# Update on the ATLAS ITk Silicon Strip Sensors – Pre-production experience


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(on behalf of the ATLAS ITk Strip Sensor working group)

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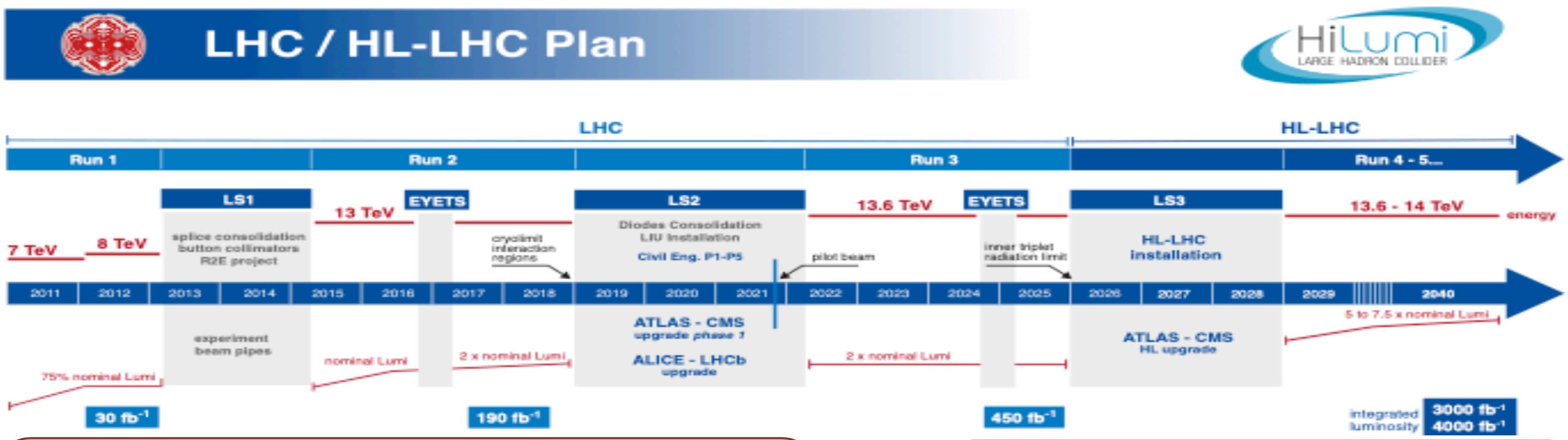
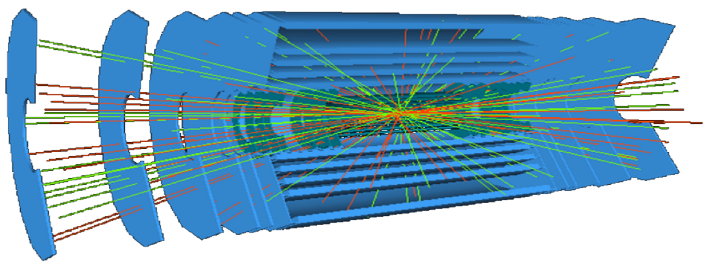
SFU
TRIUMF

# LHC Upgrades

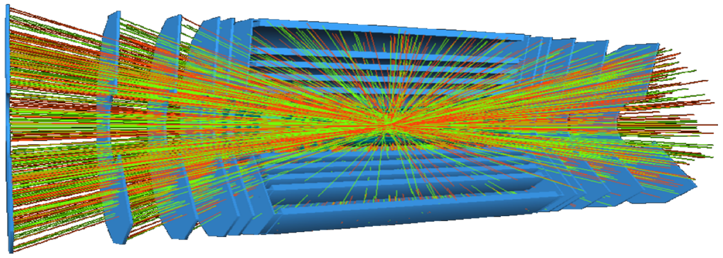



**Inner Detector:** TRT (gas detector) + Strips + Pixels (with new Insertable B-Layer)

**Phase 2:** all-silicon detector (Strips + Pixels)

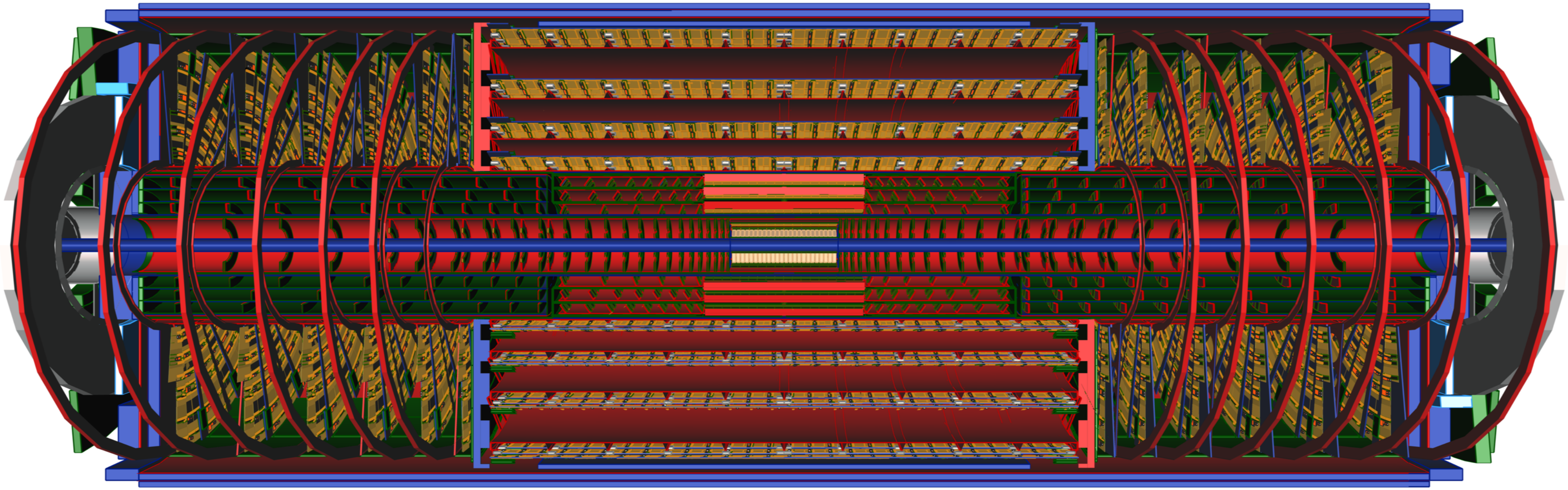


LHC: 19 → 55 pileup events



HL-LHC: 140 → 200 pileup events

# The New Inner Tracker (ITk)



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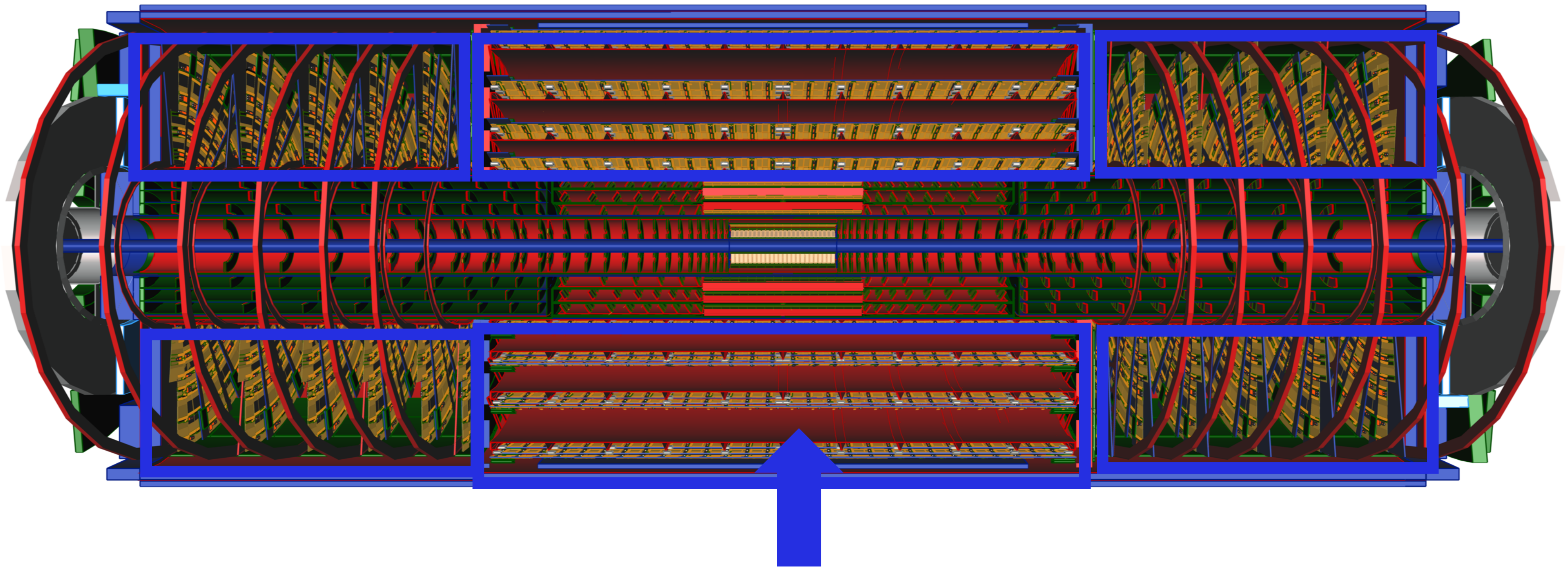


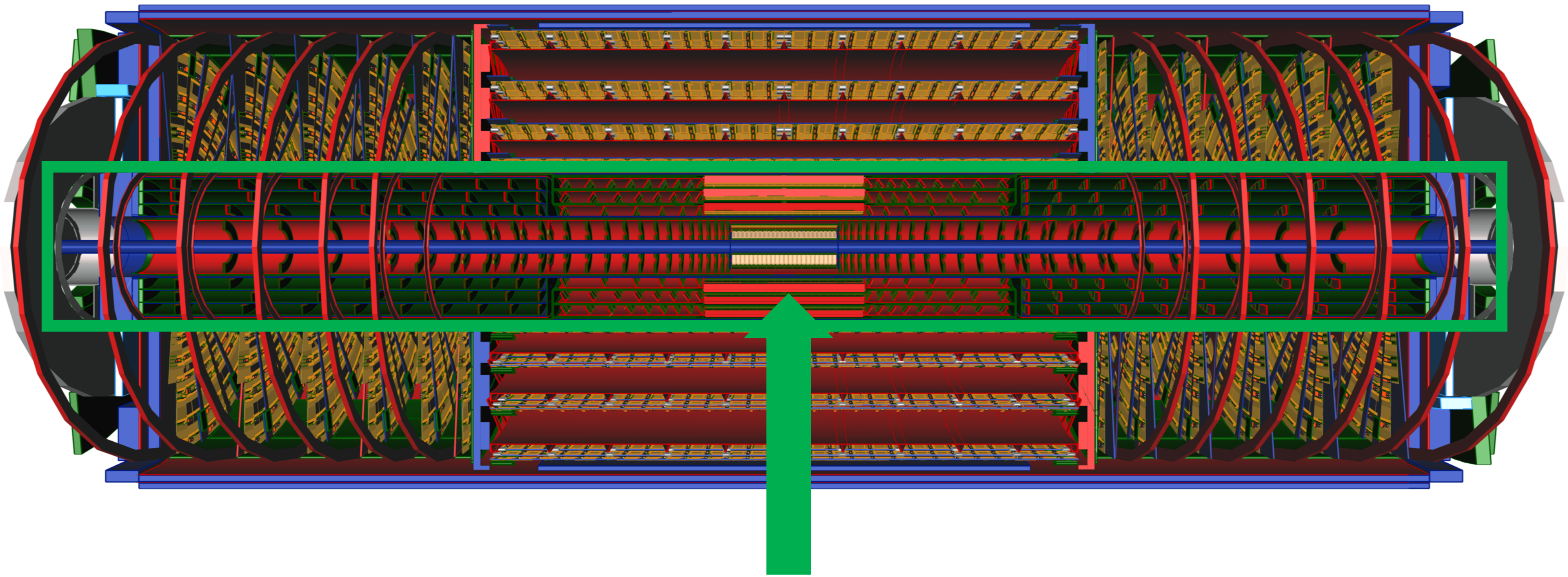
**New Strip System**

~165m$^2$ of silicon

17888 modules

~60 Mega-channels

# The New Inner Tracker (ITk)



**New Pixel System**

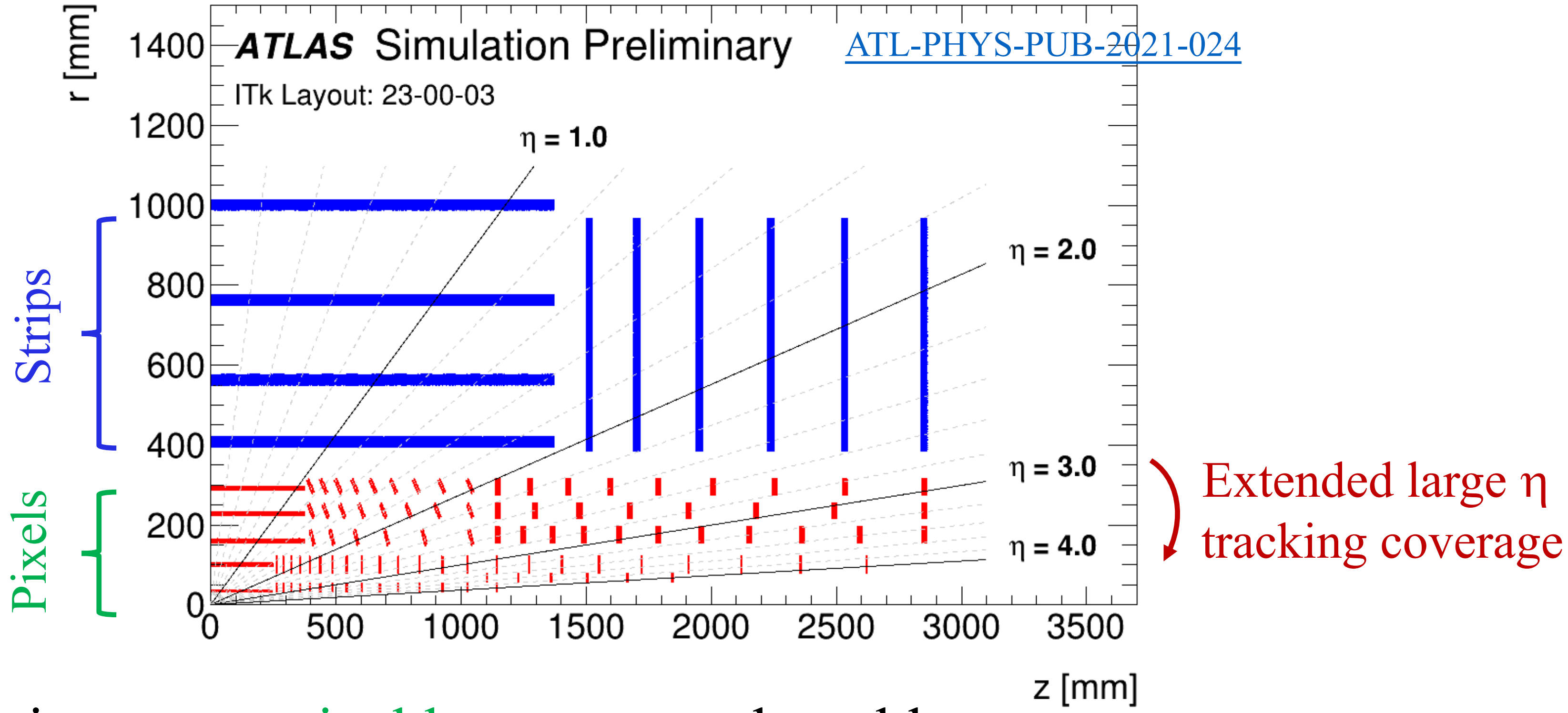
~13m$^2$ of active area

9400 modules

~1.4 Giga-channels

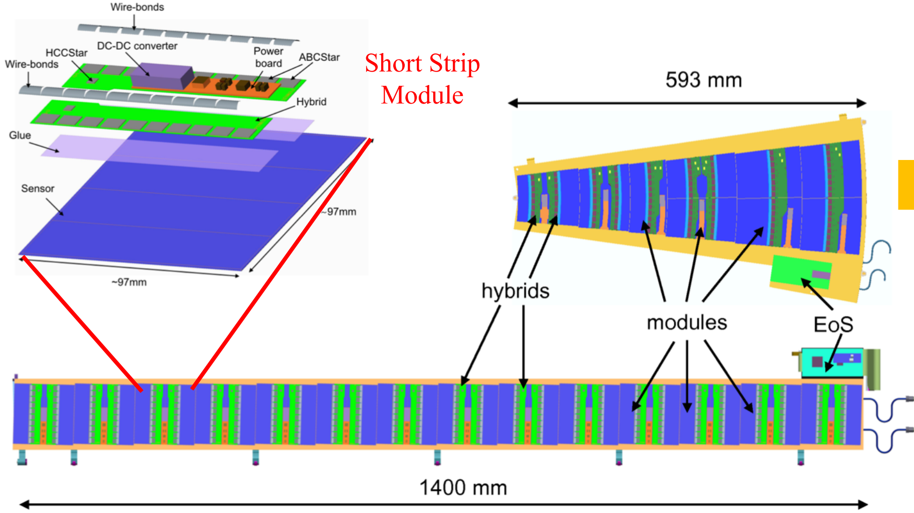
# The ITk Layout

- 4 strip and 5 pixel (flat + inclined) barrel layers
- 2×6 strip disks and a novel pixel ring structure
- Coverage up to η=4 with at least 9 space-points per track

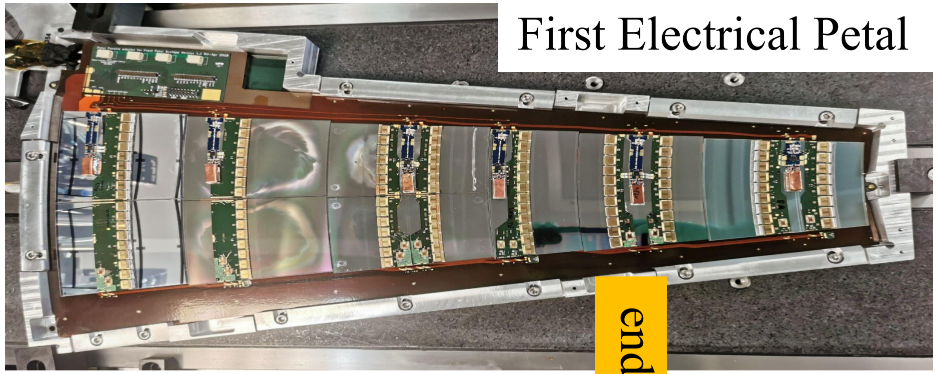



The two innermost pixel layers are replaceable
(reduce radiation damage)

# ITk Strips Components



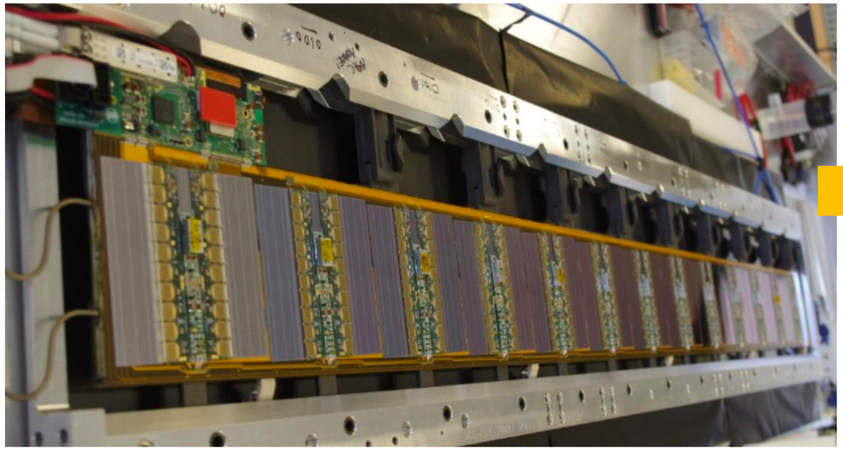

**End of Substructure (EoS)** card: handles data, clock, trigger, power

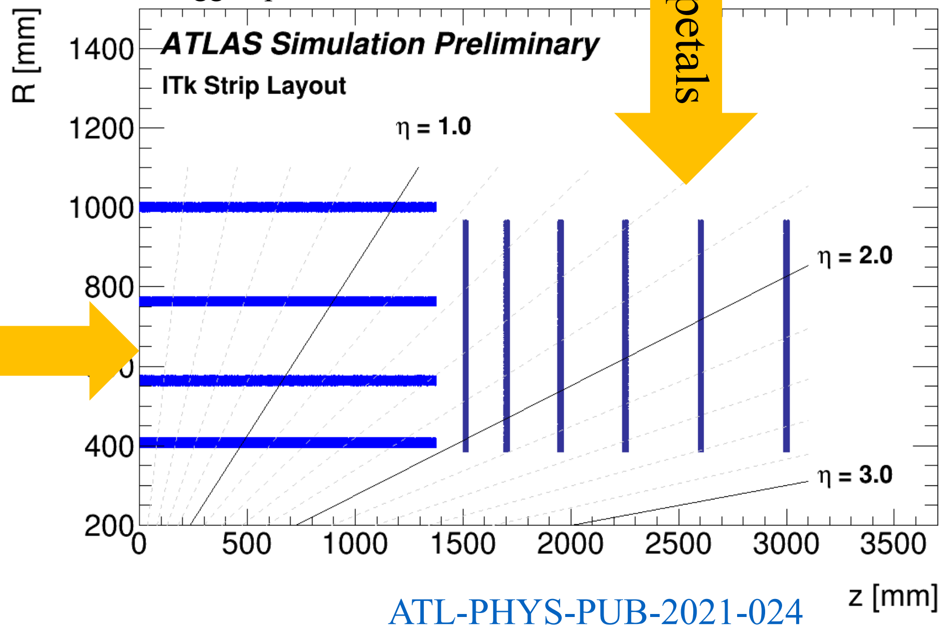


First Electrical Petal

endcap petals

## Barrel Stave



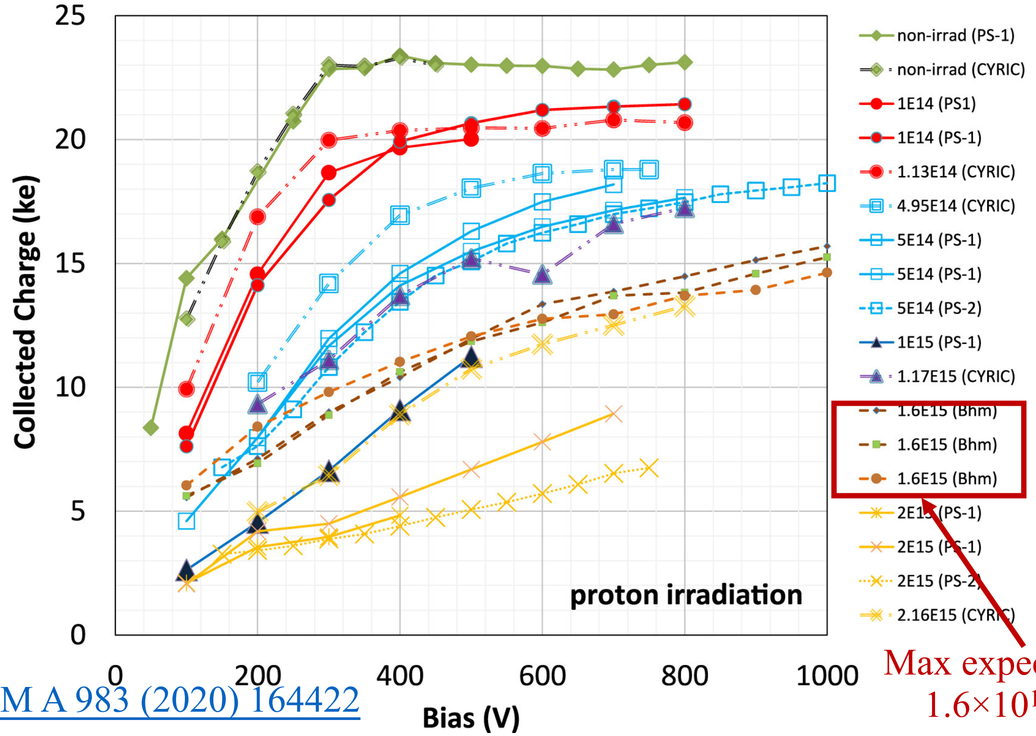



ATL-PHYS-PUB-2021-024

# ITk Strip Sensors

## 8 sensor geometries:

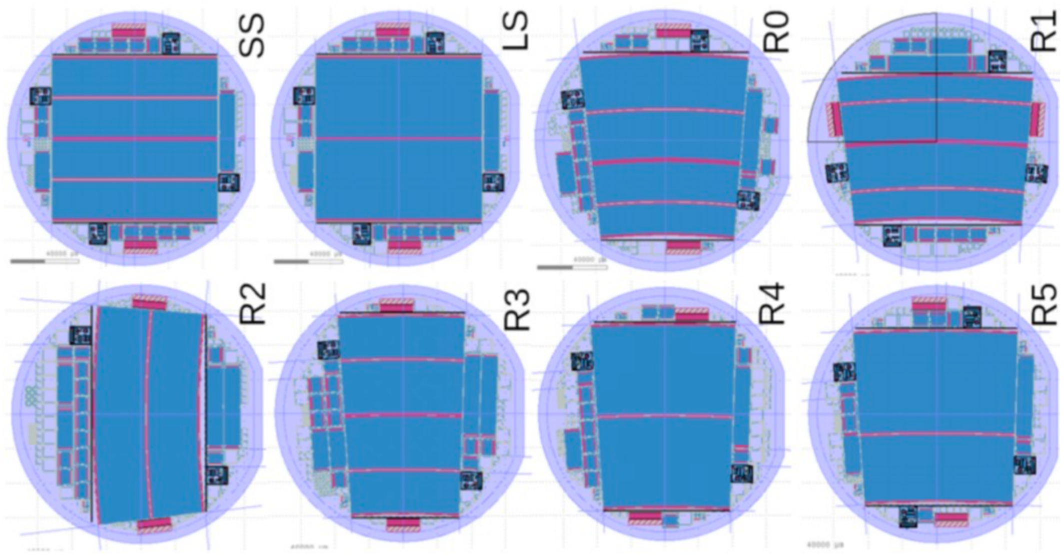
- 2 for barrel, 6 for endcaps
- 320µm thick n-in-p silicon
- 75.5µm strip pitch (**barrel**)
- 70µm – 80µm pitch in **petals**
- One sensor per wafer
  - Surrounded by test structures
- High reverse bias voltage (-500V)

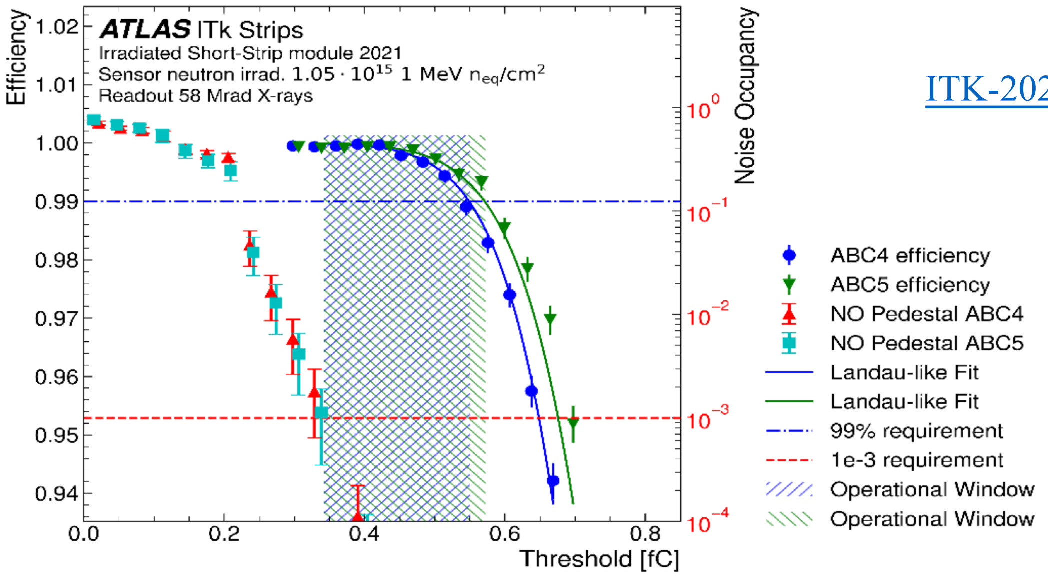



Max expected + safety
$1.6\times10^{15}$ $n_{eq}/cm^2$

NIM A 983 (2020) 164422

SS, LS are barrel, R# are end-cap




ITK-2021-003

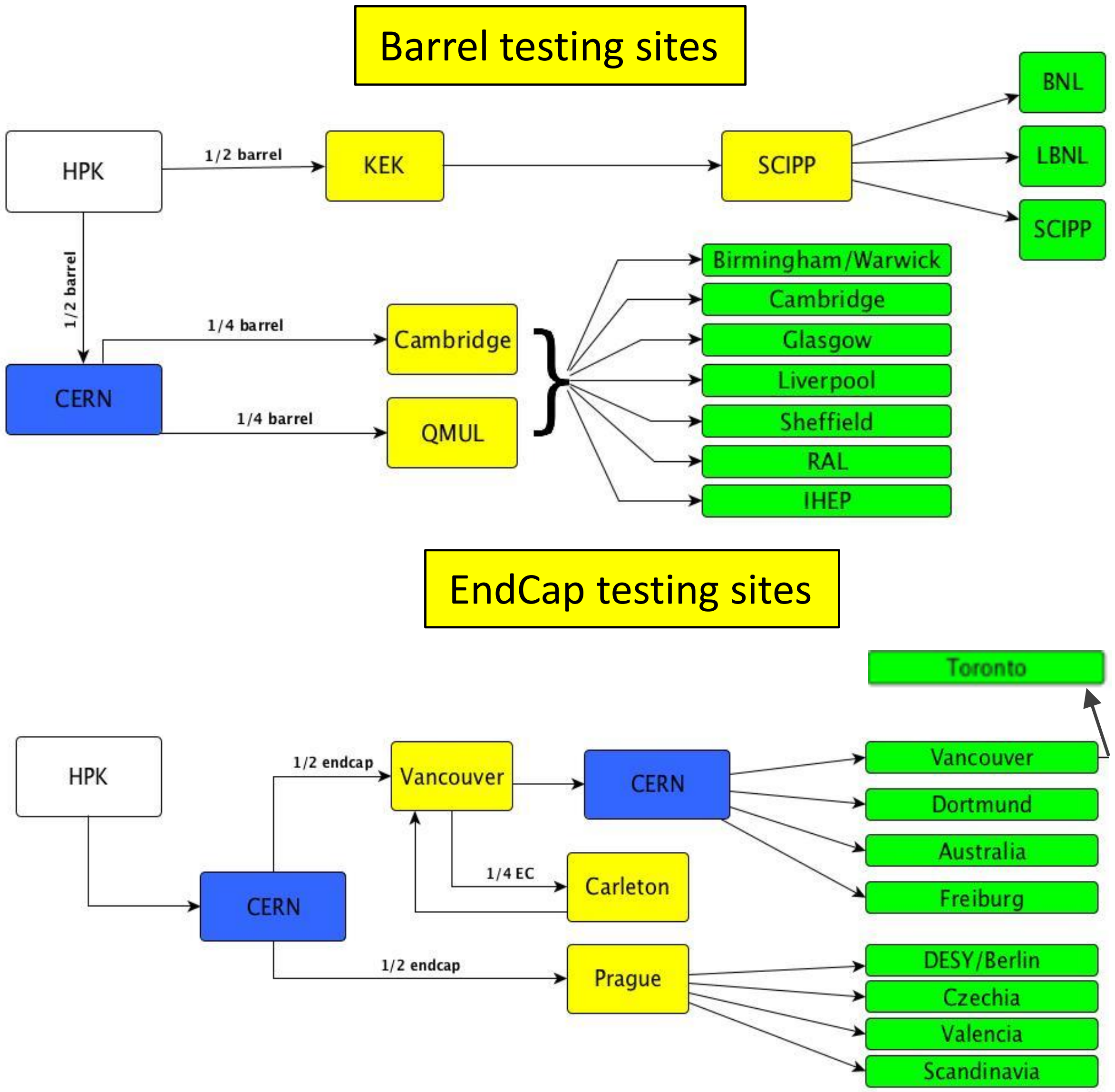
# Strip Sensor QC

## QC sensor tests

- **<u>Tests on every sensor</u>**
  - Human visual inspection (Vis. Insp.)
  - Machine visual capture (Vis. Cap.)
  - Metrology (sensor bow and thickness)
  - IV and CV
- **<u>Tests on sample sensors (2% - 10%)</u>**
  - Leakage current stability (Curr. Stab.)
  - Full strip tests (Full Str.)
  - Detailed strip tests

## QC sensor test sites

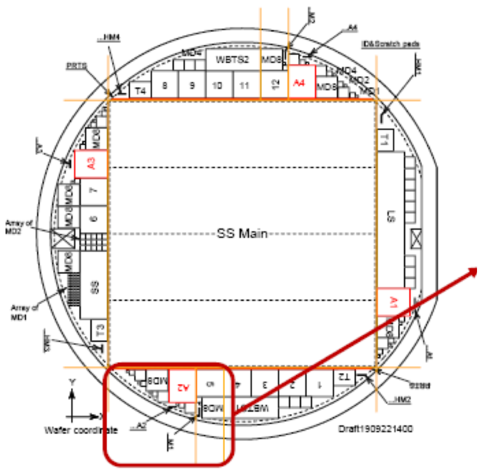
- **<u>Barrel sensors</u>**
  - KEK/Tsukuba
  - SCIPP
  - Cambridge U.
  - QMUL
- **<u>Endcap sensors</u>**
  - Prague
  - TRIUMF/SFU
  - Carleton

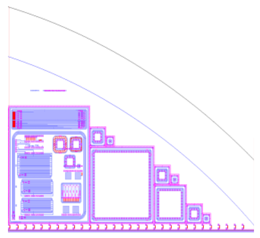


# Strip Sensor QA

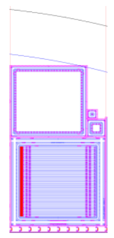
- Quality Control (QC)
  - Checks the fulfilment of the ATLAS specifications with tests on main sensors
- Quality Assurance (QA)
  - Monitors the fabrication process to detect deviations and predict tendencies of key parameters
  - Performed on test structures: minis, testchip, diode
  - Tests can be destructive: irradiations

- QA test pieces:
  - ➢ Mini
  - ➢ Testchip
  - ➢ MD8



''Testchip&MD8'

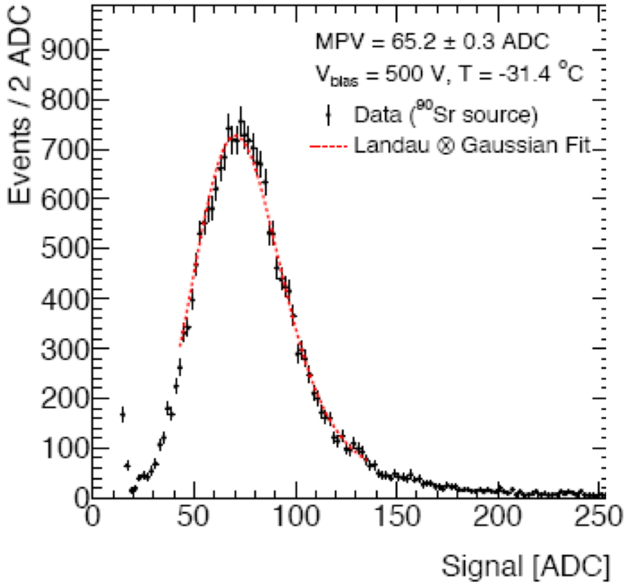


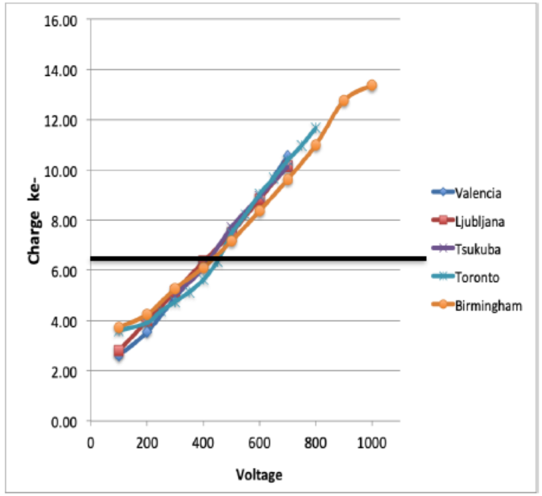
'Mini&MD8'

Irradiation plan:

- From every wafer one Testchip&MD8 and one Mini&MD8 are diced
- From every batch at least:
  - ➢ One Mini+MD8 is irradiated for displacement damage (protons or neutrons)
  - ➢ One Testchip&MD8is irradiated for ionization damage (proton or gamma)

neutrons 1.6 $10^{15}$ $n_{eq}cm^{-2}$




## QA-CCE measurements

- Irradiated mini sensors are tested after annealing for 80 minutes at 60° C
- Measurement of CCE as response to a 90Sr β-source

## QA-Testchip measurements

Direct measurement of key technological and device parameters with several test structures: Quality of field and coupling oxide, Interstrip properties, Resistivity of conductive layers,…

# Pre-production Strip Sensor QC

**List of deliveries and distribution**

- Production sensors (Barrel + Endcap): 20800
- Pre-production (5% of production): 1041
- 1016 sensors to QC sites, 25 sensors reserved for specific tasks (e.g. irradiation)
- Additional pre-production barrel sensors (prototype): 60

| | 2020-11-23 | Shipment weeks in 2020 and quantities | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Order | Calendar week | 2 | | 6 | | 8 | | 10 | | 12 | | 14 | | 16 | | | | Total |
| | The week of | 06-Jan | | 03-Feb | | 17-Feb | | 02-Mar | | 16-Mar | | 30-Mar | | 13-Apr | | 15-Jul | | |
| | Real (if different) | | | | | | | | | | | 08-Jun | | 08-Jun | | | | |
| KEK | ATLAS18SS | | | | | | | | | 159 | SCP | | | | | | | 159 |
| | ATLAS18LS | | | | | | | | | 159 | SCP | | | | | | | 159 |
| CERN | ATLAS18SS | 0 | | 20 | CAM | | | | | | | 139 | CAM | | | | | 159 |
| | ATLAS18LS | 17 | CAM | 4 | CAM | | | | | | | 138 | CAM | | | | | 159 |
| | ATLAS18SS proto | 14 | CAM | | | | | | | | | 46 | | | | | | 60 |
| | ATLAS18R0 | | | 7 | CRL | | | | | 20 | PRG | | | 18 | CRL | | | 45 |
| | ATLAS18R1 | | | 8 | PRG | | | | | 20 | VAN | | | | | 17 | PRG | 45 |
| | ATLAS18R2 | | | | | 5 | PRG | 25 | CRL | 15 | PRG | | | | | | | 45 |
| | ATLAS18R3 | | | | | 5 | PRG | 25 | CRL | | | 35 | PRG | 25 | CRL | | | 90 |
| | ATLAS18R4 | | | | | 5 | VAN | 15 | PRG | | | 45 | PRG | | | 25 | VAN | 90 |
| | ATLAS18R5 | | | | | 5 | PRG | 25 | VAN | | | 35 | PRG | | | 25 | VAN | 90 |
| | N(sensors) per de | 17 | | 39 | | 20 | | 90 | | 373 | | 392 | | 43 | | 67 | | 1041 |

| QC Cluster | No. |
|---|---|
| UK (CAM+QMUL) | 378 |
| Prague (PRG) | 205 |
| CA (CRL+VAN) | 200 |
| US (KEK+SCP) | 318 |

| | |
|---|---|
| Cambridge | CAM |
| Queen Mary | QMU |
| Prague | PRG |
| Carleton | CRL |
| Vancouver | VAN |
| SCIPP | SCP |

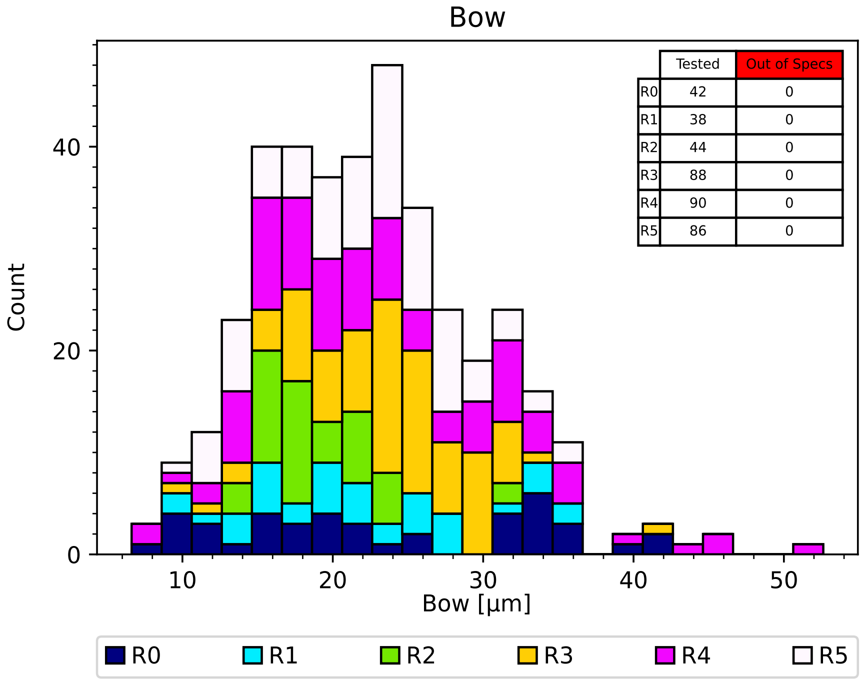
# Examples: Metrology & Visual Capture

**Goal:**

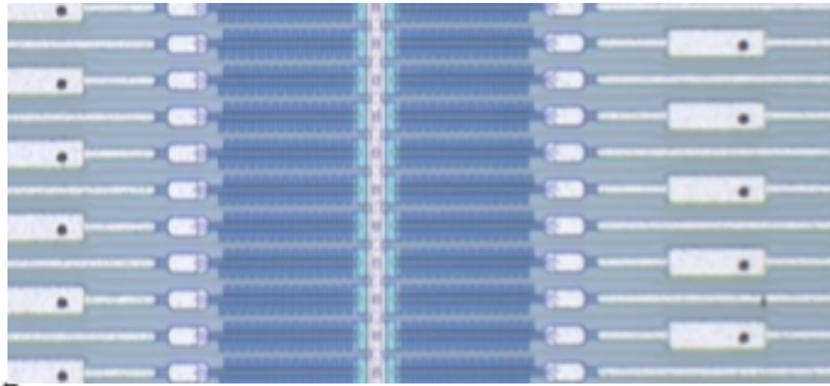
- Verify sensor shape and bow suitable for module building and stave/petal mounting.
  - Bow <200µm, thickness 320µm±15µm
- Provide a detailed snapshot of sensor condition upon arrival

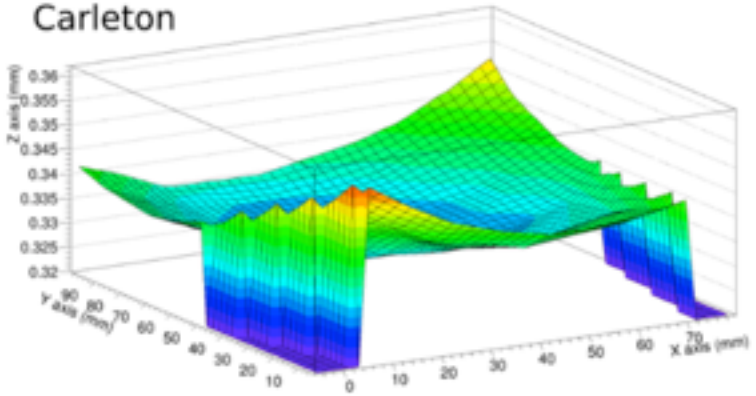
**Requirements:**

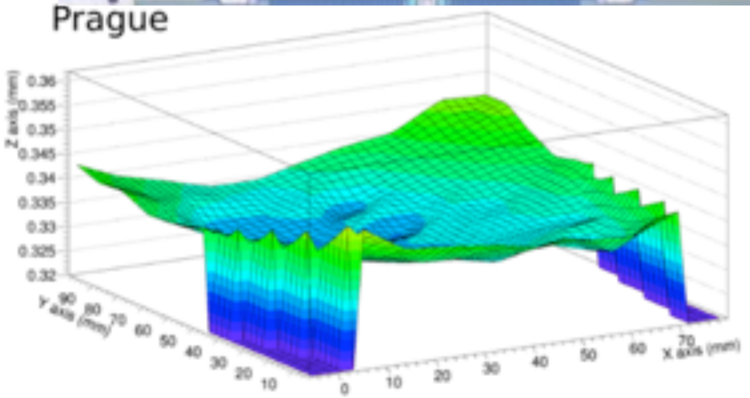
- Non-contact CMM to probe height on matrix of 11x11 points on freely suspended sensor.
  - Resolution: <5µm RMS
- Capable of fully automatic image capture of the entire sensor without intervention
  - Required minimum resolution: 10kdpi (2.54µm/pixel)




| | Tested | Out of Specs |
|---|---|---|
| R0 | 42 | 0 |
| R1 | 38 | 0 |
| R2 | 44 | 0 |
| R3 | 88 | 0 |
| R4 | 90 | 0 |
| R5 | 86 | 0 |





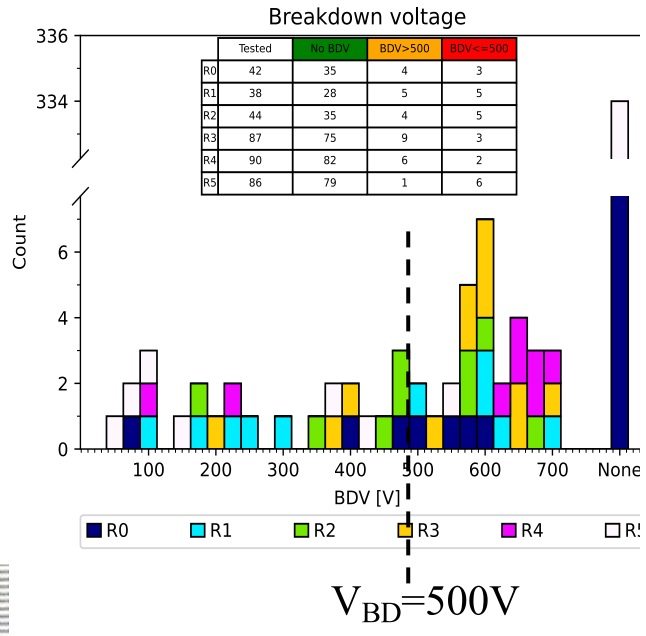
# Examples: IV/CV/Current Stability

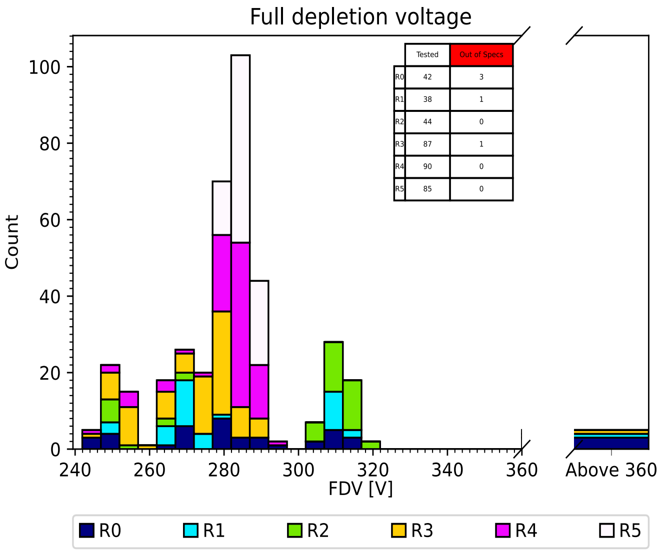
**Goal:**

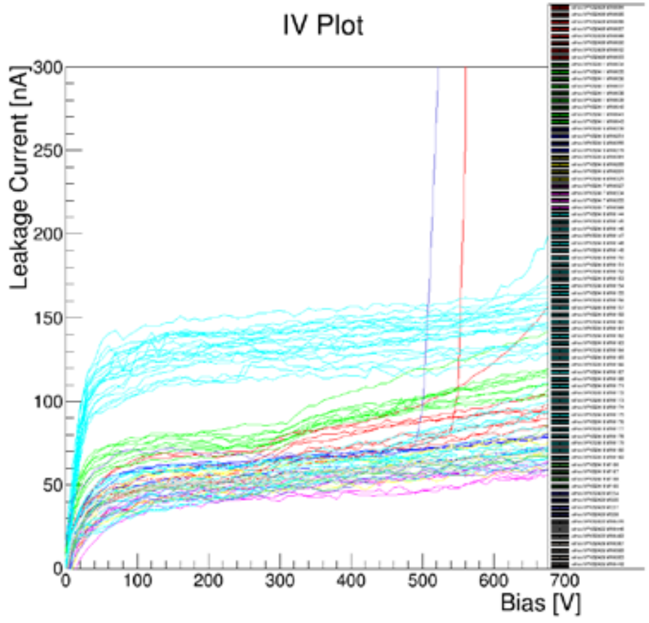
- Verify sensor basic electrical behavior
  - Breakdown voltage >500V
  - Normalized leakage current <100nA/cm$^2$ @500V, 20$^0$C
  - Depletion voltage ≤350V

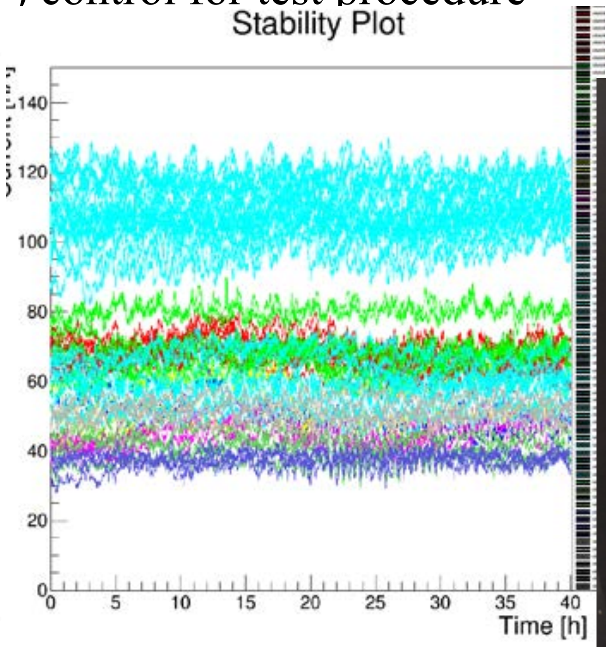
**Requirements:**

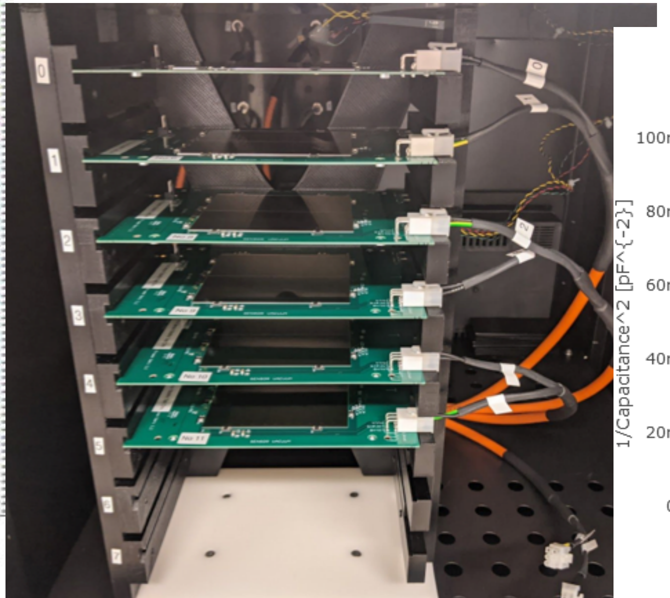
- simultaneous measurement of multiple sensors mounted and wire-bonded on sensor jigs/module frames carried out inside a ESD safe dry cabinet with active control to ensure stable and dry condition
- Automated scripts (LabVIEW) control for test procedure

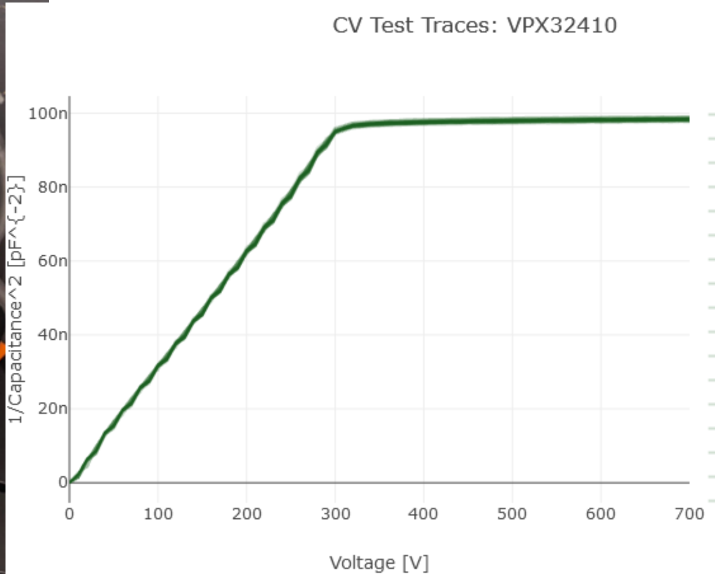


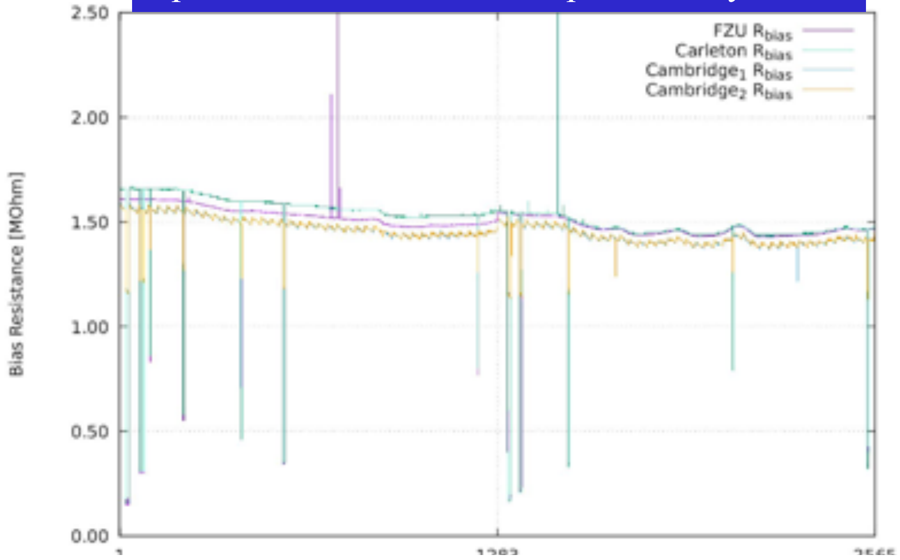


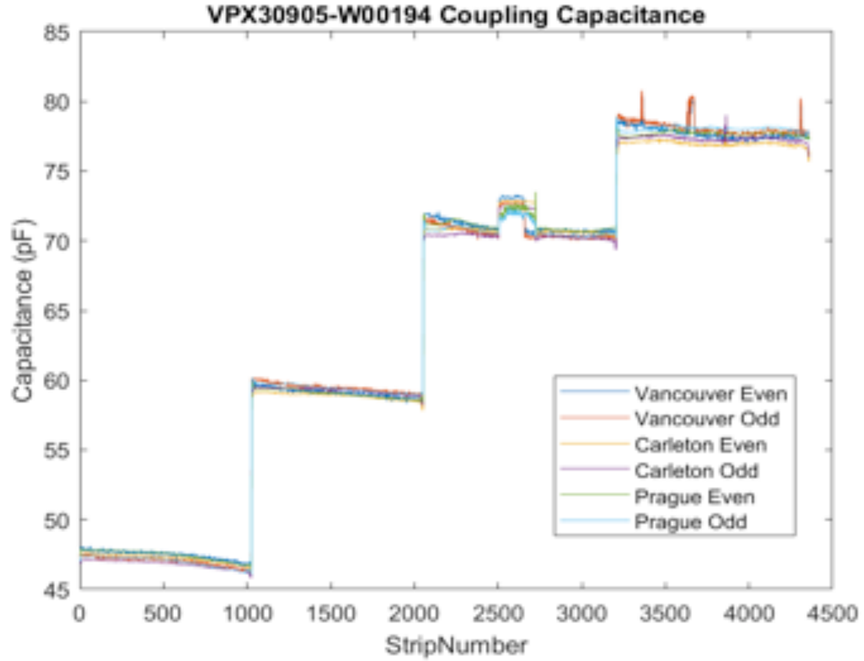
# Examples: Full Strip Test

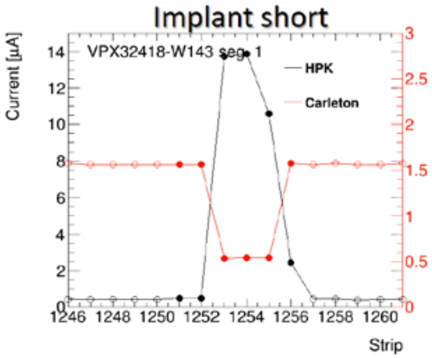
**Goal:**
- Verify the manufacturing process quality and uniformity of electrical characteristics throughout the wafer surface.
- Each individual strip is contacted to identify metal shorts, broken implants, faulty bias resistors or low inter-strip isolation, and pinholes or punch-throughs in the dielectrics.

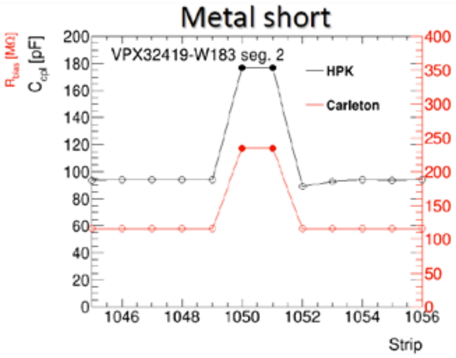
**Requirements:**
- Semi-automatic probe-station, precise SMU's, LCR meter, HV switch matrix and muxes, temperature and humidity monitoring and/or control.
- Automated scripts (LabVIEW) control for test procedure
- Endcap sensors are tested by single needle, for barrel sensors probe card can be used to speed up the test from ~14h, to < 2.5h

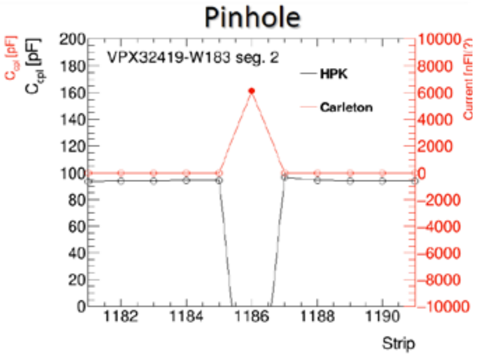
Special sensor with defects provided by HPK

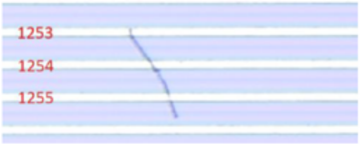




Not visible since a pinhole is expected to be under Al strip

# Pre-production Strip Sensor QC Yield

| Type | Visual Inspection | Metrology | Thickness | IV | CV | Current Stability | Full Strip |
|---|---|---|---|---|---|---|---|
| **Barrel** | 99.7% | 100% | 100% | 98.7% | 100% | 99.6% | 100% |
| **Endcap** | 99.5% | 100% | 99.3% | 96.3% | 100% | 94.8% | 93.3% |
| **Total** | **99.6%** | **100%** | **99.7%** | **97.8%** | **100%** | **98.5%** | **99%** |

- Results after extensive recovery efforts (see following slides)
  - 43 sensors failed the IV test, 20 recovered
  - 10 sensors failed the full strip test (low $R_{bias}$, high $C_{coupl}$), 6 recovered
  - Variety of recovery techniques applied
- Additional 9 sensors failed the leakage current stability test
  - Showed current variations >15%
- 4 sensors failed visual inspection upon arrival
  - 2 sensors with deep scratches, 1 with chipped edge, 1 broken

# Recovery Methods Overview

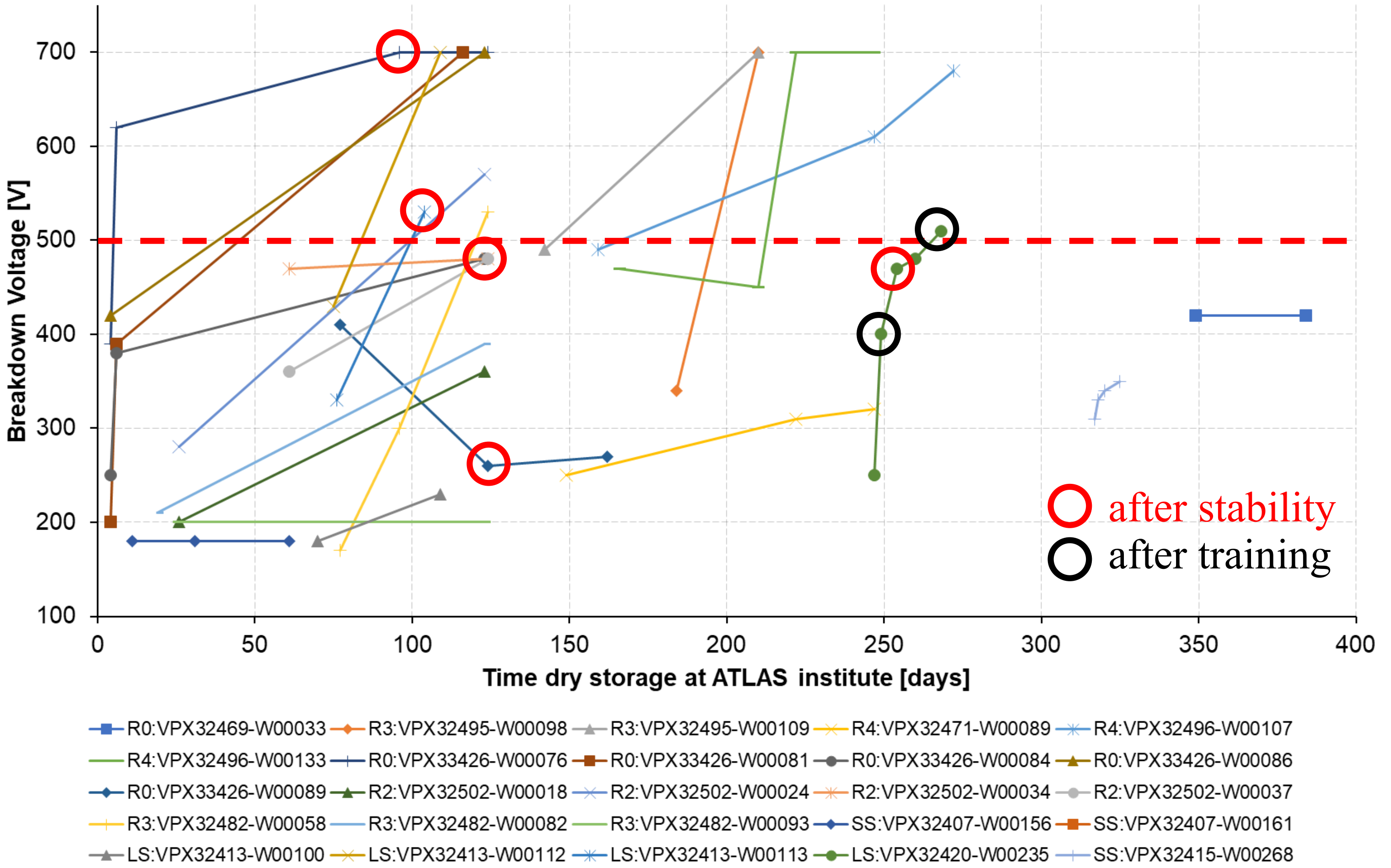
- Effect on performance after sensor dry storage for several months
  - Performed IV tests
- Additionally: bake-out and UV irradiations
- Leakage current stability test also performed, e.g. after dry storage as proxy for sensor training

| Institute | Sensors | Dry Storage | Stability Test | Bake-out | UV* |
|---|---|---|---|---|---|
| SCIPP | Barrel | 5-10% (Desiccant) | 40 hours, 300 V, dry atmosphere | 160C 16h (Oven) | - |
| QMUL | Barrel | 6.5% (Desiccant + $N_2$ purge) | 40 hours, 500 V, <2% | - | - |
| Cambridge | Barrel | 5% (Desiccant + $N_2$ purge) | 40 hours, 500 V, Dry atmosphere | 160C 16h (Vacuum oven) | - |
| Prague | End-cap | 1% (Desiccant + $N_2$ flush) | - | 160C 16h (Oven and probe station) | UV LEDs (330 mW/395-410 nm/350 mA, 0.5-1 hour) |
| Carleton | End-cap | <2% (Desiccant) | 24-40 hours, 450-700 V, <2% | 150C 24h (PECVD vacuum chamber) | - |
| Vancouver | End-cap | TRIUMF: <5% (Dry air flow) | 40 hours, 450 V, <5% | 160C 16h (Vacuum oven) | - |
| | | SFU: <5% (Desiccant + $N_2$ flow) | | | |

*UV is now routinely used for production sensor recovery

# Recovery: Dry Storage/Training

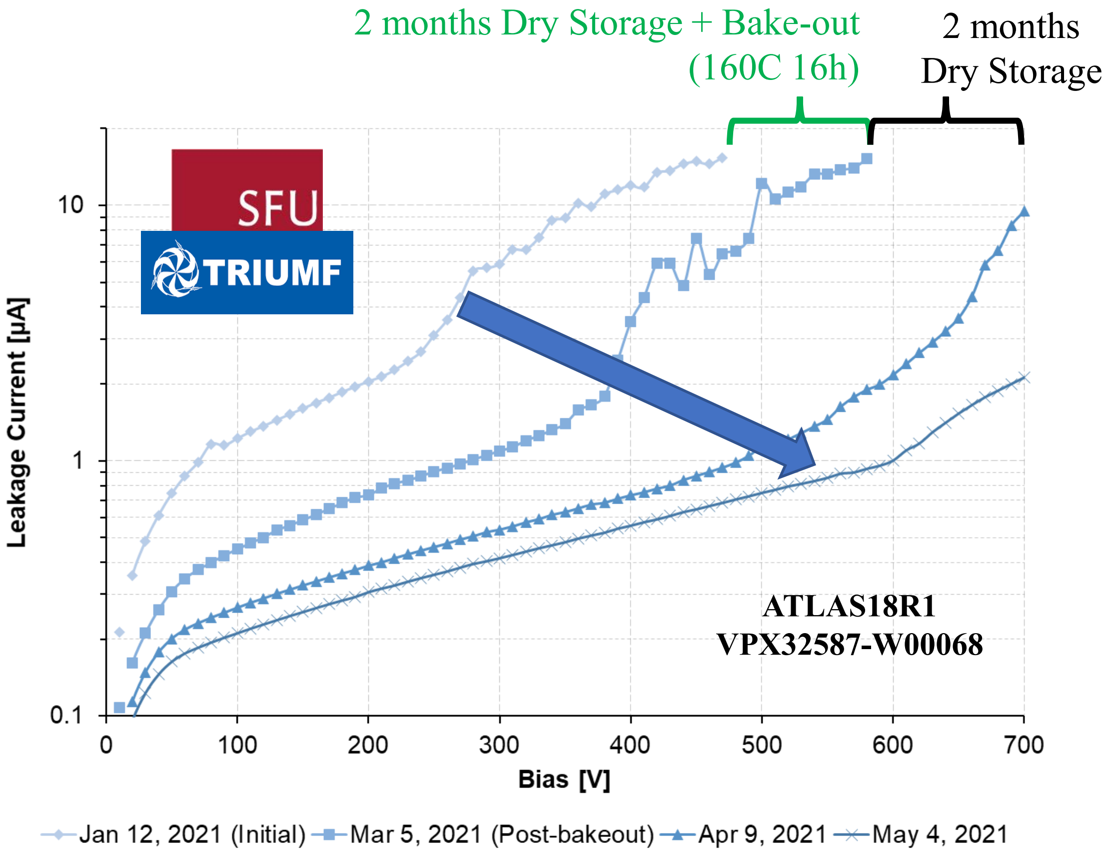
- 26 sensors were monitored during months of dry storage, occasionally complemented with training
  - 21 sensors (81%) improved showing higher breakdown voltage
  - 3 sensors remained ~same
  - 1 sensor deteriorated

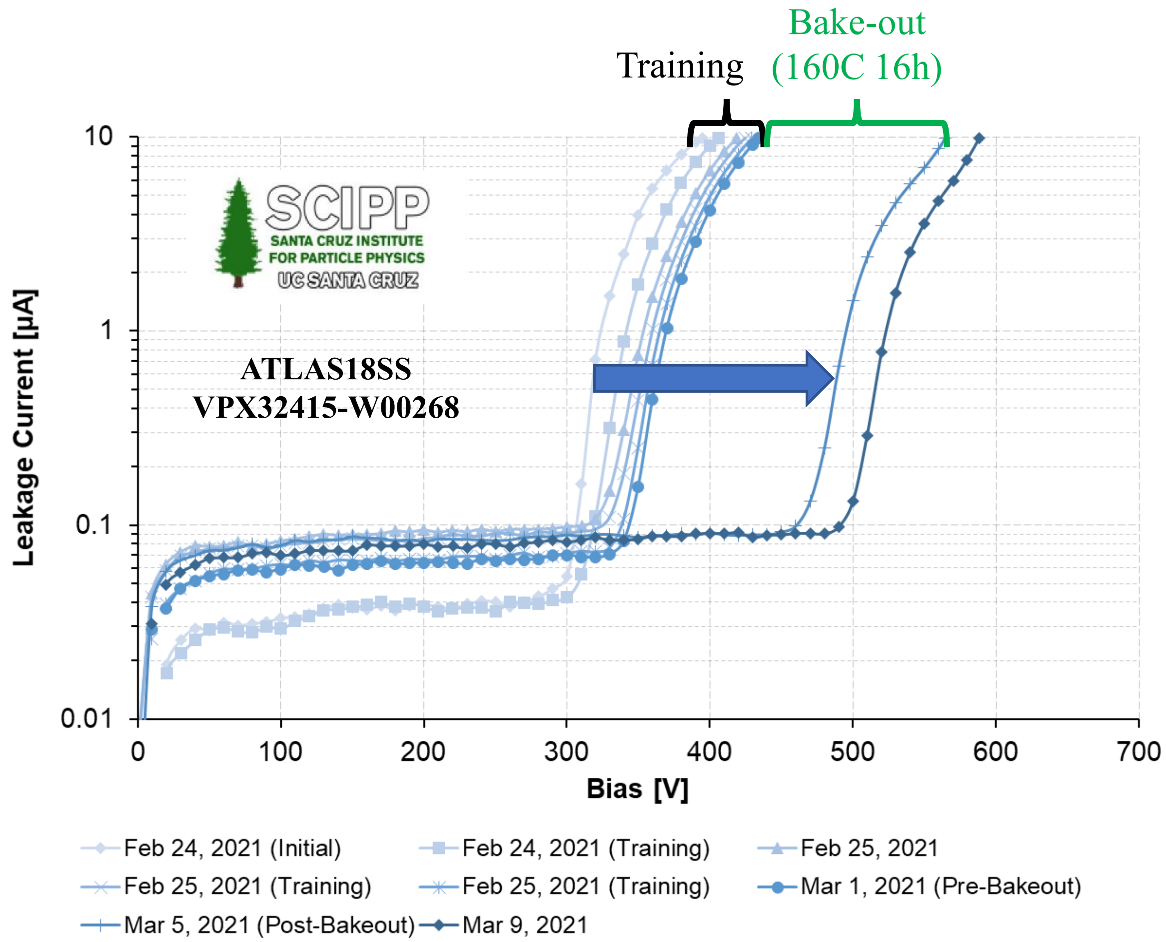



**NOTE:** Sensors that tend to improve exhibit training effect when holding at 700V for 30s during IV

# Recovery: Bake-out

- 19 sensors were baked out
  - 15 sensors (78.9%) showed improved performance after bake-out
  - 4 sensors remained ~same

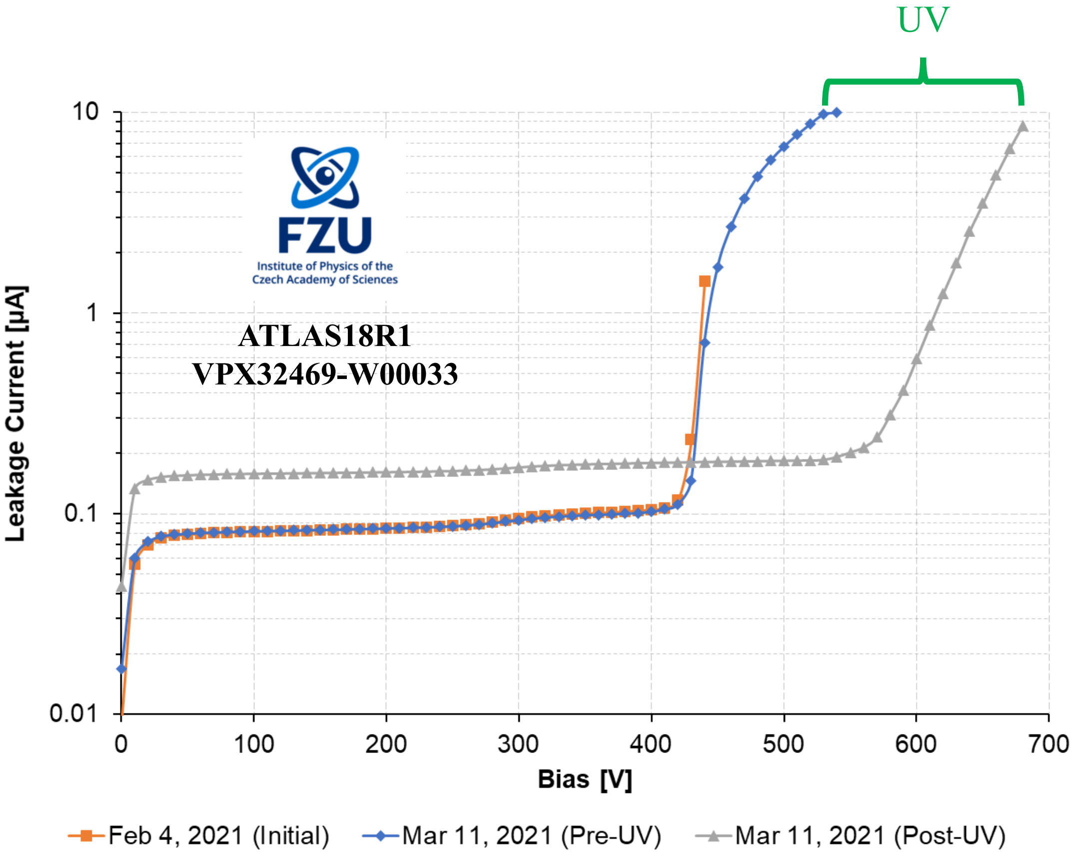


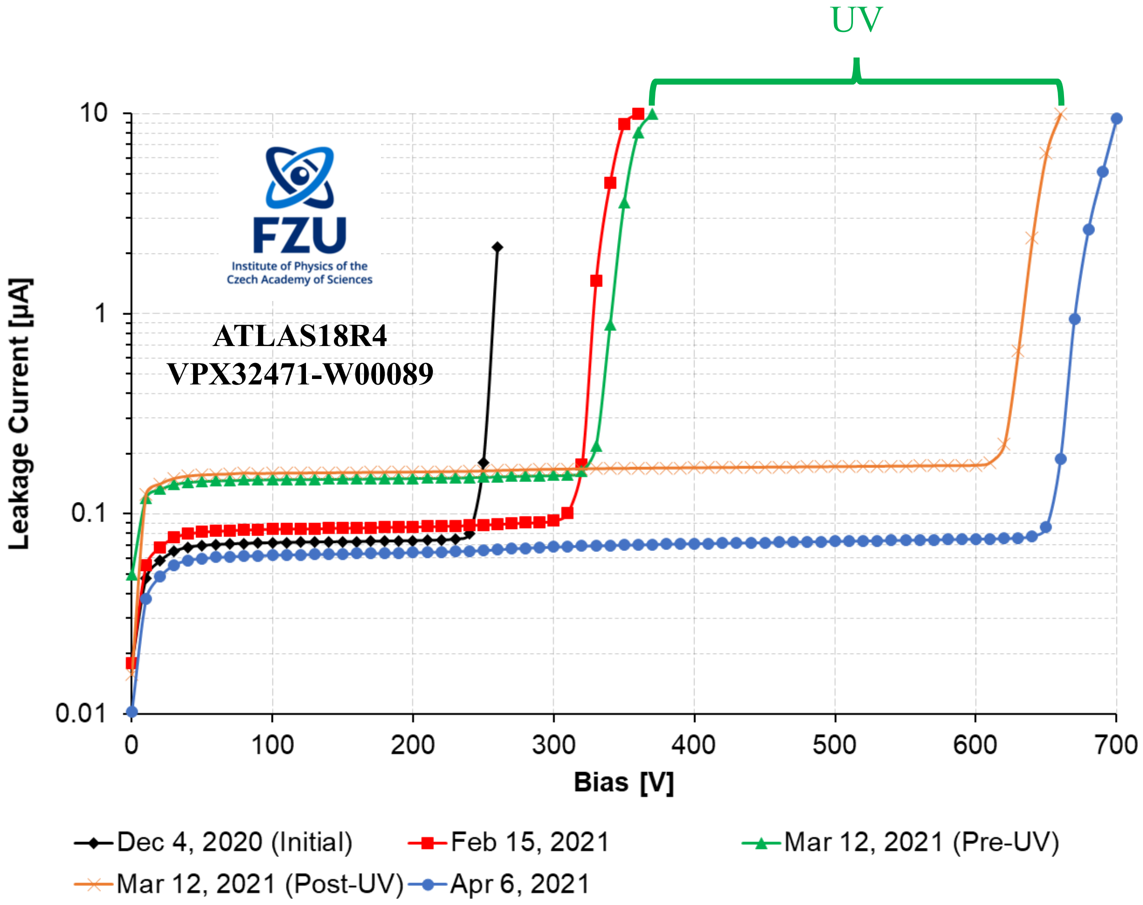




**NOTE:** Bake-out appears to accelerate the recovery of sensors that would have recovered in any case after staying in dry storage for extended periods of time

# Recovery: UV Irradiation

- 2 sensors were irradiated with UV light (centered at 354nm)
  - Both sensors improved their IV performance

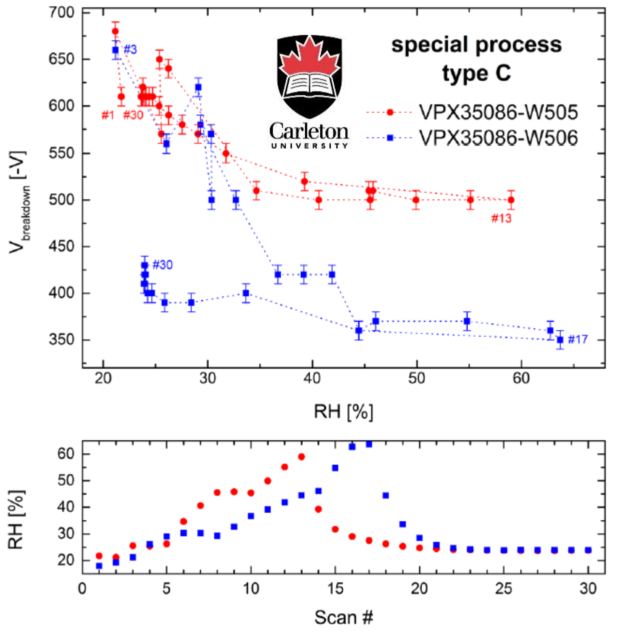


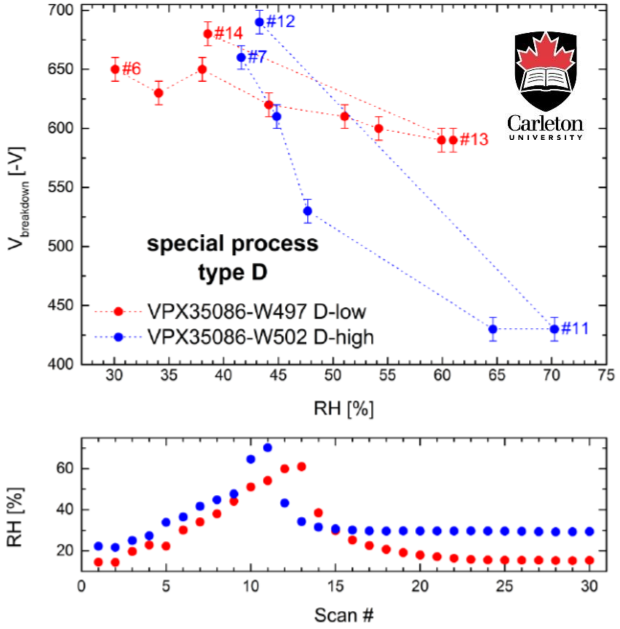




**NOTE:** UV irradiation has become the preferred performance recovery method during production

# Humidity Sensitivity

- Observed for prototype and pre-production full-size sensors
  - Appears when sensors are exposed for relatively long periods to high RH
    - Even without biasing when e.g. shipped
  - Always results in lower breakdown voltages and/or high leakage current
- Most sensors recover fast and exhibit higher breakdown voltages after dry storage
  - Effect irreversible after biasing a sensor for long periods under high RH
- HV breakdown due to hotspots located at the edge structure of the sensor
- Also studied sensors from special process splits provided by HPK in attempt to reduce effect
  - Thicker passivation (type C) allows for faster recovery after dry storage
  - Sensors with p-spray treatment (type D) show consistently higher breakdown voltages at high RH
- For production stay with original fabrication process from HPK
  - Established strict sensor storage requirements (<10% RH)
  - Minimized sensor exposure to high RH while sensor is biased
  - Log individual sensor exposure to ambient environmental conditions



# Summary

- Sensor pre-production provided excellent opportunities to prepare the infrastructure to handle production
- Part flows established and fairly well tested using CERN as the central hub
- Pre-production was a very significant ramp-up in terms of production-style testing:
  - Did NOT find major issues
  - All 8 sensor types/layouts look OK a significant accomplishment made possible with >23 layout verification iterations with HPK
- Many lessons learned all valuable for the production phase of the project
  - Handling and shipping, database interactions, damaged wafers, interactions with HPK, contract execution
- Strip sensor production commenced in 2021/08 with ~18% of production quantity delivered

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