Signal Formation in Heavily Irradiated Silicon Particle Sensors under Charge Multiplication

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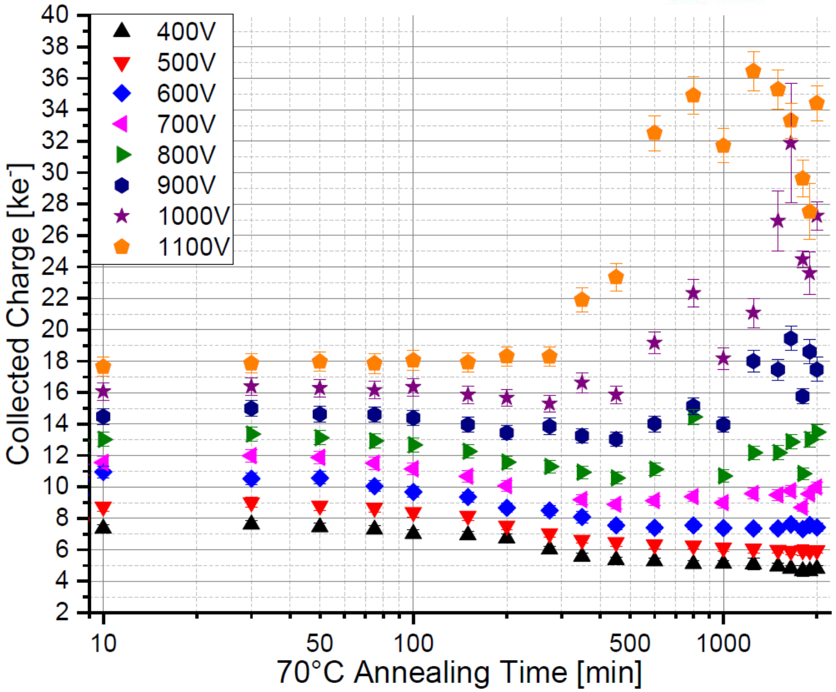
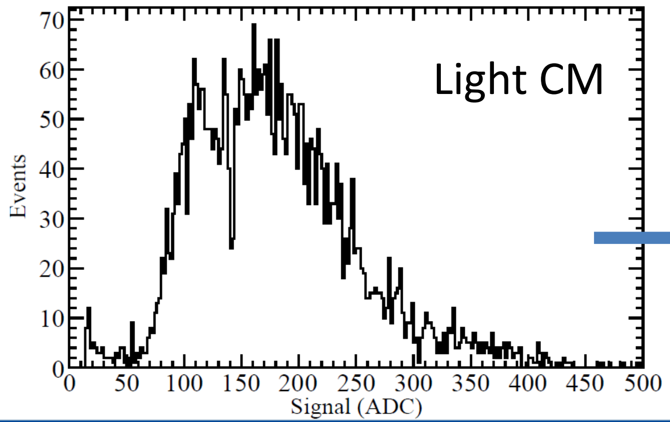
Introduction

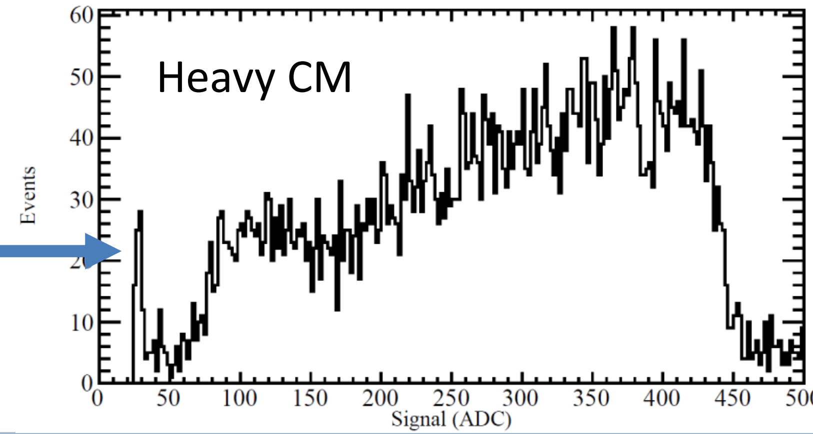
- Aims:
  - Previous studies showed that irradiated and long annealed silicon sensors undergo charge multiplication
  - Investigation of heavy charge multiplication and the signal pulse
- Materials:
  - P-type silicon strip detectors
  - Irradiated up to a fluence of 2e15 $\frac{n_{eq}}{cm^2}$
  - Annealed at temperatures between 60°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

Charge Multiplication

- Increase of charge and leakage current with continuous annealing
  - ➢ Charge Multiplication increases
- Instable effect
- No Landau distribution recognizable any more
- Saturating the readout electronics







Charge multiplication measurements

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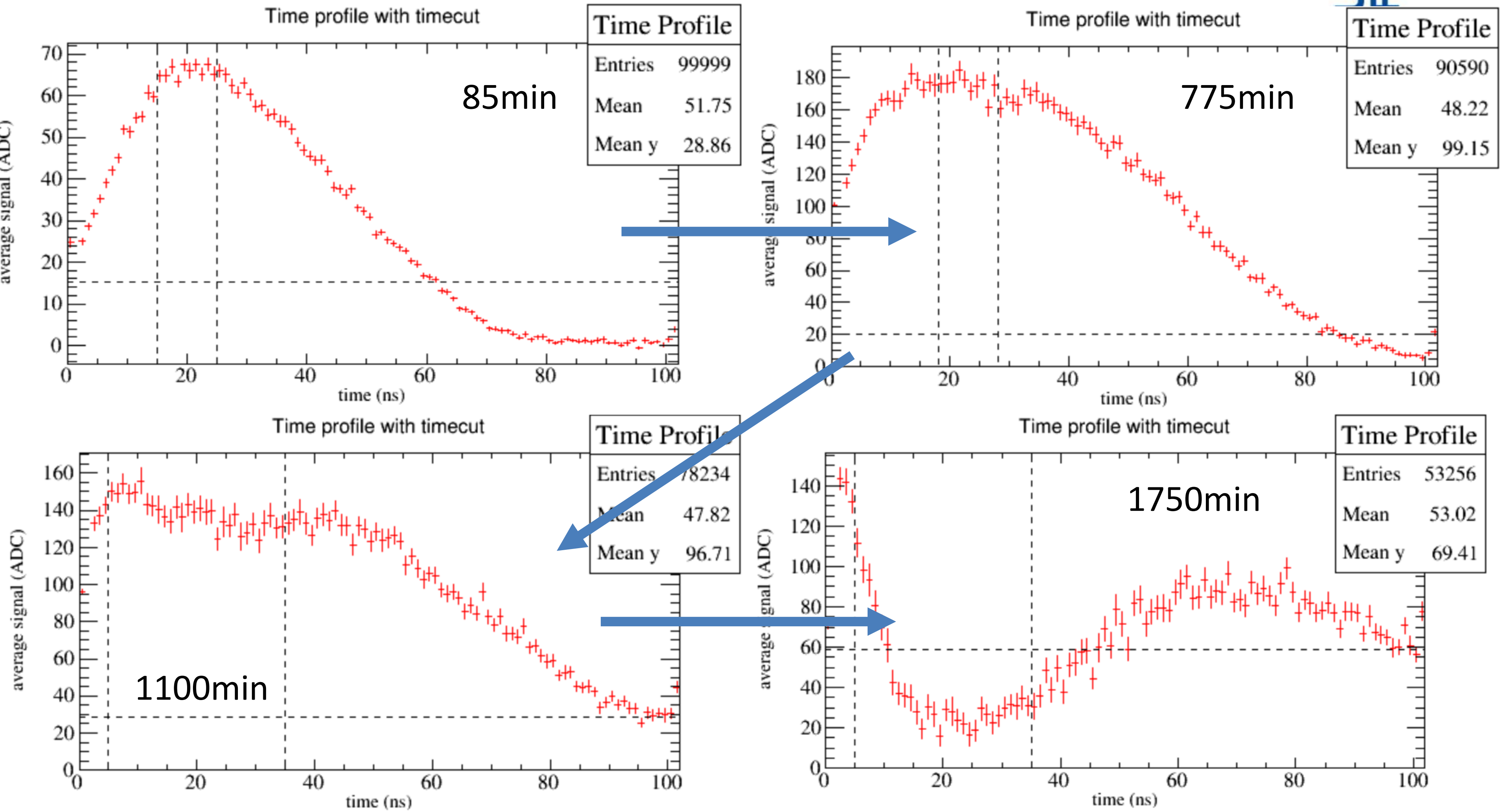
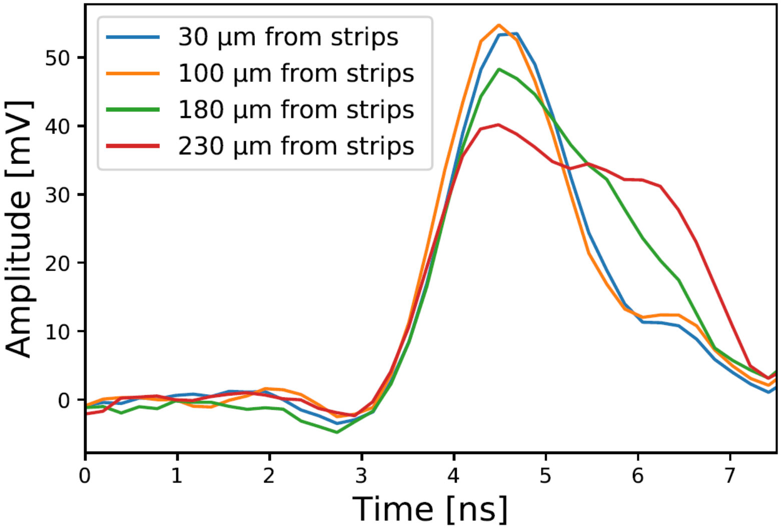
Signal pulse change in beta measurements

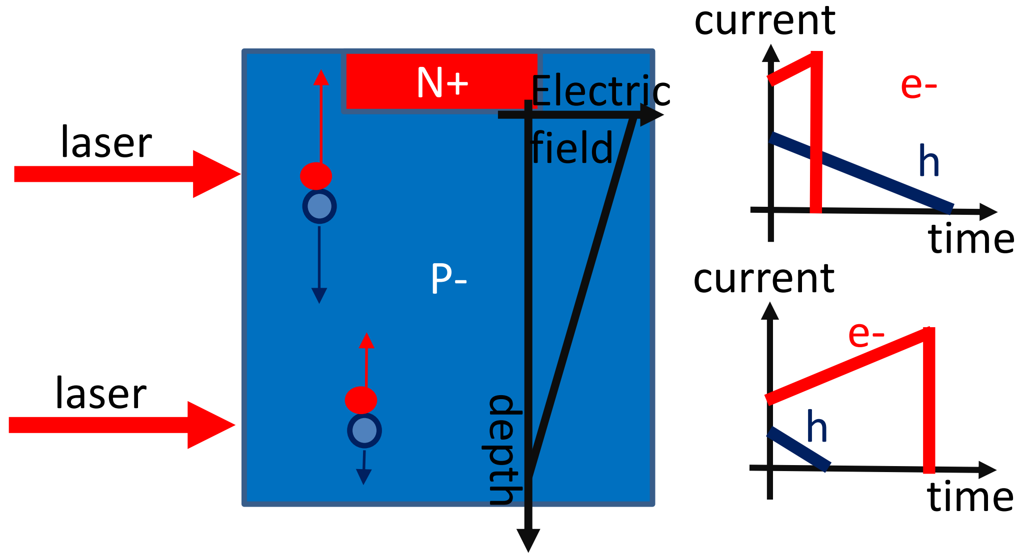


- The number of entries also decreases significantly -> Pulse exceeds the integration time
- Electronics saturate and oscillations occur

Non irradiated



Unirradiated Sensor, 400 V



- Fully depleted, signal collection also from back side
- Signal shows the sum of holes and electrons contributions
- Short pulse duration, of similar length

Edge-TCT Measurements

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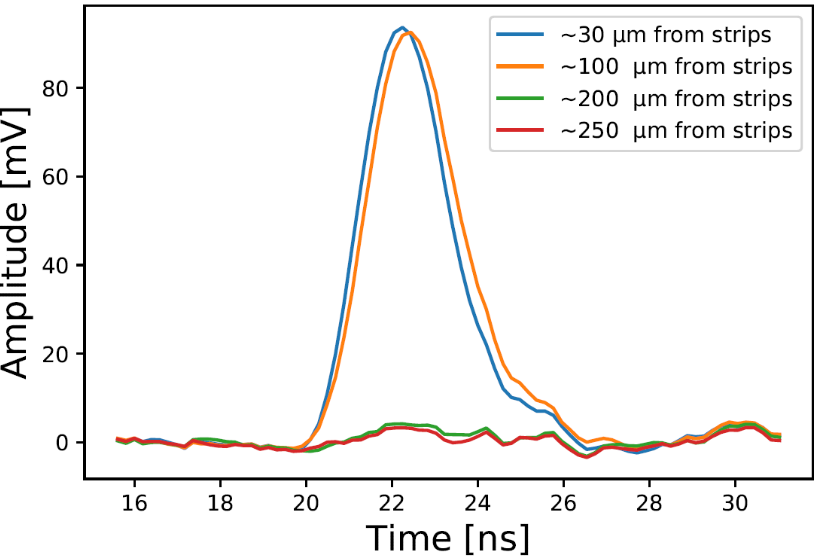
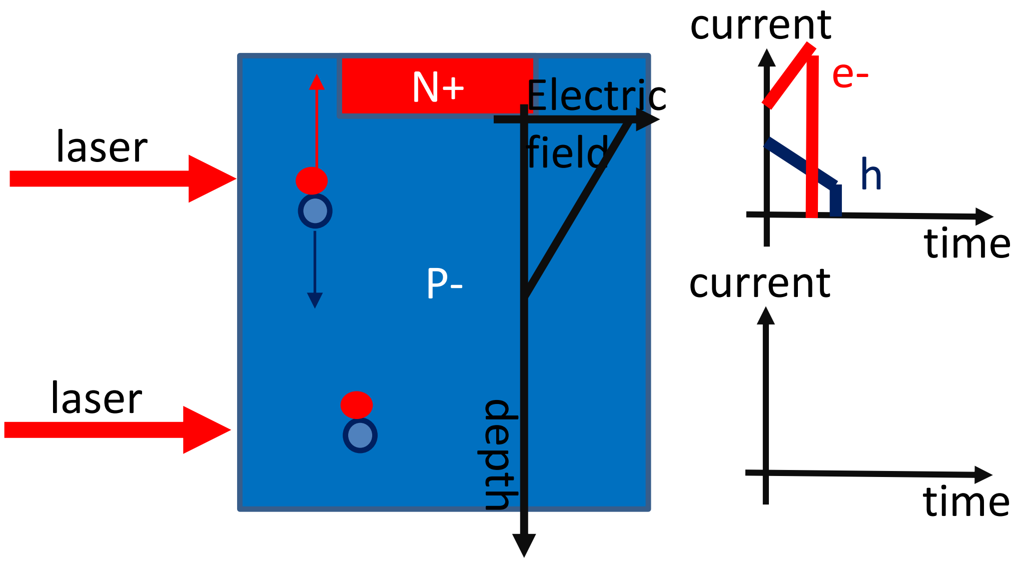
Fluence: $1 \cdot 10^{15}\ n_{eq}/cm^2$



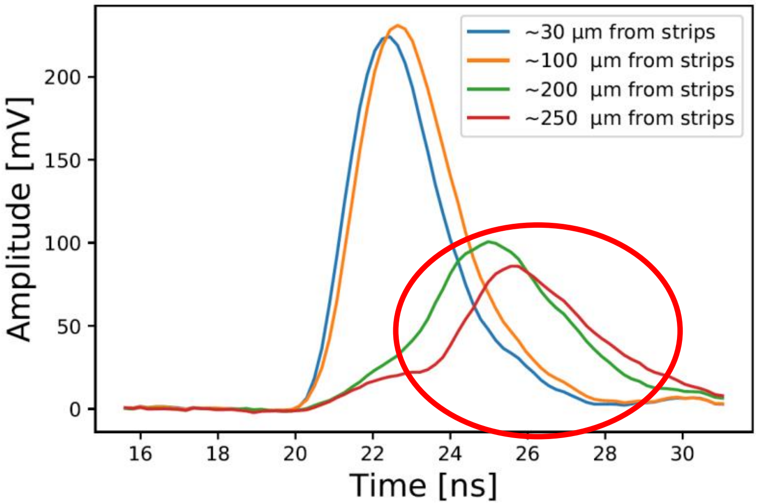


60°C 5000 min annealed Sensor, 800 V

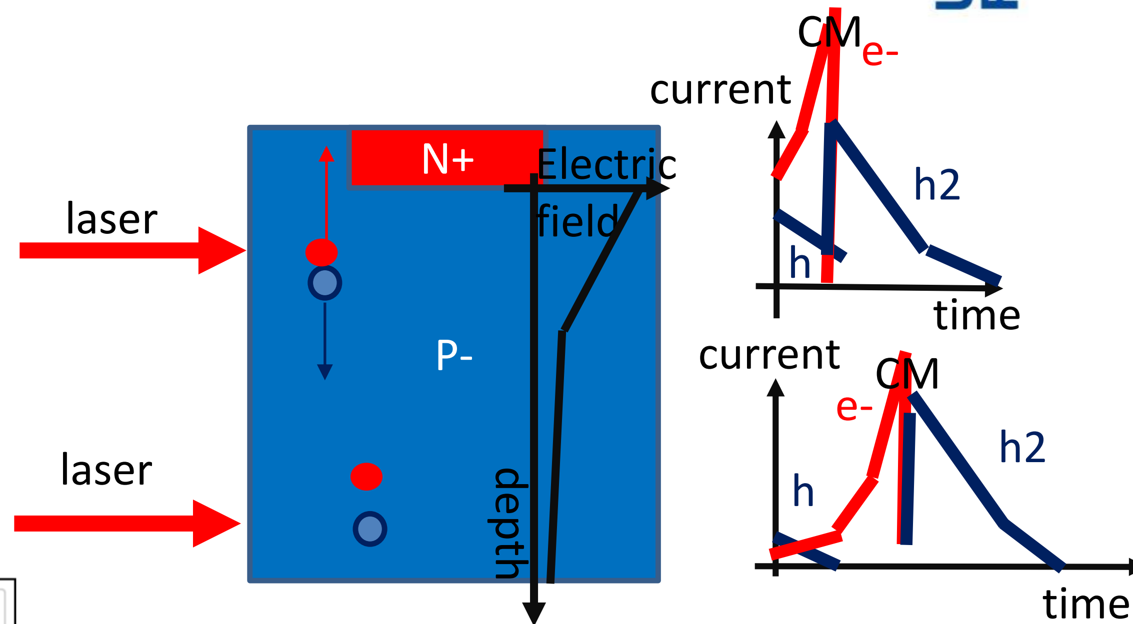
- High field at the implants but no field at the back side, no signal
- Collection happen only on the depletion region and the only signals are therefore fast
- Charge loss in case of a MIP

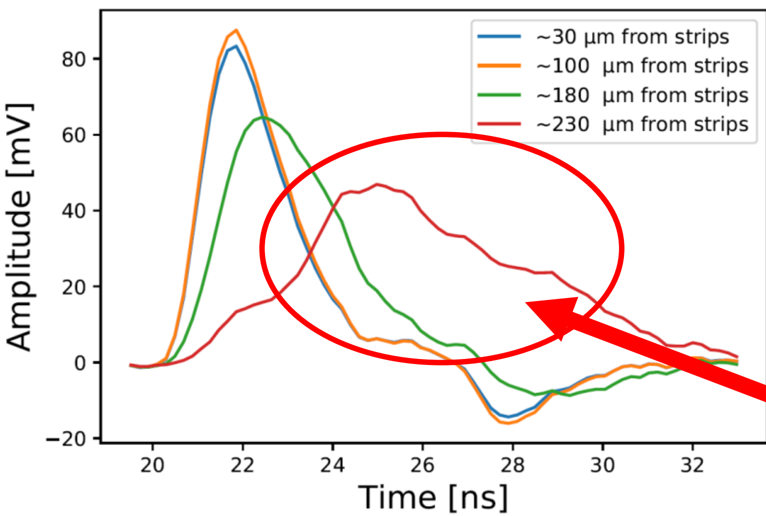
Edge-TCT Measurements

Fluence: $1 \cdot 10^{15}\ n_{eq}/cm^2$, heavy charge multiplication



60°C 5000 min annealed Sensor, 1100 V



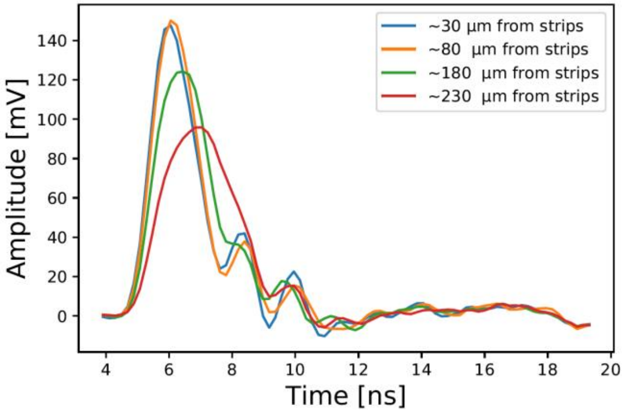


70°C 2000 min annealed Sensor, 1100 V

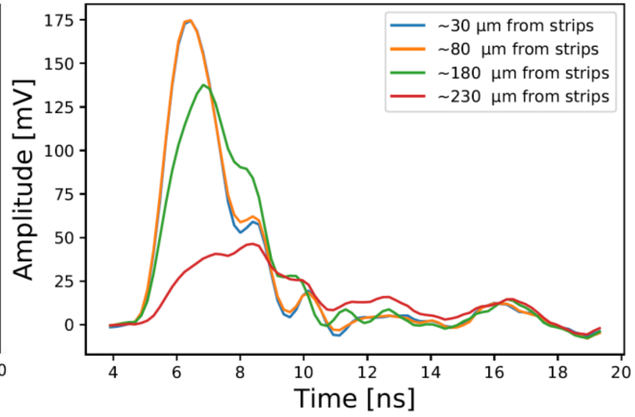
- Large hole contribution at backside:
  - Electrons reach junction and are multiplied producing a second holes cloud going back
- Can lead to a ballistic deficit

  - Is there electric field in the non depleted region?

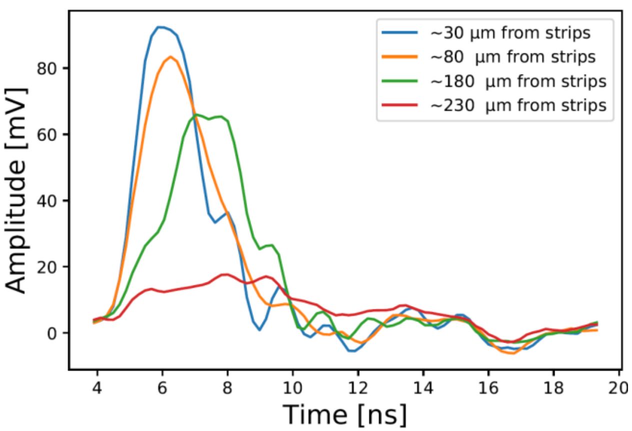
Fluence: $1 \cdot 10^{15}\ n_{eq}/cm^2$, 70°C Annealing, 1100 V



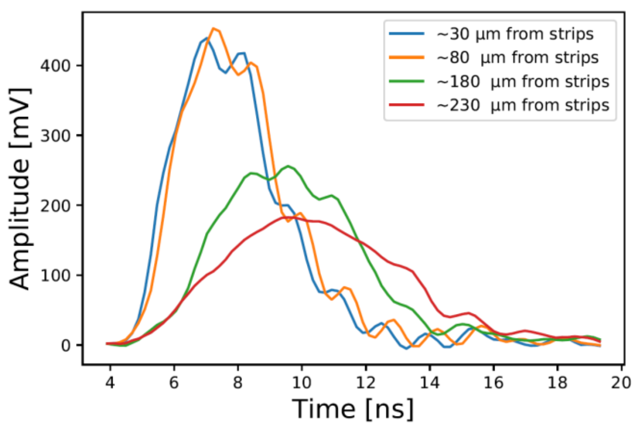
a) Beneficial Annealing, 70 min



b) Reverse Annealing, 250 min



c) Light CM, 500 min

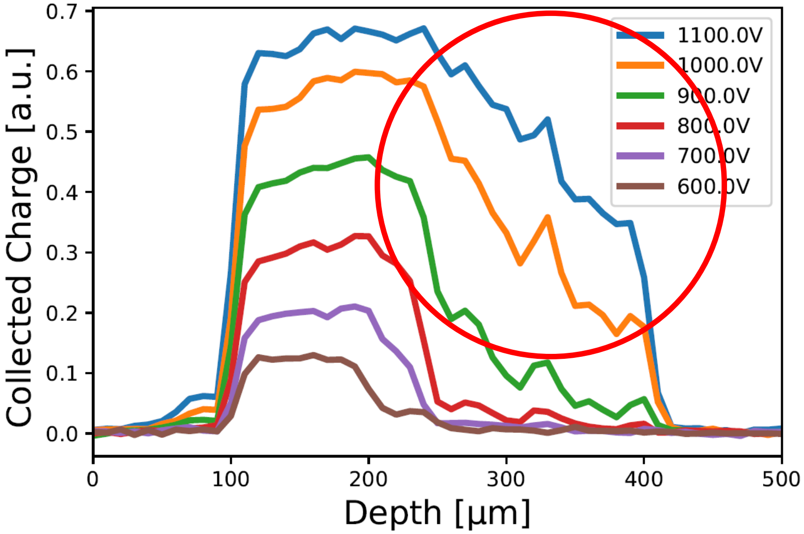


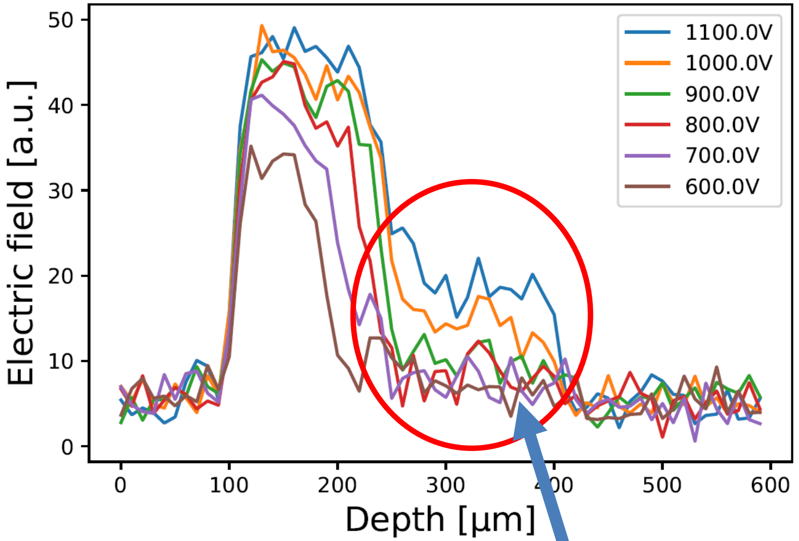
d) Heavy CM, 2000 min

- Pulse length approximately constant through entire sensor up to light charge multiplication
- Contribution at the backside vanishes in reverse annealing
- Significant increase in duration from light to heavy CM

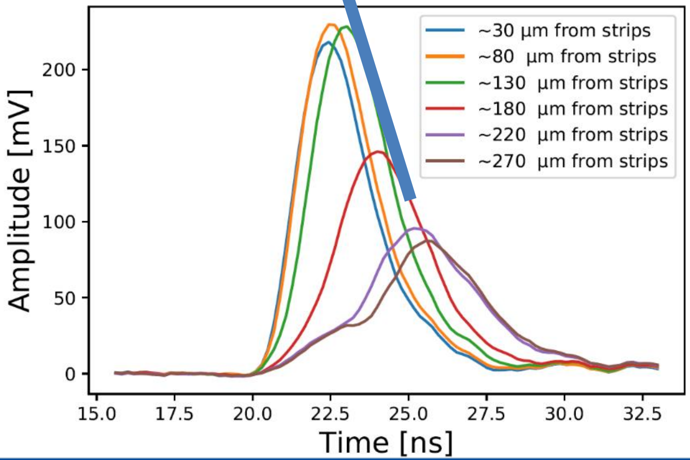
Edge-TCT Measurements

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

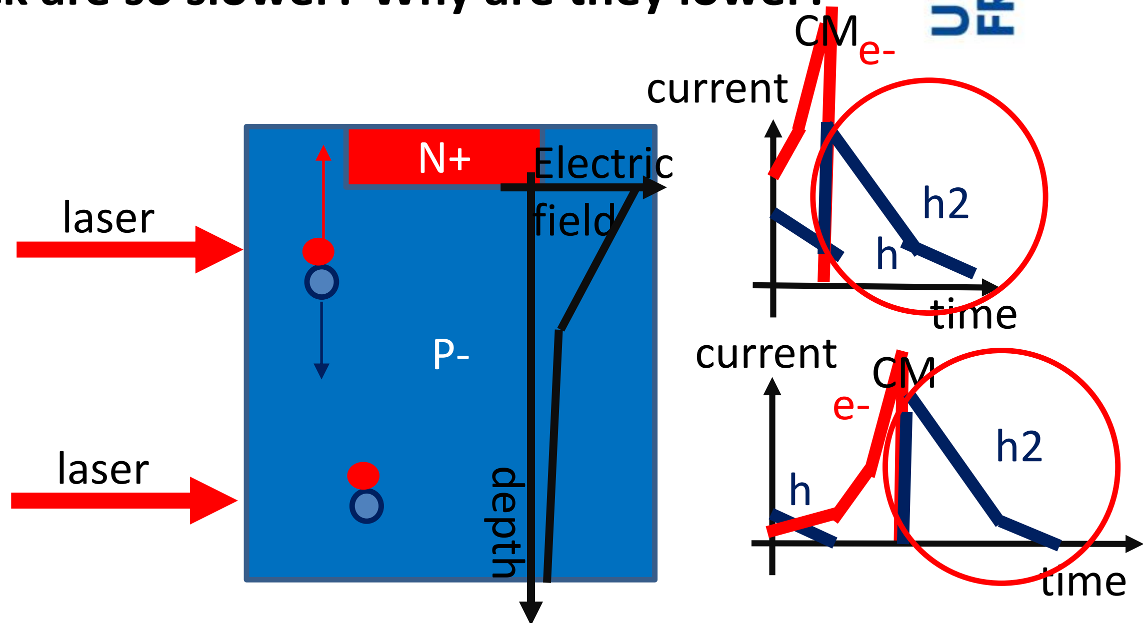


[Kram] G.Kramberger et al., Modeling of Electric field in silicon micro-strip detectors irradiated with neutrons and pions, JINST (2014)

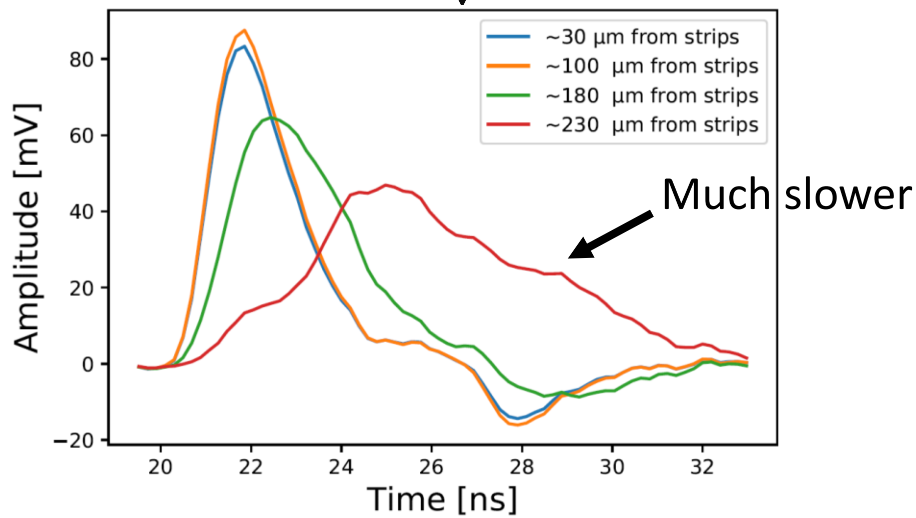
Edge-TCT Measurements

Question: why pulses from the back are so slower? Why are they lower?

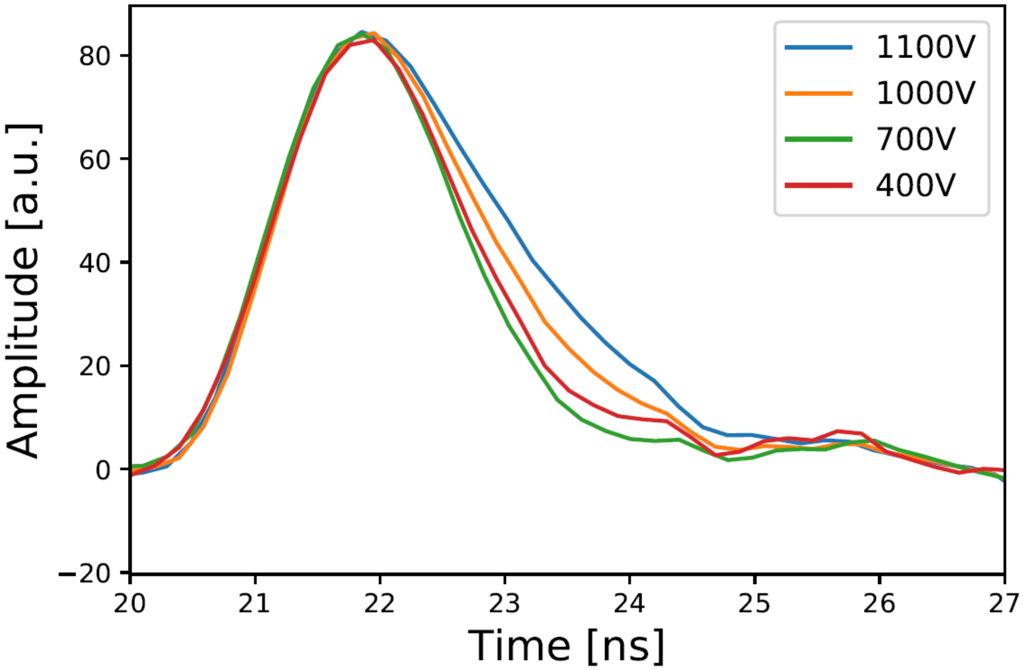
- Pulses from multiplied holes should have same steepness, as they experience the same electric field profile
- Pulse amplitude should be also the same
  - ➢ Measured a lower and much slower signal decay from the back



- Broadening and trapping of the electron cloud created in the low field region
  - ➢ Dispersed when reaching the multiplication point



Plasma Effect

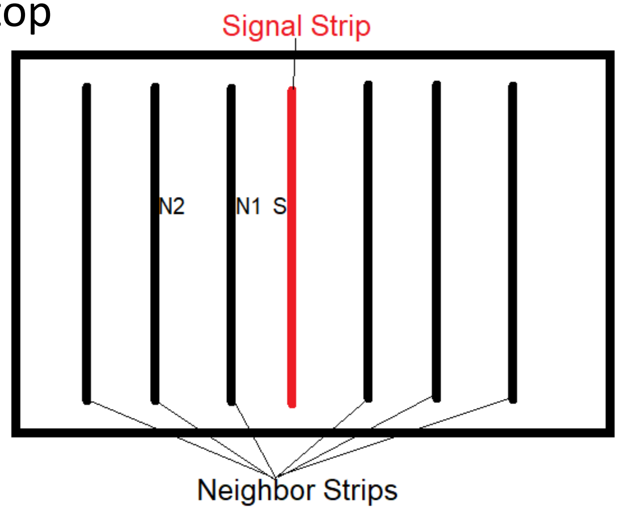


- Fluence: $1 \cdot 10^{15}\ n_{eq}/cm^2$, annealed 2000 min at 70°C
- Signal measured close to end of depletion zone

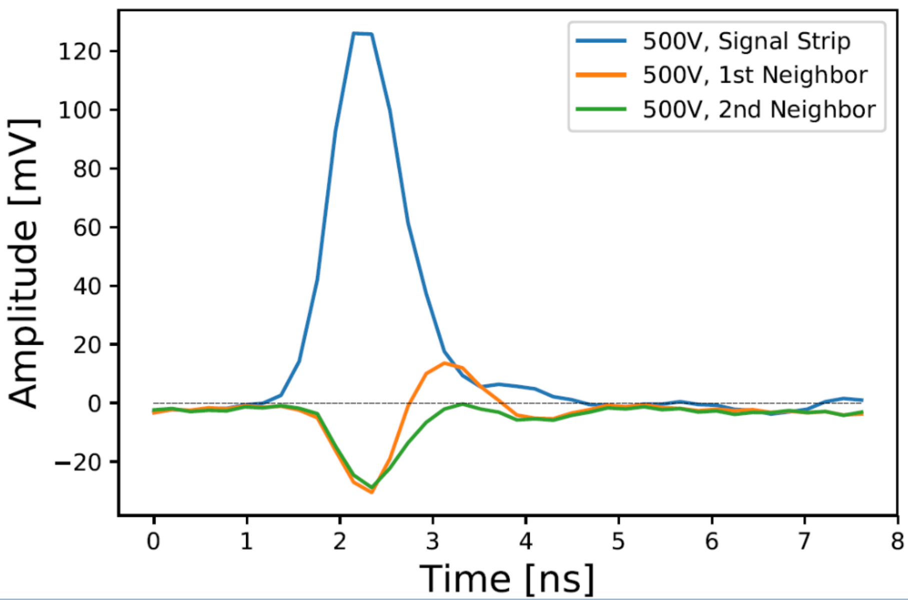
- 400 V -> 700 V: Expected faster falling edge of the signal, cause higher voltage -> higher el. field -> higher velocity
- 700 V -> 1000 V : Unexpected slower falling edge of the signal
  - Plasma effect: Multiplied holes underly a self-screening effect and travel slower
  - Carriers drift apart due to diffusion and electrostatic repulsion -> lateral spread
  - Increases charge collection time by so-called plasma time

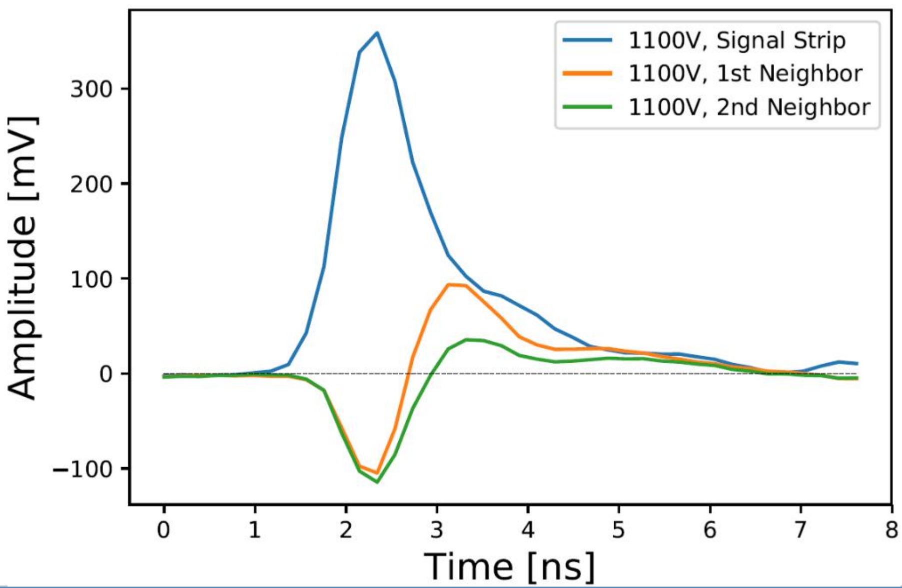
Laser on sensor top

S: Signal Strip
N1: 1st Neighbor
N2: 2nd Neighbor

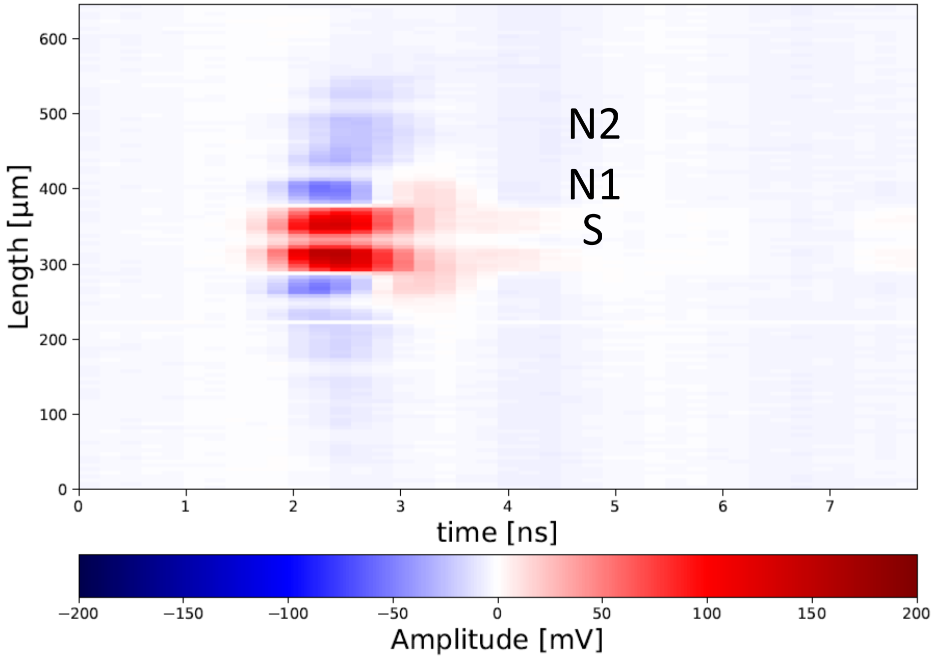


- Electrons immediately collected, holes travel to the backside
- Signal Strip: Longer pulse at 1100V due to slow, larger hole contribution
- 1st Neighbor: El. and holes visible for both voltages
- 2nd Neighbor: No hole contribution at 500V, but at 1100V -> higher cluster size at 1100V



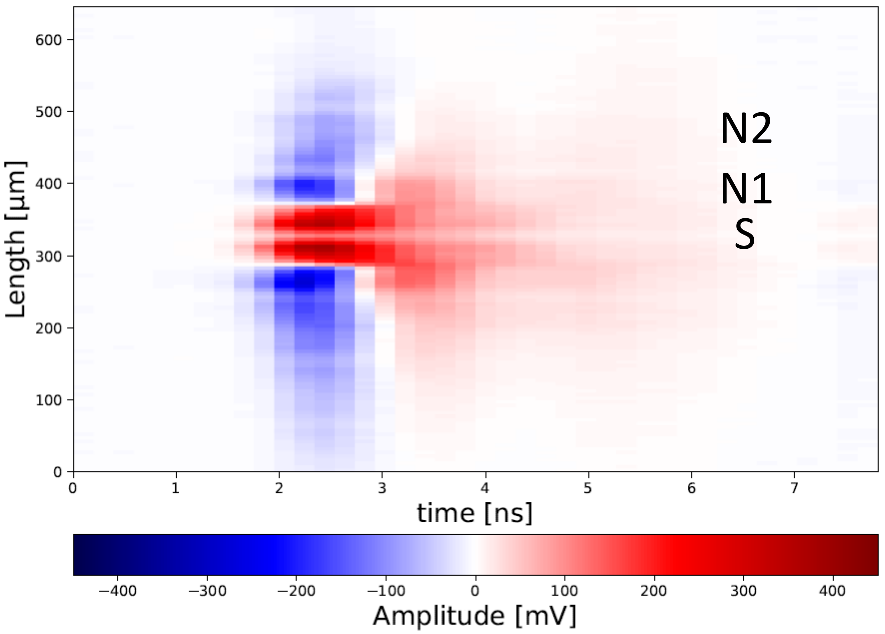


Top-TCT Measurements



Missing hole contribution at 500V also explains negative signals measured in highly irradiated sensors close to neighboring strips

- At 500V : Short signals, small hole contribution only around the signal strip
- At 1100V: Long pulses, large hole contribution, also for more neighbors
  - Plasma effect prolongs the signal
  - Electrostatic repulsion and diffusion enlargens the hole cloud
  - Increase of cluster size



Conclusion

- Heavy charge multiplication introduces a significant multiplied hole contribution

- Long pulses observed especially in back of the sensor, where no pulse is expected
  - Charge collected throughout the entire sensor area

- Electric field present also in the non depleted area (ENB)
  - Leads to long pulses due to diffusion
  - Smaller amplitude due to trapping

- Plasma effect: Multiplied holes travel through the sensor and underly a self-screening effect
  - Increase of signal pulse length
  - Can lead to a ballistic deficit

- Due to electrostatic repulsion and diffusion: Increasing cluster size due to the hole contribution

Conclusion

- Heavy charge multiplication introduces a significant multiplied hole contribution
- Long pulses observed especially in back of the sensor, where no pulse is expected
  - ➢ Charge collected throughout the entire sensor area
- Electric field present also in the non depleted area (ENB)
  - ➢ Leads to long pulses due to diffusion
  - ➢ Smaller amplitude due to trapping
- Plasma effect: Multiplied holes travel through the sensor and underly a self-screening effect
  - ➢ Increase of signal pulse length
  - ➢ Can lead to a ballistic deficit
- Due to electrostatic repulsion and diffusion: Increasing cluster size due to the hole contribution

Thanks for your attention!

Backup

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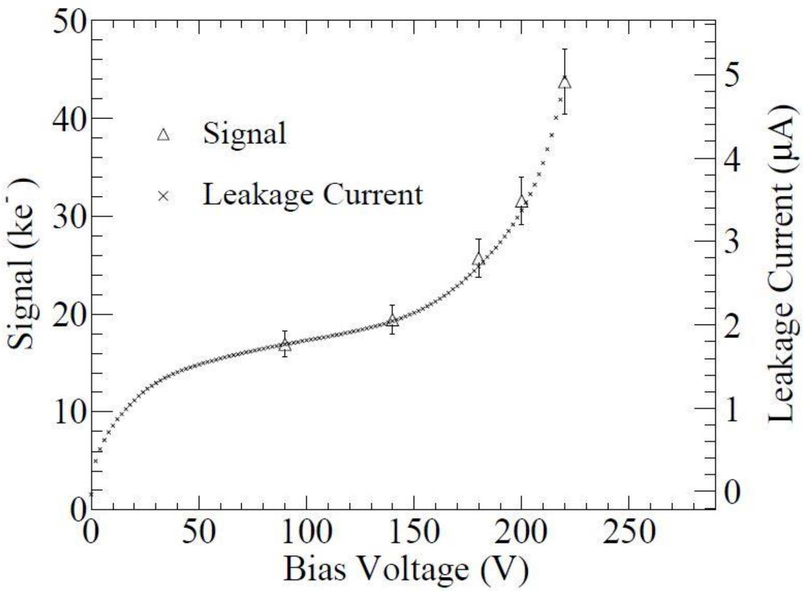
- Charge multiplication
  - High field close to strip implants saturates carrier speed and produces „hot“ carriers
  - Hot carriers cause impact ionization: electron-hole pair creation
  - Avalanche mechanisms: charge collection diverges



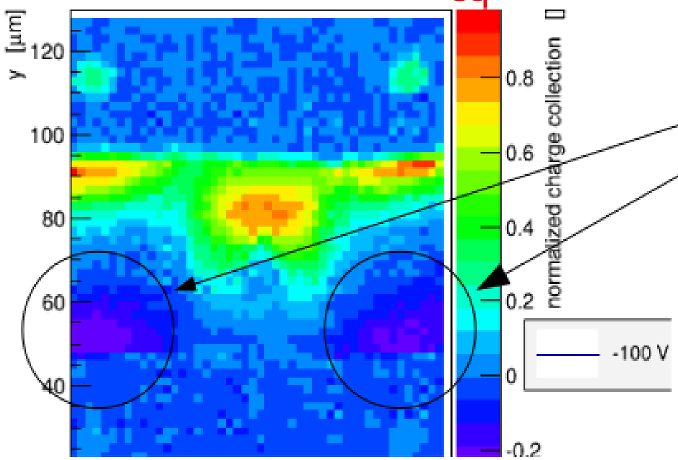
(a) $\Phi_{eq} = 1 \times 10^{15}\, n_{eq}/cm^2$ [Köh]

- Plasma effect
  - Free carriers are not negligible and influence the electric field distribution: screening effect -> charge „clouds“ travel slower.
  - Carriers drift apart due to diffusion and electrostatic repulsion -> lateral spread.
    - Increases charge collection time by so-called plasma time.

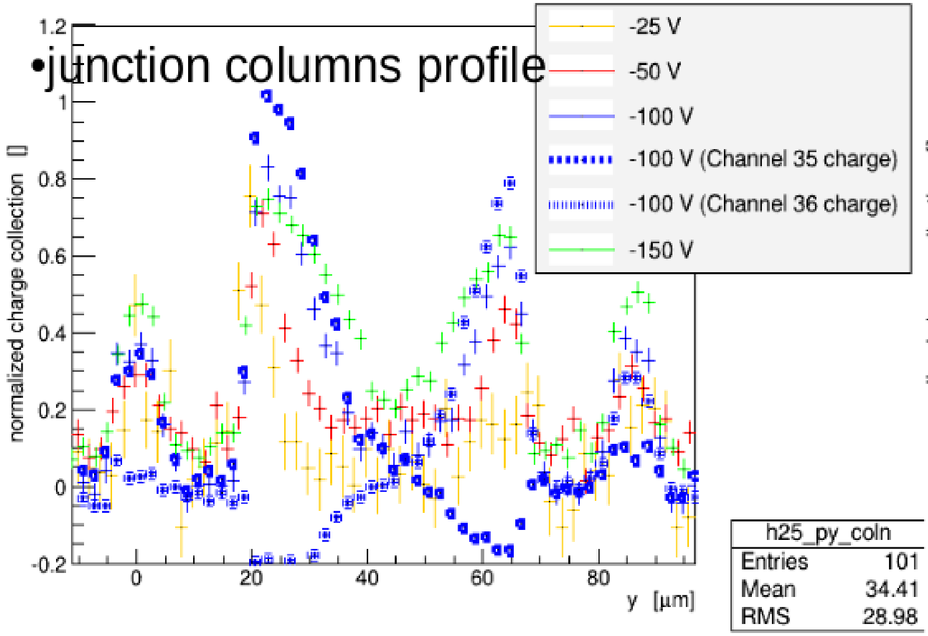
[Köh] M. Köhler, Double-Sided 3D Silicon Detectors for the High-Luminosity LHC, PhD Thesis, Freiburg(2011)

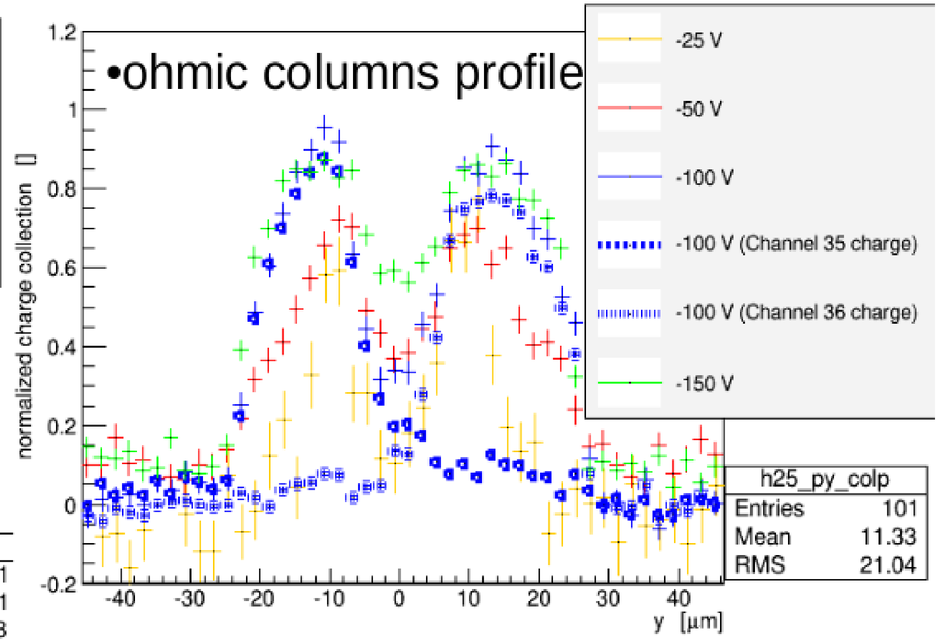
Experimental results and discussion

- Laser: 2*10^{16} n$_{eq}$/cm^2: discussion: “compensation” effect



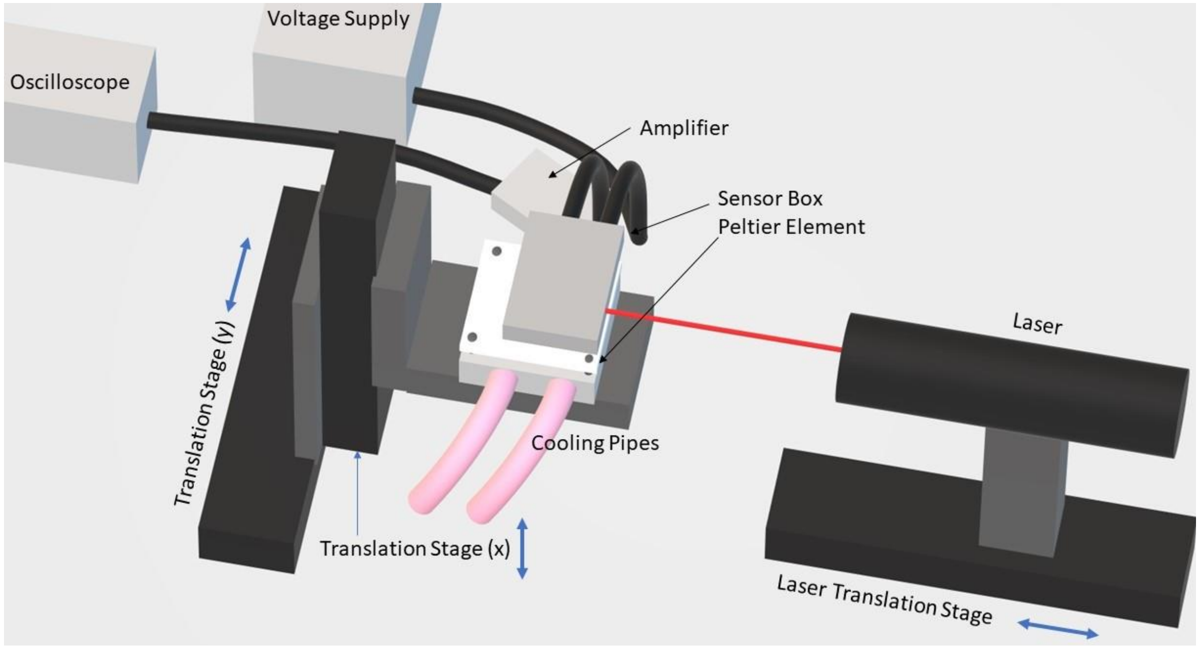
Very large and very negative zones

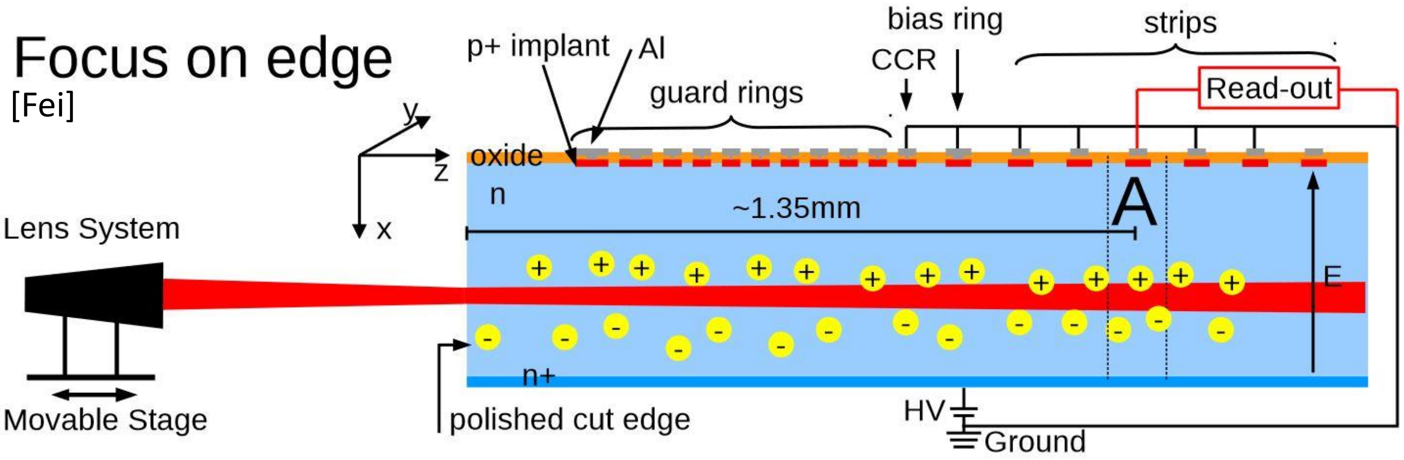




- Larger than at lower fluence: relatively higher field distributed closer to the junction columns.

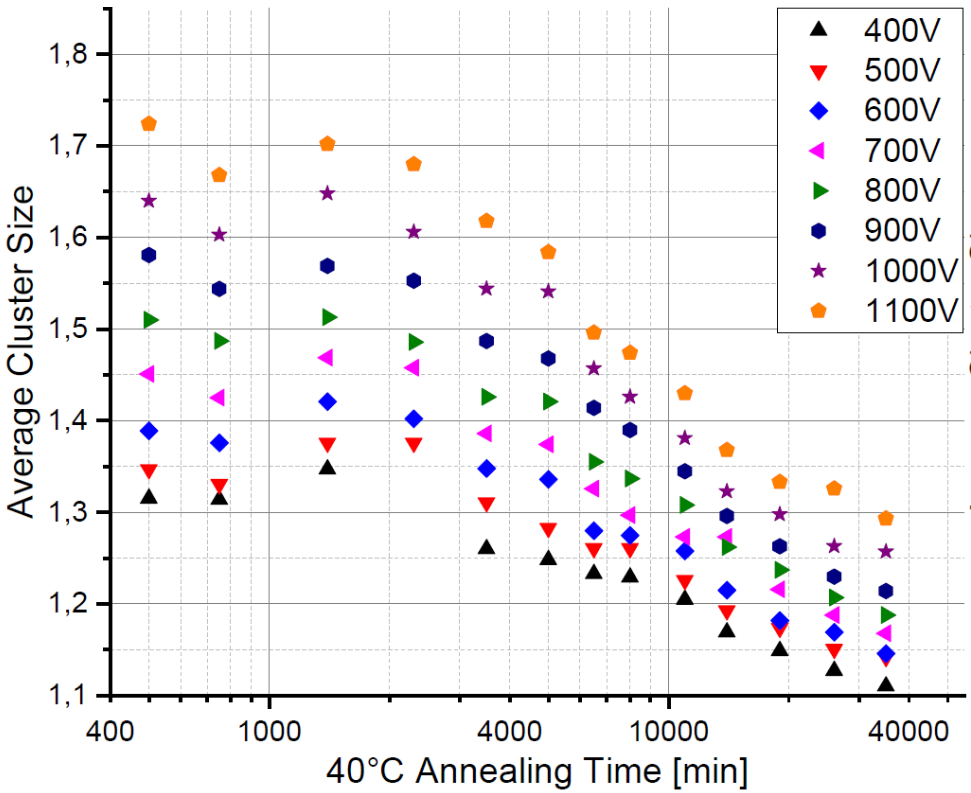
Edge-TCT Measurements

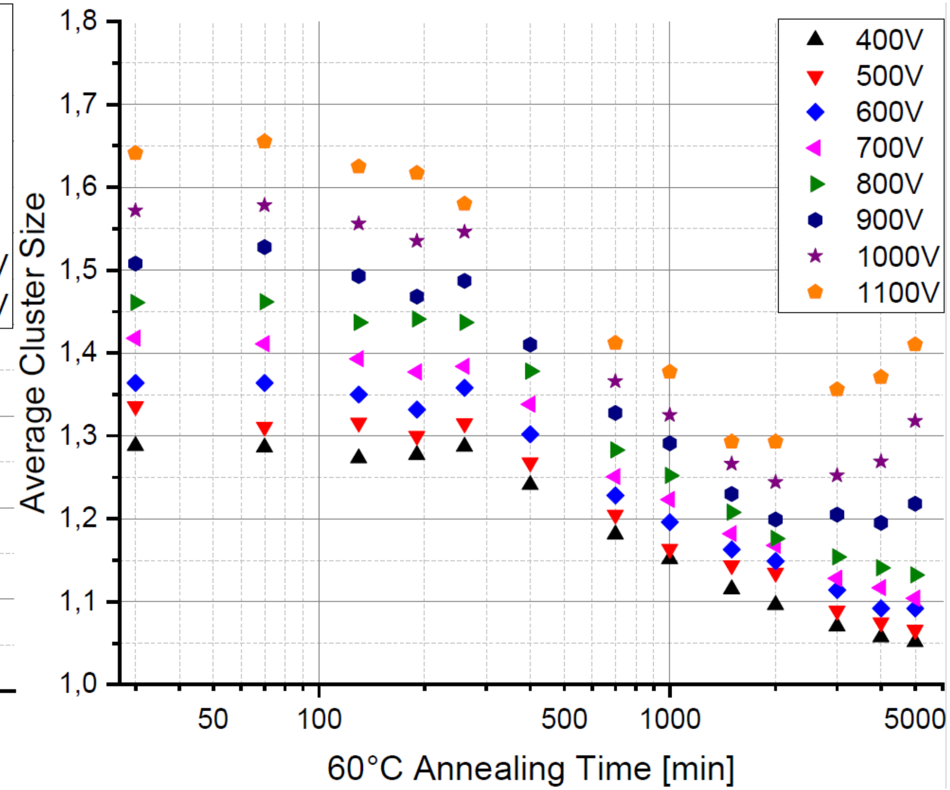




Backup:Charge Collection Measurements

Fluence: 1· $10^{15}\ n_{eq}/cm^2$





- Cluster size decreases during reverse annealing.
- Keeps decreasing in light CM due to more focused charge collection near strips.
- Increase during heavy CM, hinting to a large hole contribution, spread due to diffusion and electrostatic repulsion.

Backup:Charge multiplication measurements

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Charge multiplication doesn‘t depend on temperature:

Avalanche phenomena is not so strongly depending on temperature [1]:

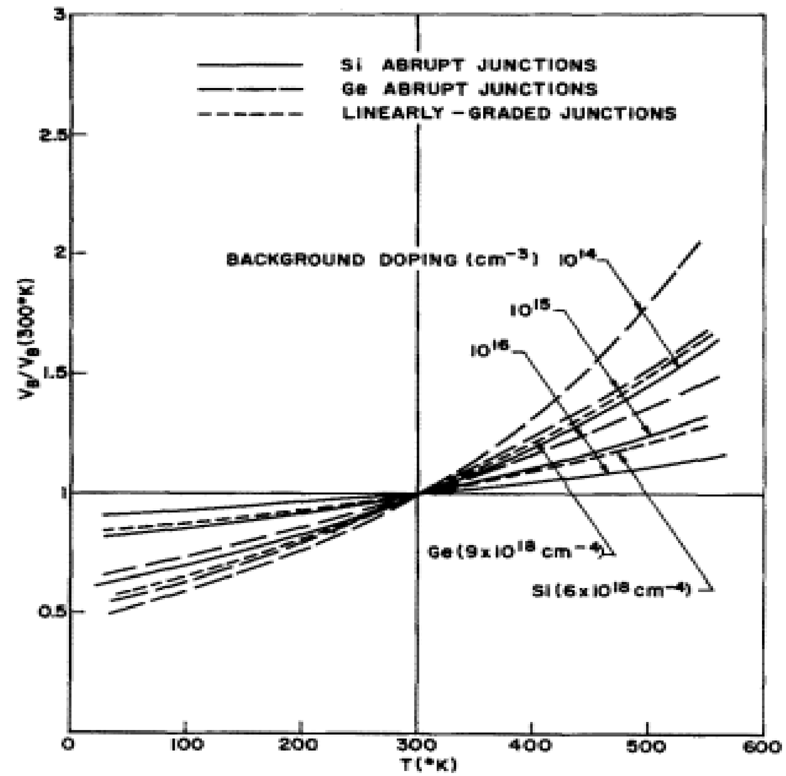

Fig. 4. Breakdown voltage vs temperature for Si and Ge *p-n* junctions. $V_B(300°K)$ is 2000, 330, and 60 V for Si and 950, 150, and 25 V for Ge for dopings of 10^{14}, 10^{15}, and 10^{16} cm^{-3} respectively. The linear-graded junctions have $V_B(300°K)$ the same as those for doping of 10^{15} cm^{-3}.

[1] Crowell and Sze, TEMPERATURE DEPENDENCE OF AVALANCHE MULTIPLICATION IN SEMICONDUCTORS, APL (1966)

Landaus 1100V