Signal formation in segmented Si planar detectors: TCAD simulated effect of SiO_2 passivation layer

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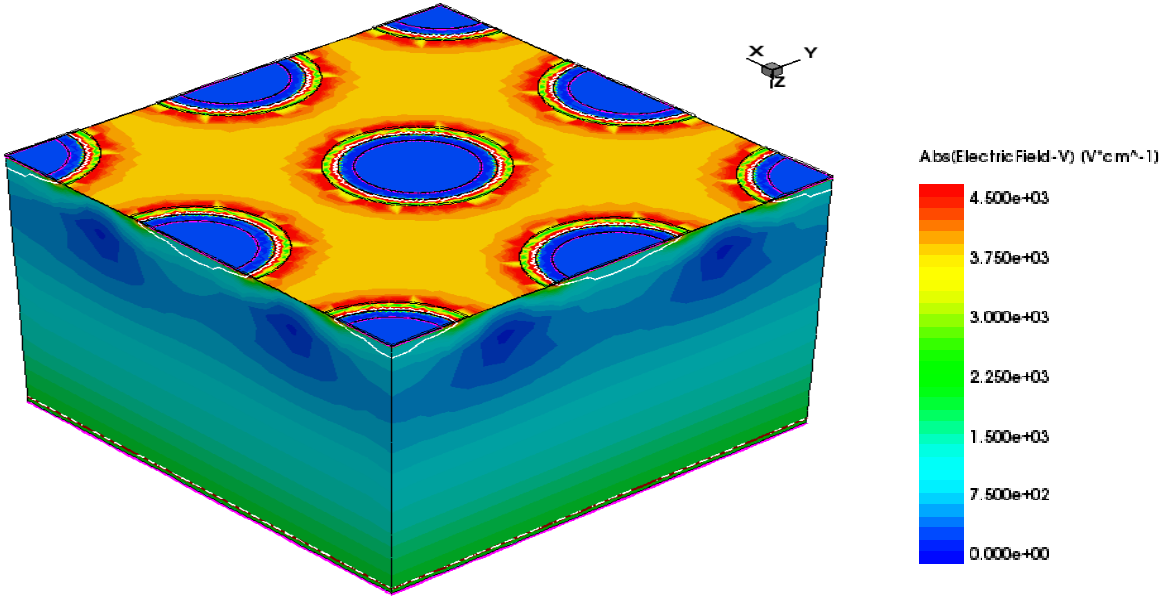


Outline

- ☐ **Motivation**
- ☐ **Simulated laser scans of strip sensors**
  - **Red & IR laser:**
    - Scans of p-on-n strip sensors
  - **Red laser:**
    - Scan of n-on-p strip sensor
  - Transient signal analysis
- ☐ **Summary & Conclusions**

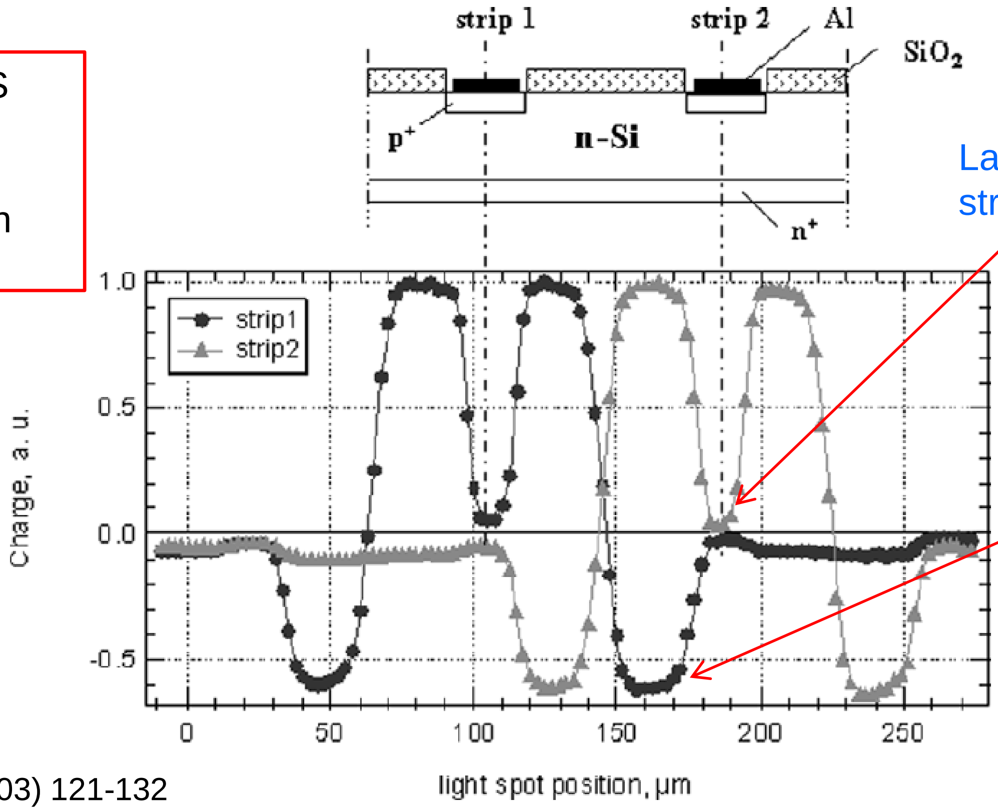
Motivation I: Effect

☐ **Observation:** Reversal of pulse polarity in the strip detector response to red laser charge injection [1,2]

☐ Measured negative signal ~30–60% of peak positive signal → CCE strongly reduced even in non-irradiated detectors

☐ **Interpretation:** If effect is due to the Si/SiO2 interface states (Q_f) → e-h pairs generated under the strip implant will produce largest signal

- Cross-strip scan of ATLAS “baby” strip detector
- Al width = implant width
- Measured on p+ -side with red laser @ V=350 V



Laser attenuation by strip Al

Reversed polarity at midgap < d < gap from collecting strip

[1,2]

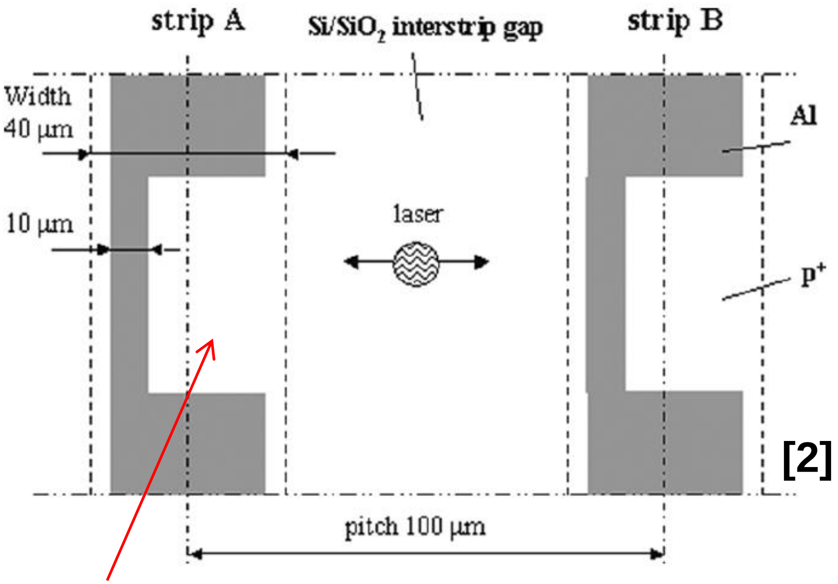
[1] V. Eremin et al., NIM A **500** (2003) 121-132

[2] E. Verbitskaya et al., IEEE Trans. Nucl. Sci. **52** (2005) NO. 5

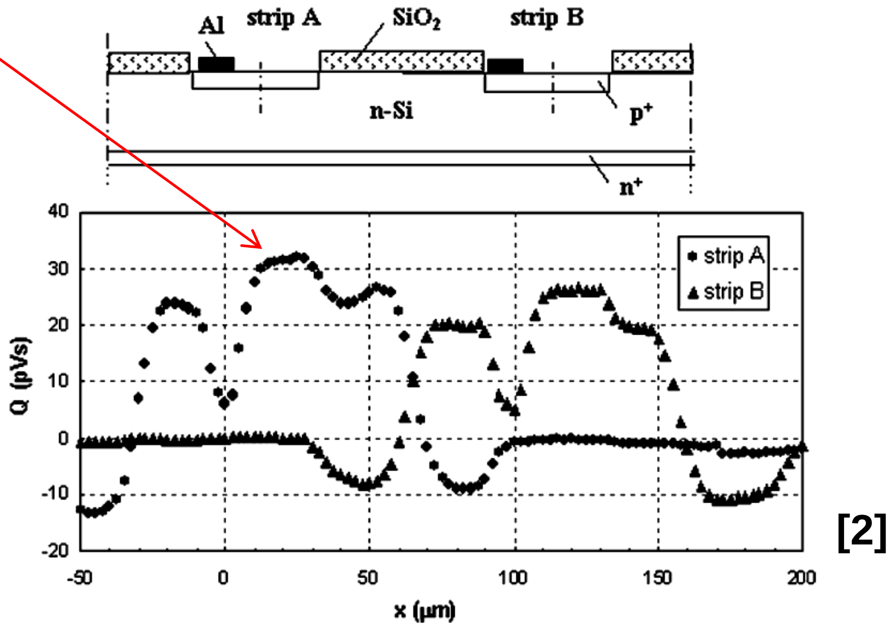
Motivation II: Measurement

- ☐ **Specially designed p-on-n strip detectors:** Red laser scans across the strips & interstrip gap
- ☐ **Measurement:** Non-irradiated detectors, $Q_f \approx 5e10\ cm^{-2}$, laser diameter 10 µm
- ☐ Highest charge collected at strip implant (oxide free region) → **Q_f dependence**

PTI "baby" strip detector design



Window in metallization on the p+ strip implant for charge injection from oxide-free region



Charge signal in PTI strip detectors across two adjacent strips @ V=400 V

Further investigation of the role of Q_f in signal formation by TCAD simulations

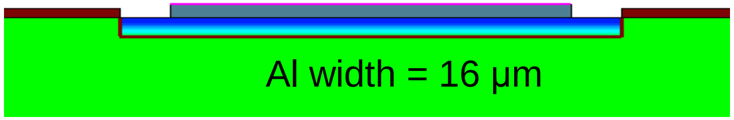
Red laser scans of p-on-n sensors

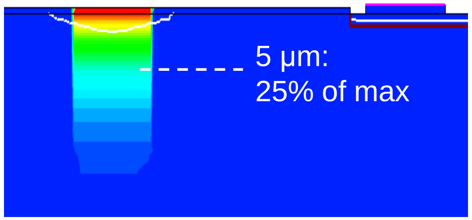
ATLAS sensor: 10 µm laser diameter

- ☐ **ATLAS:** 300 µm p-on-n, p = 80 µm, implant = 20 µm, MO = -2 µm
- ☐ 3-strip structure, charge collected at centermost strip @ V = 300 V, T = 293 K
- ☐ **Laser parameters from measurement:** λ = 0.67 µm, t_{pulse} = 1 ns, dx = 10 µm

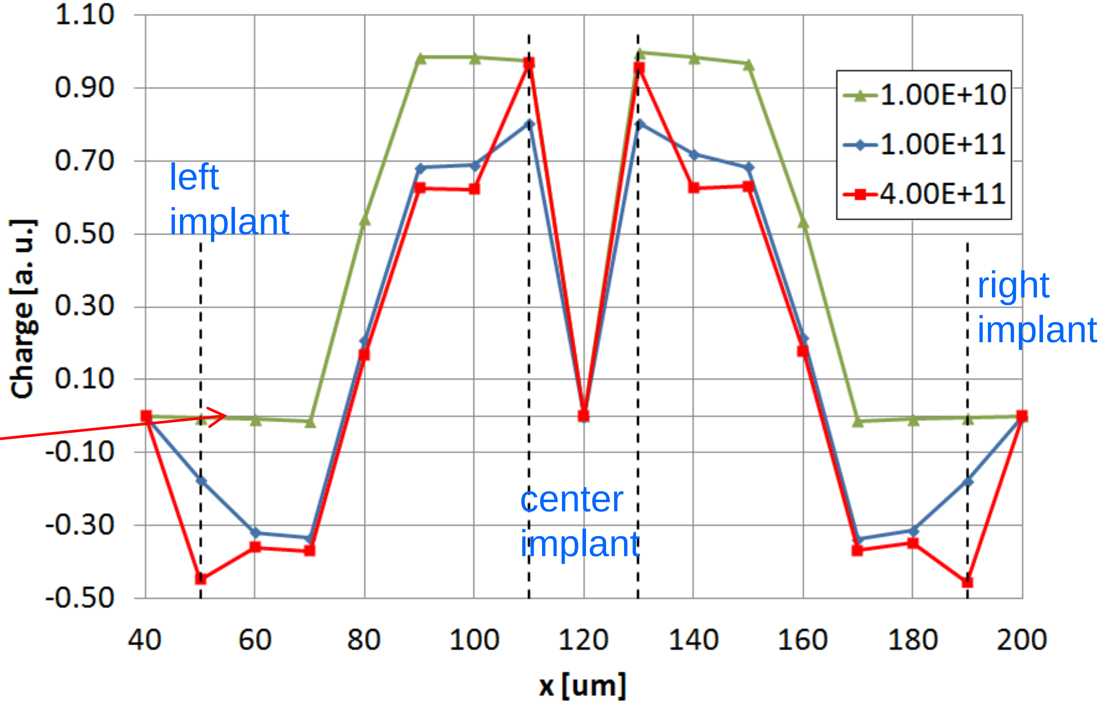
Strip implant & metallization

- ☐ d_{oxide} = 470 nm, d_{Al} = 700 nm, $d_{implant}$ = 1.0 µm



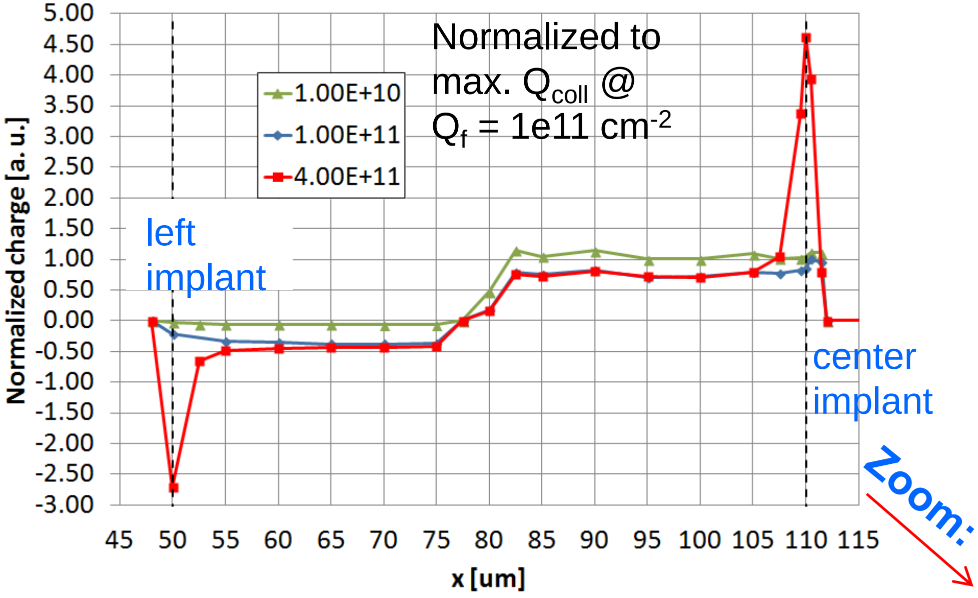


Red laser scan with varied Q_f



- ☐ Value of negative collected charge is strongly dependent on interface charge density Q_f
- ☐ Effect seems to vanish at lowest Q_f

ATLAS sensor: 1 μm laser diameter



Normalized to max. Q_{coll} @ Q_f = 1e11 cm^{-2}

left implant

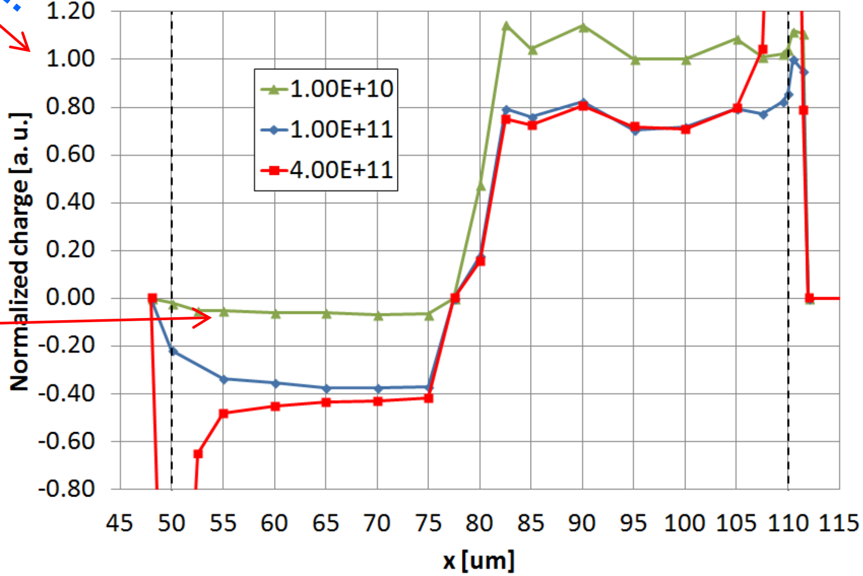
center implant

☐ Laser: λ = 0.67 μm, t_{pulse} = 1 ns, dx = 1 μm

☐ Thermal diffusion switched off, increased # of simulation points

☐ **Only left & centermost strips plotted:** identical behaviour on both sides of center strip

Zoom:



☐ **Charge carriers generated at smaller lateral space:** Clearer view to Q_{coll} behaviour

☐ Sign change of Q_{coll} within 15 μm

☐ Effect still present at lowest Q_f

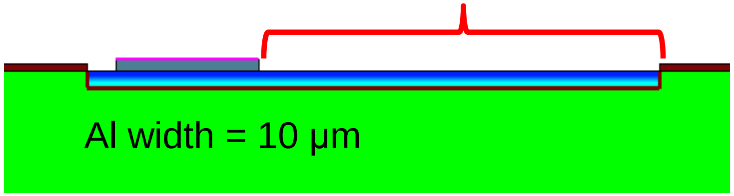
☐ **Q_f = 4e11 cm^{-2}**: Significant increase of Q_{coll} @ implant edges due to small laser diameter & increased E-field peaks (seen also at smaller scale on slide 6)

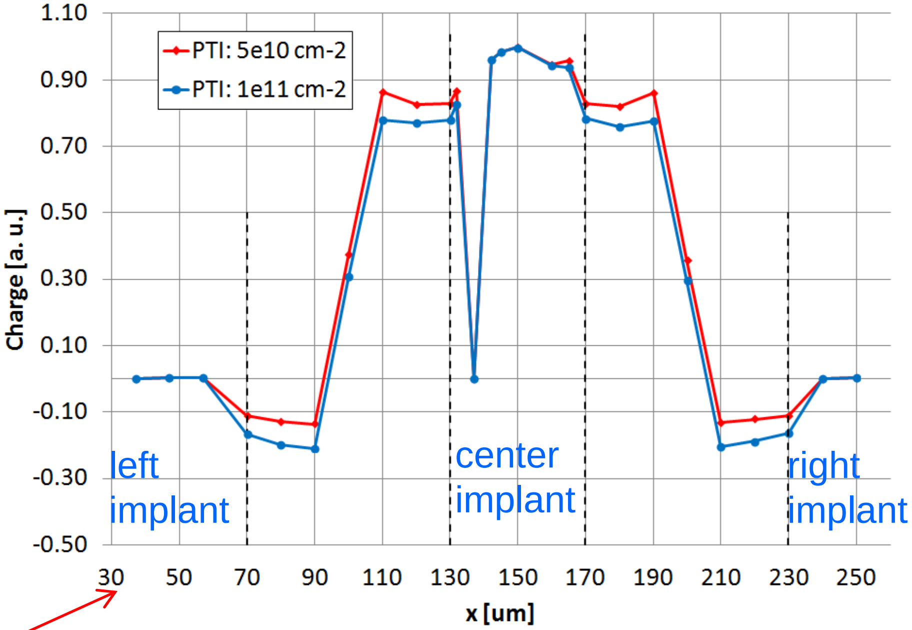
PTI sensor: 10 µm laser diameter

❑ **PTI:** 300 µm p-on-n, A = 10·10 mm^2, p=100 µm, implant=40 µm, MO = -2 µm

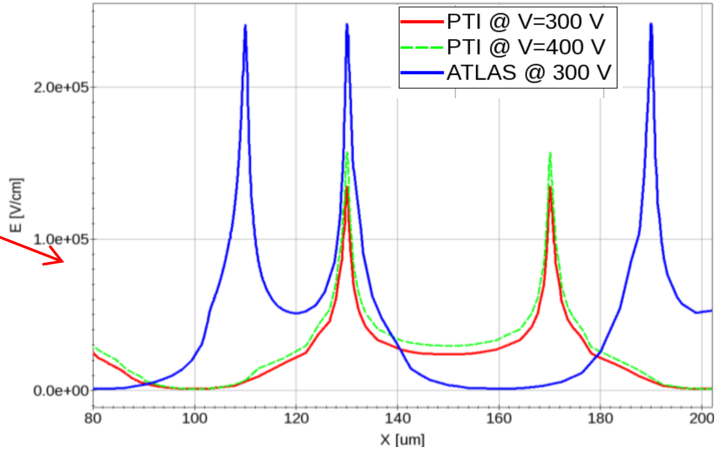
❑ 3-strips, collection at centermost strip @ V = 400 V, T = 293 K

Window in implant metallization





E-field cut parallel to surface @ 0.8 µm depth



❑ Highest Q_{coll} at implant injection → match with measurement

❑ Oxide charge influences both polarity Q_{coll}

❑ Implant width (ATLAS: 20 µm, PTI: 40 µm) plays a role in negative Q_{coll} value due to lower E-field peaks at edges → **Negative Q_{coll} @ Q_f = 1e11 cm^{-2}:**

- ATLAS @ 300 V: -33.5%
- PTI @ 400 V: -24±3%

PTI sensor: 1 µm laser diameter

❑ **PTI:** Parameters as in previous slide

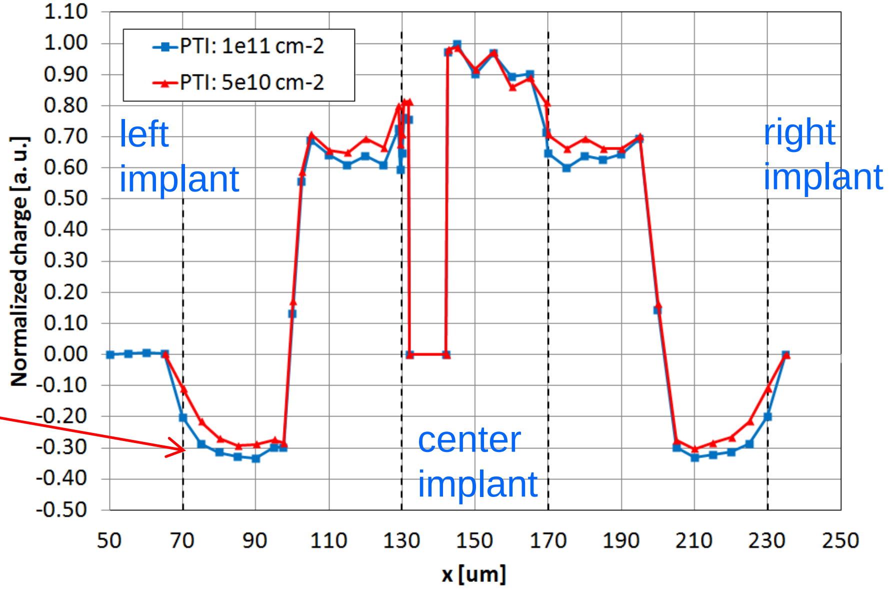
❑ Thermal diffusion switched off, increased # of simulation points

❑ **Q_f = 1e11 cm^{-2}:** Undershoot increased from previous slide @ x=90 µm by 12.5% due to smaller laser diameter

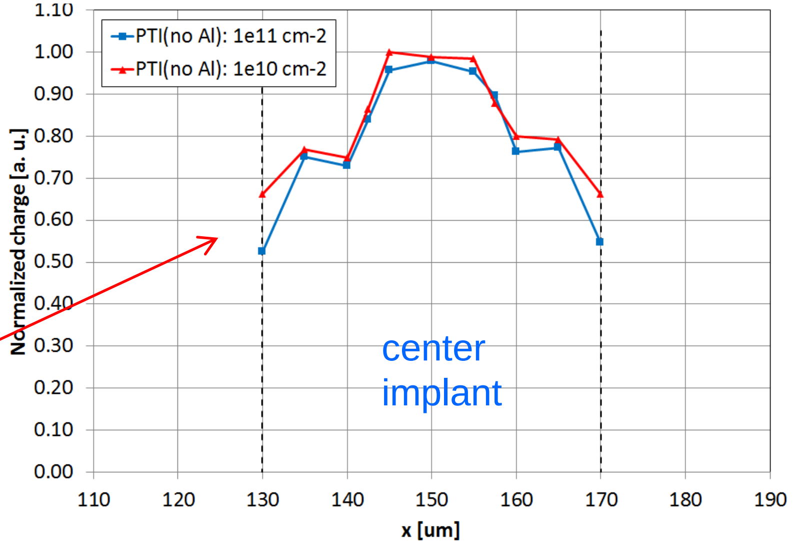
❑ Sign change of Q_{coll} close to step function @ ~100 µm

❑ **Positive signal at oxide:** ~70% of max. Q_{coll} at implant

❑ **Q_f = 4e11 cm^{-2}:** similar behavior to ATLAS design: Q_{coll}(x=70 µm) = -2.63



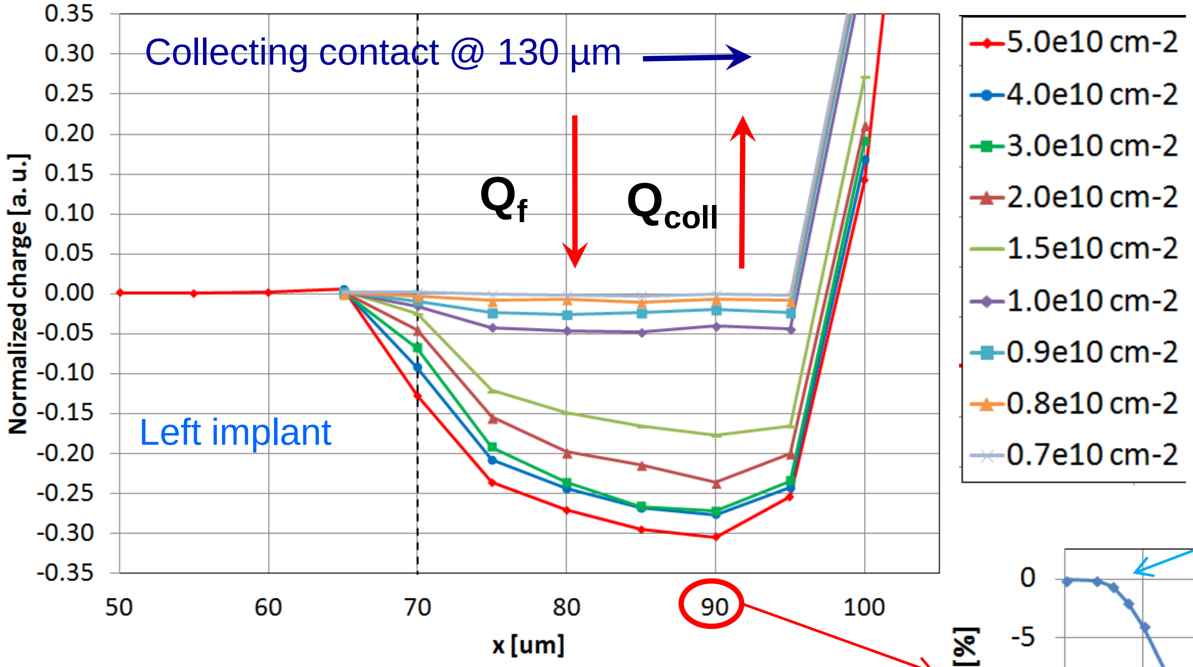
❑ **Al removed:** Highest Q_{coll} @ center of implant is physical effect (symmetrical behaviour), not due to meshing → longest distance to SiO_2/Si interface, smallest contribution from interface current



Critical Q_f scan: $Q_{coll}(x)$, $Q_{coll}(Q_f)$

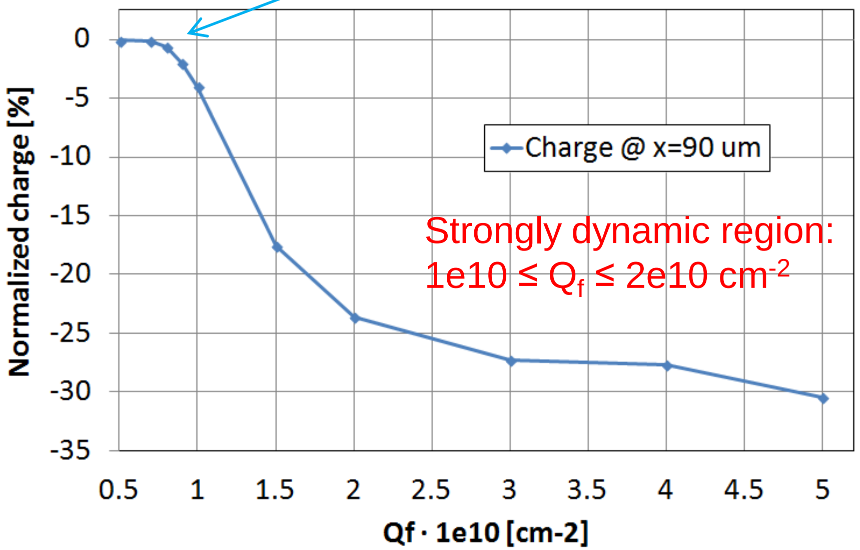
Scan for critical Q_f :

☐ PTI detector & laser with parameters from slide 8



- ☐ Negative polarity signal vanishes with decreased Q_f → **Exclusive dependence on interface charge states**

Essentially no undershoot at $Q_f \leq 0.8\text{e}10$ cm^{-2}

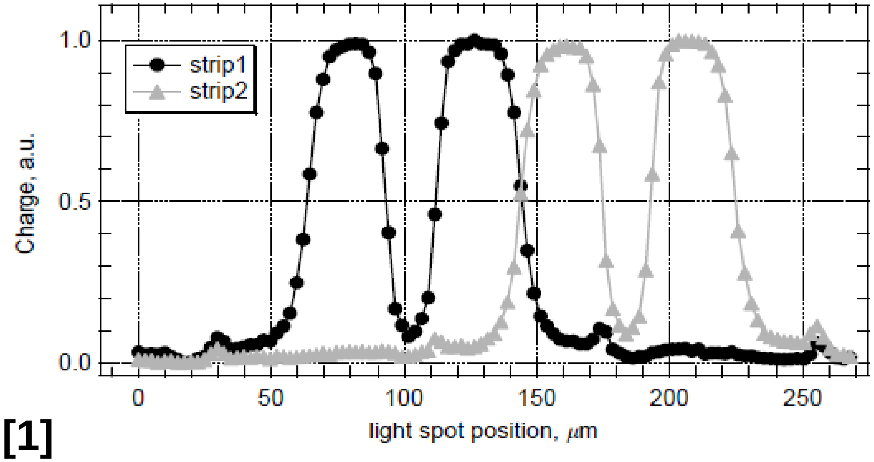


Strongly dynamic region: $1\text{e}10 \leq Q_f \leq 2\text{e}10$ cm^{-2}

IR laser scan of p-on-n sensor

IR laser scan: Measurement & simulation

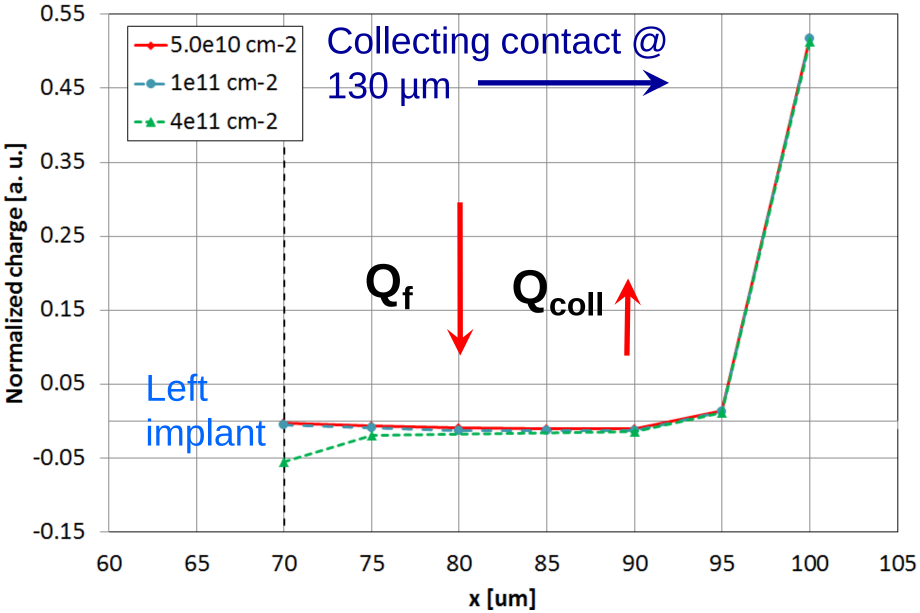
Measurement: Q_{coll} & consequent current response do not show a polarity-inverted signal



[1]

Cross-strip IR laser scan on p+ -side of ATLAS "baby" strip detector @ V=350 V

- ☐ **Simulation:** PTI p-on-n sensor parameters from previous section



- ☐ **Distance to collecting contact > gap/2:** Polarity reversal still present but significant only at very high values of Q_f
- ☐ **High Q_f:** similar to red laser results increased E-field at implant edge enhances negative signal

IR & red laser: Transient signal analysis

☐ Midgap cut:

- Mean $v_e \approx$ 6.6e6 cm/s @ V=400 V

→ calculated $t_e \approx$ 4.5 ns @ d = 300 μm

- Mean $v_h \approx$ 3.5e6 cm/s → $t_h \approx$ 8.4 ns

☐ d = distance from collecting strip

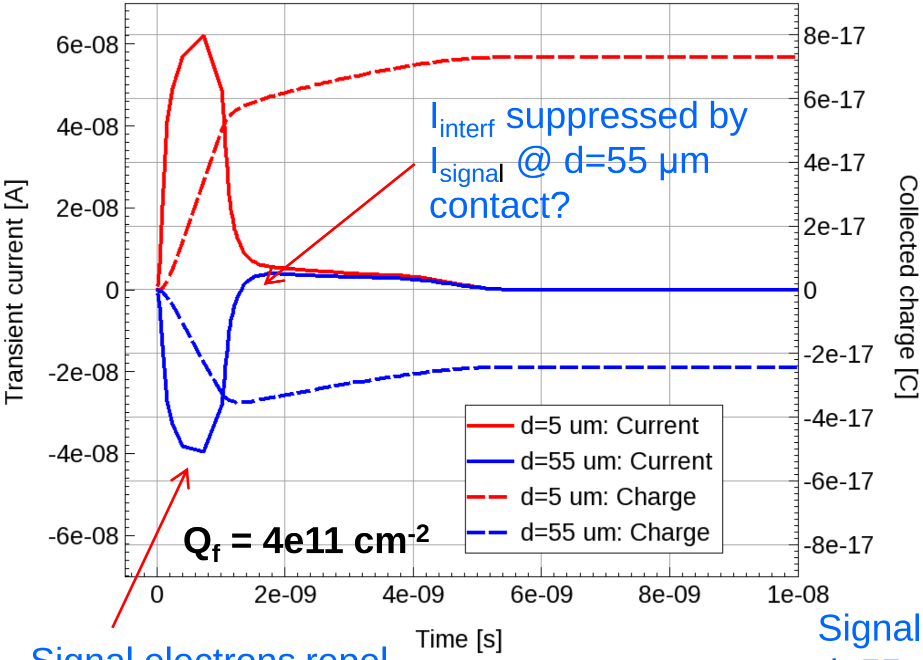
☐ Interstrip gap = 60 μm

Ramo: $I \propto q\vec{v}$, where $q = \pm e$

→ $I_{tot} = I_{signal} + I_{interface}$

→ **p-on-n:** $I_{interface}$ has always (both red & IR injection) opposite polarity to I_{signal}

Red laser: Transient signal from electron drift

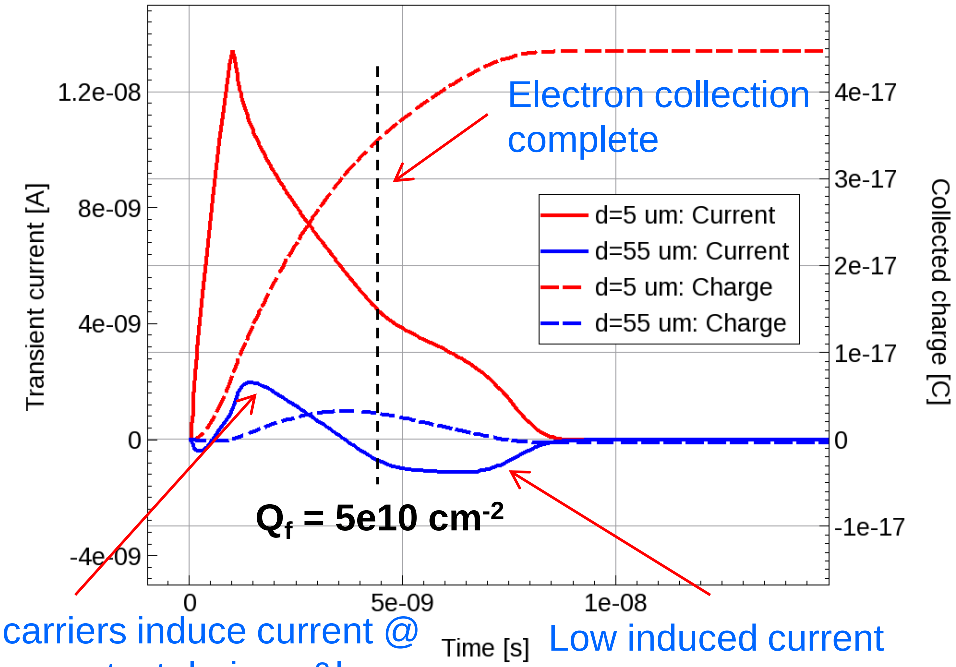


I_{interf} suppressed by I_{signal} @ d=55 μm contact?

Q_f = 4e11 cm^{-2}

Signal electrons repel interface electrons → I_{interf}

IR laser: Transient signal from e&h drift



Electron collection complete

Q_f = 5e10 cm^{-2}

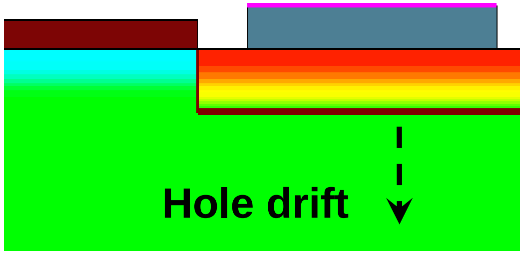
Signal carriers induce current @ d=55 μm contact during e&h drift → I_{interf} is suppressed

Low induced current from hole drift @ d=55 μm → I_{interf} dominates

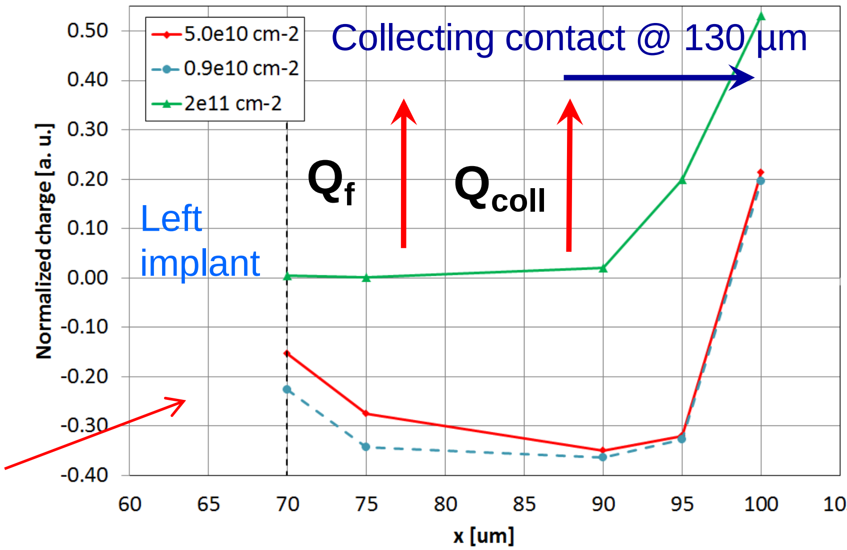
Red laser scan of n-on-p sensor

N-on-p w/ p-spray: Red laser scan

- ❑ PTI strip sensor with injection window at implant
- ❑ P-spray isolation: N_p=5x10^{15} cm^{-3}



- ❑ Opposite polarity Q_{coll} grows with decreased Q_f → **interface current from hole drift**



$I \propto q\vec{v}$, where $q = \pm e$ → $I_{tot} = I_{signal} + I_{interf}$

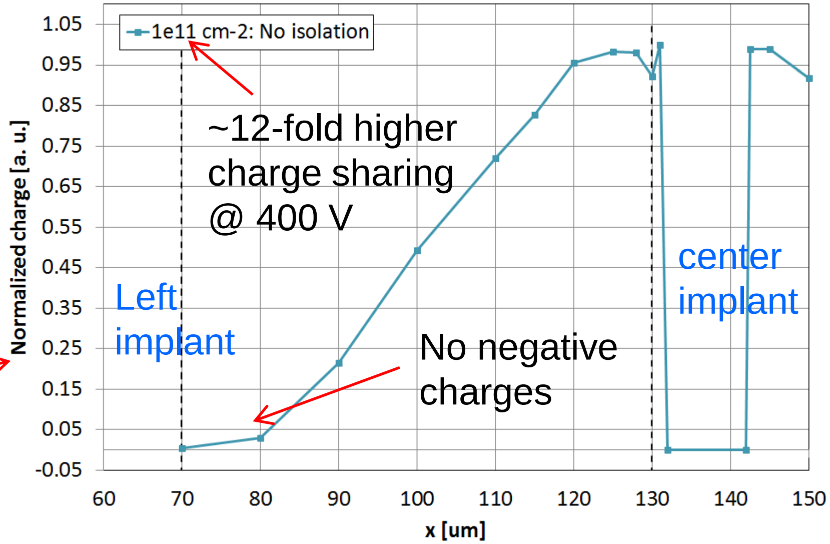
→ **n-on-p:**

- **Strips isolated:**

I_{interf} has opposite polarity to I_{signal}

- **No isolation structure:**

I_{interf} has equal polarity to I_{signal} → Q_{coll} at oxide ≥ Q_{coll} at implant from short-range injection



Summary

- ☐ Observed reversal of the pulse polarity & reduction of the signal for short-range charge injection investigated by TCAD simulations
- ☐ Red/IR laser scans for specially designed p-on-n & n-on-p sensors across the strips were conducted

- ☐ **Red laser results:**
  - **Both sensor types:** Strong dependence on oxide charge density Q_f → effect vanishes at $Q_f \leq 0.8e10\ cm^{-2}$
  - **At constant Q_f:** Effect increases by decreased beam & strip implant width
  - **N-on-p:** Negative response due to hole drift in isolation implant
- ☐ **IR laser results:**
  - Effect visible only for high Q_f values due to compensation by 'signal' carriers with longer collection distance → charge sharing

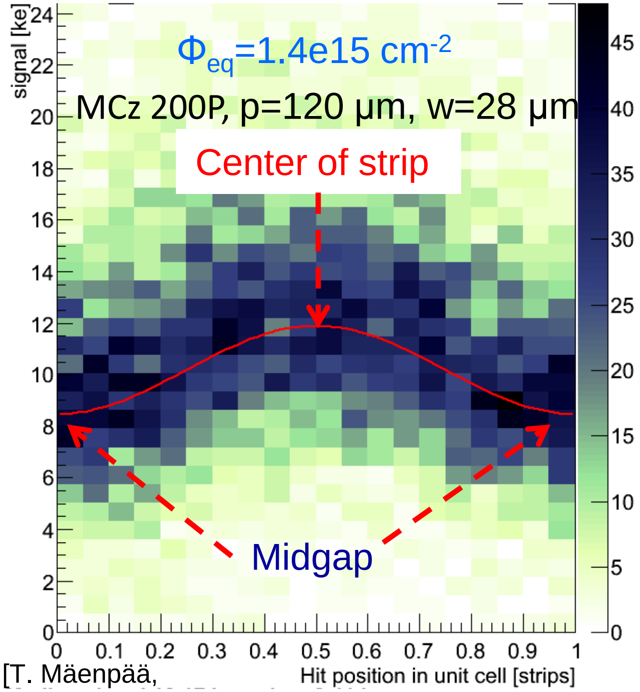
Interpretation: Generation of charge carriers at segmented side leads to drift of electrons (holes) at Si/SiO_2 interface → Transient signal = $I_{signal} + I_{interface}$ → drift of equal sign carriers leads to opposite sign contribution from $I_{interface}$

→ **Short-range charge injection: CCE is position dependent in both non-irradiated & irradiated segmented sensors**

Back-up: Measured & simulated CCE(x)

Test beam measurement:

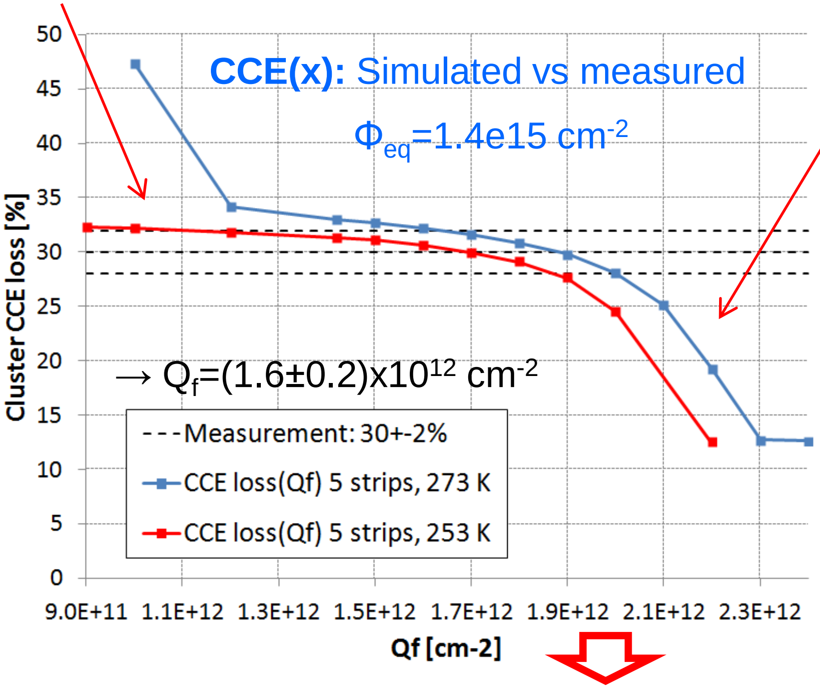
- Strips isolated
- CCE loss between strips ~30%



[T. Mäenpää, PoS(RD13)015, 2013]

❑ Traps remove both interface & signal electrons: better radiation induced strip isolation → higher CCE loss between strips

❑ Higher Q_f → more traps filled → charge sharing between strips increases → CCE loss decreases



❑ **Interpretation:** Irradiation produces non-uniform distribution of shallow traps close to surface → greater drift distance, higher trapping of carriers

[T. Peltola, JINST 9 (2014) C12010]

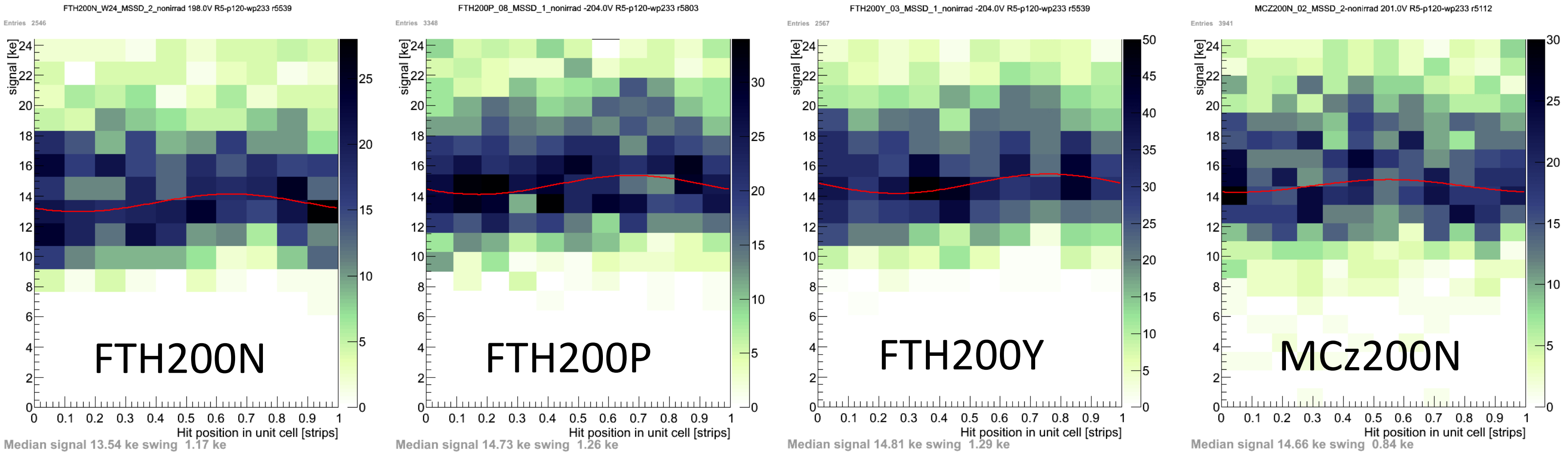
Preliminary parametrization for **Φ = 3e14 – 1.4e15 cm^{-2}**

Type of defect	**Level** [eV]	**σ_e** [cm^2]	**σ_h** [cm^2]	**Concentration** [cm^{-3}]
Deep acceptor	E_C - 0.525	1e-14	1e-14	1.189*Φ + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598*Φ - 3.959e14
Shallow acceptor	E_C - 0.40	8e-15	2e-14	14.417*Φ + 3.168e16

Backup: SiBT measured CCE loss between strips

Signal loss in-between strips (p=120µm, w/p~0.23)

non-irradiated



No loss before irrad.; after irrad. ~30% loss; all technologies similar [Phase-2 Outer TK Sensors Review]

mixed irradiated 1.5e15n_{eq}/cm^2