Determination of the electric field in highly-irradiated silicon sensors using edge-TCT measurements

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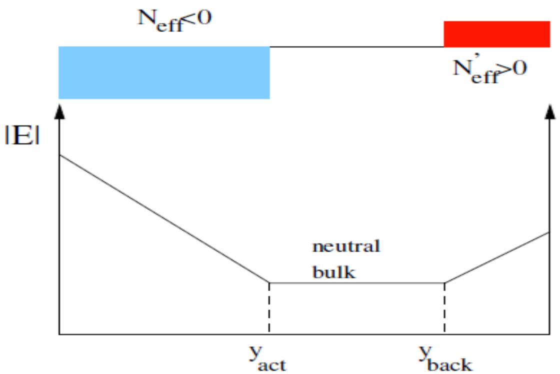
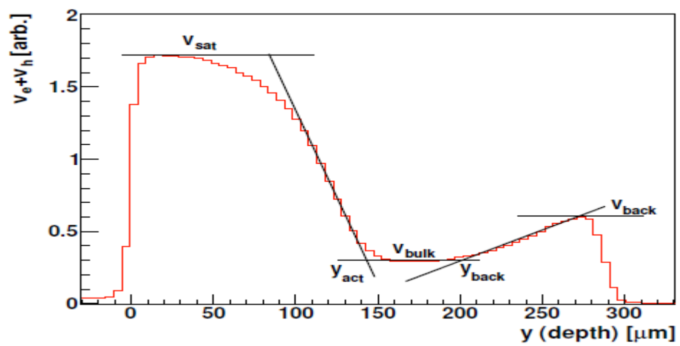
Motivation

- Modelling the electric field for heavily irradiated n^+-p sensors based on Edge-TCT measurements (the advantages will be explained)
  - measurements presented before in JINST 9 (2014) P10016, where a simple "abrupt double junction" with constant N_{eff} was tested on the measurement as several "anchor points" of the model were extracted





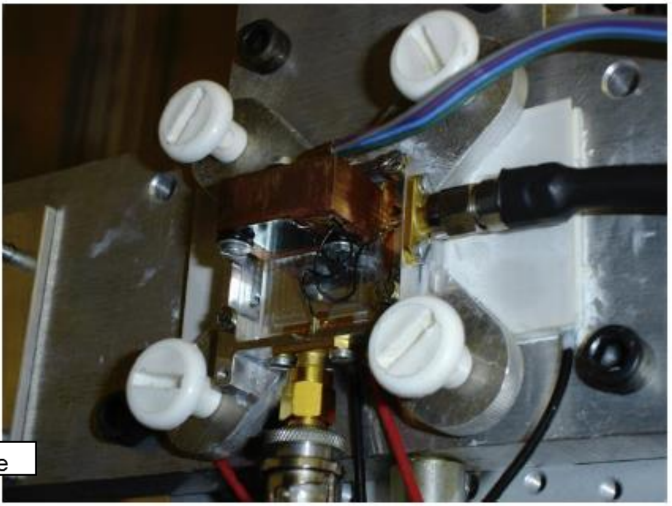
  - the method (NIMA 951 (2020) 162987) and the presentation builds on those measurements and introduces the analysis also for forward bias detectors
- It aims to develop a method allowing accurate extraction of electric field and N_{eff} from the measurements.
- It should be easily fed to the simulators (charge transport and TCAD) and should serve to understand also the fundamental reasons for the change of detector properties, where the TCAD often failed (not accurately know properties of defects, poor modelling of cluster damage, not clearly understood influence of high electric field on defect properties)

Samples and measurement technique

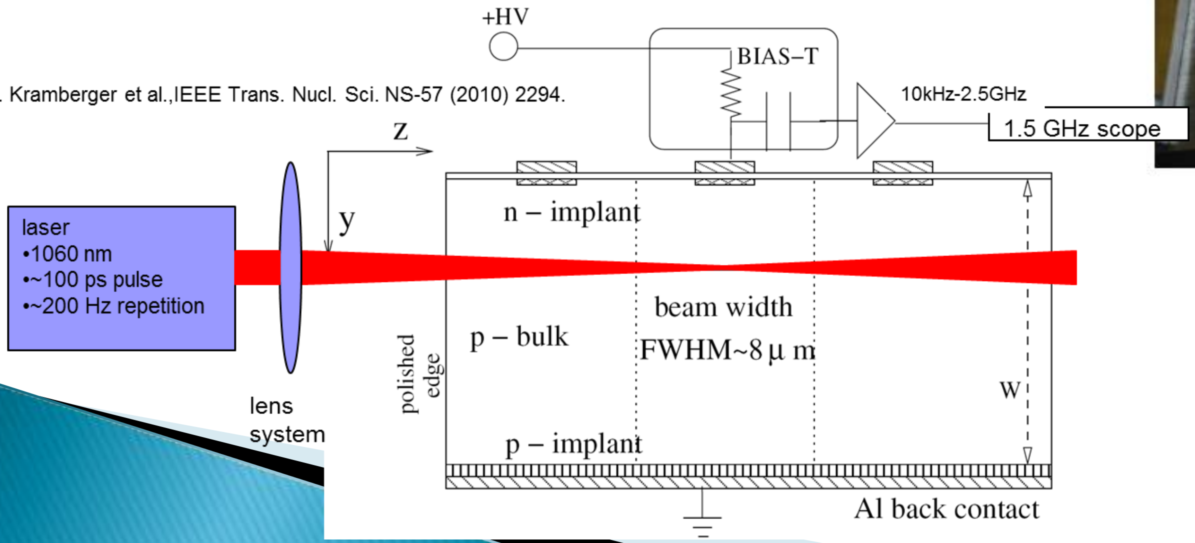
ATLAS 07 mini-strip sensors (single p-stop+p-spray isolation)

Thickness μm	Crystal orientation	pitch μm	n^+ width μm	Strip length cm	Area cm^2	B-doping cm^{-3}	U_{fd} V
300	⟨100⟩	100	20	0.8	0.62	2.8×10^{12}	180

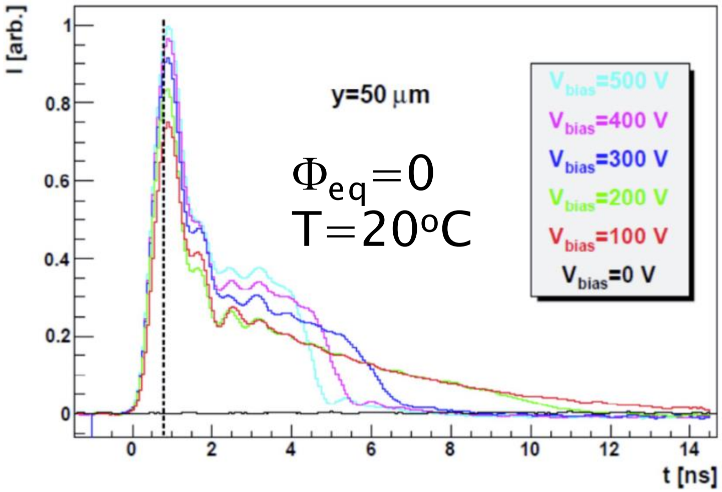
- Samples irradiated with reactor neutrons to Φ_{eq}=1,2,5,10e15 cm^{-2} and 200 MeV pions to 1.6e15 cm^{-2}
- Samples were annealed for 80 min@60ºC
- Samples were measured at -20ºC and measured in **forward** and **reverse** direction with Edge-TCT (neighbors at the same potential as the strips)



G. Kramberger et al.,IEEE Trans. Nucl. Sci. NS-57 (2010) 2294.



Velocity profiles and their limitations



Measurement of velocity profile:

$$I(\vec{r},0) = AN_{e-h}e_0(\vec{v_e}(\vec{r}) + \vec{v_h}(\vec{r})) \cdot \vec{E}_w(\vec{r})$$

$$I(y,t\sim 0) \approx \frac{Ae_0 N_{e,h}}{W}\left[\bar{v}_e(y)+\bar{v}_h(y)\right] \quad , \quad t << \tau_{eff,e,h}$$

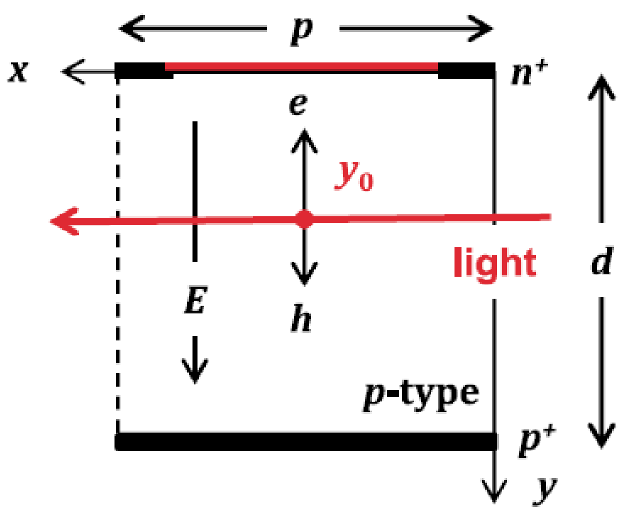
The trapping can be completely taken out of the equation!

(The major obstacle of extraction of physics parameters from time evolution in conventional/Top-TCT is severe trapping)

Different methods were tried in [0,t_{int}]

- integral
- value at different times after the injection
- slope of the current pulse rise

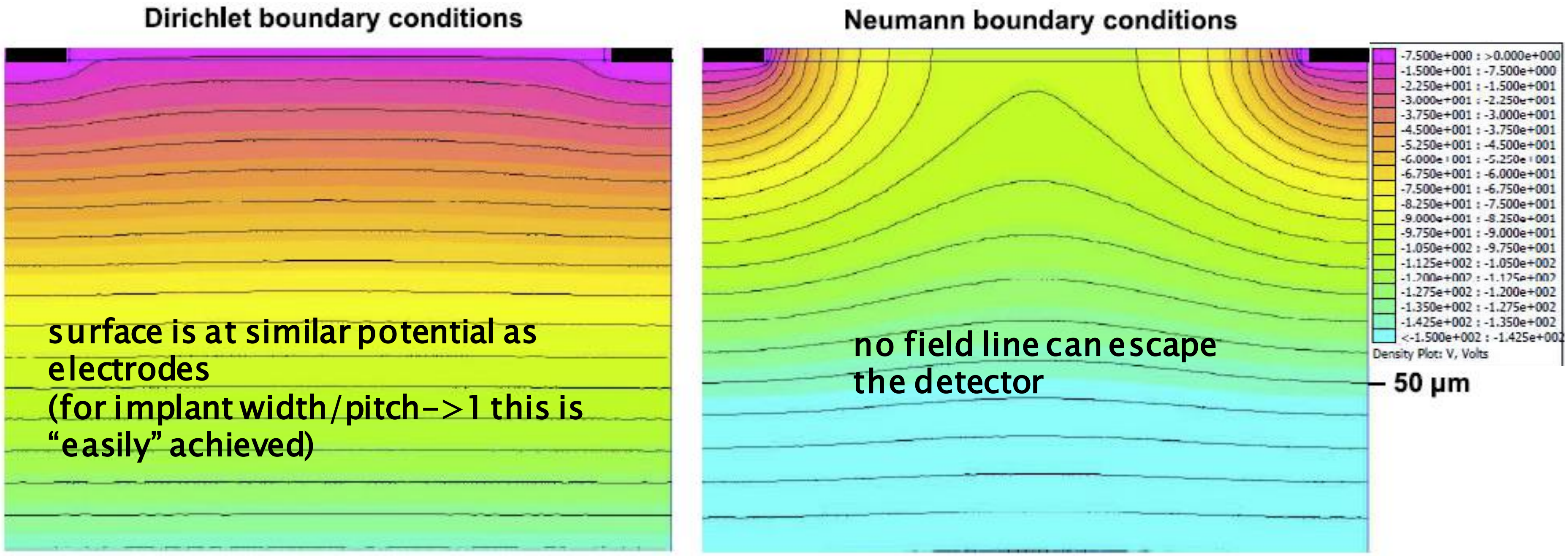
Comparable results for all – no big difference between them (comprehensive analysis in the paper)



Correctness of the above equation depends on several assumptions:

- implant width/strip pitch should be as close to 1 as possible – reducing the effect of the drift paths and effective weighting field close to the electrode plane)
- attenuation of the laser should be small over the distance of several strips – effective weighting field
- many neighbors should be bonded
- trapping is much longer than the t_{int}

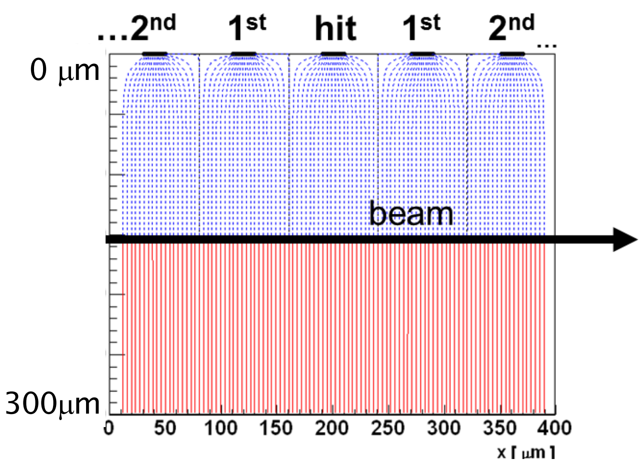
Effect of strip proximity/surface



- the surface condition (humidity/temperature, salts, impurities on the surface influence the electric field) – studied extensively in HH group (NIMA 700 (2013) 22-93, NIMA 845 (2017) 159-163,)
- as this conditions can change with time/temperature/humidity it is difficult to know them
- assumption of electric field with only E_y component close to the strips can be too simplistic – method for extraction of velocity is less precise close to the strips
- in the analysis of the data this effects can be probed/evaluated by changing the start of first (modeling) point

Effect of finite attenuation length

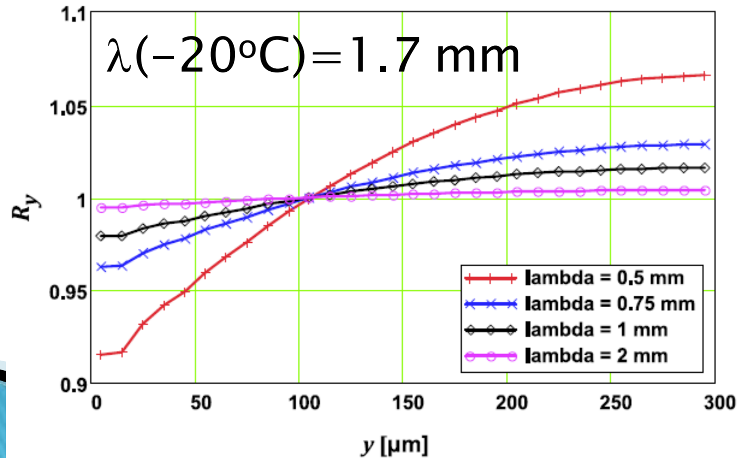
- Induction from the neighbors is affected by the attenuation. It follows from symmetry – only for infinitely large detector in x and z : $\overline{\varepsilon_w}=(0,\frac{1}{W},0)$
- Simulation of 6 neighbors was used to check the influence on effective weighting field

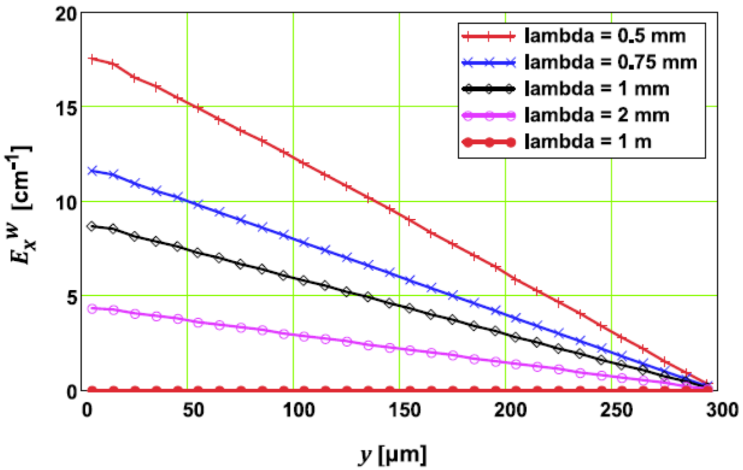


$$\overrightarrow{\varepsilon_w} = \frac{1}{p}\int \overrightarrow{E_w}(\vec{r})\exp(-\lambda_{abs}\cdot x)\,dx$$

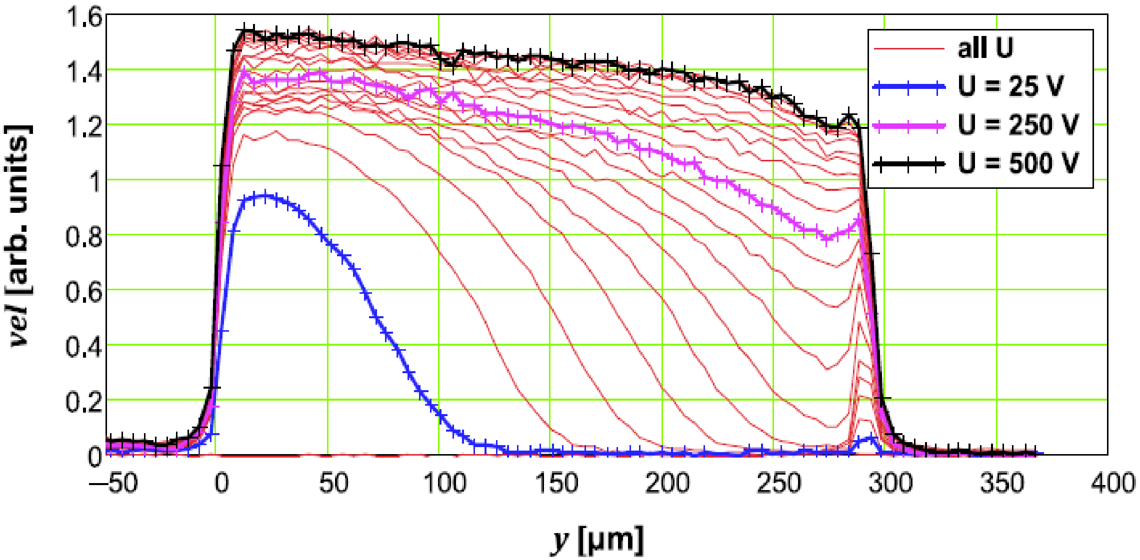
$$R_y = \frac{\varepsilon_w(\lambda_{abs})}{\varepsilon_w(\lambda_{abs}\to\infty)}$$

- For 6 strips the difference in ε_w<10% (the more strips are bonded the better) – von Neumann boundary condition – worst case
- Only for $\lambda_{abs} \to \infty$ the ε_w=(0,1/W,0)





Modeling-extraction of the Efield



- Step in y direction for the scan was 5 μm defining maximum number of point N_E points in which field E_k is calculated (free parameters of the fit) – usually 20 μm used
- the start of the field modeling was varied between 11.5-51 ~ and 273.5-283.5 μm to avoid uncertainties close to the surfaces

$$\chi^2 = \frac{1}{\sigma_{vel}^2}\sum_{k=1}^{n_k}\left(1-\frac{vel_k}{vscale \cdot u_k}\right)^2 + w_{pen}\sum_{i=2}^{n_E-1}\left(\frac{0.5\cdot(E_{i-1}+E_{i+1})-E_i}{E_i}\right)^2$$

$$u_k = \left(\mu_h(E_k)+\mu_e(E_k)\right)\cdot E_k$$

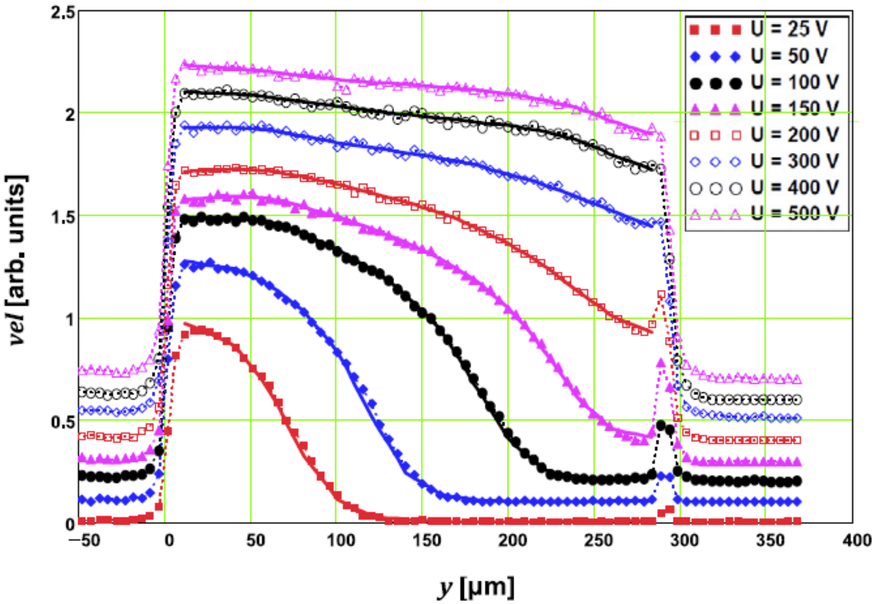
σ_{vel} – *relative uncertainty of velocities ~ 2%*
vel_k –measured velocity profiles
v_{scale} – measured scale is relative
w_{pen} – dumps large fluctuations of the field – not very important in the model, set to increase χ^2 by 50%

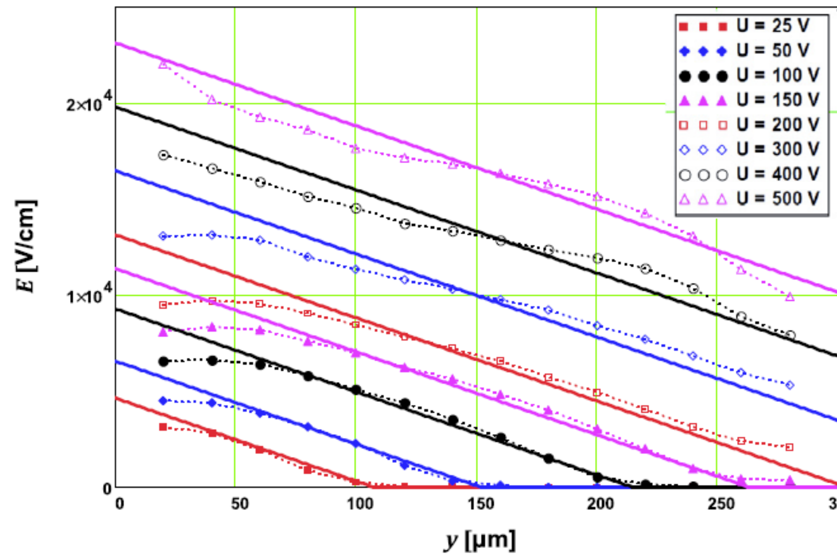
<u>Constrain:</u>

$$\int_0^d E(y)\,\mathrm{d}y = U$$

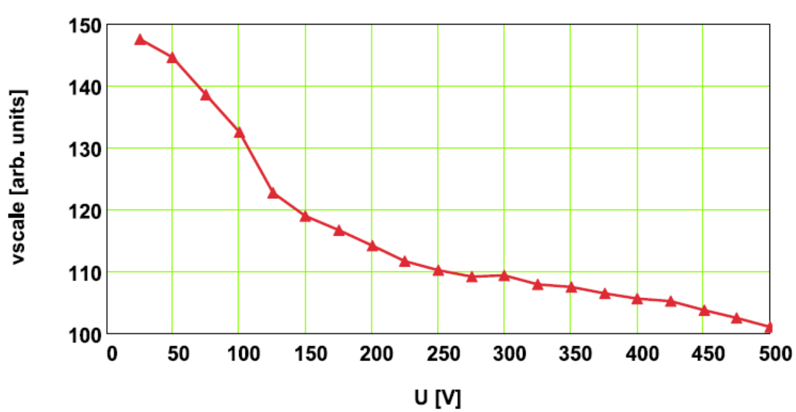
The constrain effectively also solves the cases where trapping is not negligible in comparison to t_{int} and $\tau_{eff} \neq \tau_{eff}(y)$

Electric field in non-irradiated detector

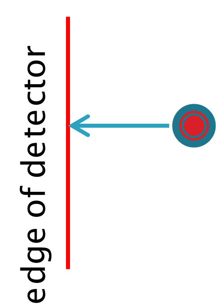




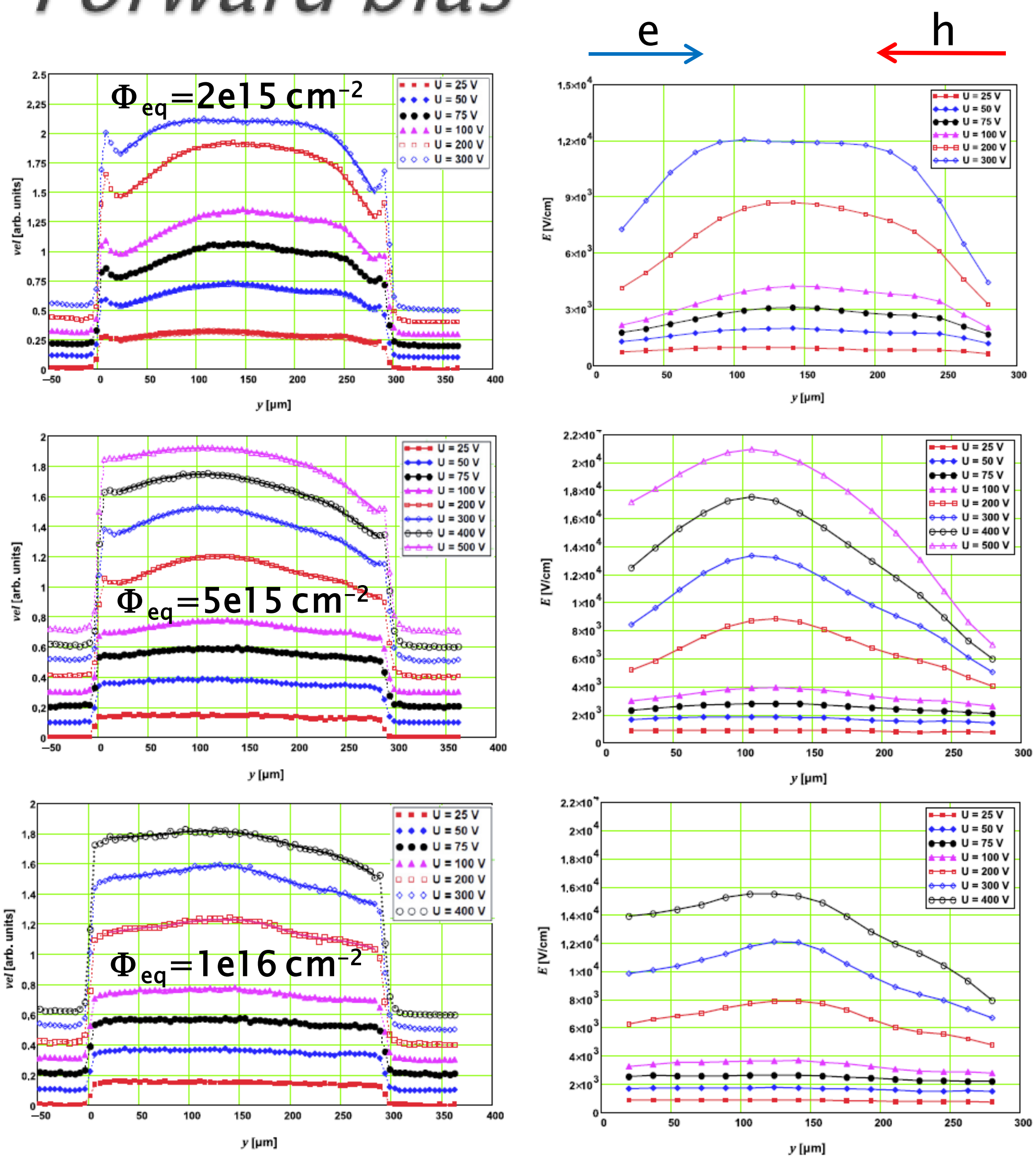
- very good agreement of the model (solid lines) with data points (shifted by 0.1 for clearer view)
- extracted electric field is in reasonable agreement with the electric field in pad detector with uniform doping and the same full depletion voltage – the agreement is worse closer to the electrode plains



v_{scale} parameter is a function of voltage, due to finite rise time of the current (a detailed analysis in the paper)



Forward bias



- At low voltages electric field is constant given by $E=U/W$. It agrees well (<20%) with "resistor" assumption

$$E=\frac{j}{e_0(\mu_e n_e+\mu_h n_h)}$$

$$n_e=\sqrt{\frac{\mu_h}{\mu_e}}\,n_i,\quad n_h=\sqrt{\frac{\mu_e}{\mu_h}}\,n_i$$

n_i=1.2e−8 cm^{-3}

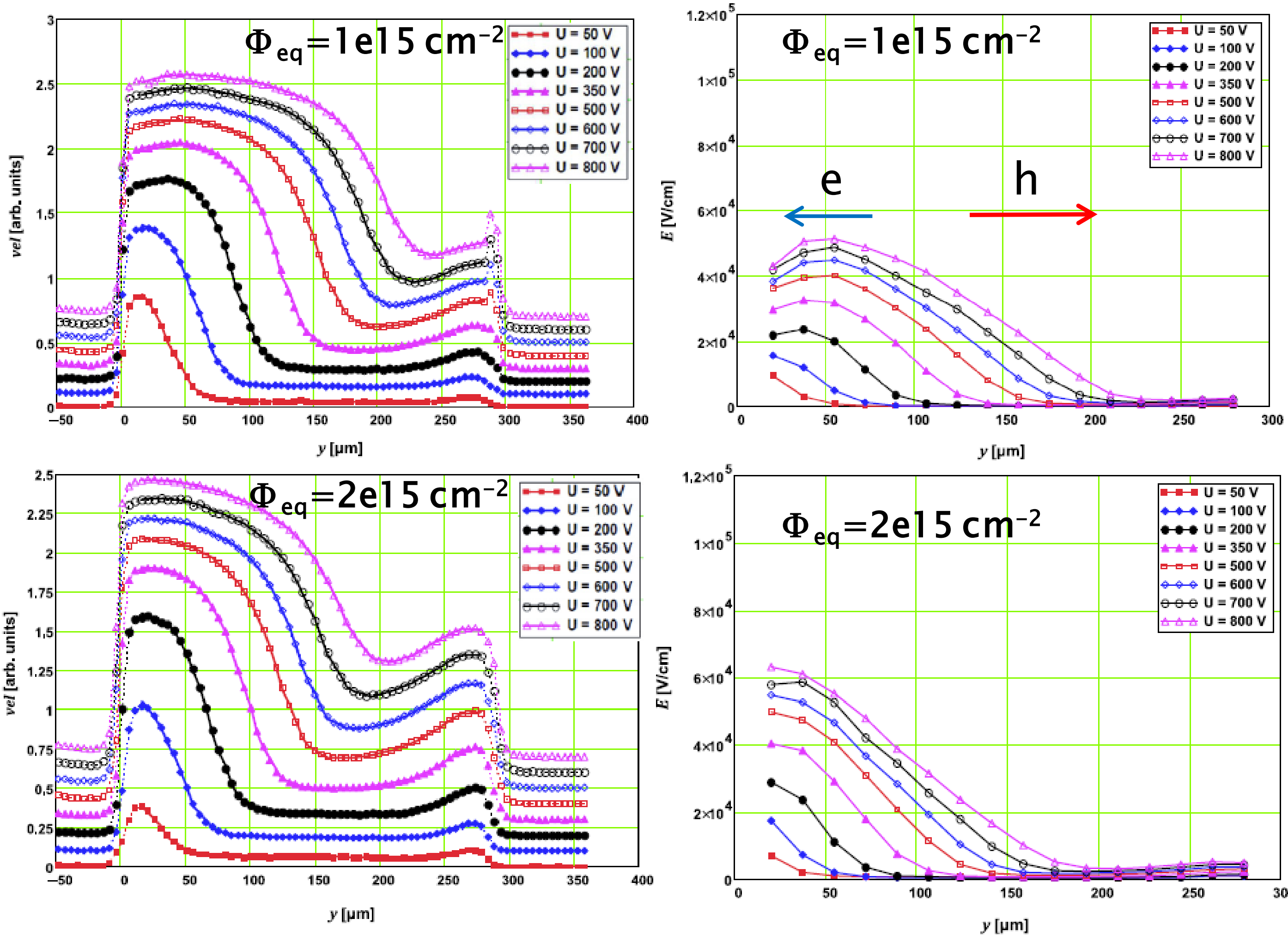
- At low/high y $n_e>>n_i$ / $n_h>>n_i$ decrease of the field to keep j=const.

The E field at both injection contacts is smaller due to enhanced concentration of injected free carriers before the recombination prevails.

- Electric field is high over all bulk, which explains improved CCE wrt to reverse bias operation.
- The dE/dy -> gives "space charge"

Reverse bias (low fluence)

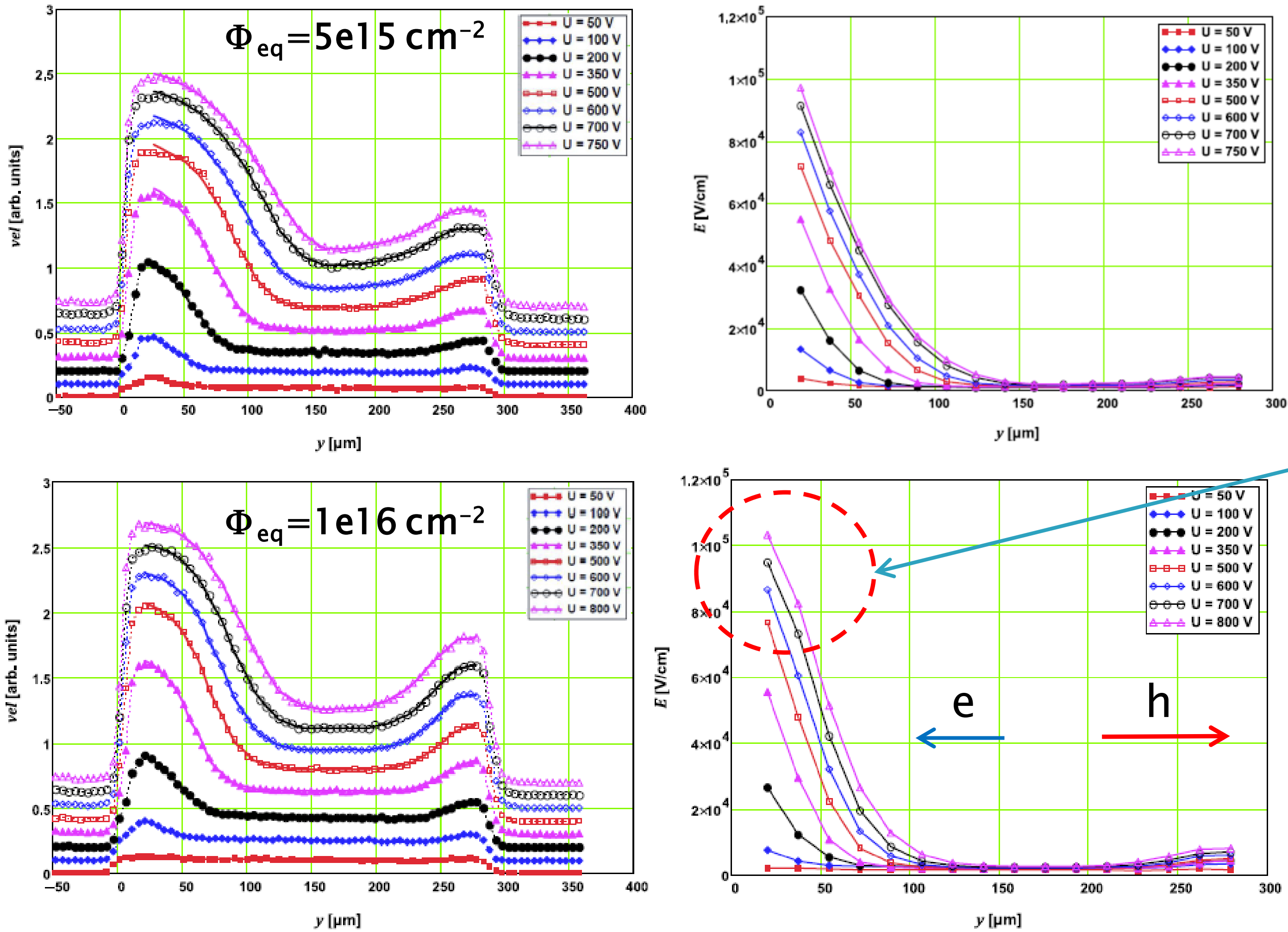
generation current instead of injection



- Inaccurate electric field determination close to the electrode
- Appearance of double junction, but the second junction is around 10x smaller
- Electric field in the ENB is sizeable and compatible with the one required for transporting the generation current from the high field region through it
- (same conditions as for forward bias in the bulk)

Electric field reaches values of ~7 V/μm at the highest fluence .

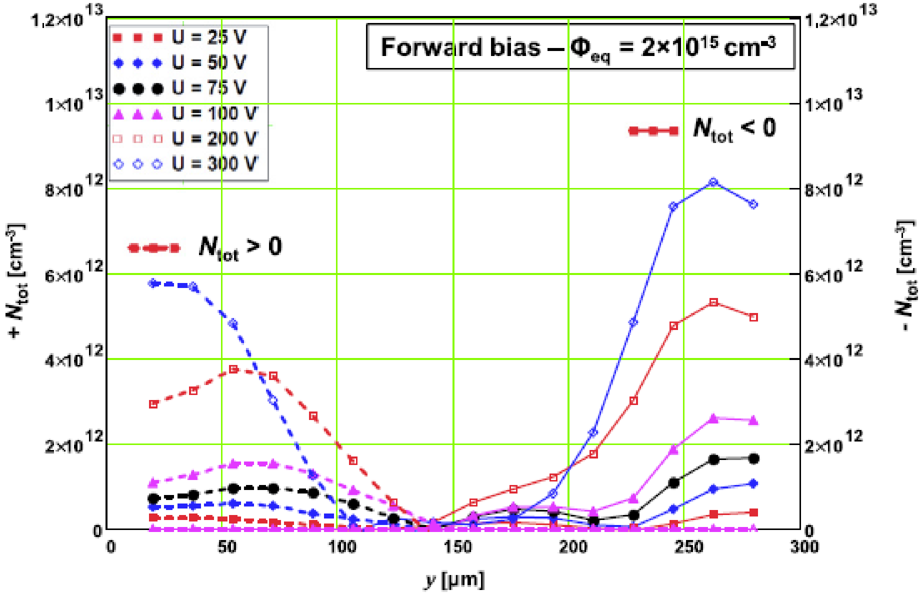
Reverse bias (high fluence)

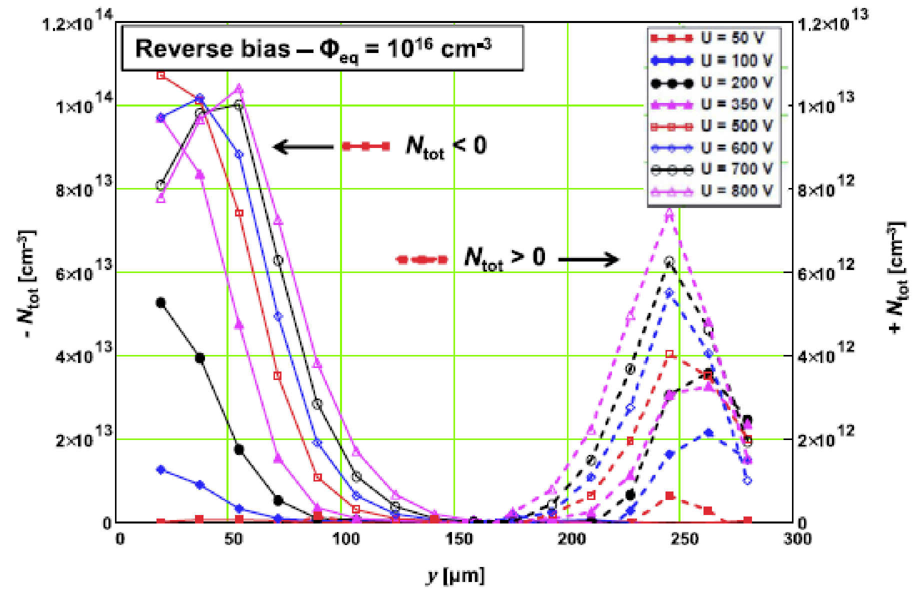


modeling influenced by gain – increase of carrier number rather than “electric field”

- ENB getting larger with fluence
- High field region decreases in size with fluence
- Electric field reaches values where multiplication starts

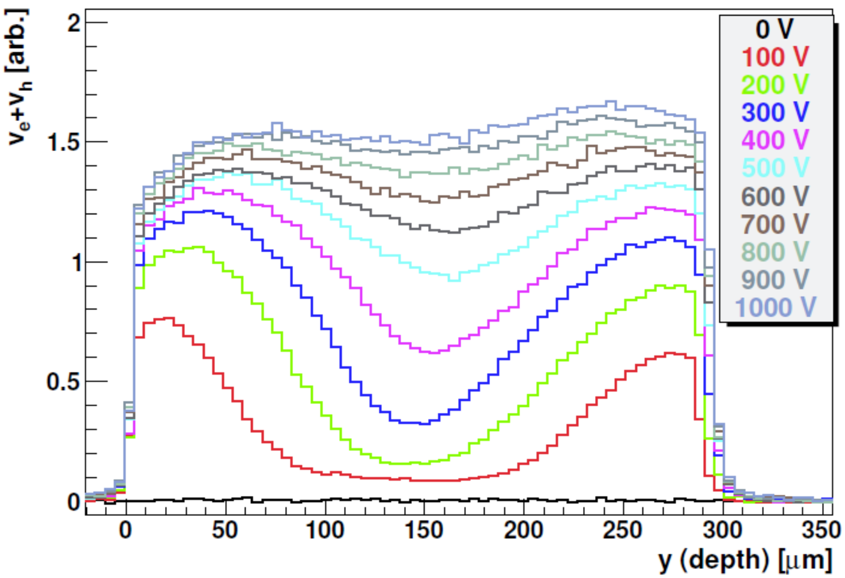
Effective doping concentration

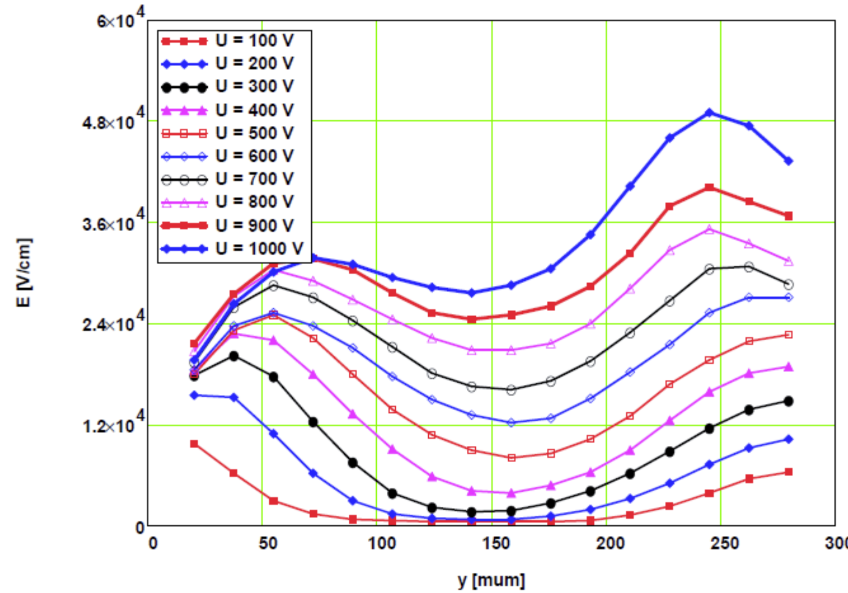




- derivative of the electric field -> N_{eff}
- Assuming the same concentration of defects in the bulk the occupation probability changes with free carrier concentration – only a fraction of defects is occupied (g~1 cm^{-1})

Pion irradiated samples





- As the defects created by different irradiation particles can be different so can be also the occupation probabilities and the electric field
- This can be clearly observed for pion irradiated samples 1.6e15 cm^{-2} (symmetrical velocity profile)
- Electric field is present at relatively low fluence in the entire bulk – no real high field and low field region
- Similar profiles were observed also for ATLAS12 sensors irradiated with 24 GeV p

Conclusions & future plans

- A method was introduced that allows extraction of electric field from Edge-TCT measurements:
  - Careful analysis of the assumptions made in velocity profiles determination was performed
  - Method was tested with non-irradiated detectors and a good agreement was observed.
- Forward bias
  - At lower bias voltages the detector bulk acts like a resistor
  - At higher injection the enhance free carrier concentration reduces the field at both contacts
- Reverse bias
  - Active layer shrinks with fluence
  - ENB conducts generation current – hence field is sizeable
  - “Double junction” is seen, but is not very large
  - At larger fluences electric field is high enough for multiplication
- Pion irradiate samples show very different behavior with almost uniform field.