Evaluation of quality control (QC) of ATLAS18 production ITk strip sensors

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on behalf of the ATLAS ITk Strip Sensor community

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Outline

1) ATLAS ITk upgrade

2) ATLAS ITk Strip sensors

3) QC sensor testing and recovery methods

4) QC test results and approvals

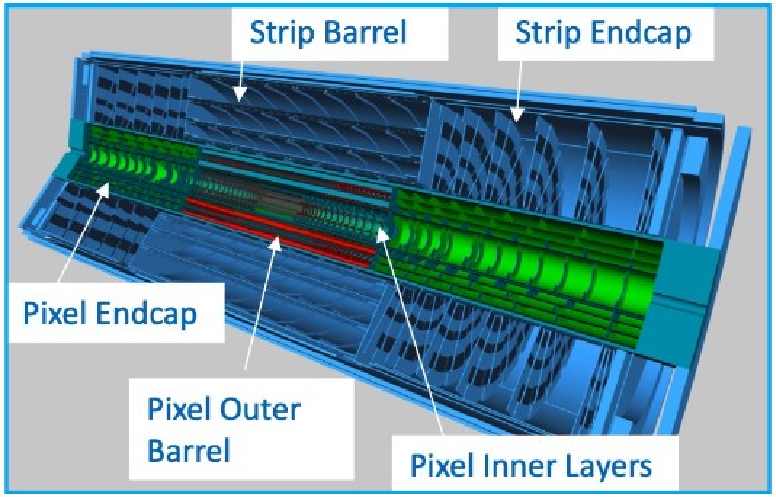
5) P-stop doping

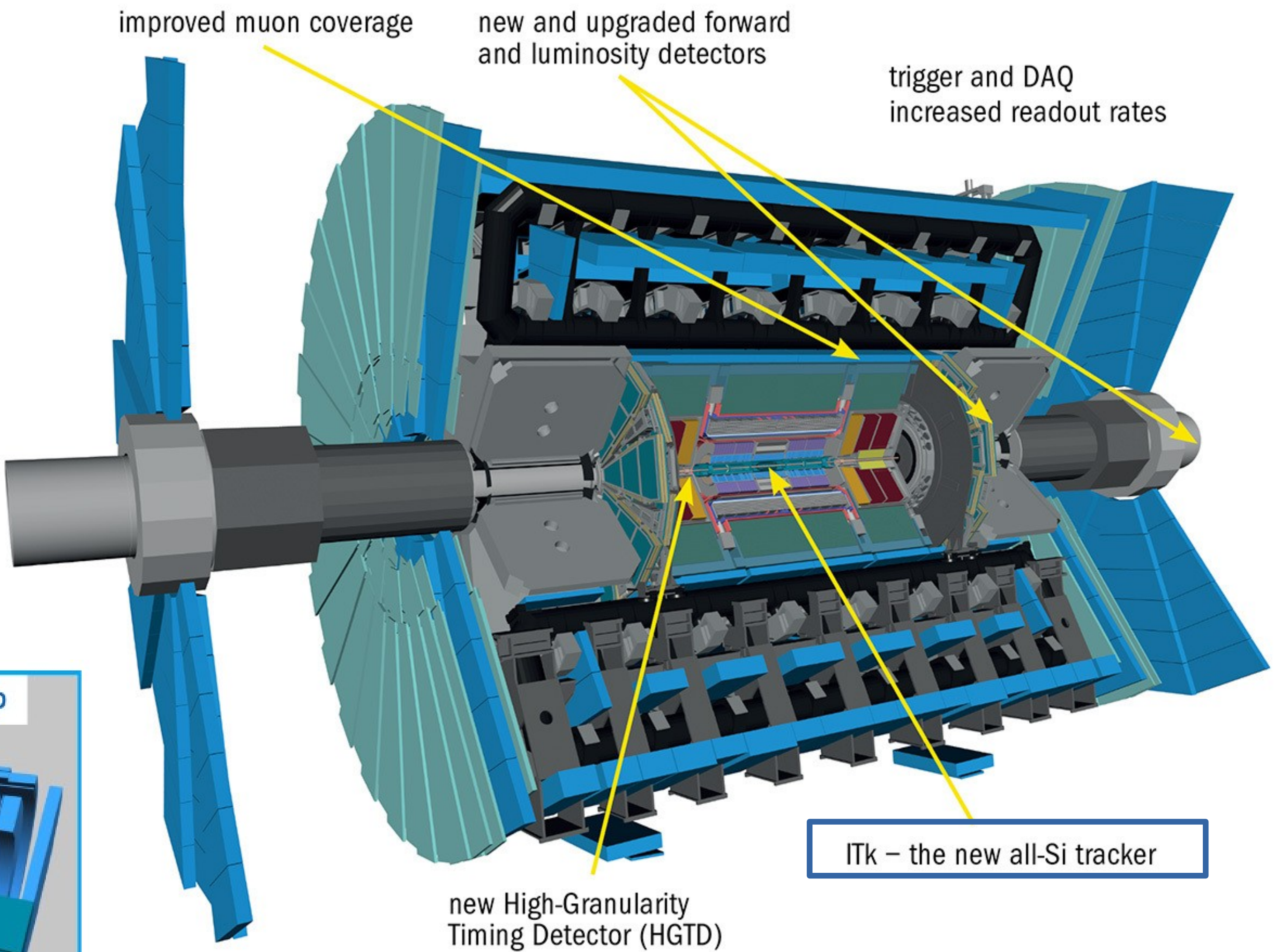
6) Summary and conclusion

ATLAS ITk upgrade

ATLAS Inner Detector will be completely replaced by the new all-silicon **ATLAS Inner Tracker**

- higher (~ 10times) radiation hardness sufficient to withstand HL-LHC conditions
  (Total Fluence: 1,1E15 neq/cm^2, Total Ionizing Dose: up to 53.2 Mrad),
- extended η coverage (|η| < 2,5 → |η| < 4),
- **strip detector** → the active area will be increased from 60 m^2 to 160 m^2 with 60M channels.



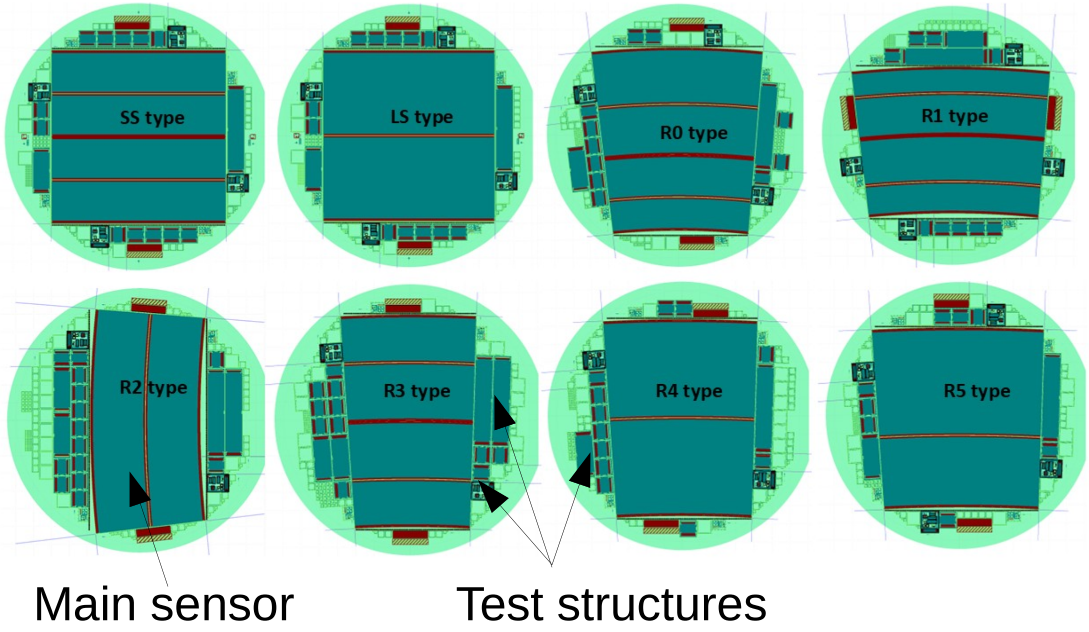


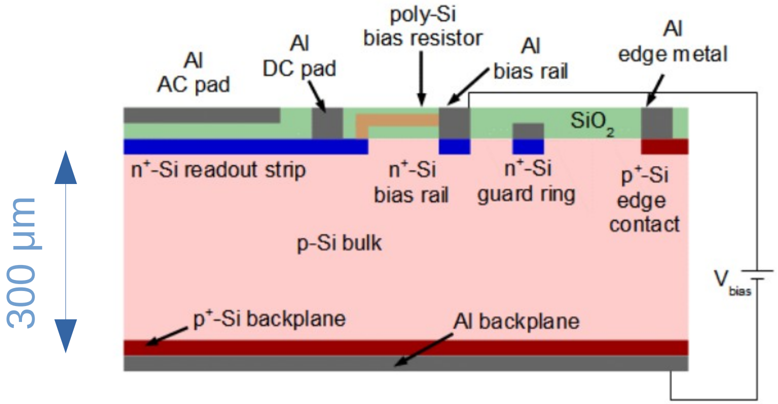
For the detailed overview about ATLAS ITk upgrade see T.Koffas's contribution Phase-2 Upgrade of the ATLAS Inner Tracker

ATLAS ITk Strip - sensors

Strips implanted on p-type silicon bulk (n+-in-p)

- single sided, AC coupled, produced by Hamamatsu Photonics (Japan)
- 320 μm thick (active thickness 300 μm)
- full depletion voltage VFD ~ 280 V (specifications VFD < 350 V)
- 8 sensor geometries:
  - 2 for the barrel, 75.5 μm strip pitch
  - 6 for the end-caps, trapezoidal + arc, 70 to 80 μm pitch
- one sensor per 6 inch wafer + test structures
- spatial resolution ~ 20 μm
- the bunch-crossing resolution ~ 25 ns
- Barrel strip length: 2.41 and 4.83 cm
- Endcap strip length: 1.5 – 6 cm
- Barrel strip pitch: 75.5 μm
- Endcap strip pitch: 70 – 80 μm



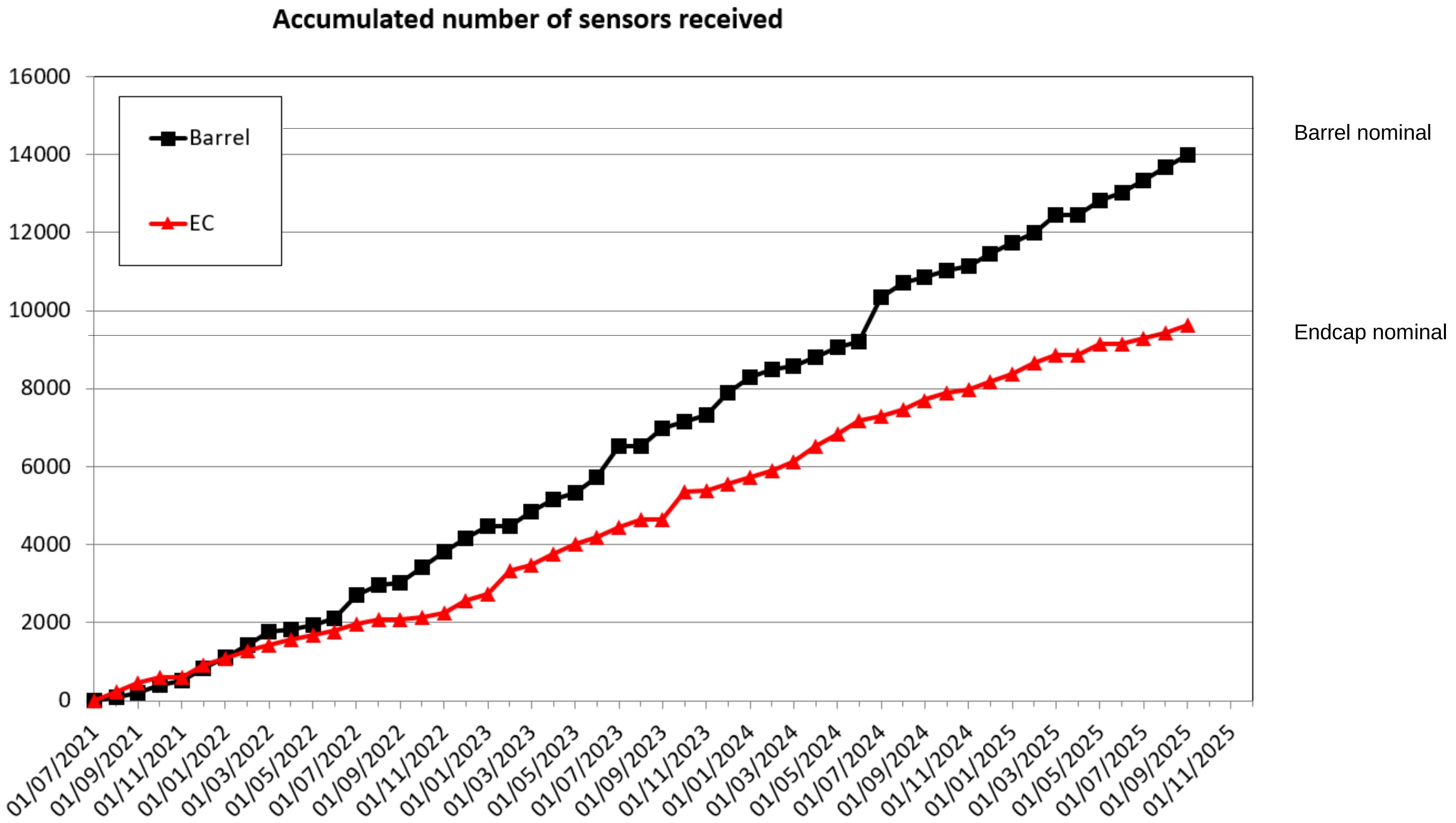


Schematic cross-section along the strip direction - Ref [1].

1) Klein C.,et al. Initial test of large-format sensors for the ATLAS ITk strip tracker Nucl. Instrum. Methods Phys. Res. A (2020)

Sensors received

- Number of production strip sensors received by ATLAS up to September 2025 - 9 625 for endcaps and 13 987 for barrels. The nominal final totals are 14 730 barrels and 9 280 endcaps.



QC main sensor testing

Upon delivery, ATLAS performs detailed measurements of sensors to monitor quality of all fabricated devices to ensure that their characteristics are within specifications defined by the ATLAS collaboration.

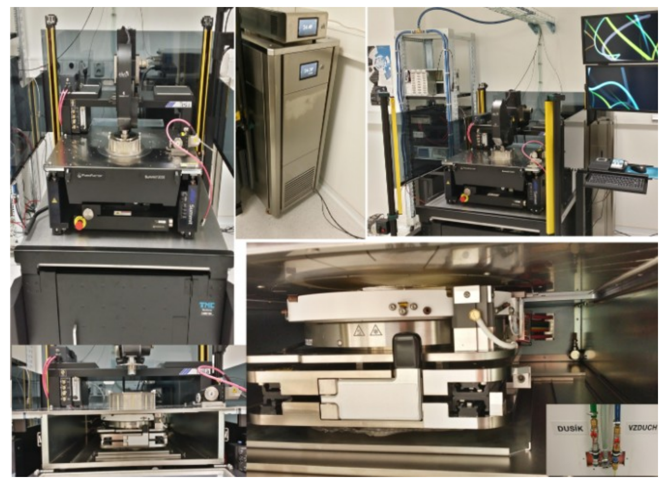
On every sensor

1) Visual Inspection,
   - look for scratches, chips, blotches etc.,
2) Visual Capture,
   - image of the whole sensor in a high resolution,
3) Mechanical bow test,
   - sensor bow < 200 µm,
4) Current-voltage (IV),
   - $V_{breakdown}$ > 500 V,
   - $I_{leakage}$ @500 V < 0,1 µA/cm^{2},
5) Capacitance-voltage (CV),
   - $V_{depletion}$ < 350 V.

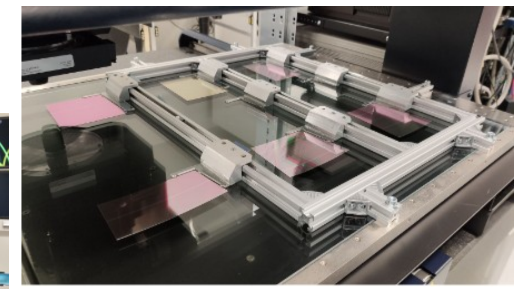
On batch subset

1) Mechanical thickness test,
   - at least one per batch,
   - sensor thickness (320 ±15) µm,
2) Leakage Current Stability: 10 – 20 % samples,
   - current fluctuations < 15 % for 24h+,
3) Full Strip Tests: 2 – 5 % samples,
   - I_{stip} < 200 nA,
   - 1 MΩ < R_{bias} < 2 MΩ,
   - $C_{coupling}$ > 20 pF/cm,
   - < 1 % failed strips per segment,
   - ≤ 8 consecutive failed strips.

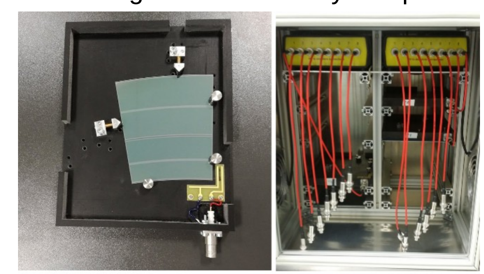
Probe stations



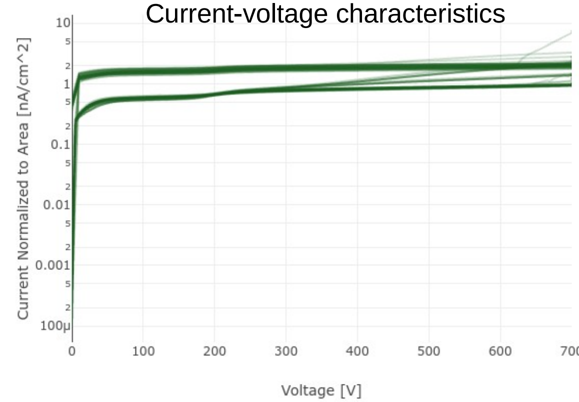
Metrology station



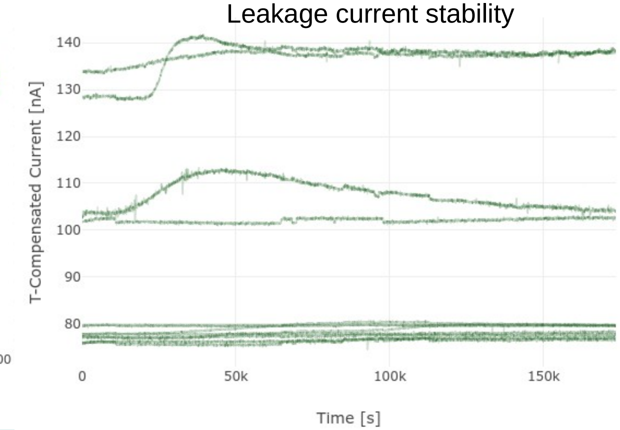
Leakage current stability setup



Current-voltage characteristics

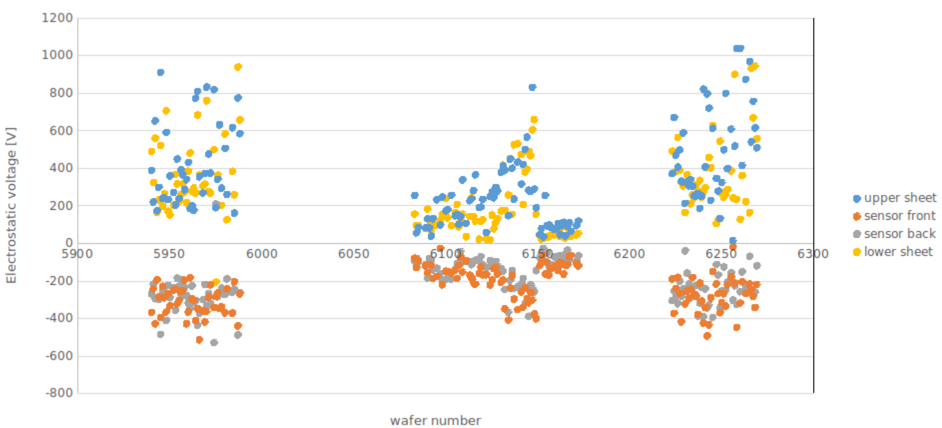


Leakage current stability

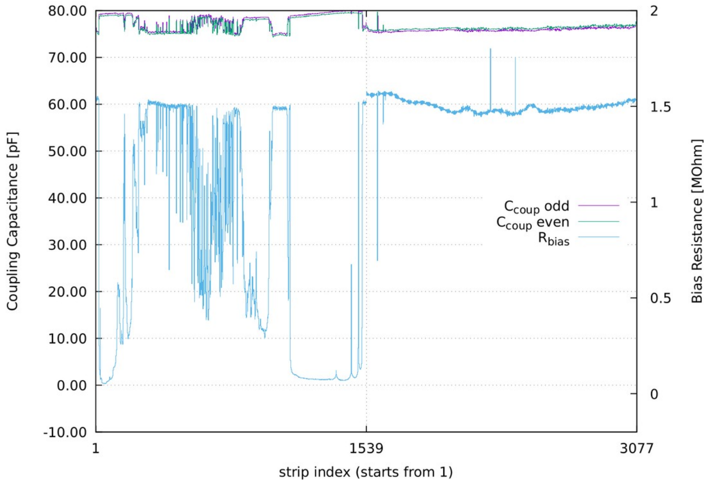


Sensors – recovery

- Strong correlation with high static charge measured on sensors and electric tests failures.
- A big part of failed sensors can be recovered with different treatments [1,2] :
  1) **UV-A** (315-400 nm) light setups with typical exposure between 2 and 8 hours,
  2) **UV-C** (100-280 nm) light setups with typical exposure of 60 seconds,
  3) **Ionizing air blowers** with typical exposure of a few minutes up to 30 minutes,
  4) High-temperature (160 ˚C) exposure ("**baking**") of sensors in an oven for more than 16 hours.

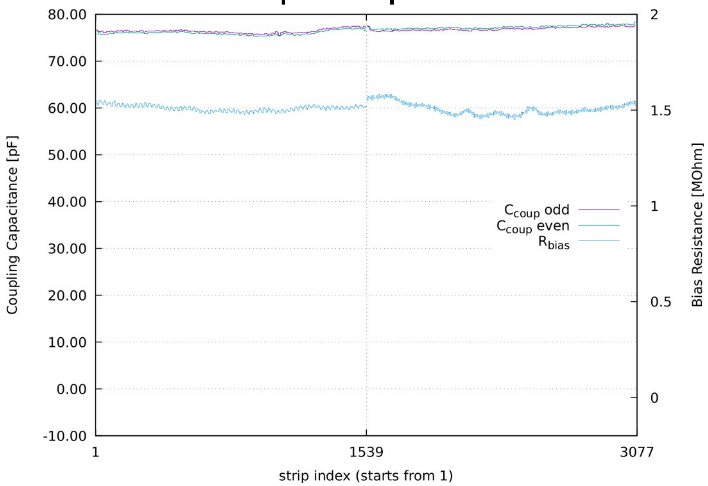


Strip test fail



UV treatment

Strip test pass



1) *Setups for eliminating static charge of the ATLAS18 strip sensors, P. Federičová et al 2024 JINST 19 C02001*
2) *Identification and recovery of ATLAS18 strip sensors with high surface static charge, E. Staats et al 2024 NIMA 1064 169446*

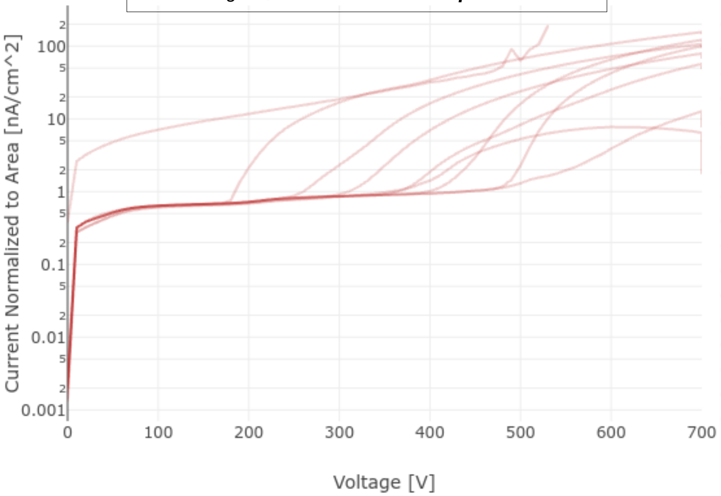
Sensors – rejection rate

- Very low rejection rate **2.8 %** (including both individual sensor and batch rejections),
  - Six batches were rejected:
    - A full batch of sensors can be rejected if its QA results are found to be out of specification or ≥ 4 sensors fail the same QC test,
    - two due to instability and non-recoverable IV breakdown, four due to non-uniform p-stop doping.
- Rejection rate **1.8 %** for individual sensor rejection.
  - The main rejection issues for individual sensors are IV failures ($V_{breakdown}$ < 500 V), Visual inspection defects (mainly scratches and chips), and Stability test.
  - No rejections attributed to bow, thickness, or CV (correlated to IV fail).
- An instability in IV tests was observed after the long-term stability test...see the poster *Analysis of unstable leakage current in ATLAS18 Strip Sensors after long-term tests – Ch. Klein*

IV fail examples

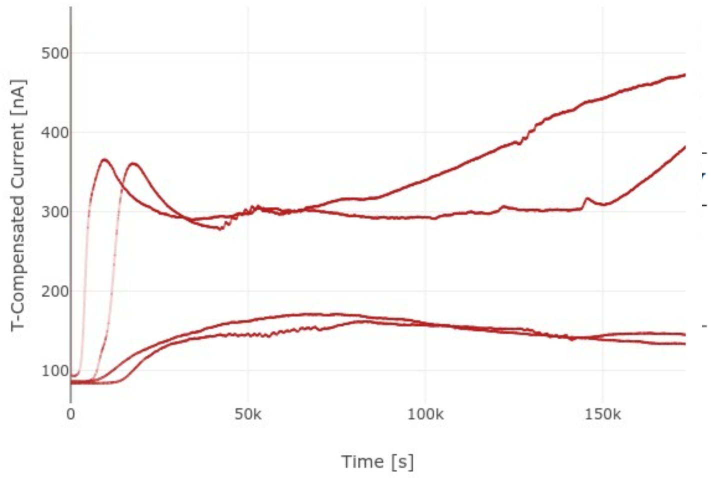
$V_{breakdown}$ > 500 V,

$I_{leakage}$ @500 V < 0,1 µA/cm²

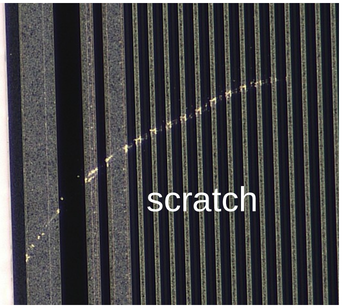


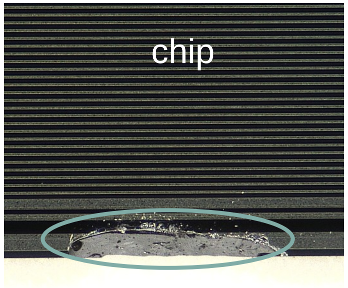
Stability fail examples

Leakage current variation < 15 %.



Visual Inspection fail examples





Sensors – accepted and rejected

- 590 batches were accepted (642 delivered).
- Results of rejection ratio for each sensor geometry moves from 1 – 10 %.
- About 98 % sensors of required total were delivered.
- The remaining number of sensors will be accepted after on-going tests and from new deliveries.

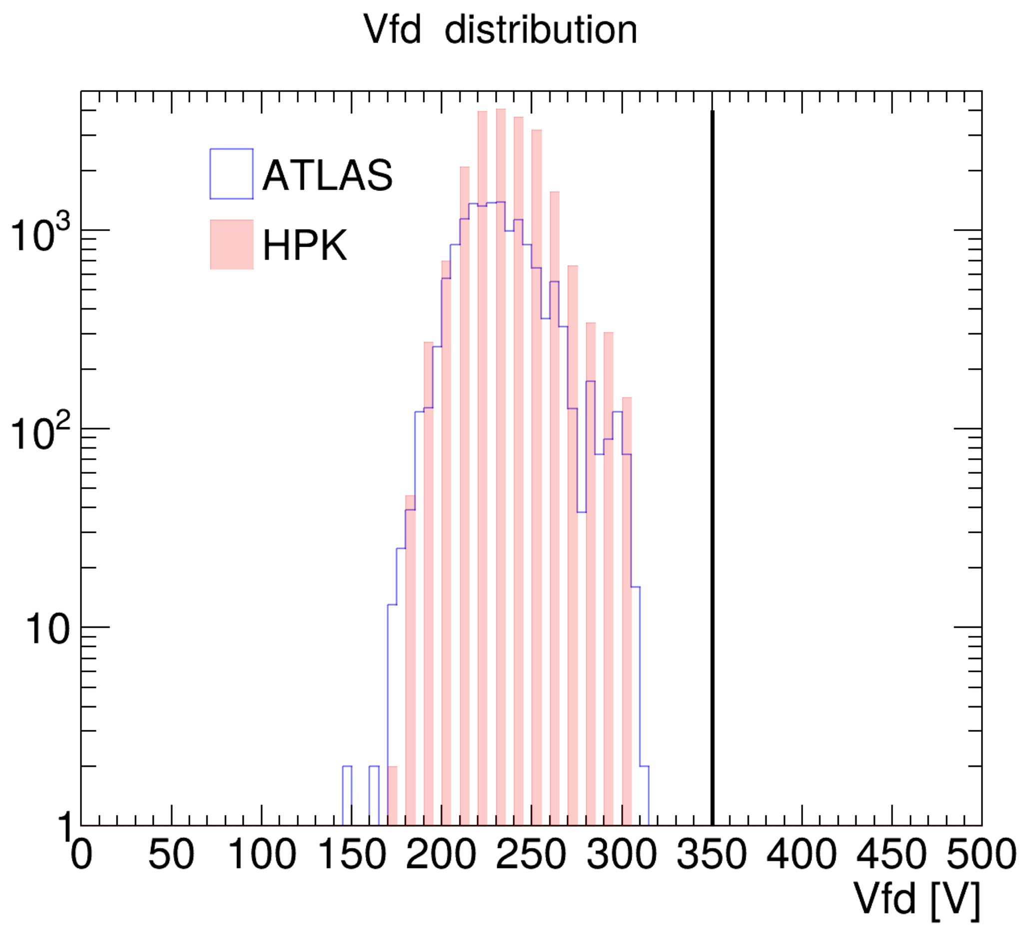
Sensor type	Total	LS	SS	R0	R1	R2	R3	R4	R5
Nominal quantity	24010	9470	5260	1040	1020	1020	2120	2030	2030
QC tested	22376	9434	3774	1040	1040	1020	2042	1996	2030
Accepted	21751	9335	3741	917*	1020	917*	1939*	1909*	1973
% tested rejected	2.8	1	0.9	12	1.9	10	5	4.4	2.8
% of final accepted	91	99	71	88	98	90	91	94	97

* include batch rejections

Sensor type	Total	SS	LS	R0	R1	R2	R3	R4	R5
Nominal quantity	24010	5260	9470	1040	1040	1020	2120	2030	2030
Delivered	23614	4517	9470	1161	1040	1109	2201	2030	2086
% delivered	98	86	100	112	100	109	104	100	103

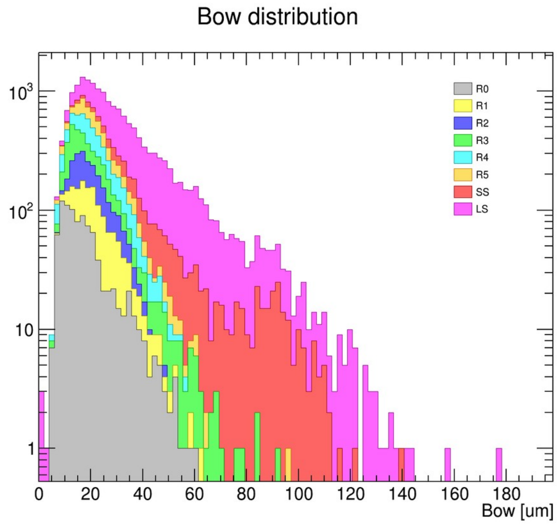
Comparison between HPK and ATLAS data

- The histogram compares the full-depletion voltage (Vfd) measured by Hamamatsu (HPK) with that obtained by the ATLAS ITk institutions.
- It can be seen that all Vfd values, both from HPK and ATLAS, met the specification of < 350 V.
- There is also very good agreement between the two data sets.

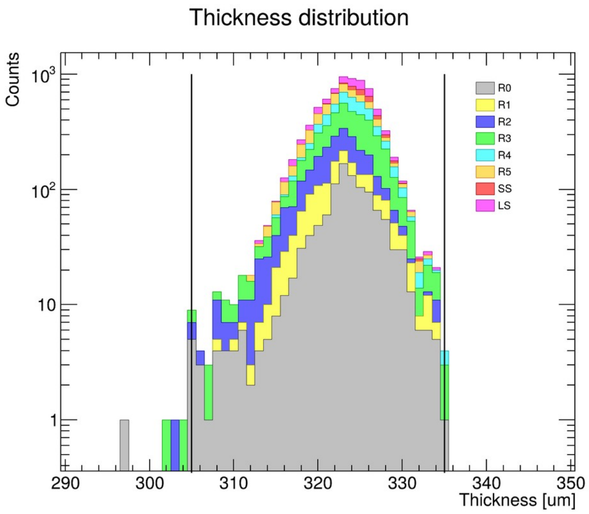


Vfd < 350 V.

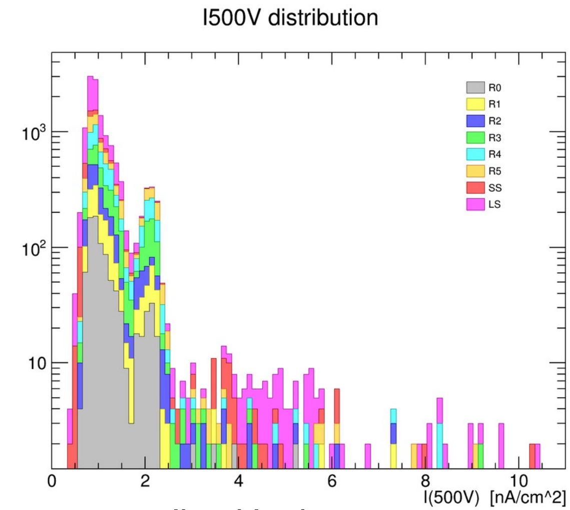
Distribution of QC sensors properties per sensor type on all sensors



Sensor bow < 200 µm.



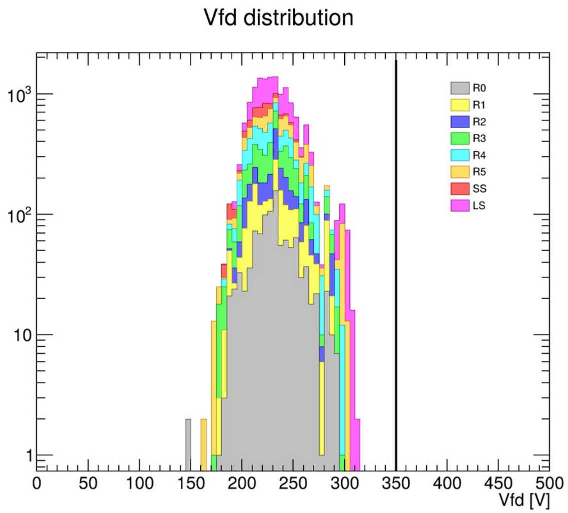
Sensor thickness 320 ± 15 µm.



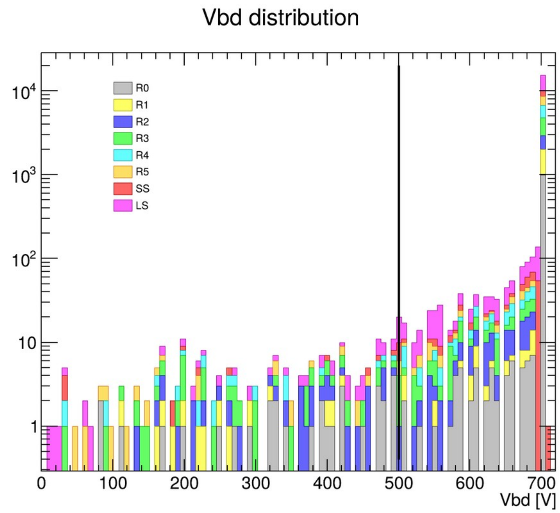
Normalised leakage current @ 500 V < 100 nA/cm^2.

- All sensor types satisfy the specification limit for bow (< 200 µm).
- The barrel sensors exhibit a slightly broader distribution compared to the endcap types.
- All sensors also comply with the thickness specification; borderline cases were manually accepted considering the measurement accuracy.
- The normalized leakage current at 500 V is well below the specification for all sensor types.

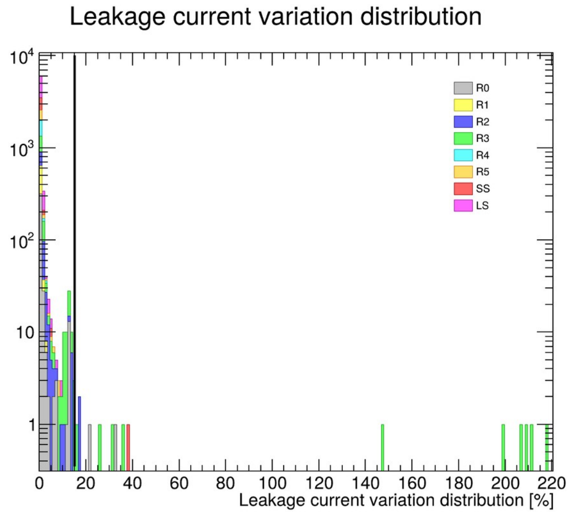
Distribution of QC sensors properties per sensor type on all sensors



Full depletion voltage < 350 V.



Breakdown voltage > 500 V.
Sensors in the final bin have no breakdown.

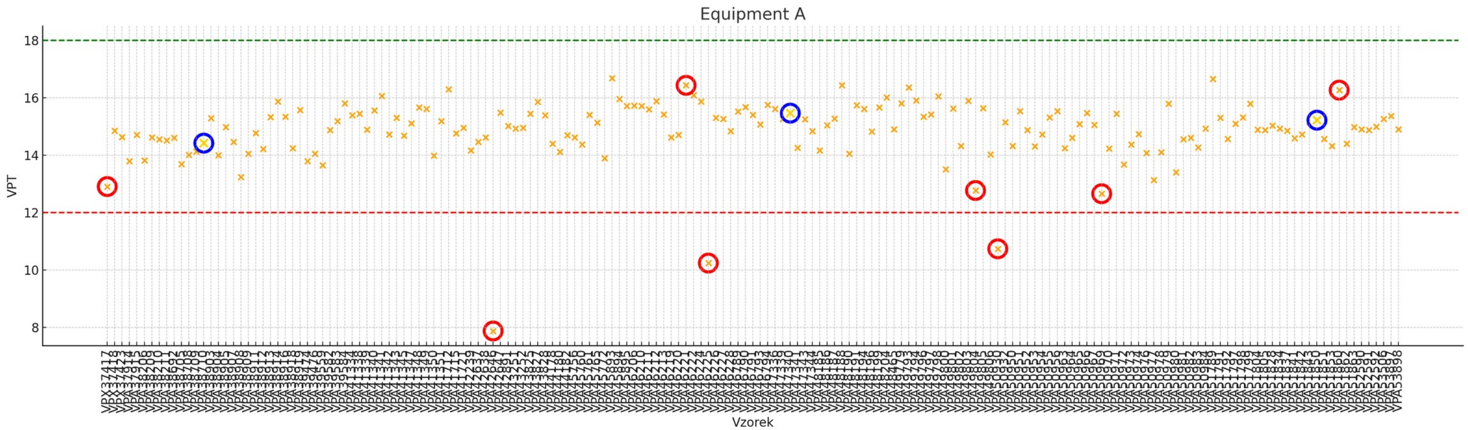


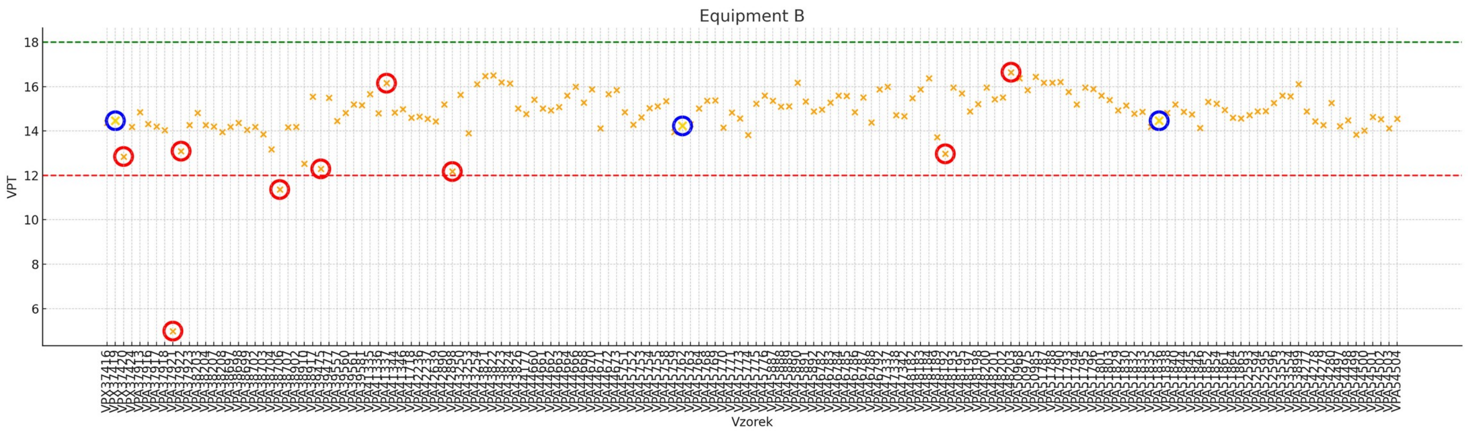
Leakage current variation < 15 %.

- The distribution of full-depletion voltage (Vfd) indicates that all sensors are well below the specification limit of 350 V.
- From the breakdown voltage distribution, it can be observed that a small fraction of sensors (~ 1%) did not meet the specification, while approximately 99% passed, with a large amount showing no breakdown.
- The leakage current variation also satisfies the specification for the majority of tested sensors (~ 99%).

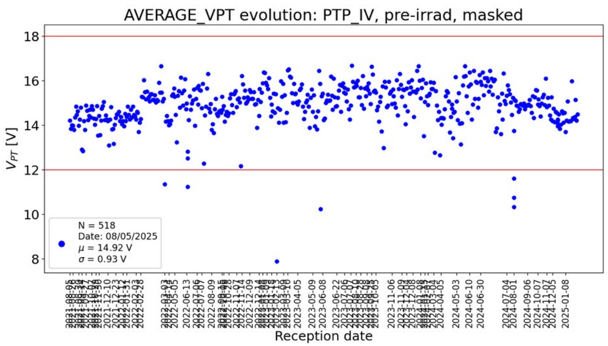
P-stop doping

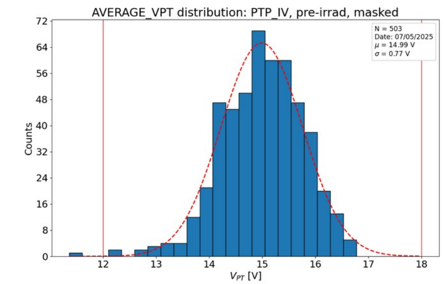
- Interstrip isolation is essential in ITk strip sensors to minimize charge sharing and maintain high spatial resolution by reducing readout noise.
- QA results indicated that the threshold voltage (V_PT) of the Punch-Through structure (PTP) is out-of-limit in several production batches.
  (see Quality Assurance during production of the ATLAS18 ITk strip sensors – R. Orr)
- To verify whether V_PT is non-uniform across a wafer or else, PTP measurements were performed on main sensors from the affected batches.
- For comparison, additional PTP measurements were performed on main sensors that either satisfied the QA specifications or were close to the specification limits (12 V < PTP_IV < 18 V), for two different furnace processes.





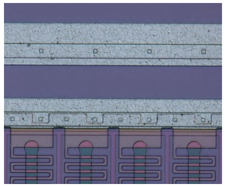
Ref [3]





Ref [3]

The acceptance limit for PTP correspond approx. 4-times the standard deviation.



PTP structure on a main sensor under a microscope

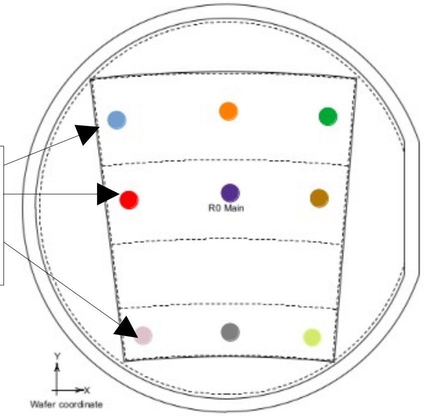
3) E. Bach, et al. "Analysis of the quality assurance results from the initial part of production of the ATLAS18 ITK strip sensors," Nucl. Instrum. Meth. A 1064, 169435 (2024)

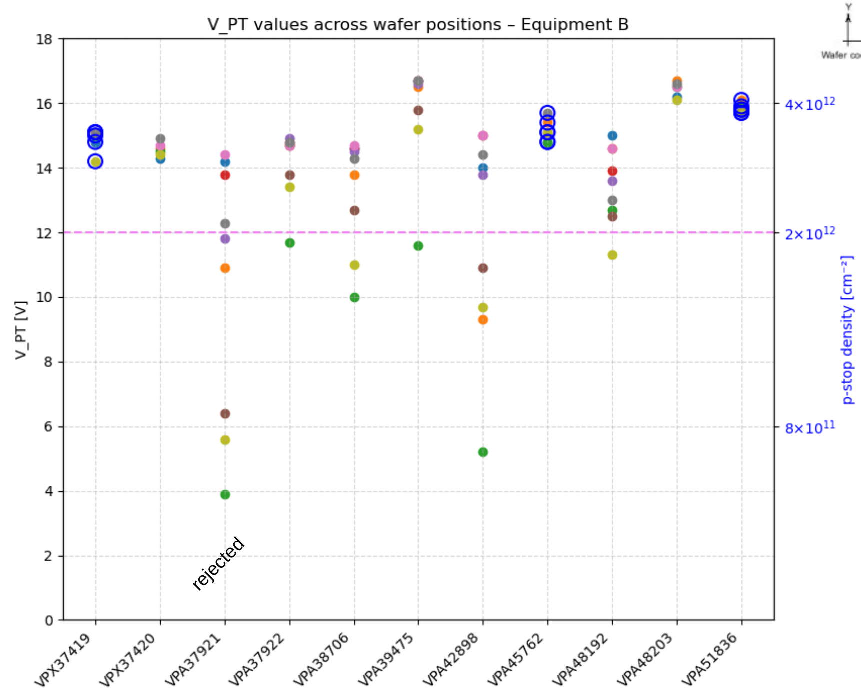
P-stop doping

- The punch-through voltage (V_{PT}) in the affected batches decreases in some cases from left to right across the sensor (i.e., with increasing strip number), consistent with a reduction in p-stop doping. Towards the right side, V_{PT} falls below the specification of 12 V.
- <u>Observed results</u>: When the QA results are within specifications, the PTP measurements on the main sensors are satisfactory as well. QA results near the specification limits do not necessarily indicate poor PTP performance on the main sensors. When the QA results deviate significantly from the specifications, the PTP results on the main sensors are also poor.

See posters :
Measurement of Threshold Voltages in PTP Structures and Estimation of P-stop Densities Across an ATLAS18 Silicon Strip Sensor Wafer Using TCAD Simulations
- Y. Unno
Evaluation of Performance of the p-stop Process Splits in ATLAS18 strip sensors, Pre- and Post-Irradiation - J. Kozáková
See talk:
Evaluation of post-irradiation performance of strip sensors affected by low p-stop issue– J. Fernandez-Tejero

The illustration of the approximate locations of the strips tested on a main sensor.





Summary and conclusion

- Strip sensor production is on-going well (started in August 2021).
- Over 98 % of full production sensors were delivered.
- The QC testing throughput is able to comfortably cover the HPK deliveries.
- Recovery efforts (UV-A, UV-C, ion blower, baking) and static charge measurements/eliminations were put into practice effectively and thus reduced the sensor rejection rate to 2,8 %.
- Nearly 21 800 strip sensors have been accepted for using in the ITk detector.
- Decreasing levels of p-stop doping was measured in some batches during production. Four production batches were rejected due to this issue.
- The distribution and shipment of sensors (between vendor and the QC sites, or the QC and Module sites) are also successfully implemented.

Acknowledgements

This work was supported by:

1) The European Structural and Investment Funds and the Ministry of Education, Youth and Sports of the Czech Republic via projects LM2023040 CERN-CZ, and FORTE - CZ.02.01.01/00/22_008/0004632.
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3) STFC grants ST/W000474/1, ST/S00095X/1, ST/X001431/1, ST/R00241X/1
4) JSPS KAKENHI 20K22346 and 23K13114
5) The US Department of Energy, grant DE-SC0010107
6) The Spanish R&D grant PID2021-126327OB-C22, funded by MICIU/ AEI/10.13039/501100011033 and by ERDF/EU

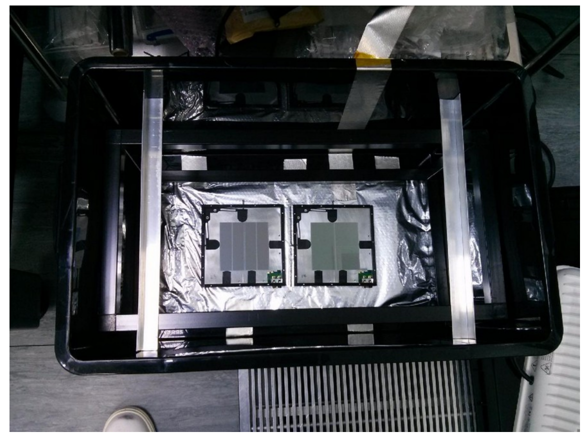
Thank you!

BACK UP

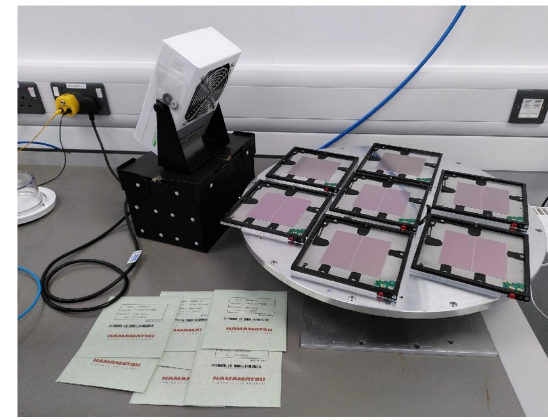
Static charge elimination setups

Vancouver UV-A setup

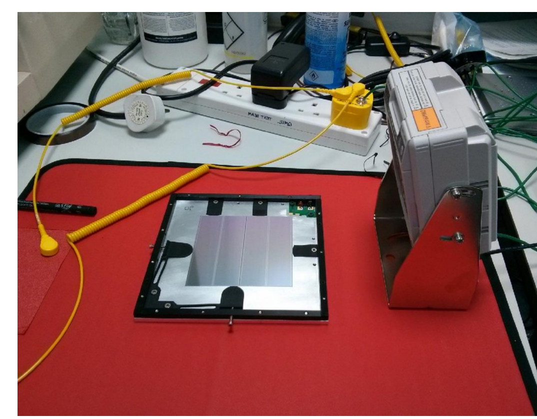
QMUL UV-C setup



Cambridge Ion Blower setup

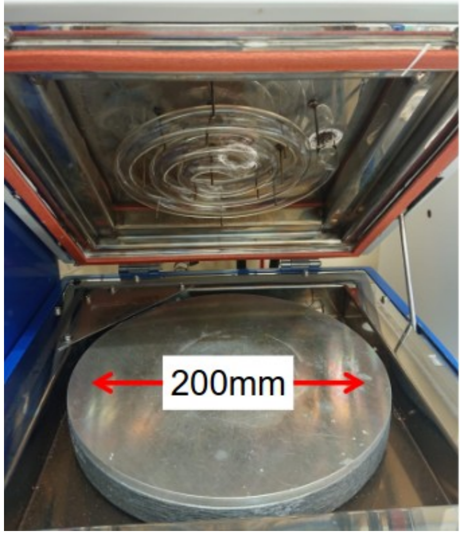


QMUL Ion Blower setup

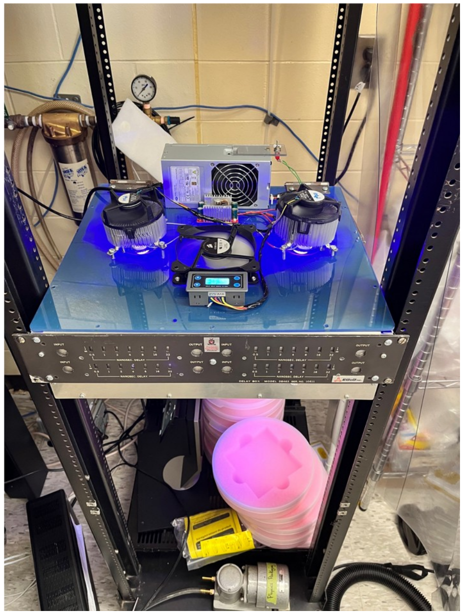


Static charge elimination setups

Carleton UV-C setup



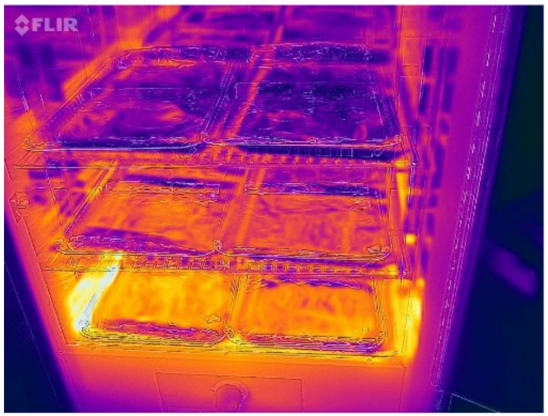
Carleton UV-A setup



Carleton Ion gun

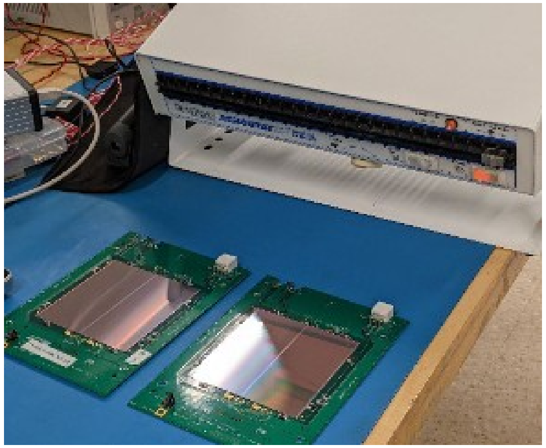
Static charge elimination setups

SCIPP baking oven



Prague Ion Blower and Ion gun

SCIPP Ion Blower setup



Prague UV-A setup

QC testing time

8 QC tests in total : 6 to be performed on every sensor + 2 on a batch subset due time consuming.

- Tests on every sensor are performed first and based on their results a subset of the batch is selected for the Current Stability test and the Full Strip test.

Usual testing time:

- IV – 20 - 30 min/sensor,
- CV – 20 - 30 min/sensor,
- Visual Inspection – 5 - 10 min/sensor,
- Visual Capture – 2 h/sensor,
- Bow and Thickness – 30 min/sensor,
- Leakage Current Stability – 40 h/test,
- Full Strip Test – 8-10 h/sensor.

- Each endcap sensors delivery contains 4-10 batches of different sensor types, typically 30-50 sensors/batch.
- Each barrel sensors delivery contains 8 batches, typically 30-50 sensors/batch.
- **Typical monthly delivery rates are 300 wafers for barrel and 180 wafers for endcap sensors.**

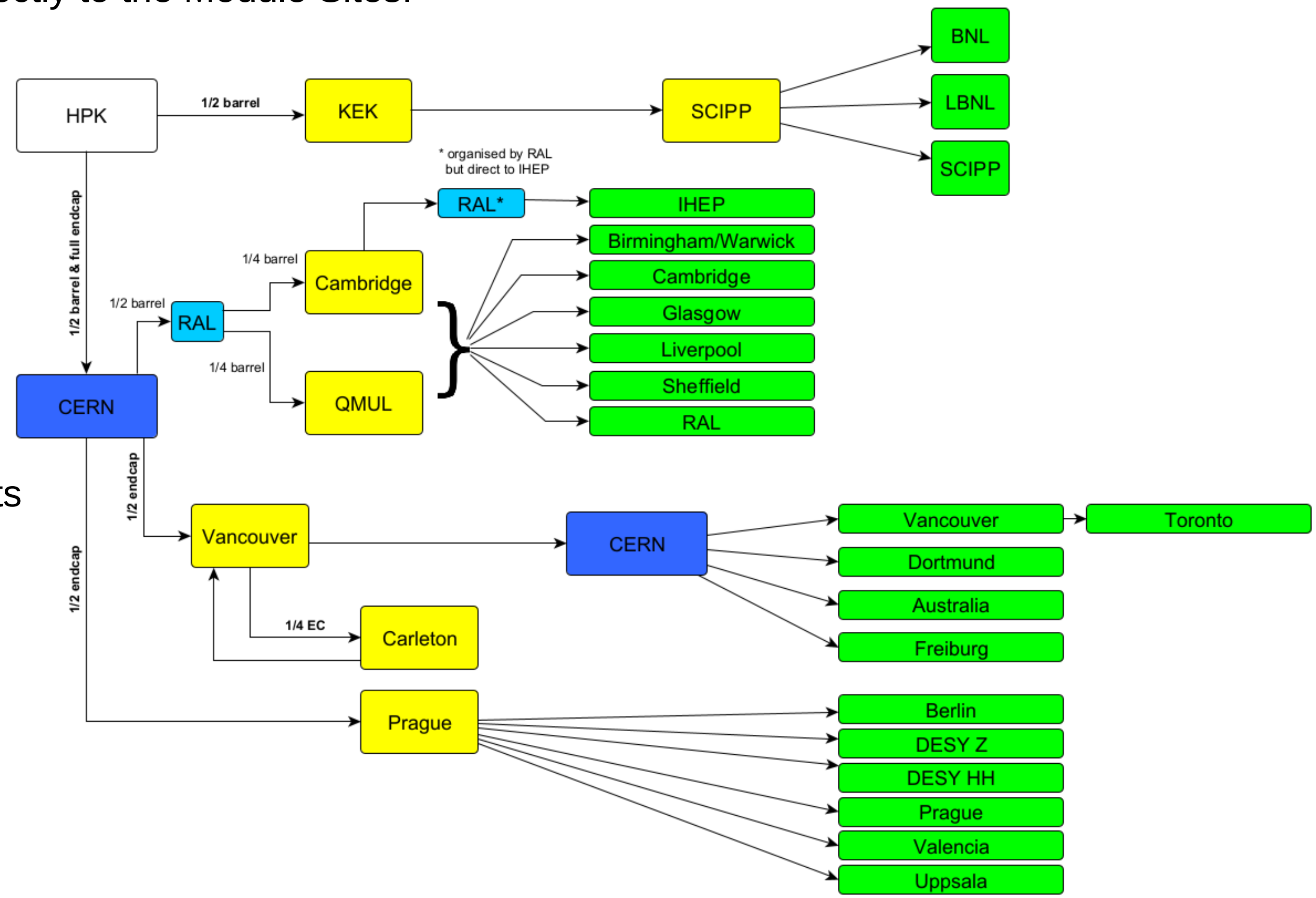
QC distribution and shipping

<u>Endcap workflow</u>

- all endcap sensors distributed through CERN
- ½ endcaps go to Prague
- ¼ each to Vancouver and Carleton
- Vancouver returns all the sensors back to CERN from where they are distributed to the Module Sites.
- Prague distributes its sensors directly to the Module Sites.

<u>Barrel workflow</u>

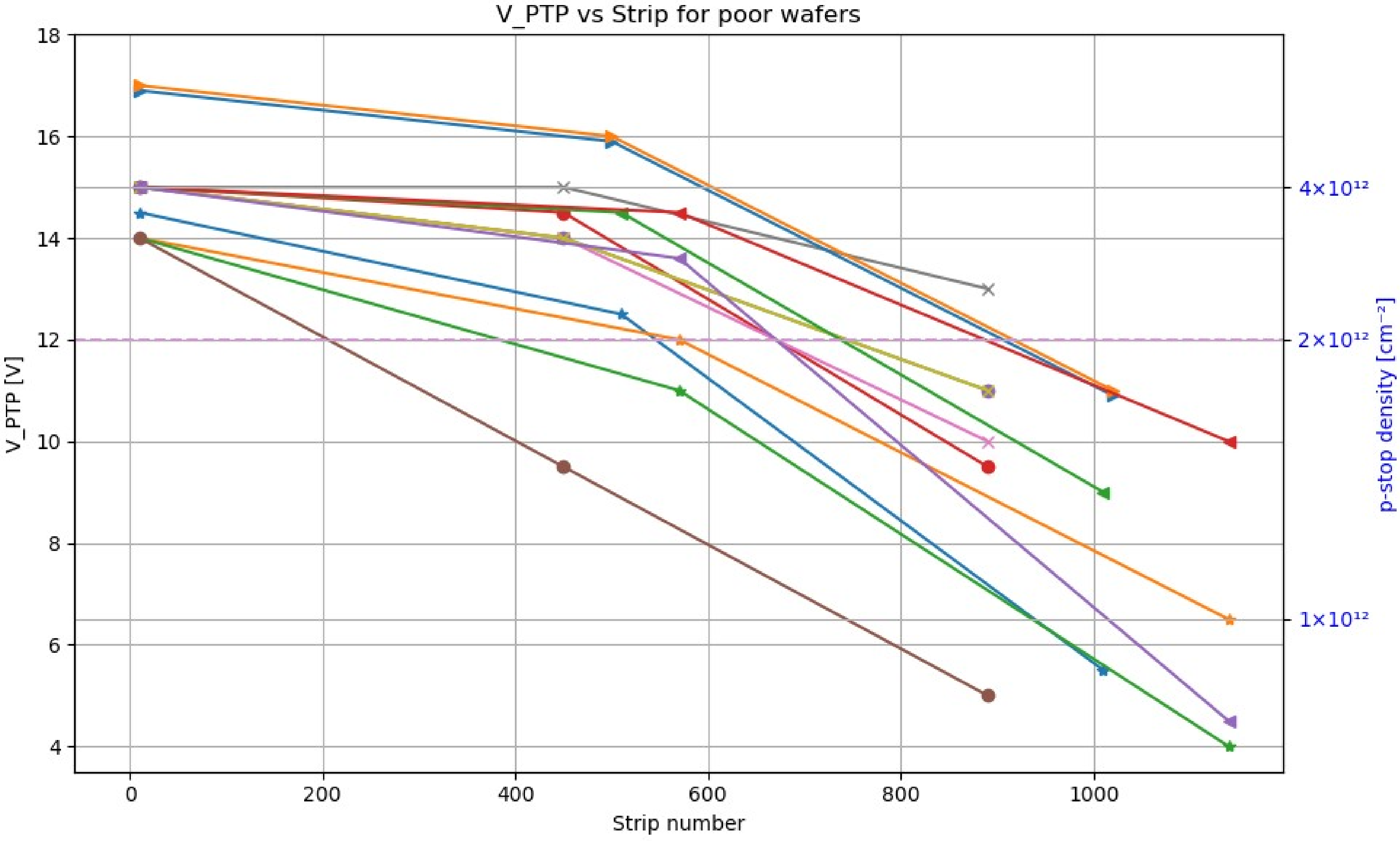
- Barrel sensors divide between KEK and CERN
- ½ barrels go to KEK and SCIPP for testing and after that sensors are distributed directly to the Module sites.
- ¼ each to Cambridge and QMUL
- Each UK site distributes directly its sensors to the Module sites.



QC sites overview - table

		Testing throughput	Additional setup
Endcap	**Prague**	40 sensors/week	UV-A setup, ion gun/blower, static charge measurement
	Carleton	20 sensors/week	UV setup, baking oven, static charge measurement, ion blower
	SFU	24 sensors/week	UV setup, baking oven, static charge measurement
Barrel	**SCIPP**	300 sensors/month	baking oven, static charge measurement, ion blower, UV
	QMUL	35 sensors/week	ion blower, UV-A/UV-C setup, static charge measurement
	KEK/Tsukuba	25 sensors/day (max 47)	?
	Cambridge	20 sensors/week	de-ioniser setup

P-stop doping



The plot shows V_{PT} distribution across the wafers exhibiting the p-stop non-uniformity.