The ATLAS ITk Strip Detector Sensors for the Phase-II LHC Upgrade

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Introduction

Sensor Layout and Construction

Results on Irradiated Samples

Long-Term Operation

Sensor Quality Control

Summary

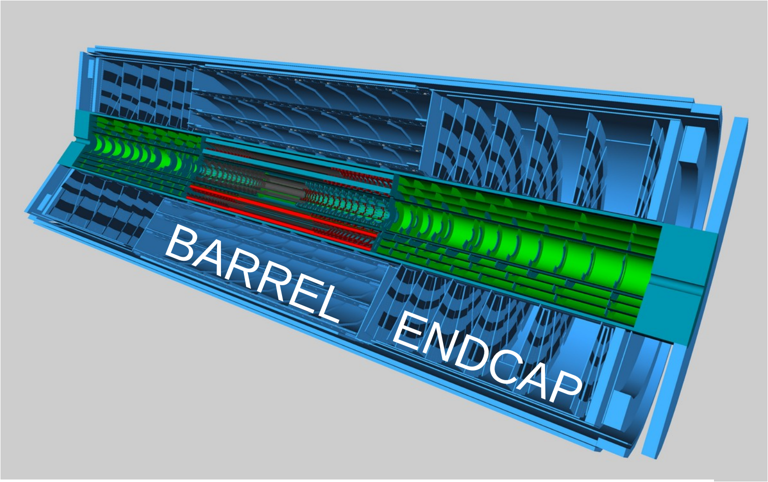
Introduction

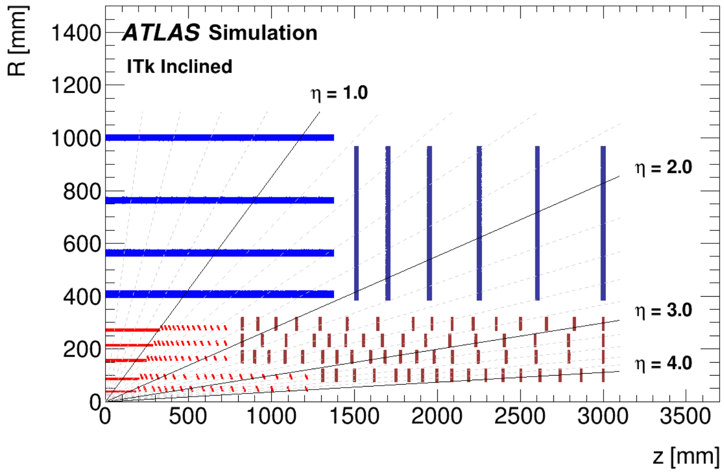
ATLAS Upgrade: the Inner Tracker (ITk)

All-Silicon Tracker with Barrel & Endcap layout

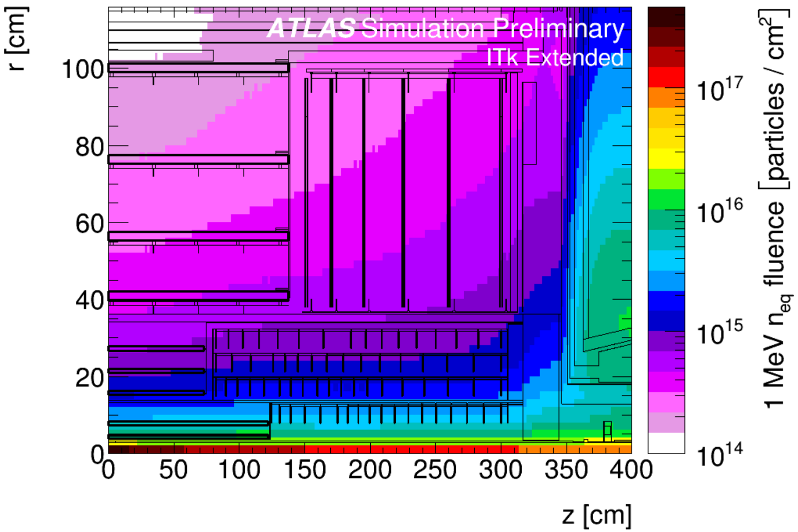
- Pixel inner layers
- ***Strips outer layers*** ← ***This talk***

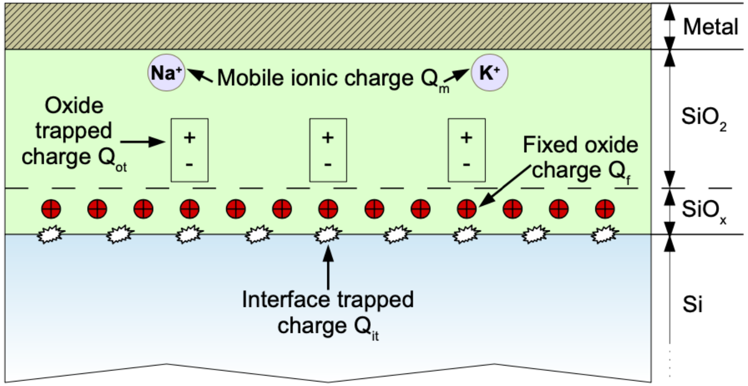
- Barrel:
  - short & long strip rectangular sensors
  - 2 double-sided layers of each
- Endcap:
  - Radial Strip orientation in endcap
  - 6 double-sided discs
- 17888 Sensors covering ~ 200m^2 area
- See talk by Craig Sawyer later today





Radiation environment



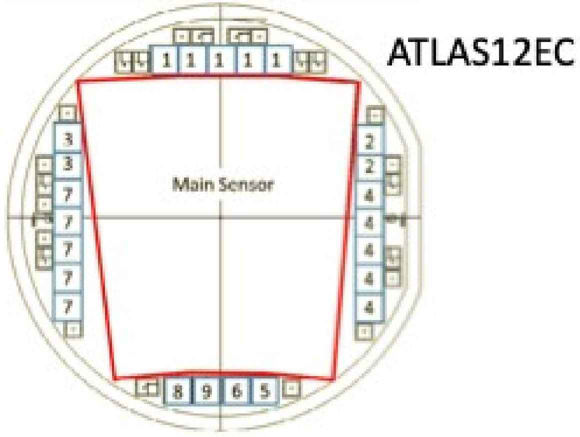


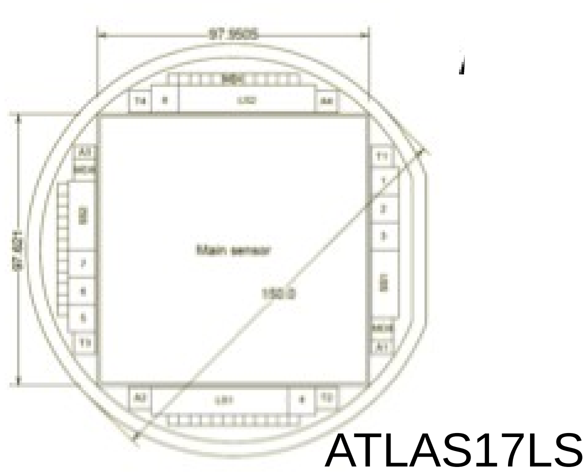
- Highest expected fluence:
  - 10.6x10^{14} 1 MeV *n*-equivalent for endcap
  - 6x10^{14} *n*-eq for barrel
- Design & test to fluence with safety factor 1.5
- Bulk damage:
  - reduced charge collection
  - increased leakage current
- Surface damage:
  - charge accumulation in SiO2 layers
  - local breakdown
  - reduction of strip isolation
- Radiation hardness verification using reactor neutrons, proton beams, gamma sources

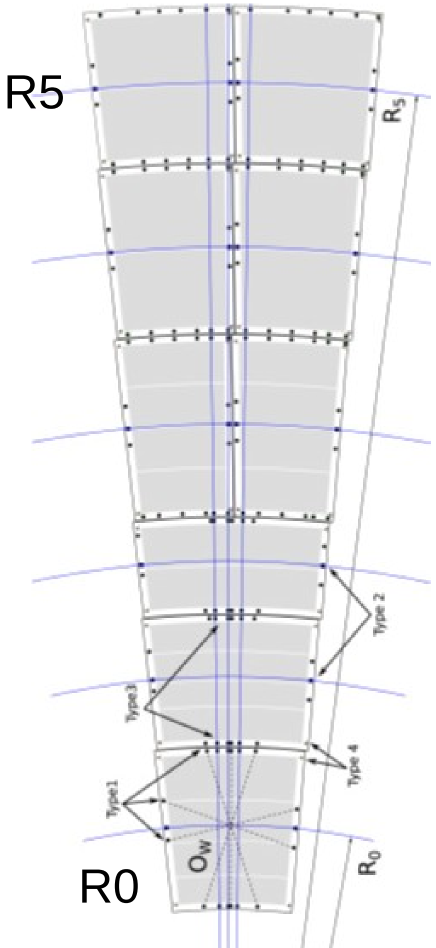
Sensor Layout and Construction

Sensor Layout

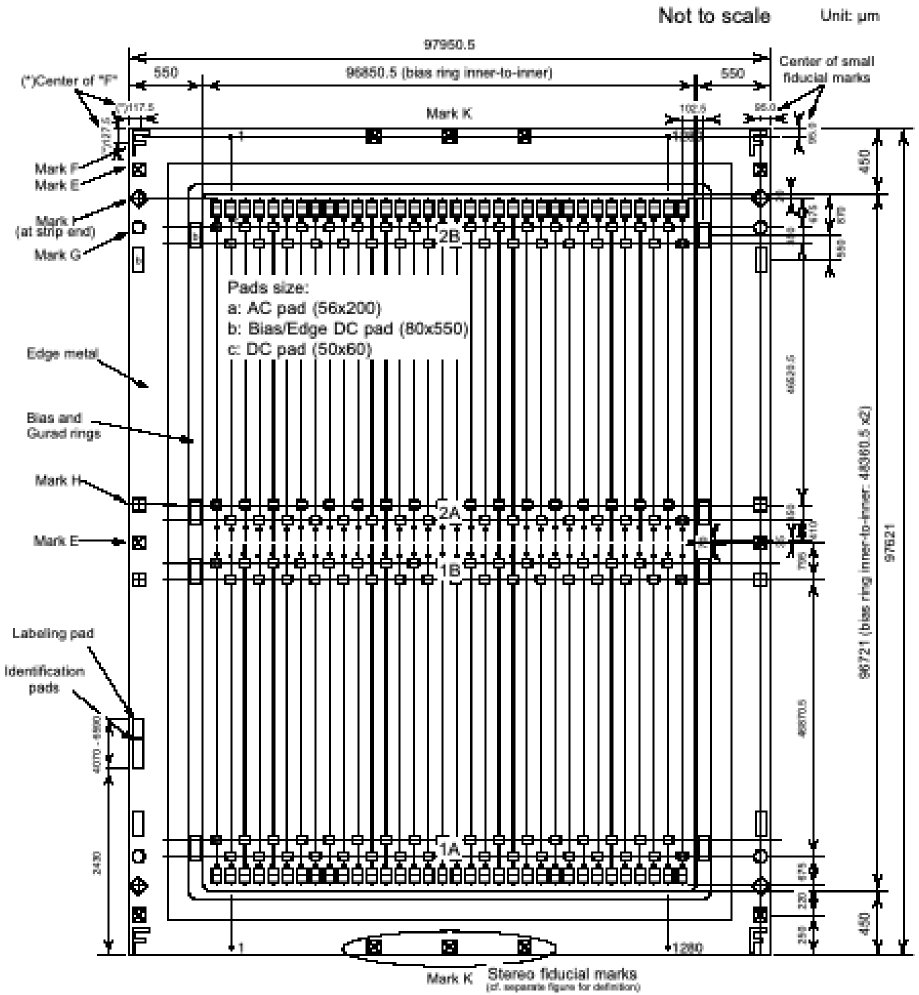
- All sensors produced on 6” wafer process
- Resulting in 6 EC sensor types:
  - R0 to R5
  - Radial strip arrangement with 20mrad offset
  - Pitch between 69 and 84µm
  - Strip count ranging from 2052 to 3592
- 2 Barrel sensor types:
  - 1280 strips at 75.5µm pitch in a column
  - Long Strip: 2 columns of 49mm strips
  - Short Strip: 4 columns of 24mm strips
- Current prototypes:
  - ATLAS12EC R0
  - ATLAS17LS (ATLAS18SS)
- test structures at periphery
  - 10x10mm mini sensors
  - Short Strip mini
  - Long Strip mini



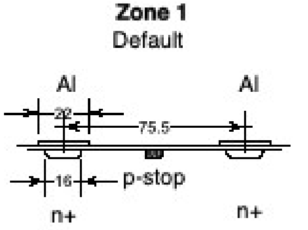


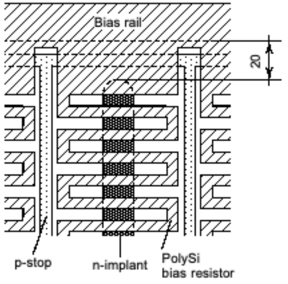


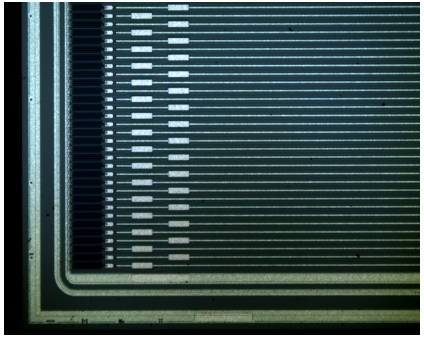
Sensor build specifications



- n^{+}-*in-p* high resistivity bulk
- 320µm thickness
- designed for partial depletion at end of life (EOL)
- p-stop traces in between strip implants
- R_{bias} and Punch-Through Protection structures embedded in sensor
- AC coupled readout



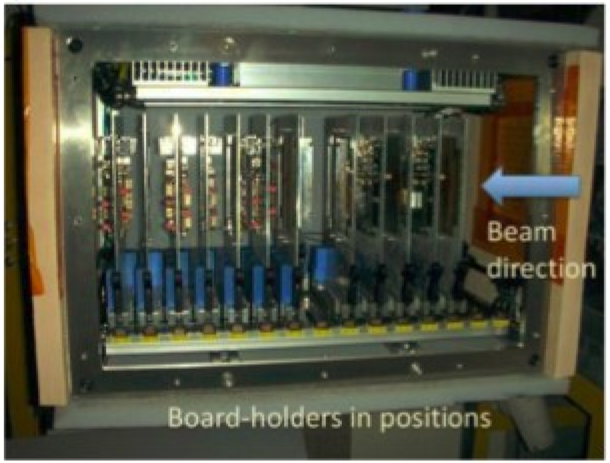




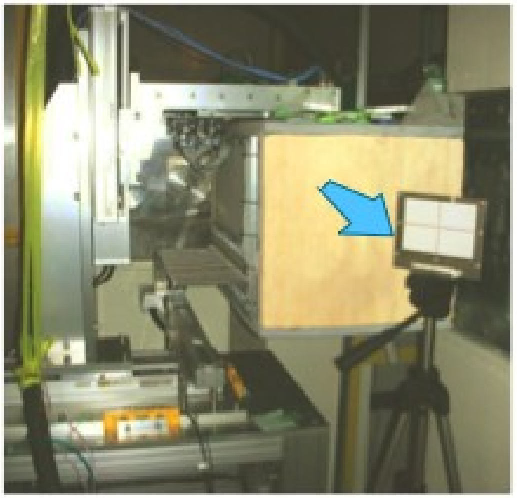
Results on Irradiated Samples

Irradiation facilities

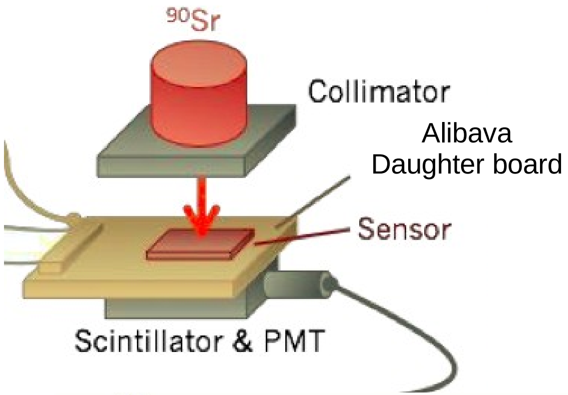
- CERN PS: 24 GeV *p* beam
- CYRIC, Tokohu Uni: 70 MeV *p*
- Birmingham: 28 MeV *p*
- Karlsruhe IT: 23 MeV *p*
- TRIGA, Ljubljana: reactor *n*
- FZU, Prague: ^{60}Co ɣ

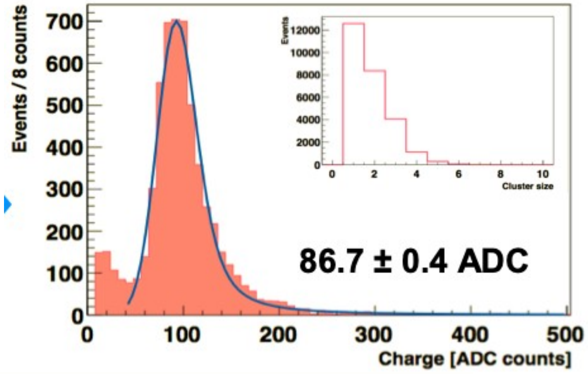


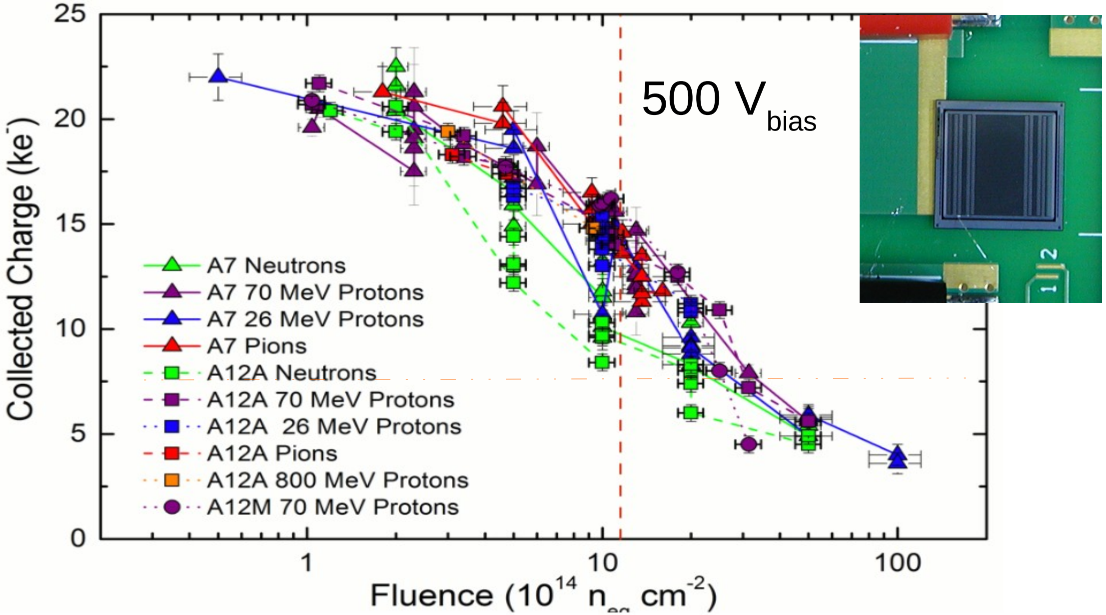
^{60}Co Terabalt, ÚJP Praha



Bulk property: Charge Collection Efficiency

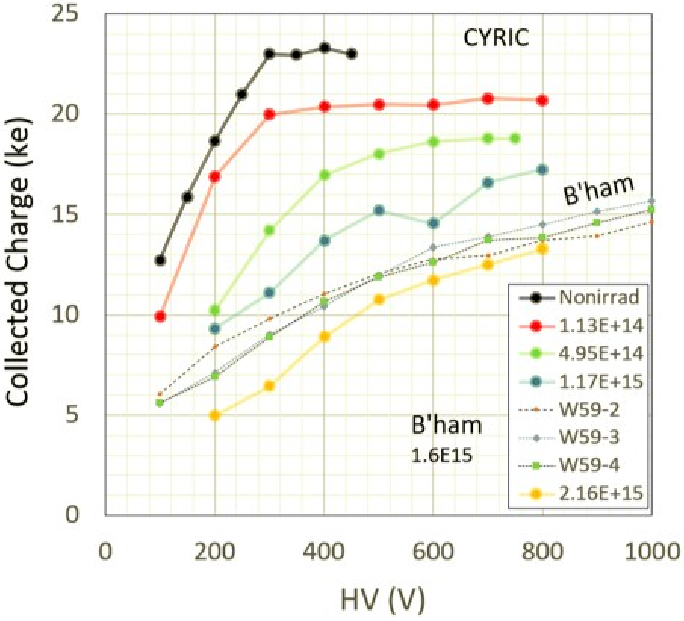


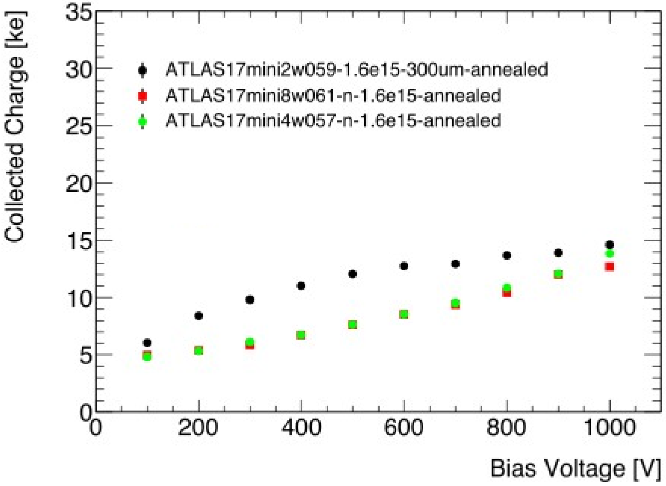


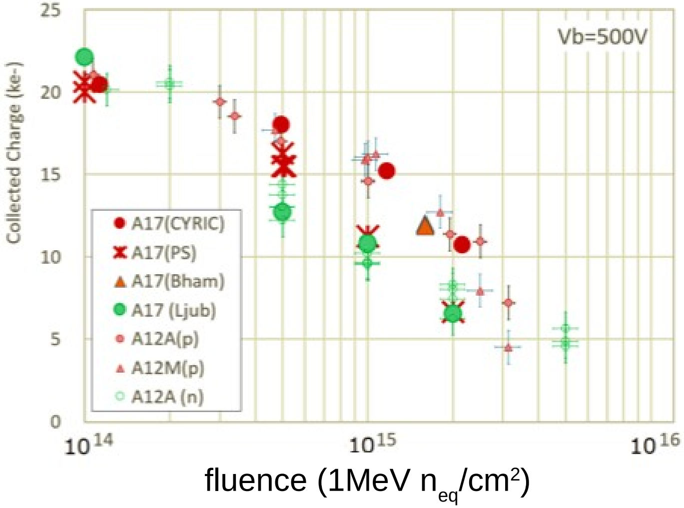


- Collimated ^{90}Sr β^- radiation to stimulate mini sensor and trigger r/o
- Low-noise analog readout
- Landau curve fits to extract charge
- Normalize using standardized unirradiated mini sensors
- 1.6×10^{15} 1MeV *n*-eq max fluence includes 1.5x safety factor
- 7500e$^-$ expected MIP charge at end-of life achieves signal to noise ratio of 12 : 1

Bulk degradation: *p* vs *n* data

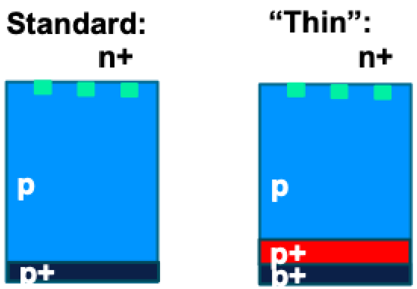




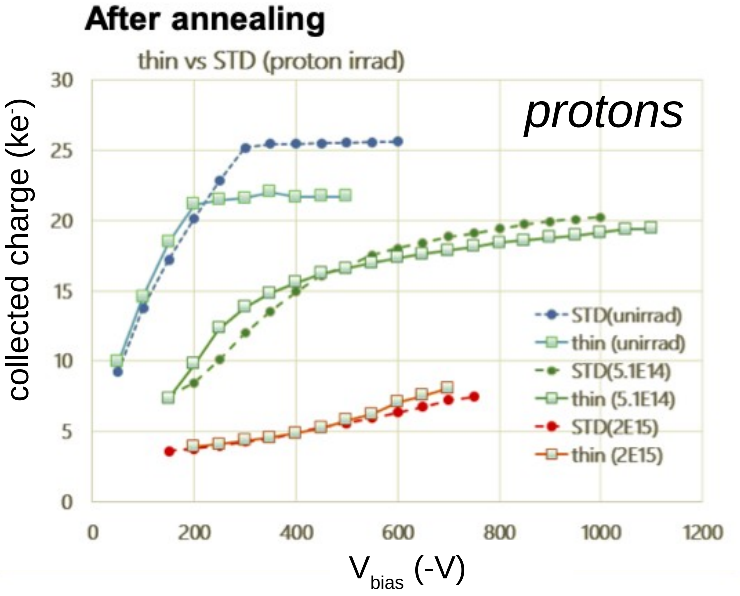


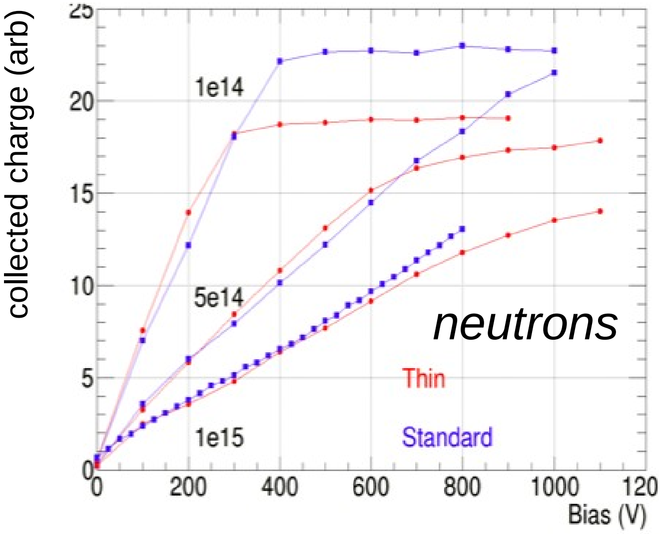
- Data shows more CCE reduction for *n* than *p*
- Neutron data used as End-of-Life performance benchmark:
  - *n* contributes > 50% of NIEL fluence
- Good agreement between A12 and A17 sensor revisions for both *p* and *n* data

STD vs reduced thickness data



- A number of A17 sensor prototypes have active thickness reduced from 300 to 240um
  - deep-diffusion of p implant at back of sensor
- Thin sensors have similar CCE at EOL
- Minimum thickness requirement can be relaxed



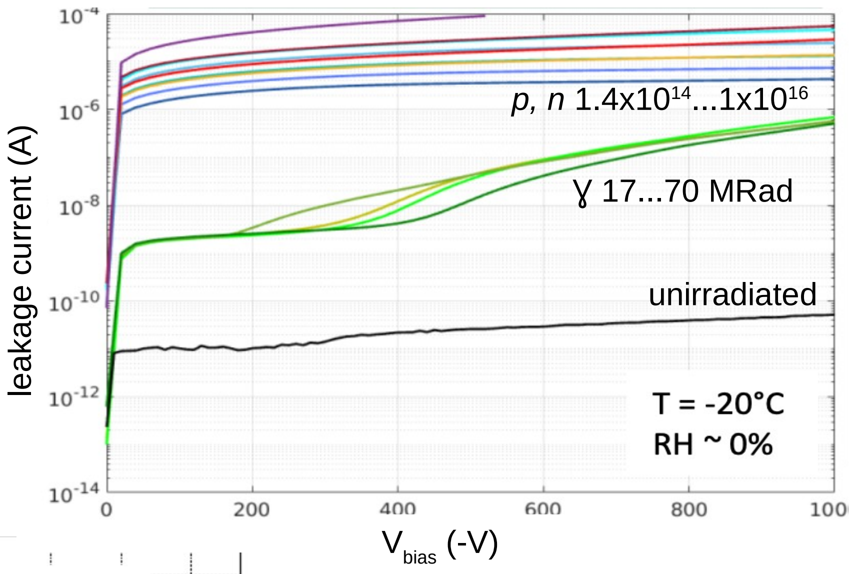


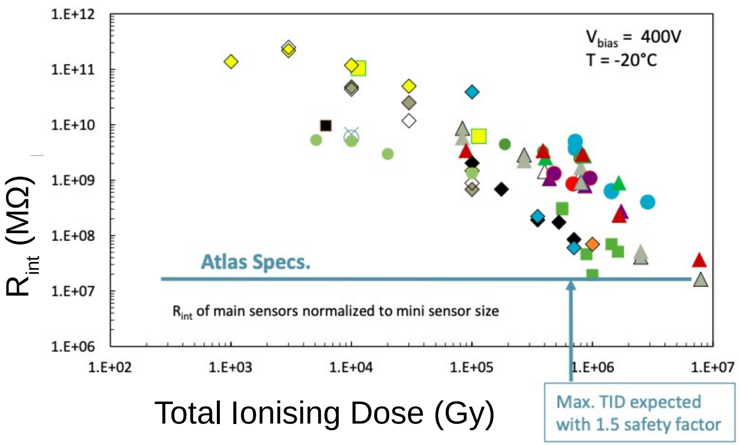
Surface damage effects

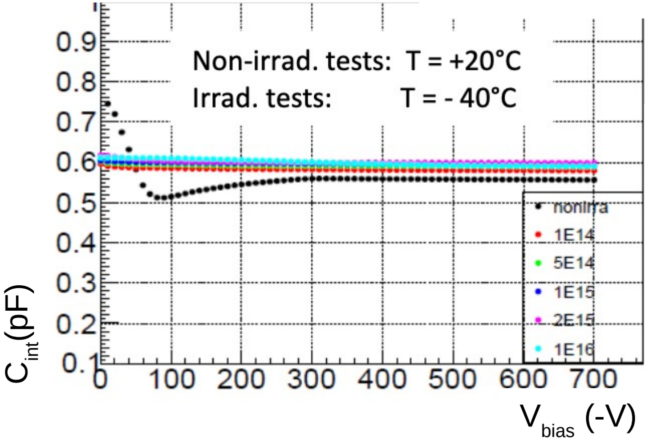
Main concerns: specifications

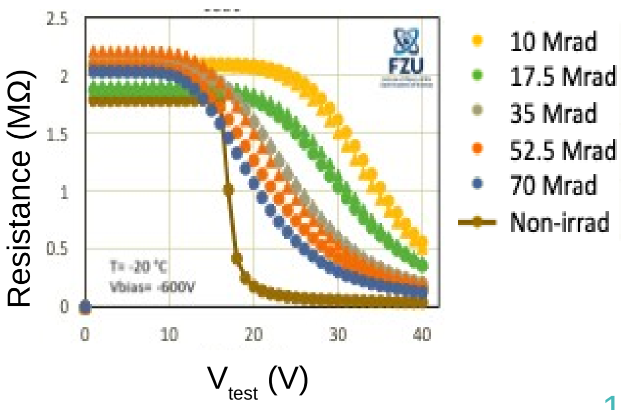
- Microdischarge onset: none < 500V
- Strip isolation: R_{int} : >10x R_{bias}
- Inter-strip capacitance C_{int} : >0.7 pF/cm
- PTP onset: 10V < V_{PTP} < 50V

...all within specifications





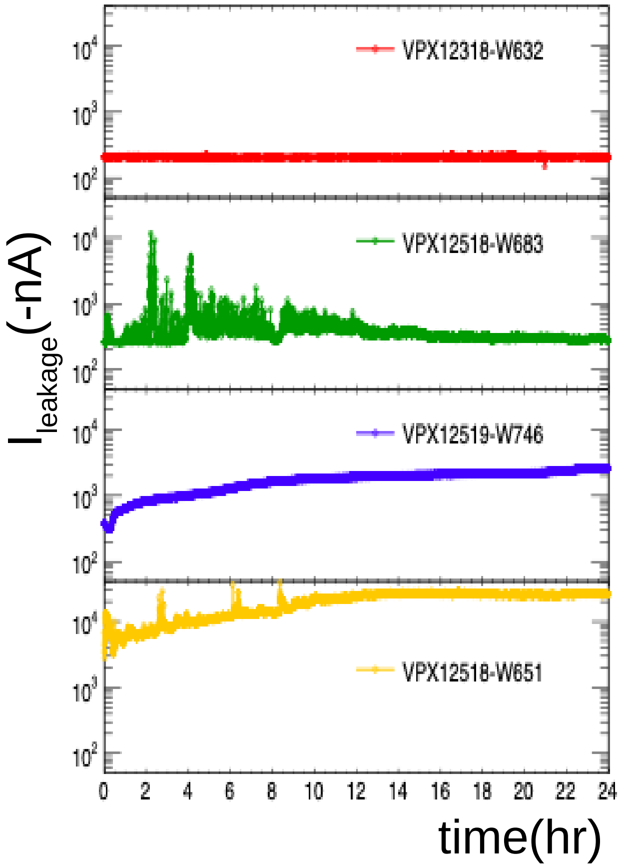


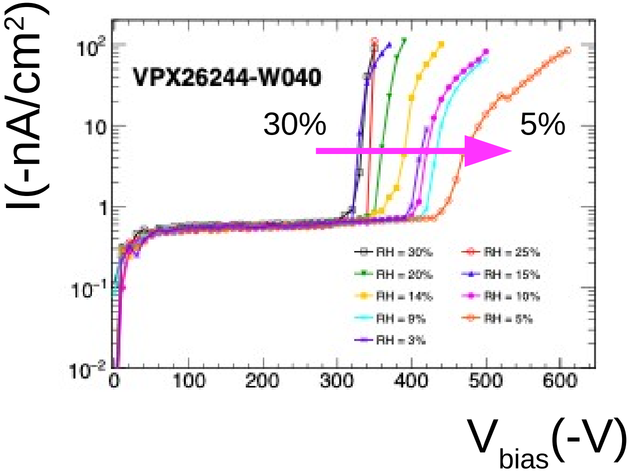


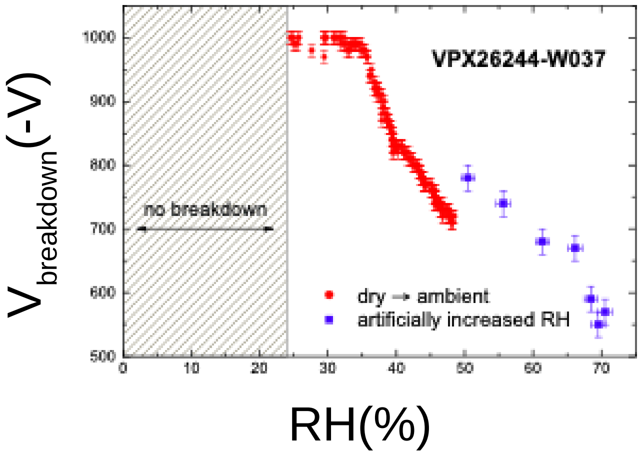
Long-Term Operation

Humidity sensitivity

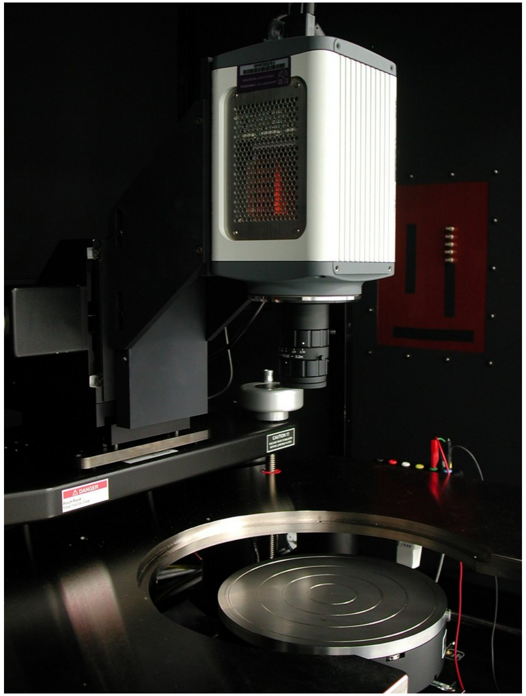
- Instability of leakage current attributed to humidity (RH)
- RH↑ - $V_{breakdown}$↓
- Reversible process
- Long term biasing in high RH has resulted in irreversible damage in several sensors

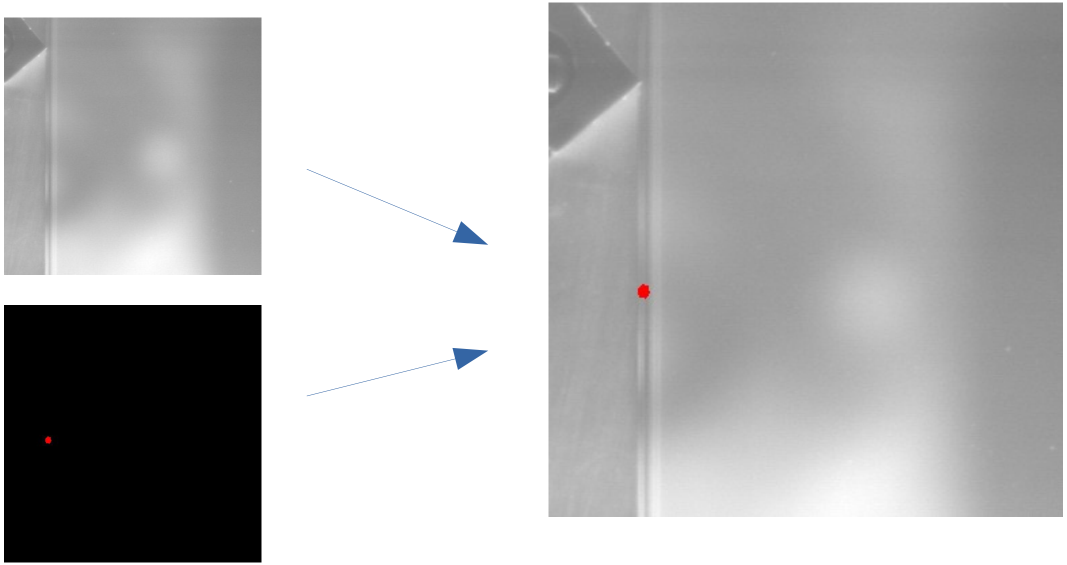






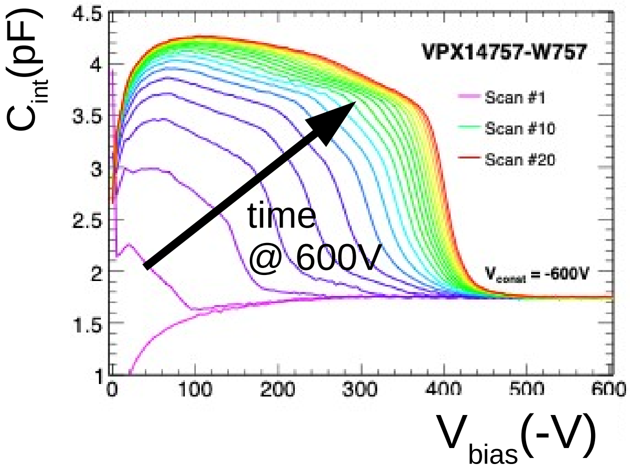
Breakdown imaging

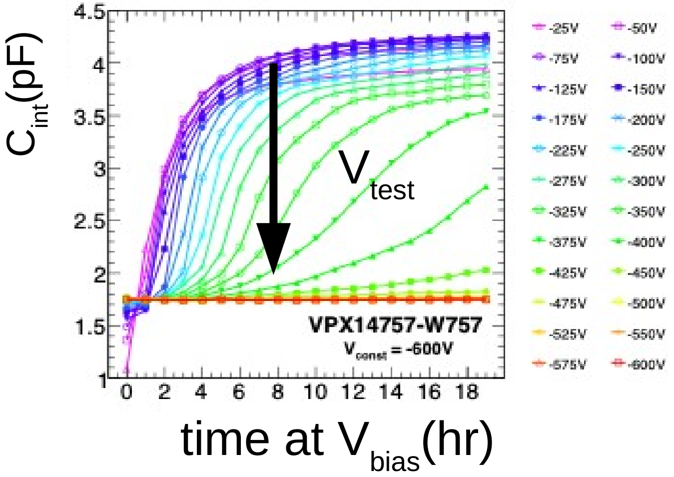


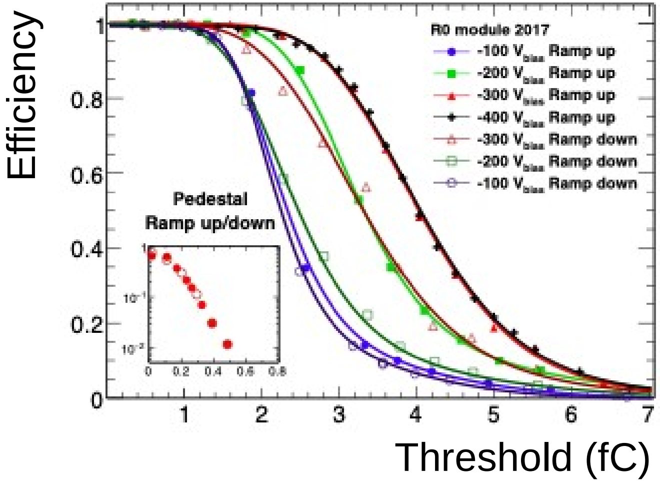


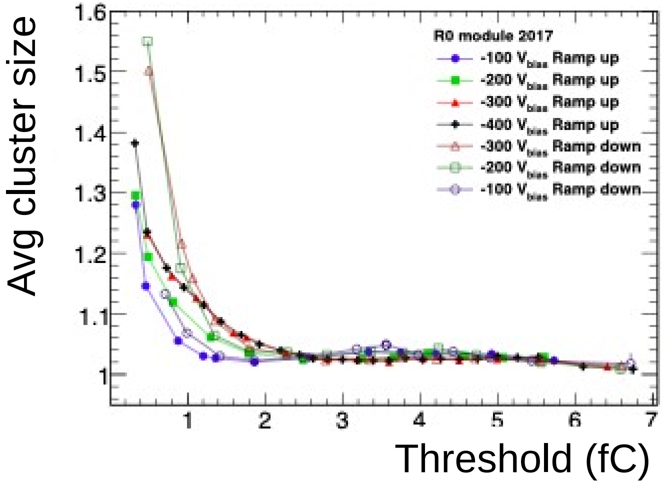
- SWIR imaging to pinpoint breakdown
- Edge metal-guard ring gap
- Sensor edge geometry design verified – passivation?
- Working with manufacturer to mitigate issue

Hysteresis effects in C_{int}



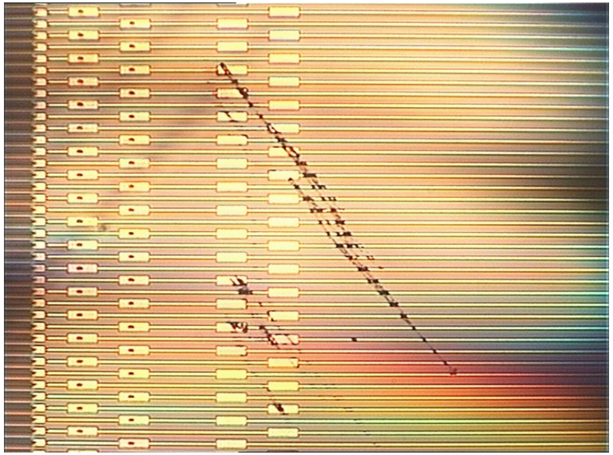
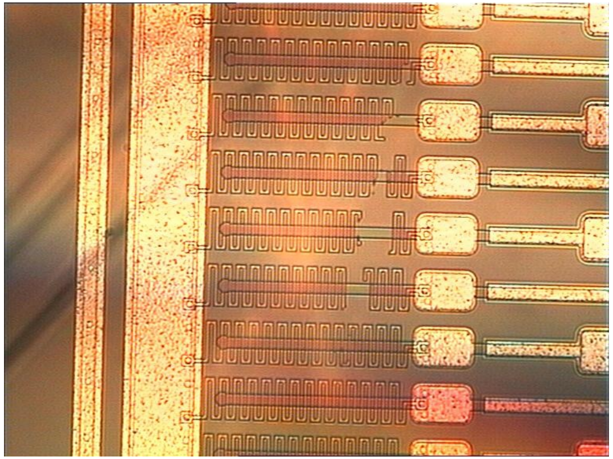
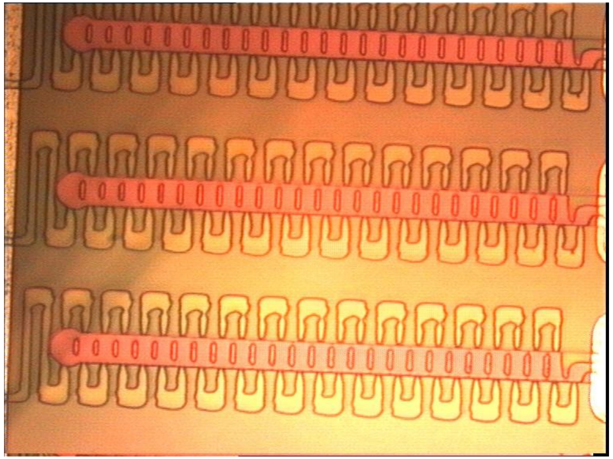






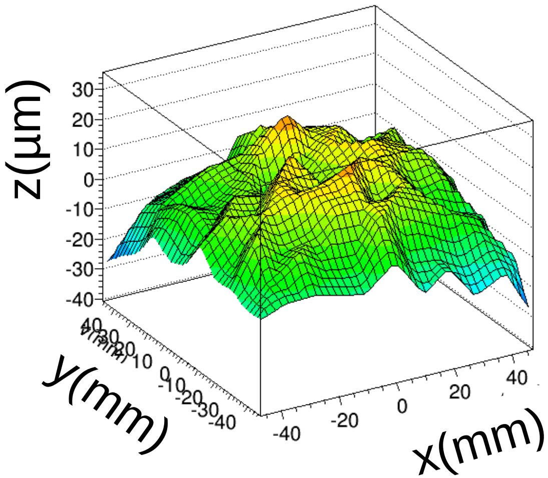
- C_{int} increases with time for V below constant V_{bias}
- Settling time O(hours) at RT, strong T dependence
- C_{int} dominant contribution to FE noise
- Effects on efficiency/noise and cluster size confirmed using test beam data
- Important when lowering V_{bias} during cold operation

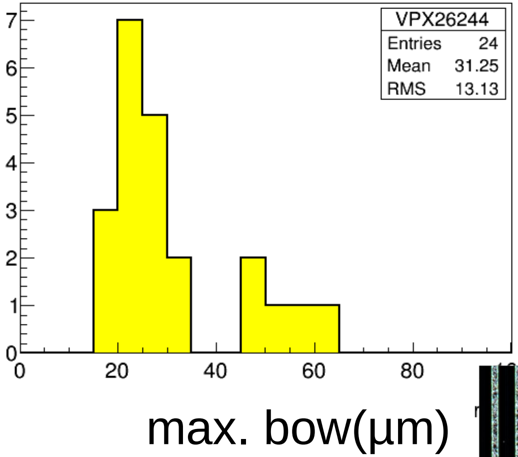
Sensor Quality Control

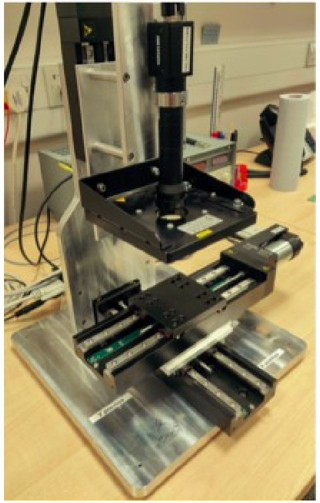
images from SCT sensors rejected during QC – D.Robinson

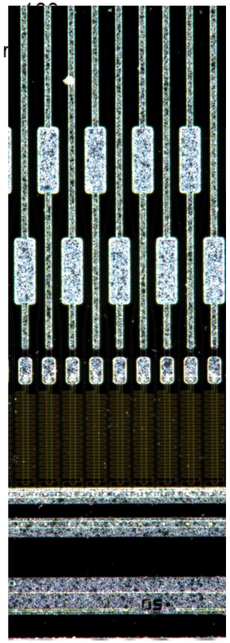
Tests on every sensor





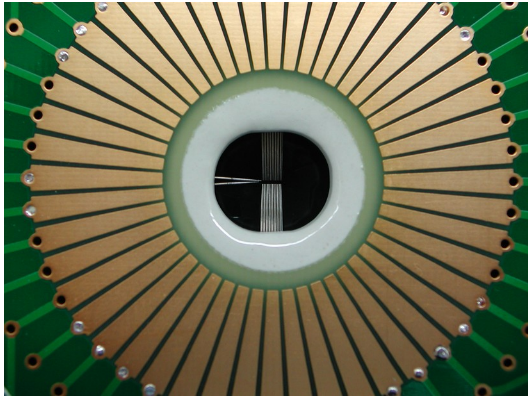
- ***Visual inspection:*** check for obvious defects
- ***Surface profile:*** confirm sensor shape as suitable
- ***Visual Capture:*** capture the sensor state at delivery
- ***I-V scan:*** reverse bias sensor "health check"
- ***C-V scan:*** confirm $V_{depletion}$, wafer resistivity, active thickness

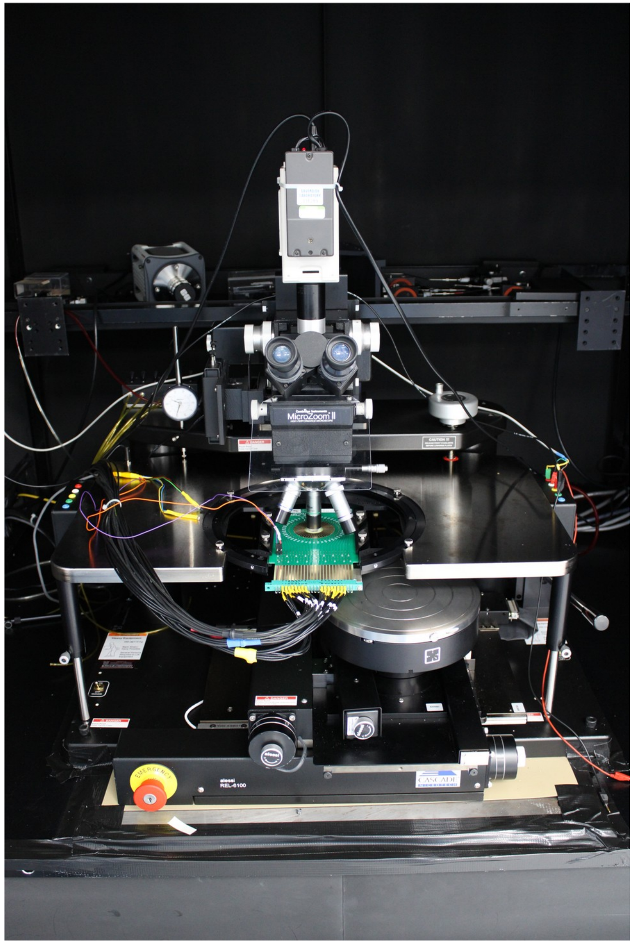




Tests on sample sensors

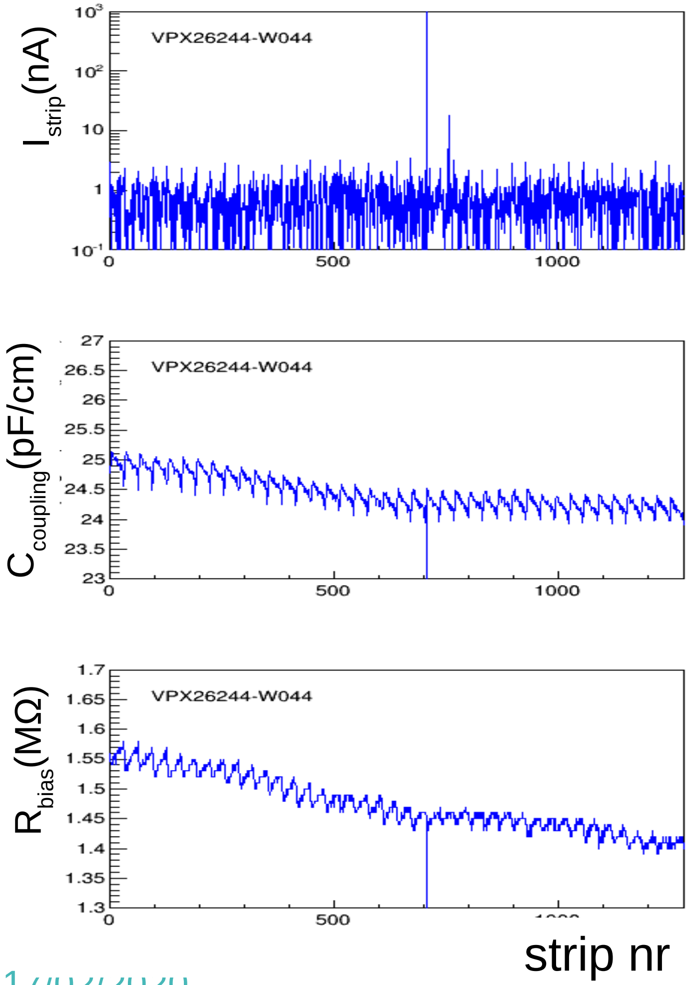
- Leakage current stability: 500 V_{bias} for 24..40 hr
- Full Strip Test between strip metal and bias rail:
  - 10V to check for shorts
  - 100V to check for oxide pinholes
  - LCR meter to measure R_{bias}-$C_{coupling}$ circuit
  - single channel or probecard operation



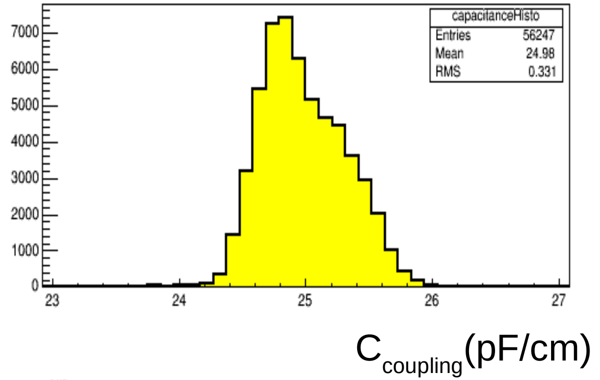


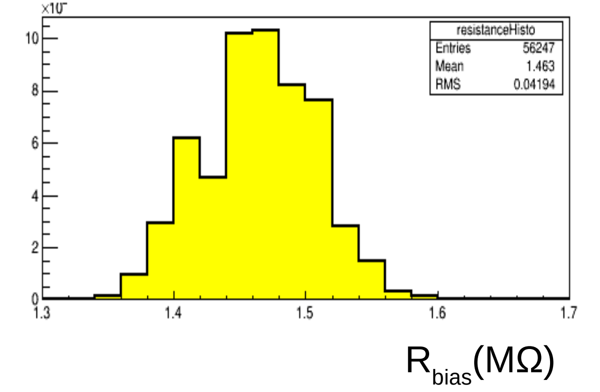
Barrel Sensor Strip Test Results

single sensor results



full batch results: 22 sensors





- About 700k barrel sensor channels probed so far
- Good test reliability
- Picked out sensors with defects
- Channel yield >99.9%
- achieved test rate of 1800 ch/hr using 32ch probecard on barrel sensors

Summary

Summary and conclusions

- Current ITk strip sensor design result of long R&D and prototyping programme
- Extensive verifications indicates radiation hardness sufficient for application
- Studies of long-term sensor stability show good sensor performance
- Excellent uniformity between sensors and channels on sensor
- Project moving into Pre-Production phase:
  - Focus now on Quality Control, Quality Assurance

Backup

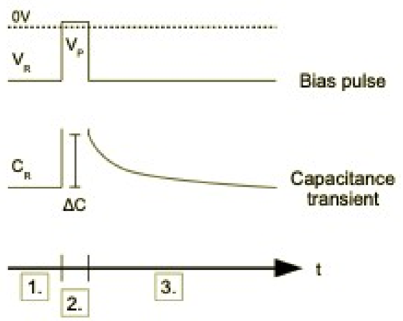
Capacitative DLTS for trap spectroscopy

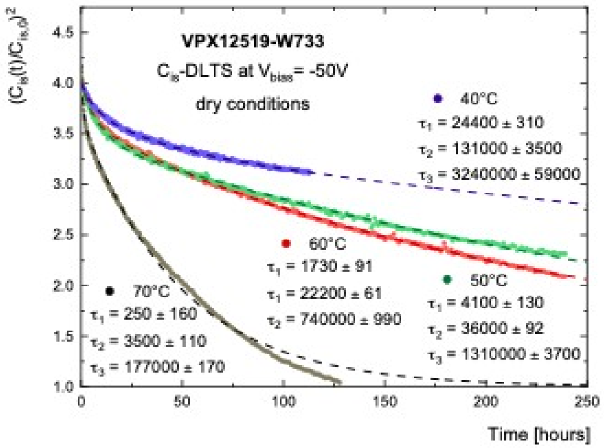
Deep Level Transient Spectroscopy usually employed to study bulk devices:

- bias pulse to saturate states
- monitor decline (I, V or C) to map relaxation to thermal equilibrium

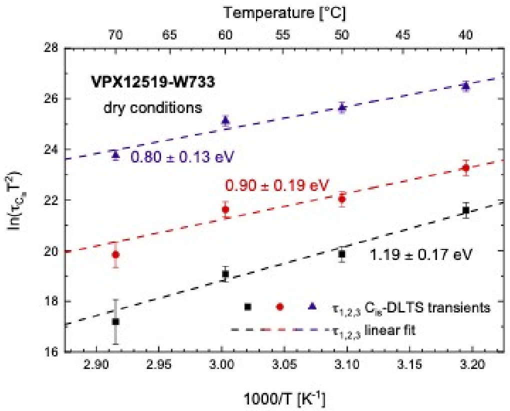
Here: use C_{int} saturation effects as bias pulse, monitor C_{int} relaxation to estimate trap energies

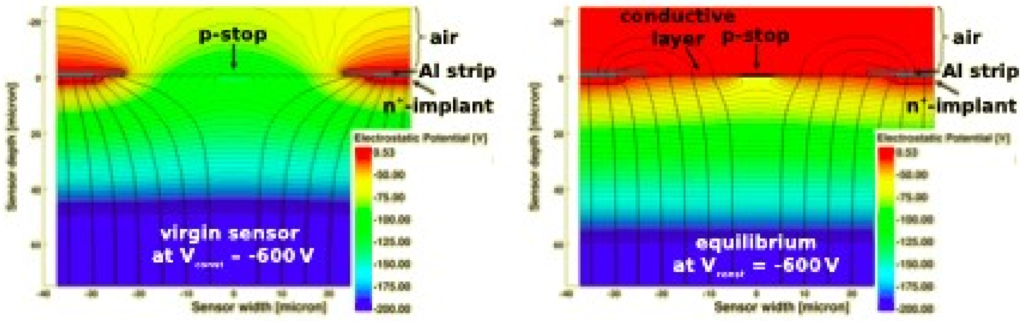
- Long-duration runs at different temperatures
- Constant environment: RH ~ 1% to suppress humidity related effects





DLTS results: trap characterisation





- Estimated trap energies relatively high O(1 eV), cross sections low
- Strong dependence on humidity
- Multiple apparent traps point to complicated “charge imprint” processes in Si-SiO2 layer
- TCAD simulations to correlate supposed device model with measurements
- Processes reversible and akin to those at play when irradiating & annealing

Consequences for ITk operation

- Sensors sensitive to humidity: keep dry
- Awareness of hysteresis effects important when changing V_{bias} during operation
- In cold, dry conditions, sensor surface conditions only settle on time scales of many days
- Mostly a concern at beginning of ITk operations