The 2017 CPAD Instrumentation Frontier Workshop,
Albuquerque, 12-14 Oct 2017

Numerical simulations of silicon radiation detectors for HL-LHC: Sensor technologies and modeling of radiation damage

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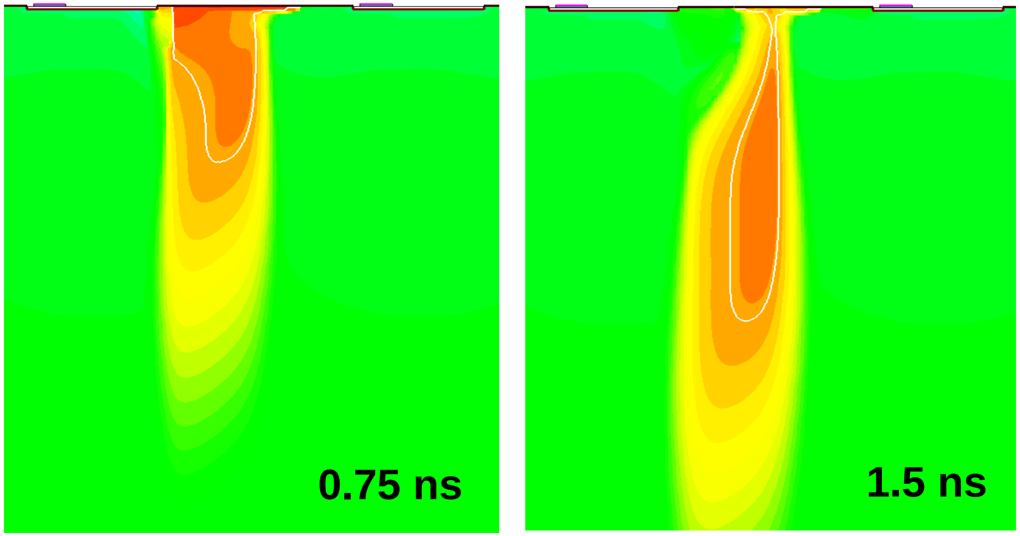
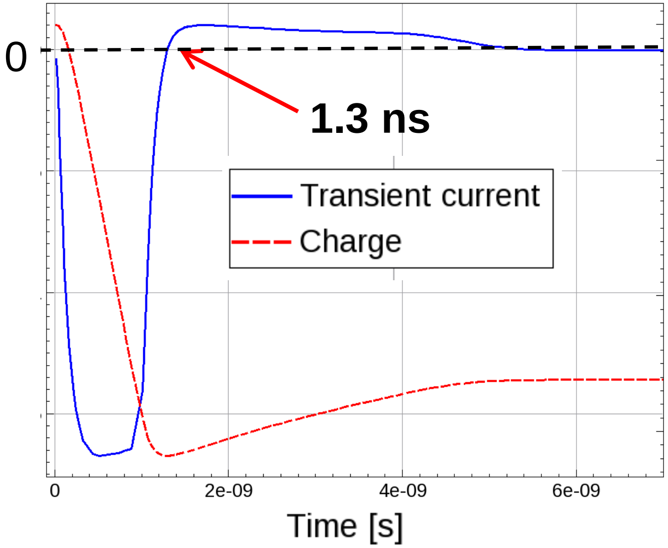




Outline

- ❑ **Motivation**
- ❑ **Sensor technology modelling**
- ❑ **Radiation induced defects in silicon:** Modelling
- ❑ **Simulated defects:**
  - **Bulk damage:** Hadrons
  - **Surface damage:** γ-radiation
  - **Bulk & surface damage:** Charged hadrons
- ❑ **Study for extreme Φ defect model**
- ❑ **Summary**

Motivation: From LHC to HL-LHC

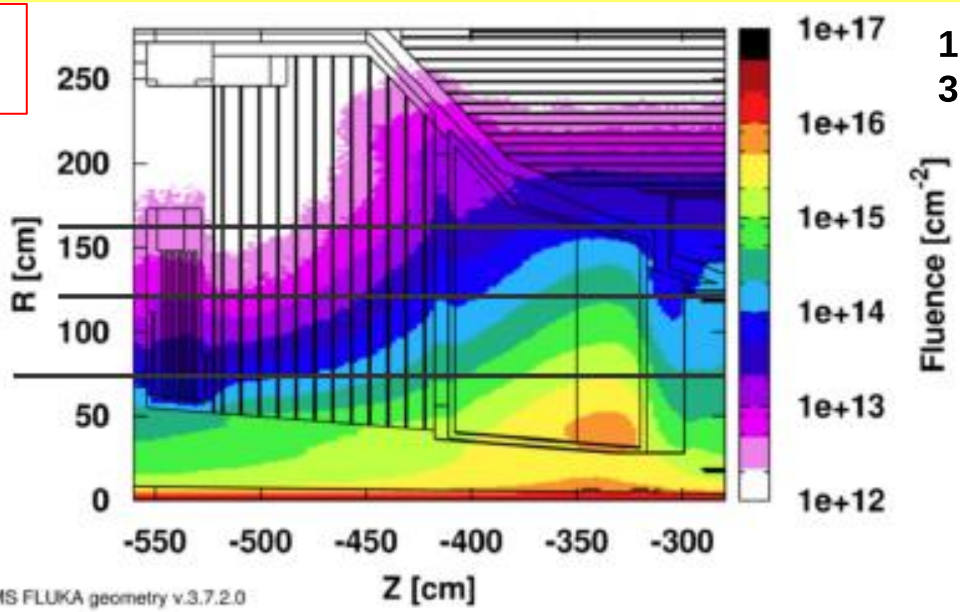
Estimated Φ in HGCAL @ HL-LHC after 10 years

Sensor thickness [μm]

$\Phi_{max}=6\times10^{14}$ → ***320***

$\Phi_{max}=2.5\times10^{15}$ → ***200***

$\Phi_{max}=1\times10^{16}$ → ***120***

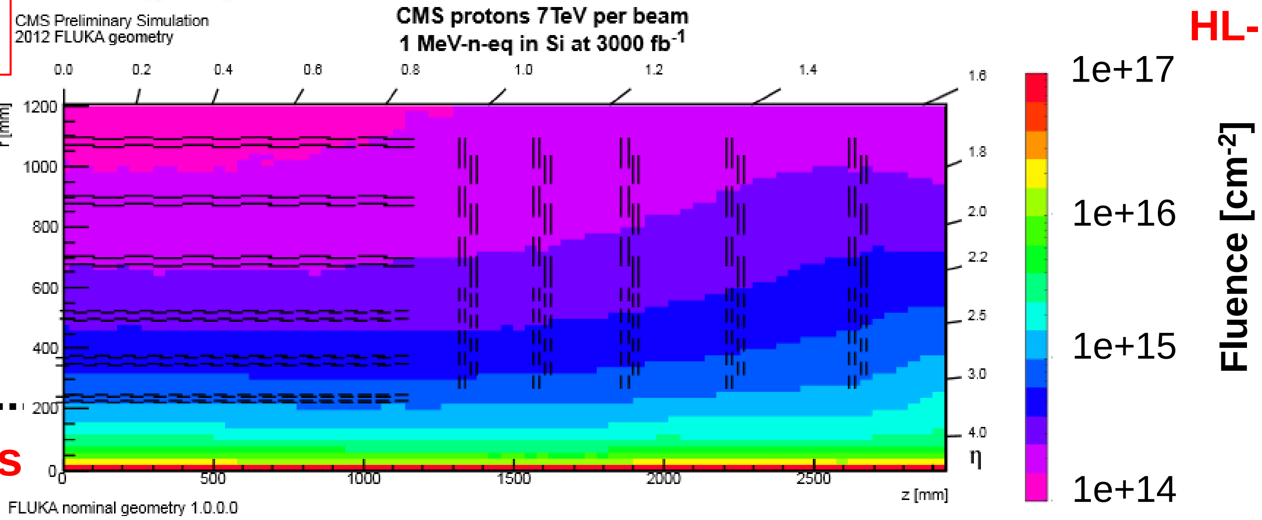


1-MeV n_{eq} in Si, HGCAL @ 3000 fb^{-1}

Si detectors exposed to hadron $\Phi > 10^{16}$ n_{eq} cm^{-2} → beyond capacity of detectors @ LHC

→ **R&D of higher radiation hardness & granularity sensors for HL-LHC**

Estimated Φ in CMS Tracker @ HL-LHC after 10 years



130 cm

Strips

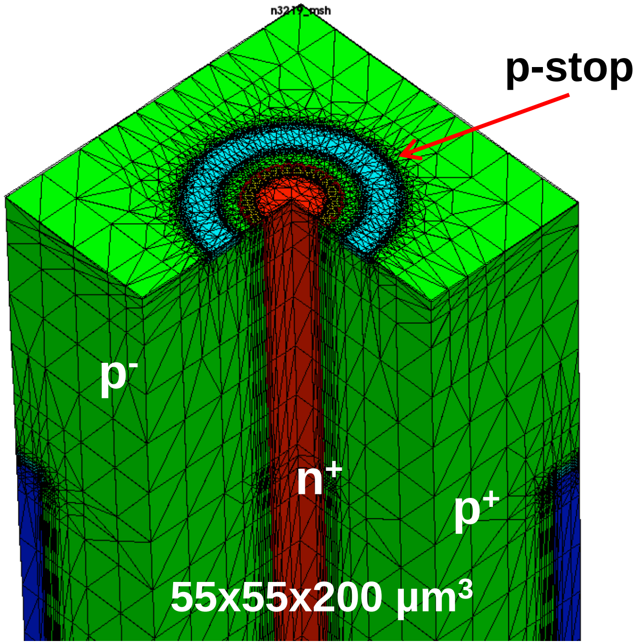
$\Phi_{max}\approx1\times10^{15}$

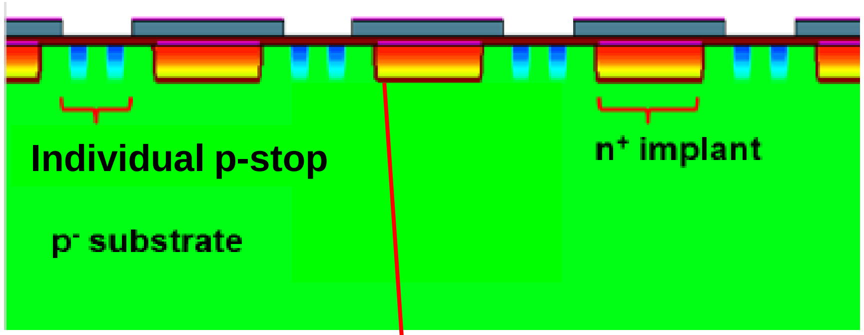
$\Phi_{max}\approx1\times10^{16}$ **Pixels**

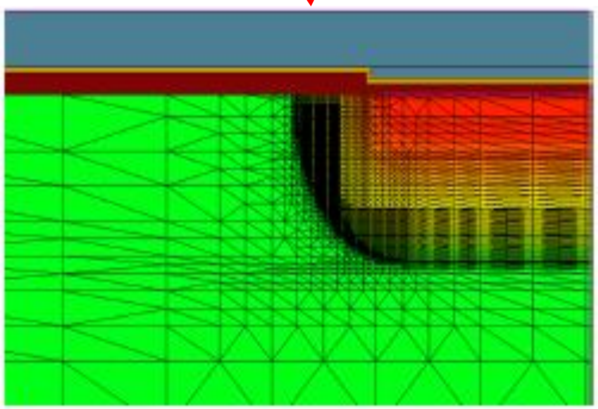
Sensor technology modelling

Simulated sensors: 2D & 3D designs

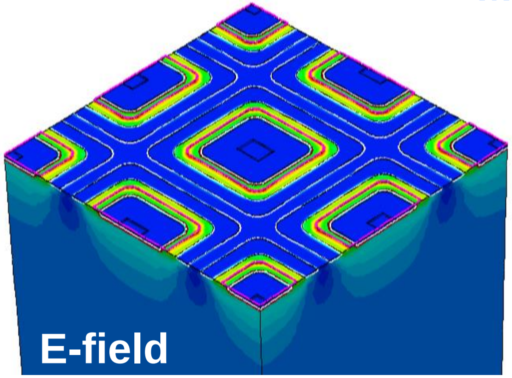
- ☐ **Pad & strip sensors:** Constant E-field in 3rd dimension → 2D structures sufficient for accurate results → extend to real device dimensions by area factor
- ☐ **Planar & 3D-columnar pixel sensors:** 3D-design required for correct modeling of E-fields



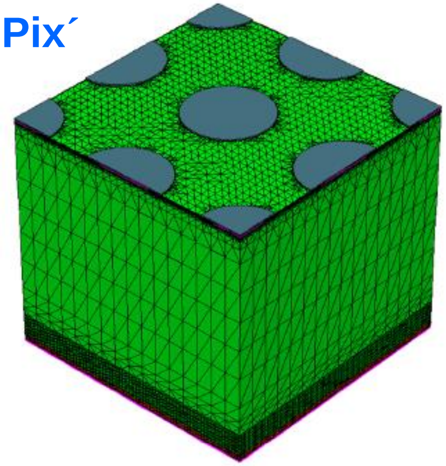




50x50 pixel sensor



´MediPix´



Radiation induced defects in Si: Modelling

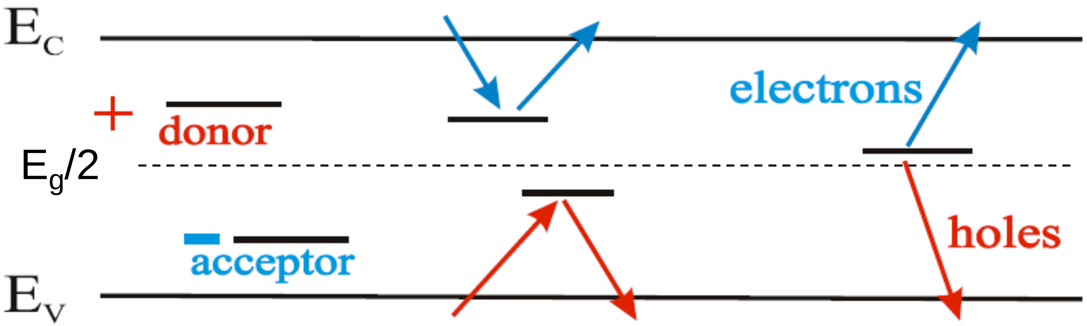
Radiation damage in Si: Defect Parameters

- ☐ Radiation (Φ_{eq} >1e13 cm^{-2}) causes damage to Si crystal structure (Φ_{eq} = 1-MeV n_{eq})
- ☐ Φ_{eq} >1e14 cm^{-2} lead to significant degradation of CCE due to charge carrier trapping

☐ **Bulk & surface damage affect detector performance:**

- **Bulk:** Deep acceptor & donor type trap levels
- **Surface:** Positive charge layer accumulated inside SiO_2

Shockley-Read-Hall Statistics



Charged defects: N_{eff} (space charge, E-field), V_{dep}

Captured e, h: trapping → CCE

Generation/ Recombination e, h: LC

[M. Moll, VERTEX 2013]

☐ 11 defect levels observed to influence irradiated Si detectors (back-up 2-4)
→ Vast parameter space to model

Defect parameters

Defect type	E_a [eV]	σ_n [cm^2]	σ_p [cm^2]	N_t [cm^{-3}]
Acceptor	E_C - x_1	O(1e-14)	O(1e-14)	$\eta_1 \cdot \Phi + c_1$
Donor	$E_V + x_2$	O(1e-14)	O(1e-14)	$\eta_2 \cdot \Phi + c_2$

Effective model needed for simulation

Defect simulations: TCAD

❑ **Motivation for Technology Computer-Aided Design (**TCAD**) simulations:**

- E-fields not possible to measure directly → Predict E-fields & trapping in irradiated sensors
- Verify measurements → Find physics behind unexpected results
- Predictions for novel structures & conditions → Device structure optimization

❑ **Principle for irradiated Si detector TCAD simulation:**

- **Minimized set:**
  - ○ **2 midgap levels DD & DA applied to reproduce & predict:** Bulk generated current + E(depth) + trapping
  - ○ **Surface damage:** Fixed charge density Q_f @ SiO_2/Si interface w/ interface traps N_{it} of varying depth distributions

❑ **Sentaurus TCAD proton & neutron defect models for Φ_{eq} =1e14 ~ 1e15 cm^{-2} @ T=253 K** [1]

Defect type	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acc.	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

Defect type	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Concentration [cm^{-3}]
Deep acc.	E_C - 0.525	1.2e-14	1.2e-14	1.55*Φ
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*Φ

(back-up 5-6)

❑ **Can trapping be explained in frame of 2-DL model?** [2]

- $\beta \approx$5e-7 s^{-1}cm^2 & Φ=1e14 cm^{-2} → τ = 20 ns
- Trapping X-section σ=1e-14 cm^2, v_{th}=2e7 cm/s

→ $N_t = 1/[\sigma v_{th} \tau]$ = 2.5e14 cm^{-3} or intro rate $\eta(N_t)$ = 2.5

$\eta(N_t)$, η(DA) & η(DD) have equal range →
2-DL model has potential to model CCE(Φ)

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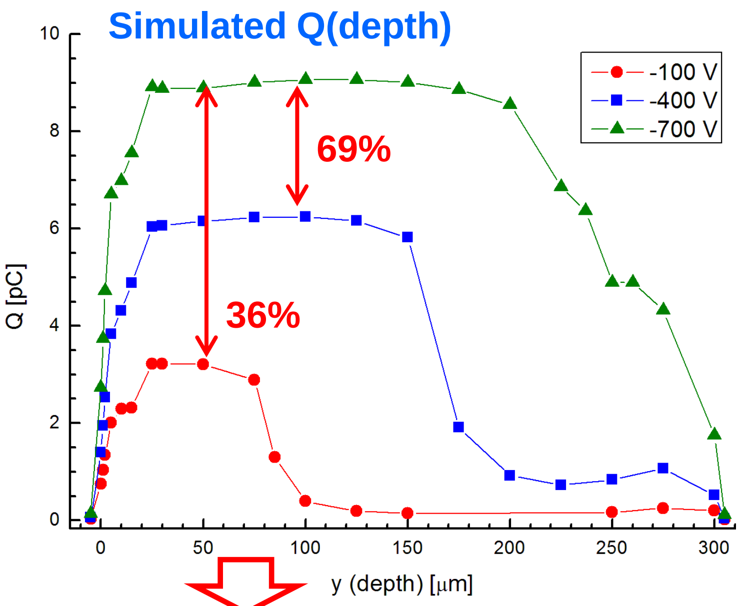
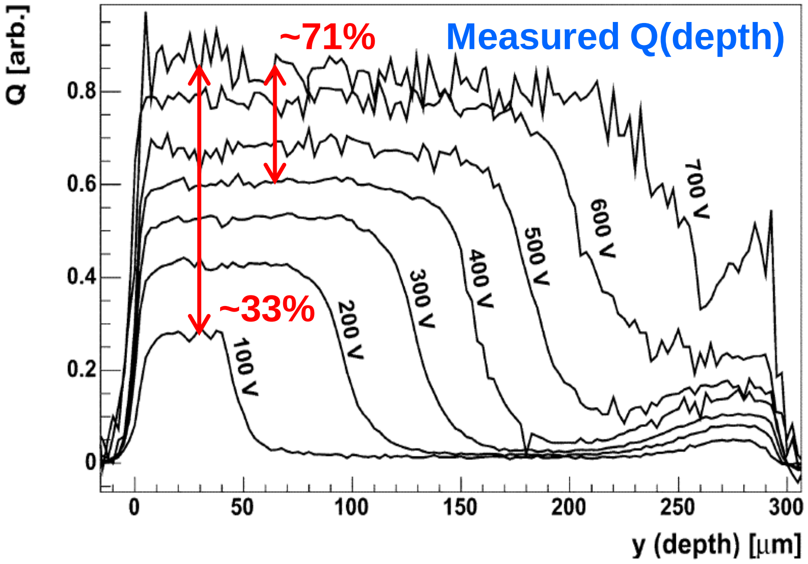
[1] R. Eber, PhD Thesis, KIT, 2013
[2] V. Eremin, RD50 SWG meeting, March 2013

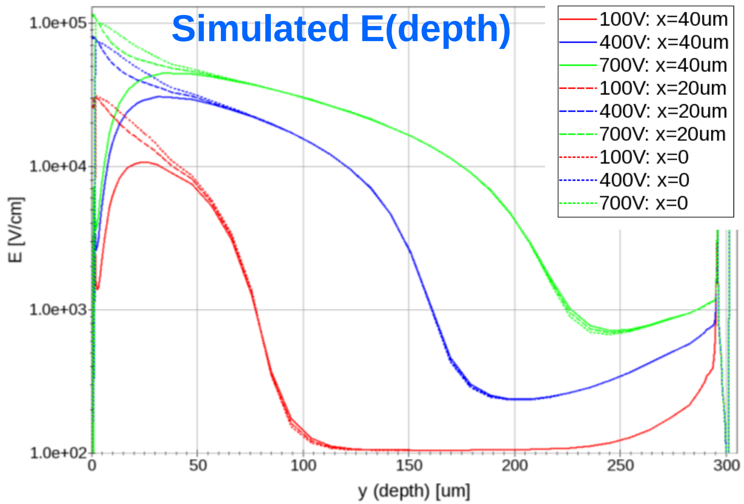
Simulated bulk damage: Hadrons

Edge-TCT: Neutron irradiated strip detector



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





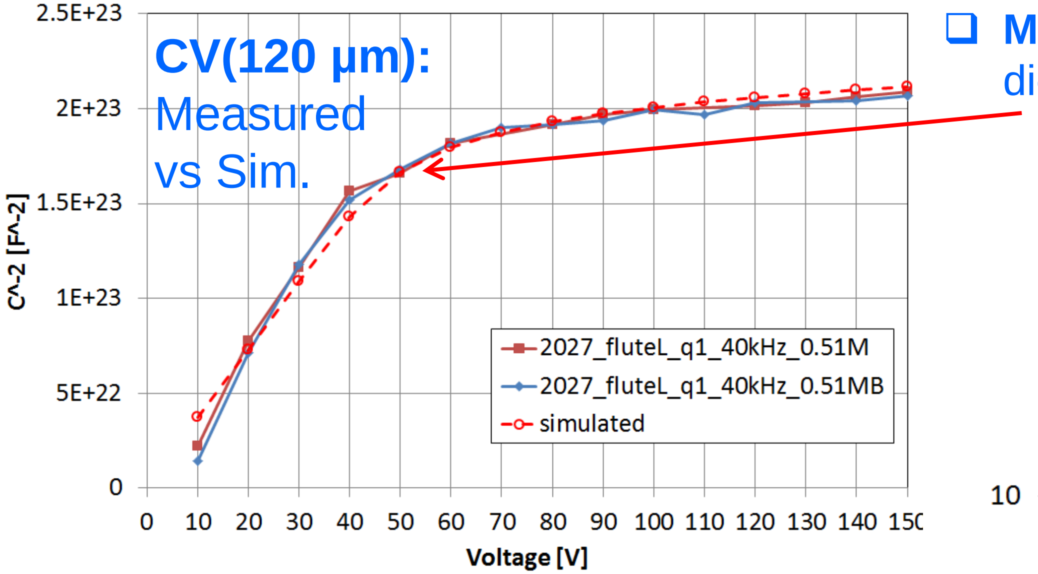
x=0:
center
of strip

300 μm n-on-p strip sensor:
Φ_{eq}(n)=5e14 cm^{-2}, Q_f=1e11 cm^{-2}, pitch=80 μm

- ❑ **Experimental:** Extract E-field from v_{dr} using edge-TCT
- ❑ Amplitudes reproduced by simulation (back-up 7)
- ❑ Depletion depth accuracy increases w/ V →

Simulation gives reliable estimation of E(depth)

CV/IV(p-on-n): 120 µm HGCAL DD-diodes



CV(120 µm):
Measured
vs Sim.

- ☐ **Measured & simulated 120 µm p-on-n** DD-diodes: V_{fd} = 47 V
  - Physical/active t = 320/117 µm
  - Err. Function SymPos=87 µm
  - N_B = 4.432e12 cm^{-3}

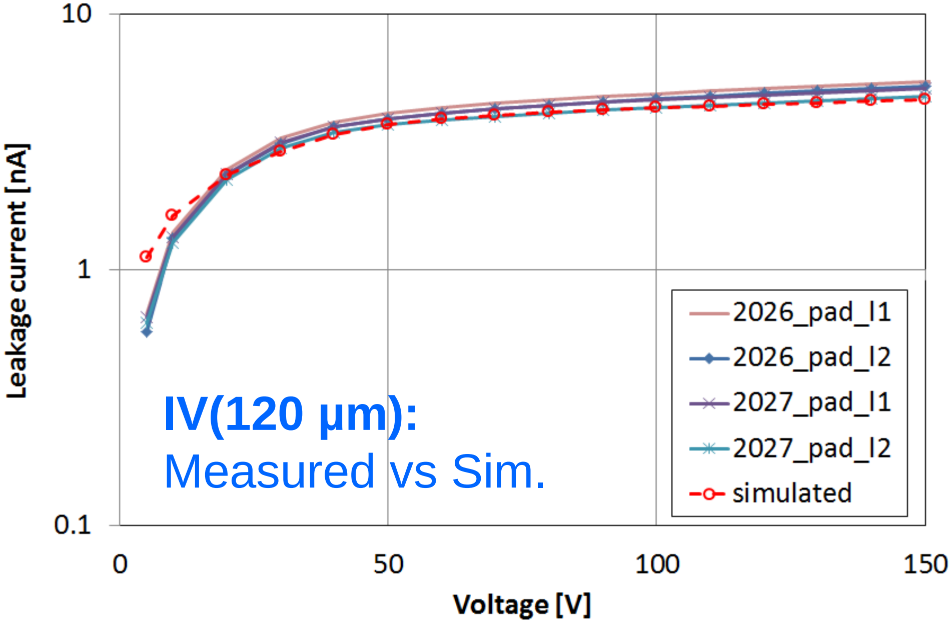
⇩

Extracted parameters to tune simulation to measured LC by carrier trapping times

- ☐ **Tuned trapping times:**
  - **120 µm**
    - ○ τ_e= 4.7e-4 s
    - ○ τ_h= 4.7e-5 s

⇩

- ☐ Trapping time influences CC → Neutron model vs τ -tuned non-irradiated sensors → **increased accuracy for simulated CCE**



IV(120 µm):
Measured vs Sim.

Irradiated HGCAL diodes: Expected CCE

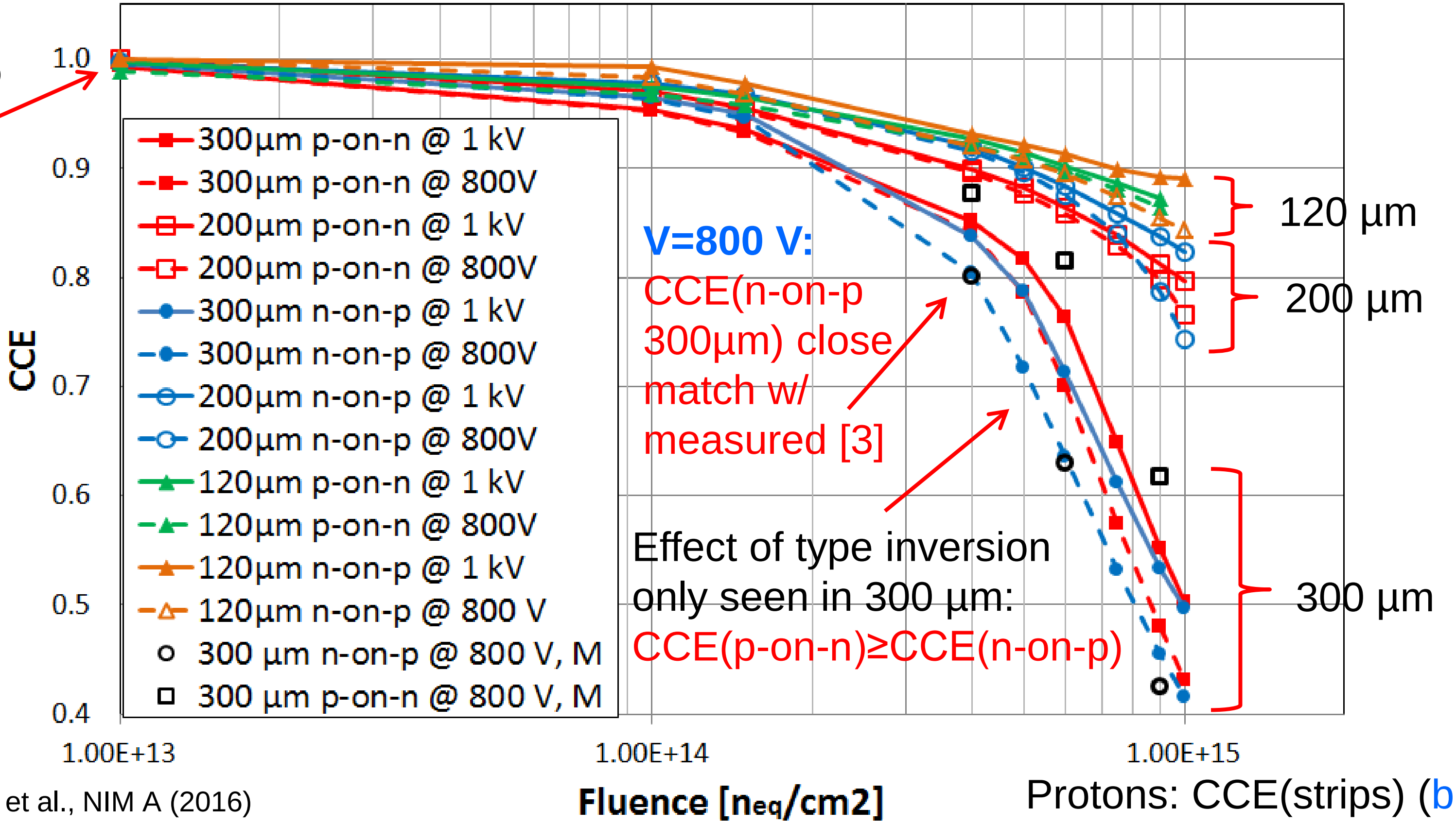
- ❑ Neutron irradiated diodes w/ tuned parameters from measurement/simulation study
- ❑ **Before irr.:** CC from MIP injection @ RT & 500 V
- ❑ **After irr.:** CC from MIP injection @ T=253 K

→ CCE = CC(after)/CC(before)

- ❑ **Increased V → 1 kV:**

CCE(n-on-p) benefits more for all thicknesses (no SCSI)

CCE=1 @ low Φ as expected



V=800 V:

CCE(n-on-p 300µm) close match w/ measured [3]

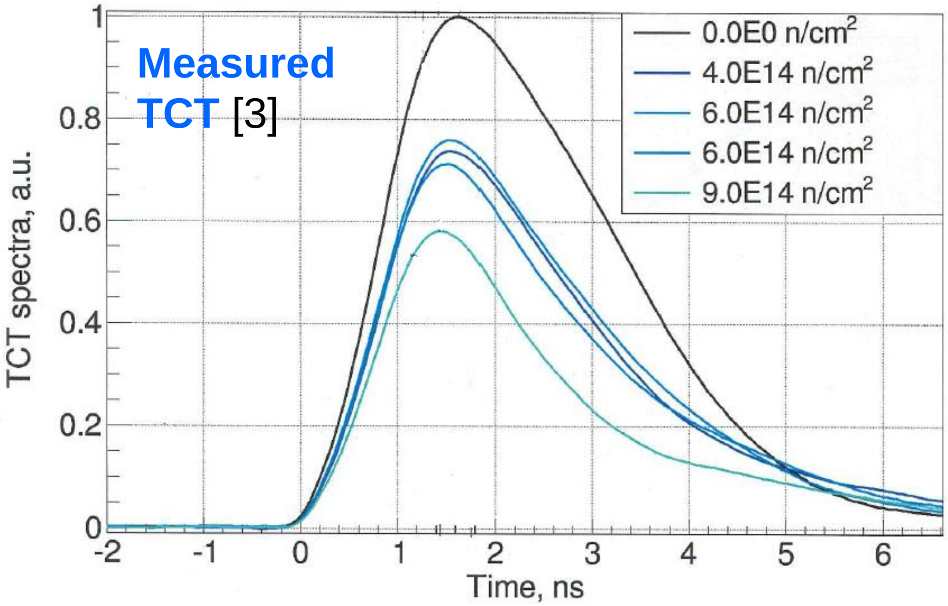
Effect of type inversion only seen in 300 µm:

CCE(p-on-n)≥CCE(n-on-p)

[3] E. Currás, et al., NIM A (2016)

Protons: CCE(strips) (back-up 8)

Signal rise time: Measured vs simulated

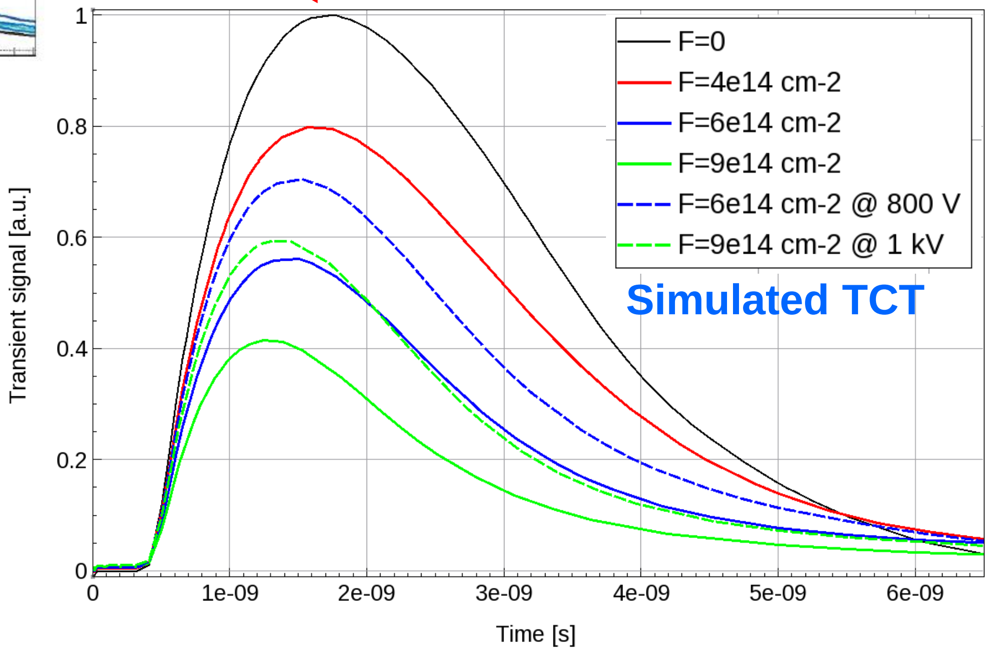

Measured TCT [3]

- ☐ **Measured & simulated:**
  - p-on-n 320 µm pad, IR front side illumination @ V=600 V, T=253 K
- ☐ **Simulation:** Neutron defect model
  - R_{bias} = 5 MΩ → signal length tuning
- ☐ **Simulated Φ = 0:** Matching signal duration, peak location & curve shape

- ☐ **Φ = 0 vs 9e14 n_{eq}cm^{-2}:**
  - **Δ**t_r(meas) ≈ 0.12 ns
  - **Δ**t_r(sim) @ 0.6-1 kV= 0.24-0.20 ns

→ simulation reproduces measured TCT signals → reliable t_r simulation study of irradiated detectors

(back-up 9-10)


Simulated TCT

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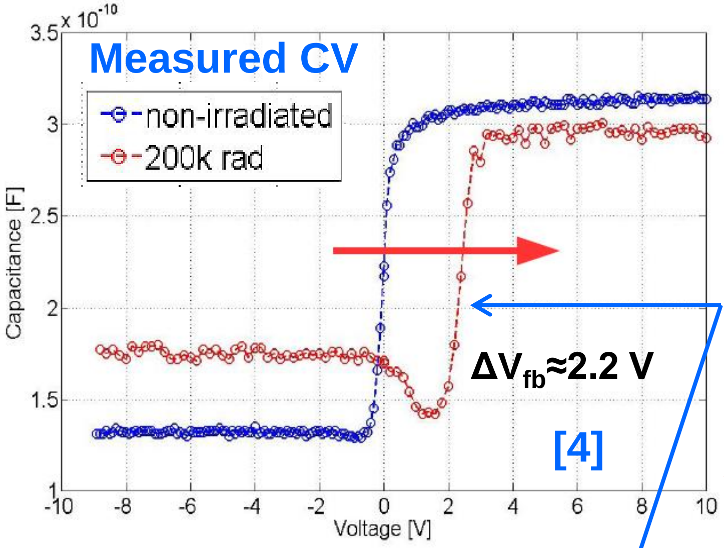
[3] E. Currás, et al., NIM A (2016)

Simulated surface damage: γ-radiation

MOS-structure: Measured & simulated V_{fb}

- γ-irradiated MOS structure w/ 40 nm thick Al_2O_3 layer
- **Simulated γ-induced surface damage:** Increased Q_f
- **Q_f & N_{it}:** No effect to V_{fb}, affect to C offset

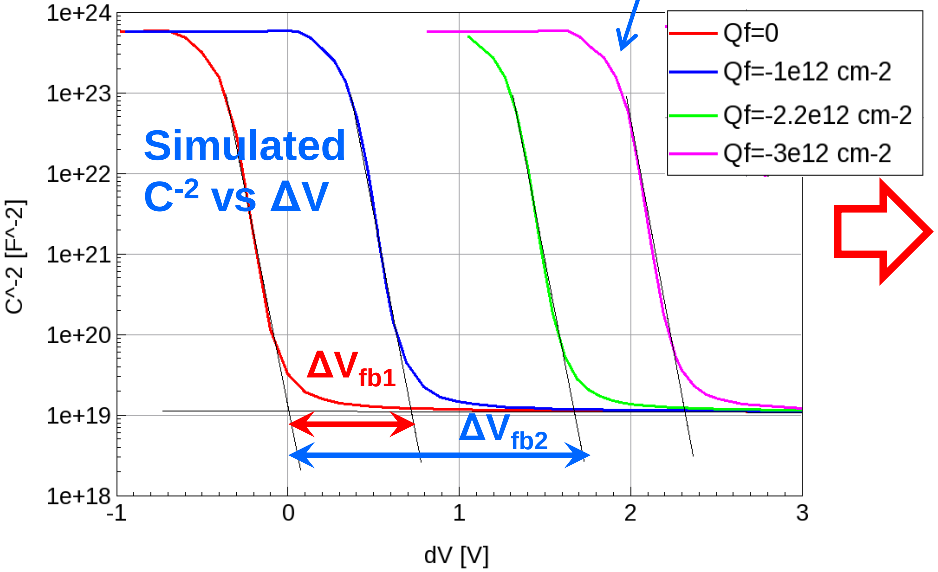
- **Meas. & sim:** Shift of V_{fb} to higher forward bias V → accumulation of negative oxide charge

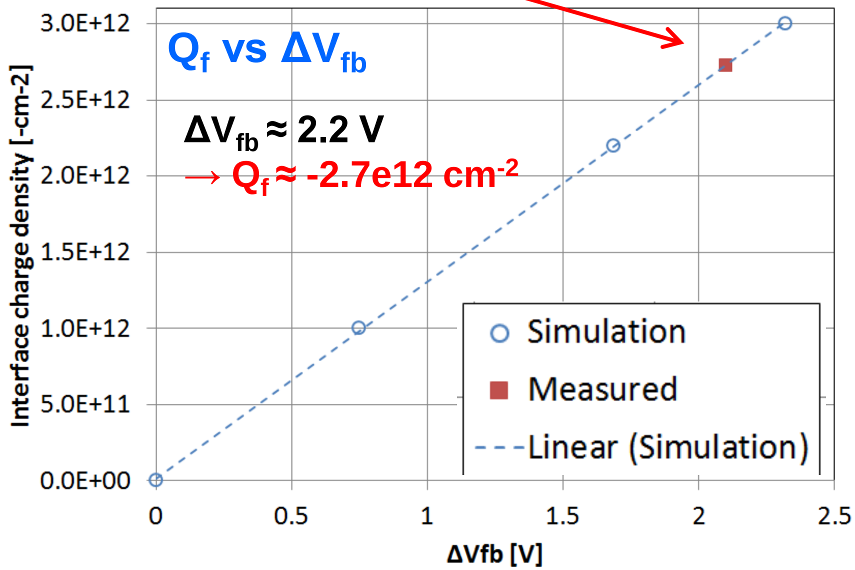

Measured CV

$\Delta V_{fb} \approx 2.2$ V

[4]

- **Meas. + sim:** Linear increase of simulated ΔV_{fb} w/ Q_f → find Q_f corresponding to measured ΔV_{fb}


Simulated C^{-2} vs ΔV


Q_f vs ΔV_{fb}

$\Delta V_{fb} \approx 2.2$ V

→ $Q_f \approx -2.7e12\ cm^{-2}$

[4] J. Härkönen et al., 10th Hiroshima Symposium, 2015

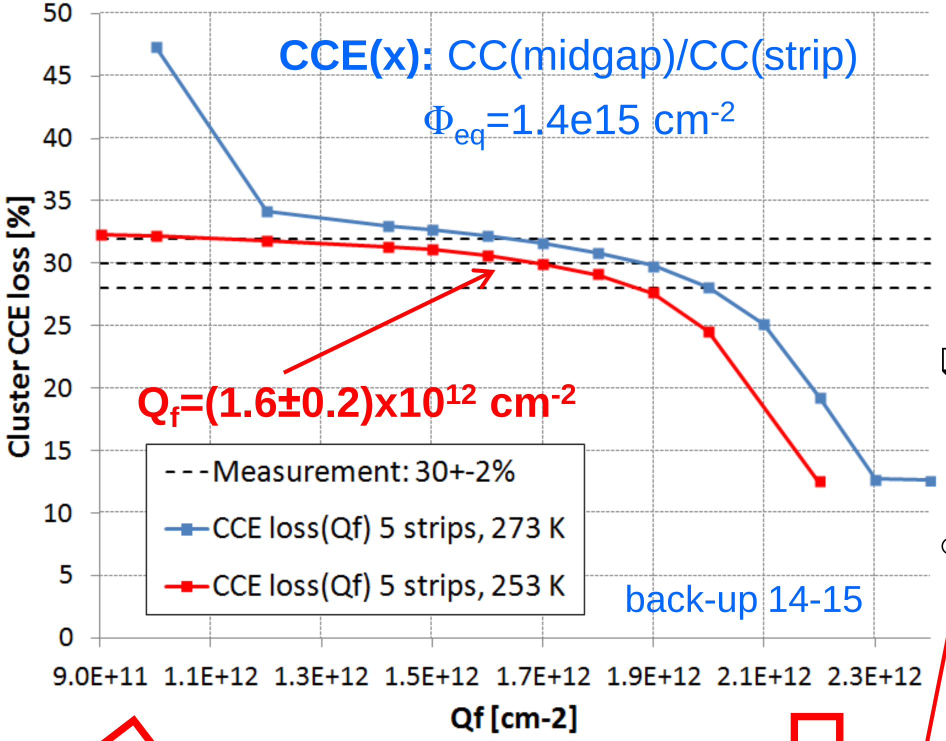
Simulated bulk & surface damage:

Charged hadrons

Bulk & surface damage: CCE(x)

☐ **Heavily irradiated strip detectors demonstrate significant position dependency of CCE [CCE(x)]**

Test beam measured:
- Strips isolated
- CCE loss ~30%



☐ **3-level model within 2 μm of device surface + proton model in bulk:**
- ○ R_{int} & C_{int} in line w/ measured also @ high Φ & Q_f (back-up 11-13)

☐ Irradiation produces shallow traps close to surface → greater drift distance, higher trapping of carriers

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

Defect type	**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

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

Irradiated sensors:
Study for extreme Φ defect model

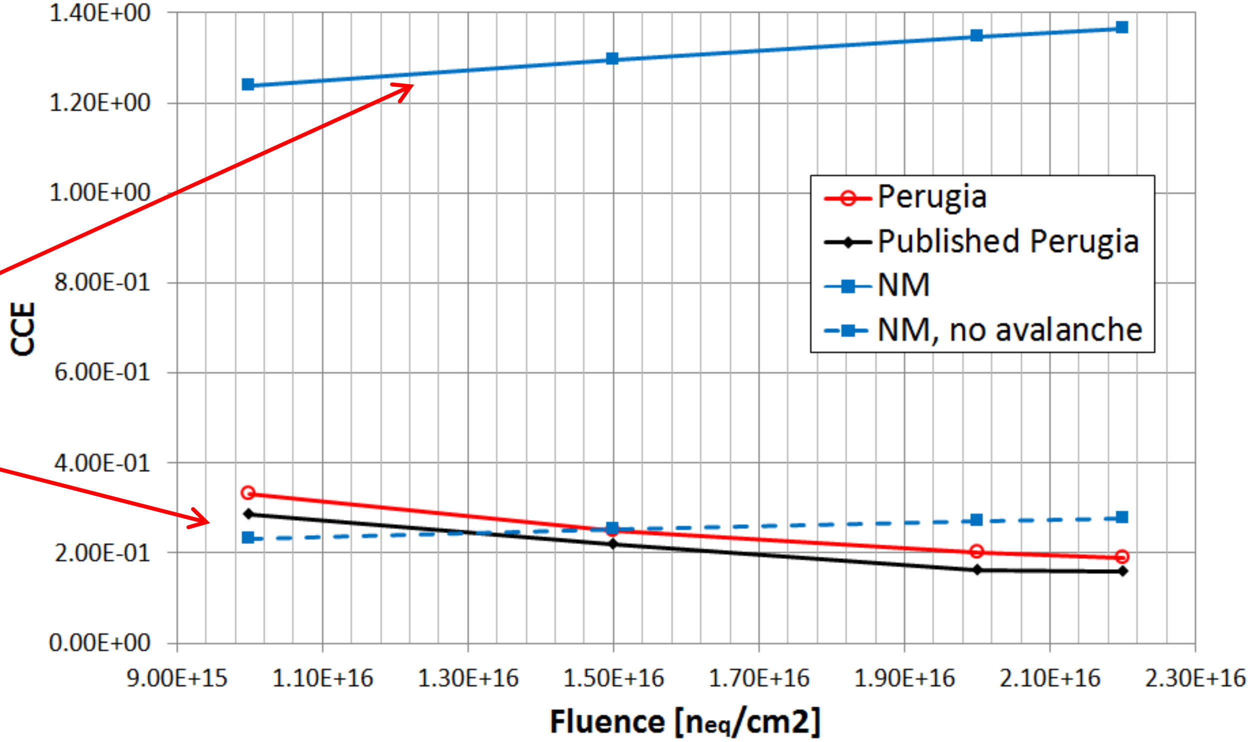
CCE: Φ ≥ 1e16 $n_{eq}cm^{-2}$

- ☐ **´Perugia model´ (PM), Φ = (0.7-2.2)e16 $n_{eq}cm^{-2}$, T=248 K** [5]
  - Reproduces measured CCE @ high Φ

Defect	E (eV)	σ_e (cm^{-2})	σ_h (cm^{-2})	η
Acceptor	$E_c - 0.42$	1.00×10^{-15}	1.00×10^{-14}	1.6
Acceptor	$E_c - 0.46$	3.00×10^{-15}	3.00×10^{-14}	0.9
Donor	$E_v + 0.36$	3.23×10^{-13}	3.23×10^{-14}	0.9

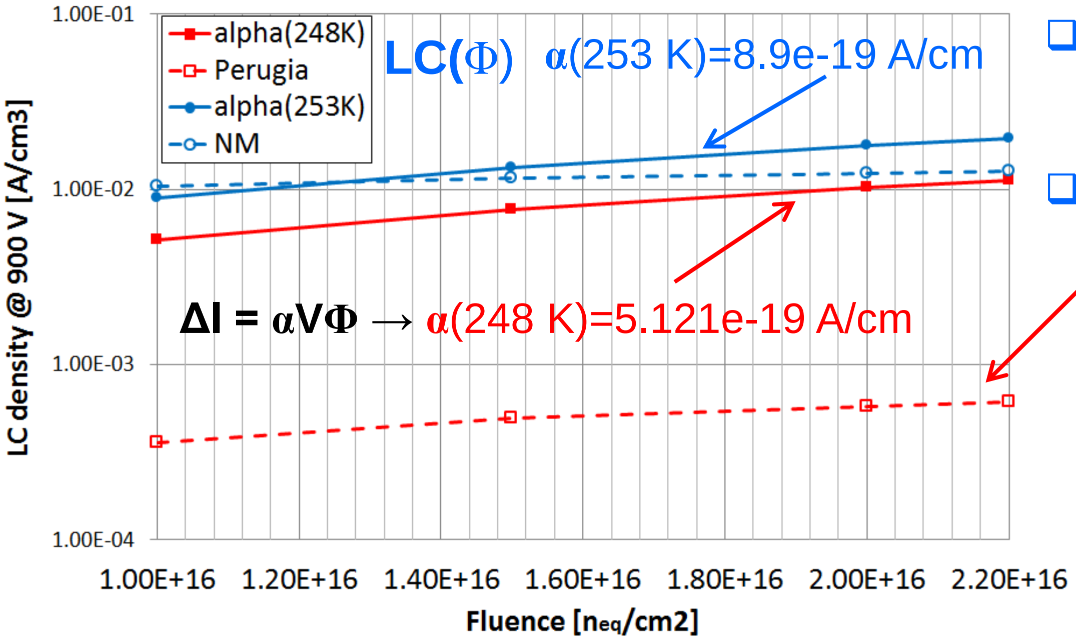
- ☐ **Neutron model:** carrier avalanche @ high E-fields switched on/off
- ☐ Φ = (1 - 2.2)e16 $n_{eq}cm^{-2}$, V = -900 V
- ☐ **n-on-p:** 300 µm thickness

- ☐ **PM:** TTU simulation vs published: ΔCCE=3.7±0.7 %
- ☐ **NM:**
  - Significant ΔCCE when avalanche switched off → NM produces too high E-fields → CM
  - Reverse CCE(Φ) for both cases → too high E-field reduces trapping



[5] D. Passeri, et al., NIM A 824 (2016) 443

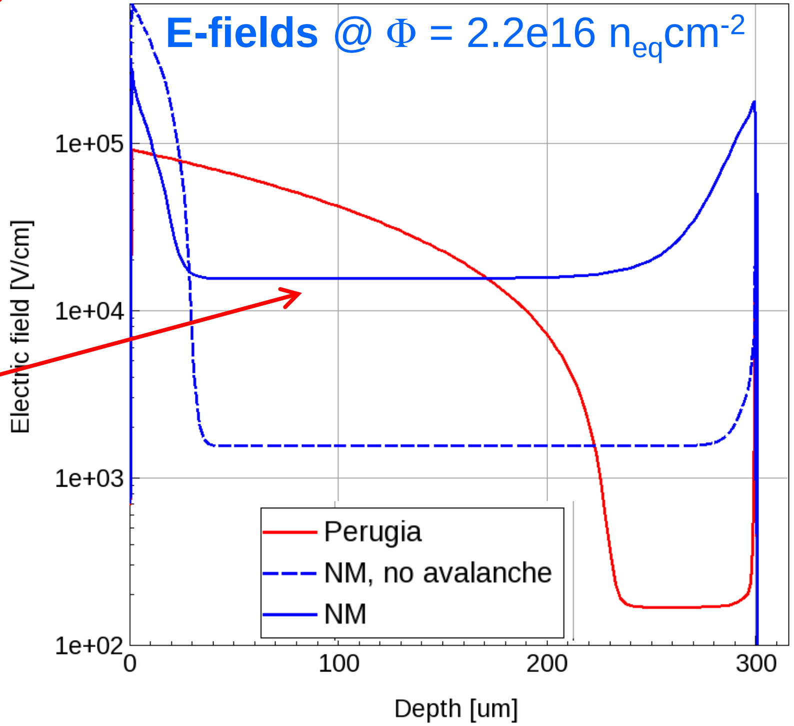
PM vs NM: LC & E-field



LC(Φ) α(253 K)=8.9e-19 A/cm

ΔI = αVΦ → α(248 K)=5.121e-19 A/cm

- **NM (T=253 K):**
  - Φ ≤ 1.5e16 : LC ok
  - Φ = 2.2e16 : 0.65 x expected LC
- **PM (T=248 K):** ~18-fold too low LC



E-fields @ Φ = 2.2e16 $n_{eq}cm^{-2}$

- **Experimental:** Double peak E-field expected
- **NM:** DP ok, too high E-field @ bulk
- **NM, no avalanche:** reduced DP, lower E-field @ bulk
- **PM:** no DP, low E-field @ d > 230 µm

- **Φ_{eq} ≥ 1e16 cm^{-2}:**
  - **PM:** CCE ok, LC & E-field profile not reproduced (deeper levels?)
  - **NM:** ~LC & DP ok, CCE not reproduced (lower trap concentration?)

Summary

- **Sensor technologies:** All sensor types studied for HL-LHC (pad, strip, planar- & 3D-pixels) reproducable by simulation

- **Modelling of radiation damage in Si bulk:** Based on effective midgap levels (DA & DD) → Neutron & proton defect models up to ~1×10^{15} $n_{eq}cm^{-2}$ → Comprehensive set of simulated detector properties matching w/ measurement:
  - **Bulk damage:** E-field distribution (vs measured edge-TCT), LC, V_{fd}, CCE, TCT signal/rise time - reproduced
  - **Surface damage:** Q_f accumulation in alumina-Si interface – combined simulation/measurement study
  - **Bulk & surface damage:** CCE(x), R_{int}, C_{int} – reproduced

- **Extreme Φ defect model:** Study underway for model that reproduces measured/expected CCE, LC & E-field distribution @ $\Phi \geq$ 1e16 $n_{eq}cm^{-2}$

Back-up 1: Defect model overview

Bulk damage

- V. Chiochia et al., [IEEE Trans. Nucl. Sci. NS-52 (2005) 1067]: 2 levels
- M. Petasecca *et al.* [NIM A 563 (2006) 192–195]: 3 levels
- Pennicard et al. [NIM A 592 (2008) 16–25]: 3 levels, increased capture cross-sections σ_n, σ_p
- E. Verbitskaya et al. [JINST 7 C02061, 2012; and NIM A 658 (2011)]: 2 levels, avalanche multiplication, 1D (“analytical”) approach
- R. Eber [PhD Thesis, 2013]: 2 levels

Surface damage

- G. Verzellesi, G. F. Dalla Betta [Nucl. Sci. Symp., 2000 IEEE (Vol.-1)]
- P. Claudio [IEEE Trans. ON Nucl. Sci., VOL. 53, NO. 3 (2006)]
- Y Unno et al., [NIM A 636 (2011) S118–S124]

Bulk & surface damage

- T. Peltola, [JINST 9 C12010, 2014]: 2 levels, +1 level in 2μm at surface
- Delhi University [R. Dalal et al., Vertex - 2014, 23rd RD50 CERN, Nov. 2013]: 2 levels + Q_F + N_{it}.
- D. Passeri, et al., [NIM A 824 (2016) 443-445]: 3 levels

Back-up 2: Electrical properties of point & extended defects relevant to detector operation

Defect Label	Assignment and particularities	Configurations and charge states	Energy levels (eV) & cross sections (cm^2)	Impact on electrical characteristics of Si diodes @ RT
E(30K)	• Not identified extended defect • Donor with energy level in the upper part of the bandgap, strongly generated by irradiation with charged particles. [10,29] • Linear fluence dependence. [this work]	$E(30K)^{0/+}$	E_c-0.1 σ_n = 2.3x10^{-14}	Contributes in full concentration with positive space charge to N_{eff}
BD	*Thermal double donor (TDD2)* - point defect • Bistable donor existing in two configurations (A and B) with energy levels in the upper part of the bandgap, strongly generated in Oxygen rich material. [24, 26, 27]	$BD_A^{0/++}$	E_C - 0.225 σ_n= 2.3 x 10^{-14}	It contributes twice with its full concentration with positive space charge to N_{eff} , in both of the configurations
		$BD_B^{+/++}$	E_C - 0.15 σ_n= 2.7 x 10^{-12}	
I_p	• Not identified point defect • Suggestions: V_2O or a Carbon related center. [22-24, 10] • Amphoteric defect generated via a second order process (quadratic fluence dependence), strongly generated in Oxygen lean material.[22-24, this work]	$I_p^{+/0}$	E_V + 0.23 σ_p= (0.5-9) x10^{-15}	No impact
		$I_p^{0/-}$	E_C - 0.545 σ_n=1.7 x10^{-15} σ_p= 9 x 10^{-14}	Contributes to both N_{eff} and LC
E_{75}	*Tri-vacancy (V_3)* - small cluster • Bistable defect existing in two configurations (FFC and PHR) with acceptor energy levels in the upper part of the bandgap. [10, 28, 30-33] • Linear fluence dependence. [this work]	FFC $V_3^{-/0}$	E_c - 0.075eV σ_n = 3.7x10^{-15}	No impact
E4		PHR $V_3^{=/-}$	E_c - 0.359 σ_n = 2.15x10^{-15}	No impact
E5		PHR $V_3^{-/0}$	E_c - 0.458 σ_n = 2.4x10^{-15} σ_p = 2.15x10^{-13}	Contributes to LC
H(116K)	• Not identified extended defect • Acceptor with energy level in the lower part of the bandgap. [10, 29] • Linear fluence dependence. [this work]	$H(116K)^{0/-}$	E_V + 0.33 σ_p=4 x 10^{-14}	Contributes in full concentration with negative space charge to N_{eff}
H(140K)	• Not identified extended defect • Acceptor with energy level in the lower part of the bandgap. [10, 29] • Linear fluence dependence. [this work]	$H(140K)^{0/-}$	E_V + 0.36 σ_p=2.5 x 10^{-15}	Contributes in full concentration with negative space charge to N_{eff}
H(152K)	• Not identified extended defect • Acceptor with energy level in the lower part of the bandgap. [10, 29] • Linear fluence dependence. [this work]	$H(152K)^{0/-}$	E_V + 0.42 σ_p=2.3 x 10^{-14}	Contributes in full concentration with negative space charge to N_{eff}

- ❑ Consistent set of defects observed after p, π, n, γ and e irradiation

[R.Radu et al., J. Appl. Phys. **117**, 164503, 2015]

Back-up 3: Defect Characterization Overview

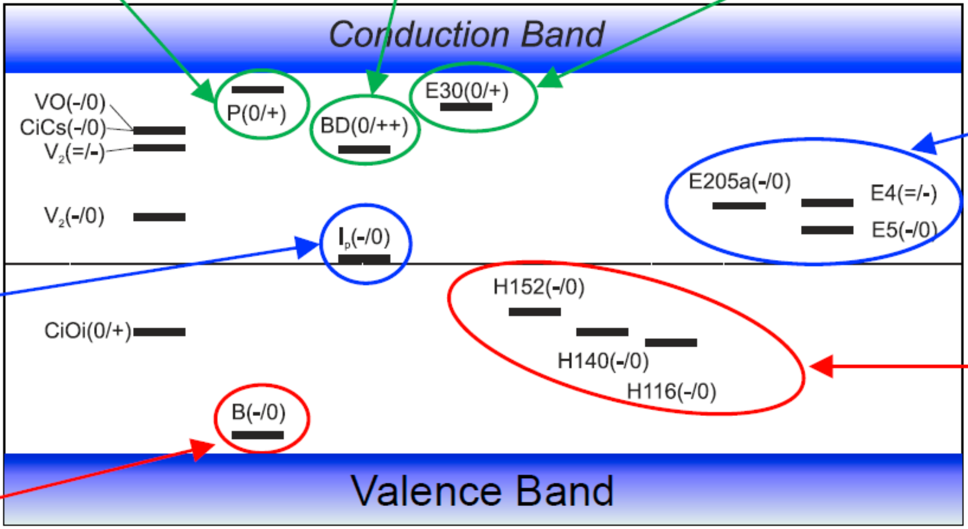
Pintilie et al, NIM A **514**, 18 (2003) & NIM A **556**, (1), 197 (2006);
E. Fretwurst et al, NIM A **583**, 58 (2007)

Phosphorus: shallow dopant
(positive charge)

positive charge
(higher introduction after proton than after neutron irradiation, oxygen dependent)

positive charge
(higher introduction after proton irradiation than after neutron irradiation)

R. M. Fleming, et al Appl. Phys. Lett. **90**, 172105 (2007);
V. P. Markevich, et al Phys. Rev. B **80**, 235207 (2009);
A. Junkes et al, Nucl. Instr. and Meth. A **525**, 612 (2010)



I. Pintilie et al, Appl.Phys. Lett. **82**, 2169 (2003)

leakage current & neg. charge
current after γ irrad, V_2O (?)

Leakage current

E4/E5: $V_3^{(=/-)}$, $V_3^{(-/0)}$

Reverse annealing
(negative charge)

Boron: shallow dopant
(negative charge)

I. Pintilie et al, Appl. Phys. Lett. **92**, 024101 (2008)

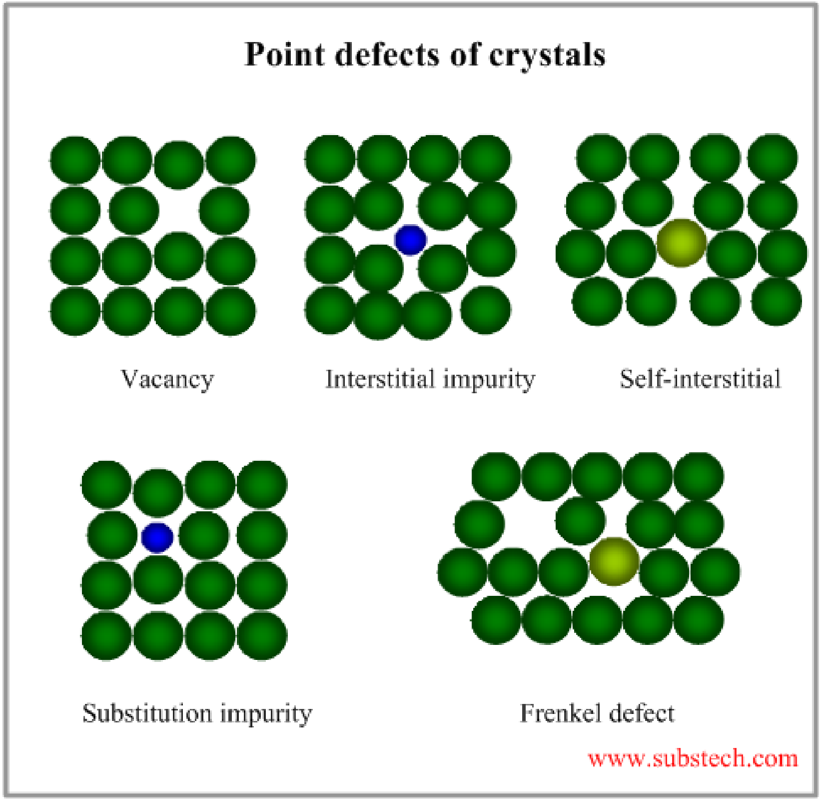
A table with levels and cross sections is given in the Annex (spare slides).

[M. Moll, VERTEX 2013]

- **Trapping:** Indications that E205a and H152K (midgap levels) are important
- Consistent set of defects observed after p, π, n, γ and e irradiation
- Understanding of defect properties/macroscopic effects is essential for the implementation of defect simulation

Back-up 4: Defects in silicon: Overlook

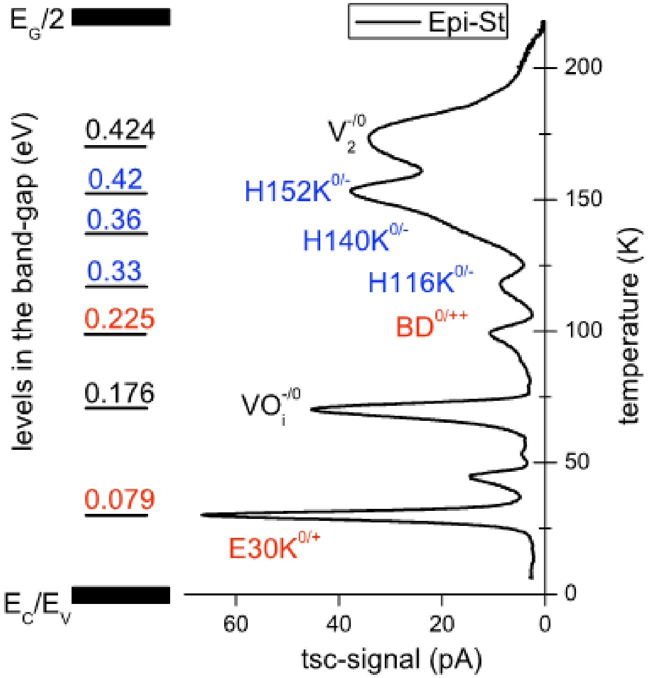
- ☐ **Each defect:** Energy level in Si bandgap or variety, depending on conglomeration of defects
- ☐ Multitude of E-levels, cross sections & concentrations: huge parameter space to model



[R. Eber, 8th Detector Workshop, Berlin, 2015]

- ☐ 11 defect levels proved to influence performance of irradiated Si detectors (see back-up 2-3) → **Effective model is needed for simulation**

Energy levels from Thermally Stimulated Current (TSC) measurement

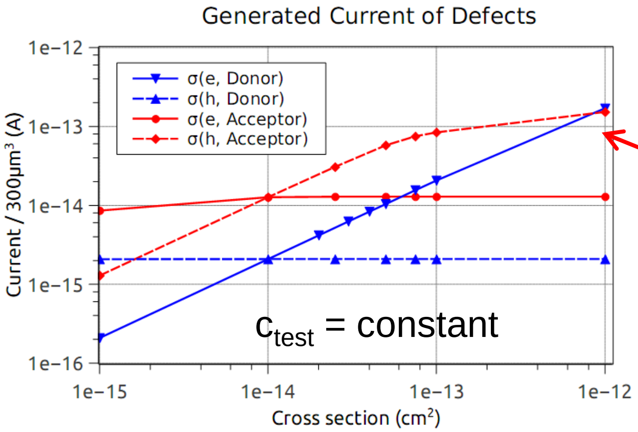


H defects: [I. Pintilie et al., Appl. Phys. Lett. **92**, 024101 (2008)]
BD: [I. Pintilie et al., NIM A **514**, 18 (2003)] & [I. Pintilie et al., NIM A **556**, (1), 197 (2006)] & [E. Fretwurst et al., NIM A **583**, 58 (2007)]
E30: [I. Pintilie et al., NIM A **611**, 52-68 (2009)]

Back-up 5: TCAD - Bulk defect models

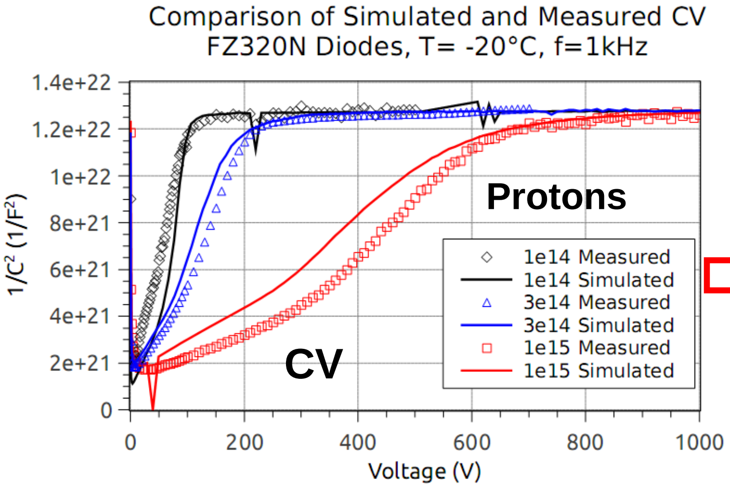
❑ **Parametrization of current generated by cross sections of each defect at a defined concentration**:

- 1st constraint given by V_{fd} → set a ratio of donors to acceptors to match → tune the current again → repeat until match with measured CV, IV → **Result:** Trap concentration(c_{test}, σ_{test}, α) for given Φ → c(Φ) by linear fit

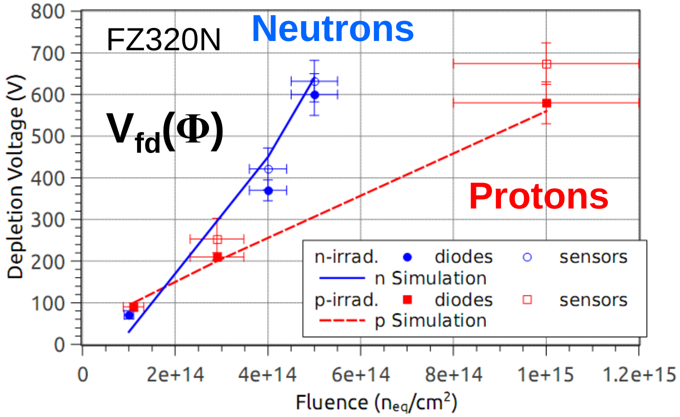


Current essentially from σ of one charge type

[R. Eber, 8th Detector Workshop, Berlin, 2015]



Proton model



Neutron model

Defect type	**Level** [eV]	**σ_e** [cm^2]	**σ_h** [cm^2]	**Concentration** [cm^{-3}]
Deep acc.	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

Defect type	**Level** [eV]	**σ_e** [cm^2]	**σ_h** [cm^2]	**Concentration** [cm^{-3}]
Deep acc.	E_C - 0.525	1.2e-14	1.2e-14	1.55*Φ
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*Φ

❑ **Sentaurus defect models for Φ_{eq} =1e14 ~ 1e15 cm^{-2} @ T=253 K**

[R. Eber, PhD Thesis, KIT, 2013]

Back-up 6: DP & LC for neutron & proton defect models

- 300 µm thick p-on-n pad detector @ T=253 K

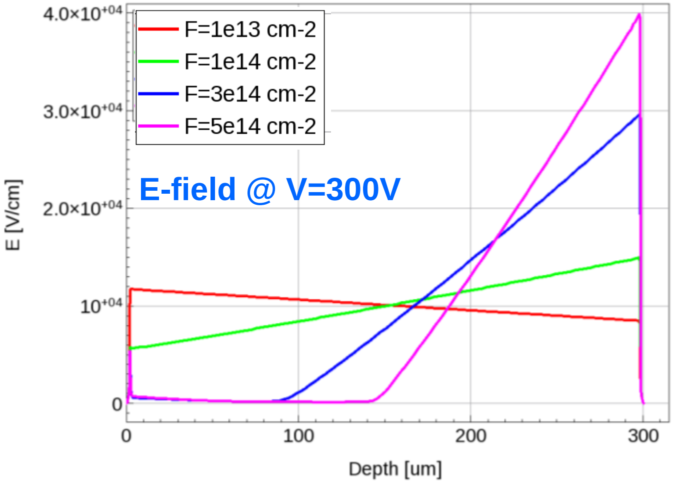
- **Fluences :**
Φ = 1e13 – 5e14 n_{eq} cm^{-2}

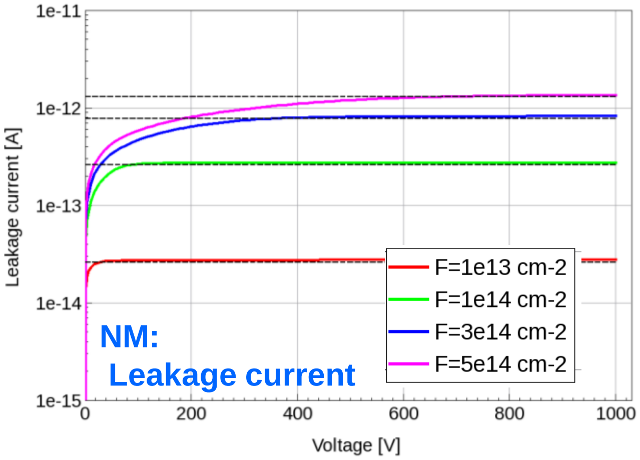
- DP is produced by both models (more pronounced in PM due to higher trap concentration for given Φ)

- **Dashed black lines:** experimental LC by
$\Delta I = \mathrm{Volume} \cdot \alpha \cdot \Phi$,
$\alpha(253K) \approx 8.9 \cdot 10^{-19}$ A·cm^{-1}

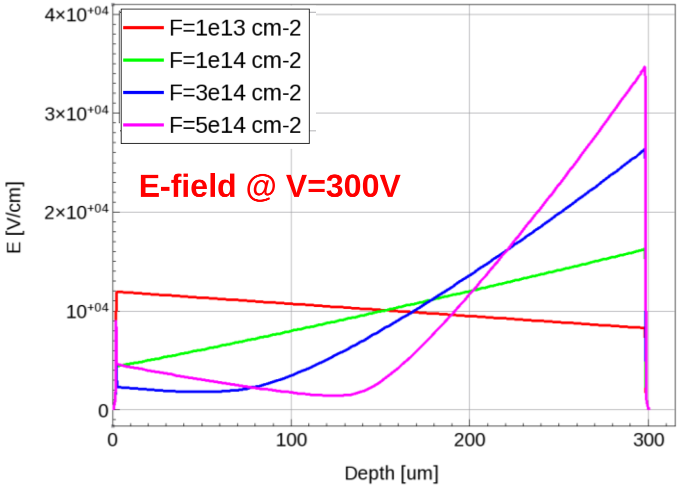
- LC has perfect match with experimental values

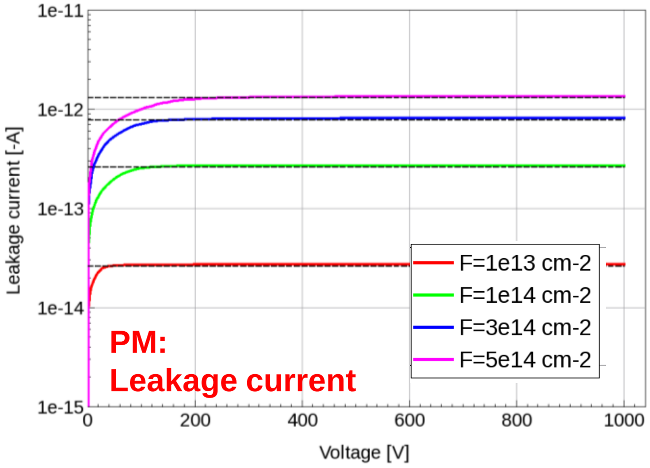
NEUTRON MODEL (NM)





PROTON MODEL (PM)

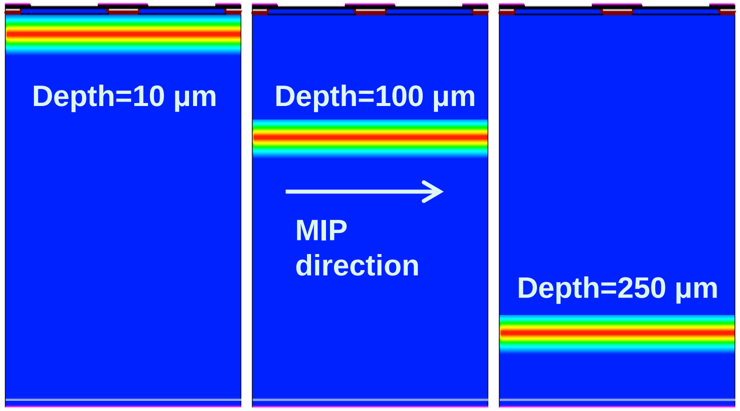


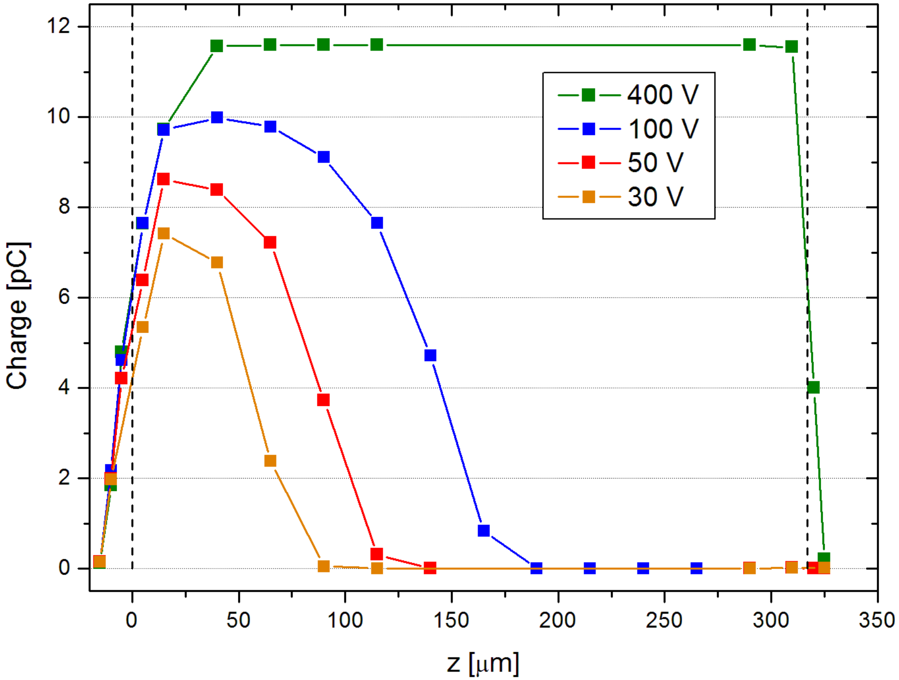


Back-up 7: Method for simulated edge-TCT

☐ **Experimental:** Extract E-field from drift velocity v_{drift} using eTCT → provides measurement of collection time $t_c \propto v_{drift}$

Principal of edge-TCT simulation:



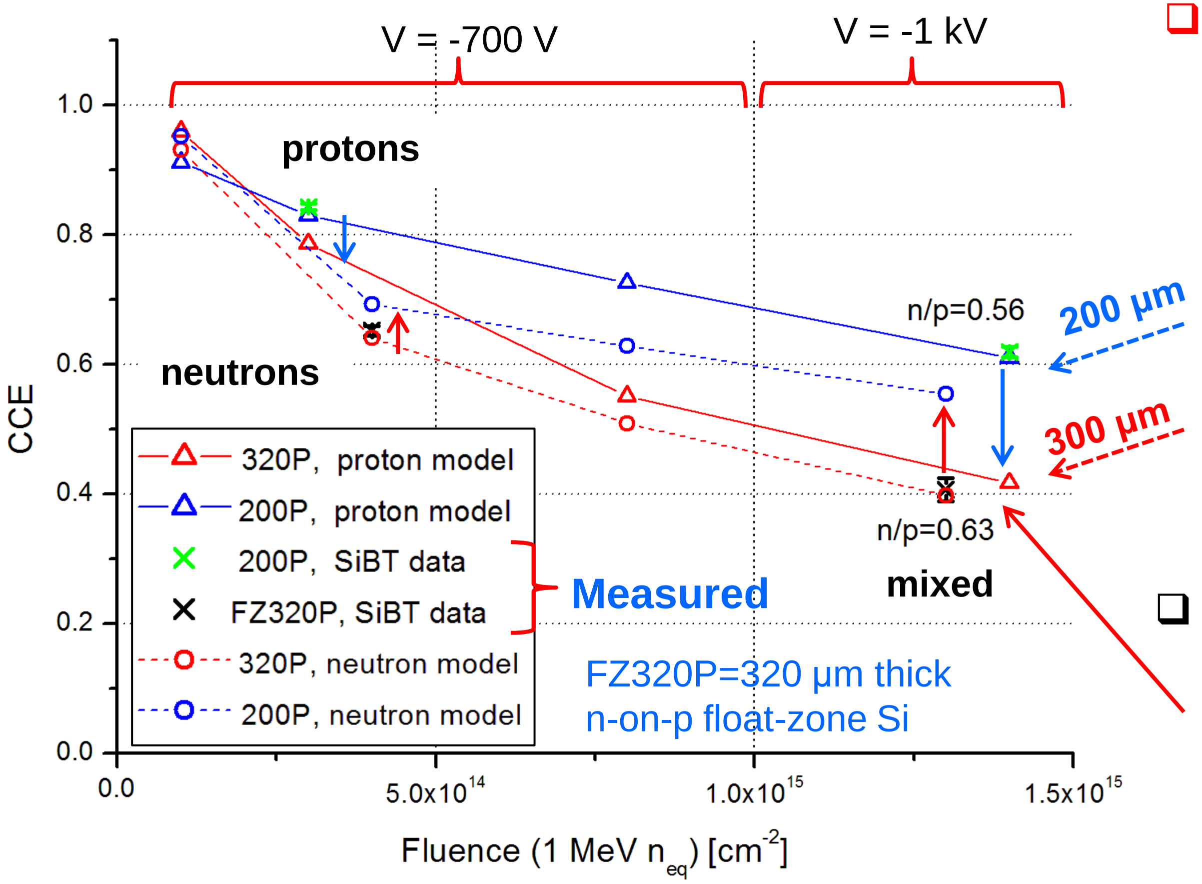


- ☐ TCAD simulated edge-TCT collected charges Q(z) for non-irradiated 320 µm p-on-n strip detector @ $V<V_{fd}$ & $V>V_{fd}$, T = 293 K
- ☐ **Dashed vertical lines:** Active region of detector (defined from center of rising & descending slopes of Q(z) distribution) → Different E-field extensions into bulk from pn-junction at z=0 are reflected by Q(z)
- ☐ **Differences in Q(z) amplitude:** Reproduced by using laterally extended device structure → extension of E-field to detector edges

Back-up 8: CCE & Trapping: Strips

- ☐ **Measured CCE:** n-on-p strip sensors in CMS test beam

Simulated CCE for 2-trap models with tuned Q_f



FZ320P=320 µm thick
n-on-p float-zone Si

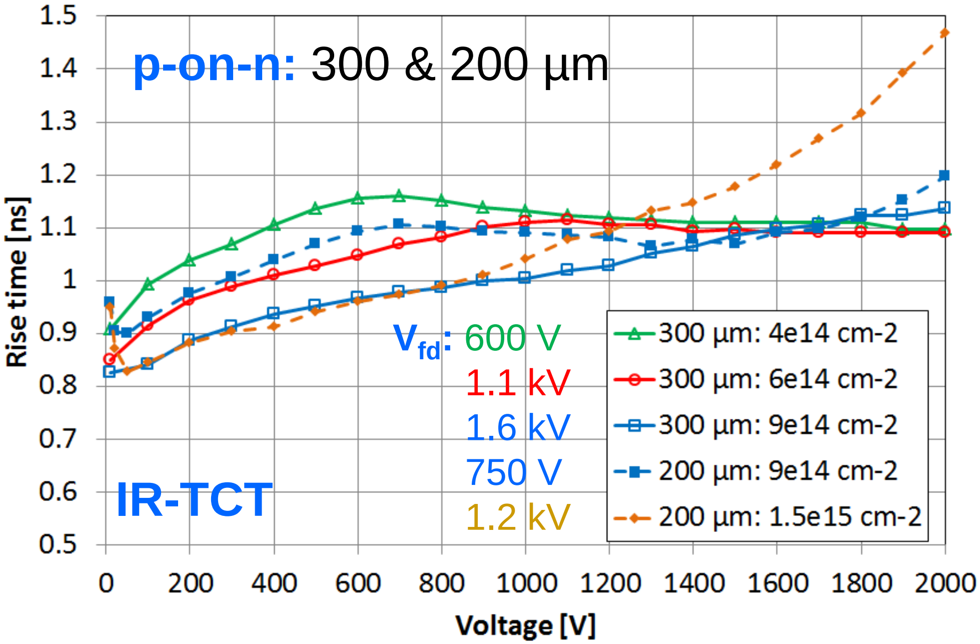
[T.Peltola, PSD10, Sept. 2014, T. Peltola, JINST 9 (2014) C12010]

- ☐ **Red/black:** Tuned Q_f to reproduce measured CCE/Extra-/interpolated Q_f

Φ_{eq} [cm^{-2}]	$Q_f(n)$ [cm^{-2}]	$Q_f(p)$ [cm^{-2}]
1e14	6e10	1.4e11
3e14	-	3e11
4e14	9e10	-
8e14	3.25e11	7.1e11
1.3e15	6e11	-
1.4e15	-	1.2e12

- ☐ Measured CCE of 300 & 200 µm strips reproduced by simulation → Fixed Q_f to predict CCE of unmeasured detectors w/ equal irradiation type/dose to measured

Back-up 9: Signal rise t: Simulated p-on-n/n-on-p



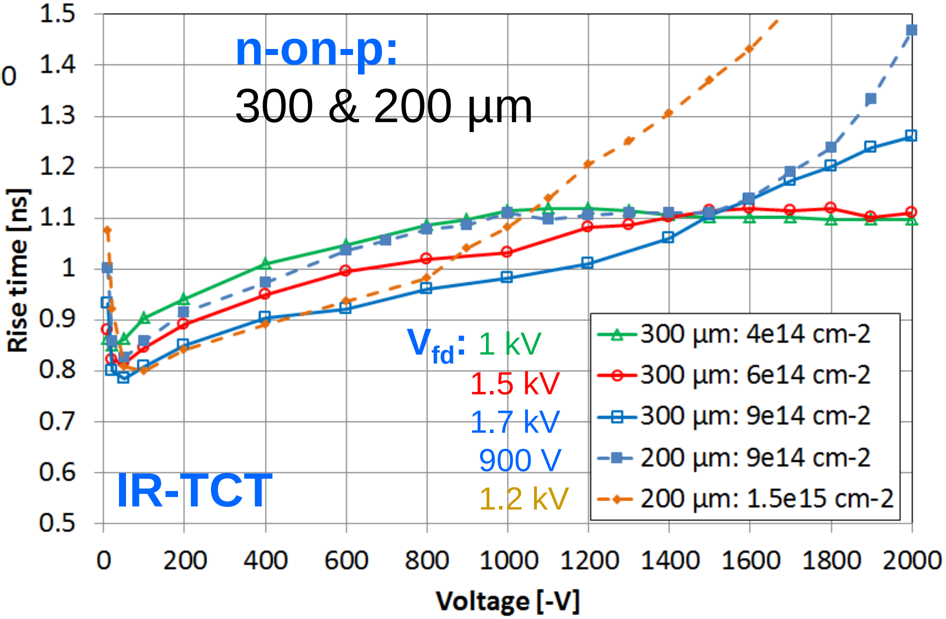
☐ t_r increases w/ V until full depletion

☐ Smallest depletion depth → shortest t_r

→ 300 µm n-on-p has shorter t_r up to 1 kV for all fluences

☐ **$\Phi \geq$ 9e14 $n_{eq}cm^{-2}$:** t_r increases after V_{fd} due to reduced trapping @ high E-field

- **HV:** Charge multiplication

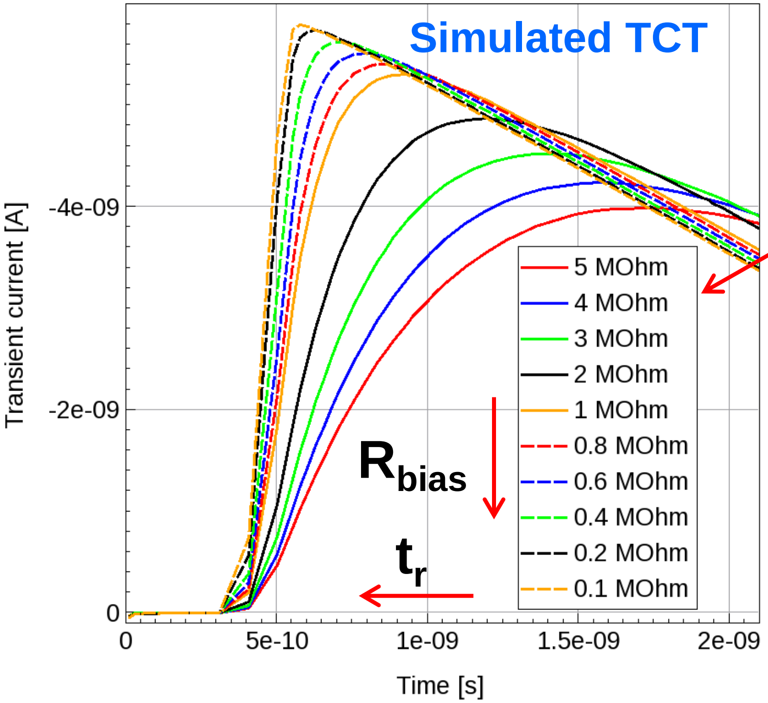


☐ **Φ = 9e14 $n_{eq}cm^{-2}$, V≤1 kV:** 200 µm has higher t_r for both sensor types

☐ t_r reduces with R_{bias} → tune R_{bias} in ~MΩ range to maintain position information

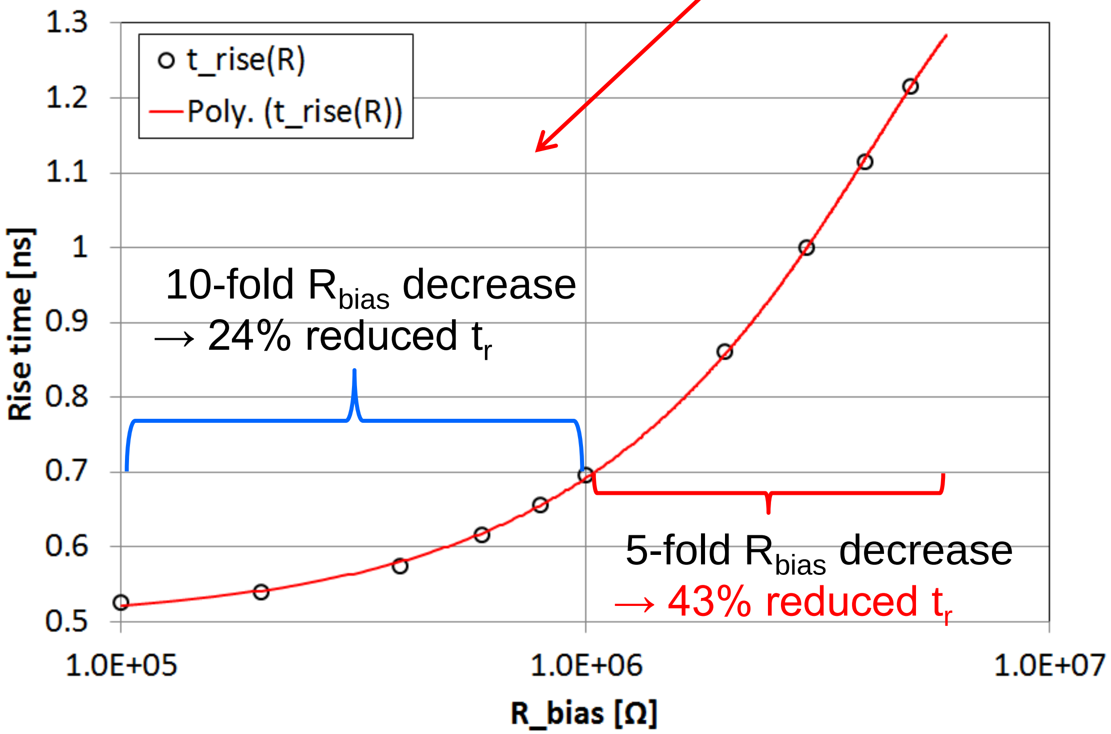
☐ 5-fold R_{bias} decrease → 43% reduced t_r (back-up 8)

Back-up 10: Signal rise t: Optimization



- **R_{bias}=5 MΩ:** Simulation reproduces measured transient signal for $\Phi = 0$
- t_r reduces with R_{bias} → tune R_{bias} in ~MΩ range to maintain position information

- R_{bias}(5 MΩ → 100 kΩ): t_r reduced by 57%



10-fold R_{bias} decrease → 24% reduced t_r

5-fold R_{bias} decrease → 43% reduced t_r

- **t_r(R_{bias}):** Perfect fit from 2nd order polynomial

Back-up 11: C_{int}: N_{int} 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

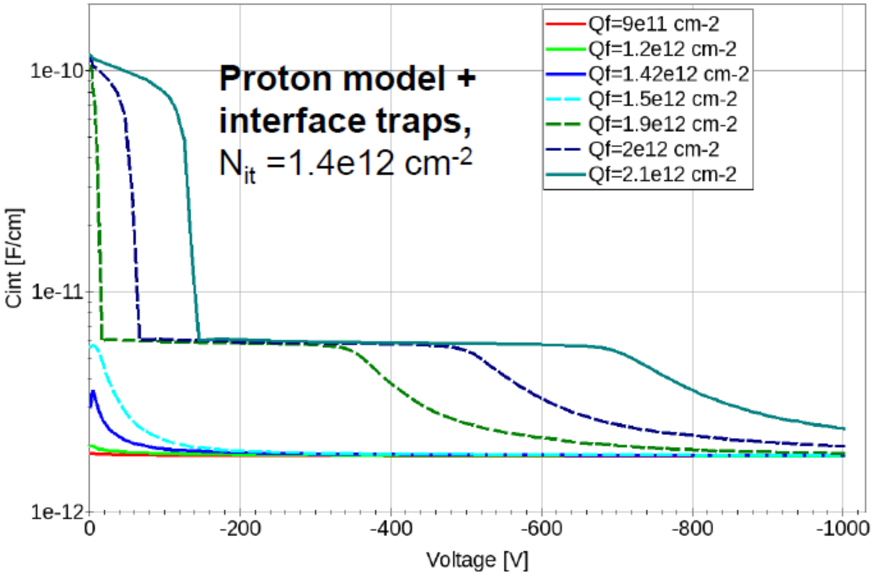
❑ **3-level model @ 2 μm from surface:**

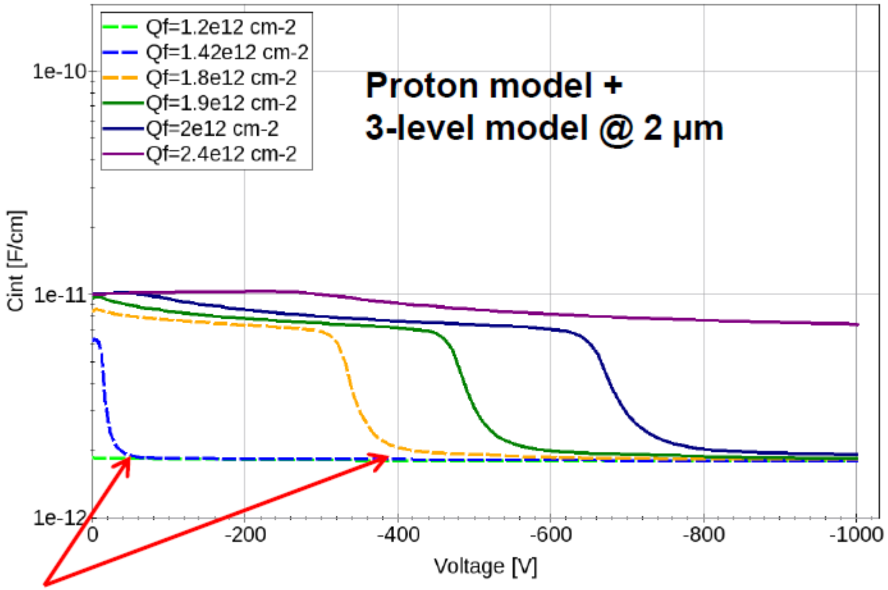
- Geometrical value ~1.8 pF/cm reached within 0-400 V when CCE loss matches measurement

❑ **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

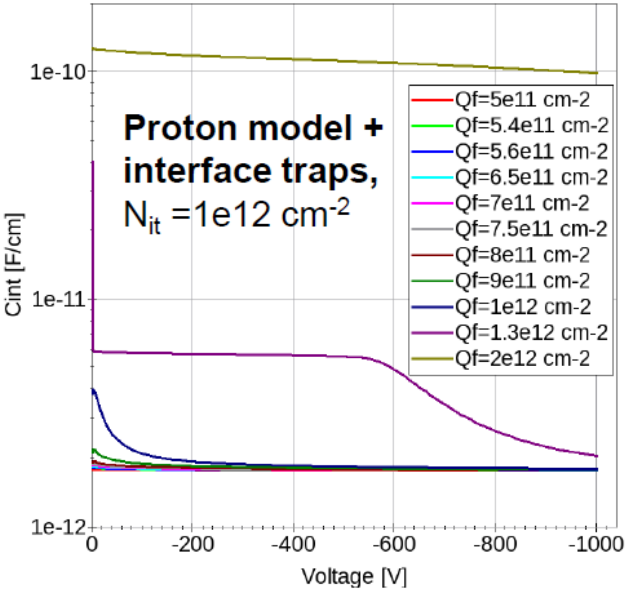


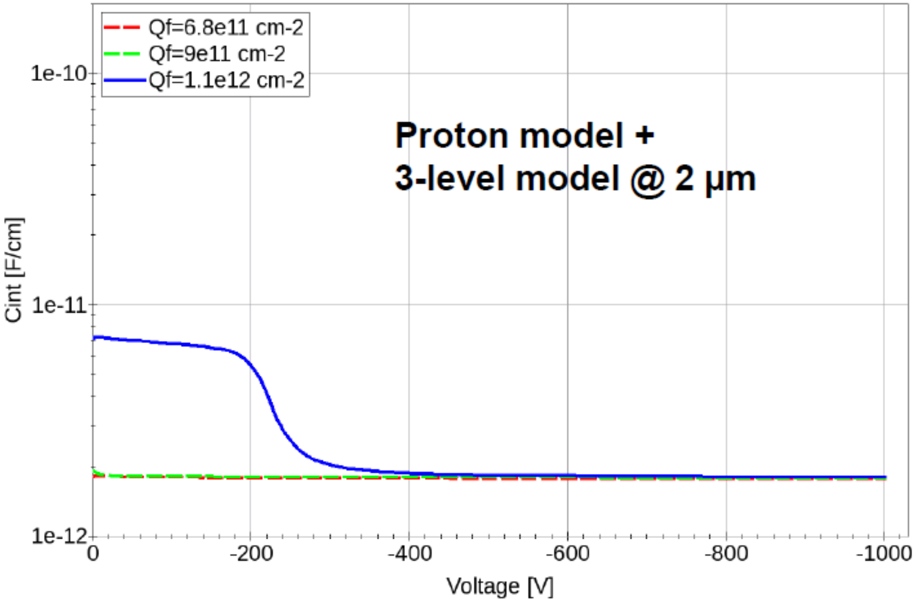


Higher Q_f → higher V needed to reach geometrical C_{int}

Back-up 12: C_{int}: N_{int} 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





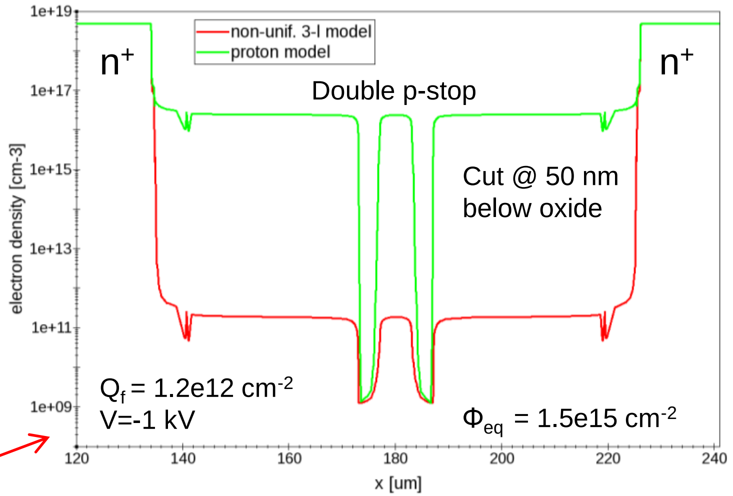
Conclusion from slides 7-10: Deeper distribution of shallow acceptors reproduces measured CCE loss between strips & C_{int} more closely

Back-up 13: Non-unif. 3-level model R_{int} & C_{int}

- Non-unif. 3-level model can be tuned to equal bulk properties (TCT, V_{fd} & I_{leak}) with proton model → suitable tool to investigate CCE(x)
- 3-level model within 2 µm of device surface + proton model in the bulk: R_{int} & C_{int} in line with measurement also at high fluence & Q_f

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 acc.	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 acc.	E_C - 0.40	8e-15	2e-14	40*Φ



n^+ n^+

Double p-stop

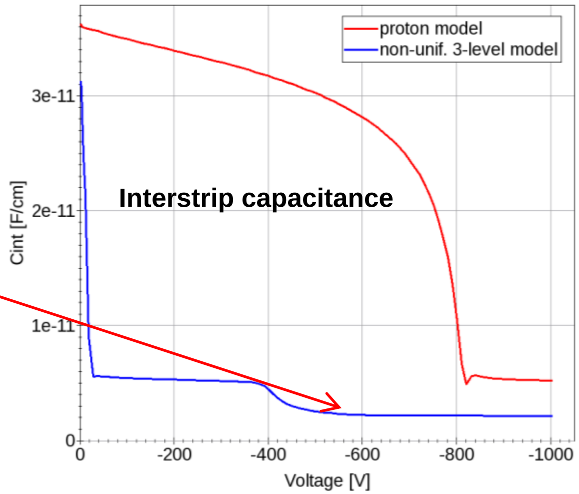
Cut @ 50 nm below oxide

Q_f = 1.2e12 cm^{-2}
V=-1 kV

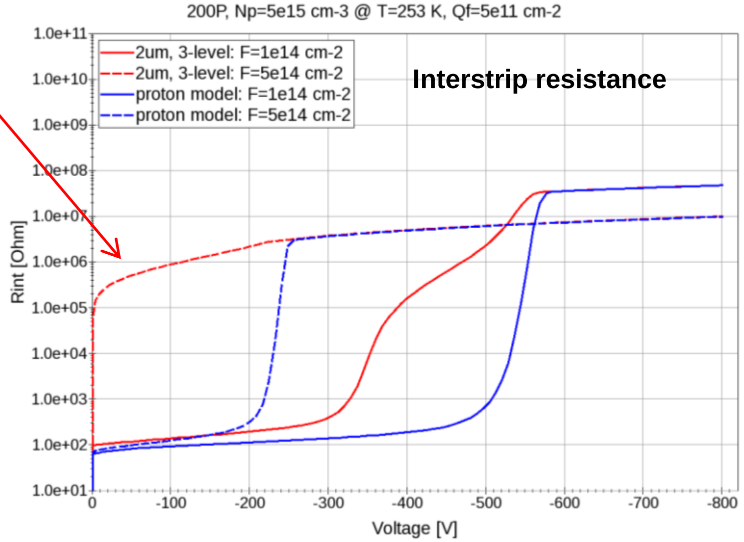
Φ_{eq} = 1.5e15 cm^{-2}

- Effect of acceptor traps in non-unif. 3-l. model is clearly visible: O(5) lower electron density to proton model between strips
- Strips are isolated at V=0 for Φ_{eq}=5e14 cm^{-2} as in real detectors

- Φ_{eq} =1.5e15 cm^{-2} & Q_f =1.2e12 cm^{-2}: C_{int} at geometrical level ~2 pF/cm (pitch=80 µm)



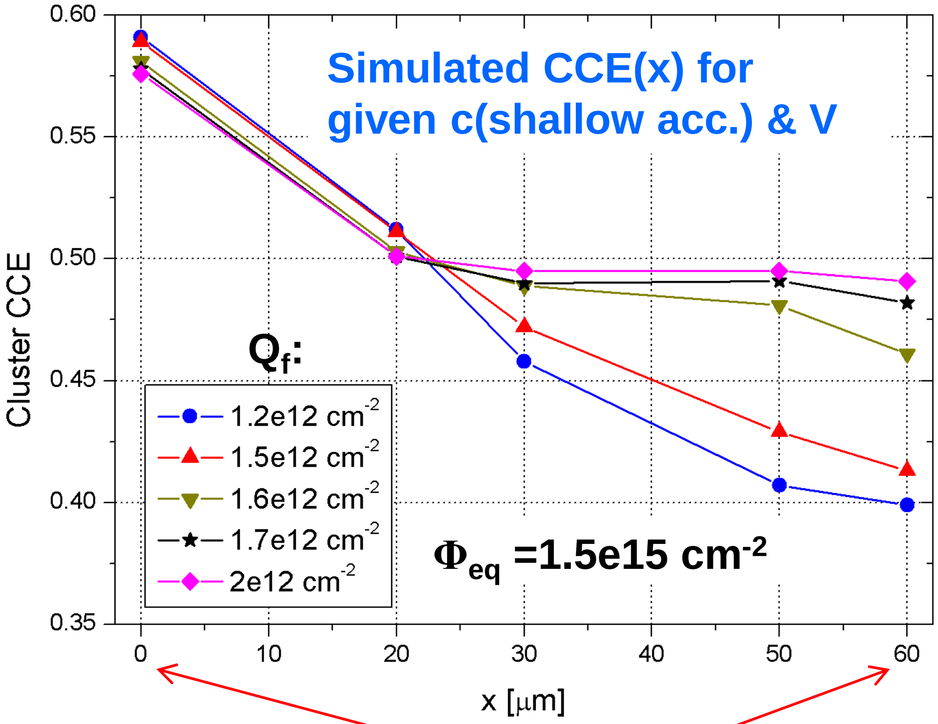
Interstrip capacitance



Interstrip resistance

Back-up 14: Bulk & surface damage: CCE(x)

☐ **Heavily irradiated strip detectors demonstrate significant position dependency of CCE [CCE(x)]**



CCE loss

16%

17%

20%

29%

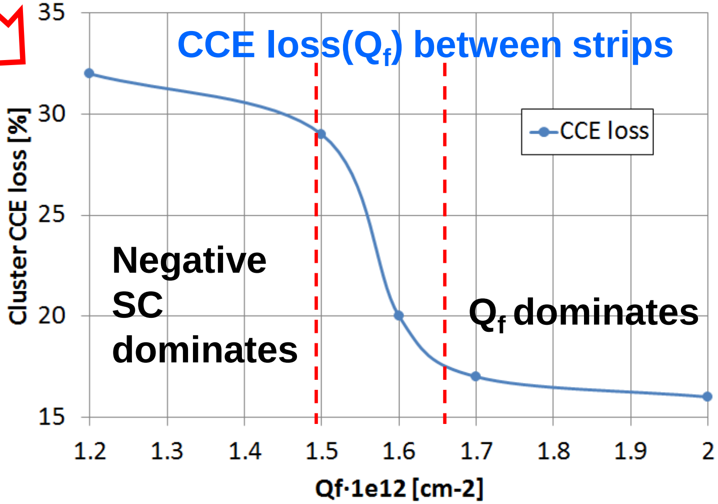
32%

☐ **Non-uniform 3-level model:**

N_{it} cannot be used: measured C_{int} not reproduced (back-up 11-12) → need deeper distribution

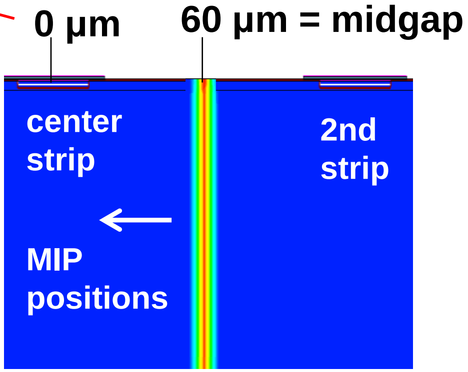
→ **3-level model within 2 μm of device surface + proton model in bulk:**

○ R_{int} & C_{int} in line w/ measured also @ high Φ & Q_f (back-up 13)



Strips isolated:
Cluster CCE decreases towards midgap

Strips shorted:
Cluster CCE independent of position



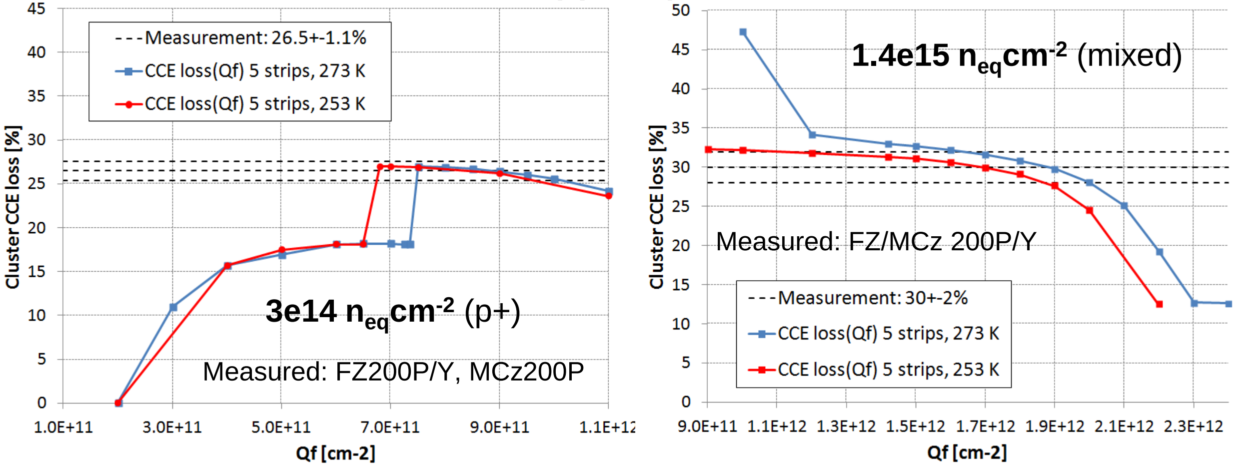
[T. Peltola, JINST 9 (2014) C12010 & T. Peltola et al., JINST 10 (2015) C04025]

Back-up 15: Measured & simulated CCE(x)

- ❑ **3-level model within 2 µm of device surface + proton model in bulk:**
  - R_{int} & C_{int} in line with measured also at high fluence & Q_f
  - Tunable to equal bulk properties (TCT, V_{fd} & LC) with proton model

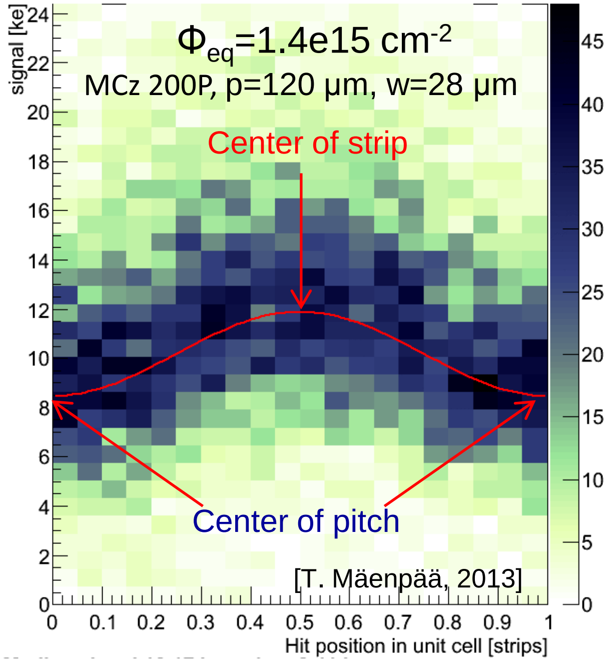
→ suitable tool to investigate CCE(x)

[T. Peltola, PSD10, 2014] **Simulated CCE(x) compared to measured:**



$Q_f=(8.5\pm1.0)\times10^{11}$ cm^{-2} $Q_f=(1.6\pm0.2)\times10^{12}$ cm^{-2}

❑ **Observation**: Heavily irradiated strip detectors demonstrate significant position dependency of CCE



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

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

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