Studies of the breakdown in R&D structures of the FBK UFSD3 production

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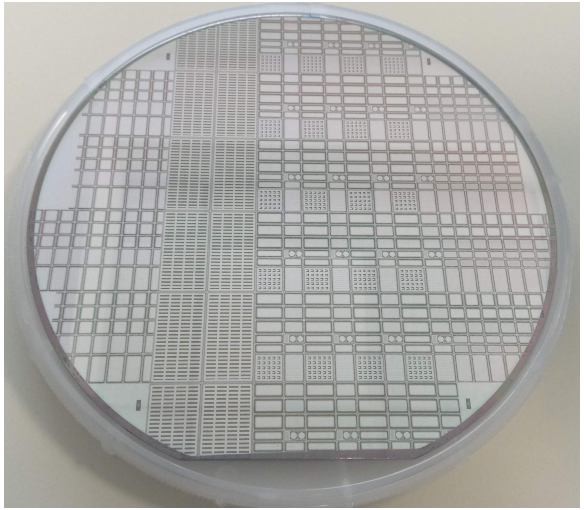
Outline

- The UFSD3 Production: I(V) curves and Breakdown
- Breakdown studies with the TCT Setup
- Breakdown studies with a CCD camera
- An unwanted effect: Pop-Corn noise

The UFSD3 production

- **UFSD3**: 3rd production of Ultra-Fast Silicon Detectors by Fondazione Bruno Kessler (FBK)
- Wide range of strip and pad arrays
- **4 solutions for the inactive area** between gain layers (pads/strips):



UFSD3 (2018)

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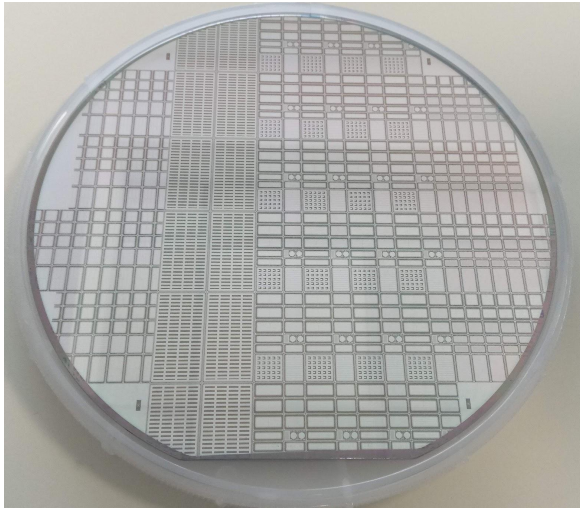

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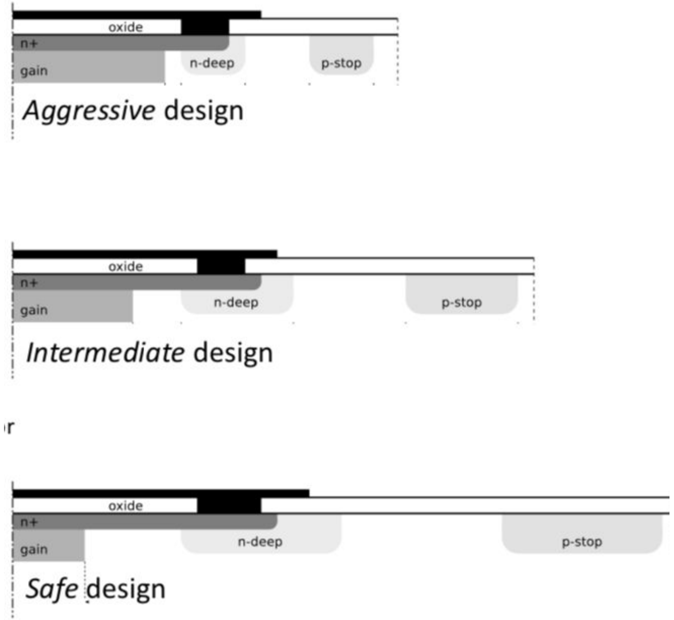
  2) "AGGRESSIVE"
  3) "MEDIUM"
  4) "SAFE"

R&D structures: Narrower inactive area width than UFSD2



UFSD3 R&D Structures (in scale)

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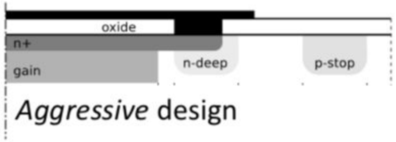
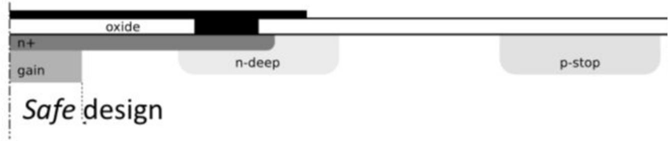
Largest width: ~40μm

Width: ~10μm



Width: ~20μm

Width: ~30μm



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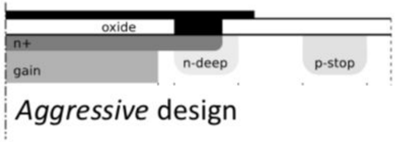
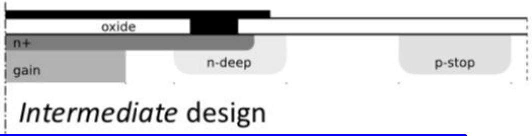
Width: ~10μm



Width: ~20μm



What is the impact of the design of the gain termination area on the sensor properties?

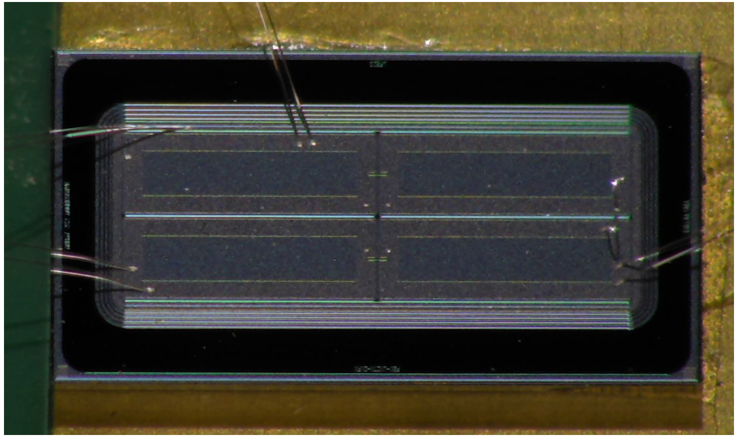
lth: ~30μm

UFSD3 R&D Structures (in scale)

Tested Sensors

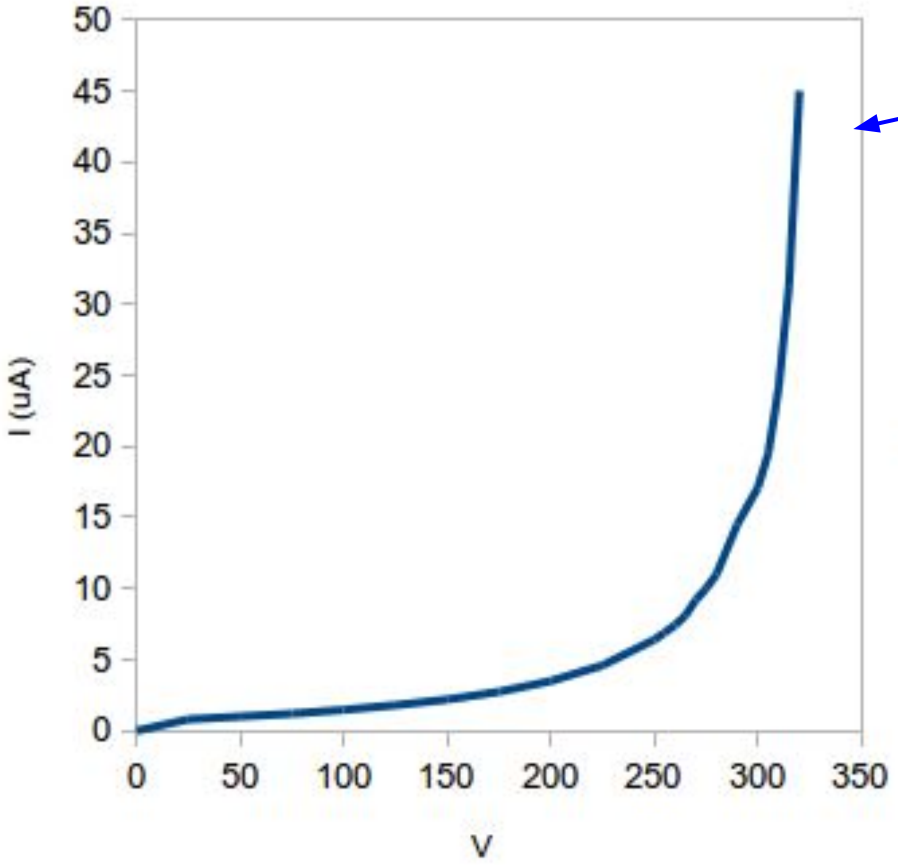
- 3 pad sensors (1x3 mm^2 pads): “SAFE”, “MEDIUM” and “AGGRESSIVE”
- Strip sensor “SUPER-SAFE” (600 µm pitch)
- Strip sensor “MEDIUM” (300 µm pitch)

➔ All devices are pre-irradiation



One of the 2x2 pad sensors tested

Different Breakdowns



"SUPER-SAFE"

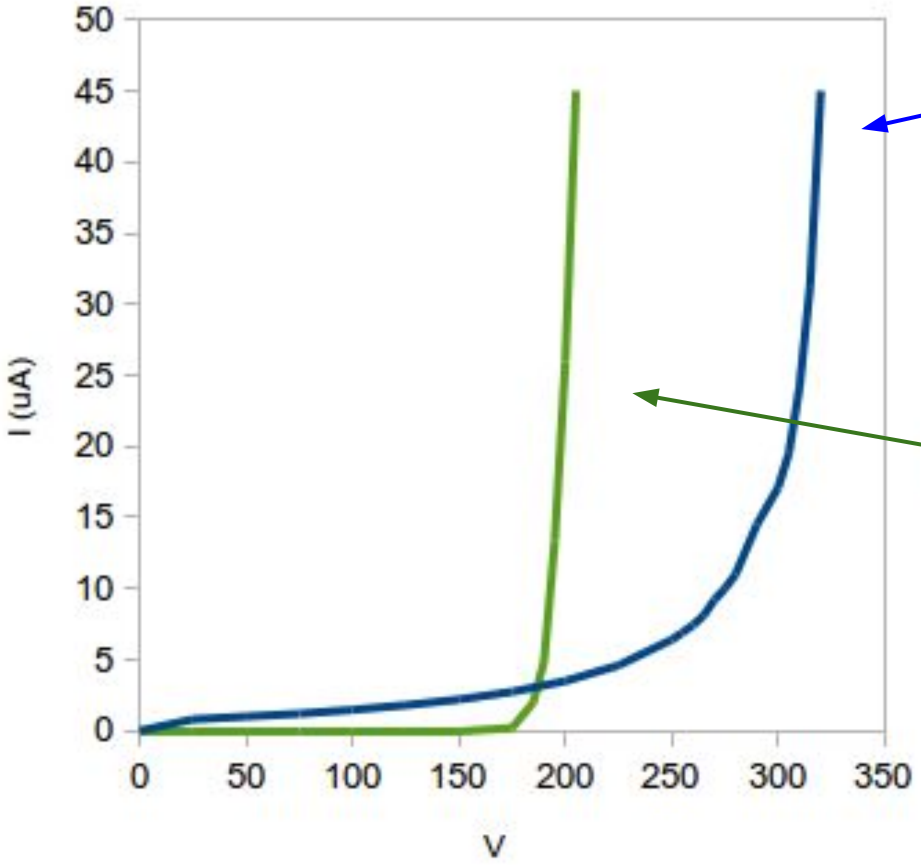
- Breakdown Voltage (V_{BD}) > 300V
- I(V) exponential

➔ Breakdown due to internal gain

➔ This is the kind of Breakdown we like

~200 - 300V is the voltage range we'd like to operate the sensors

Different Breakdowns



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- Breakdown Voltage (V_{BD}) > 300V
- I(V) exponential

➔ Breakdown due to internal gain

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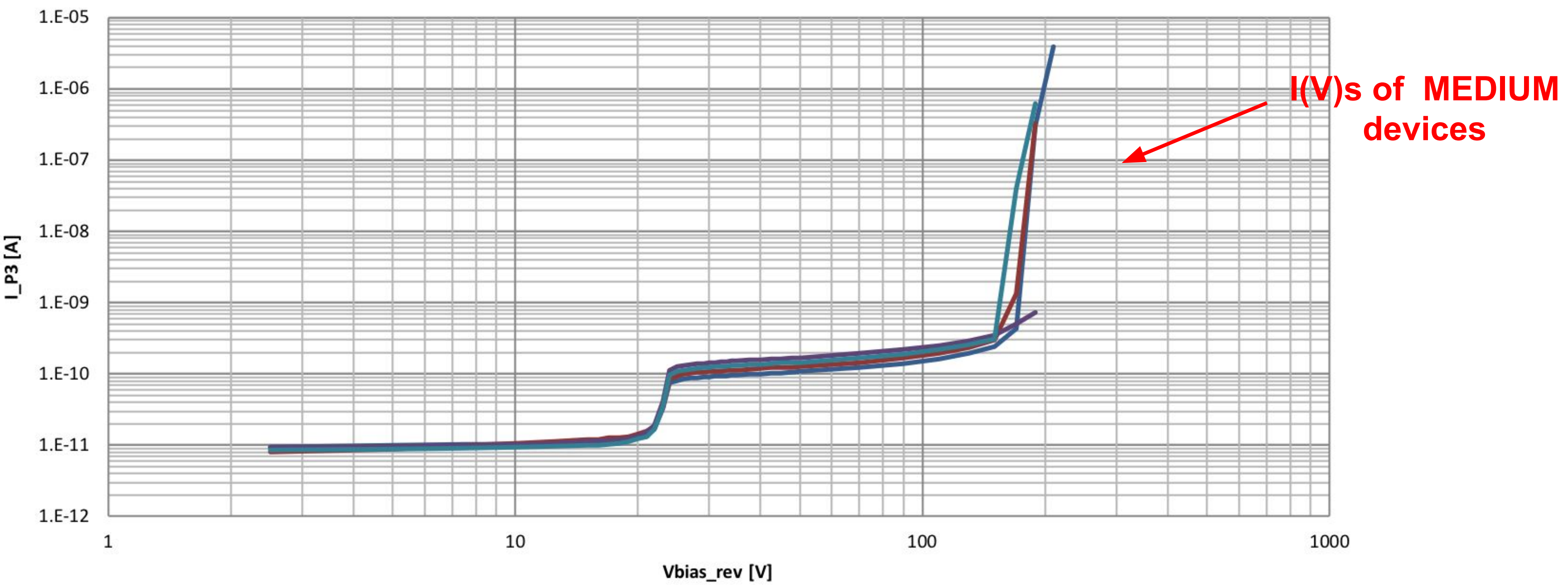
R&D Structures

- V_{BD} < 300V
- I(V) is not an exponential

➔ Early Breakdown, not due to the gain

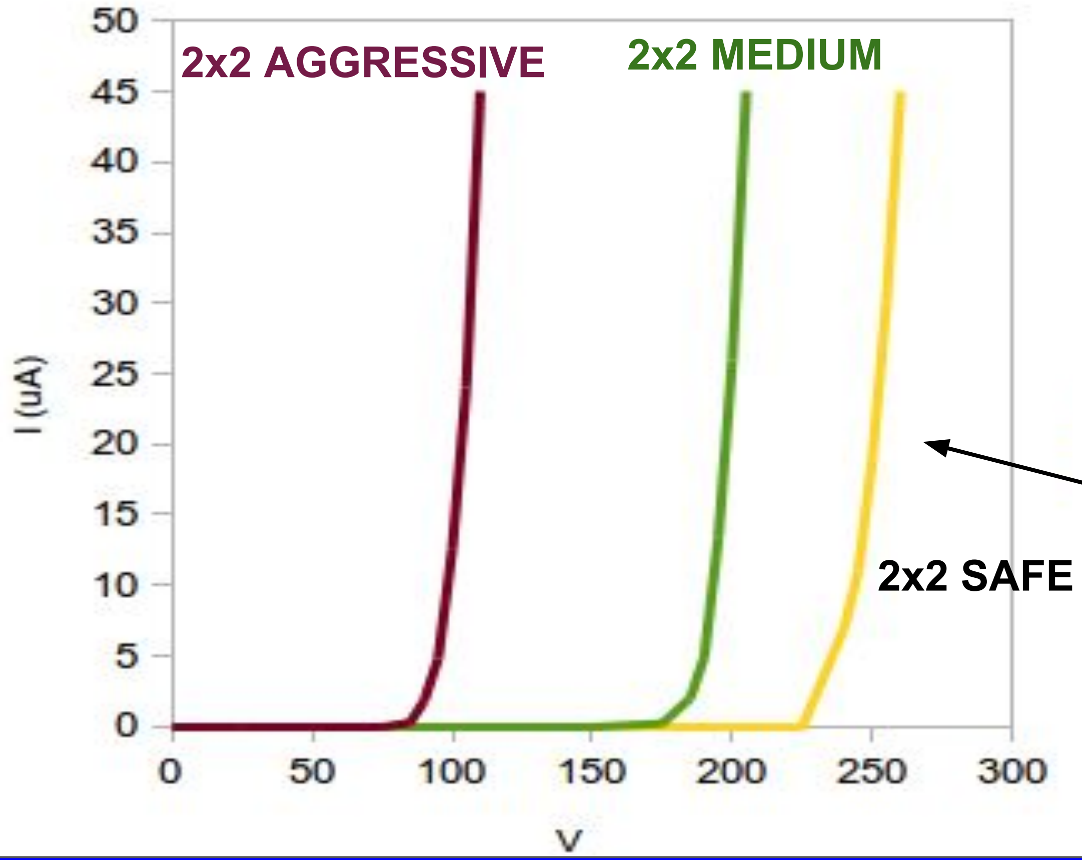
Breakdown Uniformity: R&D structure



Hundreds of pads tested → **Same V_{BD} within few volts for all R&D structures**

"SUPER-SAFE" design uniform as well (see M.Tornago talk)

Breakdown Voltage vs Width



V_{BD} strongly dependent on the width of the inactive area

This is close to what we want, but not yet ok

Inactive Area Studies

- The DUTs Breakdown (**BD**) **strongly depends** on:
  - Design of the **inactive area**
  - **Inactive area width**

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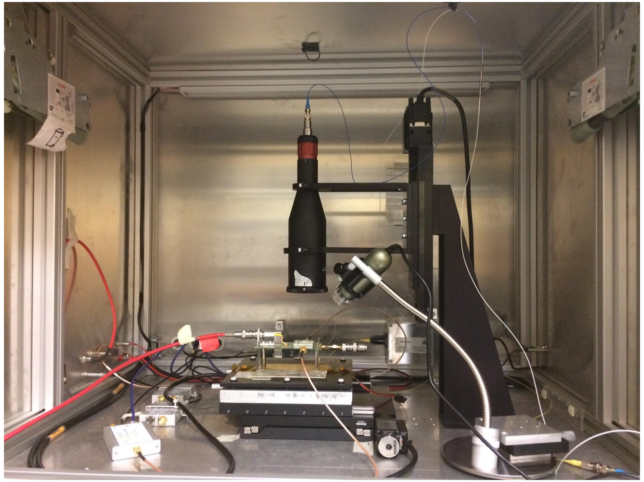
Two main tools to perform this study:

1. Mapping of the sensors using the Transient Current Technique (**TCT**) Setup
2. Observation of the sensors hot spots with a **CCD camera**

Measurements performed in Torino Silicon Lab
(University of Torino - INFN)

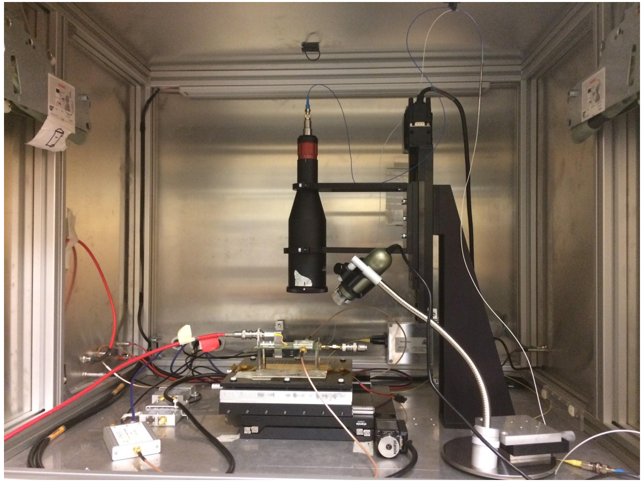
TCT



TCT Setup in Torino

Particulars TCT setup:

TCT



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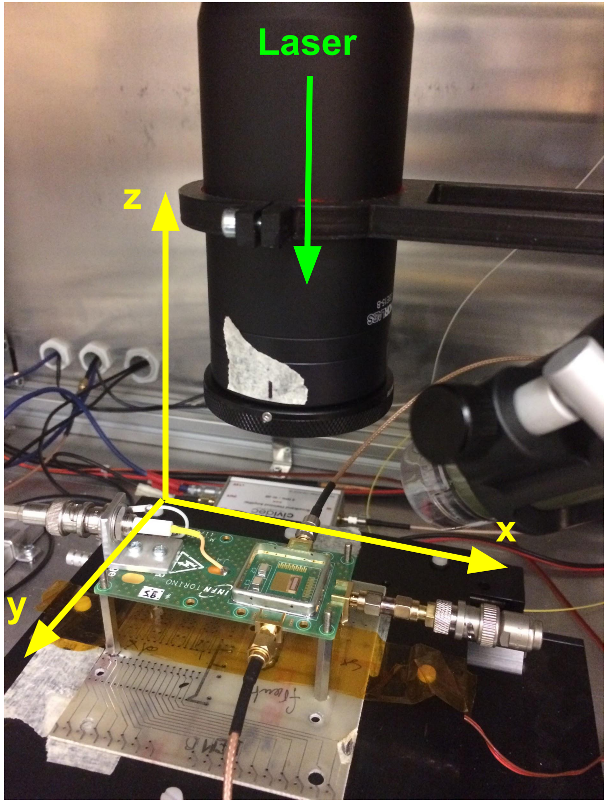
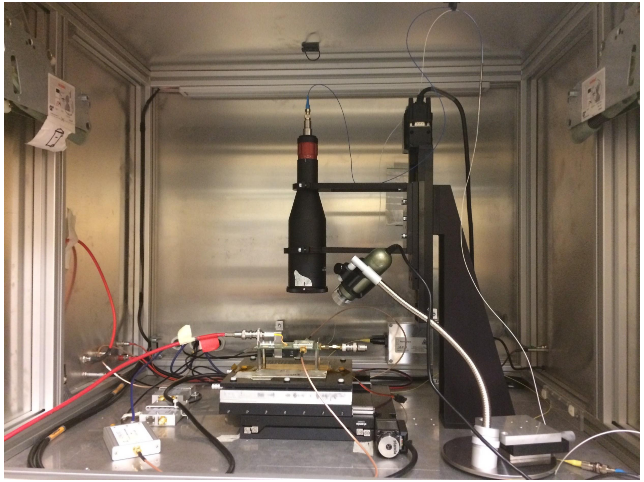


Particulars TCT setup:

- IR pulsed **laser** (1060 nm) → **10-15 µm spot**
- xy-stage with sub-µm precision
- Stage control and DAQ via Labview software

TCT



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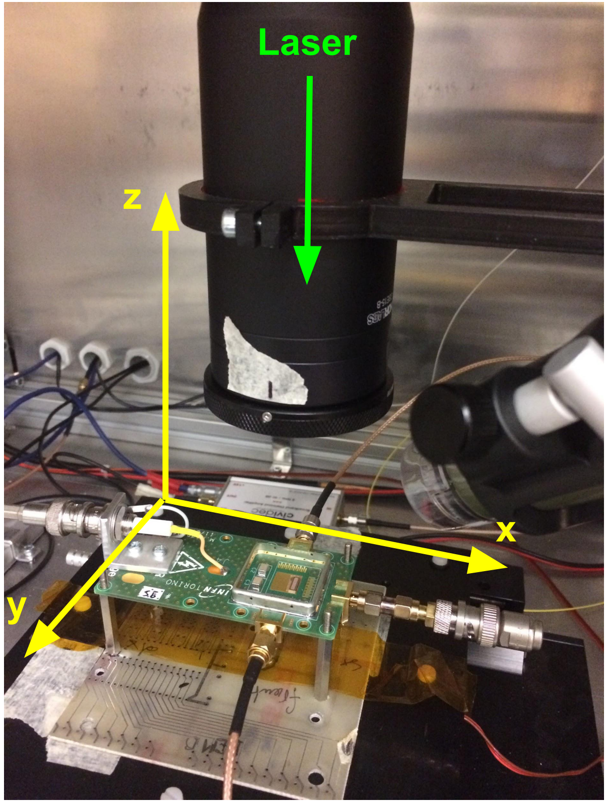

Particulars TCT setup:

- IR pulsed **laser** (1060 nm) → **10-15 μm spot**
- xy-stage with sub-μm precision
- Stage control and DAQ via Labview software
- **Automatic xy-scan + Small laser spot:**

➔ **Very precise mapping of the DUT**

A preliminary measurement: Interpad

- We measured the inactive area width* of the tested sensors with the TCT

* Inactive area width = Interpad (Interstrip) width

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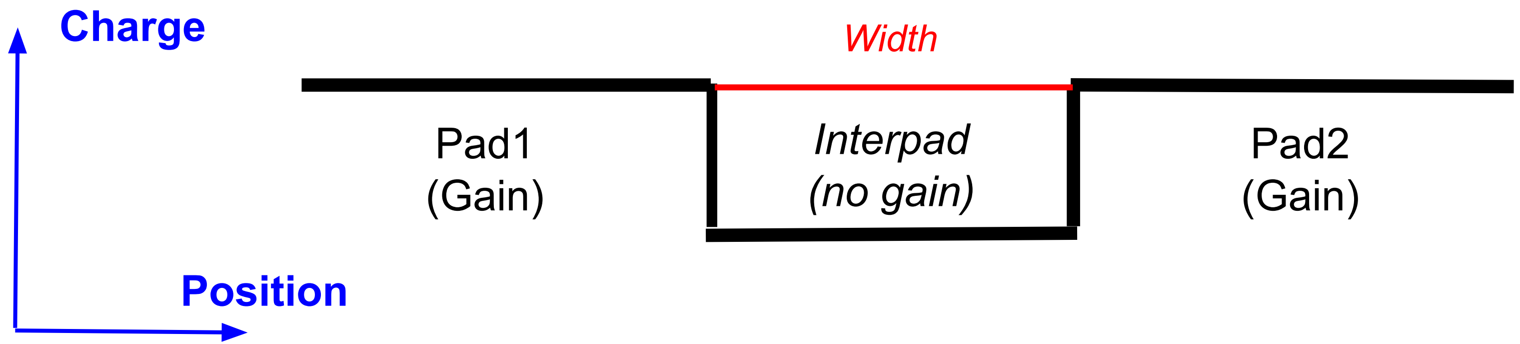
- **Get the width** by scanning two nearby pads (strips) → **charge vs position**



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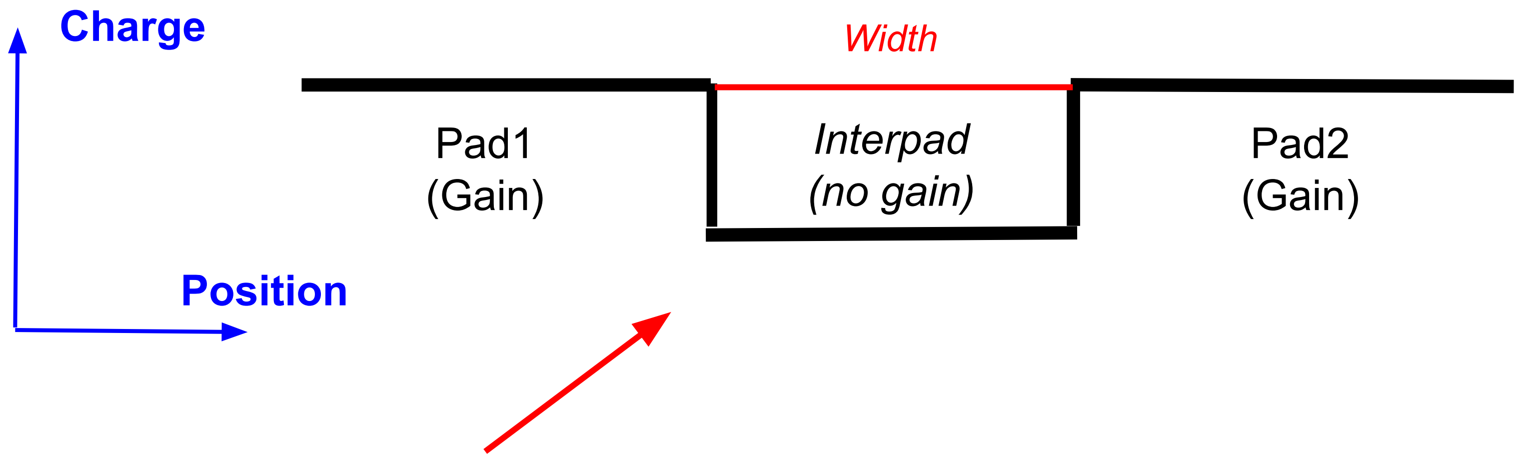

Result with a point-like spot → our spot is 10-15 μm with a gaussian shape

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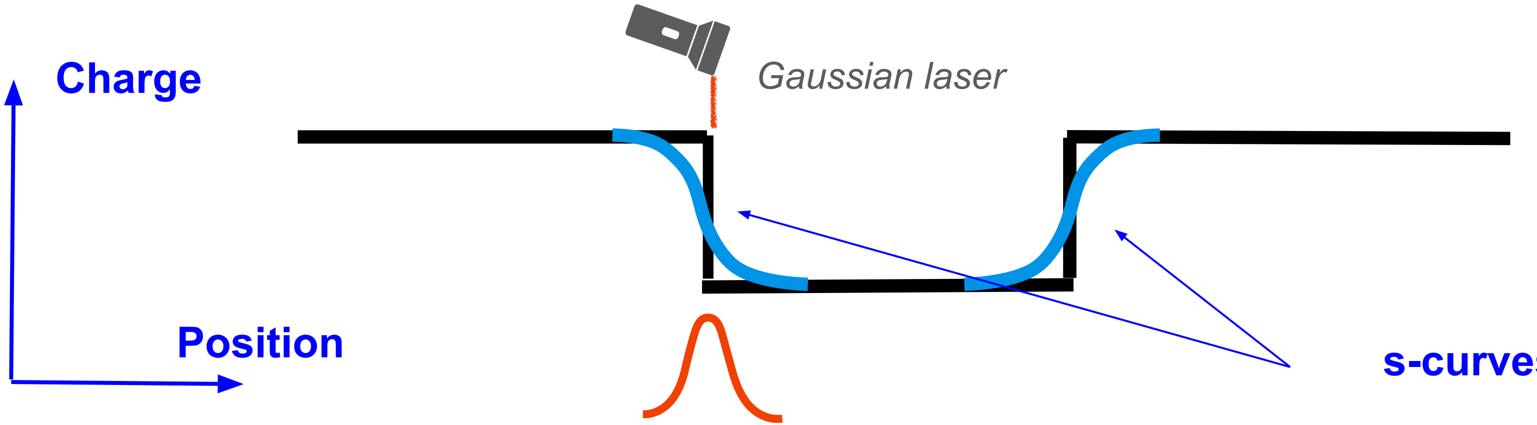

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→ The **real profile** is a convolution of the step function with a gaussian (= **s-curve**)

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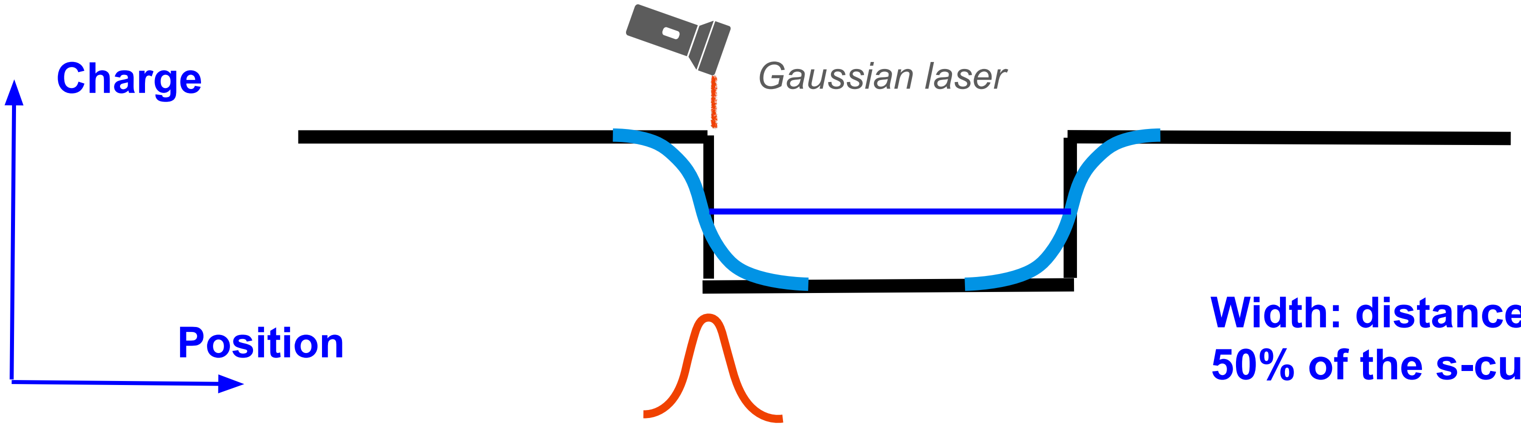
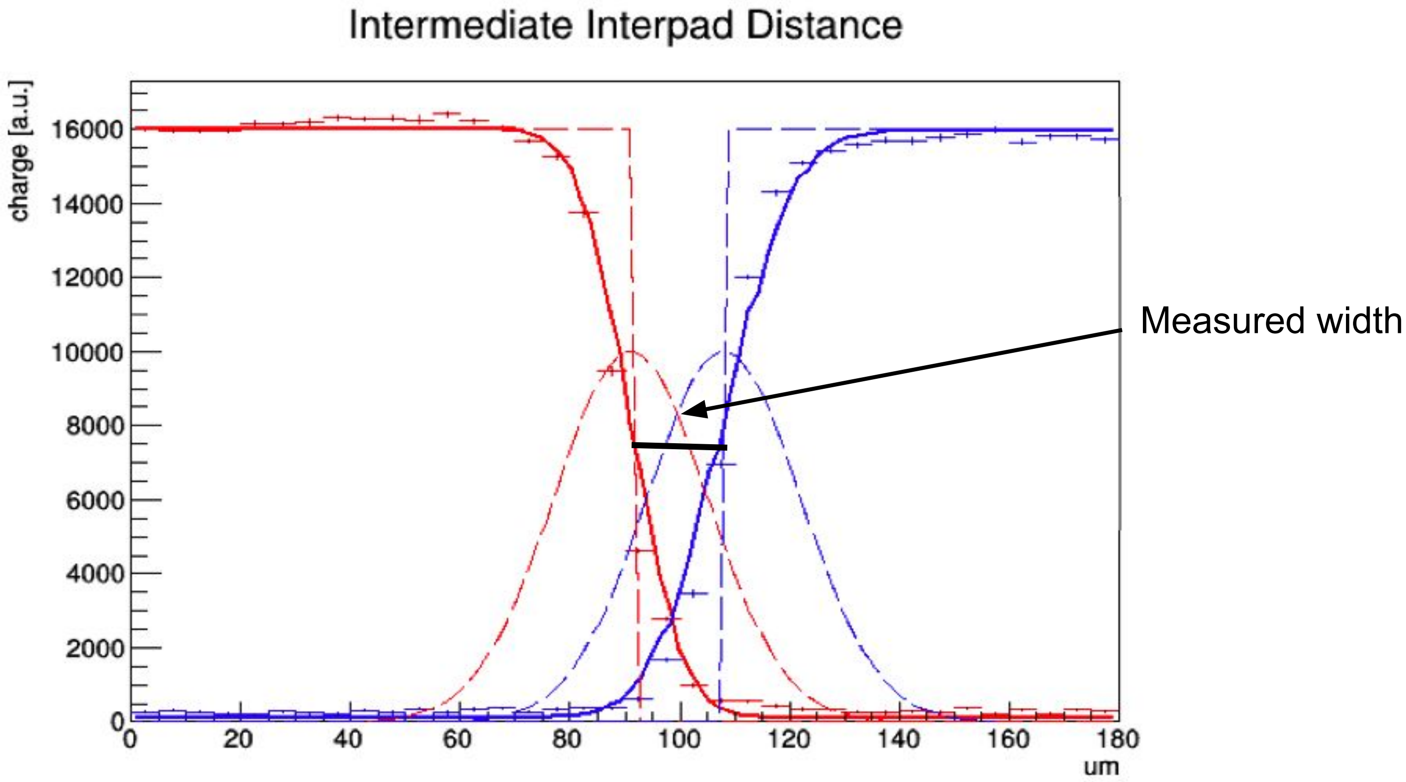


Width: distance between 50% of the s-curves

Result with a point-like spot → our spot is 10-15 μm with a gaussian shape
→ The **real profile** is a convolution of the step function with a gaussian (= **s-curve**)

Interpad Measurement: “Medium”

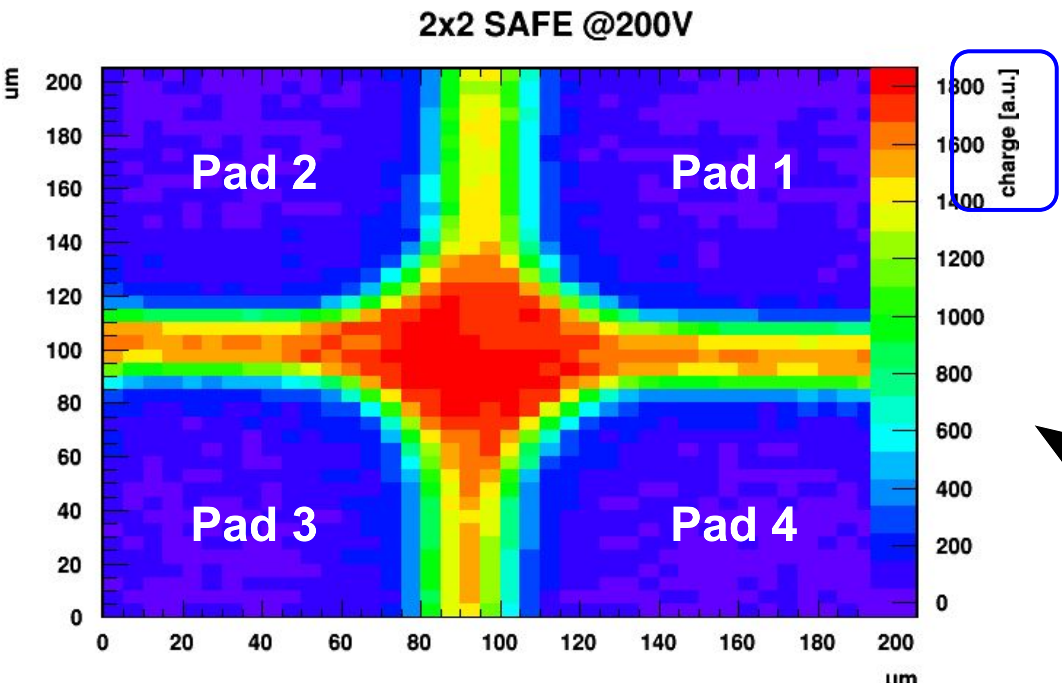


Interpad Summary

Structure	Measured distance (µm)	Laser spot (µm)	Nominal distance (µm)
AGGRESSIVE	**16.4**	7.7	11
INTERMEDIATE	**16.7**	10.1	20.5
SAFE	**30.4**	10.0	31
SUPER SAFE	**38.3**	13.4	41

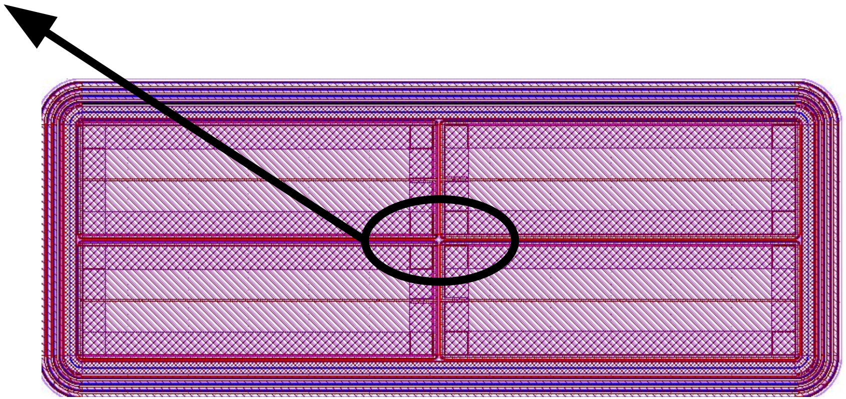
UFSD2 Interpad width: ~ 60µm

TCT: Mapping a 2x2 sensor

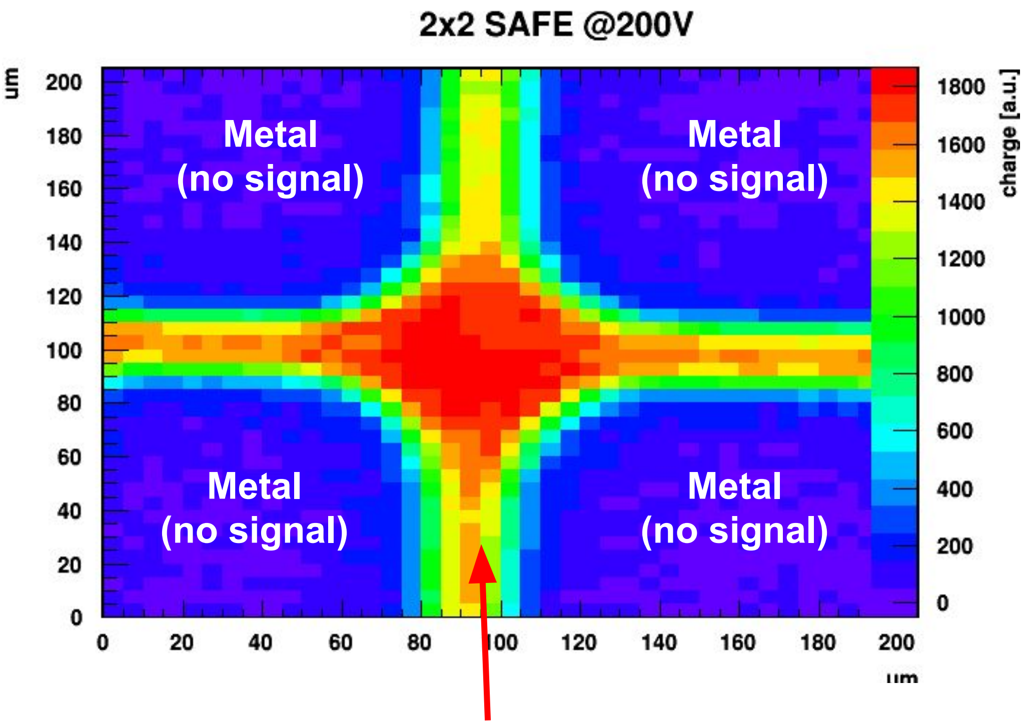


2D Map of the collected charge

- 4 pads read out
- Collected charge = Sum of the charges collected by 4 pads



TCT: Mapping a 2x2 sensor

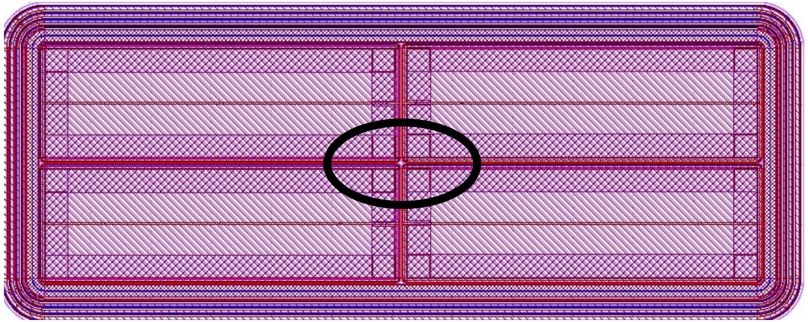


Inactive area, no front metallization

2D Map of the collected charge

- 4 pads read out
- Collected charge = Sum of the charges collected by 4 pads

Pads metallized on the front
→ Signal only in the inactive area



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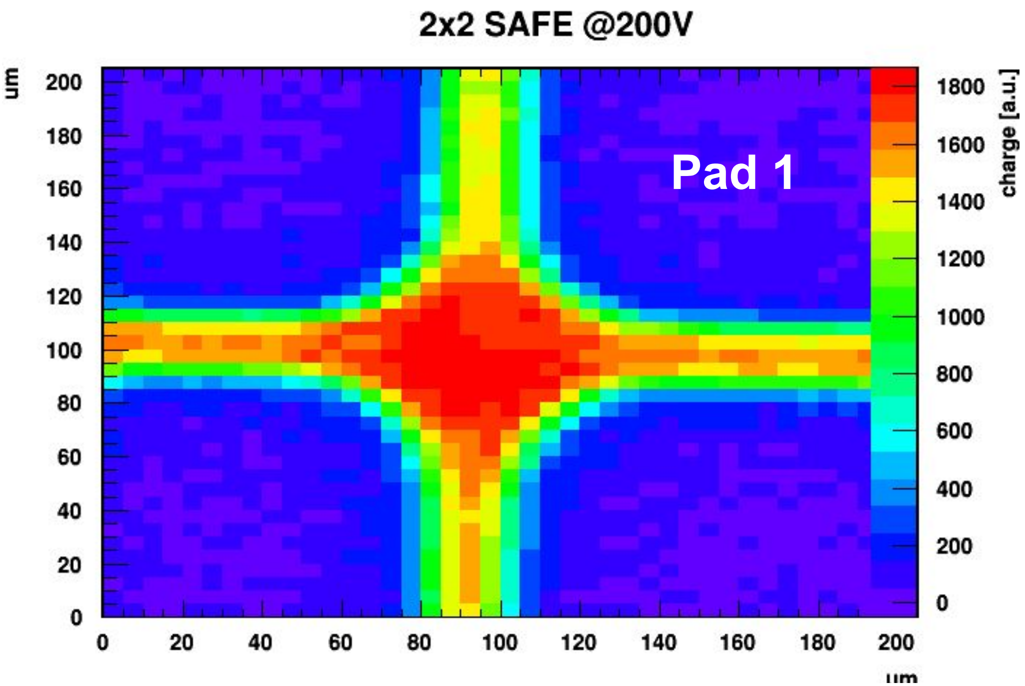

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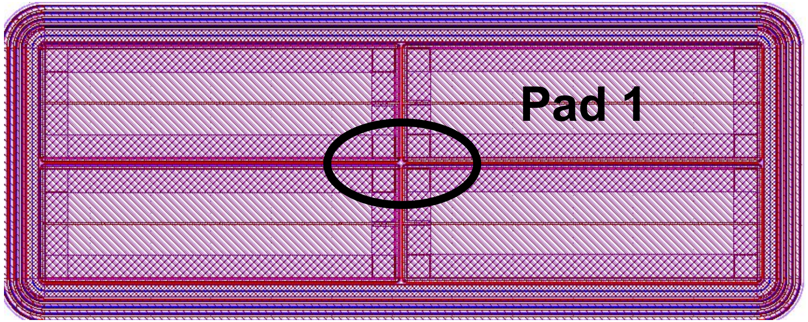
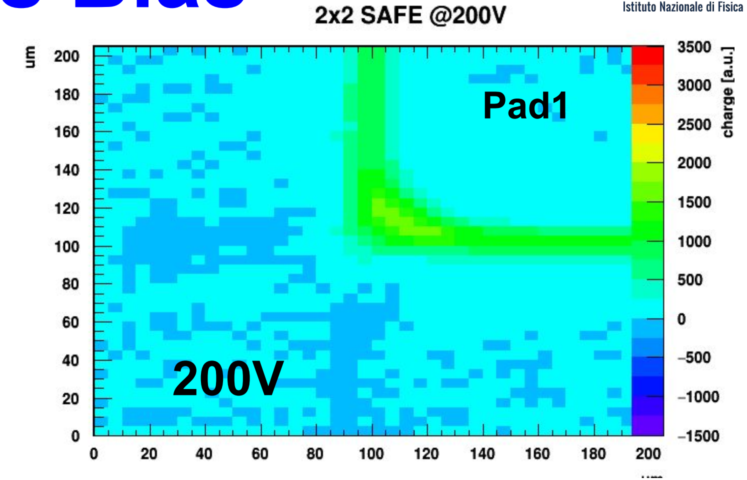
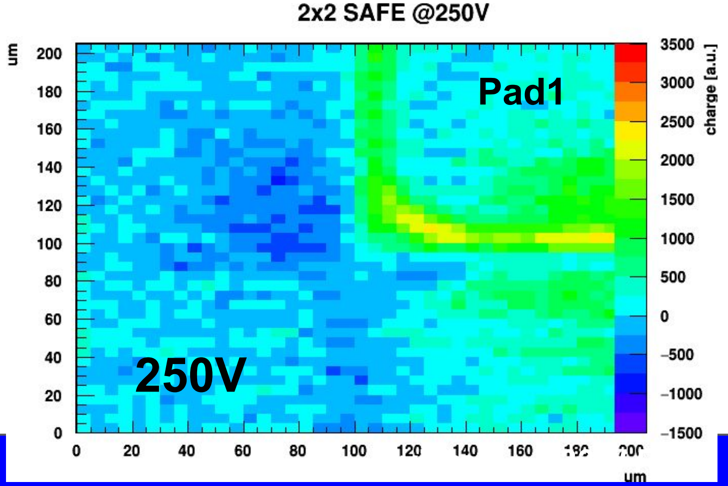


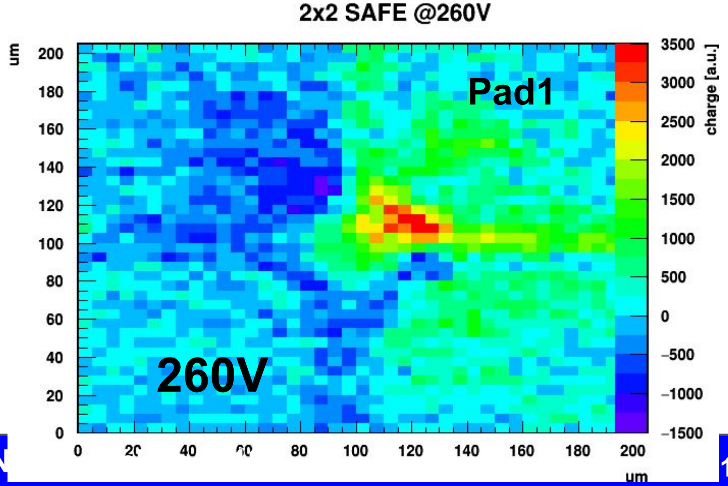
Let's now consider only the charge collected by Pad 1

TCT: Charge vs Bias

- **Charge collected by Pad 1** at 3 different voltages
- **V_{BD} ~ 250V**
- Coloured scale is different from the previous slide

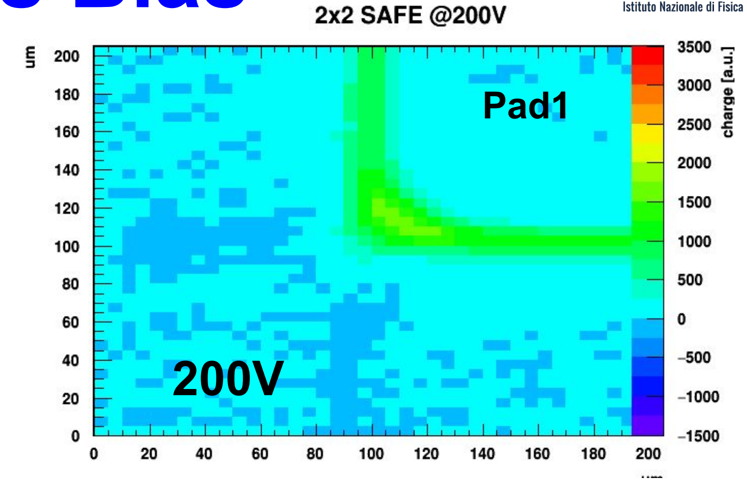


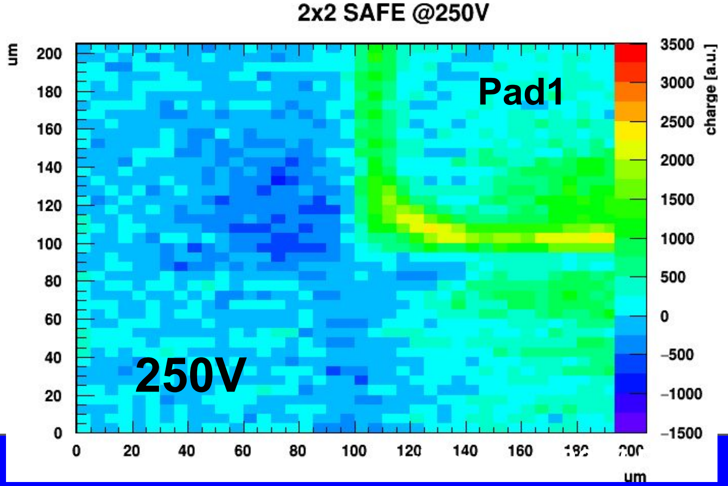


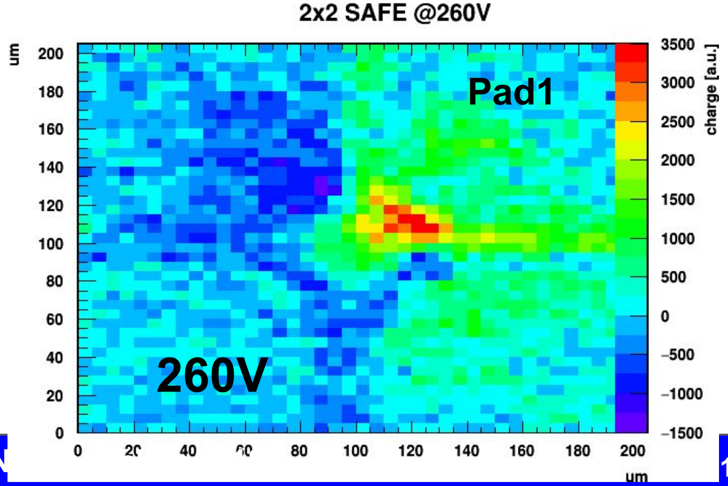


TCT: Charge vs Bias

- The collected charge should be constant (inactive area = no gain)

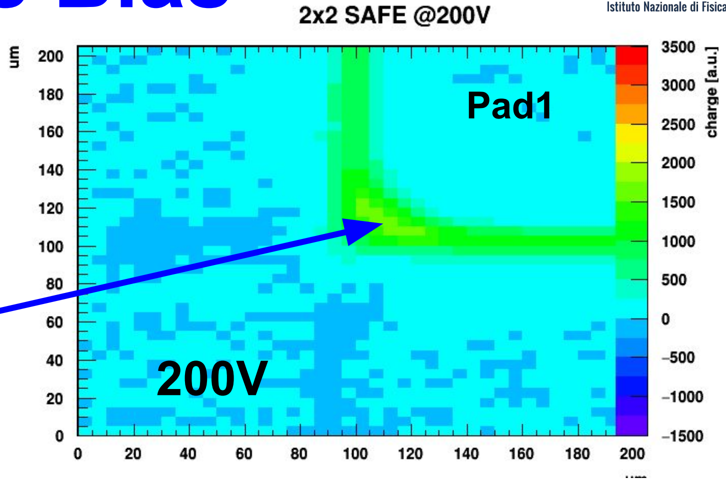


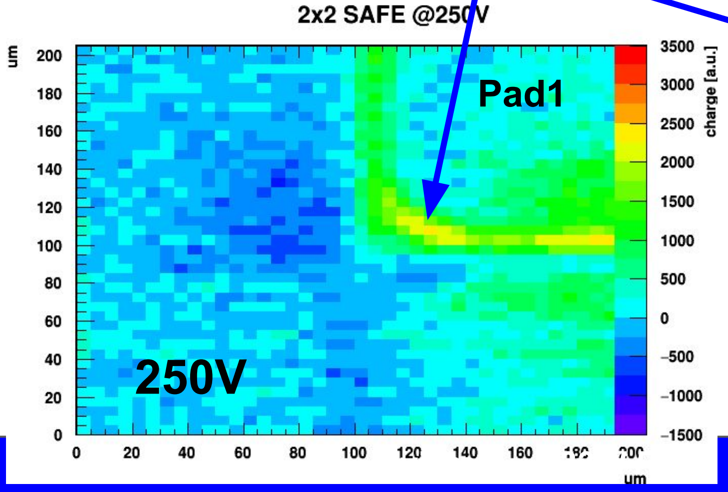


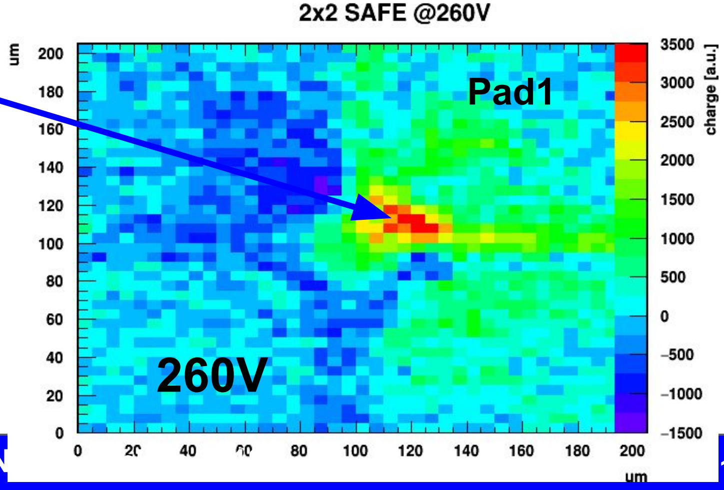


TCT: Charge vs Bias

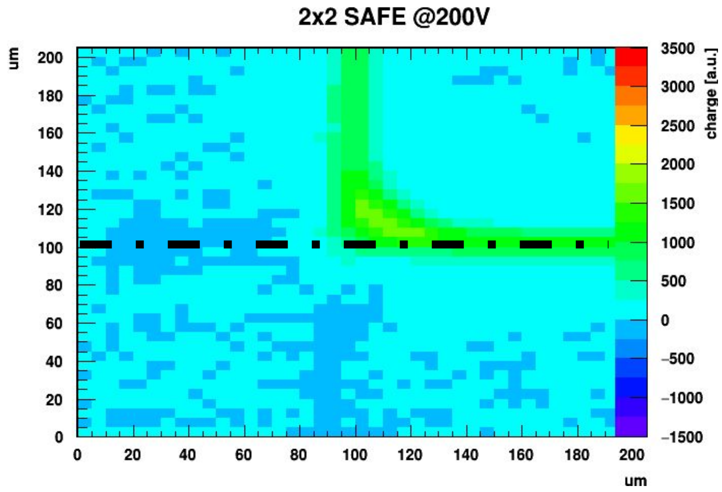
- The collected charge should be constant (inactive area = no gain)
- Instead, **the charge increases with the bias** → strong indication of charge multiplication in that region (**gain**)





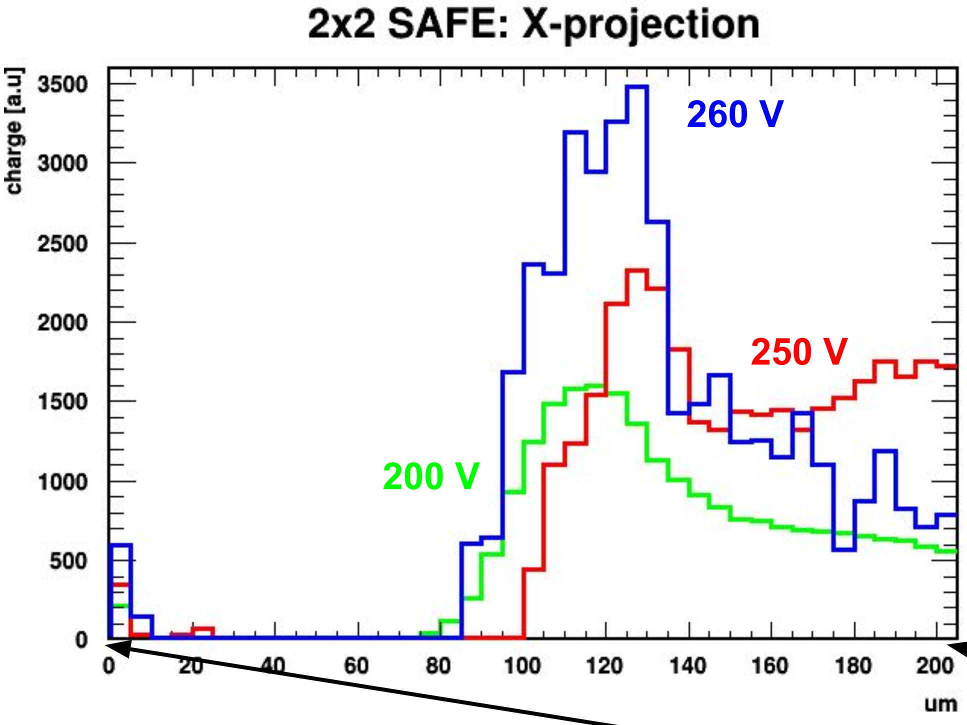


X-Projections

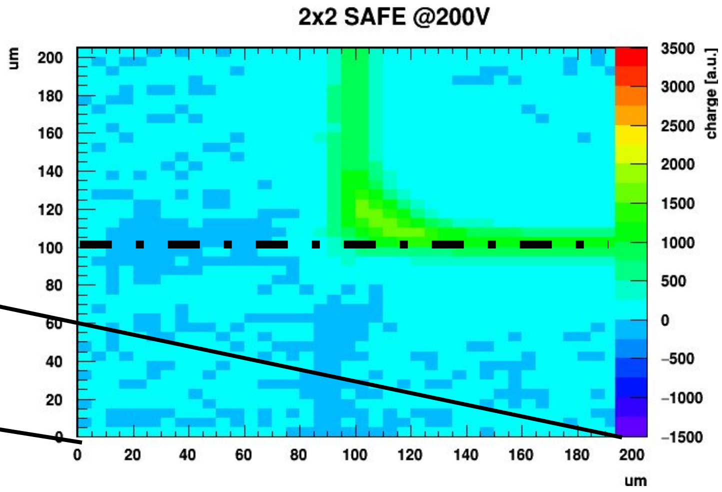


Consider the X-projection for a fixed y (Black line)

X-Projections



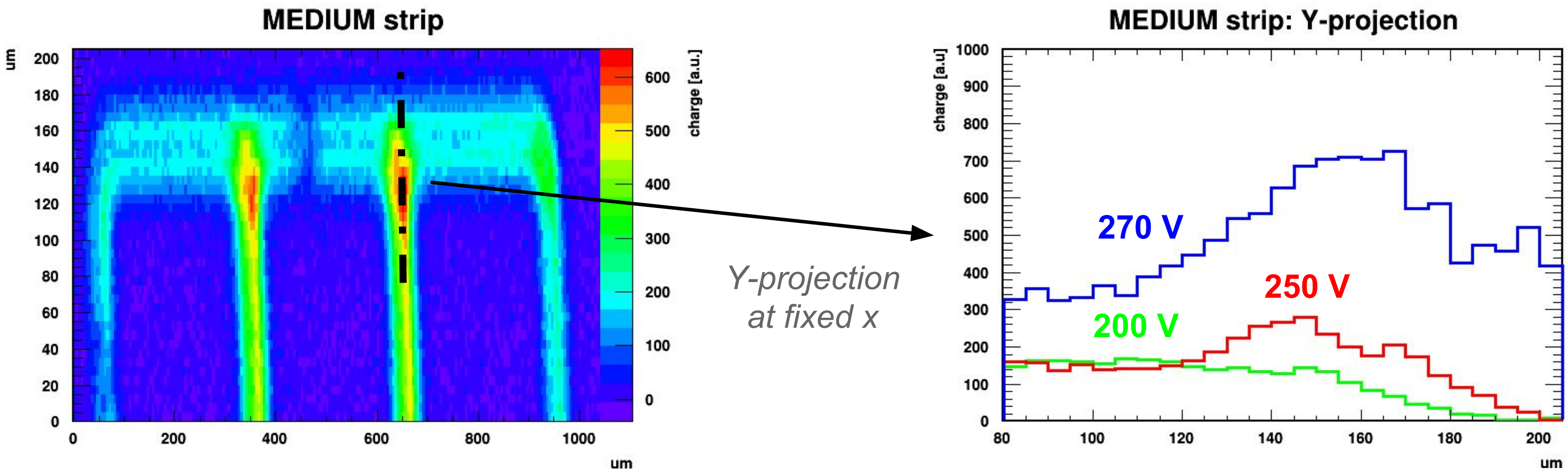
- Clear dependence of the collected charge on V_{BIAS} → **Gain shows up near BD**
- **Effect more evident in the corners**



Consider the X-projection for a fixed y (Black line)

“MEDIUM” & “AGGRESSIVE”

- **Gain** present near BD in “**MEDIUM**” and “**AGGRESSIVE**” as well
  - Present both in pad and strip sensors



“MEDIUM” & “AGGRESSIVE”

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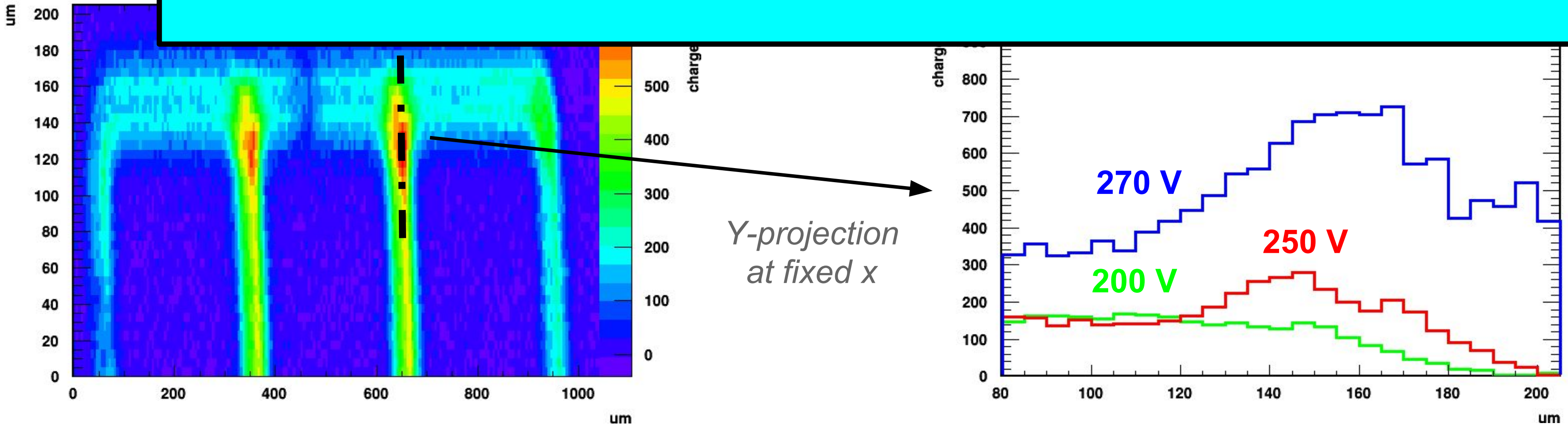
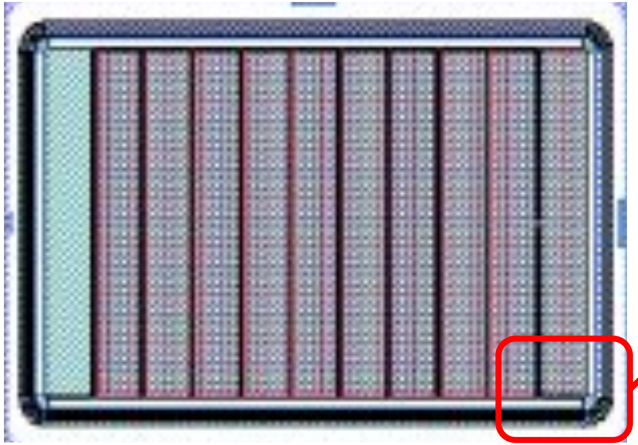
  - Present both in pad and strip sensors

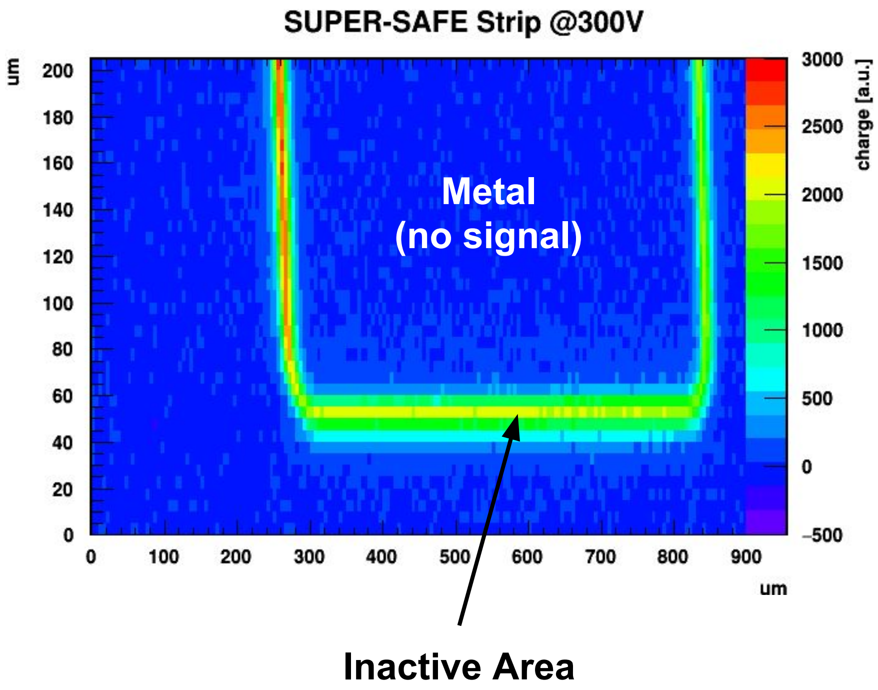
What about the “SUPER-SAFE” sensor?
(Which has a different design of the inactive area)



TCT: mapping the "SUPER-SAFE" strip

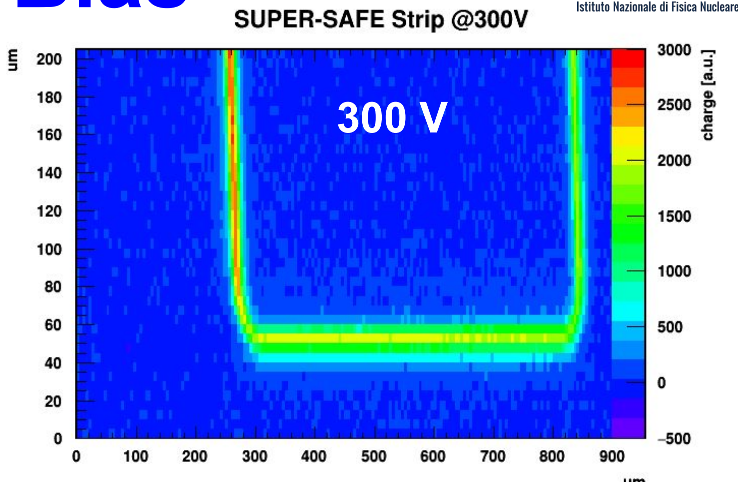
- **"SUPER-SAFE"** strip @300V
- Metallization on the front

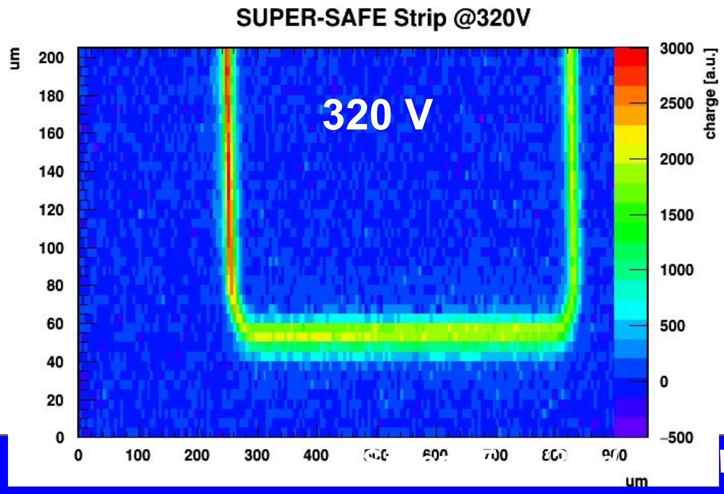


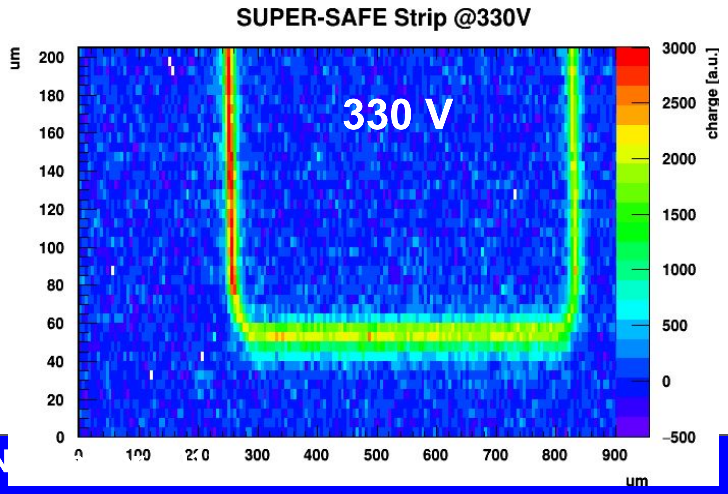


TCT:Charge vs Bias

- Charge collected by the strip at 3 different voltages
- **V_{BD} ~ 320V**
- Coloured scale is different from the previous slide

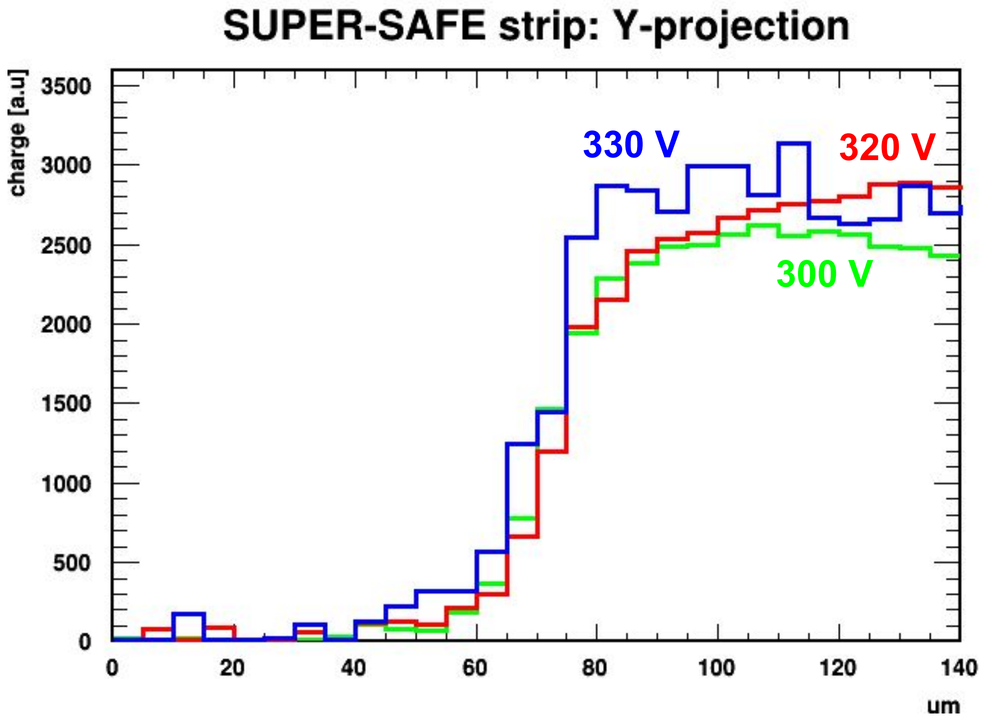


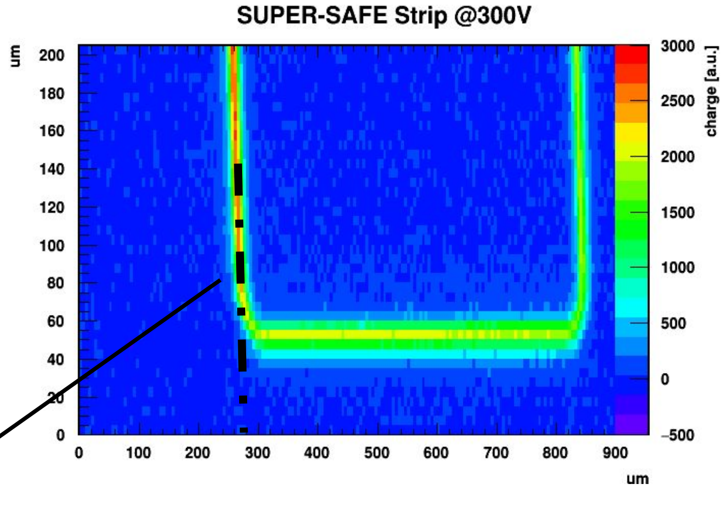




Y-Projections

Consider the Y-projection for a fixed x (Black line)

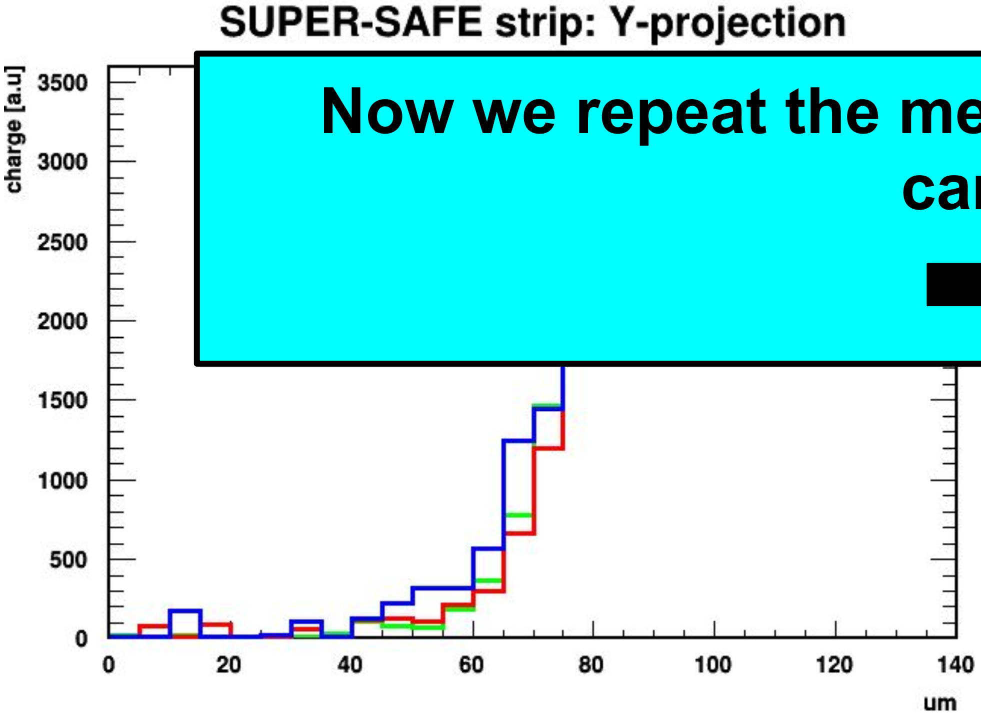




- No dependence on the bias voltage → **no gain in the inactive area for the "SUPER-SAFE" design, no sign of early BD**

Y-Projections

Consider the Y-projection for a fixed x (Black line)



Now we repeat the measurements with a CCD camera

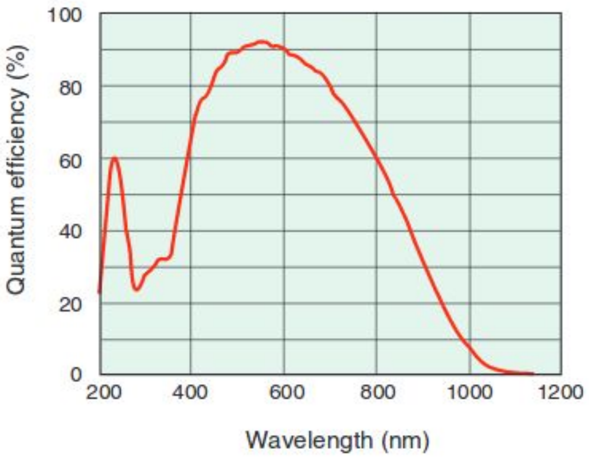
➢ No dependence on the bias voltage → **no gain in the inactive area for the "SUPER-SAFE" design**

Hamamatsu C11090-22B

- **EM-CCD Camera** working with visible light
- 1024 x 1024 pixels
- Ultra-Low light Imaging:
  - Able to **detect the hot spots*** of the DUT when it is in **BD**

* Gain = high current densities
→ emit visible photons
→ Hot Spot

Spectrum of the camera

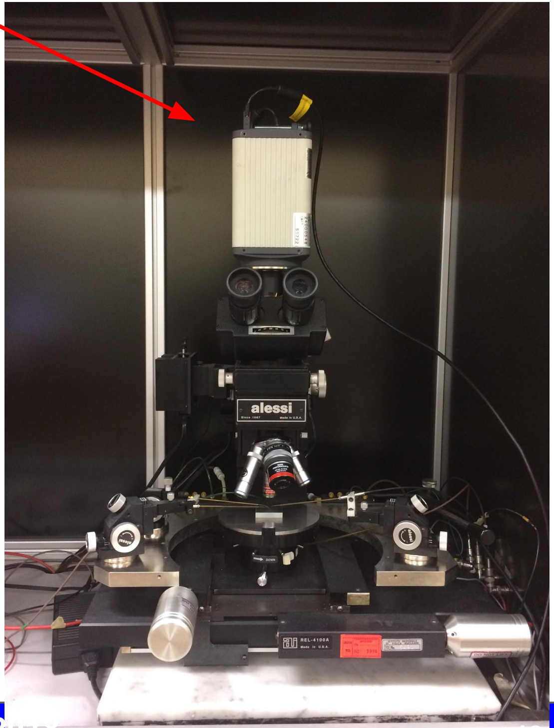


Hamamatsu C11090-22B

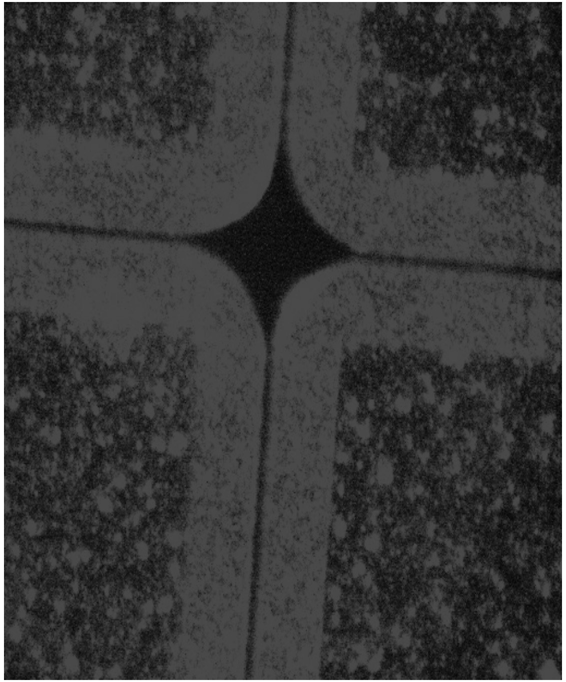
- The camera is mounted on a probe station
- 2 pictures of the sensor are taken:
  - A conventional picture taken with an external source of light
  - A picture taken in complete darkness (probe station closed) with the DUT in BD

➔ The 2 pictures are then overlapped to show in which area the hot spots come out

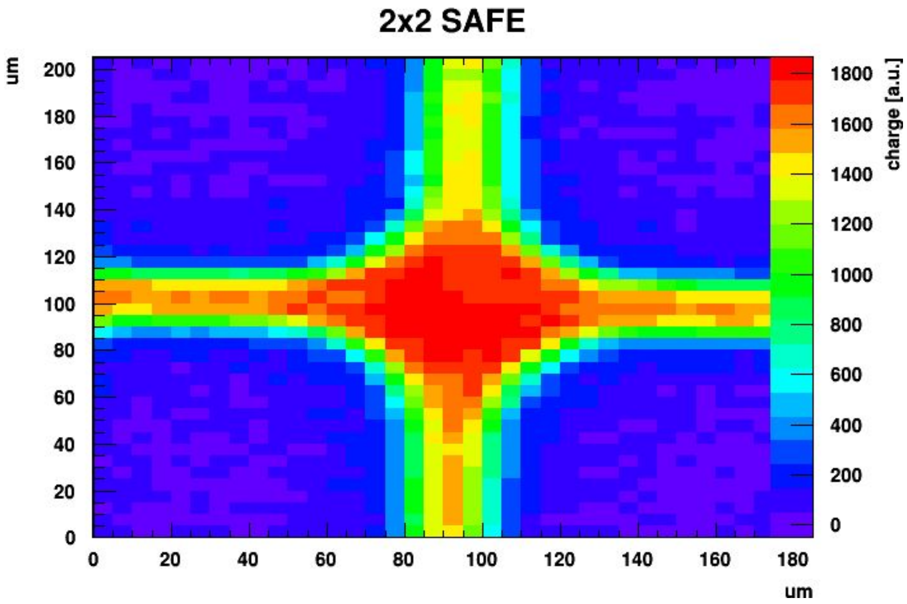
We focused on the corners of the inactive area



2x2 “SAFE”: The Hot Spots

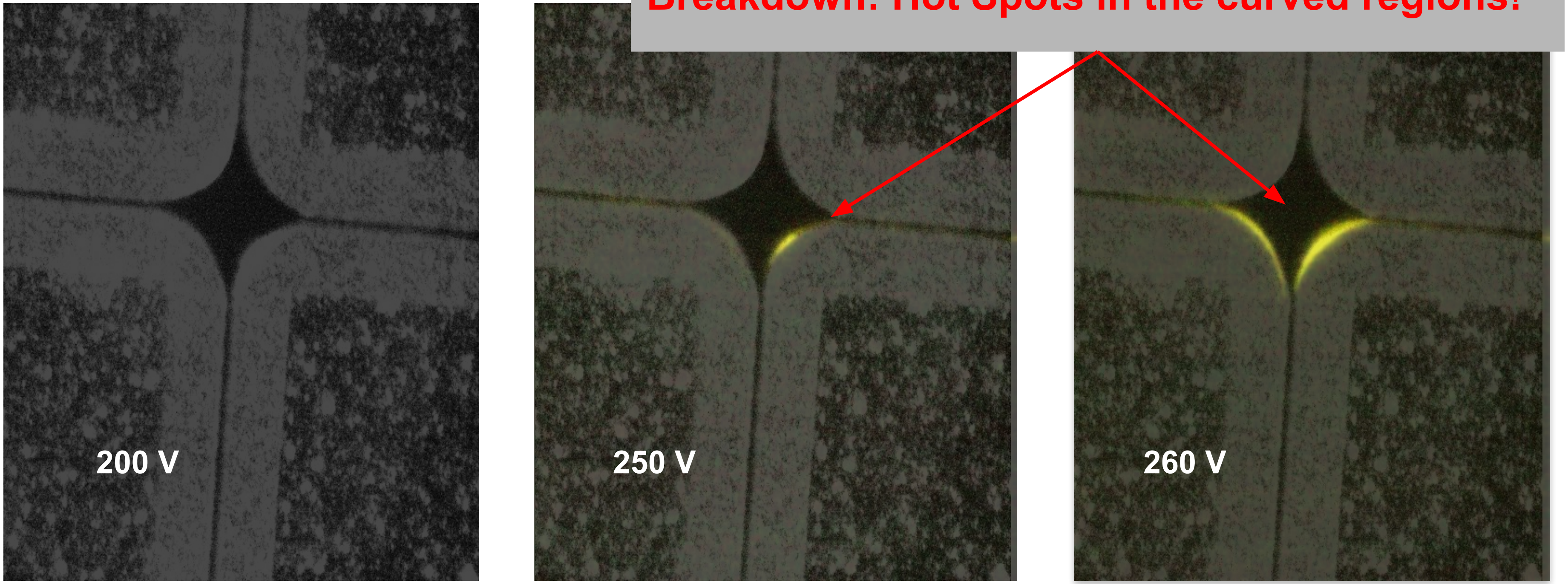


- 2x2 SAFE @200V
- No Hot Spots



2x2 "SAFE": The Hot Spots

Breakdown: Hot Spots in the curved regions!



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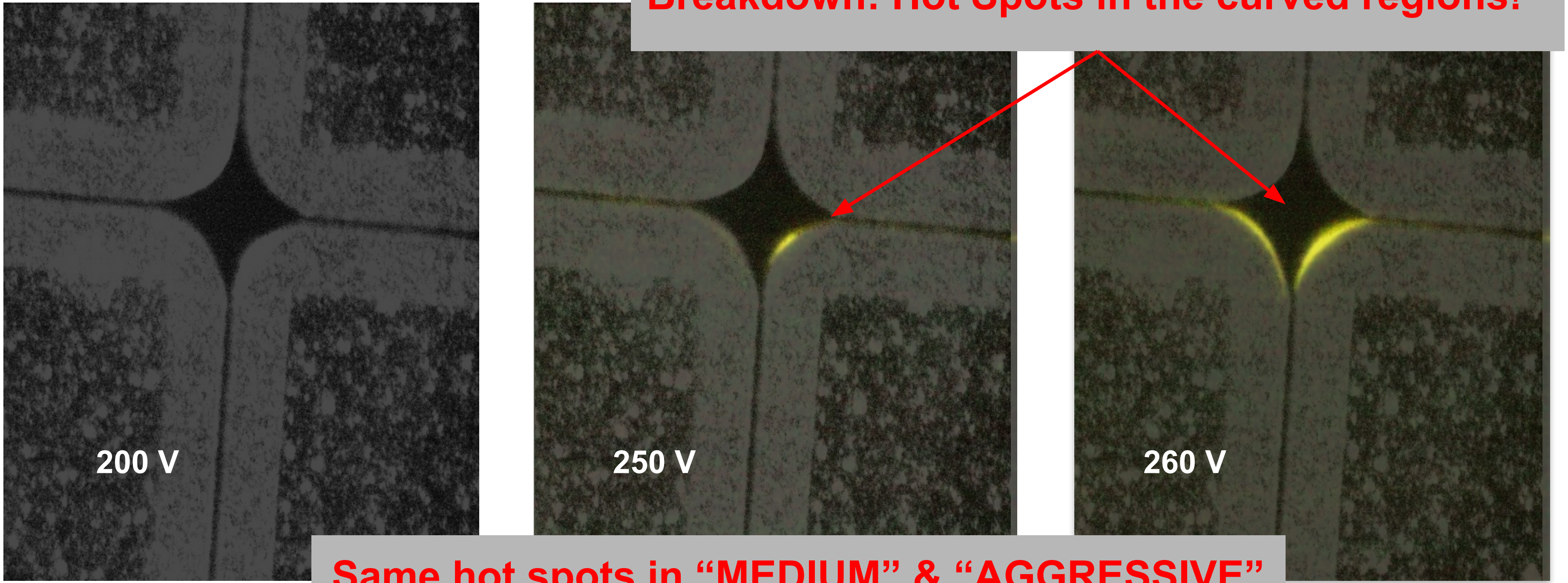
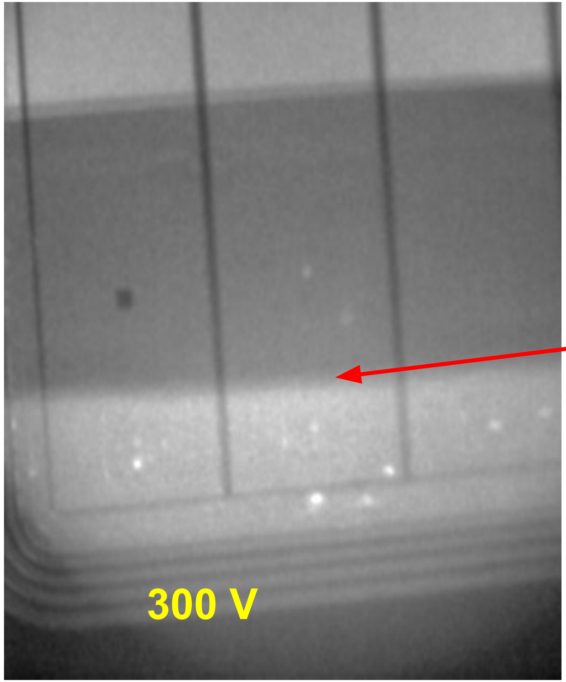
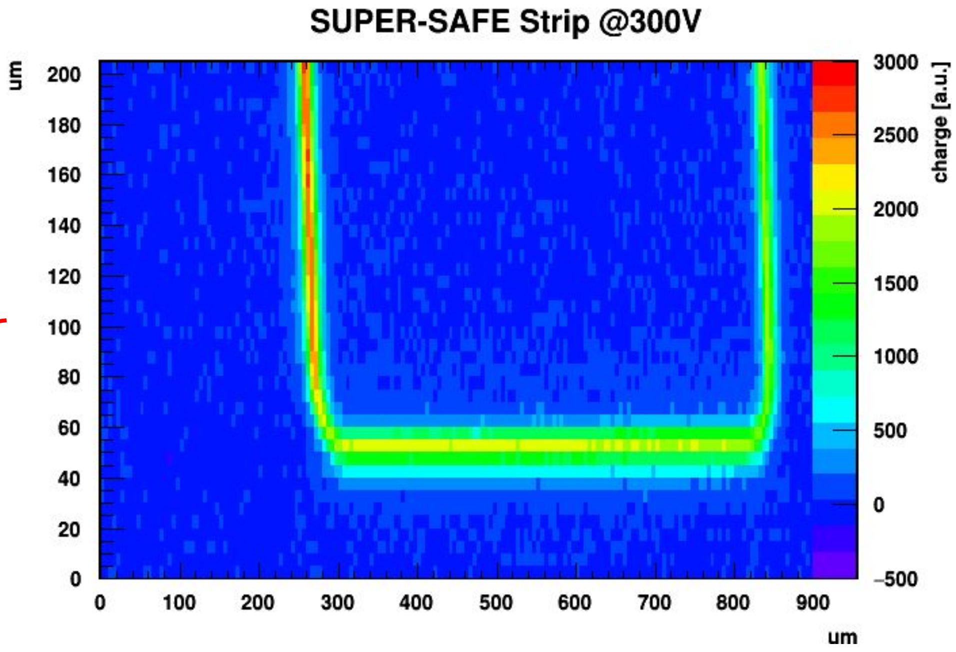


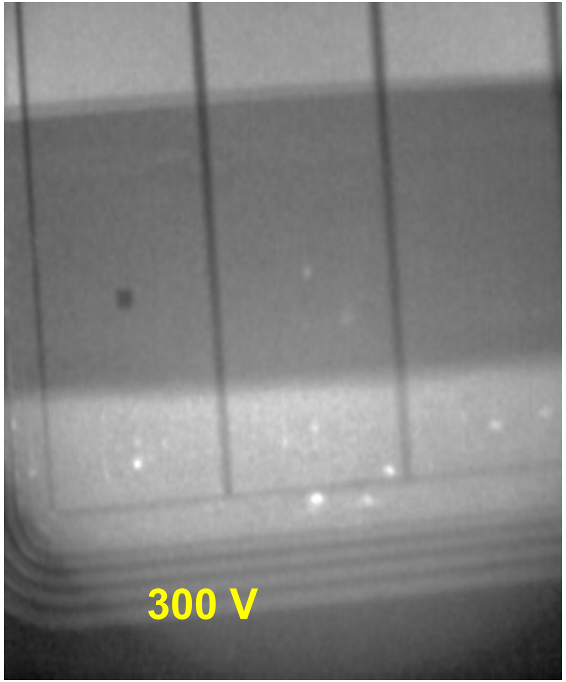
Same hot spots in “MEDIUM” & “AGGRESSIVE”

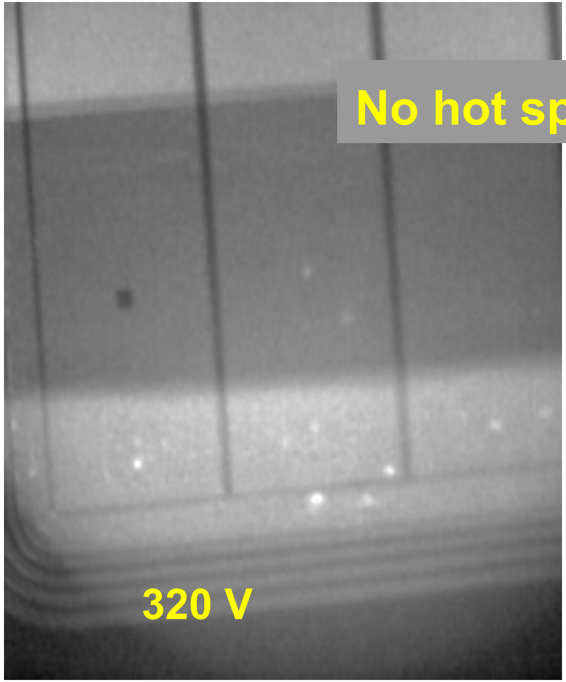
“SUPER-SAFE” strip: No Hot Spots

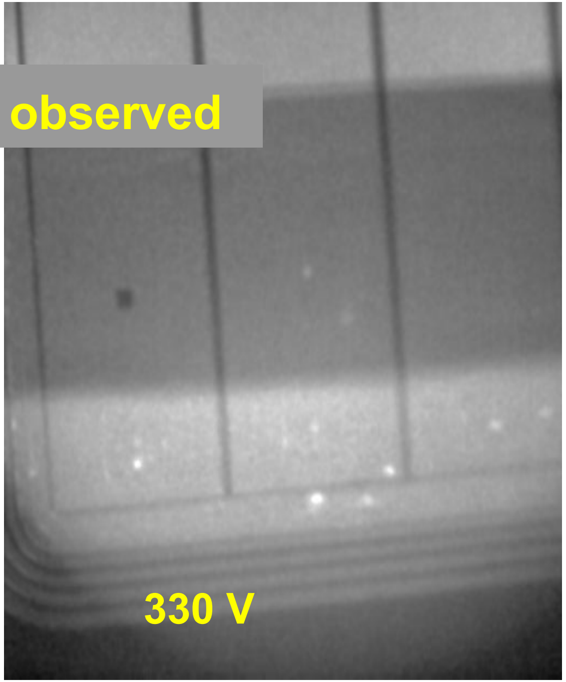




“SUPER-SAFE” strip: No Hot Spots





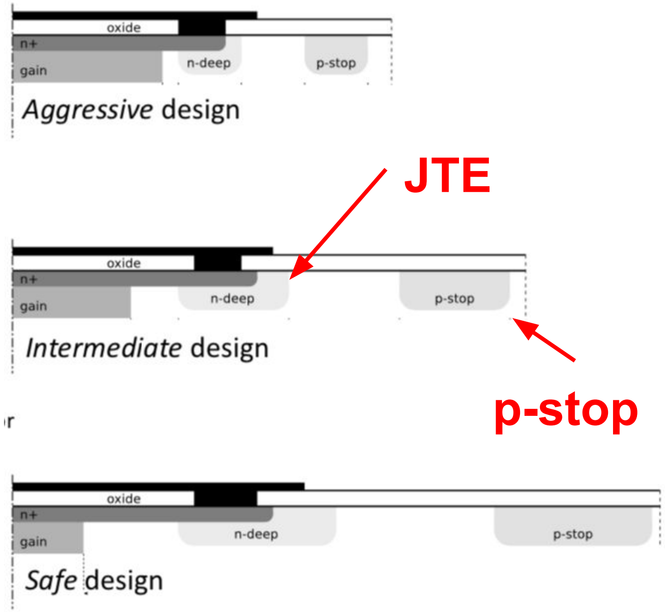


No hot spots observed

Summary on Breakdown

- **R&D Structures**: Breakdown occurs in the inactive region due to the **high electric field between JTE and p-stop**
- **Weakest spot** identified in the **corners** of the pad
- Narrower inactive area → earlier V_{BD} (since JTE and p-stop are closer)

- **"SUPER-SAFE": different design** of the inactive area → **higher V_{BD}**
  → **Gain avalanche in the pad happens before breakdown** in corners



Pop-Corn Noise

An undesired effect related to the new inactive area design:

- **Pop-Corn Noise: micro-discharges (spikes) that appear at a certain voltage**
  - the sensor can still be operated, but the noise worsens a lot
- Already observed in the previous **UFSD2** but always **few Volts before BD**
  → **Not an issue in UFSD2**, it is just an indication that BD is going to start
- Several **UFSD3** sensors show Pop-Corn at voltages **much lower than V_{BD}**
  → **Important issue**, we cannot operate the sensors at the appropriate voltage

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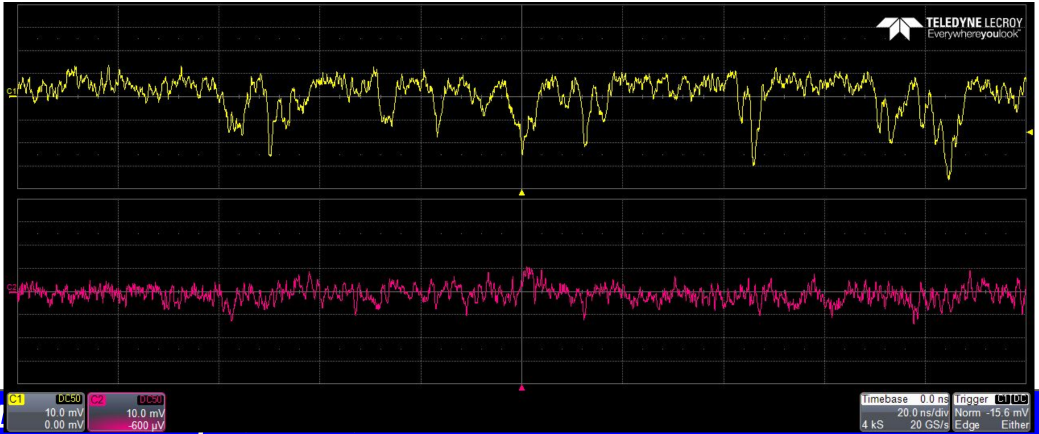
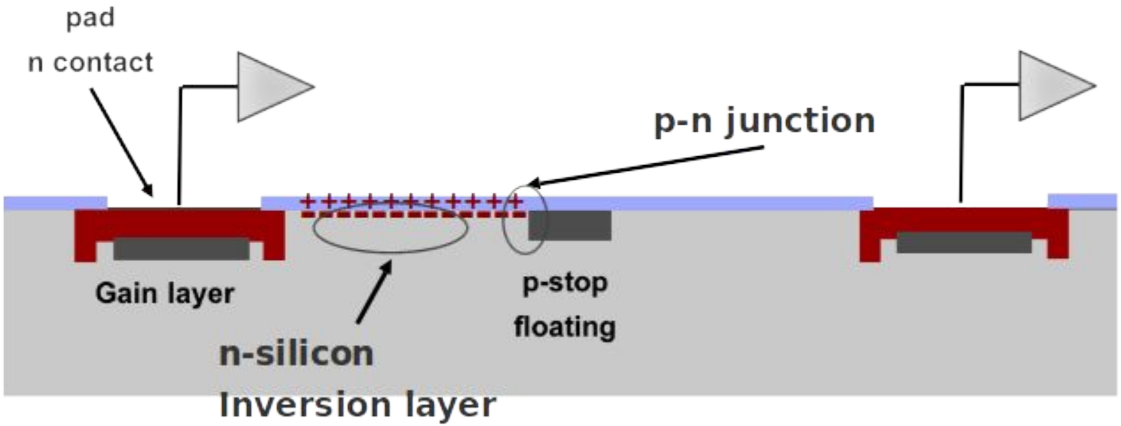
- Example of **Pop-Corn (Yellow)**
- Pink is “normal” noise of another device of the same type, shown for comparison

Taken 100V before V_{BD}



Pop-Corn & p-stop



- **The electrons under the oxide create an "inversion layer"**, acting as n-doped Silicon: this layer with the p-stop creates a p-n junction
- **The more doped is the p-stop**, the shorter is the p-n junction, and **the higher is the electric field**
- **According to literature: pop-corn noise is generated when this p-n junction is too sharp**

UFSD3 Pop-Corn

- **UFSD3 has been produced using the “stepper” technique** instead of the “mask aligner” technique.
- The stepper is able to create much sharper images, much better defined edges, higher uniformity and process speed
- **Unforeseen consequence on the p-stop: much sharper images → much sharper pn junction → Pop-Corn noise**
- We believe that the Pop-Corn noise is due to: use of the stepper + p-stop too doped

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- We believe that the Pop-Corn noise is due to: use of the stepper + p-stop too doped

→ A **possible fix** to this issue: use a **less-doped p-stop**, in order to get a less sharp pn junction

Summary & Conclusions

- **UFSD3 has 2 designs of the inactive area:**
  - UFSD2 like “**SUPER-SAFE**”: **BD due to internal gain** → the sensor can be operated at the proper voltage (**~ 300V**)
  - **3 R&D structure: BD due to high gain in the inactive area** → sensor **cannot reach 300V**
- **The inactive area design determine the type of BD and therefore the voltage that can be reached → Key point for future productions**

- **Pop-Corn Noise**: micro-discharges that appear much before BD
  → **Likely due to the “stepper” technique + highly doped p-stop**

Thank You!

Acknowledgements

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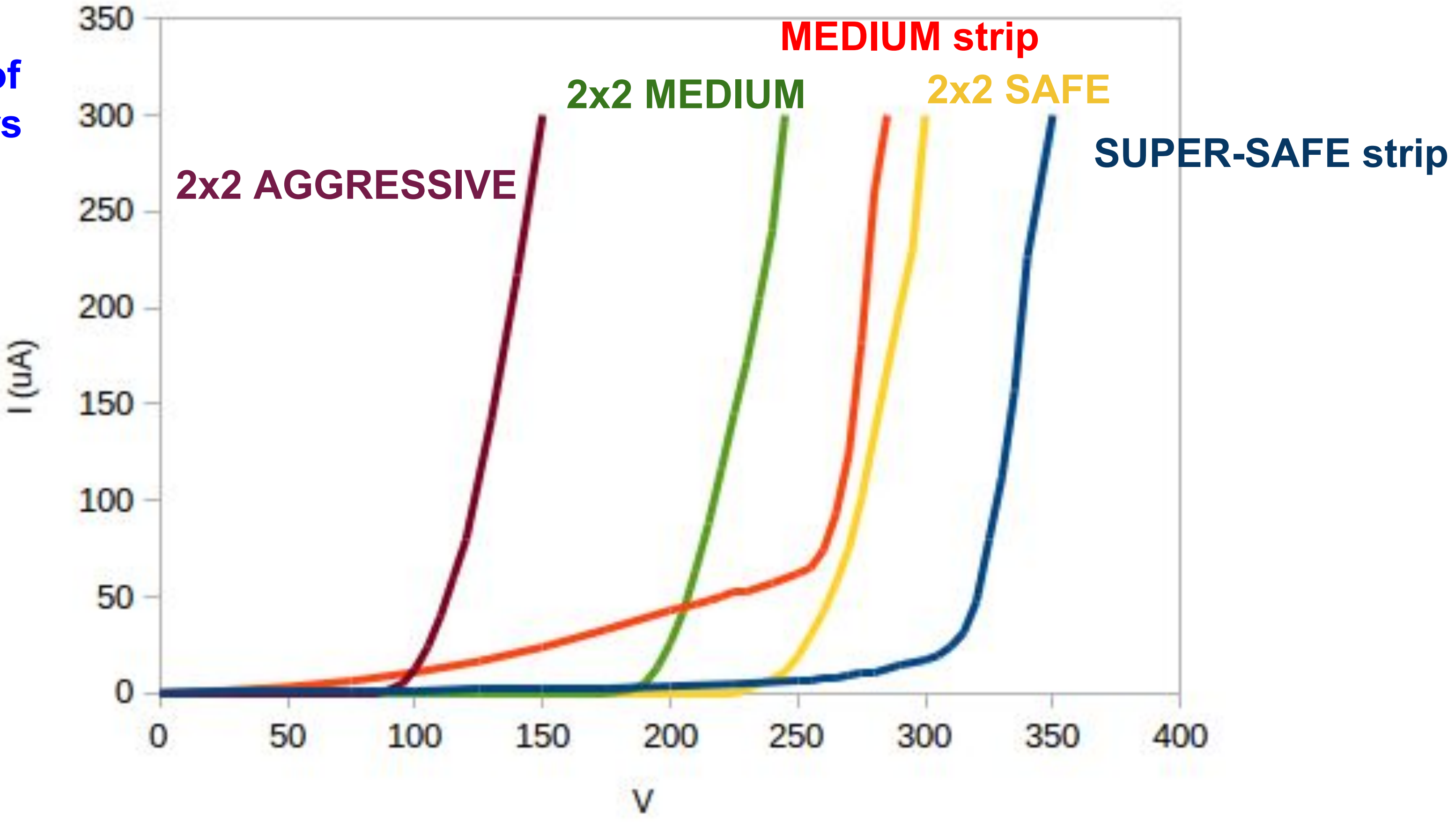
- INFN Gruppo V
- Horizon 2020, ERC - Advanced Grant UFSD
- Horizon 2020, MSCA - INFRAIA Grant AIDA2020
- Ministero degli Affari Esteri, Italia, MAE, “ Progetti di Grande Rilevanza Scientifica”

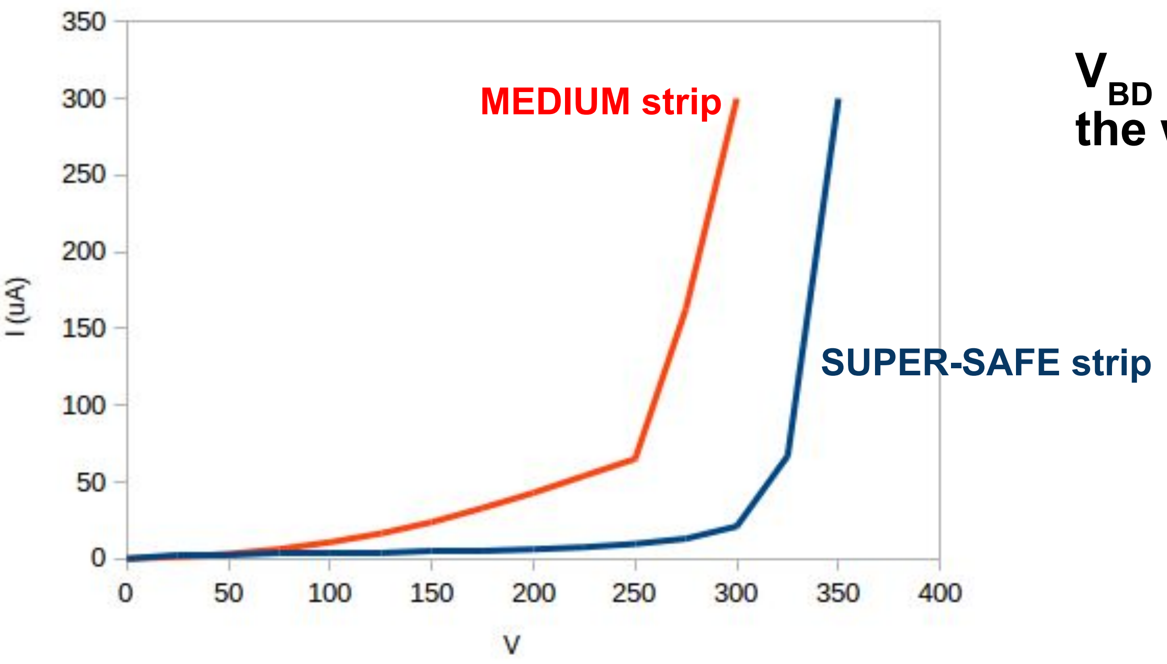
Backup

I(V) Curves

I(V) curves of the 5 sensors tested

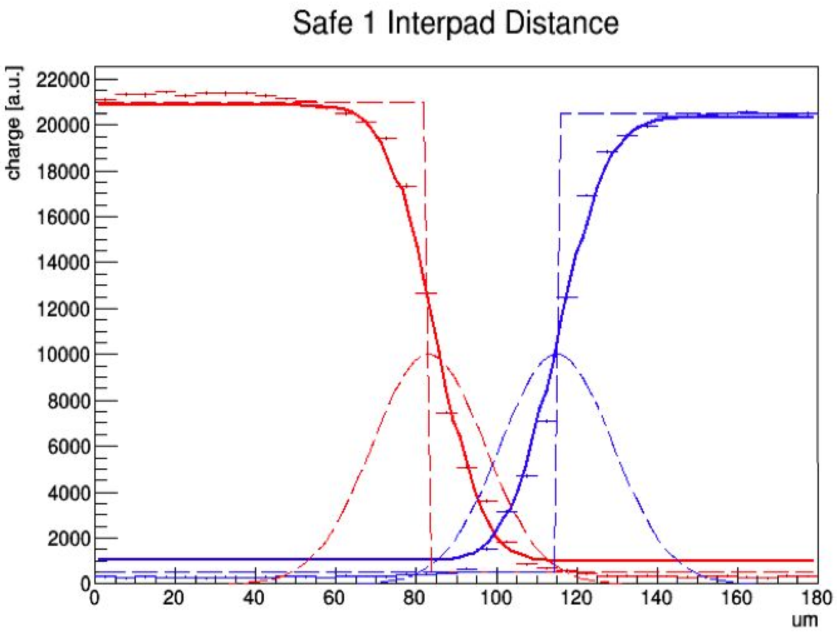


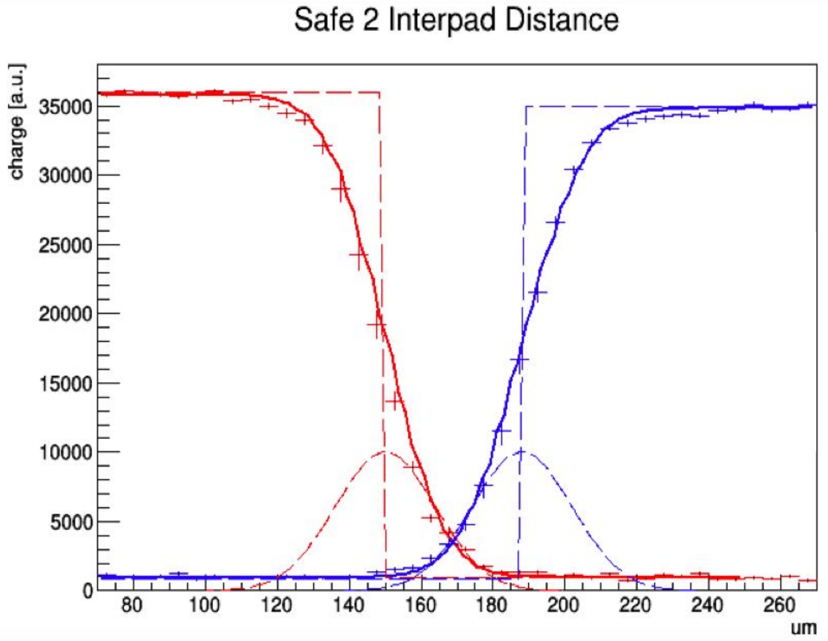
Strip Breakdown



V_{BD} is strongly dependent on the width of the inactive area

Interpad: SAFE & SUPER-SAFE



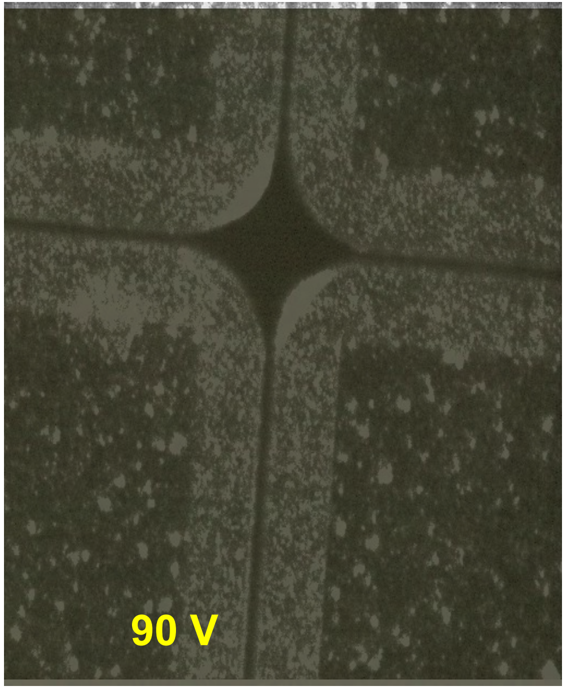


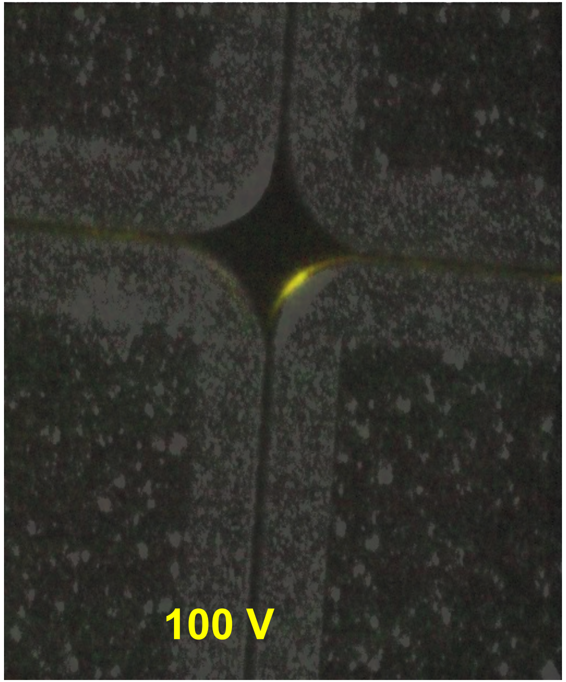
Interpad Summary

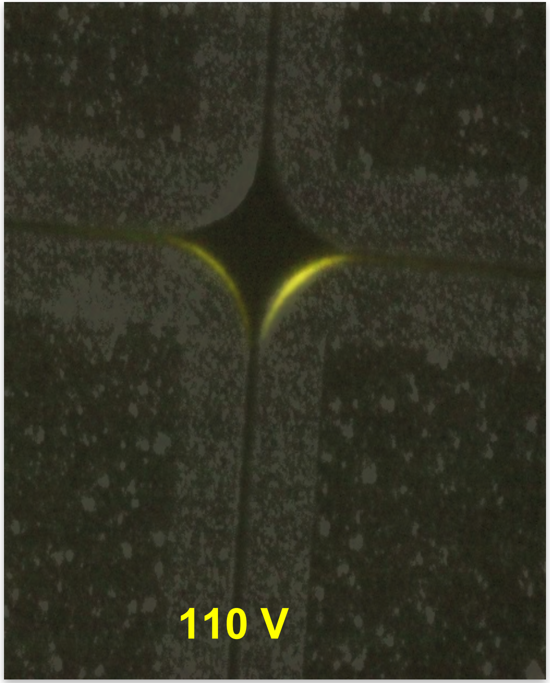
Structure	Measured distance (μm)	Laser spot (μm)	Nominal distance (μm)
AGGRESSIVE	**16.4**	**7.7**	**11**
INTERMEDIATE	**16.7**	**10.1**	**20.5**
SAFE	30.4	10.0	31
SUPER SAFE	38.3	13.4	41

Larger discrepancy if the width is narrow because of the laser spot

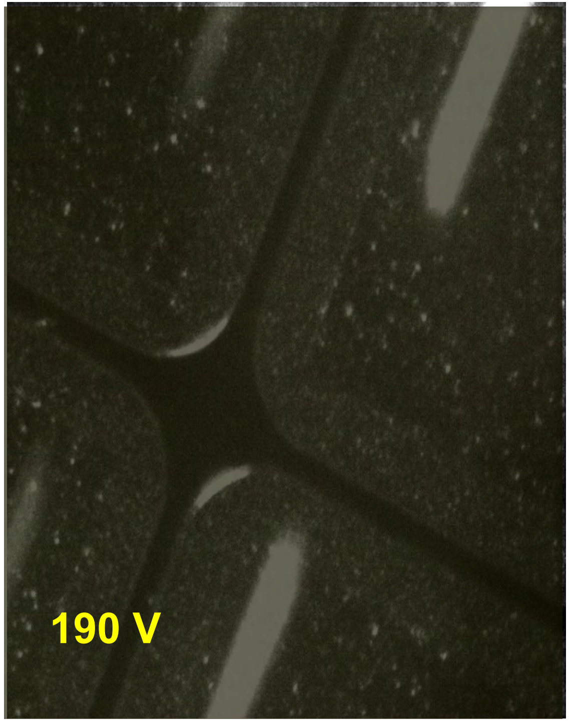
“AGGRESSIVE” Hot Spots

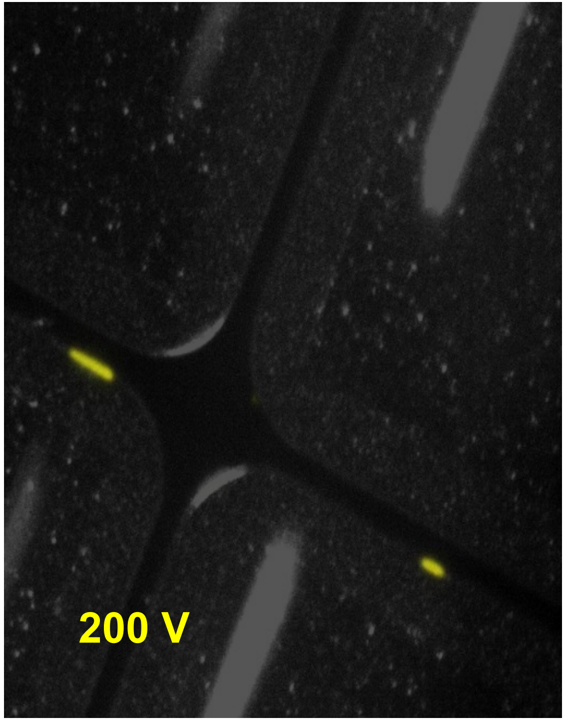


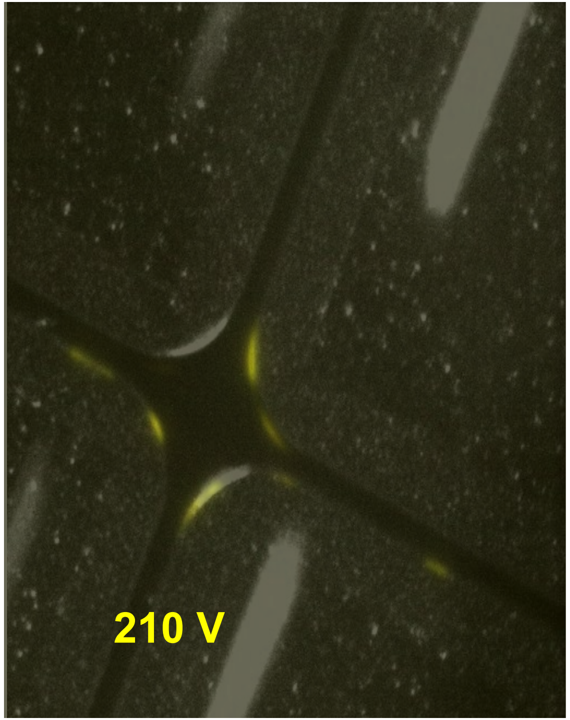




“MEDIUM” Hot Spots







Pop-Corn: The CMS Experience

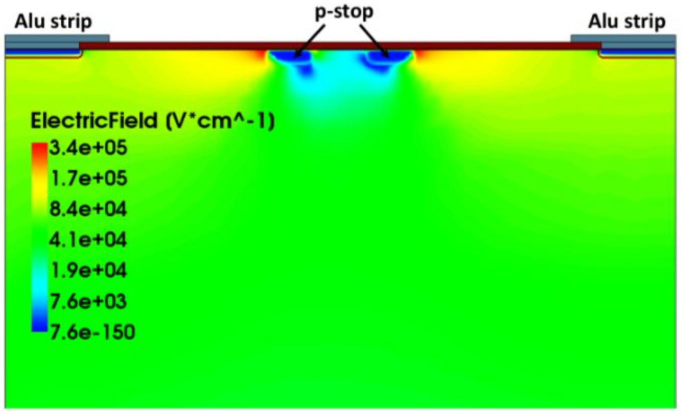


Figure 6: Section from T-CAD simulation of the V2 sample with a high p-stop doping concentration. The simulation was performed for T = 253 K and $V_{bias} = -600V$. The asymmetry between the p-stops is due to the chosen mesh density.

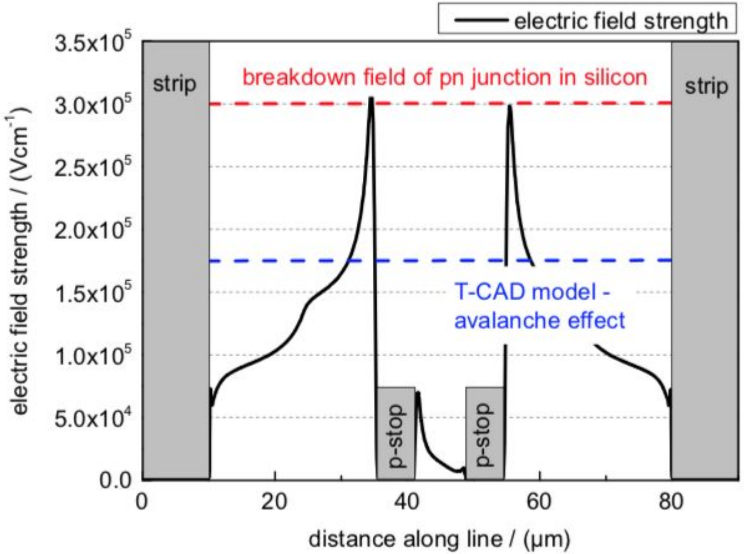


Figure 7: Maximum electric field strength distribution between two strips as a result from T-CAD simulations. The parameters correspond to the values listed in Figure 6. (The asymmetry between the p-stops is due to the choice of the mesh parameter.)

Martin Printz, KiT