Simulation of CCE for n-in-p 75 and 150 μm thick detectors irradiated up to a fluence of 1x10^{16} n.eq.

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- Introduction to the CCE simulation method
- The Overstraeten impact ionization model
- Results of the CCE simulation for diodes
- Results of the CCE simulation for strips

16th RD50 Workshop, Barcelona, 1st June 2010

Ingredients of the simulation

- Monte Carlo algorithm for the generation of electron-hole pairs along the trajectory of the particle entering the sensor and their propagation in the electric field.

- Radiation damage modeled with charge trapping and N_{eff} evolution with fluence.

- Analytical expression used to describe the electric field configuration in case of the diode simulation.

- 2-dimensional electric-field configuration for strip sensors, before and after irradiation, as calculated by the TeSCA simulation software.

- Charge multiplication in high electric field implemented with the Overstraeten model for impact ionization.

Starting from Ramo's theorem

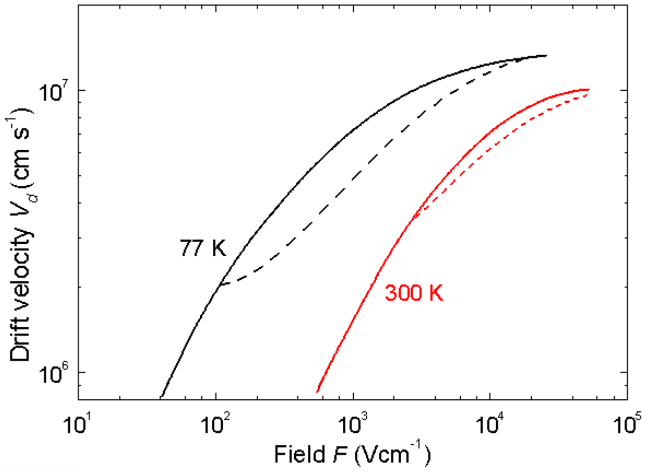
- The algorithm creates one electron-hole pair every 12.5 nm of silicon penetrated:
  - Each generated particle is propagated in the electric field to the electrodes
  - The induced current is integrated over the propagation time, with a maximum integration time of 25 ns :

$$I_{\mathrm{e,h}}(t) = \sum_{\mathrm{e,h}} \mp q\, \vec{v}_{\mathrm{dr}_{\mathrm{e,h}}}(\vec{x}_{\mathrm{e,h}}(t))\, \vec{\mathcal{E}}_{\mathrm{w}}(\vec{x}_{\mathrm{e,h}}(t)), \qquad \vec{\mathcal{E}}_{\mathrm{w}}(\vec{x}_{\mathrm{e,h}}(t)) \text{ = Ramo field}$$

$$v_{\mathrm{dr}_{\mathrm{e,h}}}(x_{\mathrm{e,h}}(t)) = \frac{\mu_{\mathrm{e,h}}\mathcal{E}(x_{\mathrm{e}}(t))}{\left(1+\left(\frac{\mu_{\mathrm{e,h}}\mathcal{E}(x_{\mathrm{e}}(t))}{v_{\mathrm{sat}_{\mathrm{e,h}}}}\right)^{\beta}\right)^{\frac{1}{\beta}}}$$

with $\beta_e = 1.09$, $\beta_h = 1.21$ at T=294K

Drift velocity dependence on electric field as in Jacoboni et al. 1977



- The charge carriers are propagated in small steps of Δt, according to:

$$\vec{x}_{\mathrm{e,h}}(t+\Delta t) = \vec{x}_{\mathrm{e,h}}(t) + \vec{v}_{\mathrm{dr}_{\mathrm{e,h}}}(\vec{x}_{\mathrm{e,h}}(t))\Delta t$$

Introduction of radiation effects

- Change of effective bulk doping concentration:

$$N_{\mathrm{eff}}(\Phi_{\mathrm{eq}}) = \begin{cases} N_0 & : \Phi_{\mathrm{eq}} = 0 \\ -\beta\Phi_{\mathrm{eq}} & : \Phi_{\mathrm{eq}} \gg 0 \end{cases}$$

- N_0 as in our thin sensor production (6.5×10^{12} /cm^3)
- β=7.1x10^{-3} from G. Kramberger et al., NIM A, 511, p. 82-87 (2003)

- Trapping is included at each time step according to G. Kramberger et al., NIM A, 481, p. 297-305 (2002):

$$N_{\mathrm{e,h}}(t) = N_{\mathrm{e,h}}(0)\cdot\exp\left(-\frac{t}{\tau_{\mathrm{eff}_{\mathrm{e,h}}}}\right) \qquad \frac{1}{\tau_{\mathrm{eff}_{\mathrm{e,h}}}} = \beta_{\mathrm{e,h}}\Phi_{\mathrm{eq}}$$

- The decision to remove one of the carriers at the step Δt is taken when a random number extracted ε [0,1] is lower than the probability of being trapped 1-exp(-Δt/τ_{eff})

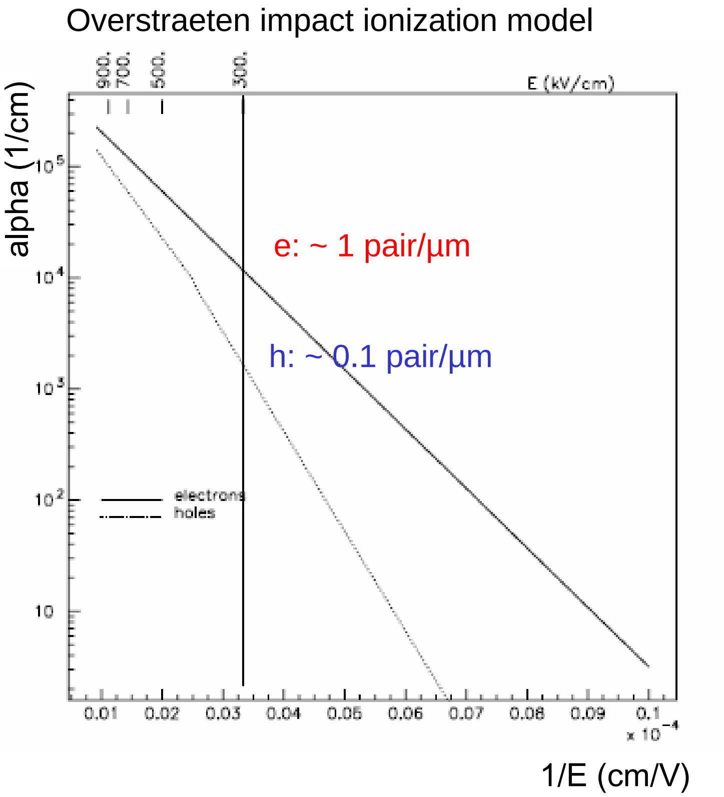
Impact ionization - Overstraeten model

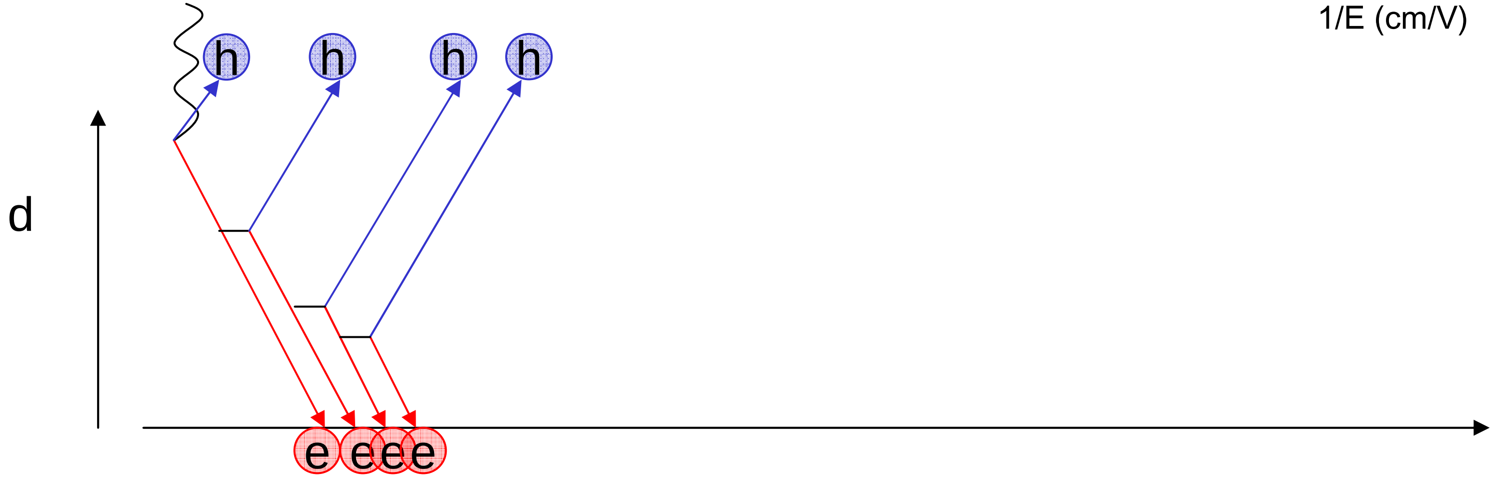
- In high electric fields electrons and holes acquire enough energy to initiate sizeable charge multiplication

Electrons >~ 300 kV/cm
Holes >~ 400 kV/cm

$$\alpha_{\mathrm{e,h}}(\mathcal{E}) = \alpha_{\infty_{\mathrm{e,h}}} \exp(-b_{\mathrm{e,h}}/\,|\mathcal{E}|).$$

- 300 kV/cm < E < 400 kV/cm
Only electrons ionize
Linear mode
Gain < 10
N(l) = exp(αl) with l=path length in high electric field


Overstraeten impact ionization model



A. Macchiolo, 16th RD50 Workshop, Barcelona, 1st June 2010

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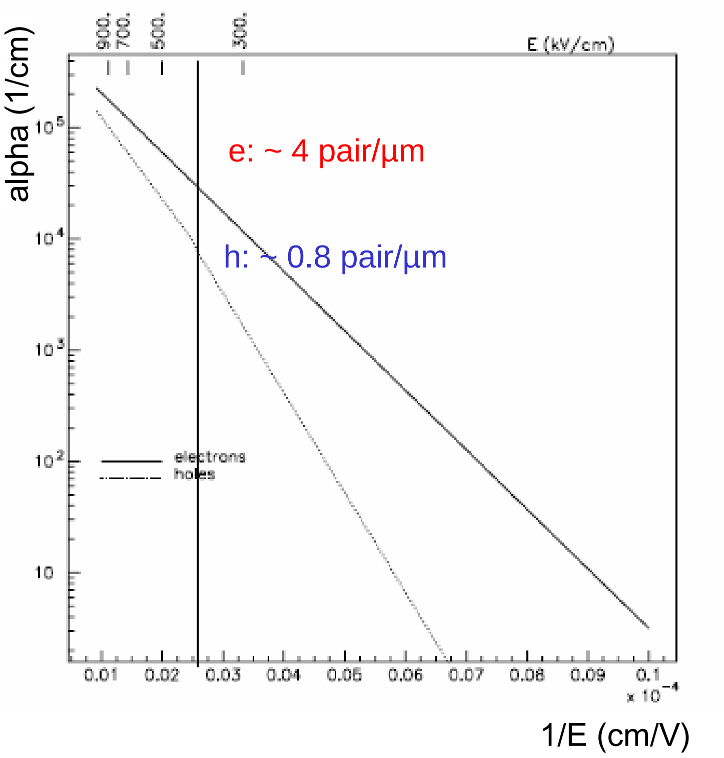
- E ~ 400 kV/cm

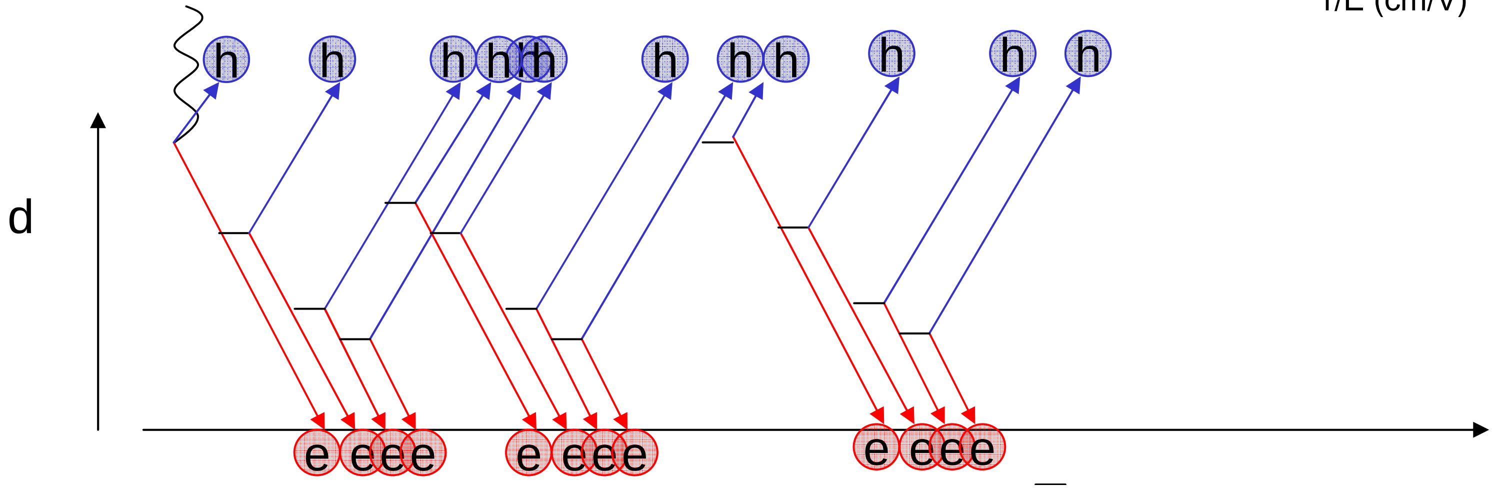
Both electrons and (rarely) holes ionize
Still linear mode
Gain: 50 – 300
Excess noise: $\sigma(N) \sim k\,N$, $k=\alpha_h/\alpha_e$

Overstraeten impact ionization model



e: ~ 4 pair/µm

h: ~ 0.8 pair/µm



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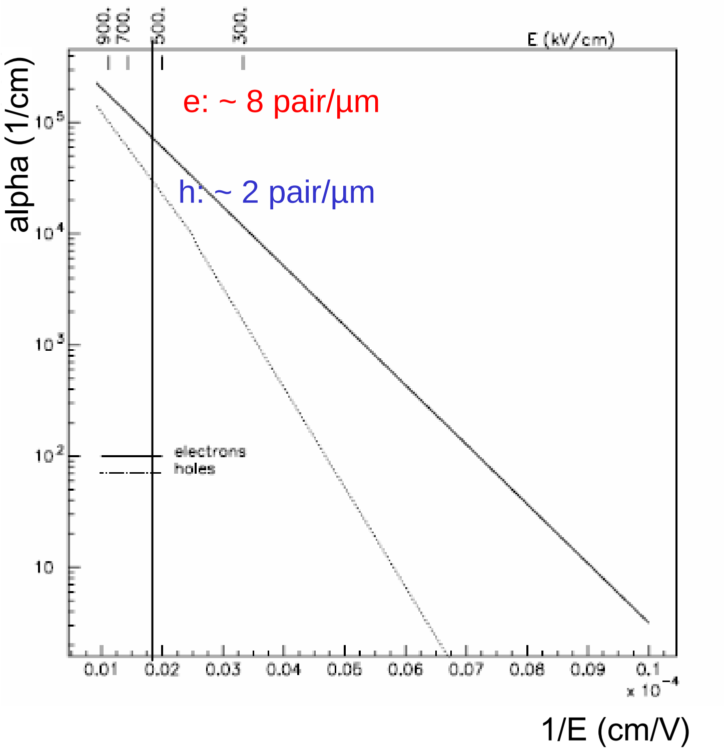
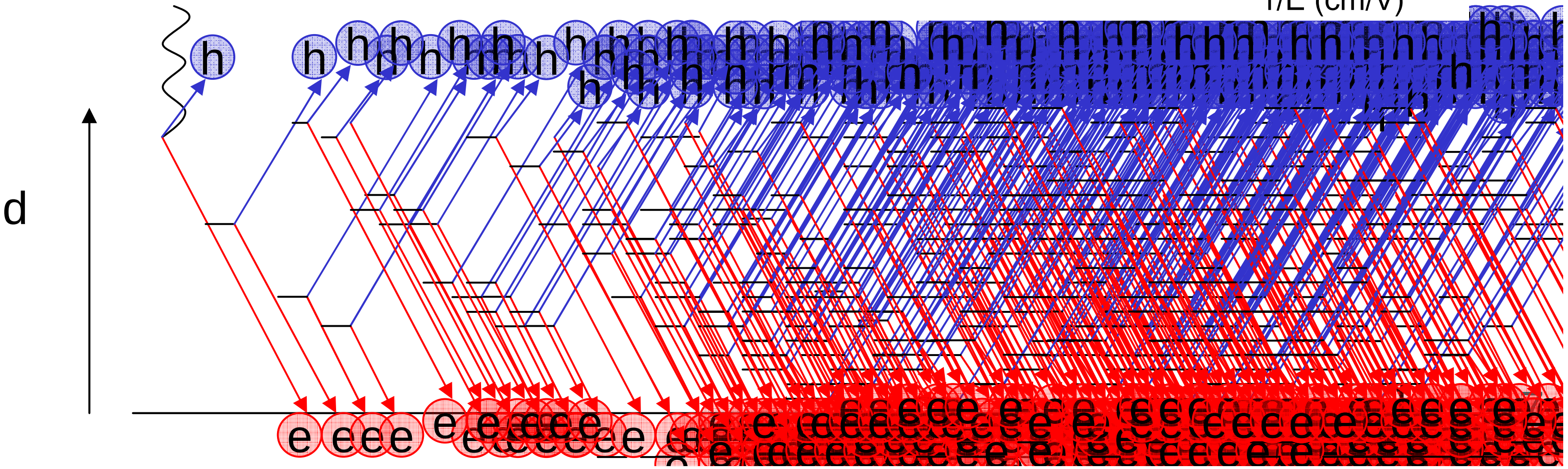
Holes >~ 400 kV/cm

$$\alpha_{\mathrm{e,h}}(\mathcal{E}) = \alpha_{\infty_{\mathrm{e,h}}} \exp(-b_{\mathrm{e,h}}/\,|\mathcal{E}|).$$

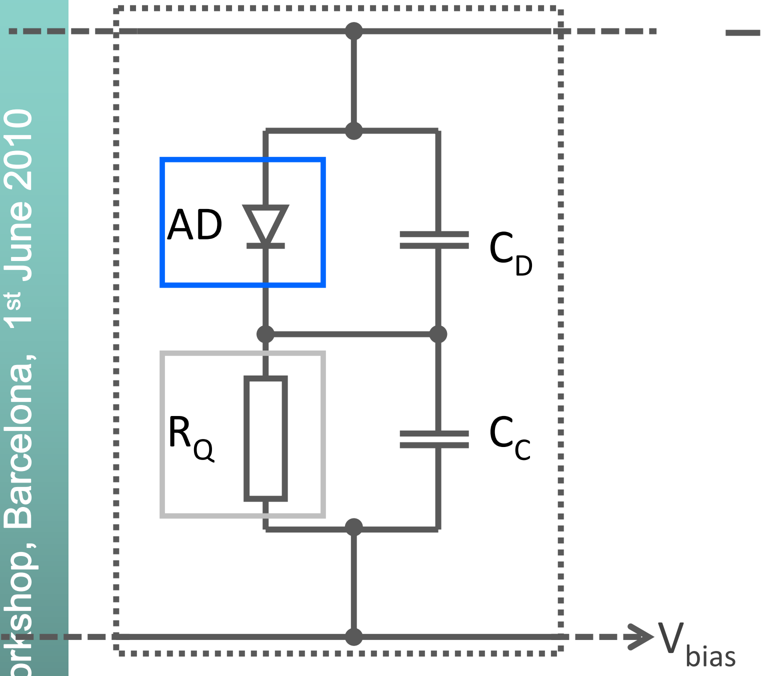
- E > 400 kV/cm
Both electrons and holes ionize
Geiger mode
Gain: infinite (breakdown)

Overstraeten impact ionization model

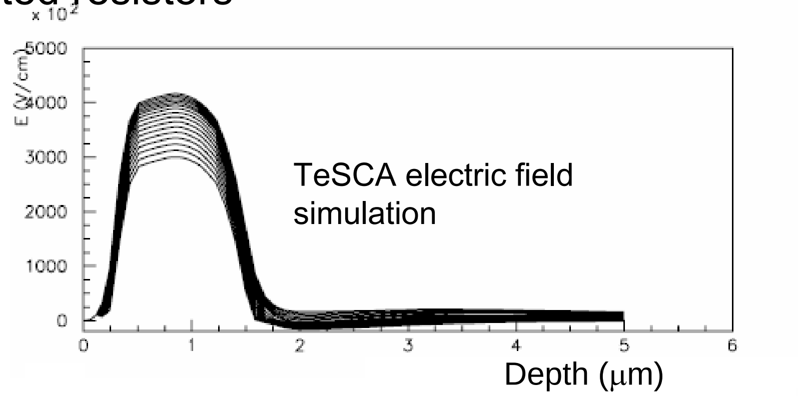




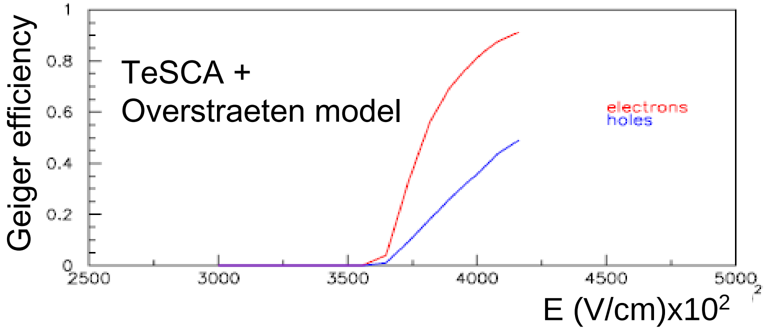
Application of the Overstraeten impact ionization model



- ➢Silicon photomultiplier operated above the breakdown voltage with passive quenching by integrated resistors

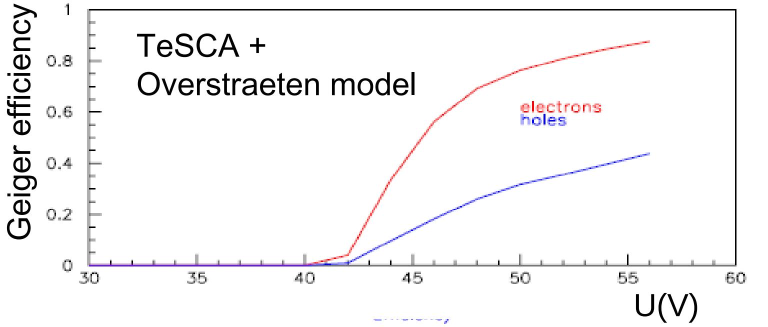


TeSCA electric field simulation



TeSCA + Overstraeten model

- ➢Example of avalanche efficiencies with realistic (TeSCA) field profiles. The measured breakdown voltage of this device was 42V. Simulation of other HF regions als agree within ± 0.5V



TeSCA + Overstraeten model

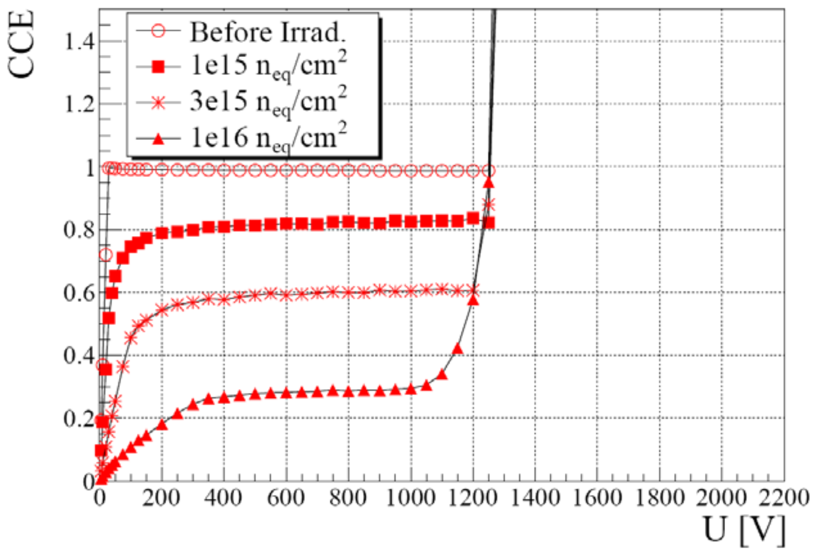
Electric field distribution in the diode

- To derive the electric field distribution in a diode a simple 1-dimensional description has been adopted:

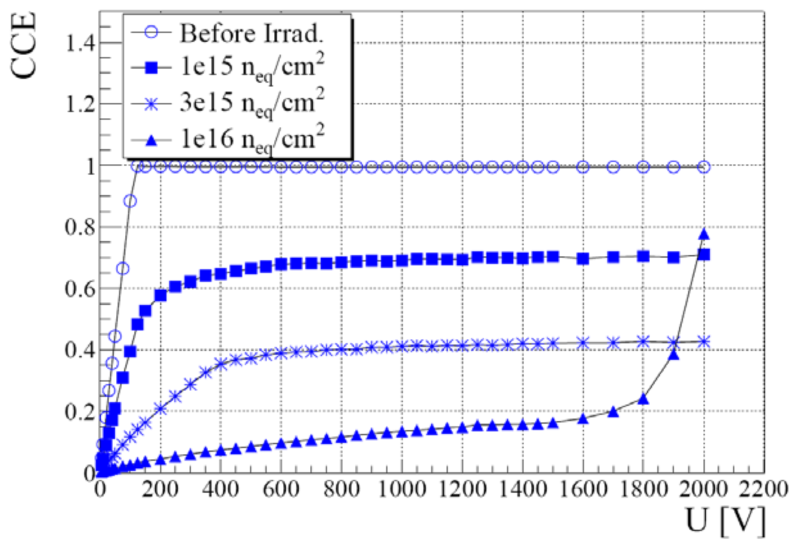
$$\vec{\mathcal{E}}(\vec{x}) = \begin{pmatrix} 0 \\ \frac{qN_{\text{eff}}}{\epsilon\epsilon_0}(\vec{x}\vec{e}_z - d) + \frac{U_{\text{fd}}-U}{d} \end{pmatrix}$$

- CCE has been derived for n-in-p sensors with the active thickness (75 and 150 μm) of our first thin sensor production.

75 μm thick diode



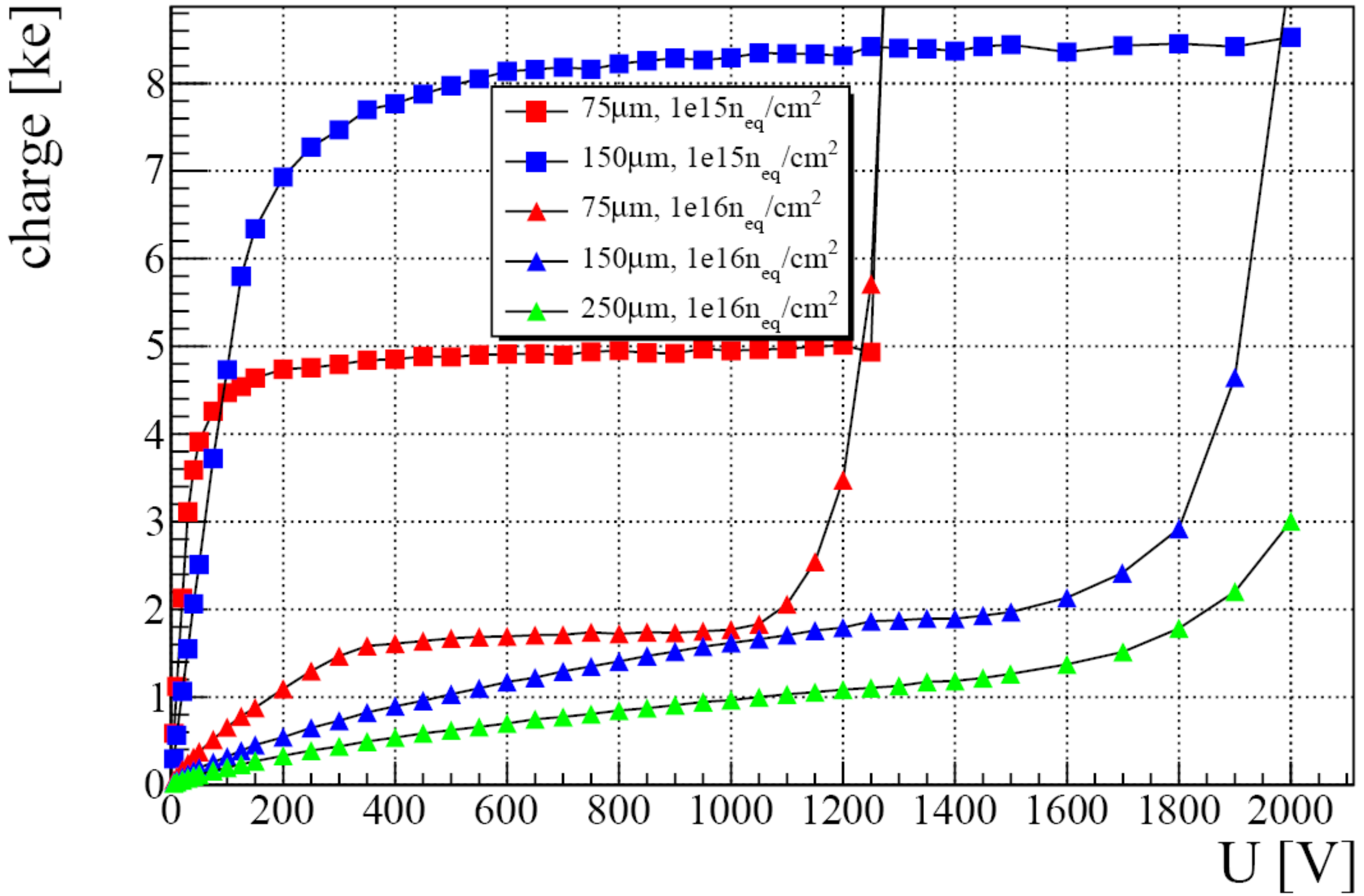
150 μm thick diode



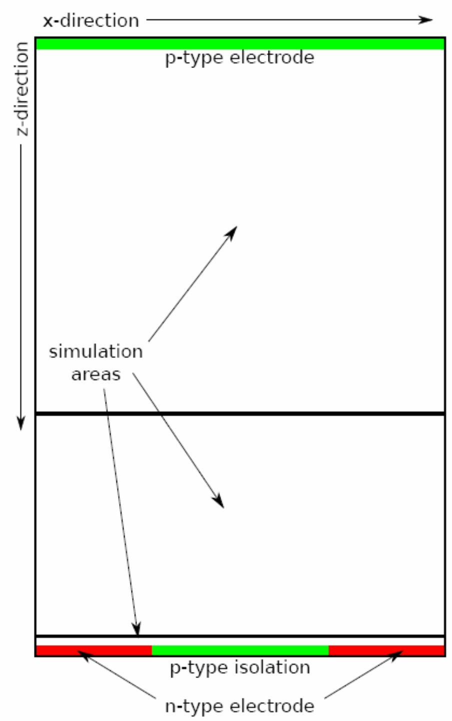
- CCE is normalized to 6Ke for the 75 μm thick detectors and to 12 Ke for the 150 μm thick detectors

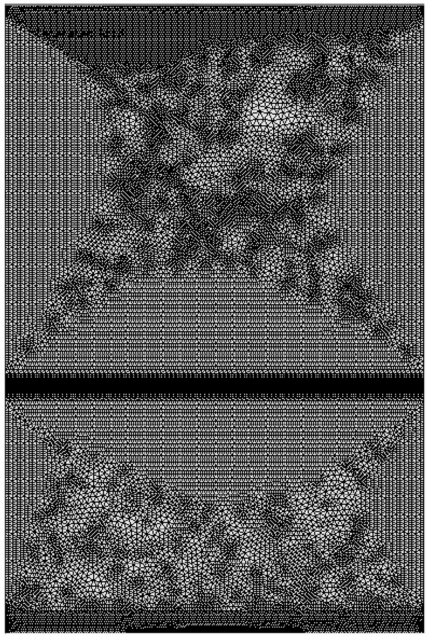
Results of the diode simulation

- The impact ionization produces in the case of the diode simulation a very steep rise of the CCE, at high bias voltages (not observed in data)

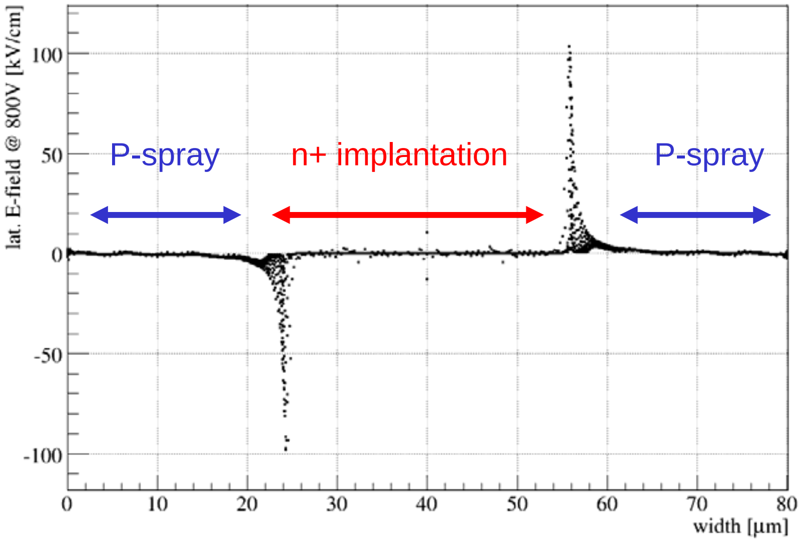


2-d electric field distribution for strip sensors





- ➢TeSCA takes as input the profile of the implant doping concentration calculated with DIOS, a commercial device simulation package.
- ➢ The parameters used are those of our first thin sensor production.
- ➢ TeSCA is used to simulate the electric field and potential distribution in the silicon sensor, producing a 2D finite element grid.



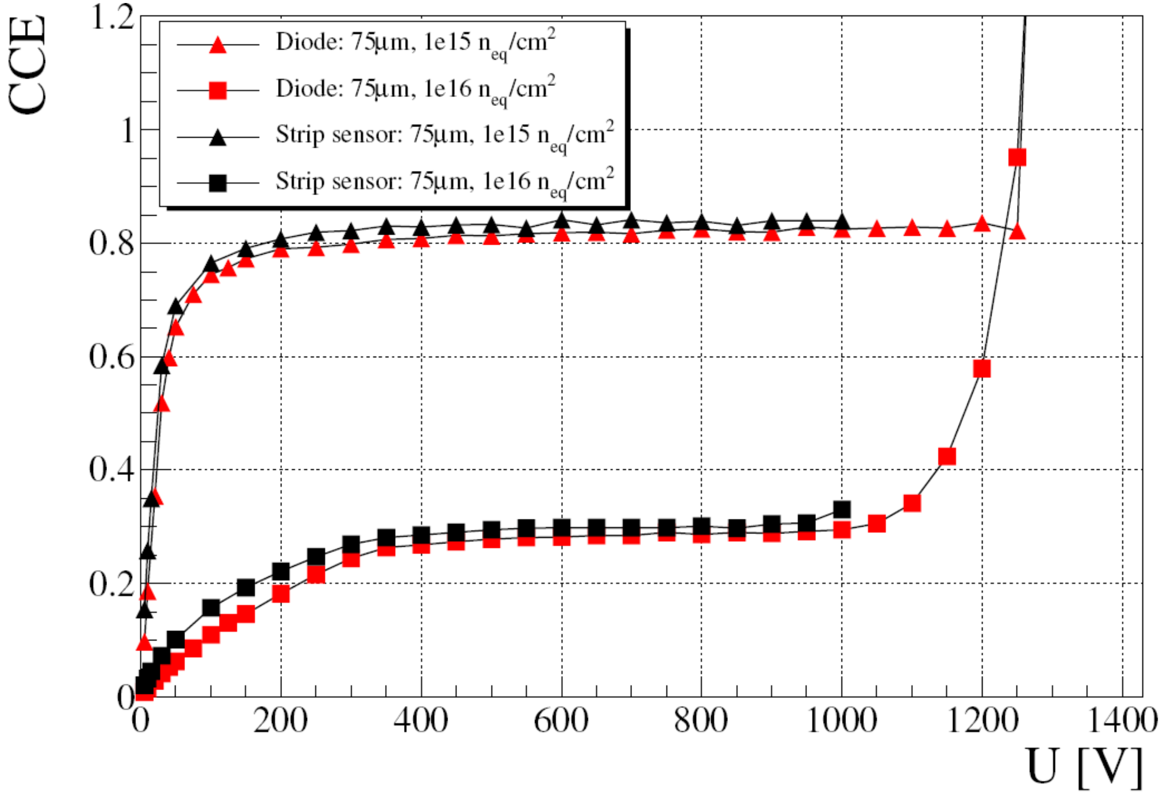
- ➢Example of the lateral component of the electric field distribution for the homogenous, p-spray option, for 0 μm<z<1μm, Φ=1x10^{16} n.eq., thickness=75 μm

- ➢Ramo field derived with the Silvaco TCAD simulation package (thanks to M. Benoit, LAL).

Simulation results for strip sensors

- Both for the strip and the diode the impinging particle has a trajectory perpendicular to the sensor surface, below the n+ implants.

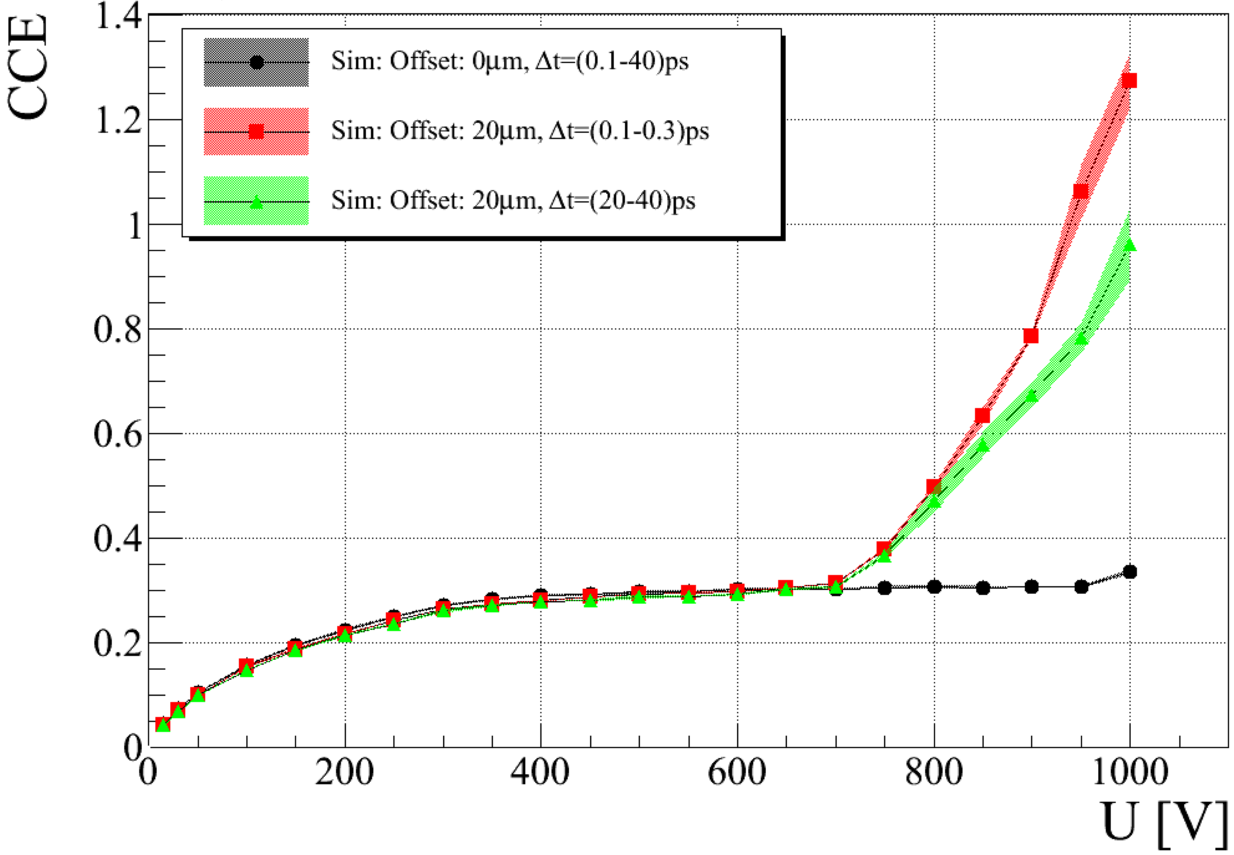
- In this configuration only a 5% difference is seen between the two geometries, even if a more complete 2d electric field description is used for the strips.



Dependence on the initial particle trajectory

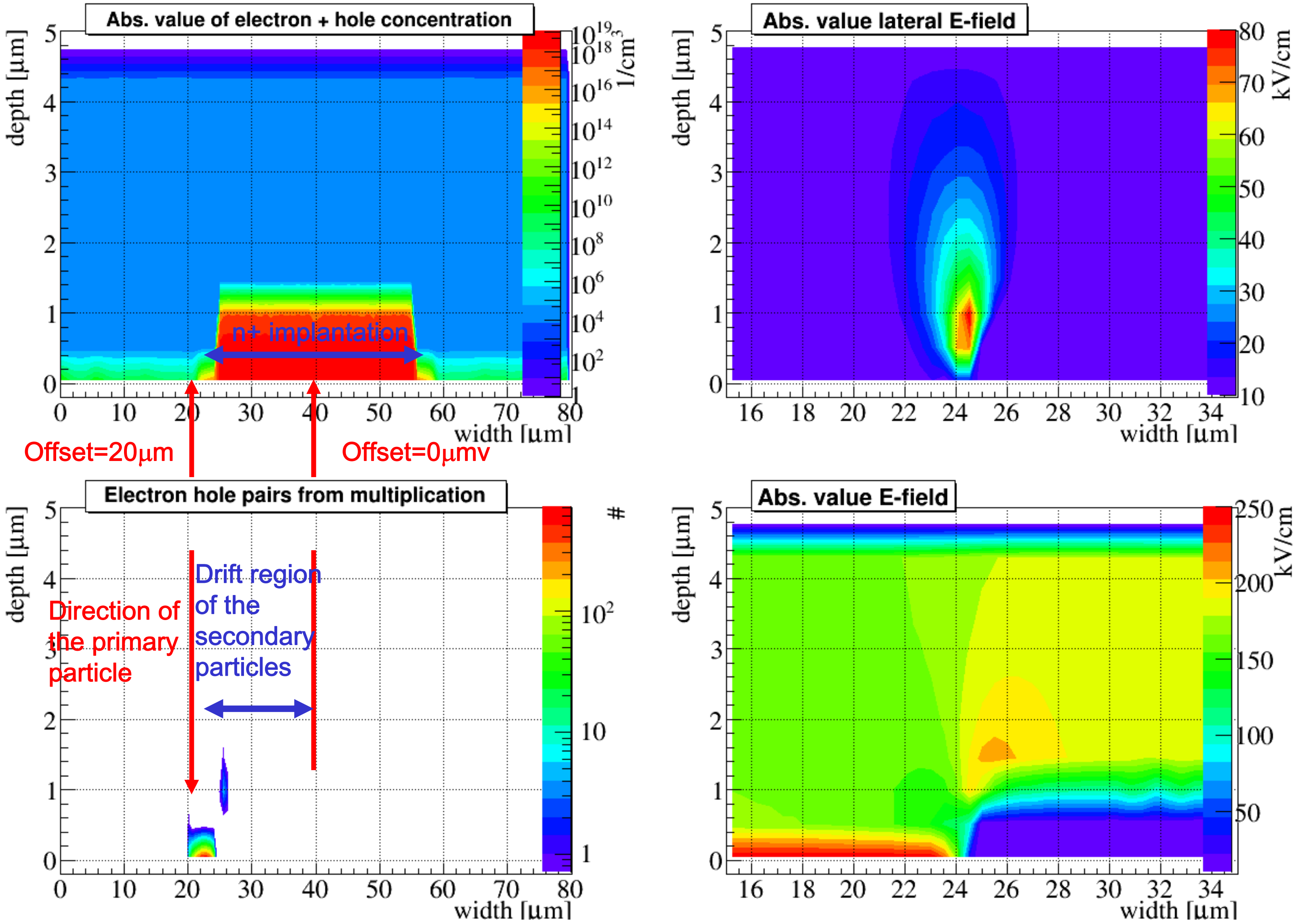
- Very strong dependence of the CCE observed as a function of the x-coordinate of the primary particle, still perpendicular to the sensor surface, but at different positions with respect to the n+ implantation.
- The CCE has been simulated for a primary particle impinging at the interface n+ implantation –p-spray, where a high value of the electric field is present.

75 μm thickness, $\Phi=1\text{x}10^{16}$ cm^{-2} n.eq.



Localized charge multiplication

- 75 μm thickness, V_{bias}=800 V, Φ=1x10^{16} cm^{-2} n.eq.



Offset=20μm

Offset=0μmv

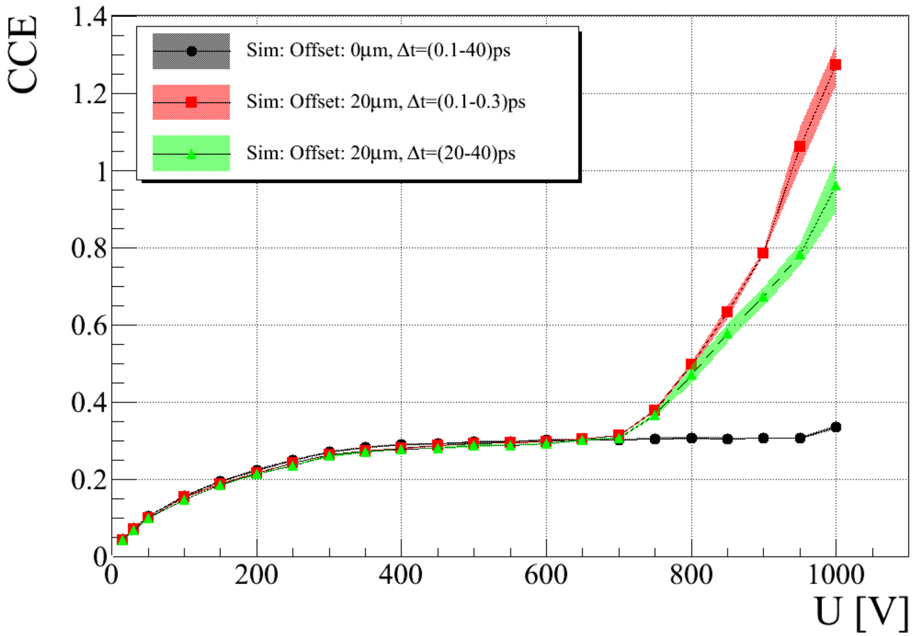
Direction of the primary particle

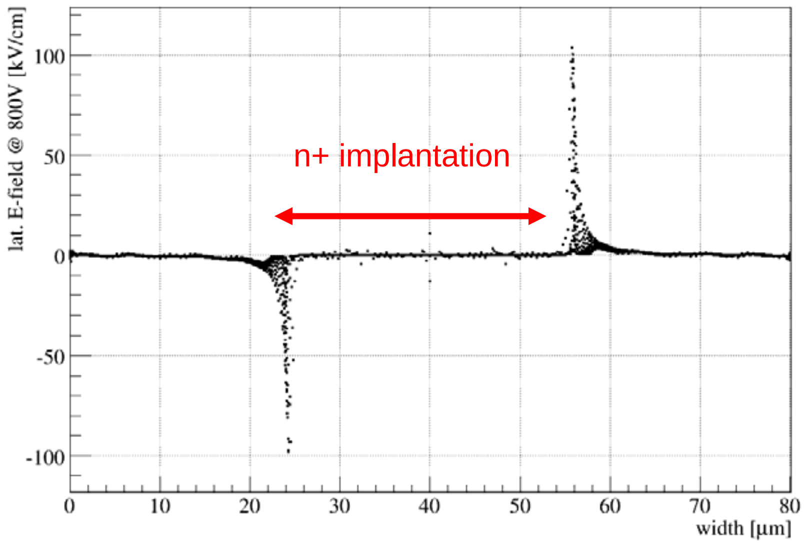
Drift region of the secondary particles

Dependence on the simulation time step

- Sharp peaks in the electric field: the lateral component at the interface between the n+ implantation and the p-spray region, the longitudinal component at z<1 μm.

- A possible interpretation of the CCE dependence on the time step can rely on the different probabilities of experiencing this very narrow and high electric field between two consecutive interactions with the electric field.





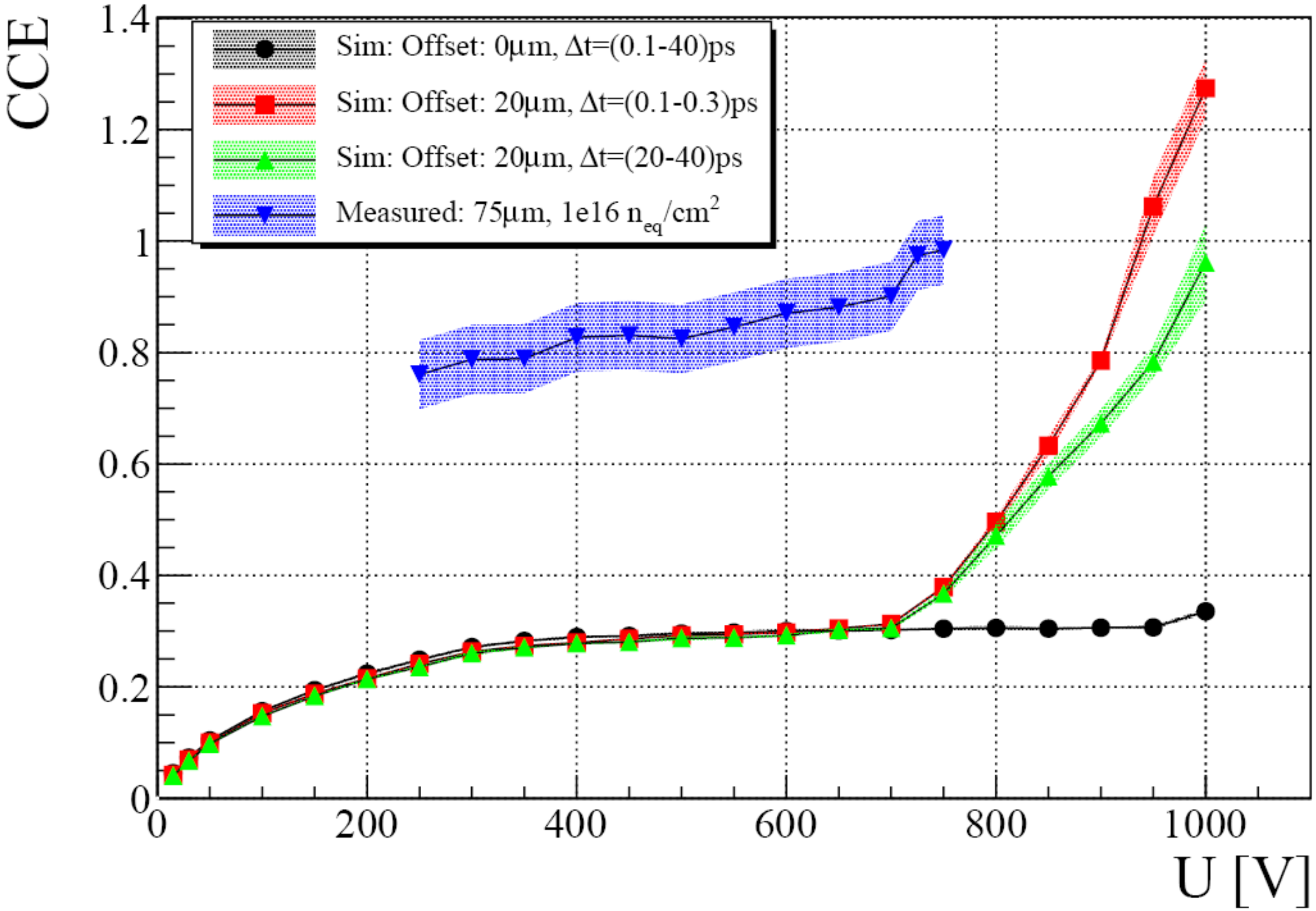
- For Δt = 1ps → Δx ~ 10^7 cm/s .1 ps = 0.1 μm, to be compared for example with the width at half maximum of the E_x peak ~ 0.2 μm

- Δt =20-40 ps (Δx=2-4 μm): only few of the electrons that move through the high electric field will interact in this sharply localized region and create new electron-holes pairs.

- In "real life" the electron mean free path in highly doped silicon is 0.03-0.05 μm, of the same order of the $|E_x|$ peak width.

Comparison with CCE measured in 75 μm thick sensors

- … or reality is always more complex than simulation. Some other effects contribute to obtain higher CCE than expected from this model for V<700V.
- For a description of the CCE measurements see talk by P. Weigell in this workshop.



Summary and Outlook

- A Monte Carlo algorithm has been developed for the simulation of the Charge Collection Efficiency in highly irradiated diodes and strip devices.

- A 2D electrical field configuration has been obtained with the Tesca simulation program for strip sensors, with the parameters relative to our first thin n-in-p sensor production, before and after irradiation.

- Assuming a particle traversing the sensor across the n+ strip implantation, with a trajectory perpendicular to the surface, the CCE predicted for the strip geometry is only 5% different than the one obtained for the diode, assuming a simple linear field configuration.

- A clear rise of the CCE is predicted for particles impinging at the n+ implantation-p-spray interface, where both the lateral and longitudinal components of the electric field have a high value.

- A simulation of the CCE behaviour for different x-values is foreseen to derive a more general picture of the CCE for strip sensors.