Evaluation of post-irradiation performance of ATLAS18 strip sensors affected by low p-stop issue

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Scope

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  - Low P-stop issue
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  - Samples and tests
  - Irradiations
- Results
  - Main sensors
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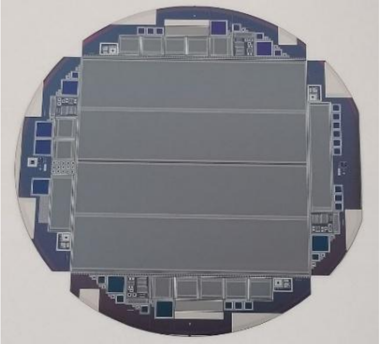
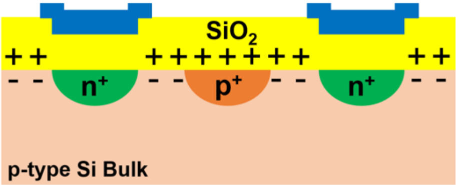
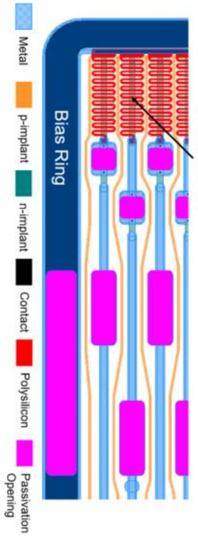
  - Rint (minis)
- Conclusion and Future Work

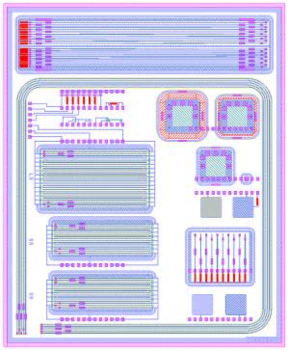
Introduction and Framework



- Production of ATLAS-ITk ATLAS18 strip sensors
  See Thomas Koffas' "Phase-2 Upgrade of the ATLAS Inner Tracker" Oral #19 in this conference
  - ➢ Need to produce ~24000 sensors (Hamamatsu HPK - Japan)
  - ➢ The ITk collaboration does the testing
    - QC: To test the actual sensors to be installed in the experiment
      See: Pavla Federicova's "Evaluation of quality control (QC) of ATLAS18 production ITk strip sensors", Oral #39 in this conference
    - QA: to monitor the technology parameters and post-irrad performance throughout prod.
      See: Robert Orr's "Quality Assurance during production of the ATLAS18 Itk strip sensors", Oral #49 in this conference
- P-stop component
  - ➢ P-stop is a p-doped layer in between the n+ strips to provide interstrip isolation pre- and post-irrad due to interface and oxide charge
- P-stop monitoring with test structures
  - ➢ MOS with P-stop
    - An MOS capacitor between the P-doped substrate and metal, with field-oxide in between
  - ➢ PTP
    - A special structure for sensor protection with important role, and effect, of the p-stop layer



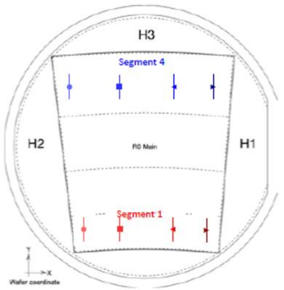


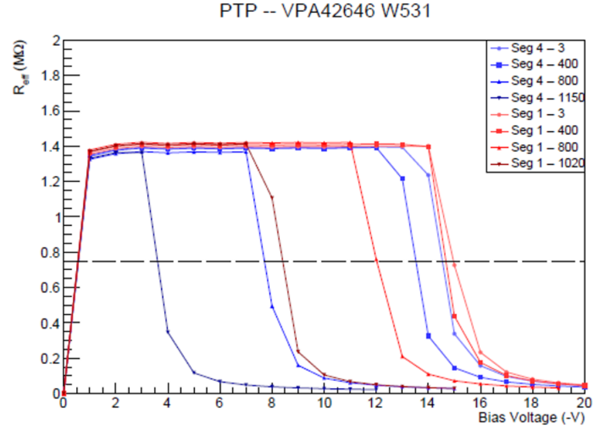


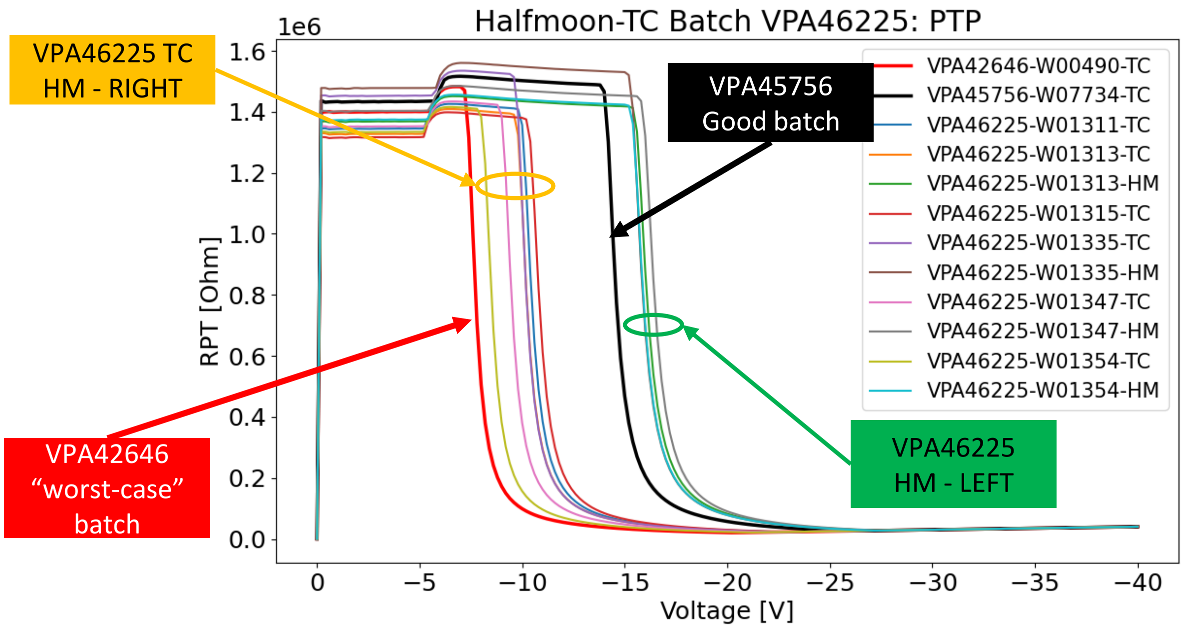
M. Ullán, et al. "Quality Assurance Methodology for the ATLAS Inner Tracker Strip Sensor Production", NIMA, vol. 981, 164521, 2020

Low P-stop Issue I

- In some batches we have seen indications of low P-stop doping
  - Seen in the MOS capacitor with P-stop as a fast depletion rate (next slide)
  - Also confirmed with PTP measurements (see below)
  - Confirmed by simulations (See: Yoshinobu Unno's poster #63 in this conference)
  - There is a clear inhomogeneity in the doping concentration within the batch and within the wafer
    - Only a small number of wafers of the batch are affected
    - **In most cases, the left side of the wafer is not affected**
  - 4 full production batches rejected for this reason
- Effect clearly seen in Punch Through Voltage:







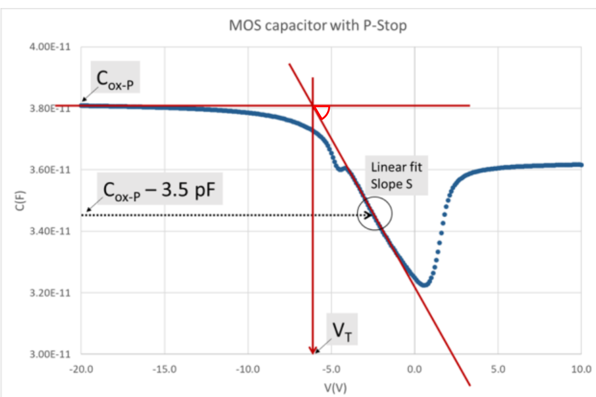
Estimated p-stop density:

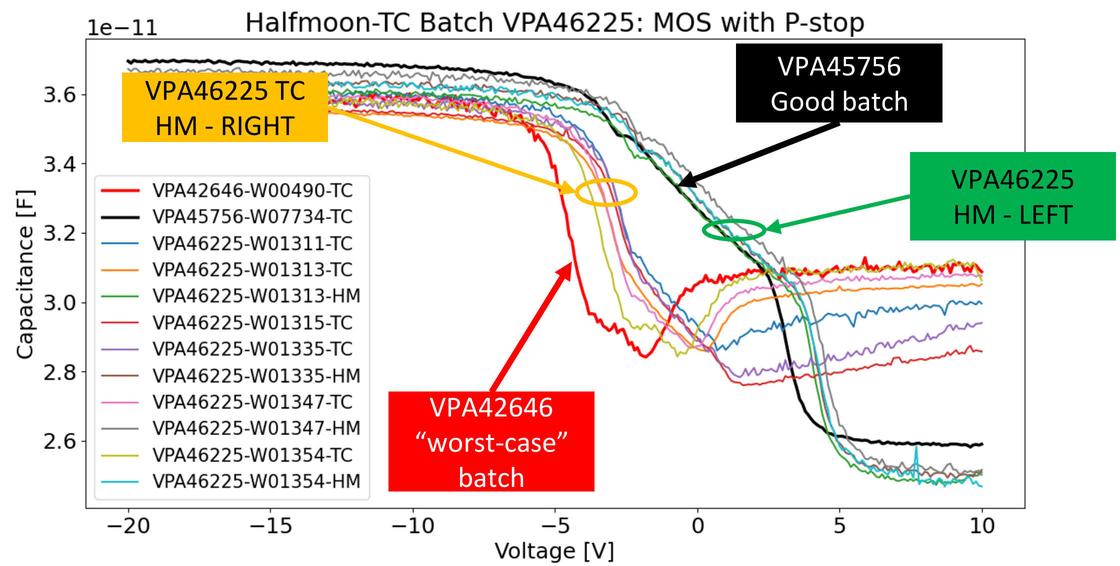
- 16 V: ~4×10^{12} cm^{-2} (1)
- 12 V: ~2×10^{12} cm^{-2} (1/2)
- 7.5 V: ~1×10^{12} cm^{-2} (1/4)
- 4 V: ~5×10^{11} cm^{-2} (1/8)

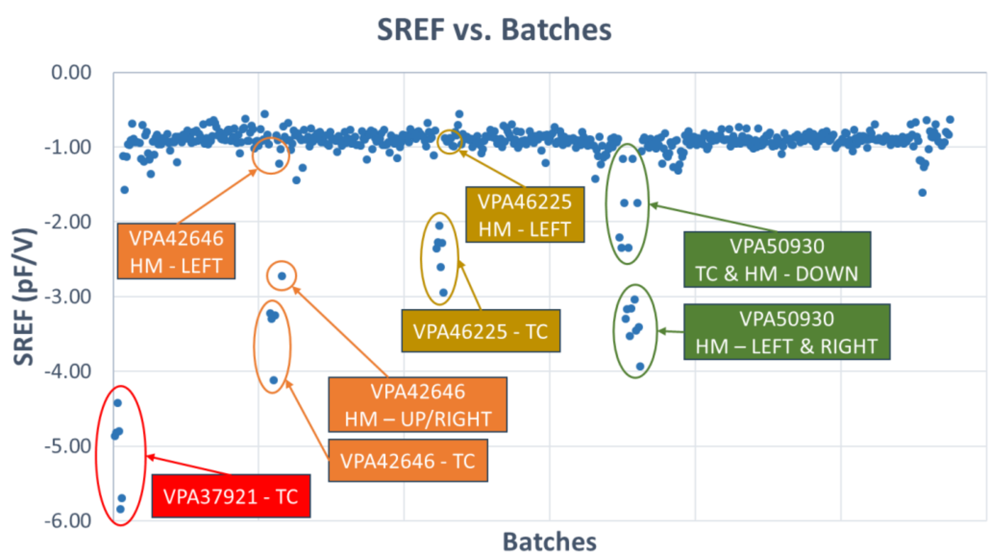
Low P-stop Issue II

MOS with P-stop

- Sref
  - ➢ Slope of the curve from accumulation to depletion
  - ➢ Clear indicator of the issue
  - ➢ Used as figure-of-merit in QA tests







Effects in MAIN sensors

- The simulations indicate that the results are compatible with an order of magnitude reduction, in the worst case, in the P-stop doping concentration
  - See:
    Yoshinobu Unno, et al, "Analysis of MOS capacitor with p-layer with TCAD simulation" NIMA 1064, 170045 (2024)
    Yoshinobu Unno, et al., "Measurement of Threshold Voltage in PTP Structures and Estimation of P-stop Density Variation Within an ATLAS18 Silicon Strip Sensor Wafer Using TCAD Simulations", poster #63, this conference.
- We have not seen clear effects in other QA/QC tests pre-irrad apart from PT voltage reduction
  - Some cases of areas of low pre-irrad interstrip isolation in main sensors (not necessarily related to low P-stop doping reduction, e.g., static charge build-up)
- We do not know if this can have direct consequences post-irrad
  - Some sensors with slightly lower P-stop doping might have passed undetected due to QA batch sampling
- This work tries to find out the consequences of the low P-stop doping on the sensors performance in the real experiment (post-irrad)

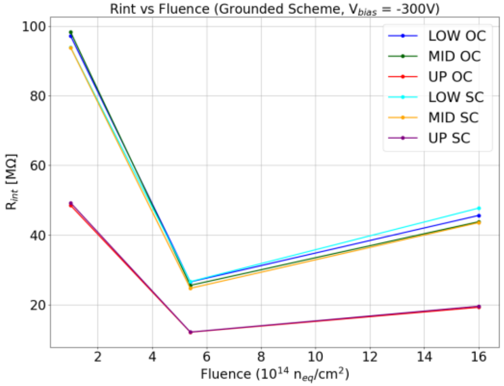
☞ The foundry has identified the origin of the problem and mitigated it

☞ Also HPK has proposed process variations to make a more robust fabrication
See: Jana Kozakova's "Evaluation of Performance of the p-stop Process Splits in ATLAS18 strip sensors, Pre- and Post-Irradiation", poster #68, this conference

Experiments

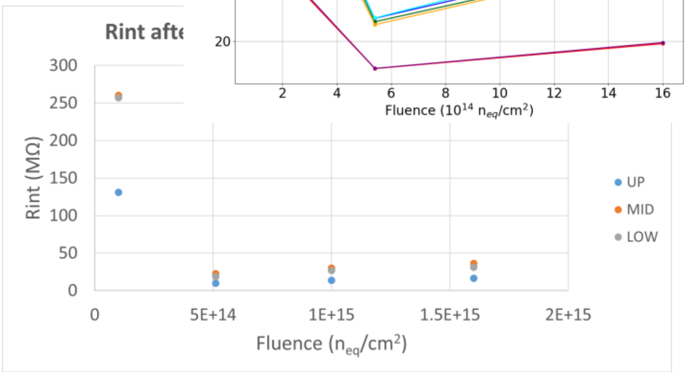
<u>Three experiments</u>:

1. Take one MAIN sensor and irradiate it with γ+n up to target fluences
   - ➢ Fast "final" result of the full degradation
   - ➢ Use the sensor with the worst (lowest) p-stop doping (W514)



2. Try some intermediate fluences with MAIN sensors
   - ➢ We have seen a "minimum" in Rint at "mid" fluence
     - ❑ 5.1e14 neq/cm2 || 21 Mrad

     [J. Fernandez-Tejero, et al. "Evolution of the electrical characteristics of the ATLAS18 ITk strip sensors with HL-LHC radiation exposure range," 2025 JINST 20 C01010]
   - ➢ This would be a "worst-case" scenario
   - ➢ We could also try other fluences close to that in order to approximate to the "minimum"

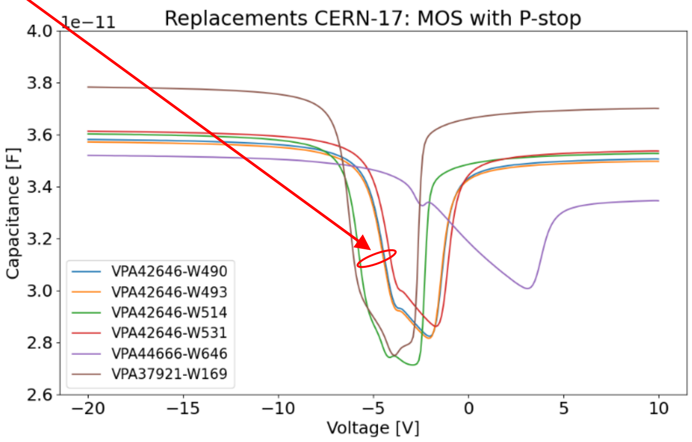


3. Irradiate several mini sensors only with gammas to see the degradation of Rint
   - ➢ Identify the TID of "fail" (Rint < 15 MOhm) for "good" and "bad" P-stop cases
   - ➢ Find the "saturation of degradation" (if any)
   - ➢ Later add neutron fluence to learn when and how the Rint "recovers" to acceptable values

Samples and tests I

Experiment 1 and 2 (MAIN sensors)

- Use main sensors from rejected batch **VPA42646** (R0, CERN-17)
  - ➢ This is a rejected batch with quite bad P-stop results
- Irradiate with gammas + neutrons
- **MAIN sensors** doses and fluences:
  - ➢ W531: 2.0 Mrad, 5e13 neq/cm2
  - ➢ W532: 4.1 Mrad, 1e14 neq/cm2
  - ➢ W493: 16.5 Mrad, 4.0e14 neq/cm2
  - ➢ W490: 21 Mrad, 5.1e14 neq/cm2
  - ➢ W514: 66 Mrad, 1.6e15 neq/cm2



- Additionally, **mini sensors** affected by low P-stop (TC tests) have been irradiated together with the MAIN sensors for CCE tests

  1) W492: 66 Mrad, 1.6e15 neq/cm2

     → This case is obtained from proton (MC40) irradiations with good CCE

  2) W531: 21 Mrad, 5.1e14 neq/cm2
  3) W493: 16.5 Mrad, 4e15 neq/cm2

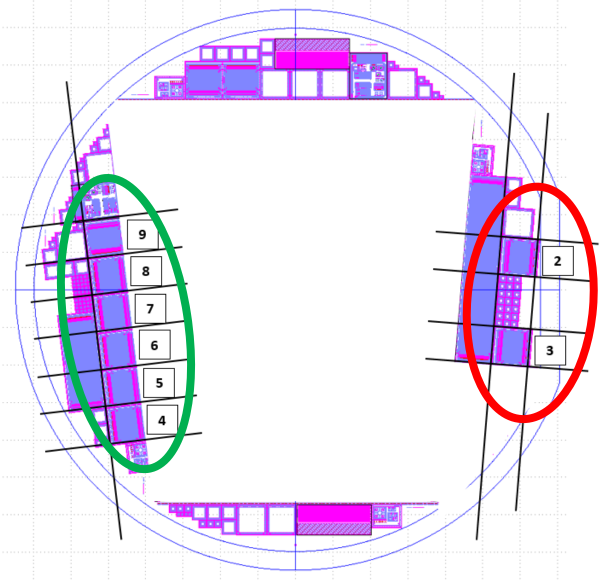
Measurements:

- Rint, CCE of minis

Samples and tests II

Experiment 3 (mini sensors)

- Dice minis from the Halfmoons (HM) of affected wafers
  - W490, W493, W514 and W531
  - We know that the low P-stop effect is affecting the right side of the wafers → dice minis from the left and the right HM of those wafers, we can have minis with proper P-stop and with low P-stop, in order to do the whole experiment with good sensors and "bad" sensors
- Batch **VPA42646 (R0)**
  - Wafers: **W490, W493, W514**
- Dice 6 minis of each type (good/left, bad/right),
  - Dicing scheme
- Irradiate up to 6 doses:
  1, 3, 5, 10, 21, 66 Mrad
- Later, also complete with neutron irradiations

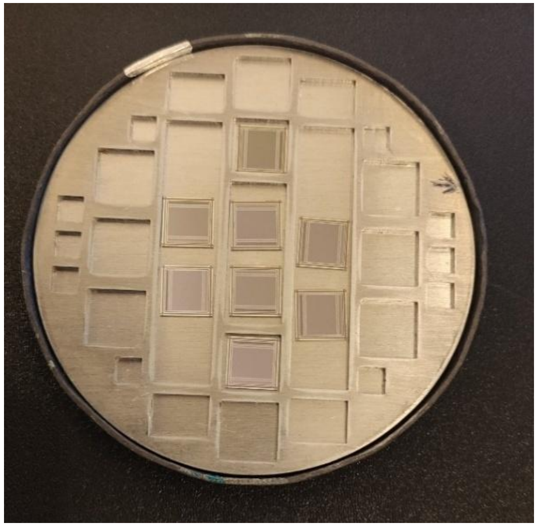


Irradiations (γ & n)

- MAIN sensors
  - 5 cases
- Mini sensors for CCE tests
  - 3 cases
- Mini sensors for damage study (TID)

Wafer	type	Position on the wafer	Gamma irradiation
W490	MINI 4	left	1 Mrad
W490	MINI 5	left	3 Mrad
W490	MINI 6	left	5 Mrad
W490	MINI 7	left	10 Mrad
W490	MINI 8	left	21 Mrad
W490	MINI 9	left	66 Mrad
W490	MINI 3	right	1 Mrad
W490	MINI 2	right	3 Mrad
W493	MINI 3	right	5 Mrad
W493	MINI 2	right	10 Mrad
W514	MINI 3	right	21 Mrad
W514	MINI 2	right	66 Mrad

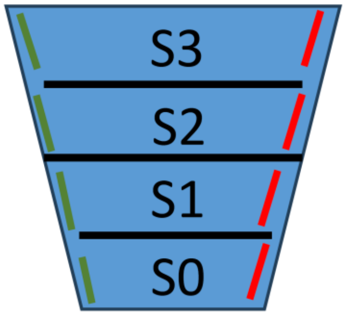
Setup for gamma irradiations of MAIN sensors and minis

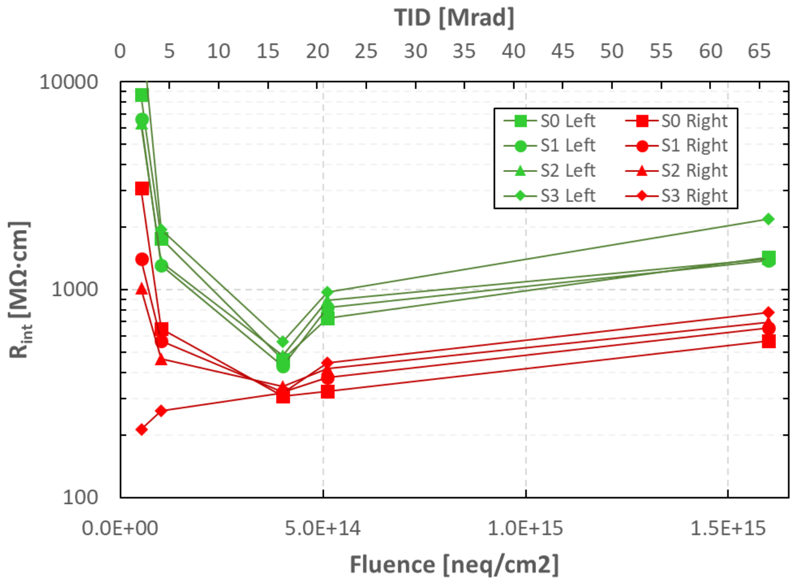


Results: MAIN sensors (Rint)

MAIN sensors (γ + n)

- Experiment 1 (target γ+n) and 2 (intermediate γ+n)
- Interstrip resistance (Rint) measurements at left/good and right/bad strips of the sensor
- Decrease of Rint up to 4e14 neq/cm2 and then increase for higher fluences
  - Initial influence of TID effects (Rint ↓)
  - Later, displacement damage dominates (Rint ↑)
- **Significantly lower Rint values at right side of the sensor for all cases → low P-stop**
  - Density estimated to be ~0.5 to 1x10^{12} cm^{-2} (~1/8 to 1/4) using TCAD simulations
- **Still well within specifications**
- One "special case" we will discuss later

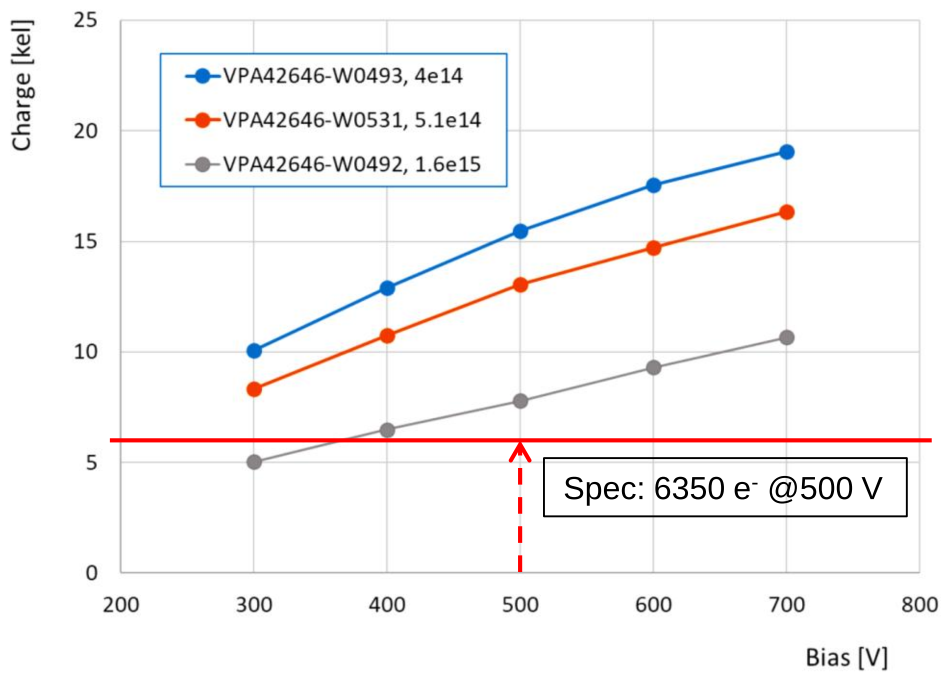




Results: CCE

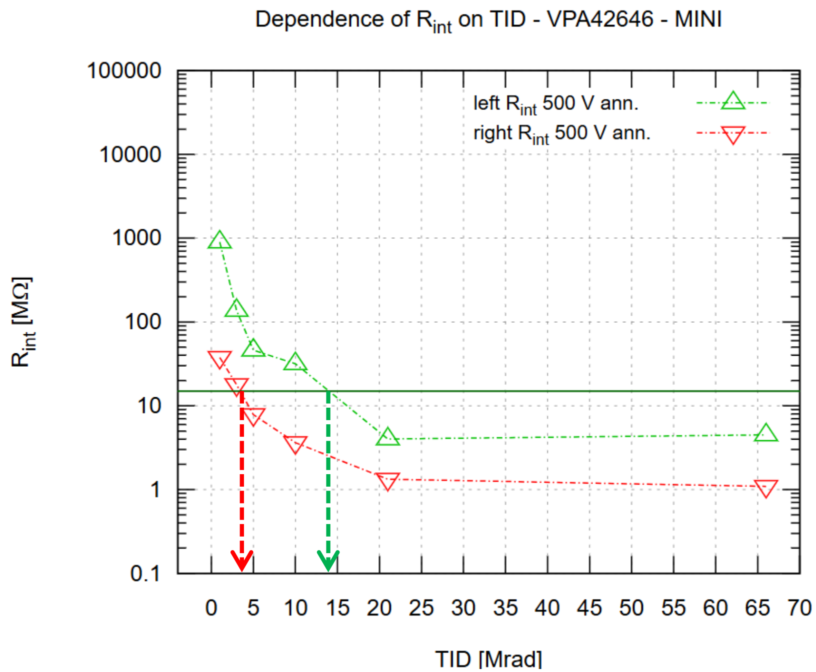
CCE results

- Mini sensors from VPA42646 irradiated together with full size sensors (γ + n)
- **All samples passed threshold of specifications (6350 e⁻ @500V)**



Results: minis (Rint ← γ/TID)

- Experiment 3: Rint of minis from affected/not affected by low P-stop

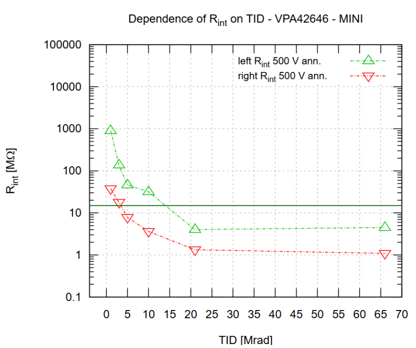


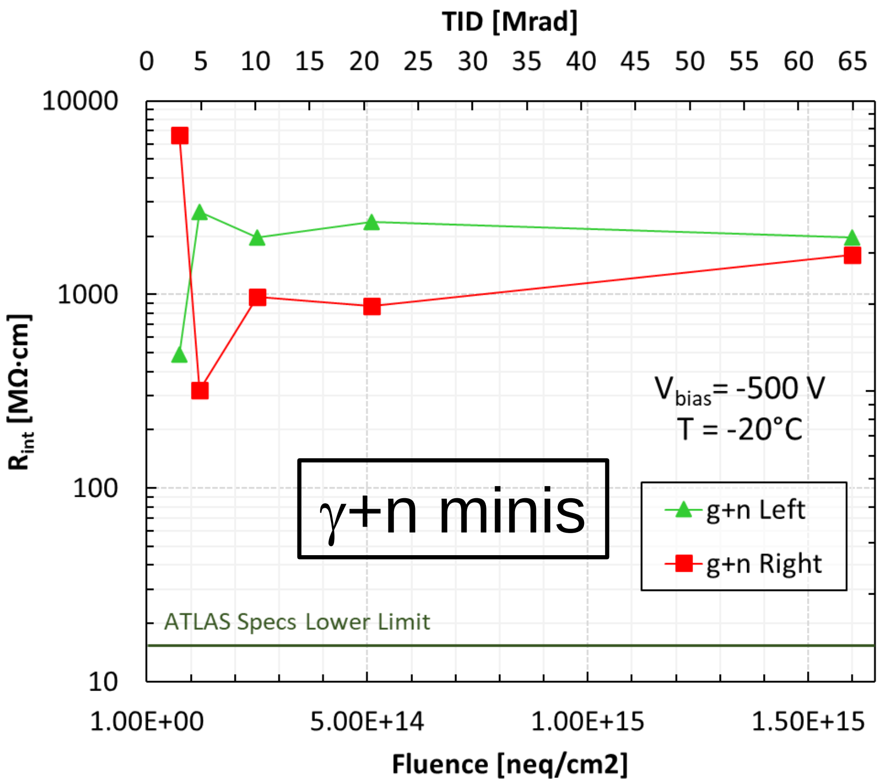
- ➢ **Dose at which Rint < specs is significantly lower for low P-stop cases**
  - ~14 Mrad for "good" minis // ~4 Mrad for low P-stop minis
  - ☞ Only gammas !! → therefore worse than expected in the real experiment
- Saturation of TID damage
- Next: complete with neutron irradiations to see the Rint evolution in the real scenario

Results: minis (Rint ← γ+n)

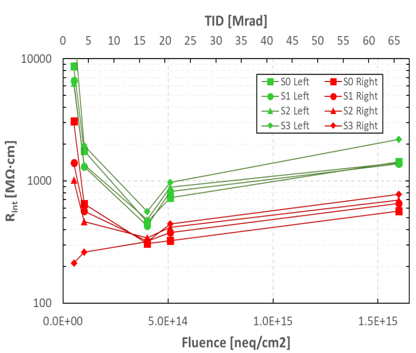
- Rint @500 V for γ+n irradiated minis
- **Rint significantly lower for low P-stop minis**
  - **Still well above specifications**
- **Minimum of Rint possibly influenced by P-stop doping level**
  - Will investigate the position (and value) of the minimum

γ minis





γ+n MAIN



Conclusion

- During the ~4.5 years production of the ATLAS-ITk strip sensors, we have found some cases (batches) in which the doping of the P-stop layer was significantly lower than expected
  - ➢ We have identified this through specific test structures, during Quality Assurance (QA) tests, and also with tests in the actual sensors (QC)
  - ➢ Nevertheless, the sensors remain within specifications pre-irrad
  - ➢ In this work we try to identify the effect of this low P-stop doping in the real experiment (post-irradiation)
- **MAIN sensors: Significantly lower interstrip resistance (Rint) values for low P-stop strips → Still well within specifications**
- **CCE results (mini sensors): All samples well above specifications**
- **Gamma irradiations (minis): Dose at which Rint < specs is significantly lower for low P-stop cases**
- **Minis (γ+n): Rint significantly lower for low P-stop minis**
  - ➢ **Still well above specifications**

☞ Next: Detailed quantitative search of minimum of Rint vs. TID+NIEL

Thank you

Backup

Results: MAIN sensors (Rint)

MAIN sensors (γ + n)