Investigation of electric field and evidence of charge multiplication by Edge-TCT

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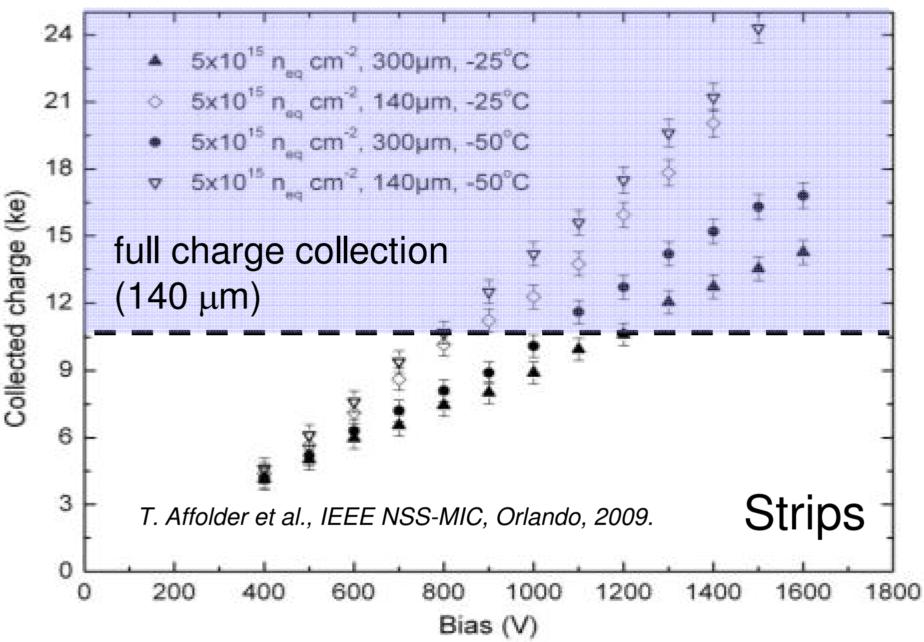
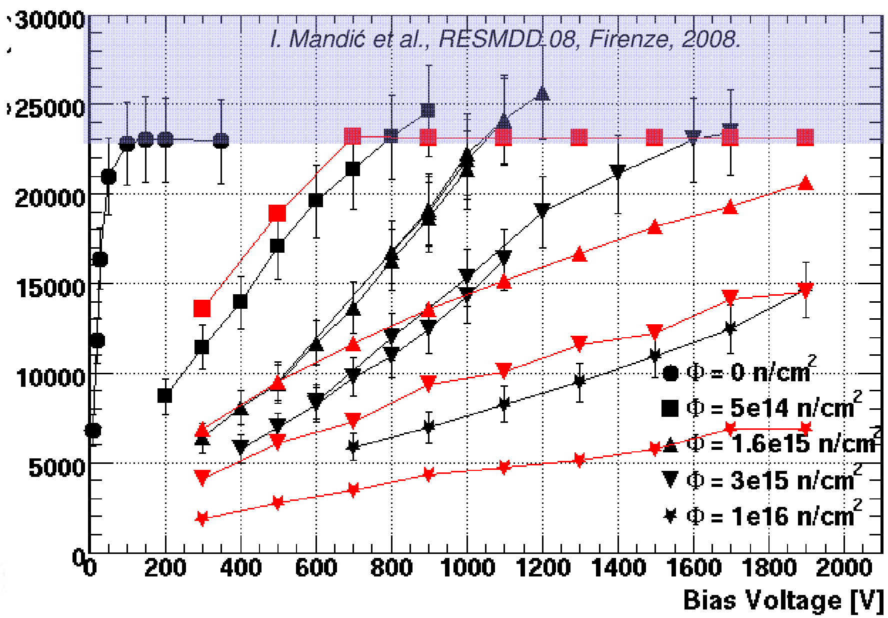
Motivation

- High CCE measured from different groups with silicon strip detectors at high fluences and high bias voltages (L'pool, Ljubljana). **Device modeling using extrapolated parameters from low fluence region fails completely!**

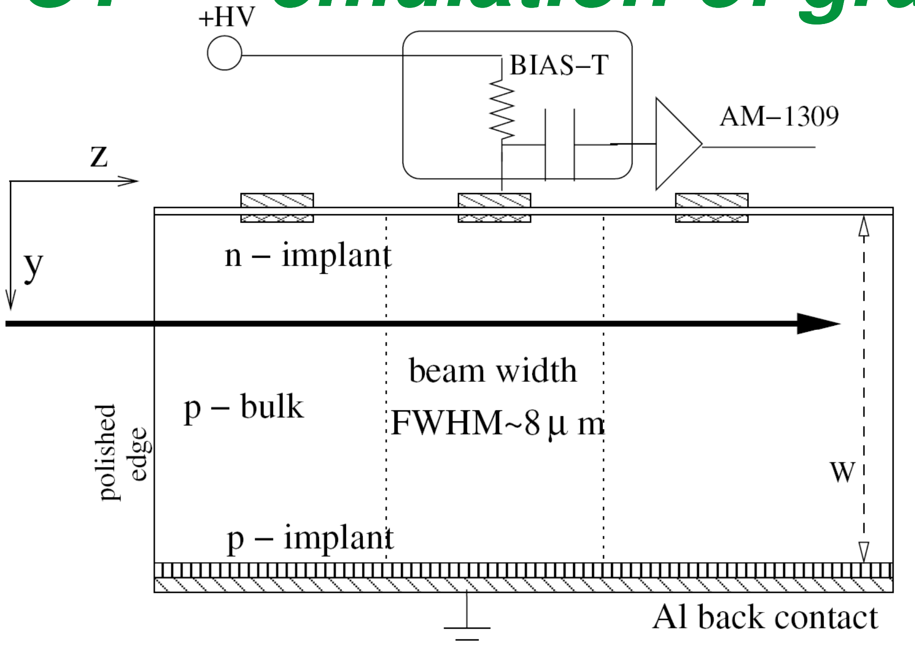




- **We need a new tool to identify electric field and multiplication effects!** Ideal tool for investigation of electric field and charge multiplication in silicon detectors (paticularly heavily irradiated) is Edge-TCT!

The work presented in this work is submitted to IEEE-TNS.

"Edge-TCT" – emulation of grazing technique



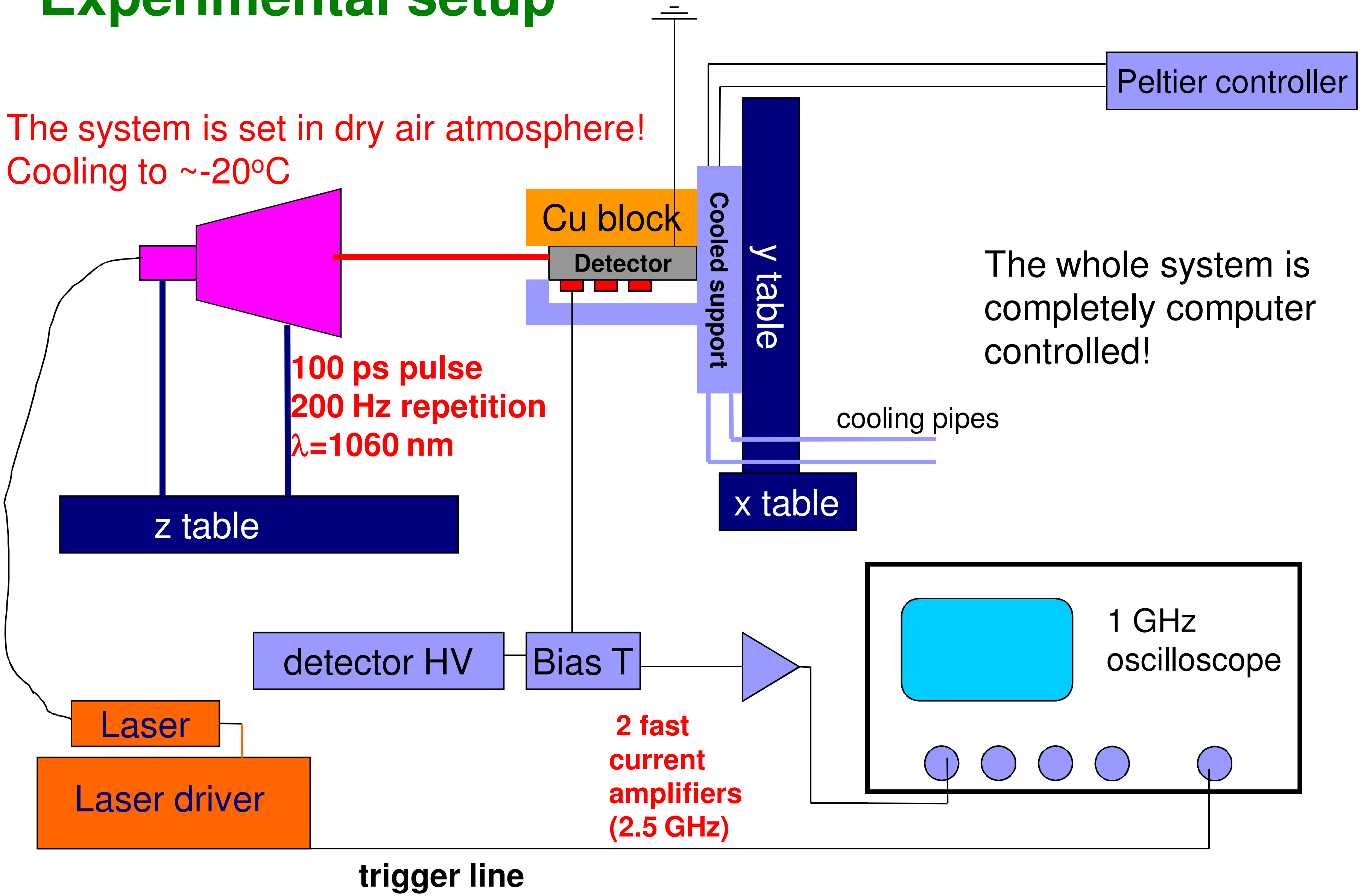
Advantages:

- Position of e-h generation can be controlled by moving tables
- the amount of injected e-h pairs can be controlled by tuning the laser power
- easier mounting and handling
- not only charge but also induced current is measured – a lot more information is obtained

Drawbacks:

- Applicable only for strip/pixel detectors if 1060 nm laser is used (light must penetrate guard ring region)
- Only the position perpendicular to strips can be used due to widening of the beam! Beam is "tuned" for a particular strip
- Light injection side has to be polished to have a good focus – depth resolution
- It is not possible to study charge sharing due to illumination of all strips

Experimental setup



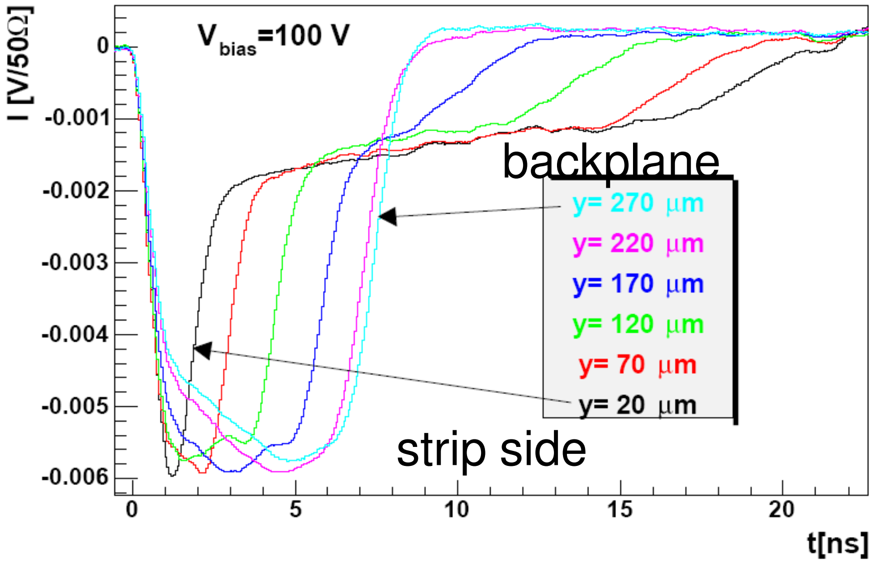
Samples

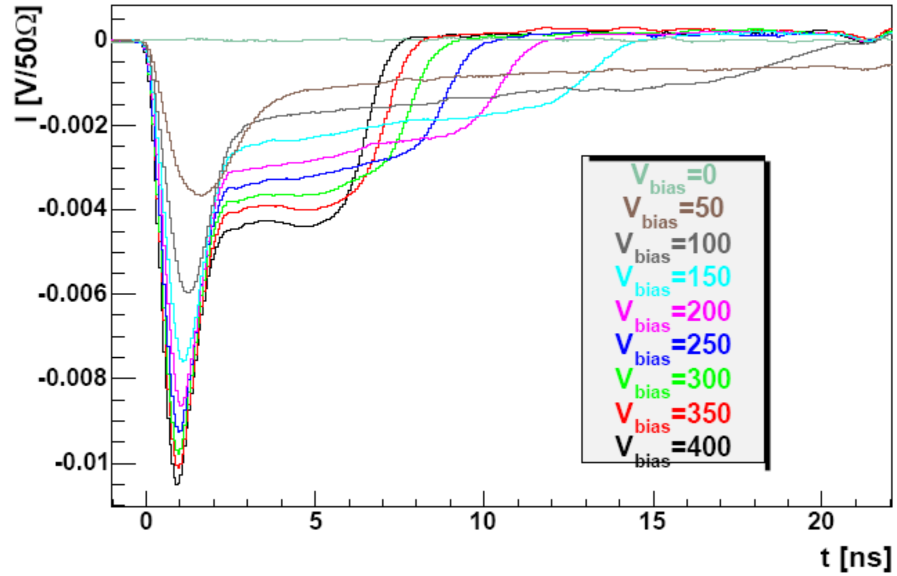
- n^+-p Micron SSD detector (1x1 cm^2) ATLAS geometry (RD50 Micron run)
  - 300 μm thick
  - 80 μm pitch
- Initial full depletion voltage – $V_{fd} \sim 16$ V
- 3 polished samples were available:
  - non-irradiated
  - $\Phi_{eq}=5\cdot10^{14}$ cm^{-2} (reactor neutrons), measured at -5^{o}C
  - $\Phi_{eq}=5\cdot10^{15}$ cm^{-2} (reactor neutrons), measured at -20^{o}C *(IBL target fluence)*

Samples were annealed for 80 min at 60^{o}C before the measurements!

For behavior during annealing see next talk (M. Milovanović)!

Current pulses – non-irradiated!





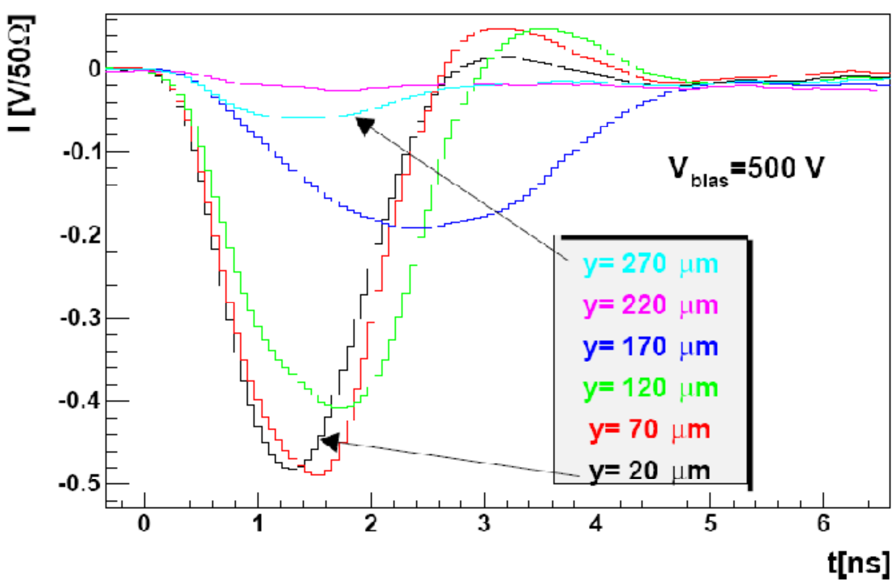
<u>Position scan at 100 V:</u>

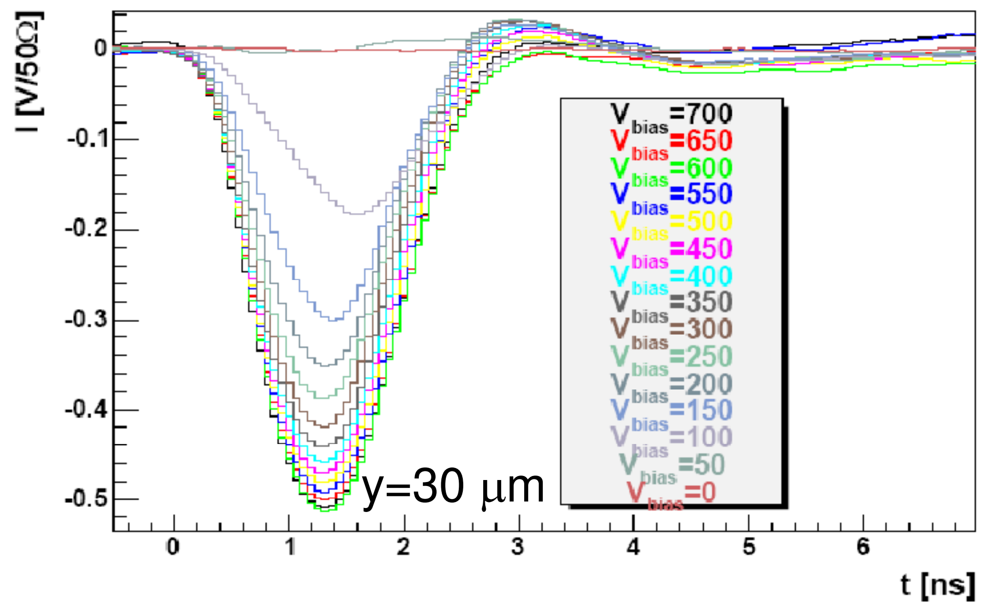
- Long tail from drift of holes
- Current due to electron drift is superimposed!
- Shortest signal at y=220 μm (equal drift length of electrons and holes)

<u>Bias scan at y=20 μm:</u>

- Hole tail is getting shorter with bias
- Electron peak is getting higher with bias (the peak time is getting shorter)

Current pulses – $\Phi_{eq}=5\cdot10^{14}\ cm^{-2}$





Expected V_{fd} from a diode measurements ~ 800 V!

Position scan at 500 V:

- Depth of *E* field region can be seen (y~200 μm)
- "Double peak" can be observed – larger signal at the back than in the center
- Signals are short – larger bias + trapping

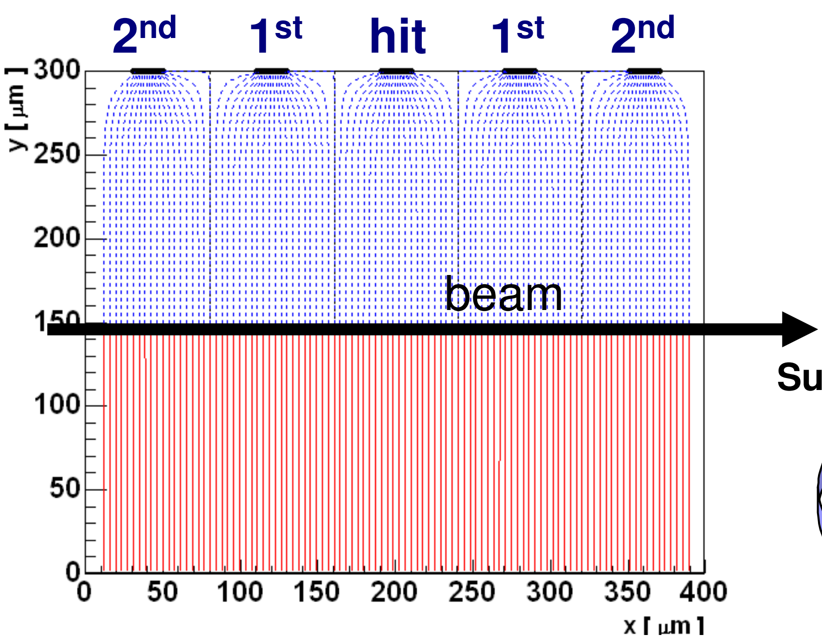
Bias scan at y=30 μm:

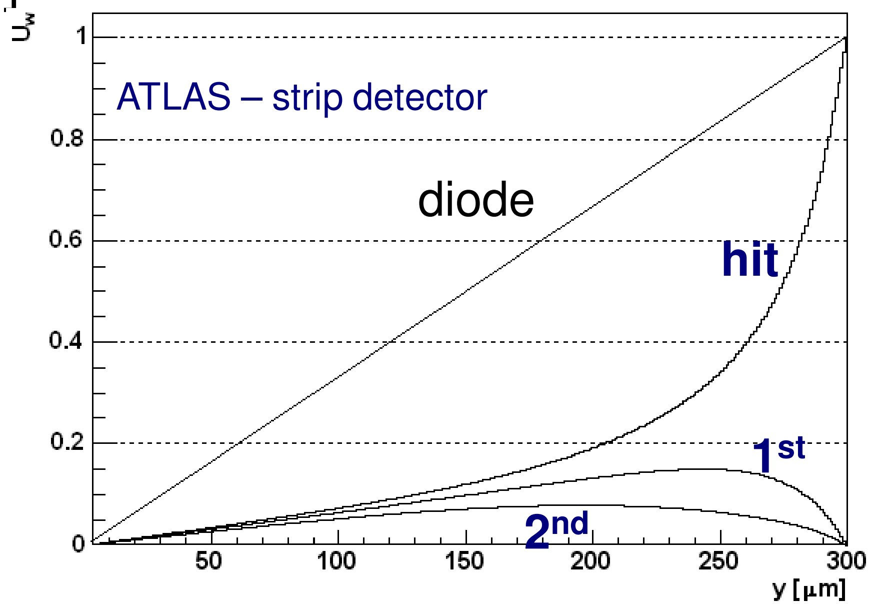
- Width and height increase with bias (larger depleted region)
- Strong trapping of holes!
- Peaking time is reduced with higher bias

Analysis of the pulses!

$$I_{e,h}(t) = A\, e_0\, N_{e,h} \exp(-\frac{t}{\tau_{eff,e,h}}) \left[\vec{v}_{e,h}(t) \cdot \vec{E}_w(t)\right]$$

A-amplification of the amplifier
e_0-elemetary charge
$N_{e,h}$-number of electron hole pairs created by laser
$\tau_{eff,e,h}$ – trapping times
$v_{e,h}$ – drift velocity
E_w – weighting field





Neighboring strips induce opposite polarity currents close to strips and the same close to the back!

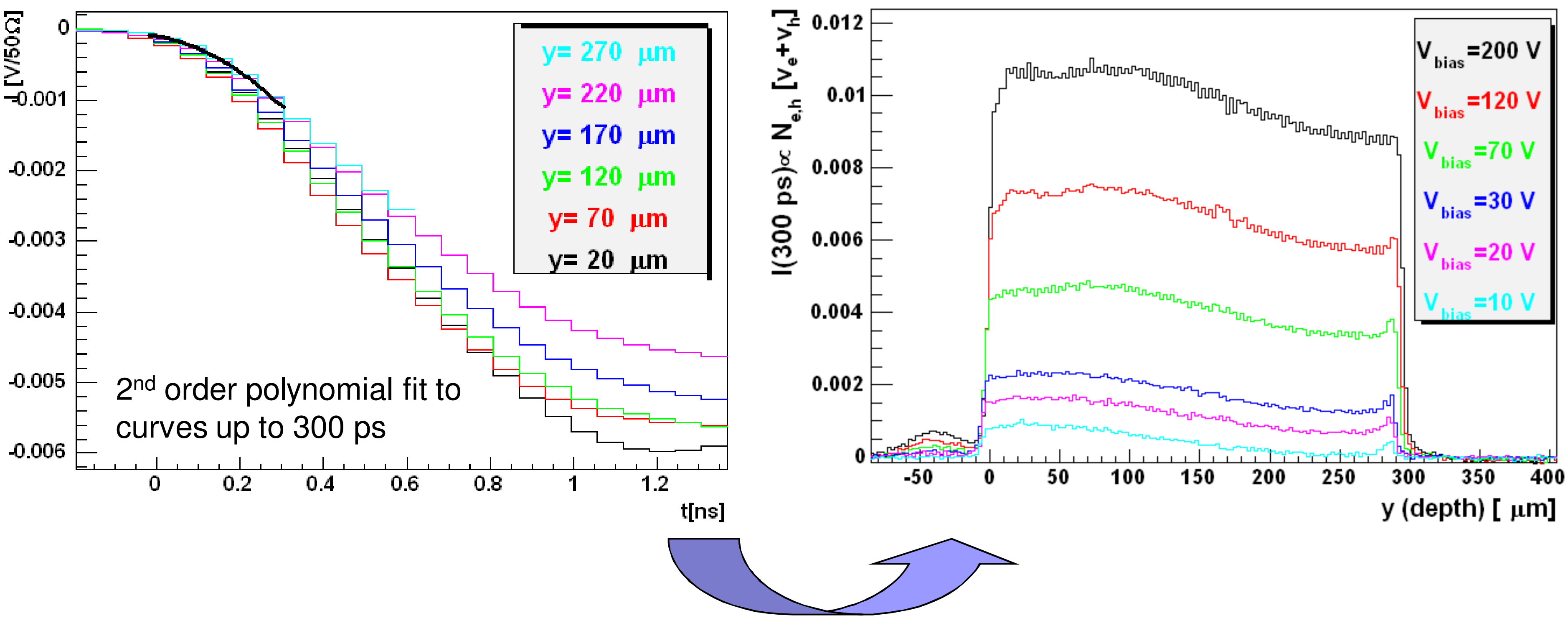
Sum of signals from all strips = weighting field of a diode!
(sum of U_w from all strips)

$$I_{e,h}(t) \approx A e_0 N_{e,h} \exp(-\frac{t}{\tau_{eff,e,h}}) \frac{\overline{v}_{e,h}}{W}$$

Prompt current method - PCM

$$I(y,t\sim 0)\approx \underbrace{\frac{A e_0 N_{e,h}}{W}}_{=\text{const.}}\left[\bar{v}_e(y)+\bar{v}_h(y)\right] \quad , \quad t \ll \tau_{eff,e,h}$$

Rise time of our system was 600 ps (10%-90%). Current taken at 300 ps was used to determine **velocity profile** ! The trapping can be completely taken out of the equation!



G. Kramberger,Investigation of electric field and evidence of charge multiplication by Edge-TCT , 15th RD50 Workshop, CERN, 2009

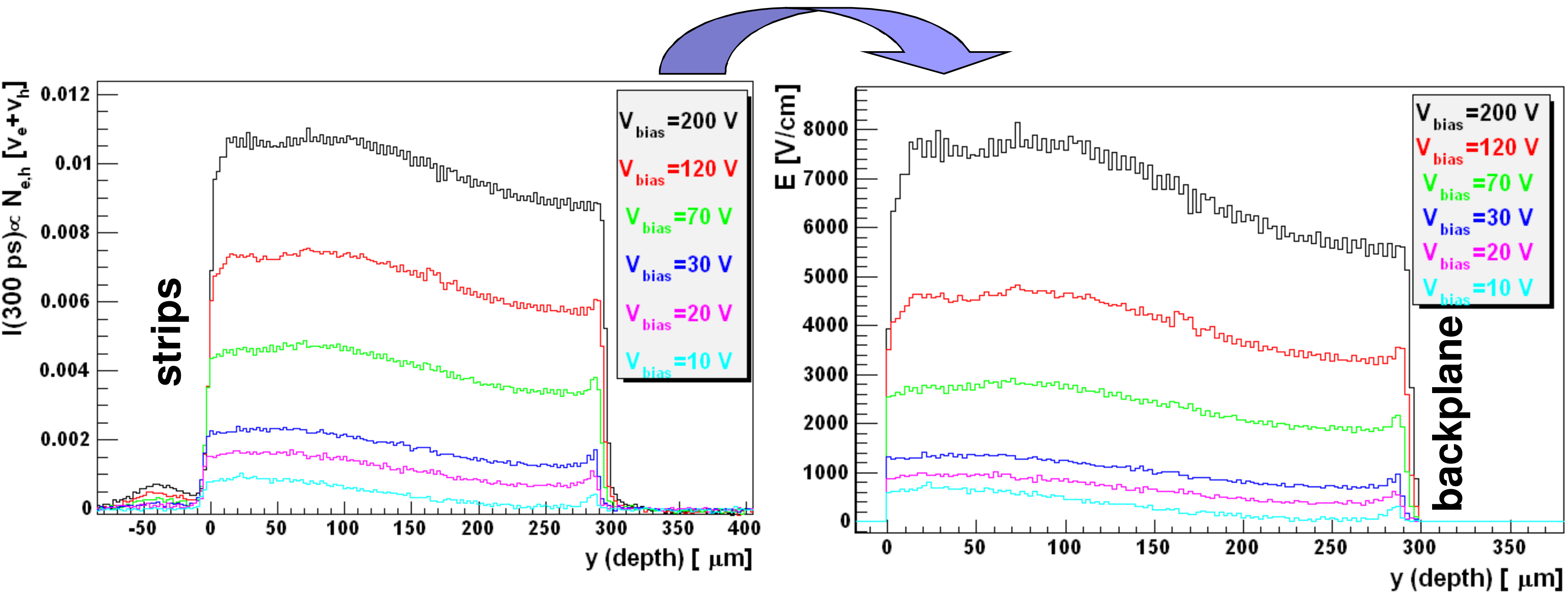
PCM – extraction of electric field

$$I(y) \approx \frac{A e_0 N_{e,h}}{W} \left[\mu_e + \mu_h \right] \overline{E}(y)$$

$$V_{bias} = \int_0^W \overline{E}(y) dy \Rightarrow \frac{A e_0 N_{e,h}}{W}$$

Constraint on bias voltage can be used to determine the proportionality!

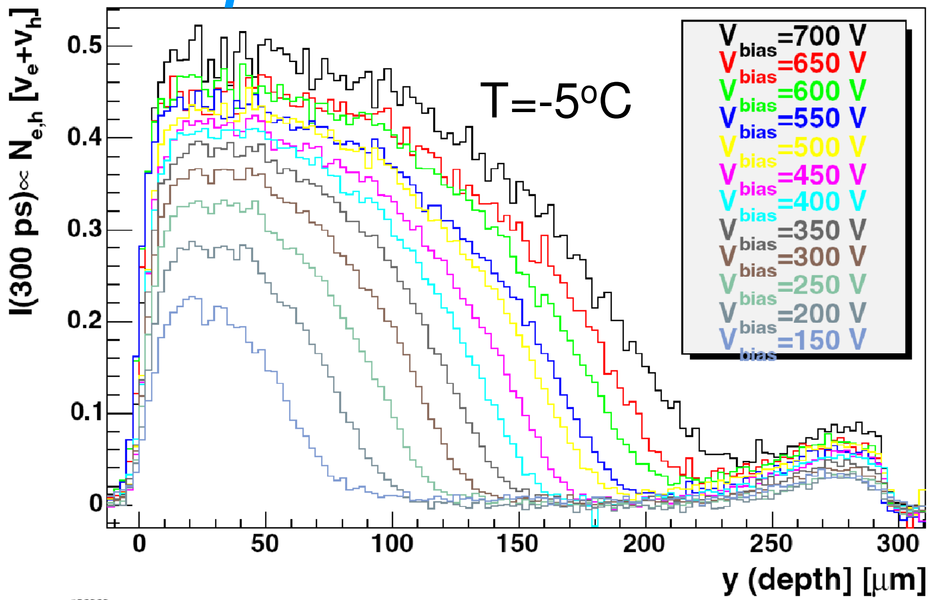
non-irradiated detector

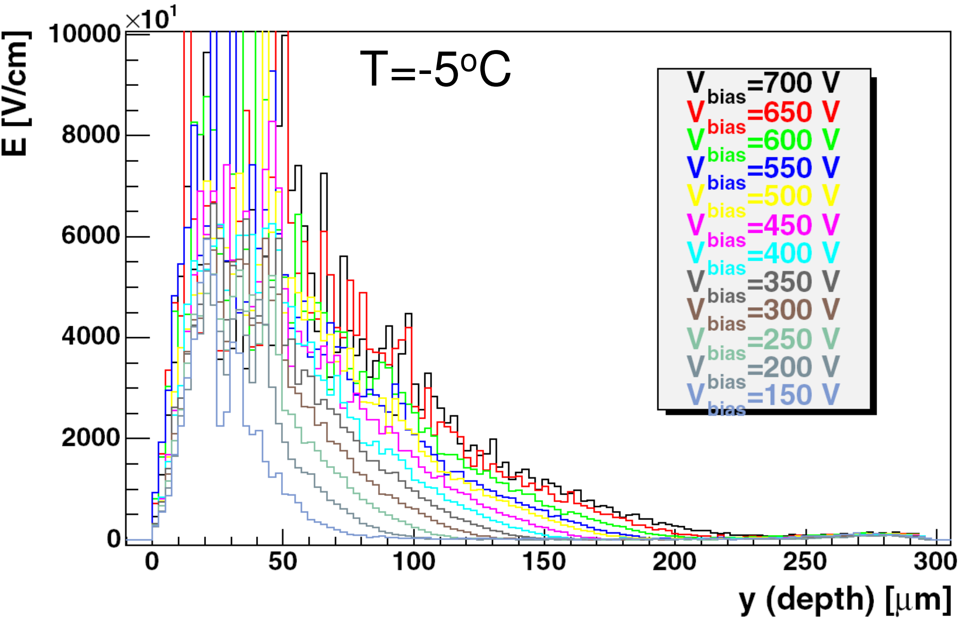


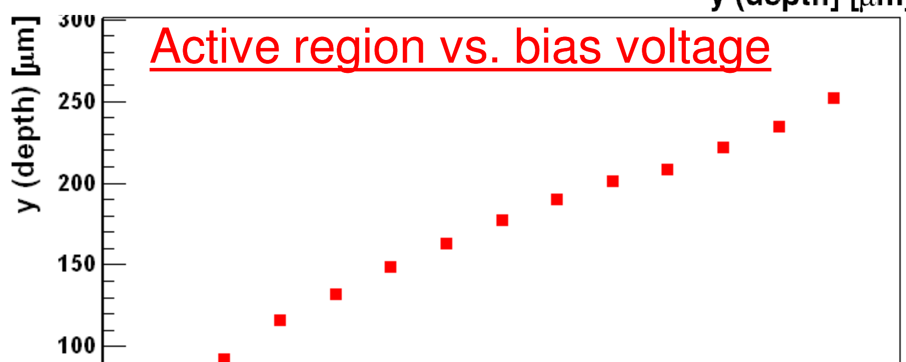
G. Kramberger,Investigation of electric field and evidence of charge multiplication by Edge-TCT , 15th RD50 Workshop, CERN, 2009

PCM – electric field for $\Phi_{eq}=5\cdot 10^{14}$ cm^{-2}

- Growth of active region with bias voltage can be observed.
- E at the back is much smaller than at front.
- At the strips the velocity depends only weakly on electric field and the uncertainty is large
- Growth of active region defined as point where $E \rightarrow 0$ agrees with homogenous N_{eff}.





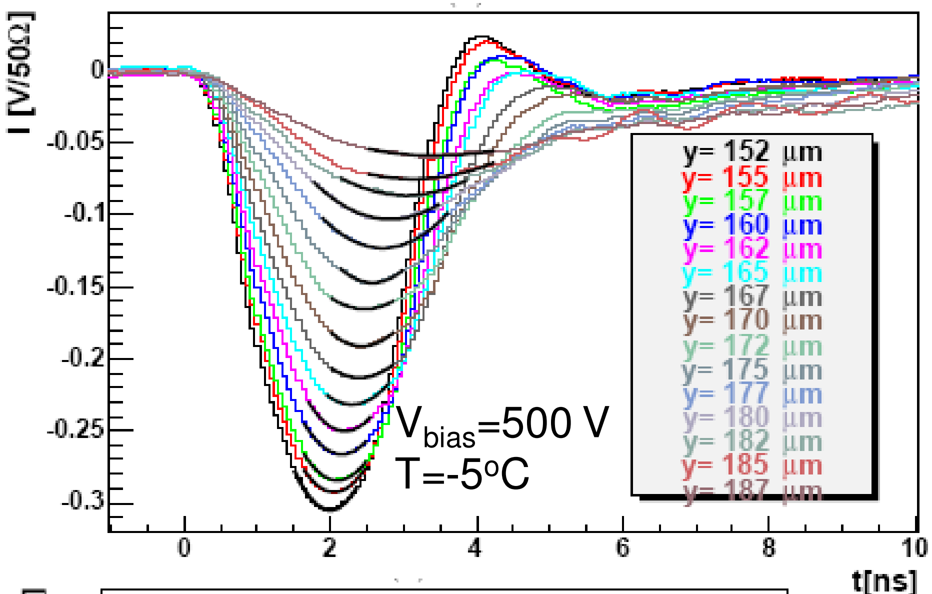


V_{fd} of a diode from the same material ~ 800 V

Delayed peak method - DPM

Is there a way to determine absolute velocity?

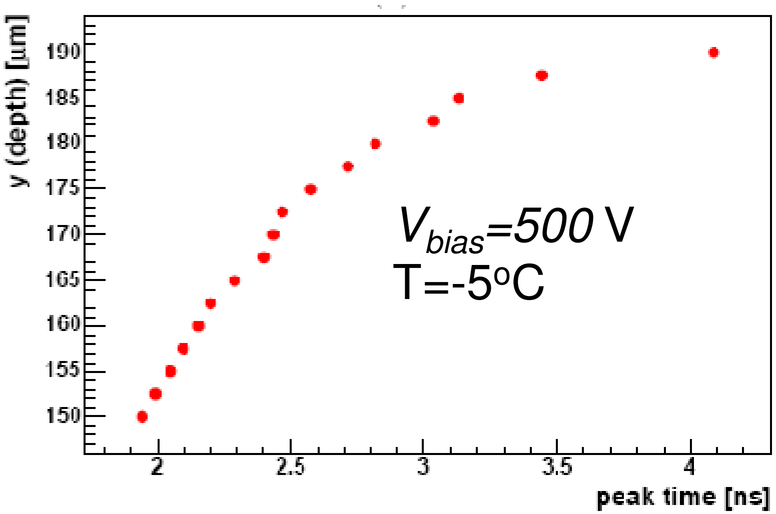
Position measurements are suitable for that:



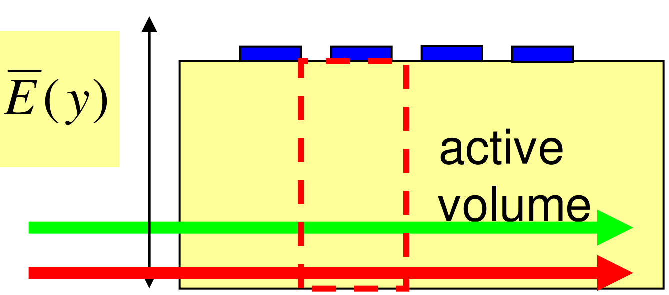
Arrival of electrons at the strips results in peak current, but:

- trapping can influence the peak position
- hole current can shift peak position

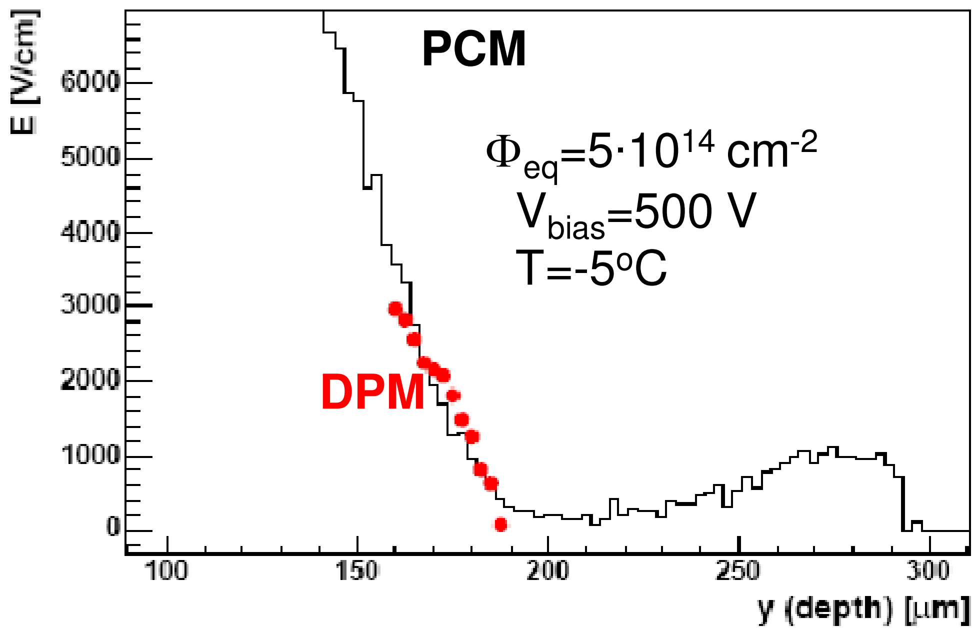
At the edge of the active region one can assume small hole contribution



$$\overline{v}_e(y) = \frac{\Delta y}{\Delta t} = \mu_e \overline{E}(y)$$

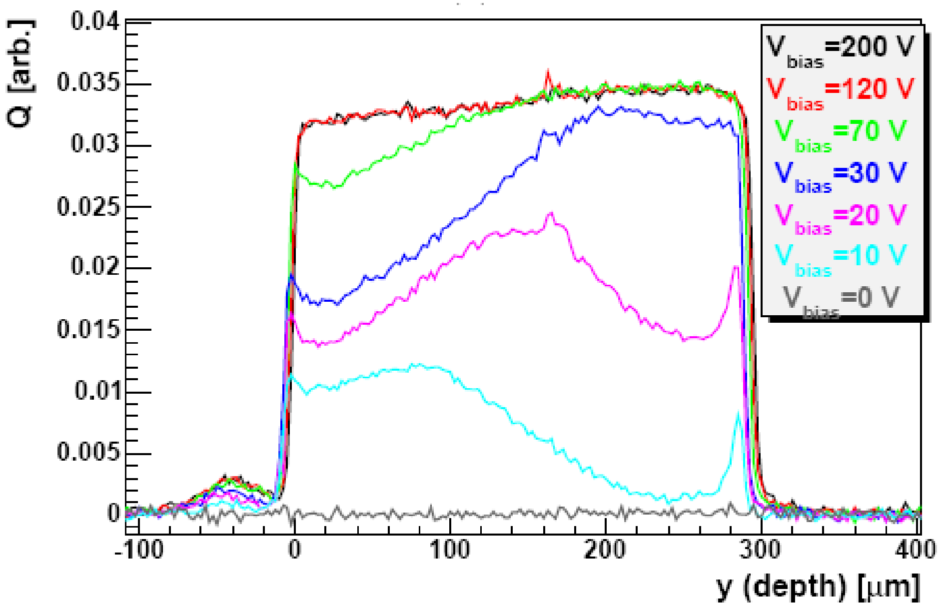


How well do the data from DPM and PCM agree?



Good agreement was found.
Methods can be used to cross-check each other.

Charge collection profile



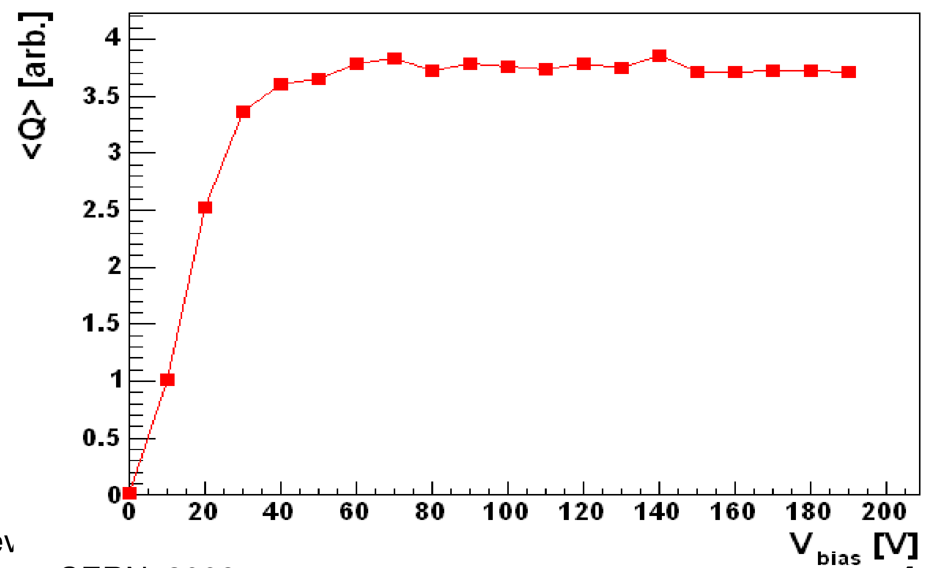
Identification of regions of high and low detector efficiency – "grazing technique"!

Non-irradiated detector:
- peak at the back (junction due to different p^+,p concentrations)
- at $V<V_{fd}$ front is more efficient
- at $V>V_{fd}$ back is more efficient, due to ballistic deficit
- at $V>>V_{fd}$ all regions are equally efficient

What about efficiency for m.i.p.

$$\boxed{Q_{mip} \propto \langle Q \rangle = \frac{1}{W}\int_0^{25ns} Q(y)\,dy}$$

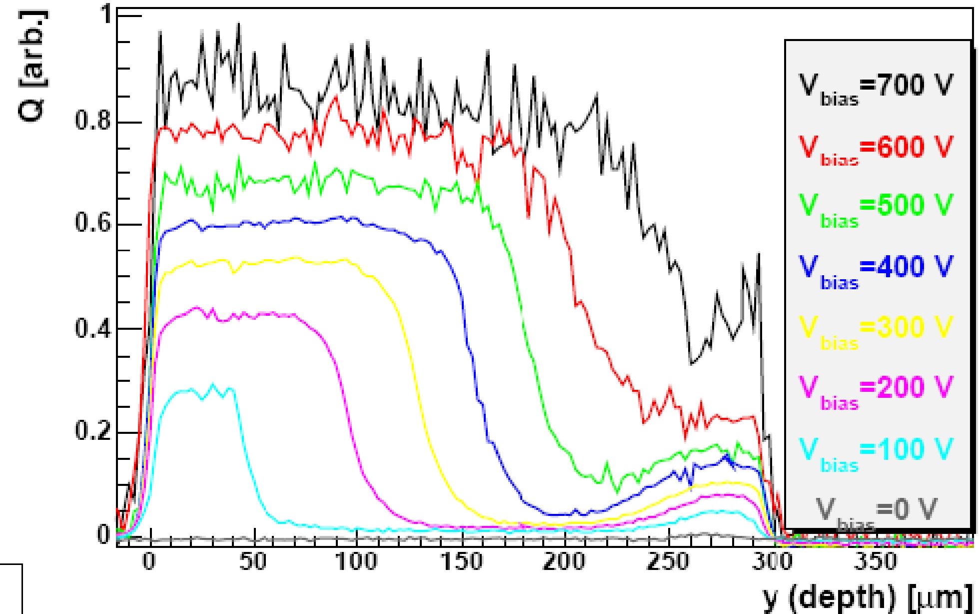
Due to low V_{fd} you need to significantly over-deplete!



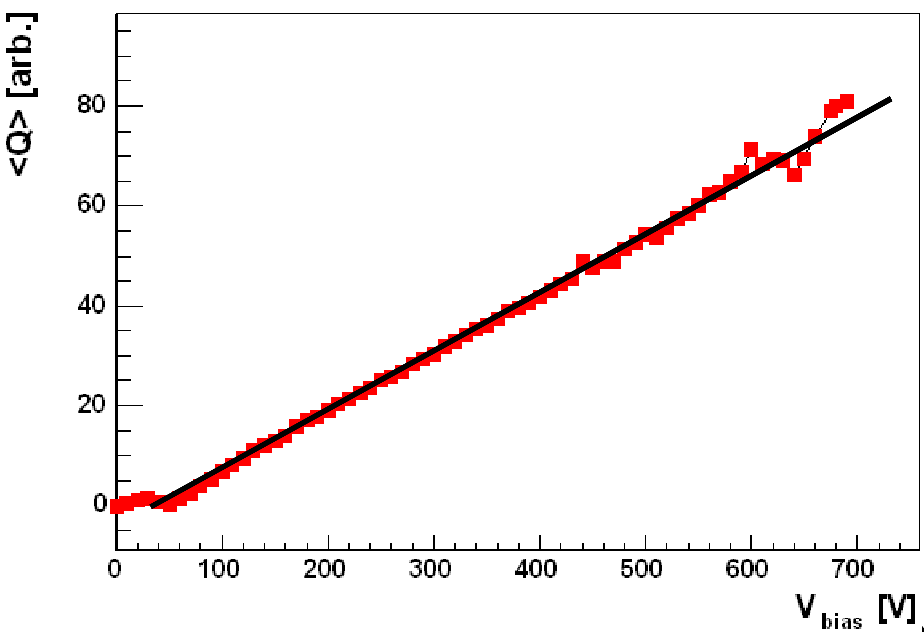
Charge collection profile $\Phi_{eq}=5\cdot10^{14}$ cm^{-2}

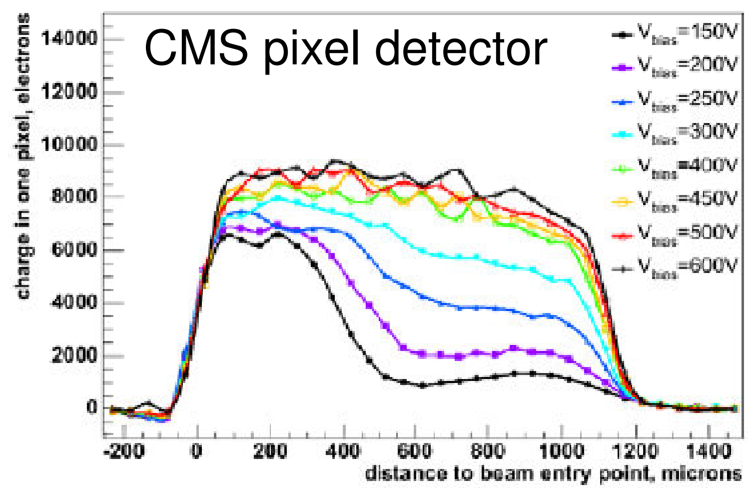
- *Q(y)* in active region is almost constant, but smaller than at higher bias (carriers not drifting through entire weighting field)
- The active region grows with bias voltage

$$Q_{mip} \propto w \cdot \frac{w}{W} \rightarrow Q_{mip} \propto V_{bias}$$



V. Chiochia et al., 8th RD50 Workshop, Prague, 2006



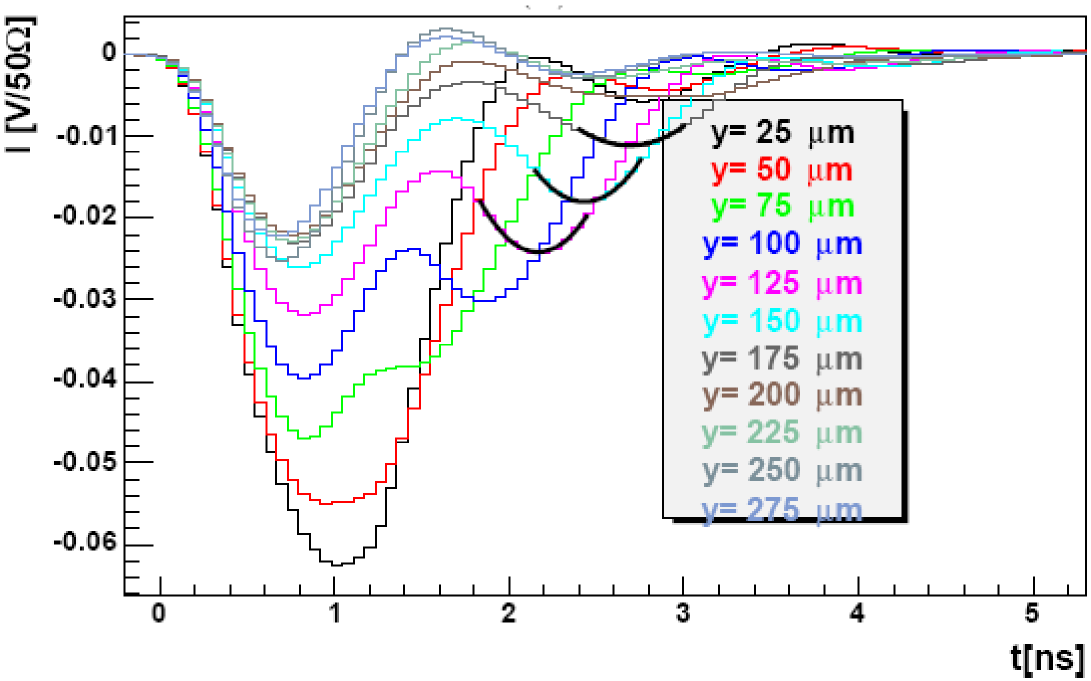


Detector irradiated to $5 \cdot 10^{15}$ cm^{-2}

Different evidences were found which all lead to the conclusion that charge multiplication takes place in the device!

1st observation: A second peak emerges in the induced current signals which is related to electron drift (it shifts when moving away from the strip)!

It can only be explained by electrons entering very high field at the strips where they multiply. The second peak is a consequence of holes drifting away from the strips!



The change of 2nd peak amplitude can be used to estimate electron trapping times:

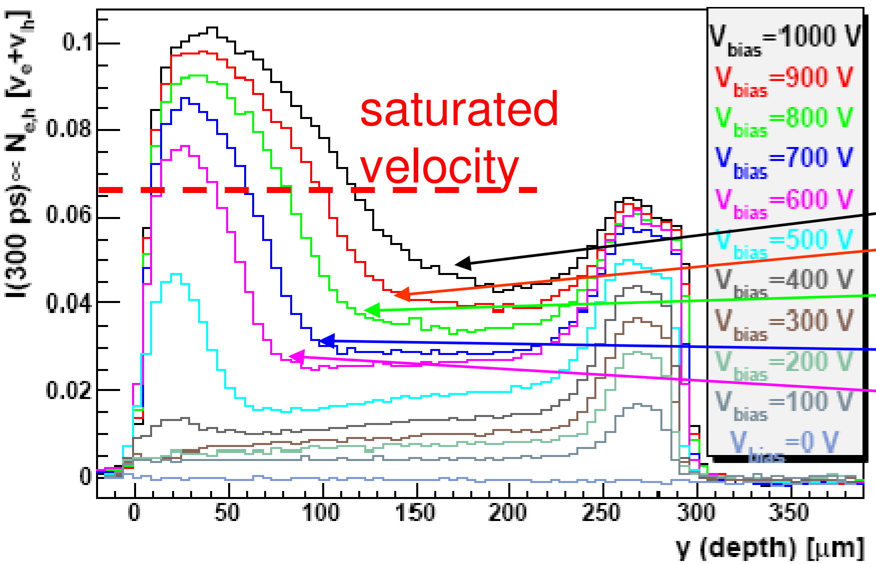
$$\frac{I(y=175\mu\text{m}, t_{p2}=2.69\,\text{ns})}{I(y=125\mu\text{m}, t_{p2}=2.16\,\text{ns})} \approx \exp\left(-\frac{\Delta t_{p2}}{\tau_{eff,e}}\right) \rightarrow \tau_{eff,e} = 670\,ps$$

$\tau_{eff,e}$~*600* ps in good agreement with measurements of effective trapping times!

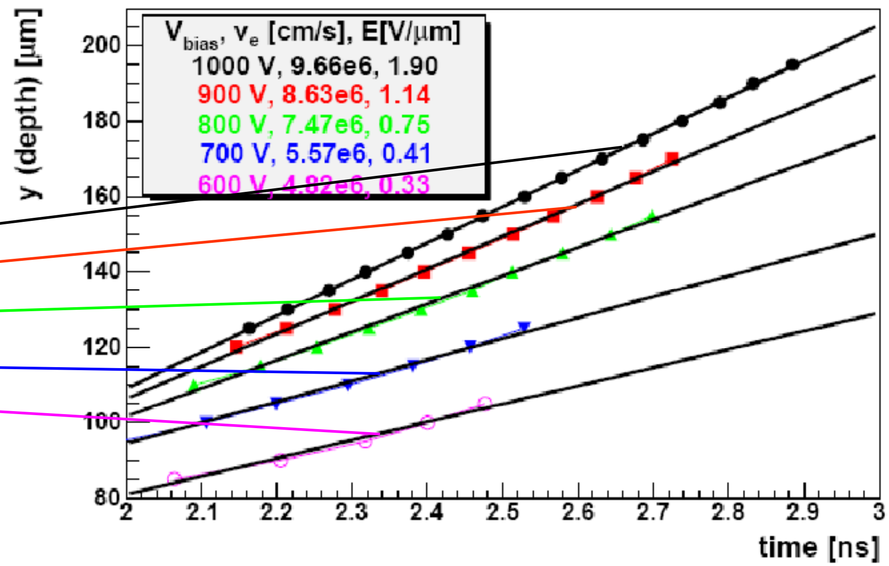
From short decay of I(y=25 μm) one can conclude that $\tau_{eff,h}$ is short (in 700 ps holes drift 50-60 μm. At y<100 μm the field is present)

2nd observation: Velocity and electric field profiles do not give consistent picture if number of drifting carriers does not increase in some parts of the detector.

Prompt current method – velocity profile

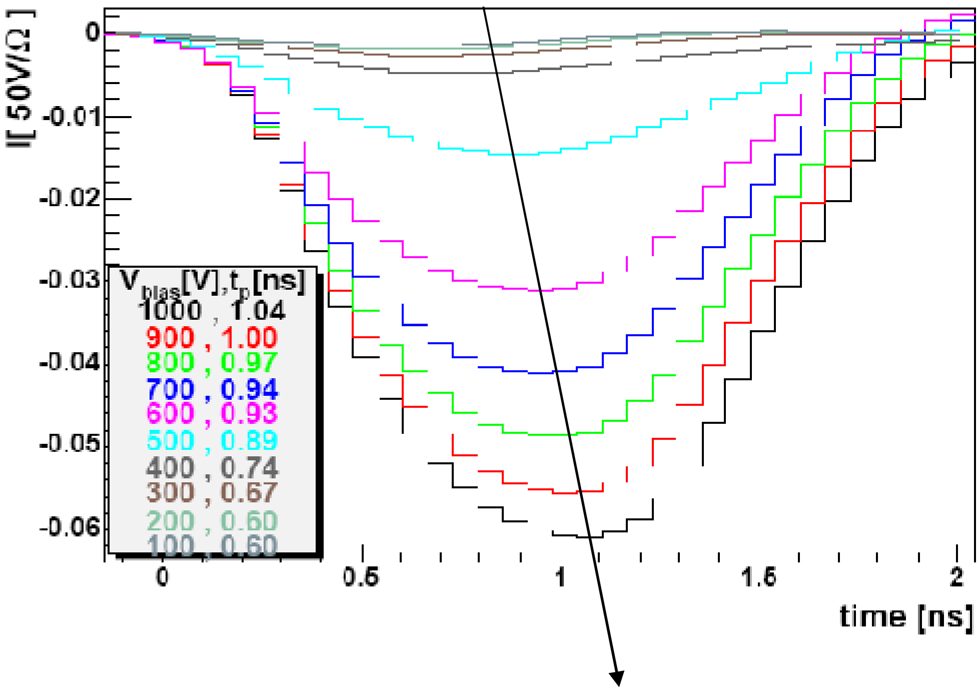


Arrival of electrons used for DPM



- Lower fields at the strip side for low voltages
- **Significant field in the detector at moderate voltages – *E*>0.33 V/μm for 600 V.**
- Due to saturation of velocity the determination of the field becomes impossible, but the signal still rises at small *y*!

3rd observation: The peak in the initial current at y=30 μm is prolonged at higher voltages. Drift of multiplied holes prolongs the signal.

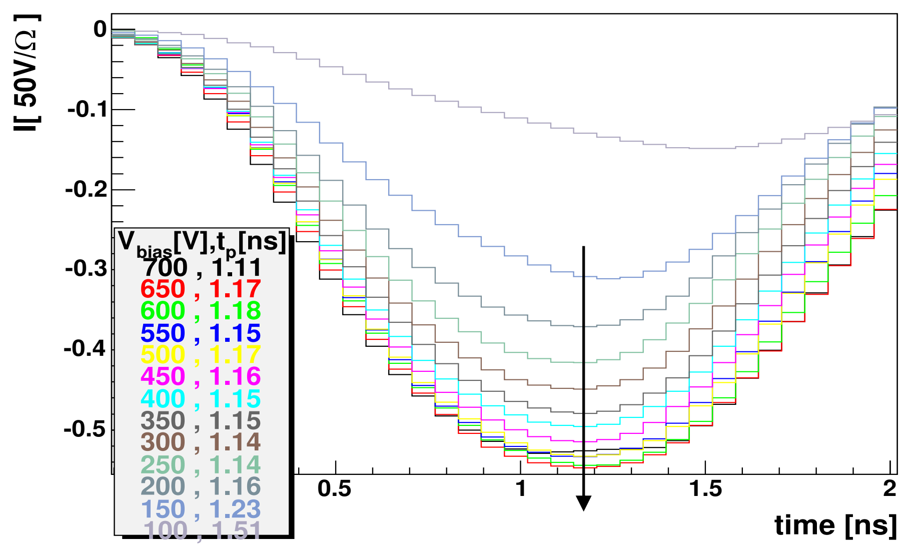


The shift of the signal is of the same order as:

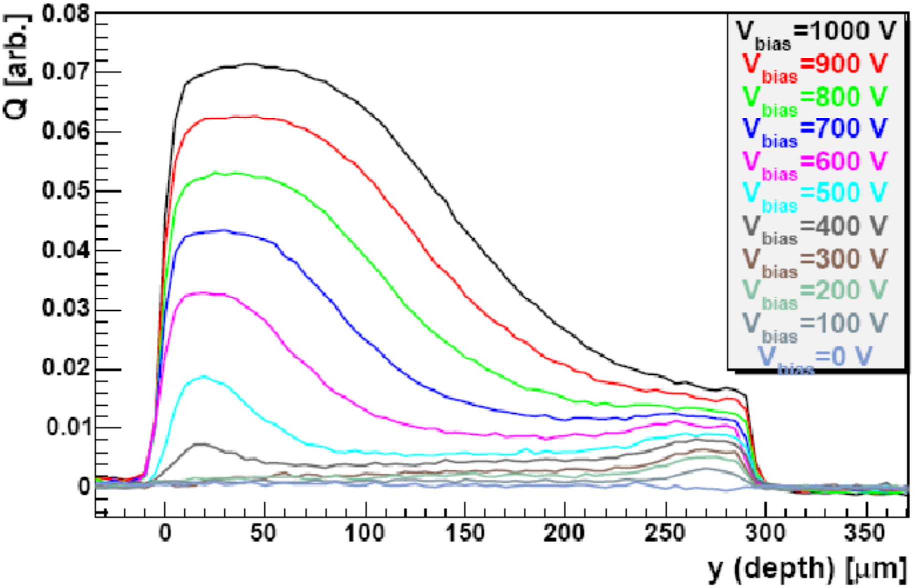
$v_{sat,e} \cdot t_{shift} = 30$ μm

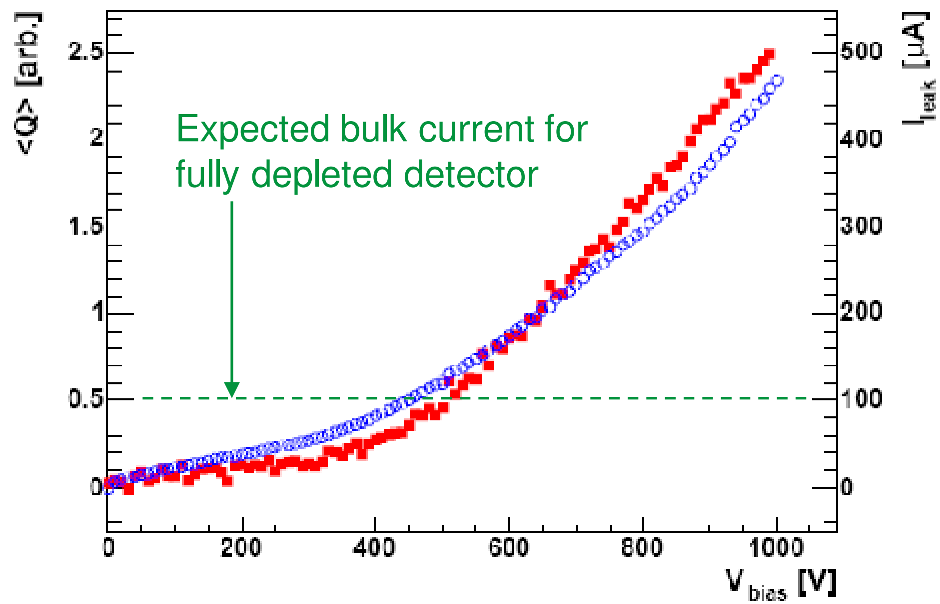
the time needed for electrons to get to the strips!

For detector at $5 \cdot 10^{14}$ cm^{-2} the shift does not exist once the drift velocity saturates!



4th observation: Charge collection profile and Q_{mip} correlation with current





High bias voltage significantly improves charge collection!

Leakage current and <Q> are correlated!

Conclusions

- Edge-TCT is a very powerful tool for investigation of irradiated silicon detectors
- Two methods: Prompt current pulse and Delayed Current Pulse were proposed to determine charge collection, velocity and electric field profiles
- The results of non-irradiated and detector irradiated to $5\cdot10^{14}$ cm^{-2} are in agreement with expectations.
- Several evidences were found of charge multiplication in the device irradiated to $5\cdot10^{15}$ cm^{-2}
- Substantial electric field is present in whole detector already at moderate voltages

Future

- Quantization of the avalanche multiplication and its dependence on voltage fluence and annealing
- Building a new device model
- Imapact of device processing ?