RD50

VERTEX2015: The 24th International Workshop on Vertex Detectors, Santa Fe, 1-5 June 2015

HELSINKI INSTITUTE OF PHYSICS

Simulation of radiation-induced defects

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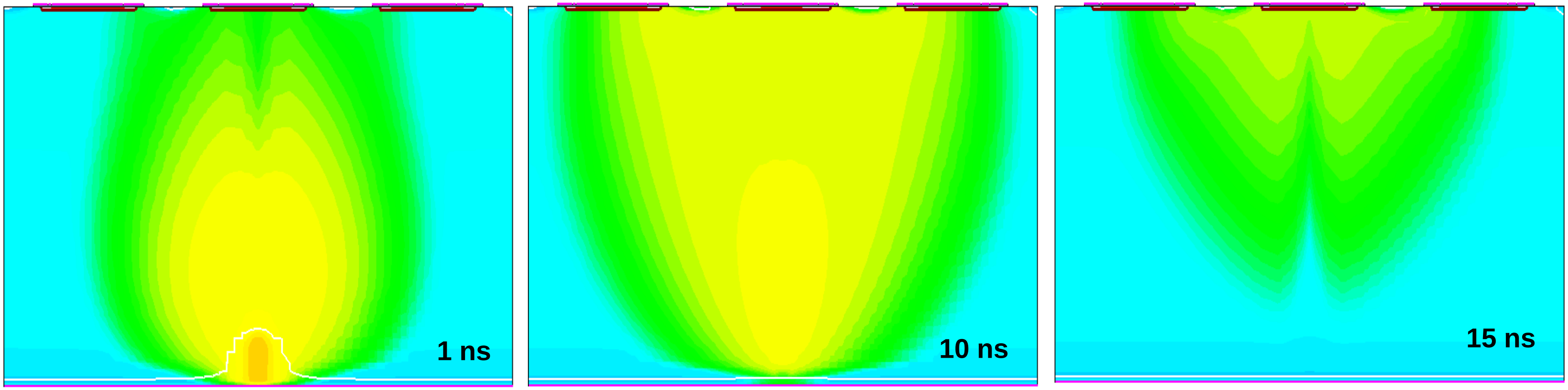

Outline

❑ **Motivation**

❑ **Radiation induced defects**

❑ **Simulated defects**

  - Implementation: From PTI to TCAD models
  - Bulk damage
  - …and surface damage

❑ **Summary**

❑ **Work in progress/future efforts**

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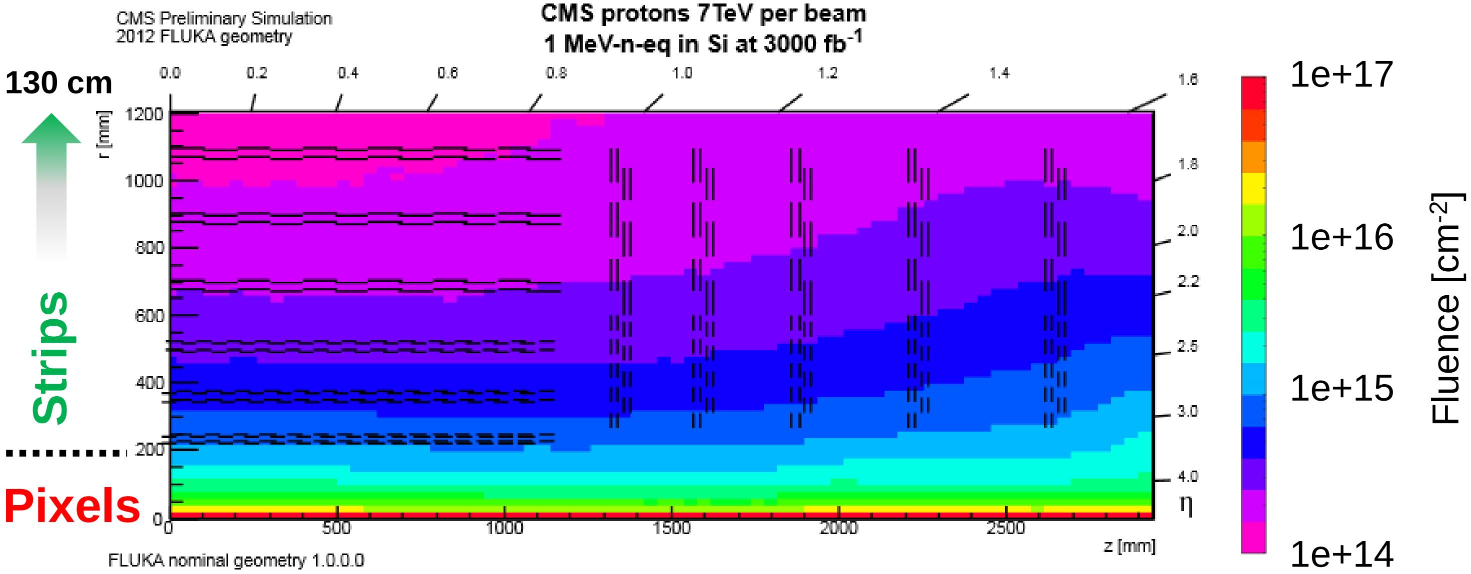
Motivation I: HL-LHC

❑ **Upgrade:** LHC → High Luminosity LHC (HL-LHC)
  - Expected ∫L = 3000 fb^{-1} after 10 years of operation
  - Pseudorapidity coverage from η = 2.5 → 4

❑ **Challenges for tracker:**
- Higher radiation hardness
- High occupancy → higher granularity
- Reduce material budget → thin sensors (~200 μm)

Estimated fluences in CMS Tracker at HL-LHC after 10 years of operation



Silicon detectors will be exposed to hadron fluences more than 10^{16} n_{eq} cm^{-2}
→ beyond the performance level of detectors used currently at LHC

RD50 mission: development of silicon sensors for HL-LHC

Radiation induced defects

RD50 **Radiation damage in silicon:** Defect Parameters

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

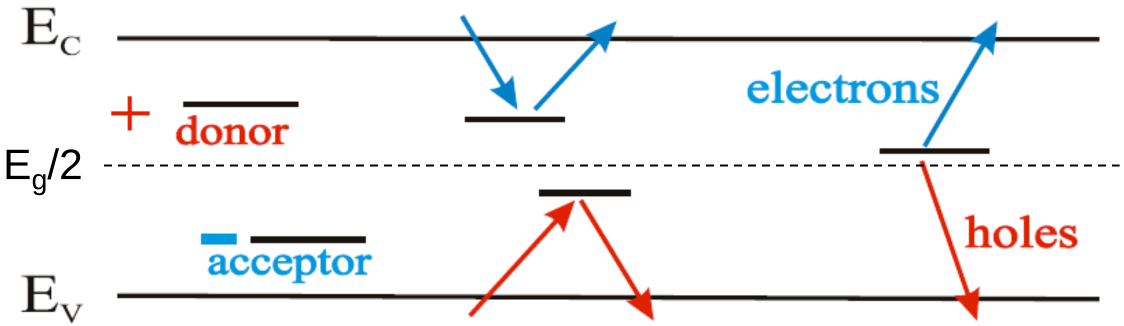
☐ Both bulk & surface damage affect the detector performance:

- **Bulk damage:** Introduces deep acceptor and donor type trap levels
- **Surface damage:** Positively charged layer accumulated inside SiO_2

→ affect to sensor performance through the SiO_2/Si interface

☐ Defect parameters:
type : acceptor, donor,…
E_a : activation energy
$\sigma_{n,p}$: capture cross section
N_t : concentration

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]

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)	$\eta_2 \cdot \Phi + c_2$

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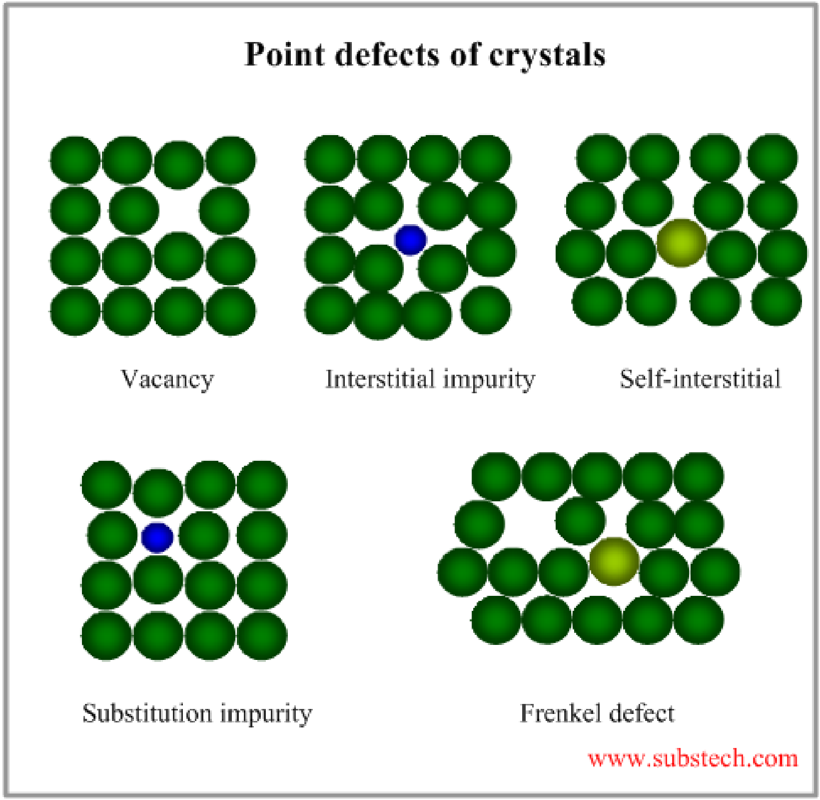
Defects in silicon

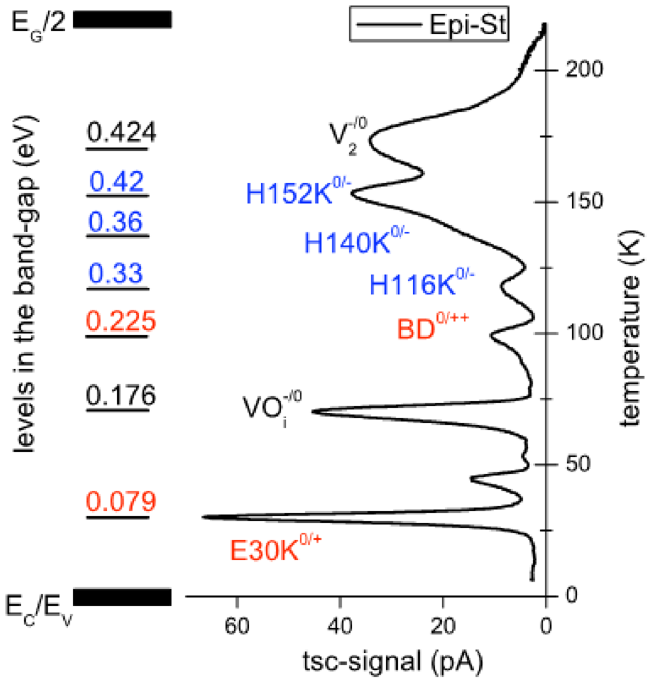
- Each defect has an energy level in Si bandgap or a variety, depending on the conglomeration of defects
- Multitude of energy levels, cross sections & concentrations: huge parameter space to model!



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

- 11 defect levels proved to influence the 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)]

Simulated defects: Implementation

RD50 **PTI model:** E-field distribution in irradiated detectors

Principle for irradiated detectors simulation

- **On basis of minimized set:** microscopic parameters of irradiated Si to reproduce the detector performance at certain operational conditions
- **2 midgap energy levels DD and DA applied to reconstruct & predict:**
  Bulk generated current + E(x) + trapping

Parameterization for custom made software

[V. Eremin, 20th RD50 Workshop, 2012]

- Parameters for **pronounced Double Peak (DP) effect** (not corresponding to correct description of other detector properties):

Trapping of free carriers from detector reverse current to midgap energy levels of radiation induced defects leads to DP E(x)

Bulk generated current calculated from single level PTI model

Type of defect	**Level** [eV]	$\sigma_{e,h}$ [cm^2]	**Introduction rate** [cm^{-1}]
Deep acceptor (DA)	E_C - 0.525	1e-15	1
Deep donor (DD)	E_V + 0.48	1e-15	1
Current generating level	E_C - 0.65	1e-13	1

V. Eremin, E. Verbitskaya, Z. Li. "The Origin of Double Peak Electric Field Distribution in Heavily Irradiated Silicon Detectors", NIM A 476 (2002) 556.

[V. Eremin, RD50 SWG meeting, March 2013]

RD50 **PTI model:** Simulated E-field in irradiated detector

PTI 1D simulations:

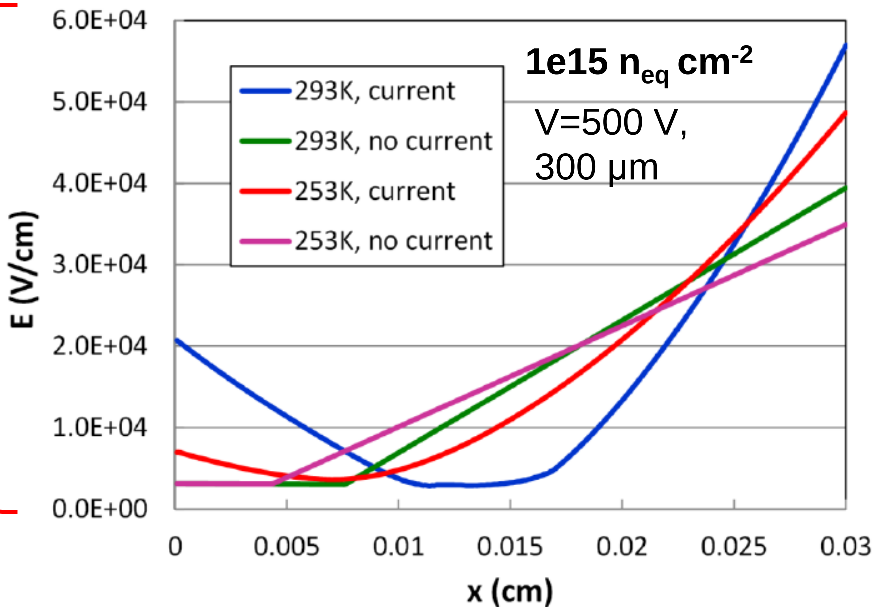
- ❑ *E(x)* profile formation in irradiated Si detector described as:

Carrier generation + trapping to midgap DDs and DAs

❑ **TCAD:** Not possible to introduce exclusively current by adding PTI trap E = E_C - 0.65eV (current governed in non-irradiated device by SRH, Auger & radiative recombination)

Alternative approach:
Generation may be considered via carrier lifetime

[V. Eremin, RD50 SWG meeting, March 2013]



[E. Verbitskaya, RD50 SWG meeting, March 2013]

Can trapping be explained in the frame of 2-DL model?

❑ **Estimations:**

- β = 5e-7 $s^{-1}cm^2$ and fluence Φ = 1e14 cm^{-2} → trapping time τ = 20 ns
- trapping cross-section σ = 1e-14 cm^2
- thermal velocity V_{th} = 2e7 cm/s

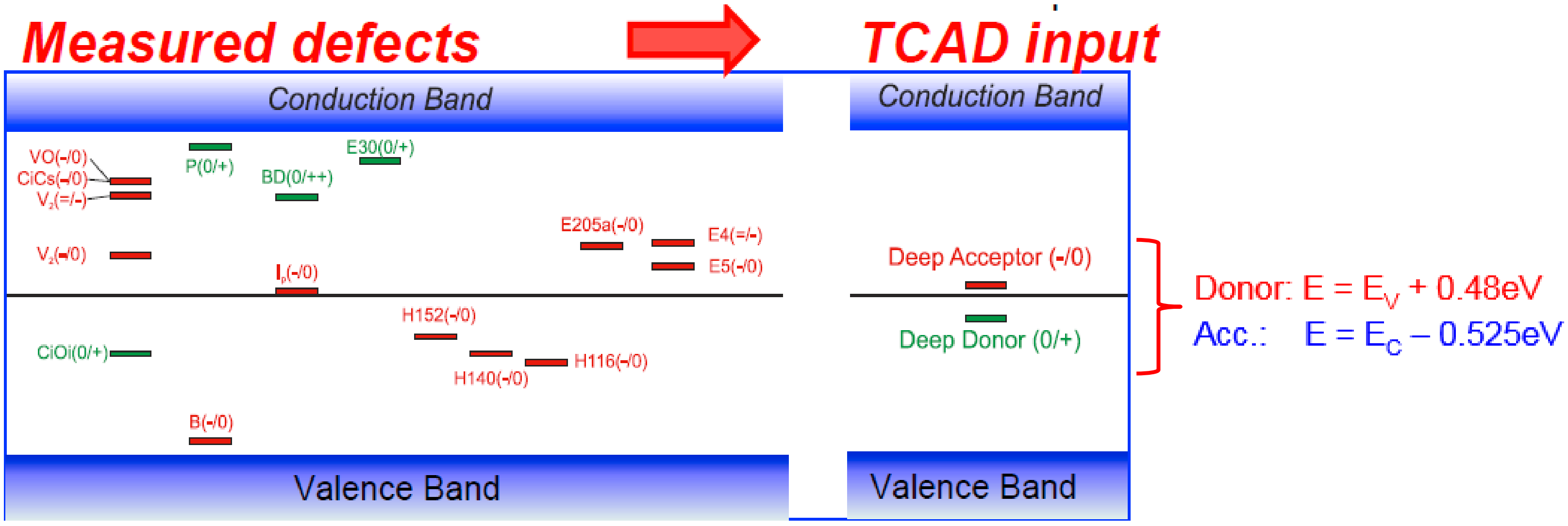
→ $N_t = 1/[\sigma V_{th}\tau]$ = 2.5e14 cm^{-3} or intro rate $\eta(N_t) = 2.5$

- From PTI bulk generated current parameterization:
  - ○ η(DA) = 1.6
  - ○ η(DD) = 0.8

$\eta(N_t)$, η(DA) & η(DD) have equal range
→ **2-DL model has a chance to be extended to CCE(Φ)**

Defect simulations: TCAD

- ❑ **Why 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 ‘weird’ results
  - ▪ Predictions for novel structures & conditions → device structure optimization in 2D/3D
- ❑ **Applied frameworks:** Synopsys Sentaurus & Silvaco ATLAS TCAD tools
- ❑ **Working with ‘effective levels’ for simulation of irradiated devices**
  - ○ **Bulk damage:** approximated by 2 deep levels from PTI model
  - ○ **Surface damage:** Fixed charge density Q_f placed at SiO_2/Si interface w/ interface traps N_{it} of varying depth distributions
  - ○ **Defect concentrations & cross sections tuned to match experimental data**



Donor: $E = E_V + 0.48eV$
Acc.: $E = E_C - 0.525eV$

[M. Moll, VERTEX 2013]

Simulated defects:
Bulk damage

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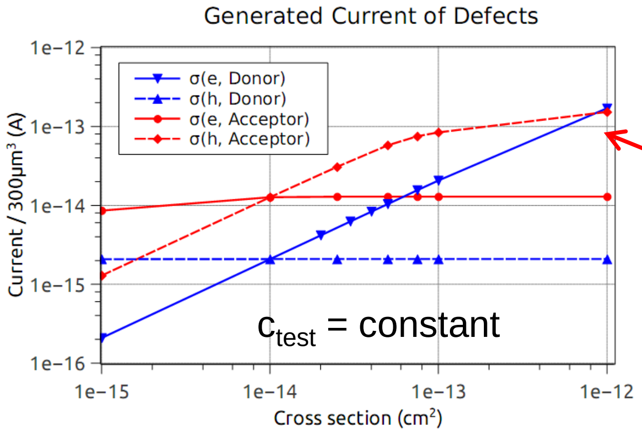
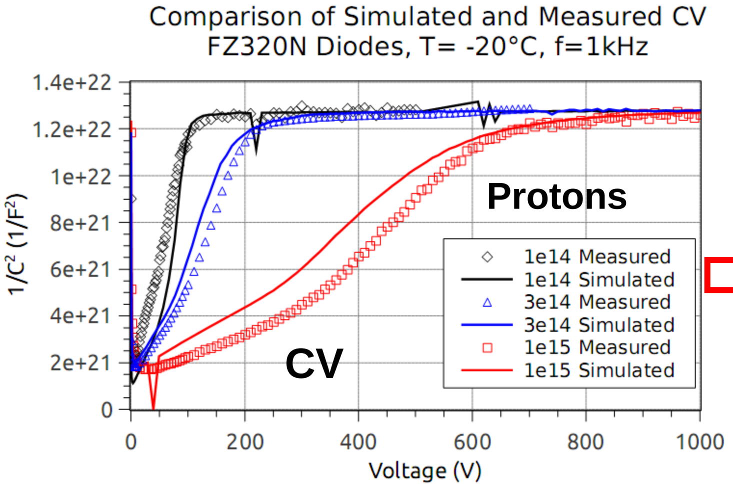
Sentaurus TCAD: Bulk defect models

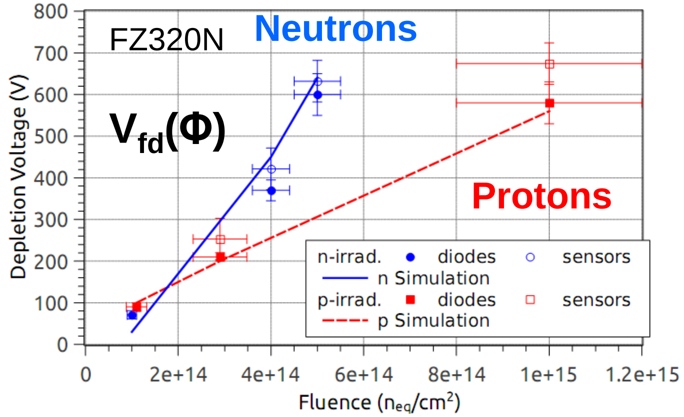
- ❑ **Parametrization of current generated by cross sections of each defect at a defined concentration**:
  - 1st constraint given by V_{fd} → set a ratio of donors to acceptors to match → tune the current again → repeat until match with measured CV, IV → **Result:** Trap concentration(c_{test}, σ_{test},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



Current essentially from σ of one charge carrier type

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





Proton model

Type of defect	Level [eV]	σ_e [cm²]	σ_h [cm²]	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

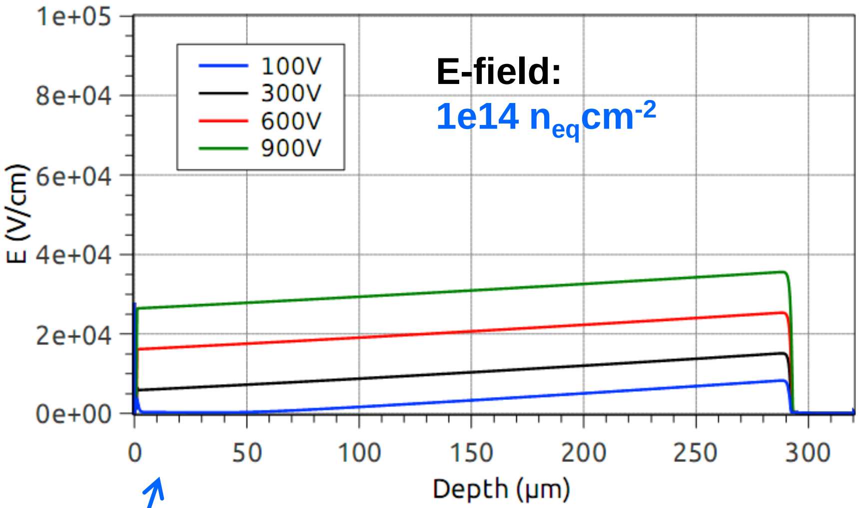
Neutron model

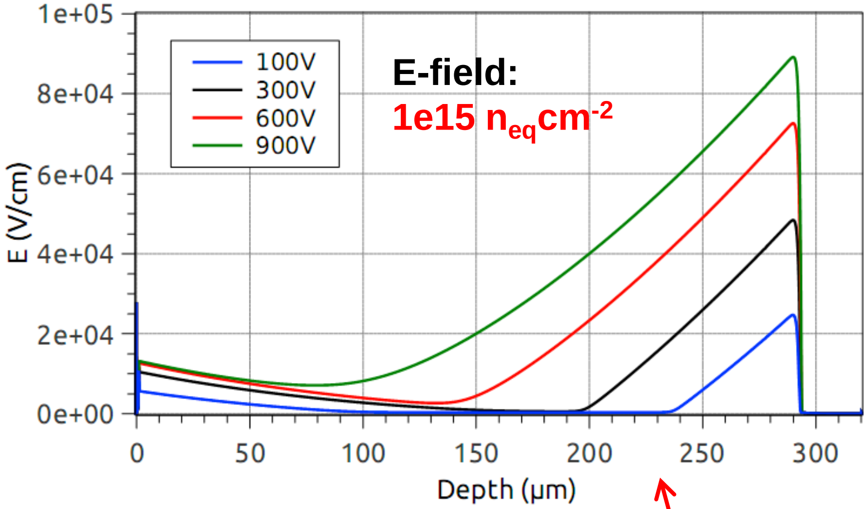
Type of defect	Level [eV]	σ_e [cm²]	σ_h [cm²]	Concentration [cm⁻³]
Deep acceptor	E_C - 0.525	1.2e-14	1.2e-14	1.55*Φ
Deep donor	E_V + 0.48	1.2e-14	1.2e-14	1.395*Φ

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

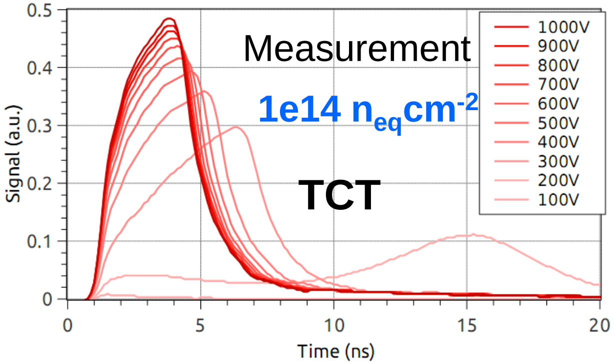
- ❑ **Sentaurus defect models for Φ_{eq} =1e14 ~ 1.4e15 cm^{-2} @ T=253 K**

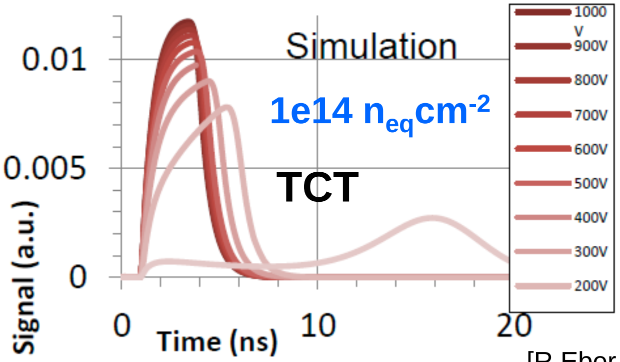
Proton model: From TCT to E-field

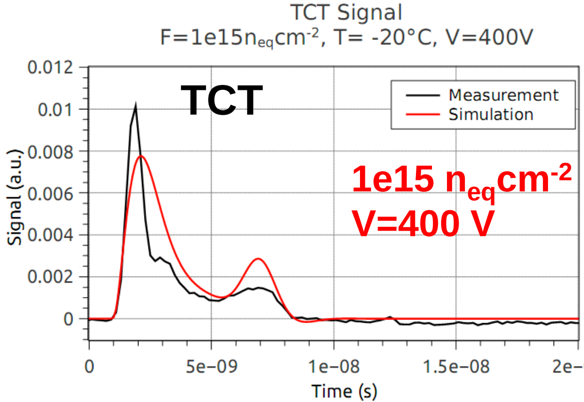




- ❑ Double peak E-field simulated by matching TCT pulses (DP & LC: back-up 4)
- ❑ Carrier drift in double peak E-field produces DP in TCT
- ❑ **Matching TCT signals w/ measured:** basic requirement for reliable CCE simulations







[R.Eber, 22nd RD50 Workshop, June 2013]

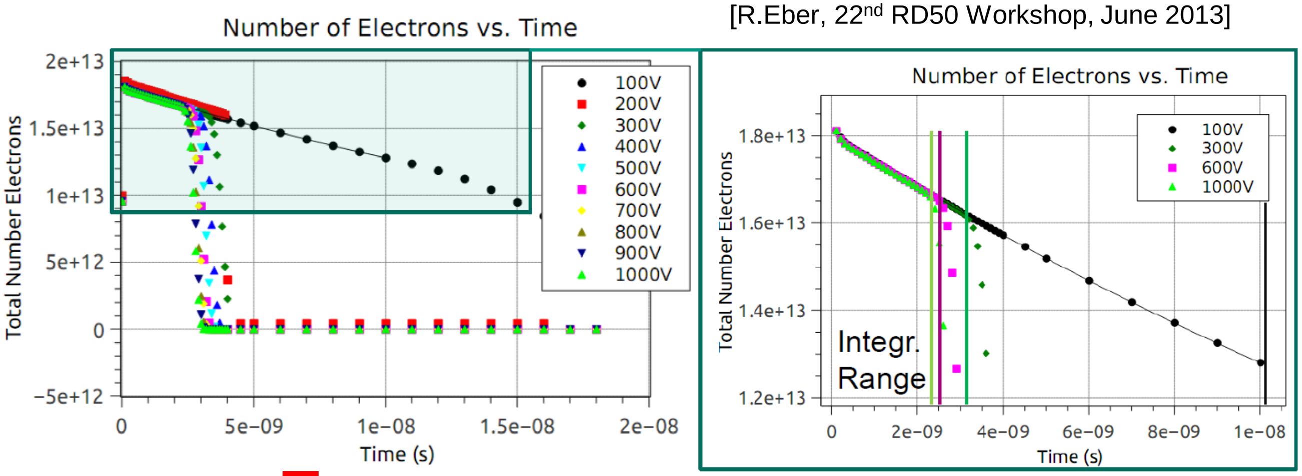
Proton model: Trapping time

Electrons in the device:

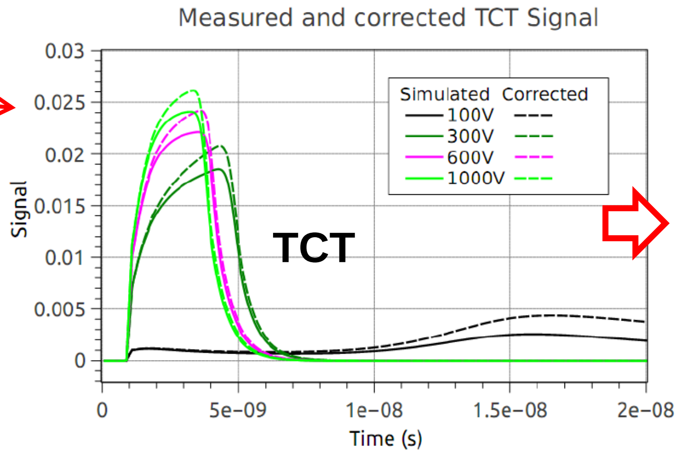
- ❑ Integration of electron density at each t → total # of electrons
- ❑ **Simple approach:** fit linear decay with trapping time τ
- ❑ Mean τ(1e14 cm^{-2}) ≈ **28.5 ns**

$$n_e = n_{e0} \times \exp(-\frac{t-t_0}{\tau})$$

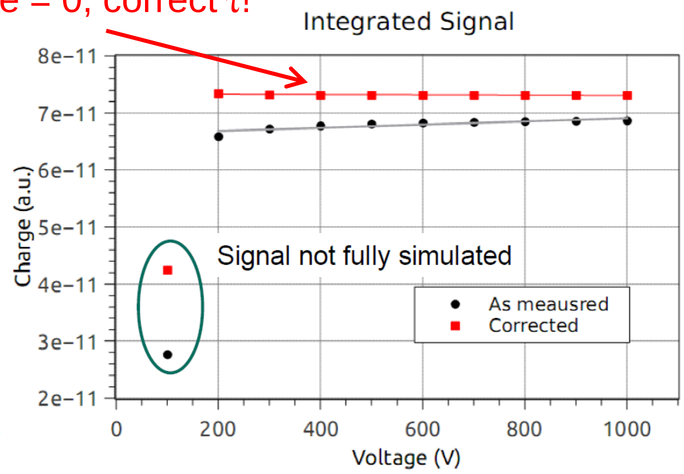
[R.Eber, 22nd RD50 Workshop, June 2013]



- ❑ Signal corrected by trapping time



Slope = 0, correct τ!



- ❑ **τ ≈ 28.5 ns is in the range also found in the literature:**

(τ ~25 ns @ 1e14 n_{eq}cm^{-2} e.g. by G.Kramberger et al., NIMA 476, 645 and NIMA 481, 297)

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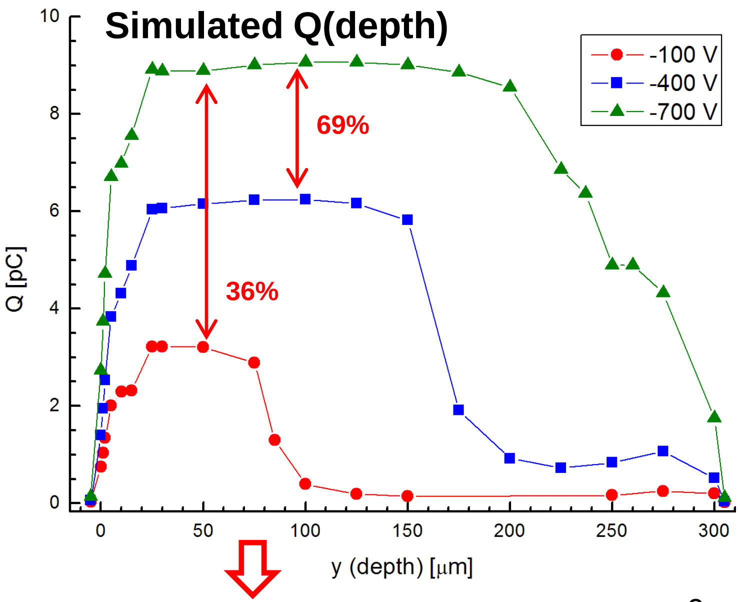
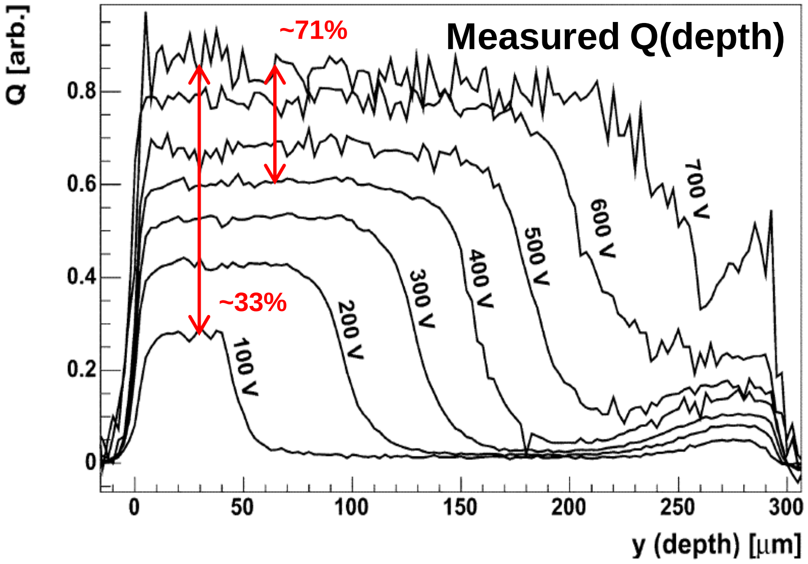
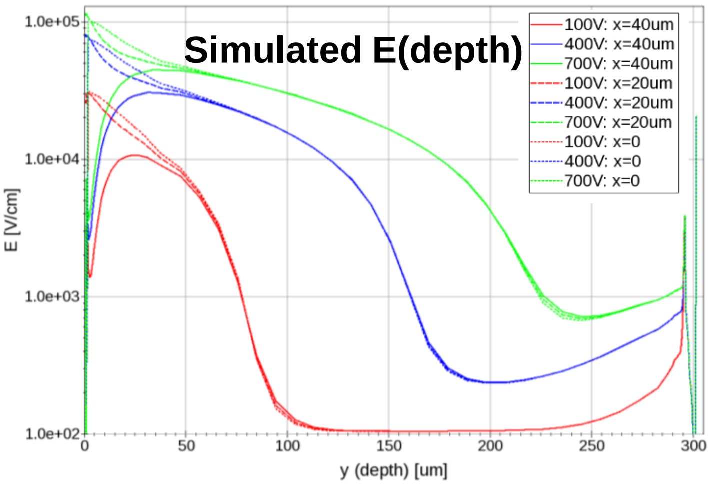
Edge-TCT: Neutron irradiated strip detector



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





x=0:
center
of strip

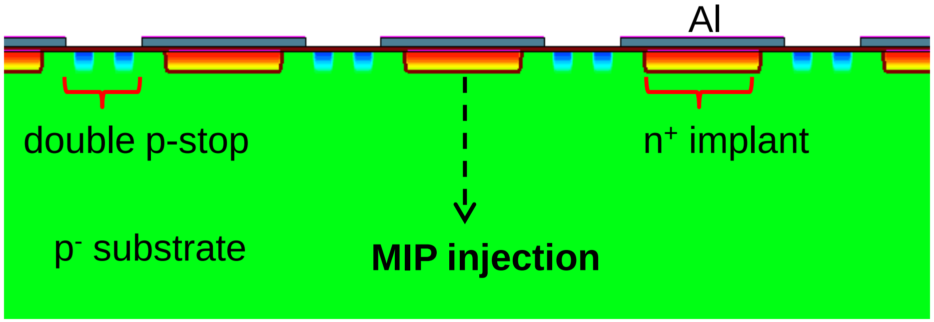
300P strip sensor, Φ_{eq}(n)=5e14 cm^{-2}, Q_f=1e11 cm^{-2}, w_{ps}=20 μm, w_{impl}=20 μm, pitch=80 μm

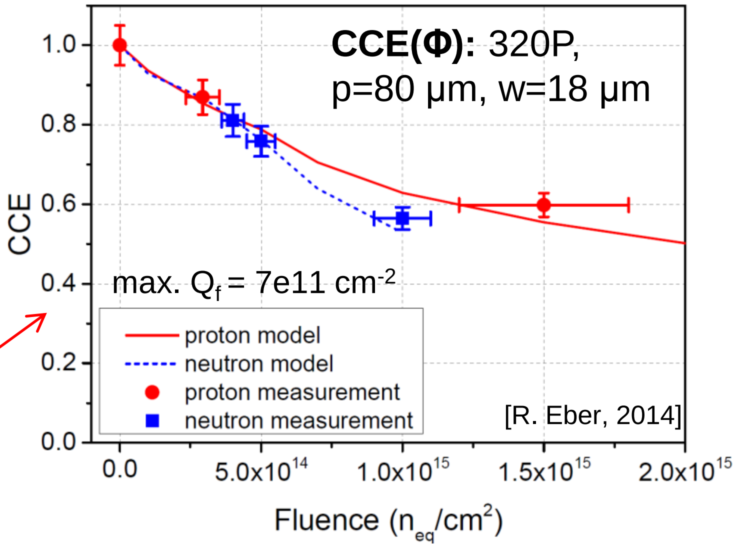
- ☐ **Experimental goal:** extract E-field from drift velocity using edge-TCT
- ☐ Measured amplitudes reproduced by simulation (see back-up 5 for method)
- ☐ Simulated depletion depth ~10-30 μm deeper at lower V → accuracy increases with voltage
- ☐ **Simulation gives reliable estimation of E(depth)**

[T. Peltola, 23rd RD50 Workshop, 2013]

CCE & Trapping I

Simulated n-on-p strip detector front surface (not to scale)





❑ **Simulated CCE:** close agreement with measurement

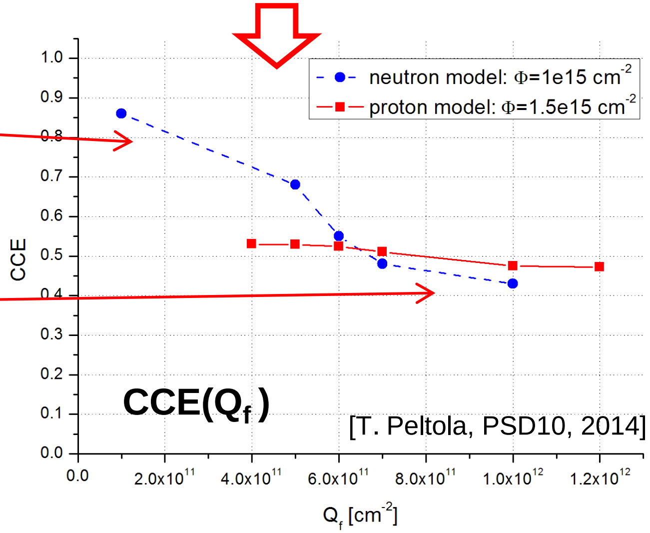
❑ **Problem:** need to use low Q_f values @ high Φ to preserve strip isolation in n-on-p sensors

❑ **Simulated CCE has dependence on Q_f :**

▪ Too low Q_f for high Φ → too high CCE due to charge multiplication

▪ Too high Q_f → no strip isolation & undepleted region extends from front surface & negative component of Q_{coll} increases → too low CCE

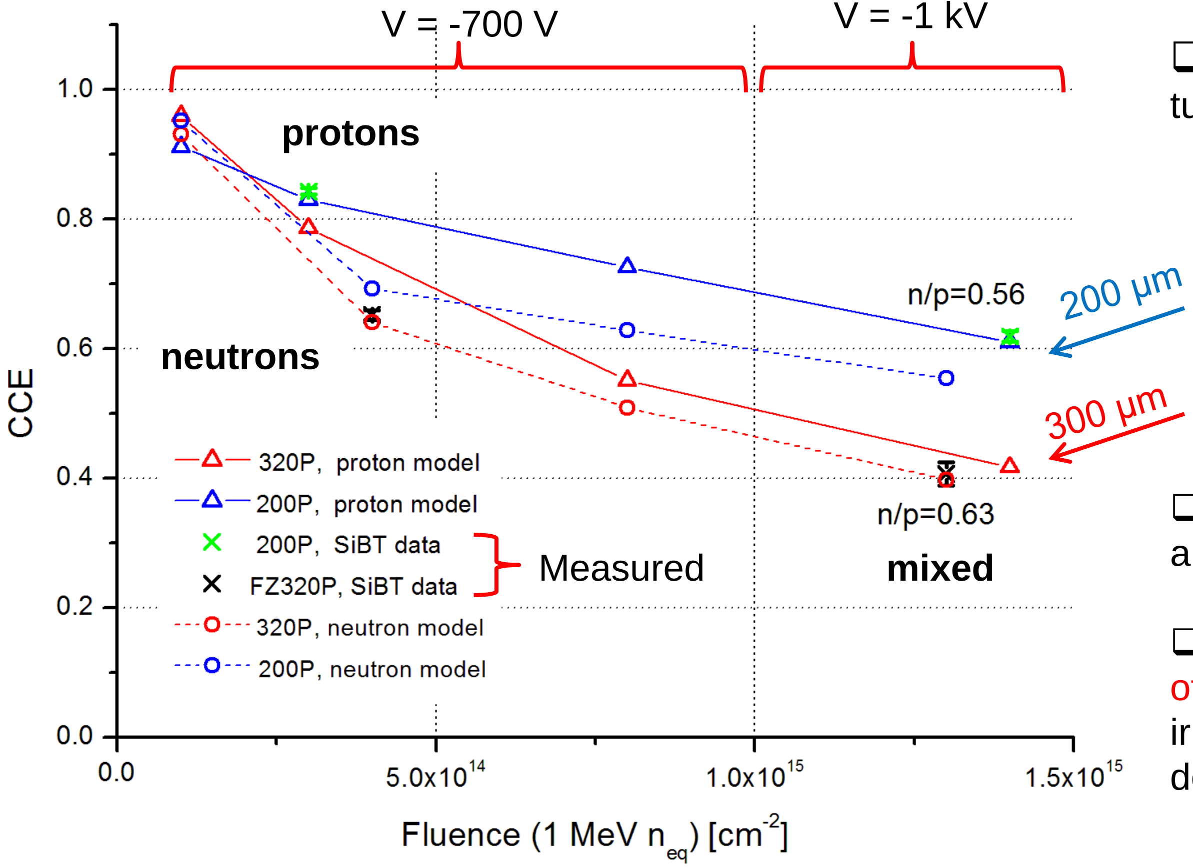
→ Q_f can be applied as further tuning parameter for CCE (find 'correct' Q_f)



CCE & Trapping II

- Same set of data used to simulate CCE measurements taken in a CMS test beam with strip sensors

- E.g. FZ320P = 320 µm thick n-on-p float zone silicon sensor



[T.Peltola, PSD10, Sept. 2014]

- CCE simulations using 2 trap model + tuned Q_f

Fluence [cm^{-2}]	Q_f(neutron) [cm^{-2}]	Q_f(proton) [cm^{-2}]
1e14	6e10	1.4e11
3e14	-	3e11
4e14	9e10	-
8e14	3.25e11	7.1e11
1.3e15	6e11	-
1.4e15	-	1.2e12

- Test beam measured CCE of FZ320P and MCz/FZ200P samples is reproduced

- Fixed Q_f values used to **predict CCE of non-measured detectors** w/ equal irradiation type/dose to measured detectors

Simulated defects:

…and surface damage

Silvaco TCAD: Bulk & surface damage

❑ Delhi Univ. defect model for Silvaco ATLAS

Bulk damage model (for proton irradiation)
-Produce experimentally measured currents for irradiated diodes
- Correct full depletion voltages (say, ~500V for 1e15neq/cm² fluence of proton irradiation)
- Produces electric fields from both sides

Bulk:

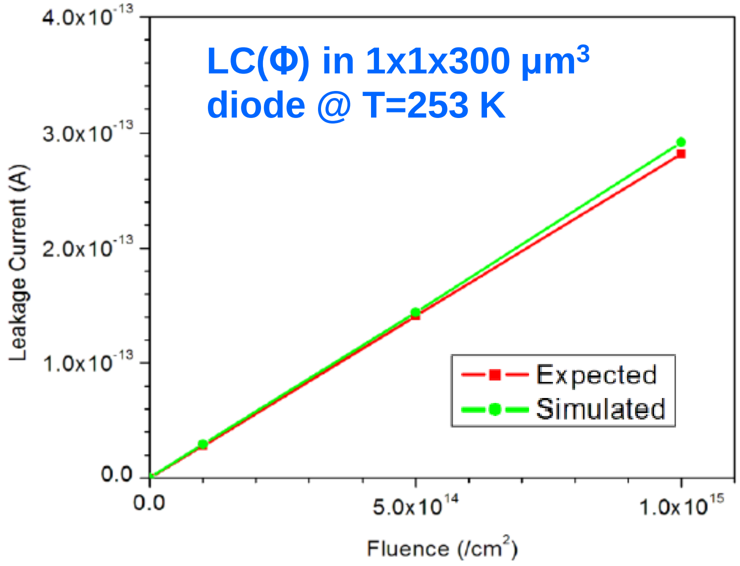
Type of defect	Level [eV]	σ_e [cm^2]	σ_h [cm^2]	Introduction rate [cm^{-1}]
Acceptor	E_C - 0.51	2e-14	2.6e-14	4
Donor	E_V + 0.48	2e-14	2e-14	3

Estimation for N_{it} implementation: $N_{it} \approx Q_f$ [1]

Surface:

Interface trap	Level [eV]	$\sigma_{e,h}$ [cm^2]	Density (N_{it}) [cm^{-2}]
Deep Acceptor	E_C - 0.60	1e-15	$0.6 \cdot Q_f$
Shallow Acceptor	E_C - 0.39	1e-15	$0.4 \cdot Q_f$

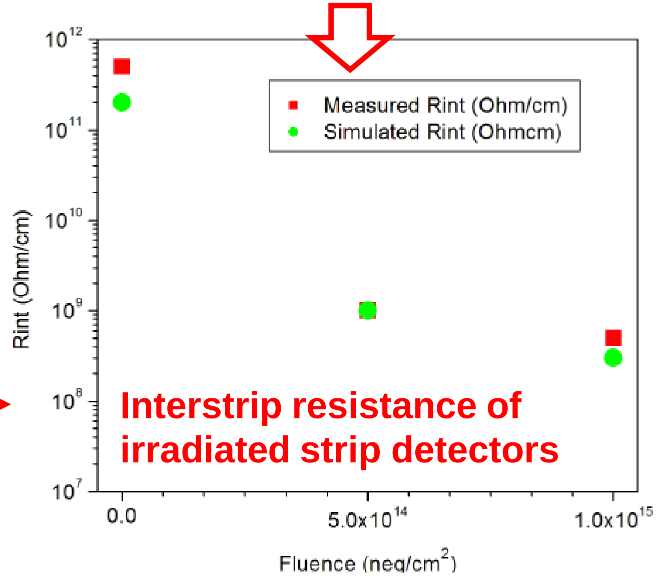
[R. Dalal, 25th RD50 Workshop, 2014]



LC(Φ) in 1x1x300 µm^3 diode @ T=253 K

Bulk

Surface



Interstrip resistance of irradiated strip detectors

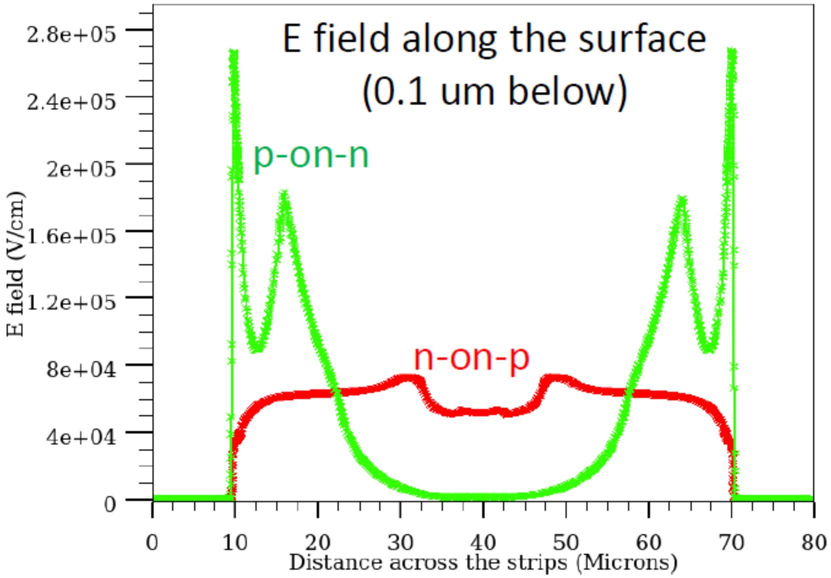
Measured:
[A. Dierlamm, VERTEX 2012]

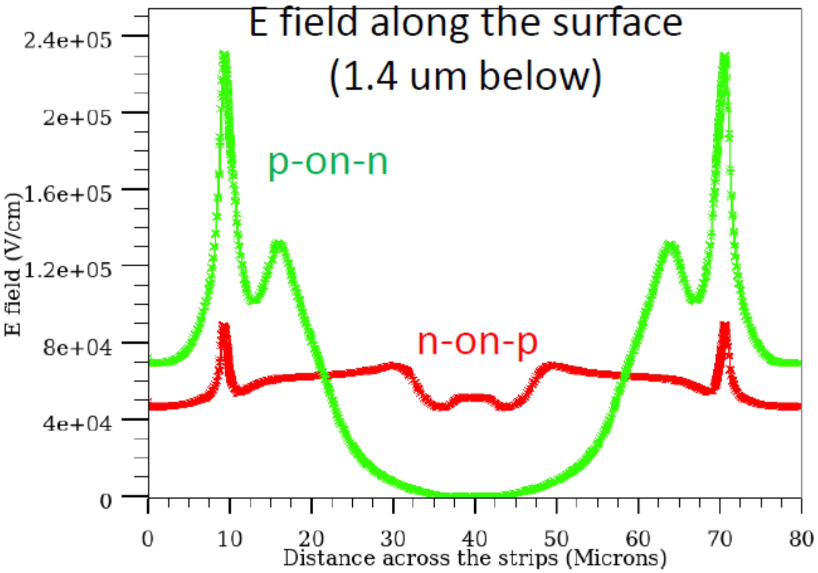
- ❑ Close agreement for measured & simulated R_{int}
- ❑ **Errors:** Measured R_{int} variations in different samples & simulated R_{int} (assuming different Q_f)

[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”

RD50 **DU model:** Peak E-fields in p-on-n & n-on-p sensors

Φ_{eq} =1e15 cm^{-2}, $Q_f = N_{it}$ = 1.2e12 cm^{-2} @ V=500 V



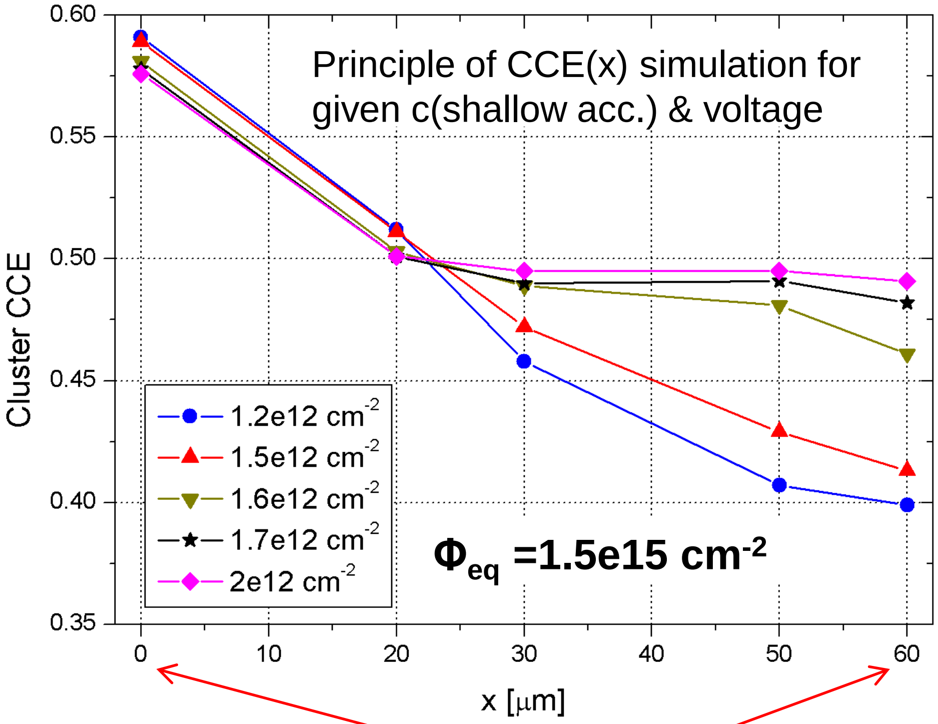


- ☐ **Peak E-fields in Silvaco:** significantly lower for n-on-p sensor for given voltage
  - Micro-discharges much more probable in p-in-n sensors
  - Q_f & N_{it} are used (in equal amounts) for the surface damage

[R. Dalal, 25th RD50 Workshop, 2014]

Sentaurus: CCE(x)

- ☐ **Heavily irradiated strip detectors demonstrate significant position dependency of CCE**



CCE loss

16%

17%

20%

29%

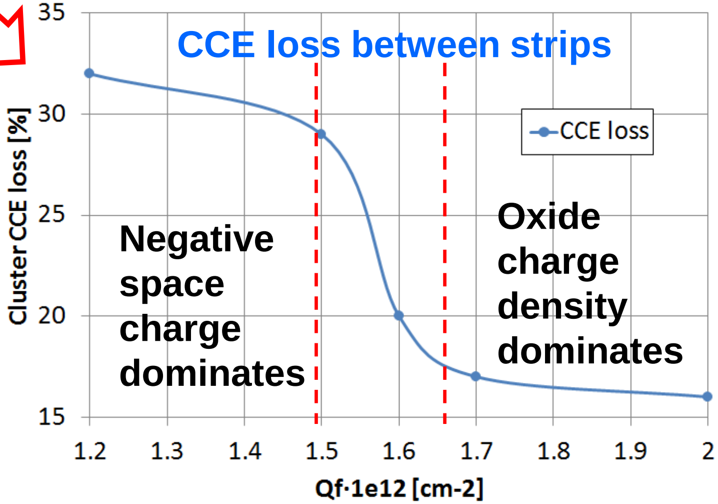
32%

- ☐ **Sentaurus non-uniform 3-level model:**

N_{it} cannot be used: measured C_{int} not reproduced (see back-up 6-7) → need deeper distribution

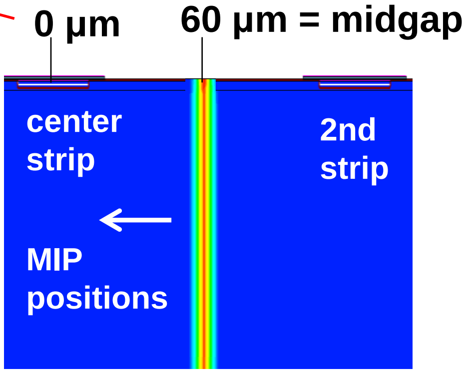
→ **3-level model within 2 µm of device surface + proton model in bulk:**

- ○ R_{int} & C_{int} in line w/ measured also at high Φ & Q_f (see back-up 8)
- ○ Tunable to bulk properties (TCT, V_{fd} & LC) of proton model → suitable tool to study CCE(x)



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]

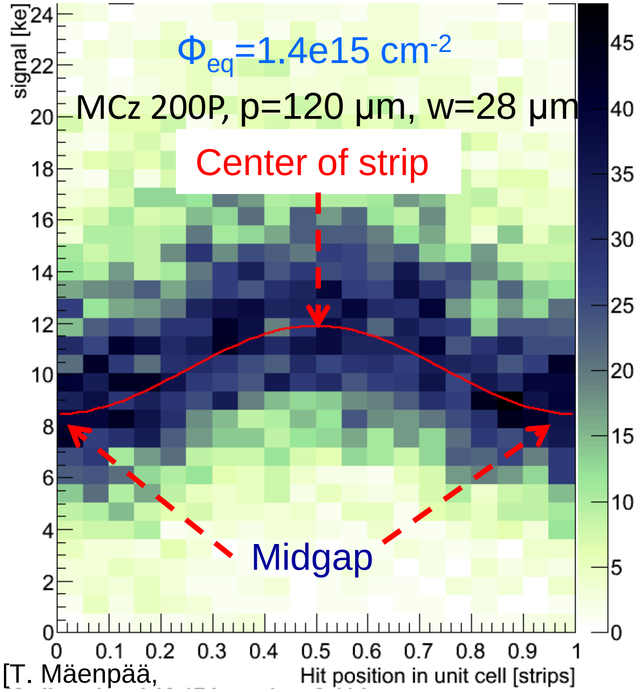
Measured & simulated CCE(x)

Test beam measurement:

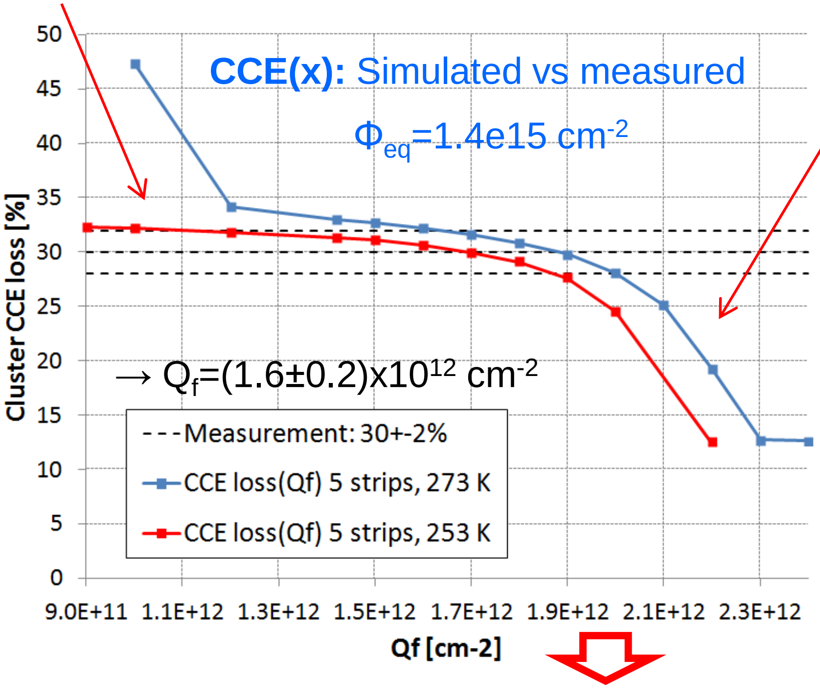
- Strips isolated
- CCE loss between strips ~30%

❑ 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



[T. Mäenpää, PoS(RD13)015, 2013]



See back-up 9-10

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

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

Summary: Defect simulations in RD50

Motivation: Simulations are essential in e.g. device structure optimization & predicting E-fields and trapping
Objective: Develop an approach to model & predict the performance of irradiated silicon detectors (diode, strip, pixel, 3D) using professional software (Sentaurus, Silvaco)

Measured defects: Initial input to the simulations

Simulation of radiation damage in Si bulk: Based on effective midgap levels (DA & DD levels w/ energies E_c - (0.525 ± 0.025) eV and E_v + 0.48 eV). Model 1st proposed in 2001 → entitled later as 'PTI model'

Main idea: Two peaks in the E(z) profile of both proton & neutron irradiated detectors explained via interaction of the carriers from bulk generated current w/ electron traps & simultaneously w/ hole traps

1st successful quantitative models: Proton & neutron models, for simulation of LC, V_{fd} & CCE were built on PTI model's two deep levels

Recent implementations: Additional traps at SiO_2 /Si interface or close to it → scope of simulations expanded to include R_{int}, C_{int}, & CCE(x) of strip sensors irradiated up to ~1.5×10^{15} $n_{eq}cm^{-2}$

Work in progress/future efforts

- ☐ **Comparison of simulated E(x) w/ results of edge-TCT**
  - Measured edge-TCT data for:
    - Modeling tools calibration (non-irradiated detectors)
    - Models development/proofs (Φ & V dependences for irradiated detectors)

- ☐ **CCE(Φ) modeling up to 2e16 $n_{eq}cm^{-2}$ for pixel & 3D detectors**

- ☐ **The new subject – 'Interstrip resistance radiation hardness'**

http://www.cern.ch/rd50

[V. Eremin, 25th RD50 Workshop, 2014]

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 + $N_{it.}$

RD50

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 (cm²)	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 $\sigma_n = 2.3\text{x}10^{-14}$	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 $\sigma_n = 3.7\text{x}10^{-15}$	No impact
E4		PHR $V_3^{=/-}$	E_c - 0.359 $\sigma_n = 2.15\text{x}10^{-15}$	No impact
E5		PHR $V_3^{-/0}$	E_c - 0.458 $\sigma_n = 2.4\text{x}10^{-15}$ $\sigma_p = 2.15\text{x}10^{-13}$	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

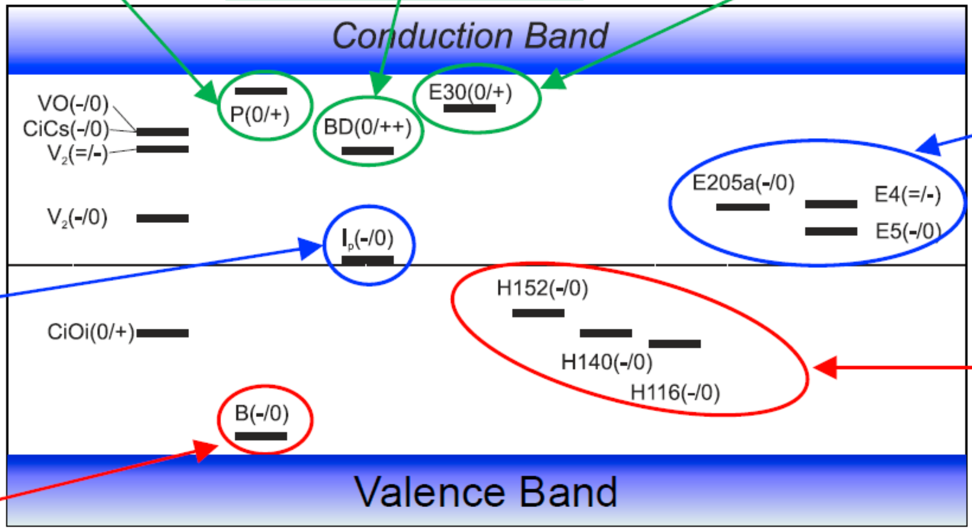
Pintilie et al, NIM A **514**, 18 (2003) & NIM A **556**, (1), 197 (2006);
E. Fretwurst et al, NIM A **583**, 58 (2007)

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

Boron: shallow dopant
(negative charge)

Reverse annealing
(negative charge)

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

[M. Moll, VERTEX 2013]

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

- **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

RD50 Back-up 4: DP & LC of Sentaurus defect models

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

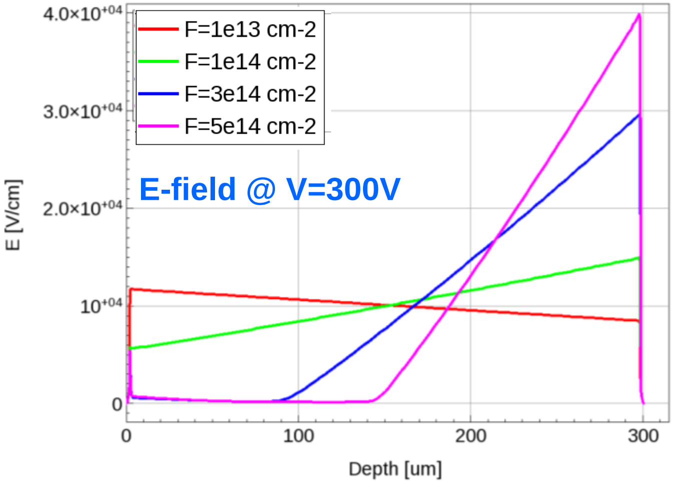
- **Fluences :**
Φ = 1e13 – 5e14 n_{eq} cm^{-2}

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

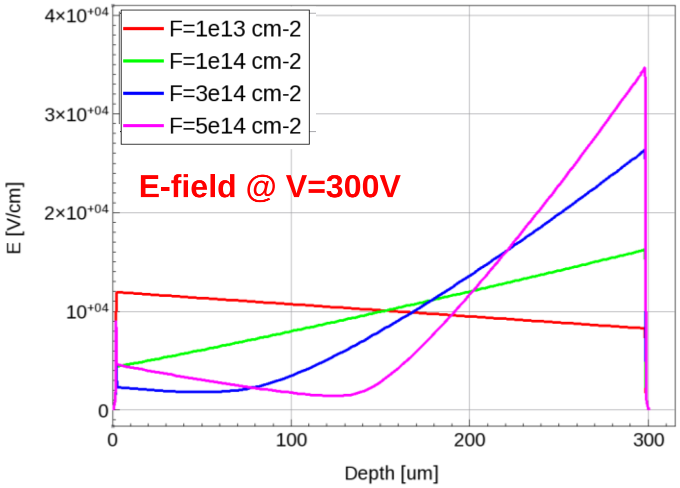
- **Dashed black lines:** experimental LC by
$\Delta I = \text{Volume} \cdot \alpha \cdot \Phi$,
$\alpha(253K) \approx 8.9 \cdot 10^{-19}$ A·cm^{-1}

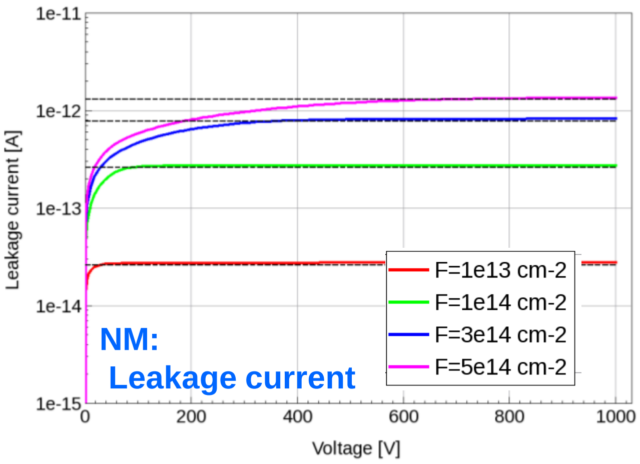
- LC has perfect match with experimental values

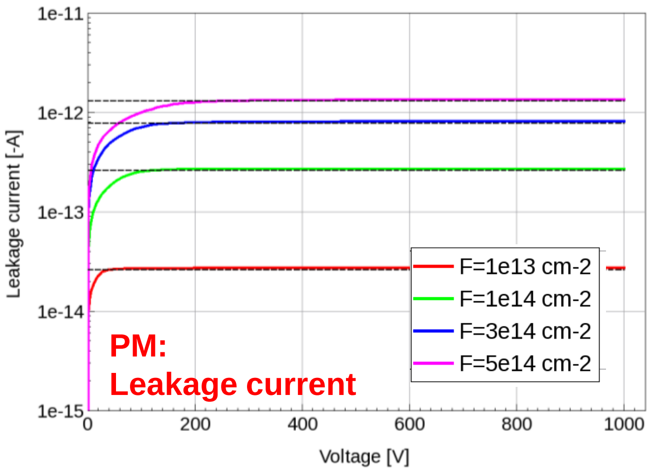
NEUTRON MODEL (NM)



PROTON MODEL (PM)







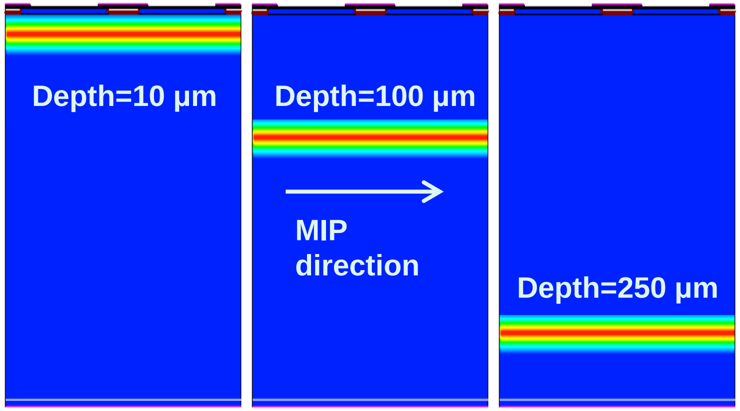
Back-up 5: Method for simulated edge-TCT

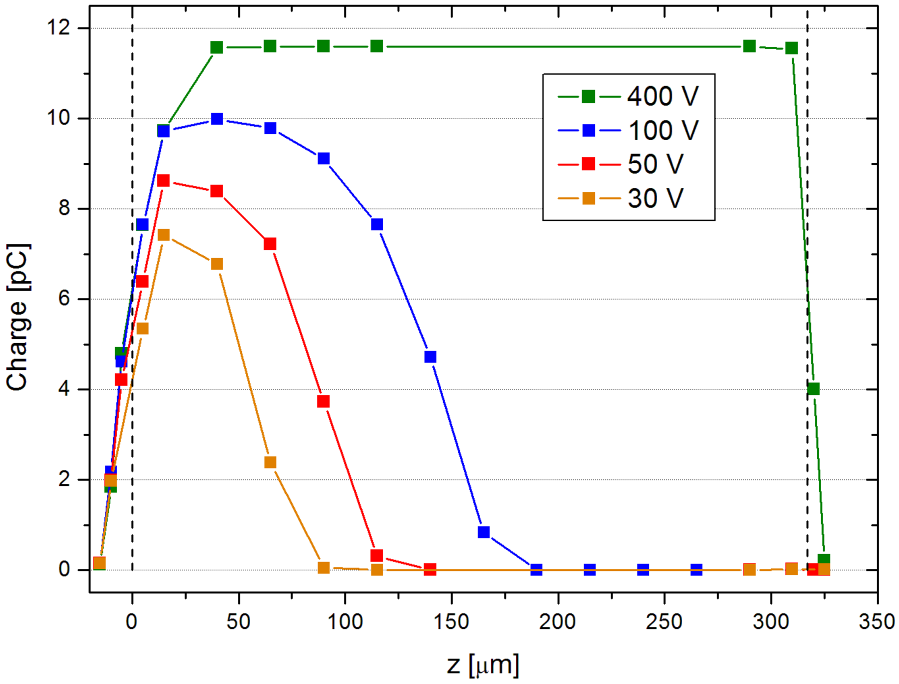
❑ **Goal:** extract electric field E from drift velocity v_{drift} using eTCT

❑ 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?

Principal of edge-TCT simulation:





❑ Synopsys Sentaurus simulated edge-TCT collected charges Q(z) at voltages both below and above V_{fd} for a non-irradiated 320N strip detector at T = 293 K.

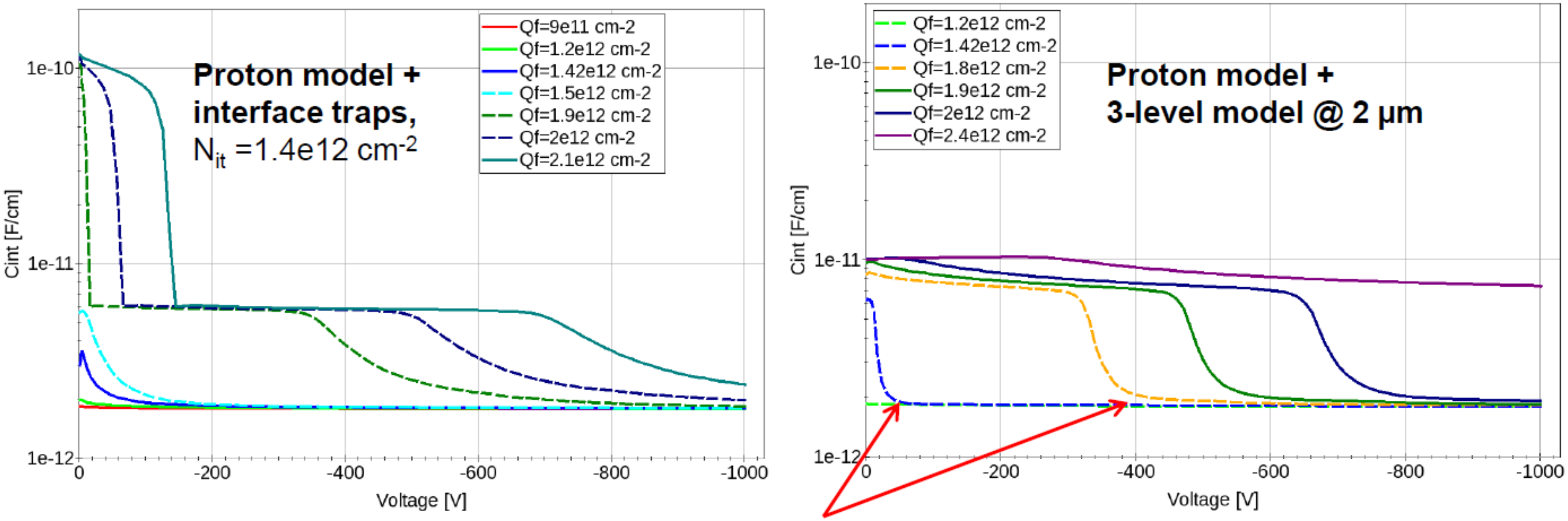
❑ **Dashed vertical lines:** active region of the detector, defined from the center of the rising and descending slopes of the Q(z) distribution. The different electric field extensions into the bulk from the pn-junction at the front surface (front: z=0, backplane: z=320 µm) are clearly reflected by Q(z)

❑ **Differences in Q(z) amplitude:** Reproduced by using laterally extended device structure → extension of E-field to the detector edges is taken into account

Back-up 6: 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

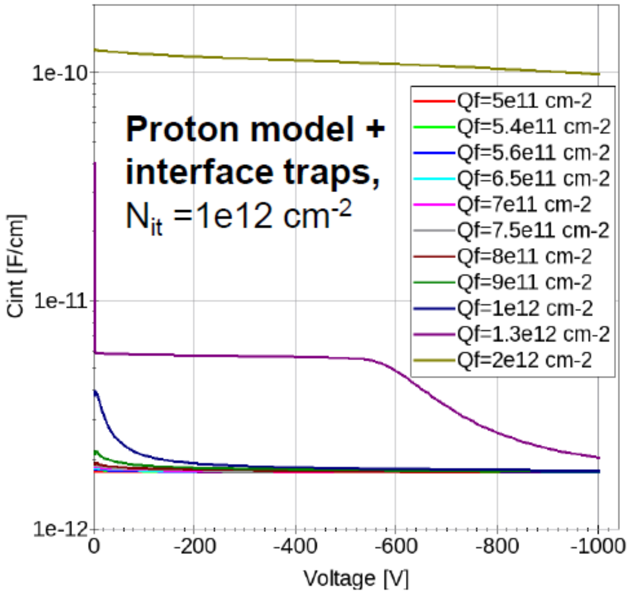
❑ **Measurement:** C_{int} ~1.8 pF/cm reached at 0 V

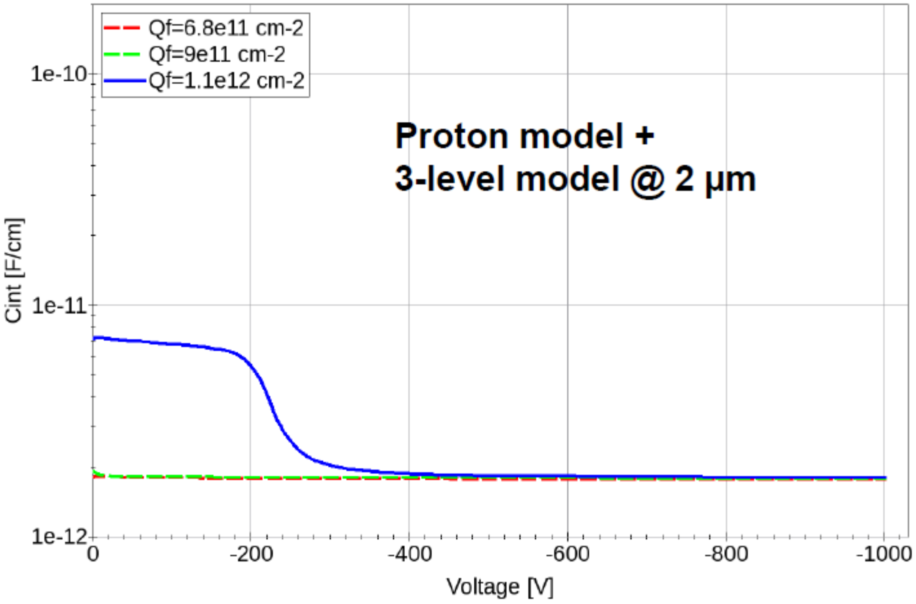


Higher Q_f → higher V needed to reach geometrical C_{int}

Back-up 7: 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

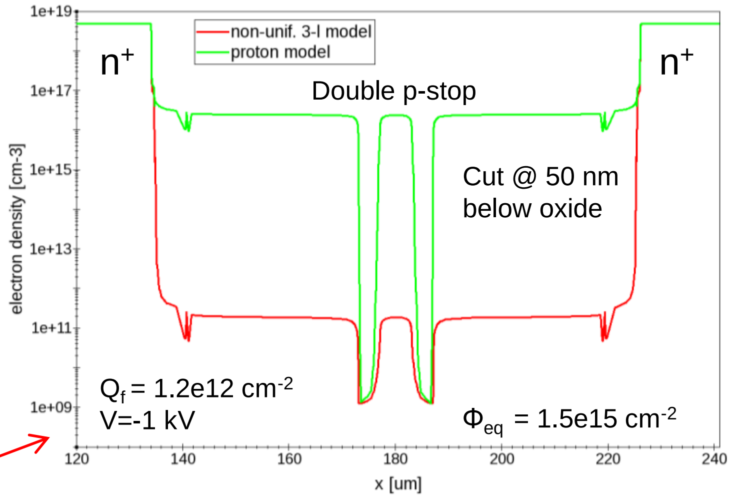




⇨ **Conclusion from slides 7-10:** Deeper distribution of shallow acceptors reproduces measured CCE loss between strips & C_{int} more closely

Back-up 8: 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

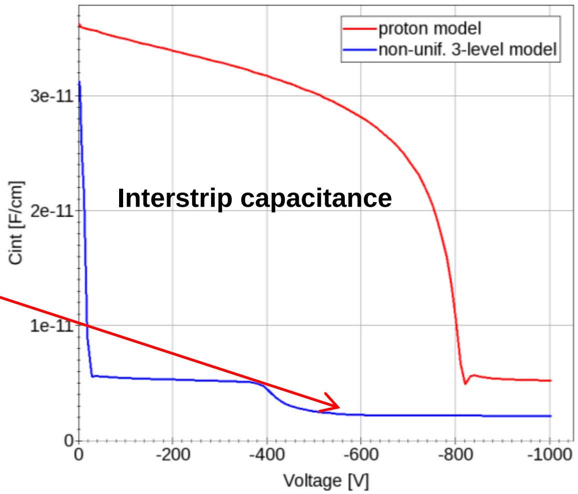


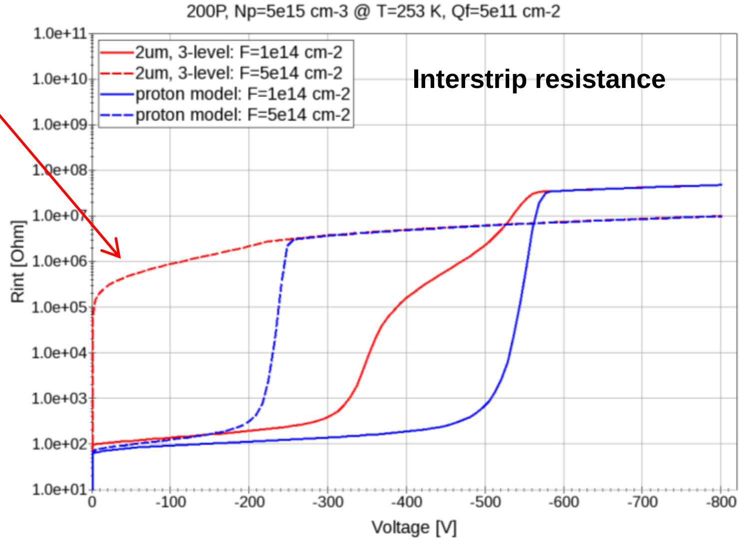
3-level model within 2 µm of device surface

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

- 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)



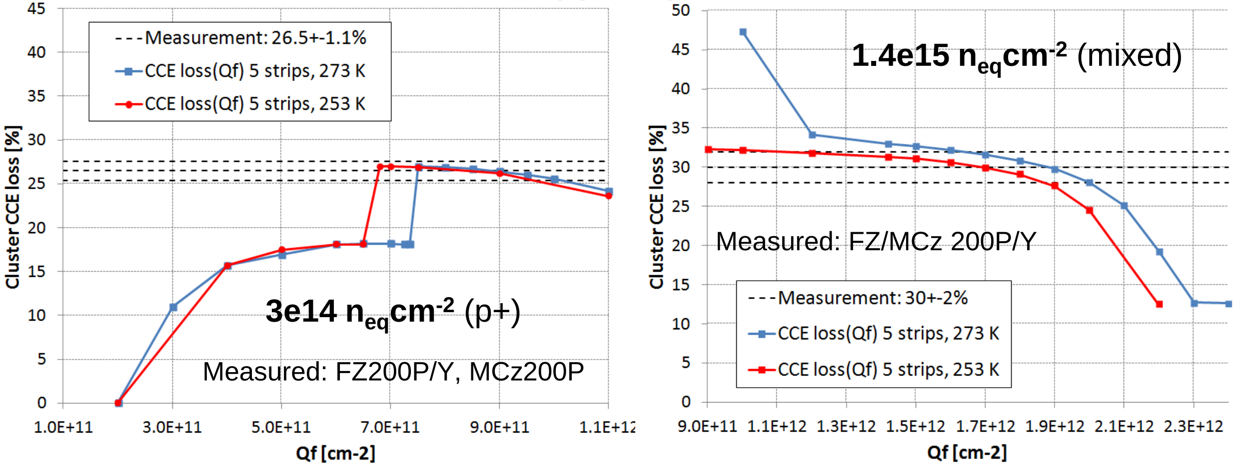


RD50 **Back-up 9:** Measured & simulated CCE(x)

- **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

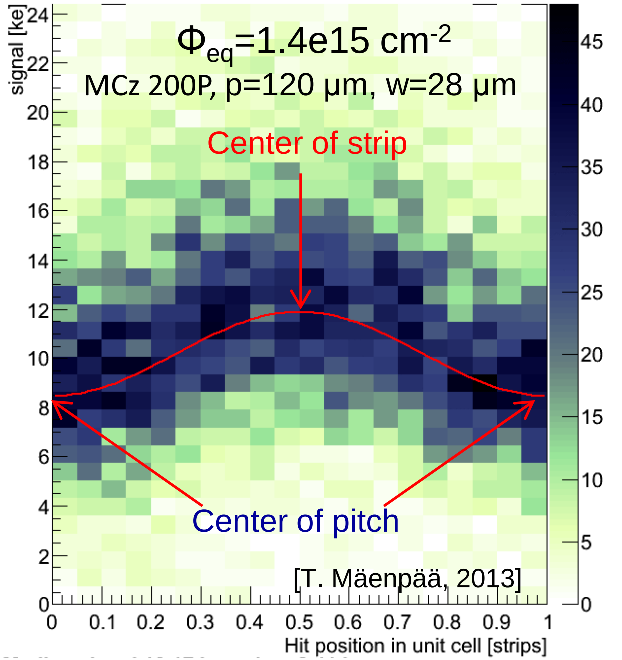
  → suitable tool to investigate CCE(x)

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



Q_f=(8.5±1.0)x10^{11} cm^{-2} Q_f=(1.6±0.2)x10^{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

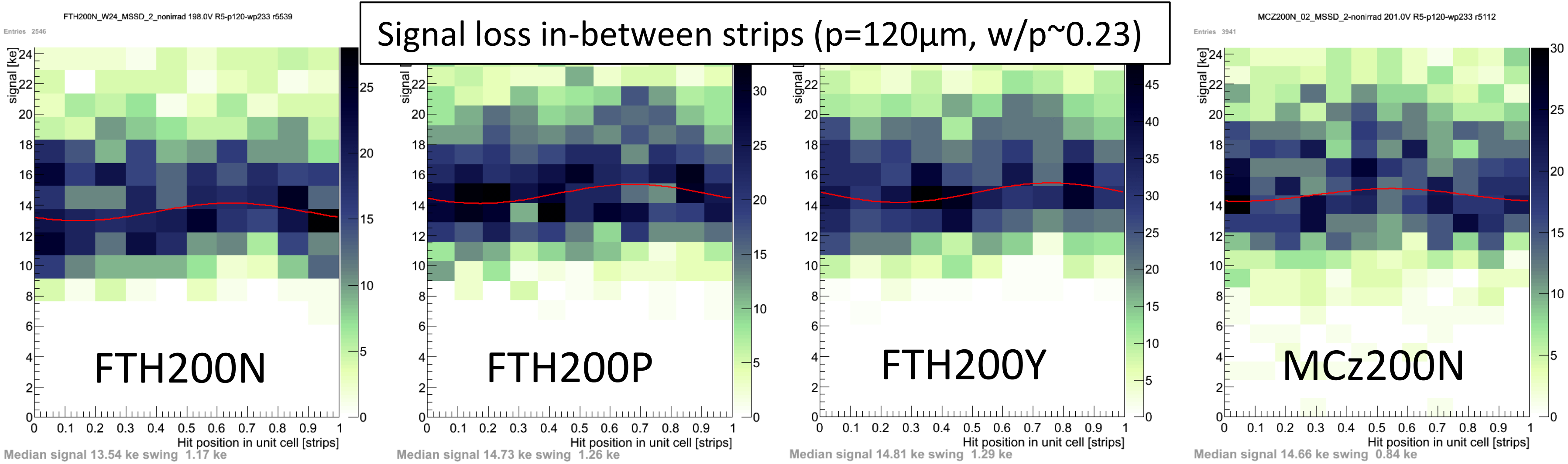
Preliminary parametrization for Φ = 3e14 – 1.4e15 cm^{-2}

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

RD50 **Back-up 10:** SiBT measured CCE(x) between strips

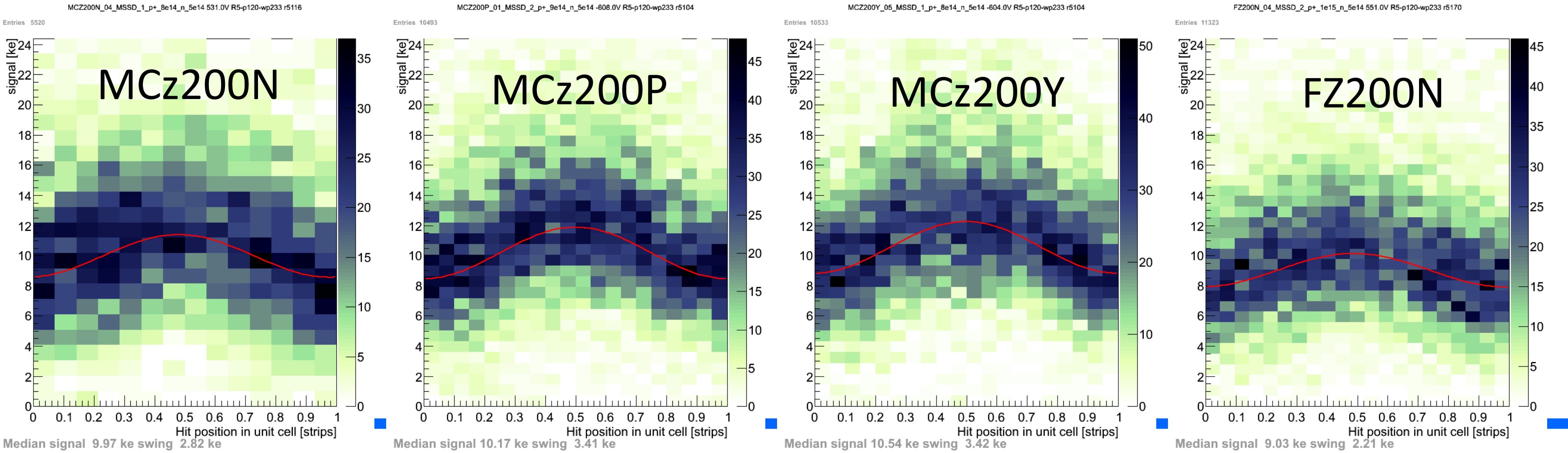
Signal loss in-between strips (p=120µm, w/p~0.23)

non-irradiated



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

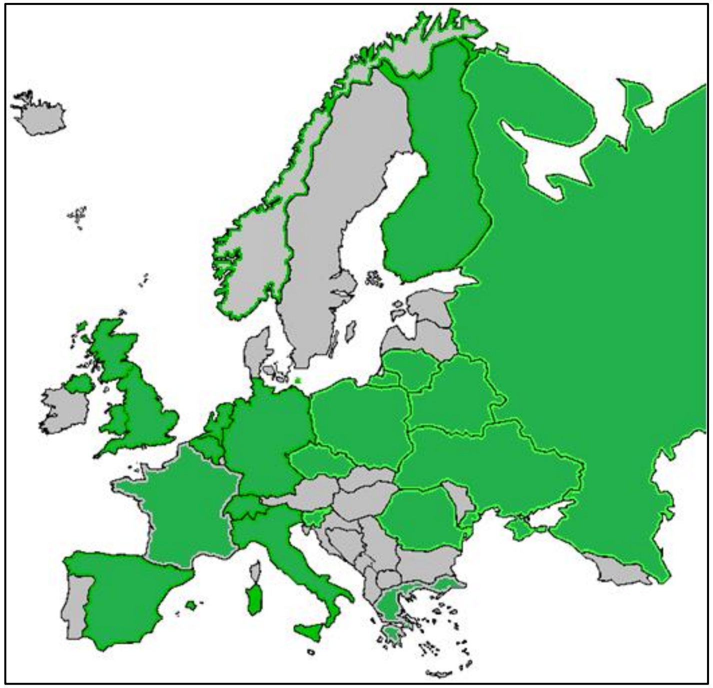
mixed irradiated 1.5e15n_{eq}/cm^2



RD50

Back-up 11: The RD50 Collaboration

- ☐ **RD50: 280 Members from 49 Institutes**
  - **41 European institutes**
  - **6 North-American institutes**
  - **1 Middle East institute**
  - **1 Asian institute**



http://www.cern.ch/rd50