Quality Assurance / Quality Control of the LGAD sensors for CMS ETL

20.2.2024

Federico Siviero

on behalf of the CMS ETL group

Outline

- The CMS MIP Timing Detector (MTD)
    - The Endcap Timing Layer (ETL)
    - Sensors for ETL
- The ETL sensor QA/QC strategy
    - Process Quality Check
    - Sensor Quality Check

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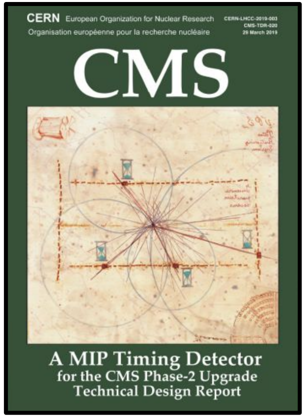
The CMS MIP Timing Detector (MTD)

- MTD will provide accurate timing of charged tracks during the High-Luminosity phase of the LHC (HL-LHC)
- It will be divided into 2 sections:
  - BTL: Barrel Timing Layer
  - **ETL: Endcap Timing Layer**

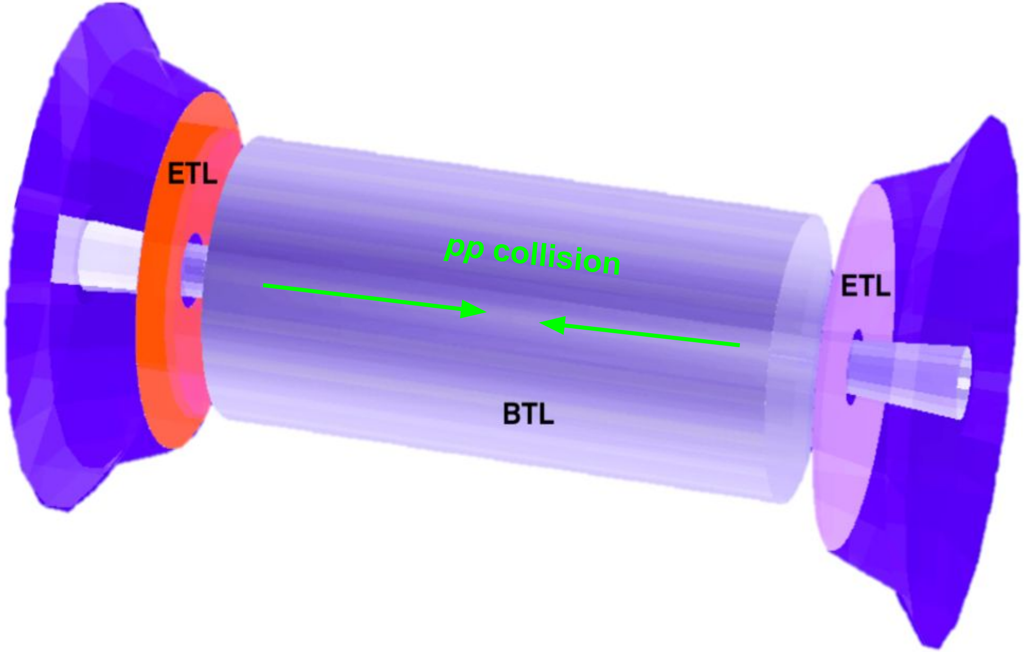


CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire
CERN-LHCC-2019-003
CMS-TDR-020
29 March 2019

CMS

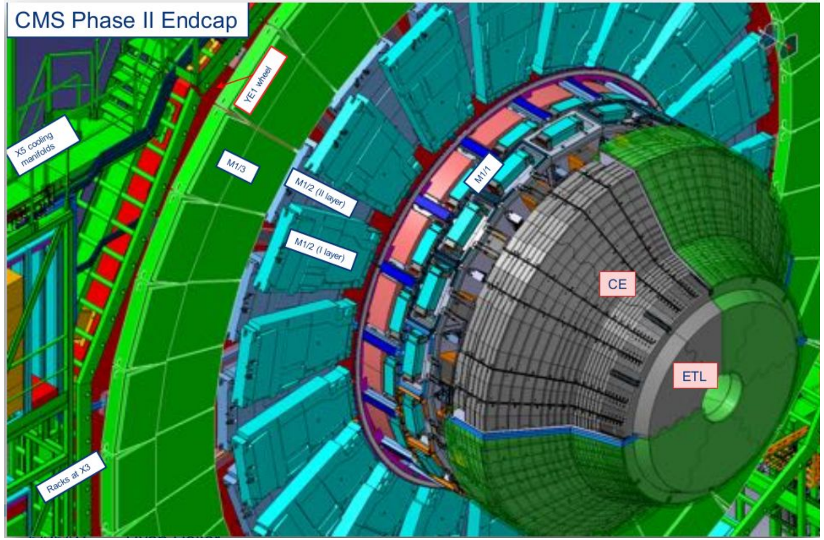
A MIP Timing Detector
for the CMS Phase-2 Upgrade
Technical Design Report

MTD TDR



Endcap Timing Layer (ETL)

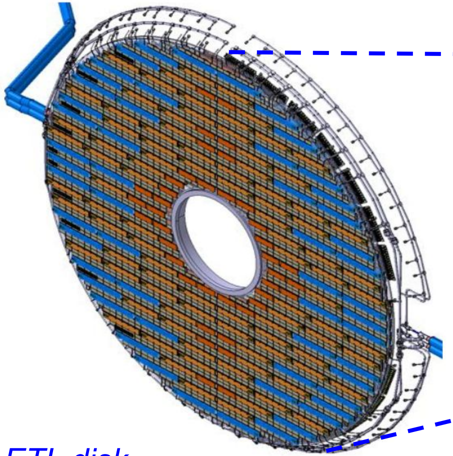
- ETL will be mounted on the nose of the CMS CE calorimeter
- 2 double-sided disks on each side of CMS (+z / -z)



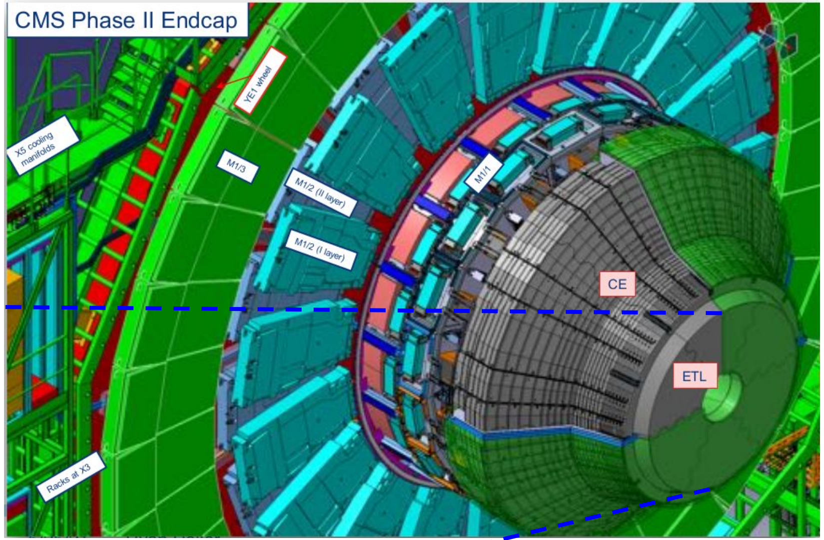
Endcap region of the CMS detector

Endcap Timing Layer (ETL)

- ETL will be mounted on the nose of the CMS CE calorimeter
- 2 double-sided disks on each side of CMS (+z / -z)
- Coverage:
    - z ~ 3 m from pp interaction
    - ~0.3 m < R < ~1.2 m
    - $1.6 < |\eta| < 3.0$
    - Surface ~ 14 m^2



ETL disk

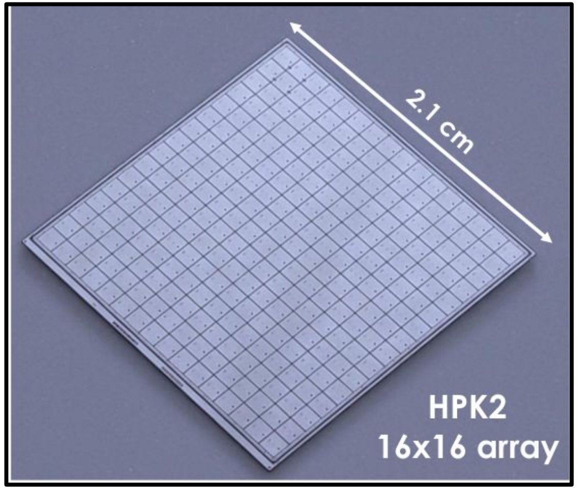


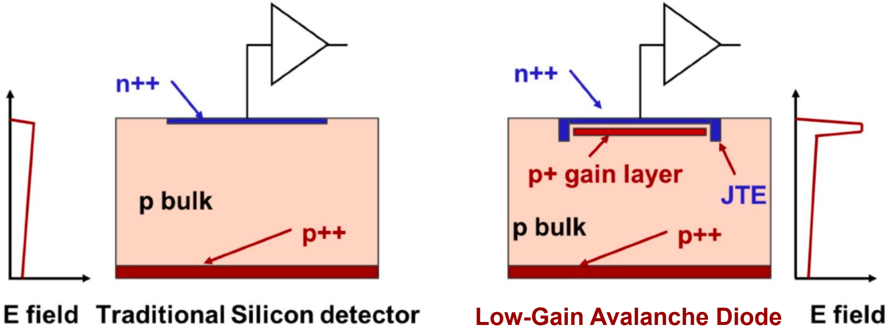
Endcap region of the CMS detector

Sensors for ETL: LGAD

- **ETL will be instrumented with LGAD sensors, with a 16x16 pad array**
    - 1.3 x 1.3 mm^2 pads for a total surface of 21.4 x 21.6 mm^2

- **ETL LGADs can achieve:**
    - Single hit **time resolution < 50 ps**
    - Delivered **Charge > 8 fC**
    - Maintain performance up to the end of detector operation (Φ ~ 1.5-2.5e15 n_{eq}/cm^2 in the most irradiated regions of ETL)





- LGADs will be bump-bonded to the ETL read-out ASIC (ETROC)

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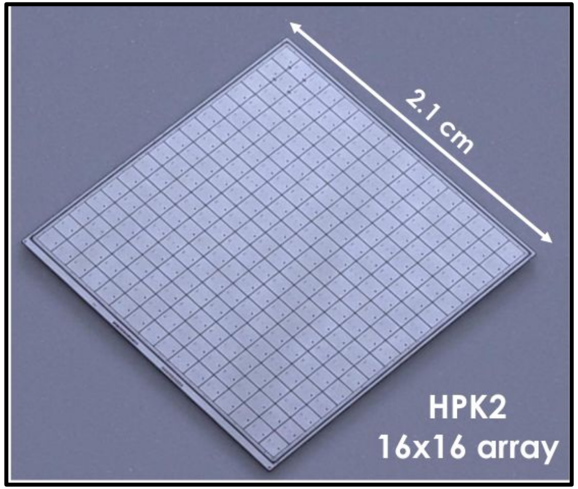

The LGAD schedule

- ➢ 2023: Market Survey completed, we identified 3 potential vendors
- ➢ 2024: Freeze LGAD specifications + define quality management (QA/QC) procedures for the sensors production → Invitation to Tender and final selection of the vendor(s)
- ➢ 2025: Beginning of the sensor production for ETL

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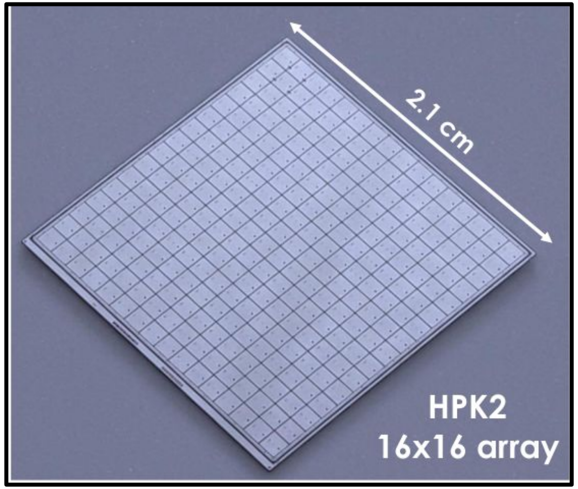

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Today I will focus on this

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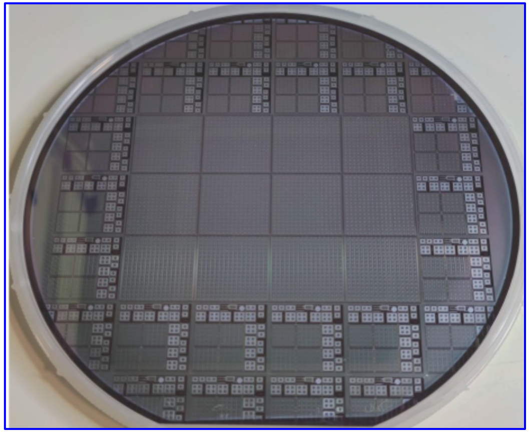
The ETL sensor QA/QC strategy

- **ETL will comprise ~ 35k LGAD sensors** (20% spare sensors included)
- **How do we ensure they are working and within specifications?** → that's the purpose of the quality management procedures described in this presentation
- Quality management is split in Quality Assurance (QA) and Quality Control (QC)
  - **QA:** actions taken to ensure the sensor meets specifications
  - **QC:** monitor results after the sensor is produced
- QA/QC to be carried out both at vendors and at the ETL testing sites

LGADs production schedule

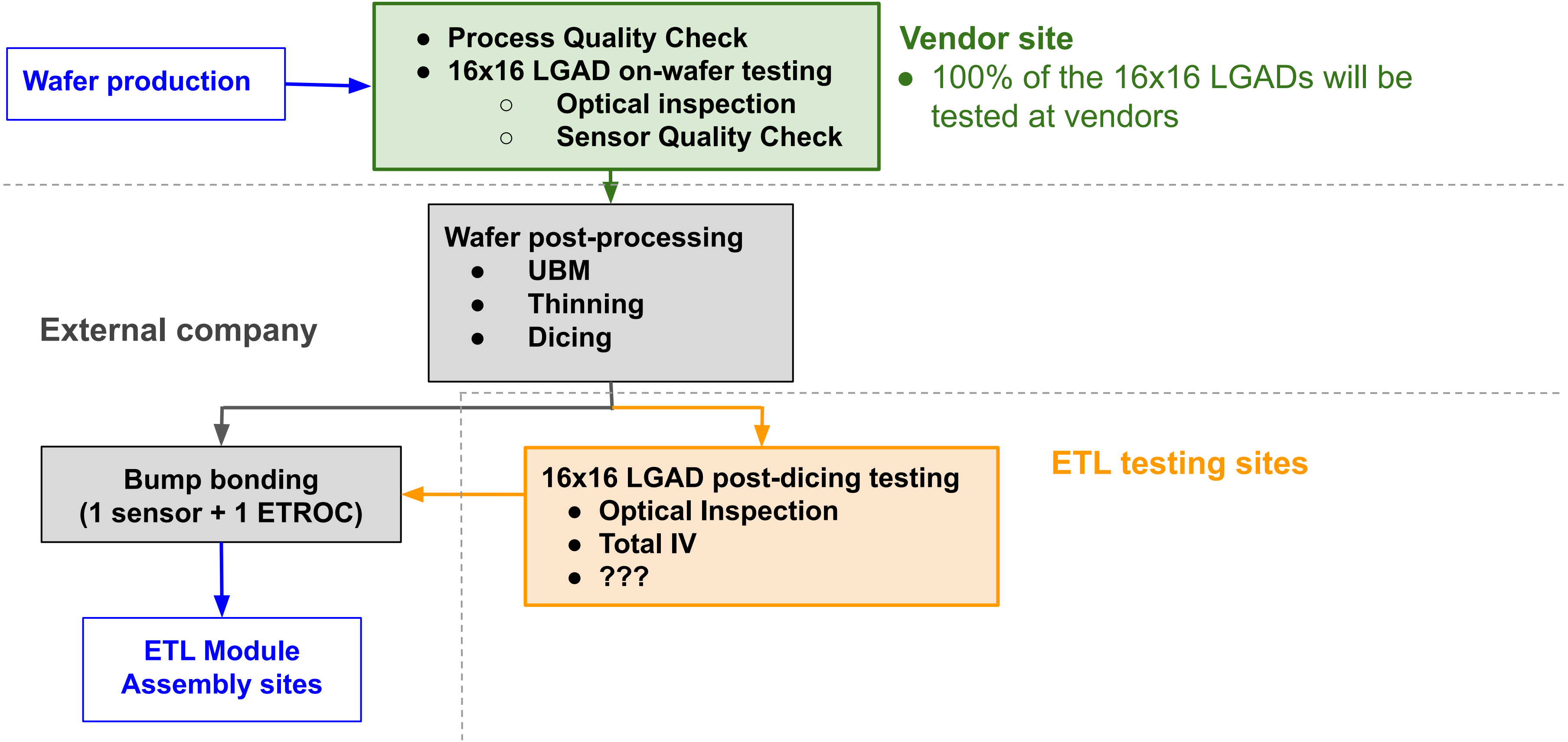
- Sensors will be delivered in **batches**, starting August 2025
- A **pre-production series (5% of the total)** will be delivered a few months in advance, will be used to set the sensors **acceptance ranges**, based on the parameters discussed in the following

Batch	Delivery date
Pre-production (5%)	February 2025
Face 1 (20%)	August 2025
Face 2 (25%)	December 2025
Face 3 (25%)	March 2026
Face 4 (25%)	July 2026



A wafer of the FBK UFSD4 production

ETL QA/QC plans



Wafer production

- **Process Quality Check**
- **16x16 LGAD on-wafer testing**
  - **Optical inspection**
  - **Sensor Quality Check**

Vendor site

- 100% of the 16x16 LGADs will be tested at vendors

External company

Wafer post-processing

- **UBM**
- **Thinning**
- **Dicing**

Bump bonding
(1 sensor + 1 ETROC)

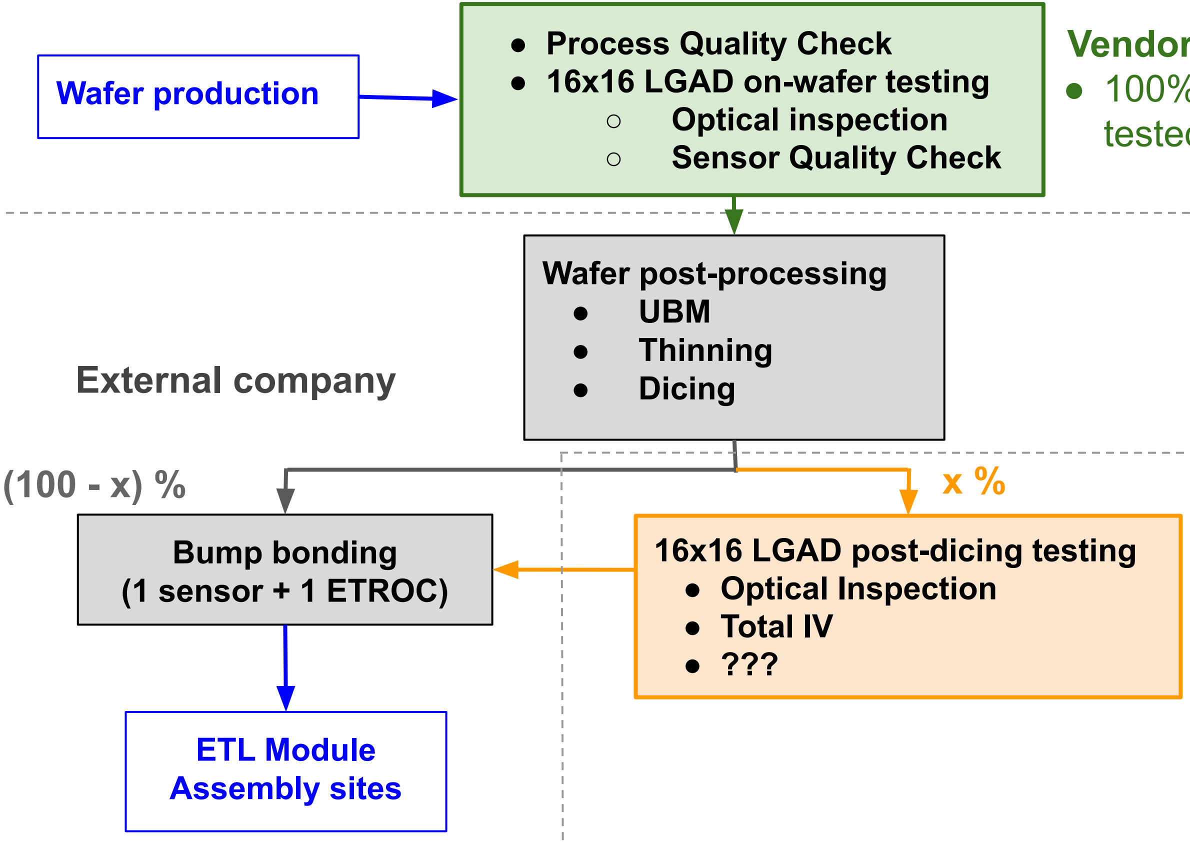
ETL Module Assembly sites

16x16 LGAD post-dicing testing

- **Optical Inspection**
- **Total IV**
- **???**

ETL testing sites

ETL QA/QC plans



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(100 - x) %

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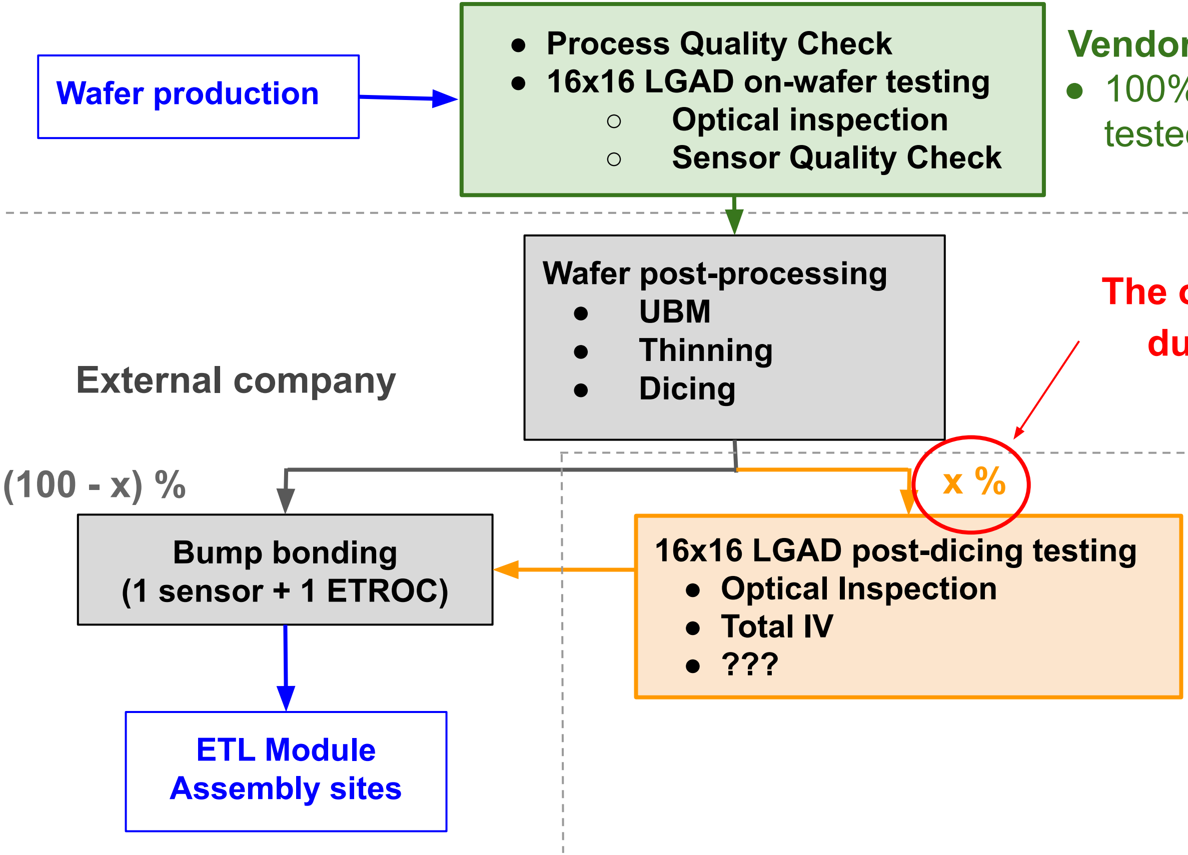
- A certain fraction of the diced 16x16 will be re-tested, the remaining part will go directly to bump bonding

ETL QA/QC plans: pre-production



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Wafer post-processing

- **UBM**
- **Thinning**
- **Dicing**

The optimal fraction will be determined during the pre-production, testing 100% of the diced sensors

(100 - x) %

x %

Bump bonding (1 sensor + 1 ETROC)

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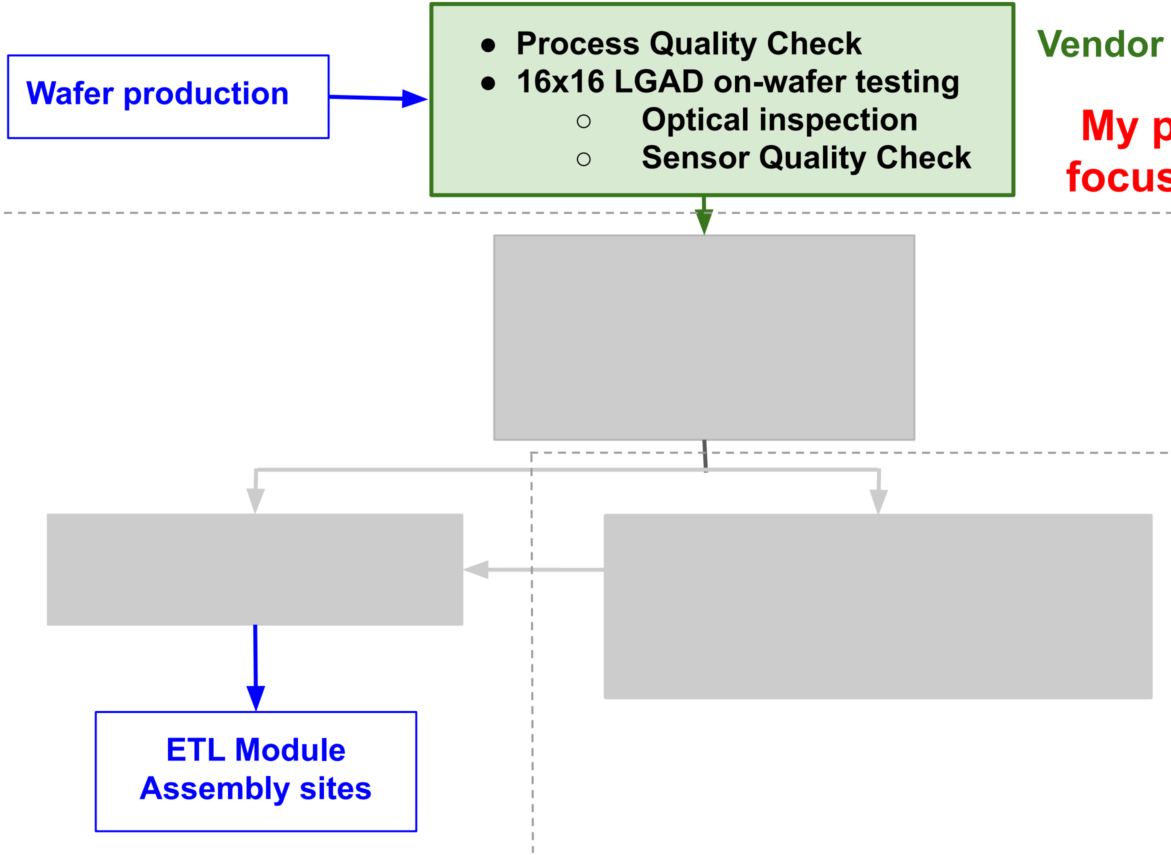

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ETL Module Assembly sites

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My presentation today will focus on QA/QC carried out by vendors

QA/QC at Vendors

Wafer production →

- **Process Quality Check**
- **16x16 LGAD on-wafer testing**
  - **Optical inspection**
  - **Sensor Quality Check**

Vendor site

- **Process Quality Check (PQC)**: check quality of all the process steps
- **16x16 LGADs on-wafer testing:**
  - **Optical Inspection:** no scratches or any other visible damage
  - **Sensor Quality Check (SQC):** on-wafer characterization of the sensors

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Process Quality Check (PQC)

Aim of the PQC: **check quality of the process steps using test arrays** that will be placed on wafer

The test array will comprise

- Process Control Monitor (PCM) structures to measure oxide charges and thicknesses, resistivities
    - Acceptance ranges on PCM defined internally by vendors
- A single LGAD to perform a CV: measure gain implant profile and gain layer depletion voltage (VGL)
    - Acceptance ranges on implant profile and VGL will be fine-tuned after pre-production

Example of a test array

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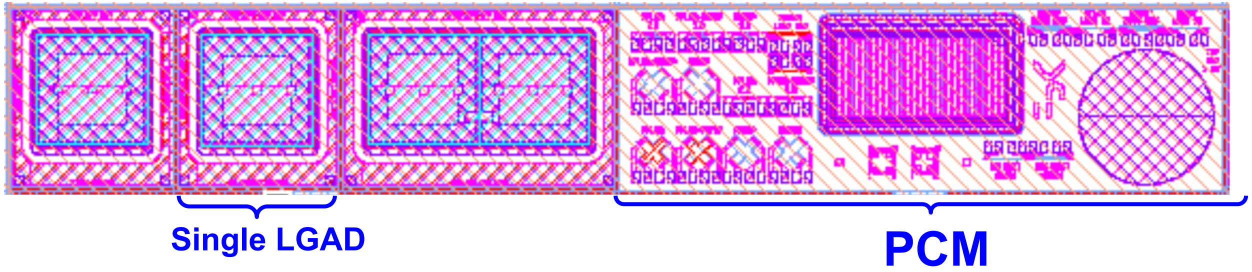
→ If all the parameters are within acceptance ranges, the wafer can proceed to the SQC phase



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The aim of the SQC is twofold:

1) **Identify sensors not working or with parameters not in the acceptance ranges**

- We identified 3 main parameters to achieve this:
  - Breakdown Voltage (VBD)
  - Leakage Current in the sensor operation range
  - Presence of bad pads

Extracted from a total IV
(256 pads + guard-ring grounded)
performed on the 16x16 LGADs

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SQC Parameter 1: VBD

- To compute the Breakdown Voltage (VBD), we identified the k-factor method [1]
- The k variable measures the relative increase of the sensor current (for a fixed ΔV) normalized to the absolute value of V and I
    - $k(I,V) = (\Delta I / \Delta V)*(V / I)$ $\begin{cases} k \sim 1 \text{ Ohmic resistor} \\ \text{VBD defined as first voltage at which } k > k_{THR} \end{cases}$
    - k_{THR} to be fine tuned, it will be in the 15-25 range
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[1] N. Bachetta et al. https://doi.org/10.1016/S0168-9002(00)01207-9

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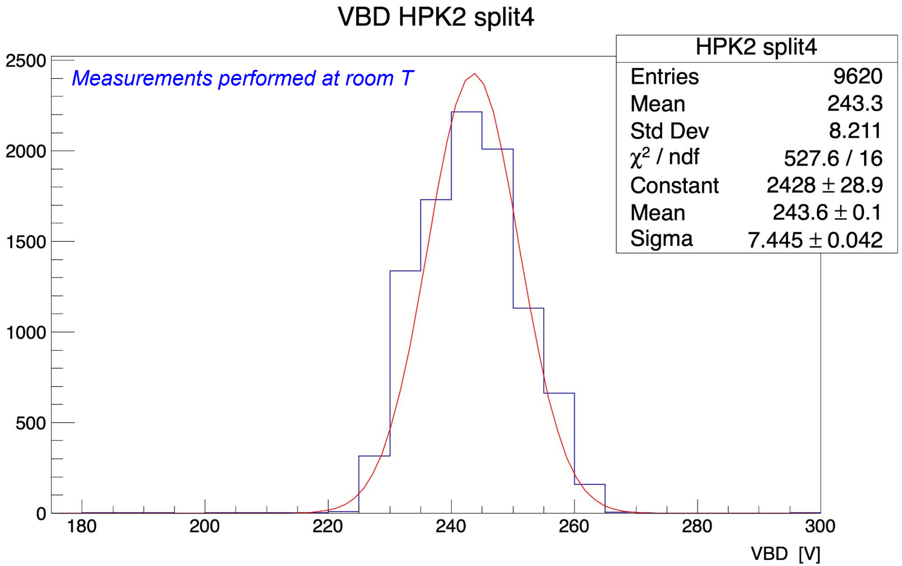
- To fully exploit the k-factor method, we will request on-wafer IVs with a variable voltage step size:
  - We require fine steps (2 to 5 V) from 0 V to full depletion and as close to the BD.
  - 10 V steps are suitable in the intermediate region

SQC Parameter 1: VBD → requirements

- For a given vendor, the VBD distribution (@ room T) is computed over a large statistics of sensors
  - **Sensors going in BD outside μ ± 3σ will be rejected,** where μ, σ are the mean and the std. deviation of the distribution
- We will use pre-production data to fine-tune this acceptance range



An example of VBD distribution, from the HPK2 production (on-wafer tests on single pads, room T)

SQC Parameter 2: Leakage Current

- For the sensors leakage current check:
  - An **upper limit I** $_{\mathbf{MAX}}$ is set on the total sensor leakage current (all pads + guard-ring at room T)
  - The maximum voltage of operation $\mathbf{V}_{\mathbf{MaxOp}}$ is defined as the voltage up to which the *sensor noise* ~ *electronics_noise* and no *micro-discharges* are present (see backup for details)

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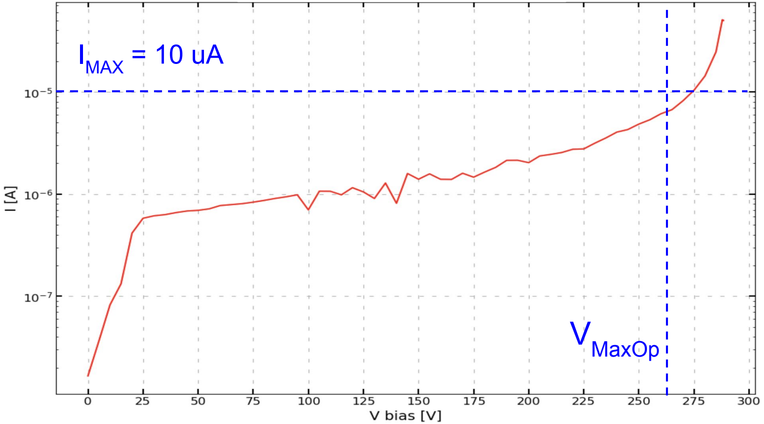
A sensor with $I < I_{MAX}$ up to V_{MaxOp}



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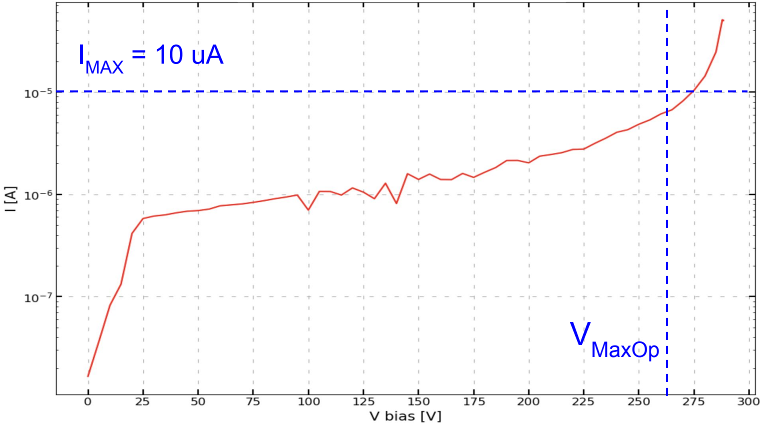
  - If the **leakage current exceeds I_{MAX} at any voltage lower than V_{MaxOp}**, the sensor is **rejected**
- A rough estimate for I_{MAX} based on available sensors:
  - I_{MAX} ~ 10-20 uA for designs with carbonated Gain Layer
  - I_{MAX} ~ 1-5 uA for designs without carbonated Gain Layer



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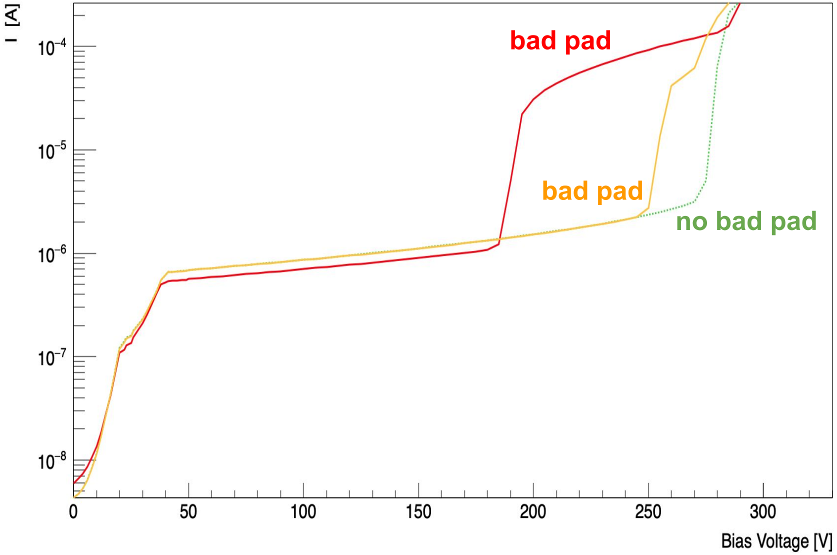

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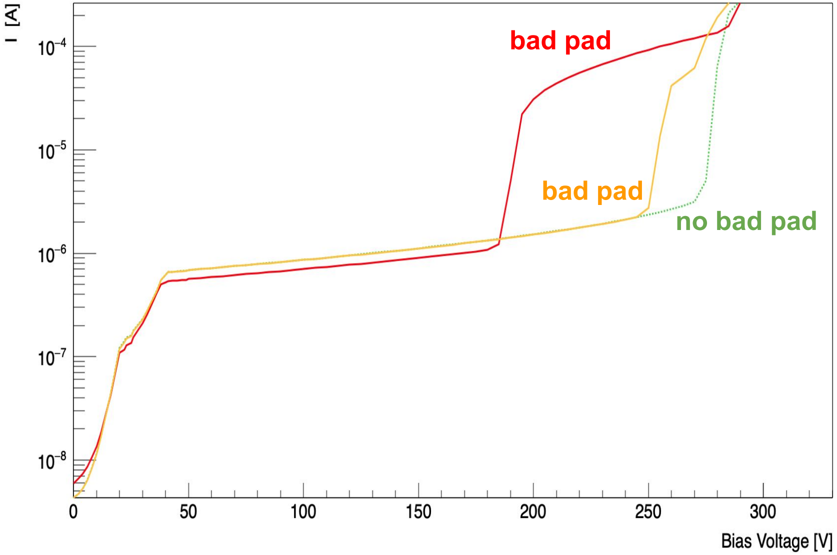

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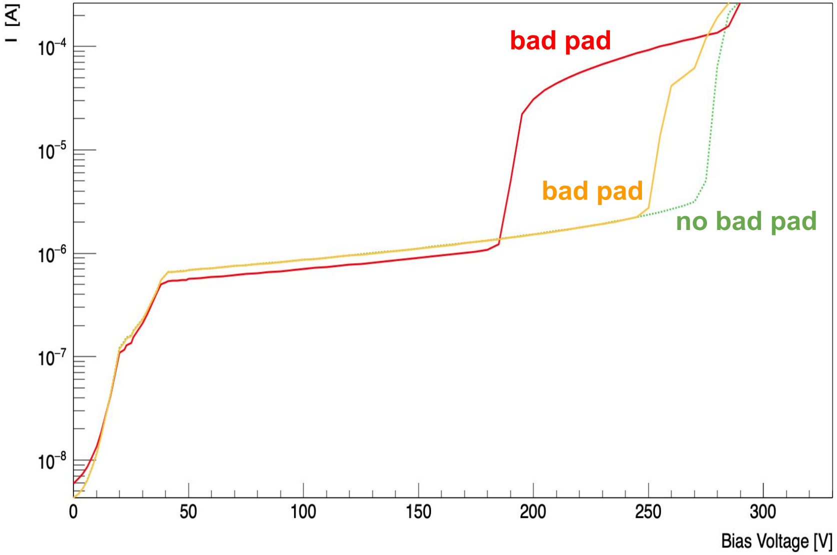

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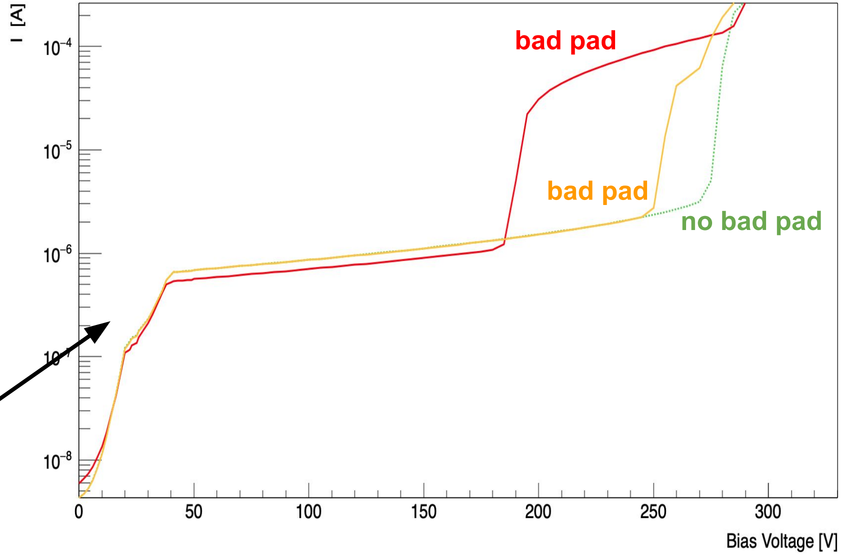
Bad pads can impact the total IV in different ways

- Early BD of the whole array
- BD and current level within specs, but a region of the sensor going in BD earlier



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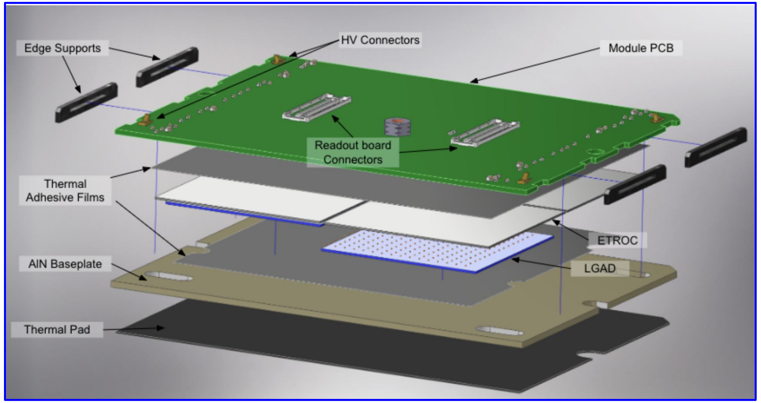

ETL module: Four LGADs bump-bonded to the ETROC ASIC, arranged between the module PCB and a baseplate

Why grouping?

1) LGADs will be assembled in modules (4 sensors/module) on the ETL disks: they will have a common bias voltage line → need to ensure that sensors have a similar doping
2) Modules comprising sensors with a higher doping will be used to instrument regions more exposed to radiations (because of their higher radiation hardness)

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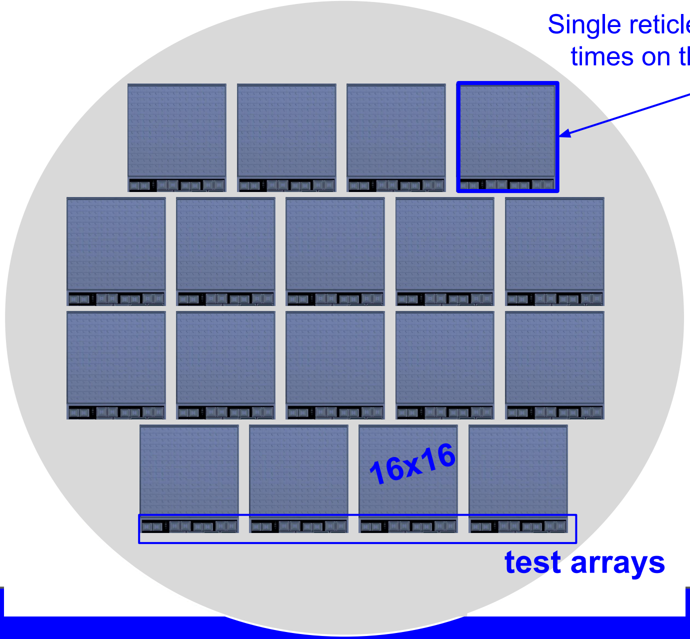

not realistic sketches

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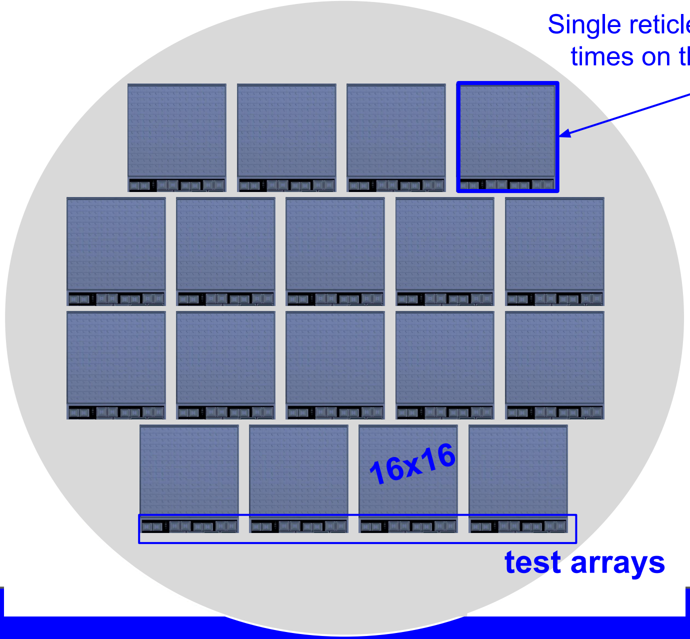
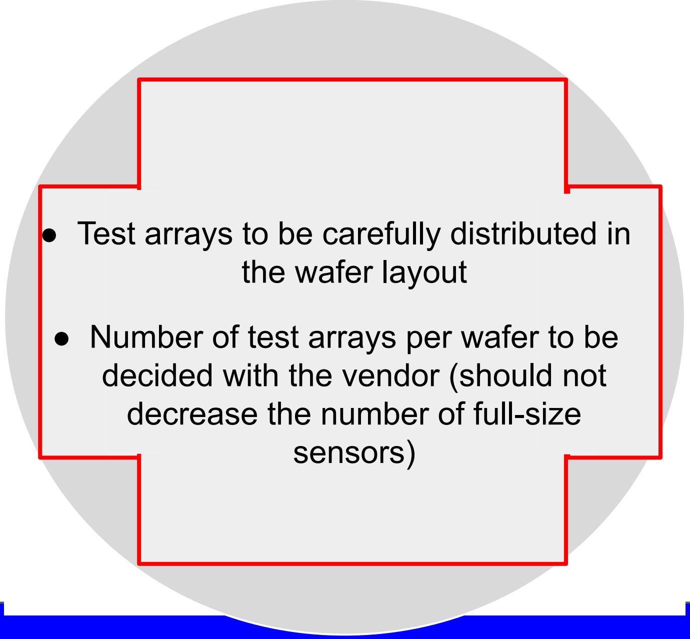
- Straightforward when using a **reticle.** Otherwise, careful placement to be implemented in the **mask layout**



not realistic sketches

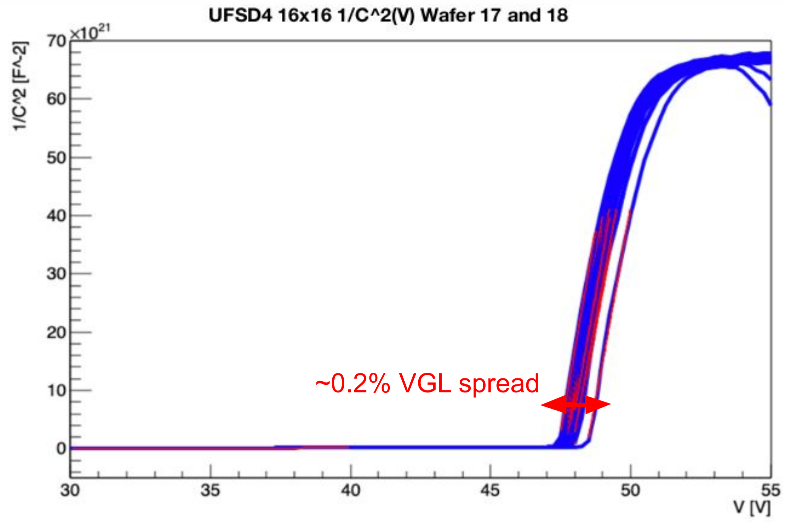


- Test arrays to be carefully distributed in the wafer layout
- Number of test arrays per wafer to be decided with the vendor (should not decrease the number of full-size sensors)

***SQC Parameter 4*: Uniformity of VGL**

- The 16x16 sensors will be distributed over the full wafer area → **we wish to place the test arrays such to closely map the full-size sensors position** (layout will be discussed with vendors)
- Straightforward when using a **reticle.** Otherwise, careful placement to be implemented in the **mask layout**

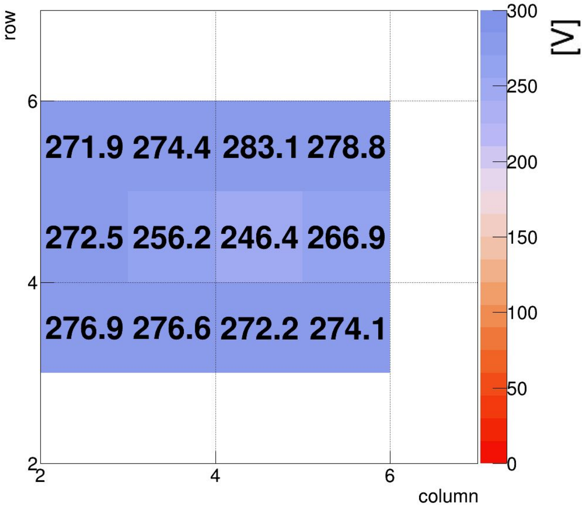
Test structures mapping the wafer in the same way as the 16x16 → **no need to extract VGL from the 16x16 sensors, use the PQC CV results** (from the single LGAD) instead



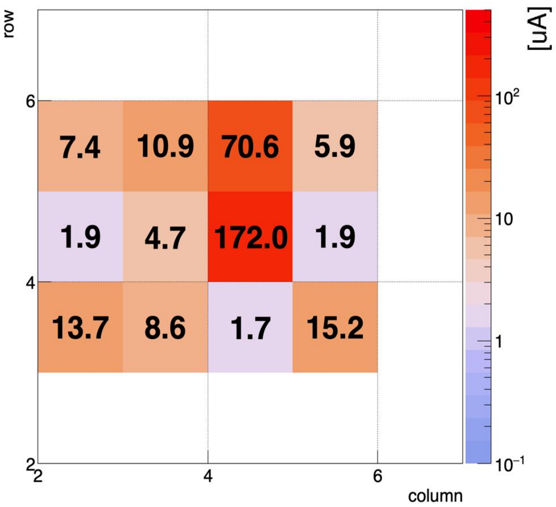
$1/C^2$ vs V tests on two wafers of the UFSD4 production: ~0.2% VGL spread is measured

Outcome of the SQC

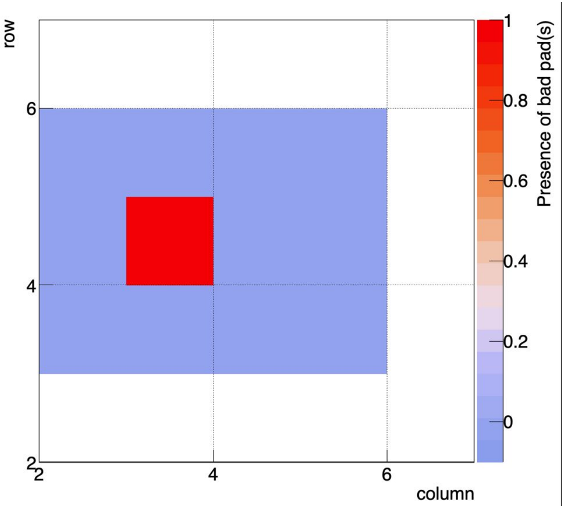
- **The outcome of the SQC will be summarized in the wafer quality maps**:
    - Breakdown Voltage (VBD)
    - Leakage current measured at V_{MaxOp}
    - Presence of noisy pad(s) [0= no noisy pads; 1= presence of noisy pads]



VBD



I @ V_{MaxOp}

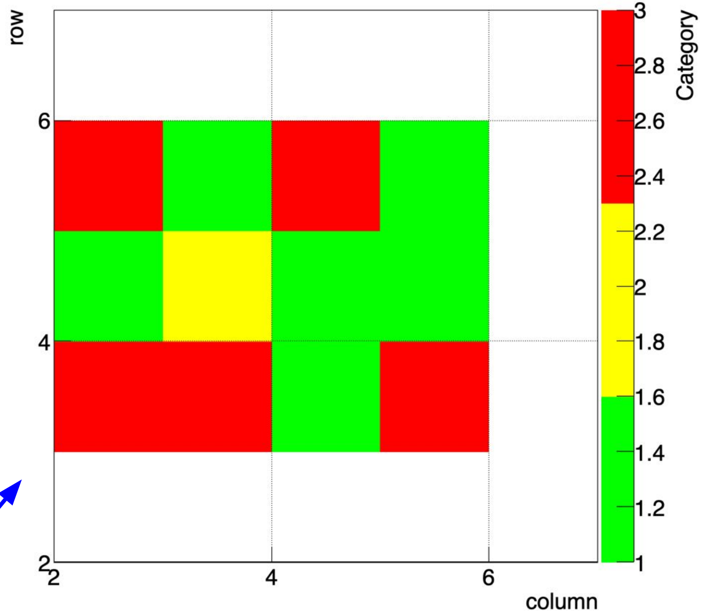


Bad Pad(s)

Sensors categories

Based on the SQC parameters, the 16x16 sensors will be divided into categories, reflecting their quality

- **GOOD:** sensors working as expected, all parameters within acceptance ranges
- **BAD:** sensors with one or more parameters out of acceptance ranges
- **MEDIUM:** Breakdown and leakage current level within specifications, but a bad pad is present
    - Only a very small fraction of the 16x16 will fall into this category: a bad pad usually causes the sensor to be tagged as BAD



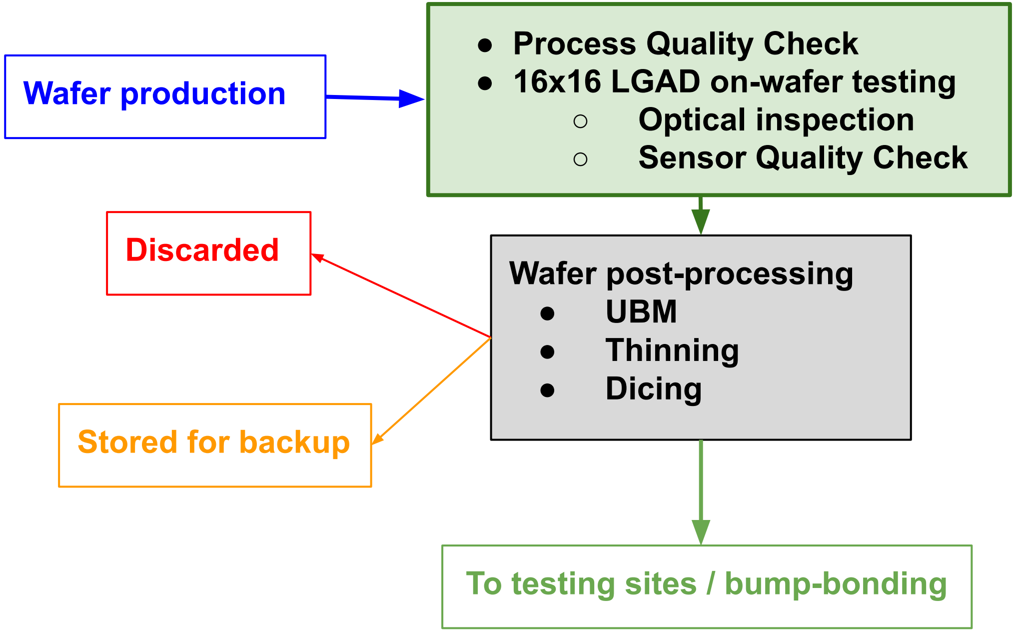
Categories will be summarized in the wafer quality map

(this map for illustrative purposes only, not realistic)

Sensors categories

After the wafer post-processing:

- **GOOD** sensors will be grouped according to their VGL and will go to testing sites / bump-bonding
- **BAD** sensors will be discarded
- **MEDIUM** sensors will be stored for backup or further investigations



Wafer production

- **Process Quality Check**
- **16x16 LGAD on-wafer testing**
  - **Optical inspection**
  - **Sensor Quality Check**

Wafer post-processing
- **UBM**
- **Thinning**
- **Dicing**

Discarded

Stored for backup

To testing sites / bump-bonding

Summary & Outlook

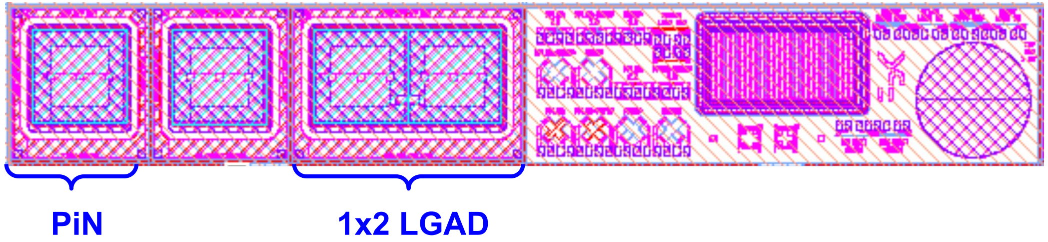
- ETL will be installed in the CMS detector during HL-LHC, providing accurate timing of charged tracks for the entire lifetime of the detector
- **ETL will be made of 16x16 pad array LGADs** → the first production sensors will be ready in 2025
- **We need to test ~35k LGADs and ensure their quality and performance!**
- **That's the purpose of the QA/QC procedures described in this presentation:**
    - In the PQC phase, test structures will be used to check the quality of the process steps and the gain implant
    - During the SQC, the breakdown voltage and leakage current of the 16x16 will be measured, checking also for the presence of bad pads
        - All the **above parameters can be extracted from a total IV** (256 pads + guard-ring grounded)
    - Qualified sensors will be grouped based on their gain layer doping and will be used in the further steps
        - **Grouping based on CV** tests performed during the PQC **on single LGADs**
- After post-processing, a fraction of diced sensors will be re-tested at the testing sites → QA/QC procedures for this step to be finalized soon!

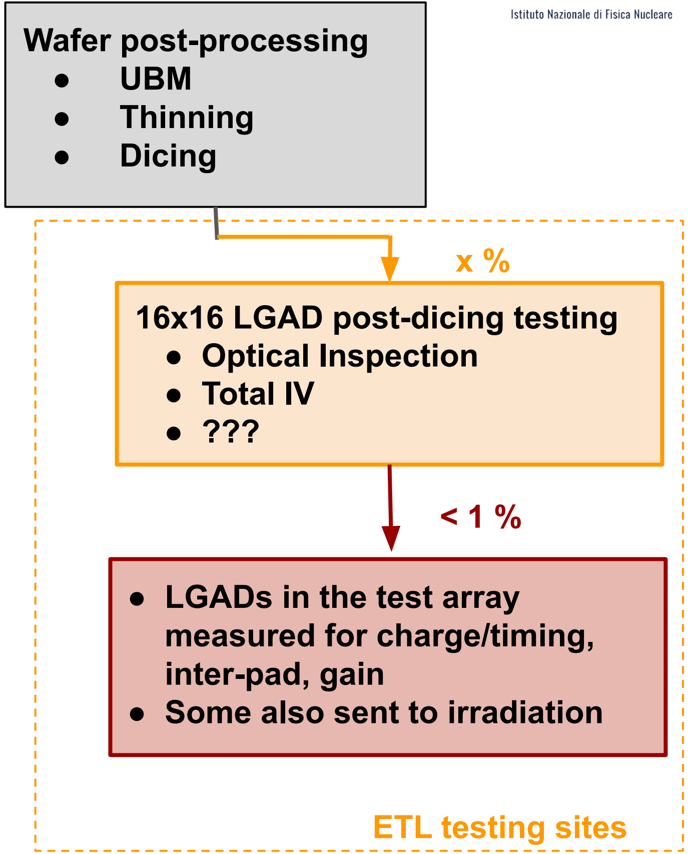
Thank You!

BACKUP

Test array

- The test arrays will also include structures for the QA/QC at the testing sites (*not covered in this talk*) :
    - 1x2 LGAD array: inter-pad width (TCT)
    - LGAD-PiN pair: gain curve (TCT) and charge/timing performance
- Only a small fraction of the test arrays (<1%) will be tested
- A subset will be sent to irradiation and re-tested afterwards





Wafer post-processing
- **UBM**
- **Thinning**
- **Dicing**

x %

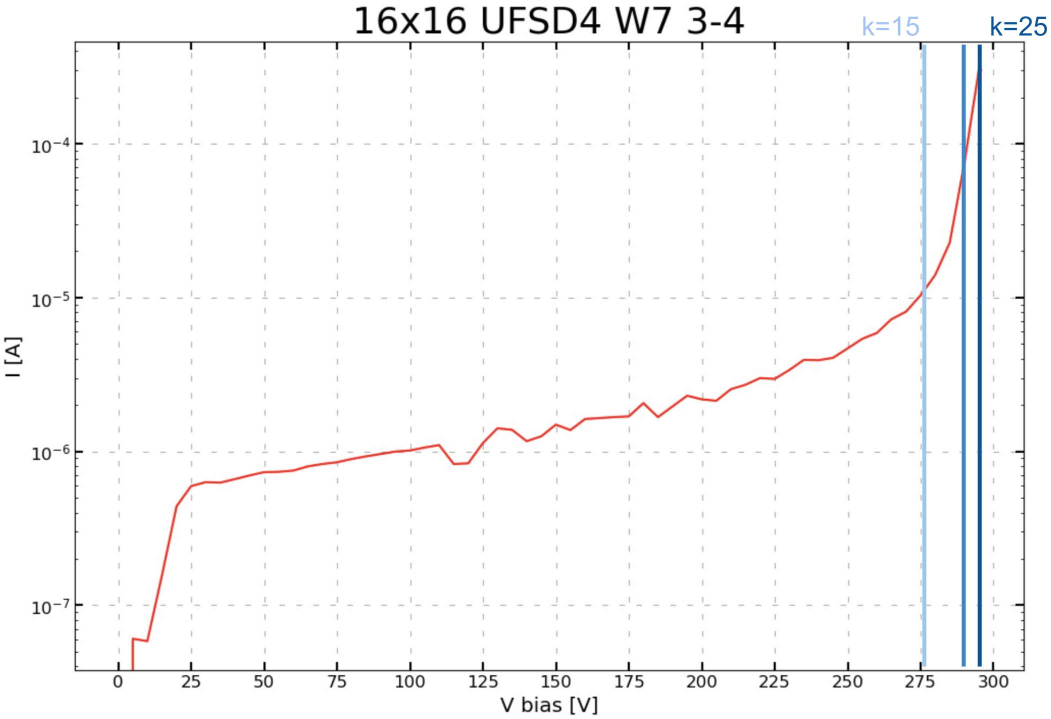
16x16 LGAD post-dicing testing
- **Optical Inspection**
- **Total IV**
- **???**

< 1 %

- **LGADs in the test array measured for charge/timing, inter-pad, gain**
- **Some also sent to irradiation**

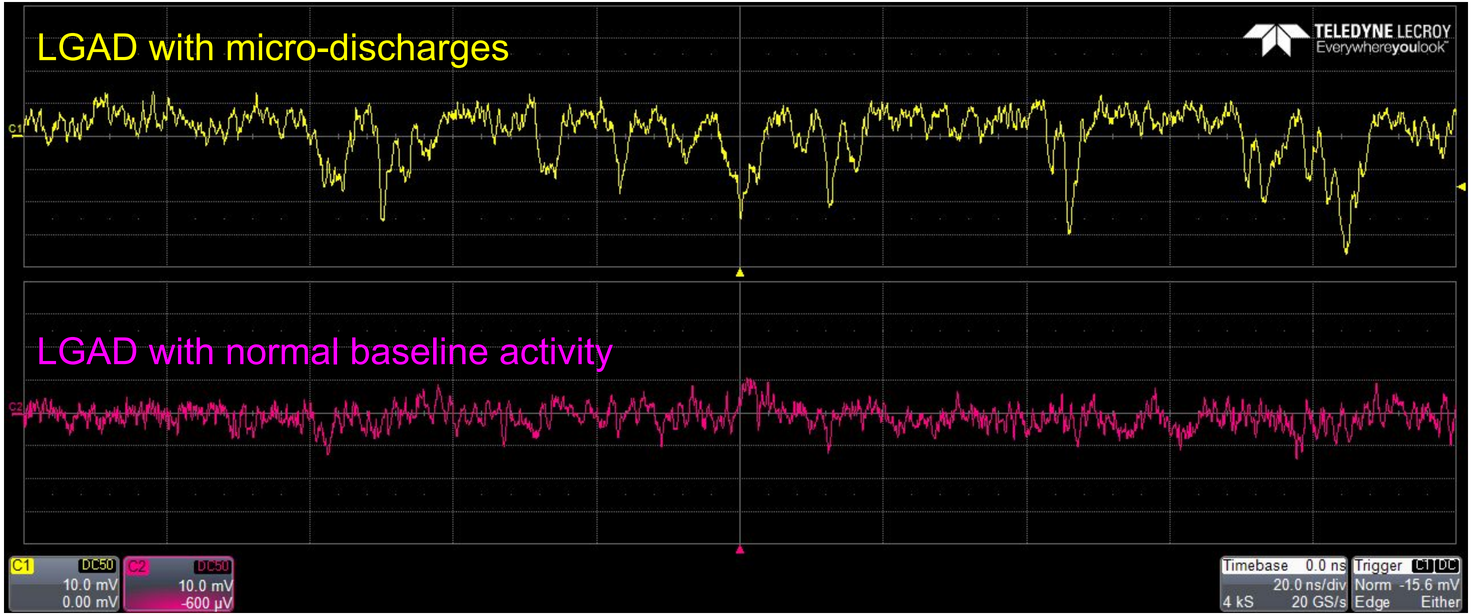
ETL testing sites

SQC Parameter 1: VBD → an example



- VBD as measured by different k thresholds
- k = 15, 20, 25
- VBD goes from ~275 V (k=15) to ~ 295 V (k=25)

Micro-discharges



C1 DC50 10.0 mV 0.00 mV

C2 DC50 10.0 mV -600 µV

Timebase 0.0 ns 20.0 ns/div 4 kS 20 GS/s

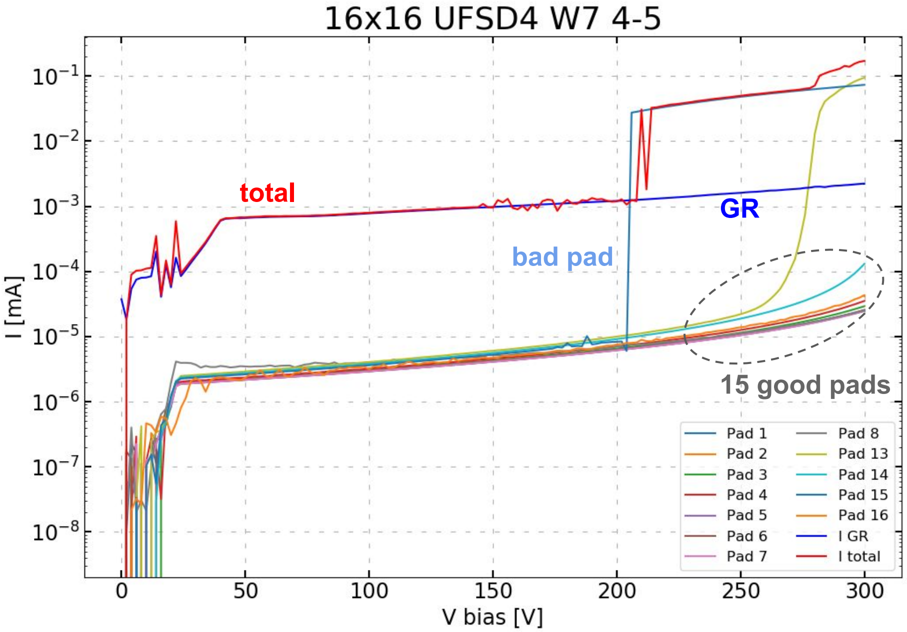
Trigger C1 DC Norm -15.6 mV Edge Either

- In LGAD arrays with a correct design of the inter-pad region, micro-discharges are observed a few Volts before breakdown
- Sensors cannot be reliably operated when the micro-discharges show up

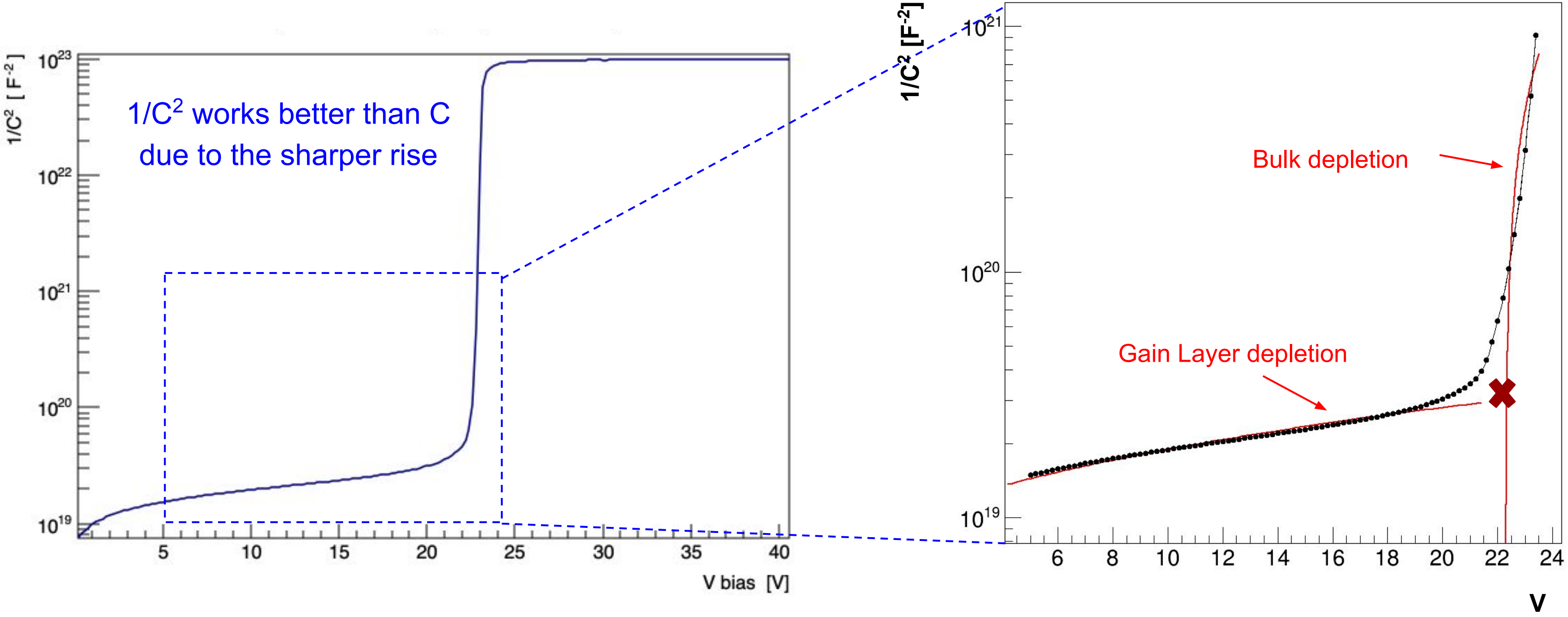
SQC Parameter 3: Bad pads

Effect of a bad pad in a 16x16

- In this test, we measured the total current, the guard-ring (GR) and the 16 pads of a column, one of which is bad
- The total current is determined by the bad pad, while good pads have the expected IV
- This sensor shows very high current much before V_{MaxOp} and early BD → would be rejected

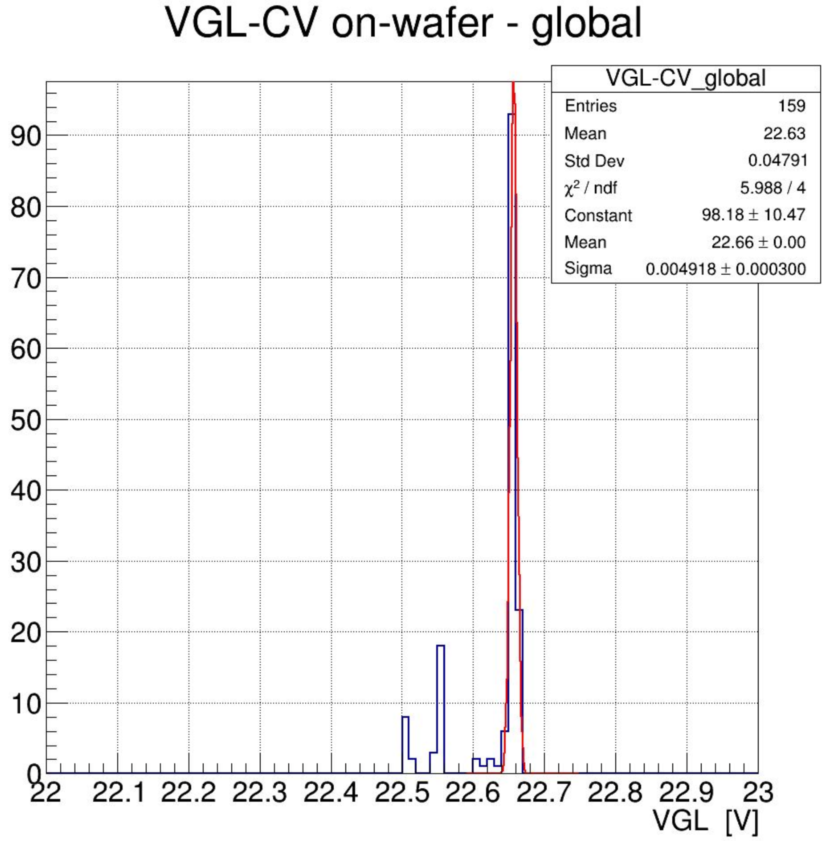


SQC Parameter 4: Uniformity of VGL


1/C^2 works better than C due to the sharper rise

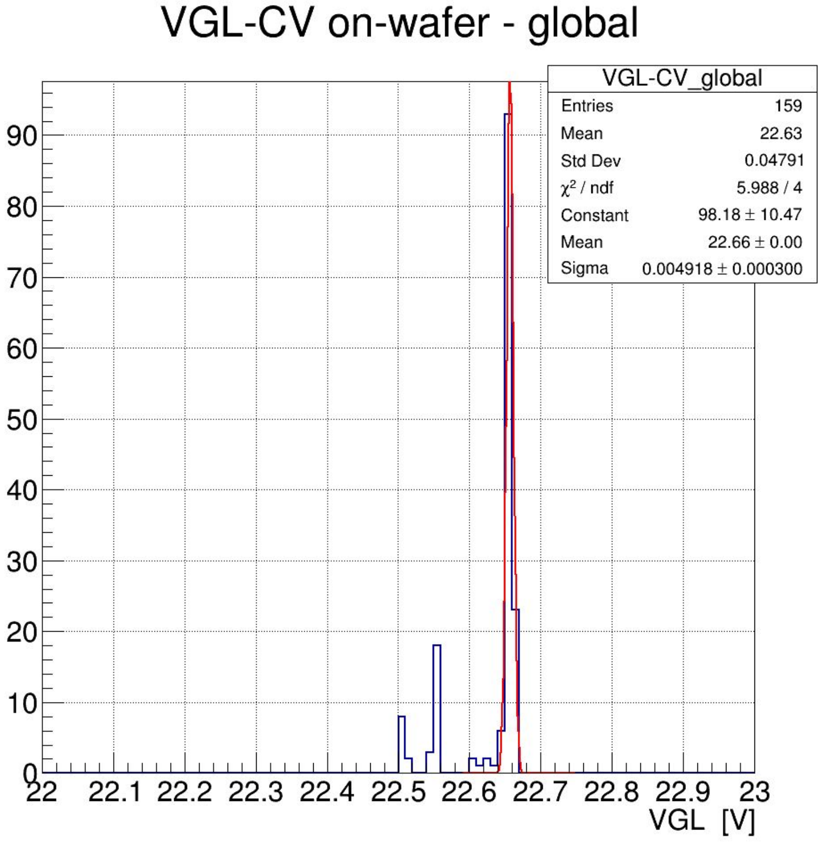
VGL will be measured on the single LGAD with a standard method: intercept of two linear fits on the 1/C^2 curve

***SQC Parameter 4*: Uniformity of VGL**



- Relative uncertainty on the VGL extraction method, σ/μ = 0.02%
- This result was achieved by measuring many times the pads of a single 16x16 LGAD, to rule out the contribution from doping non-uniformity

SQC Parameter 4: Uniformity of VGL



- Relative uncertainty on the VGL extraction method, σ/μ = 0.02%
- This result was achieved by measuring many times the pads of a single 16x16 LGAD, to rule out the contribution from doping non-uniformity

➢ Given its very low relative uncertainty, this method allows distinguishing sensors with a 1-2% doping difference

➢ **By performing a CV on the test structures, we can group the 16x16 based on their doping**