Prolonged signals from silicon strip sensors showing enhanced charge multiplication

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Overview

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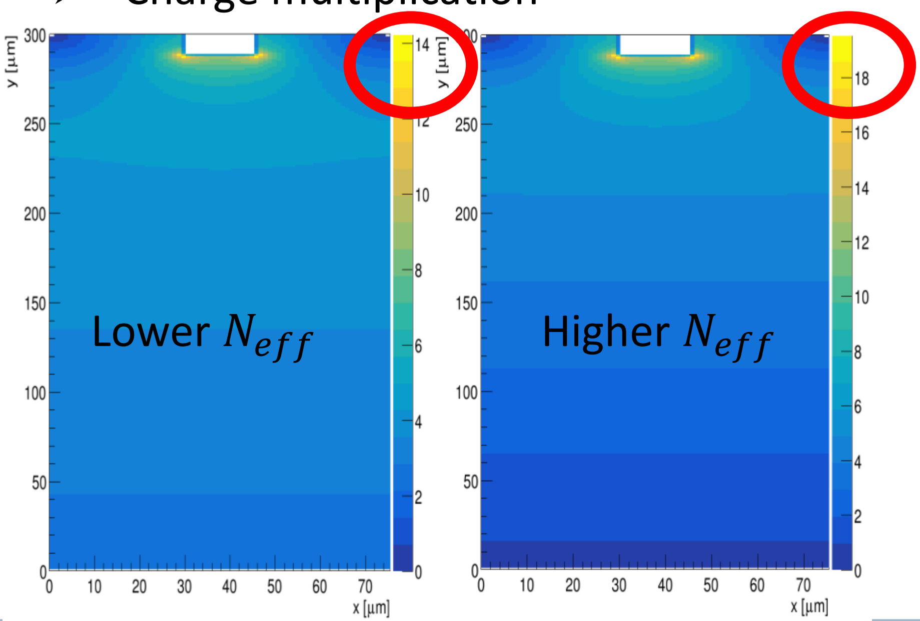
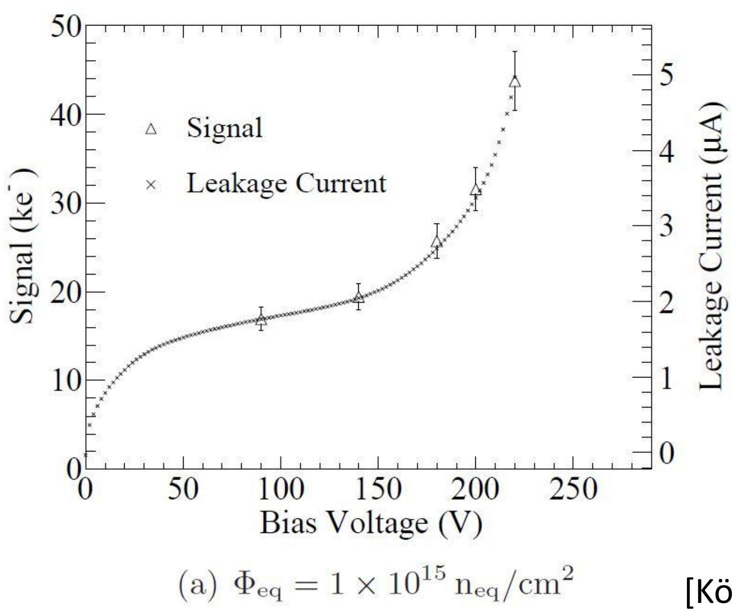
- Aims:
  - Characterization of charge multiplication (CM) in irradiated and long annealed silicon sensors
  - Investigation of the signal changes occurring in enhanced CM
- Materials:
  - P-type strip sensors
  - Minis: 1 x 1 $cm^2, 300\ \mu$m thickness
  - Irradiated with neutrons up to fluences of $2 \cdot 10^{15}\ n_{eq}/cm^2$
  - Annealed at temperatures between 40°C and 80°C
- Methods:
  - Charge collection, electric field and signal pulse measurements:
    - Beta-source measurements using the ALIBAVA readout system
    - Edge and top-TCT measurements
  - Simulations of the observed phenomena using kDetSim Software

Introduction

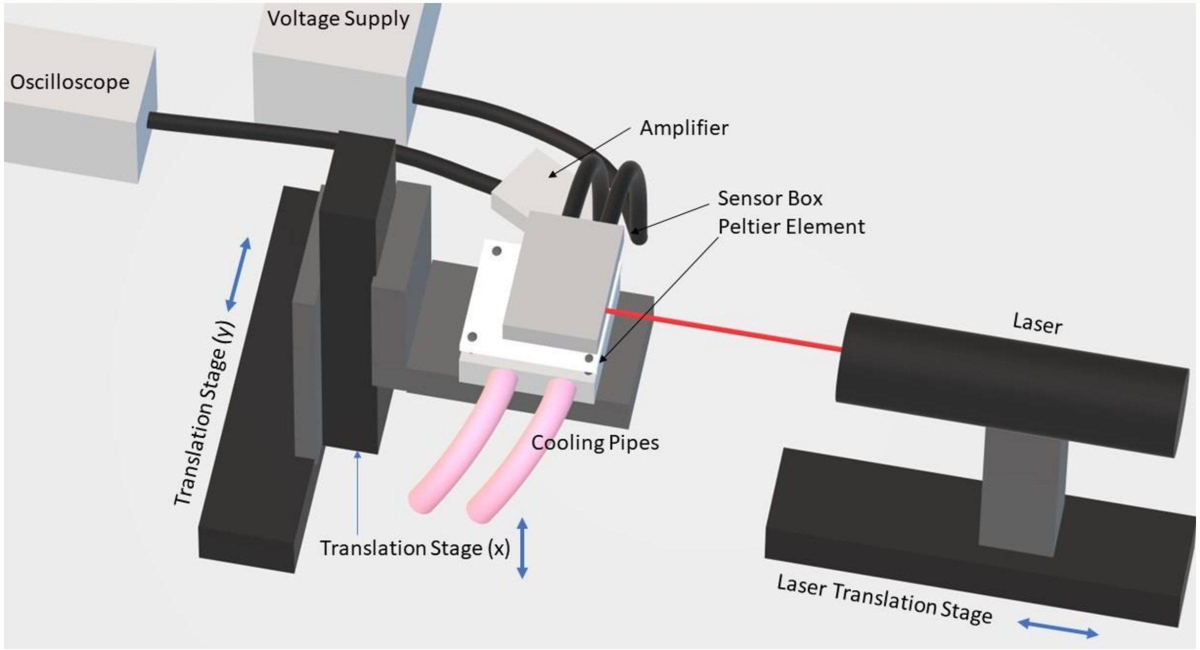
- Radiation damage leads to a large amount of defects in silicon, which migrate/ change during annealing
- Higher fluences and long-term annealing lead to a decrease in charge collection efficiency and depletion depth and an increase of the effective doping concentration
- High doping concentration leads to high el. field close to the strip implants
  - ➢ Impact ionization, electron-hole pair creation
  - ➢ Charge multiplication

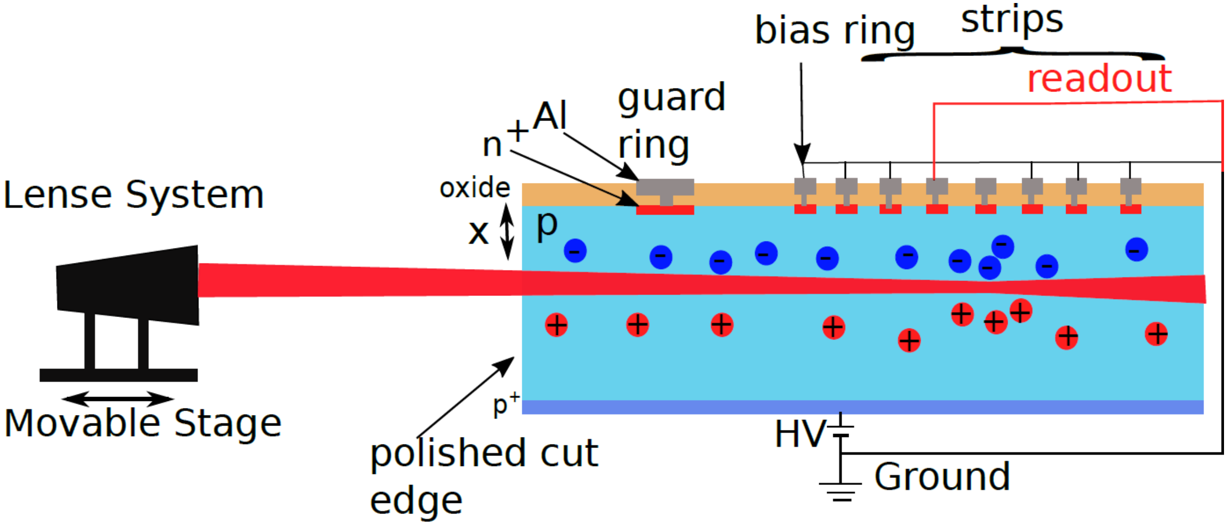




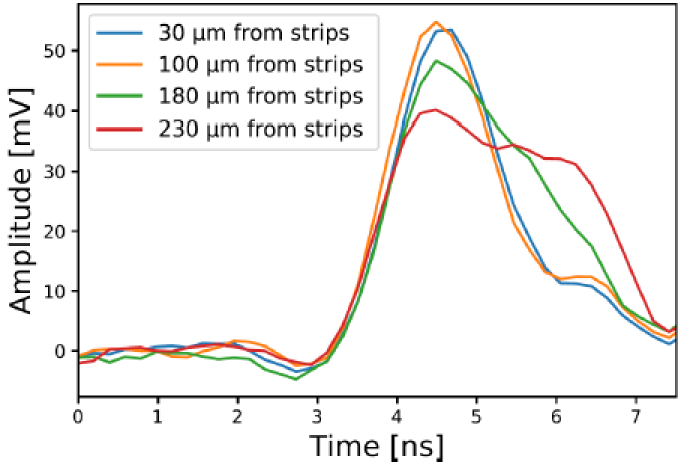
[Köh]

Edge-TCT Measurements

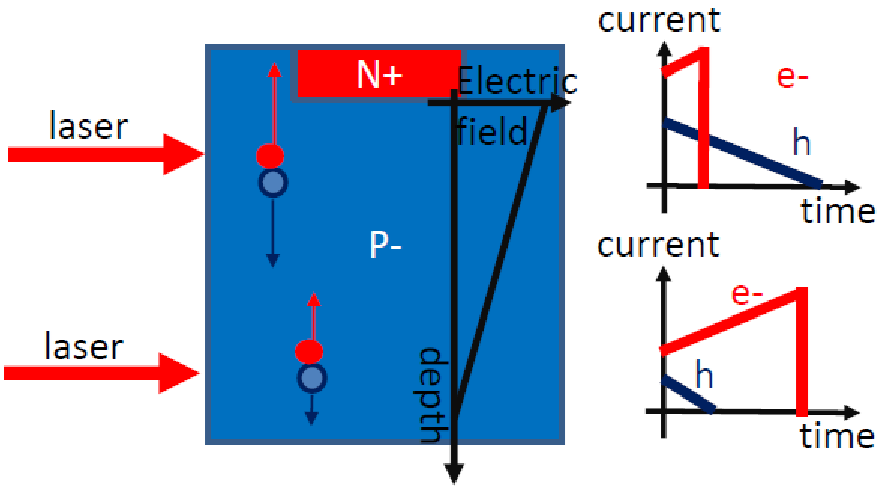




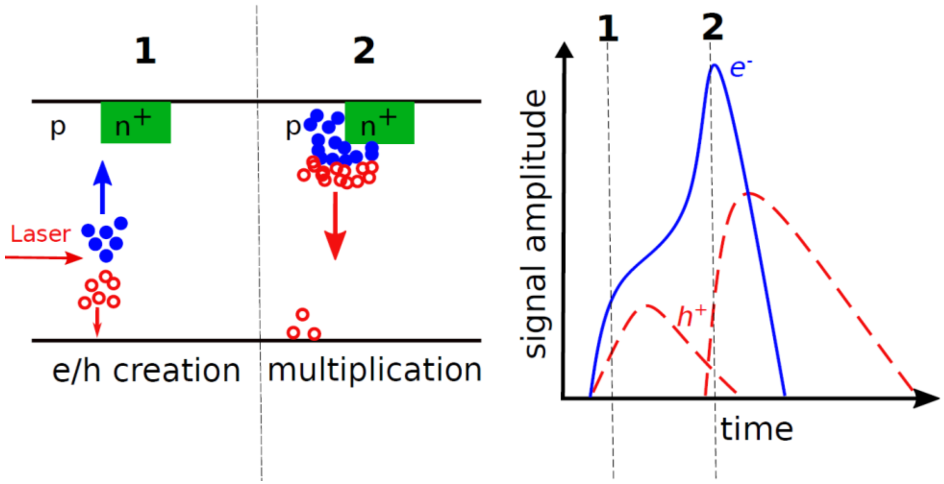
Signal Formation



Unirradiated Sensor, 400 V

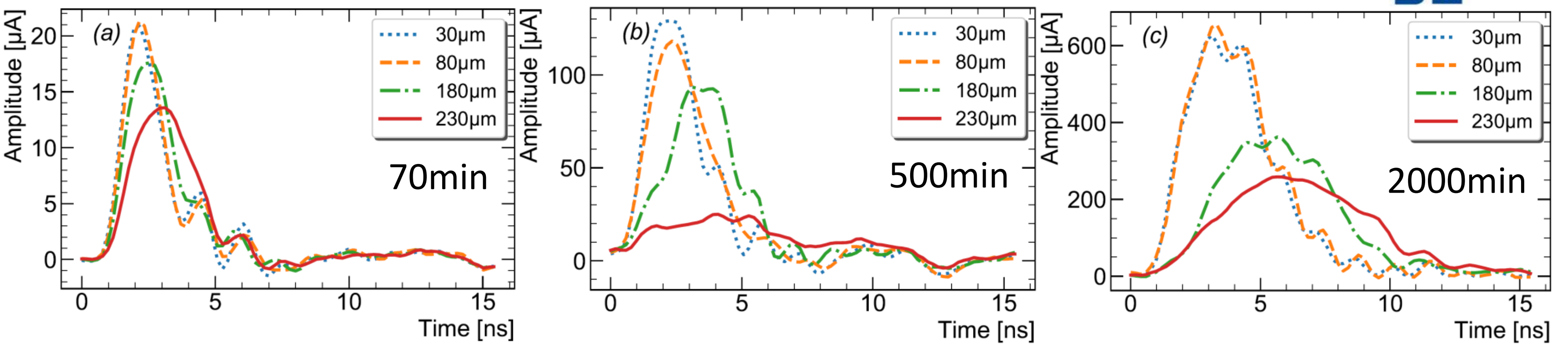


- Signal pulse length expected to be approximately constant
- If sensor is not fully depleted, no signal is expected from the non depleted area
- In charge multiplication: additional contribution to the signal first from the multiplied electrons, then from the multiplied holes



Signal Change during annealing

$1 \cdot 10^{15}\, n_{eq}/cm^2$, annealed at 70°C, 1100 V



- Strong increase due to CM, but similar duration for 70 and 500 min (light CM)
- Signal in sensor back vanishes in light CM due to decrease of depletion width

- Increase of signal duration in enhanced CM (2000 min)
- Appearance of signal from sensor back again
  - ➢ Exhibiting the most significant changes
  - ➢ Longer and slower than expected

Observed for all sensors with fluences above $1 \cdot 10^{15} n_{eq}/cm^2$ after long annealing times

Charge collection and velocity profile

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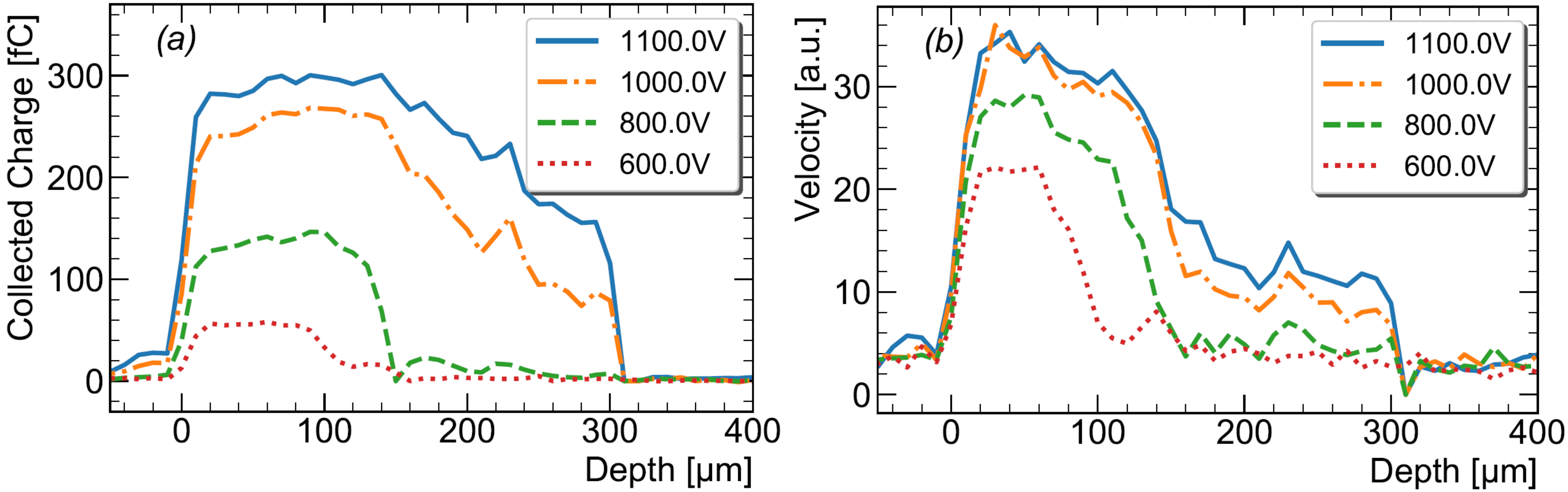
$1 \cdot 10^{15}\, n_{eq}/cm^2$, annealed 600 min at 80°C

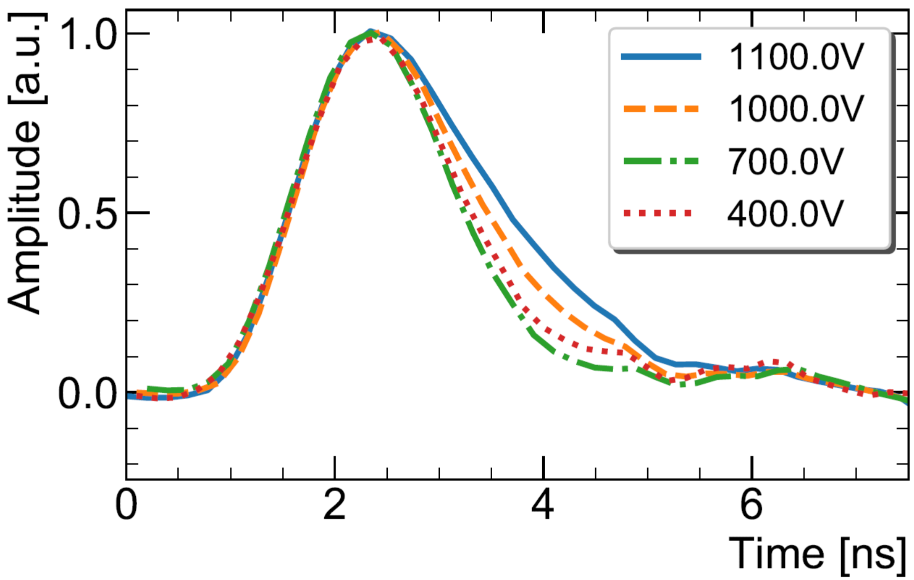


- Growth of depletion zone clearly visible from 600 V to 800 V, for higher voltages charge is collected throughout entire sensor area
- Appearance of a field in the “neutral bulk” beyond depleted region [1]
- El. field corresponds directly to measured velocity
  - ➢ Substantial el. field throughout entire area beyond expected width of depleted area
  - ➢ Velocity saturation in the depleted area, short transition area to a low field region
  - ➢ In the non depleted area, field nearly flat and much smaller than in the region closer to the strips

[1] Kramberger et al., JINST 9, 10016 (2014)

Another peculiarity of the signal pulse

$1 \cdot 10^{15}\ n_{eq}/cm^2$, 2000 min annealed at 70°C



- Laser position within active area close to strips
- Increase of voltage should increase the slopes
- Rising edge: Saturation of velocity, no change
- Falling edge: Expected steeper fall from 400 V to 700 V
- For voltages above 1000 V: Unexpected slower decrease of the pulse

Summary of observed features of enhanced CM:

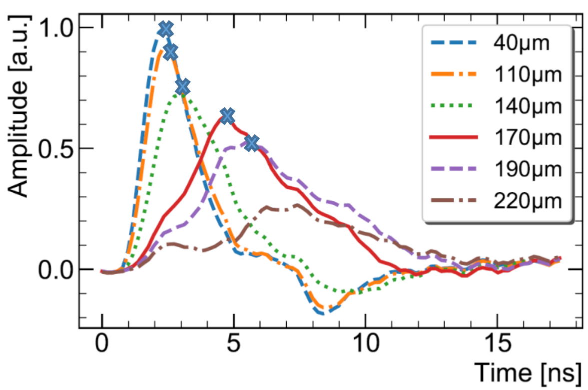
- Significant signal coming from the region closer to the sensor backplane
- Pulses are extremely slow in this region, the higher the multiplication, the slower the pulses
- Pulse duration at high voltages seems to be longer through the entire sensor area

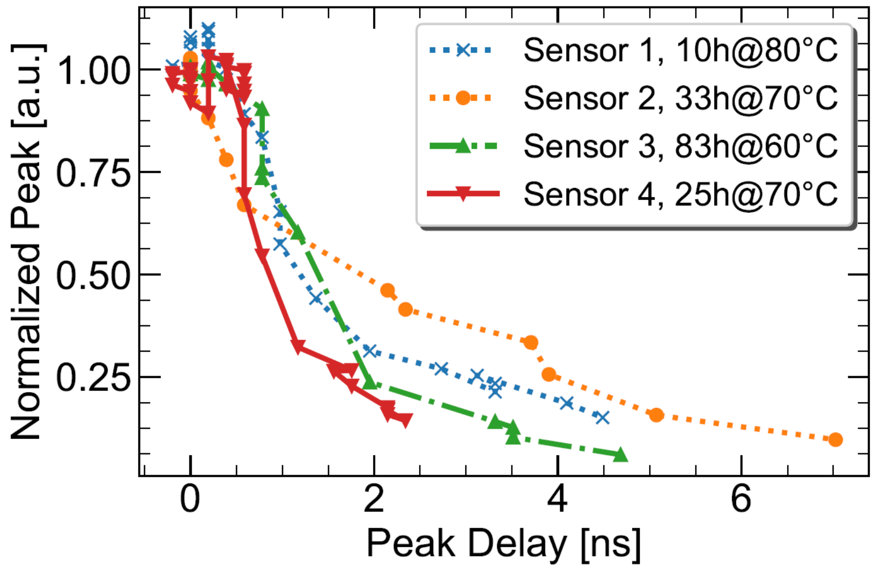
Explanations: Bulk field and Trapping

- Signals from the lower bulk assumed to be electrically neutral due to a substantial field there
  - Low field sustains electron drift to high el. field area where they are multiplied
  - The low field increases the diffusion
  - Trapping and recombination reduces the number of electrons and thereby the amplitude

- The decrease of amplitude and the time delay of the peak are exponentially related

- Different sensors have similar decays
  - Time constants between 1.8 ns and 2.9 ns, compatible with effective trapping times of electrons in silicon at measurement temperatures





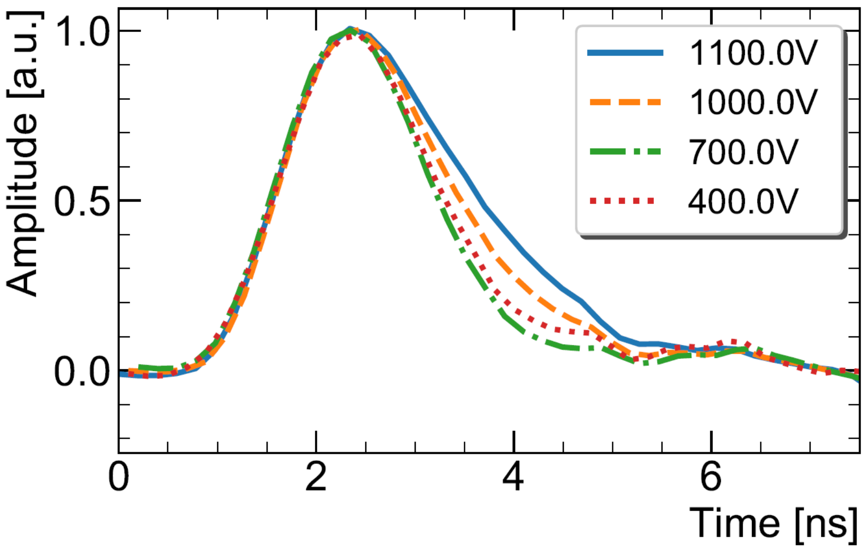
Sensor 1-3: $1 \cdot 10^{15} n_{eq}/cm^2$, Sensor 4: $2 \cdot 10^{15} n_{eq}/cm^2$

Explanations: Plasma Effect

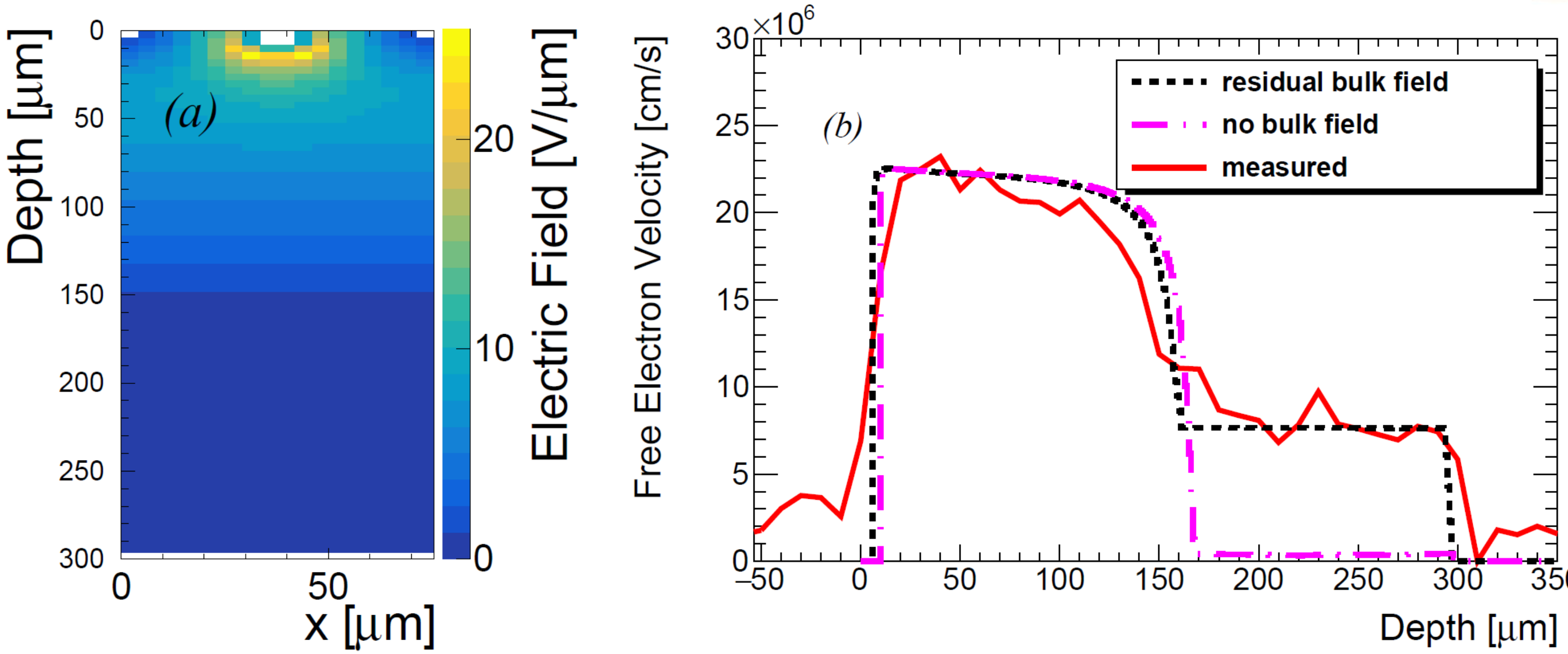
- When electrons get multiplied close to the strip implants a large cloud of secondary holes is created and experiences a so called plasma effect:

  - ➢ Hole cloud travels towards sensor back
  - ➢ Shields itself from the present el. field
  - ➢ Lateral Spread and electrostatic repulsion

- Confirmed in Top-TCT measurements, more strips see a positive hole signal



Simulations



- Sensor geometry, temperature, voltage were set as well as estimated properties from the measurements (carrier lifetimes, rectangular eff. doping concentration, ionization depth)
- The el. field profile shows the high field region close to the strips, where the multiplication occurs
- The measured velocity profile could be reproduced by the simulations with these assumptions

Simulations

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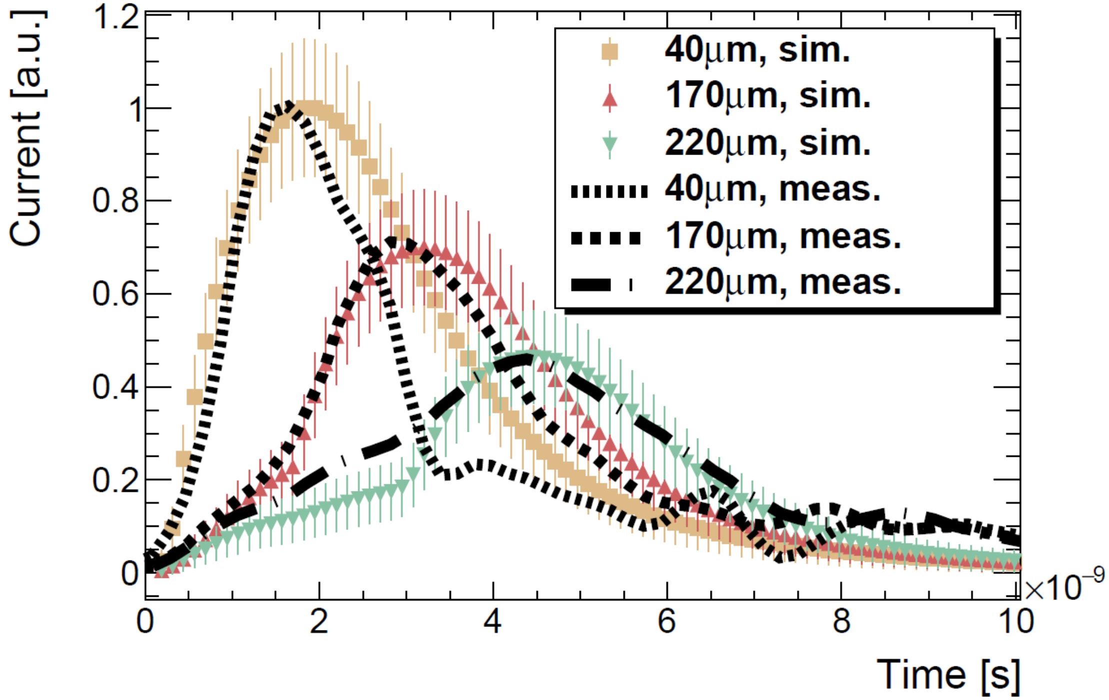
- To reproduce rise and fall time of fast pulses a simple CR-RC shaper with a differentiation and integration time constants of 0.6 and 0.7 ns was used

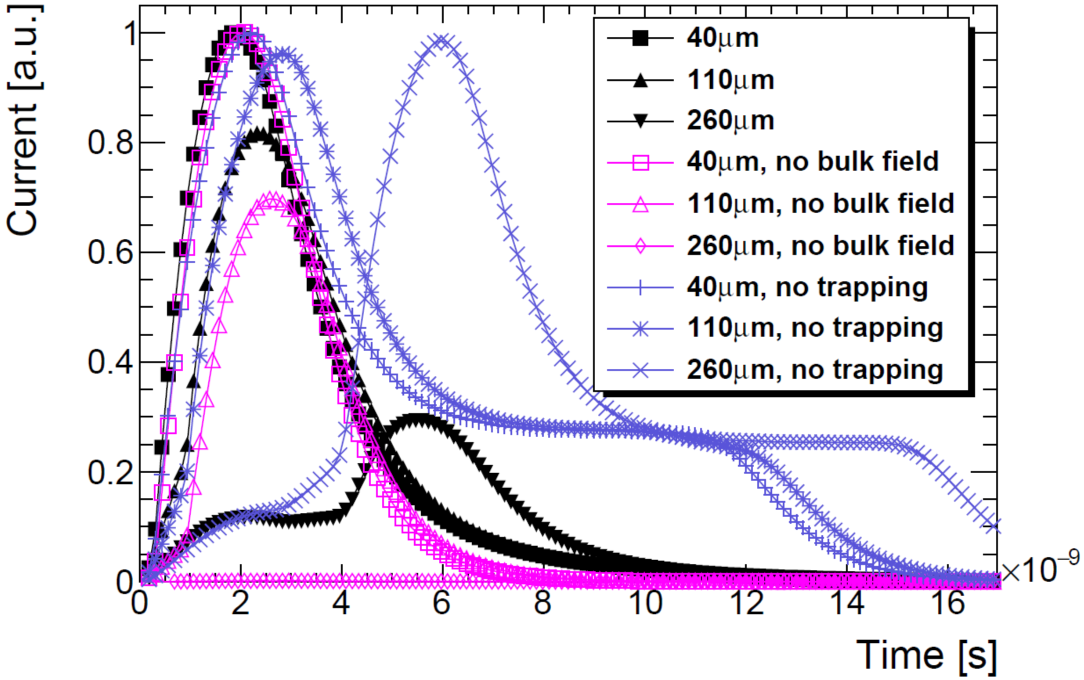
- Simulated signals at various illumination depths agree well with measured signals:
  - ➢ Decrease of amplitude
  - ➢ Longer signal duration



- Shows that pulse shape and duration are determined by trapping and presence of el. field in the bulk

Simulations

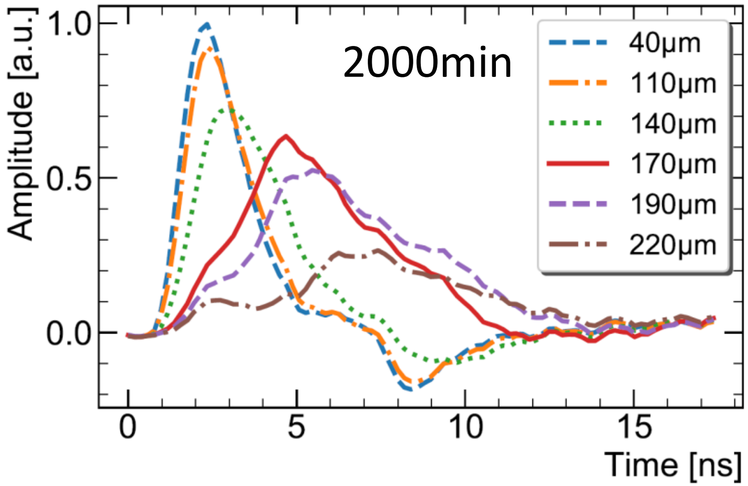
- **Comparison of simulated pulses**
  - without a field in the bulk, but trapping
  - with a field in the bulk, but no trapping
  - with bulk field and trapping



- Without trapping: almost constant amplitude, even longer pulses (slow holes)
- Without bulk field: decreasing amplitude, but no signal from illumination closer to the sensor backplane
- With bulk field and trapping: Decreasing signal, longer pulses especially close to sensor back

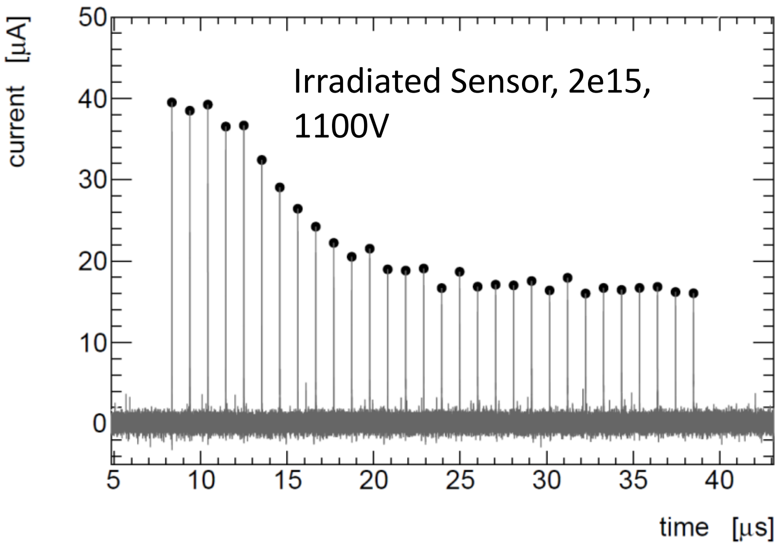
- Note that a MIP creates free charge through entire sensor depth
  - ➢ The signal created by a MIP is approximately the sum of all signals measured using edge-TCT

Ongoing investigations



- Signals are not only longer and smaller, they also exhibit a change of slope of falling pulse – in same el- field?
  - ➢ The deeper the illumination, the flatter the decrease
  - ➢ Diffusion of electron cloud before multiplication is not enough to explain

  Might be explained with trapped charge changing the el. field (polarization effect)



- 30 subsequent laser pulses sent
- Decrease of amplitude visible
  - ➢ First pulses must have influence on the sensor properties
- Expected to origin in trapping: Not happening in non irradiated sensors
- Shows that trapped charge can have a severe influence
- Currently under further investigations

Conclusion

- Prolonged pulses have been observed in silicon strip sensors showing enhanced CM

- The observed pulses can be explained by three key points:
  - Low but substantial field beyond junction region
  - High trapping probabilities
  - High charge in small volume experiences self-screening and electrostatic repulsion (plasma effect)

- Simulations agree with the measured pulses and confirm the origin of the prolonged pulses

- Although unexpected in strip sensors, this phenomenon is anticipated to be seen in sensors exploiting charge multiplication while having also low field regions, e.g 3D silicon detectors or Low-Gain Avalanche Diodes (LGADs)

- Ongoing trapping studies to understand its effect in the sensor, first measurements confirmed that trapped charges <u>can</u> change the present el. field (polarization effect)

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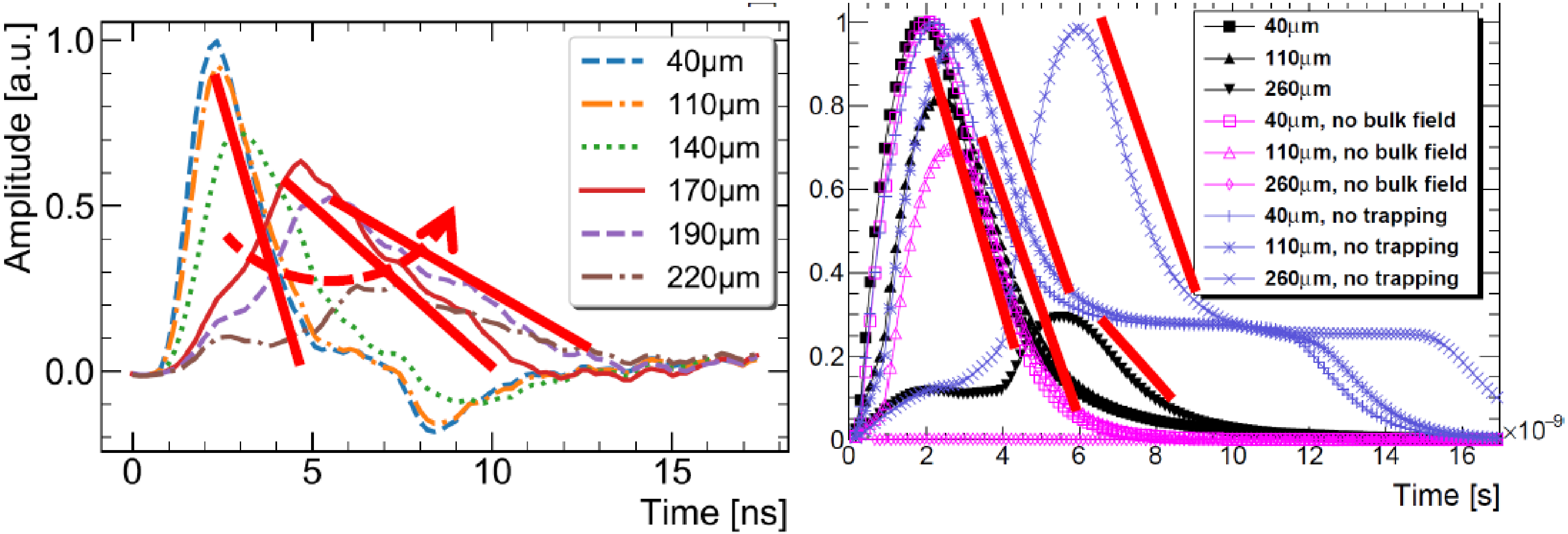
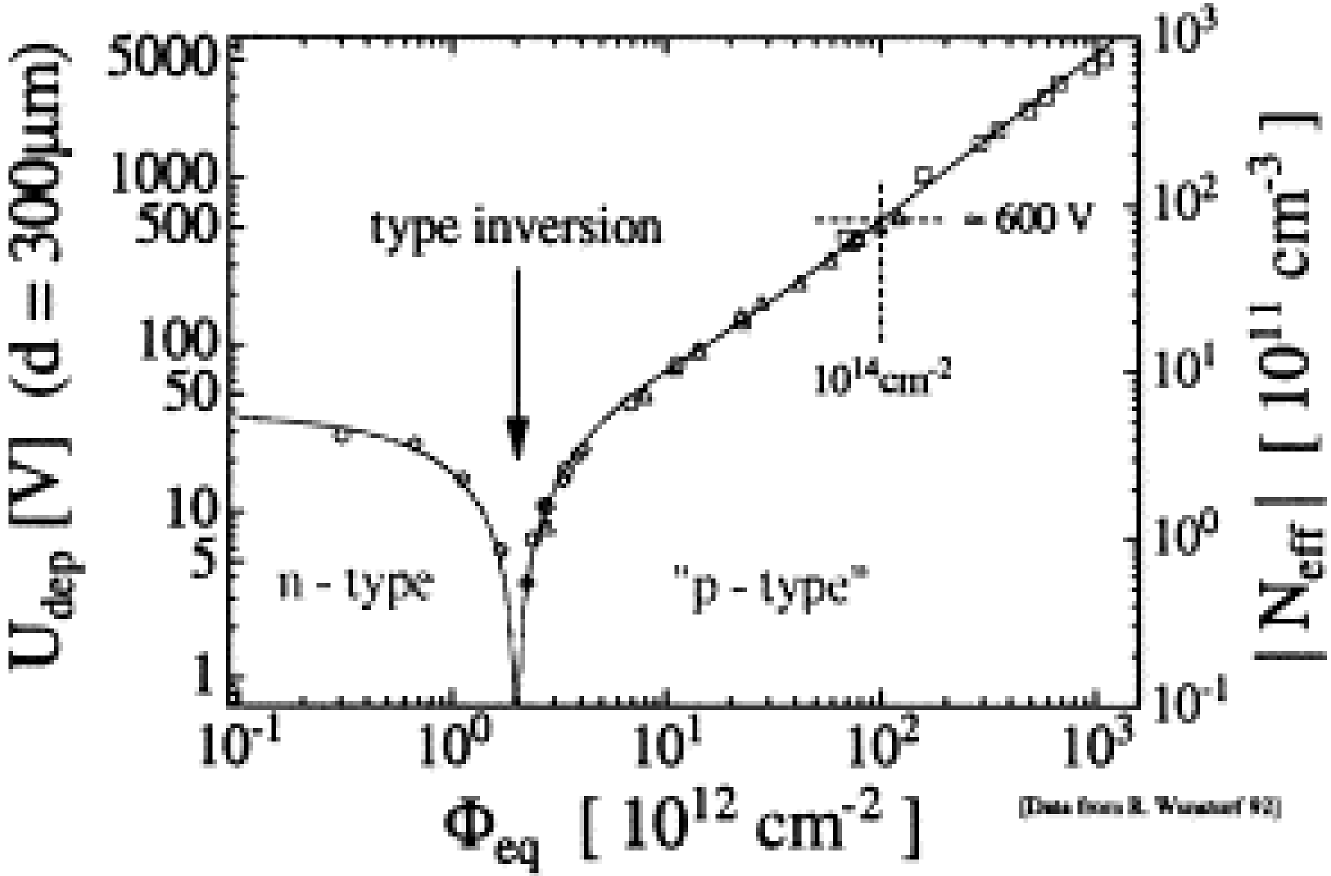
Thank you for your attention!

Trapping Effects in Simulations



- Extreme change in slope not seen in simulations (mainly amplitude changes and only due to trapping, in case…)

Backup: Type Inversion



Backup: Impact on pulse shape

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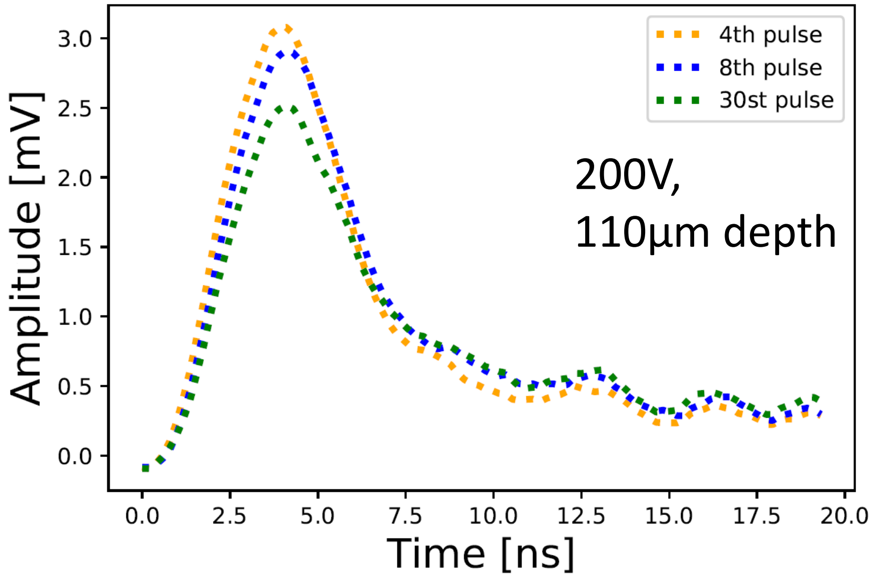
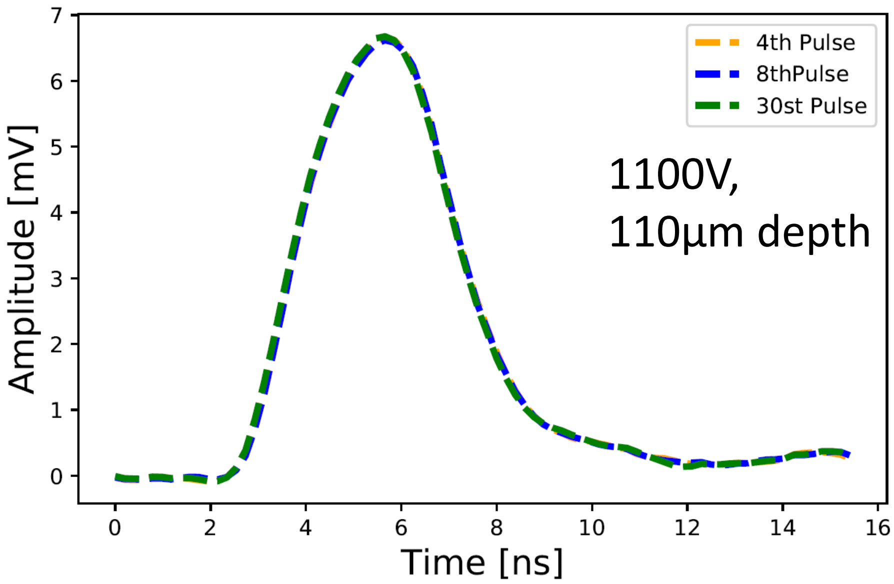
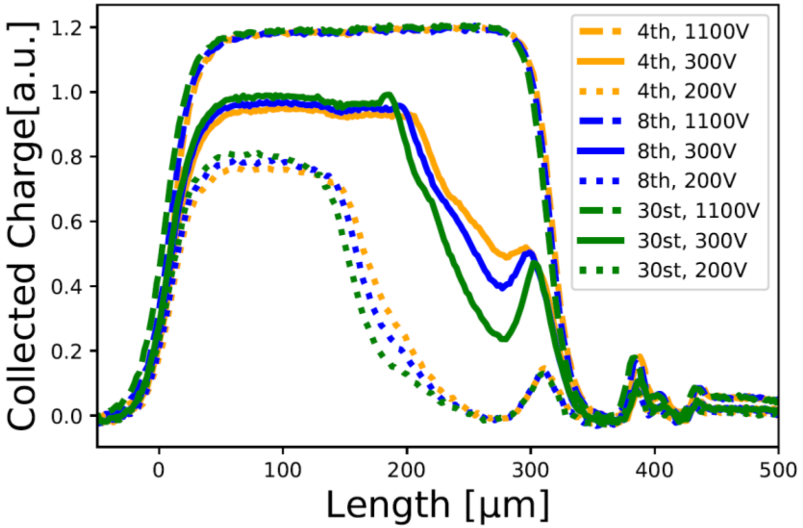
$1e14\frac{n_{eq}}{cm^2}$, annnealed, Edge TCT measurement



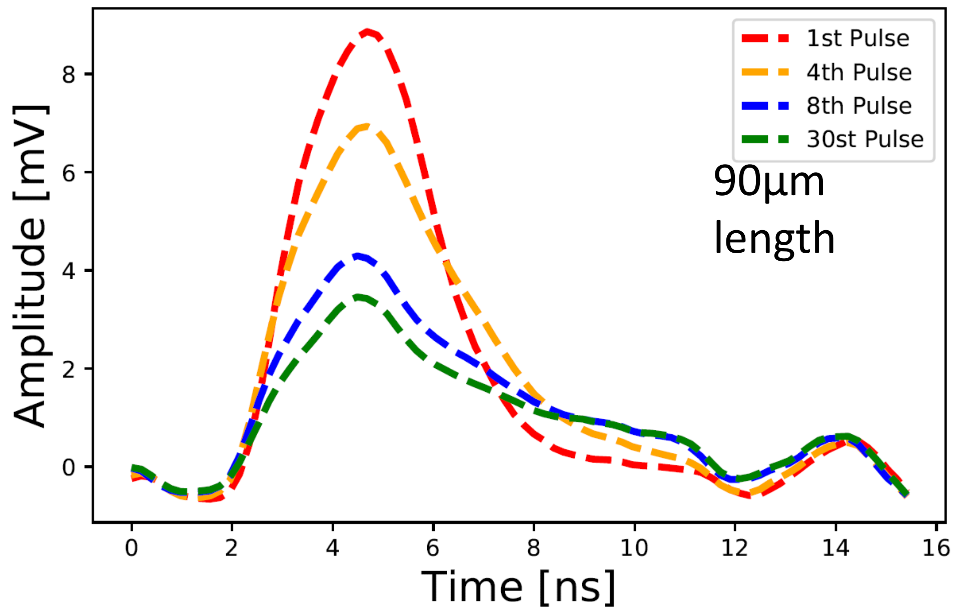


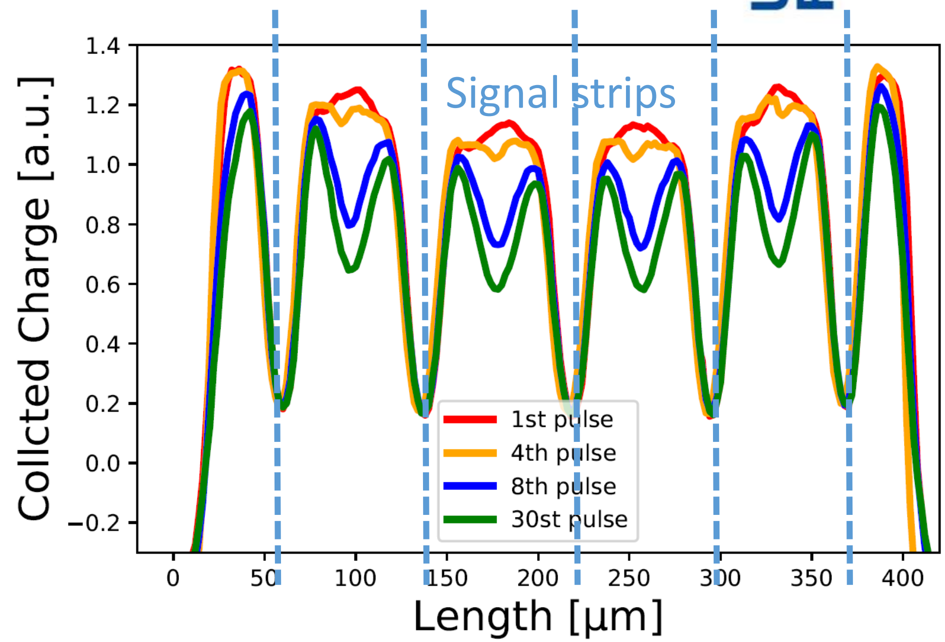
- The effect appears for low fluences only when the sensor is not fully depleted
- Depletion region shrinks -> effect only in the lower part of the sensor
- Hints to trapping of electrons: Effect only visible if electrons are created in the region around the end of the depletion width



Backup: Pulse shape change

$1e15 \frac{n_{eq}}{cm^2}$, 500V, Top-TCT, long annealed



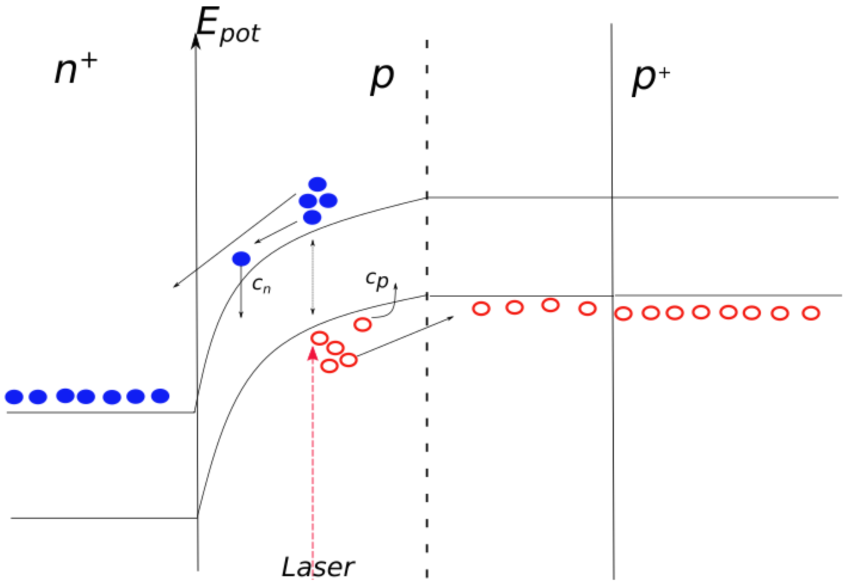


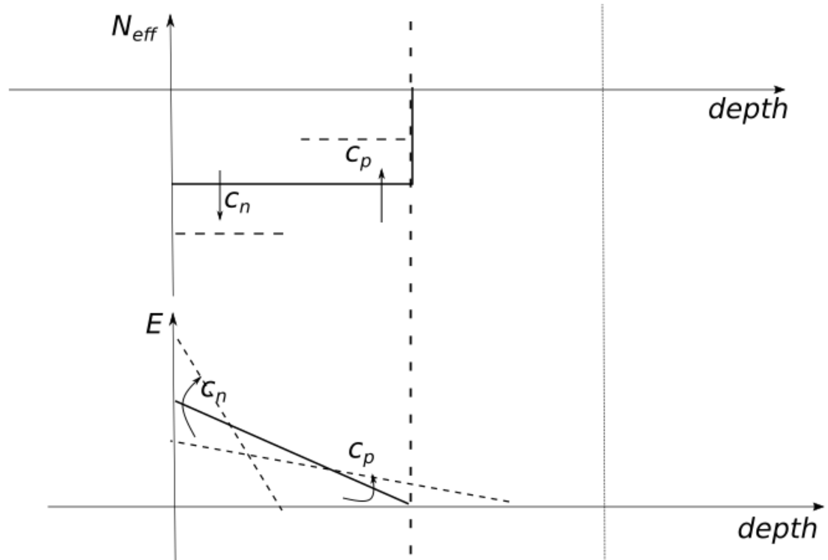
- (NOTE: longer pulses, since 2 strips are collecting, longer drift times and slightly worse focus)

- Long annealed: Lower signal due to higher N_{eff}, higher trapping probability and smaller depletion width
- Emphasizes that the most significant change is happening between two strips
  - ➢ Hints to an influence of the strip segmentation
  - ➢ Change of slope more pronounced: Hole trapping probability increases during annealing
  - ➢ Hints to electrons getting trapped/ recombined as well

Backup: Interpretation (WORK IN PROGRESS)

<1st-order sketches for interpreting the results:

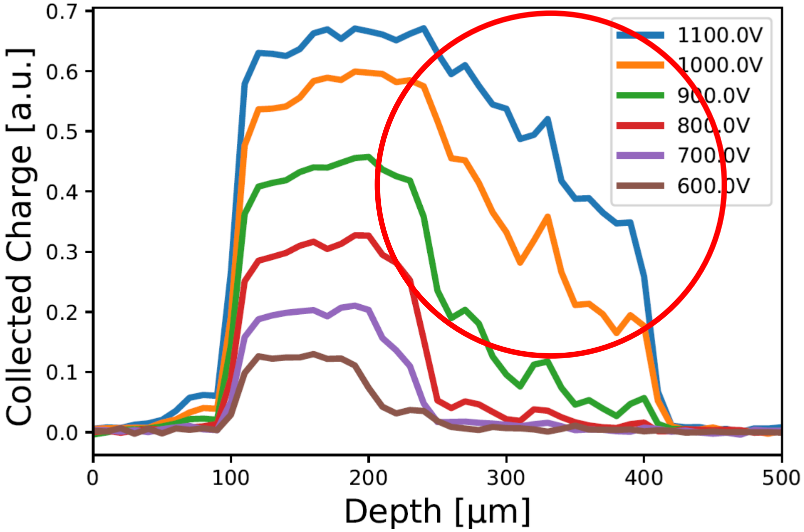


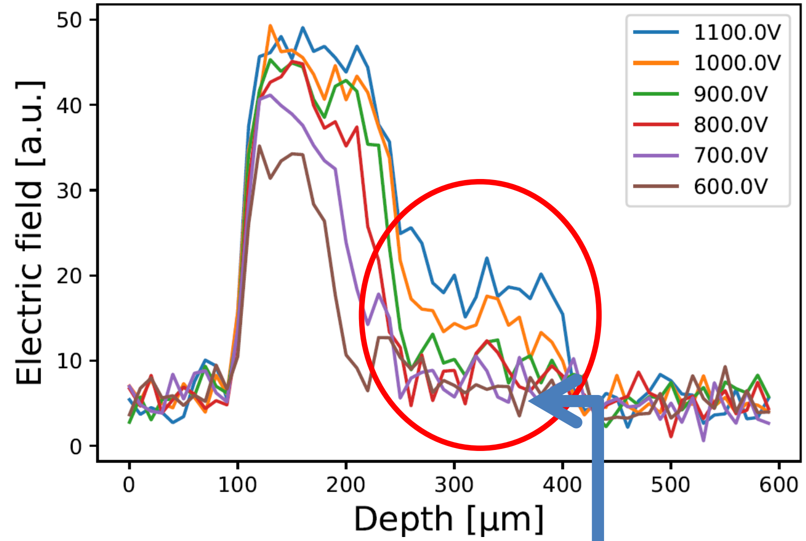


Localised capture of holes (c_p) $\rightarrow$ less negative N_{eff} $\rightarrow$ steeper E-field
Localised capture of electrons (c_n) $\rightarrow$ more negative N_{eff} $\rightarrow$ less steep E-field

- Change of E-field profile can be observed with TCT from signal shape:
- Observation of differences between signals created on top (mainly holes travelling) and on bottom (mainly electrons travelling)
- Observation of differences between different annealing times (changes on holes/electrons trapping times)
  - ➢ Try to identify what and how is trapped, how the polarization grows (distributions change)

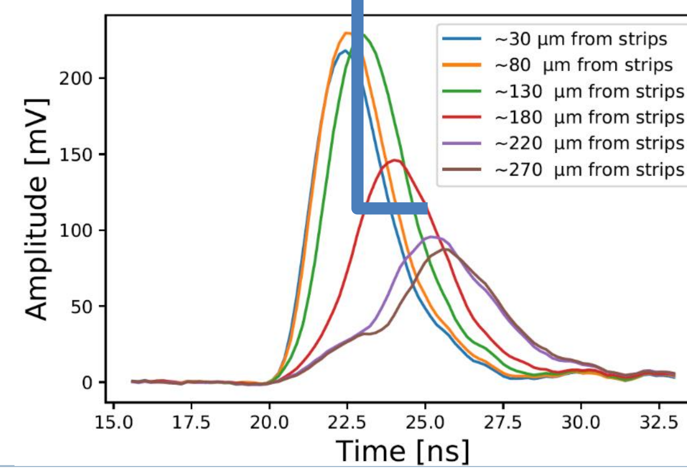
Collected charge and el. field after 600 min of 80°C annealing.





·No abrupt depletion zone visible anymore for high voltages and still high charge

➢Electric field also in the "neutral" bulk (ENB)[Kram] allowing electrons to reach the junction and multiply

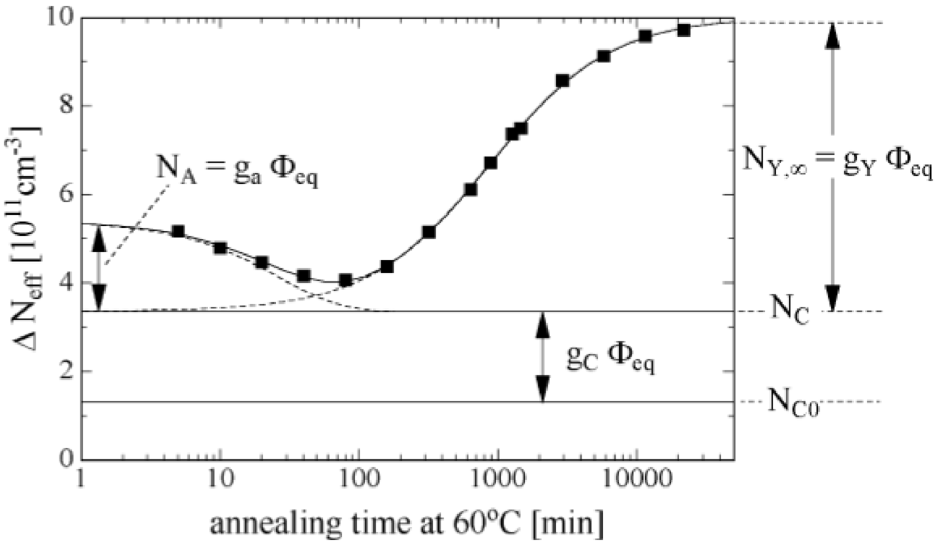


[Kram] G.Kramberger et al., Modeling of Electric field in silicon micro-strip detectors irradiated with neutrons and pions, JINST (2014)

Annealing

General annealing behaviour:

- Beneficial: Decrease of effective doping concentration
- Reverse: Increase of up to saturation value.
- Depletion volume and charge collection increase and then decrease.
- Charge multiplication if electric field can increase up to produce avalanche.
- Leakage current decreases.
- Strong temperature dependence.



[Ham] M.Moll, Radiation Damage in Silicon Particle Detectors, Universität Hamburg , (1999)

Hamburg Model:

$$\boxed{\Delta N_{eff} = N_0 e^{-\frac{t}{\tau}} + N_C + N_\infty\left(1 - e^{-kt}\right)}$$

Where: $k, \frac{1}{\tau} \propto e^{-\frac{\varepsilon}{k_B T}}$

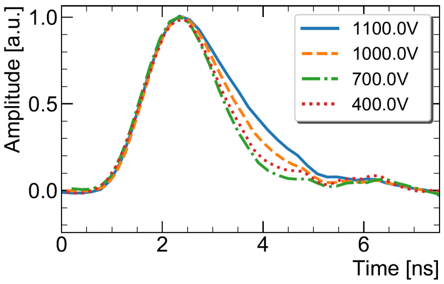
-> faster movement of defects at higher temperatures. [2]

$$\boxed{\alpha(t) = \alpha_I \exp\left(-\frac{t}{\tau_I}\right) + \alpha_0 - \beta \ln\left(\frac{t}{t_0}\right)}$$

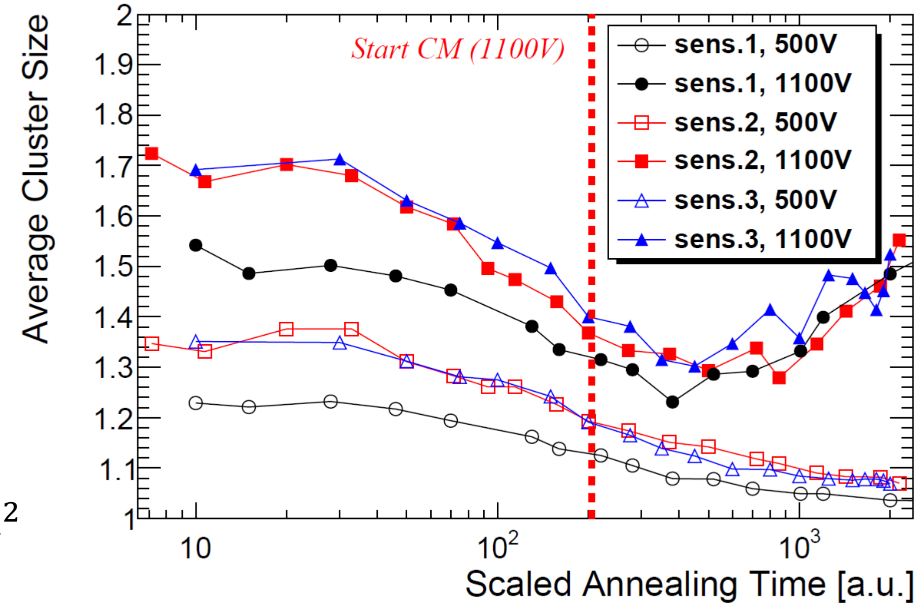
-> dependence of damage parameter on annealing time.

Explanations: Plasma Effect

- When electrons get multiplied close to the strip implants a large cloud of secondary holes is created and experiences a so called plasma effect:
  - Hole cloud travels towards sensor back
  - Shields itself from the present el. field
  - Lateral Spread and electrostatic repulsion



- Broad hole cloud increases cluster size
  - In light CM cluster size decreases due to the concentrated high el. field at the strip implants
  - In enhanced CM more strips get signal from the broad hole cloud



Sensor 1: $1 \cdot 10^{15} n_{eq}/cm^2$

Sensor 2,3: $2 \cdot 10^{15} n_{eq}/cm^2$

Conclusion

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- The observed pulses can be explained by three key points:
  - Low but substantial field beyond junction region, sustaining the drift of electrons to the high field region for deep illumination and the drift of multiplied holes towards the sensor backplane
  - High trapping probabilities decreasing the number of electrons reaching the high field area
  - High charge in small volume experiences self-screening and electrostatic repulsion (plasma effect), decreasing carrier speed through entire sensor depth

- Simulations agree with the measured pulses and confirm the origin of the prolonged pulses

- Although unexpected in strip sensors, this phenomenon is anticipated to be seen in sensors exploiting charge multiplication while having also low field regions, e.g 3D silicon detectors or Low-Gain Avalanche Diodes (LGADs)

- Ongoing trapping studies to understand its effect in the sensor, first measurements confirmed that trapped charges <u>can</u> change the present el. field (polarization effect)