Analysis of TCT measurements of highly irradiated silicon pad diodes under forward bias

Erika Garutti, Robert Klanner, Christian Scharf
Institut für Experimentalphysik
Universität Hamburg

SPONSORED BY THE
Federal Ministry
of Education
and Research

PHYSICS
AT THE
TERA
SCALE
Helmholtz Alliance

Analysis of TCT mea[illegible]nts of highly irradiated silicon p[illegible]es under forward [illegible]

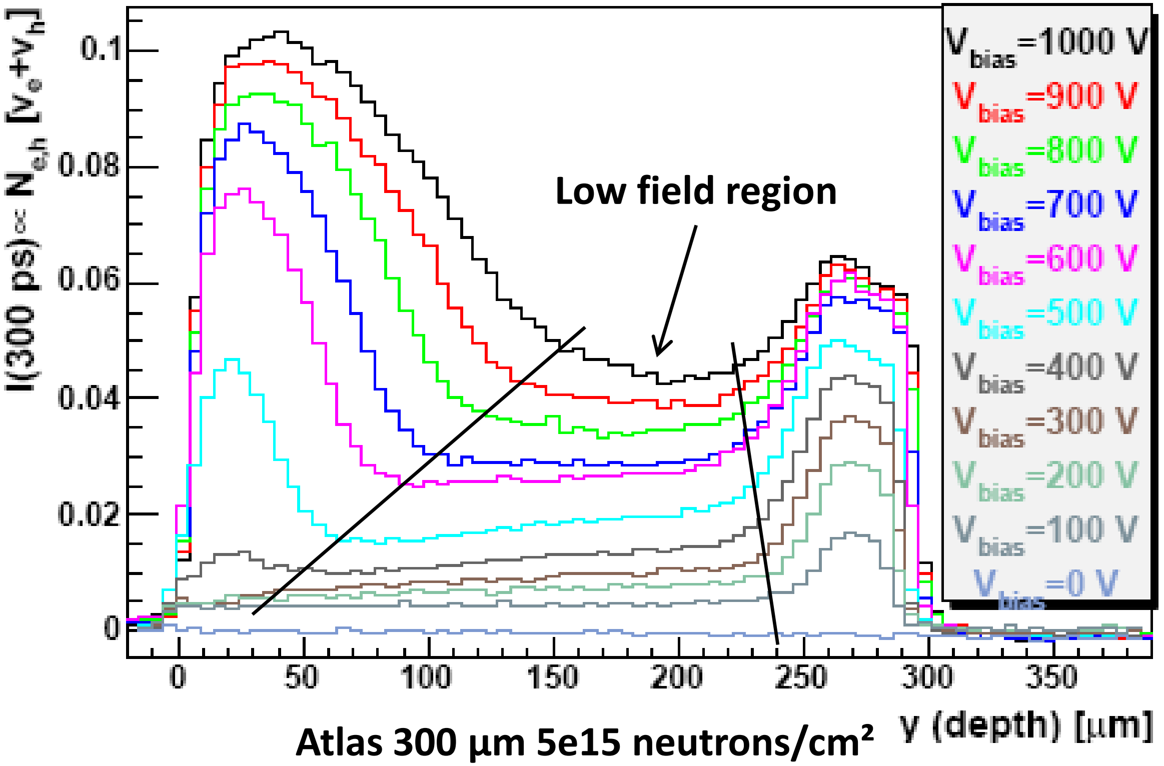
Preliminary

Erika [illegible] Robert Klanner, Christian Scharf
[illegible]titut für Experimentalphysik
Universität Hamburg

SPONSORED BY THE
Federal Ministry
of Education
and Research

PHYSICS
AT THE
TERA
SCALE
Helmholtz Alliance

Motivation



Low field region

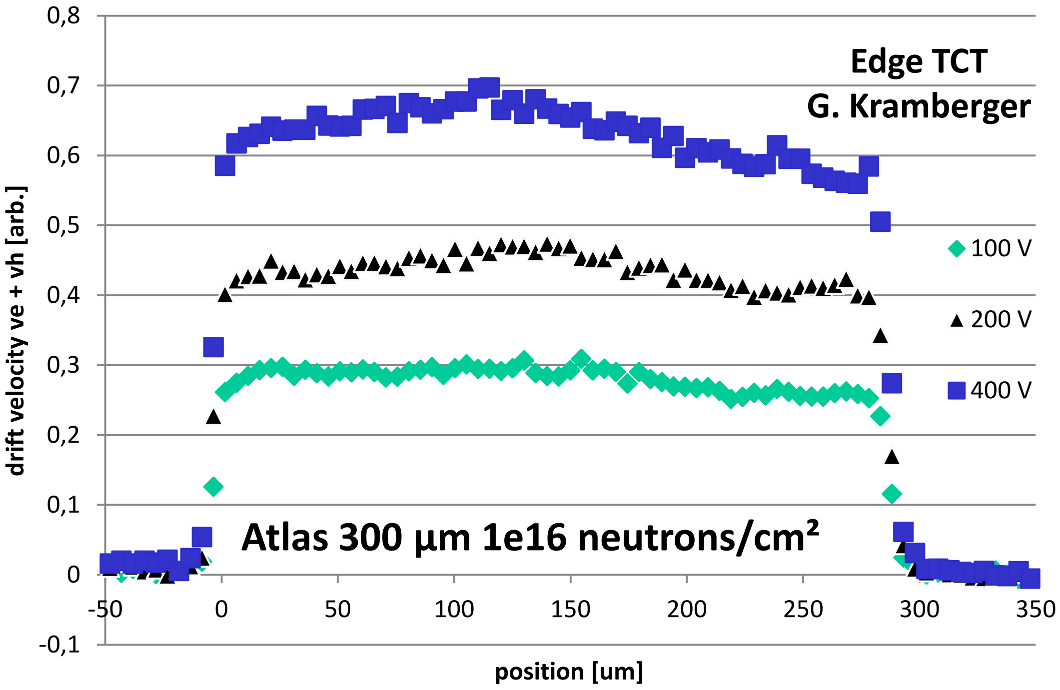
Atlas 300 µm 5e15 neutrons/cm²

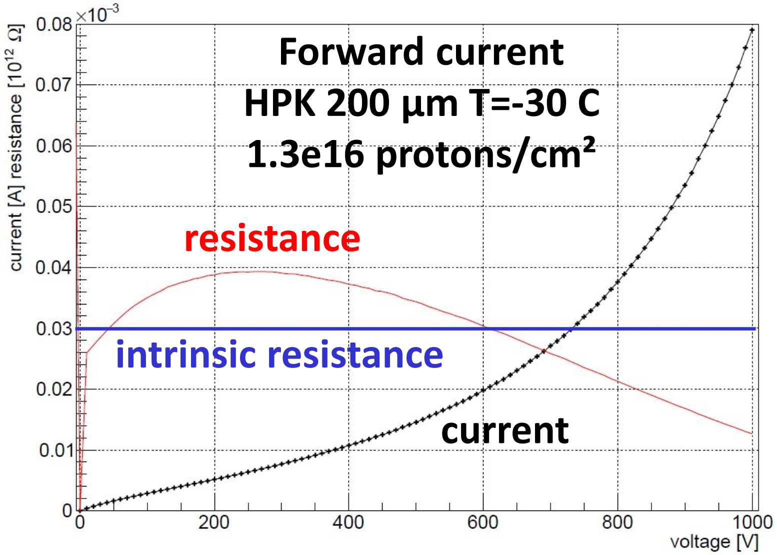
Edge TCT
G. Kramberger
Vertex 2010

Let‘s have a look at reverse biased highly irradiated sensors:

- **„Double junction“** with high field near contacts
- Moderate E-field and low trapping in between
- **Many unknown parameters:** $v_{e,h}(x), \tau_{e,h}(x), E(x)$

Motivation





Forward bias makes life easy: $v_{e,h} = const$ → electric field $E = const$

Similar to low field region for reverse bias

- Carrier densities $n_e \approx n_h$ → behaves like a resistor (intrinsic material)
- Constant trap occupation → $\tau_{e,h} = const$

Experimental method

Transient Current Technique

- Pulsed laser generates e-h pairs
- Charge carriers drift in E-field

$\rightarrow \boldsymbol{I \propto v_d(E) \cdot exp(-{}^{t}/_{\tau})}$

Sensors: Float-zone and MCZ silicon n- and p-bulk **pad diodes**

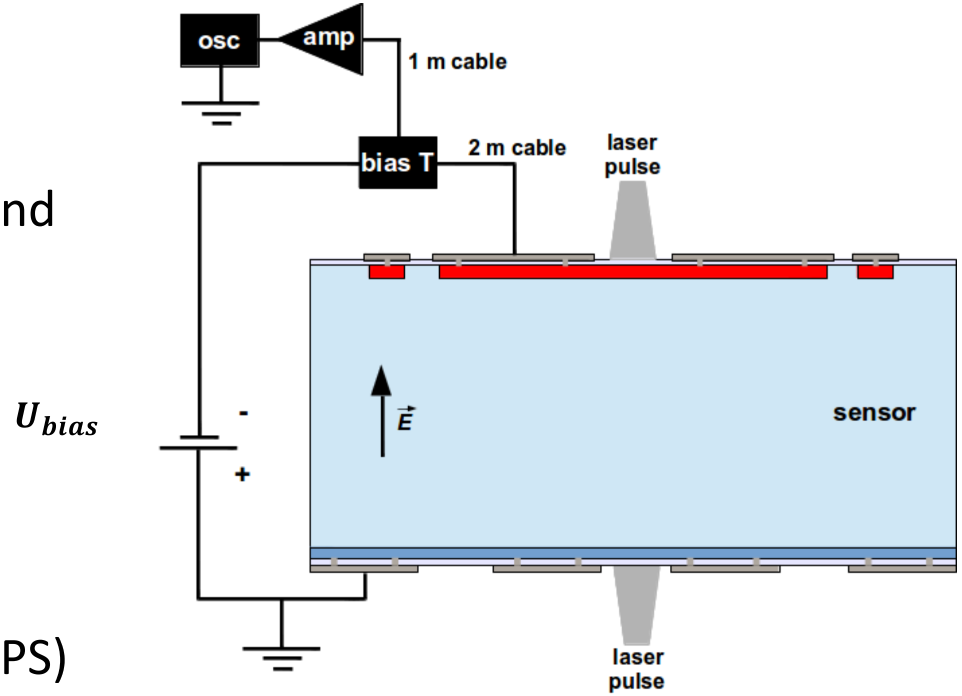
<u>**Measurements**</u>

Reference non irradiated

- 400 V – 500 V

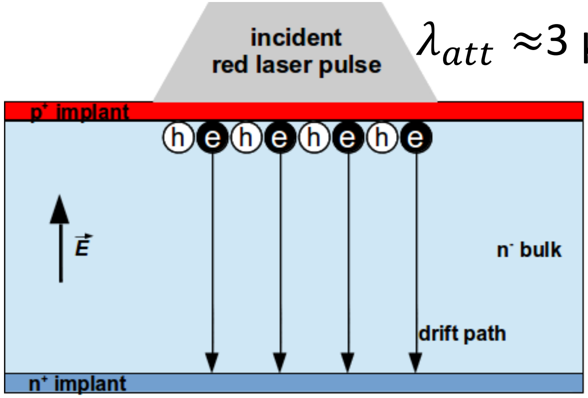
Irradiated

- Fluence 1e15 – 1.3e16 protons/cm² (PS)
- -1000 V < $U_{bias} \leq$ 1000 V @ -30 C



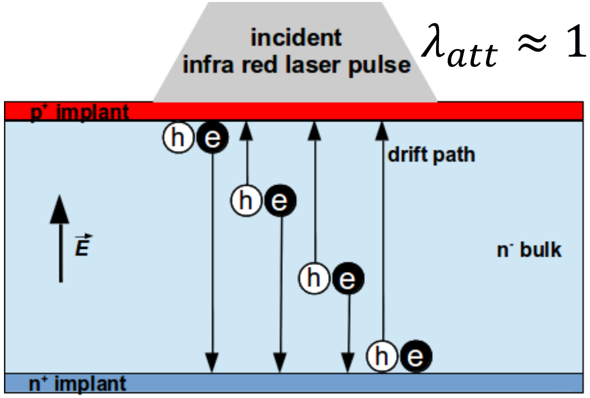
Transient Current Technique

- **Red laser** 675 nm
  → signal induced by drift of **e or h**
- **Infrared laser** 1063 nm
  → simultaneous **e and h** drift

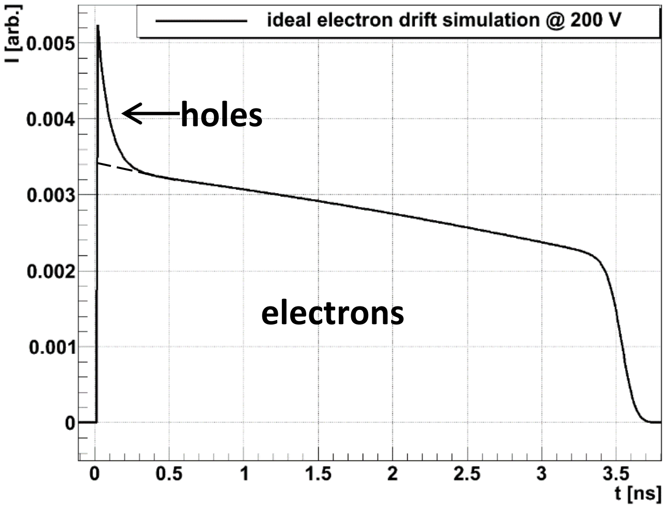


$\lambda_{att} \approx 3$ µm

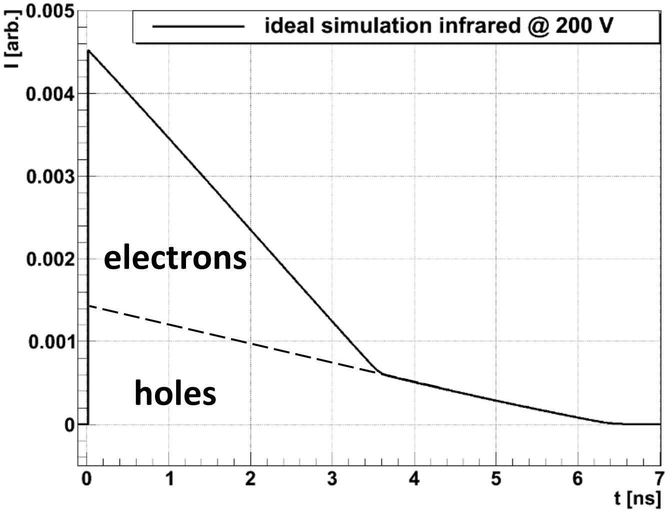
initial charge distribution



$\lambda_{att} \approx 1$ mm

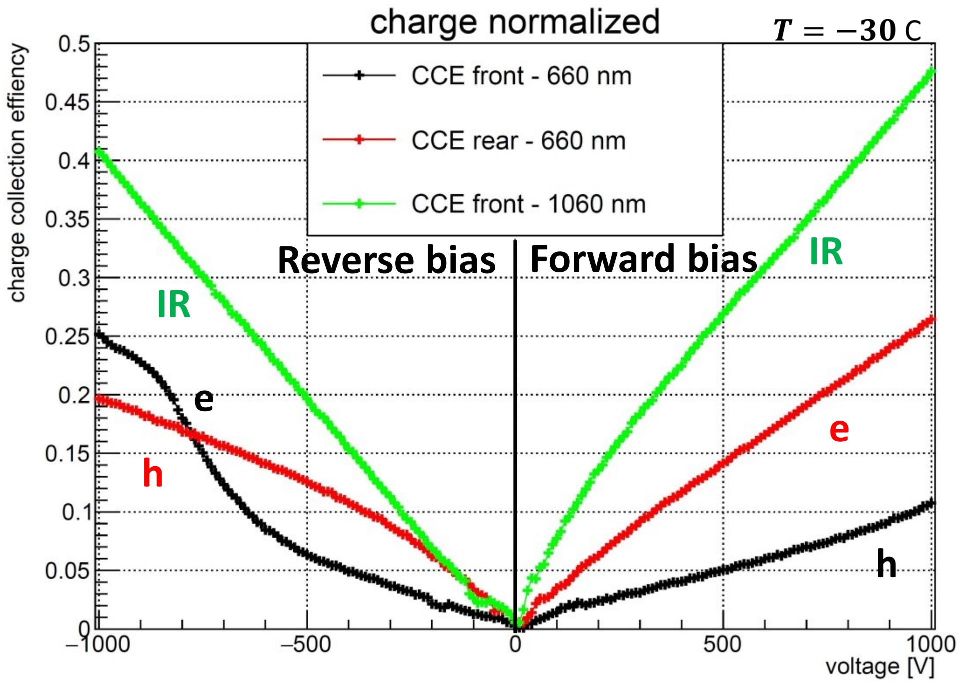


drift simulation
200 µm sensor
@ 200 V



First results

The charge collection length



HPK p+n pad sensor
Thickness w =200 µm
1.3e16 protons/cm²

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

→ **Determine charge collection length $\lambda_{e,h} = v_{e,h} \cdot \tau_{e,h}$ for red laser:**

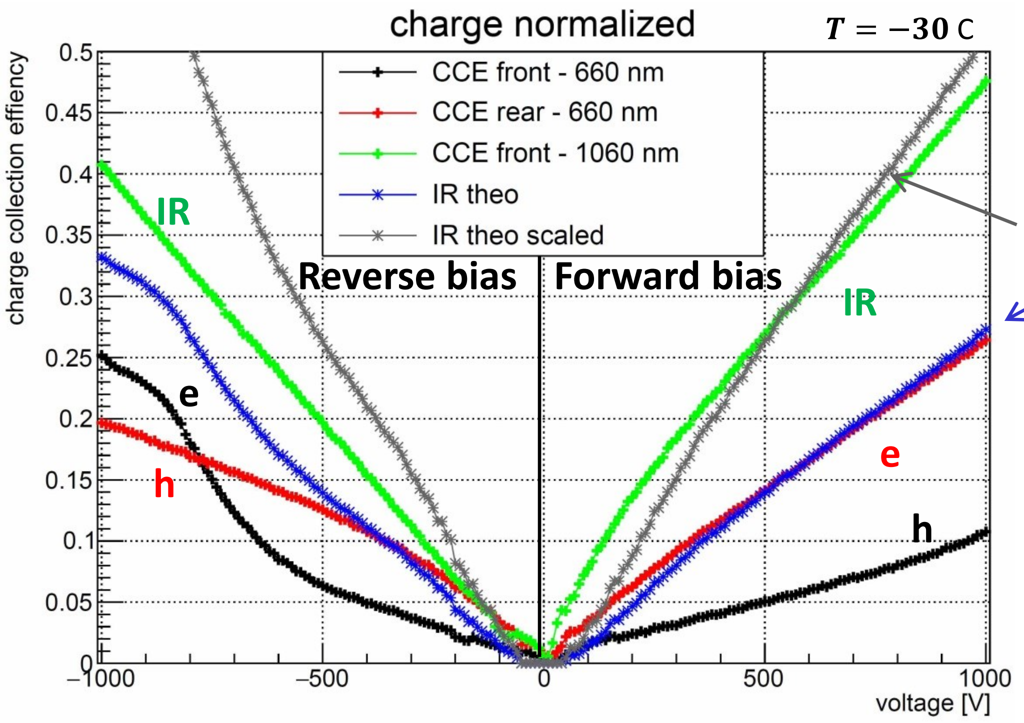
- $$Q_{red} \approx Q_{dep}\left[\frac{w-\lambda_{att}}{w} \cdot \frac{\lambda_{e,h}}{w}\left(1 - e^{-\frac{w}{\lambda_{e,h}}}\right) + {}^{\lambda_{att}}/_{w}\right]$$

Q_{dep}: Deposited charge
λ_{att}: Attenuation length

Charge drifting through the sensor

Charge collected at illuminated electrode ($\lambda_{att} \ll \lambda$)

CCE for infrared laser



Q_{IR} calculated from $\lambda_{e,h}$ with

$Q_{dep,IR} = 1.9 \cdot Q_{ref,IR}$

$Q_{dep,IR} = Q_{ref,IR}$

for both cases

$Q_{dep,red} = Q_{ref,red}$

200 µm HPK p+n
1.3e16 p/cm²

Now we know $\lambda_{e,h}$ → Determine CCE for infrared laser ($\lambda_{att} \rightarrow \infty$):

- $$Q_{IR} \approx Q_{dep,IR}\left(\frac{\lambda_e}{w}\left(1-\frac{\lambda_e}{w}\left(1-e^{-\frac{w}{\lambda_e}}\right)\right)+\frac{\lambda_h}{w}\left(1-\frac{\lambda_h}{w}\left(1-e^{-\frac{w}{\lambda_h}}\right)\right)\right)$$

Fair approximation for $Q_{dep,IR} = 1.9 \cdot Q_{ref,IR}$ → **Does the light absorption change?**

Charge collection in forward bias

Indeed: Absorption coefficient changes with irradiation also for low wavelength

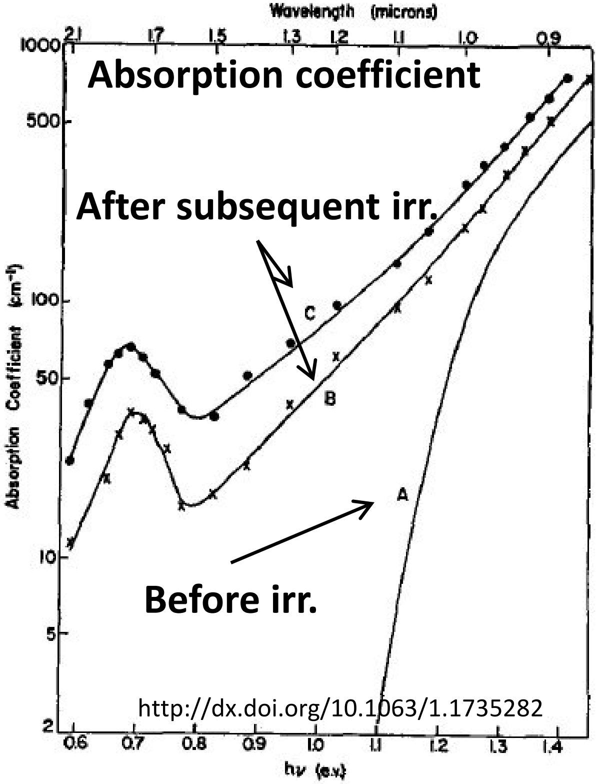
- Excitation of defect levels
- Bare silicon pieces, diodes, and strip sensors at PS for proton irradiation

→ Measure **absorption for relevant fluences and wavelengths**

→ Measure absorption with bias voltage

  → Filling of traps

→ FTIR defect spectroscopy possible

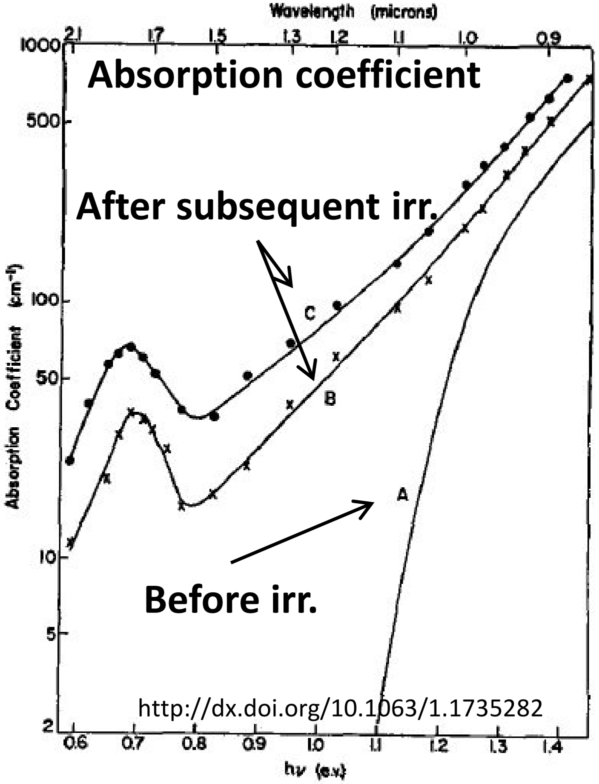


http://dx.doi.org/10.1063/1.1735282

Charge collection in forward bias

Indeed: Absorption coefficient changes with irradiation also for low wavelength

- Excitation of defect levels
- Bare silicon pieces, diodes, and strip sensors at PS for proton irradiation
  - → Measure **absorption for relevant fluences and wavelengths**
  - → Measure absorption with bias voltage
    - → Filling of traps
  - → FTIR defect spectroscopy possible

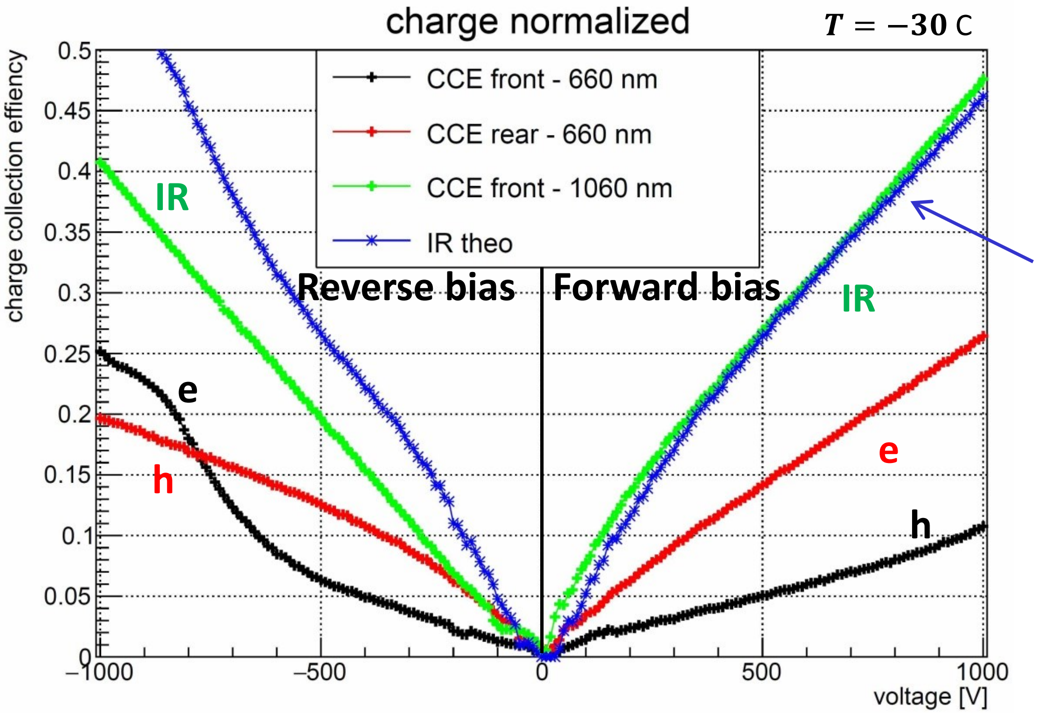


http://dx.doi.org/10.1063/1.1735282

Next steps:

- **Check** $Q_{dep,red} = \frac{Q_{ref,red}}{1.9}$
- **Assume** $Q_{dep,IR} = 1.9 \cdot Q_{ref,IR}$ **and** $Q_{dep,red} = Q_{ref,red}$
- **Disentangle drift velocity and trapping**
- $\boldsymbol{I(t) \propto q \cdot v \cdot e^{-vt/\lambda}}$
  - → Fit the drift velocity v to transients
  - → Extract $\tau_{e,h}$

CCE for infrared laser



Q_{IR} calculated from $\lambda_{e,h}$ with

$$Q_{dep,IR} = Q_{ref,IR}$$

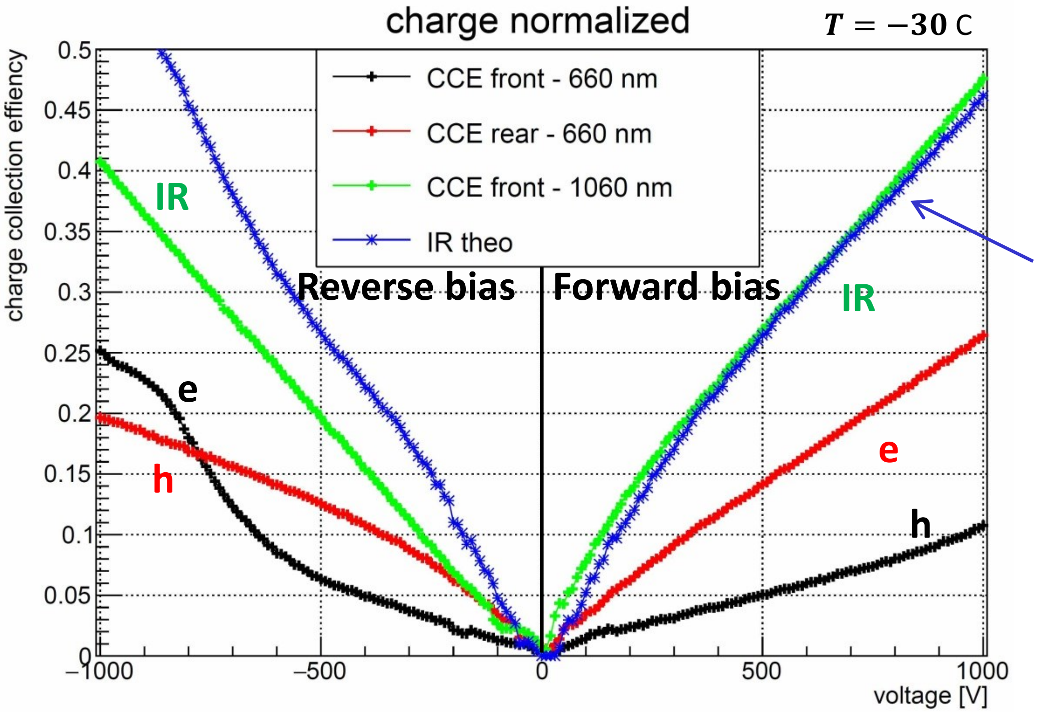
$$Q_{dep,red} = \frac{Q_{ref,red}}{1.9}$$

200 µm HPK p+n
1.3e16 p/cm²

Increase absorption for red laser → Obtained values of $\lambda_{e,h}$ larger

- Better approximation of CCE for $Q_{dep,red} = \frac{Q_{ref,red}}{1.9}$
- **We need to know λ_{att}** as function of wavelength and fluence
- And use correct term for CCE:

CCE for infrared laser



Q_{IR} calculated from $\lambda_{e,h}$ with

$$Q_{dep,IR} = Q_{ref,IR}$$

$$Q_{dep,red} = \frac{Q_{ref,red}}{1.9}$$

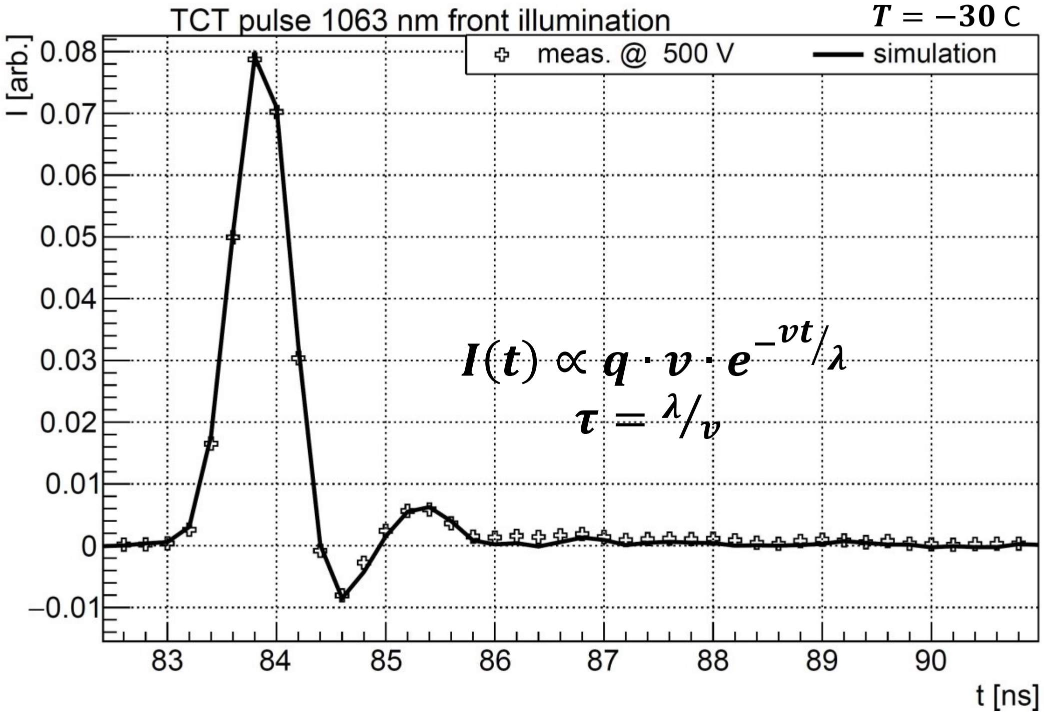
200 µm HPK p+n
1.3e16 p/cm²

Increase absorption for red laser → Obtained values of $\lambda_{e,h}$ larger

- Better approximation of CCE for $Q_{dep,red} = \frac{Q_{ref,red}}{1.9}$
- **We need to know λ_{att}** as function
- And use correct term for CCE:

$$\frac{\frac{\lambda_e \lambda_\gamma \left(\left(1-e^{-\frac{d}{\lambda_e}}\right)\lambda_e + \left(-1+e^{-\frac{d}{\lambda_\gamma}}\right)\lambda_\gamma\right)}{\lambda_e-\lambda_\gamma} + \lambda_h \lambda_\gamma \left(1 - e^{-\frac{d}{\lambda_\gamma}} + \frac{\left(-1+e^{-d\left(\frac{1}{\lambda_h}+\frac{1}{\lambda_\gamma}\right)}\right)\lambda_h}{\lambda_h+\lambda_\gamma}\right)}{d\left(1-e^{-\frac{d}{\lambda_\gamma}}\right)\lambda_\gamma}$$

Drift velocity and trapping



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

$$\tau = \lambda/v$$

200 µm HPK p+n
1.3e16 GeV p/cm²

Infrared illumination
@ 500 V forward

Normalized with
$Q_{dep,IR} = 1.9 \cdot Q_{ref,IR}$

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

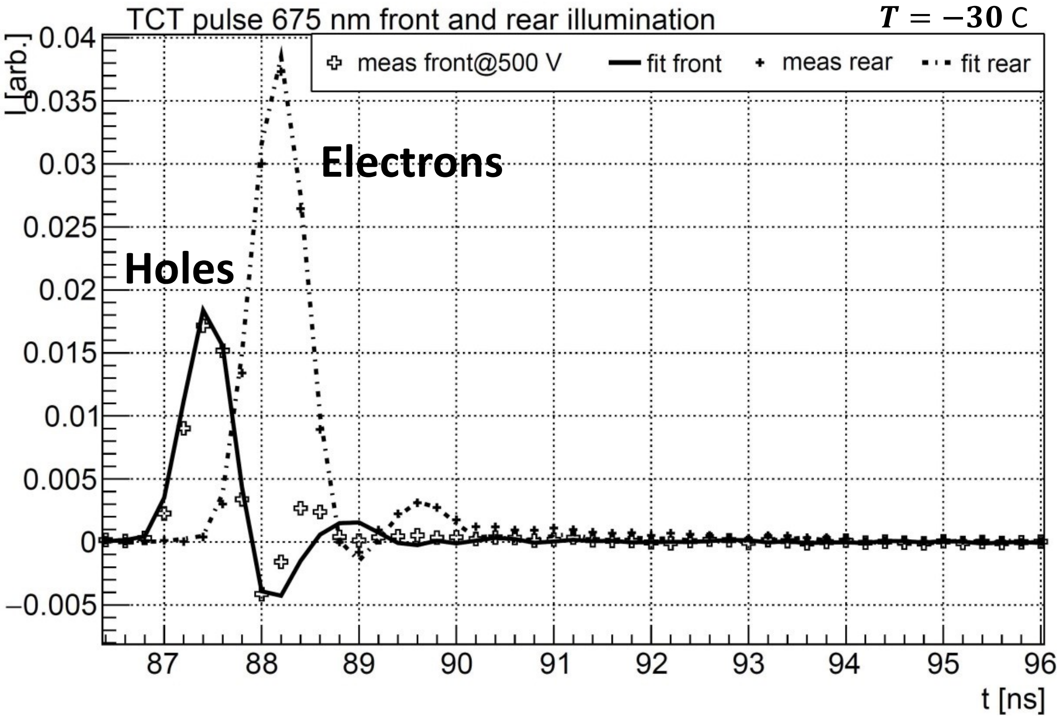
- v **reduced** by 35 % → compare ~10^{16} /cm³ ionized impurities
- **Very low trapping for** 1.3e16 GeV p/cm²:
  - $\boldsymbol{\tau_e = 400}$ **ps**
  - $\boldsymbol{\tau_h = 140}$ **ps**

„Safety margin"
$Q_{dep,red} = \frac{Q_{ref,red}}{1.9}$:

- v **increased** by 20 %
  → unphysical
  - $\boldsymbol{\tau_e = 460}$ **ps**
  - $\boldsymbol{\tau_h = 180}$ **ps**

Christian Scharf
chscharf@physnet.uni-hamburg.de

Transients for the red laser



200 µm HPK p+n
1.3e16 GeV p/cm²

Red laser illumination @ 500 V forward

Normalized with
$Q_{dep} = Q_{ref,red}$

- Electron drift is nicely described
- Hole drift is not well described
    - Transfer function not accurate enough →

To be continued
More samples!

Conclusion and outlook

Conclusion and outlook

- New **method to determine** the **drift velocity and trapping** in forward bias **established**
  - Determine charge collection length λ from CCE
  - Fit drift velocity to transients $I(t) \propto q \cdot v \cdot e^{-vt/\lambda}$
  - Calculate $\tau(E) = \lambda/v$
- **Absorption length** of light **changes** with irradiation
- **Reduction of the drift velocity?**
- **Very high lifetimes of electrons and holes**

- **Agenda:**
  - Measure light absorption in irradiated silicon → Q_{dep} for IR and red laser
  - Determine $v(E)$ and $\tau(E)$ systematically for different fluence + bias + material

→ **Apply results for the low field region to better understand reverse bias**

Thanks for your attention

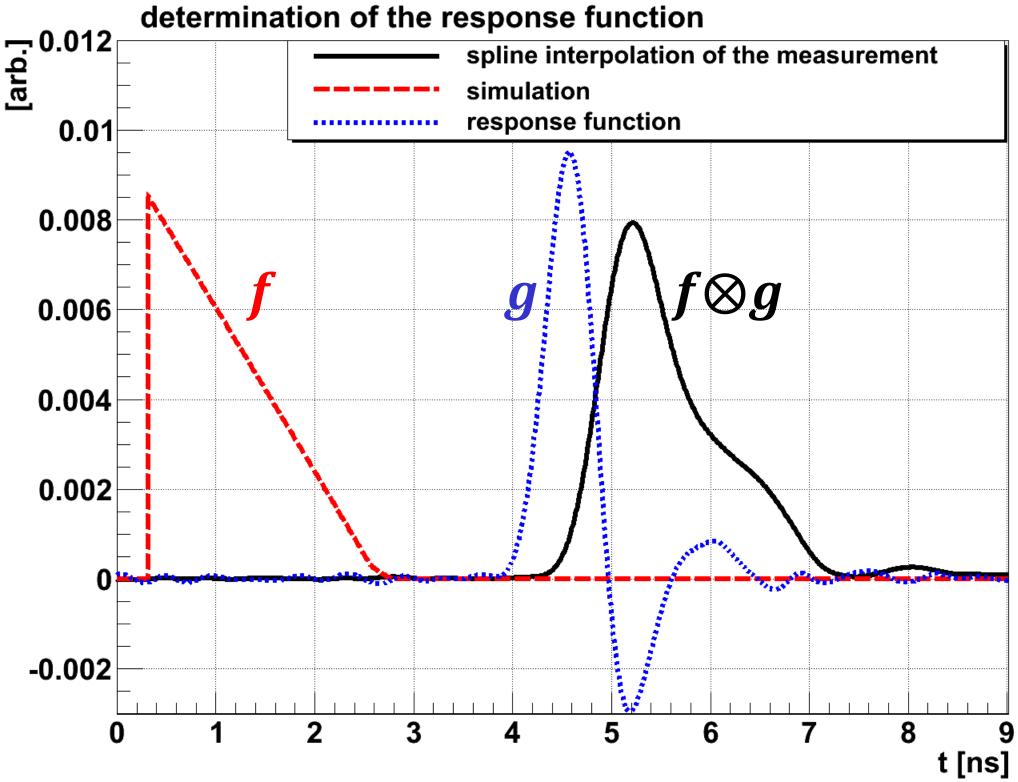
Special thanks to
J. Becker, E. Fretwurst , R. Klanner

Christian Scharf
chscharf@physnet.uni-hamburg.de

Backup

Electronics transfer function

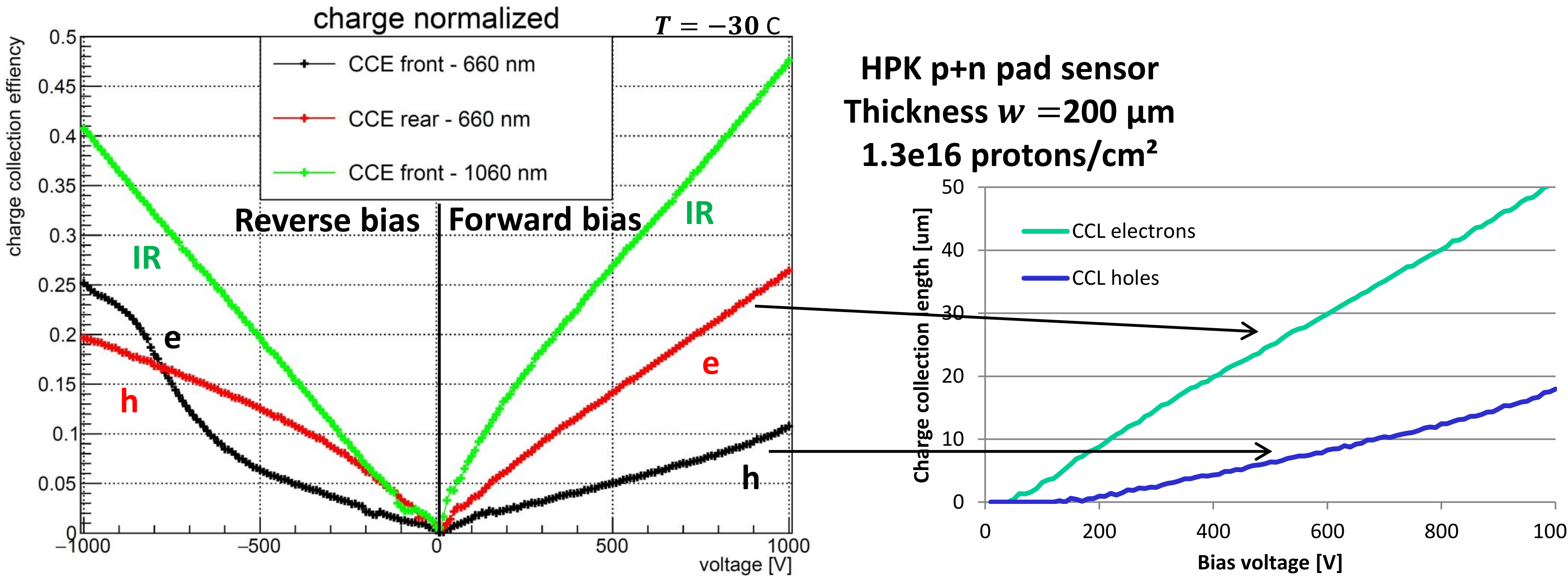
Convolution theorem: $\mathcal{F}\{f \otimes g\} = \mathcal{F}\{f\} \cdot \mathcal{F}\{g\}$



infrared laser
200 µm sensor
@ 1000 V and 313 K

Transfer function of the read-out circuit → $g = \mathcal{F}^{-1}\left\{\frac{\mathcal{F}\{measurement\}}{\mathcal{F}\{simulation\}}\right\}$

The charge collection length



HPK p+n pad sensor
Thickness w =200 µm
1.3e16 protons/cm²

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

→ **Determine charge collection length $\lambda_{e,h} = v_{e,h} \cdot \tau_{e,h}$ for red laser:**

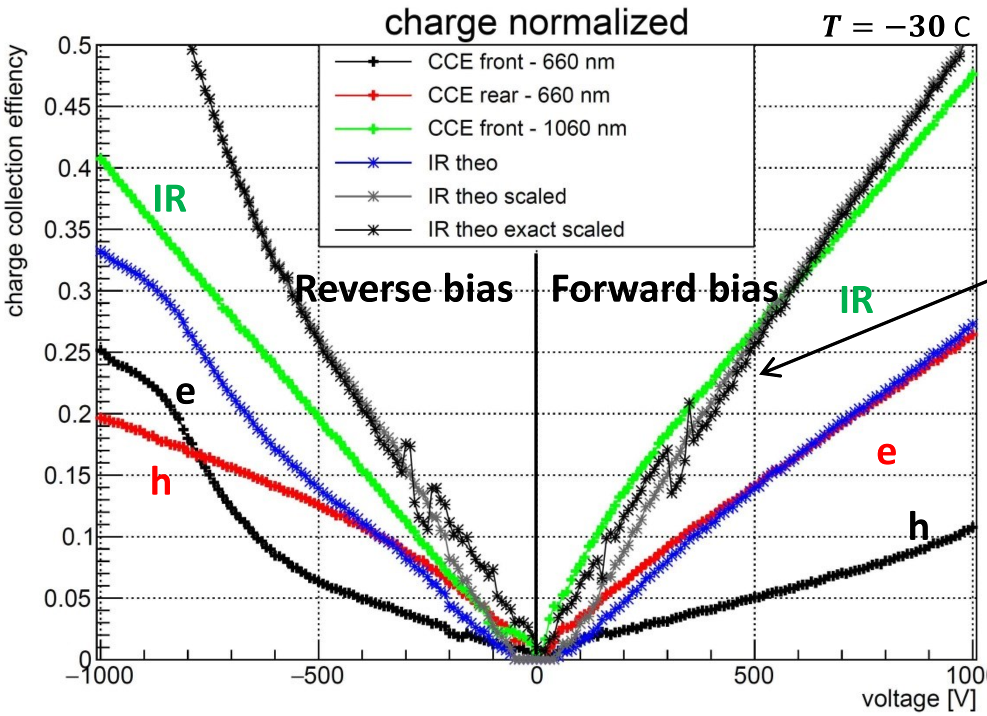
- $$Q_{red} \approx Q_{dep}\left[\frac{w-\lambda_{att}}{w} \cdot \frac{\lambda_{e,h}}{w}\left(1 - e^{-\frac{w}{\lambda_{e,h}}}\right) + {}^{\lambda_{att}}/_{w}\right]$$

Q_{dep}: Deposited charge
λ_{att}: Attenuation length

Charge drifting through the sensor

Charge collected at illuminated electrode ($\lambda_{att} \ll \lambda$)

Charge collection in forward bias



Q_{IR} calculated from $\lambda_{e,h}$ with

$$Q_{dep,IR} = 1.9 Q_{ref,IR}$$
$$Q_{dep,red} = Q_{ref,red}$$

200 µm HPK p-in-n
1.3e16 p/cm²

Use correct term for CCE:

$$\frac{\frac{\lambda_e \lambda_\gamma \left(\left(1-e^{-\frac{d}{\lambda_e}}\right)\lambda_e + \left(-1+e^{-\frac{d}{\lambda_\gamma}}\right)\lambda_\gamma\right)}{\lambda_e-\lambda_\gamma} + \lambda_h \lambda_\gamma \left(1 - e^{-\frac{d}{\lambda_\gamma}} + \frac{\left(-1+e^{-d\left(\frac{1}{\lambda_h}+\frac{1}{\lambda_\gamma}\right)}\right)\lambda_h}{\lambda_h+\lambda_\gamma}\right)}{d\left(1-e^{-\frac{d}{\lambda_\gamma}}\right)\lambda_\gamma}$$

Improvement for low + high bias but not yet stable