Non-uniform 3-level defect model & status of edge-TCT simulations

23rd RD50 Workshop

November 13th - 15th 2013

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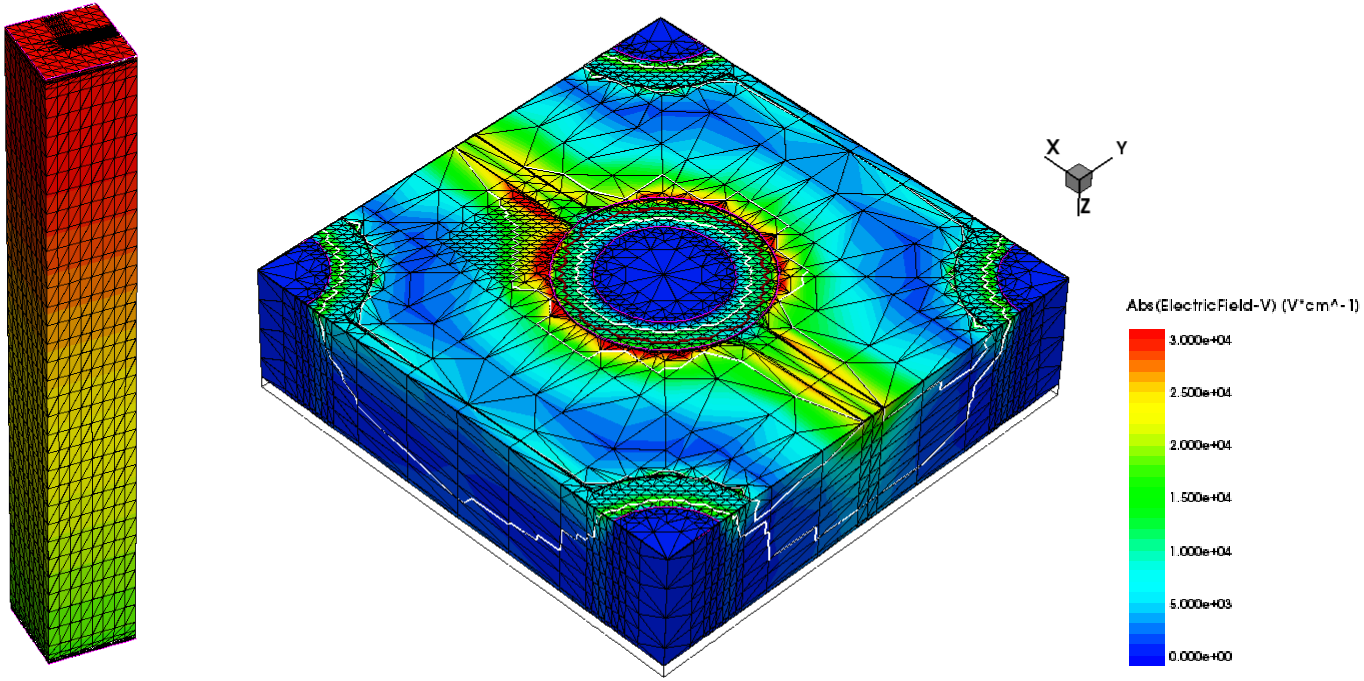


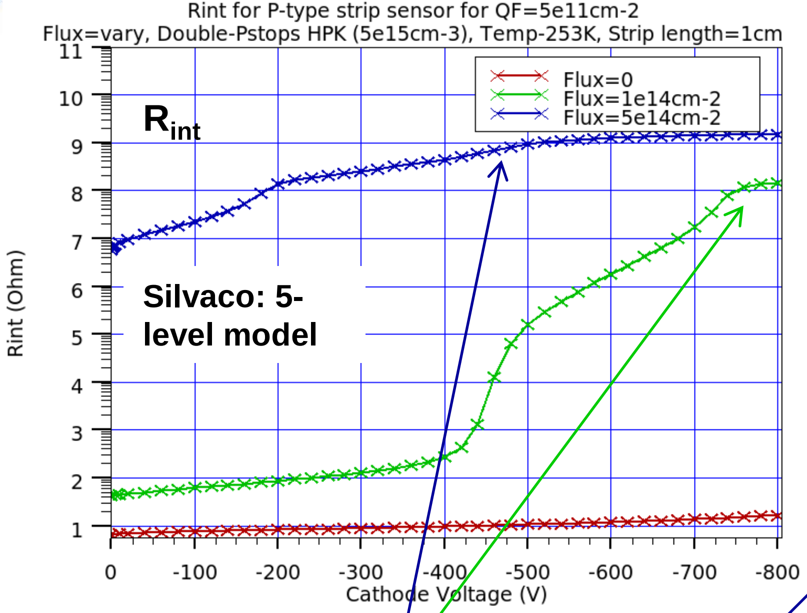
Outline

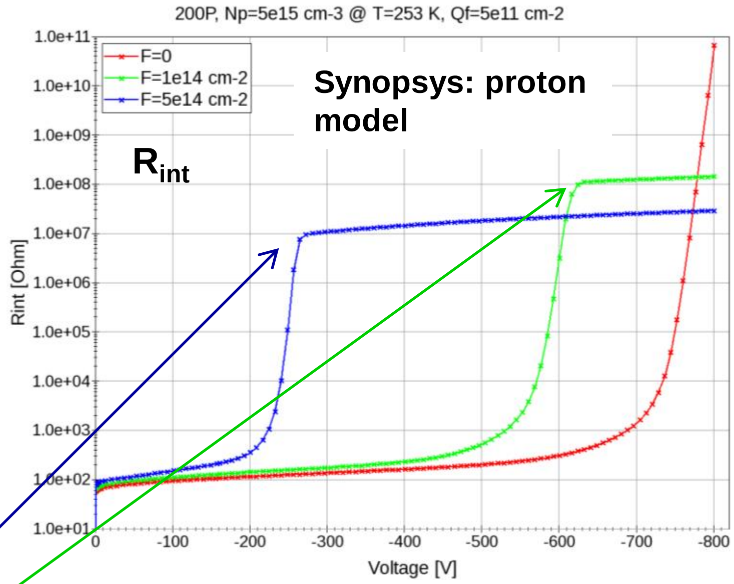
- ☐ **3-level non-uniform defect model for Synopsys TCAD**
  - Motivation: proton model surface damage problems
  - 3-level implementation: bulk vs surface region
  - Comparison with SiBT measured CCE loss

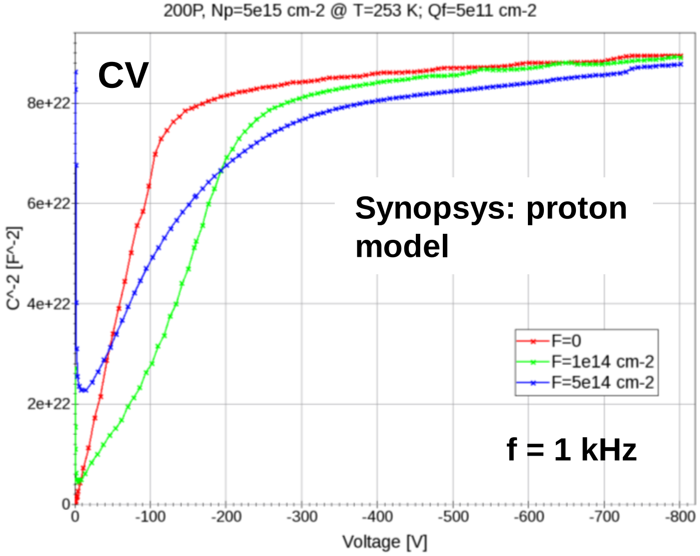
- ☐ **Edge-TCT simulations of MSSD**
  - Non-irradiated:
    - ○ Two approaches to observed $\Delta Q(z)_{max}$ @ $V < V_{fd}$
    - ○ Comparison with measurement @ $V > V_{fd}$
  - Irradiated:
    - ○ Neutrons: Simulation vs measured
    - ○ Protons: 3-level model vs proton model

Non-uniform 3-level proton model

R_{int}: Synopsys proton model vs Silvaco 5-level model







- 5-level model:
  - Value of R_{int} increases with fluence
  - Isolation at V=0 for high fluence
- Proton model:
  - Value of R_{int} decreases with fluence
  - Some compensation for inversion layer electrons → isolation at lower V with higher fluence, but no isolation at V_{abs} < 200 V → **No match with measurements**
- Significant differences to measurements also in C_{int} and CCE loss between the strips for high oxide charges

⇨ **Proton model requires further tuning to model surface damage of a real detector**

Proton model tuned by a shallow acceptor level

- **3-level model uniform concentration in Si bulk**

Levels from Petasecca defect model for p-type [1]

Level [eV]	σ_n [cm^{-2}]	σ_p [cm^{-2}]	Intro. rate [cm^{-1}]
E_C - 0.42	2e-15	2e-14	1.613

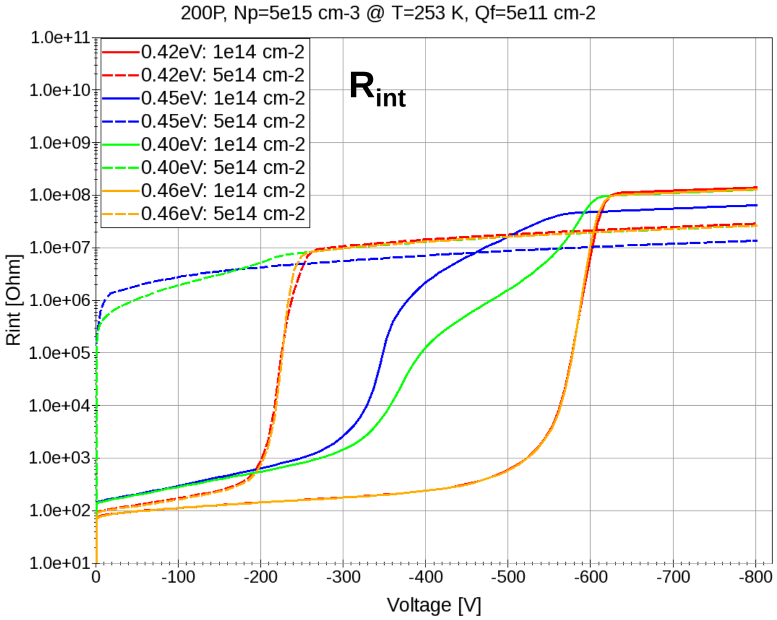
Level [eV]	σ_n [cm^{-2}]	σ_p [cm^{-2}]	Intro. rate [cm^{-1}]
E_C - 0.46	5e-15	5e-14	0.9

Levels from DU 5-level defect model

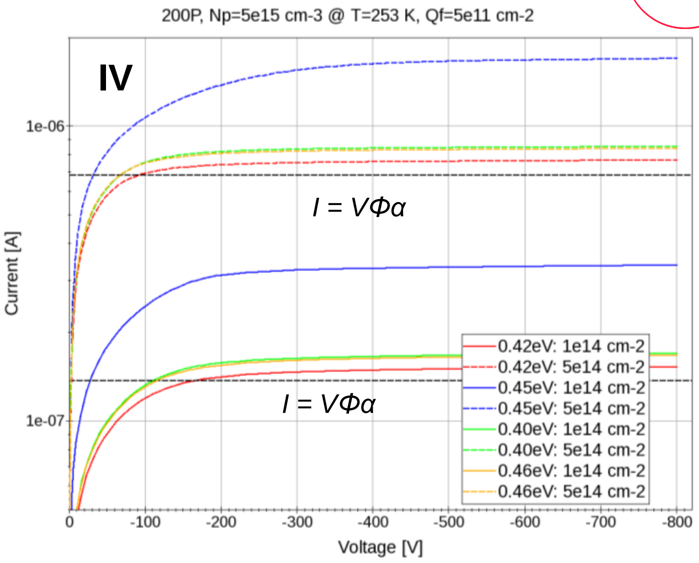
Level [eV]	σ_n [cm^{-2}]	σ_p [cm^{-2}]	Intro. rate [cm^{-1}]
E_C - 0.45	8e-15	2e-14	40

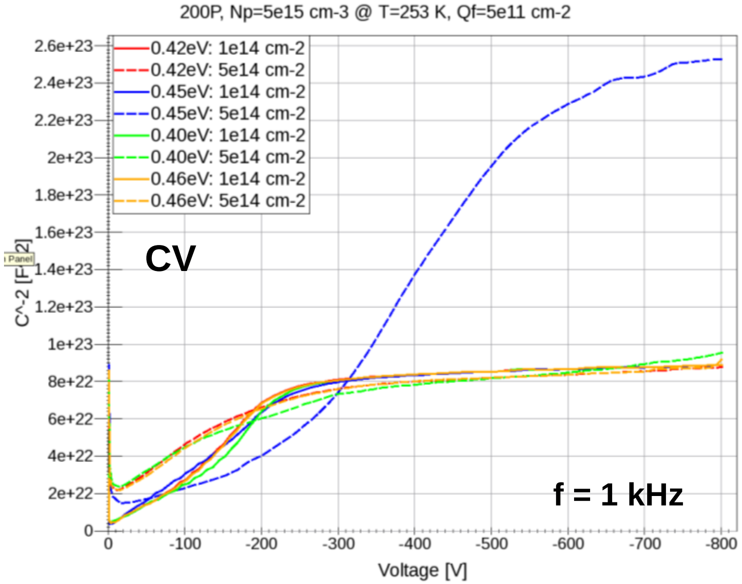
Level [eV]	σ_n [cm^{-2}]	σ_p [cm^{-2}]	Intro. rate [cm^{-1}]
E_C - 0.40	8e-15	2e-14	40

Provides isolation, correct V_{fd} and ~correct I_{leak} @ F = 5e14 cm^{-2}



[1] M. Petasecca et al. NIM A 563 (2006) 192-195.





CCE-scans for proton model & 3-level model (E_c- 0.4 eV)

Constant dose, varied Q_f :

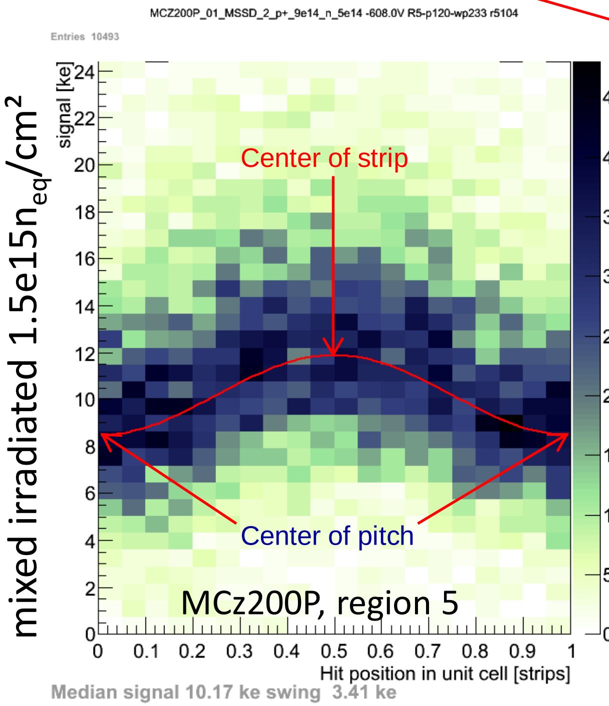
☐ 200P device, region 5

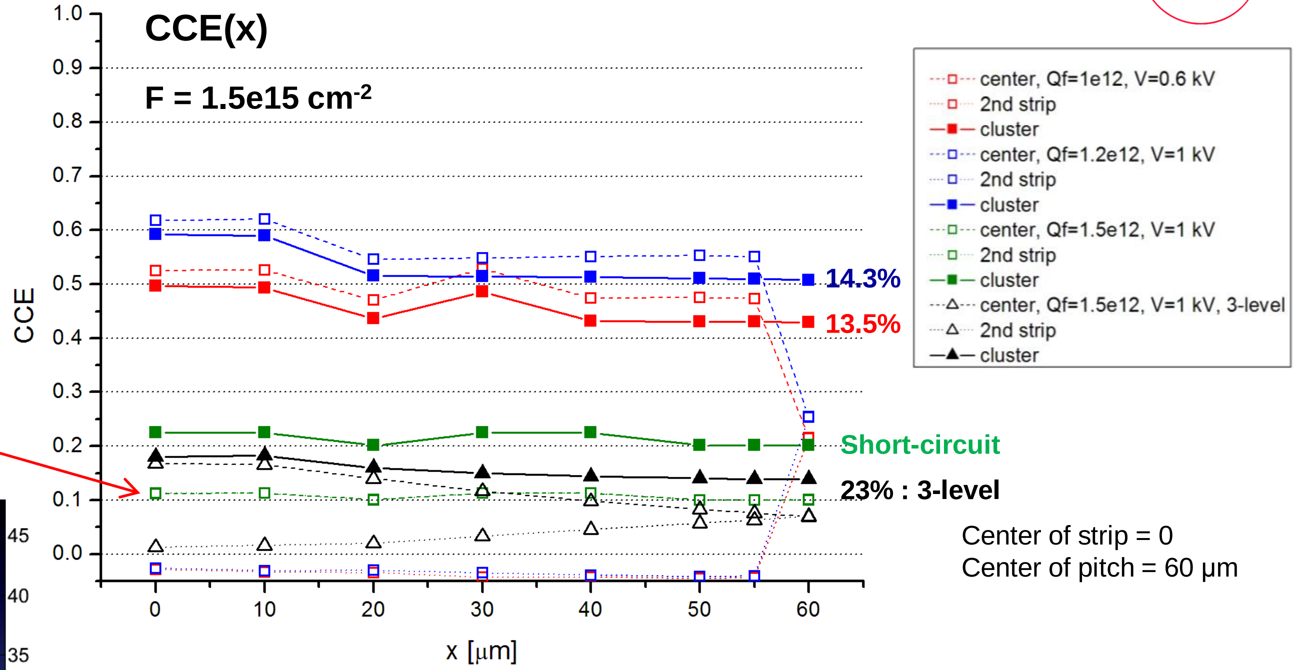
☐ Double p-stop N_p = 1e16 cm^{-3}, width = 4 µm, depth = 1.5 µm, spacing = 6 µm

Proton model:

☐ CCE loss @ Q_f = 1.2e12 cm^{-2} ~15% → half of measured loss

☐ At Q_f = 1.5e12 cm^{-2} charge sharing between strips is equal → no isolation





3-level model uniform concentration in the Si bulk:

☐ Isolation at Q_f = 1.5e12 cm^{-2} : Improved CCE loss, significantly deteriorated absolute CCE values

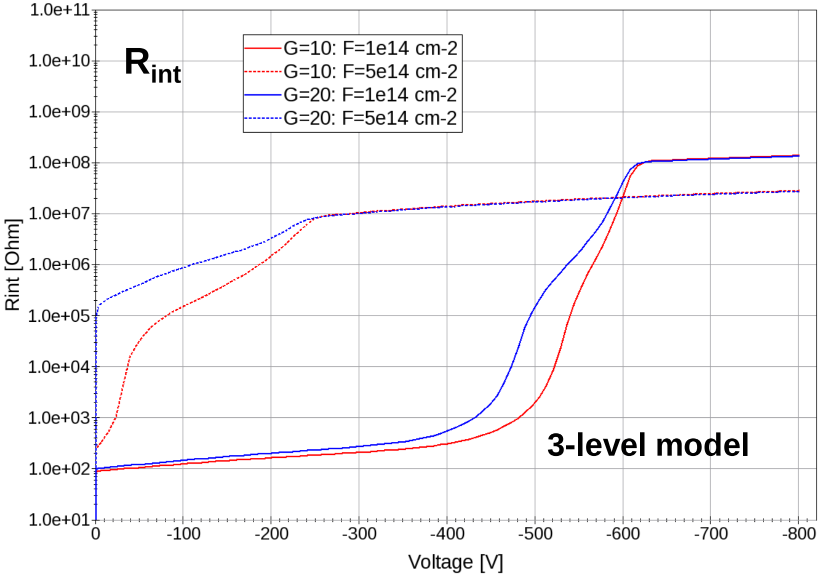
☐ **SiBT measured CCE loss between the strips (center of the pitch) @ Φ = 1.5e15 cm^{-2}: ~30%**

Figure: T. Mäenpää (2013)

3-level model: E_c- 0.4 eV level tuning

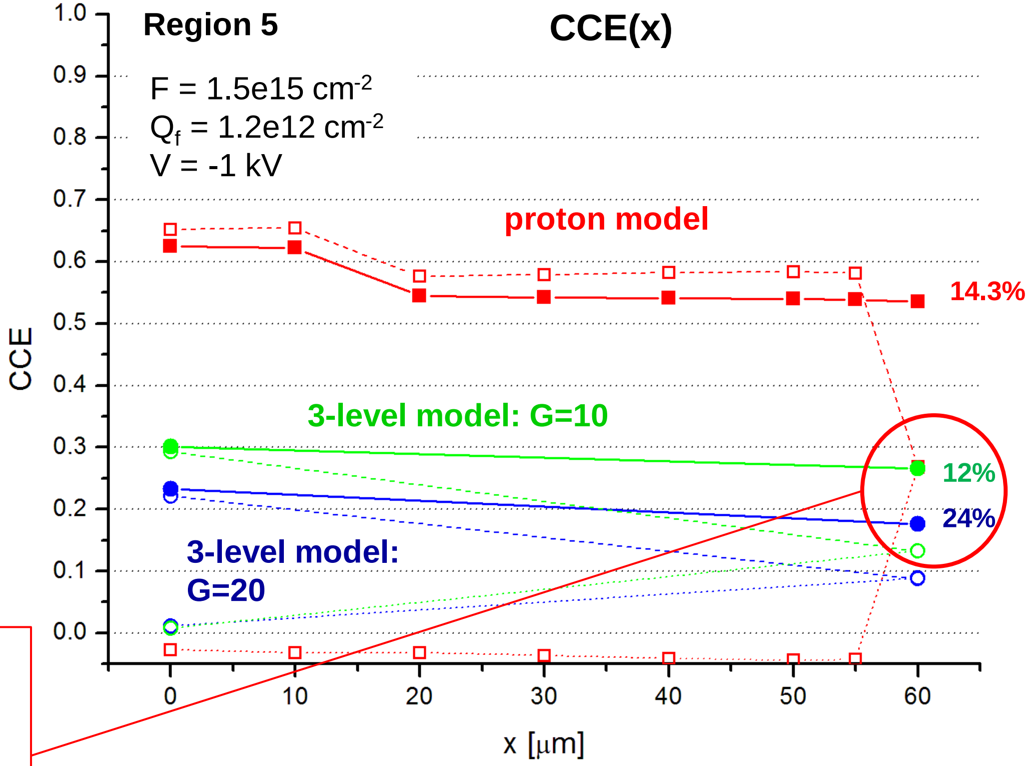
- ❑ Current intro rate G varied to find matching CCE with original model
- ❑ G = 20: R_{int} has high values at V=0

200P, Np=5e15 cm-3, Ec-0.4 eV @ T=253 K, Qf=5e11 cm-2



- ❑ CCE loss has negative space charge dependence: better radiation damage induced strip isolation → larger CCE loss between the strips
- ❑ In addition to inversion layer electrons, also signal electrons experience compensation by the radiation induced negative space charge

- ❑ **3-level model uniform concentration in the Si bulk**



- ❑ Shallow level concentration decreases: higher CCE, lower CCE loss between strips, lower isolation

⇨ **3-level model implementation throughout the Si bulk not succesful → new approach needed**

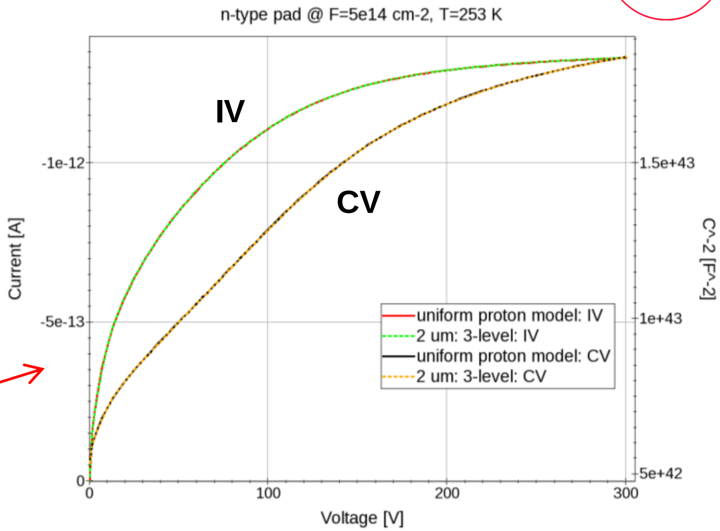
3-level model exclusively close to detector surface

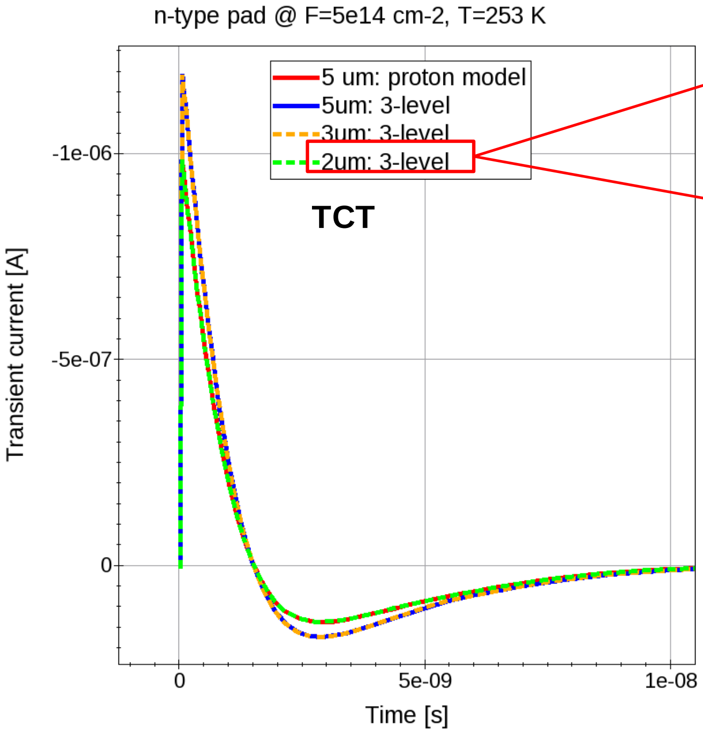
Proton model tuned w/shallow acceptor level = 3-level model

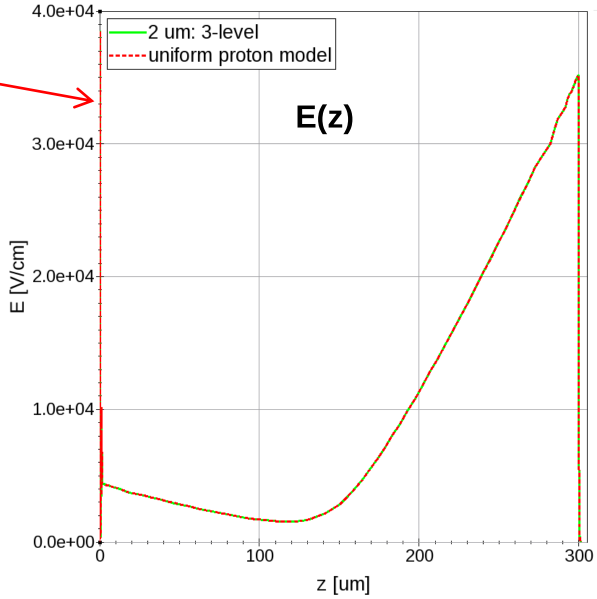
Proton model

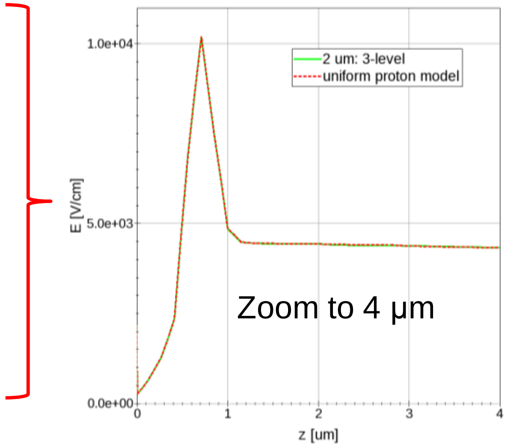
Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acceptor	E_C - 0.525	1e-14	1e-14	1.189**F* + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598**F* - 3.959e14
Shallow acceptor	E_C - 0.40	8e-15	2e-14	40**F*

- ☐ Observed non-uniformity of c_{ox} is modeled by non-uniform defect distribution
- ☐ Region 1 (next to surface): 3-level model, region 2 (Si bulk): proton model
- ☐ 3-level model in region 1 with d = 2 µm: perfect match to proton model for CV, IV, TCT and E(z)



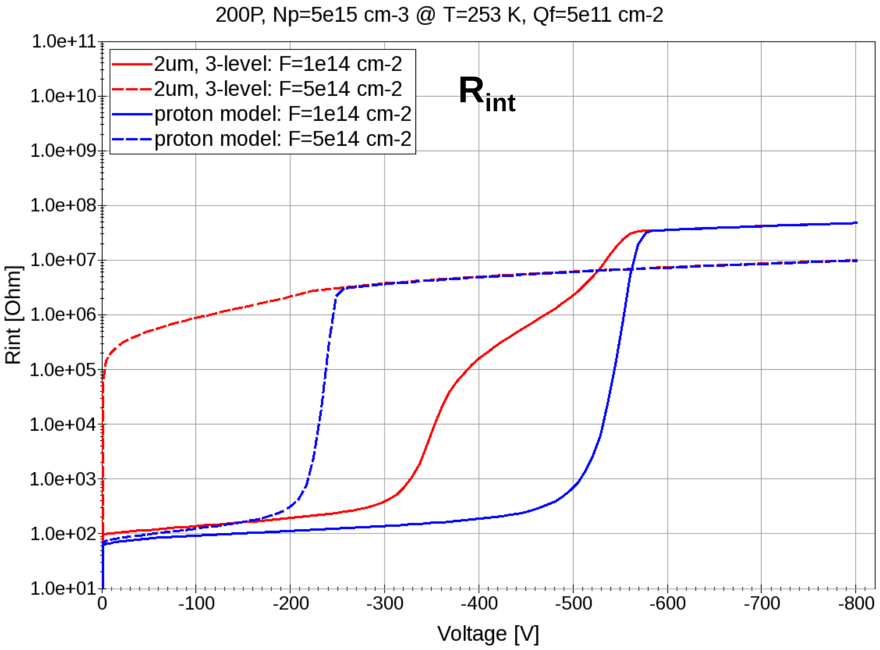


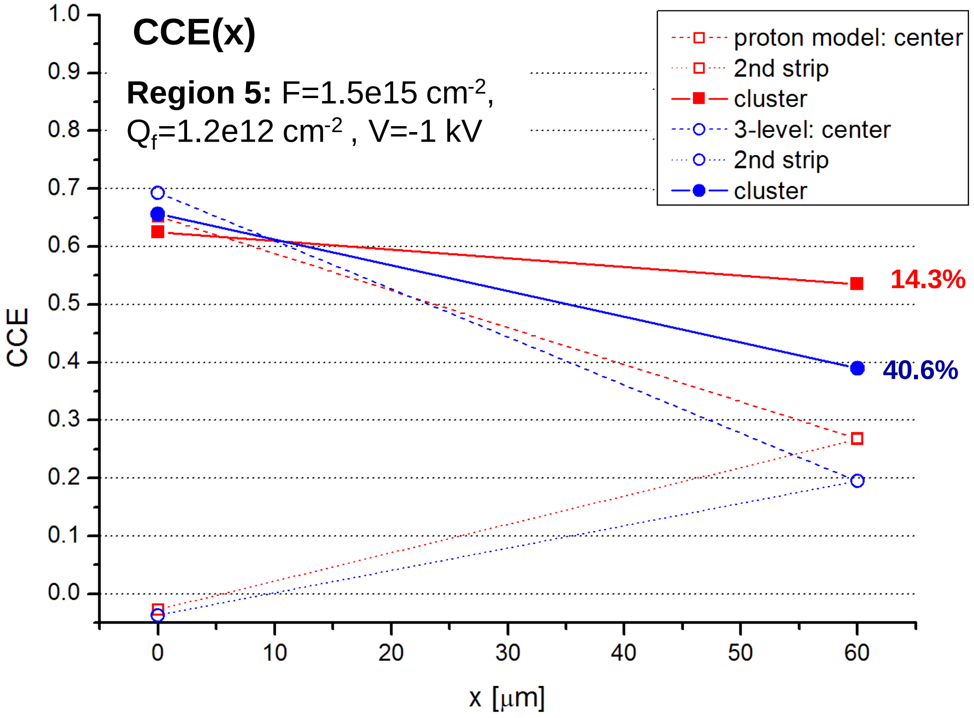




3-level model in region 1(d=2 μm): R_{int} & CCE-scan

- Strips are isolated at V=0 for F=5e14 cm^{-2} as in DU 5-level model
- Difference to 5-level model: R_{int} decreases with increased fluence

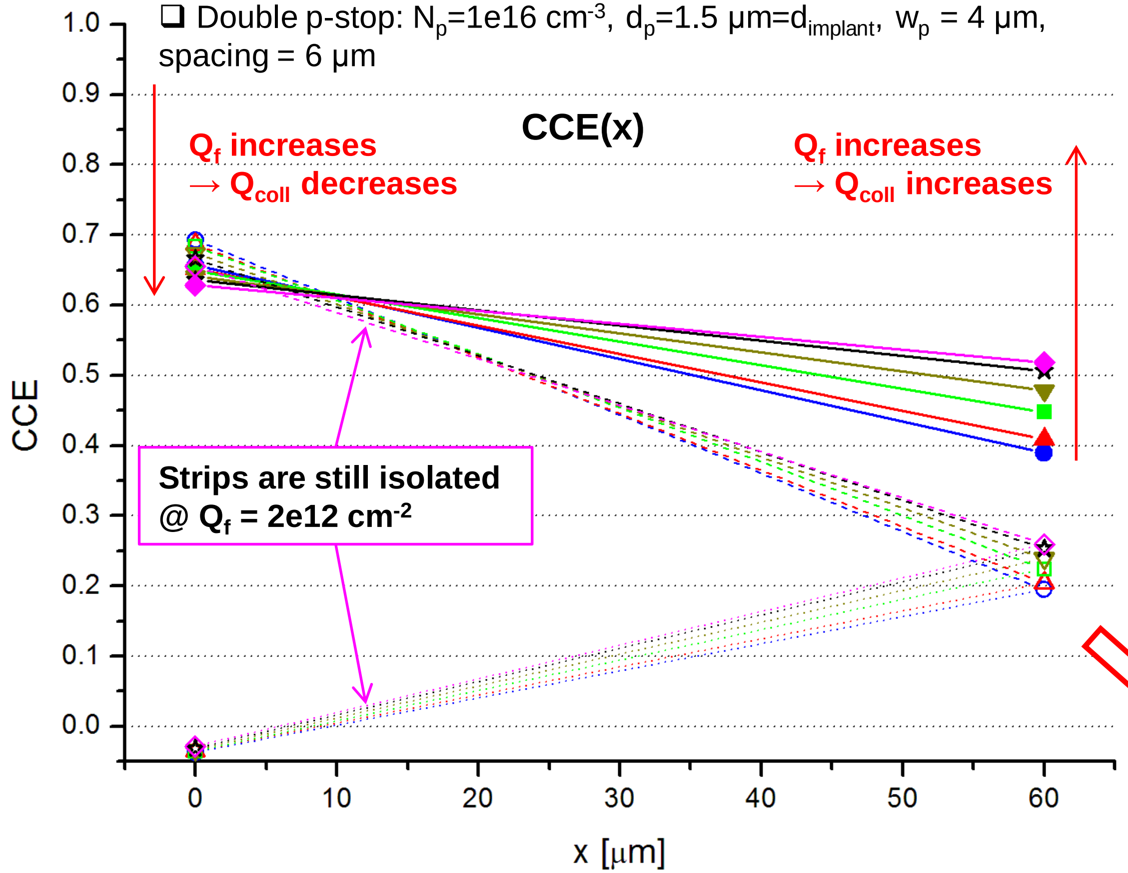




- CCE value matching proton model at center of the strip
- CCE loss in the middle of the pitch now higher than measured CCE loss (~30%) → Q_f lower than in real device for the given dose of protons → larger fraction of signal electrons are recombined in the negative space charge region

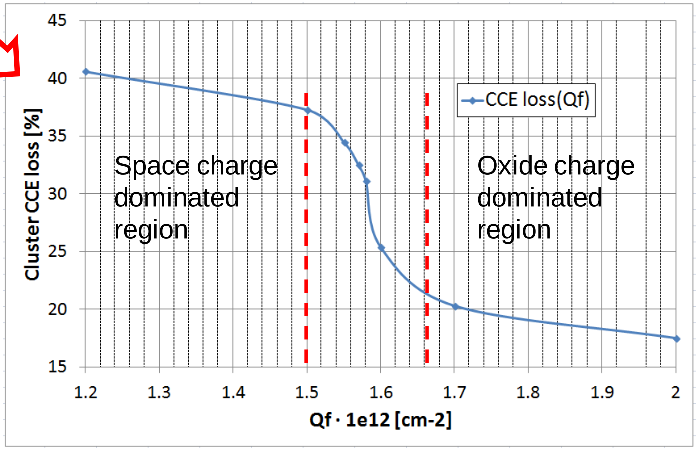
3-level model in region 1(d=2 µm) vs measured: CCE loss

- ❑ **Region 5:** F=1.5e15 cm^{-2}, V=-1 kV, T=253 K
- ❑ Double p-stop: N_p=1e16 cm^{-3}, d_p=1.5 µm=$d_{implant}$, w_p = 4 µm, spacing = 6 µm



CCE loss:

CCE loss	Legend
40.6%	Qf=1.2e12: center 2nd strip cluster
37.3%	Qf=1.5e12: center 2nd strip cluster
31.1%	Qf=1.58e12: center 2nd strip cluster
25.4%	Qf=1.6e12: center 2nd strip cluster
20.3%	Qf=1.7e12: center 2nd strip cluster
17.5%	Qf=2e12: center 2nd strip cluster

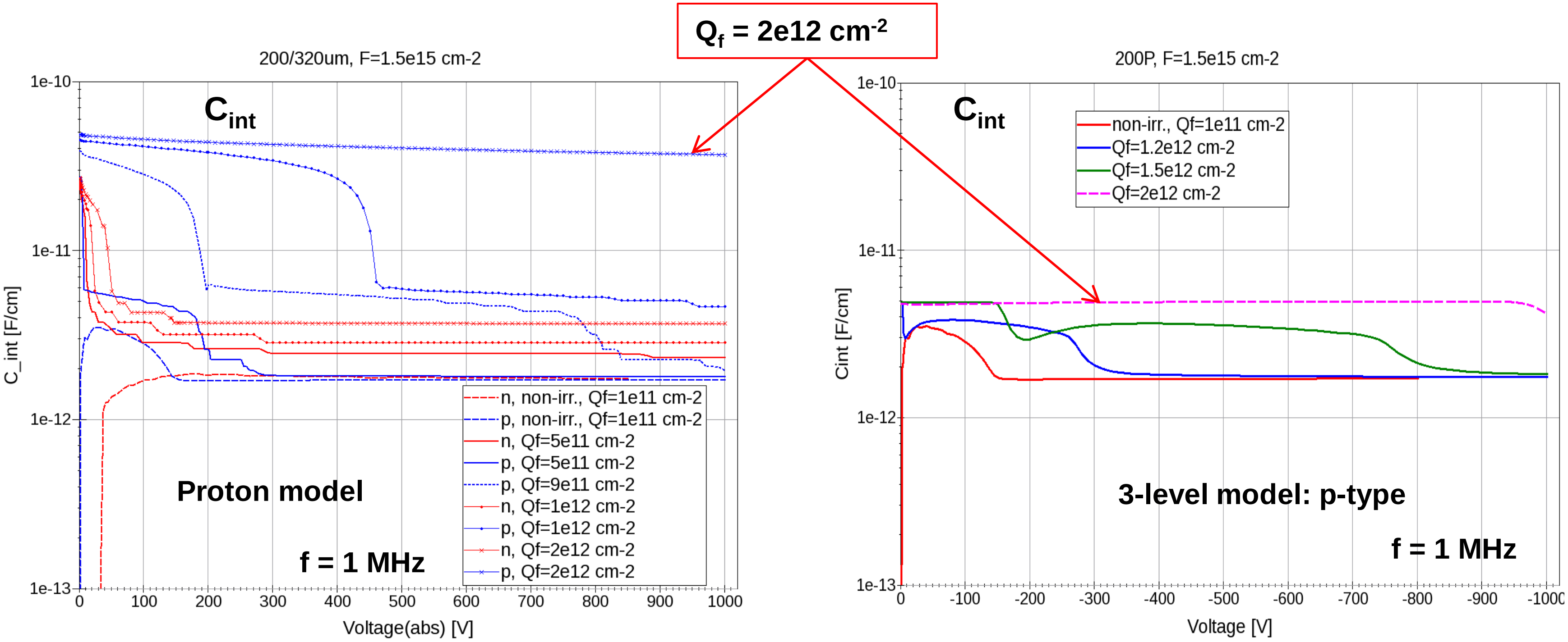


- ❑ Oxide charge is varied to find SiBT observed CCE loss ~30% between the strips
- ❑ Cluster CCE loss has a narrow dynamical region where the traps are filled by the inversion layer electrons

3-level model in region 1(d=2 μm) vs proton model: C_{int}

- ☐ Region 5 @ T = 253 K, Φ = 1.5e15 cm^{-2}
- ☐ Double p-stop: N_p = 1e16 cm^{-3}, depth = 1.5 μm, width = 4 μm, spacing = 6 μm

- ☐ 3-level model produces geometrical $C_{int}(V)$ within V=-1 kV up to Q_f = 1.5e12 cm^{-2} (proton model: Q_f = 5e11 cm^{-2})


Q_f = 2e12 cm^{-2}

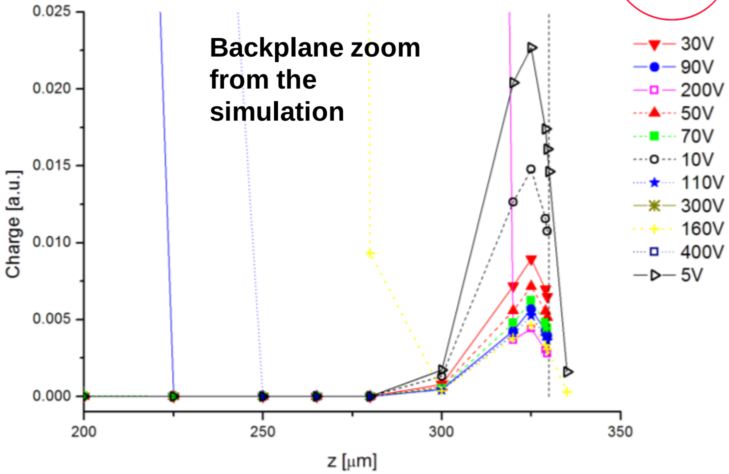
⇨ **3-level model within 2 μm of device surface + proton model in the bulk: correct R_{int}, C_{int}, CCE and CCE loss between the strips**

Edge-TCT simulations

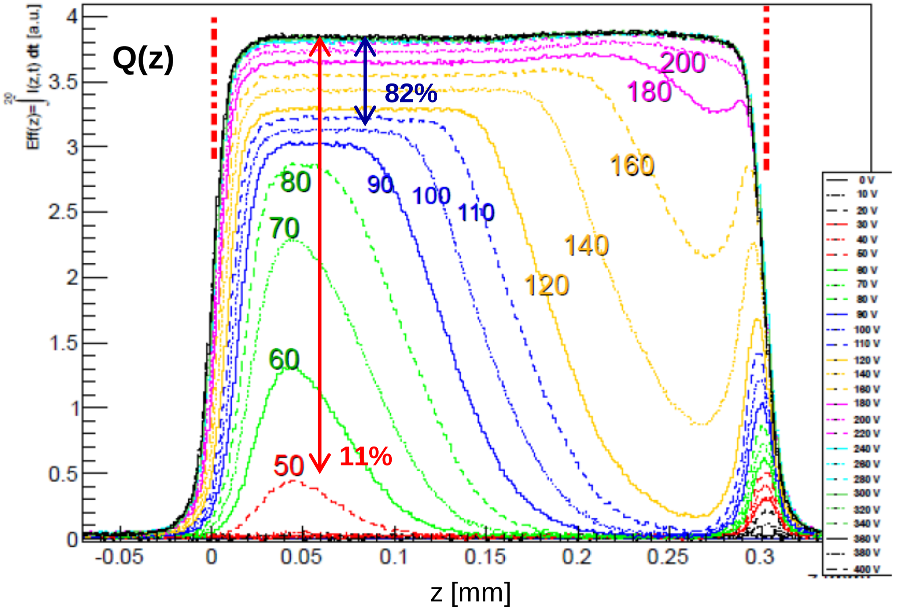
edge-TCT: non-irradiated MSSDs

☐ Simulated structure and parameters correspond to the measured HPK detector (320N, V_{fd} ~ 210 V, region 7-80)

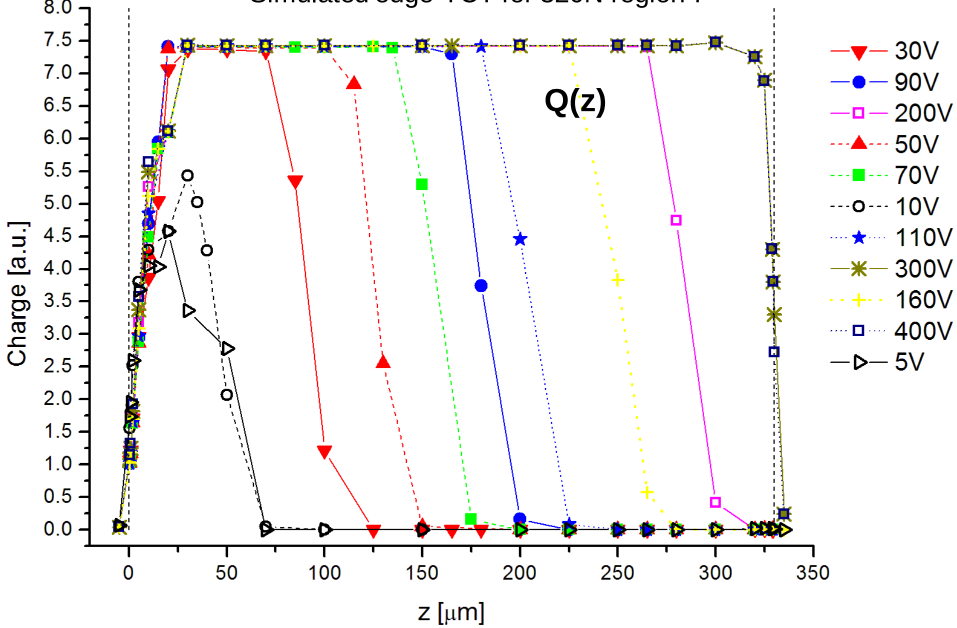
☐ **Problem:** At V < V_{fd} simulation does not reproduce measured differences in maximum Q(z) for different voltages, e.g. 50 V: measured ~11%, simulated ~96%



FZ320N region 7 eTCT-measurement (M. Fernandez 2013). V_{fd} ~ 210 V

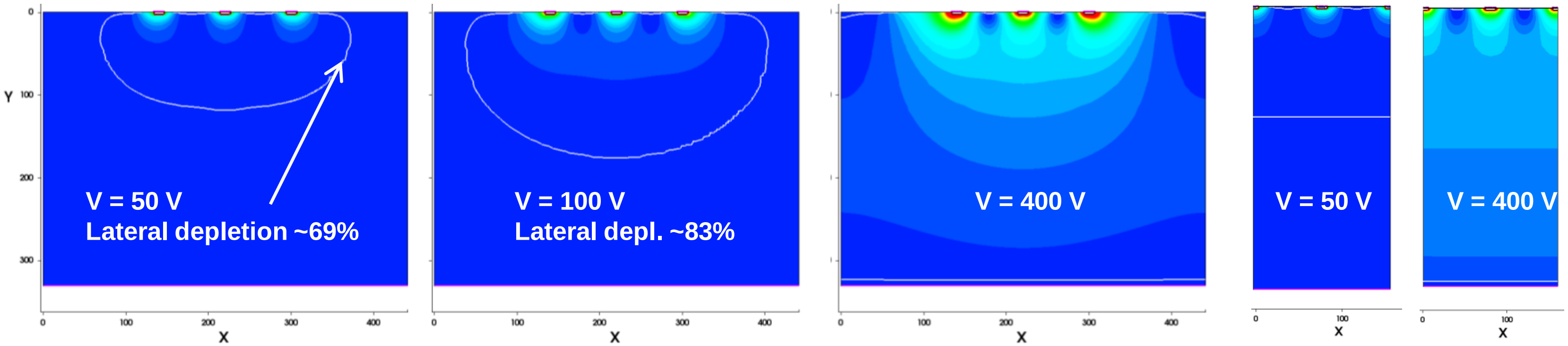


Simulated edge-TCT for 320N region 7



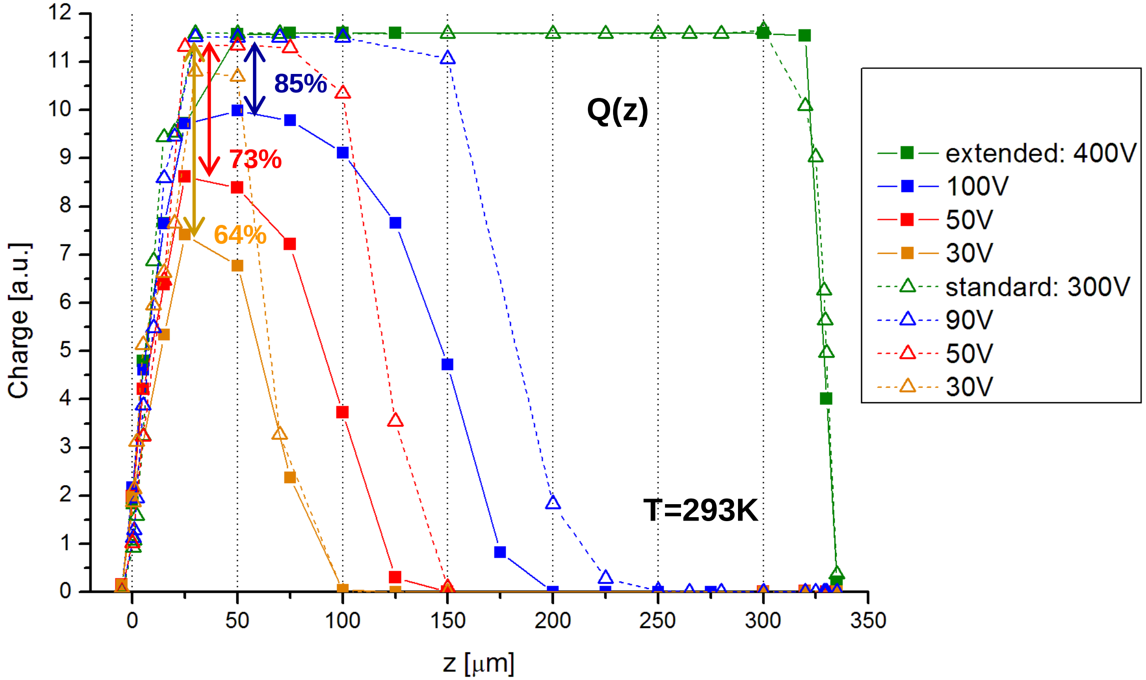
non-irr. edge-TCT: extended vs standard structure

320N extended structure **320N standard structure**



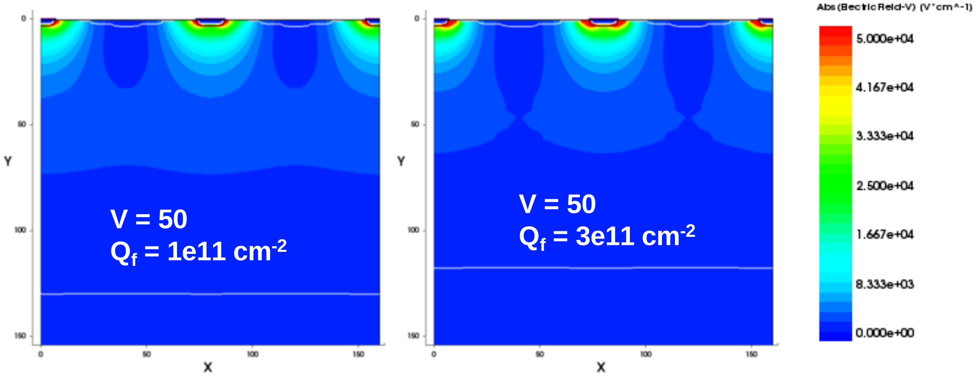
- Measured differences in Q_{max} @ $V < V_{fd}$ are reproduced by the extended structure
- ΔQ_{max} @ $0.3^* V_{fd}$: measured ~61%, simulated ~85%
- ΔQ_{max} correlates with difference in lateral extension of electric field
- Extension moves V_{fd} : 280V → 325V

- **Problem:** Consistent Q(z) curves only by averaging over the 3 strips



non-irr. edge-TCT: oxide charge variation

Standard structure: Electric field distributions

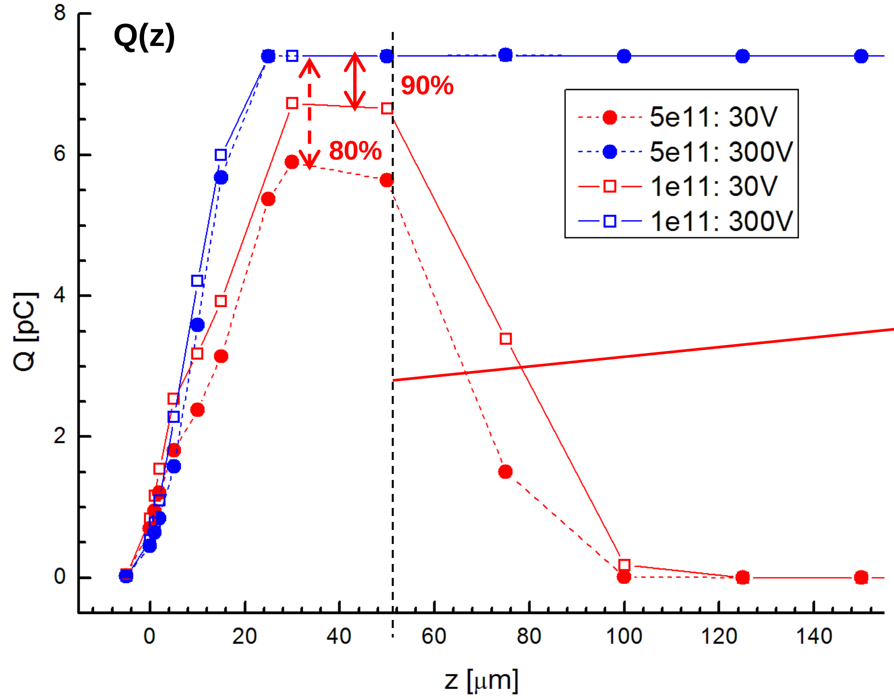


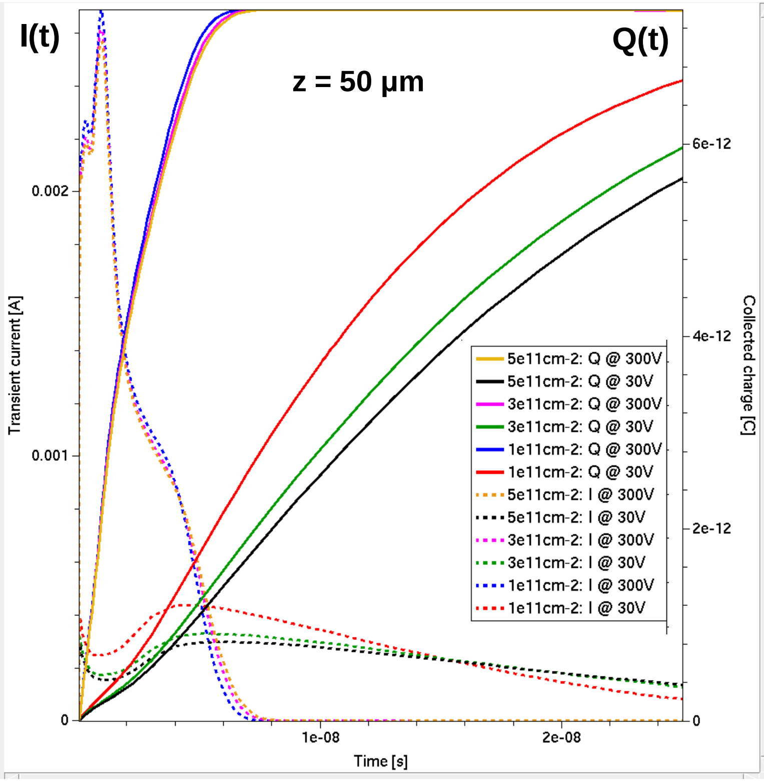
❑ Increased Q_f decreases Q_{coll} @ $V < V_{fd}$

❑ ΔQ_{max} @ 0.1* V_{fd} : measured few %'s, simulated (Q_f = 5e11 cm^{-2}) ~80%

❑ **Problem:** Effect of higher Q_f with ~realistic values is not sufficient to reproduce observed ΔQ_{max}

❑ Next step: extended structure + high oxide charge?

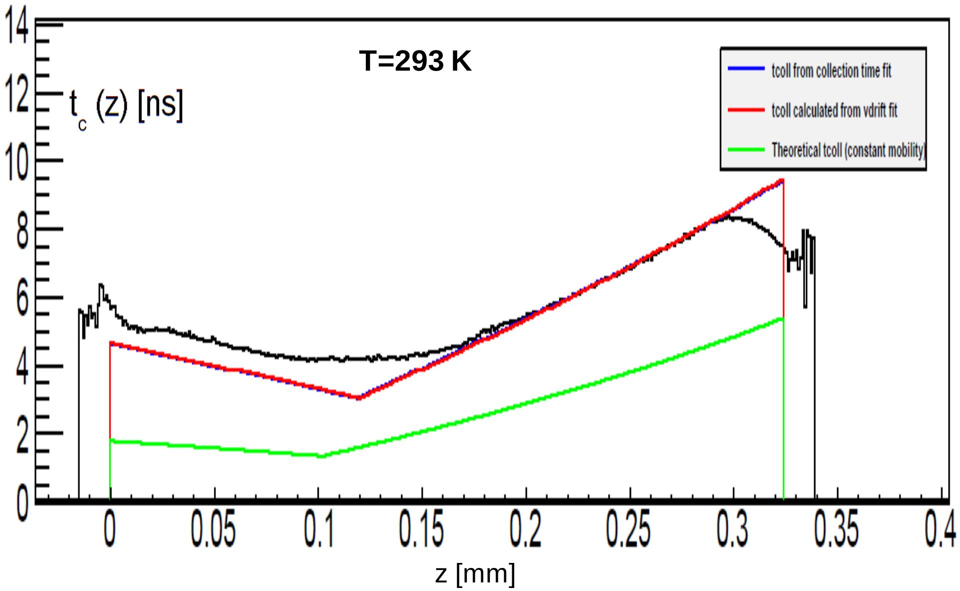




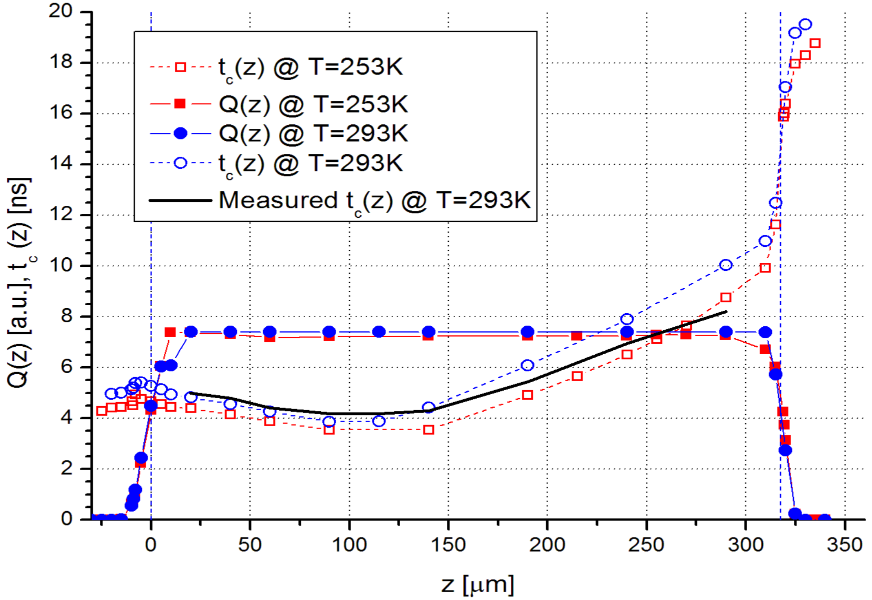
non-irr. edge-TCT: VTT detector collection time

- **Slides 16-18: Update to results presented at 22nd RD50**

Measured & fitted collection time @ V=400 V (M. Fernandez 2013)



Simulated collection time & collected charge @ V=400 V

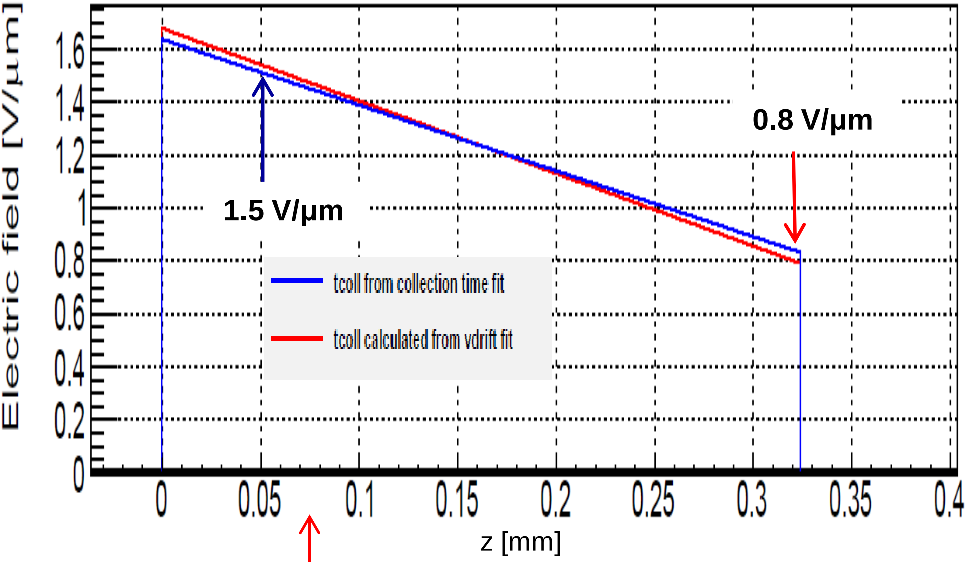


- **V > V_{fd}**
- VTT detector: strip w=14 µm, implant w=10 µm, pitch=80 µm
- Signal collection time t_c: time that takes to collect 0.98*Q_{max}
- Measurement: t_c was set to zero when thickness < laser z-position < 0
- z = 0: middle of the rising slope of Q(z)

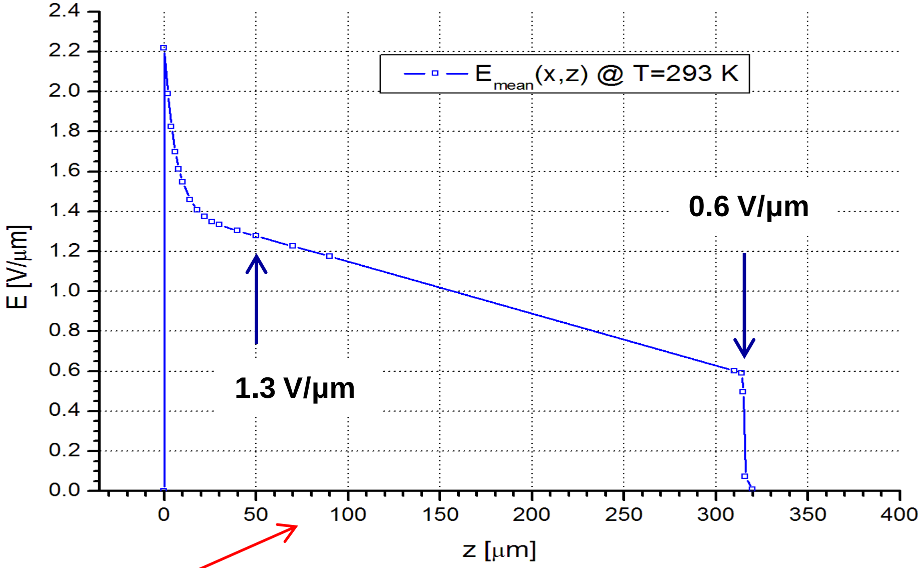
- Simulated t_c values @ T=293 K very close to measurement at 25 ≤ z ≤ 150
- Difference to measured values increases towards backplane

non-irr. edge-TCT: VTT detector E(z)

Calculated E(z) from $v_{drift}(z)$, $t_c(z)$ fits@ V=400 V (M. Fernandez 2013)



Simulated 320N E(z) @ V=400 V

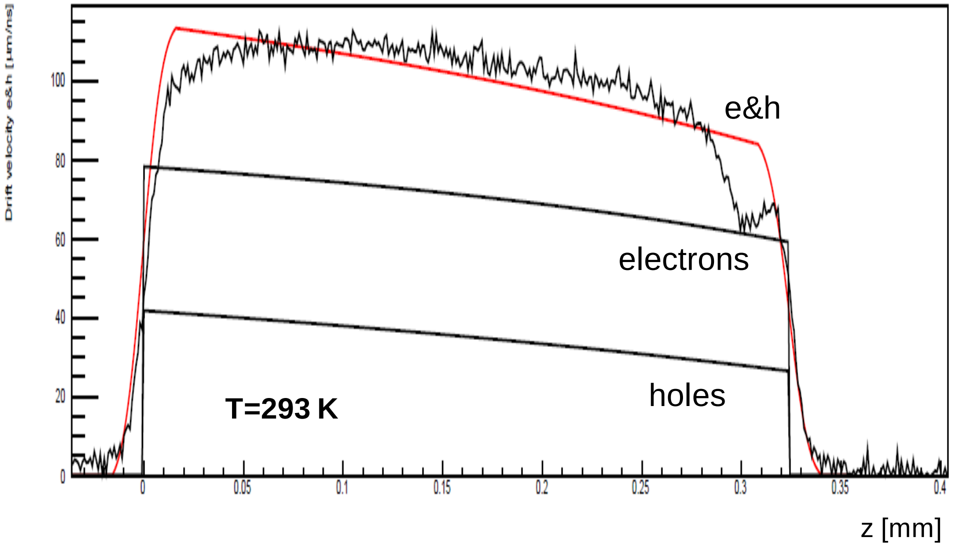


- E(z) is calculated from fits with linear approx.
- Simulated average E(x,z) determined from E(z) cuts from x=center of pitch to x=center of strip with 5 μm steps

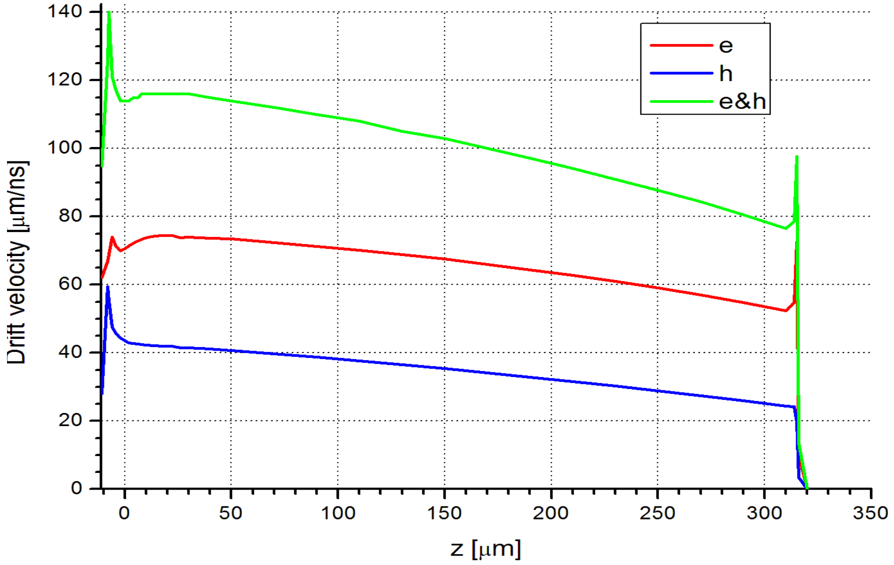
- Simulated slope @ T=293 K is within 7% of the calculated slope between z = 30 - 320 μm

non-irr. edge-TCT: VTT detector $v_{drift}(z,x)$

Measured & fitted $v(z)_{drift}$ @ V=400 V (M. Fernandez 2013)

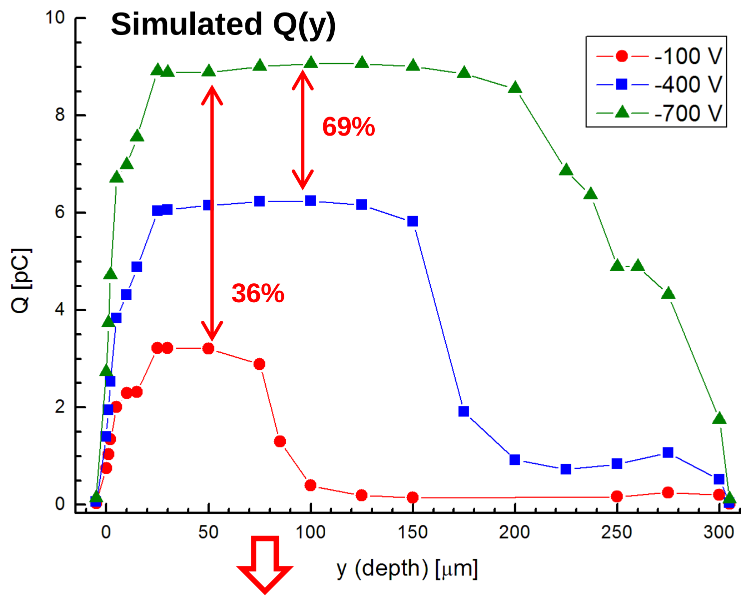


Simulated average $v(z)_{drift}$ @ V=400 V

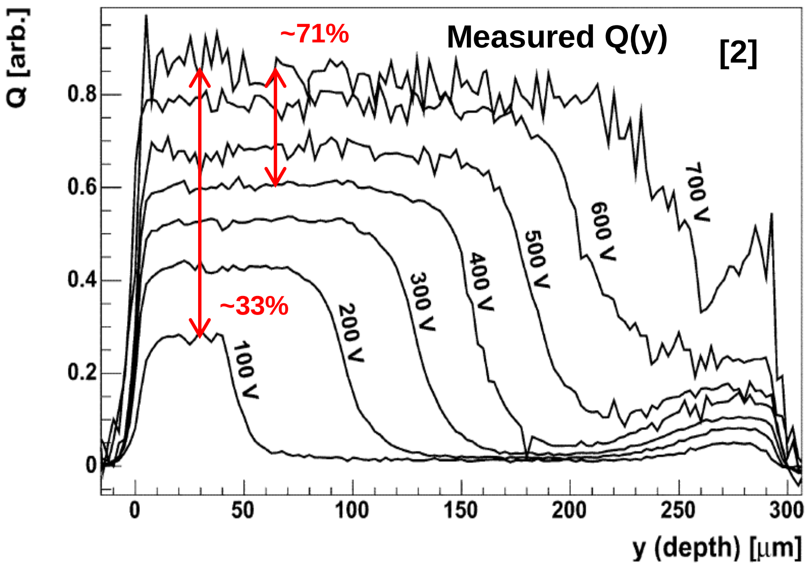


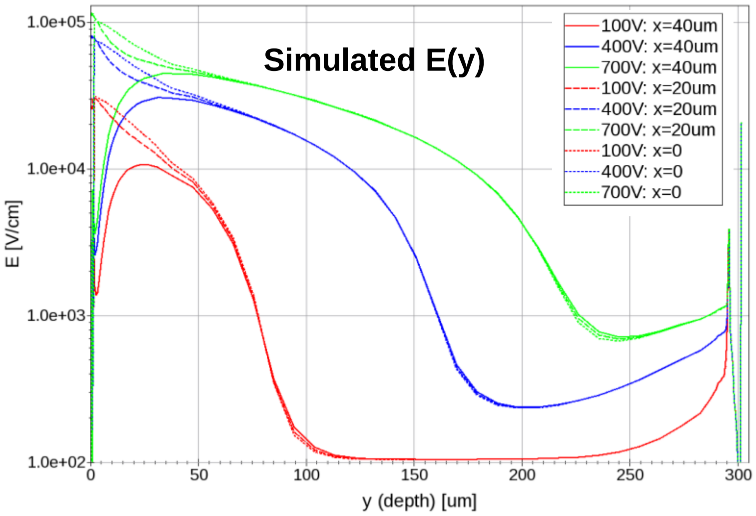
- Simulated average $v(z)_{drift} = \mu_{e,h}(z, x = 40\ldots80\ \mu m) E(z, x = 40\ldots80\ \mu m)$ @ T=293 K
- Average $v(z)_{drift}$ curves close to measured and fitted curves also at $z \geq 0\ \mu m$
- Main difference of average $v(z)_{drift}$ to measured/fitted curves: peaks in hole and e&h curves at $z < 0\ \mu m$

edge-TCT: Neutron irradiated 300P detector



300P @ F=5e14 cm-2, Qf=1e11 cm-2, T=253 K





x=0: center of strip

Parameters [2] (Black font from the paper):

- 300P, T=253 K, Φ_{eq}(n) = 5e14 cm^{-2}, Qf = 1e11 cm^{-2}
- N_{bulk} = 2.07e11 cm^{-3} → V_{fd} (non-irr.) ≈ 16 V
- d_p = 1.5 µm, w_p = 20 µm
- $d_{implant}$ = 1.5 µm, $w_{implant}$ = 20 µm, w_{strip} = 34 µm
- pitch = 80 µm, d_{back} = 7 µm, R_{bias} = 0.6 MΩ, strip length = 1 cm

- Neutrons: low Q_f increase → no need for 3-level implementation
- Measured $\Delta Q(y)_{max}$ reproduced by simulation
- Double peak effect visible in both Q(y) plots
- Simulated depletion region ~10-30µm deeper at lower voltages
- Simulation gives reliable information of E(y)

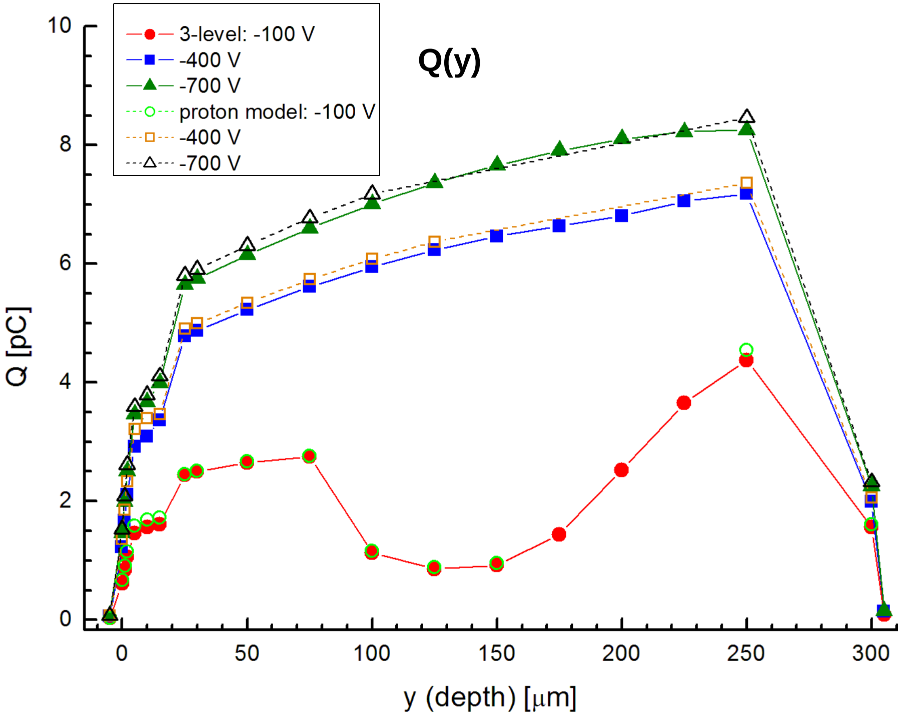
- Neutron defect model: see backup

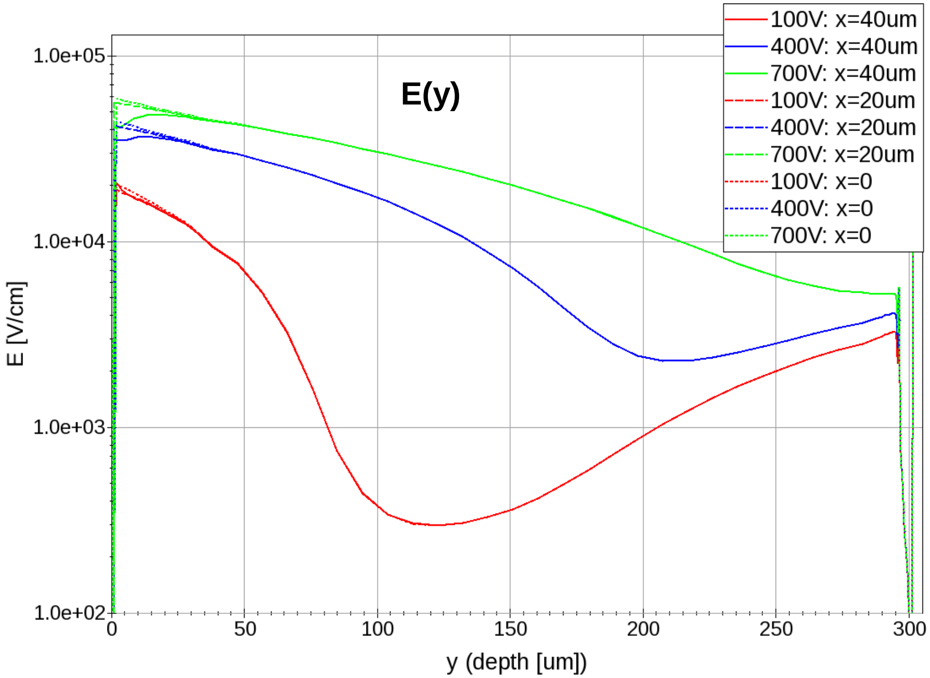
[2] G. Kramberger et al. IEEE Trans. Nucl. Sci. 57 (2010) 2294-2302.

edge-TCT: Proton irradiated 300P detector

- Similar structure & parameters to previous slide, except Q_f = 5.23e11 cm^{-2}
- Both 3-level model and proton model applied

- Similar behavior for both models, proton model has slightly higher Q_{coll} at high voltages, as expected
- Matching E(y) for both models





Summary

- 3-level model close to detector surface solves the surface damage problems observed in Synopsys proton model
  - R_{int}, C_{int} and CCE loss between strips agree with measurements
  - No effect on previous experimentally matching proton model results

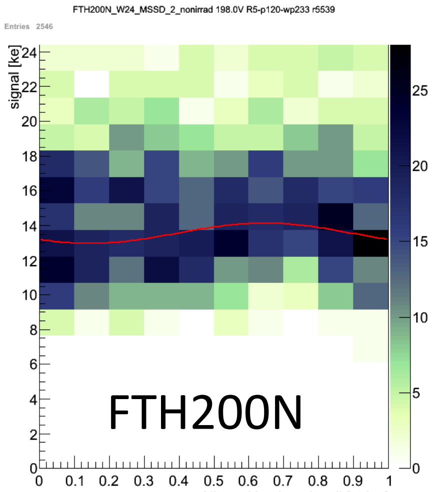
- Simulated edge-TCT of non-irradiated detector:
  - **$V < V_{fd}$**: Measured $\Delta Q(z)_{max}$ for varying voltages difficult to reproduce → further investigation needed
  - **$V > V_{fd}$**: Close agreement with measurement

- Simulated edge-TCT of irradiated detector:
  - **Neutrons**: close agreement with measurement → simulation produces reliable E(z) information
  - **Protons**: 3-level and proton model produce similar results

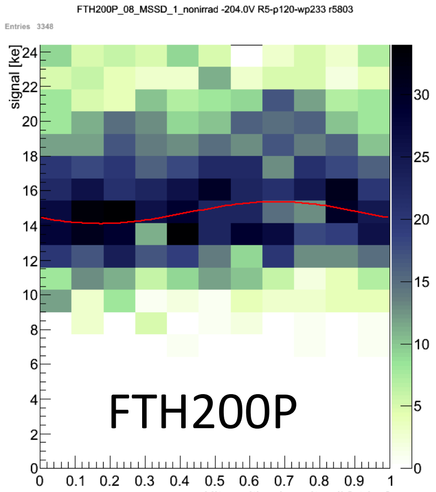
Backup: SiBT measured CCE loss between strips

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

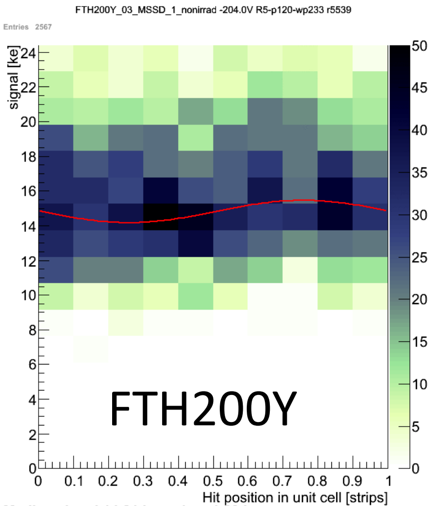
non-irradiated



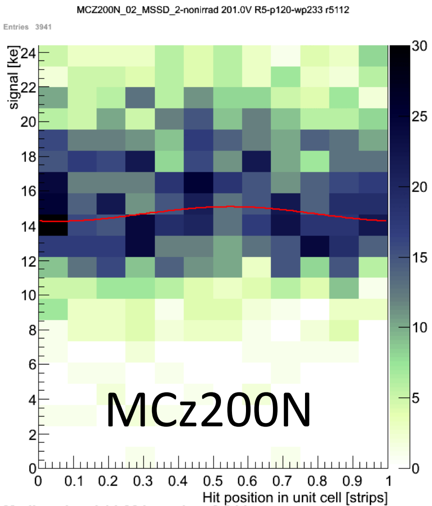
Median signal 13.54 ke swing 1.17 ke



Median signal 14.73 ke swing 1.26 ke



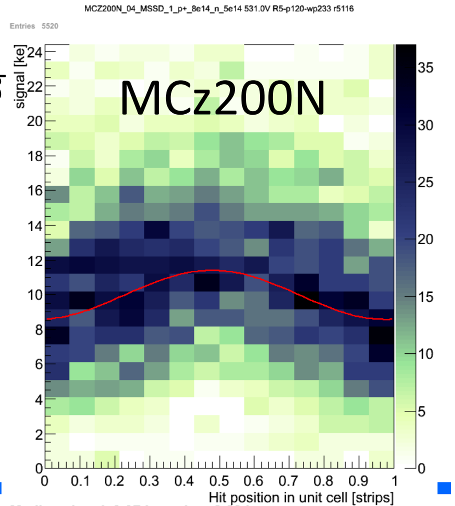
Median signal 14.81 ke swing 1.29 ke



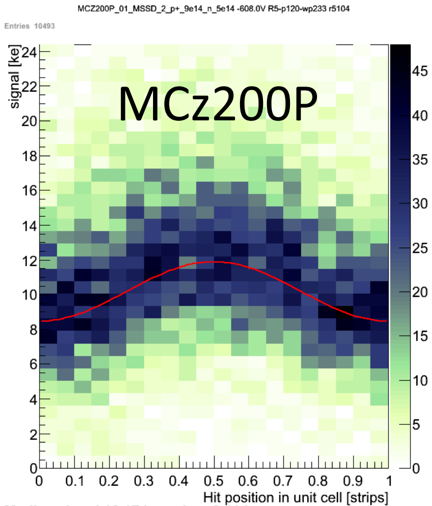
Median signal 14.66 ke swing 0.84 ke

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

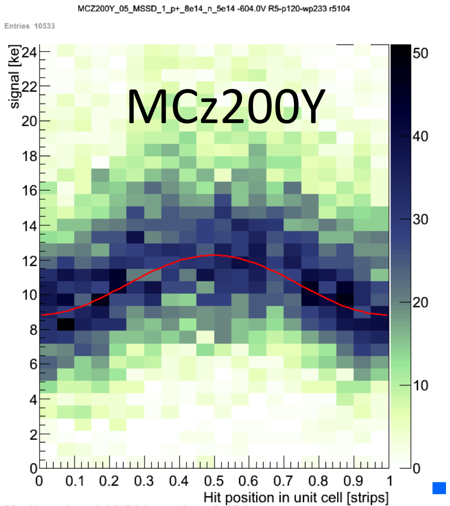
mixed irradiated 1.5e15n$_{eq}$/cm^2



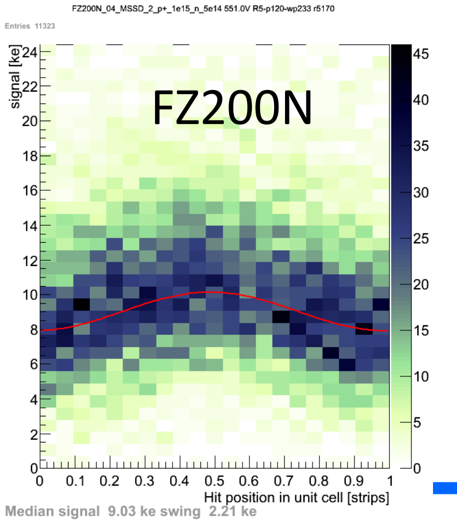
Median signal 9.97 ke swing 2.82 ke



Median signal 10.17 ke swing 3.41 ke



Median signal 10.54 ke swing 3.42 ke



Median signal 9.03 ke swing 2.21 ke

Backup: Radiation damage models

Silvaco: 5-trap model

Trap	Energy Level	Intro.	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	0.525eV	3.0	1x10^{-14}	1.4x10^{-14}
Acceptor	0.45eV	40	8x10^{-15}	2x10^{-14}
Acceptor	0.40eV	40	8x10^{-15}	2x10^{-14}
Donor	0.50eV	0.6	4x10^{-14}	4x10^{-14}
Donor	0.45eV	20	4x10^{-14}	4x10^{-14}

Synopsys: 2-trap models

Proton model (tuned by R. Eber)

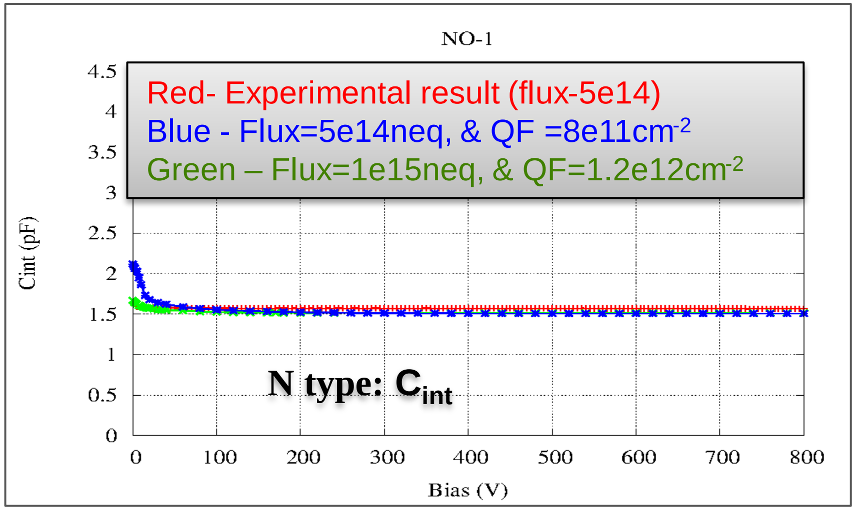
Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acceptor	E_C - 0.525	1e-14	1e-14	1.189*F + 6.454e13
Deep donor	E_V + 0.48	1e-14	1e-14	5.598*F - 3.959e14

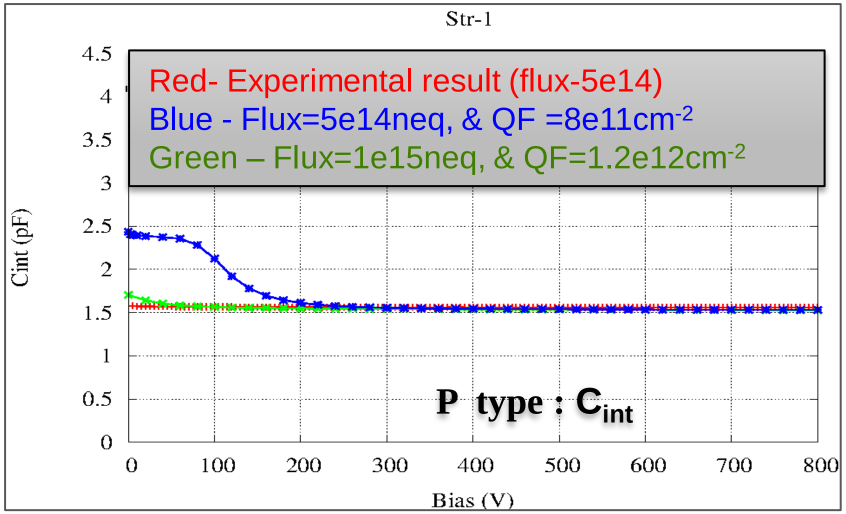
Neutron model (tuned by R. Eber)

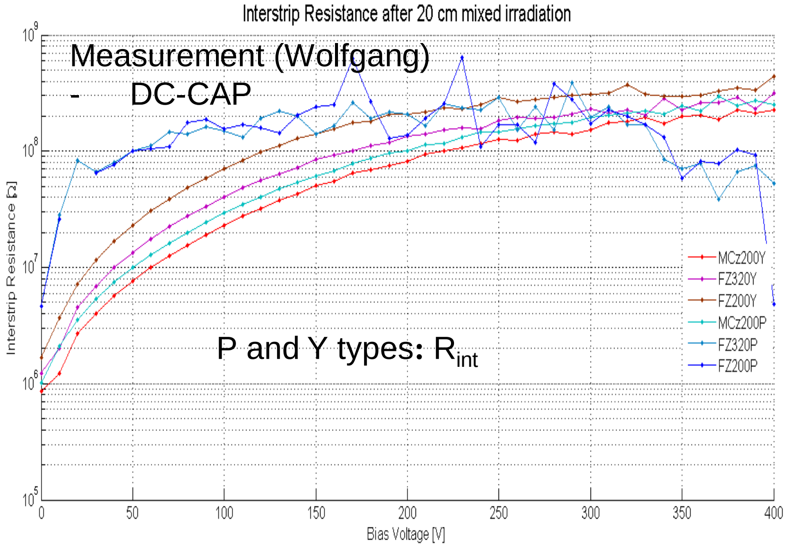
Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acceptor	E_C - 0.525	1.2e-14	1.2e-14	1.55*F
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*F

Backup: Measured & 5-trap model C_{int}, R_{int}

Simulation vs. Measurement







Backup: edge-TCT method

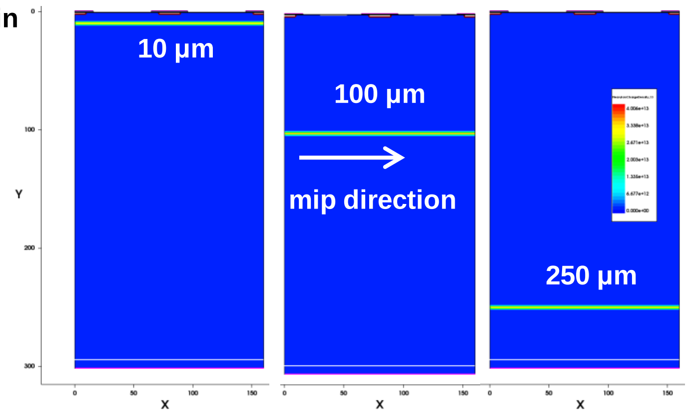
☐ **Goal:** extract electric field E from drift velocity v_{drift} using eTCT

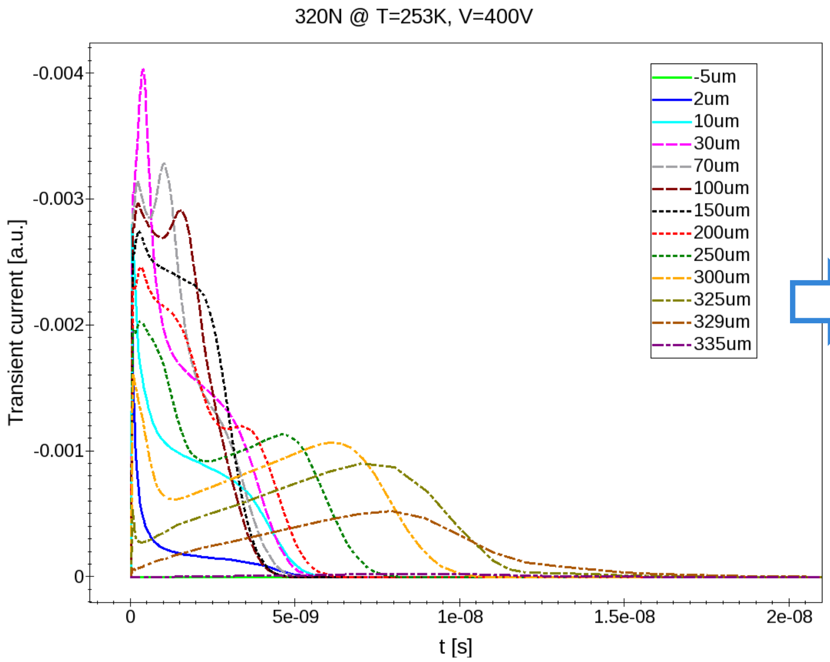
☐ eTCT provides measurement of collection time t_c that is proportional to the v_{drift}

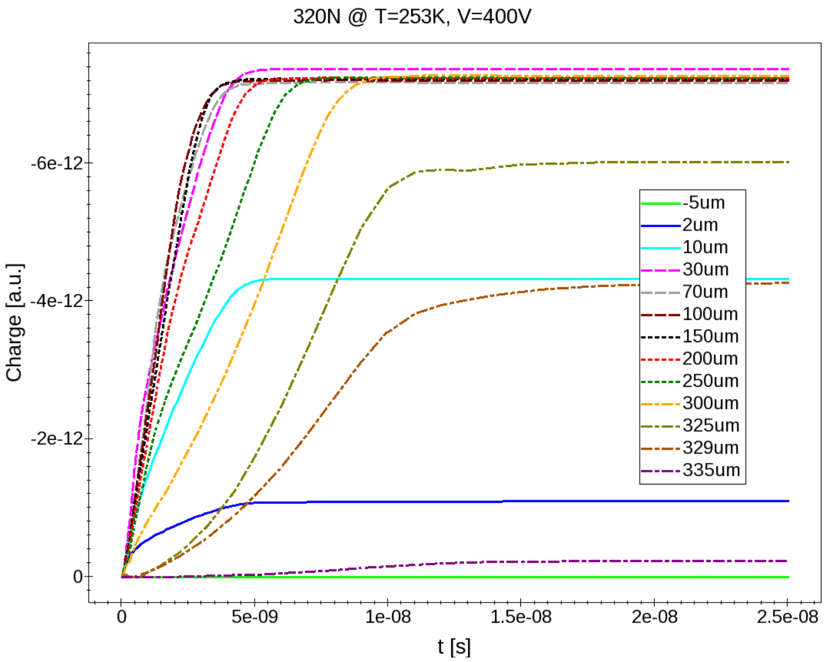
☐ v_{drift} is related to the E → possible to determine E out of drift velocity?

☐ Collected eTCT generated transient signals and charges as a function of injection distance:

MIP trajectories in 300N device:







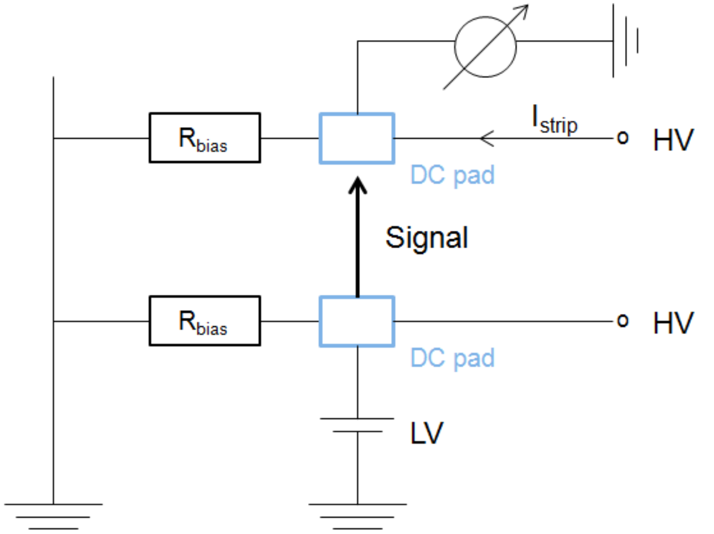
Backup: Interstrip resistance simulations

- 3 strip structure, $V_{strip1} = V_{strip3} = 0$, V_{strip2} = LV and 0 V
- V = -HV at the backplane

- Interstip resistance (R_{int}) is defined as (Induced Current Method):

$$R_{int} = \frac{V_2(LV)}{\frac{I_1(LV)+I_3(LV)}{2} - \frac{I_1(0)+I_3(0)}{2}}$$

- R_{int} is plotted as a function of applied voltage V



Electrical circuit diagram of R_{int} measurement

R_{int} simulation principle