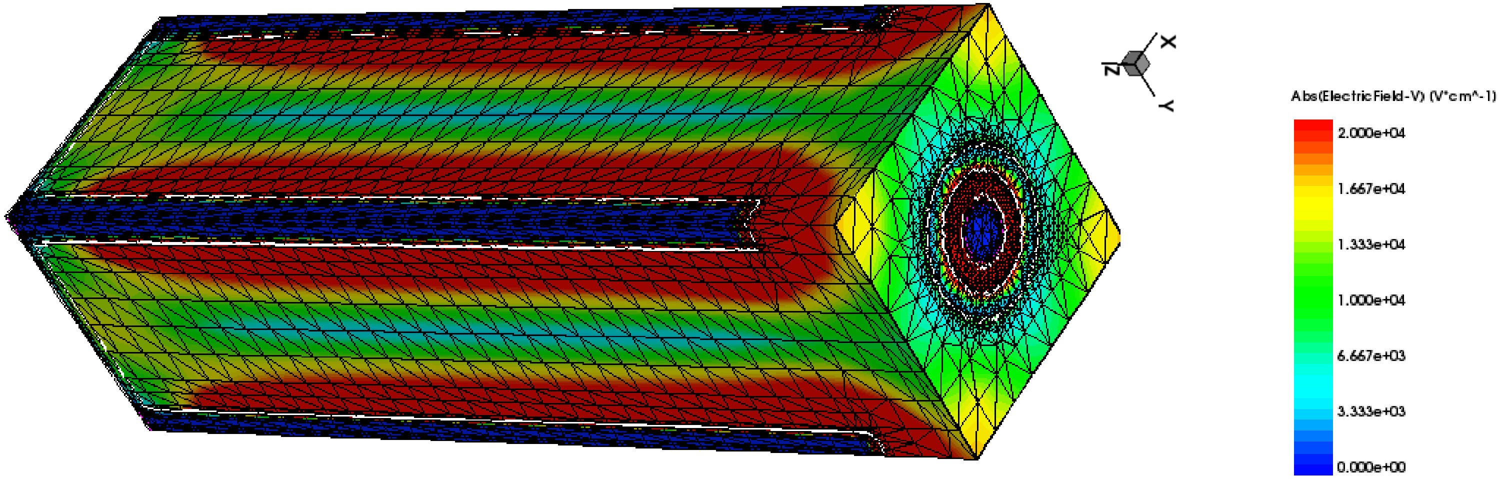
TCAD simulated surface damage in proton irradiated strip sensors:

Investigation of interface traps vs non-uniform 3-level model

25th RD50 Workshop, 19-21 Nov. 2014

T. Peltola1), J. Härkönen1)

1)*Helsinki Institute of Physics, CMS Upgrade Project.*



Outline

- ☐ **Simulated surface properties after proton irradiation**
  - Motivation: Measured & simulated CCE(x)
    - Interface traps vs non-uniform 3-level model
  - Simulations & comparison with measurements

- ☐ **3D sensor simulations**
  - Motivation
  - Simulated structure & electrical characteristics
  - Hit position dependency of the signal

- ☐ **Summary**

Simulated surface properties after proton irradiation

Motivation: Measured & simulated CCE(x)

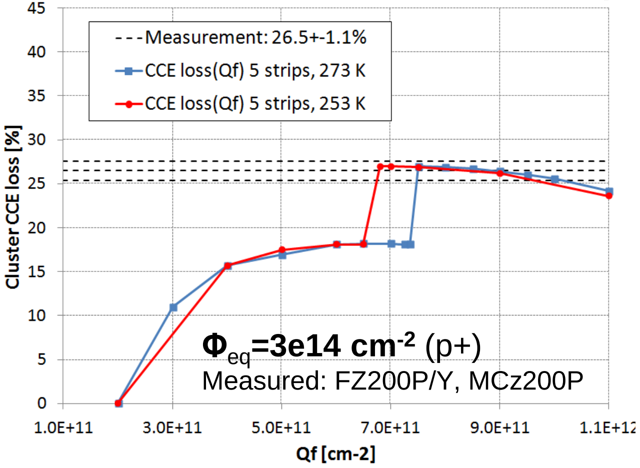
❑ **TCAD:** Synopsys Sentaurus

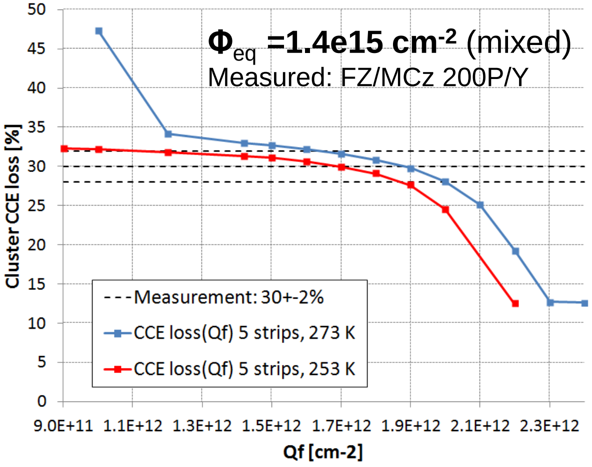
❑ **Proton model:** Tuned by R. Eber from the PTI-model

❑ **3-level model within 2 µm of device surface + proton model in bulk:**

- R_{int} & C_{int} in line with measurement (see back-up slides) also at high fluence & Q_f
- Can be tuned to equal bulk properties (TCT, V_{fd} & I_{leak}) with proton model → suitable tool to investigate CCE(x)

200P sensor, p=120 µm, w=28 µm:

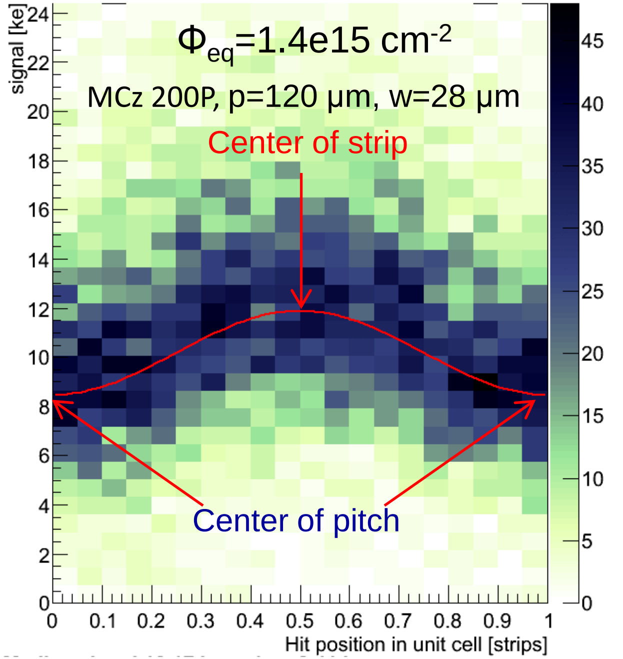




$Q_f=(8.5\pm1.0)\times10^{11}$ cm^{-2}

$Q_f=(1.6\pm0.2)\times10^{12}$ cm^{-2}

❑ **Test beam measured position dependency of CCE** [T. Mäenpää, 2013]



Measured: strip isolation ok, CCE loss between strips ~30%

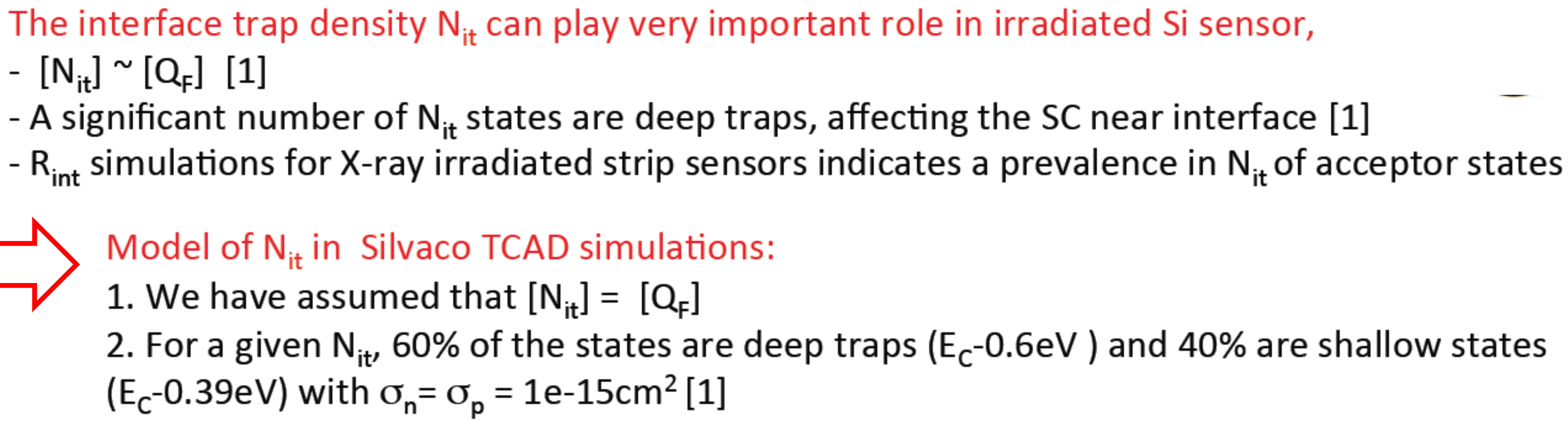
❑ Preliminary parametrization of the model for fluence range 3e14 – 1.5e15 cm^{-2}

3-level model within 2 µm of device surface

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 + 3.1675e16

Motivation : Interface traps

From Delhi University contribution to Phase II talk of simulation WG:



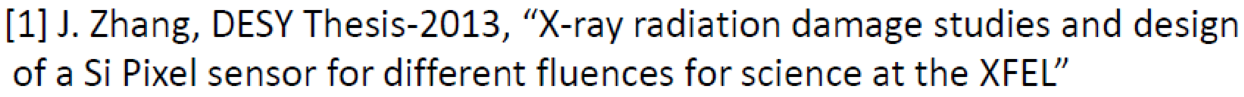
The interface trap density N_{it} can play very important role in irradiated Si sensor,

- $[N_{it}] \sim [Q_F]$ [1]
- A significant number of N_{it} states are deep traps, affecting the SC near interface [1]
- R_{int} simulations for X-ray irradiated strip sensors indicates a prevalence in N_{it} of acceptor states

Model of N_{it} in Silvaco TCAD simulations:

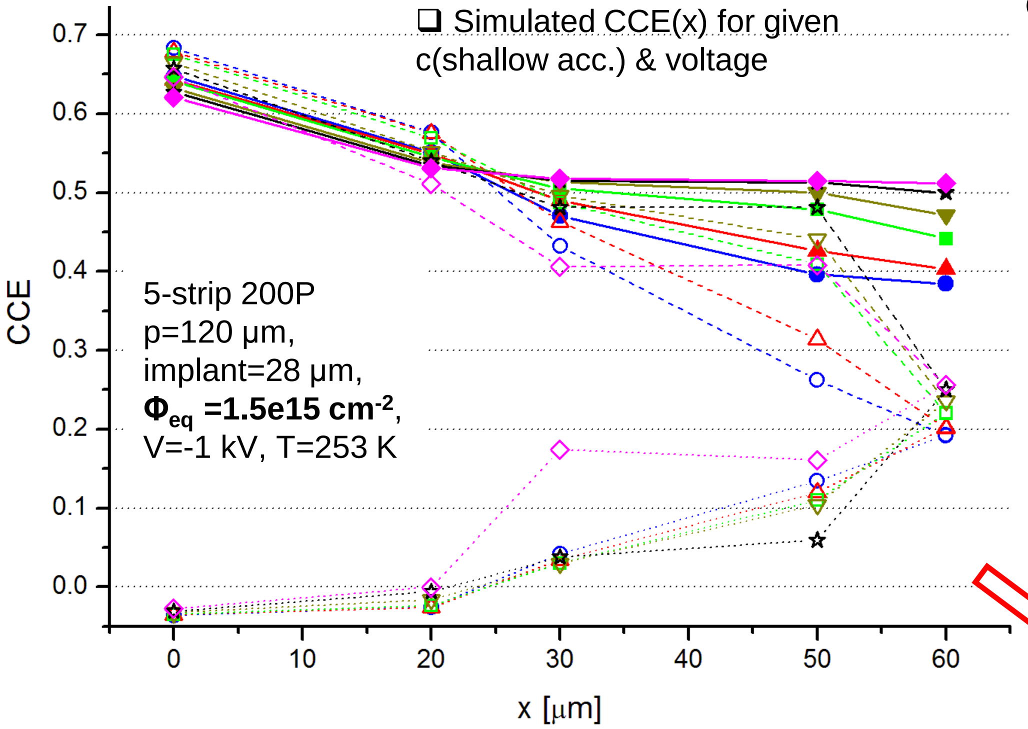
1. We have assumed that $[N_{it}] = [Q_F]$
2. For a given N_{it}, 60% of the states are deep traps (E_C-0.6eV) and 40% are shallow states (E_C-0.39eV) with $\sigma_n = \sigma_p = 1e\text{-}15cm^2$ [1]

☐ Promising results of simulated R_{int} for Silvaco ATLAS
☐ Is it possible to replace 3-level model close to surface with N_{it} in Synopsys Sentaurus?
☐ Opportunity to study the depth distribution of trap levels responsible of observed CCE loss between strips?



[1] J. Zhang, DESY Thesis-2013, “X-ray radiation damage studies and design of a Si Pixel sensor for different fluences for science at the XFEL”

CCE(x): Simulation method



- Simulated CCE(x) for given c(shallow acc.) & voltage

5-strip 200P
p=120 µm,
implant=28 µm,
Φ_{eq} =1.5e15 cm^{-2},
V=-1 kV, T=253 K

CCE loss:

40.6%

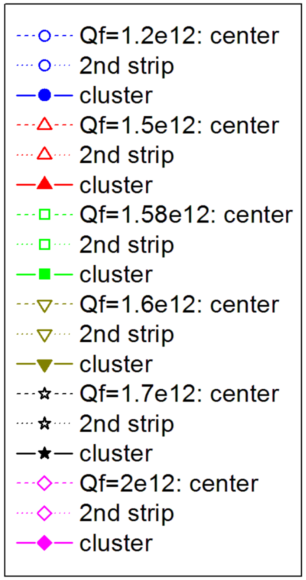
37.3%

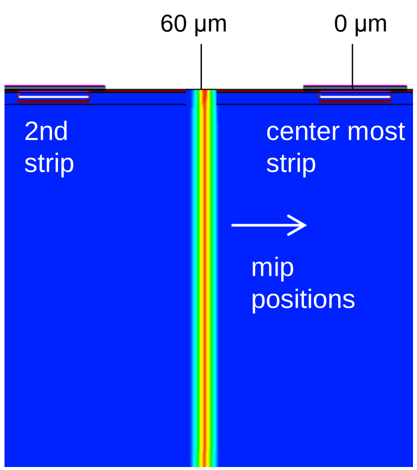
31.1%

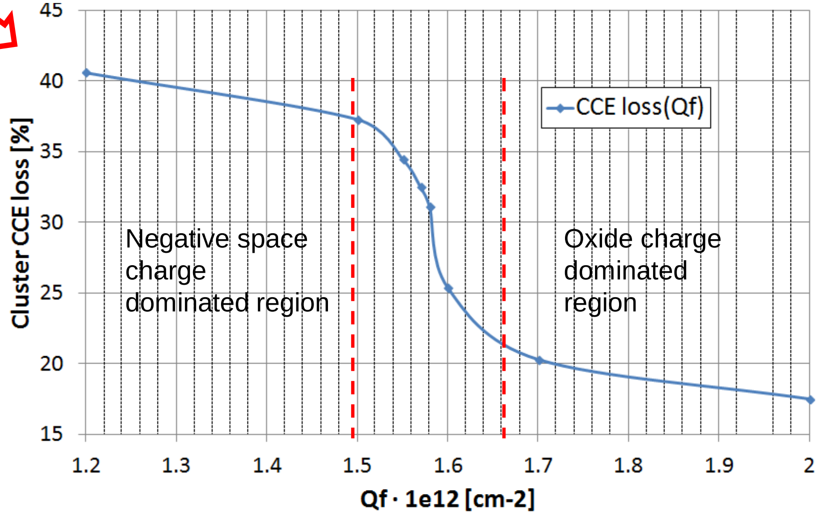
25.4%

20.3%

17.5%







- **When strips are isolated:** Q_{coll} at center strip increases as position of charge injection moves closer & Q_{coll} at 2nd strip drops down

- Acceptor traps remove both accumulation layer & signal electrons: better radiation damage induced strip isolation → larger CCE loss between the strips
- Increased Q_f → more traps are filled → charge sharing between strips increases, undepleted region between strips grows → CCE loss decreases

CCE(x): Implementation of interface traps

❑ **1: parameters used in Silvaco**

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Density [cm^{-2}]
Deep acceptor	E_C - 0.60	1e-15	1e-15	$0.6 \cdot N_{it}$
Shallow acceptor	E_C - 0.39	1e-15	1e-15	$0.4 \cdot N_{it}$

❑ **2: 1 shallow acceptor**

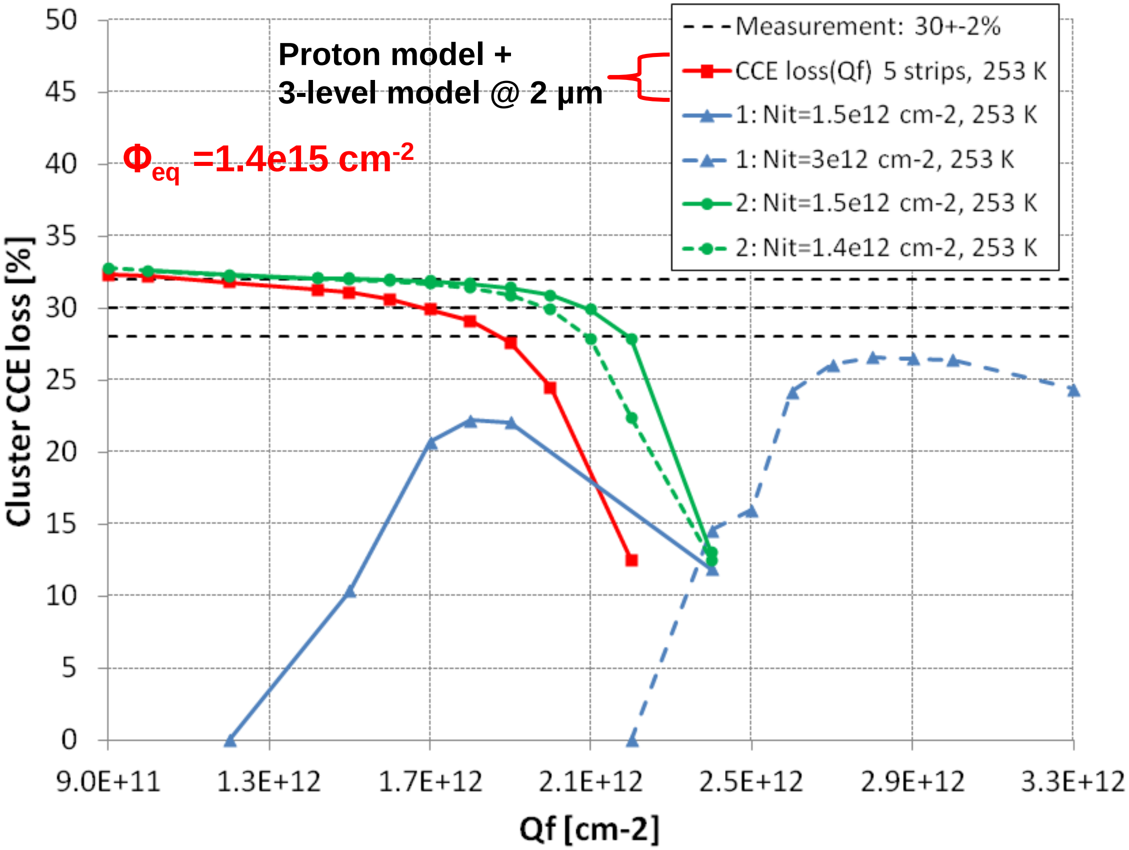
Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Density [cm^{-2}]
Shallow acceptor	E_C - 0.40	8e-15	2e-14	$1.0 \cdot N_{it}$

❑ 5-strip 200P region 5 sensor @ V=-1 kV, T=253 K

❑ Simulated radiation damage:
- Proton model + interface traps from table 1(2)
- Proton model + 3-level model @ 2 μm from surface

❑ **1:** Measured CCE loss is not reproduced with realistic Q_f values
- Deep acceptors increase negative undershoots at strips with longer drift distances of carriers → CCE loss goes to zero also at high Q_f

❑ **2:** Measured CCE loss is reproduced @ $Q_f=(1.9 \pm 0.3)10^{12}$ cm^{-2} for N_{it}=1.5e12 cm^{-2}, $Q_f=(1.8 \pm 0.3)10^{12}$ cm^{-2} for N_{it}=1.4e12 cm^{-2} → possible to tune Q_f range of matching CCE loss

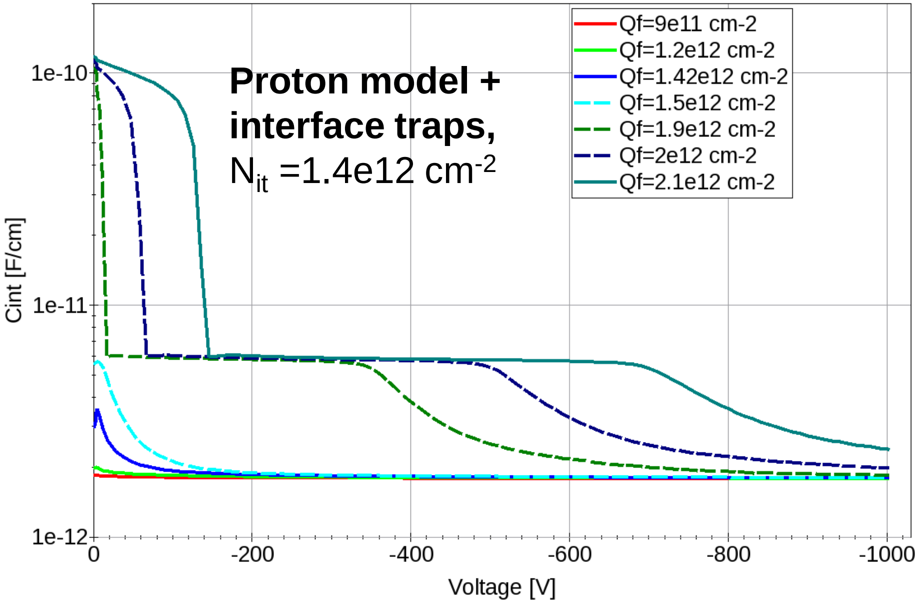

Proton model + 3-level model @ 2 μm

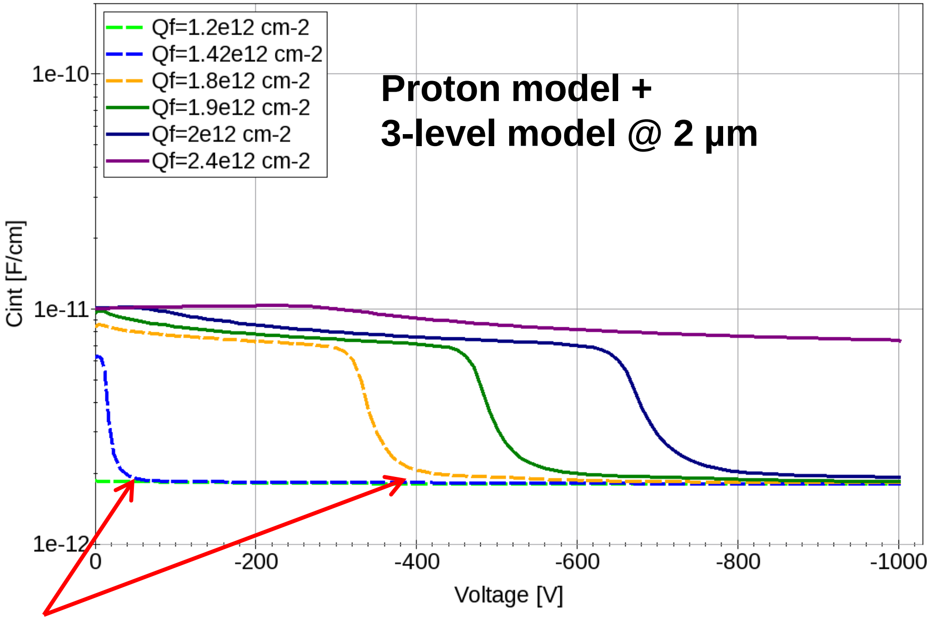
Φ_{eq} =1.4e15 cm^{-2}

C_{int}: N_{it} vs non-unif. 3-level model @ Φ_{eq} = 1.4e15 cm^{-2}

- Device structure corresponding to previous slide
- **Dashed lines:** Q_f values where CCE loss between strips matches measurement
- **3-level model @ 2 μm from surface:**
  - Geometrical value ~1.8 pF/cm reached within 0-400 V when CCE loss matches measurement
- **Interface traps:**
  - Geometrical value reached within 180 V -1 kV when CCE loss matches measurement
  - Over O(1) higher initial values at high Q_f

- **Measurement:** C_{int} ~1.8 pF/cm reached at 0 V





Higher Q_f → higher V needed to reach geometrical C_{int}

CCE(x): Interface traps @ Φ_{eq} = 3e14 cm^{-2}

☐ 5-strip 200P region 5 sensor @ V=-1 kV, T=253 K

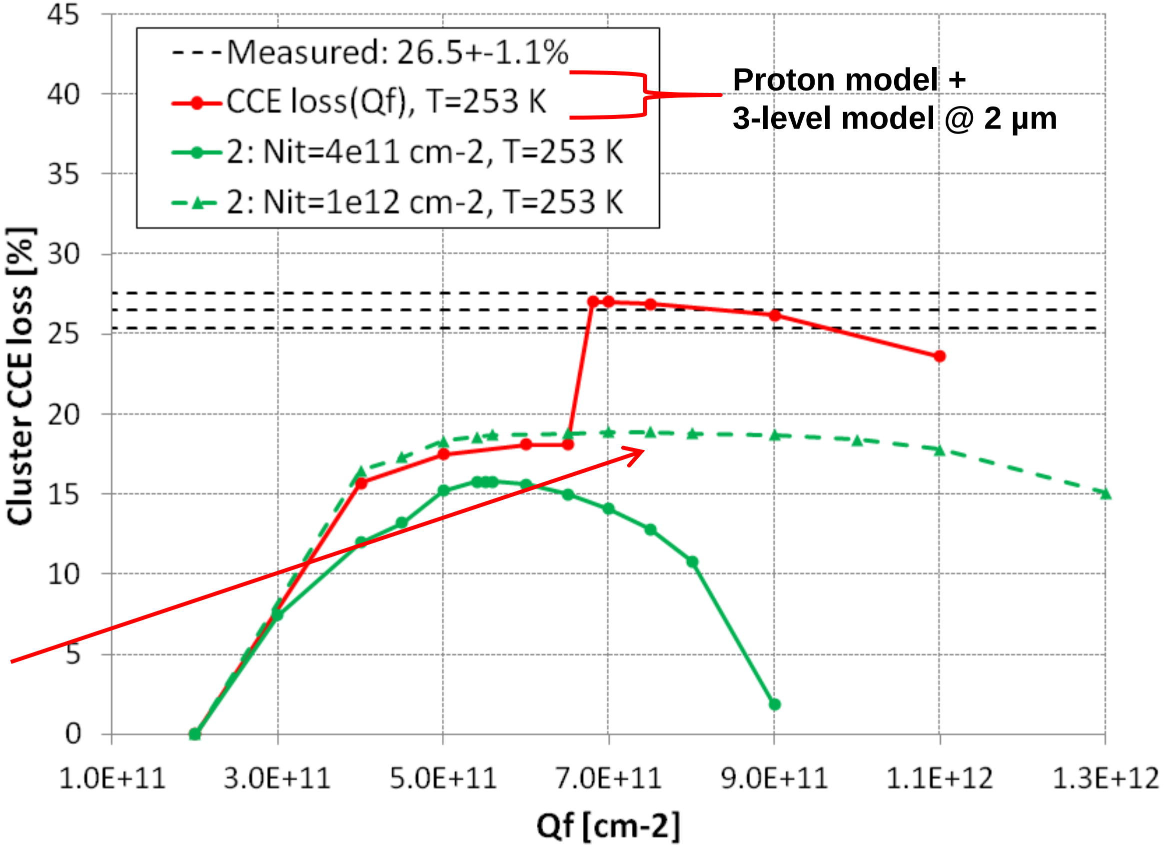
☐ Simulated radiation damage:

- Proton model + interface traps from table 2
- Proton model + 3-level model @ 2 µm from surface

☐ 2: 1 shallow acceptor

Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Density [cm^{-2}]
Shallow acceptor	E_C - 0.40	8e-15	2e-14	1.0*N_{it}

☐ **2:** Measured CCE loss is not reproduced with realistic Q_f values → not possible to parametrize $N_{it}(\Phi)$ with trap levels/parameters under test

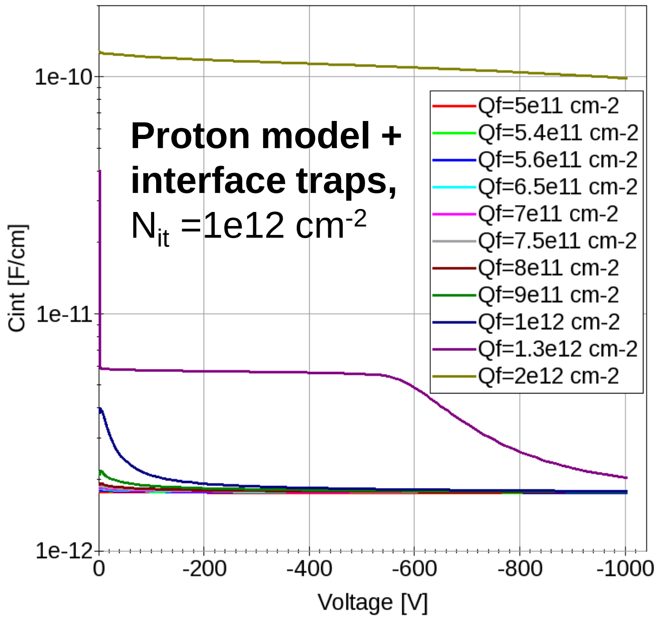


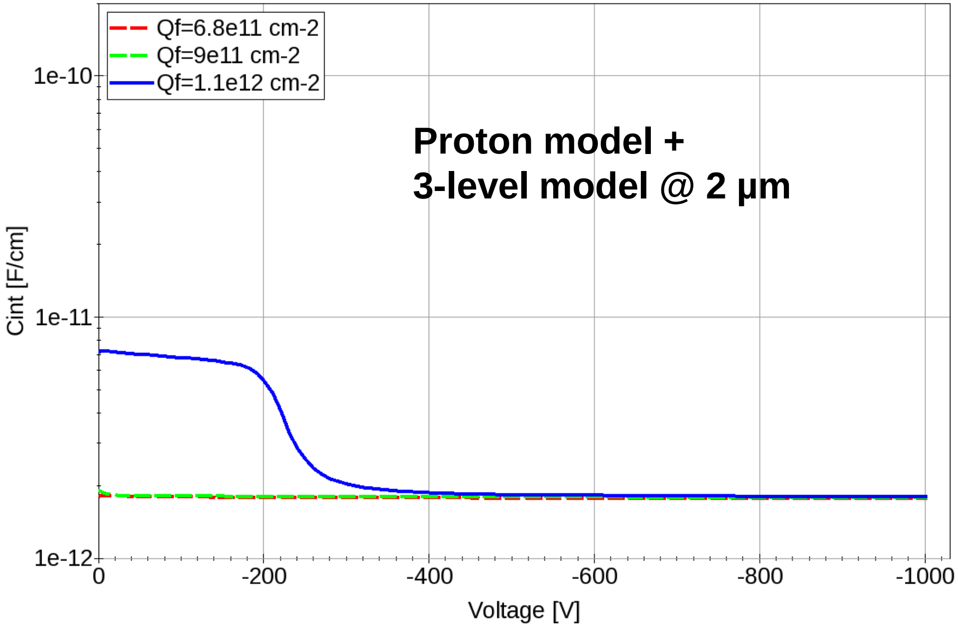
Proton model + 3-level model @ 2 µm

Very high N_{it} still produces only ~18% CCE loss between strips

C_{int}: N_{it} vs non-unif. 3-level model @ Φ_{eq} = 3e14 cm^{-2}

- Device structure corresponding to previous slide
- **3-level model @ 2 µm from surface:**
  - Geometrical value ~1.8 pF/cm reached at 0 V when CCE loss matches measurement
- **Interface traps:**
  - Geometrical value reached at low V up to Q_f =1e12 cm^{-2} (no match with measured CCE loss)
- **Measurement:** C_{int} ~1.8 pF/cm reached at 0 V





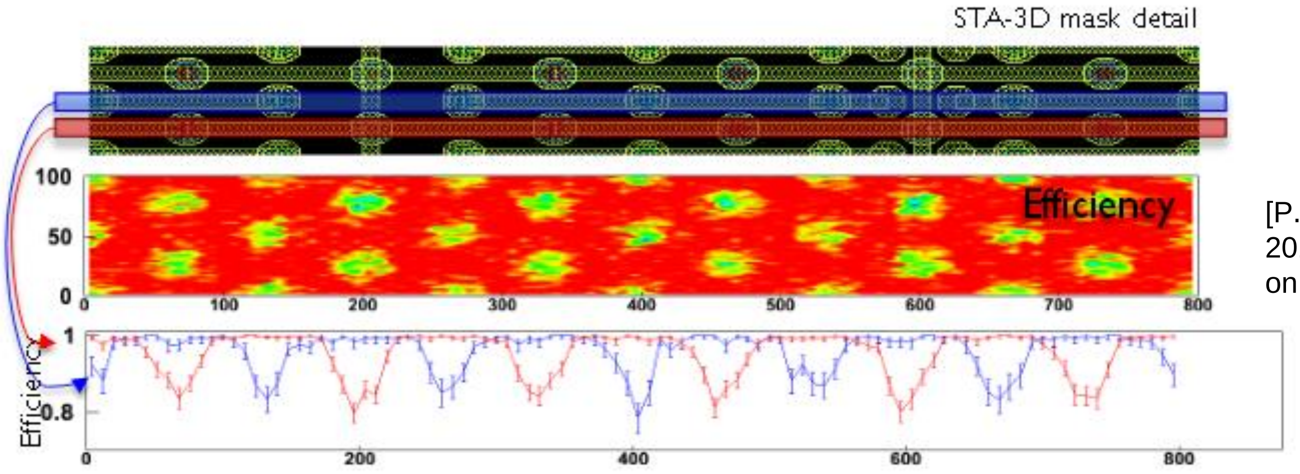
Conclusion from slides 7-10: Deeper distribution of shallow acceptors reproduces measured CCE loss between strips & C_{int} more closely

3D sensor simulations

Columnar 3D sensor simulations: Motivation

- ❑ **3D sensors:** Most promising choice for extremely high fluence environments. Now populate 25% of the ATLAS IBL
- ❑ **3D geometry:** Large signal & reduced trapping probability → **higher radiation tolerance**
- ❑ **Downsides of 3D sensors include hit position dependent signal size:**

Electrodes are parallel to track (B=0, 0°) at normal incidence



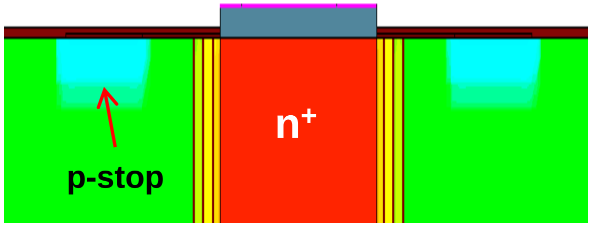
[P. Hansson et al., SLAC, 2010 Vienna Conference on Instrumentation]

- ❑ **TCAD simulations can also be applied for the design optimization of 3D sensors**
- ❑ **Possible to simulate hit position dependence of 3D sensor with realistic thickness?**

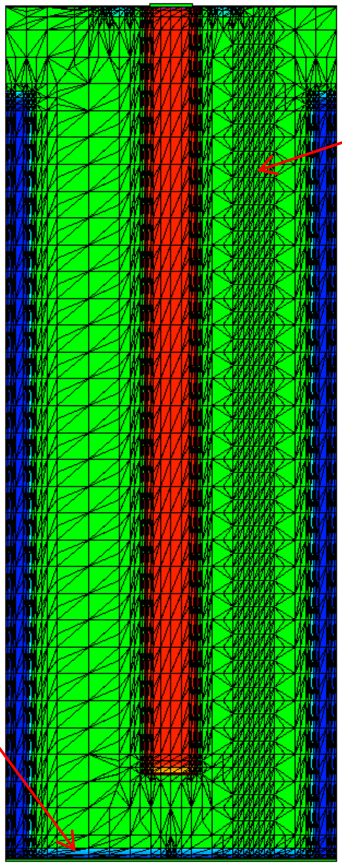
Double type column 3D-sensor simulations: structure

- **Double-side double type column 3D-sensor structure**
- 55x55x200 μm^3 structure, 250 nm oxide layer & 500 nm Al on both planes
- P-type bulk with 180 μm n$^+$/p$^+$ columns (r = 5 μm)
- All p$^+$ contacts connected together by the backplane Al
- p-stop depth = 1.5 μm, r_{in} = 10 μm , r_{out} = 15 μm

DC-coupled front contact (R_{bias} = 50 Ω)



Diagonal cut



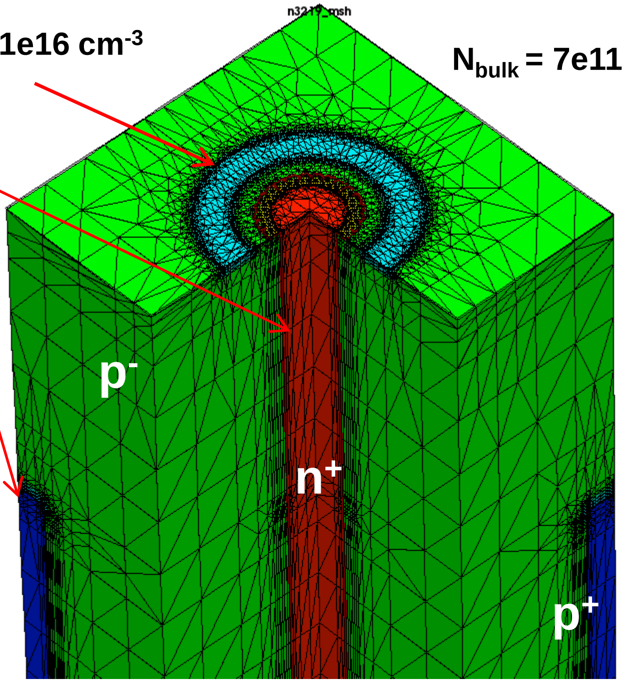
- **Reduced mesh size around MIP trajectory**

- **29 615 mesh points (> 30 k: memory allocation crash)**
- **Column doping profiles by error function**

- **p$^+$ doping at backplane to reduce low field region**

Doping profiles

(Oxide layer transparent for clarity)



N_{ps} = 1e16 cm^{-3}

N_{bulk} = 7e11 cm^{-3}

$N_{p,n}$ = 5e18 cm^{-3}

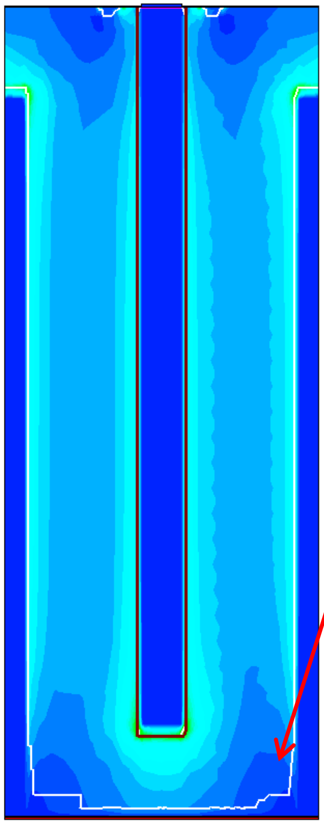
Timo Peltola, RD50 Workshop, 21 Nov 2014

Double-column 3D-sensor: Electrical characteristics

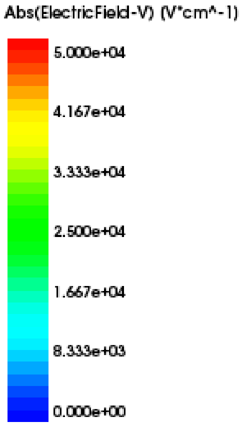
- **Symmetrical E distribution is produced:** hot spots at column ends
- **Full depletion voltage $V_{fd} \approx 10$ V: agrees with measured**

Diagonal cuts:

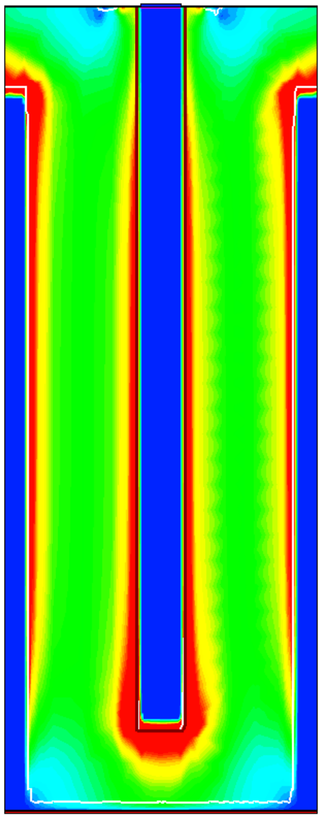
E @ V=-20 V:

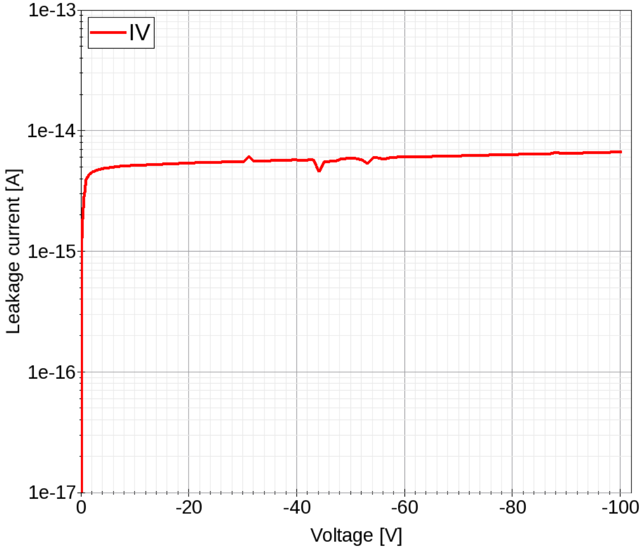


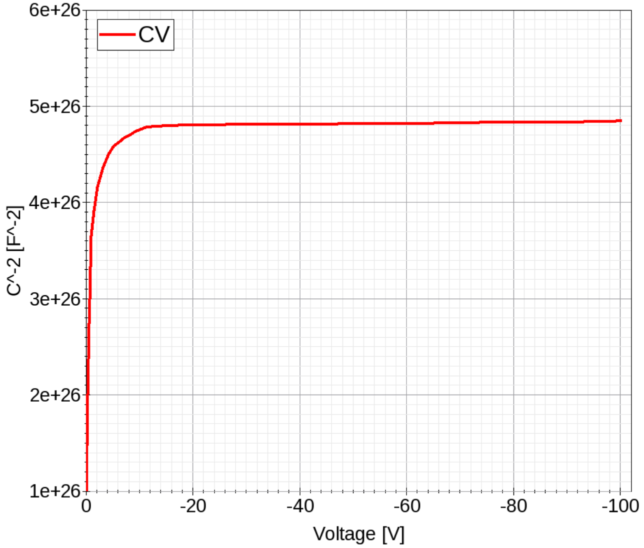
- **Low field regions @ p-stop curvatures & p-column corners**



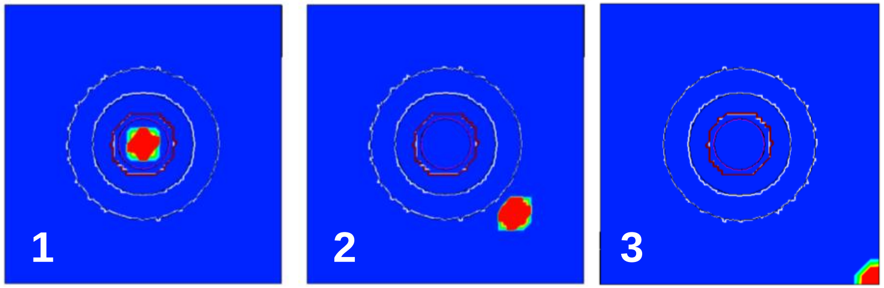
E @ V=-100 V:





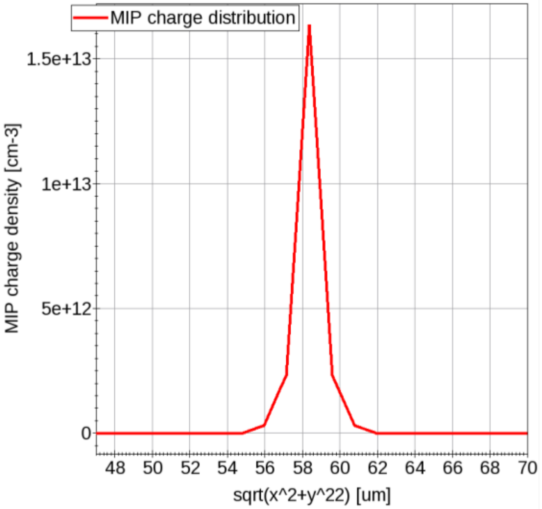


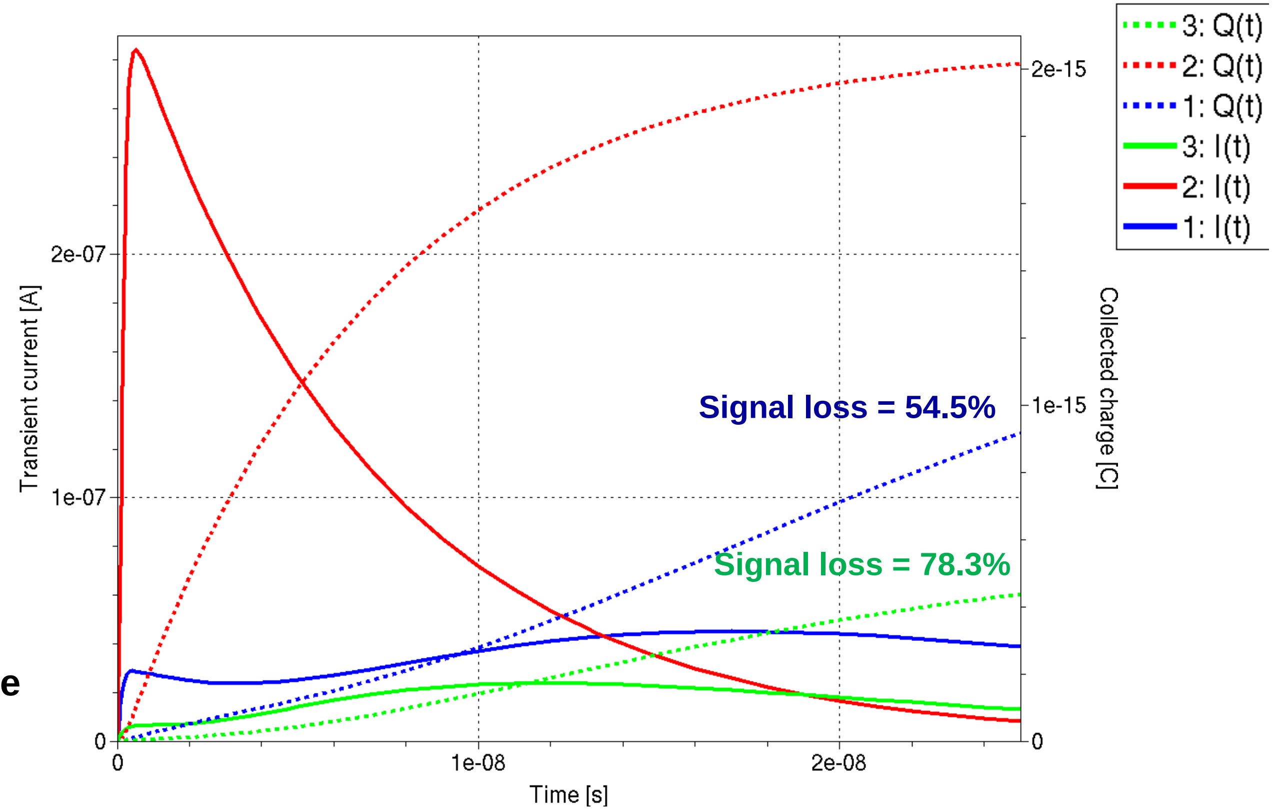
Double-column 3D-sensor: Signal hit position dependency



- ☐ **Hit position 1: n+ column**
- ☐ **Hit position 2: halfway between columns**
- ☐ **Hit position 3: p+ column**
- ☐ **Operation @ V = -100 V**
- ☐ **Long collection time: to be investigated (mesh size, collection electrode parameters?)**

Gaussian spread of MIP generated charge density, LET: σ = 1 μm





- ☐ **Charge collection in electrode region: Measured signal loss 40-60% [J. Hasi, PhD thesis]**

Summary

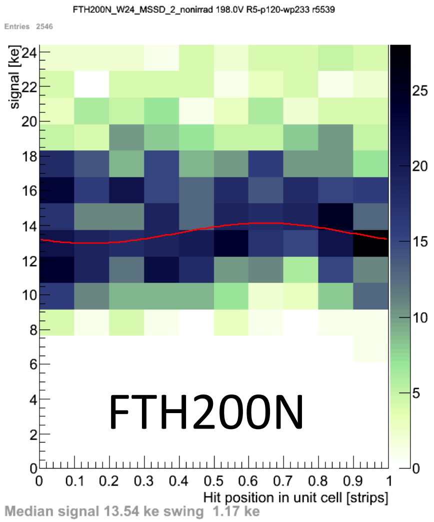
- ☐ **2-level model + interface traps & non-uniform 3-level model were applied for CCE(x) & C_{int} simulations in Sentaurus TCAD**
- ☐ **Interface traps:**
  - ▪ Deep & shallow acceptors do not reproduce agreement with measurement for the investigated fluence & Q_f range
  - ▪ One shallow acceptor reproduces measured CCE(x) @ Φ_{eq}= 1.4e15 cm^{-2}, no match at lower fluence → high initial C_{int} values & geometrical value reached only after > 180 V
- ☐ **Interpretation:** Deeper distribution of shallow acceptors reproduces measured surface properties more closely

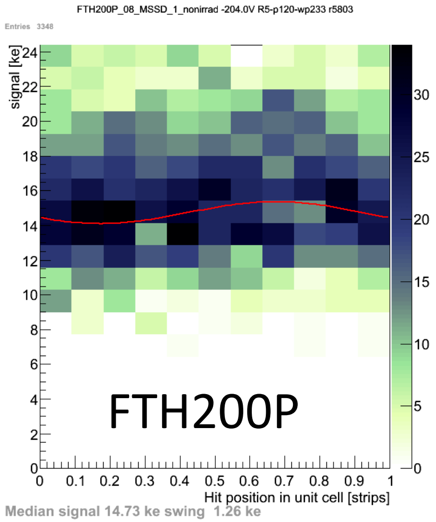
- ☐ **Double-side double type column 3D-sensor simulated succesfully**
  - ▪ Hit position dependence reproduced: over 50% smaller charge collected from column hit
  - ▪ Further investigation needed for unexpectedly long collection times

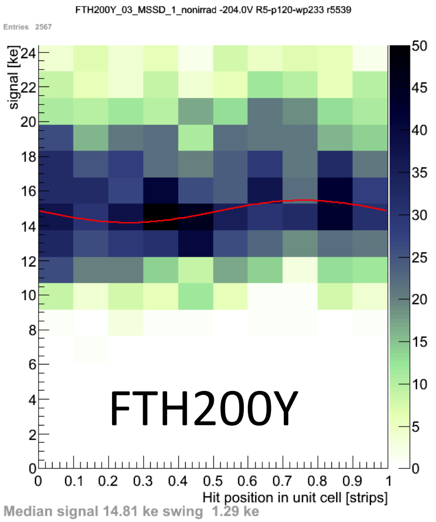
Backup: SiBT measured CCE loss between strips

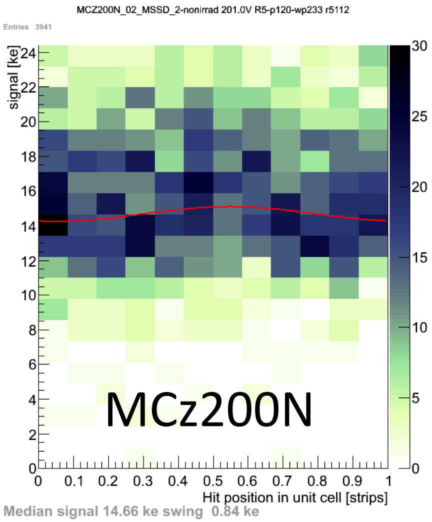
Signal loss in-between strips (p=120µm, w/p~0.23)

non-irradiated



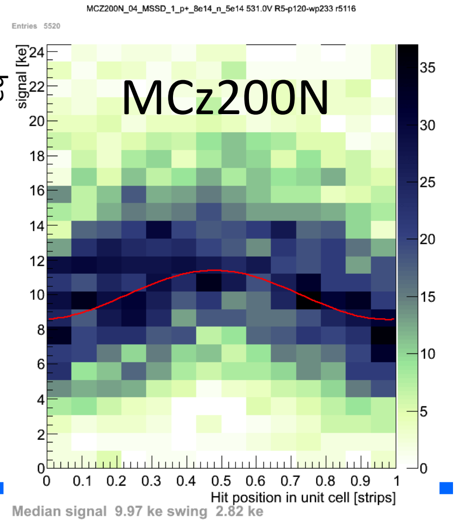


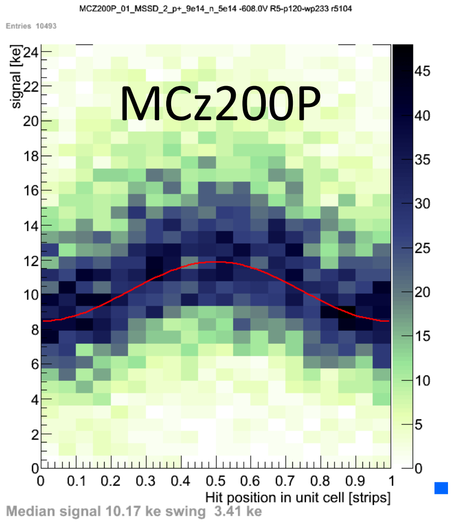


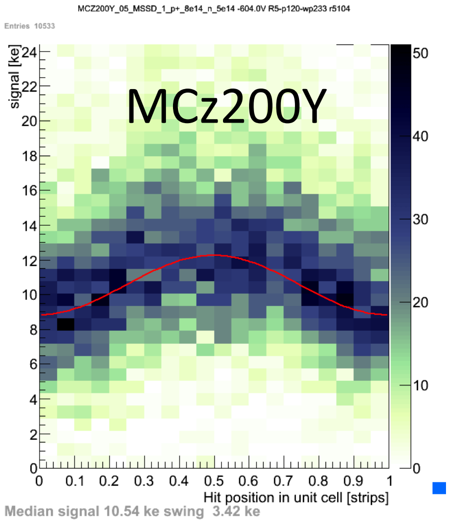


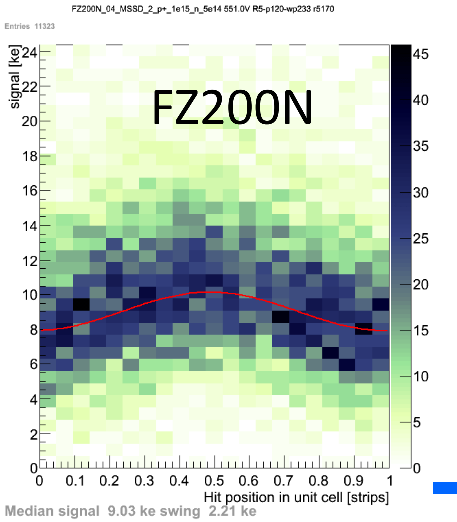
No loss before irrad.; after irrad. ~30% loss; all technologies similar [Phase-2 Outer TK Sensors Review]

mixed irradiated 1.5e15n_{eq}/cm^2









Backup: Measured R_{int} & C_{int}

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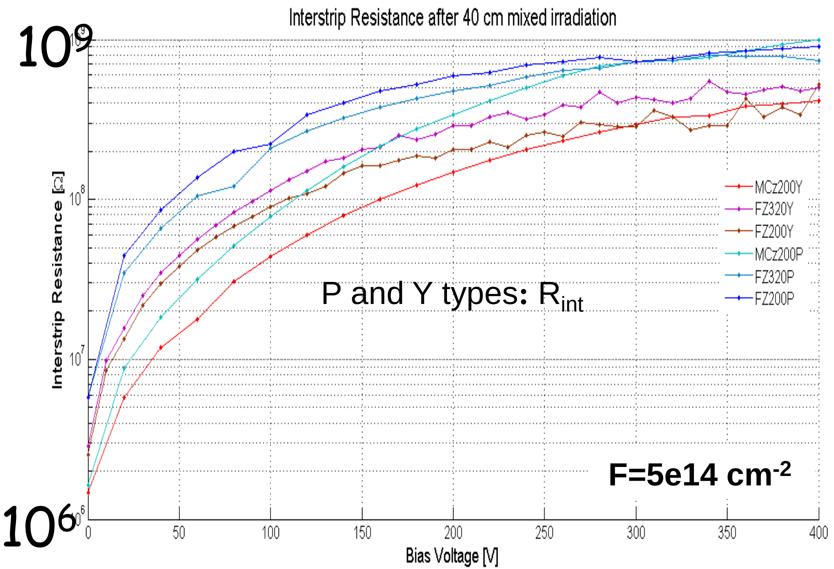
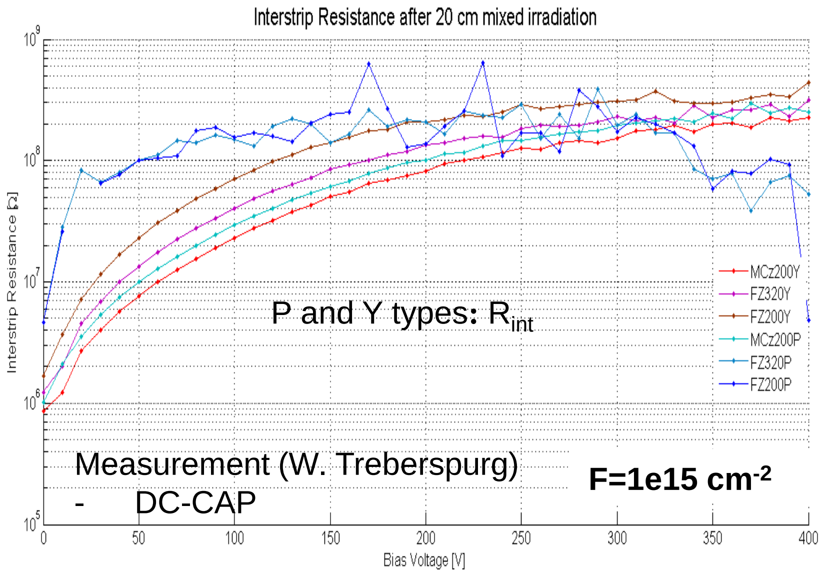


P and Y types: R_{int}

F=5e14 cm^{-2}

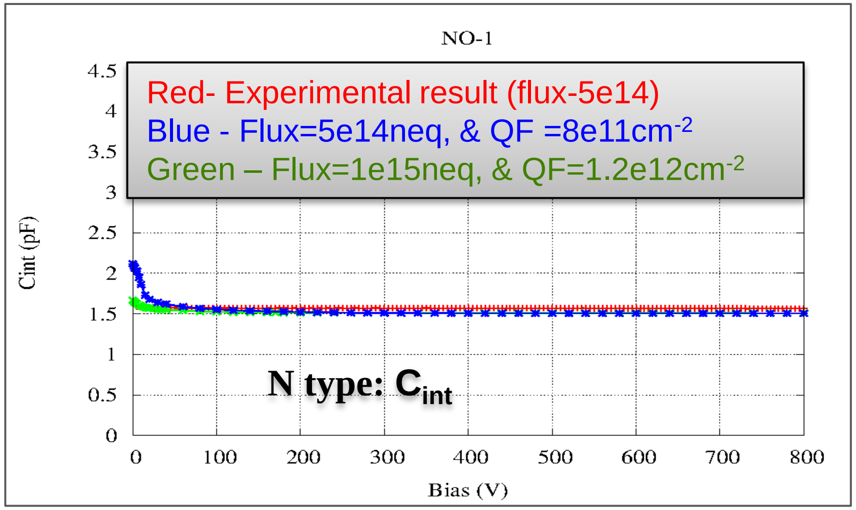


P and Y types: R_{int}

Measurement (W. Treberspurg)
- DC-CAP

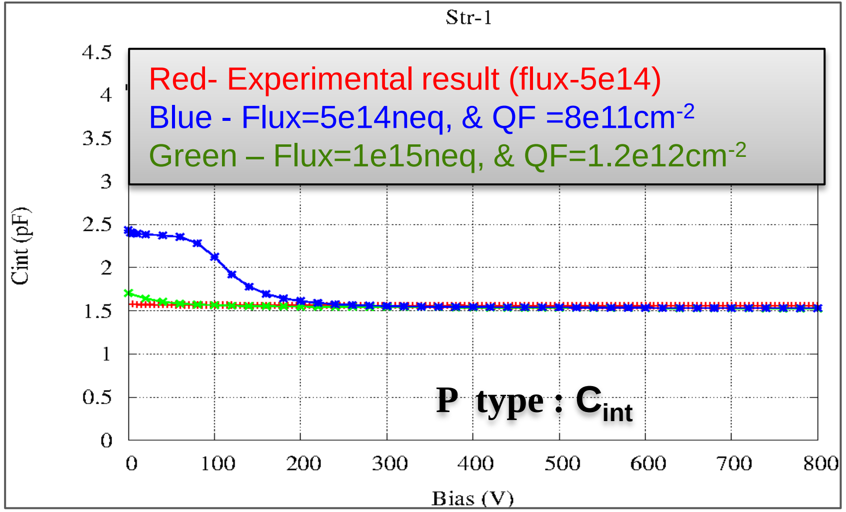
F=1e15 cm^{-2}

Simulations by Silvaco Atlas 5-trap model



Red- Experimental result (flux-5e14)
Blue - Flux=5e14neq, & QF =8e11cm^{-2}
Green – Flux=1e15neq, & QF=1.2e12cm^{-2}

N type: C_{int}



Red- Experimental result (flux-5e14)
Blue - Flux=5e14neq, & QF =8e11cm^{-2}
Green – Flux=1e15neq, & QF=1.2e12cm^{-2}

P type : C_{int}

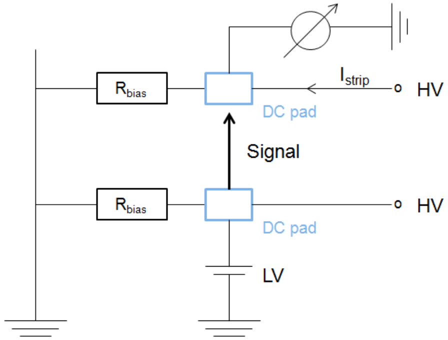
Backup: simulated R_{int} & C_{int}

- ❑ 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):

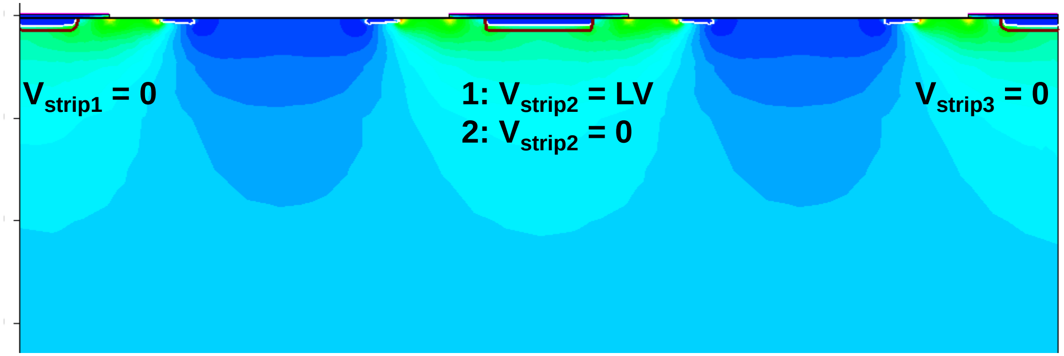
$$R_{int} = \frac{V_2(LV)}{\frac{I_1(LV)+I_3(LV)}{2} - \frac{I_1(0)+I_3(0)}{2}}$$

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

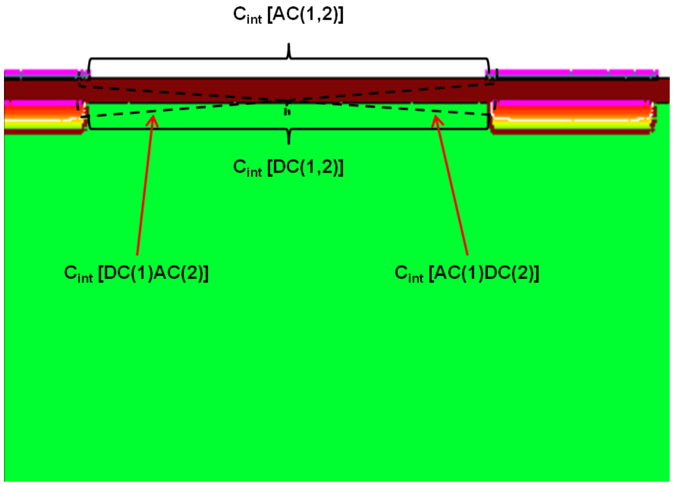
- ❑ **Electrical circuit diagram of R_{int} measurement :**



R_{int} simulation principle



C_{int} simulation principle



C_{int} = 2*[AC(1,2)+DC(1,2)+AC(1)DC(2)+DC(1)AC(2)]