Quality Assurance During Production of ATLAS18 ITk Strip Sensors

Robert S. Orr

On behalf of the ATLAS ITk Collaboration

The 14th international "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors

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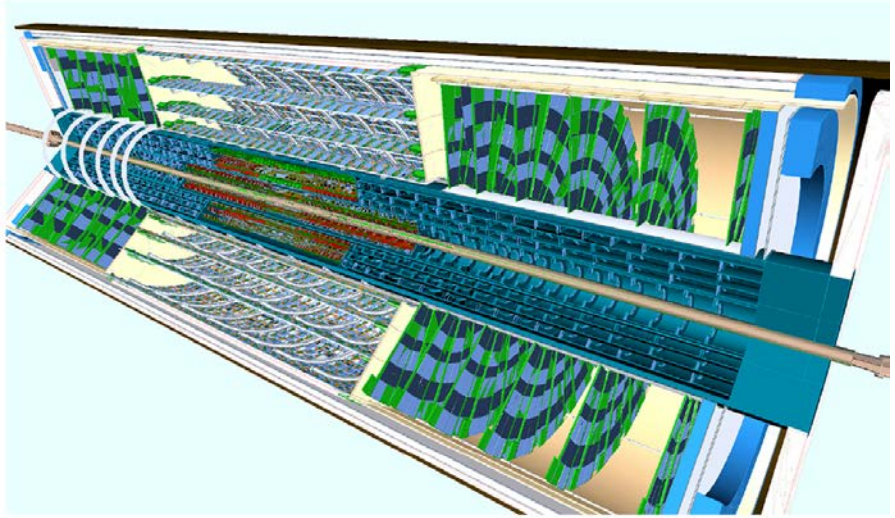
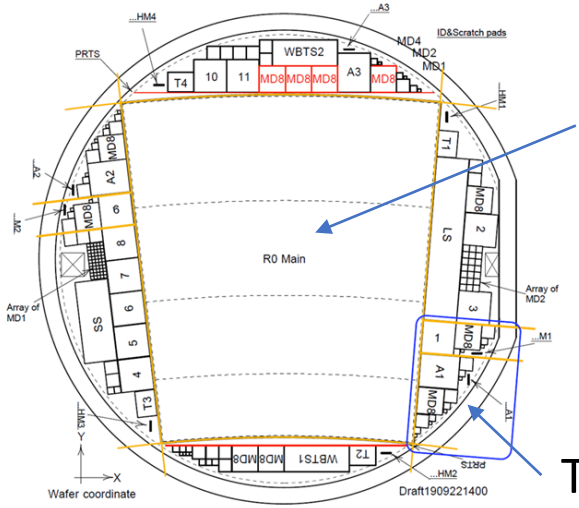
ATLAS Inner Tracker Upgrade



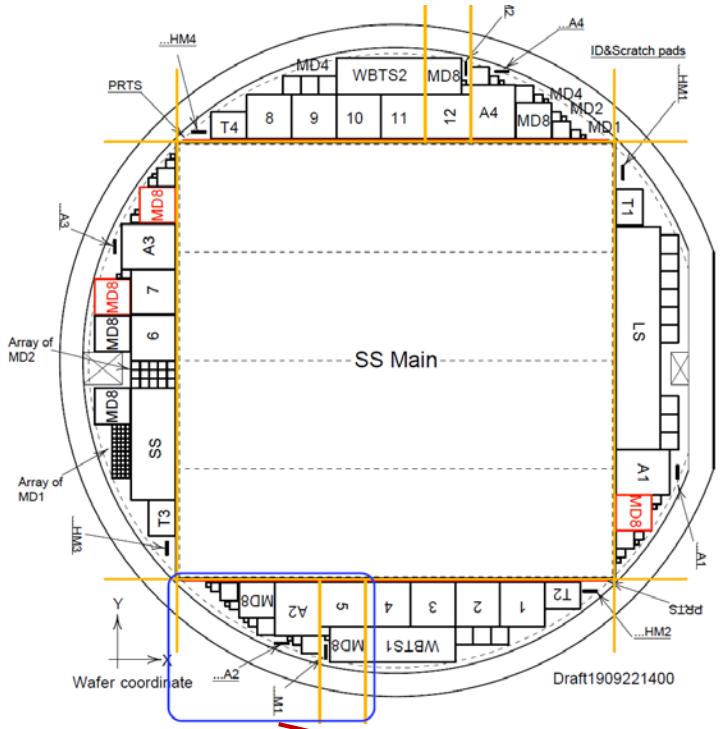
Endcap wafer

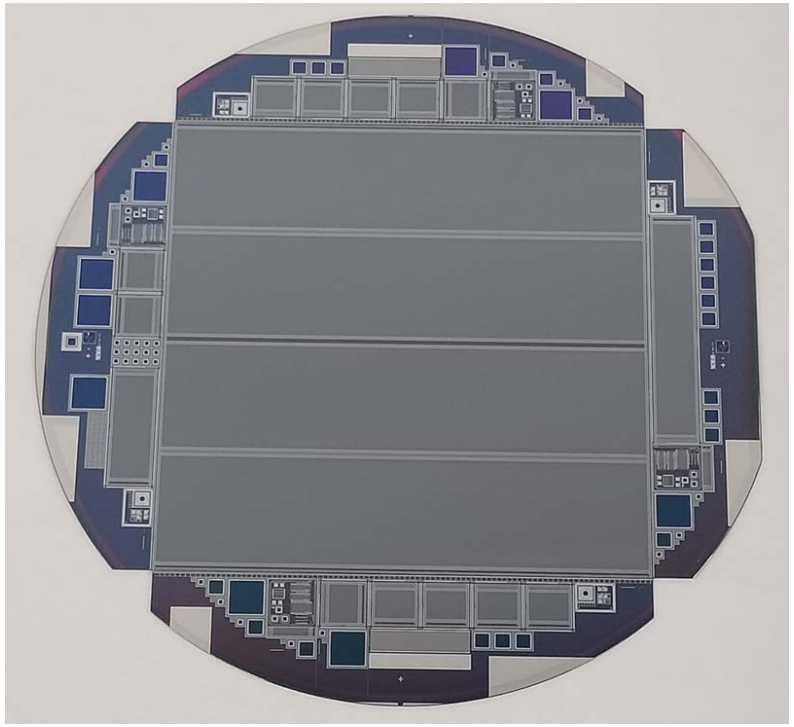


- Overall description of the project is given in the talk by Thomas Koffas
- For the purposes of this talk the main points concerning the wafers are
  - Designed for high radiation environment of the HL-LHC
  - High resistivity - FZ
  - 6’’ wafer
  - n-type strips in p-type bulk, partial depletion operation possible, fast, avoid type inversion, rad hard.
  - P-stop - ensure strip isolation
  - PTP structure - to protect against “beam dump”
  - AC – coupled readout, DC pads for diagnostics
  - Guard ring, Bias resistors, Bias ring, Slim edge

Maintaining Production Quality of Sensors

- The total sensor production for the ITk comprises 24010 sensors
- To ensure consistent quality and performance, we perform:
  - Quality Control – checking the physical and electrical parameters of the full size sensors during production – see talk by Pavla Federicova.
  - Quality Assurance
    - Quality Assurance (QA) is the systematic process of preventing defects during production, rather than identifying them after the fact. It uses well defined testing procedures to monitor the production process, ensuring consistent process control and minimizing variability.
    - QA is done on test structures fabricated at the periphery of the same wafers used to produce the actual sensors, thus ensuring that these structures are a good representation of the sensor quality.
    - The QA procedures are applied to both un-irradiated test structures and samples irradiated to about ~1.5 times the radiation fluence expected in 14 years of detector operation

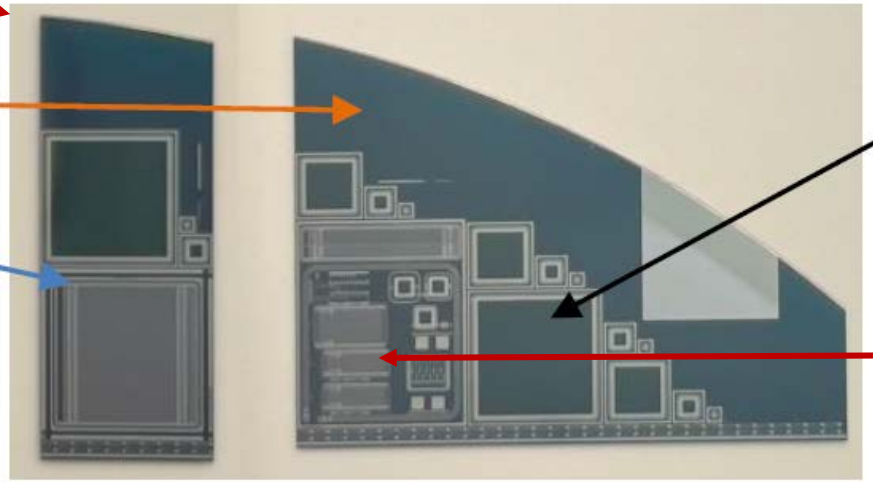




Wafer with Full Size Sensor
and
Test Structures

Test Chip + Monitor Diode

Miniature Sensor (mini)
+
Monitor Diode (MD8)



Monitor Diode (MD8)

Test Chip

Test chips, MD8 , and minis are irradiated at several facilities

Test Chips -- n+gamma $16\times10^{14}\ \mathrm{n}_{eq}\ \mathrm{cm}^{-2}$ + $66Mrad$

Minis -- neutrons or protons $16\times10^{14}\ \mathrm{n}_{eq}\ \mathrm{cm}^{-2}$

MD8 -- neutrons $5.1\times10^{14}\ \mathrm{n}_{eq}\ \mathrm{cm}^{-2}$

After irradiation the samples are annealed at 60C for 80 Mins

Batch – HPK wafer production

↓

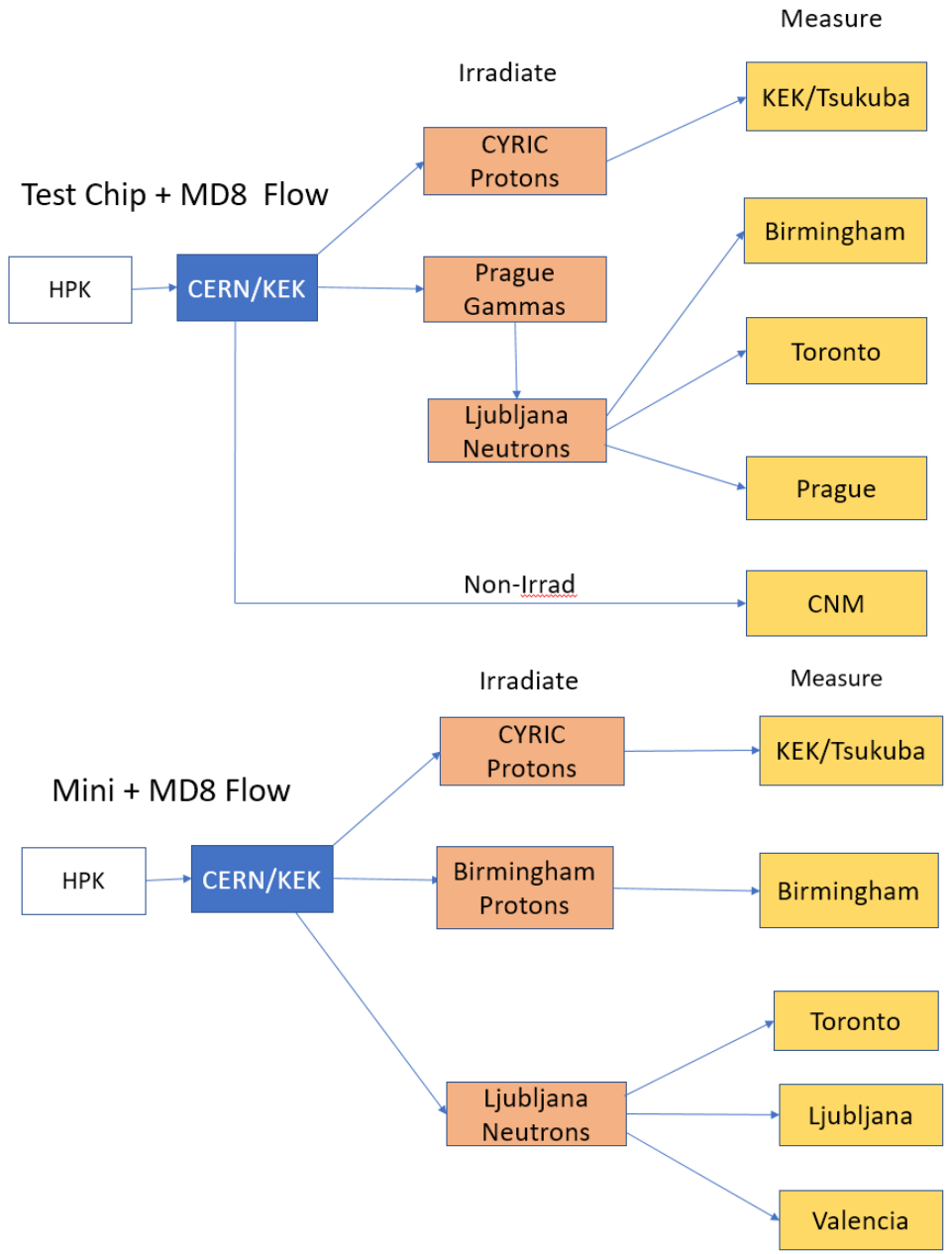
QA set – Diced Test chip + MD8 , Mini + MD8

↓

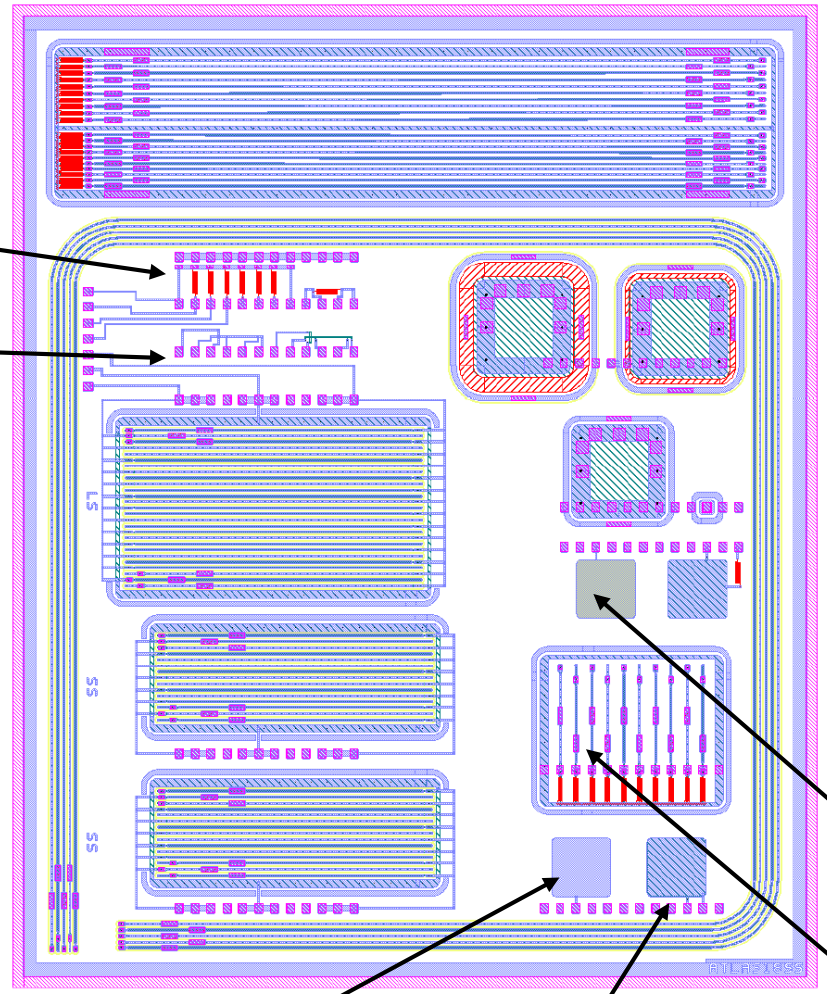
QA piece - TC + MD8, or Mini + MD8

- 23950 QA sets received from 651 batches = 98.4% of production
- 2576 sampled QA pieces delivered to QA sites

- 596 Batches accepted so far
- 6 Batches rejected on basis of QA or QC, or QA, QC combined



Test Chip Structures Used in QA Production Measurements



Bias resistors

Cross-bridge resistors
- strip metal & implant resistance

Interdigitated Strips
Interstrip resistance & capacitance

Field oxide capacitor
Field oxide thickness
Flatband voltage

Coupling capacitor
Value & breakdown voltage

MOS capacitor with p-stop implant – in surface of bulk silicon
p-stop capacitance / thickness / p-stop density

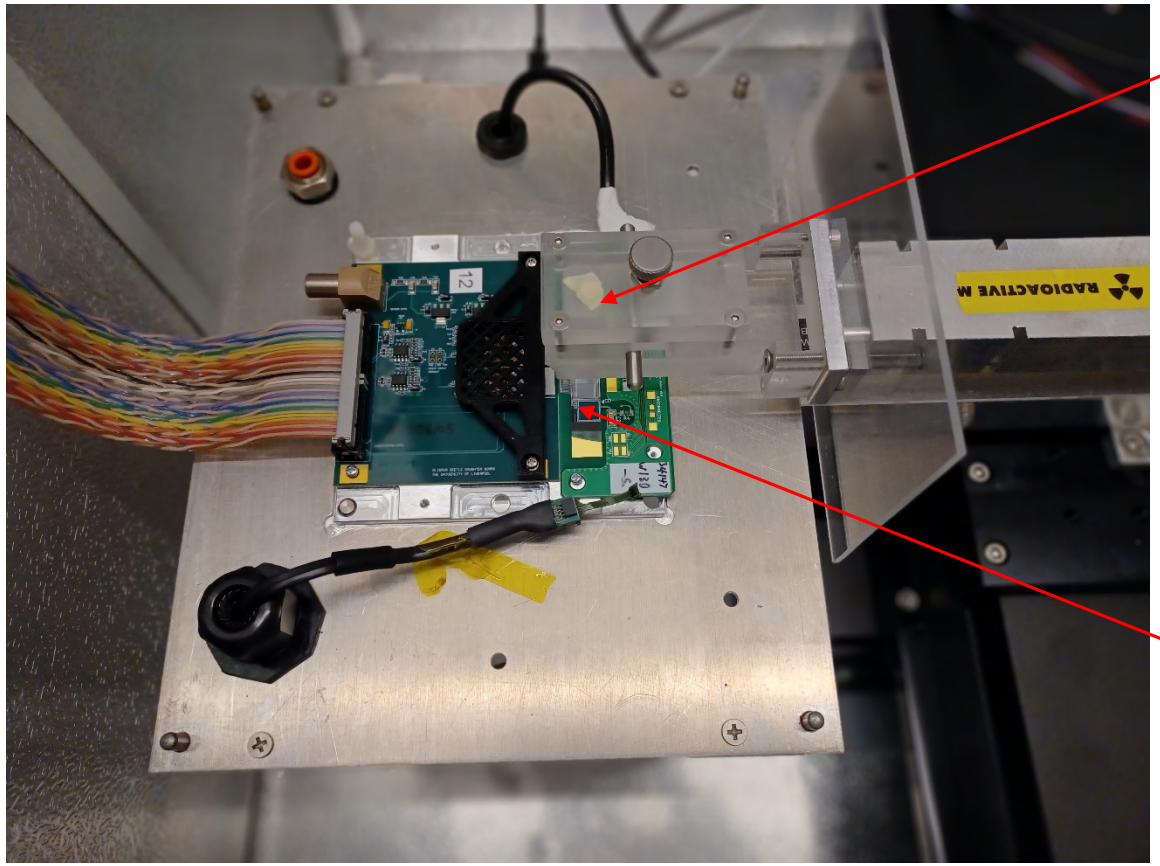
Punch-Through-Protection Structure
PTP breakdown voltage

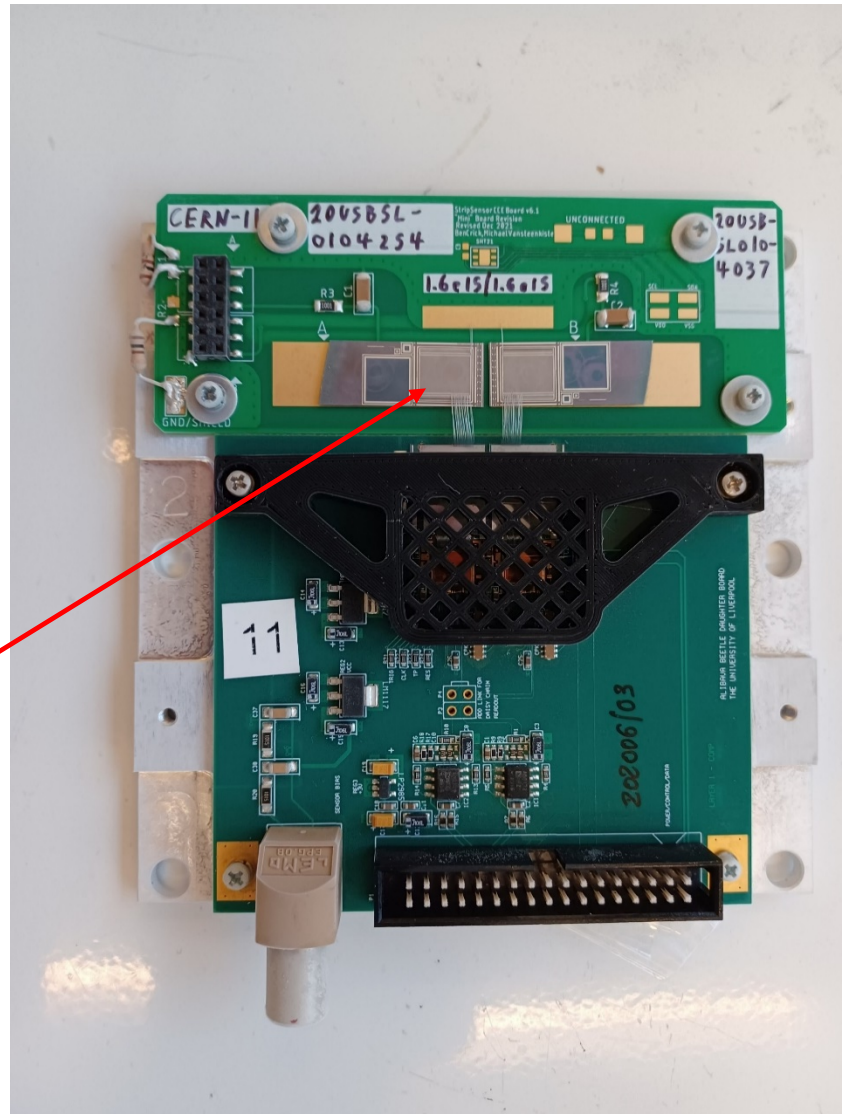
- The Test Structures used in QA are accessible via probe station pads and wirebond pads
- There are additional structures available for specific studies.

- Probe station is used for pre-irradiation measurements.
- Done at room temperature

- Wirebonded chips are used for irradiated measurements. These are done using a custom built automatic setup.
- Done at -20 C to reduce leakage current.

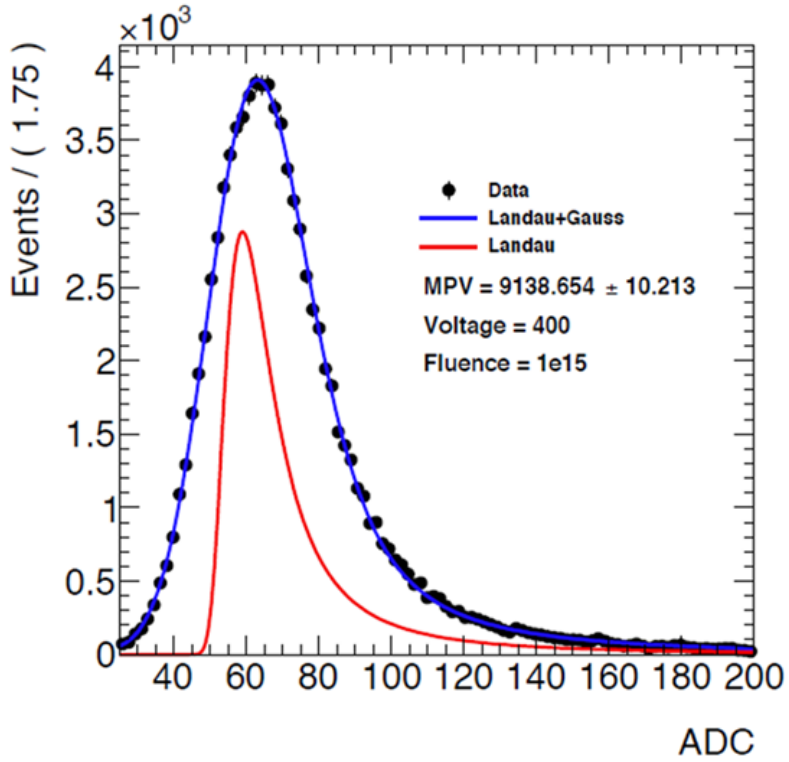
Measurement of Charge Collection of Miniature Sensors



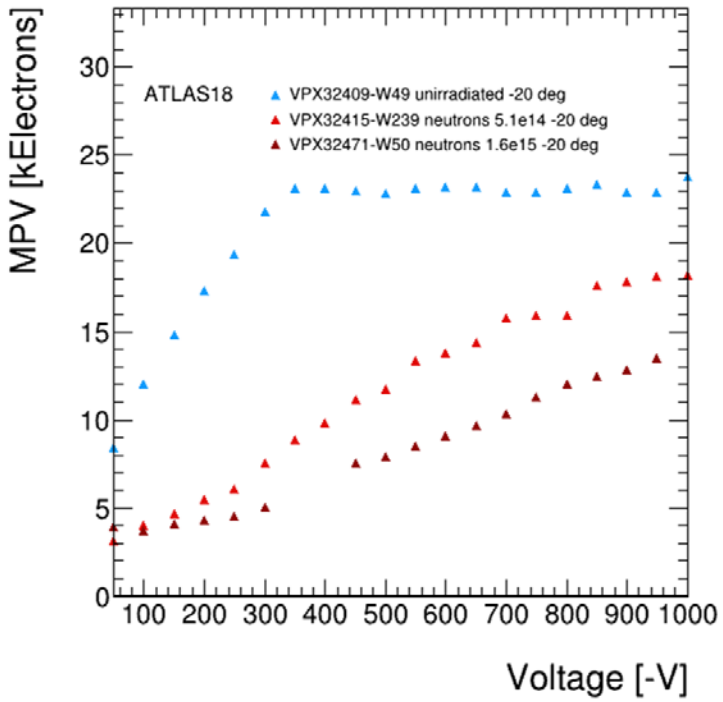


Uses Alibava readout system to measure pulse height spectrum of mini sensor exposed to beta source after neutron irradiation.
Measurements done in freezer at -21 C – Ljubljana uses Peltier cooling

Collected Charge in Neutron Irradiated mini sensors



Typical Pulse Height Distribution with beta source



Unirradiated

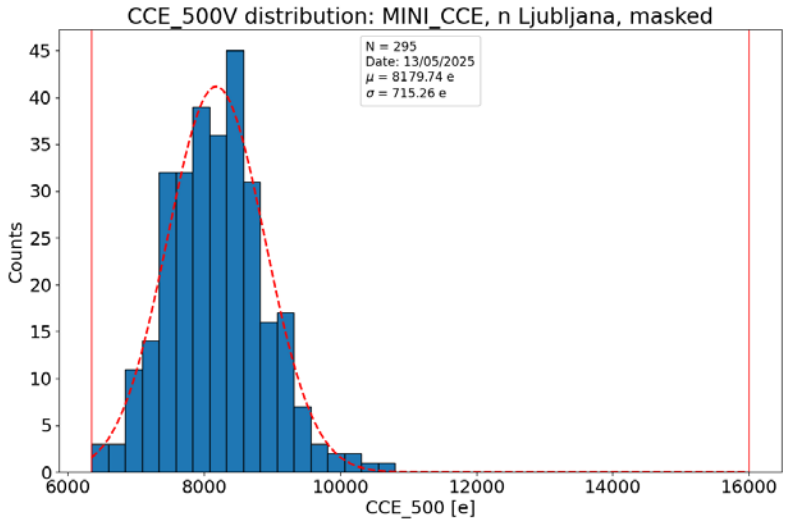
5.1×10^{14} n_{eq} cm^{-2}

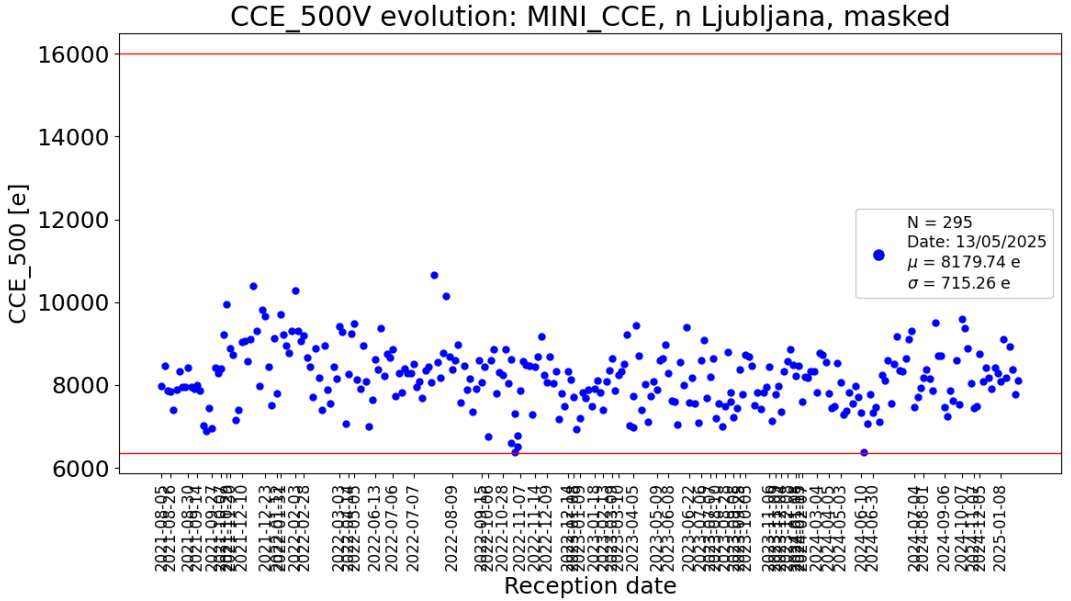
1.6×10^{15} n_{eq} cm^{-2}

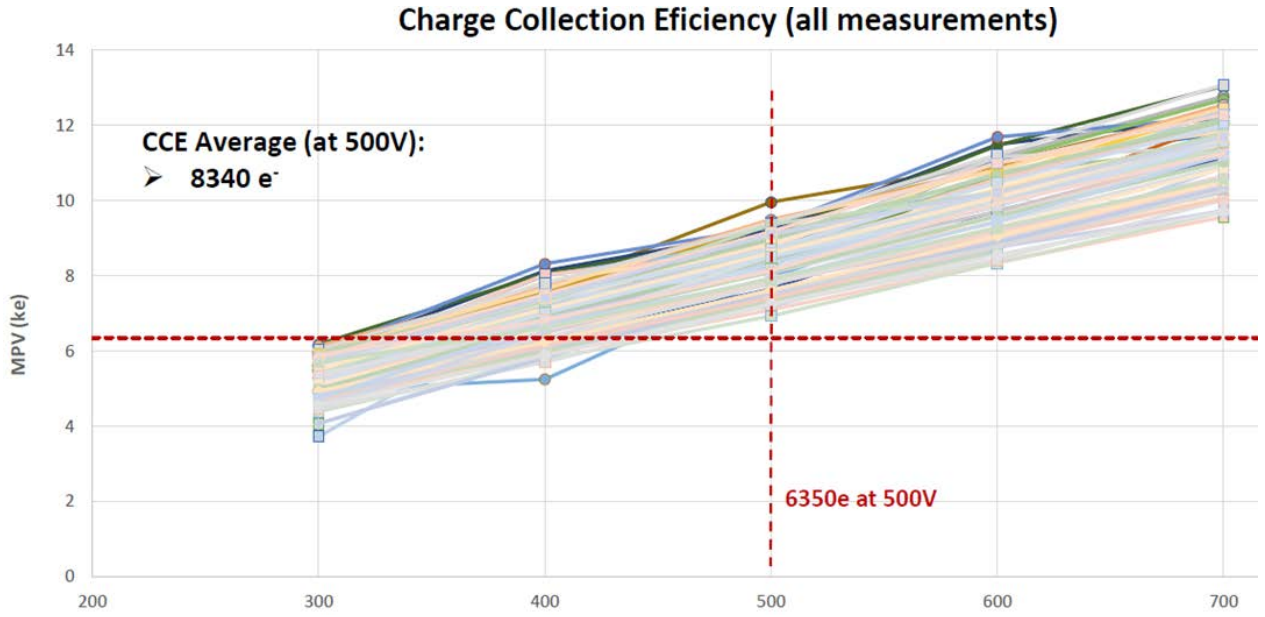
Effect of Irradiation on Collected Charge

- Due to the formation of traps, hadron irradiation reduces the charge collected for a given amount of primary ionization.
- At some point this would compromise the efficiency of track finding

Collected Charge in Neutron Irradiated mini sensors



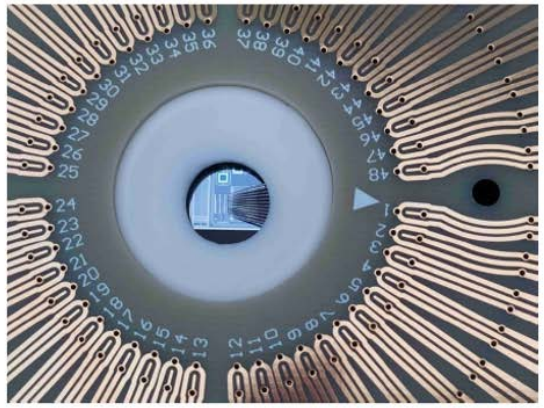




- Acceptance criterion corresponds to Signal/Noise = 10 , and corresponds to detector end-of-life

Measurement of Test Chip Parameters

- Automatic probe table with probe card interface B2220A

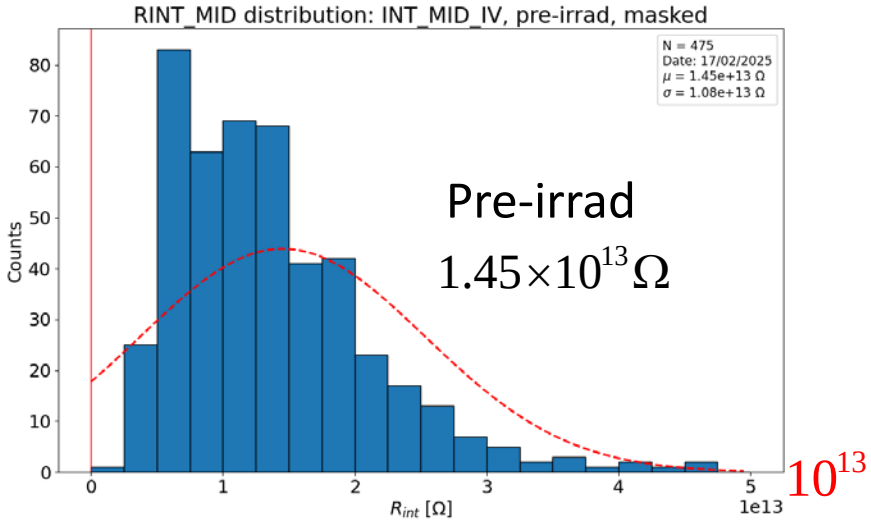


- Measurements at +20 °C and ~40% RH

- Pre-Irrad Test Chips are measured on an automatic probe station
- Data collected at room temperature and humidity

- Irradiated Test Chips are wirebonded to custom PCBs
- Data collected at -20 C using a custom built automatic system.
- Measurements at four sites

Interstrip Resistence

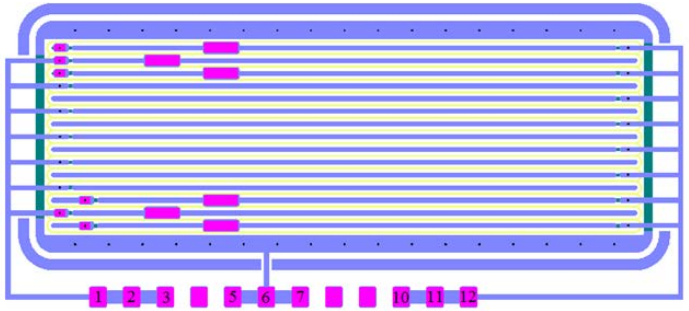


Pre-irrad

$1.45 \times 10^{13} \Omega$

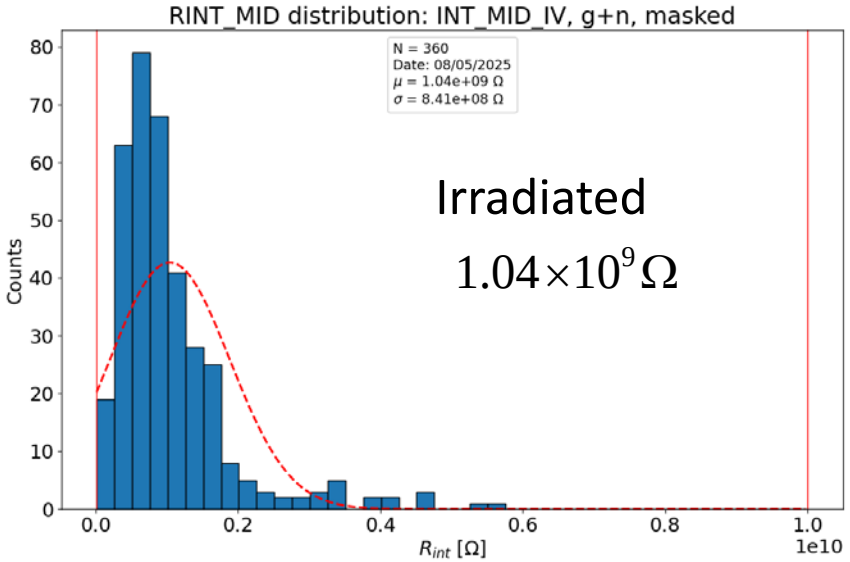
10^{13}

There are three similar structures to give long strip and two short strip spacings. Middle short strip data shown.



$$R_{int} = 2 \cdot R_{meas}$$

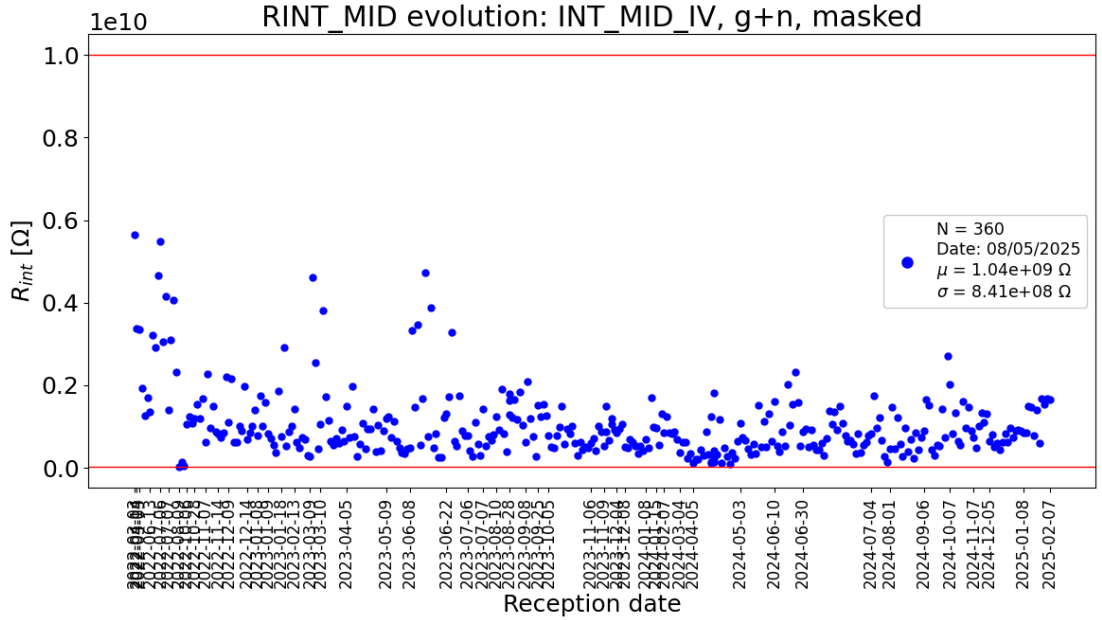
- Due to connection scheme



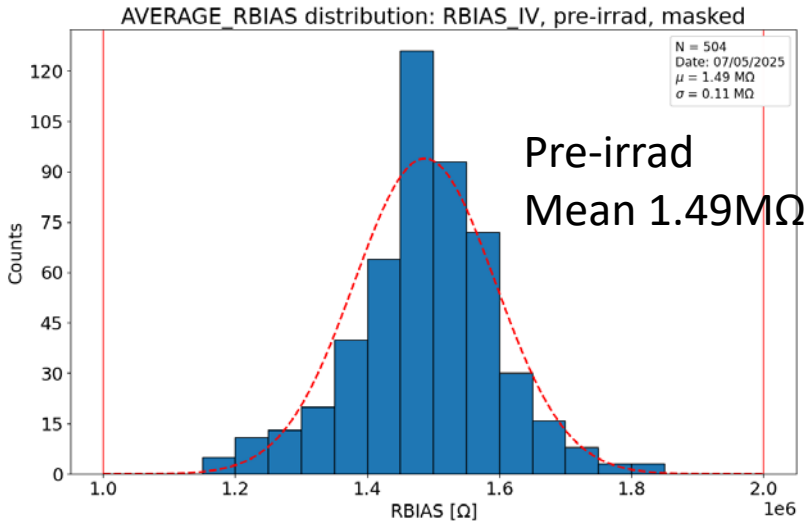
Irradiated

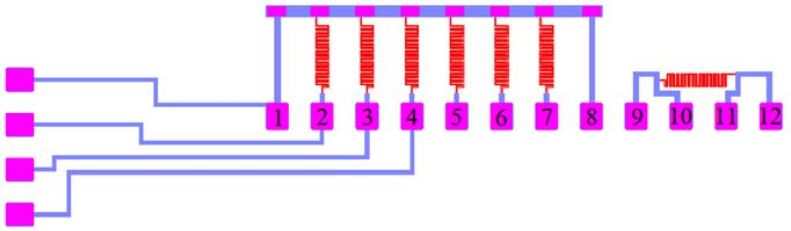
$1.04 \times 10^{9} \Omega$

10^{10}

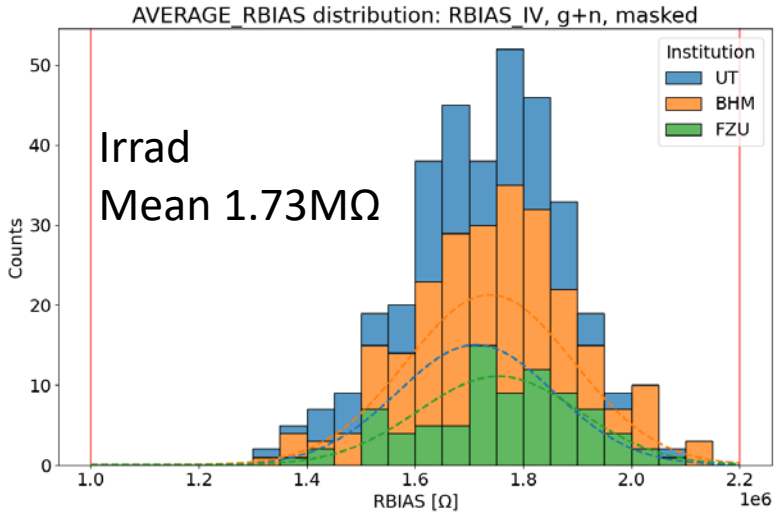


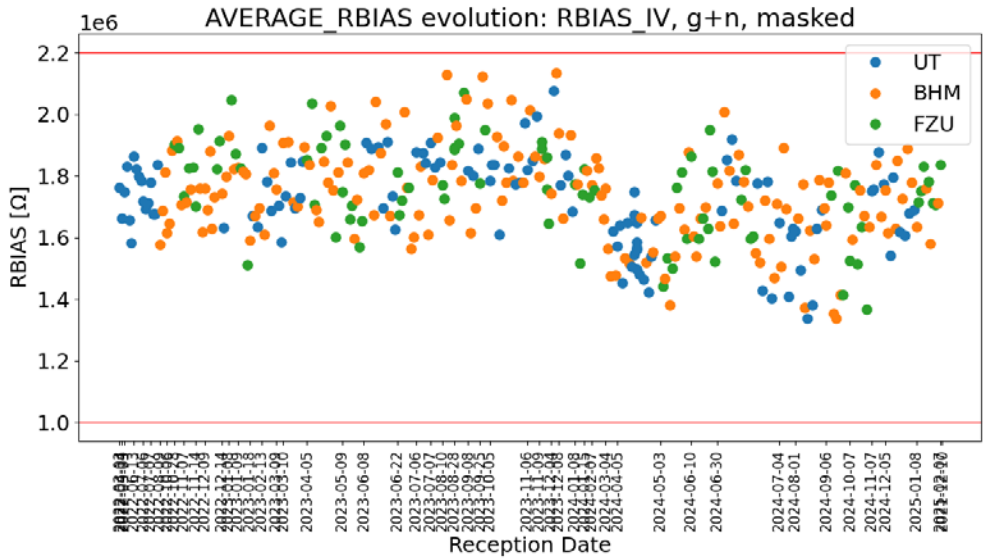
Bias Resister



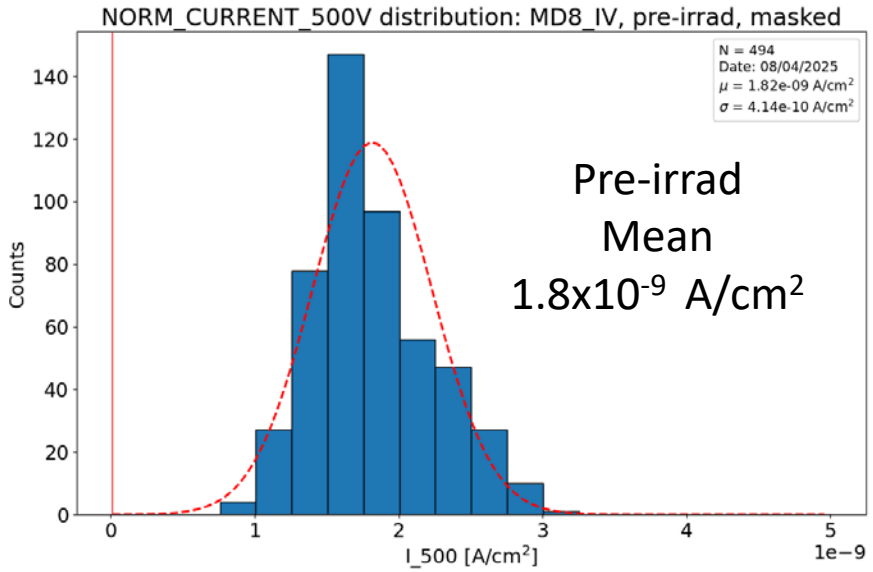


- The value of the polysilicon bias resistors increases somewhat on irradiation, due to the decrease in temperature between the non-irradiated and irradiated measurements. A temperature correction is applied to the measured values.
- There are some variations in the evolution during production.
- The measurements from the three sites are very compatible.



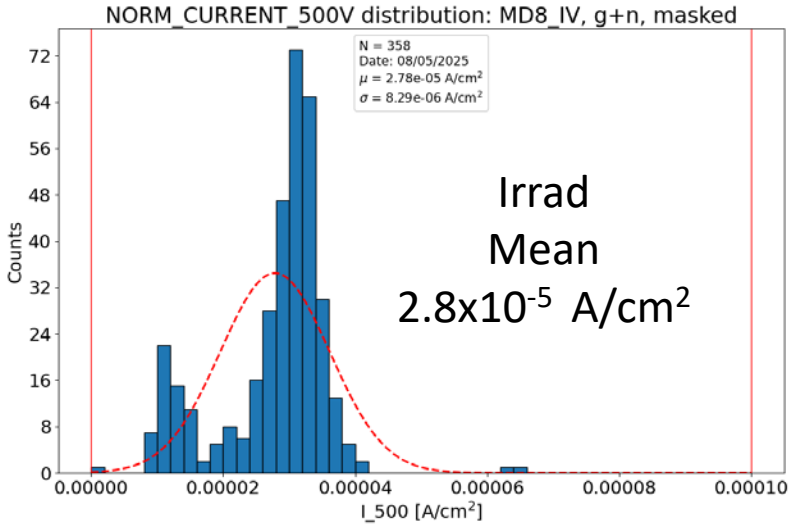


Leakage Current

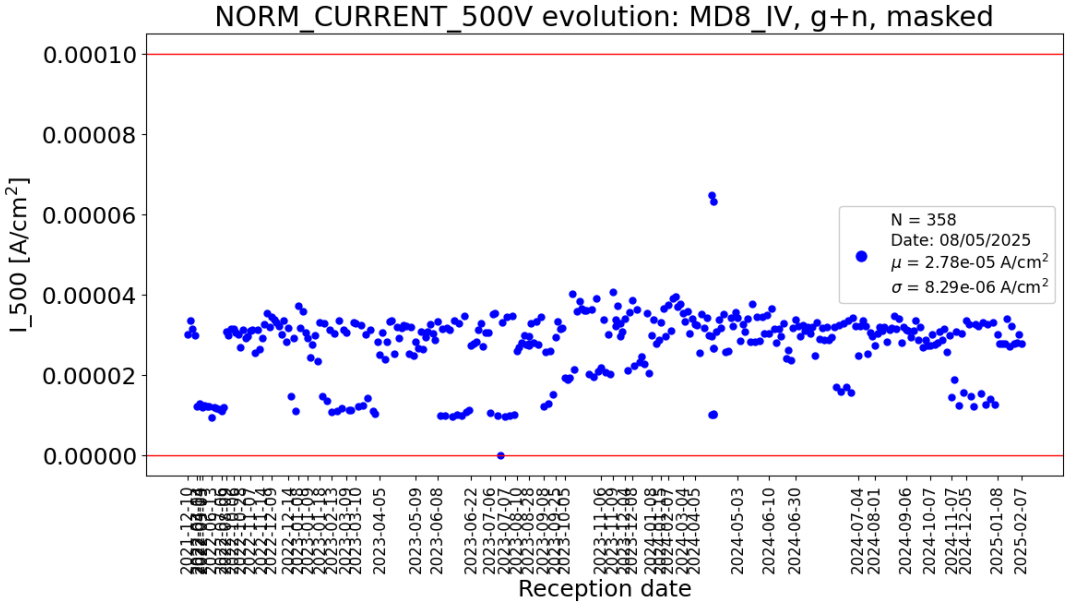


Pre-irrad
Mean
1.8×10^{-9} A/cm^2

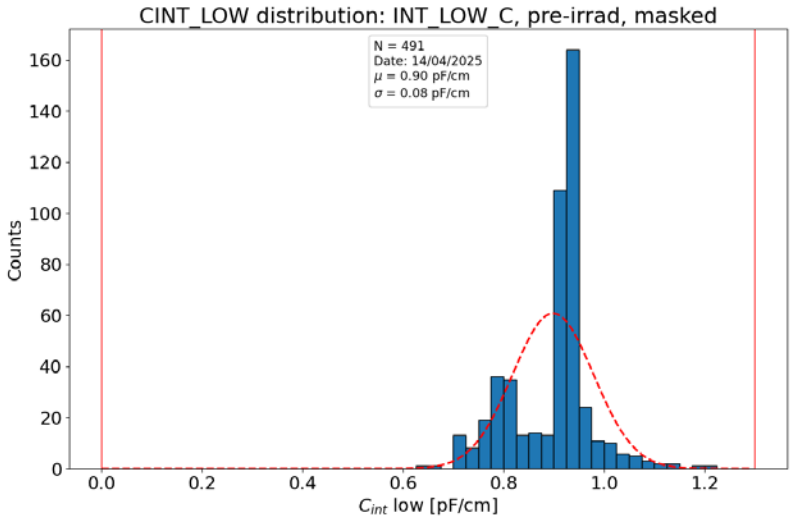
- The end of life leakage current will be a major factor in determining the operability of the detector
- The detector leakage current is monitored using the MD8 on the Test Chip irradiated with ϒ+n.
- As expected, irradiation increases the leakage current by four orders of magnitude – but the values remains within acceptable limits, and is constant during production
- The small peak is due to one site initially measuring at -24C, due to high current problems in preproduction.



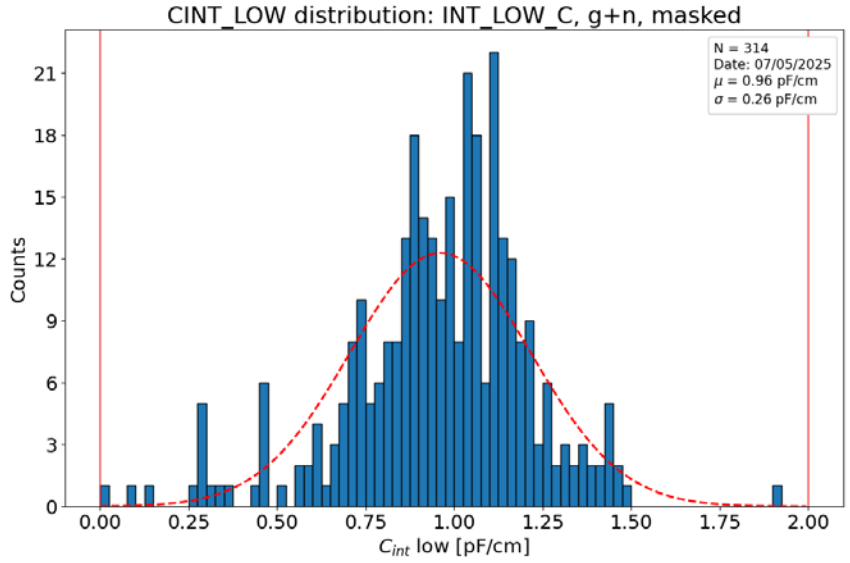
Irrad
Mean
2.8×10^{-5} A/cm^2

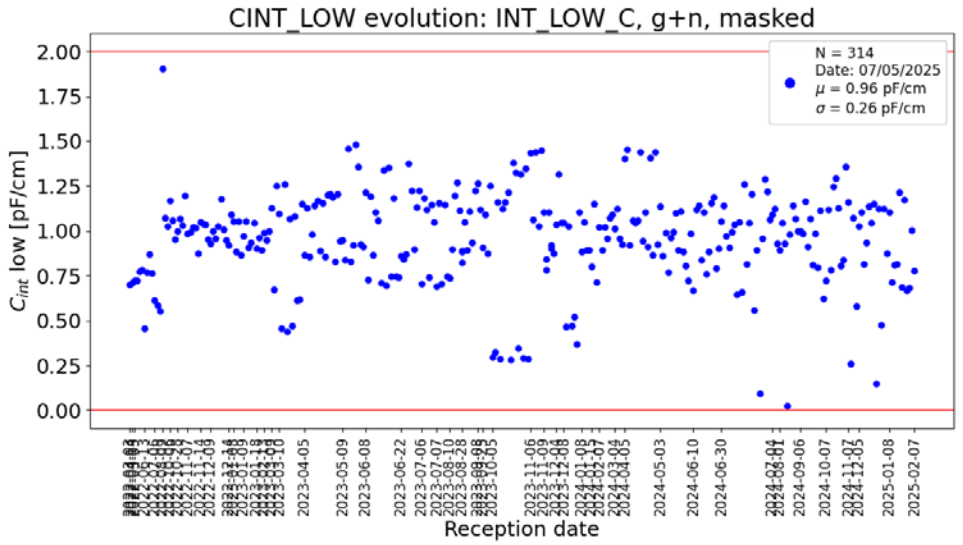


Interstrip Capacitance

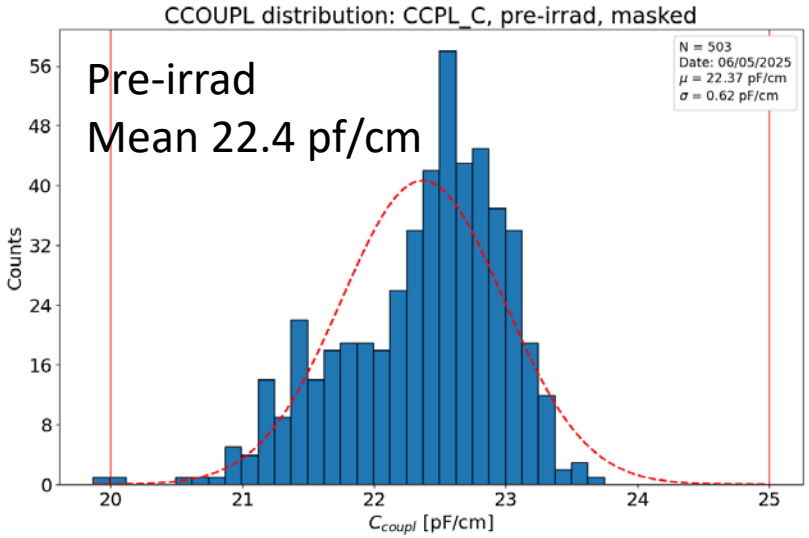


- Interstrip capacitance is measured using the same structure as are used for the interstrip resistance measurement
- Due to the capacitance of the switching array used in the irradiated measurement system, the correction for this is of the same order as the interstrip capacitance
- This leads to the broadening of the irradiated distribution.
- Nonetheless, we see that the value of the capacitance does not appreciably change on irradiation, and does not evolve in production

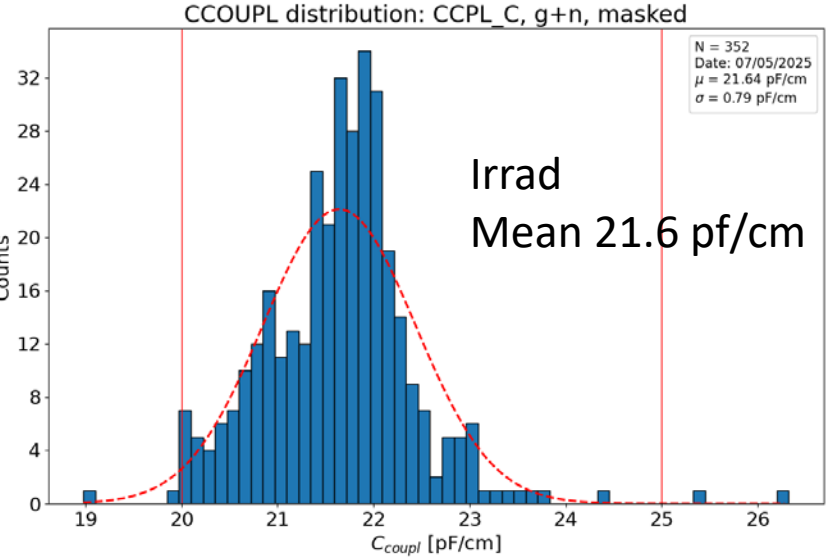


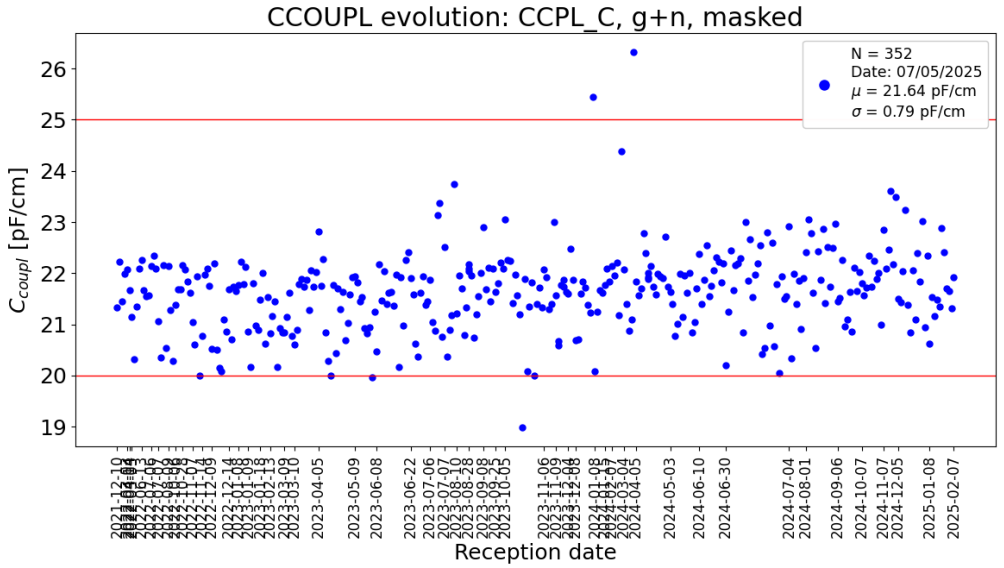


Coupling Capacitor

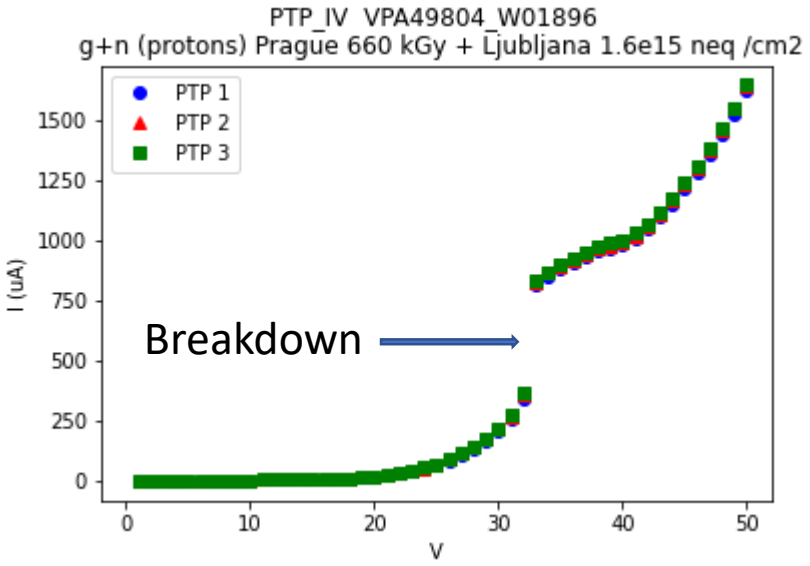


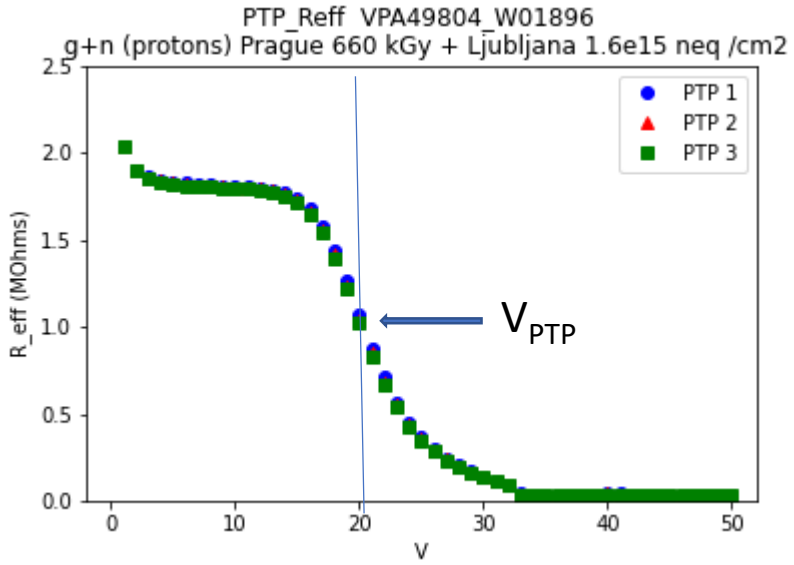
- The strip to readout coupling capacitor is a major determinant of the detector performance.
- On irradiation, the value changes somewhat, but this is within the calibration uncertainty of the irradiated measurement.
- The value is constant within acceptable limits
- The low shoulder appears in both the probe station measured distribution and the wirebond measured - is probably a real feature

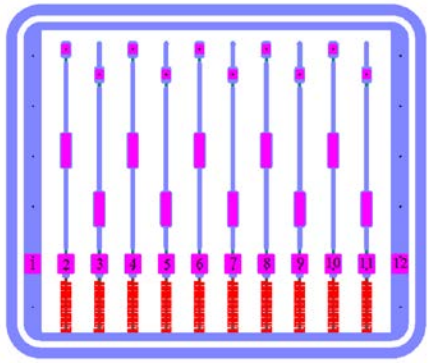




Punch Through Protection Structure

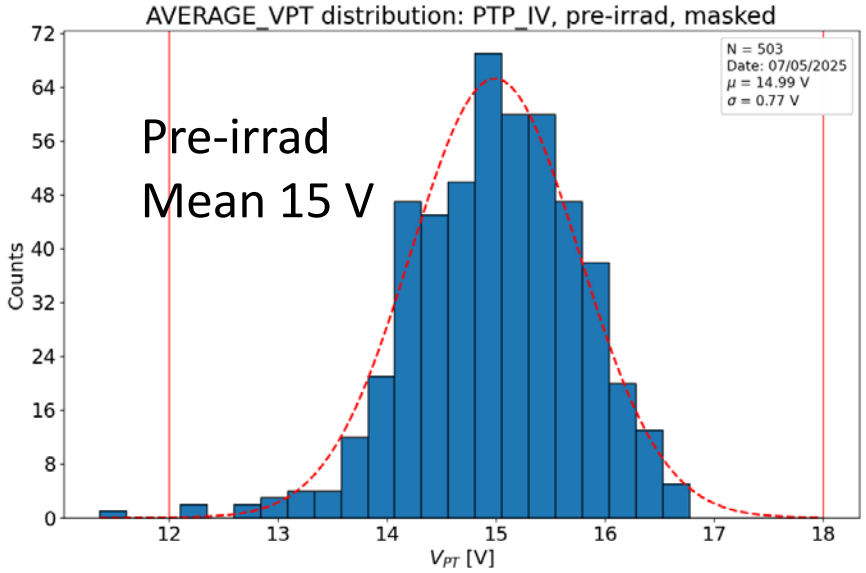


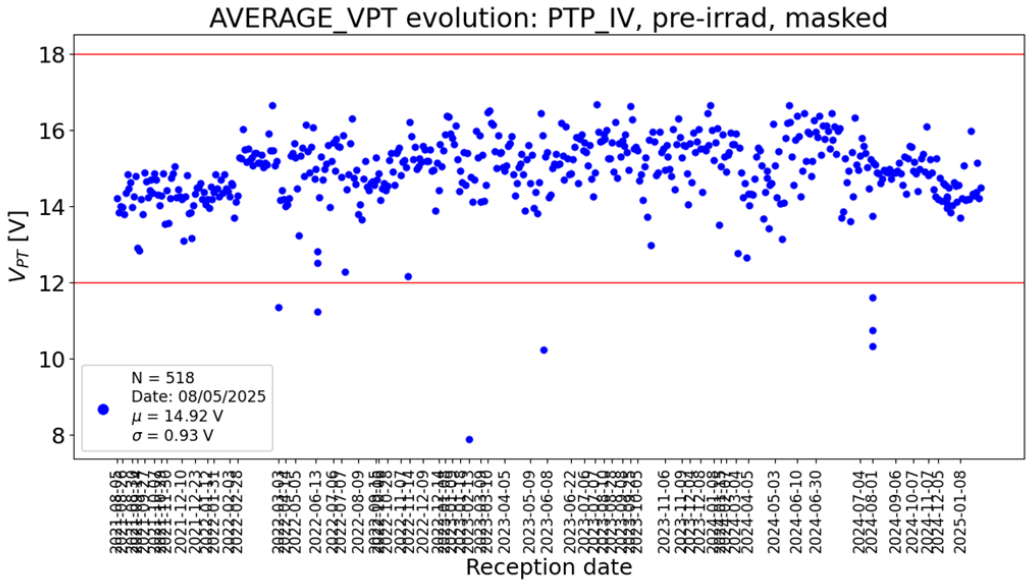


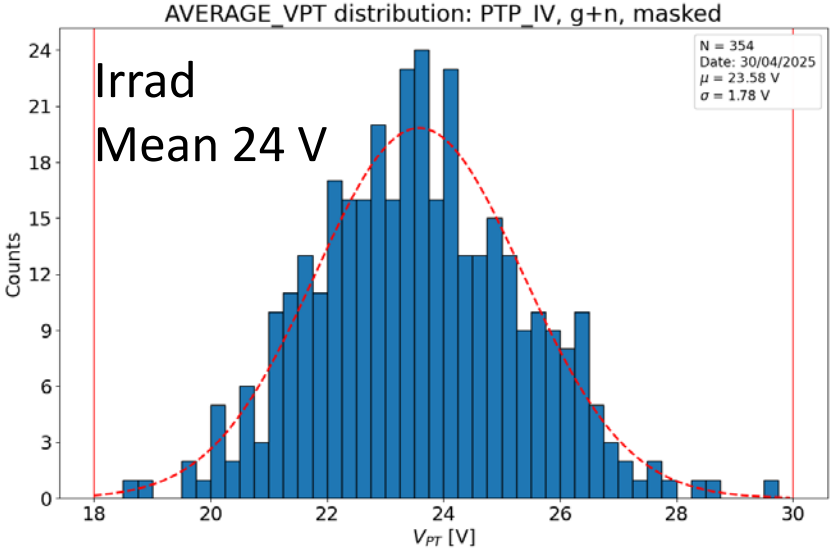


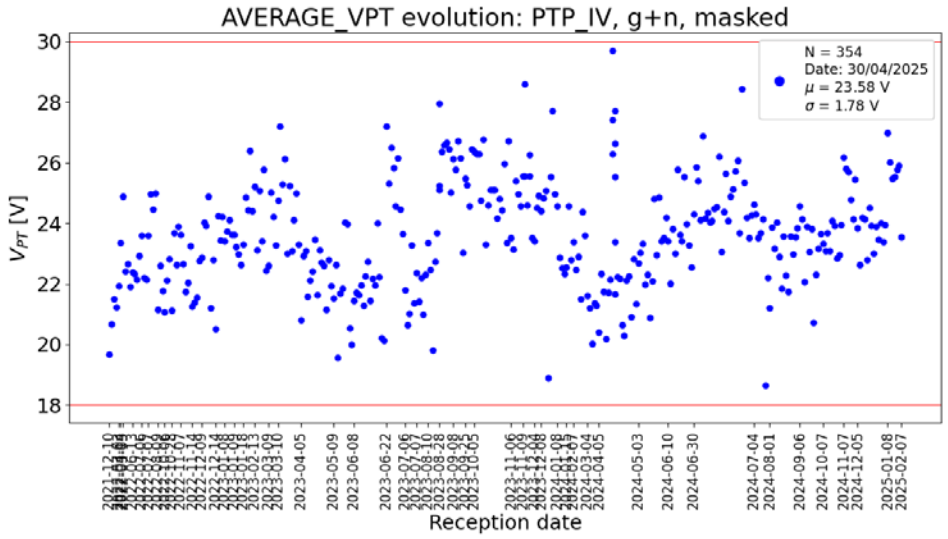
- In normal operation there is no potential difference across the coupling capacitor.
- If the potential difference between the strips and the backplane were reduced by a large ionization in the bulk, the bias potential could appear across the coupling capacitor – and so damage it.
- The PTP structure is a narrow gap region between the bias and the strip implants with a p-stop implant in between – it will break down if a large potential develops, and ground the strip – thus protecting the strip from large currents.
- The performance is monitored by means of an IV curve, and a calculation of the effective resistance of the structure.

Punch Through Protection Structure

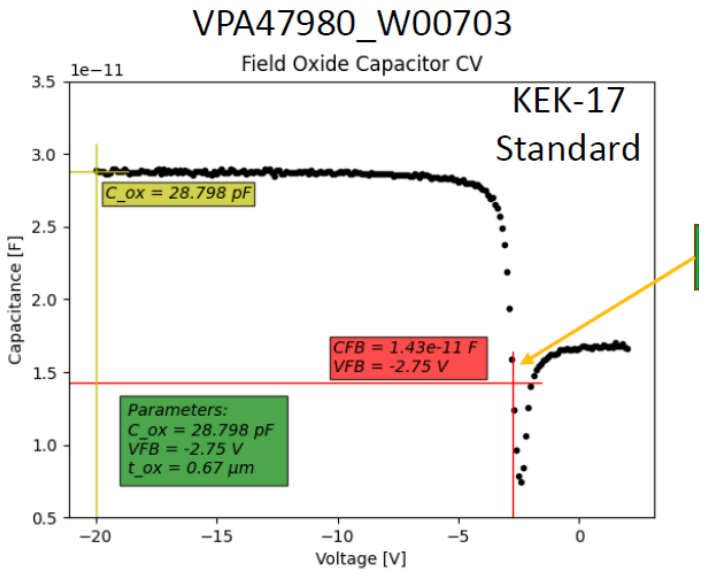








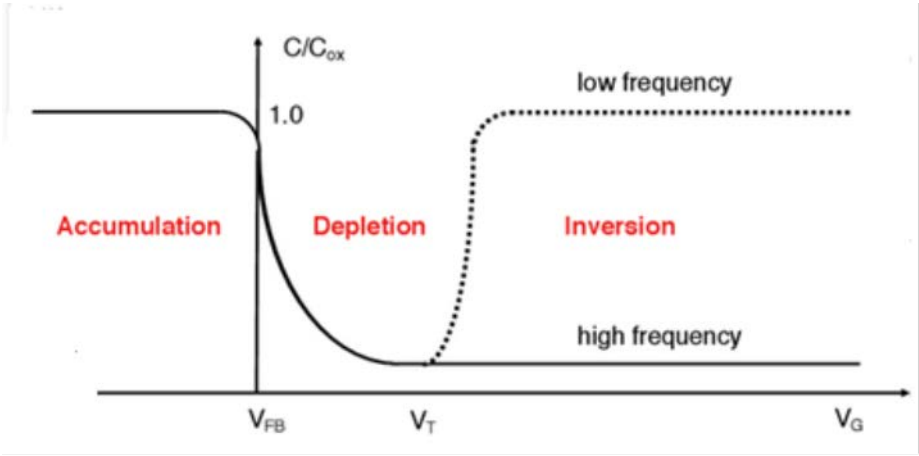
Field Oxide Capacitance and Thickness from Field Oxide Cap

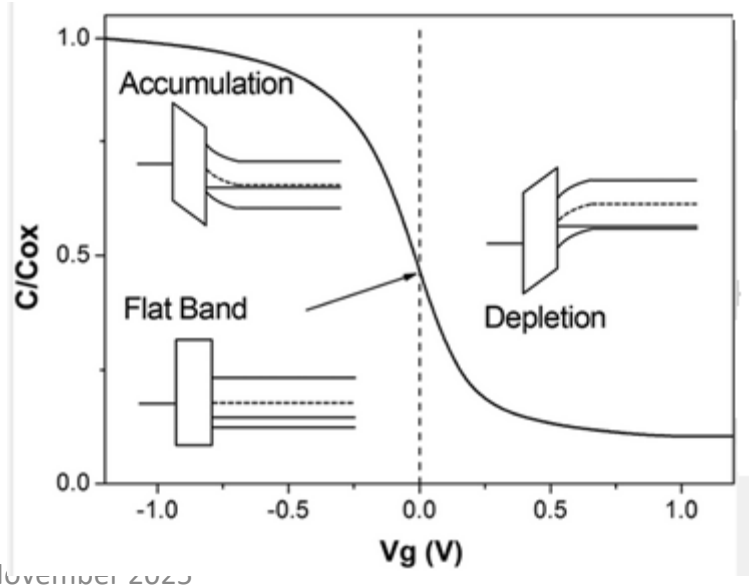


- The oxide capacitance – and hence thickness - is extracted from a CV plot in the the high accumulation region.
- The flatband voltage is then given by

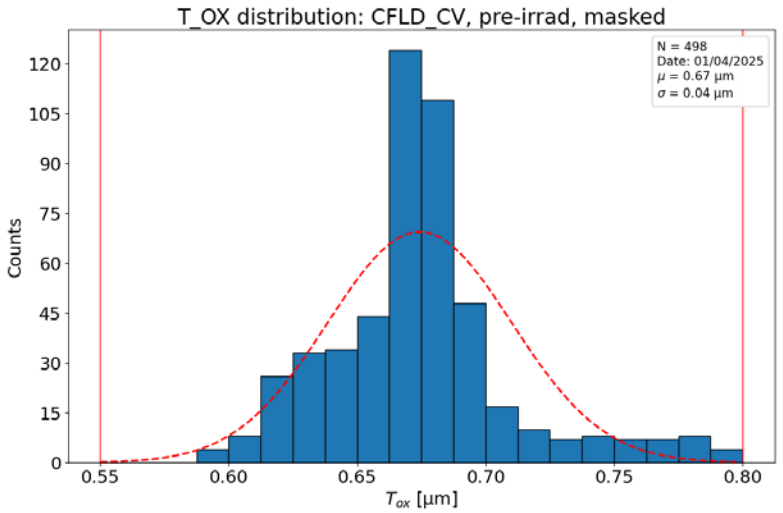
$$V_{FB} \longrightarrow \frac{1}{C_{FB}} = \frac{1}{C_{ox}} + \frac{\lambda_d}{\varepsilon_{Si}} \qquad \lambda_d = \sqrt{\frac{\varepsilon_{Si} \cdot k \cdot T}{q^2 \cdot N_A}}$$

- V_{FB} is a measure of the interface charge between the oxide & silicon

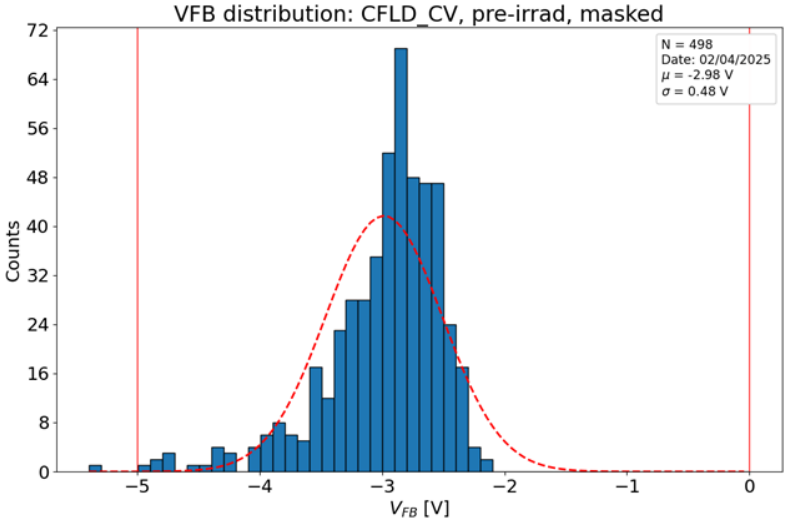


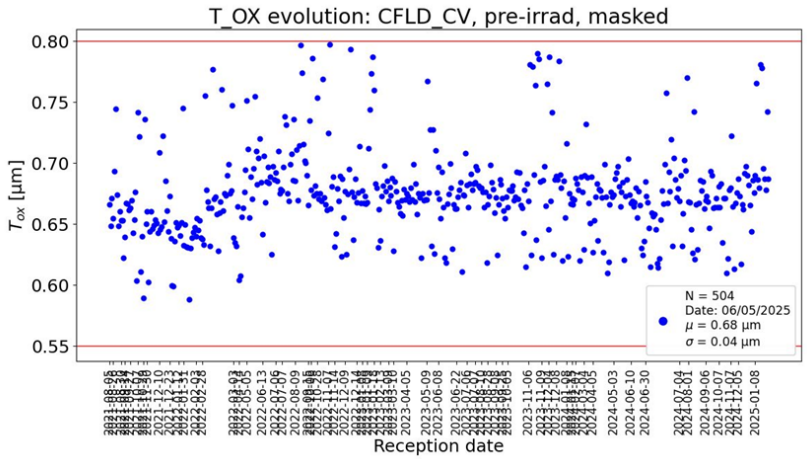


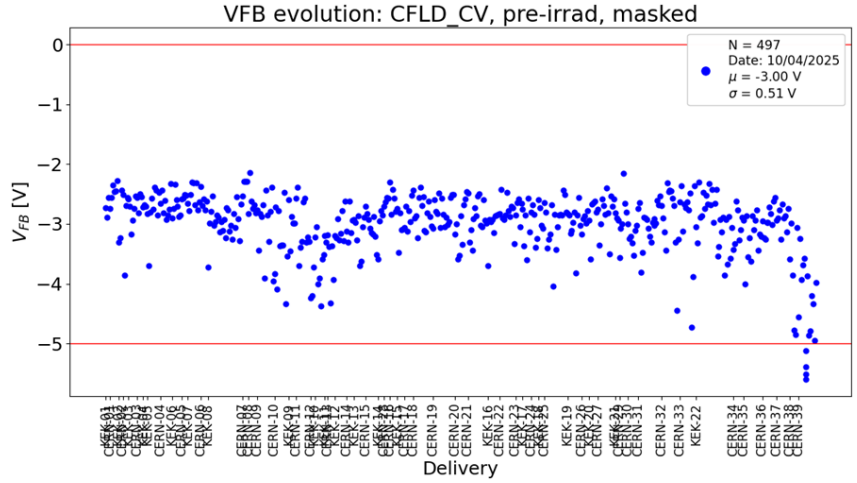
Field Oxide Capacitance and Thickness from Field Oxide Cap



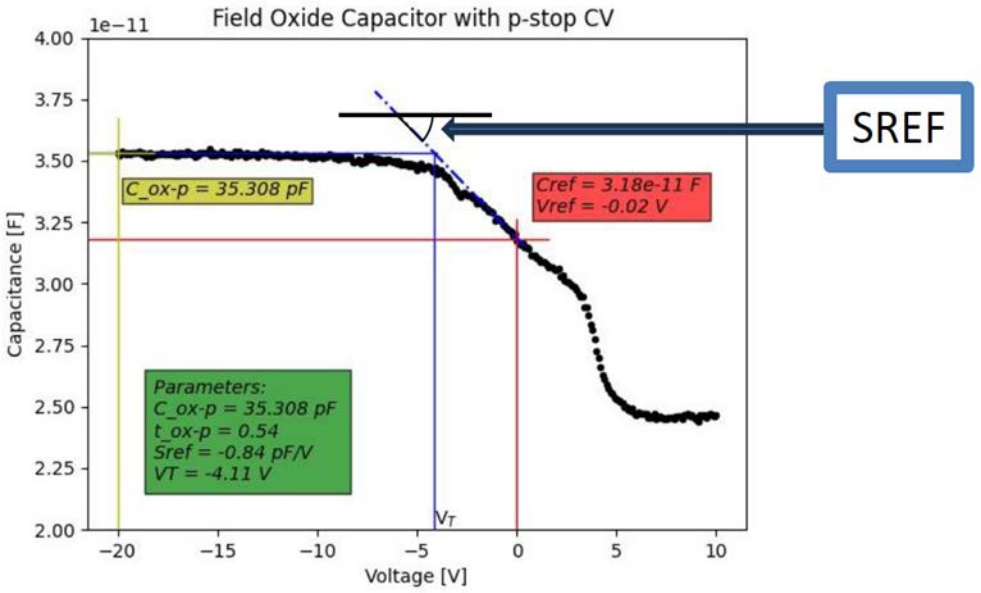
- During production the field oxide thickness, and hence flatband voltage, has remained constant within the acceptance limits.
- Recent batches exhibit a drop off in V_{FB}
- None of the other measured parameters reflect this change in V_{FB}
- This could reflect a lower quality oxide, perhaps due to large trapped charge.
- HPK has understood and rectified this effect – *see talk by Miguel Ullan*



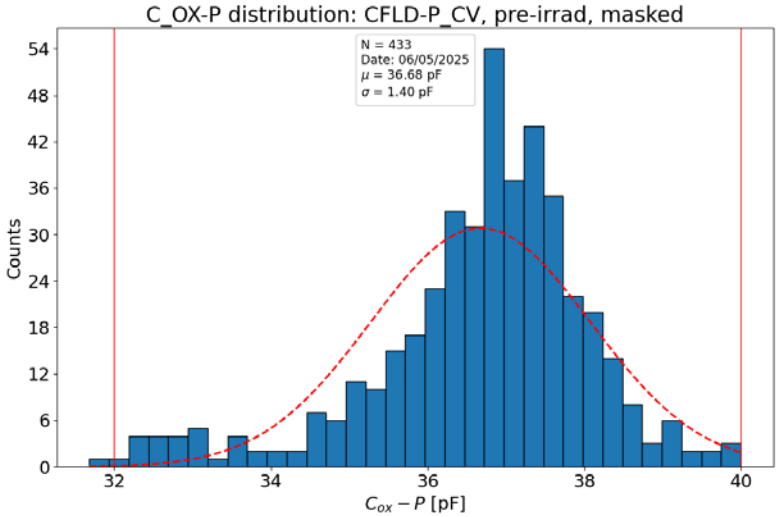


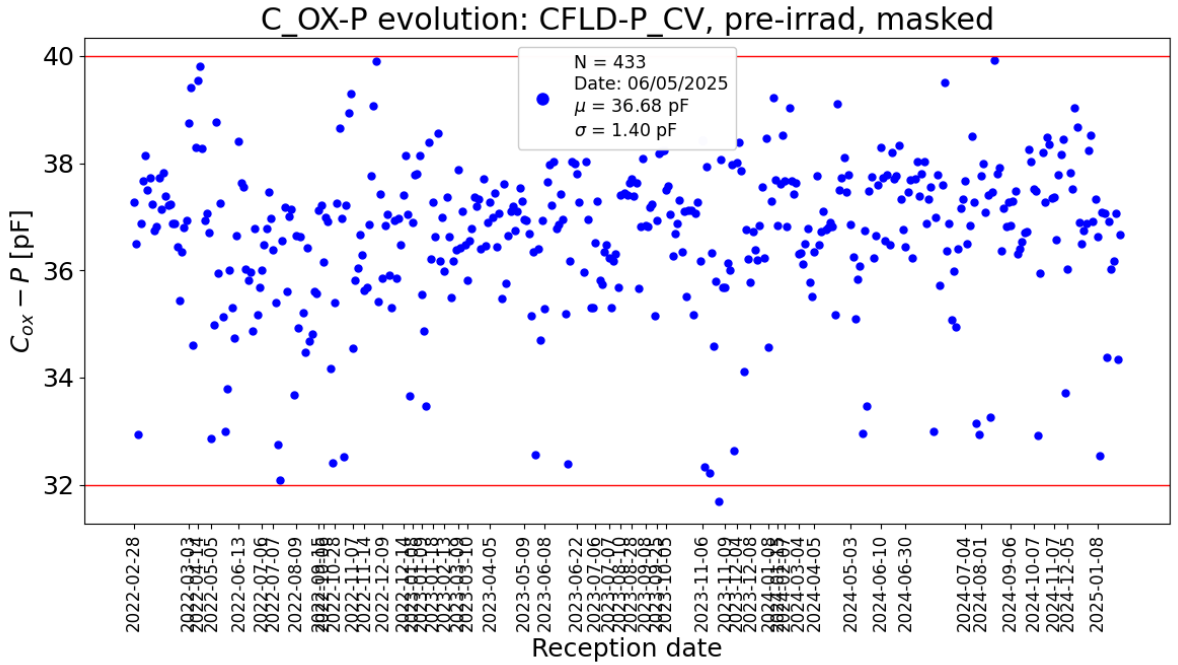


P-stop Oxide Capacitance and Thickness from Field Oxide Cap with p-implant Layer

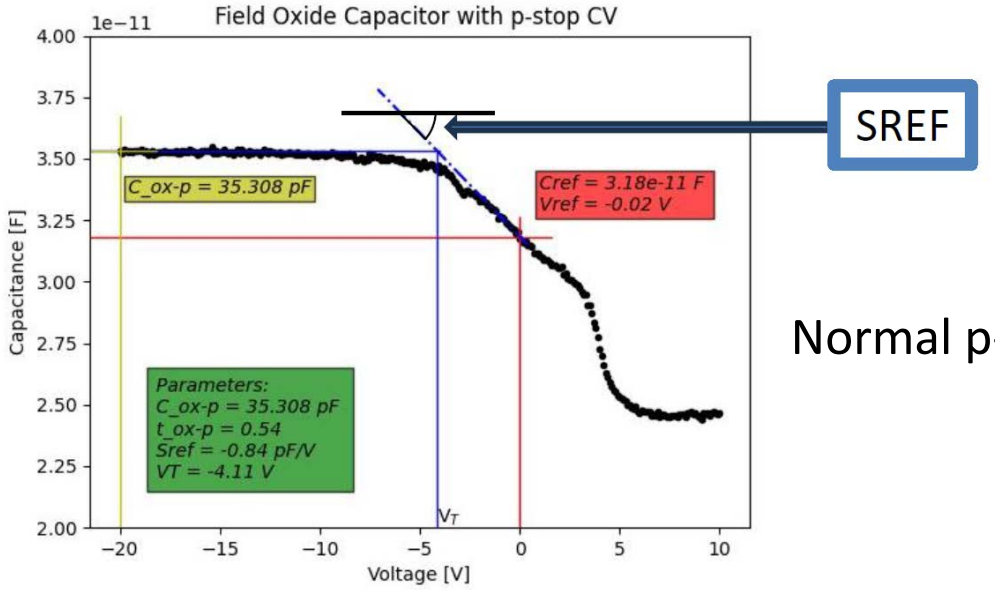


- The capacitance, and hence thickness, of the p-implant layer is again extracted from a CV plot
- It has generally remained within acceptable limits
- However there is a tail to low values, and there are outliers.
- More on this in a moment

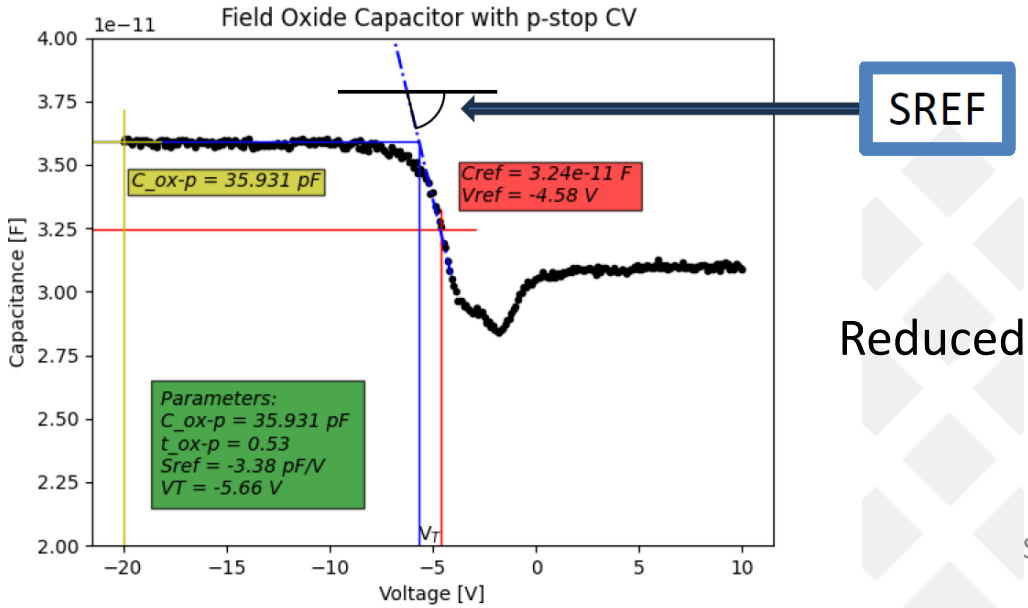




P-stop Oxide Capacitance and Thickness from Field Oxide Cap with p-implant Layer



Normal p-doping

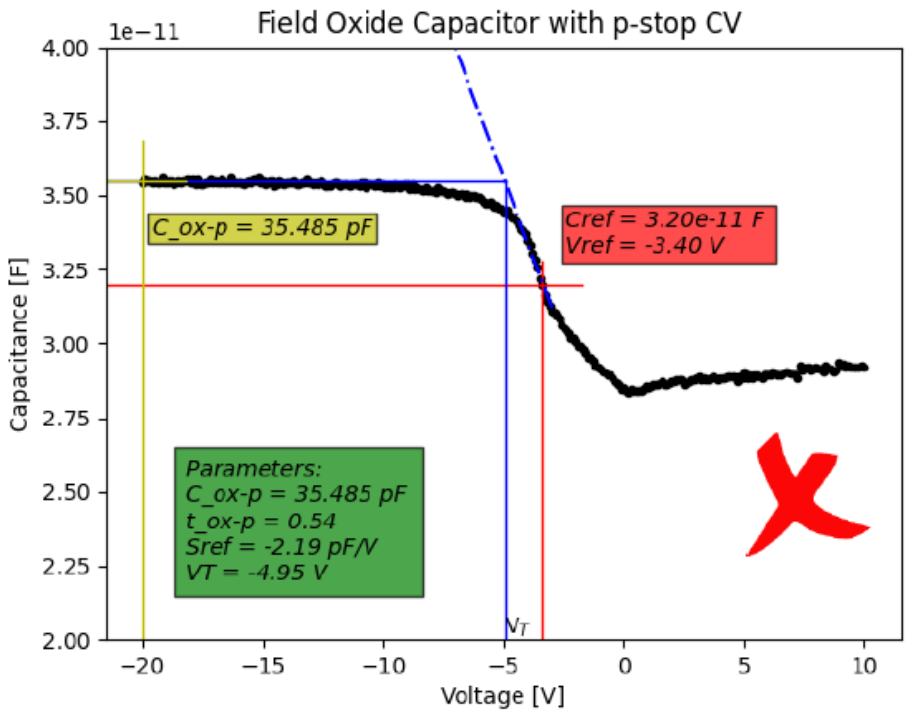


Reduced p-doping

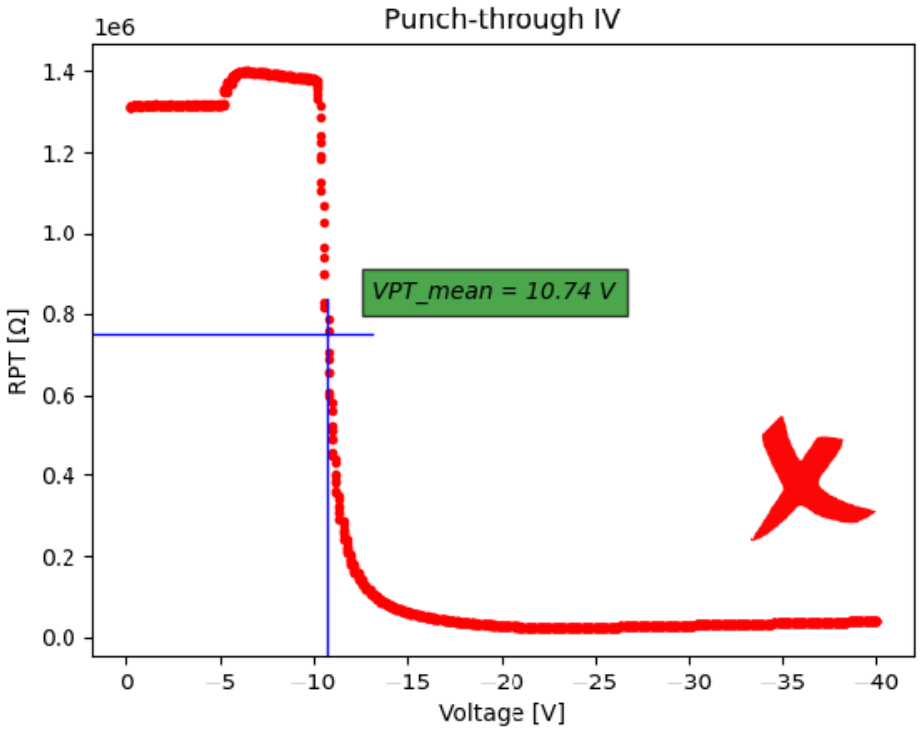
- Structurally the p-stop capacitor is a MOS capacitor with a p-stop implant in the silicon below the MOS oxide layer.
- The p–stop implant affects the depletion rate of the silicon under the implant.
- The CV curve going from enhancement to depletion thus allows us to monitor the p-stop doping level – a faster depletion rate reflects a lower p-stop doping level.
- This is reflected in the initial rate of the capacitance change – parametrized by SREF in the figures opposite.
- This effect manifested itself in a batch rejected on both QA and QC criteria (*see talk by Pavla Federicova for QC, and Miguel Ullan for details*)

Rejected batch failing QA criteria due to lower p-doping

VPA50930_W03074_7_A2_CFLD-P_CV_001



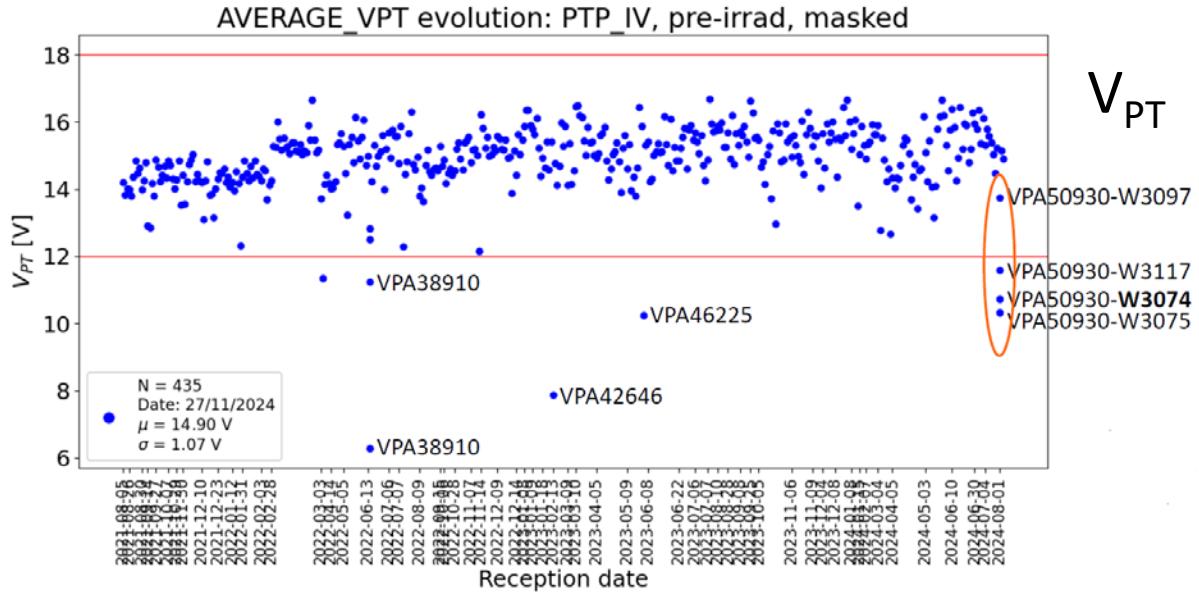
VPA50930_W03074_7_A2_PTP_IV_001



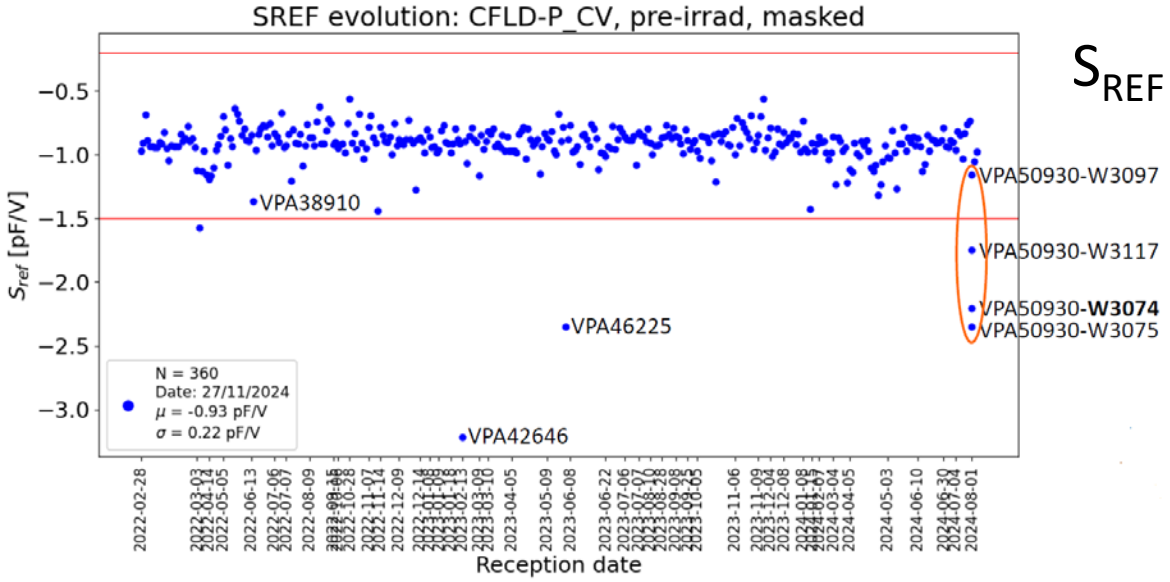
S_{REF} -2.2 V *cf* normal ~ -1 pF/V

Punch through voltage reduced to 10.7 V *cf* normal 15 V

Rejected batch failing QA criteria due to lower p-doping



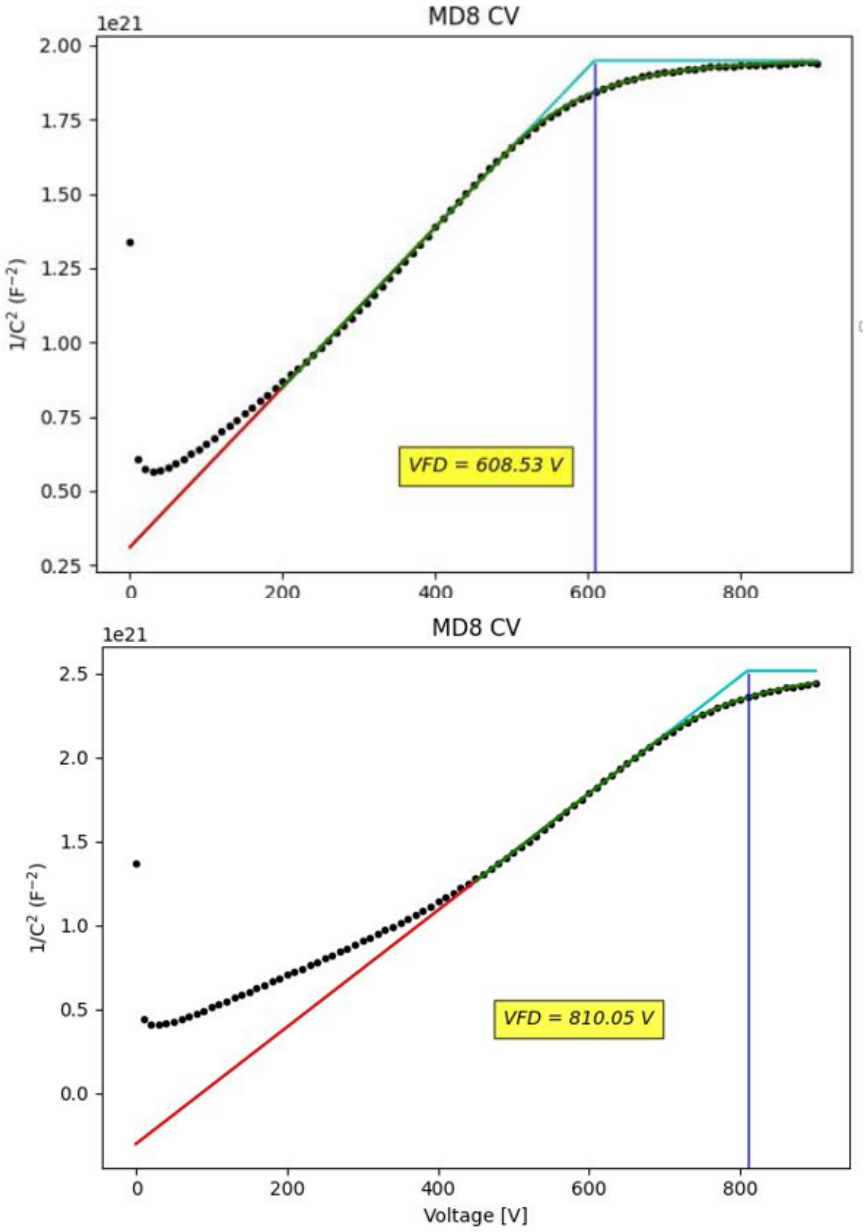
V_{PT}



S_{REF}

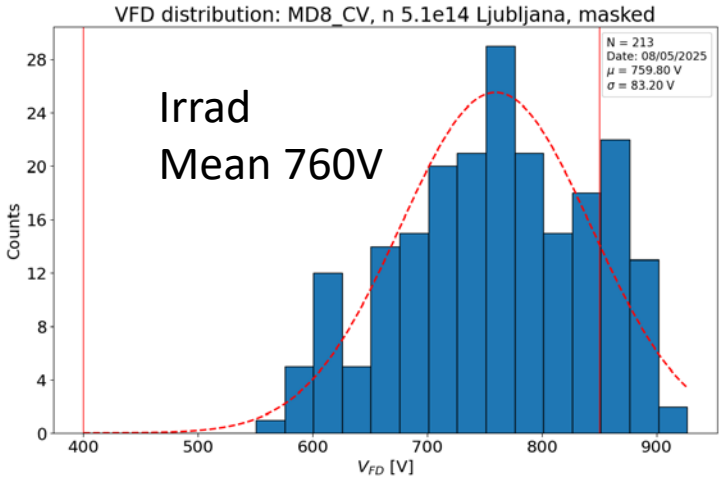
Anomalous p-doping seen in properties of both punch through protection and CV measurement of MOS capacitor with p-stop implant

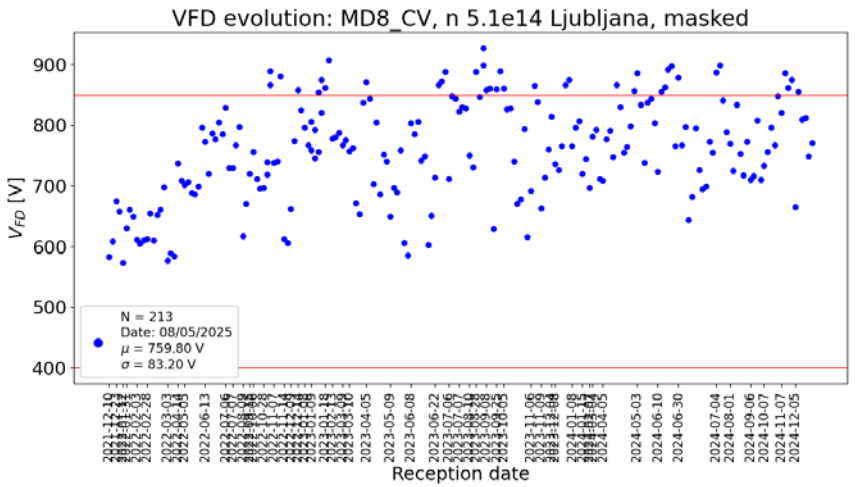
Capacitance vs Voltage for MD8 Diodes

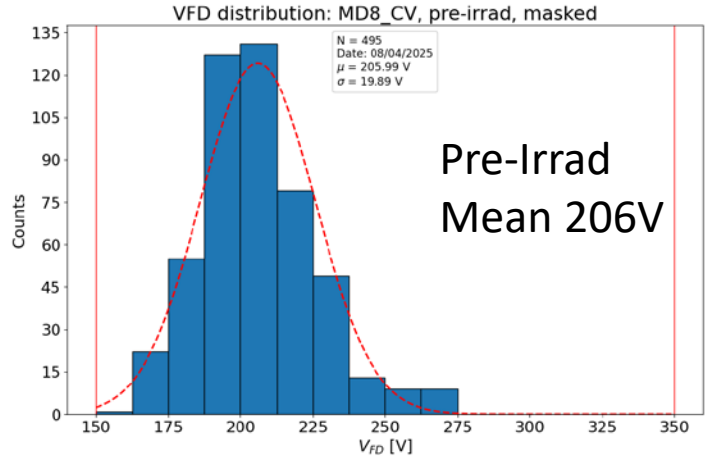


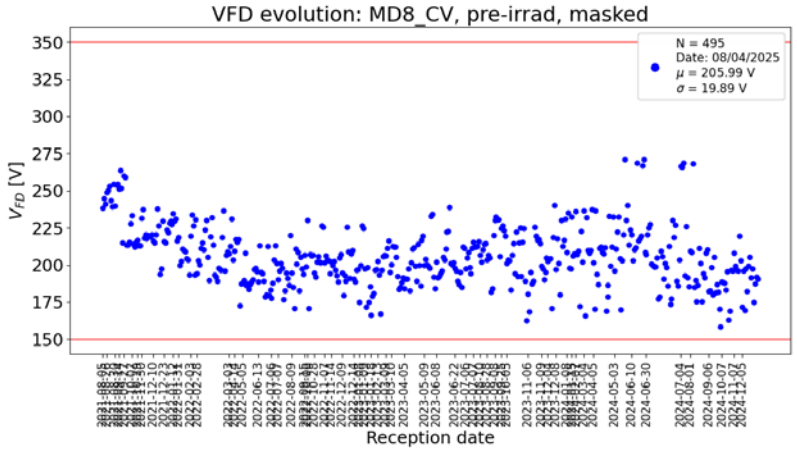
- The measurement monitors the full depletion voltage after neutron irradiation to 5.1×10^{14} $n_{eq}cm^{-2}$
- This fluence is a factor of three less than used in the ϒ+n irradiation of the Test Chips.
- The CV setup cannot exceed 1000V, so the irradiation fluence is reduced in order to bring the VFD into the measurable range
- The lower acceptance limit was somewhat arbitrarily set to 600V – the intention being to monitor for any drastic changes. The upper acceptance limit was set to 850 V – but we accept values beyond that – see next slide.
- The VFD is extracted from an empirical fit.

Comparison of MD8 CV pre-irrad and irrad time development.









- The pre-irrad and irrrad VFD show a marked time development , in opposite magnitude, over the first year of production.
- The dispersion of values also increases.
- This effect is not yet understood, and is being actively investigated.

Conclusions

- ATLAS ITk has developed an effective QA procedure based on the test structures on the periphery of the production wafers.
- The test procedures are based on the measurement of a large number of parameters of the test structures.
- The use of both probe station based measurement of non-irradiated, and wirebonded pcb measurement of irradiated structures has allowed us to carry out measurements simultaneously at several site – thus increasing the sample size of the QA parts.
- The QA procedure is complementary to the QC procedure.
- Out of 596 batches processed so far, four have been reject on QA grounds – all on p-stop doping anomaly. A total of 6 batches, or 1%, have been rejected on QA/QC grounds
- We have accumulated a high statistics sample of the basic semi-conductor properties of the ATLAS-18 sensors – this will allow further detailed investigations of general interest.