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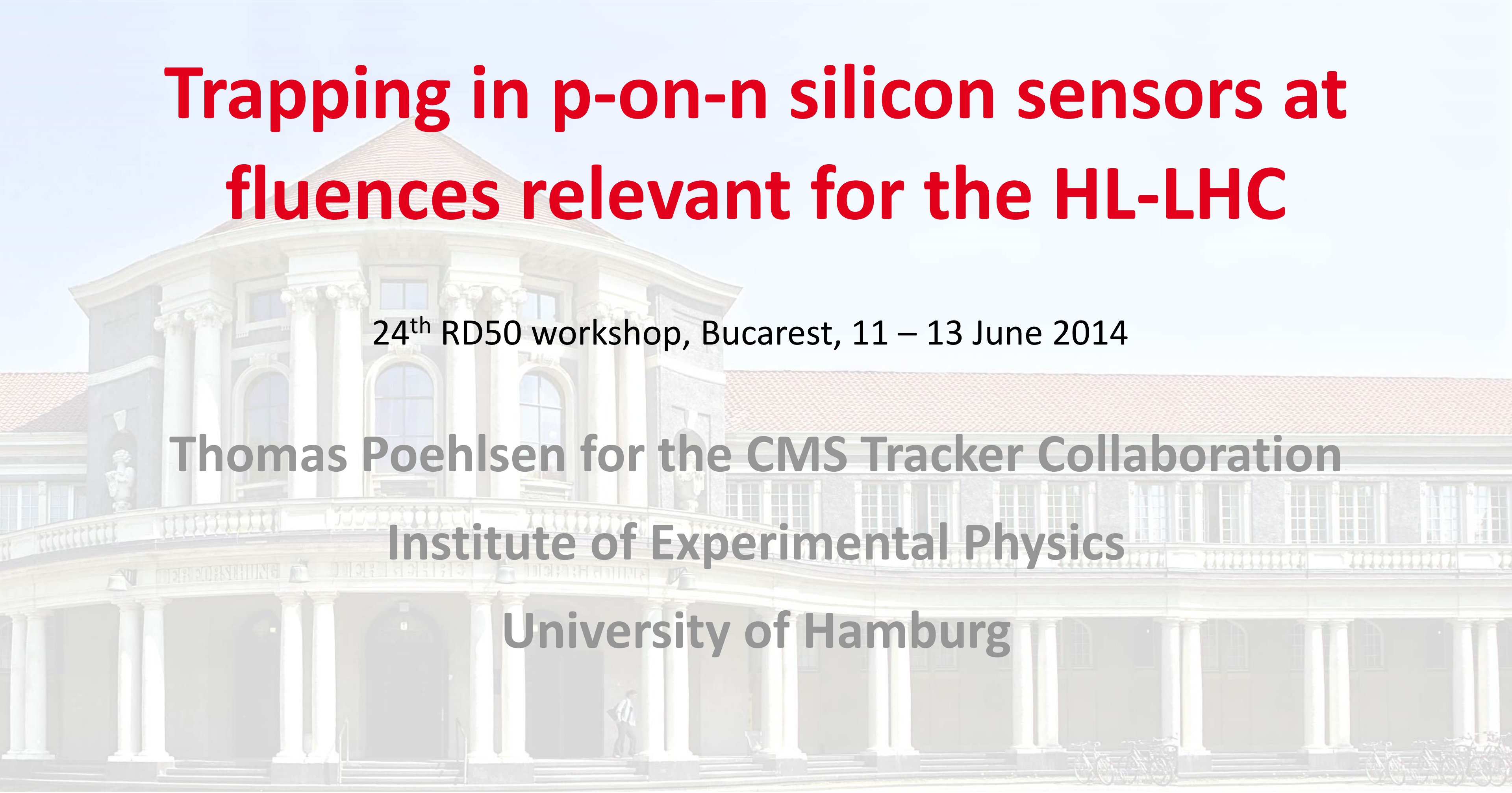


Trapping in p-on-n silicon sensors at fluences relevant for the HL-LHC

24th RD50 workshop, Bucarest, 11 – 13 June 2014

Thomas Poehlsen for the CMS Tracker Collaboration

Institute of Experimental Physics

University of Hamburg

Thomas Poehlsen
thomas.poehlsen@desy.de

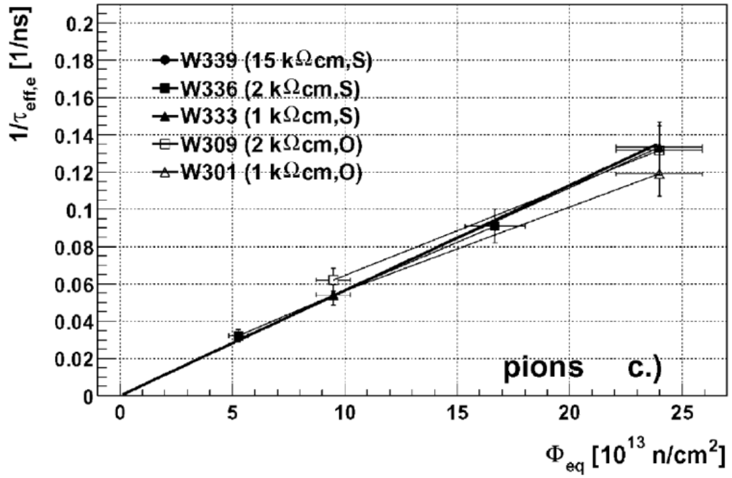
Motivation

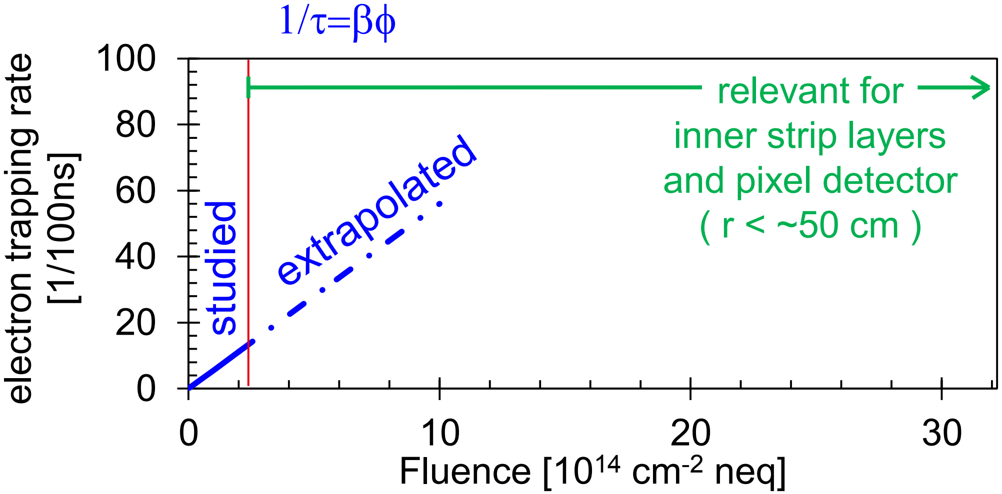
- A correct description of charge losses in the Si bulk is essential in order to simulate the detector performance at the HL-LHC, especially in the inner detector layers.

- So far trapping in CMS tools is based on effective trapping rates according to G. Kramberger:

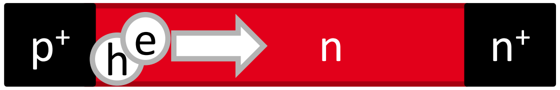
$$\frac{1}{\tau_{e,h}} = \sum_i \frac{1}{\tau^i_{e,h}} = \sum_i N^i_{e,h} \cdot \sigma^i_{e,h} \cdot v_{e,h} = \beta_{e,h} \cdot \phi$$

G. Kramberger et al., NIM A 481 (2002) 297–305





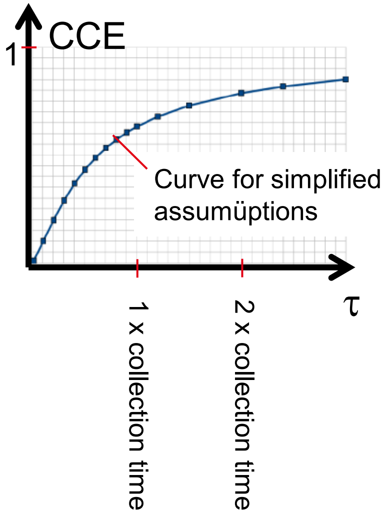
Method to determine the trapping rates



1. Use red laser TCT measurements (672 nm)
⇒ Study electron and hole drift separately

2. Simulate red laser TCT measurements assuming
- **Electric field** based on **2 effective defects*** (Donor: $E_V + 0.48$ eV, Acceptor: $E_C - 0.525$ eV)
  Different E-field distributions are tested
- **Drift velocity** independent of irradiation dose
- Effective **trapping rate** independent of position (-> only two free parameters: τ_e, τ_h)

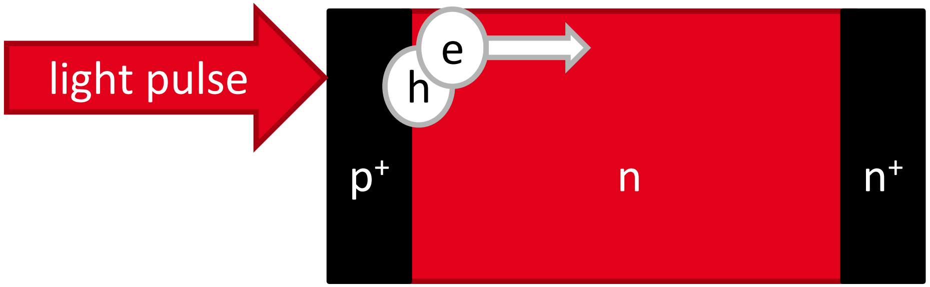
3. Fit the CCE at a given voltage (*V* = 600 V) using 1 free fit paramater:
τ_e (for front illumination) or τ_h (for rear illum.)



4. Perform cross-checks:
a) Compare measured and simulated TCT signals I(t)
b) Predict the CCE for measurements using infrared laser light

***EVL model:** NIM A 476 (2002) 556-564.

Transient current technique (TCT)



red laser light pulse:

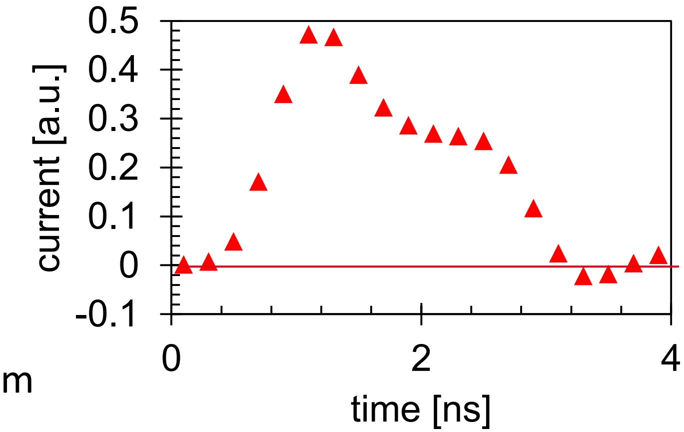
- 672 nm, 3.5 µm penetration depth
- FWHM 40 ps
- generates N = ~ 1 million e-h pairs

⇒ induced current (pad sensor) : $I = \sum_{\text{free carriers } i} \frac{q_i}{d} \cdot \frac{\Delta x_i}{\Delta t}, \qquad \frac{\Delta x_i}{\Delta t} \approx v_{dr} = \mu(E) \cdot E$

$$Q = \int I\,dt\,, \qquad CCE = \frac{Q_{irradiated}}{Q_{non-irradiated}} = \frac{Q}{Q_0}$$

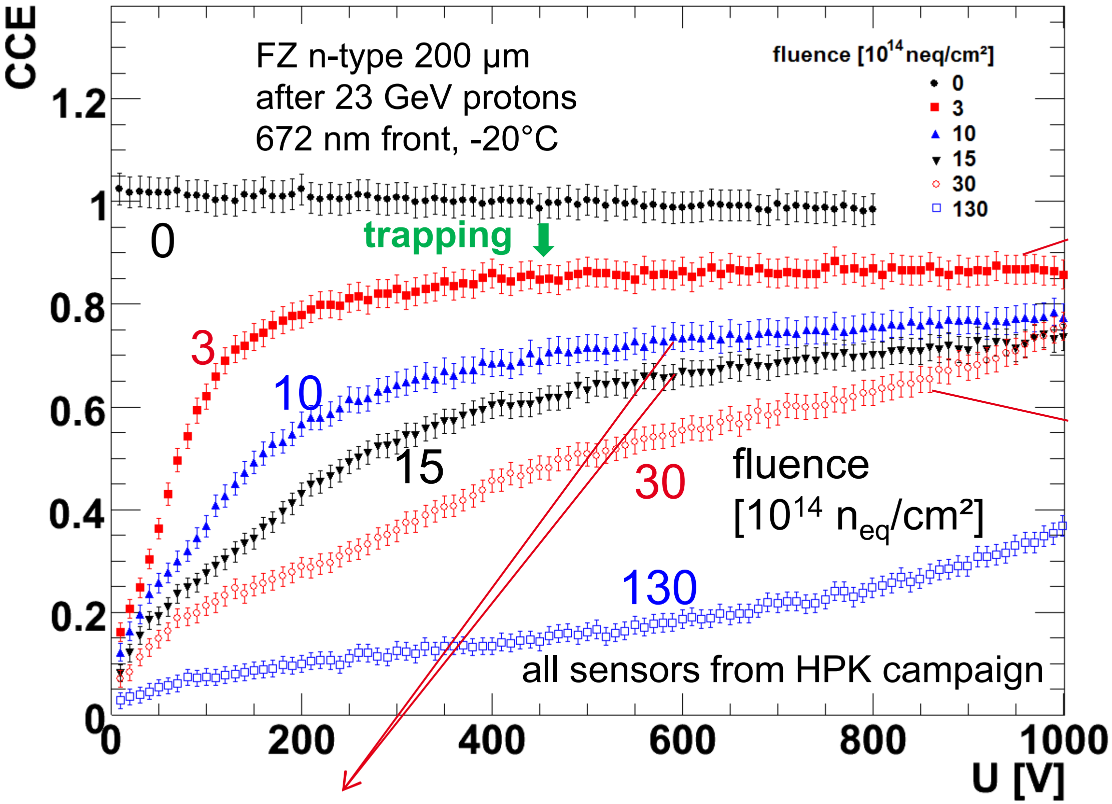
readout:

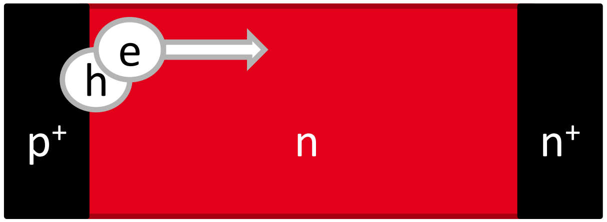
- digital oscilloscope (bandwidth 1 GHz, 512 averages)
- 10 x Phillips current amplifier
- diode capacitance of ~2 pF for the used diodes with d=200 µm



Transient current technique (TCT) –> CCE for different fluences (23 GeV protons)

$$CCE = \frac{Q_{irradiated}}{Q^{400V}_{non-irradiated}} = \frac{Q}{Q_0}$$





CCE uncertainty: 3%
(2% syst. due to voltage dependence,
2% reproducibility)

Here protons only (not mixed):
⇒ comparable with earlier studies

Study in detail: 10 and 15·10^{14} neq/cm² at 600 V (simulate I(t) in PixelAV)
CCE => trapping rate (for electrons), assuming E(x), v_{dr}(E)

E(x) – Tuning of two effective defects

Fit by Morris Swartz et al. using TCAD and self-written „PixelAV“ simulation program and grazing angle measurements (arXiv:physics/0605215):
For 285 µm thick pixel sensors (125 µm x 125 µm, DO-FZ, n-in-n, p-spray)

Tuned: N_D, N_A, σ_e^D, σ_h^D, σ_e^A, σ_h^A

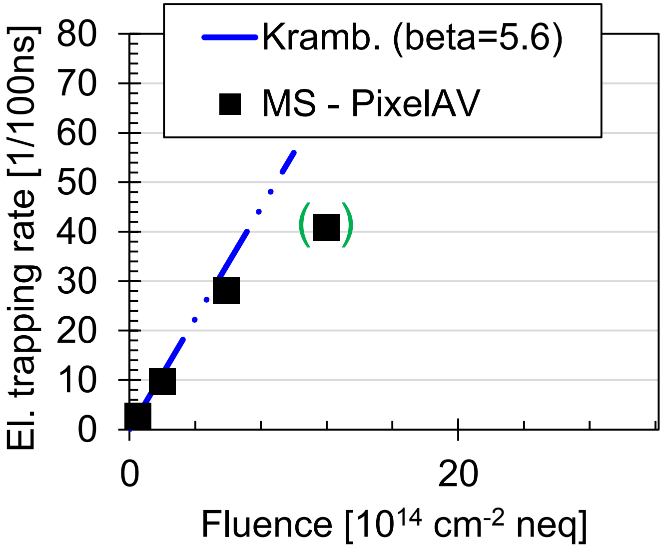
arXiv:physics/0605215

Private communic.
M. Swartz

Φ [10^{14} $\mathrm{n_{eq} cm^{-2}}$]	0.5	2.0	5.9	12
N_A [10^{14} $\mathrm{cm^{-3}}$]	1.9	6.8	16	30.
N_D [10^{14} $\mathrm{cm^{-3}}$]	2.5	10	40	69.
$\sigma_e^{A/D}$ [10^{-15} $\mathrm{cm^2}$]	6.60	6.60	6.60	3.8/0.94
σ_h^A [10^{-15} $\mathrm{cm^2}$]	1.65	1.65	1.65	3.8
σ_h^D [10^{-15} $\mathrm{cm^2}$]	6.60	6.60	1.65	0.94
Γ_e [10^{-2} $\mathrm{ns^{-2}}$]	2.7	9.6	28.	41
Γ_h [10^{-2} $\mathrm{ns^{-2}}$]	3.6	13.	38.	55.

defects to describe E-field

trapping rates used **in PixelAV**



E(x) – Tuning of two effective defects

Fit in TCAD by Robert Eber (KIT) using **current**, **capacitance** and **red laser TCT** meas.
after **23 MeV proton irradiation,** 300 µm thick, dd-FZ p-on-n pad sensors

IV, CV & TCT

tuned: $N_D, N_A, \sigma_e^D, \sigma_h^D, \sigma_e^A, \sigma_h^A$

- Donor

$$N_D = 5.6\,\phi_{eq} - 4 \cdot 10^{14}$$
$$\sigma_e^D = \sigma_h^D = 10^{-14} cm^2$$

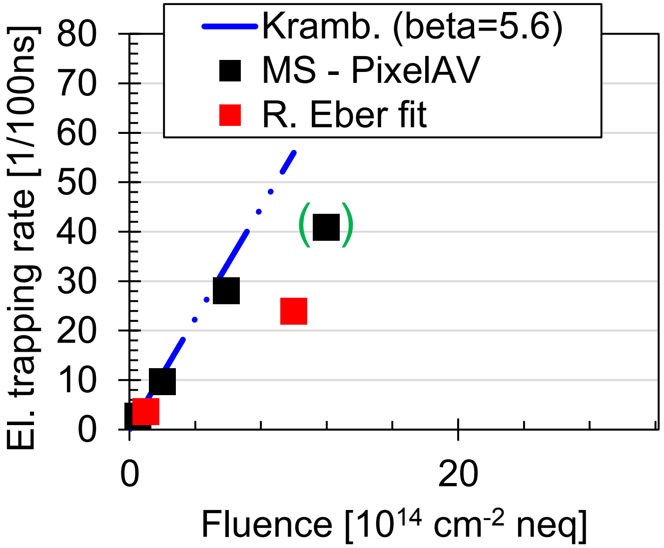
- Acceptor

$$N_A = 1.2\,\phi_{eq} + 0.65 \cdot 10^{14}$$
$$\sigma_e^A = \sigma_h^A = 10^{-14} cm^2$$

50% initial donor removal

(fluence range: 10^{14} to 10^{15} $\mathrm{n_{eq}/cm^2}$)

see Robert Eber's thesis:
KIT – EKP-2014-00012
(ekp.kit.edu/391.php)

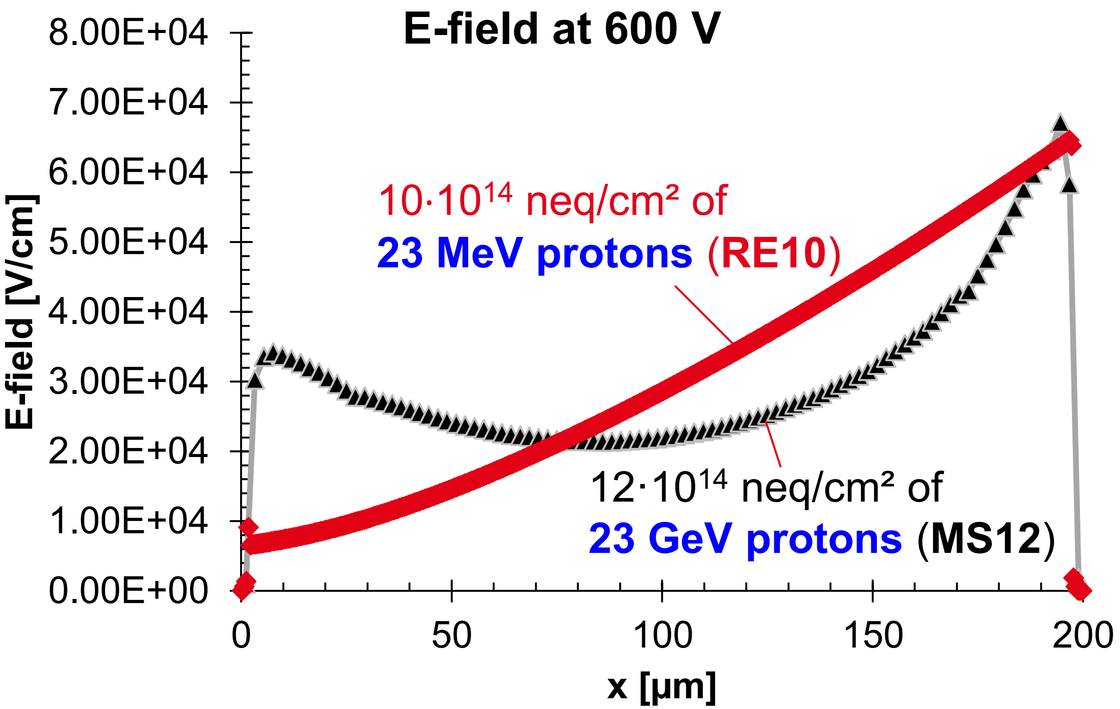


Next step: Determine the effective trapping rates directly from measured charge losses

E(x) – Simulation of TCT measurements

Studies by **Morris Swartz (MS12)** and by **Robert Eber (RE10)**

both: tune two eff. defects -> different E-fields! … **different proton energies used**

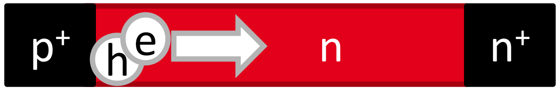


$10 \cdot 10^{14}$ neq/cm² of **23 MeV protons** (**RE10**)

$12 \cdot 10^{14}$ neq/cm² of **23 GeV protons** (**MS12**)

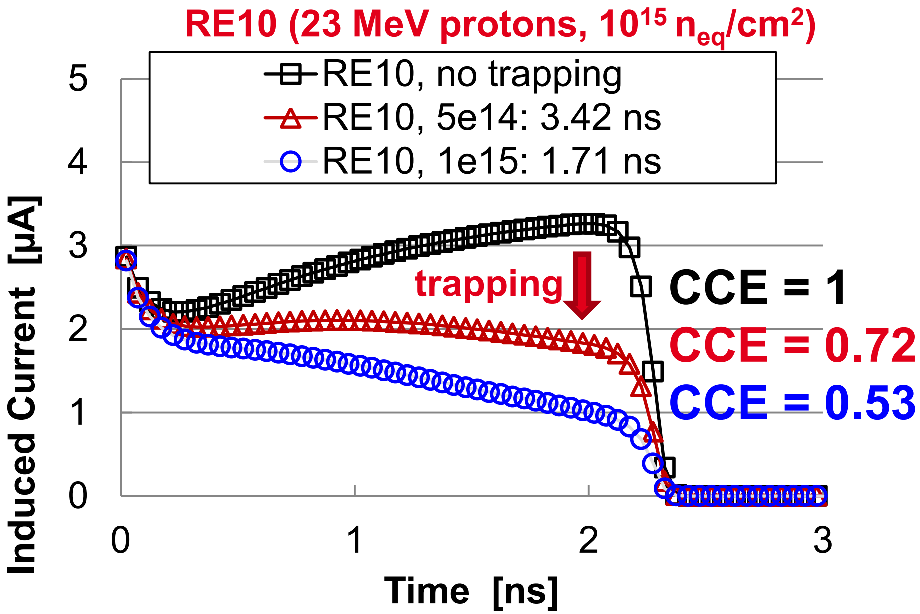
Modified PixelAV:

- time-resolved signals
- linear weighting potential
- drift velocity for <100> Si (independent of dose)
- 40 000 eh pairs are generated at the front (3.5 µm penetration):

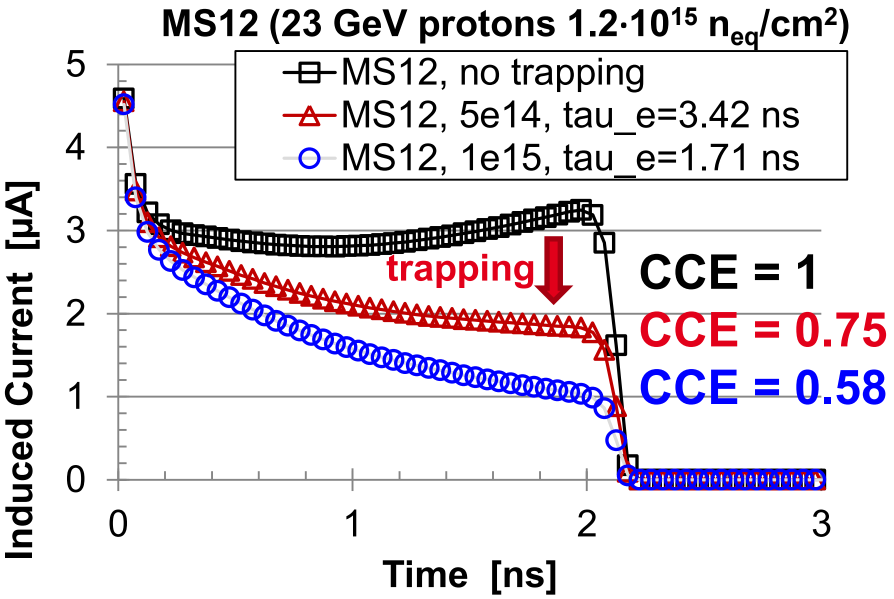


- vary the trapping time τ_e (τ_h) to describe the CCE (assume $\tau_{e,h}$ independent of position)
- determine τ_e for both E-fields

Time-resolved current signals



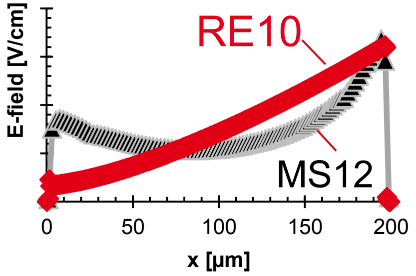
RE10 (23 MeV protons, 10^{15} n_{eq}/cm^2)



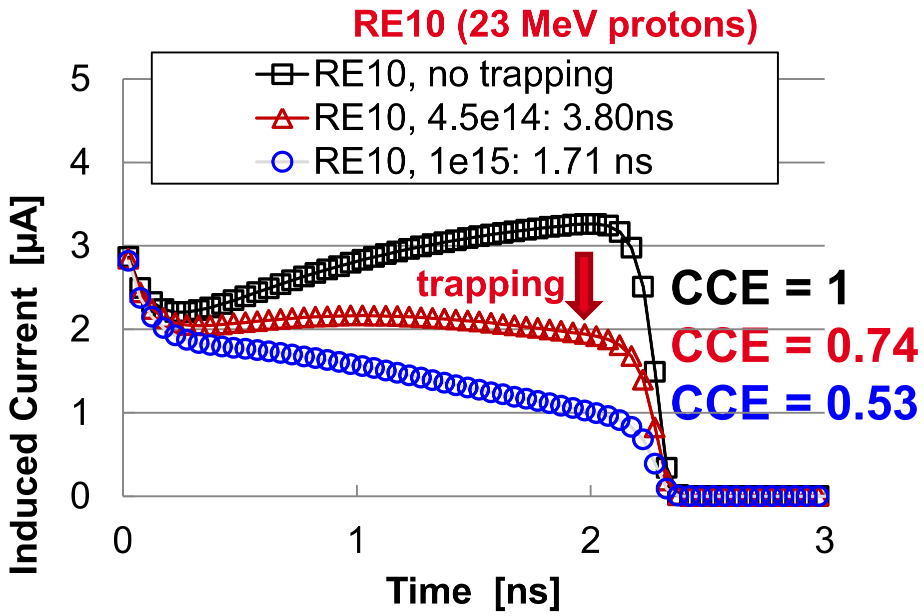
MS12 (23 GeV protons $1.2 \cdot 10^{15}$ n_{eq}/cm^2)

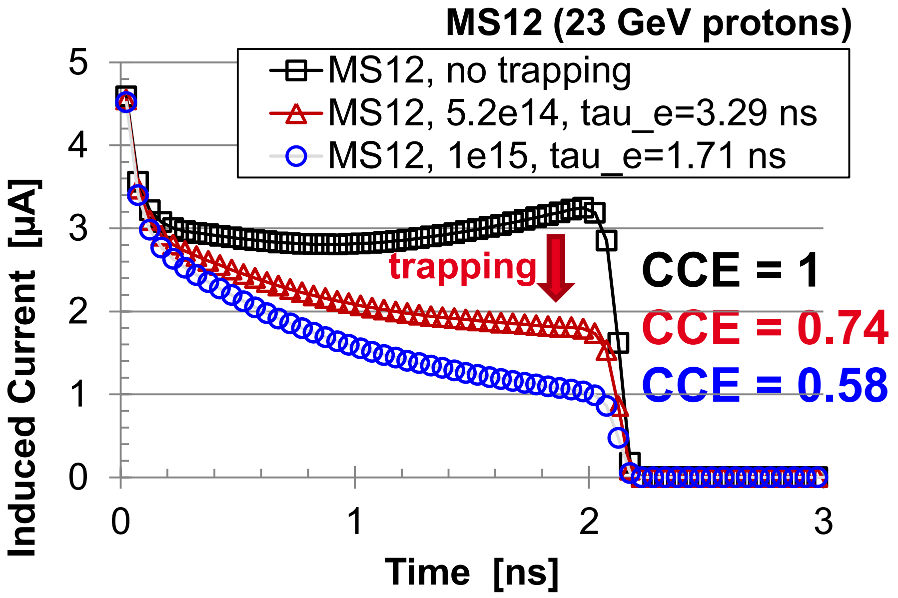
CCE measured = 0.74 (after 23 GeV proton irradiation to 1e15)

⇒ adjust trapping time



Time-resolved current signals


RE10 (23 MeV protons)

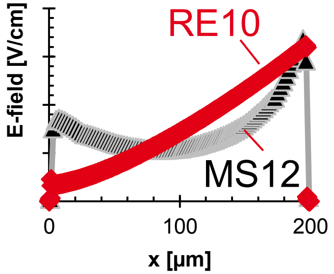

MS12 (23 GeV protons)

CCE measured = 0.74 (after 23 GeV proton irradiation to 1e15)

for 10·10^{14} neq/cm² :

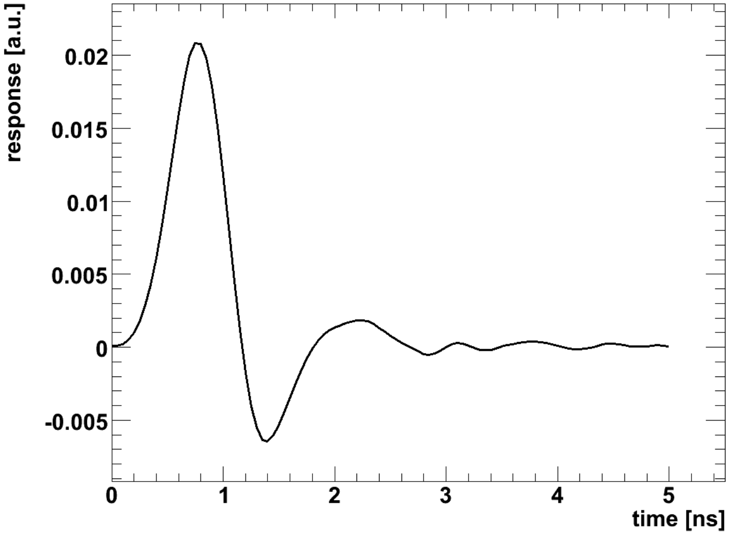
$\Rightarrow$ $\tau = 3.3$ ns ± 0.4 ns $_{CCE}$ if we assume the field **MS12 (23 GeV protons)**

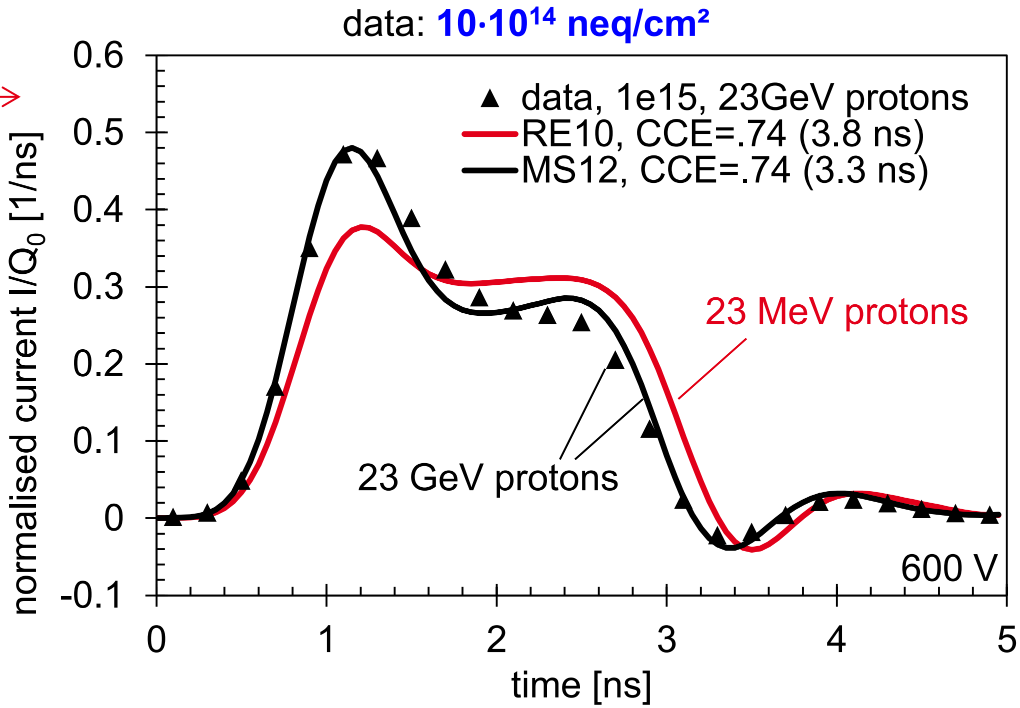
$\Rightarrow$ $\tau = 3.8$ ns ± 0.4 ns $_{CCE}$ if we assume the field **RE10 (23 MeV protons)**



Time-resolved current signals – simulated and measured

Convolute simulated signal with **response of our TCT setup** to a delta function →





Measured TCT signal very compatible with the E-field according to M. Swartz (**MS12**)

for $10\cdot10^{14}$ neq/cm² :

⇒ **τ = 3.3 ns ± 0.4 ns $_{CCE}$** if we assume the field **MS12 (23 GeV protons)** ✓

⇒ τ = 3.8 ns ± 0.4 ns $_{CCE}$ if we assume the field **RE10 (23 MeV protons)**

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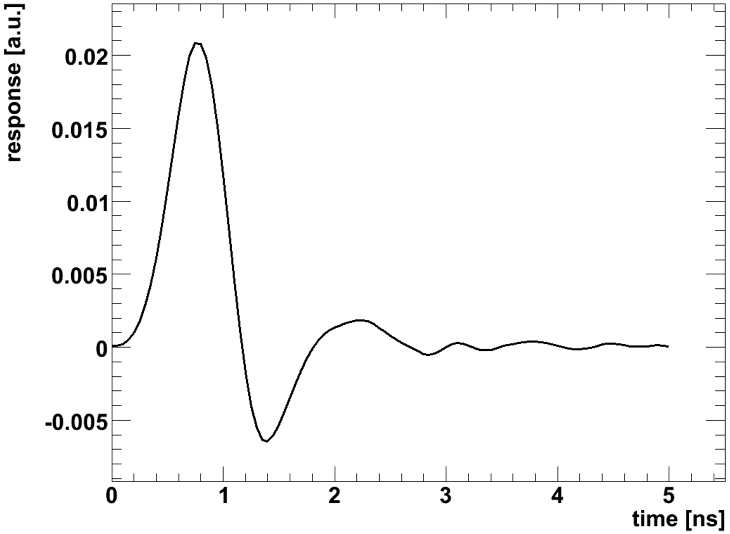
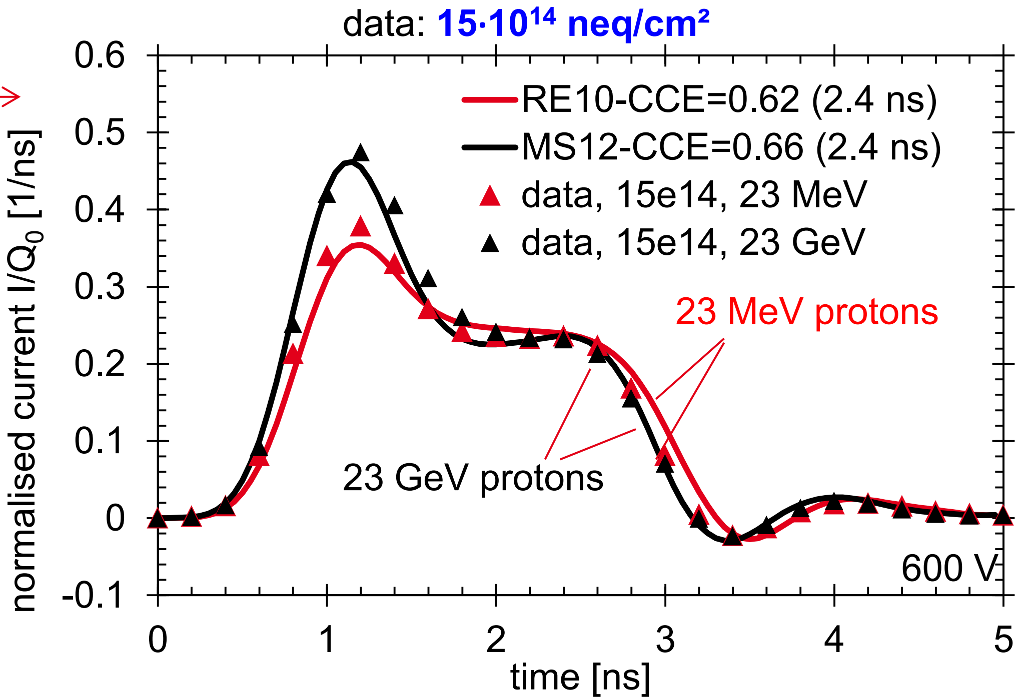
Time-resolved current signals – simulated and measured

Convolute simulated signal with **response of our TCT setup** to a delta function →





Measured TCT signal very compatible with the correct E-fields used

for $15\cdot10^{14}$ neq/cm² :

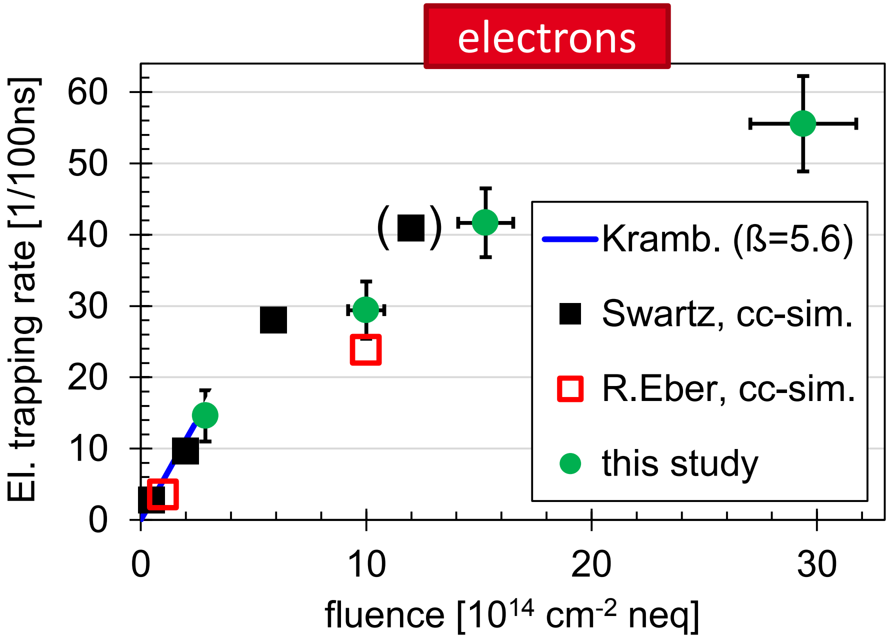
⇒ $\tau = 2.4$ ns ± 0.3 ns $_{\mathrm{CCE}}$ ✓ (for **23 GeV protons**, using **E-field MS12**)

⇒ $\tau = 2.4$ ns ± 0.3 ns $_{\mathrm{CCE}}$ ✓ (for **23 MeV protons**, using **E-field MS10**)

Results on the trapping rate

After 23 GeV protons:

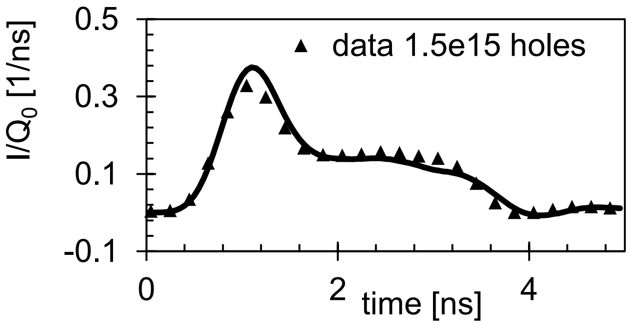
ϕ_{neq} [neq/cm^2]	$1/\tau_e$ [1/100 ns]
$3 \cdot 10^{14}$	$14.5 \pm 3.5_{\text{(CCE)}} \pm 0.5_{\text{(E-field)}}$
$1 \cdot 10^{15}$	$30 \pm 4_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$
$1.5 \cdot 10^{15}$	$42 \pm 4_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$
$3 \cdot 10^{15}$	$55 \pm 6_{\text{(CCE)}} \pm 6_{\text{(E-field)}}$

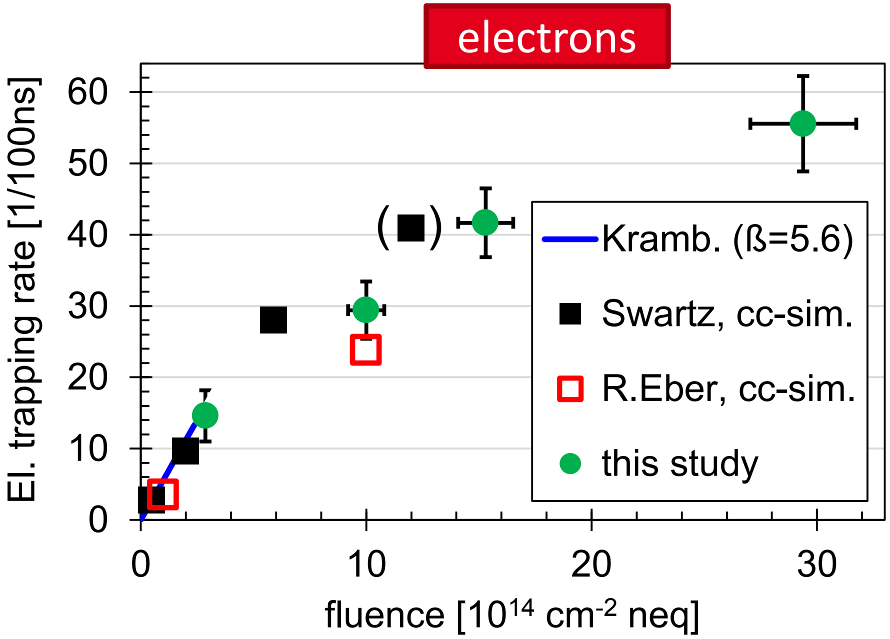


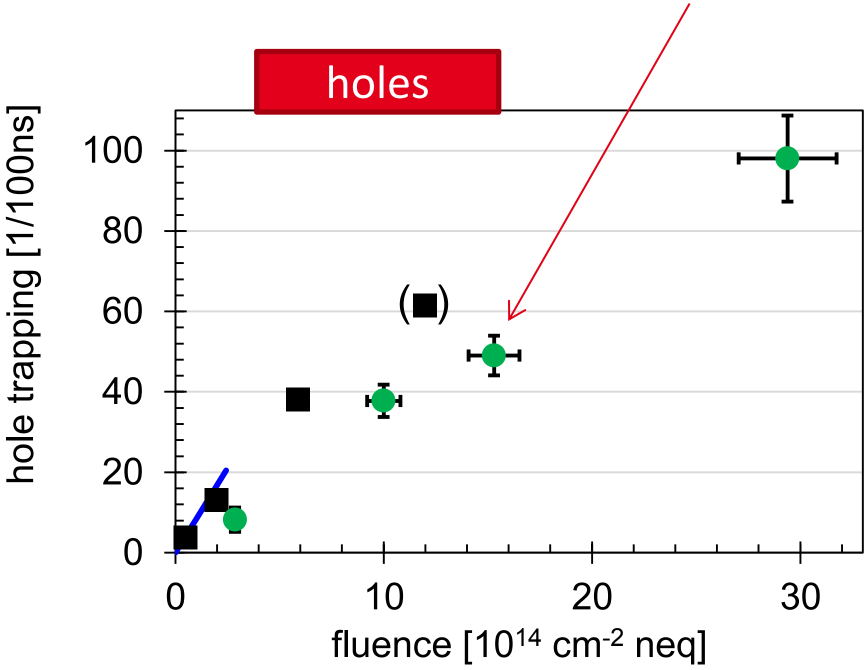
Results on the trapping rate

After 23 GeV protons:

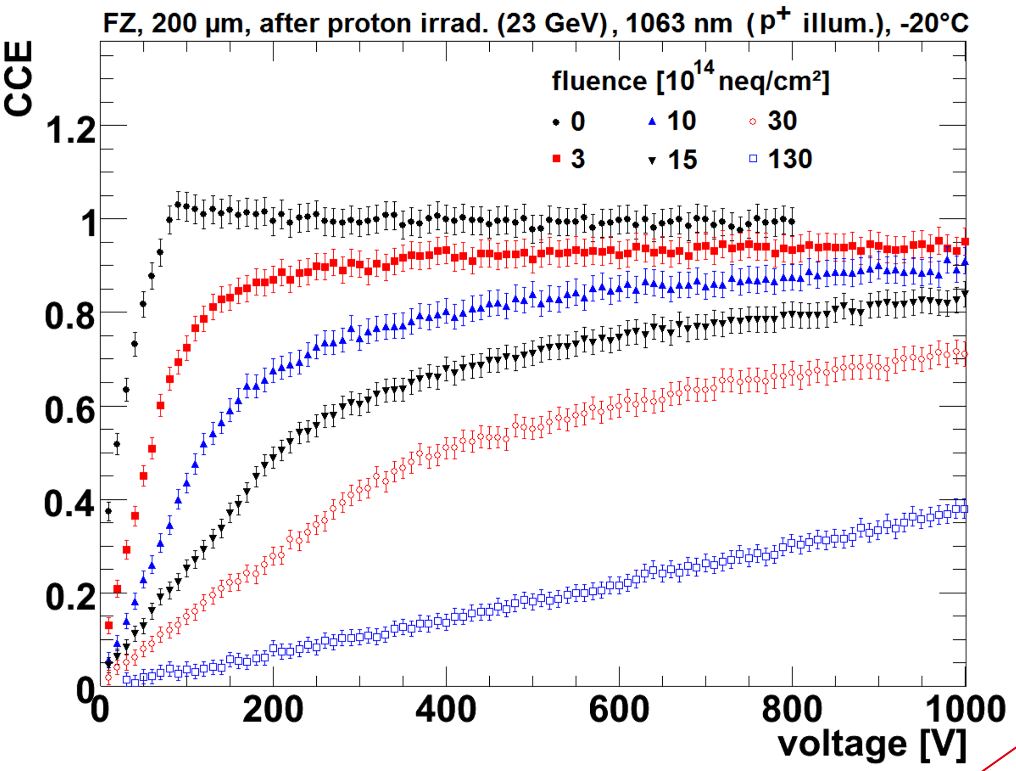
ϕ_{neq} [neq/cm^2]	$1/\tau_e$ [1/100 ns]	$1/\tau_h$ [1/100 ns]
$3 \cdot 10^{14}$	$14.5 \pm 3.5_{\text{(CCE)}} \pm 0.5_{\text{(E-field)}}$	$8.5 \pm 2.5_{\text{(CCE)}} \pm 0.5_{\text{(E-field)}}$
$1 \cdot 10^{15}$	$30 \pm 4_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$	$38 \pm 4_{\text{(CCE)}} \pm 4_{\text{(E-field)}}$
$1.5 \cdot 10^{15}$	$42 \pm 4_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$	$49 \pm 5_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$
$3 \cdot 10^{15}$	$55 \pm 6_{\text{(CCE)}} \pm 6_{\text{(E-field)}}$	$98 \pm 10_{\text{(CCE)}} \pm 12_{\text{(E-field)}}$

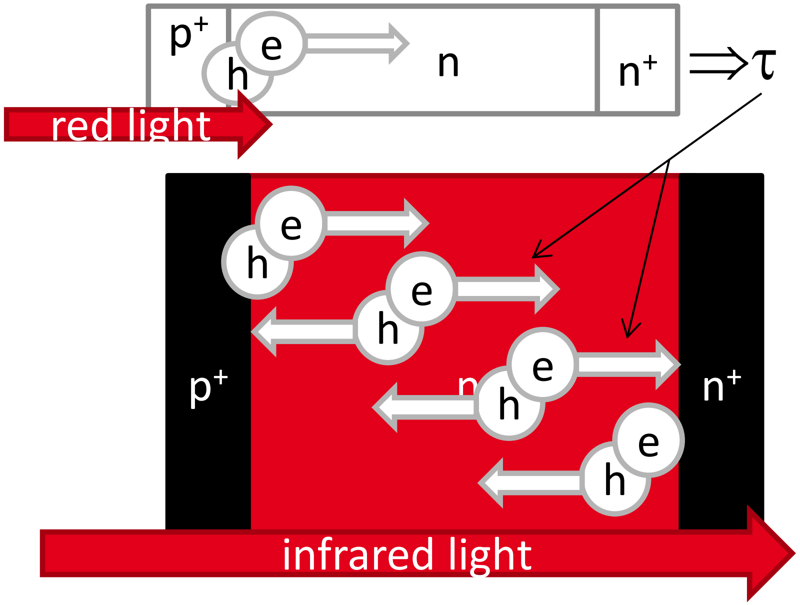






Check on infrared TCT measurements





this study

Kramberger extrapolated

At 600 V:

ϕ_{neq} [neq/cm^2]	CCE simulated A	CCE measured	CCE simulated B
$3 \cdot 10^{14}$	0.92 ± 0.03	0.93 ± 0.03	0.85 ± 0.02
$1 \cdot 10^{15}$	0.76 ± 0.03	0.85 ± 0.03	0.60 ± 0.03
$1.5 \cdot 10^{15}$	0.70 ± 0.03	0.75 ± 0.03	0.50 ± 0.03
$3 \cdot 10^{15}$	0.51 ± 0.03	0.60 ± 0.03	0.27 ± 0.02

Summary

Electron and hole drift (front- and rear-side illumination) **described using simulations**.

- **E(x) depends on the proton energy** used for irradiation **(23 GeV ≠ 23 MeV)**

Effective trapping rates have been determined for fluences **relevant at the HL-LHC, (up to ~$3 \cdot 10^{15}$ neq/cm^2)** assuming uniform trapping rates.
At 600 V the results have little dependence on the E(x) assumptions.

For charge carriers generated along the sensor depth using IR light:
⇒ **CCE predictions** low, but **improved by a factor of ~3** compared to extrapolations

Comment: Higher CCE than expected also seen in 150 µm thick Epi sensors.

After neutron irrad: see my talk, 20th RD50, after proton irrad: see DESY-THESIS-2009-022 (Jörn Lange)

Outlook:
Shall there be another study on trapping at high fluences?

Studies might be extended to
- MCz and p-type Silicon (so far FZ silicon with n-bulk only)
- mixed irradiation (protons + neutrons) (so far protons only)
- Use position-dependent trapping rates ? => additional free parameters !

Summary

Electron and hole drift (front- and rear-side illumination) **described using simulations**.

- **E(x) depends on the proton energy** used for irradiation **(23 GeV ≠ 23 MeV)**

Effective trapping rates have been determined for fluences **relevant at the HL-LHC, (up to ~$3 \cdot 10^{15}$ neq/cm²)** assuming uniform trapping rates.
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Outlook:
Shall there be another study on trapping at high fluences?

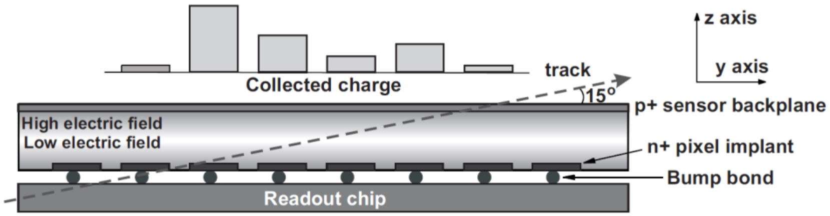
Thank you!

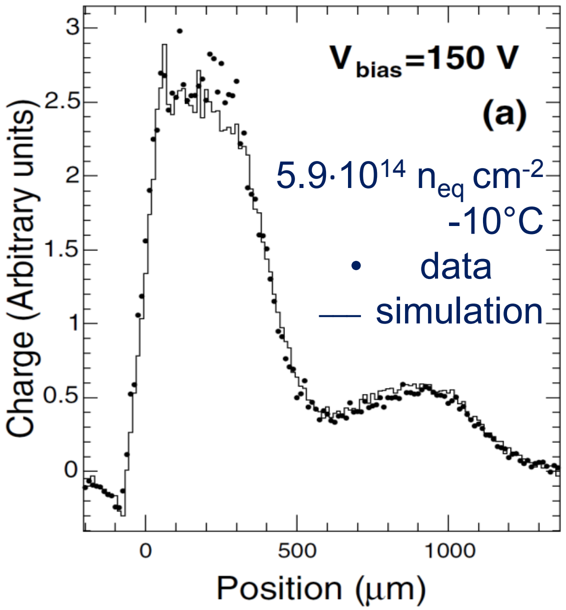
Backup →

Tuning of two effective defects

Fit by Morris Swartz et al. using TCAD and self-written „PixelAV“ simulation program to describe grazing angle measurements (arXiv:physics/0605215):

For 285 μm thick pixel sensors (125 μm x 125 μm, n-in-n with p-spray isolation)





Tuned: $N_D, N_A, \sigma_e^D, \sigma_h^D, \sigma_e^A, \sigma_h^A$

preliminary

$\Phi\ [10^{14}\ \mathrm{n_{eq} cm^{-2}}]$	0.5	2.0	5.9	12
$N_A\ [10^{14}\ \mathrm{cm^{-3}}]$	1.9	6.8	16	30.
$N_D\ [10^{14}\ \mathrm{cm^{-3}}]$	2.5	10	40	69.
$\sigma_e^{A/D}\ [10^{-15}\ \mathrm{cm^2}]$	6.60	6.60	6.60	3.8/0.94
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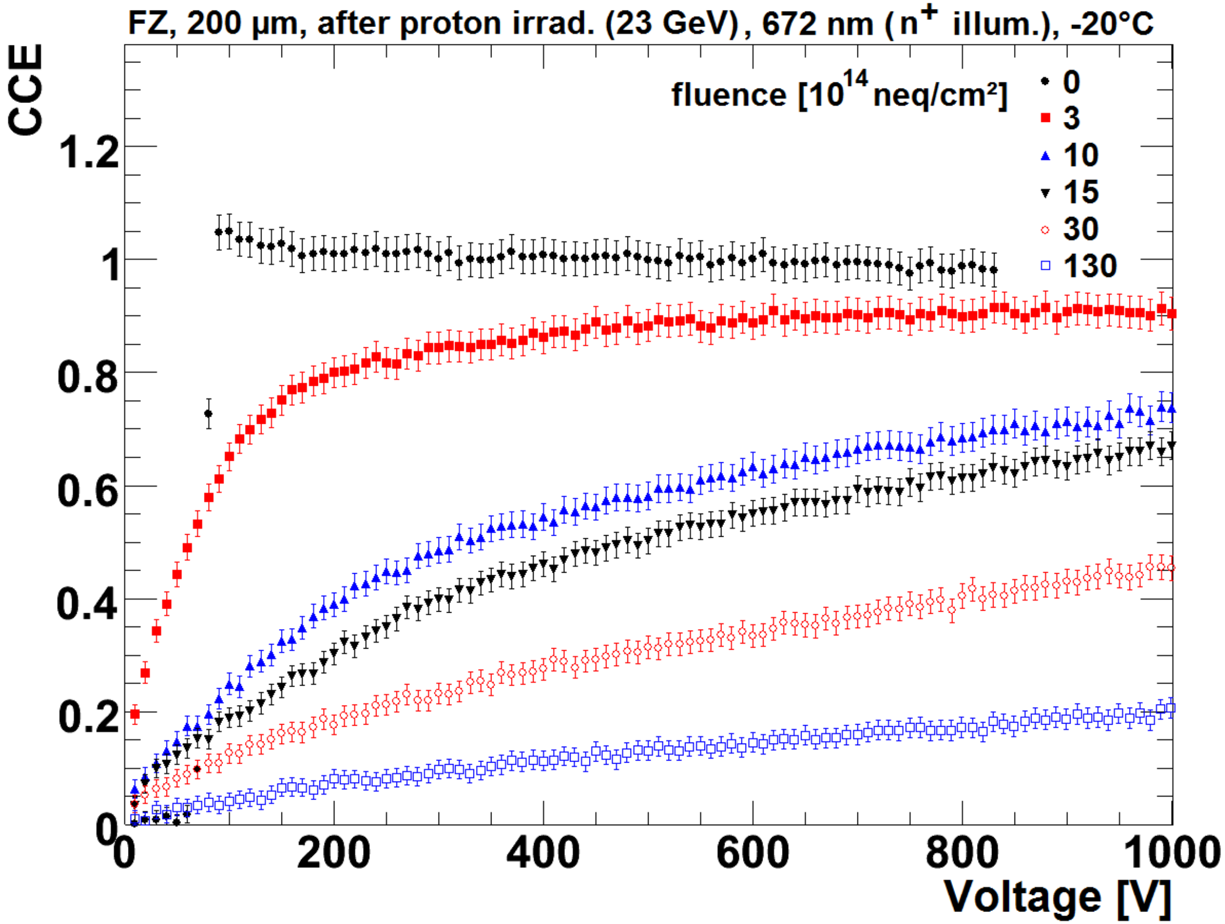
$\Gamma_e\ [10^{-2}\ \mathrm{ns^{-2}}]$	2.7	9.6	28.	41.
$\Gamma_h\ [10^{-2}\ \mathrm{ns^{-2}}]$	3.6	13.	38.	55.

defects to describe E-field

trapping rates used **in PixelAV**

CCE for holes (illumination at n^+)

$$CCE = \frac{Q_{irradiated}}{Q^{400V}_{non-irradiated}} = \frac{Q}{Q_0}$$



Thomas Poehlsen
thomas.poehlsen@desy.de

Universität Hamburg
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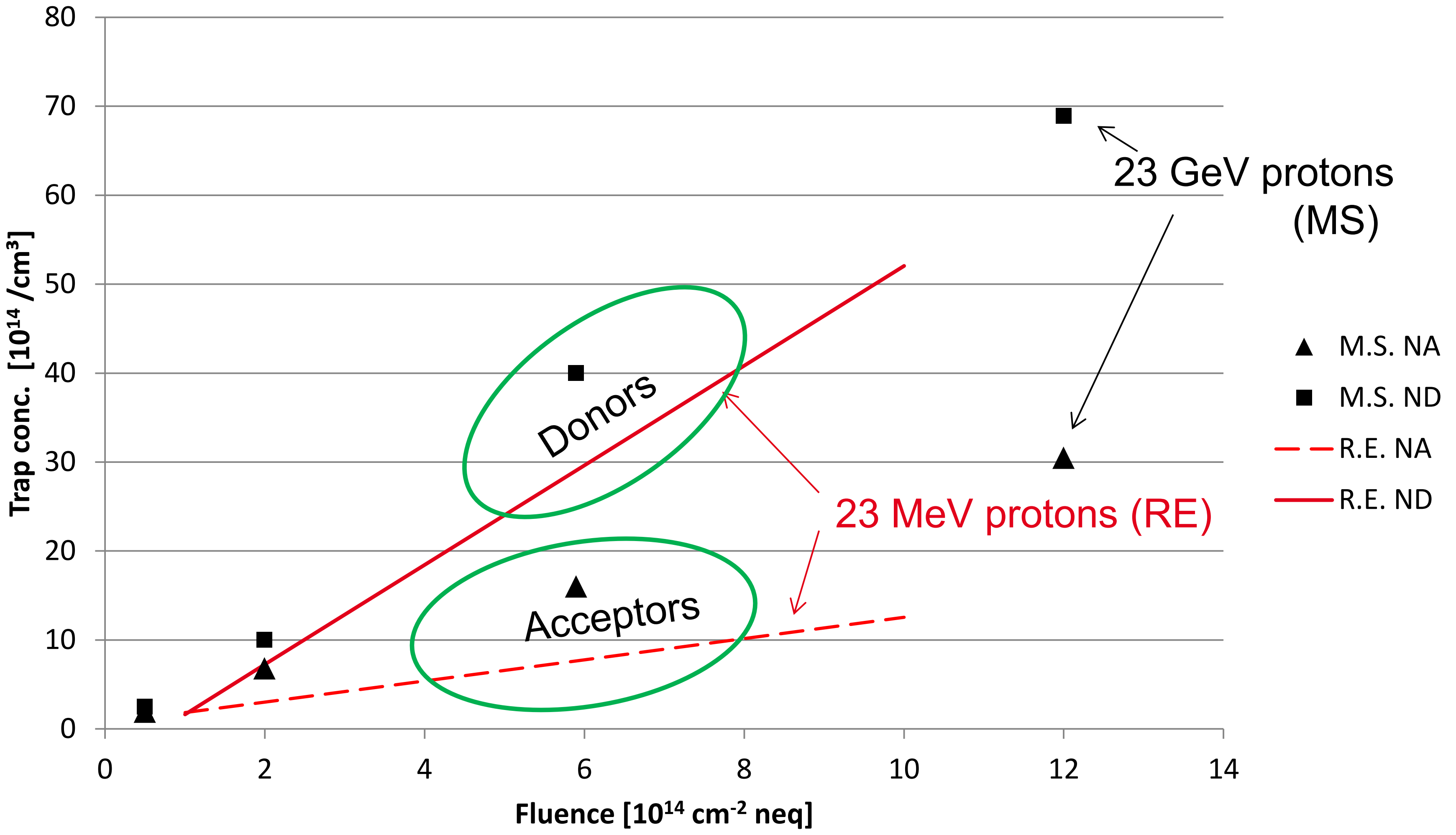
Defect concentration according to M. Swartz and R. Eber



Bulk damage

Due to non-ionising energy loss (NIEL) **defects** in the Si lattice are generated

$\Rightarrow$ **new states in the energy band gap –** responsible for …

- … additional **space charge** -> **operation voltages / thin sensors / oxygen conc.**
- … **current generation** -> heat and noise -> **more cooling**
- … **charge trapping** -> signal reduction -> **ROCs with suffic. low threshold**

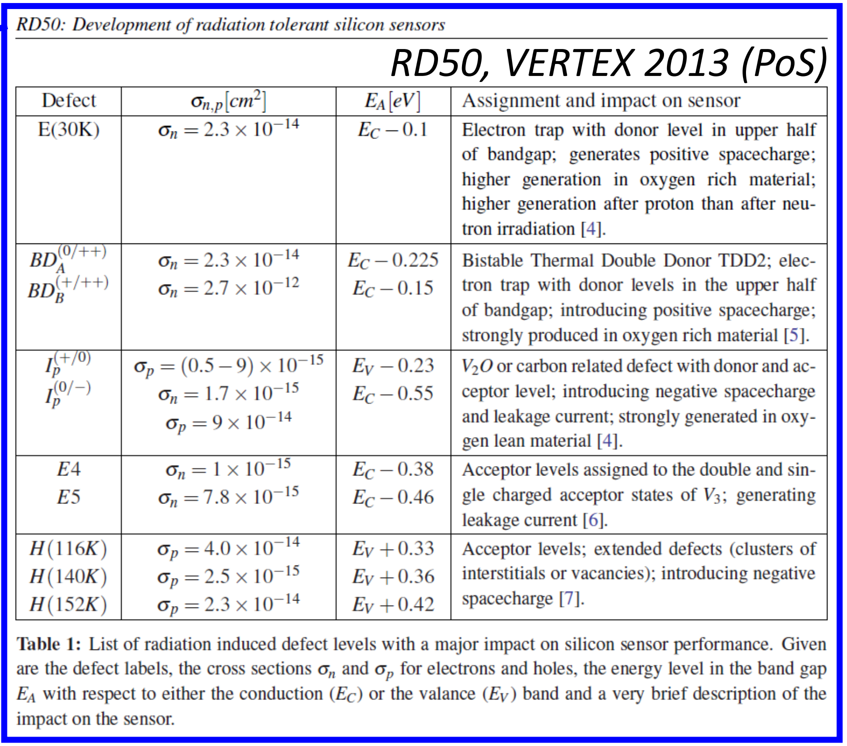
Defects may be simplified to an **2 effective defects***:

- „Donor“ at $E = E_V + 0.48$ eV
- „Acceptor“ at $E = E_C - 0.525$ eV

Concentrations and cross sections can be tuned in order to agree with charge collection measurements.
Typically free parameters are:

$$N_D,\ N_A,\ \sigma_e^D,\ \sigma_h^D,\ \sigma_e^A,\ \sigma_h^A$$

***EVL model:** NIM A 476 (2002) 556-564.



RD50: Development of radiation tolerant silicon sensors

RD50, VERTEX 2013 (PoS)

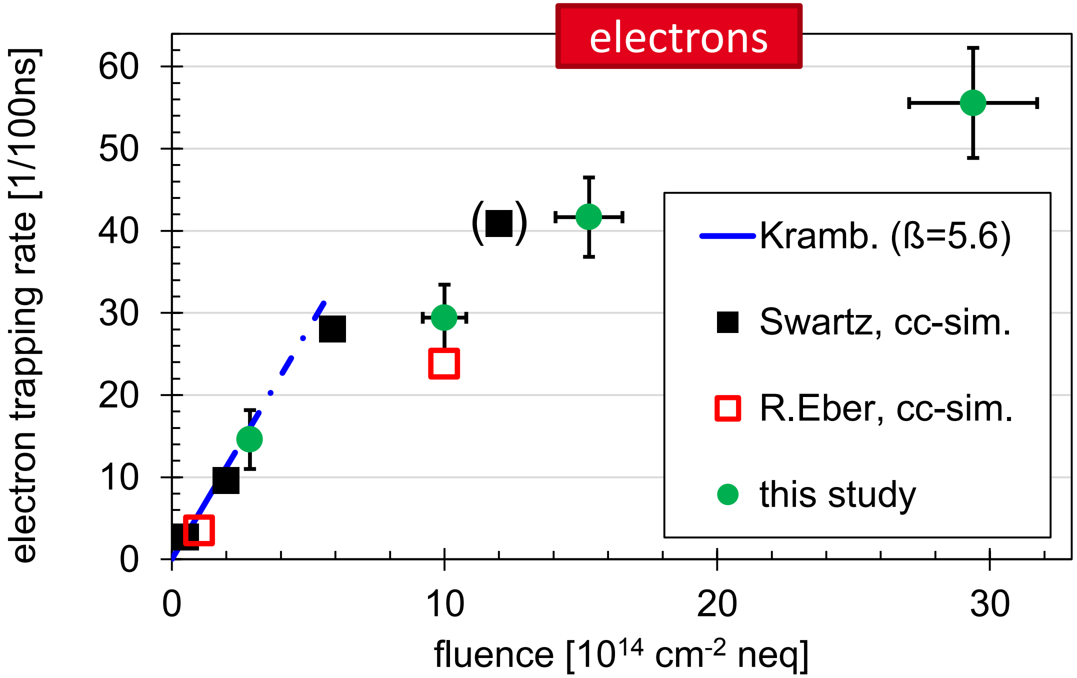
Defect	$\sigma_{n,p}[cm^2]$	$E_A[eV]$	Assignment and impact on sensor
E(30K)	$\sigma_n = 2.3 \times 10^{-14}$	$E_C - 0.1$	Electron trap with donor level in upper half of bandgap; generates positive spacecharge; higher generation in oxygen rich material; higher generation after proton than after neutron irradiation [4].
$BD_A^{(0/++)}$ $BD_B^{(+/++)}$	$\sigma_n = 2.3 \times 10^{-14}$ $\sigma_n = 2.7 \times 10^{-12}$	$E_C - 0.225$ $E_C - 0.15$	Bistable Thermal Double Donor TDD2; electron trap with donor levels in the upper half of bandgap; introducing positive spacecharge; strongly produced in oxygen rich material [5].
$I_p^{(+/0)}$ $I_p^{(0/-)}$	$\sigma_p = (0.5-9) \times 10^{-15}$ $\sigma_n = 1.7 \times 10^{-15}$ $\sigma_p = 9 \times 10^{-14}$	$E_V - 0.23$ $E_C - 0.55$	V_2O or carbon related defect with donor and acceptor level; introducing negative spacecharge and leakage current; strongly generated in oxygen lean material [4].
$E4$ $E5$	$\sigma_n = 1 \times 10^{-15}$ $\sigma_n = 7.8 \times 10^{-15}$	$E_C - 0.38$ $E_C - 0.46$	Acceptor levels assigned to the double and single charged acceptor states of V_3; generating leakage current [6].
$H(116K)$ $H(140K)$ $H(152K)$	$\sigma_p = 4.0 \times 10^{-14}$ $\sigma_p = 2.5 \times 10^{-15}$ $\sigma_p = 2.3 \times 10^{-14}$	$E_V + 0.33$ $E_V + 0.36$ $E_V + 0.42$	Acceptor levels; extended defects (clusters of interstitials or vacancies); introducing negative spacecharge [7].

Table 1: List of radiation induced defect levels with a major impact on silicon sensor performance. Given are the defect labels, the cross sections σ_n and σ_p for electrons and holes, the energy level in the band gap E_A with respect to either the conduction (E_C) or the valance (E_V) band and a very brief description of the impact on the sensor.

Results on the trapping rate

After 23 GeV protons:

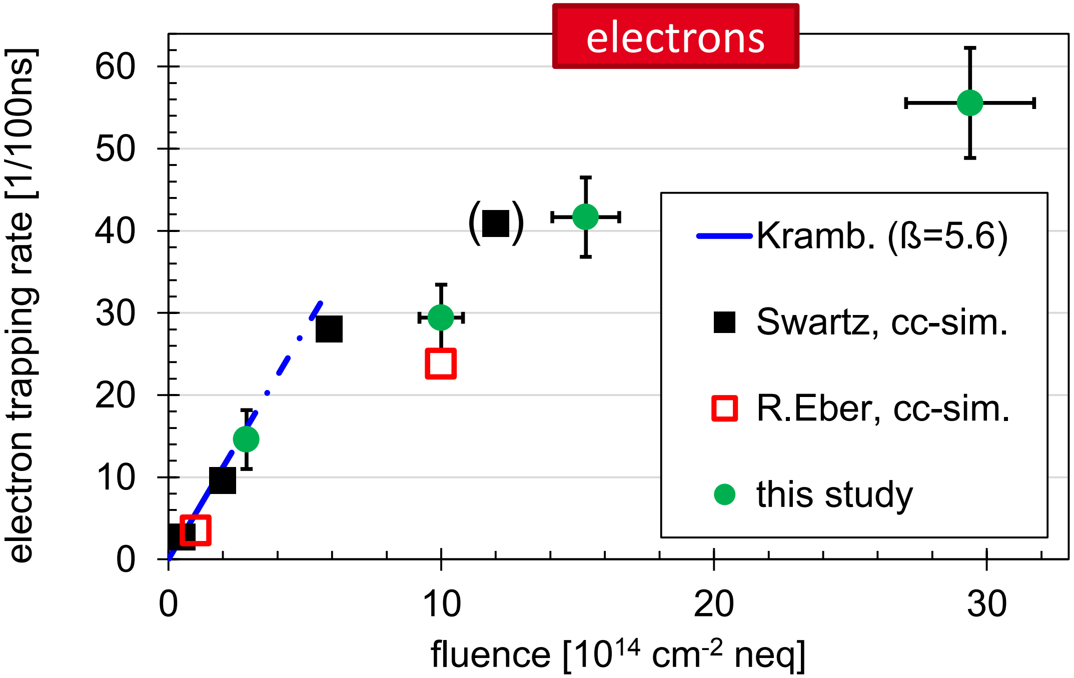
ϕ_{neq} [neq/cm^2]	$1/\tau_e$ [1/100 ns]
$3 \cdot 10^{14}$	$14.5 \pm 3.5_{\text{(CCE)}} \pm 0.5_{\text{(E-field)}}$
$1 \cdot 10^{15}$	$30 \pm 4_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$
$1.5 \cdot 10^{15}$	$42 \pm 4_{\text{(CCE)}} \pm 3_{\text{(E-field)}}$
$3 \cdot 10^{15}$	$55 \pm 6_{\text{(CCE)}} \pm 6_{\text{(E-field)}}$

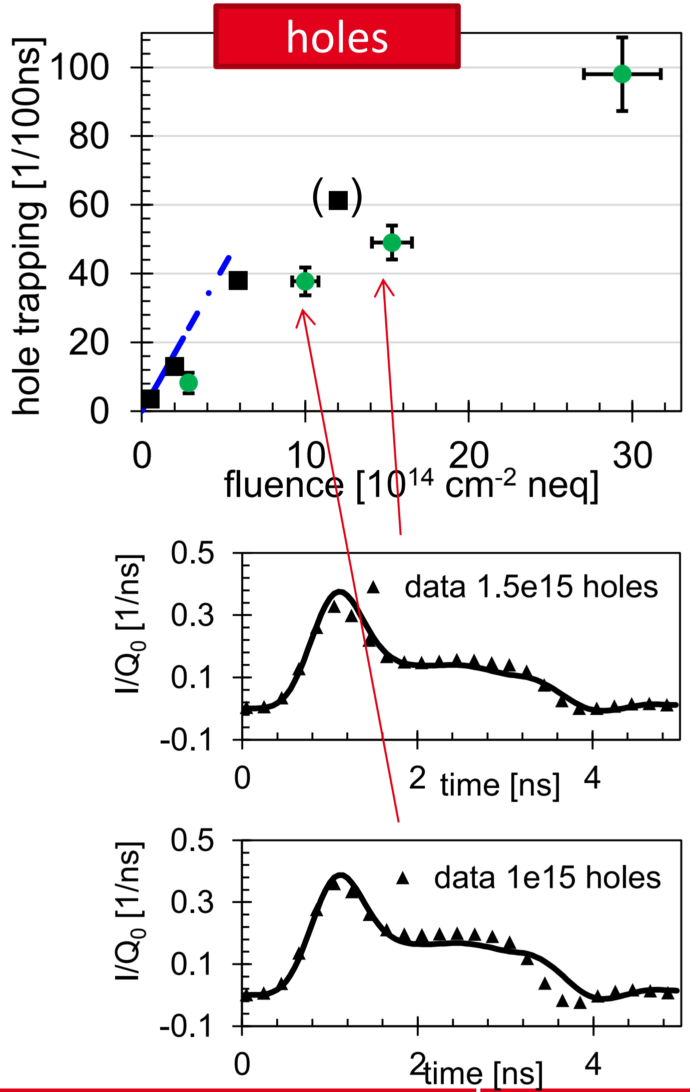


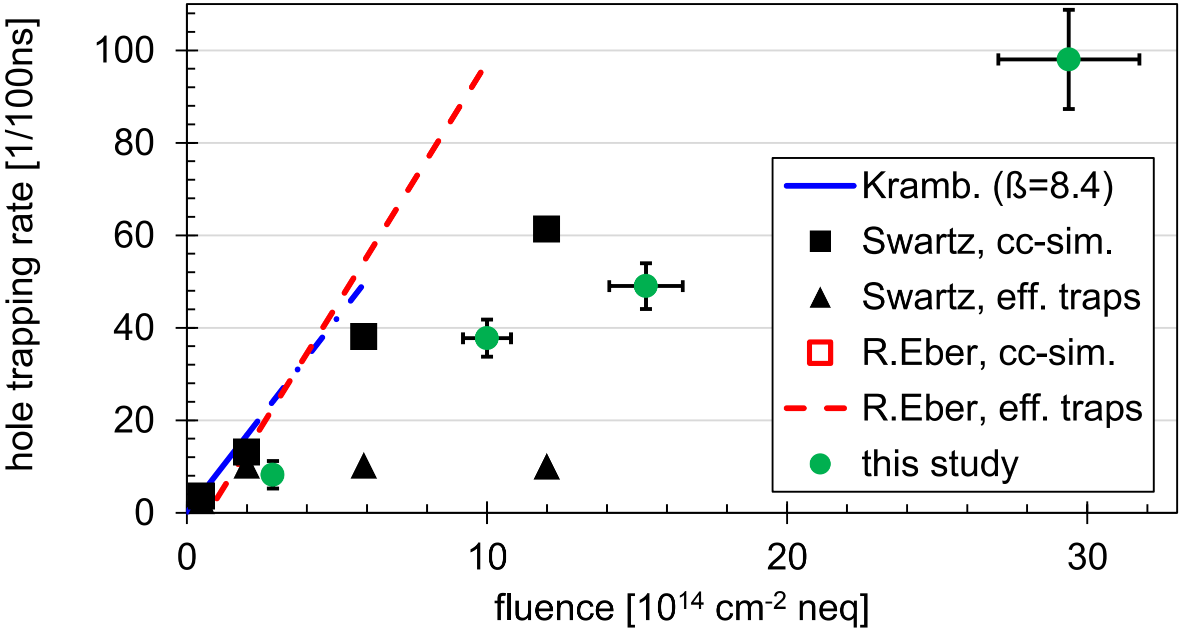
Results on the trapping rate

After 23 GeV protons:

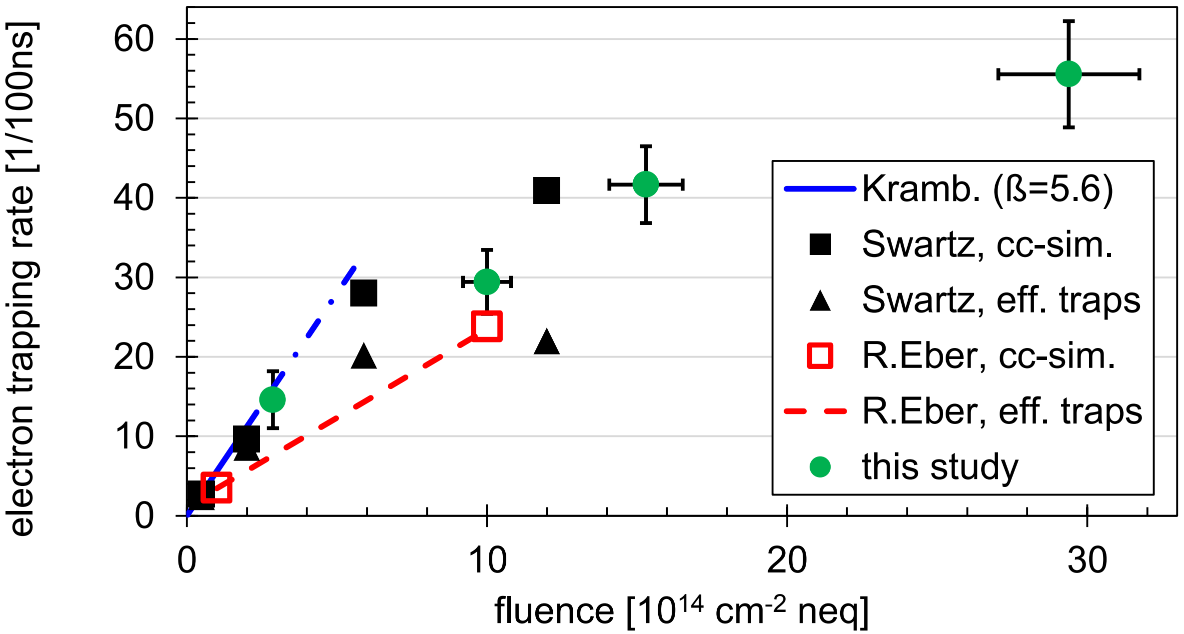
ϕ_{neq} [neq/cm^2]	$1/\tau_e$ [1/100 ns]	$1/\tau_h$ [1/100 ns]
$3 \cdot 10^{14}$	$14.5 \pm 3.5_{(\mathrm{CCE})} \pm 0.5_{(\mathrm{E\text{-}field})}$	$8.5 \pm 2.5_{(\mathrm{CCE})} \pm 0.5_{(\mathrm{E\text{-}field})}$
$1 \cdot 10^{15}$	$30 \pm 4_{(\mathrm{CCE})} \pm 3_{(\mathrm{E\text{-}field})}$	$38 \pm 4_{(\mathrm{CCE})} \pm 4_{(\mathrm{E\text{-}field})}$
$1.5 \cdot 10^{15}$	$42 \pm 4_{(\mathrm{CCE})} \pm 3_{(\mathrm{E\text{-}field})}$	$49 \pm 5_{(\mathrm{CCE})} \pm 3_{(\mathrm{E\text{-}field})}$
$3 \cdot 10^{15}$	$55 \pm 6_{(\mathrm{CCE})} \pm 6_{(\mathrm{E\text{-}field})}$	$98 \pm 10_{(\mathrm{CCE})} \pm 12_{(\mathrm{E\text{-}field})}$







Thomas Poehlsen
thomas.poehlsen@desy.de

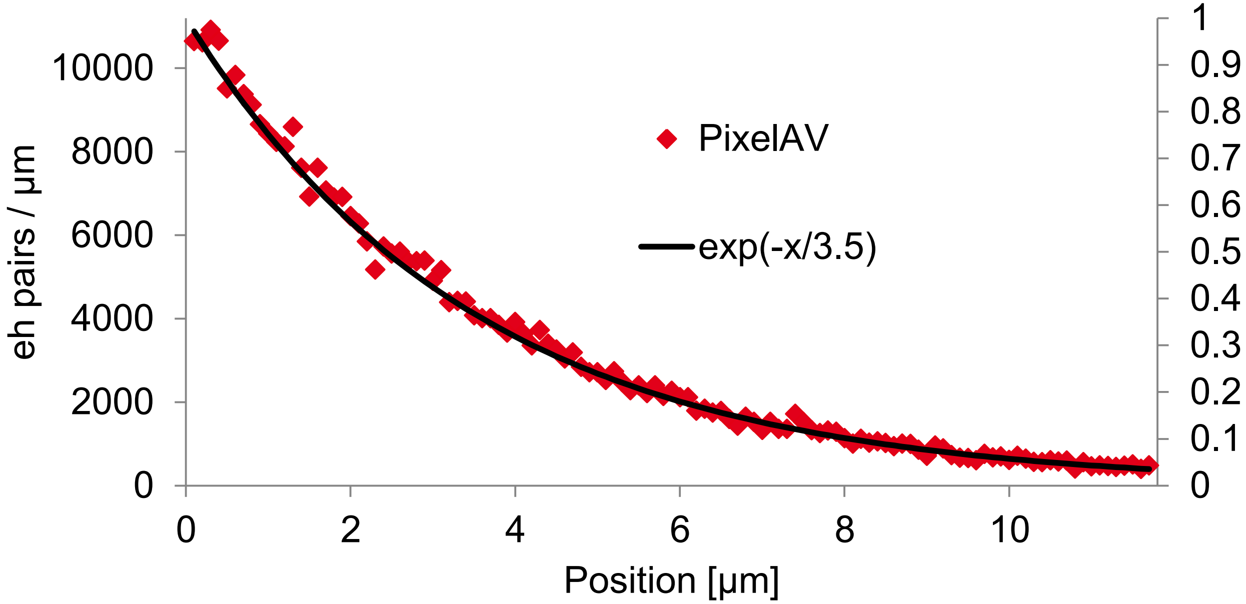

electron trapping rate [1/100ns]
60
50
40
30
20
10
0
0
10
20
30
fluence [10^{14} cm^{-2} neq]
Kramb. (ß=5.6)
Swartz, cc-sim.
Swartz, eff. traps
R.Eber, cc-sim.
R.Eber, eff. traps
this study

Eh-pair generation by laser light in PixelAV

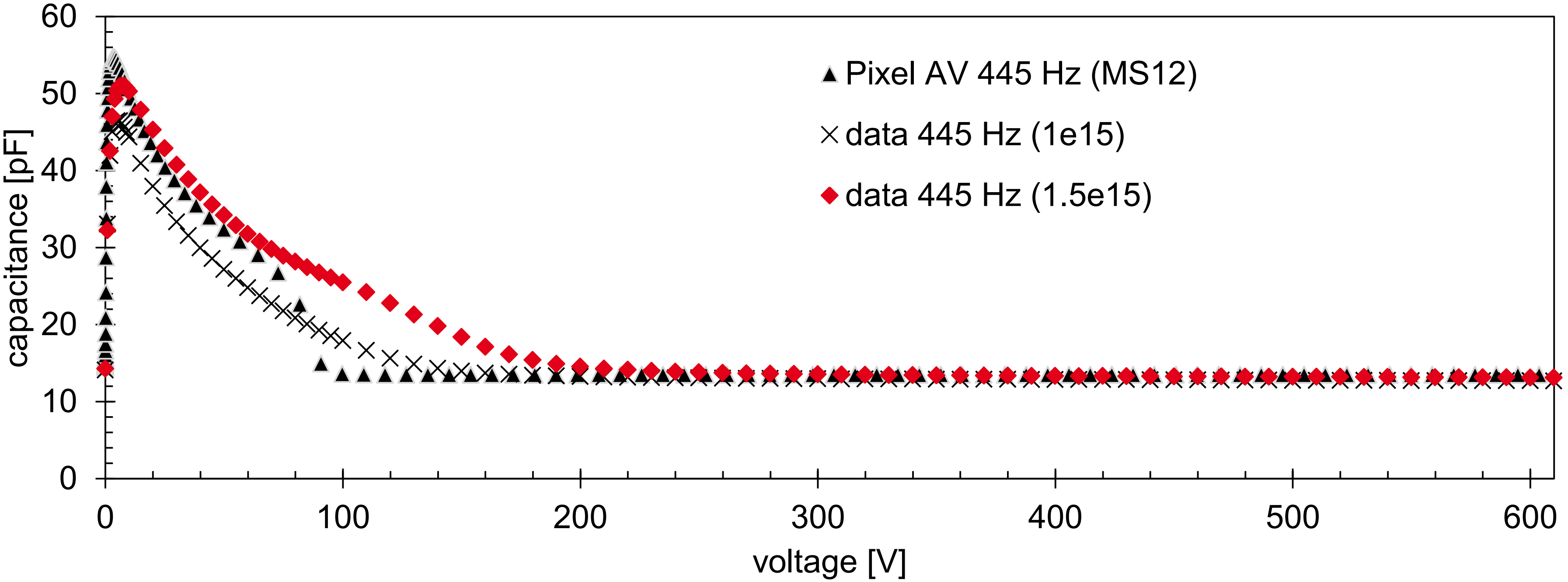
Each eh pair is generated with a random generator.

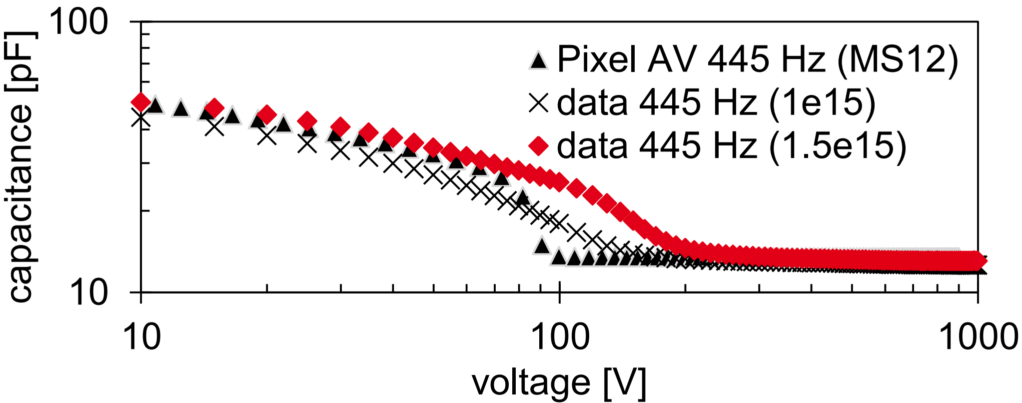
The generated eh pairs are distributed according to a penetration depth of 3.5 µm

40 000 eh pairs are generated at the front:

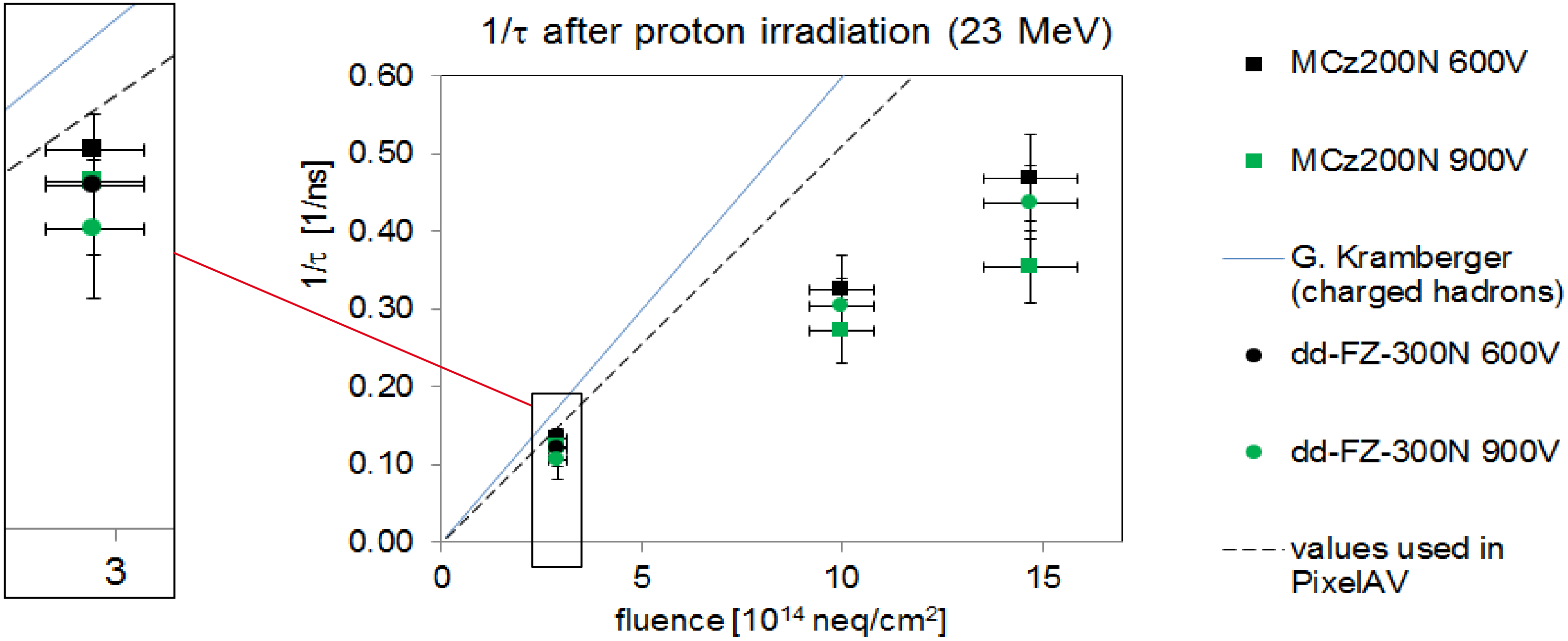


CV curves: 2 x data and 1 x simulation





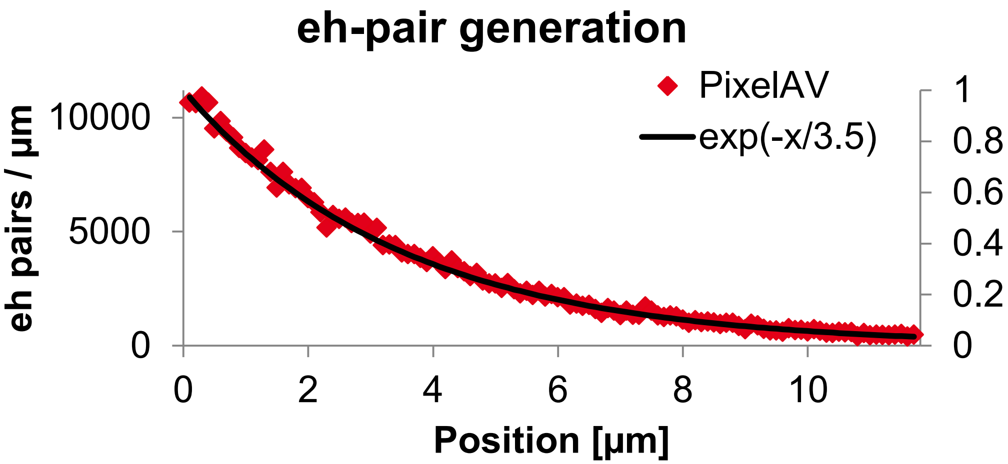
Electron trapping rates in 200 and 300 µm thick sensors



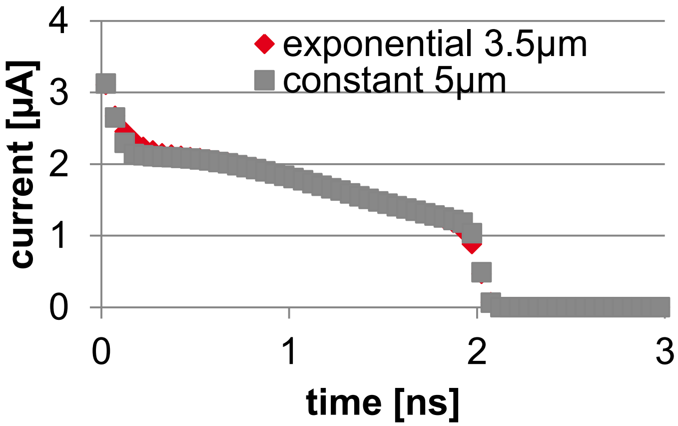
For this plot E=const was assumed

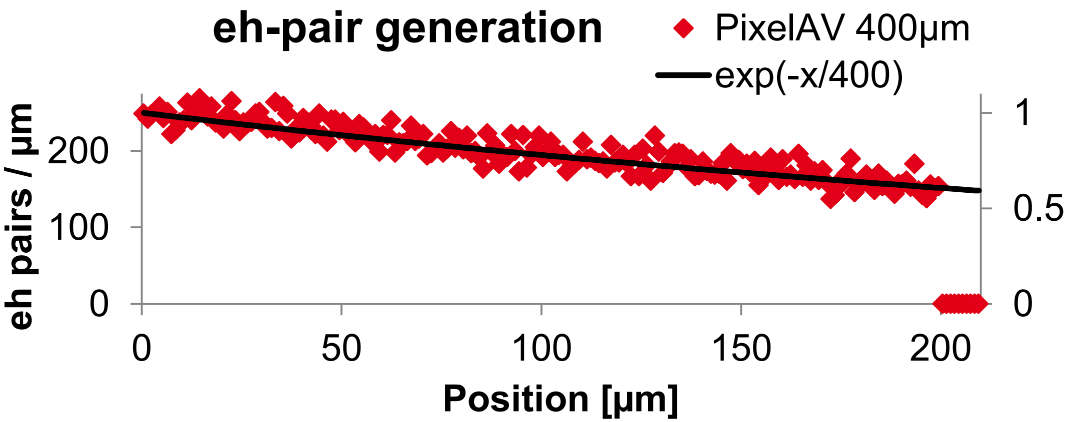
Trapping times for electrons at high fluences are lower compared to expectations by G. Kramberger also for MCz and dd-FZ 300 µm thick materials.

Charge deposition with light

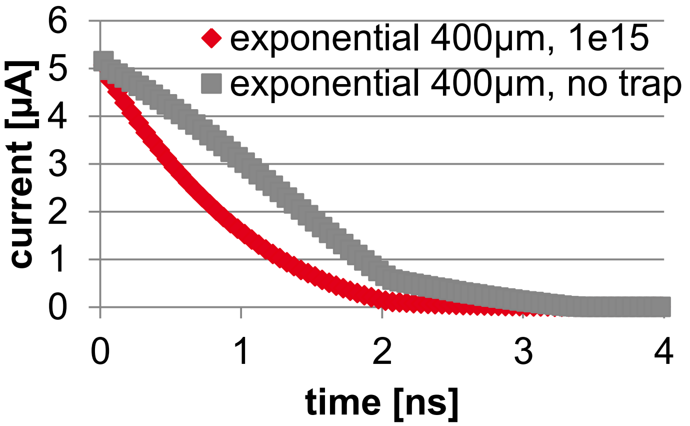


eh-pair generation





eh-pair generation



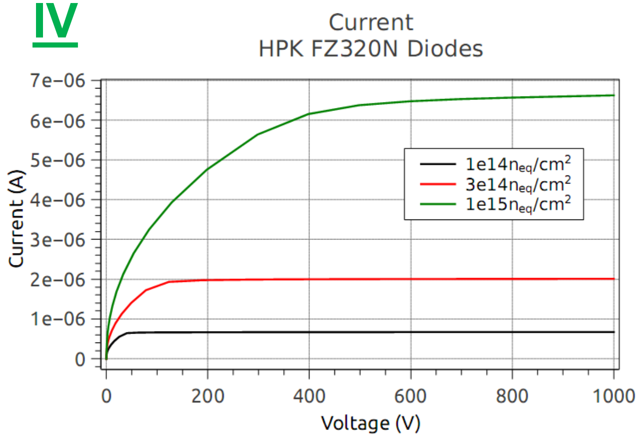
Eh-pair generation implemented for different Apsorption lengths ✓

Tuning of the effective 2-defect model

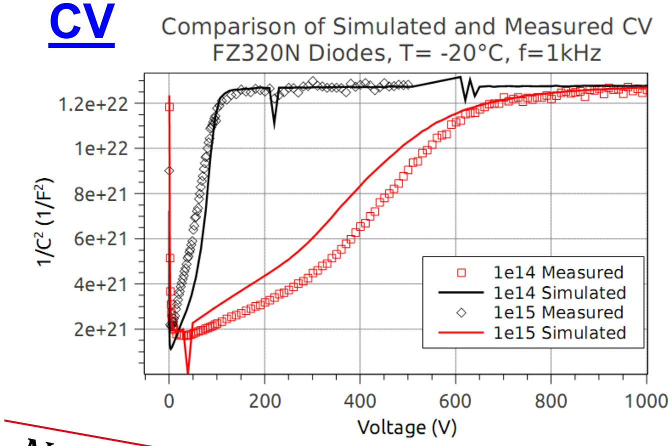
Fit in TCAD by Robert Eber (KIT) using **current**, **capacitance** and **red laser TCT** meas.
after **23 MeV proton irradiation,** 300 µm thick, dd-FZ p-on-n pad sensors

see Robert Eber's thesis:
KIT – EKP-2014-00012
(ekp.kit.edu/391.php)

IV

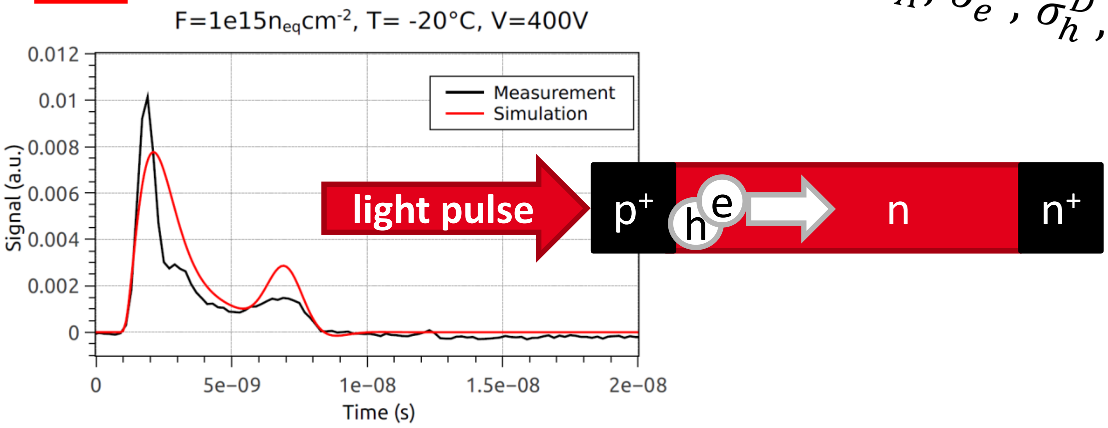


CV



$N_D, N_A, \sigma_e^D, \sigma_h^D, \sigma_e^A, \sigma_h^A \rightarrow$

TCT



Parameters tuned:

- Donor

N_D ▪ c = 5.598 * **F** – 3.959e14

$\sigma_{e,h}^D$ ▪ X(e) = X(h) = 1.0e-14cm2

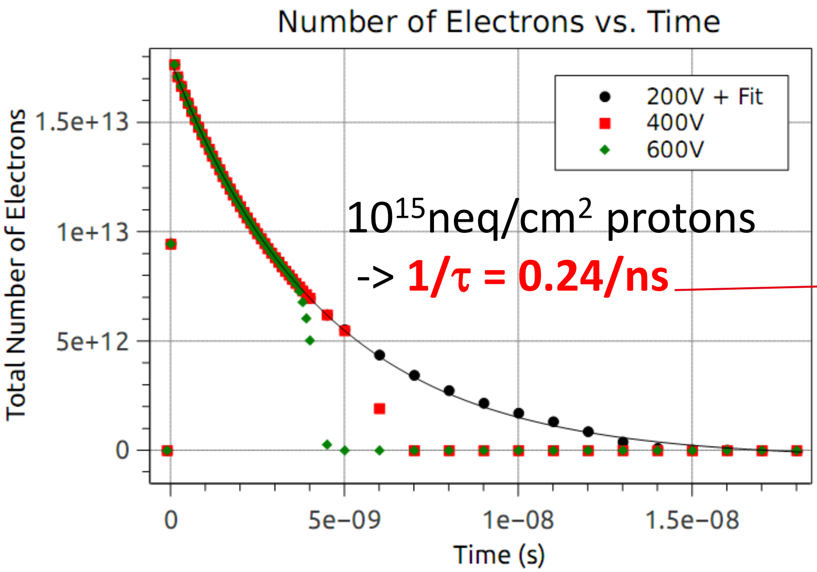
- Acceptor

N_A ▪ c = 1.189 * **F** + 0.645e14

$\sigma_{e,h}^A$ ▪ X(e) = X(h) = 1.0e-14cm2

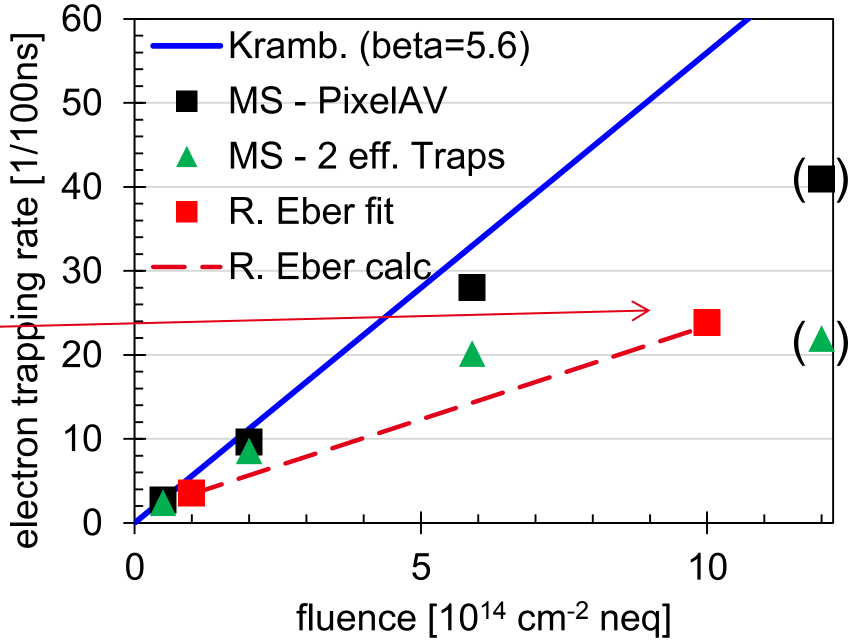
50% initial donor removal

Tuning of the effective 2-defect model … and consequences for trapping



10^{15}neq/cm^2 protons

-> **$1/\tau = 0.24$/ns**



Defect parameters were extracted with two different approaches:

- R. Eber: capacitance, current and red laser TCT measurements in TCAD
- M. Swartz: grazing-angle test beam measurements in PixelAV supported by TCAD

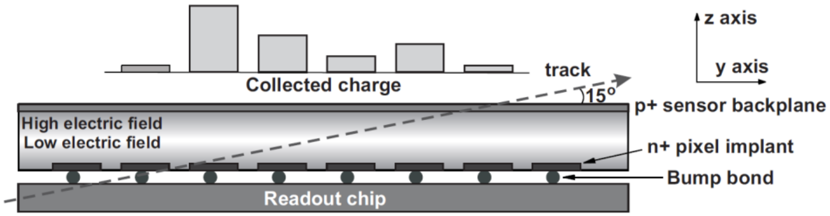
⇒ Trapping rates lower than expected at high fluences !

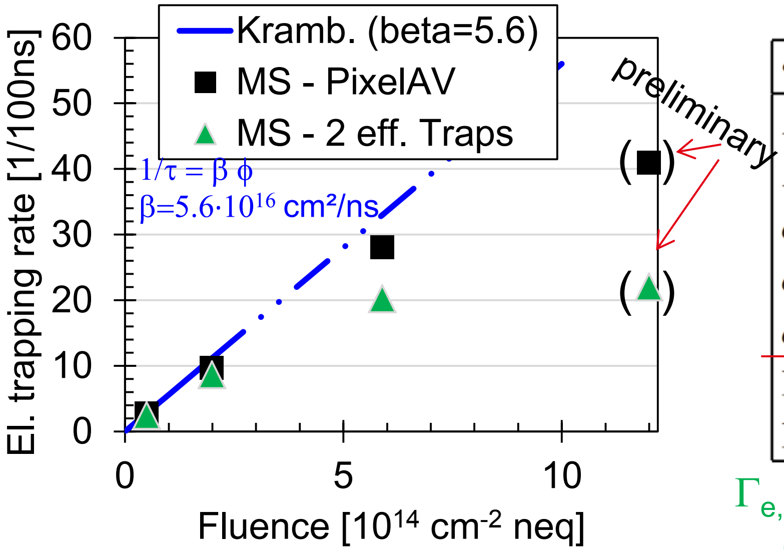
Can we determine the effective trapping rate directly from measured charge losses?

Tuning of two effective defects

Fit by Morris Swartz et al. using TCAD and self-written „PixelAV“ simulation program to describe grazing angle measurements (arXiv:physics/0605215):

For 285 µm thick pixel sensors (125 µm x 125 µm, n-in-n with p-spray isolation)





preliminary

Φ [10^{14} n$_{eq}$cm^{-2}]	0.5	2.0	5.9	12
N_A [10^{14} cm^{-3}]	1.9	6.8	16	30.
N_D [10^{14} cm^{-3}]	2.5	10	40	69.
$\sigma_e^{A/D}$ [10^{-15} cm^2]	6.60	6.60	6.60	3.8/0.94
σ_h^A [10^{-15} cm^2]	1.65	1.65	1.65	3.8
σ_h^D [10^{-15} cm^2]	6.60	6.60	1.65	0.94
Γ_e [10^{-2} ns^{-2}]	2.7	9.6	28.	41
Γ_h [10^{-2} ns^{-2}]	3.6	13.	38.	55.
$\Gamma_{e,\text{calculated from traps:}}$	**2.4**	**8.6**	**20.**	**22.**

$(\Gamma_e = 1.91e7\ \text{cm/s} \cdot \sigma_e^A \cdot N_A)$

defects to describe E-field

trapping rates used **in PixelAV**

trapping rates **in TCAD** (E-field)