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PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Light absorption and charge collection of highly irradiated silicon sensors

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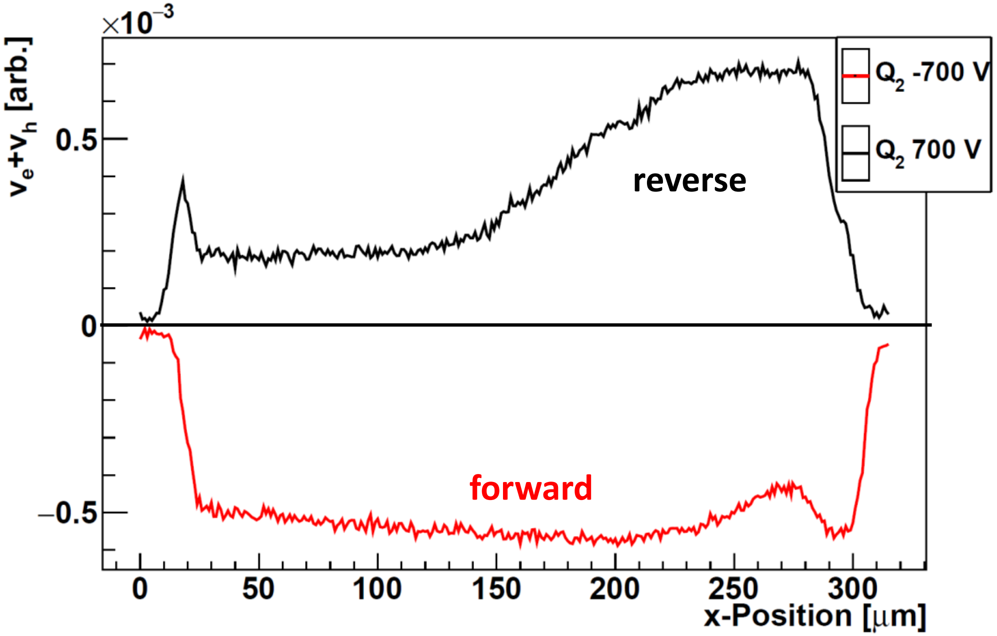
Motivation

$$\sum v_{e,h} \propto E$$



Strip sensor
285 µm n-type CiS
7.25e15 /cm²
-30 °C

Reverse bias:

- Trapped charge carriers inhomogeneous create space charge
- Hard to extract $E(x), v_{e,h}(\Phi), \tau_{e,h}(\Phi)$

Forward bias: $v_{e,h} \approx const$ → $E \approx const$ & $\tau_{e,h} \approx const$

- Similar to low field region for reverse bias

→ **use charge collection length $Q(x) = Q_0 e^{-x/\lambda_{e,h}}$ with $\lambda_{e,h} = v_{e,h} \cdot \tau_{e,h}$**

Absorption length needed to determine $Q_0(\alpha)$!

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Experimental method

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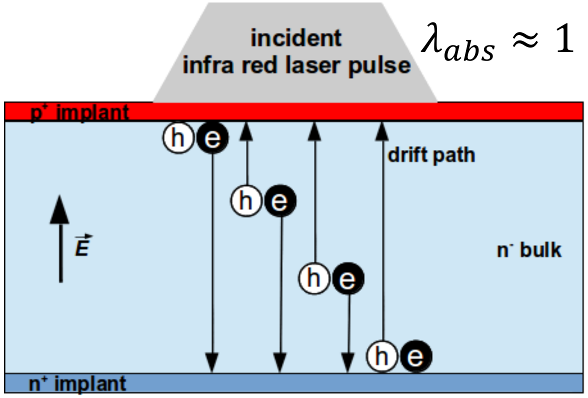
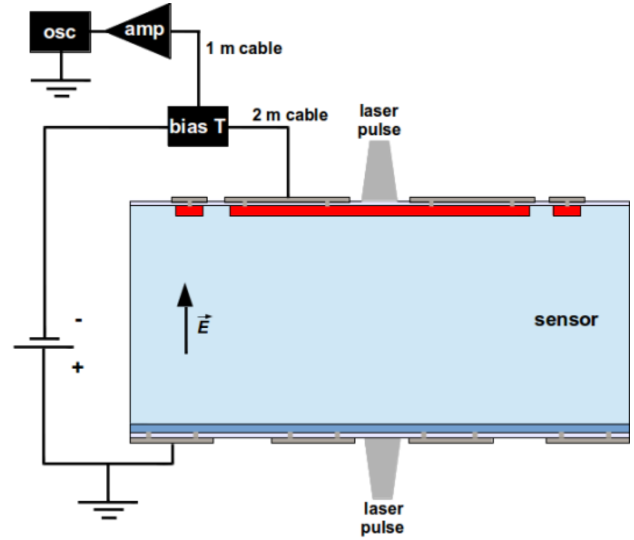
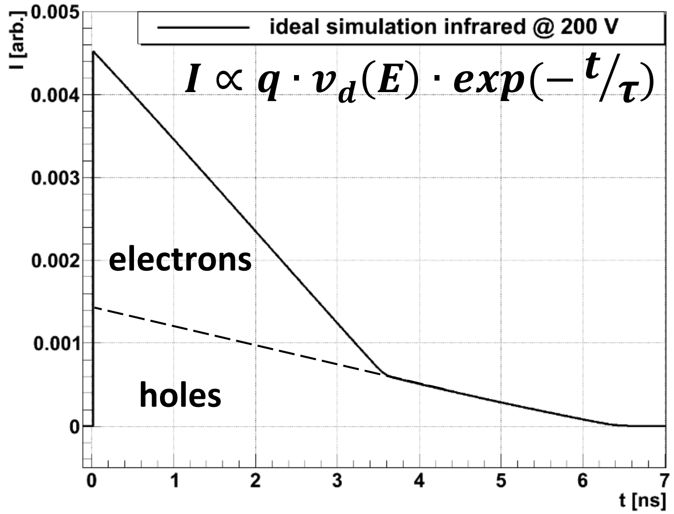
Transient Current Technique

- **Infrared laser** 1063 nm
  → simultaneous **e and h** drift



$\lambda_{abs} \approx 1$ mm @+20 °C





drift simulation
200 µm pad diode
@ 200 V

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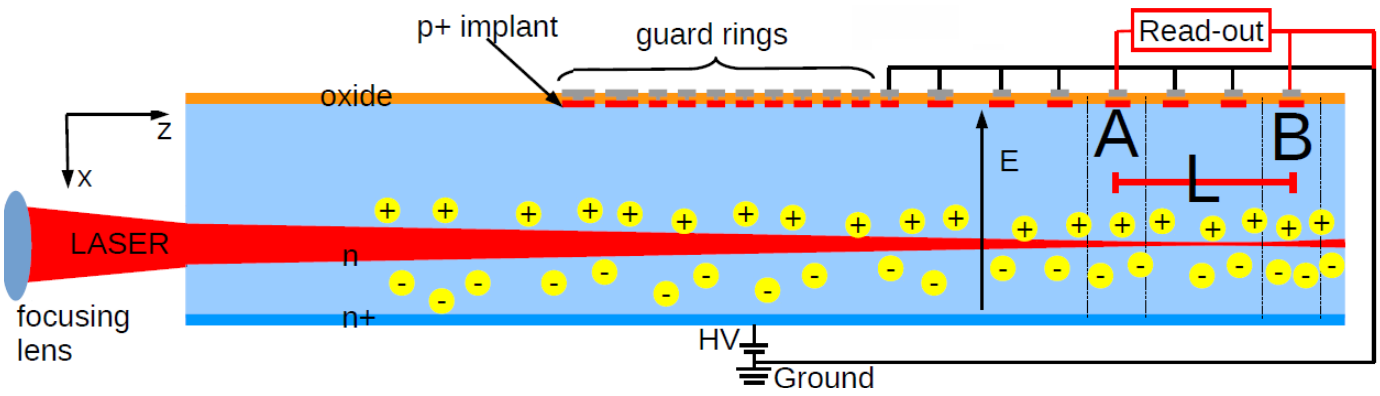
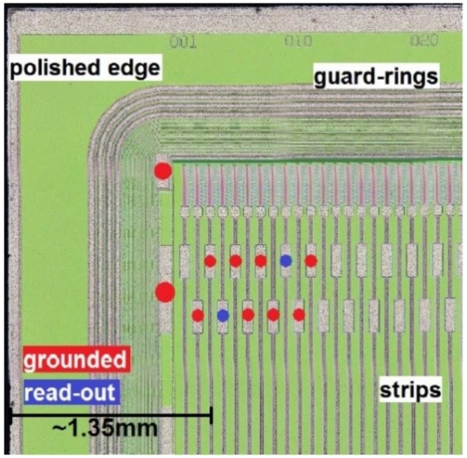
Edge Transient Current Technique

- **Infrared laser** 1052 nm
  → signal induced by drift of **e and h**

$\lambda_{abs} \approx 0.7$ mm @+20 °C





→ **F. Feindt Master thesis [DESY-THESIS-2017-006]**

- **Edge illumination of strip sensors**
  → charge carriers created at defined depth in the sensor
- **Two read-out channels**
  → absorption can be measured between two strips

Weighting field is assumed constant
Distortion of the electric field near the strips not accounted for

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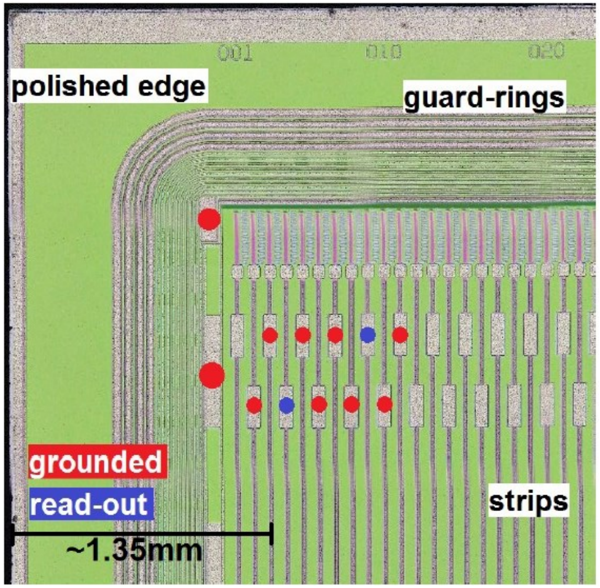
Investigated structures

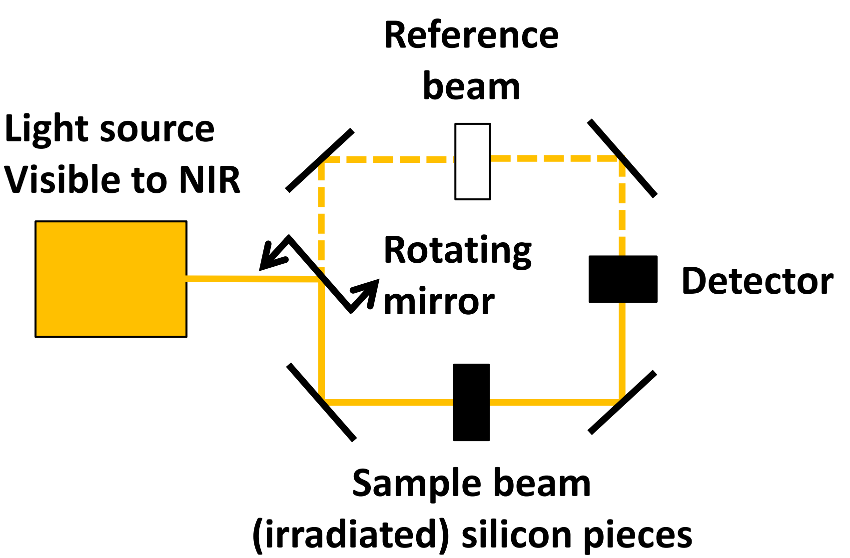
Investigated structures irradiated to 9E14 – 1.3E16 n_{eq}/cm^2

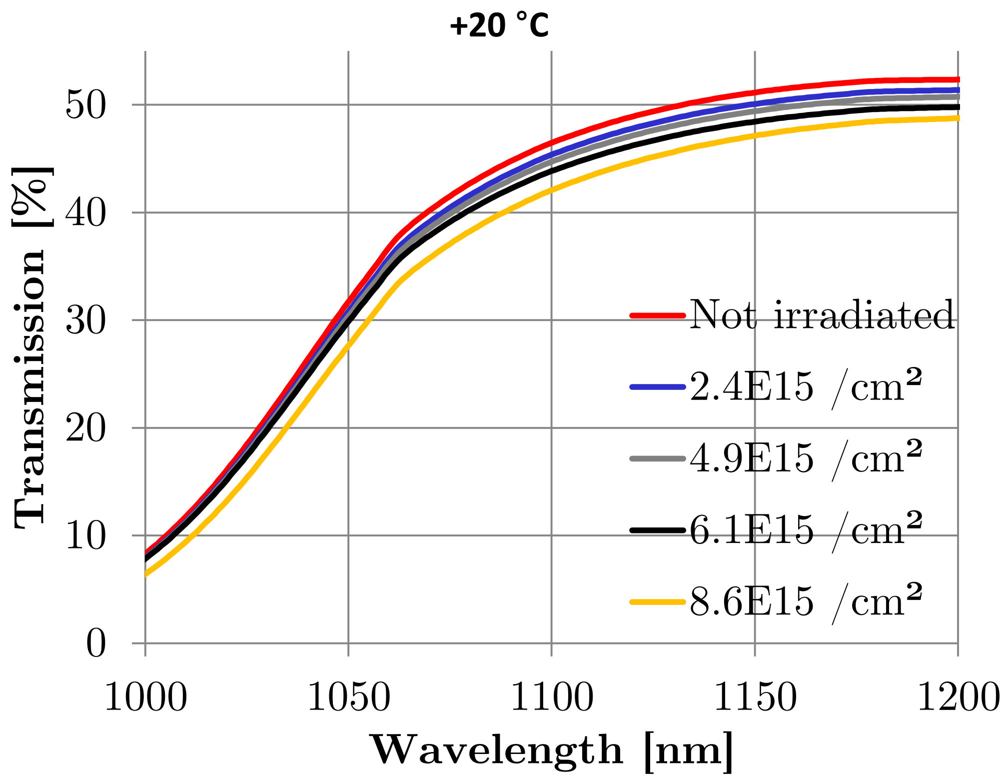
- **Bare silicon wafers (not processed)**
- **Diodes**
  - Initial doping N_D = (8E11 – 4E12) /cm³
  - Hamamatsu, float-zone: n- and p-type, 200 µm, area 5 mm² & 25 mm²
  - Hamamatsu, Magnetic Czochralski: p-type, 200 µm , area 5 mm² & 25 mm²
  - CiS, float-zone, n-type, 285 µm, 25 mm²
- **Strip sensors**
  - CiS, float-zone, n-type, 285 µm, N_D = 8E11 /cm³
    - Pitch 80 µm
    - Implant 18 µm
    - Aluminum 16 µm



Results

Absorption of light in irradiated silicon

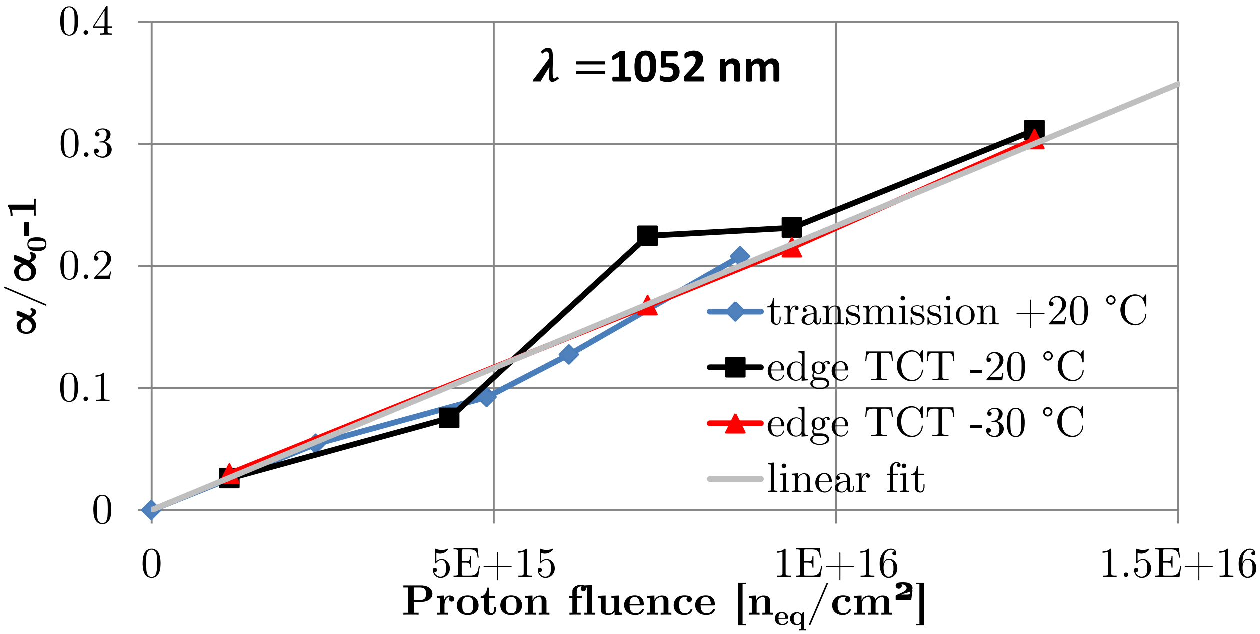




NIR light transmission measured for wide range of wavelengths

- **Absorption increases** @ RT and without bias voltage
  → compare results w/ edge-TCT measurements w/ bias voltage @ low T

Absorption of light in irradiated silicon



Absorption coefficient $\alpha \propto n_{abs}(\Phi)$ → Plot $\frac{\alpha(\Phi,T)}{\alpha_0(T)} - 1$ vs. Φ

- ***T* dependence for damage induced absorption = interband absorption**

$$\rightarrow \boldsymbol{\alpha(\Phi,\lambda,T) = \alpha_0(\lambda,T) \cdot \left(1 + \frac{\Phi}{\Phi_{abs}(\lambda)}\right)}$$

$\Phi_{abs}(1052\ nm) =$ 4.30E16 /cm²
$\Phi_{abs}(1064\ nm) =$ 3.32E16 /cm²

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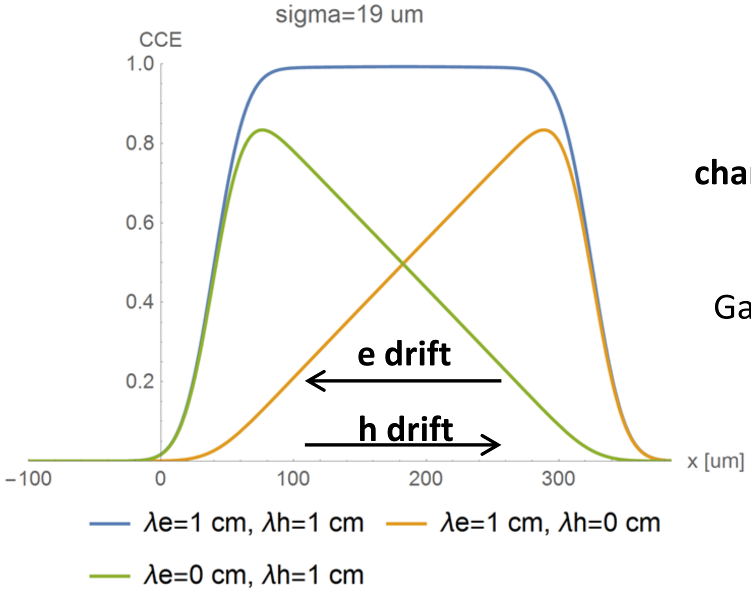
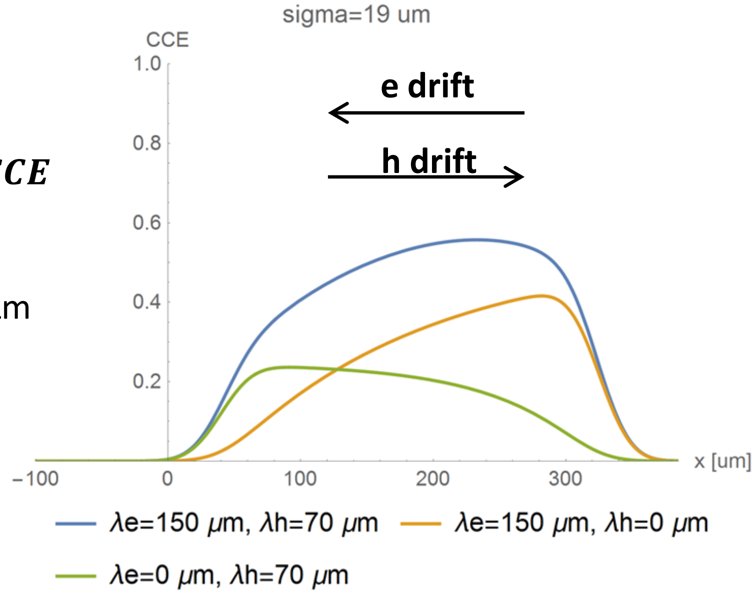
Edge TCT charge profile



charge collection efficiency CCE
vs. laser position x
of a 285 µm sensor w/
Gaussian laser beam σ=19 µm

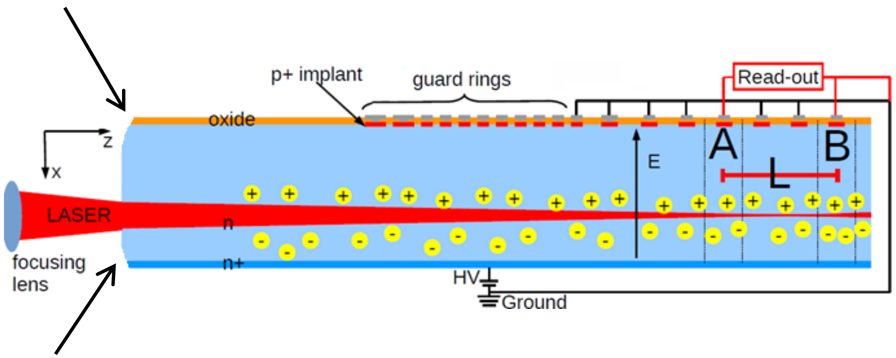


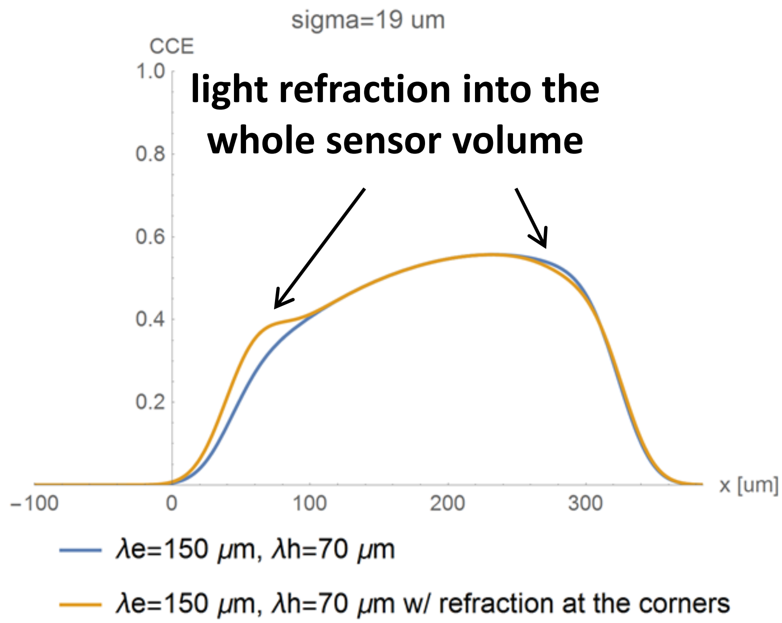
Use edge-TCT charge profile to determine charge collection length $\lambda_{e,h}$

- Assume $E(x) = const$ and $\tau_{e,h} = const$

$$Q(x) = q \cdot \frac{\int_0^d \left(\int_{x_0}^d e^{-\frac{(x_0-x)^2}{2\sigma^2}} \cdot e^{-\frac{x-x_0}{\lambda_{ccl}^e}} dx \right) dx_0 + \int_0^d \left(\int_0^{x_0} e^{-\frac{(x_0-x)^2}{2\sigma^2}} \cdot e^{-\frac{x_0-x}{\lambda_{ccl}^h}} dx \right) dx_0}{d\sigma\sqrt{2\pi}} \quad (5.12)$$

Edge TCT charge profile





Rounding of the edge & reflections modifiy the initial charge distribution (also affects the velocity profile)

- Use superposition of two Gaussian beams (wide & narrow) near edges
  → fit $\lambda_{e,h}$ to measurements

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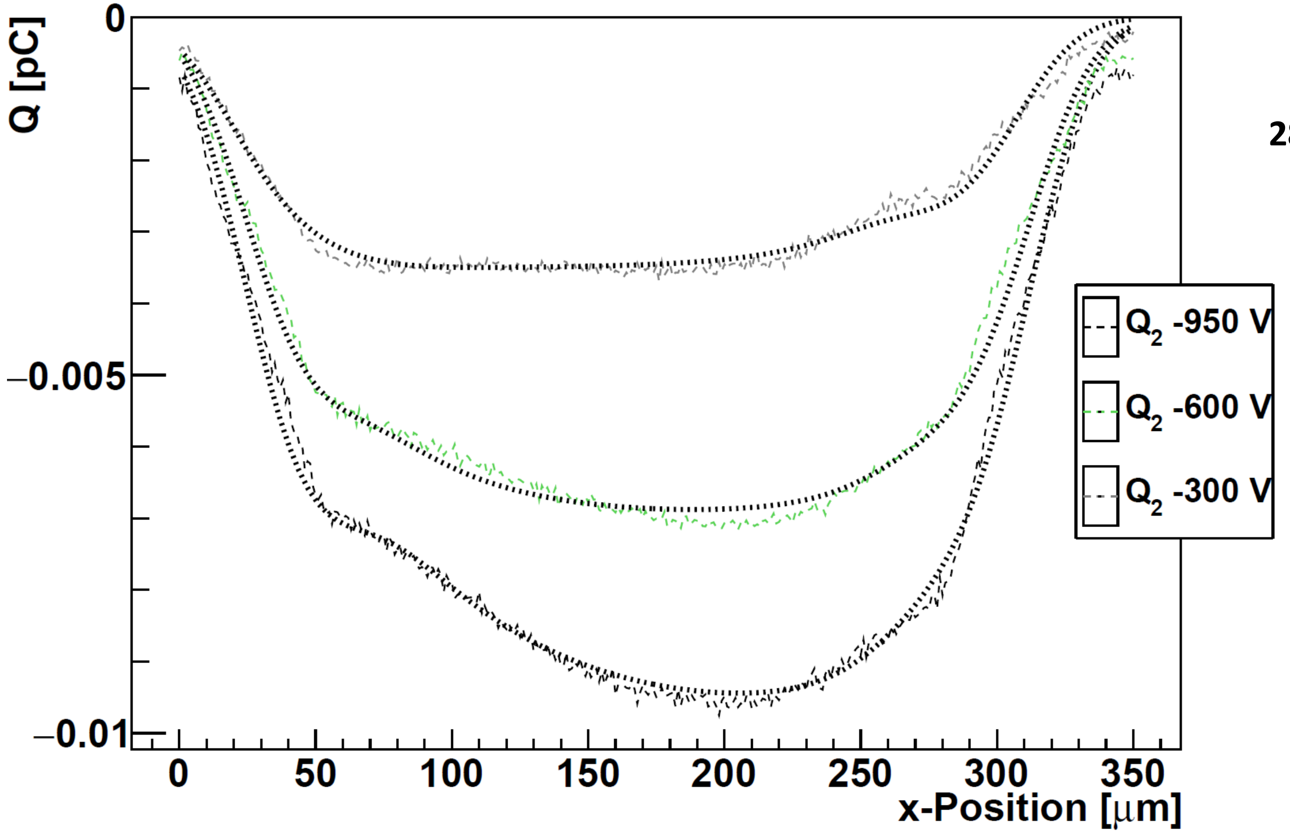
Fit of the charge profile



Strip sensor
285 µm n type CiS
7.25e15 /cm²
-30 °C
2nd strip

- **Obtaining $\lambda_{e,h}$ by fitting the $CCE(x)$** seems to work

→ measurements + analysis ongoing for -20 °C and -30 °C @ fluences 4.4E15 – 1.3E16 /cm² and for both read out strips

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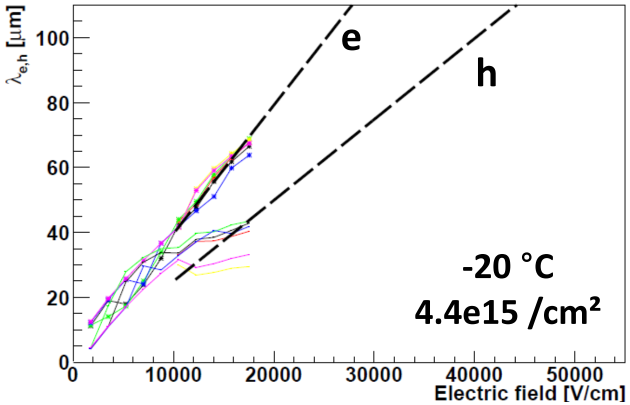
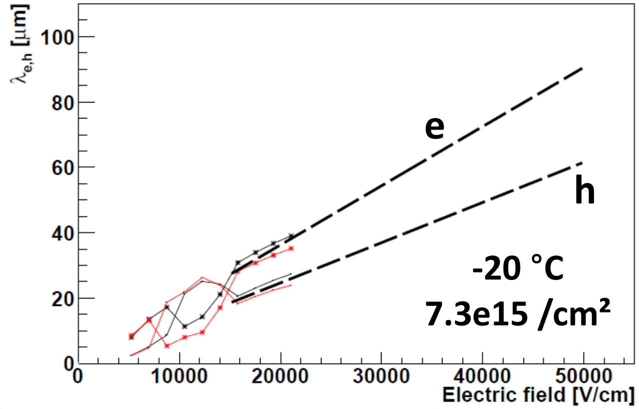
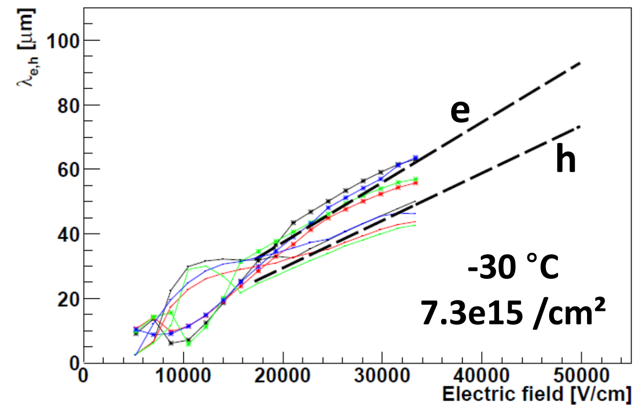
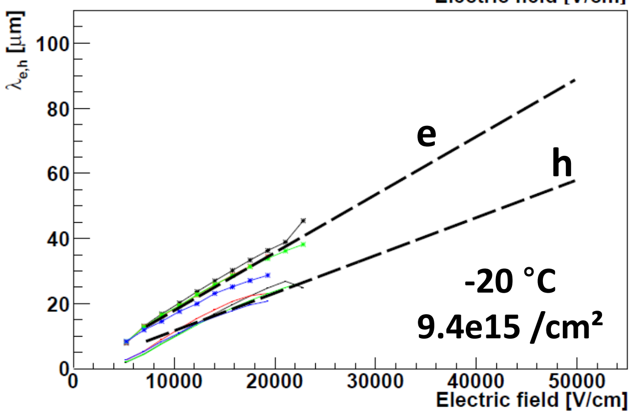
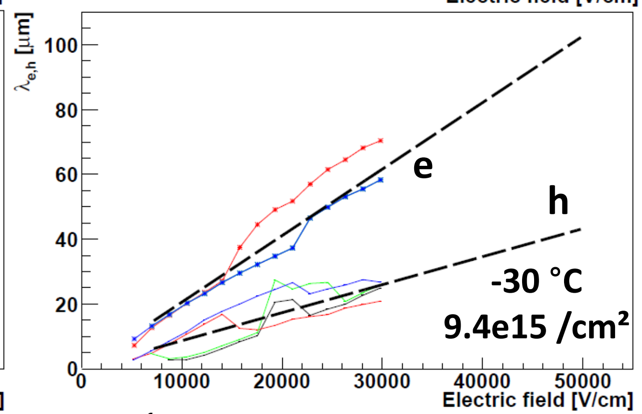
The charge collection length

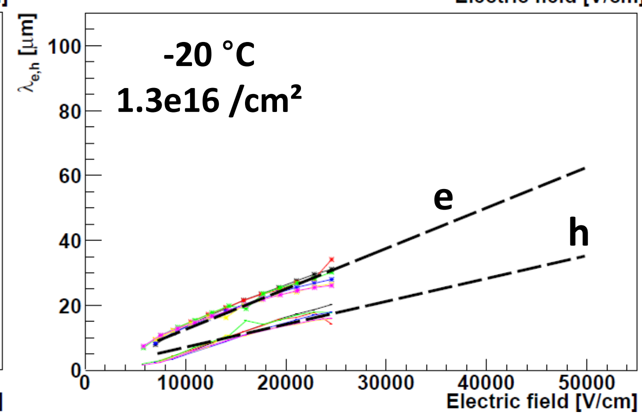








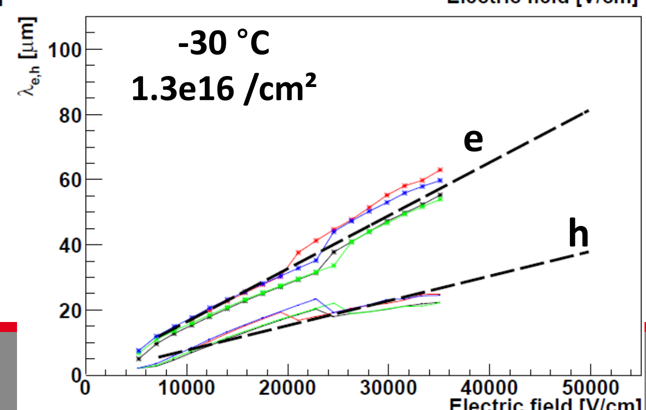




Charge collection length $\lambda_{e,h} \propto {}^{1}/_{n_{trap}}$

- $\lambda_{e,h}(E) = v(E)\tau = \mu\tau \cdot E \approx const \cdot E$

→ E dependence of $\mu(E)$ and $\tau(E)$ seem to cancel in the investigated region



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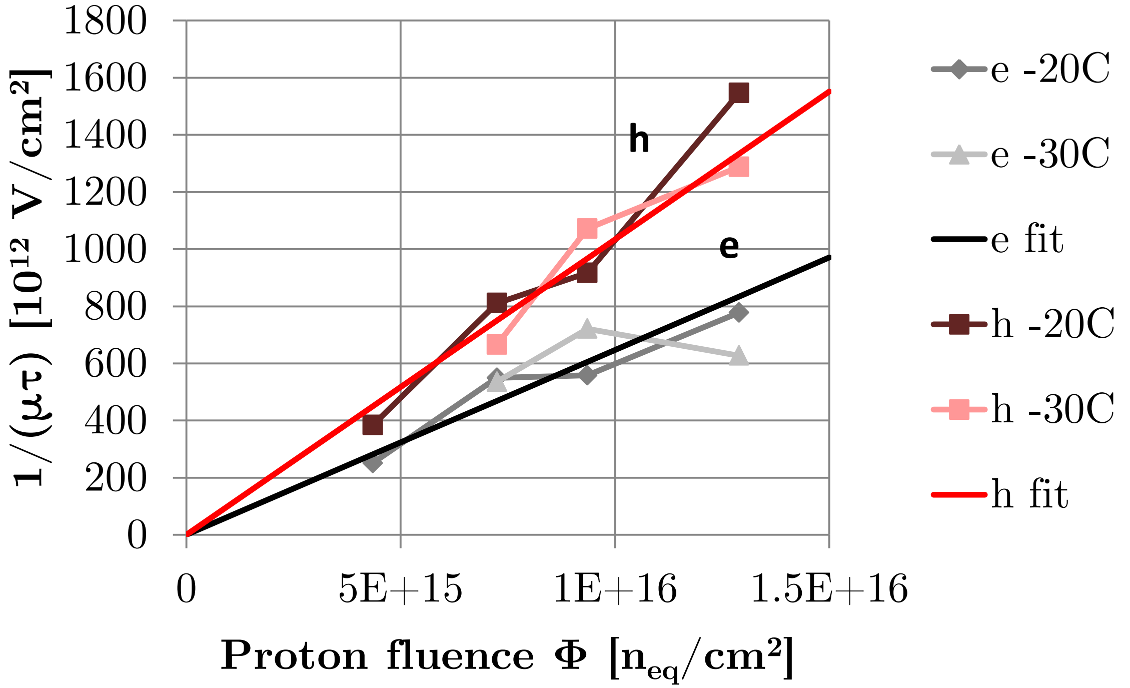
The charge collection length



Charge collection length $\lambda_{e,h} \propto {}^{1}/_{n_{trap}}$

- $\lambda_{e,h}(E) = v(E)\tau = \mu\tau \cdot E$
- Assume $\frac{1}{\mu\tau}(\Phi) = c_{ccl} \cdot \Phi$

$$\rightarrow \boldsymbol{\lambda_{e,h}(E,\Phi) = \frac{E}{c_{ccl} \cdot \Phi}}$$

preliminary results:

$c_{ccl,e}$ = 6.47E-10 V

$c_{ccl,h}$ = 1.03E-9 V

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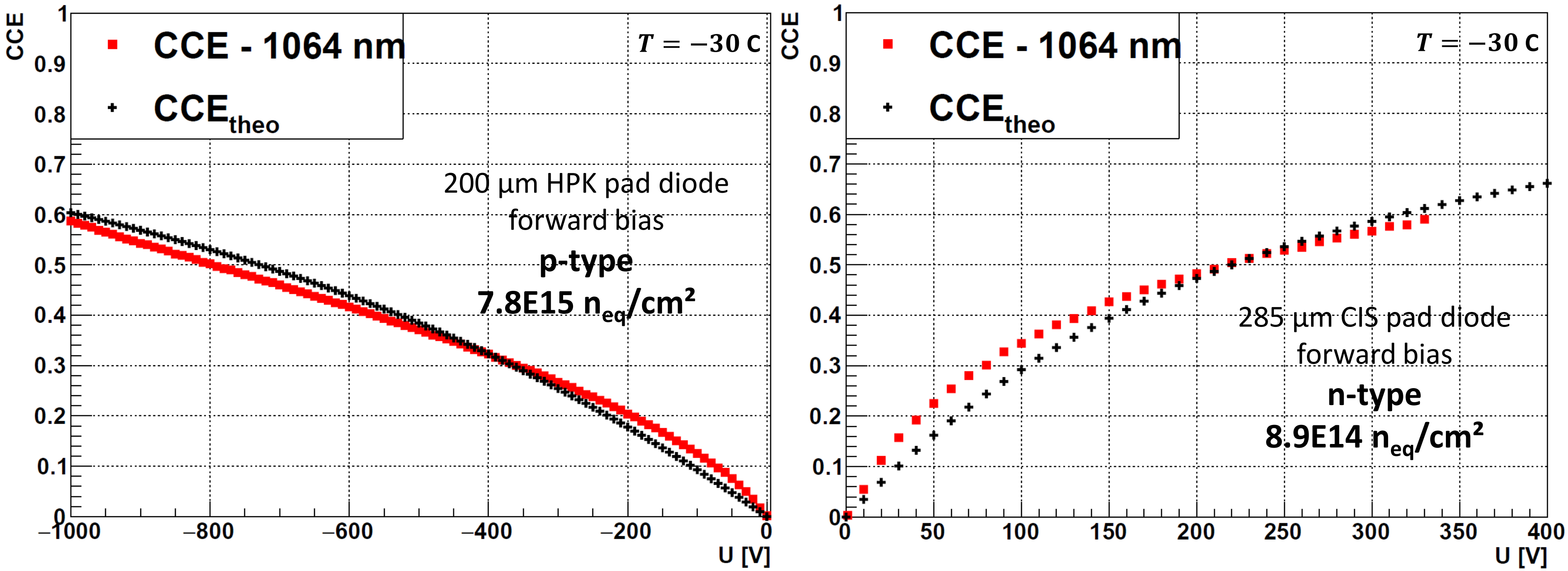
CCE for pad diode



With measured $\alpha(\Phi, \lambda, T)$ and $\lambda_{e,h}(E, \Phi)$ → predict CCE for pad diodes

- Many different fluences and materials available
- Large pad implant → homogenous e-field near junction, no surface oxide effects

→ used for cross-check

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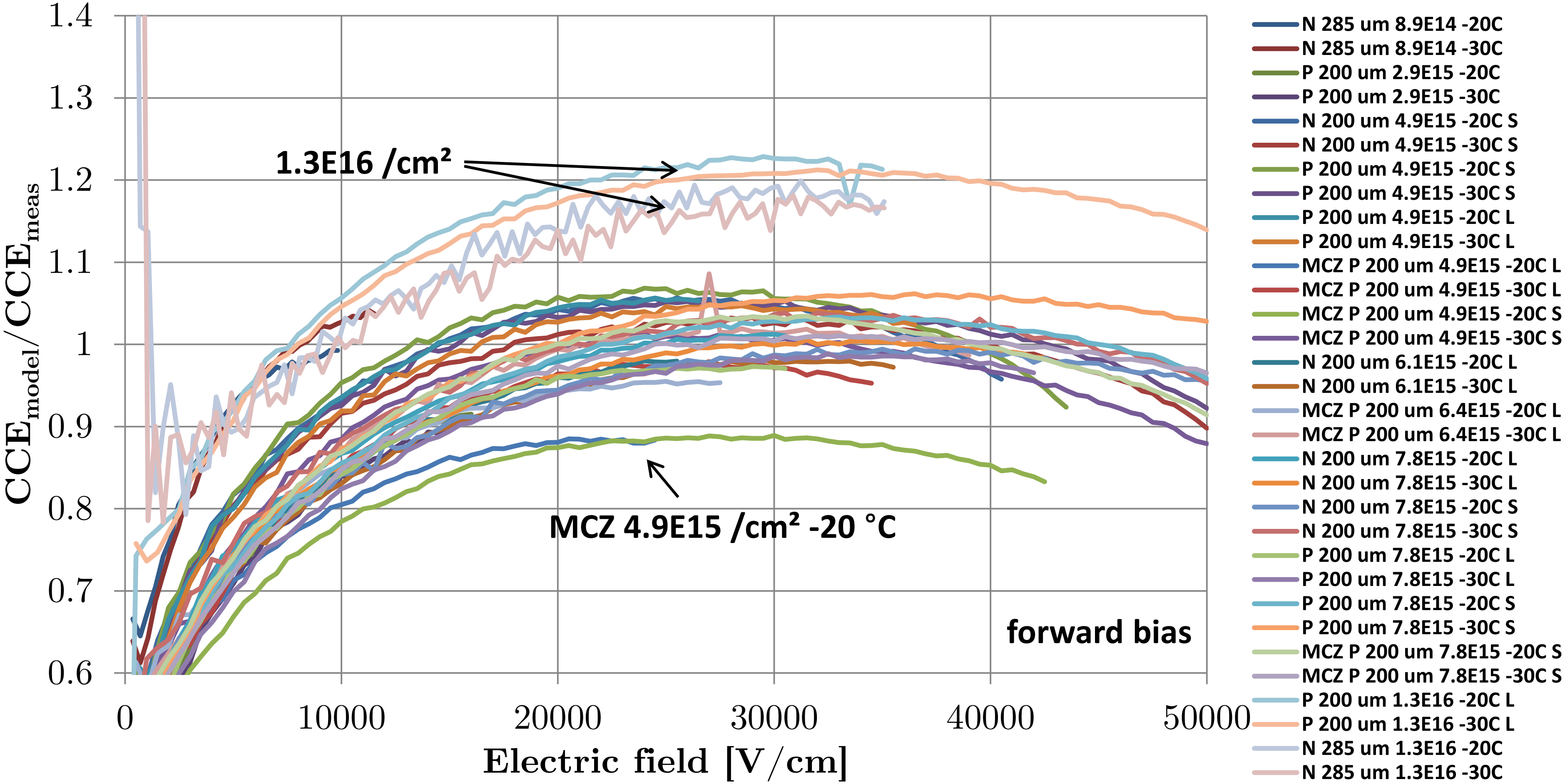
CCE for pad diode



Measurement and model w/ CCL from edge TCT agree for high fields but…

- 1.3E16 /cm² overestimated + large discrepancy for E <15 kV/cm

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Conclusion and outlook

Conclusion and outlook

- Absorption coefficient $\boldsymbol{\alpha(\Phi, \lambda, T)}$ of near-infrared light determined
  - **Absorption length needed to compare CCE_{laser} and CCE_{MIP}!**

- Charge collection length determined for forward bias $\boldsymbol{\lambda_{e,h}(E, \Phi)}$ from edge-TCT
  - Cross-checked with diode TCT

Simple model with 3 parameters predicts forward CCE for wide range of fluences, electric fields, and independent of material

Conclusion and outlook

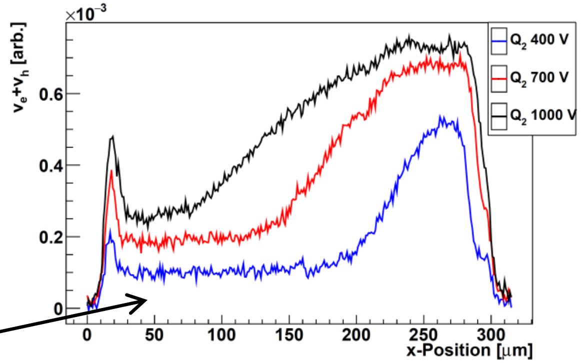
- Absorption coefficient $\boldsymbol{\alpha(\Phi, \lambda, T)}$ of near-infrared light determined
  - **Absorption length needed to compare CCE_{laser} and CCE_{MIP}!**

- Charge collection length determined for forward bias $\boldsymbol{\lambda_{e,h}(E, \Phi)}$ from edge-TCT
  - Cross-checked with diode TCT

Simple model with 3 parameters predicts forward CCE for wide range of fluences, electric fields, and independent of material

- **Agenda:**
  - Fit drift velocity to transients $\boldsymbol{I(t) \propto q \cdot v \cdot e^{-vt/\lambda}}$

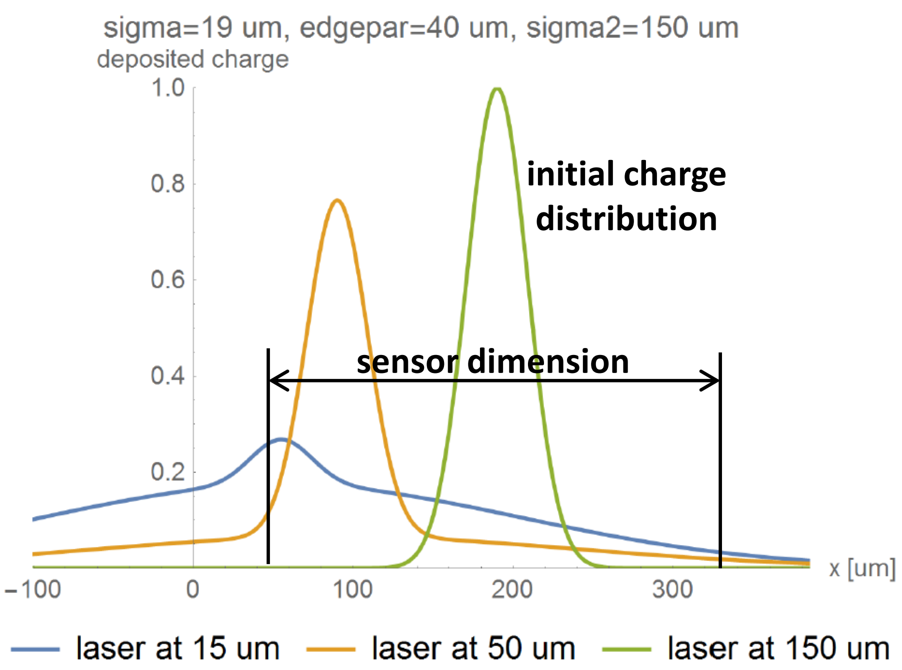
→ $\boldsymbol{v_{e,h}(E, \Phi)}$ **and** $\boldsymbol{\tau_{e,h}(E, \Phi) = \frac{\lambda_{e,h}}{v_{e,h}}}$

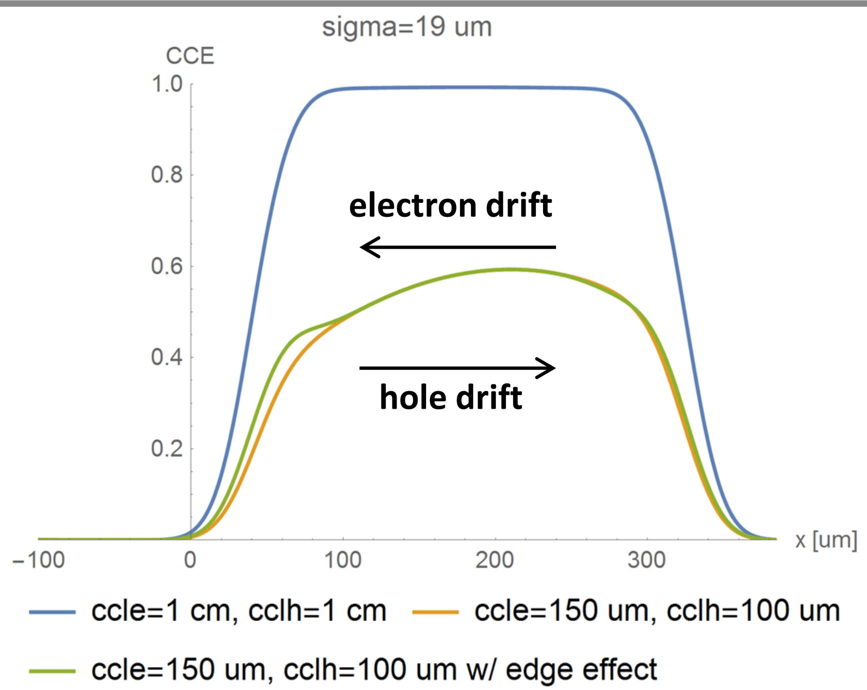


→ **Apply results for the low field region under reverse bias**

Backup

Fit of the charge profile





At the corners rounding of the edge and internal reflections modifiy the initial charge distribution (affects the velocity profile)

→ introduce edge parameter
→ fit charge collection length to measurements

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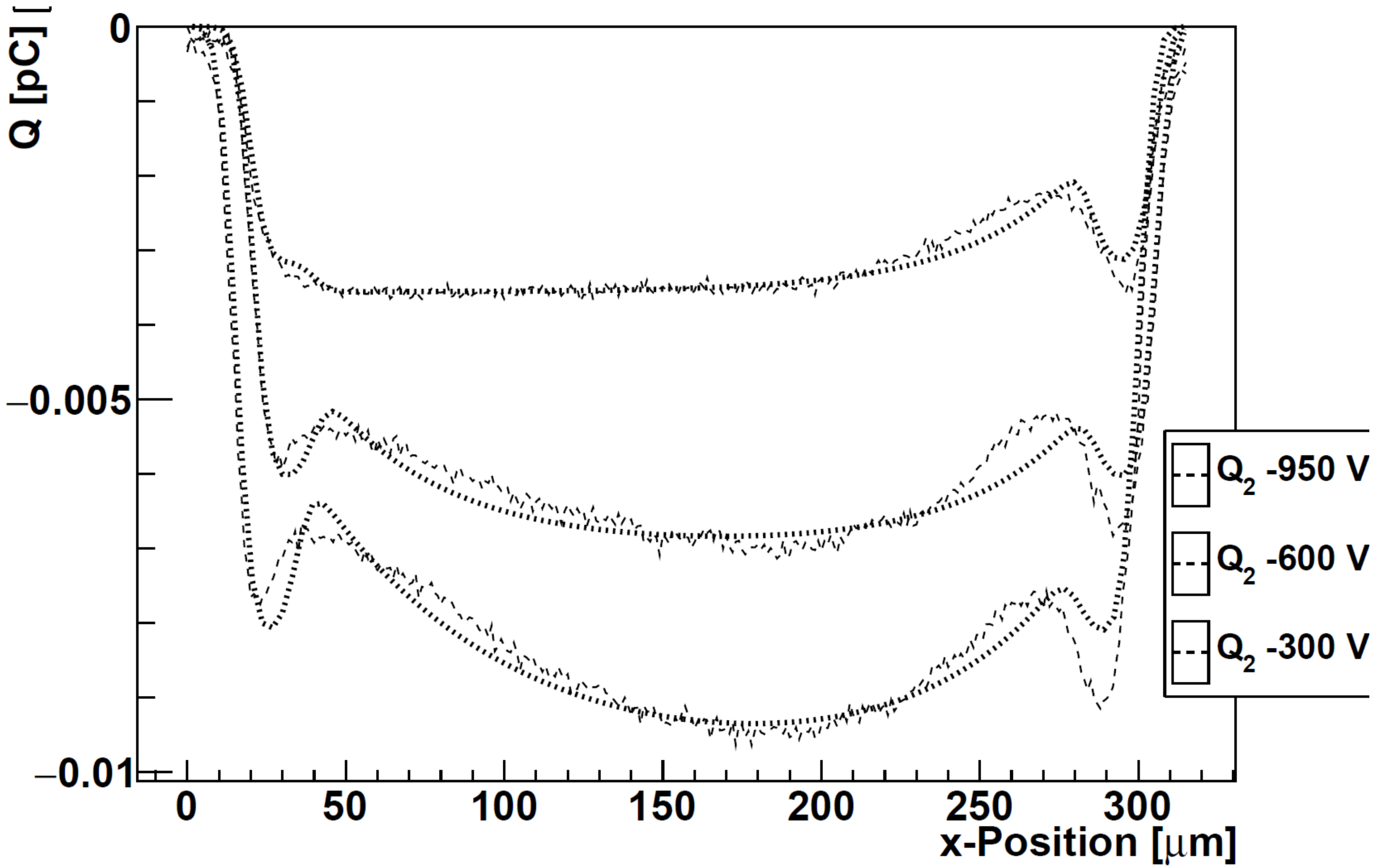
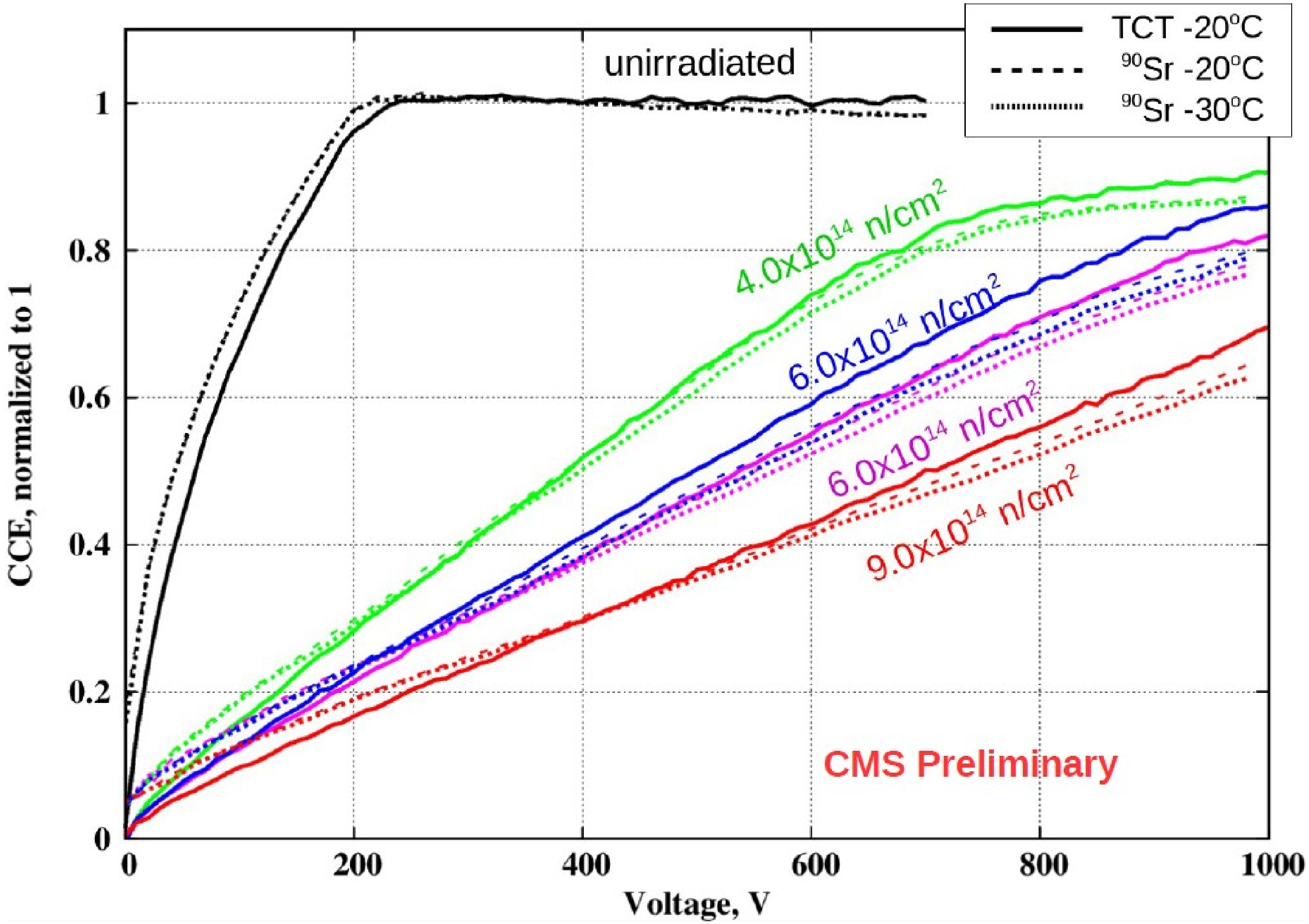
Charge profile

Strip sensor
285 µm n type CiS
7.25e15 /cm²
-30 °C



CCE pad diodes TCT vs. MIP



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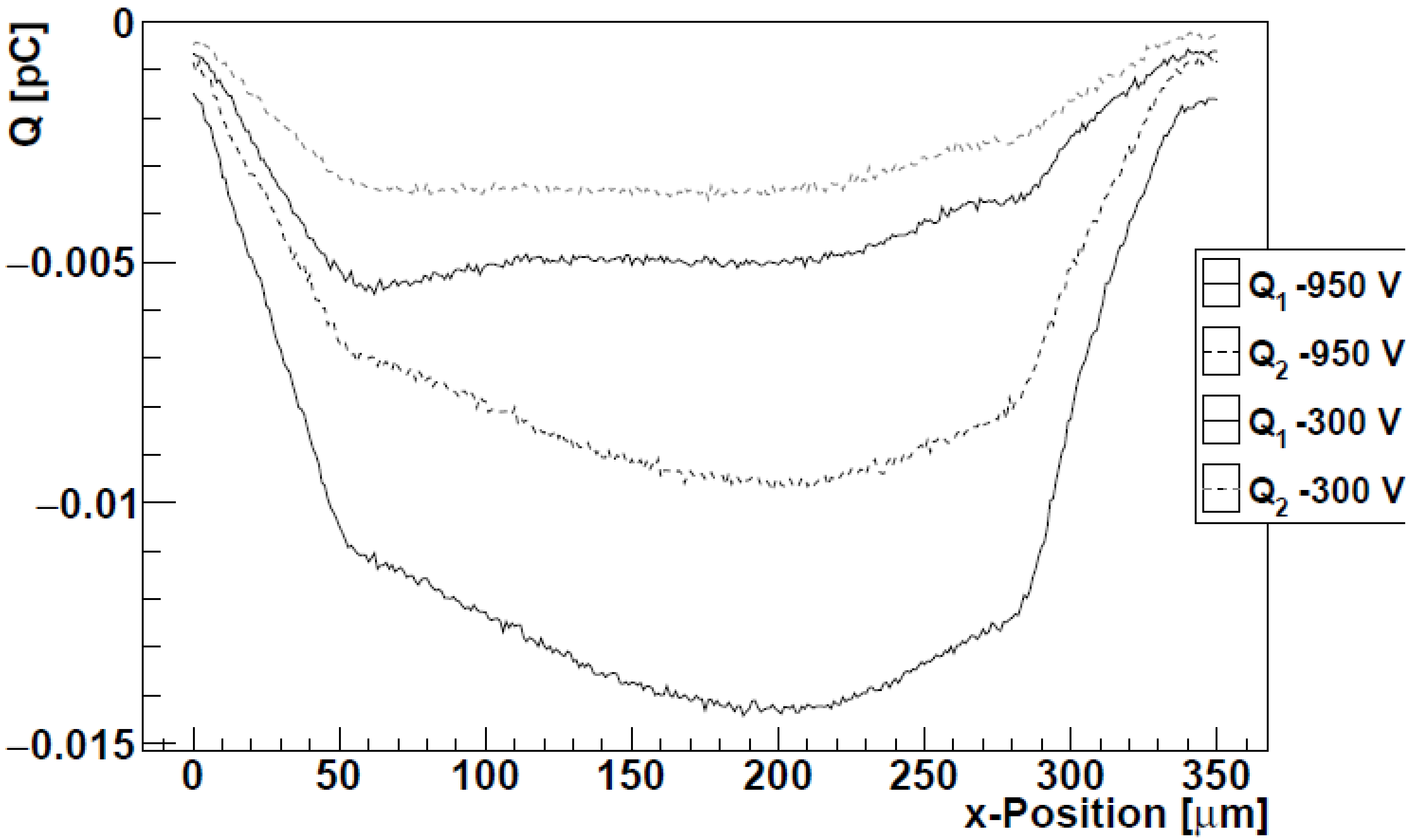
Charge profile

Strip sensor
285 µm n type CiS
7.25e15 /cm²
-30 °C



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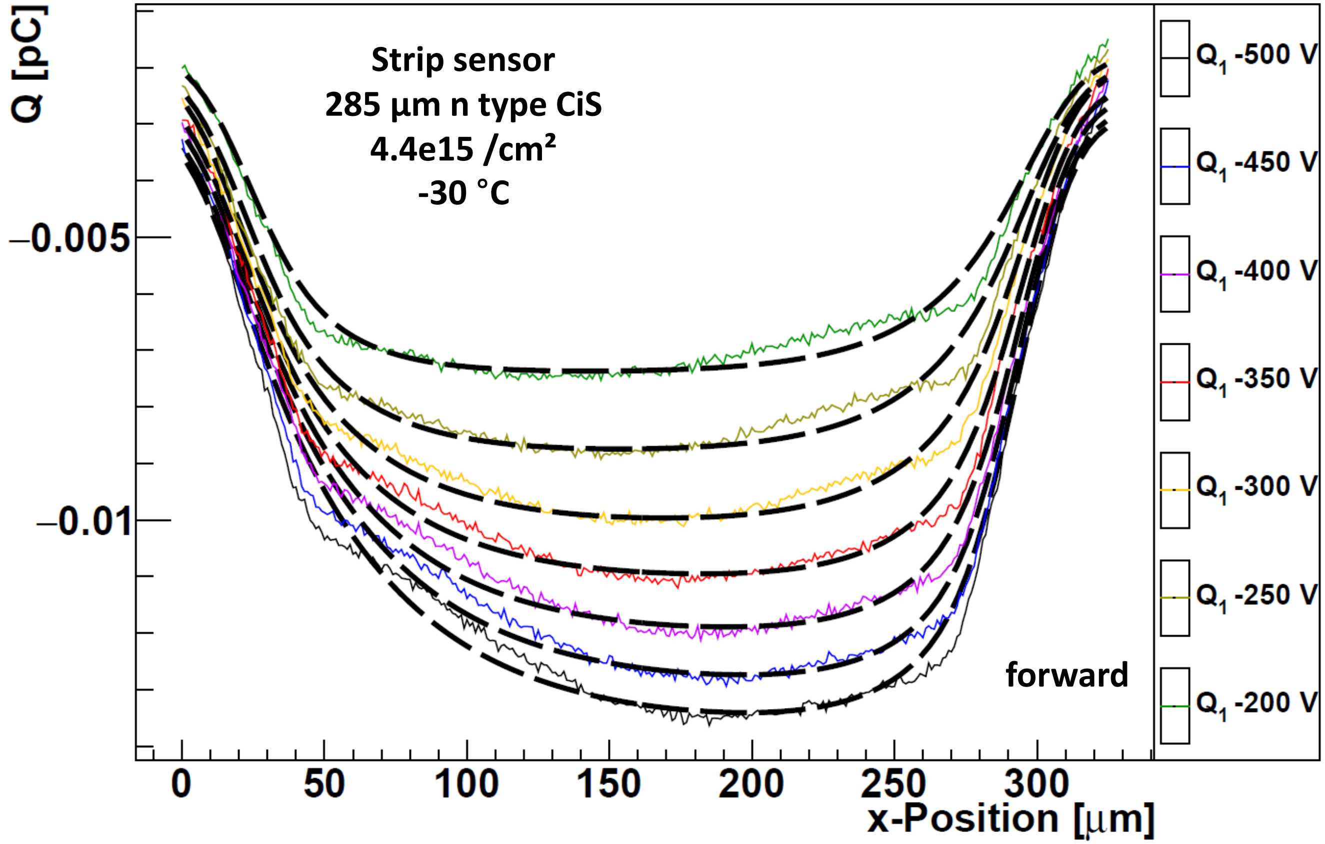
Fit of the charge profile



- **Obtaining $\lambda_{e,h}$ by fitting the $CCE(x)$** seems to work

→ measurements + analysis ongoing for -20 C and -30 C @ fluences 1E15 – 1.3E16 /cm² and for two read out strips

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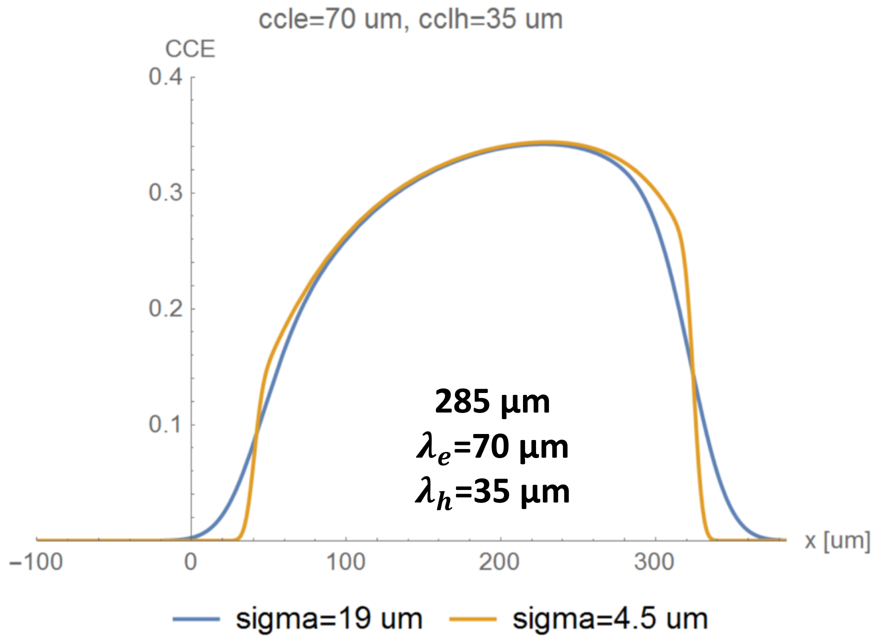
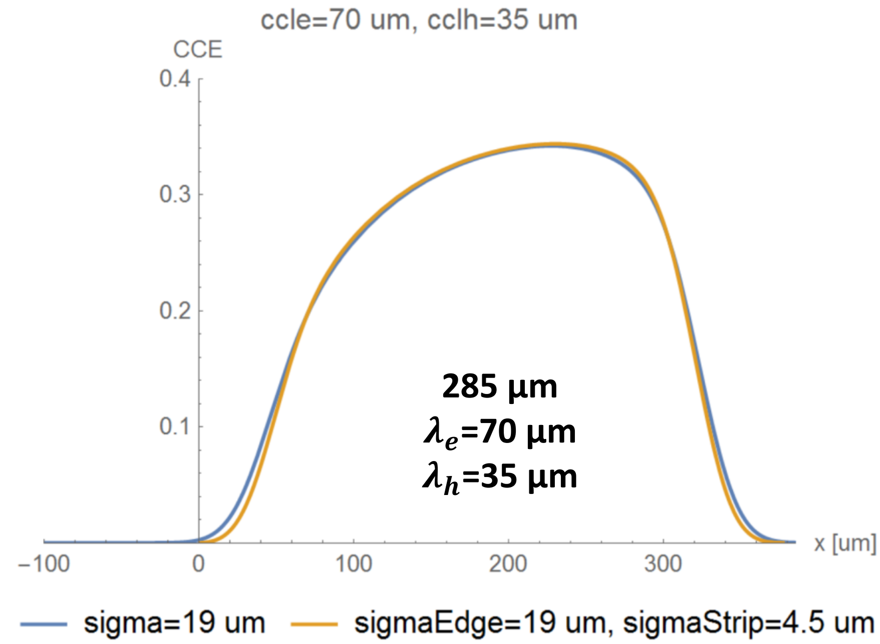
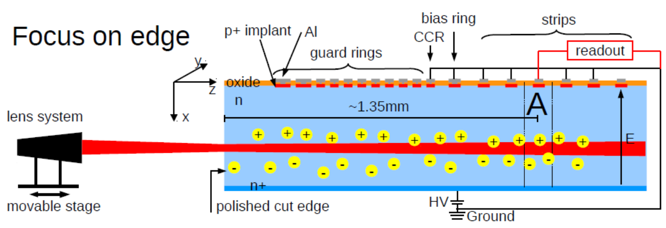
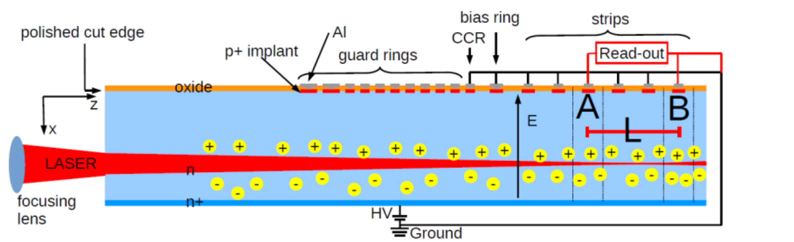
Fit of the charge profile









- Better to put the focus @ the edge of the sensor??
  → most measurements w/ focus between read out strips…

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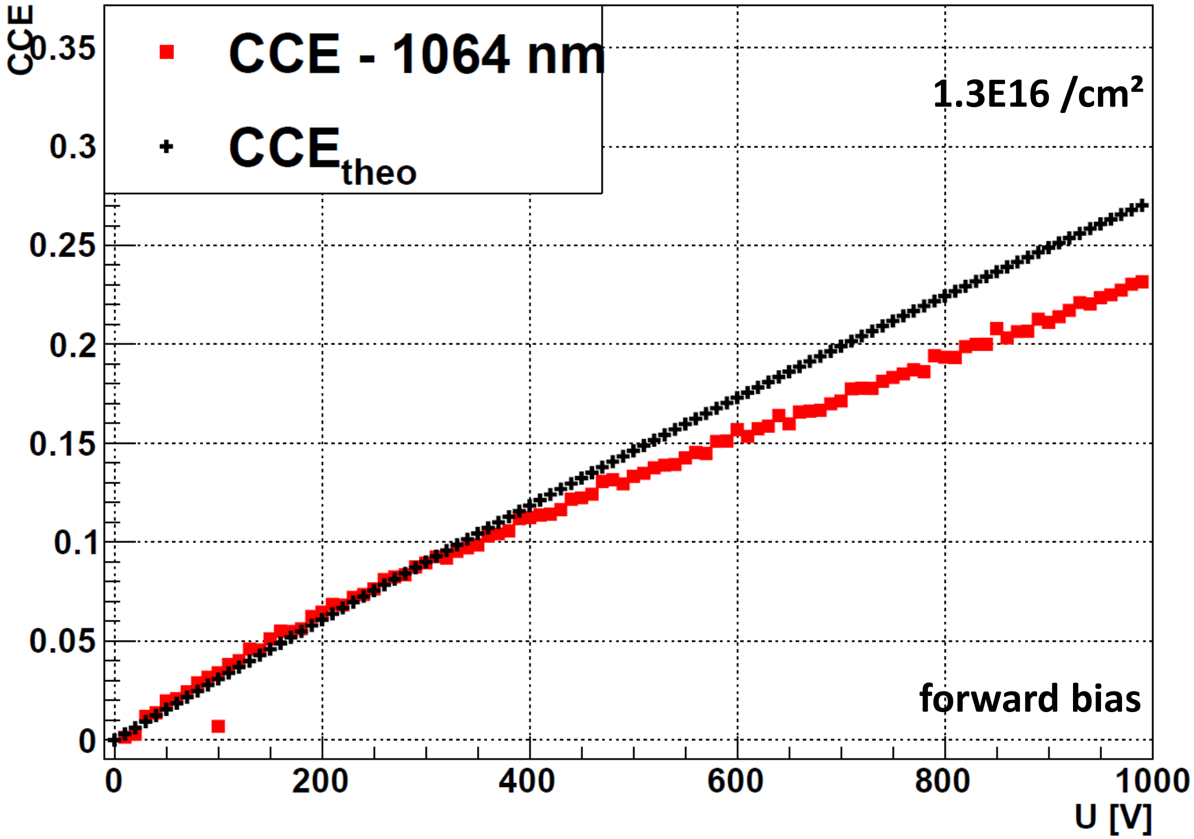
CCE for pad diode



- 1.3E16 /cm² overestimated

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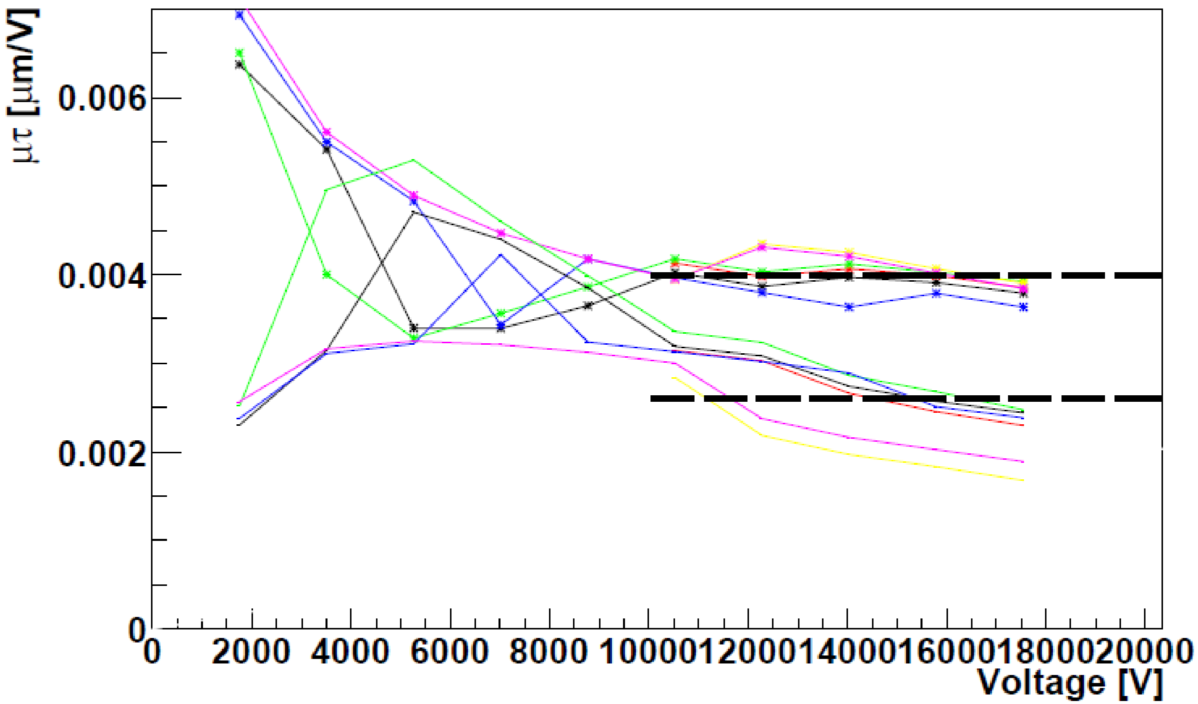
The charge collection length



Strip sensor
285 µm n type CiS
-20 °C
4.4e15 /cm²
forward

$$\mu(E) = \frac{e \cdot \tau_{scatter}(E)}{m}$$

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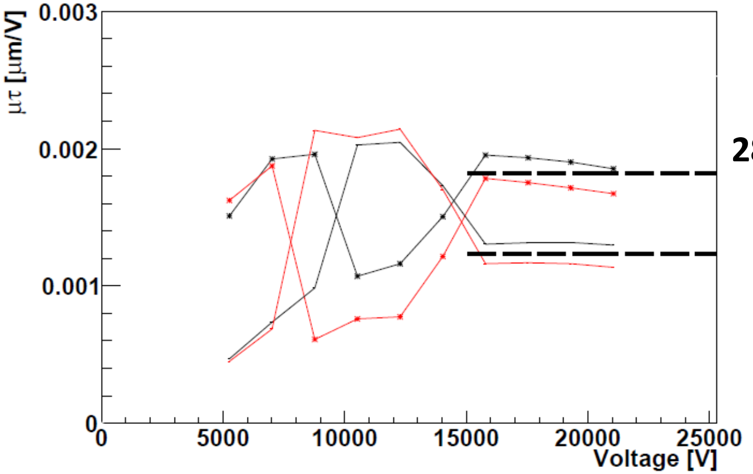
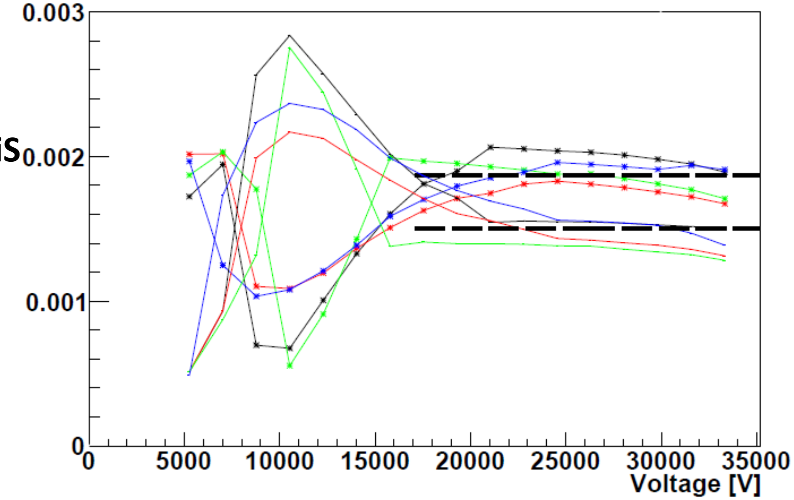
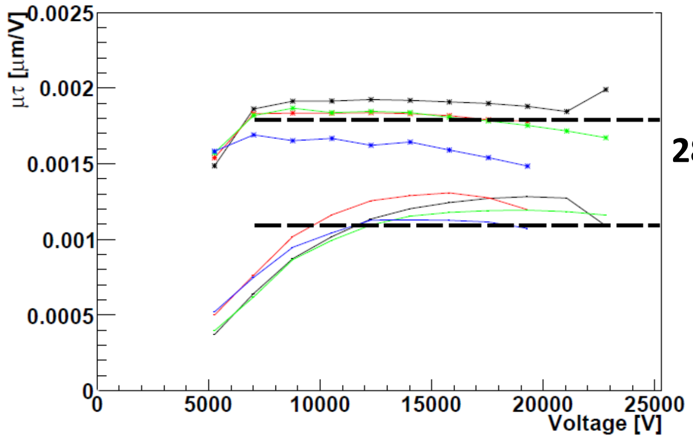
The charge collection length

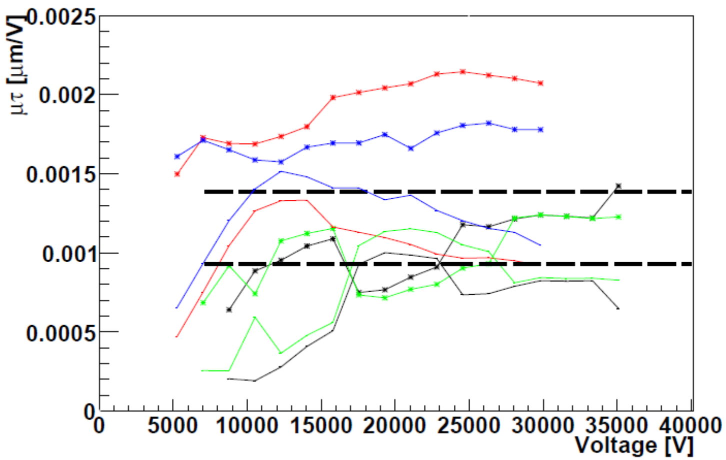


Strip sensor
285 μm n type CiS
-20 °C & -30 °C
7.3e15 /cm²
forward





Strip sensor
285 μm n type CiS
-20 °C & -30 °C
9.4e15 /cm²
forward



- $\lambda_{e,h} = v\tau = \mu E\tau \approx const \cdot E$

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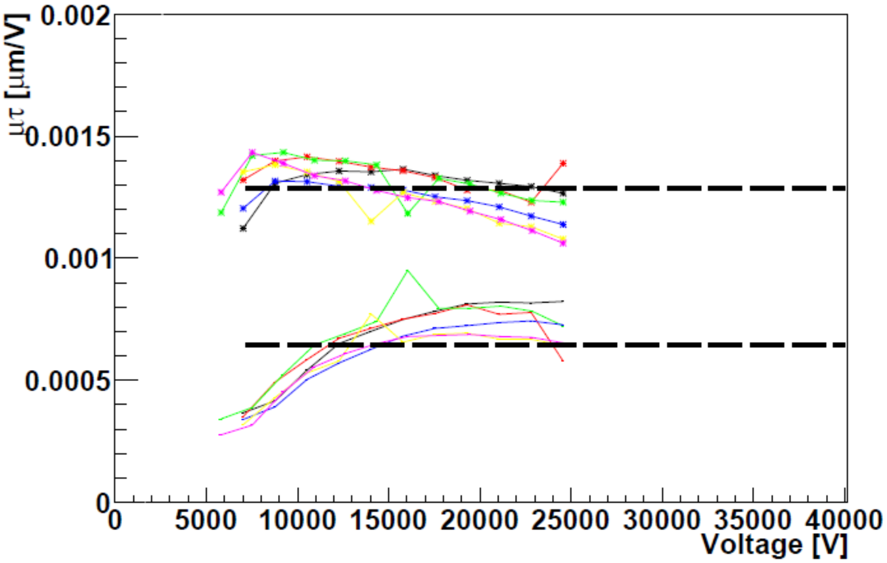
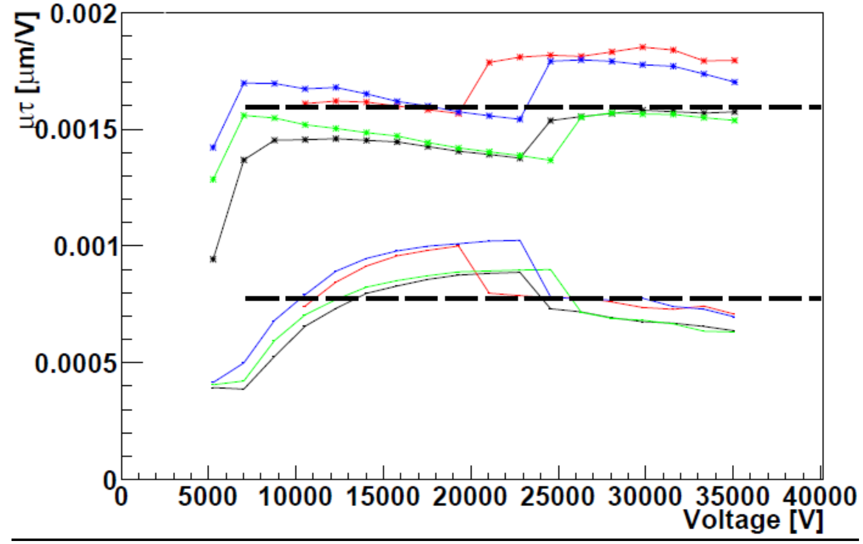
The charge collection length

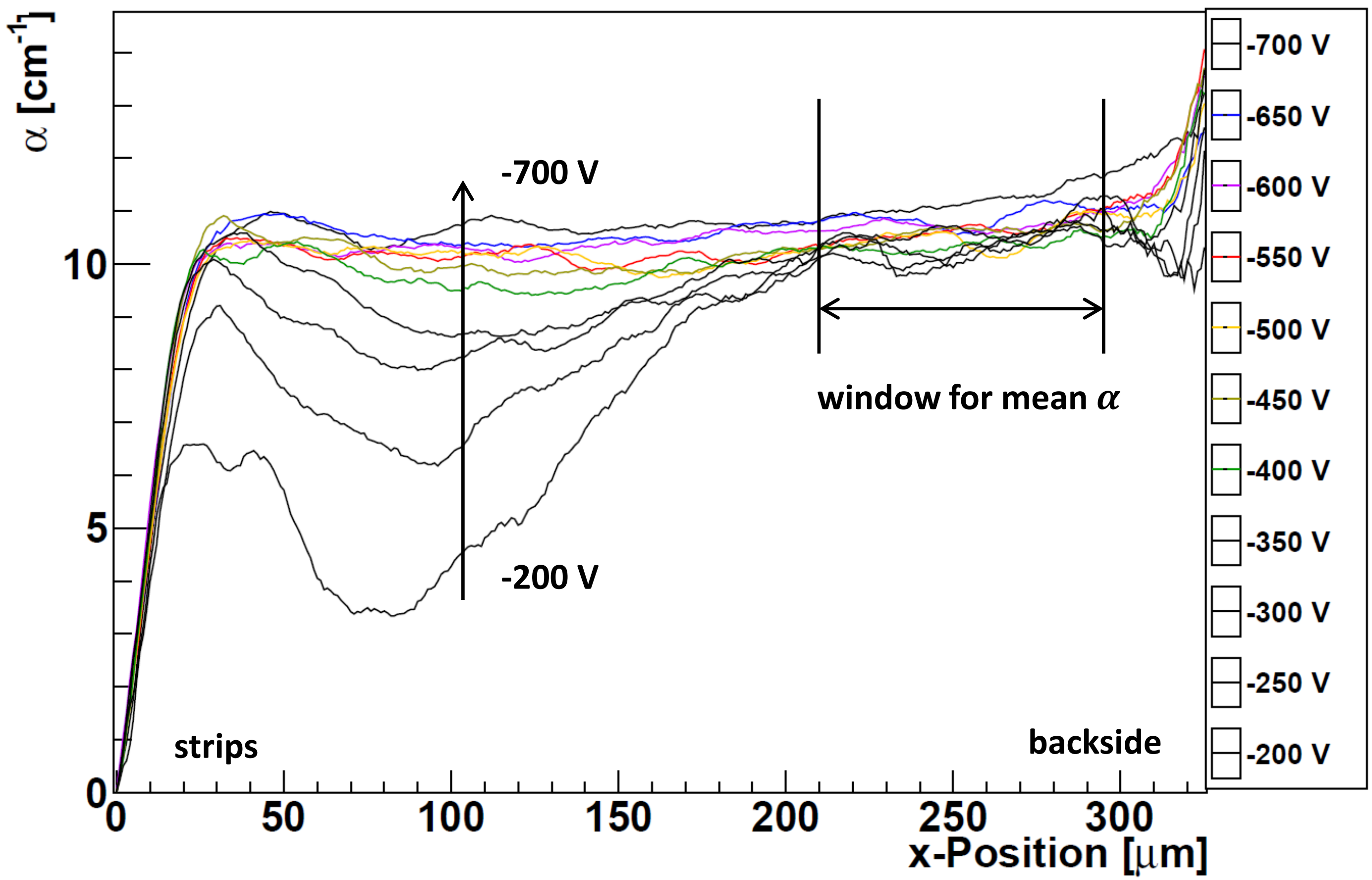




Strip sensor
285 μm n type CiS
-20 °C & -30 °C
1.3e16 /cm²
forward

- $\lambda_{e,h} = v\tau = \mu\tau E \approx const \cdot E$

Absorption from edge TCT



285 µm n type CiS
9.7e15 /cm²
-20 °C
forward bias
smoothed

- Absorption coefficient depends on voltage and position in the sensor
  → investigate absortion away from strips where E-field homogeneous

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Drift velocity and trapping

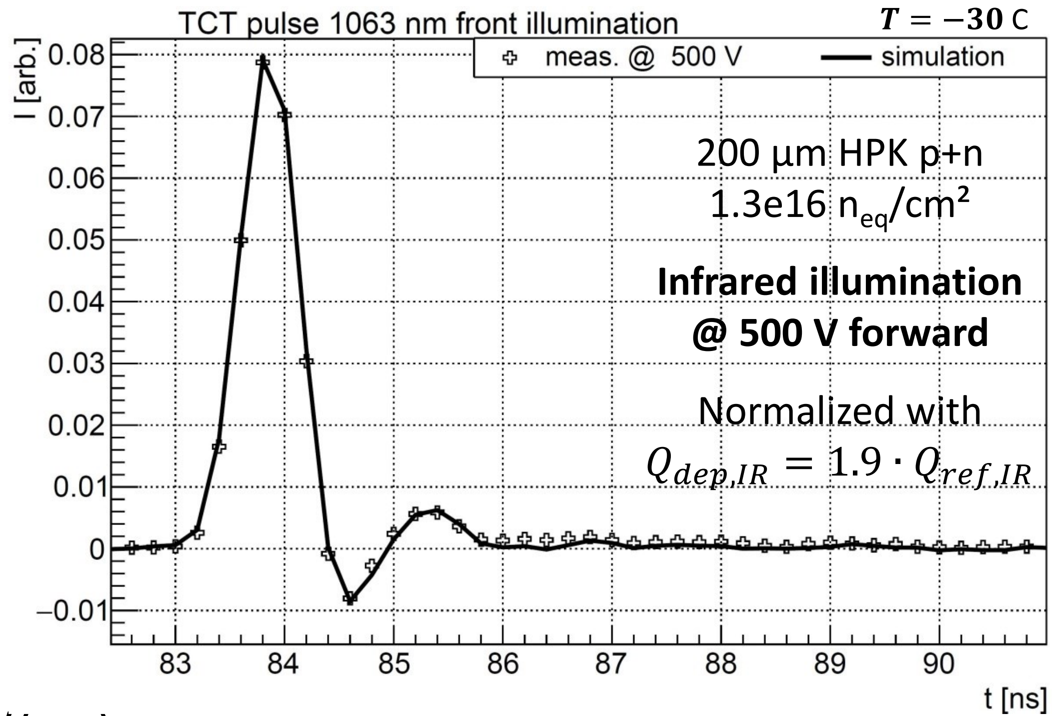
Next step:

- **Disentangle drift velocity and trapping:**

$$I(t) \propto q \cdot v \cdot e^{-vt/\lambda}$$

→ **Fit the drift velocity v to transients with $\lambda_{e,h}$ from CCE**

→ Extract $\tau_{e,h} = \lambda/v$



Simulation fits nicely (here $E = 25$ kV/cm)

- v **reduced** by 35 % compared to non irradiated
  - → Expected v reduction for ~10^{16} /cm³ ionized impurities
- **Carrier lifetimes for** 1.3e16 n_{eq}/cm^2:
  - $\tau_e = 400$ **ps**
  - $\tau_h = 140$ **ps**

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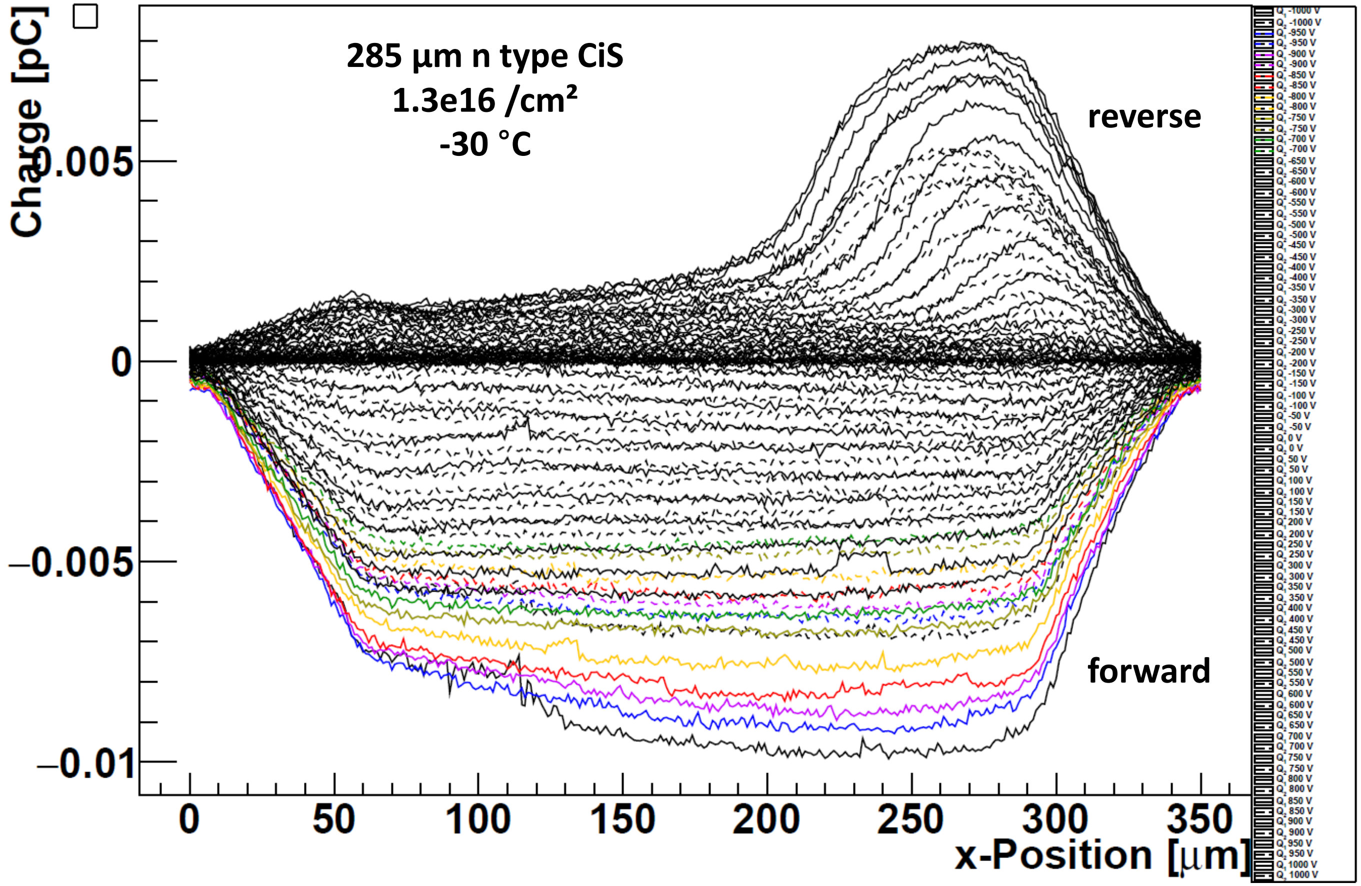
Edge-TCT charge profile



- Collected charge measured at different depth (x-position) in strip sensor
  → read out two strips and determine absorption @ 1052 nm

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