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Observation of an inactive region in irradiated silicon diodes

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RD50

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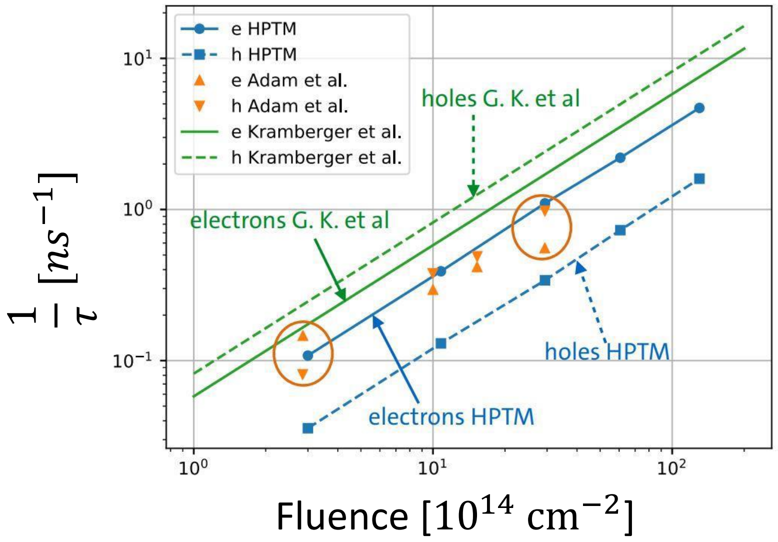
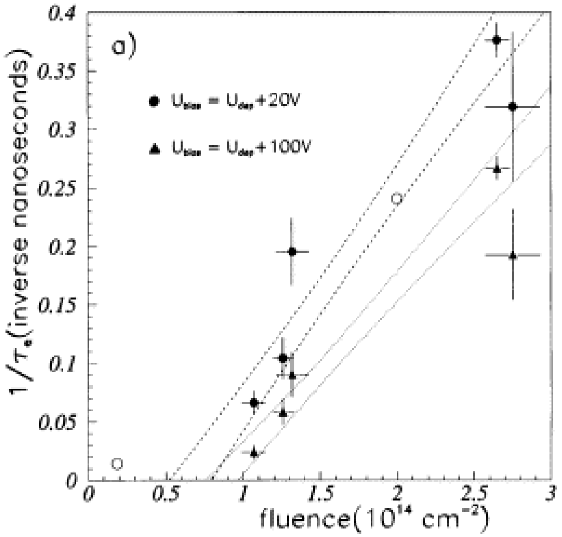
Motivation

- Trapping times important for accurate prediction of detector performance
  - Verify simulation data and modify sensor designs
  - How much irradiation can a detector tolerate
- Results of determined trapping times for electron and holes ($\frac{1}{\tau_e}$, $\frac{1}{\tau_h}$)
  - Laser light (Kramberger et al Link): $\frac{1}{\tau_e} < \frac{1}{\tau_h}$
  - Alpha particles (Beattie et al Link): $\frac{1}{\tau_e} > \frac{1}{\tau_h}$
  - Hamburg Penta Trap Model (HPTM) simulation: $\frac{1}{\tau_e} > \frac{1}{\tau_h}$
- Published trapping time measurments contradict each other

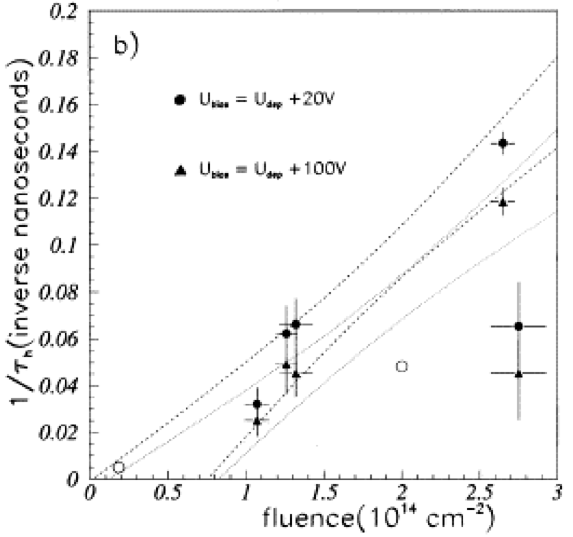
Kramberger et al



Beattie et al: Electrons



Holes



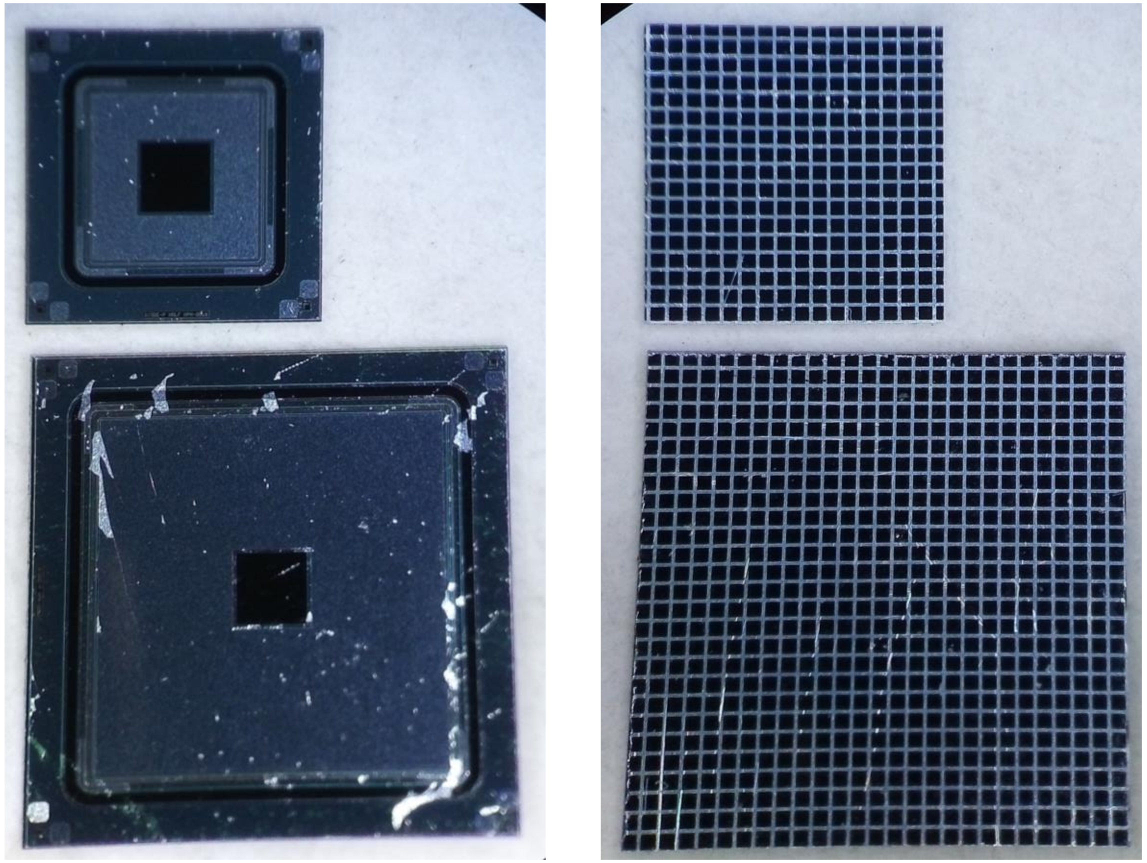
Investigated Diodes

- n^+-p-p^+ configuration by Hamamatsu
- 150 μm active thickness
- Boron doped $N_A \approx 4.5 \times 10^{12}\mathrm{cm}^{-3}$
- Full depletion voltage $V_{dep} \approx 75$ V
- Front: n^+-p, Rear: p^+-p
- Active area $\approx 2.5 \times 2.5\ \mathrm{mm}^2$ or $5 \times 5\ \mathrm{mm}^2$
- Irradiated in Karlsruhe[1]
    - 23 MeV protons, $\kappa = 2.20$
    - Three diodes irradiated with

$$\Phi_{eq} = 2.0 \times 10^{15}\mathrm{cm}^{-2},\quad 8.6 \times 10^{15}\mathrm{cm}^{-2},\quad 1.2 \times 10^{16}\mathrm{cm}^{-2}$$

κ: hardness factor

Front side / Rear side

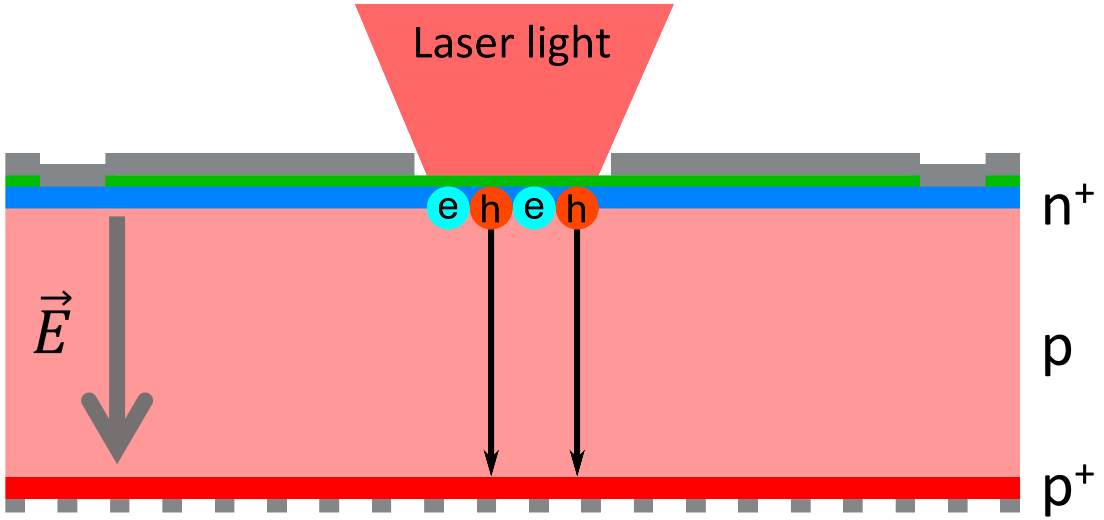


1: Irradiation Center Karlsruhe, ZAG Cyclotron AG

Transient Current Technique (TCT)

- Used to investigate signal of sensors
- Pulsed red-light laser
  - 660 nm and 1 kHz repetition rate
- ^{241}Am source
  - 320 kBq activity, $E_0 = 5.4$ MeV
- Both sources have attenuation length of few μm in silicon
- Signal induced mainly by one charge carrier type

Front side laser light illumination of a fully depleted diode



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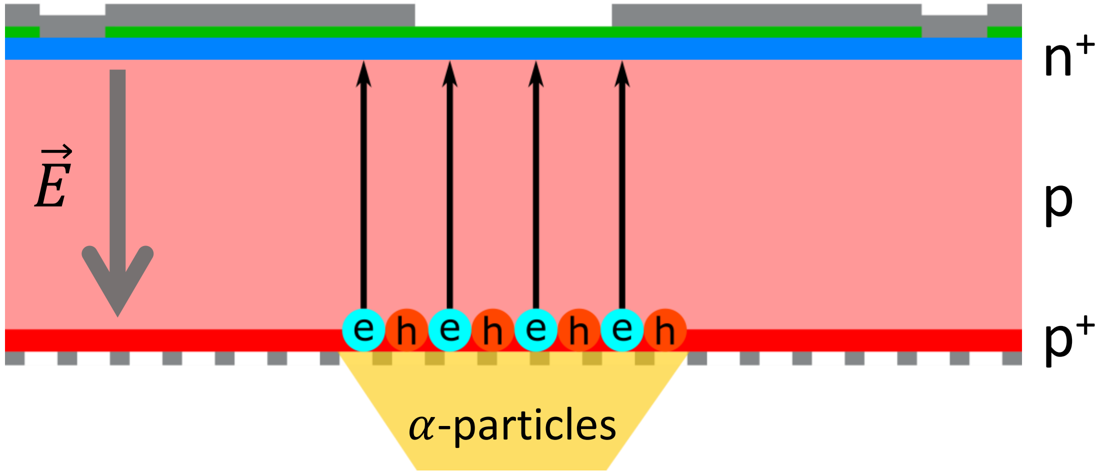
- Signal induced mainly by one charge carrier type

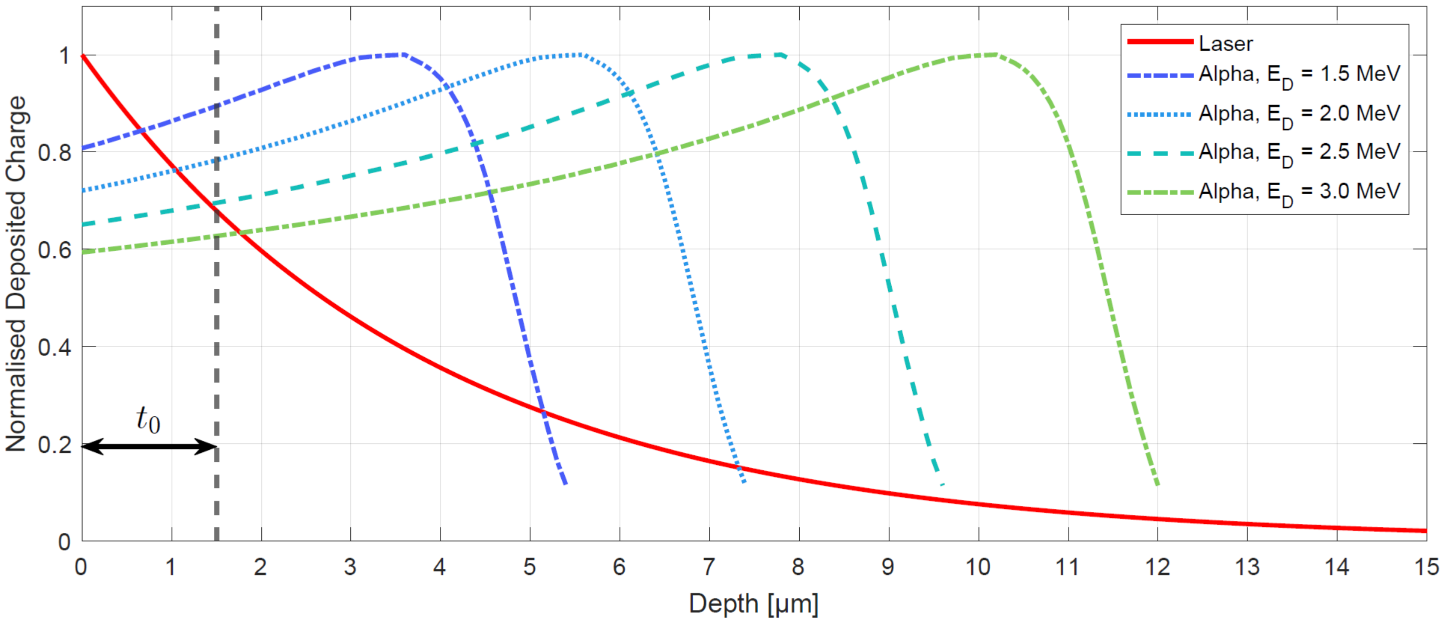
Rear side α-particle illumination of a fully depleted diode



Charge Deposition Profiles

- Laser light
  - Exponential attenuation
  - Deposit most charge at surface
- Alpha particles
  - Bragg curves
  - Deposit most charge at end of particle range
- Using both sources enables the study of different depths in silicon

Absorption profiles of light and α-particles in silicon at -20 °C



The smaller the α-particle energy, i.e. E_D the more charge is deposited at the surface

E_D: energy of α-particles at the active region of the diode (n^+ or p^+ implant)

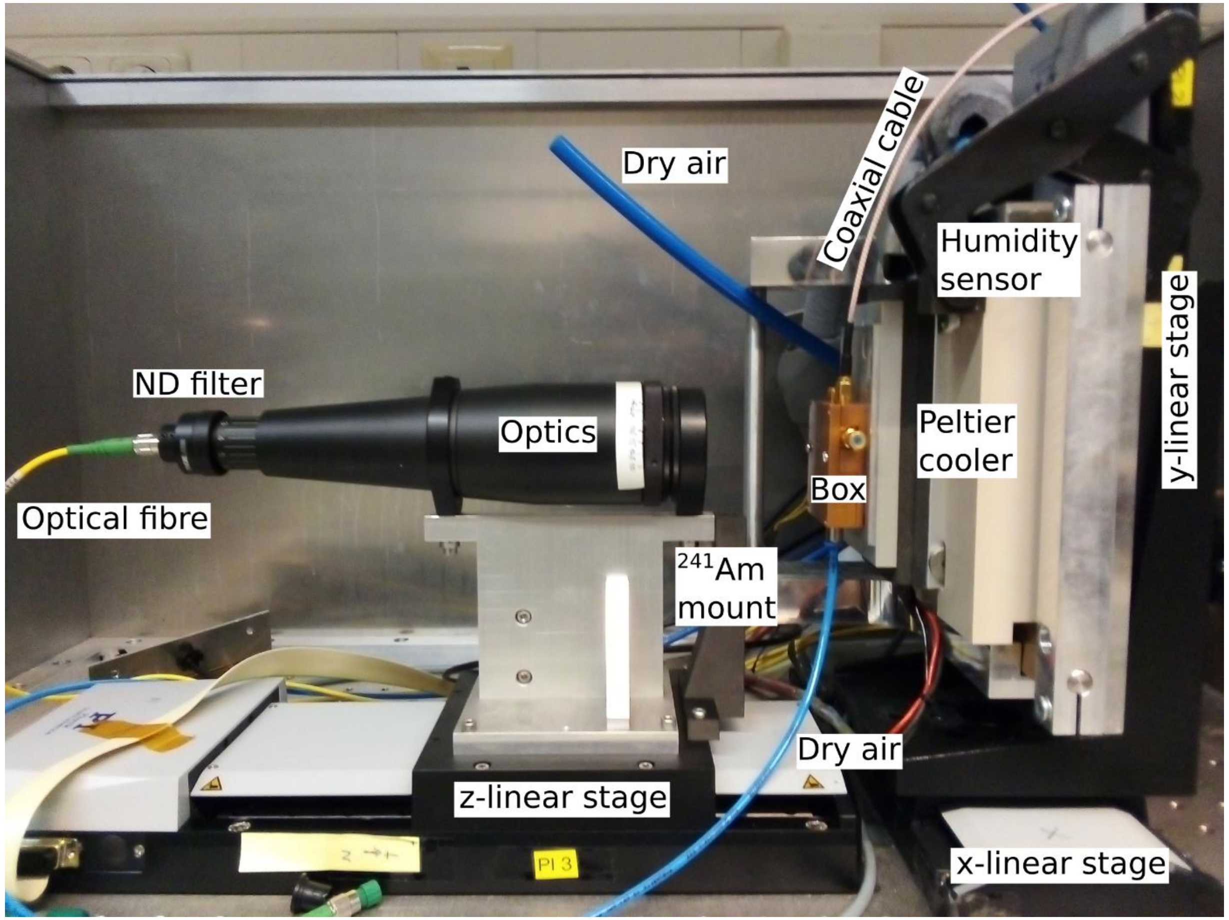
TCT Setup

- Setup can be cooled down and flushed with dry air
- 3 linear stages position the diode
- Amplifier with gain of 100
- Digital Oscilloscope
  - 2.5 GHz bandwidth
  - 40 GS/s sampling rate

Measurement conditions

- Relative humidity below 4 %
- Temperature: -20 °C

TCT measurement setup



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Measurement conditions

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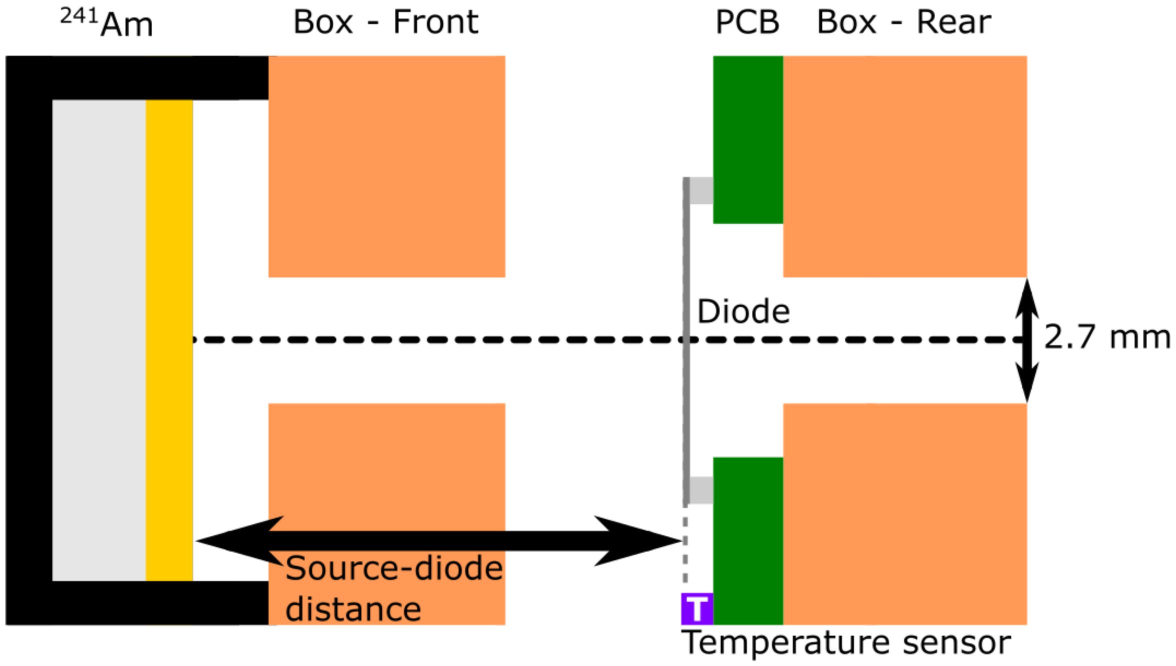
Layout inside box with alpha-source

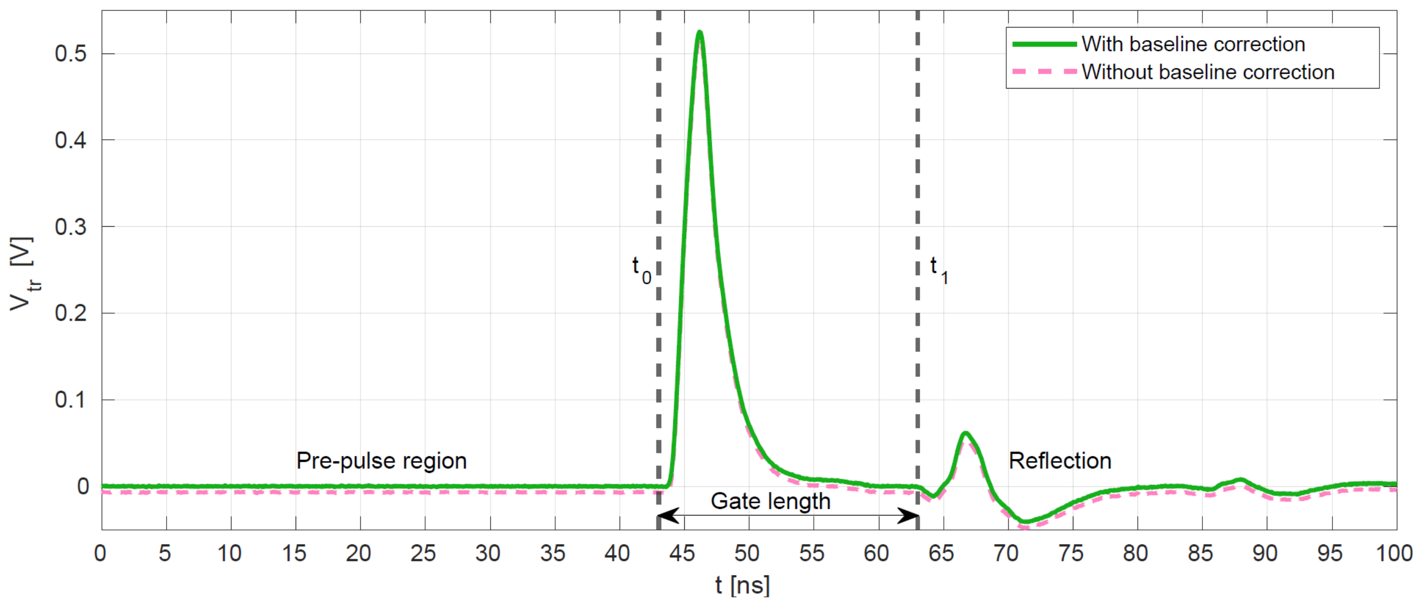


Minimum source-diode distance	Front	Rear
[mm]	14.1	12.5

Current Transient

Rear side laser light illumination of a non-irradiated diode at 200 V and -20 °C

- Average of 512 waveforms
- Voltage shift from baseline
- Signal reflection at amplifier
- Non-irradiated diodes
  - Reverse bias: 50 V – 300 V
- Irradiated diodes
  - Reverse bias: 300 V – 800 V



- Collected Charge of a diode

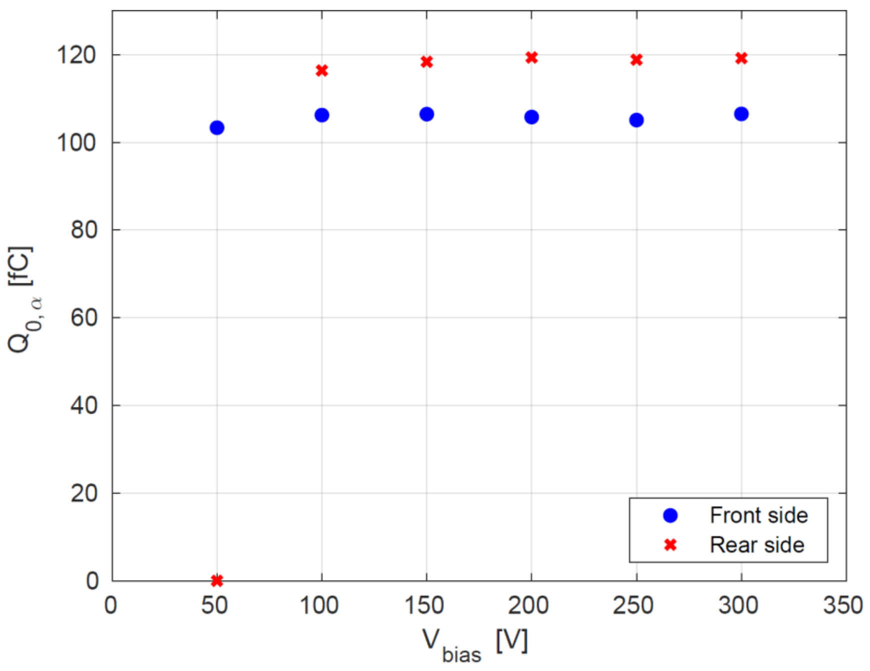
$$Q_m = \int_{t_0}^{t_1} \frac{V_{tr}(t)}{50\,\Omega \cdot 100} dt \, , \mathrm{t}_1 - \mathrm{t}_0 = 20 \text{ ns}$$

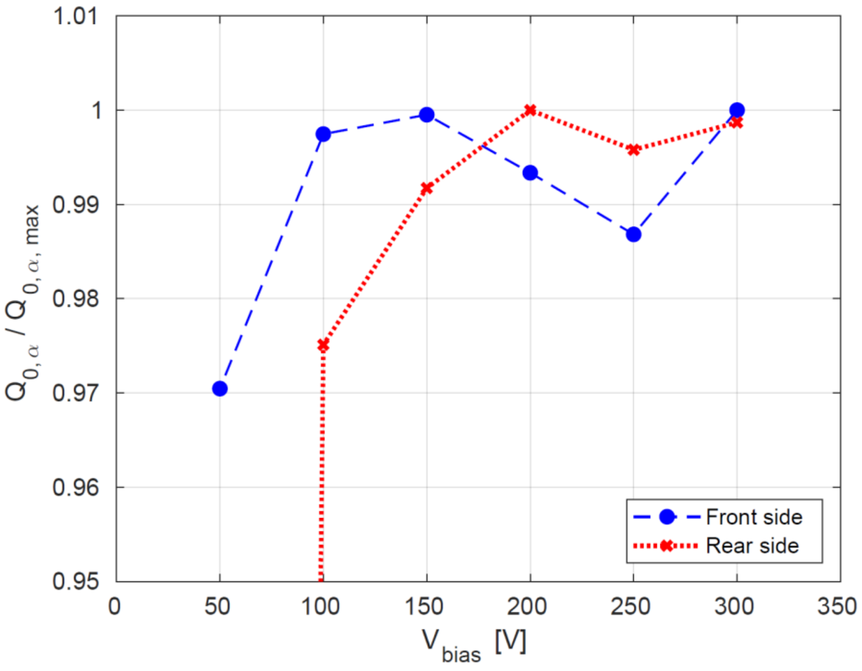
Collected charge = integral of baseline corrected transient

Charge Collection – α-particles

Charge collection of non-irradiated diode at -20 °C and minimum source-diode distance

- Source can be placed closer to rear than front side
- The smaller E_D the smaller is $Q_{0,\alpha}$





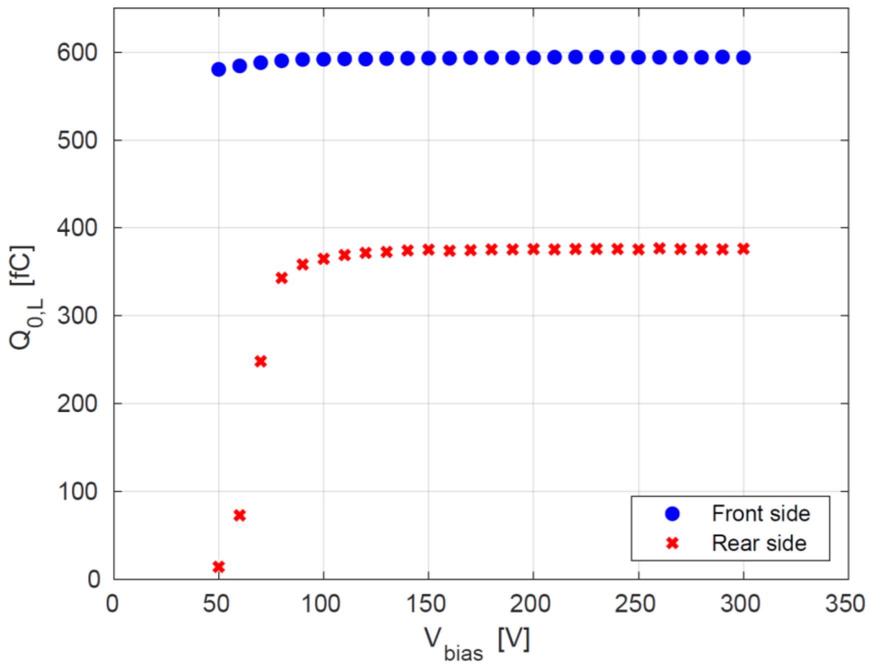
α-particles at -20 °C	Front	Rear
$Q_{0,\alpha}$ (300 V) [fC]	106.5	119.0

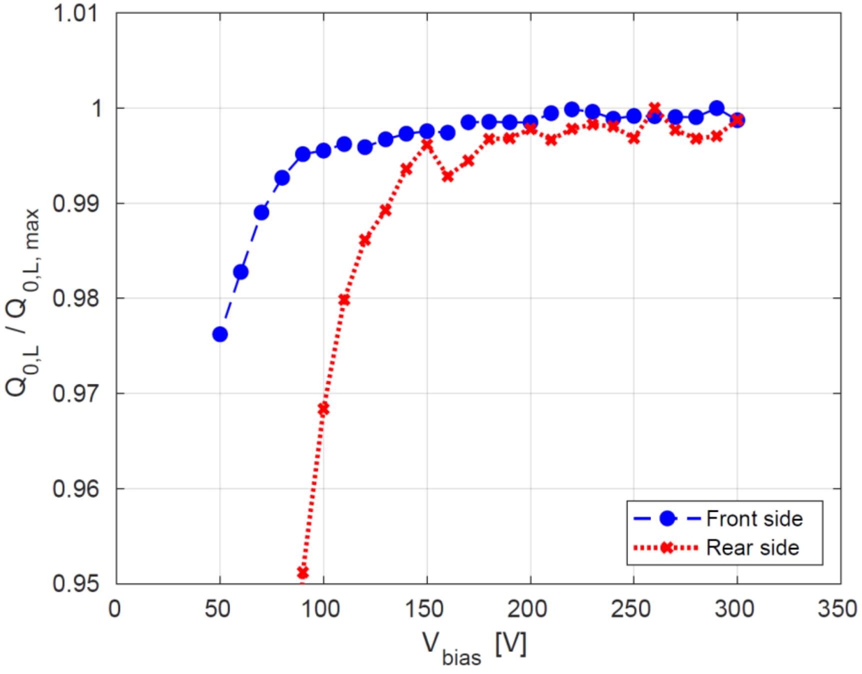
Above V_{dep} charge is independent of V_{bias} within 3 %

Charge Collection – Laser Light

Charge collection of non-irradiated diode at -20 °C

- Different charges for each side due to different optical conditions





Laser light at -20 °C	Front	Rear
$Q_{0,L}$ (300 V) [fC]	593.9	376.2

Above V_{dep} charge is independent of V_{bias} within 2 %

Charge Collection Efficiency (CCE)

- CCE for laser light measurements

$$\mathrm{CCE}_{\Phi,L} = \frac{Q_{\Phi,L}(V_{bias})}{Q_{0,L}}$$

- CCE for α-particle measurements

$$\mathrm{CCE}_{\Phi,\alpha} = \frac{Q_{\Phi,\alpha}(V_{bias}, E_D)}{Q_{0,\alpha}(E_D)}$$

- Assumption: CCE of non-irradiated diode is 100 %

Q_0: collected charge of a non-irradiated diode at 300 V

CCE Results

$\Phi_{eq} = 2.0 \times 10^{15}\text{cm}^{-2}$

Front side

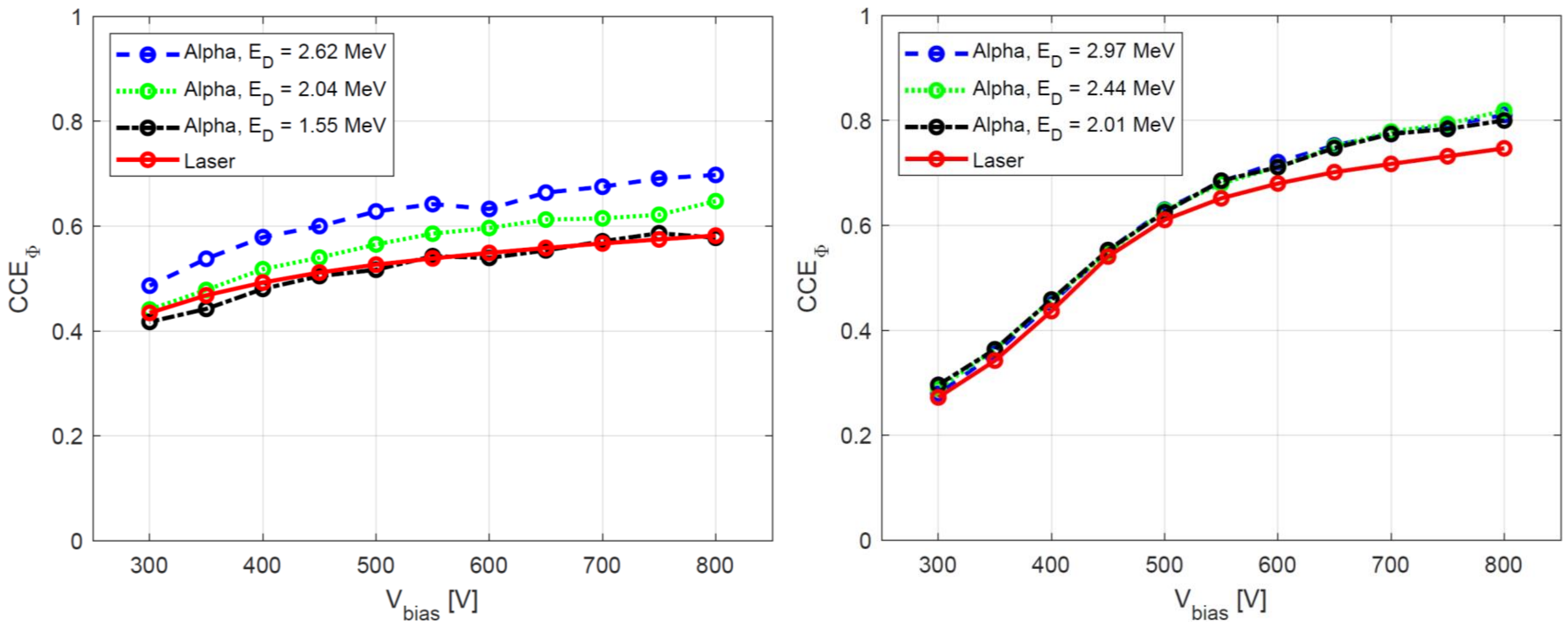
- $\text{CCE}_{\Phi,\alpha}$ decreases with decreasing E_D
- $\text{CCE}_{\Phi,\alpha} \approx \text{CCE}_{\Phi,L}$ at $E_D = 1.55$ MeV

Rear side

- $\text{CCE}_{\Phi,\alpha}$ is not a function of E_D

Front side illumination at −20 °C

Rear side illumination at −20 °C



Front: n^+-p junction

Rear: p^+-p junction

CCE Results

$\Phi_{eq} = 8.6 \times 10^{15} \mathrm{cm}^{-2}$

Front side

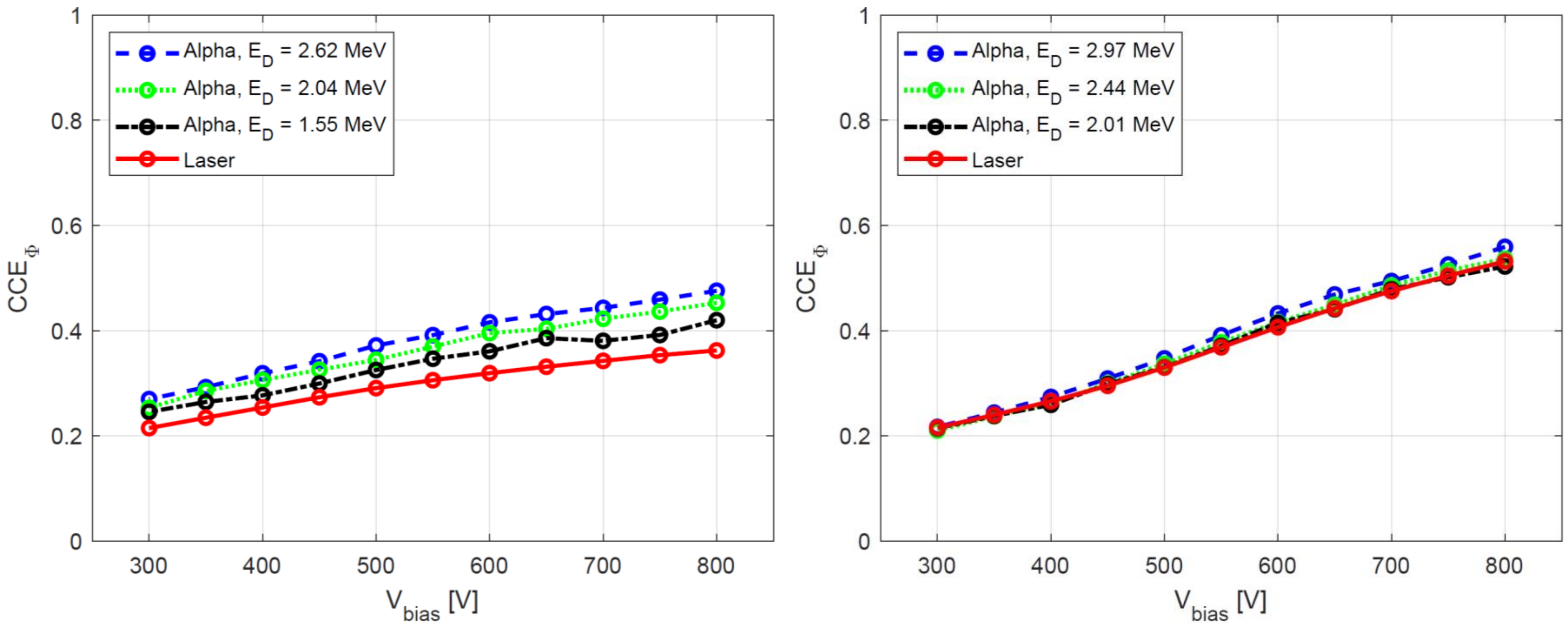
- $\mathrm{CCE}_{\Phi,\alpha}$ decreases with decreasing E_D
- $\mathrm{CCE}_{\Phi,\alpha}$ is larger than $\mathrm{CCE}_{\Phi,L}$ for all E_D

Rear side

- $\mathrm{CCE}_{\Phi,\alpha}$ is not a function of E_D
- $\mathrm{CCE}_{\Phi,\alpha} \approx \mathrm{CCE}_{\Phi,L}$

Front side illumination at −20 °C

Rear side illumination at −20 °C



Front: n⁺-p junction

Rear: p⁺-p junction

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CCE Results

$\Phi_{eq} = 1.2 \times 10^{16} \text{cm}^{-2}$

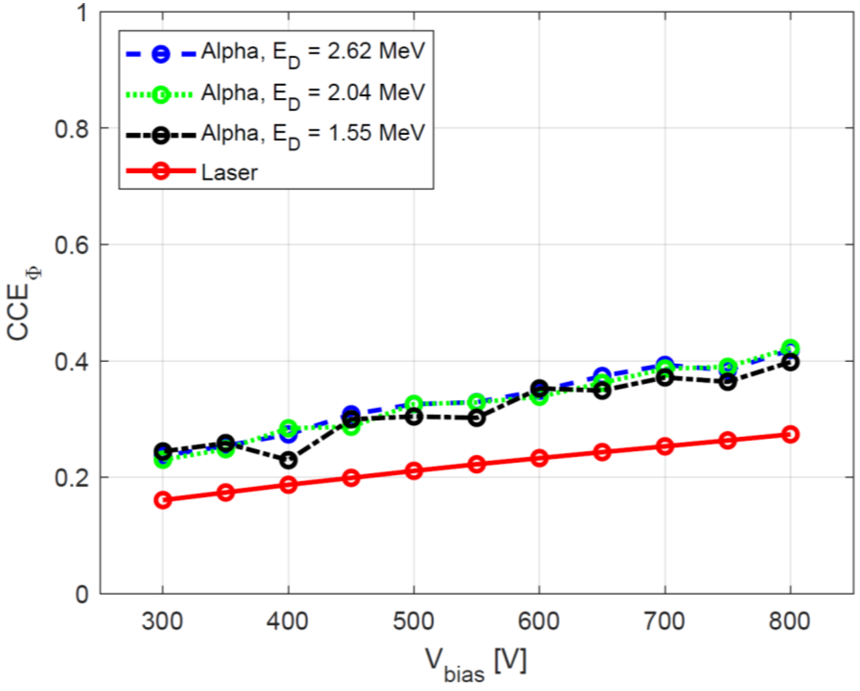
Front side

- $\text{CCE}_{\Phi,\alpha}$ barely changes with E_D
- $\text{CCE}_{\Phi,\alpha}$ is larger than $\text{CCE}_{\Phi,L}$ for all E_D

Rear side

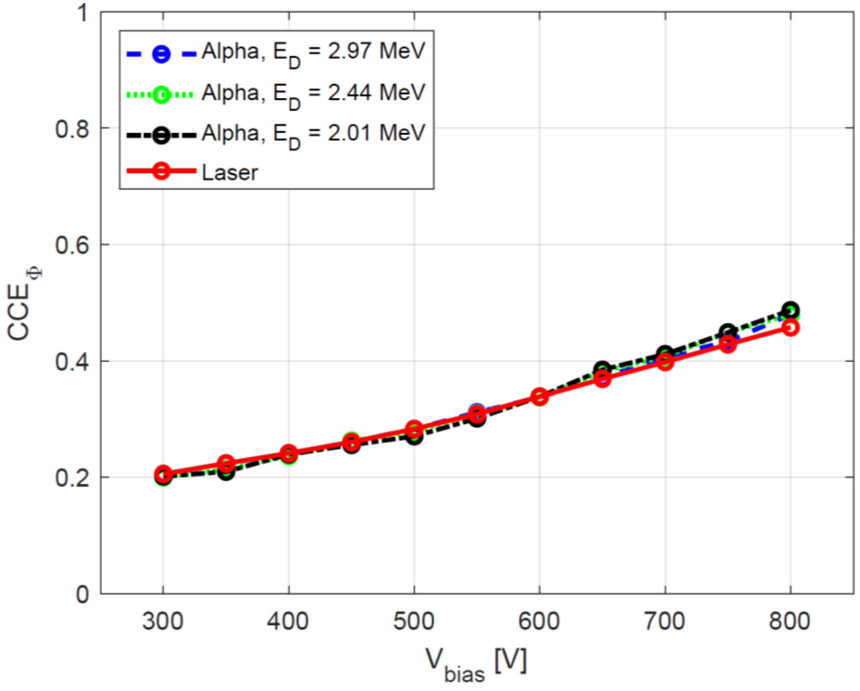
- $\text{CCE}_{\Phi,\alpha}$ is not a function of E_D
- $\text{CCE}_{\Phi,\alpha} \approx \text{CCE}_{\Phi,L}$

Front side illumination at −20 °C



Front: n⁺-p junction

Rear side illumination at −20 °C



Rear: p⁺-p junction

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CCE Summary

Front side

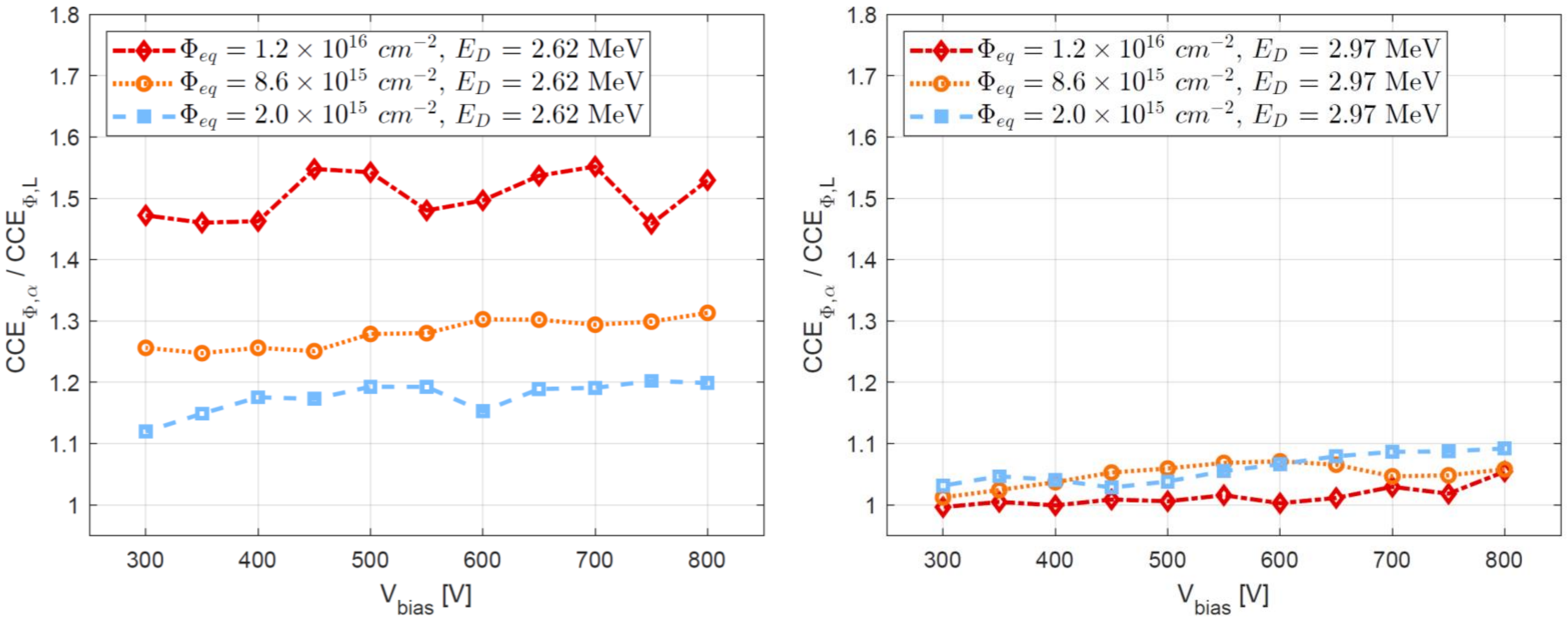
- $\mathrm{CCE}_{\Phi,\alpha}$ is function of E_D for the first two diodes
- The ratio $\frac{\mathrm{CCE}_{\Phi,\alpha}}{\mathrm{CCE}_{\Phi,L}}$ increases with Φ_{eq}

Rear side

- $\mathrm{CCE}_{\Phi,\alpha}$ independent of E_D
- $\frac{\mathrm{CCE}_{\Phi,\alpha}}{\mathrm{CCE}_{\Phi,L}} \approx 1$

Front side illumination at −20 °C

Rear side illumination at −20 °C



Front side results hint to the presence of a field-free region

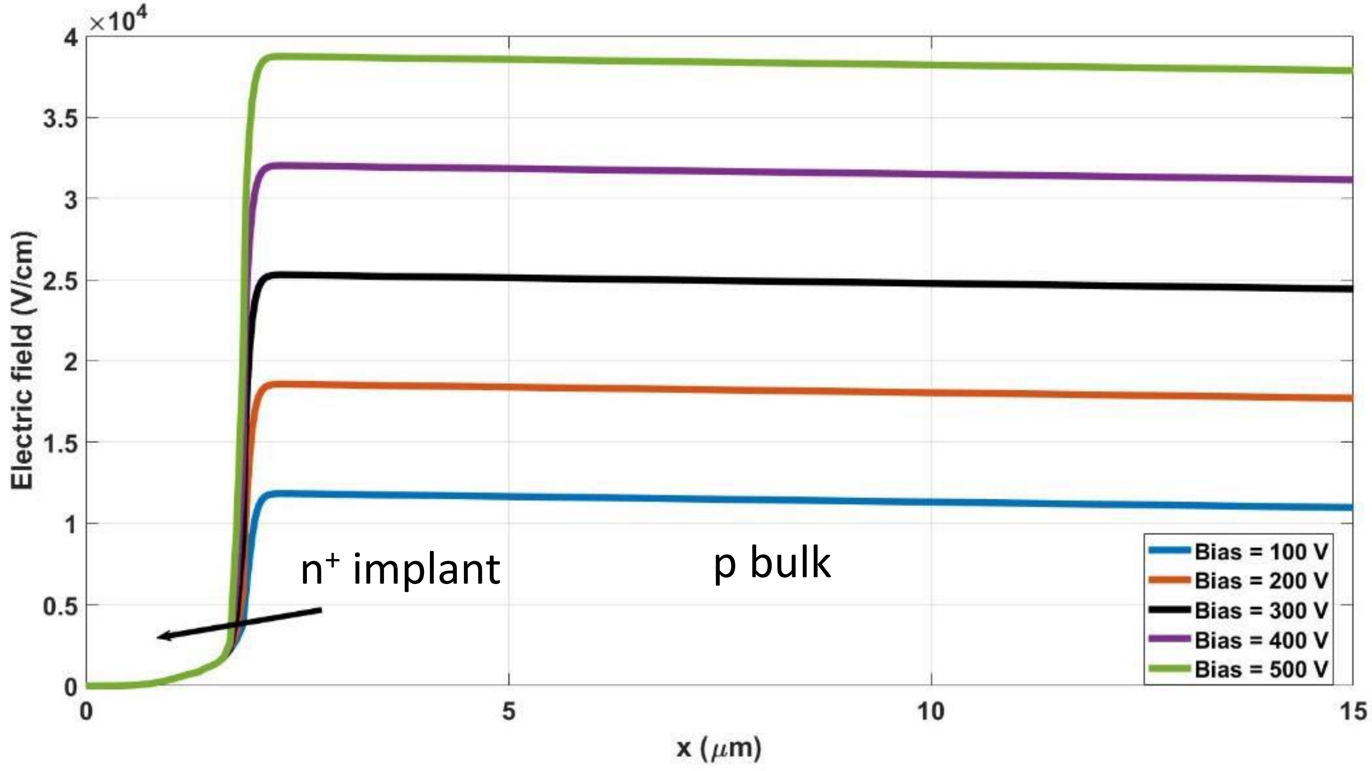
Device TCAD model

- Existence of field-free region at n^+-p junction
- Remains field free independent of the bias voltage
- Holes diffuse through field free region
- Non-irradiated: $\tau_d \ll \tau_{e,h}$
- Irradiated: $\tau_d \approx \tau_{e,h}$

τ_d: diffusion time through inactive region

$\tau_{e,h}$: trapping time of electrons and holes

Simulated electric field profile in a non-irradiated diode at $-20\ °C$



Model for Inactive Region

- Charge measurements are sensitive to inactive region after irradiation
- α-particles: $M_{\Phi,\alpha}(V, E_D, t_0) = \underbrace{Q_{0,\alpha} \cdot \mathrm{CCE}_{\Phi,\,\mathrm{active}}(V)}_{\text{Charge without inactive region}} \cdot \underbrace{\left(1 - \frac{\int_0^{t_0} \left(\frac{dE}{dx}\right)_{Si} dx}{E_D}\right)}_{\text{Inactive region impact}}$
- Laser light: $M_{\Phi,L}(V, t_0) = Q_{0,L} \cdot \mathrm{CCE}_{\Phi,\,\mathrm{active}}(V) \cdot \exp\left(-\frac{t_0}{\lambda_{abs}}\right)$
- $\mathrm{CCE}_{\Phi,\,\mathrm{active}}(V)$ and t_0 are unknown → free parameters

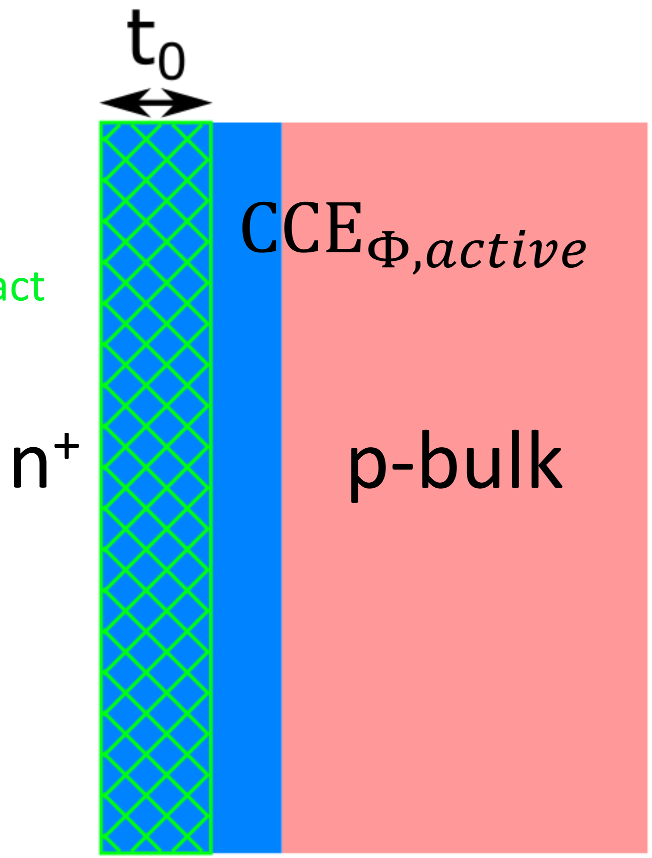
$Q_{0,\alpha} = \mathrm{K} \cdot E_D$

M_Φ : expected charge of irradiated diode for α or laser illumination

$\left(\frac{dE}{dx}\right)_{Si}$: total stopping power of α-particles in silicon

λ_{abs}: absorption length of 660 nm light in silicon (4.5 µm at −20 °C)

Cross-section of irradiated diode with modeled inactive region at n^+-p junction



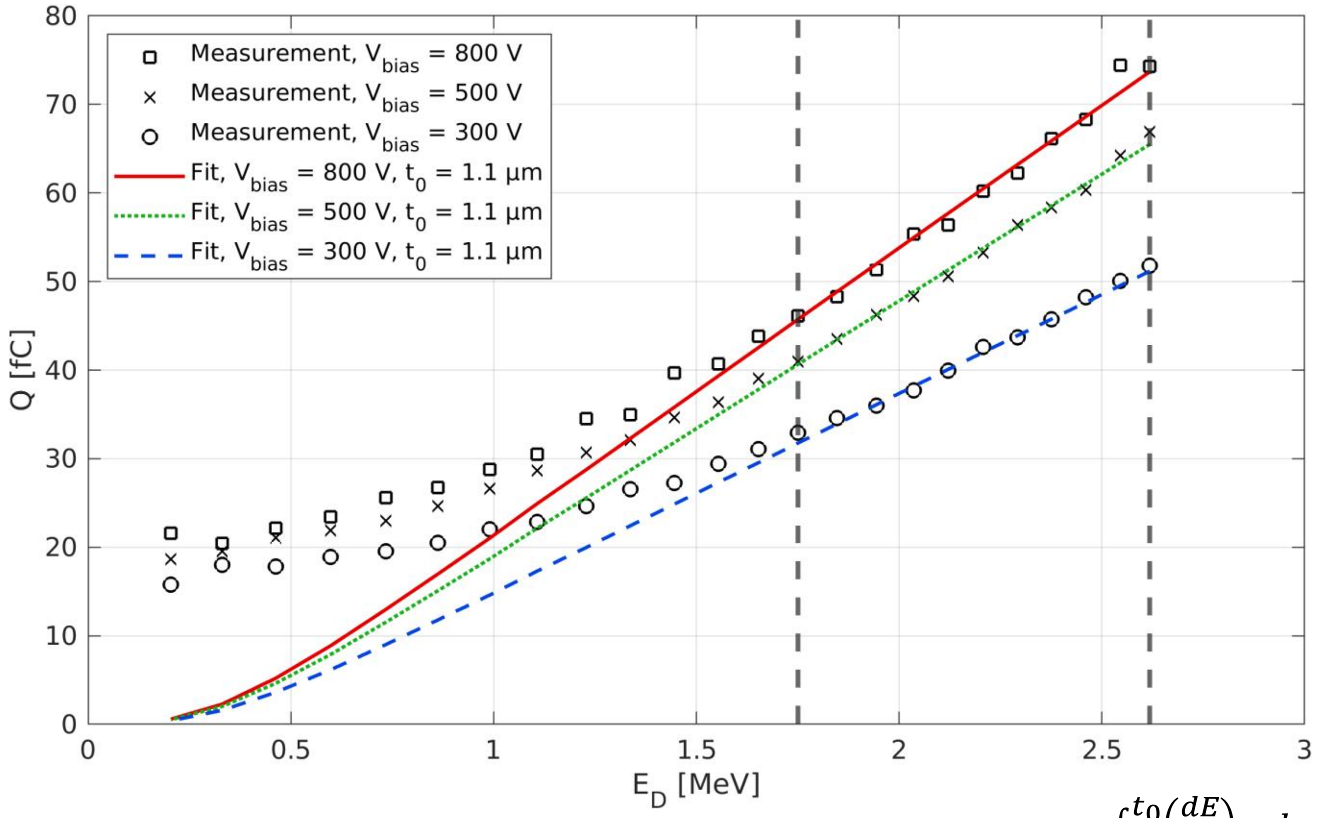
Model – α-particles

$\Phi_{eq} = 2.0 \times 10^{15}\text{cm}^{-2}$

- Good description of charge at high values of E_D
- Threshold effect influences charge below $E_D = 1.7$ MeV
- Fit range decreased to first 11 data points

Φ_{eq} [cm^{-2}]	t_0 [µm]
$2.0 \cdot 10^{15}$	1.1
$8.6 \cdot 10^{15}$	1.4
$1.2 \cdot 10^{16}$	2.6

Front side α-particle illumination at -20 °C



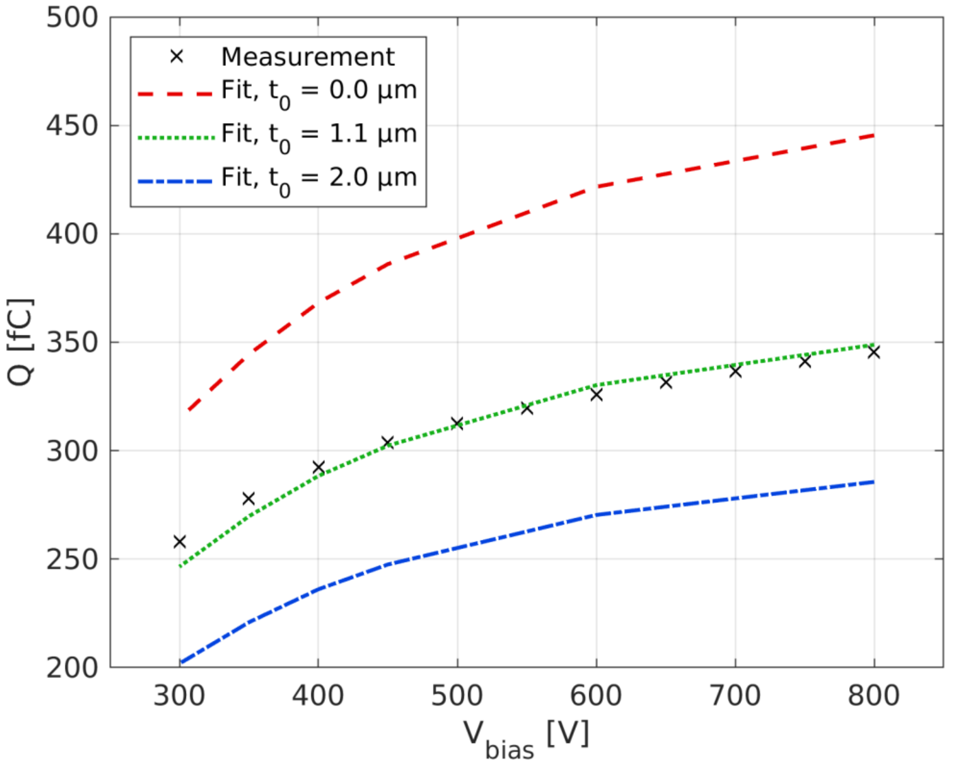
Fit function: $M_{\Phi,\alpha}(V, E_D, t_0) = K \cdot E_D \cdot \text{CCE}_{\Phi,\,\text{active}}(V) \cdot \left(1 - \frac{\int_0^{t_0} \left(\frac{dE}{dx}\right)_{Si} dx}{E_D}\right)$

Fit parameters: $K = 42.8$ fC/MeV, $E_0 = 4.65$ MeV, $t_0 = 1.1$ µm

Model – Laser Light $\Phi_{eq} = 2.0 \times 10^{15}\mathrm{cm}^{-2}$

- Comparison of expected charge using three different t_0
- Underestimation of t_0 leads to exaggerated charge
- Good description of charge at thickness $t_0 = 1.1\ \mu\mathrm{m}$

Front side laser light illumination at -20 °C



The prior CCE results can be understood through this model

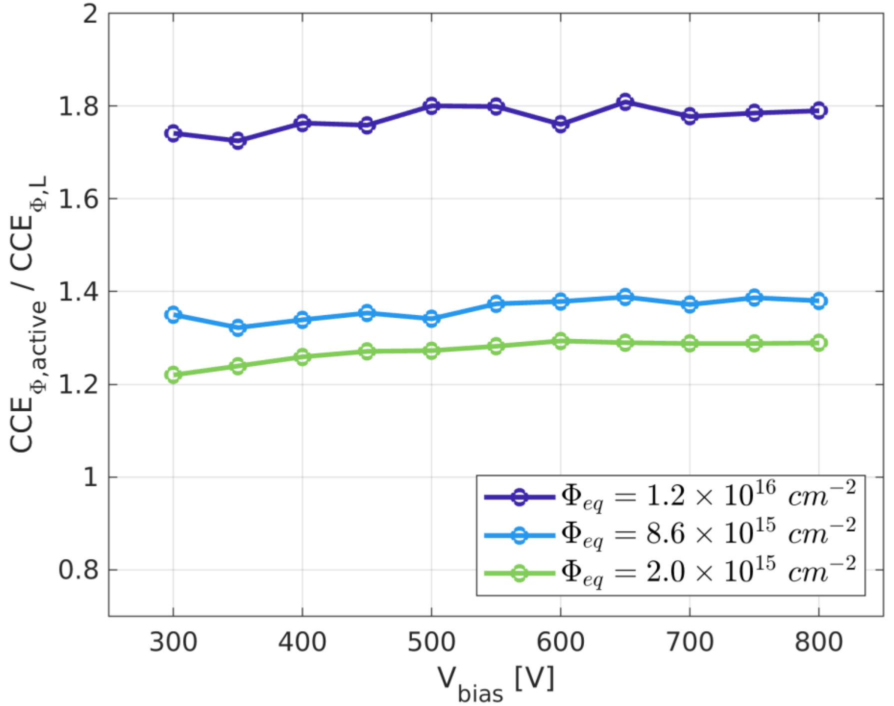
Fit function: $M_{\Phi,L}(V, t_0) = Q_{0,L} \cdot \mathrm{CCE}_{\Phi,\,\mathrm{active}}(V) \cdot \exp(-\frac{t_0}{\lambda_{abs}})$

Fit parameters: $K = 42.8\ \mathrm{fC/MeV},\ E_0 = 4.65\ \mathrm{MeV}$

Underestimation of CCE

- Impact of incative region estimated using $\frac{\mathrm{CCE}_{\Phi,\,active}(V)}{\mathrm{CCE}_{\Phi,\,L}(V)}$
- Ratio independent of $\mathrm{V_{bias}}$ within $\pm 4\ \%$
- At highest fluence:
  CCE with inactive region under-estimated by 78 % using laser TCT

Front side laser light illumination at -20 °C, underestimation of $\mathrm{CCE}_{\Phi,L}$



Impact of inactive region increases with irradiation fluence Φ_{eq}

Conclusion

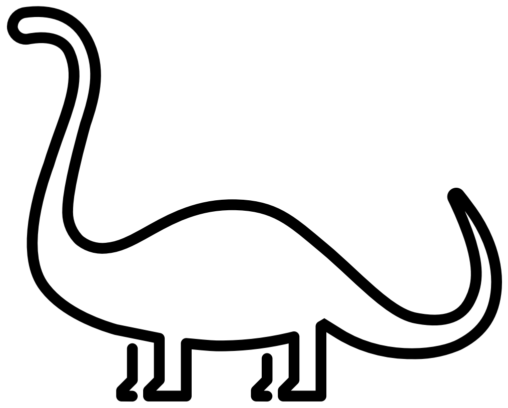
What have we learned?

- Front side CCE influenced by inactive region with minimal charge collection
  - Estimated thickness: 1.1 µm – 2.6 µm
- No evidence for an inactive region in the rear side is found

Outlook

- We can not expect the determined $\frac{1}{\tau_{e,h}}$ of both sources to agree without correcting for this inactive region
- A correction for an inactive region must be applied to CCE measurements

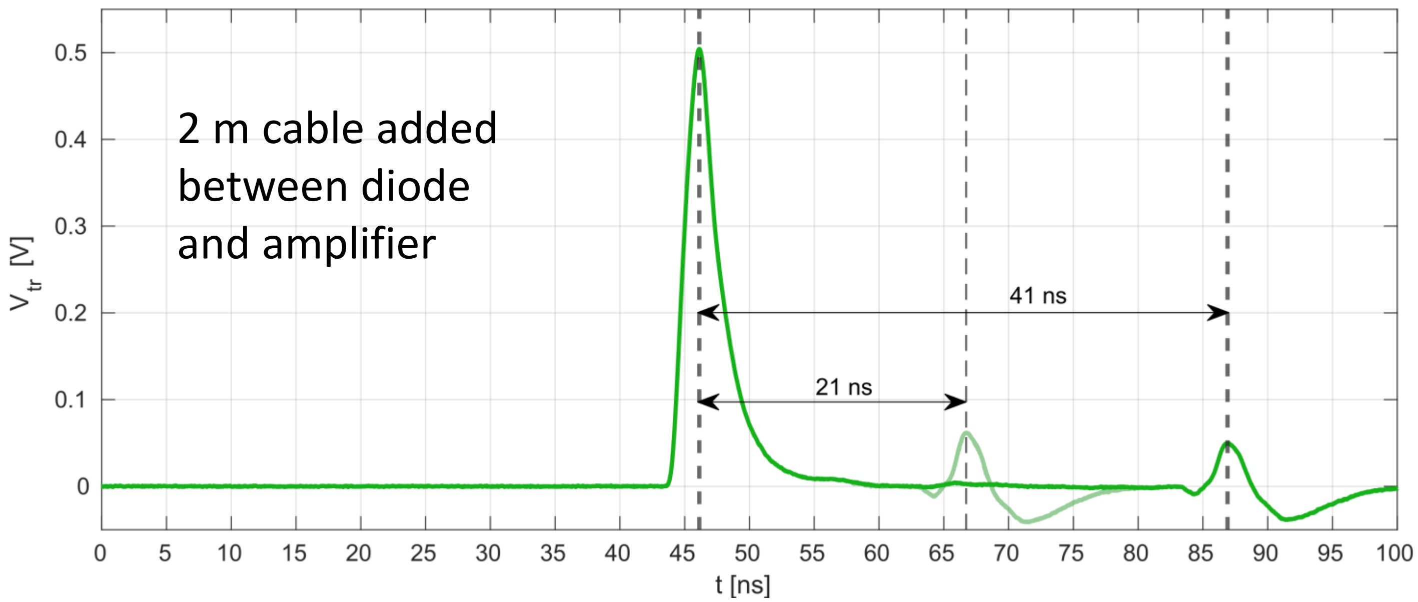
Backup Slides



Current Transient

- Average of 512 waveforms
- Voltage shift from baseline
- Signal reflection at amplifier
- Non-irradiated diodes
  - Reverse bias: 50 V – 300 V
- Irradiated diodes
  - Reverse bias: 300 V – 800 V

Rear side laser light illumination of a non-irradiated diode at 200 V and -20 °C



- Collected Charge of a diode

$$Q_m = \int_{t_0}^{t_1} \frac{V_{tr}(t)}{50\,\Omega \cdot 100} dt \,, \mathrm{t}_1 - \mathrm{t}_0 = 20 \text{ ns}$$

Longer cables shift reflection but reduce amplitude slightly

Questions

Whats the proportionality factor between Q_0 and E_D?

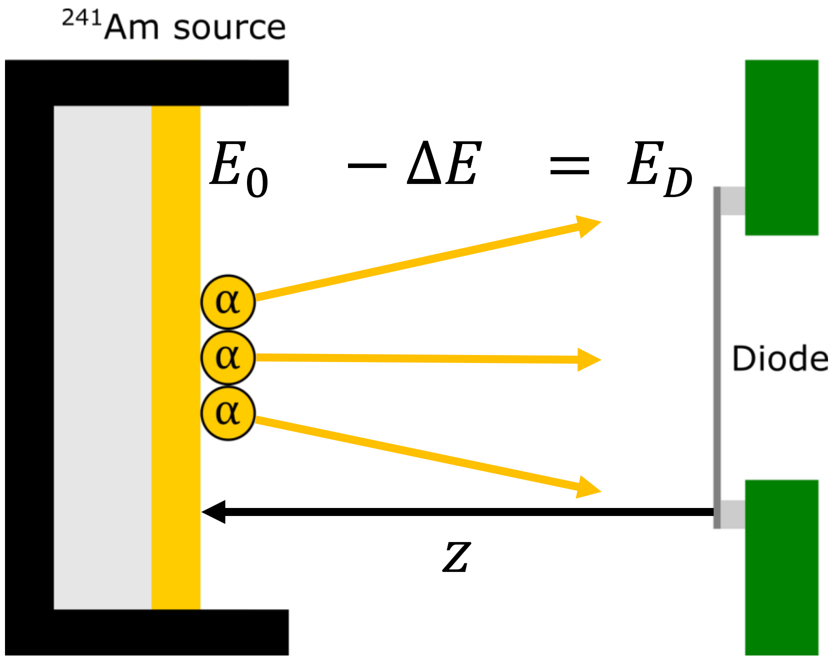
How large is the α-particle energy at the active volume of the diode?

Energy of α-particles and Charge

- Expected charge: $Q(z) = K \cdot E_D(z)$
- $E_D(z) = E_0 - \Delta E_{air}(z) - \Delta E_{Al} - \Delta E_{SiO_2}$
- $\Delta E_j = \rho_j \cdot \int_a^b \left(\frac{dE}{dx}\right)_j dx, \quad j = \{\mathrm{air}, \mathrm{Al}, \mathrm{SiO_2}\}$
- Theory: $E_0 \approx 5.4\ \mathrm{MeV}$, $K = 44.1\ \mathrm{fC/MeV}$
- Take E_0 and K as free parameters and fit $Q(z)$ to $Q_m(z)$

E_0: initial energy of alpha particles
ΔE: energy loss in respective medium
$\frac{dE}{dx}$: total stopping power
ρ: density of medium
Q_m: measured charge

Drifting α-particles on their way to the diode



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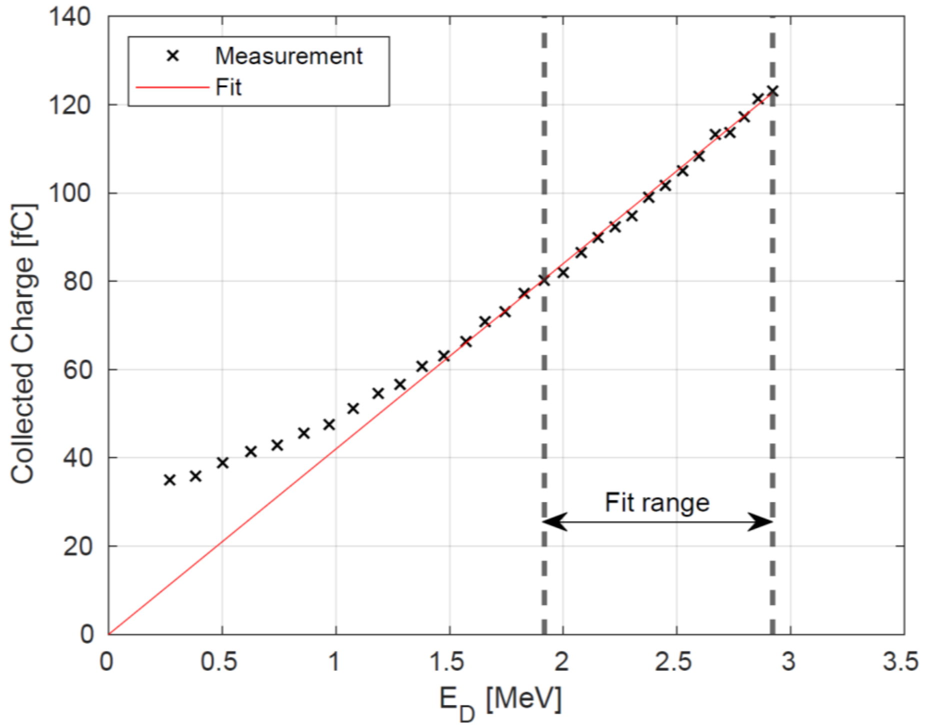
Fit to Collected Charge

Front side α-particle illumination of non-irradiated diode at 20 °C

- Charge increases proportionally for high E_D
- Charge deviates from linear behaviour below $E_D = 1.5$ MeV
- Oscilloscope triggers on the transient signal
  - This causes the threshold effect
- Fit range limited to avoid threshold effect



	Front side	Rear side
E_0[MeV]	4.65 ± 0.01	4.59 ± 0.01
K [fC / MeV]	42.8 ± 1.0	41.5 ± 0.9

Fit function: $Q(z) = K \cdot (E_0 - \Delta E_{air}(z) - \Delta E_{Al} - \Delta E_{SiO_2})$

Fit parameters: $K = 42.8$ fC/MeV, $E_0 = 4.65$ MeV

Question

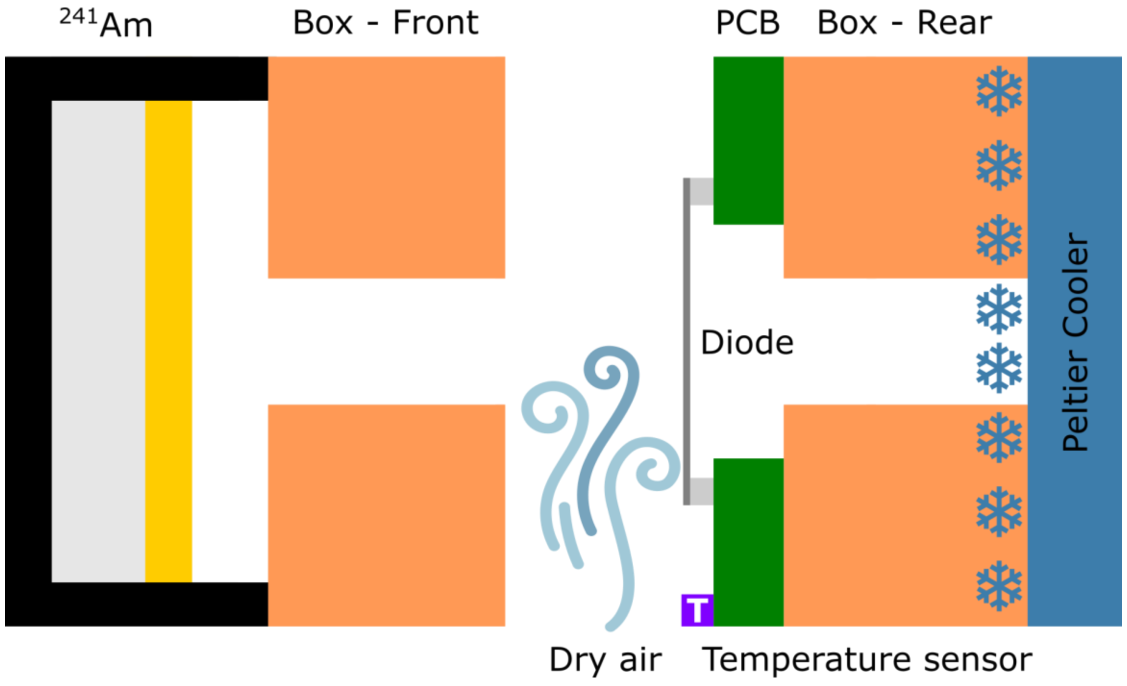
What is the air density
after cooling the setup?

Air Density after Cooling

- Irradiated diodes are measured at -20 °C
- T drops $\Longrightarrow \rho_{air}$ increases
  $\Longrightarrow E_D$ decreases (How much?)
- Energy loss: $\Delta E_{air} = \rho_{air} \int_a^b \left(\frac{dE}{dx}\right)_{air} dx$
- Use free parameter ρ_{air} to fit charge

Results	Front side	Rear side
ρ_{air} [kg m^{-3}]	1.348 ± 0.016	1.336 ± 0.020

Cooling the diode for front side TCT



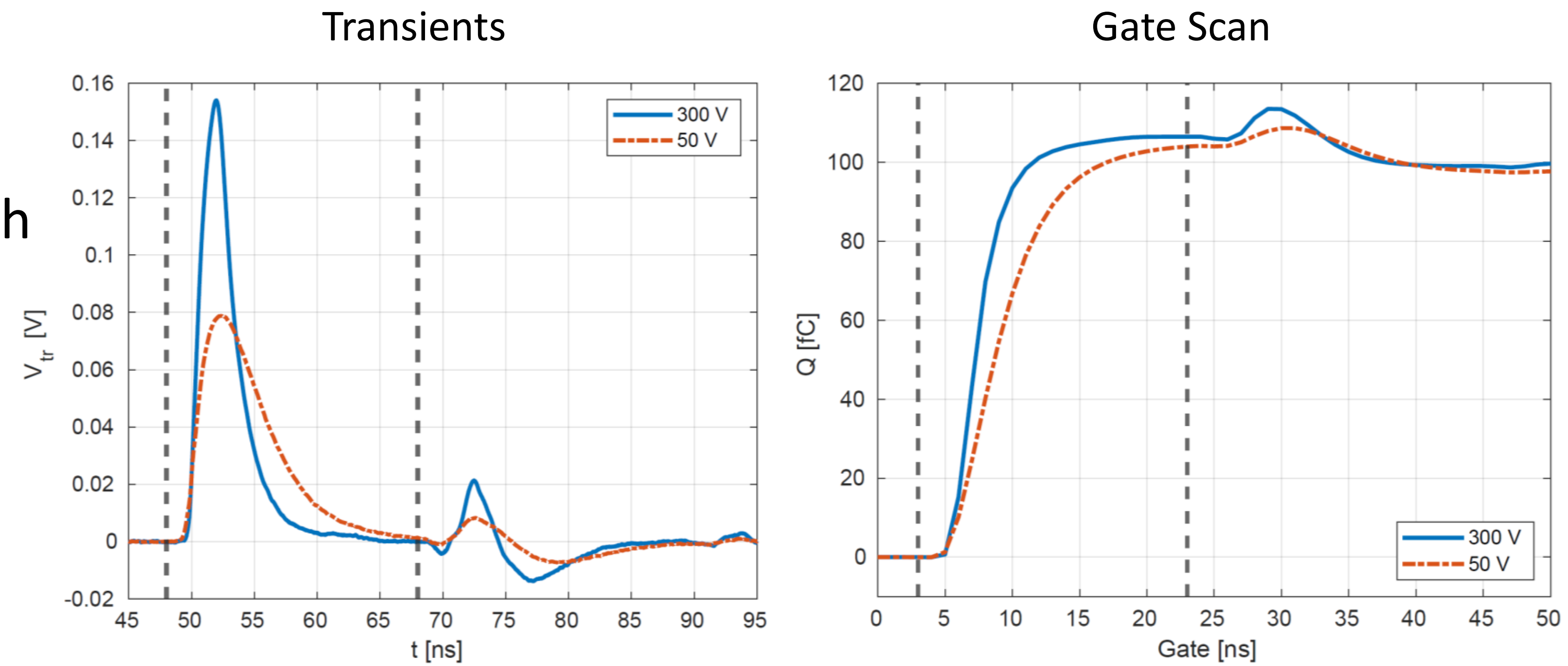
Neutral-density filter

- ND-filter transmit fraction of optical power
- Optical density / absorbance: $0.5 = A = \log_{10}\frac{I_0}{I} \;\Rightarrow\; \frac{I}{I_0} \approx 0.316$
- I_0: incoming light intensity
- I: transmitted light intensity

Gate Length Calculation

- Goal: obtain maximum collected charge
- Q grows with gate length
- Optimum gate length at $\Delta t = 20\ \mathrm{ns}$
- Reflection reduces Q beyond that gate

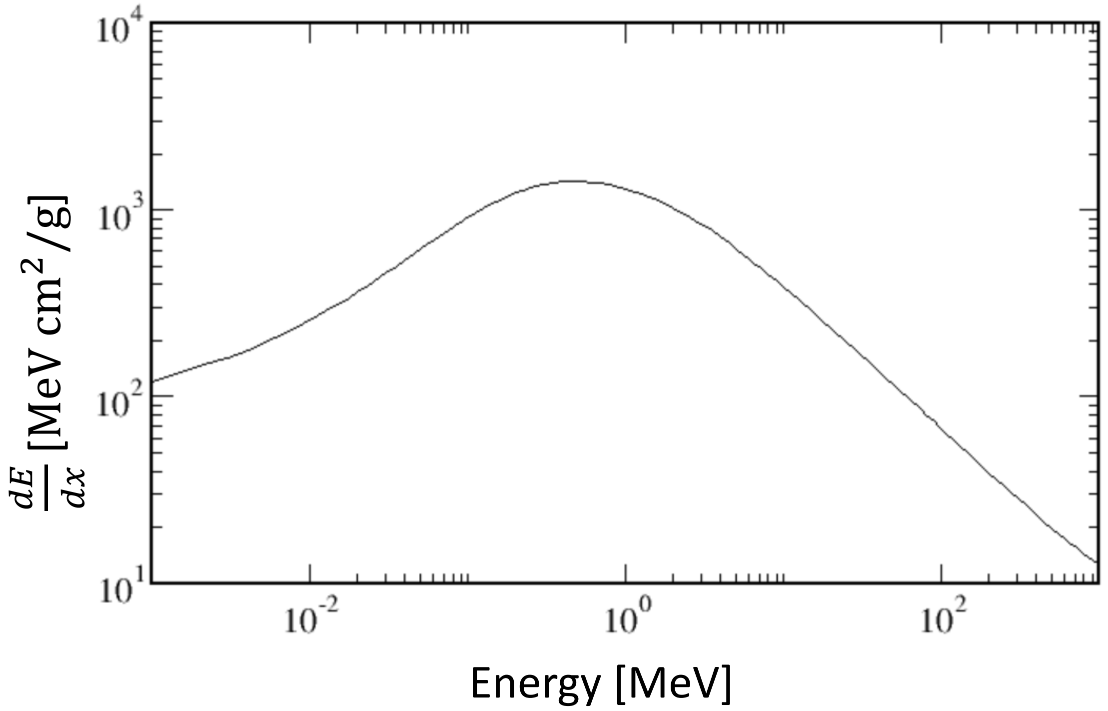
Front side alpha particle illumination of non-irradiated diode at $-20\ ^{\circ}C$



Energy of α-particles and Charge

- Expected charge: $Q(z) = K \cdot E_D(z)$
- $E_D(z) = E_0 - \Delta E_{air}(z) - \Delta E_{Al} - \Delta E_{SiO_2}$
- $\Delta E = \rho \cdot \int_a^b \left(\frac{dE}{dx}\right) dx$
- Theory: $E_0 \approx 5.4\ \mathrm{MeV}$, $K = 44.1\ \mathrm{fC/MeV}$
- Take E_0 and K as free parameters and fit $Q(z)$ to $Q_m(z)$

Total stopping power $\left(\frac{dE}{dx}\right)$ of α-particles in silicon



E_0: initial energy of alpha particles
ΔE: energy loss in respective medium
$\frac{dE}{dx}$: total stopping power
ρ: density of a substance

Energy of α-particles and Charge

$E_D(z) = E_0 - \Delta E(z)$
$Q(z) = K \cdot E_D(z)$

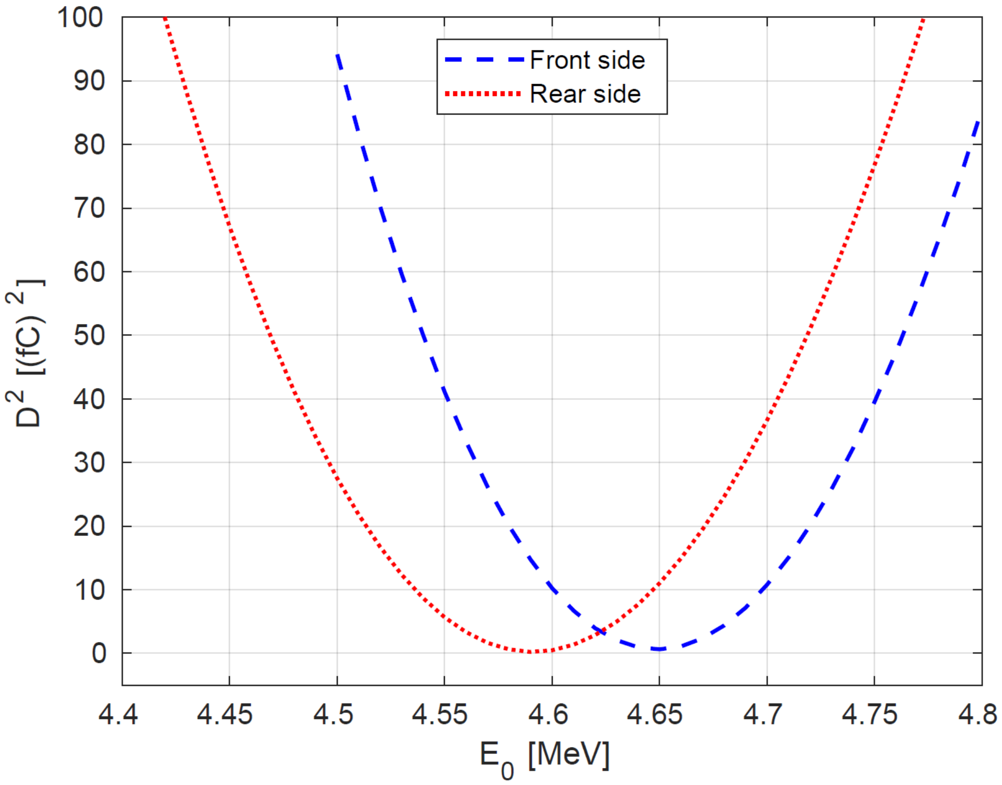
- Minimise deviation to measurement

$$D^2 = \sum_{i=1}^{n_z} \frac{(Q(z_i) - Q_m(z_i))^2}{n_z}$$

	Rear side	Front side
E_0[MeV]	4.59 ± 0.01	4.65 ± 0.01
K [fC / MeV]	41.5 ± 0.9	42.8 ± 1.0
D_{min} [fC]	0.474	0.796

- $\frac{D_{min}}{\langle Q \rangle} < 1\,\%$ $\Rightarrow$ Good fit to the charge

D^2 as a function of E_0 minimised over K



Minimum of D^2 gives best pair of values!

n_z : number of z-positions taken for the fit

Energy of α-particles and Charge

$E_D(z) = E_0 - \Delta E(z)$
$Q(z) = K \cdot E_D(z)$

- Minimise deviation to measurement

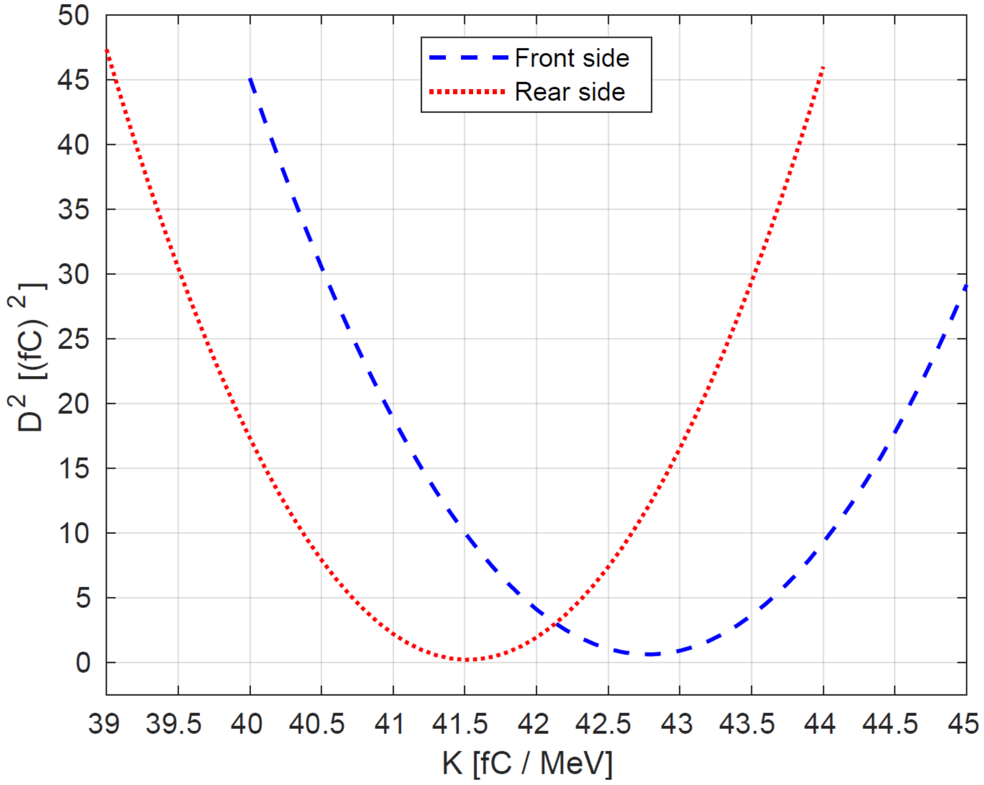
$$D^2 = \sum_{i=1}^{n_z} \frac{(Q(z_i) - Q_m(z_i))^2}{n_z}$$

	Rear side	Front side
E_0[MeV]	4.59 ± 0.01	4.65 ± 0.01
K [fC / MeV]	41.5 ± 0.9	42.8 ± 1.0
D_{min} [fC]	0.474	0.796

- $\frac{D_{min}}{\langle Q \rangle} < 1\,\%$ $\Rightarrow$ Good fit to the charge

n_z : number of z-positions taken for the fit

D^2 as a function of K minimised over E_0

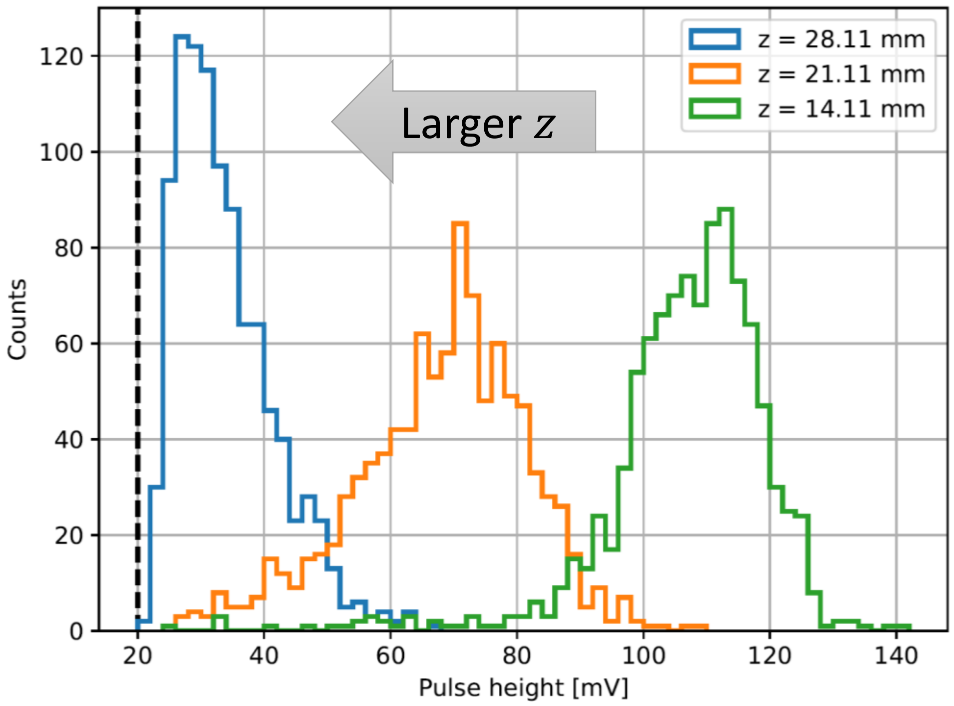


Minimum of D^2 gives best pair of values!

Threshold Effect

- Oscilloscope: $20\ \mathrm{mV}$ internal threshold trigger
- Trade-off between:
  - Obtaining whole energy spectrum
  - Minimising noise
- Smaller transients are not measured
- Bias towards higher average transient amplitudes
  ⇒ Average measured charge increases

Distribution of 1000 transients, α-particle illumination of non-irradiated diode at 120 V and 20 °C



The larger z the more low amplitude transients are cut off by the trigger

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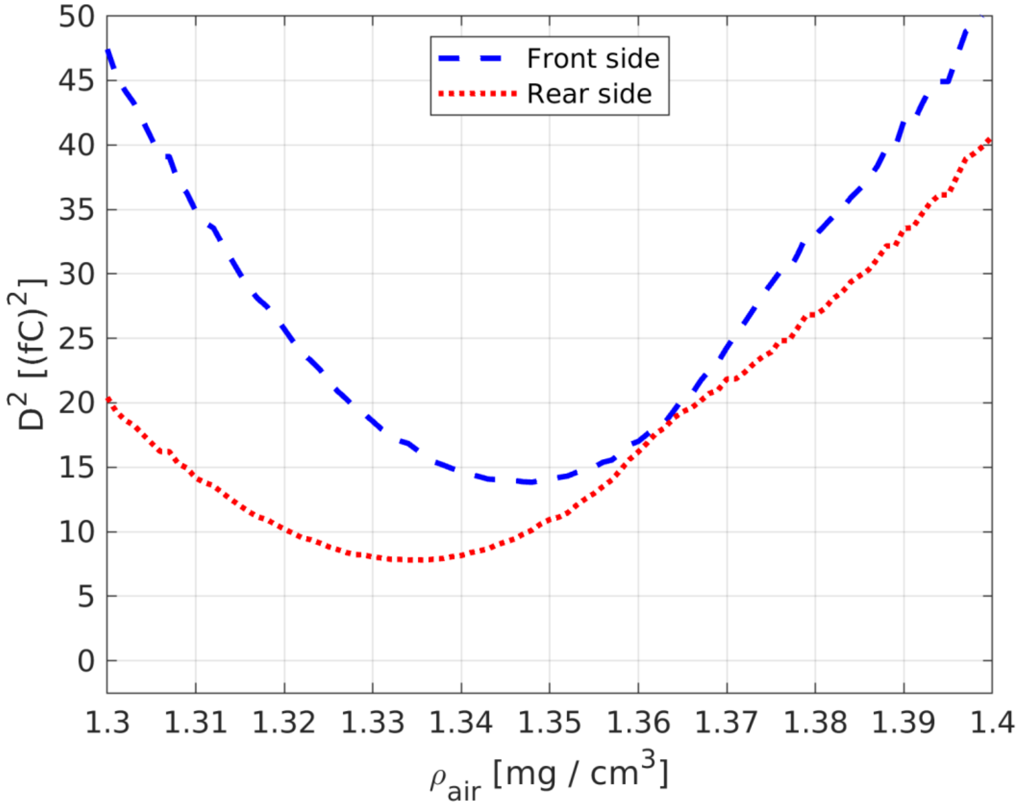
Air Density after Cooling

$$D^2 = \sum_{i=1}^{n_z} \frac{(Q(z_i) - Q_m(z_i))^2}{n_z}$$

- Irradiated diodes are cooled prior to TCT
- T drops $\Longrightarrow \rho_{air}$ increases
  $\Longrightarrow E_D$ decreases (How much?)
- Energy loss: $\Delta E_{air} = \rho_{air} \int_a^b \left(\frac{dE}{dx}\right) dx$
- Use free parameter ρ_{air} to fit charge

	Rear side	Front side
ρ_{air} [mg cm^{-3}]	1.336 ± 0.020	1.348 ± 0.016
D_{min} [fC]	2.793	3.720
Air pressure [hPa]	1003	1009
T [°C]	-11.7 ± 4.0	-12.4 ± 5.0

D^2 as a function of ρ_{air} after cooling down to -20 °C



Determining Dead Layer Thickness

- Deviation from measured charge for α-particles:

$$D_\alpha^2 = \frac{1}{n_V \cdot n_E} \sum_{i=1}^{n_V} \sum_{j=1}^{n_E} \left(M_{\Phi,\alpha}(V_i, E_j) - Q_{\Phi,\alpha}(V_i, E_j) \right)^2$$

- Deviation from measured charge for laser light:

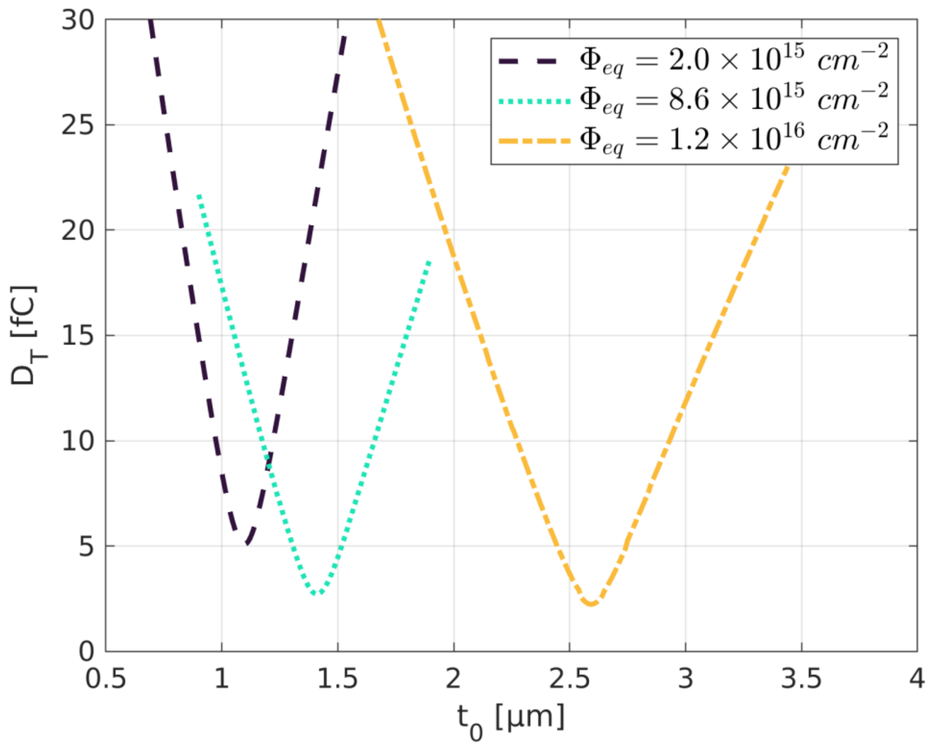
$$D_L^2 = \frac{1}{n_V} \sum_{i=1}^{n_V} \left(M_{\Phi,L}(V_i) - Q_{\Phi,L}(V_i) \right)^2$$

$\Rightarrow$ Total deviation: $D_T = \sqrt{D_\alpha^2 + D_L^2}$

Φ_{eq} [cm^{-2}]	t_0 [µm]	$D_{T,min}$ [fC]
$2.0 \cdot 10^{15}$	1.1	5.1
$8.6 \cdot 10^{15}$	1.4	2.7
$1.2 \cdot 10^{16}$	2.6	2.2

$n_{V,E}$: number of voltages or α-particle energies taken for the fit

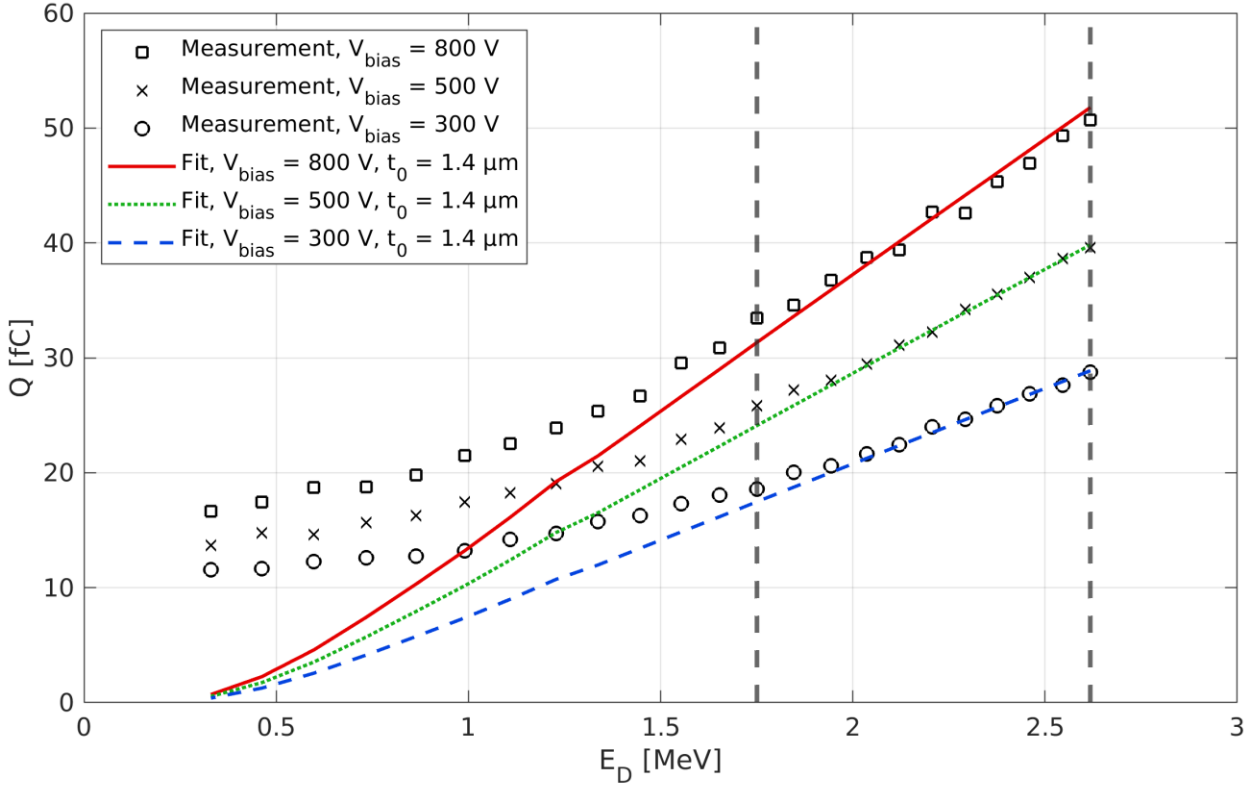
D_T as a function of t_0 for several irradiated diodes at -20 °C



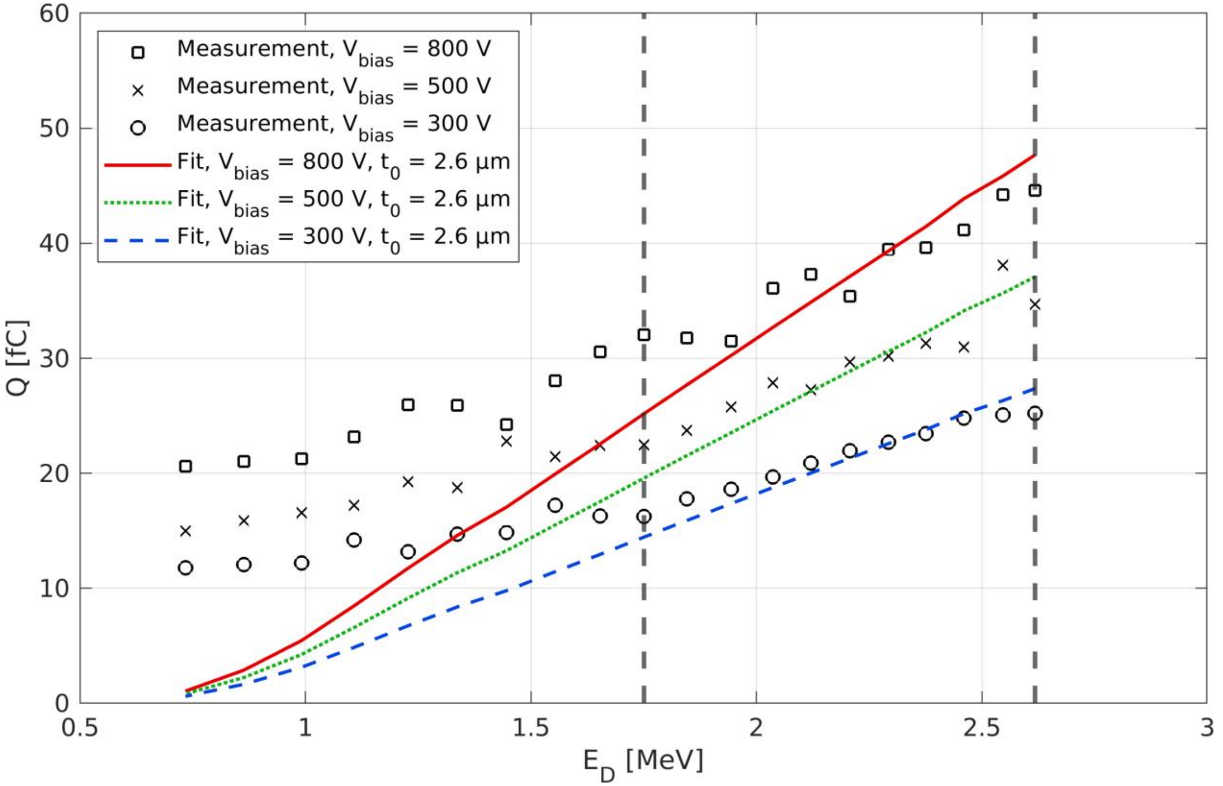
The larger Φ_{eq} the bigger is t_0

Model – α-particles

Front side α-particle illumination at -20 °C, $\Phi_{eq} = 8.6 \times 10^{16}\mathrm{cm}^{-2}$



Front side α-particle illumination at -20 °C, $\Phi_{eq} = 1.2 \times 10^{16}\mathrm{cm}^{-2}$

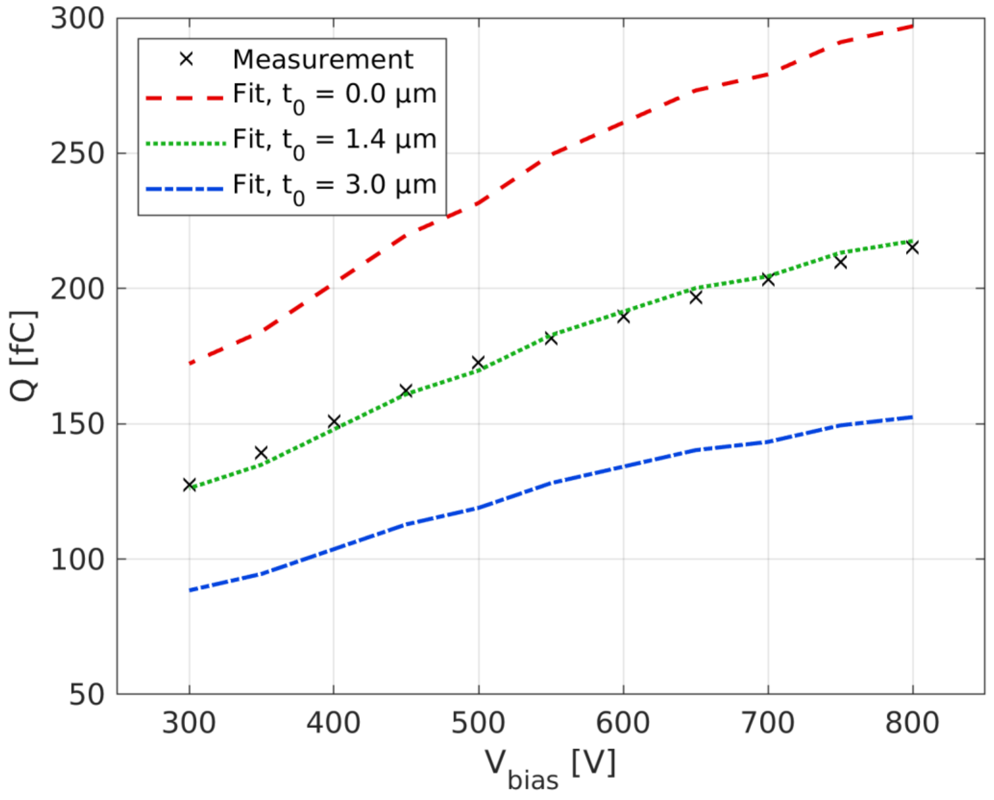


Fit function: $M_{\Phi,\alpha}(V, E_D, t_0) = K \cdot E_D \cdot \mathrm{CCE}_{\Phi,\,\mathrm{active}}(V) \cdot \left(1 - \frac{\int_0^{t_0} \left(\frac{dE}{dx}\right)_{Si} dx}{E_D}\right)$

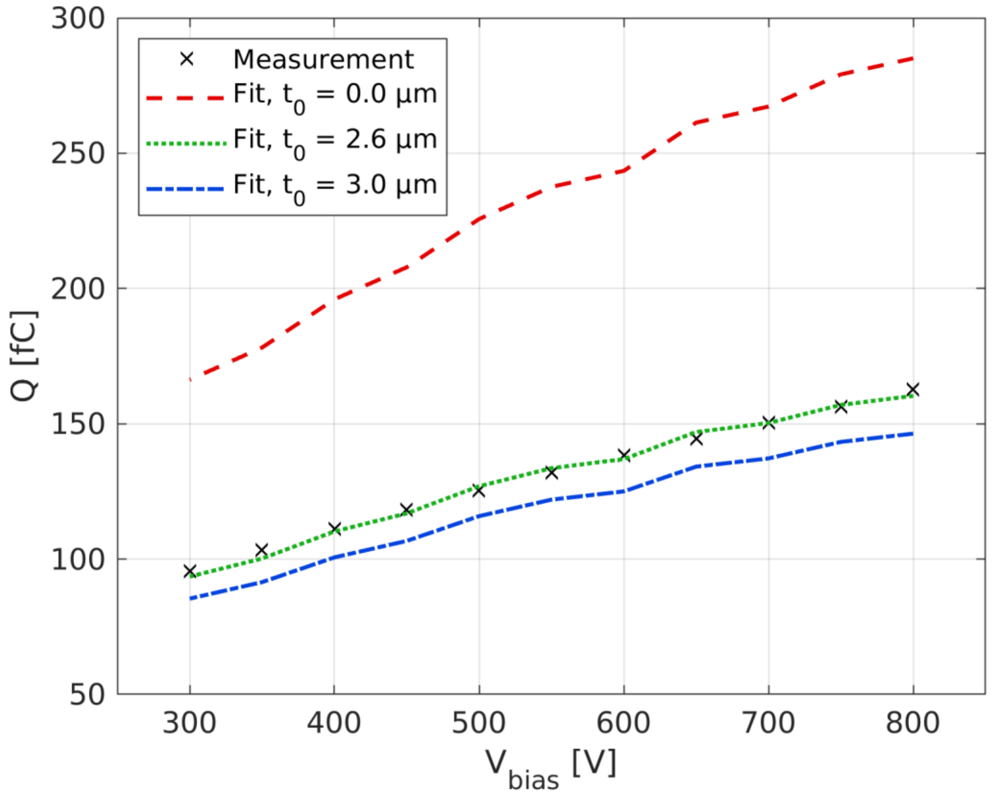
Fit parameters: $K = 42.8\ \mathrm{fC/MeV},\ E_0 = 4.65\ \mathrm{MeV}$

Model – Laser Light

Front side laser light illumination at -20 °C, $\Phi_{eq} = 8.6 \times 10^{16} \mathrm{cm}^{-2}$



Front side laser light illumination at -20 °C, $\Phi_{eq} = 1.2 \times 10^{16} \mathrm{cm}^{-2}$



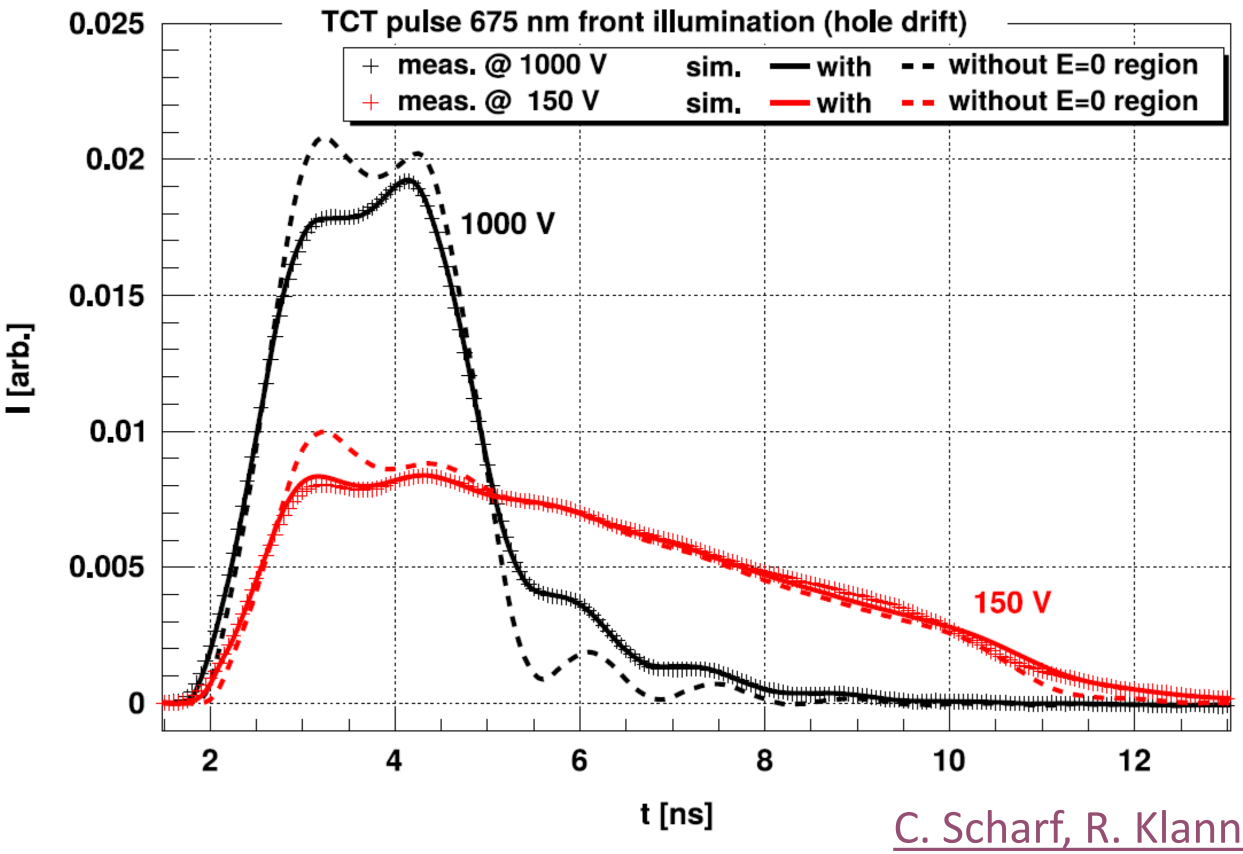
Fit function: $M_{\Phi,L}(V, t_0) = Q_{0,L} \cdot \mathrm{CCE}_{\Phi,\,\mathrm{active}}(V) \cdot \exp(-\frac{t_0}{\lambda_{abs}})$

Fit parameters: $K = 42.8\ \mathrm{fC/MeV},\ E_0 = 4.65\ \mathrm{MeV}$

Simulation

Current transients of p-type HPK diode, 675 nm laser light front illumination at 293 K. Solid lines: Simulation with field-free regions of 1.6 μm at n^+-p side

- Fit of simulated transients to measured transients
- Adding field-free region of 1.6 μm at n^+-p side results in good description
- Not understood why field-free regions are not required for p^+-n diodes



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