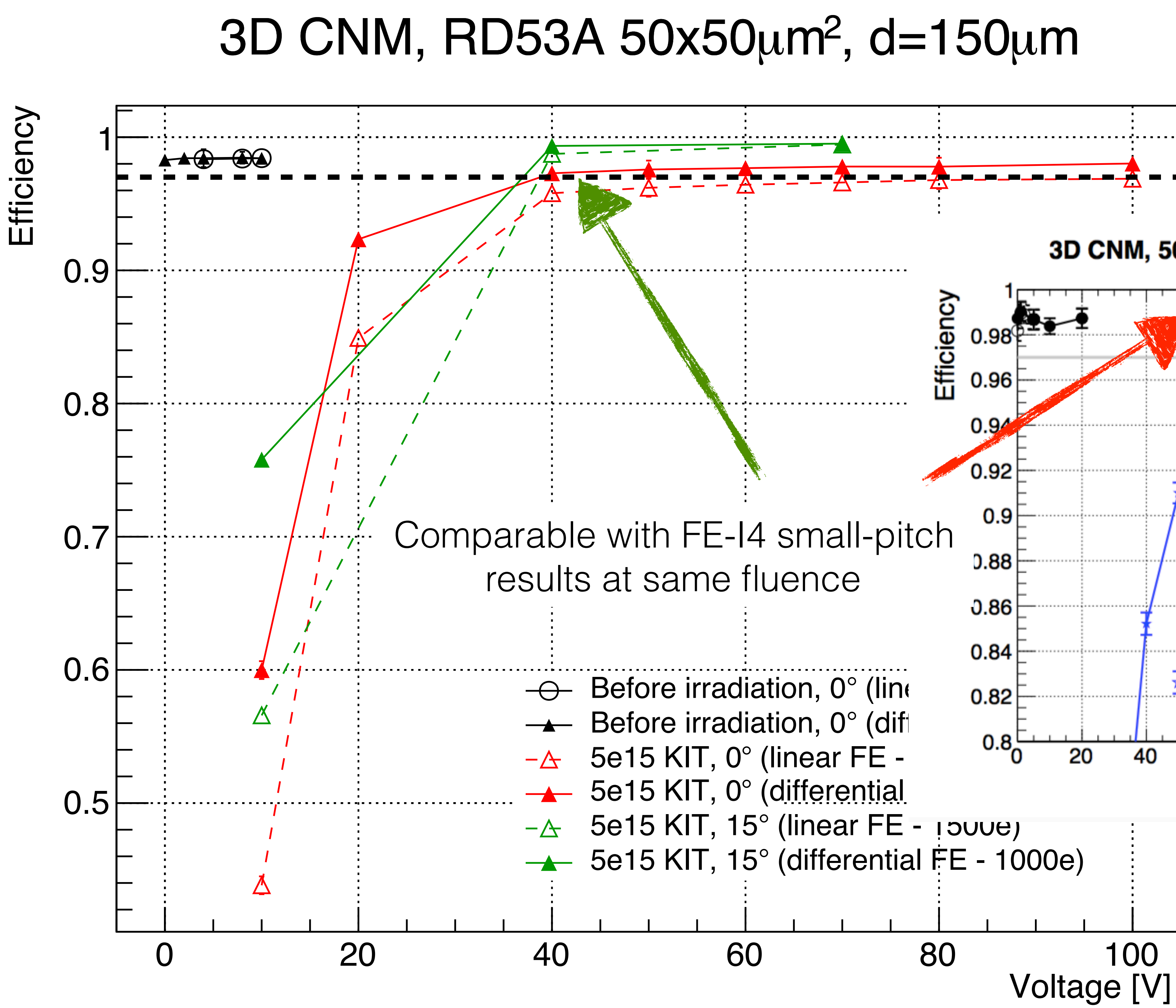

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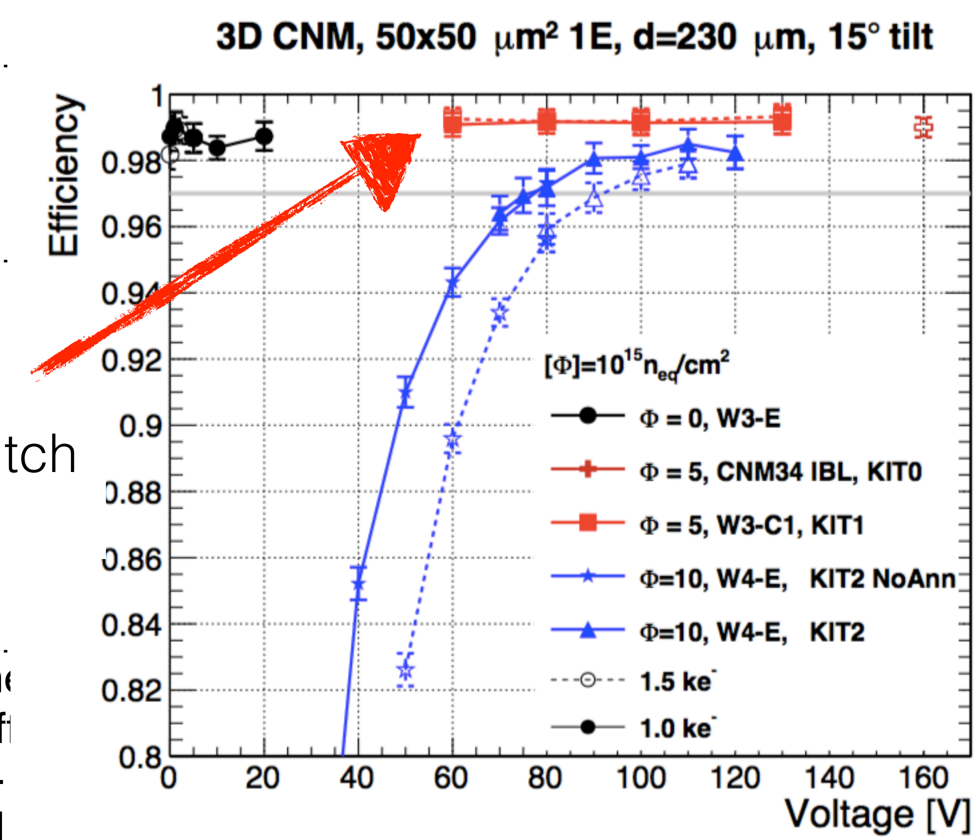
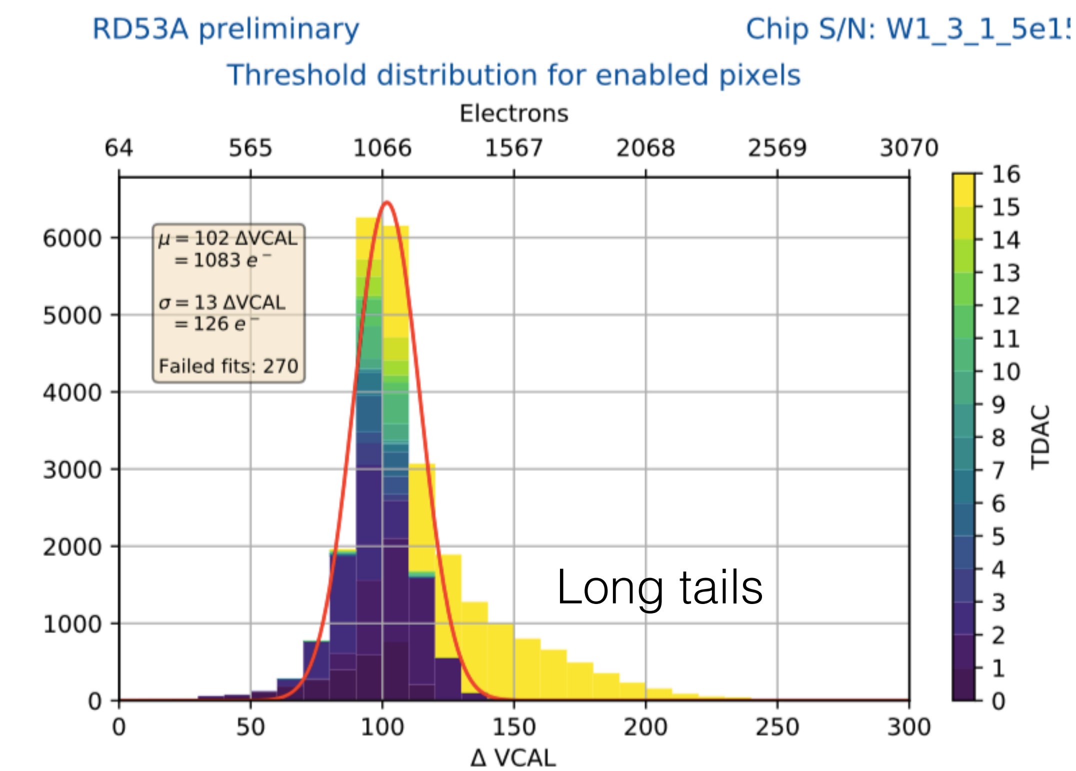
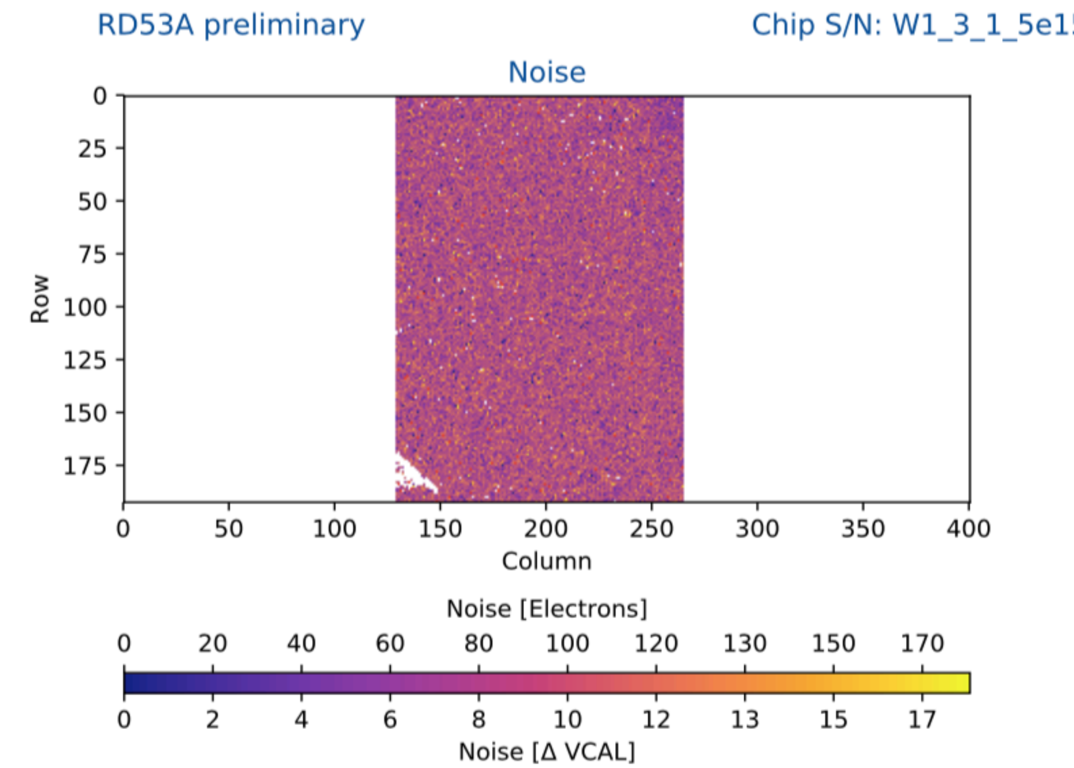
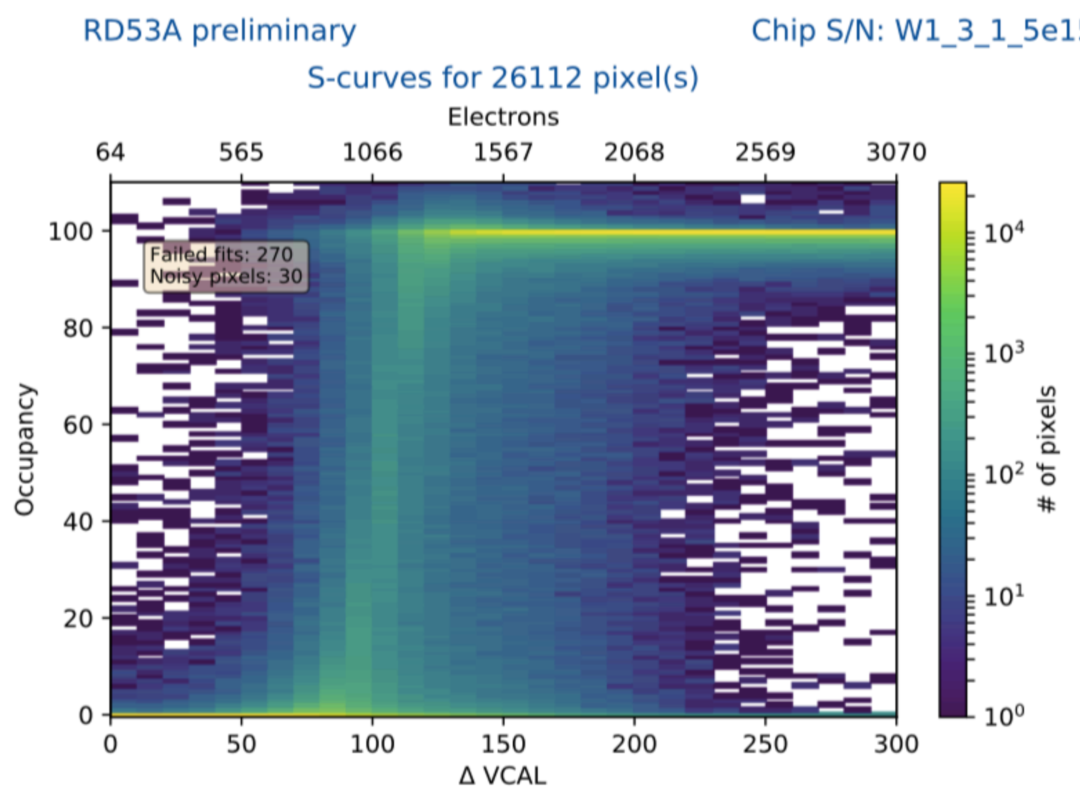
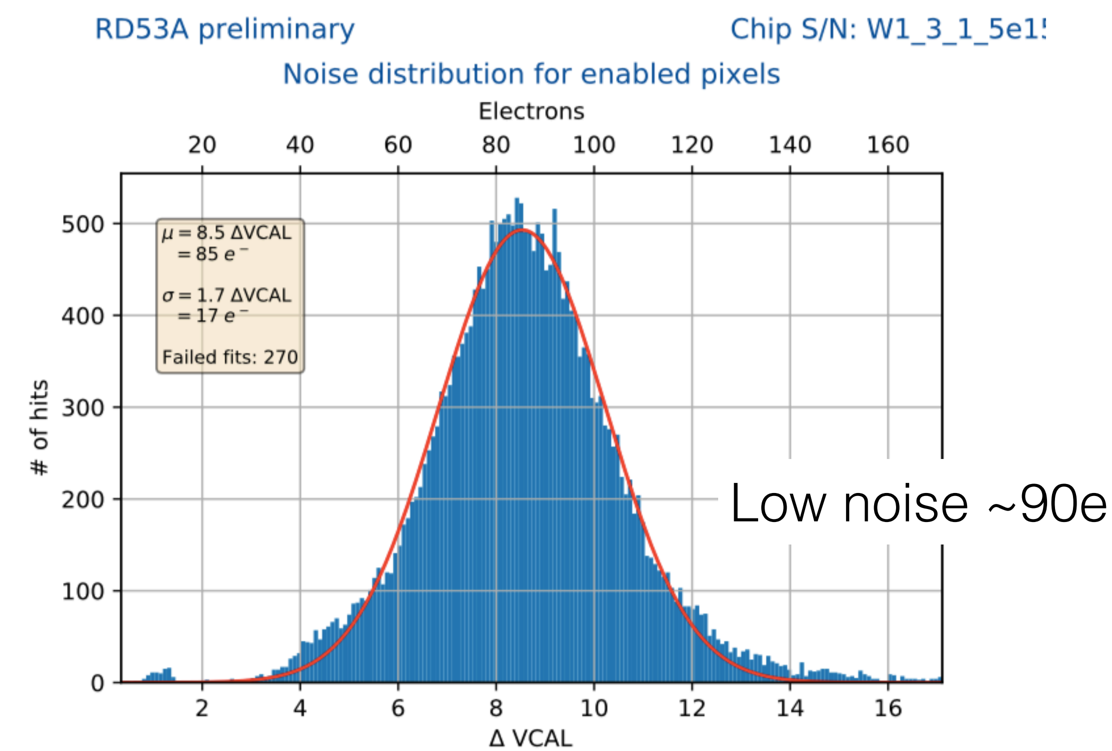


25x100 μm^2 1E - 5e15 n_{eq}/cm^2 KIT - Tuning linear FE



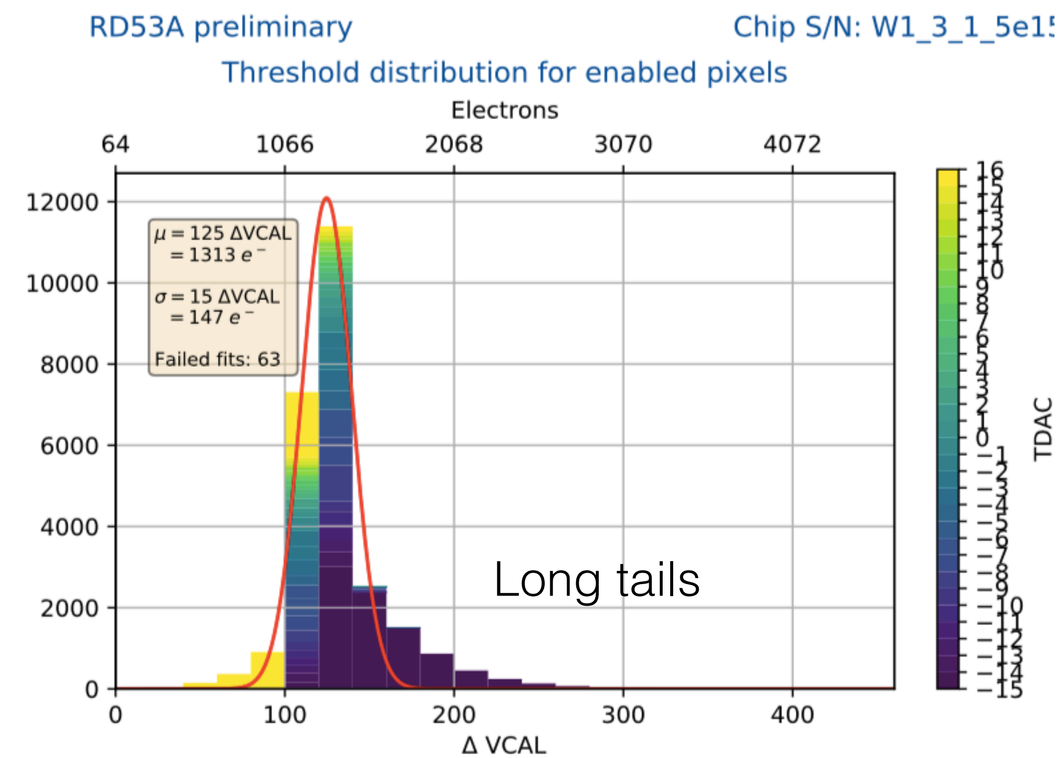


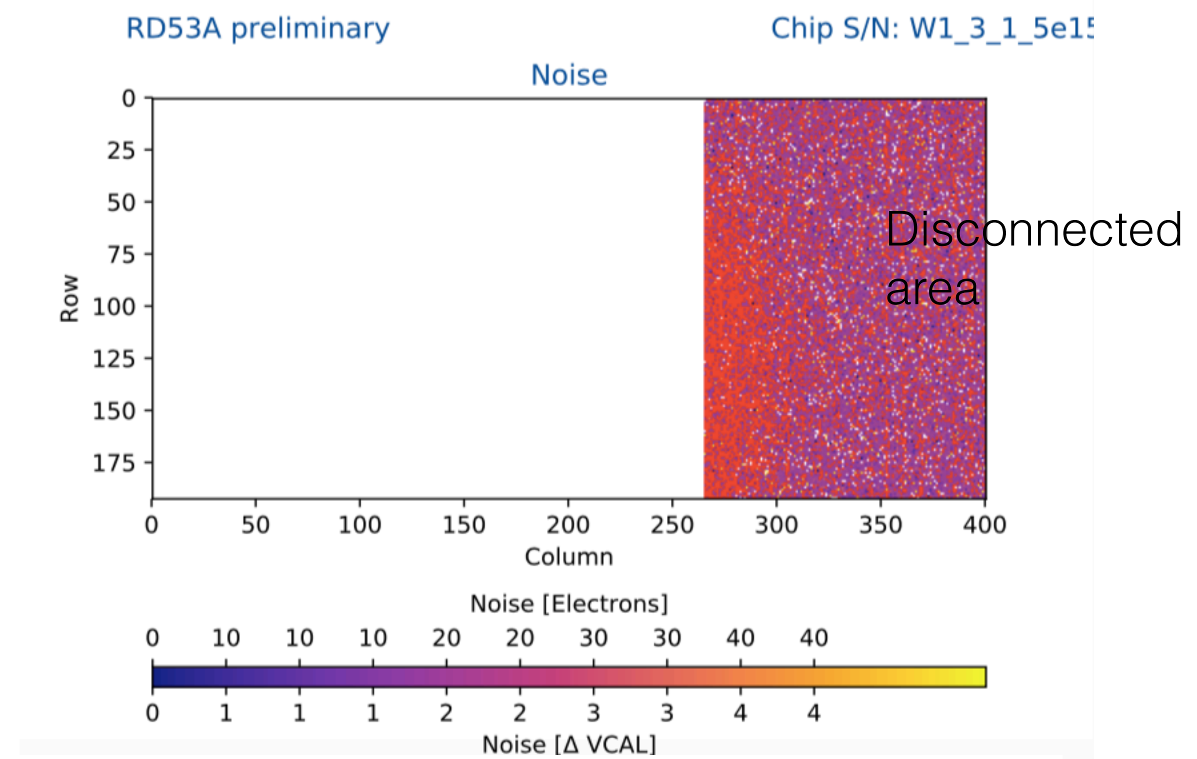


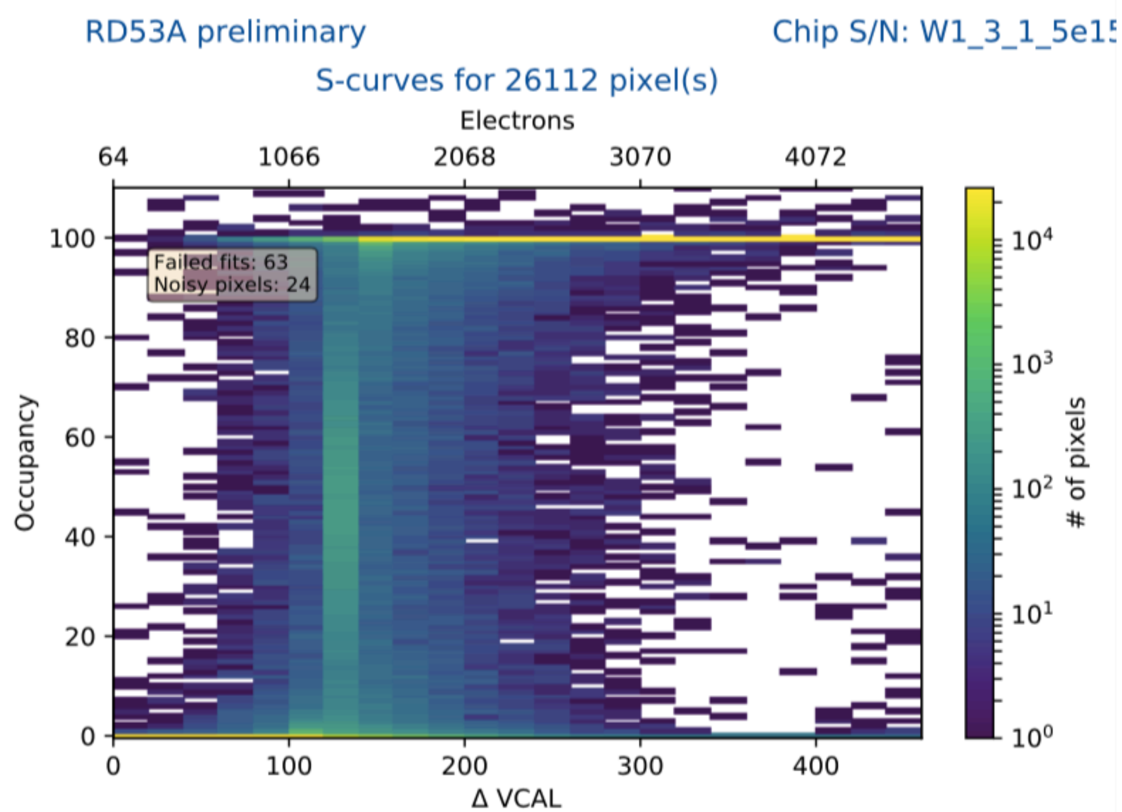


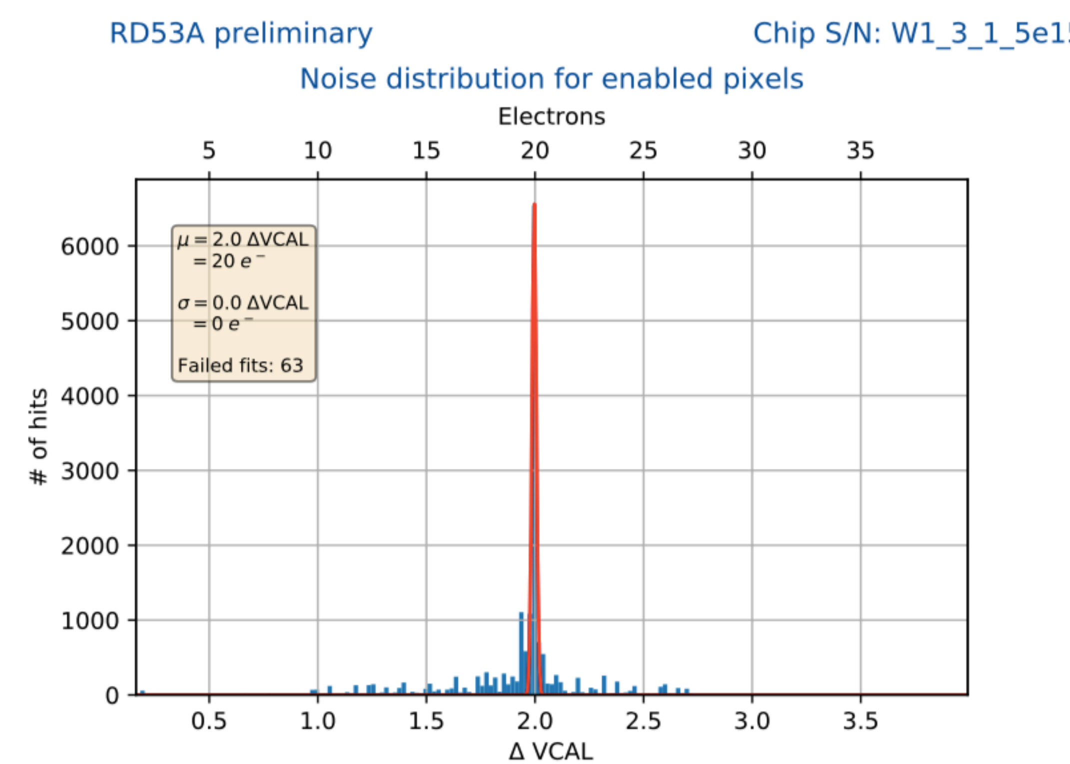
- Differential FE calibrated to threshold of ~1000e with a noise dispersion of ~90e

25x100 µm² 1E - 5e15 n_{eq}/cm^2 KIT - Tuning diff. FE



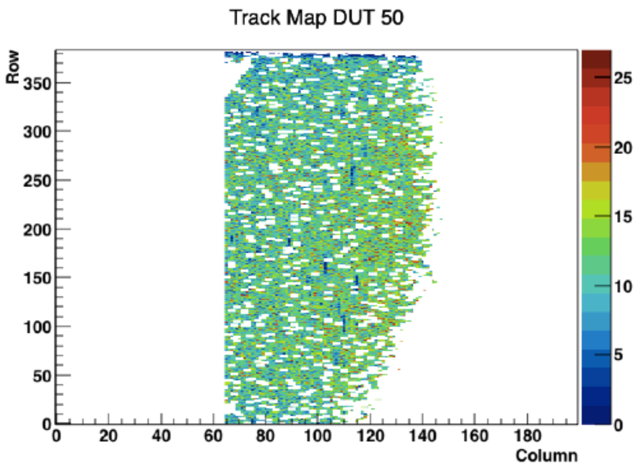


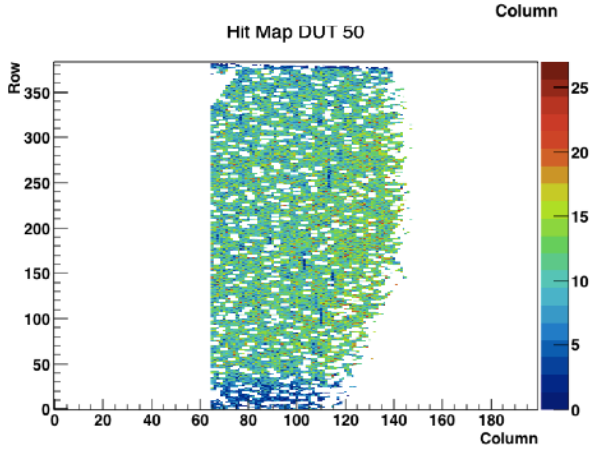


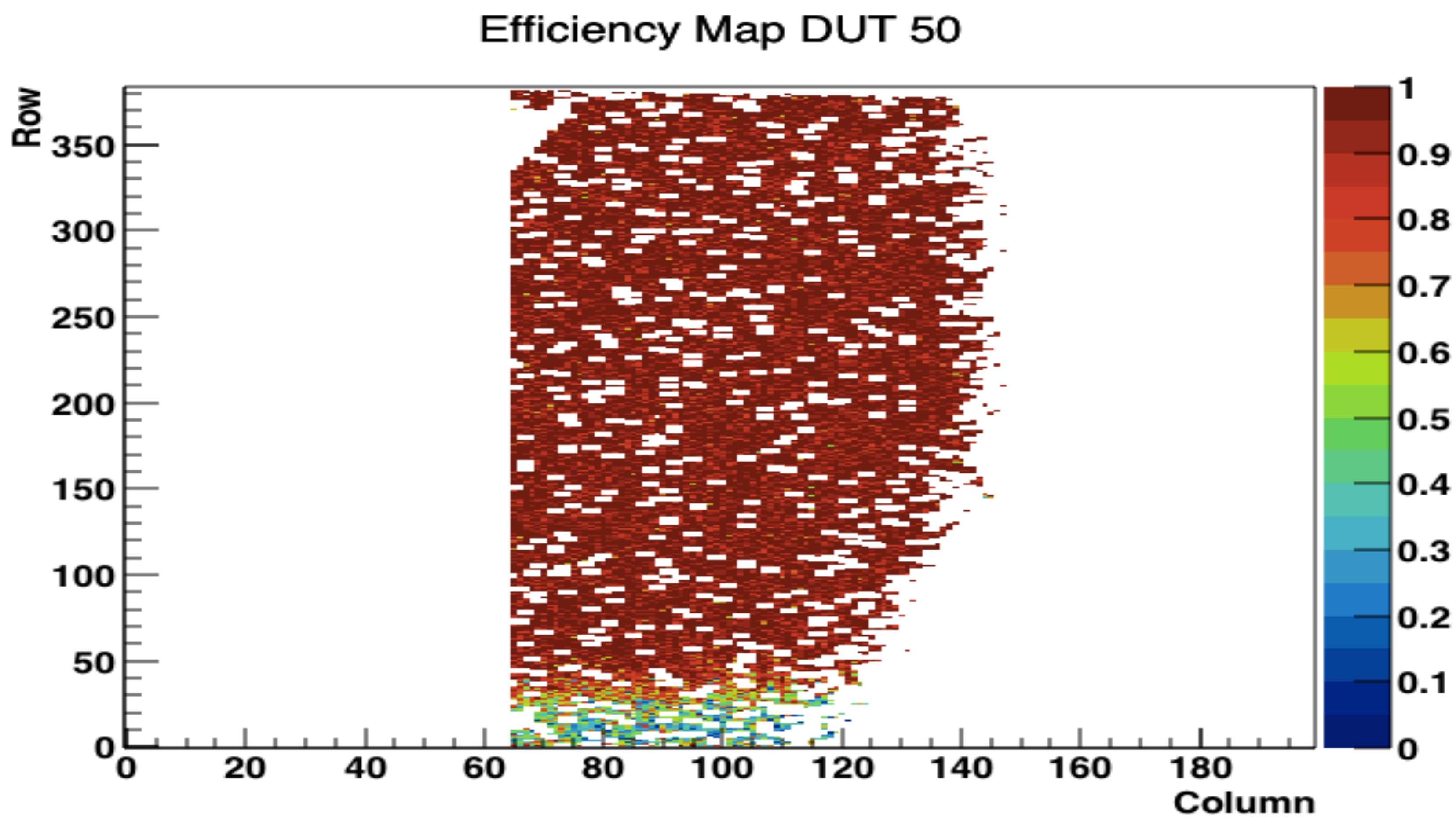


- Differential FE calibrated to threshold of ~1200e

25x100 μm^2 1E - 5e15 n_{eq}/cm^2 KIT - 0^o - 40V



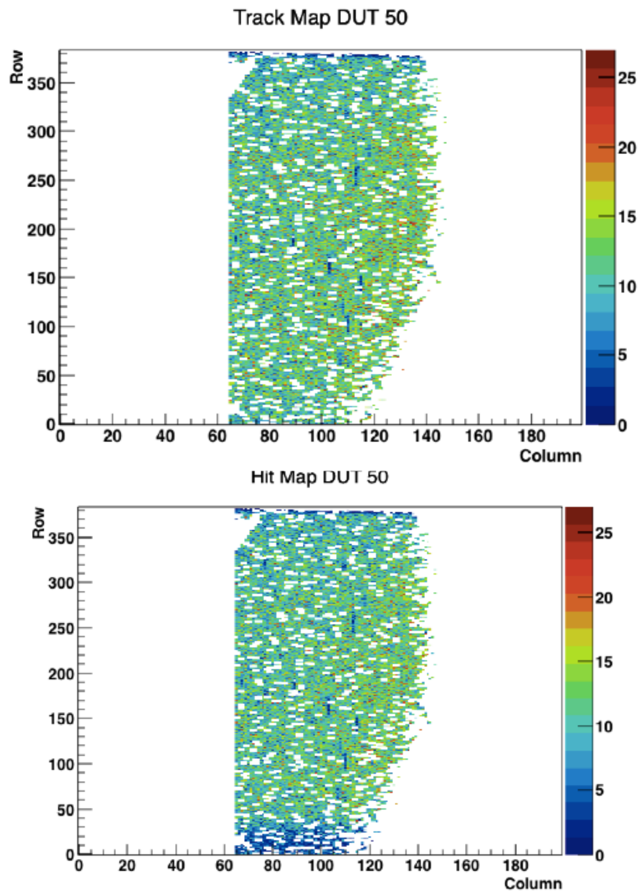


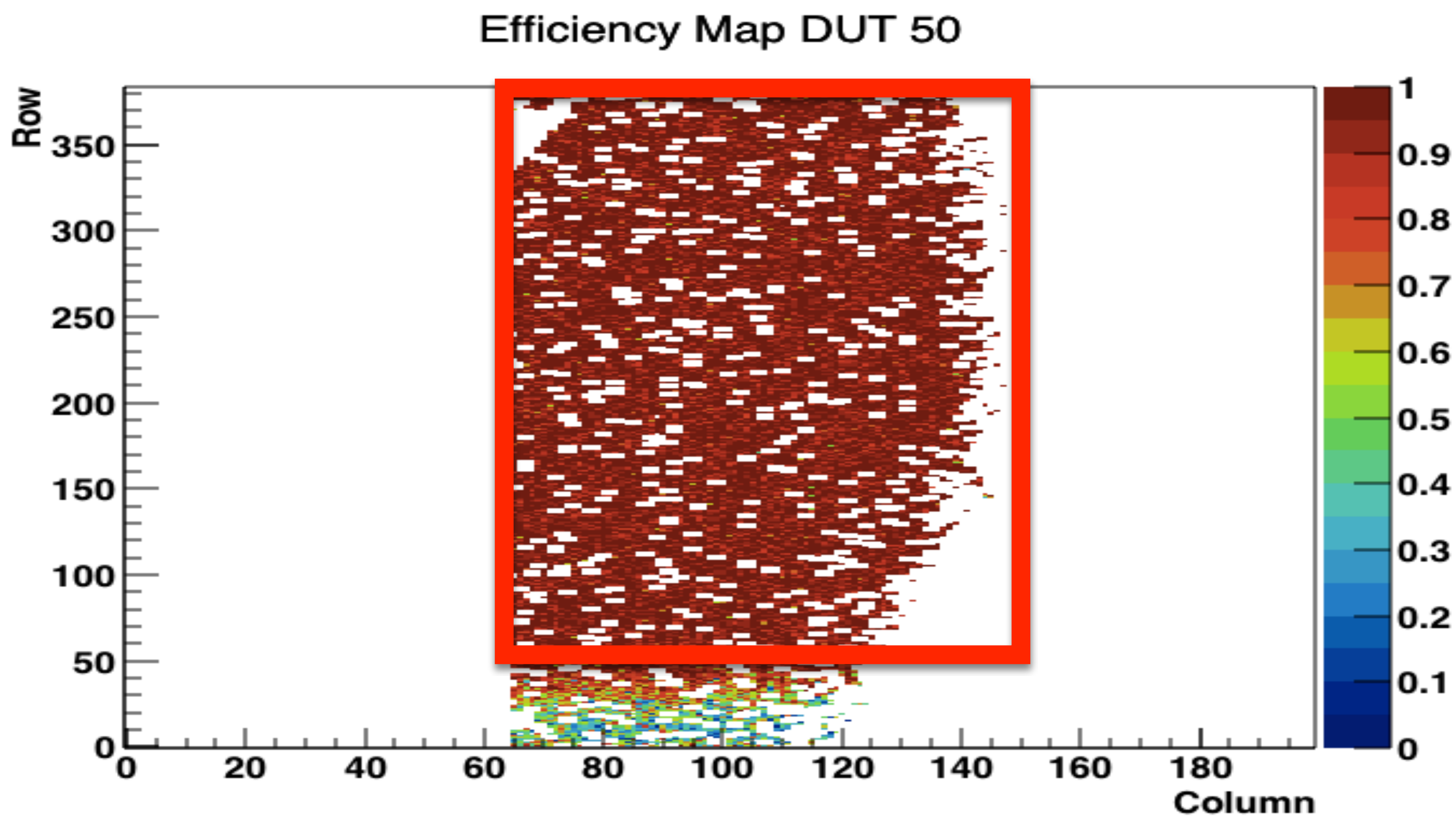


Efficiency map:

- A lower efficiency band is visible at bottom part of the sensor (disappearing at higher voltages)
  - Suspect it has been irradiated to higher fluences due to a scattering of proton beam on the metal protection of the board during irradiation
    - ➡ As already observed for irradiations of AFP module at KIT (J. Lange et al., JINST 10 C03031 (2015))
- Restricted region of interest to calculate efficiency

25x100 µm^2 1E - 5e15 n_{eq}/cm^2 KIT - 0^o - 40V





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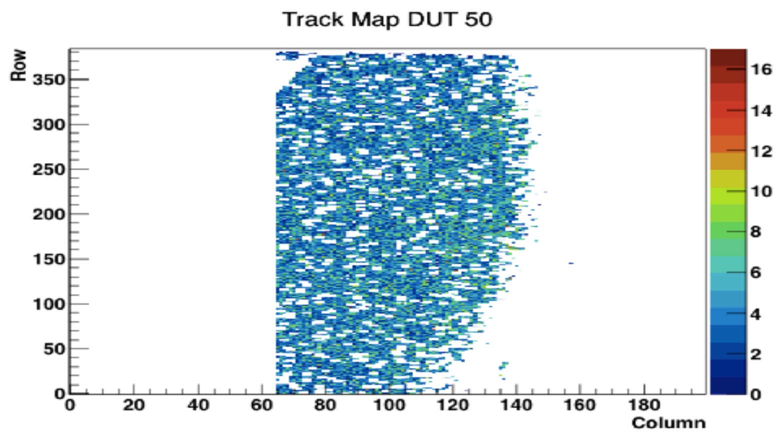
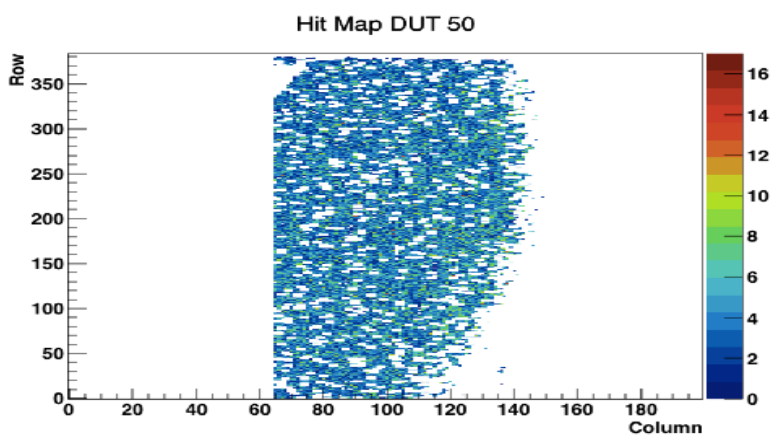
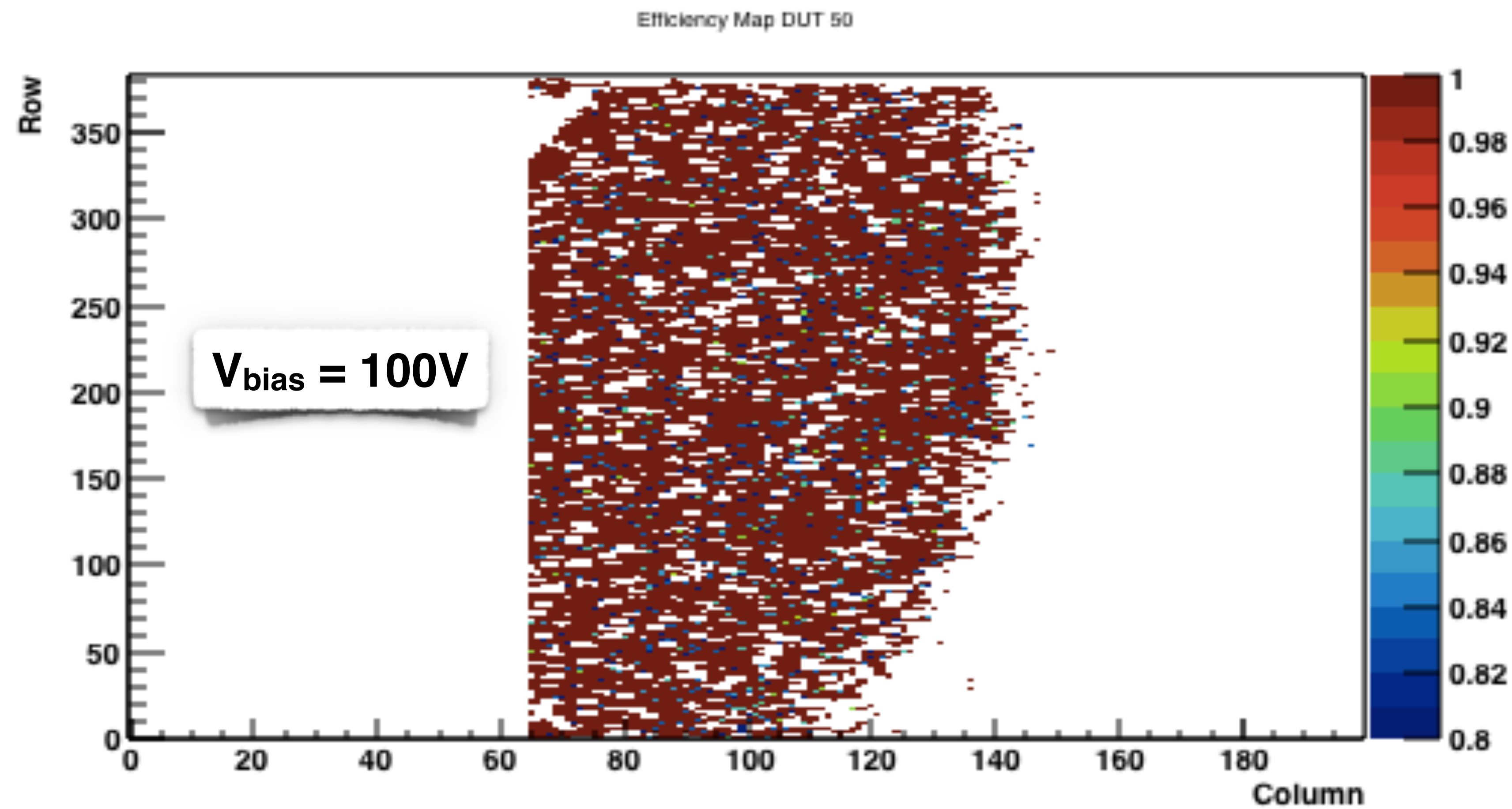
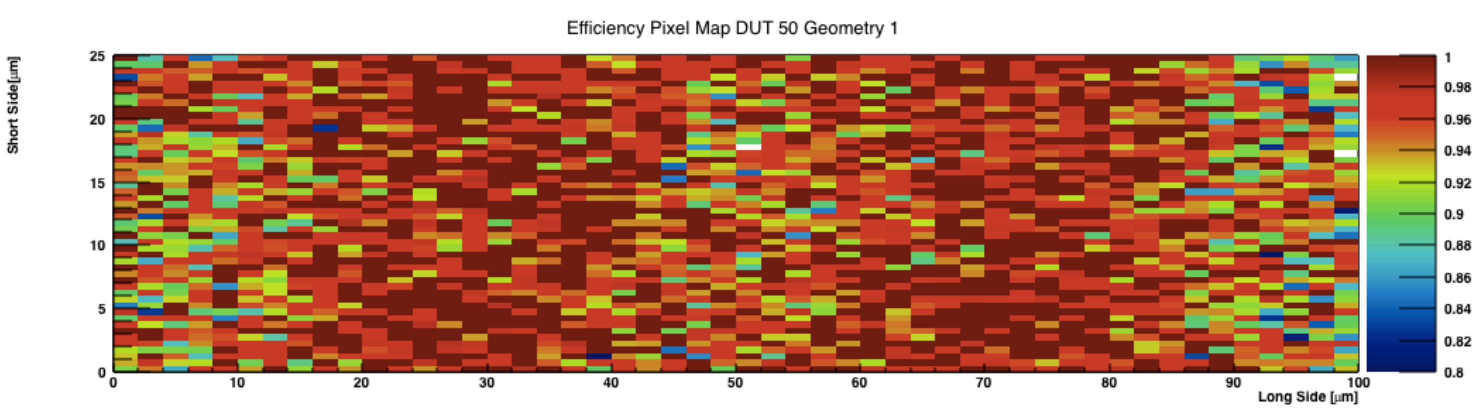
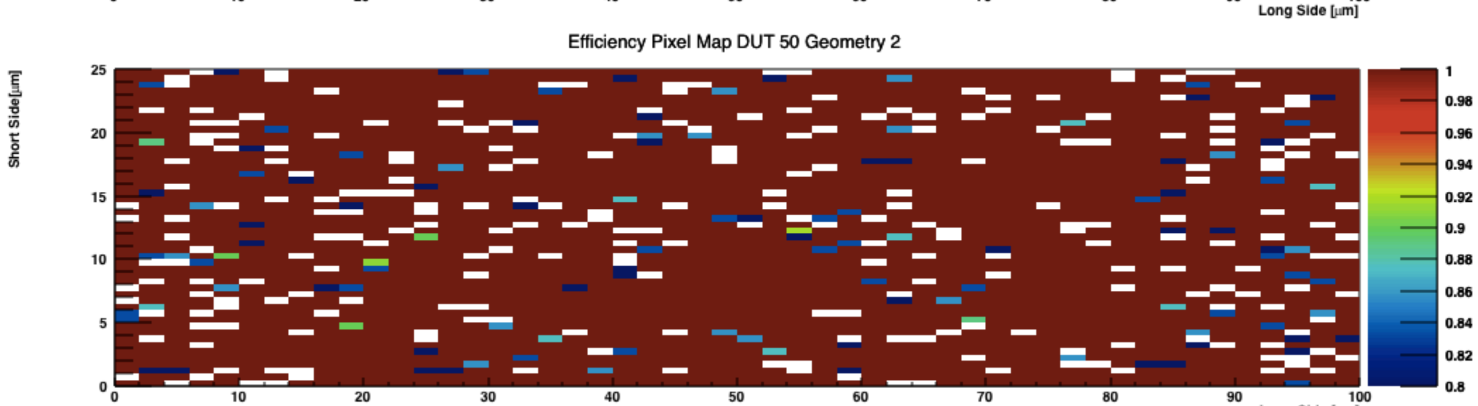
25x100 μm² 1E - 5e15 n_{eq}/cm^2 KIT - 0°





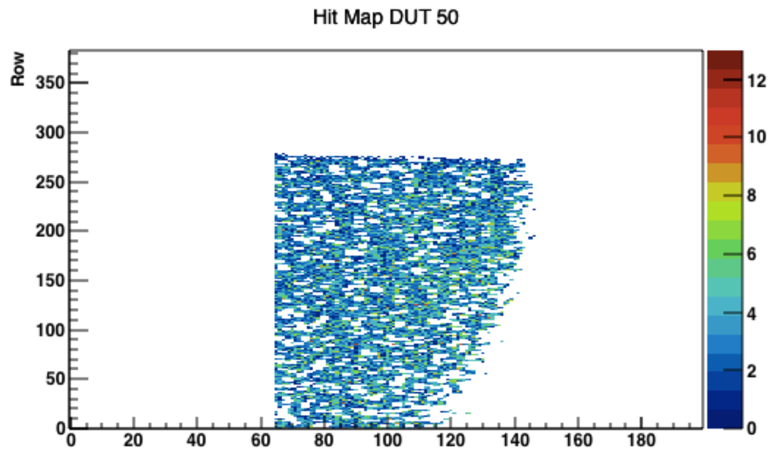


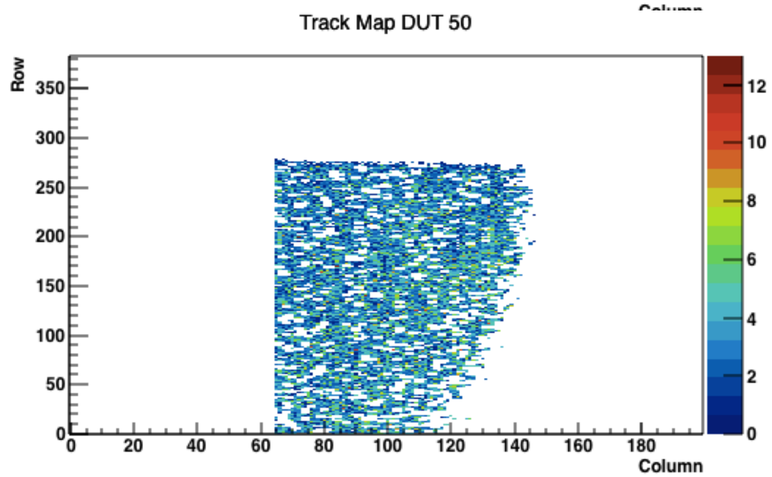


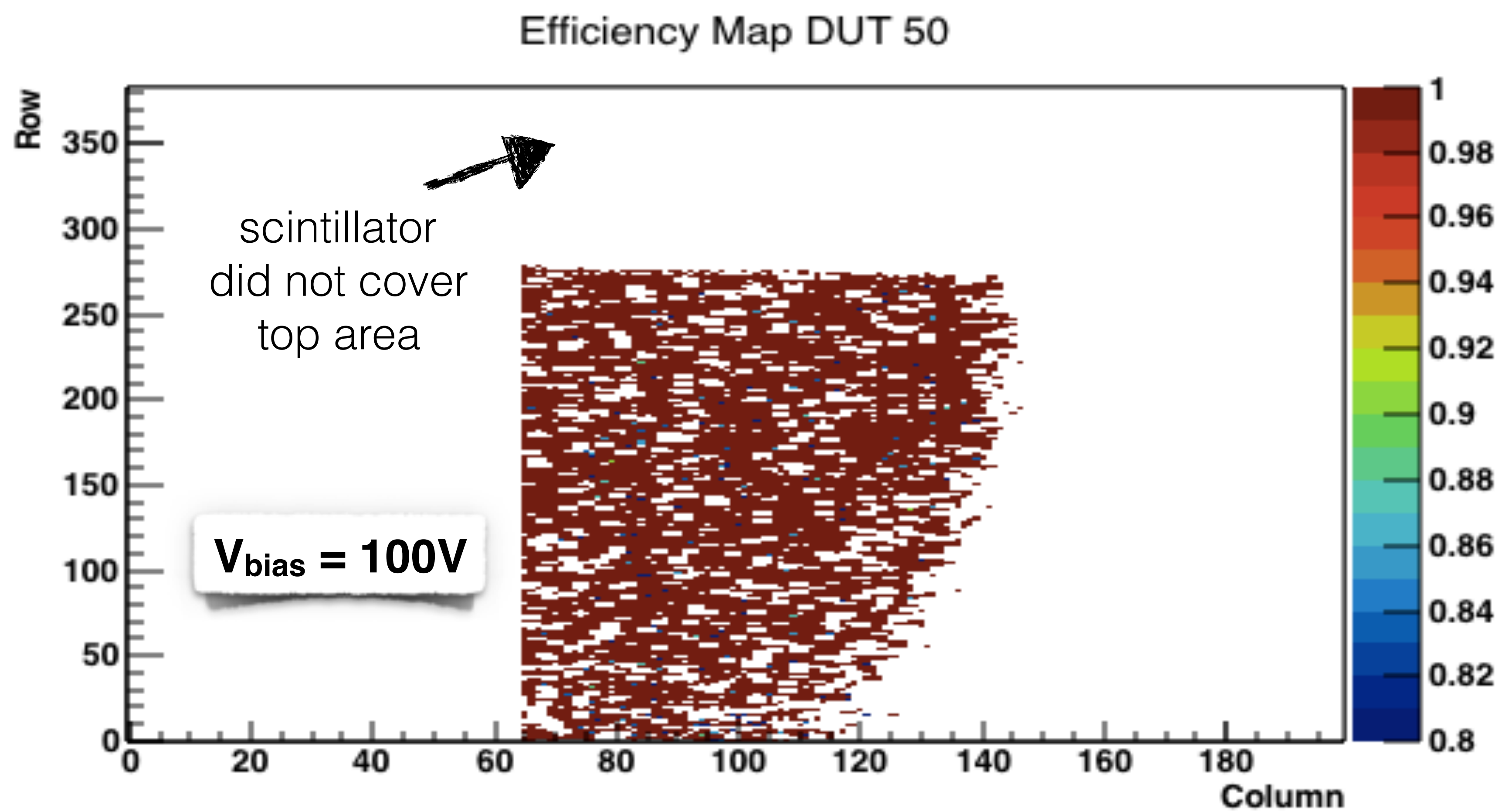


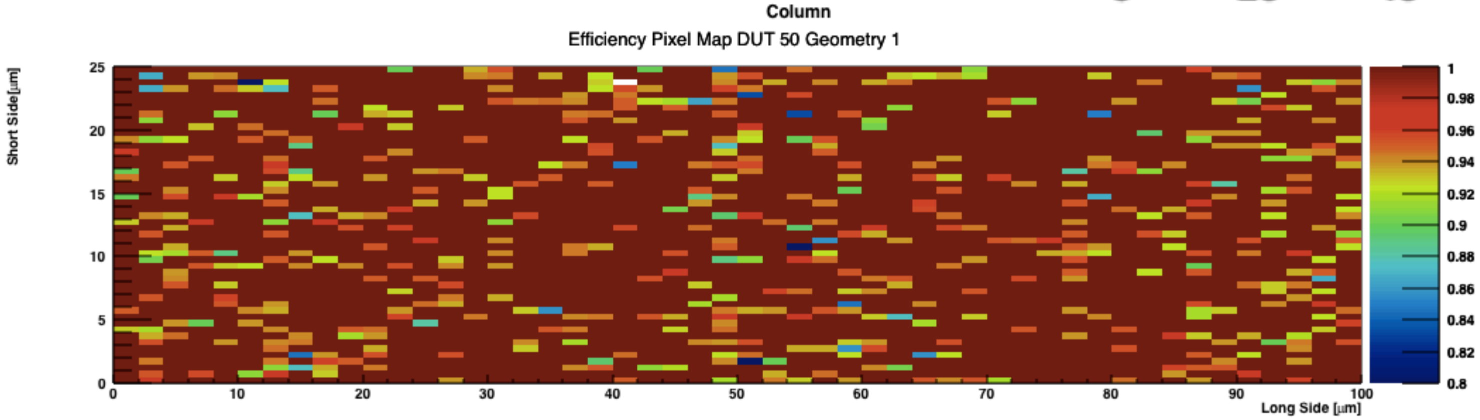
- Efficiency map:
  - Visible disconnected areas
  - Uniform overall efficiency
- In pixel map:
  - LIN: visible inefficiency due to columns
    - Smeared, probably due to not perfect alignment
  - DIFF: more uniform efficiency distribution
    - low statistic due to large portion of FE disconnected

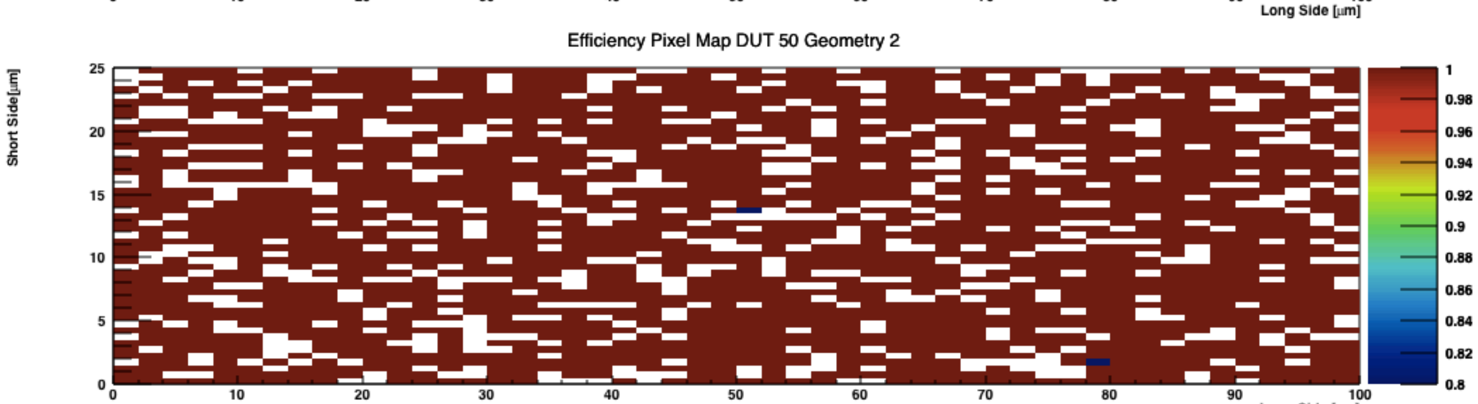
25x100 μm² 1E - 5e15 n_{eq}/cm^2 KIT - 15°





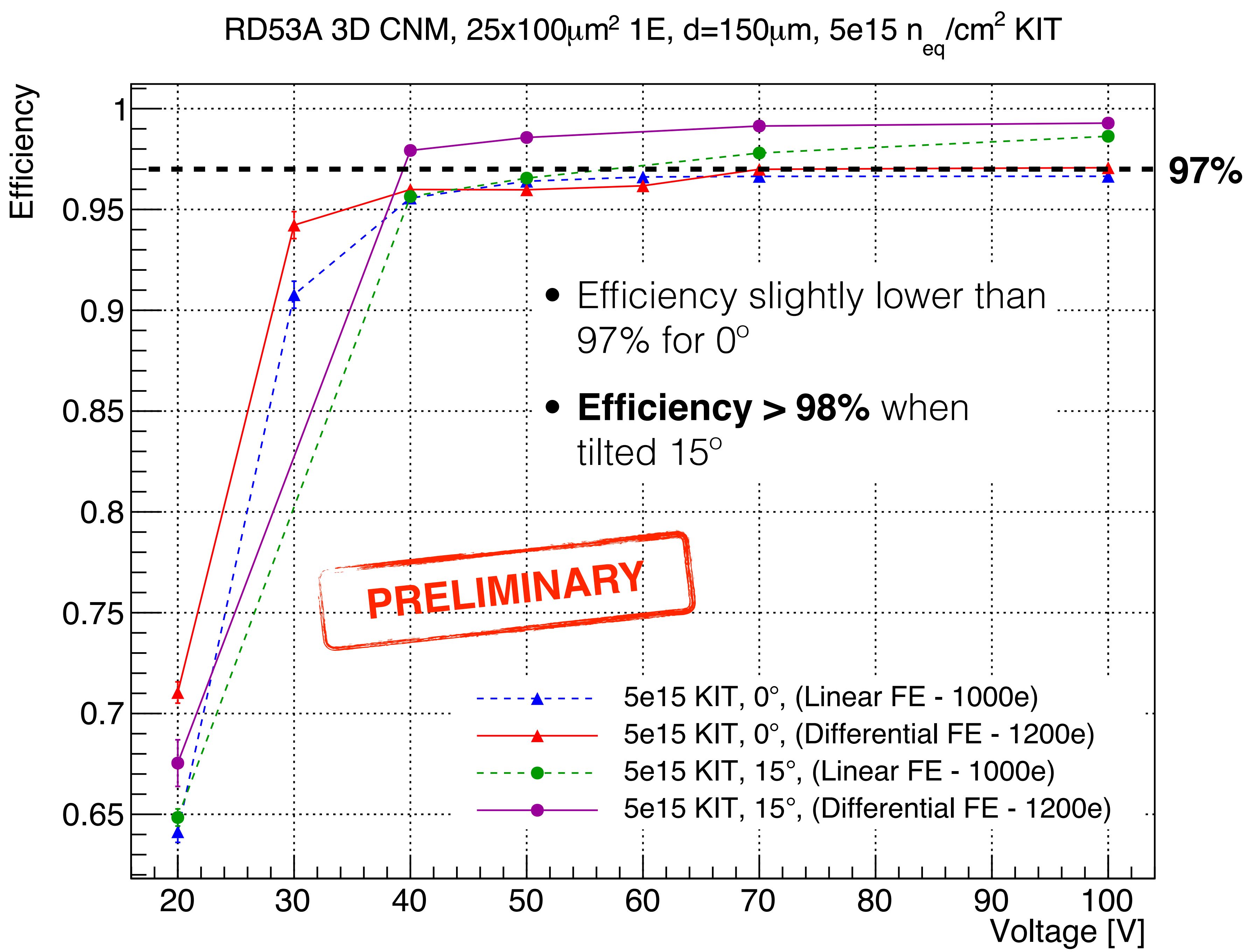






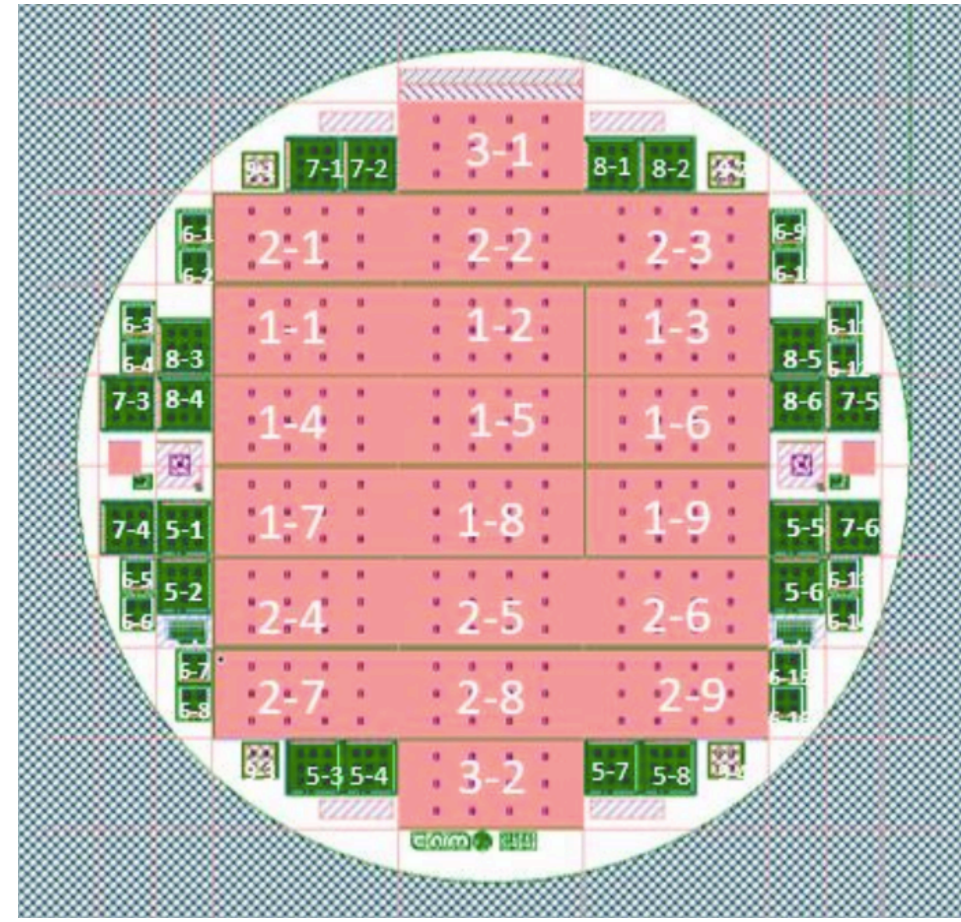
- Efficiency map:
  - Visible disconnected areas
  - Uniform overall efficiency
- In pixel map:
  - LIN: inefficiency due to columns undistinguishable
  - DIFF: more uniform efficiency distribution
    - low statistic due to large portion of FE disconnected

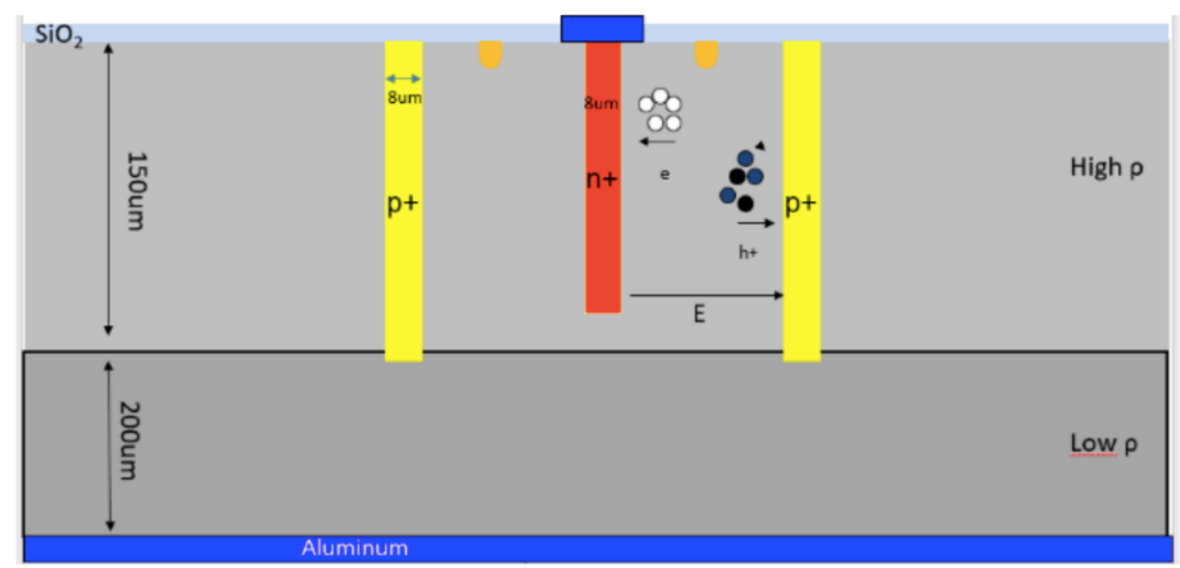
25x100 μm² 1E - 5e15 n_{eq}/cm² KIT - Efficiency



CNM Si-Si wafer run

- On going CNM run (AIDA)
  - Design fully compatible with 3D sensor specifications
    - Single Sided process on **Si-Si** wafers,
    - 150 μm active thickness, 200 μm handle wafer
    - 130 μm column depth, 8μm column diameter
  - 9 RD53 50x50 μm^2 (1-x)
  - 9 RD53 25x100 μm^2 2E (2-x)
  - 2 RD53 25x100 μm^2 1E (3-x)
- New sensors ready early next year (February)





Conclusions

- **First results of 150 µm thick RD53A uniformly irradiated to 5e15 n_{eq}/cm^2 at KIT**
  - **50x50 µm²**
    - 97% hit efficiency at 40V at 1ke for differential FE at 1ke
    - Slightly lower (96.6%) for linear FE at 1.5ke
    - **About 99% hit efficiency in both linear and differential FEs when tilted 15°**
  - **25x100 µm² 1E**
    - ~97% hit efficiency at 70V for both FEs
    - **Respectively about 98% and 99% hit efficiency for linear differential FE at 70V when tilted 15°**

Future plans:

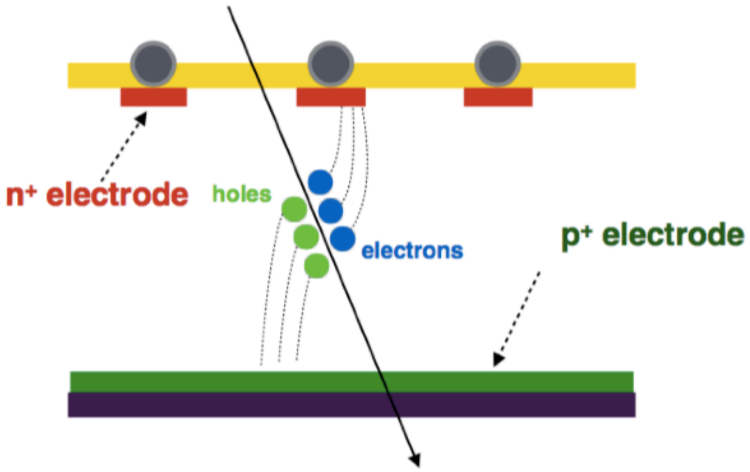
- Analysis and new measurements on going for modules irradiated at PS to 1e16 n_{eq}/cm^2
- One module sent for **irradiation at CYRIC (Japan) to 1e16 n_{eq}/cm^2**
- New CNM run of **Si-Si wafer** on going
  - New sensors early next year

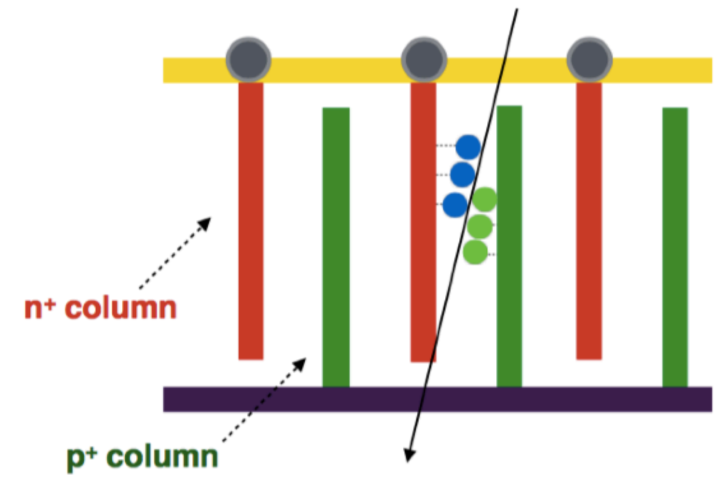
Thanks for your attention!

Backup

3D vs Planar

Planar





3D

- **Inter-electrode distance** = sensor **thickness**
  number of produced electrons-holes pairs = initial **signal**
- How to maintain high efficiency though whole lifetime?
  - **Thin detector**: reduce probability of electron-hole pairs being trapping by bulk defects by decreasing inter-electrode distance
    - BUT -> smaller signal
  - **Increase bias voltage** to keep bulk depleted
    - BUT -> higher power dissipation

- Electrodes not placed on the surface but columns inserted in the bulk
- Electrons-holes pairs drift towards columns
- **Inter-electrode distance decoupled from sensor thickness** -> inter-electrode distance can be reduced without decreasing the signal!

Pros:

- Lower depletion voltage
- Faster charge collection
- Smaller trapping probability

Radiation hardness!!

Con:

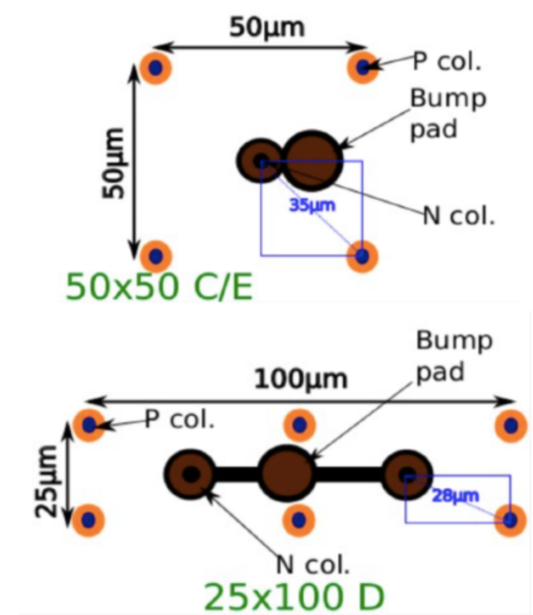
- Very complex production process

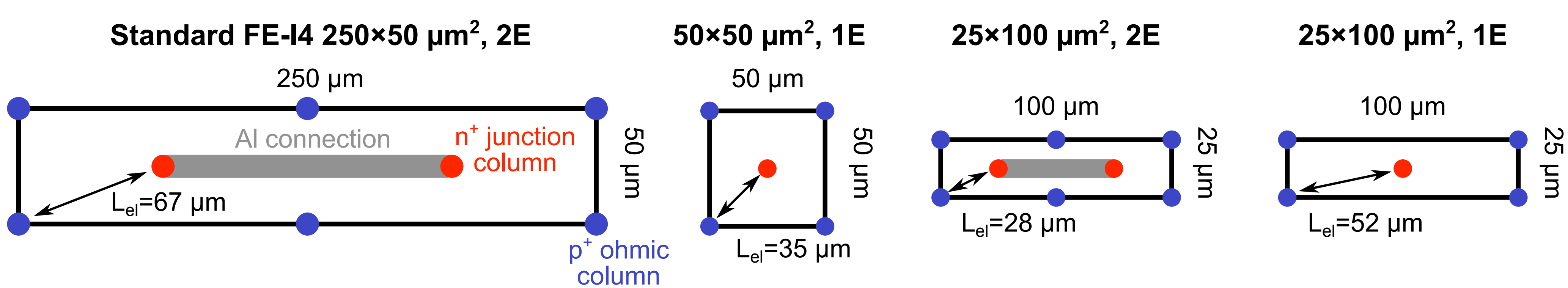
3D Design open issues

✓ Collected charge, production yield

✗ Hit occupancy, especially for forward tracks

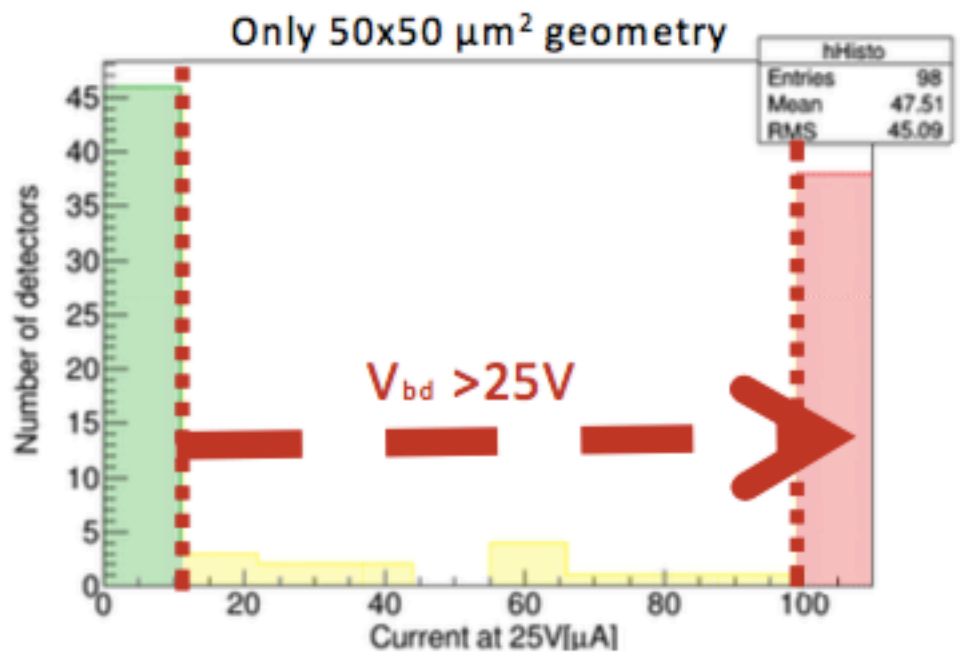
- **Pixel size?**
  - IBL: standard FE-I4 50x250 μm² with two n+ columns, 67 μm inter-electrode distance
  - HL-LHC options:
    - **50x50 μm²**: easier to produce, 35 μm inter-electrode distance
    - **25x100 μm²**: better resolution in ϕ
      - 2 n+ columns (2E): smaller inter-electrode distance (28 μm) but difficult to fit solder bump inside
      - 1 n+ columns (1E): less problematic, but radiation hard enough with 53 μm inter-electrode distance?

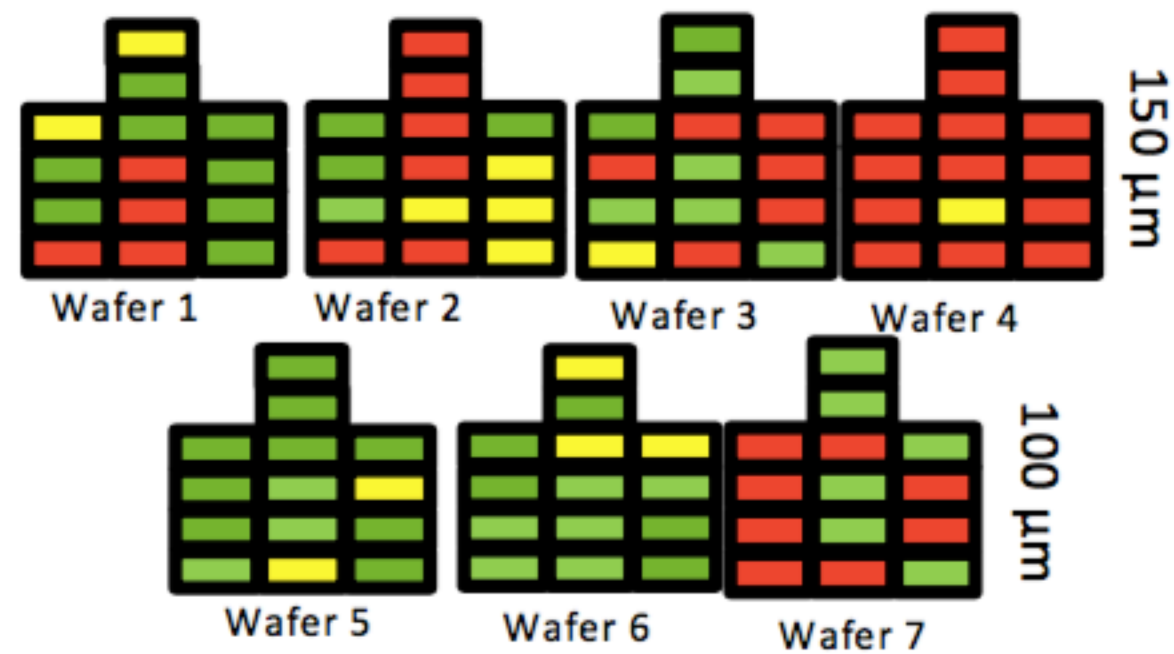




50x50 μm² production yield

- **Overall promising yield of 50x50 μm² design**
  - Breakdown voltage > 25 V and Leakage current < 10 μA
- **Large number of sensors available for characterisation**
  - Including also 25x100 μm^2 geometries both 1E and 2E



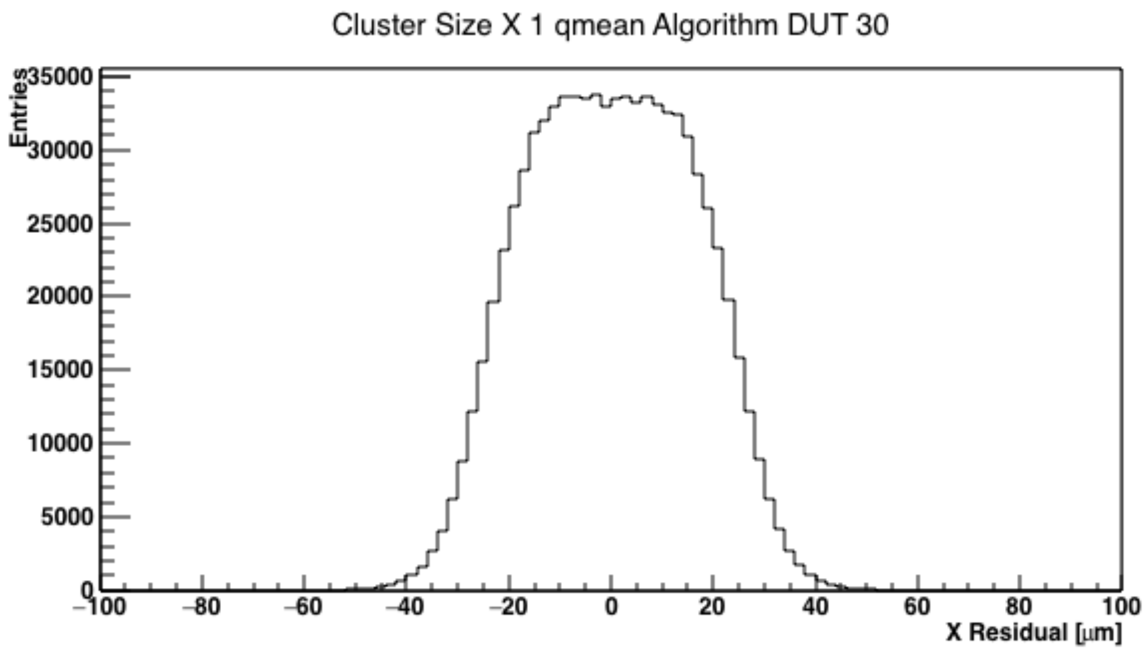


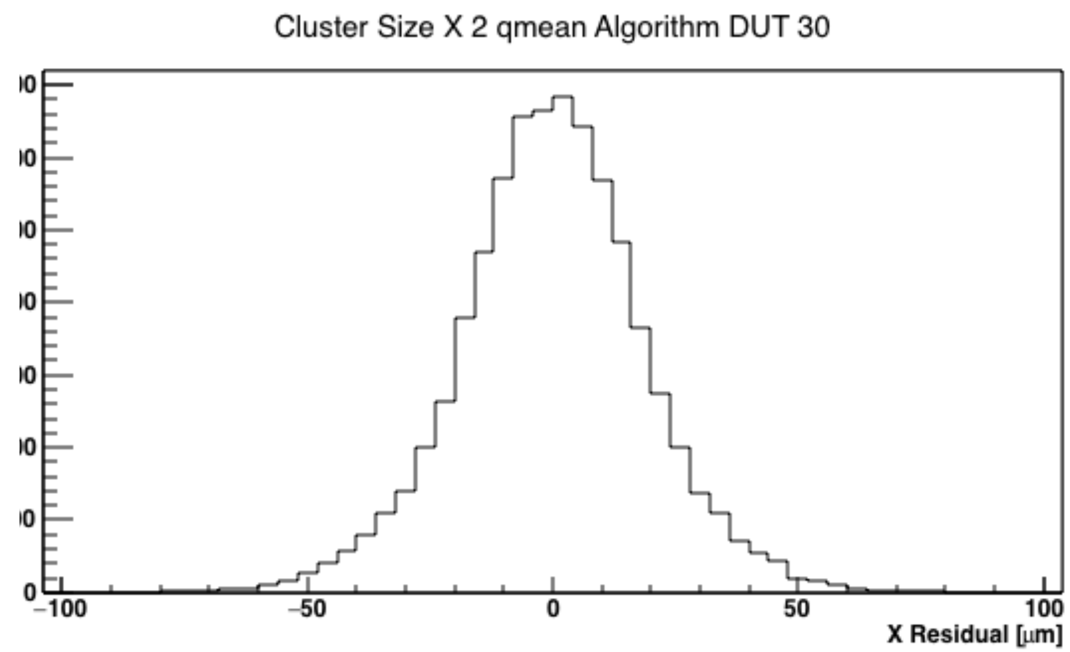
- **Next steps towards the first RD53A 3D modules:**
  - Removing of the temporary metal (done)
  - Electroless UBM at CNM -> done for Wafer 4, ongoing on 2 more wafers
  - Flip-chip to RD53A chips at IFAE
  - Assembly and wire-bonding to SCC
  - Characterisation with the YARR system

50x50μm² - 5e15 n_{eq}/cm^2 KIT - Residuals

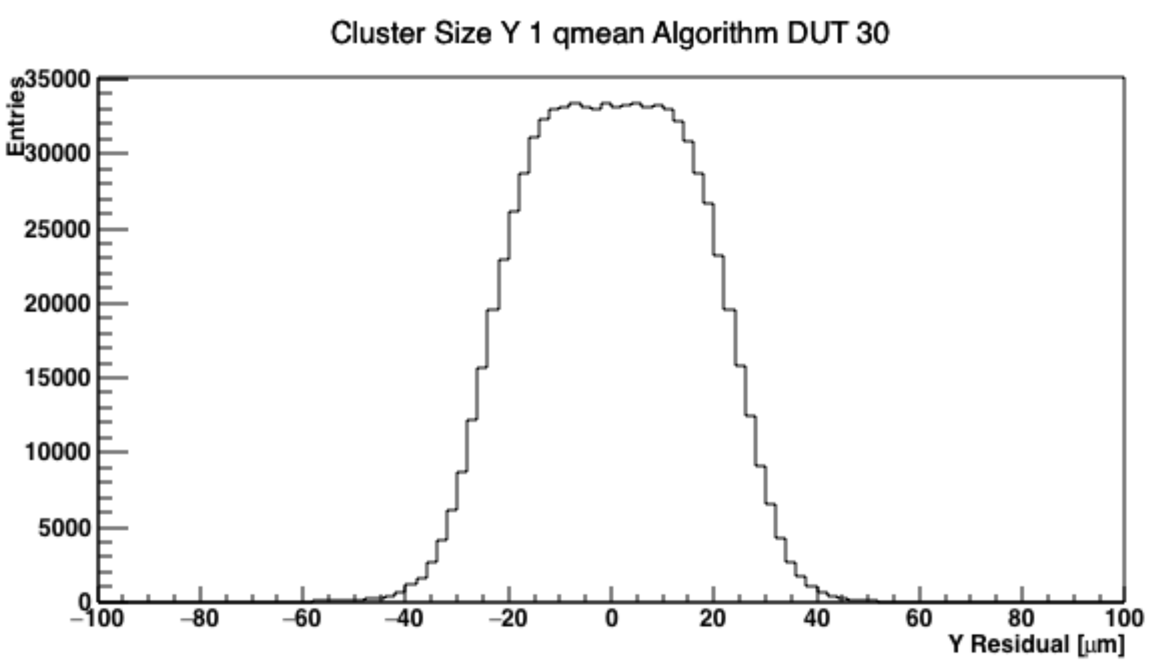
Cluster Size 1 | **Cluster Size 2**

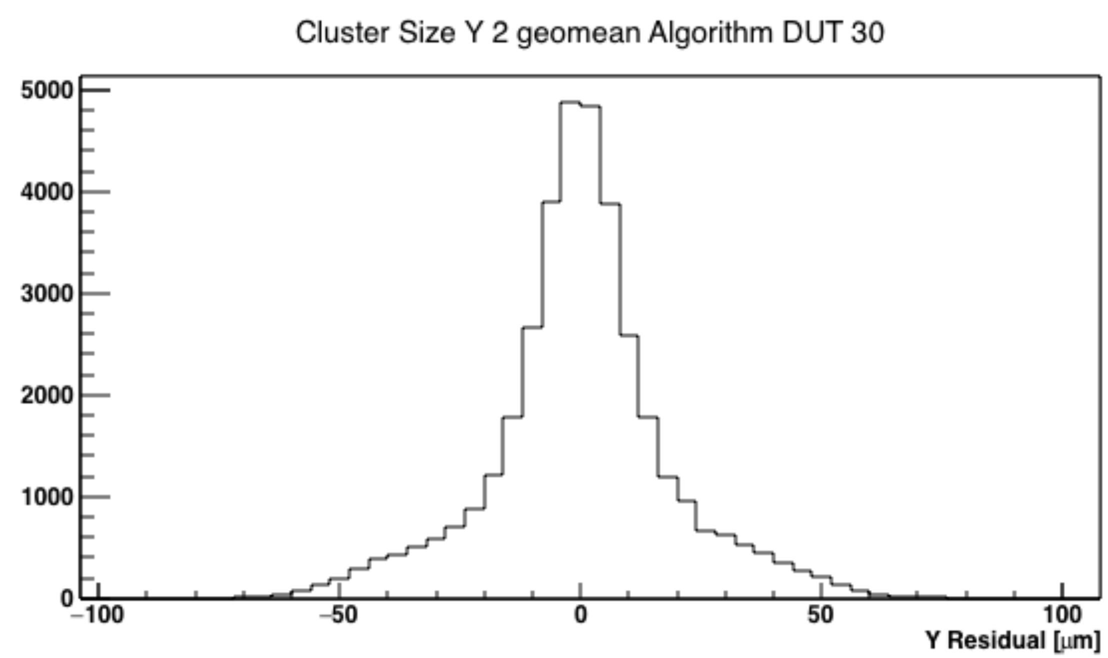
X





Y

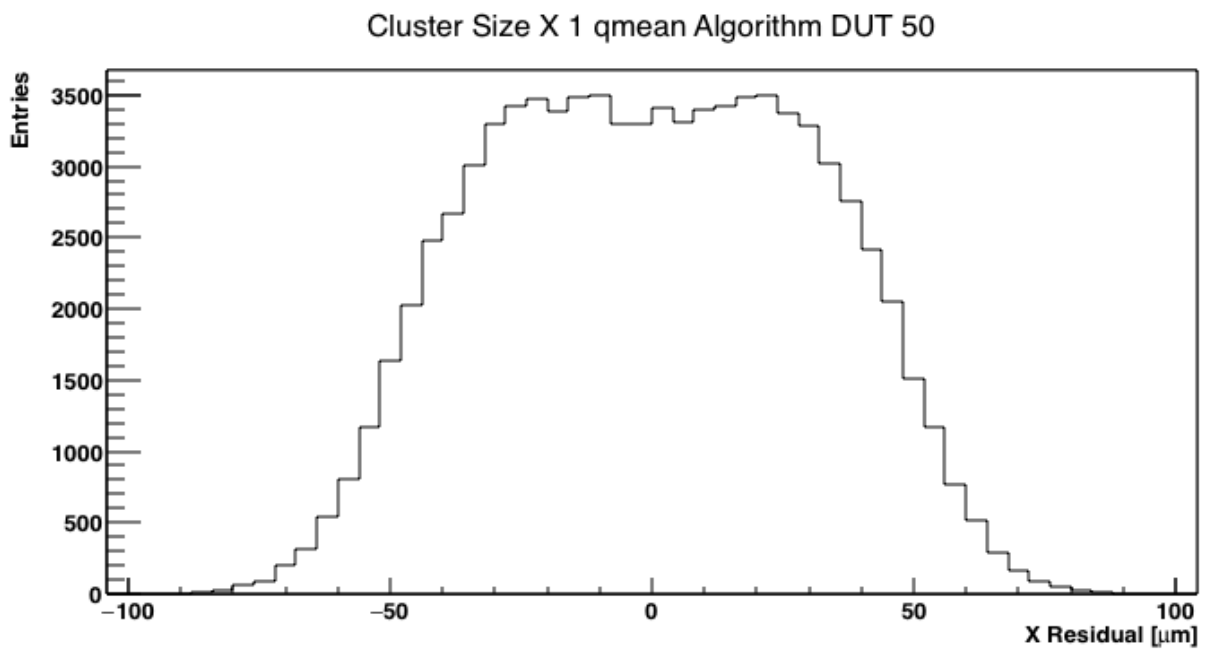


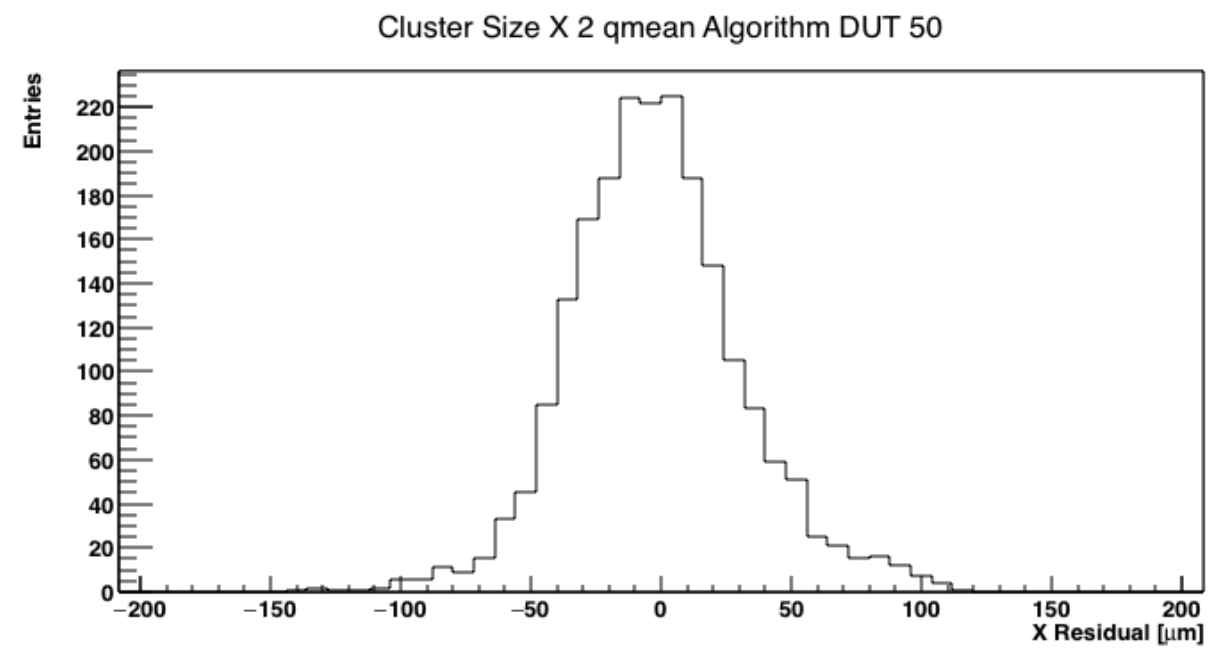


25x100 μm² 1E - 5e15 n_{eq}/cm^2 KIT - Residuals

Cluster Size 1 | **Cluster Size 2**

X





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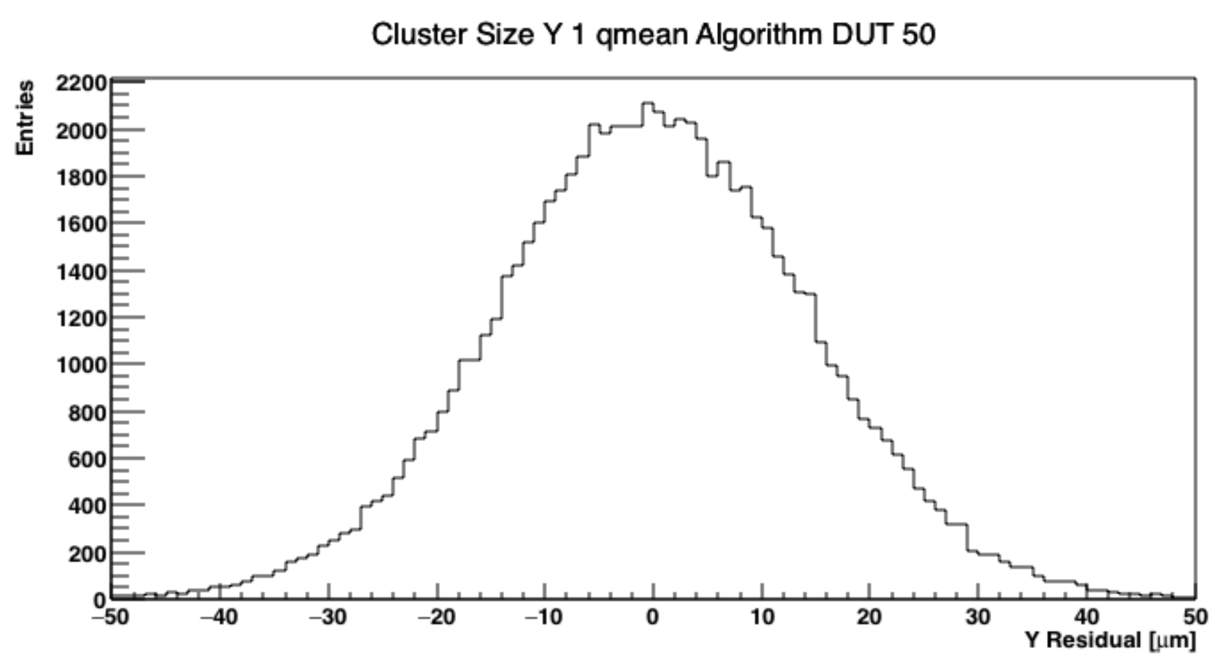
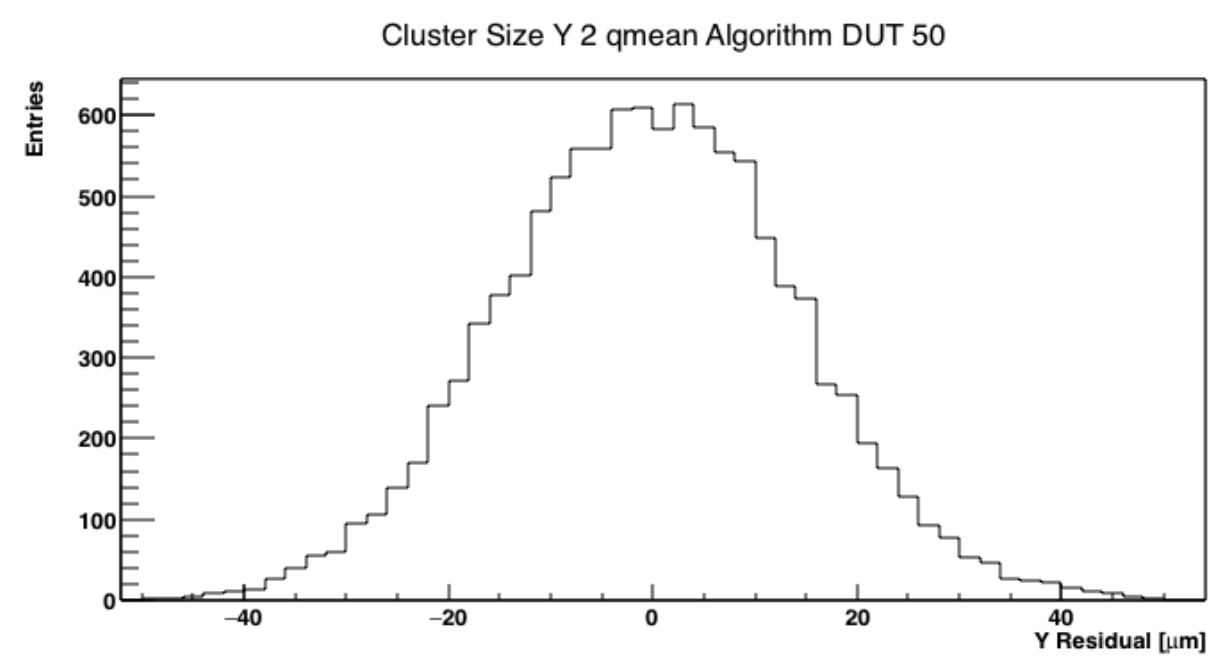
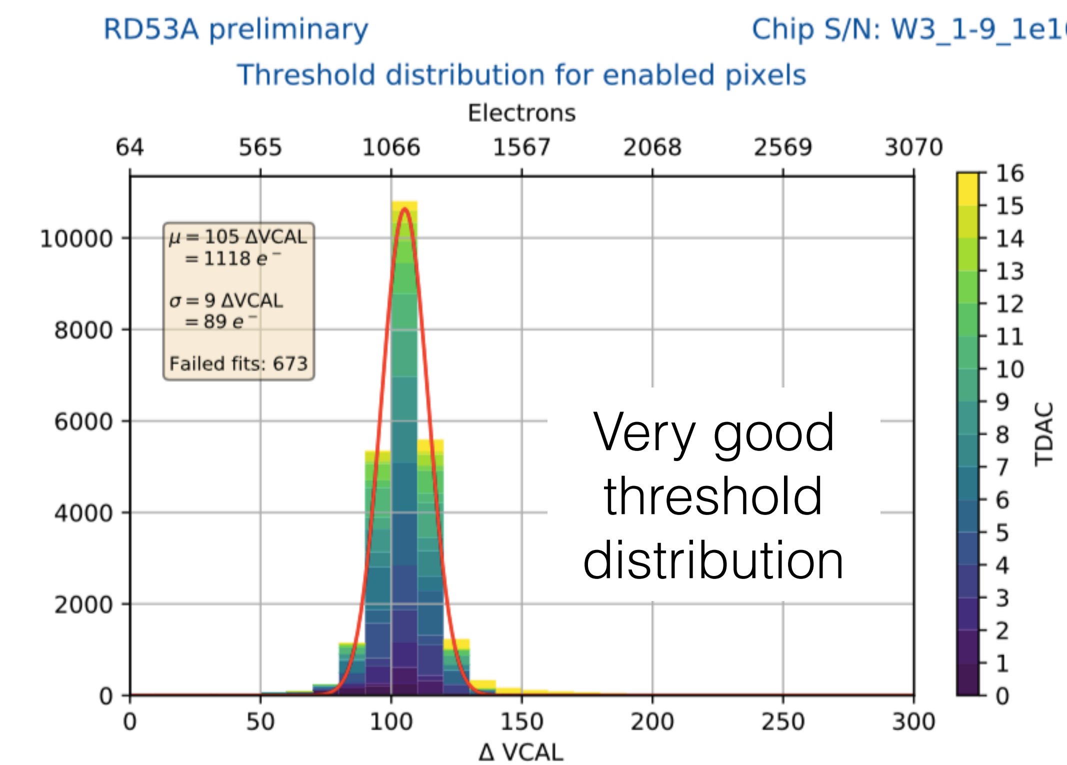
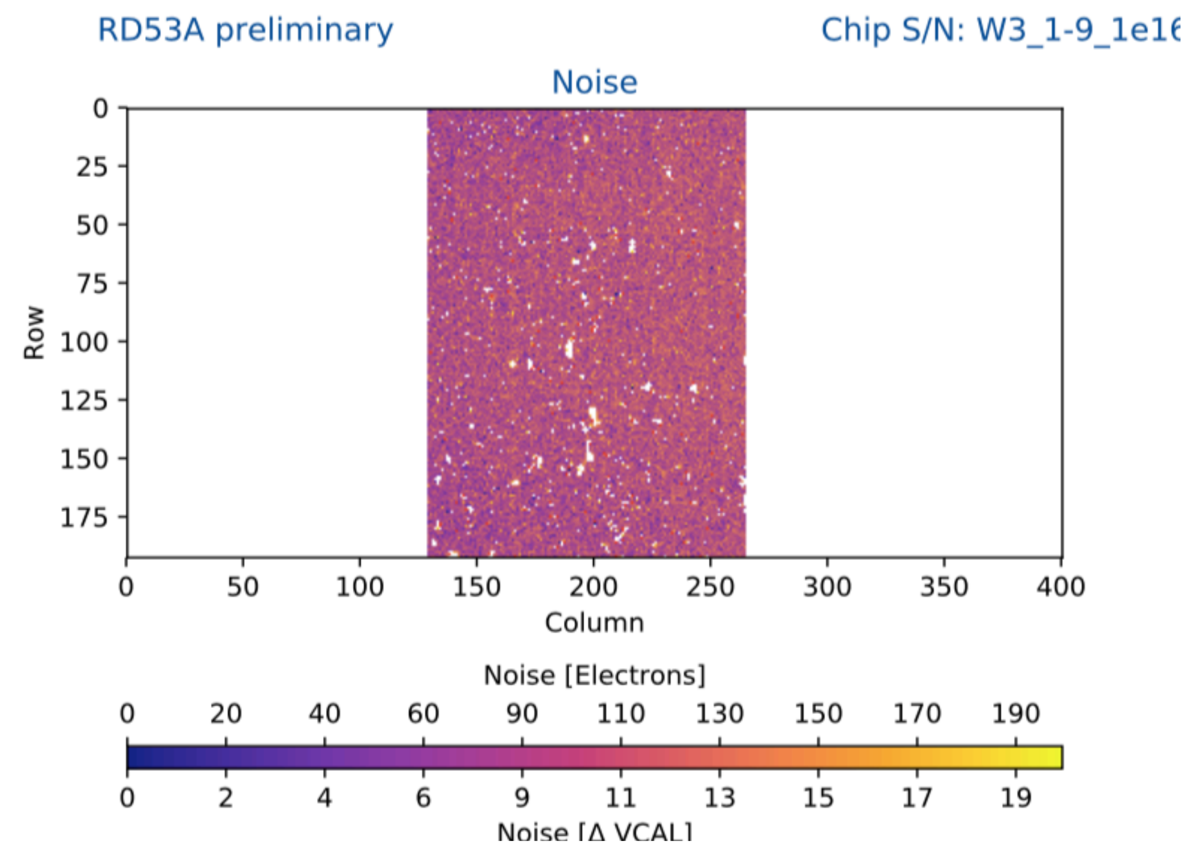


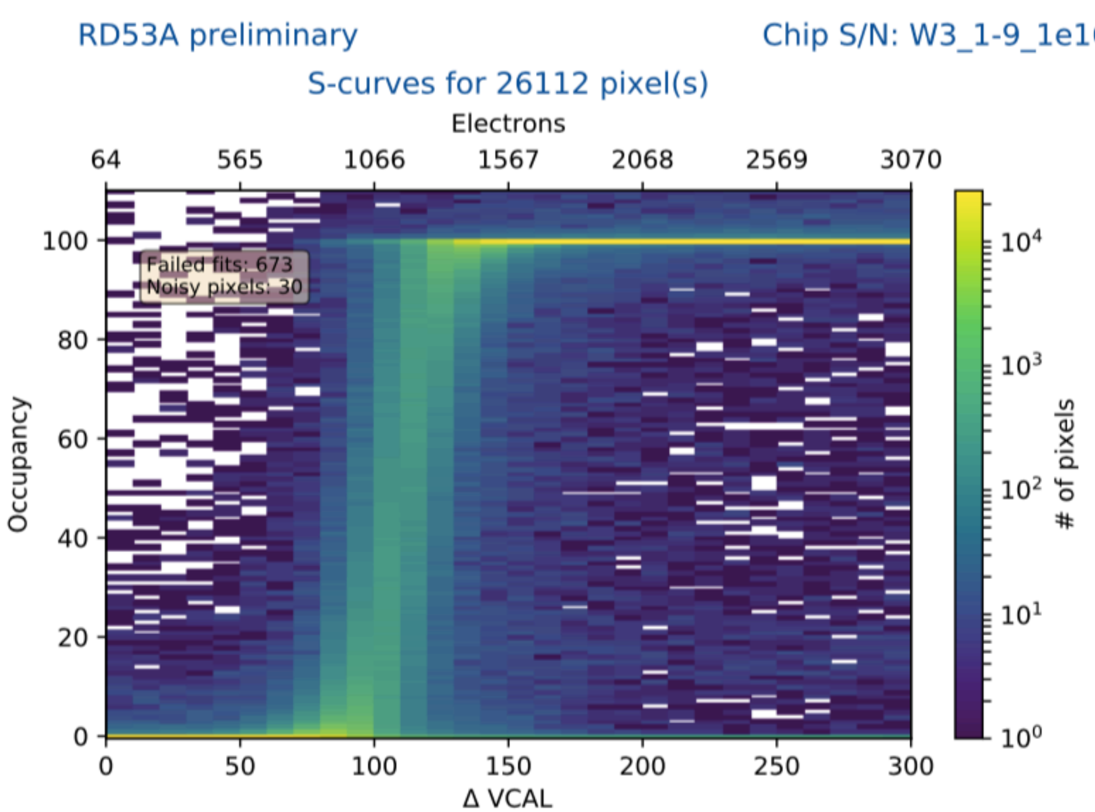


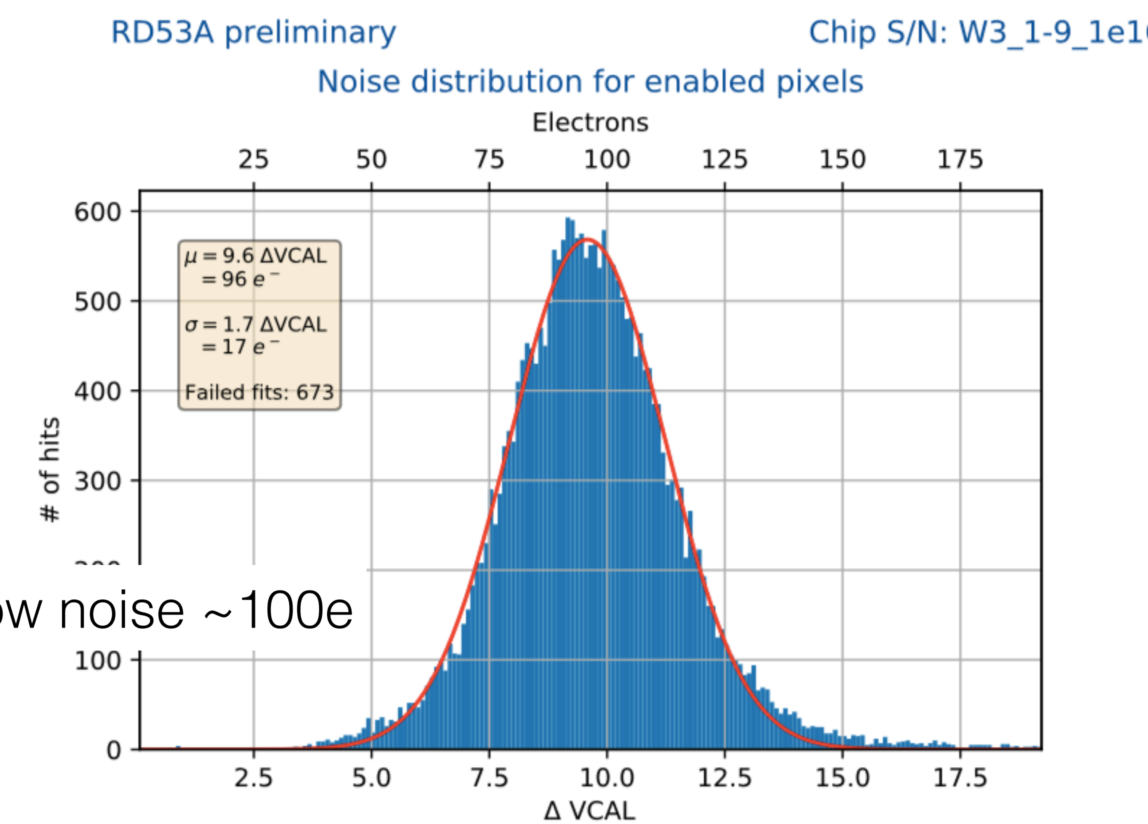
50x50µm² - 1e16 PS - Tuning linear FE



Very good threshold distribution

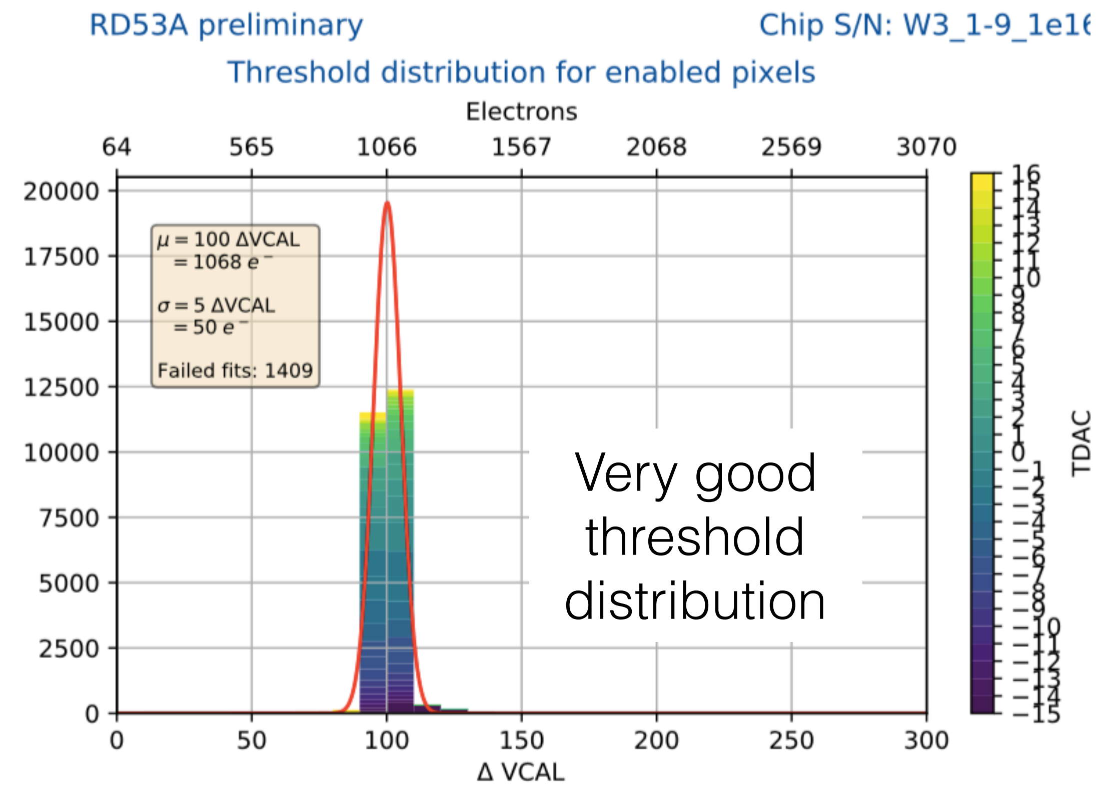




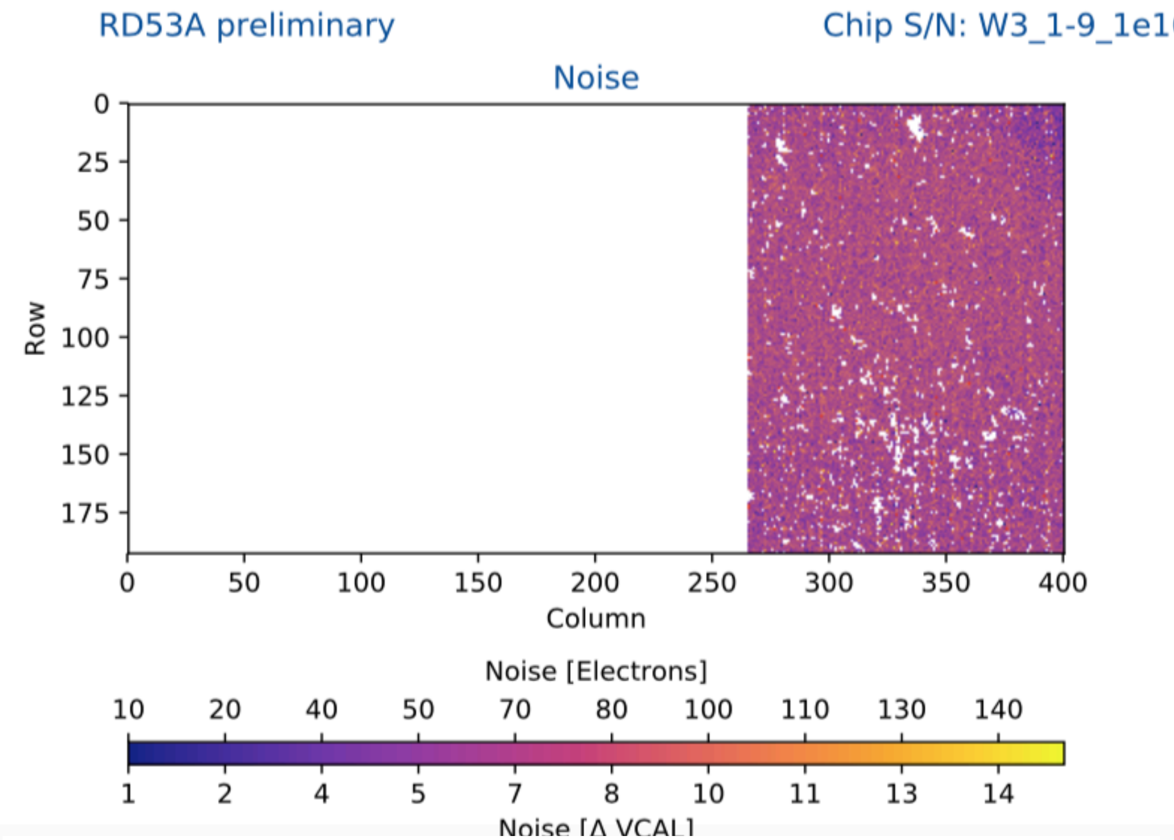


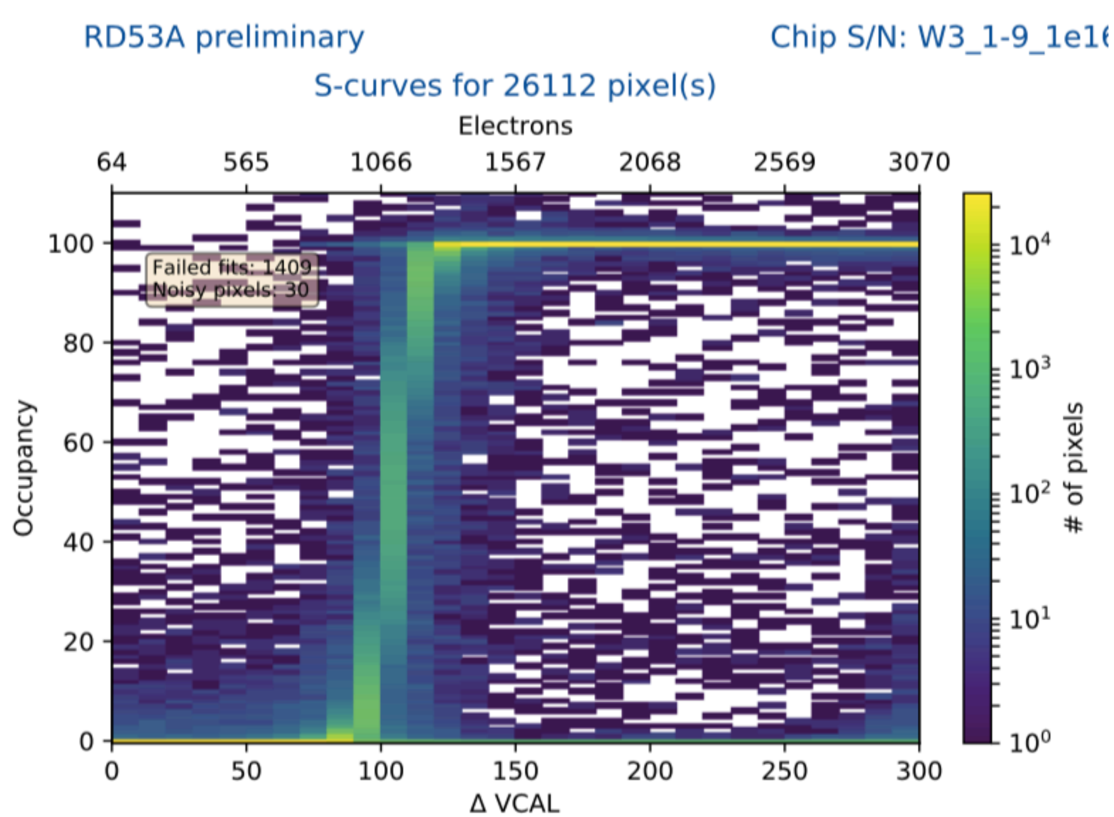
Low noise ~100e

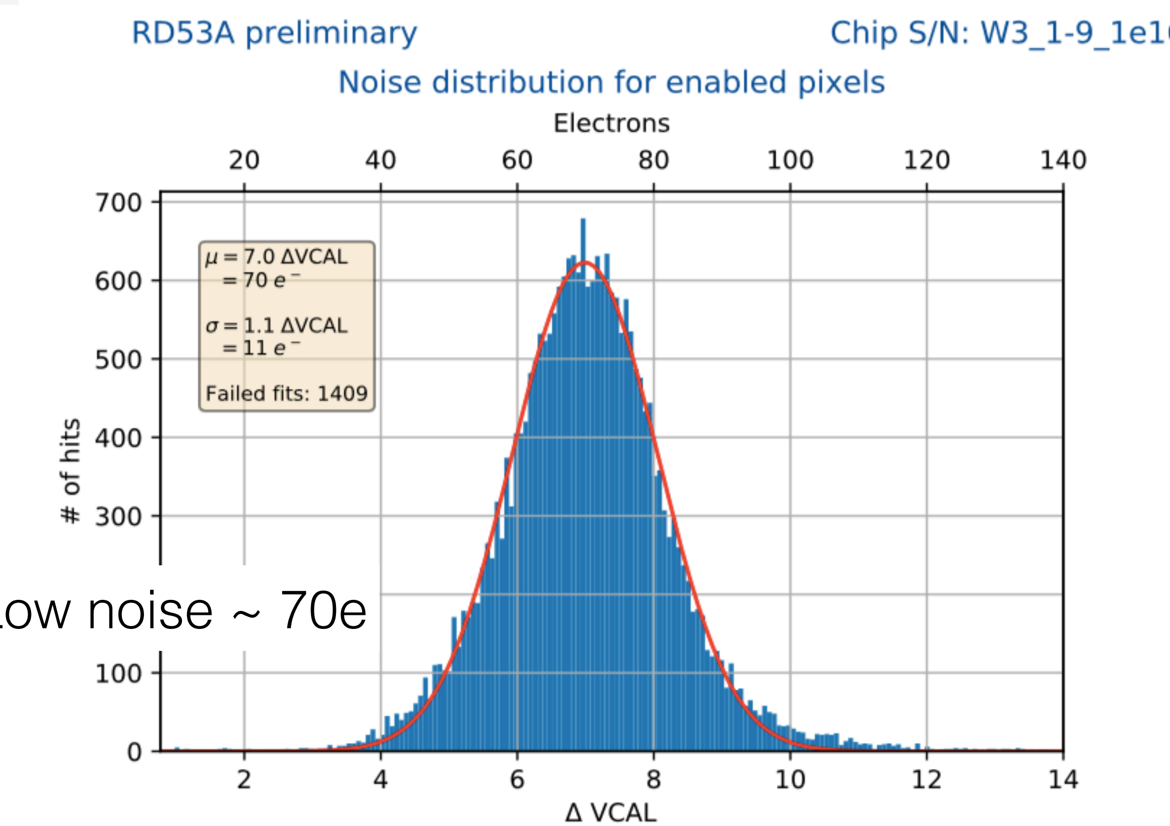
50x50μm² - 1e16 PS - Tuning differential FE



Very good threshold distribution







Low noise ~ 70e