# Signals in thin-pixel detectors for SLHC

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MPI-HLL project review

# Motivation (I)

All LHC experiments will use silicon for vertex detectors!
What about the SLHC – can silicon still be used for efficient tracking?
Degradation of performance of irradiated silicon detectors **(bulk)**:

- **increase of $|N_{eff}|$**

  Significant improvement in last years:

  Material: DOFZ, Czochralski, epitaxial material

  Geometry: semi-3D, 3D and thin detectors

  Operational conditions: cryogenic operation, current induced devices (CID)

- **Increase of leakage current**
- **loss of drifting charge – trapping**

**CERN:**
**RD48**
**RD39**
**RD50**

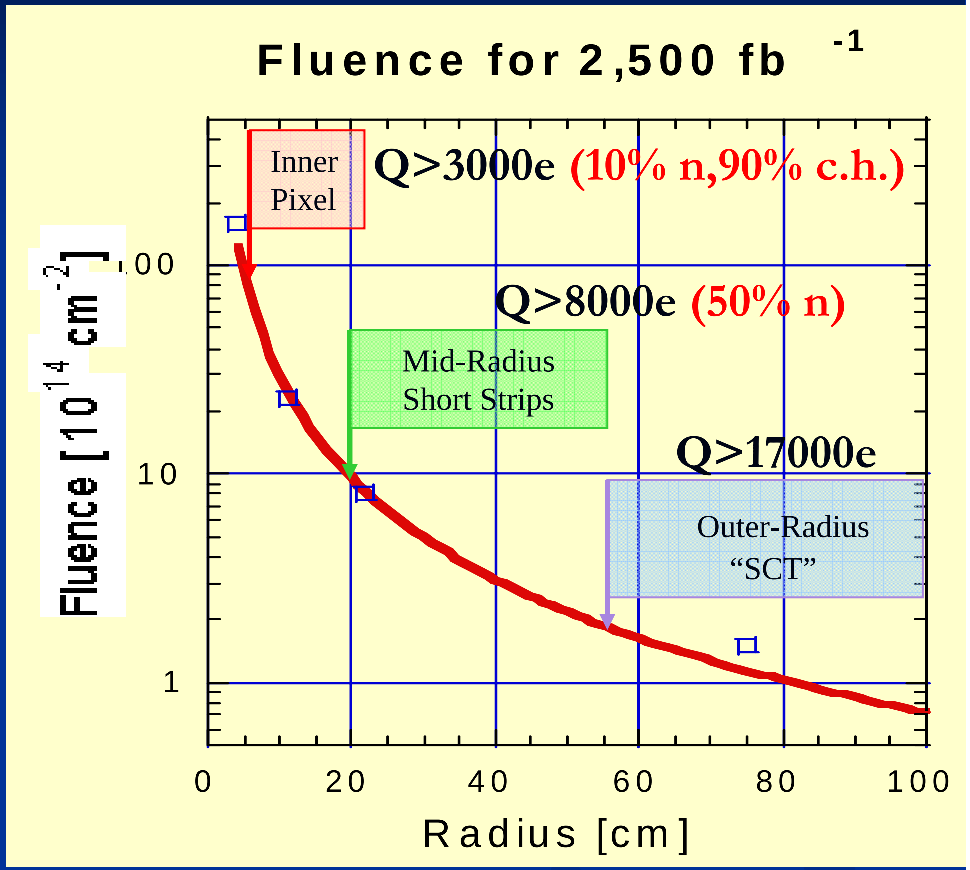
***Determine the signal in irradiated detectors!***

***only the planar detectors will be discussed***

# Motivation (II)

Two main problems after the upgrade of LHC
- Occupancy increase
- Radiation damage

Reduction of pixel size
- **smaller pitch**
  - smaller capacitance ☺
- thinner detectors ? , due to $\tau_{eff,e,h} << t_{drift}$
  - larger capacitance ☹
  - smaller leakage current ☺
    no thermal runaway, shot noise
  - smaller material budget (better physics)
  - smaller depletion voltage ($V_{fd} \sim N_{eff} D^2$)




**How much charge can we expect for the pixel detectors?**
**Does thinning down the detector help?**

**Simulation is used to answer the questions.**

# Induced current in segmented detectors

$$I = q\vec{v}\cdot\vec{E}_w \quad ; \quad \Delta U_w = 0; \vec{E}_w = \nabla U_w$$

$$Q = \int_{t=0}^{t} I dt$$

$$Q = q[U_w(\vec{r}) - U_w(\vec{r}_0)]$$

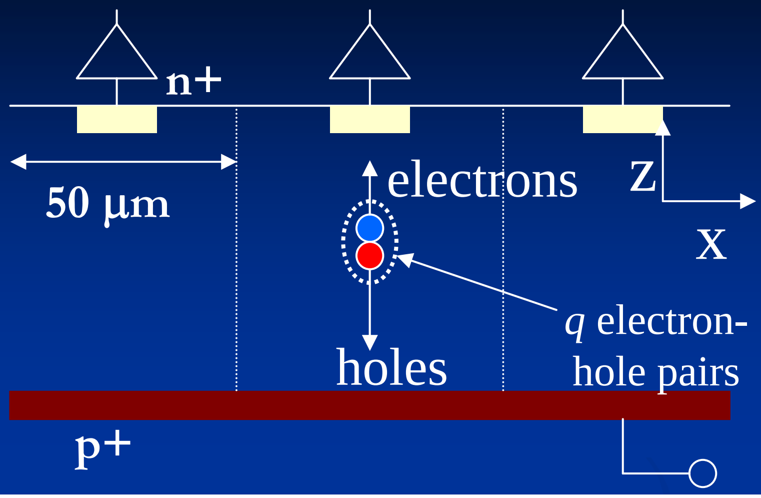
$$Q_{e-h} = Q_e + Q_h$$

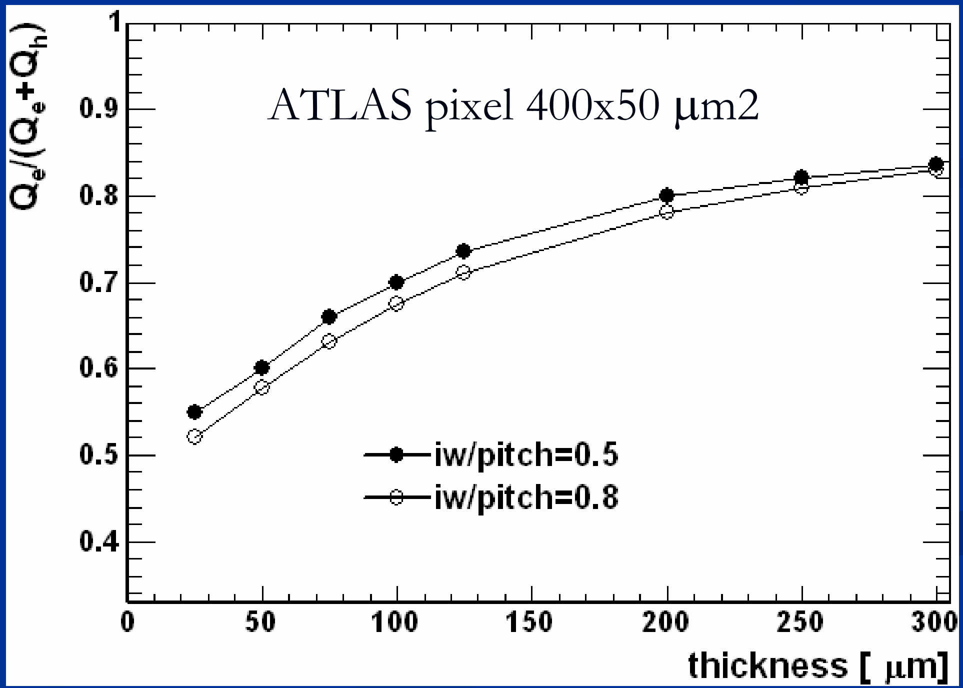
$$Q_{track} = \sum_{all\ pairs} Q_e + Q_h = Q_e^t + Q_h^t$$

$$\rho \approx 75 \frac{e}{\mu m}$$

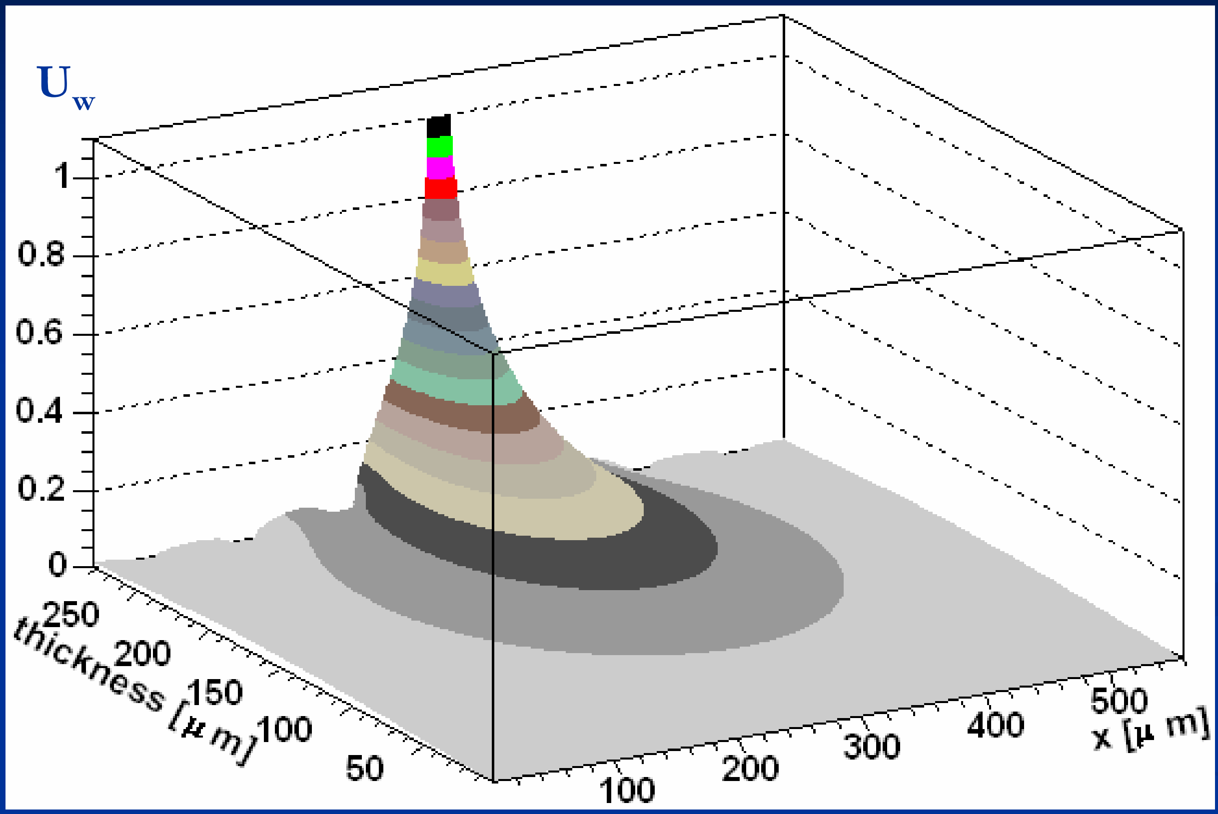
$$Q_e^t = -\rho \int_0^{thickness} (1 - U_w(z'))\, dz' = 0.83\, Q_{track}$$

$$Q_h^t = \rho \int_0^{thickness} -U_w(z')\, dz' = 0.17\, Q_{track}$$




As long as the drift of $q$ is completed there is **no difference** in $|Q_{track}|$ between both detector types!




$U_w$ describes the coupling between the sensing electrode and any point in detector!

$$\Delta U_w = 0$$

$$U_w = 1 \text{ ; for the sensing electrode}$$

$$U_w = 0 \text{ ; for all the rest}$$

$U_w$ along the plane y=0 (middle of the pixel)

# ... and trapping complicates equations

$$Q = \int_{t=0}^{t} I dt = \cdot \int_{t=0}^{t} q(t')\vec{v}\vec{E}_w dt'$$ ← Induced charge by drift of a point like charge

$$Q = \int_{t=0}^{t} q \exp\left(\frac{-t'}{\tau_{eff}}\right) \mu \, \vec{E} \cdot \vec{E}_w dt'$$

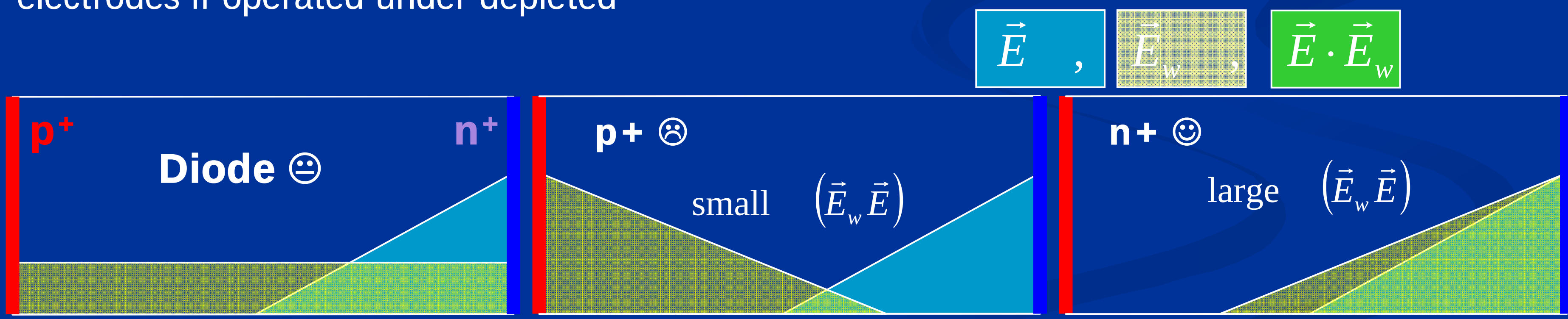
trapping — mobility — scalar field

✓The drift of electrons will be completed sooner and consequently less charge will be trapped!

- •Trapping term ( $\tau_{eff,e} \sim \tau_{eff,h}$ )
- •Drift velocity ( $\mu_e \sim 3\mu_h$ )

➡ $n^+$ readout should perform better than $p^+$

✓The **E·E$_w$** product should be as larger as possible all over the detector i.e. the main junction at electrodes if operated under depleted



# Simulation of ATLAS pixel detector for SLHC

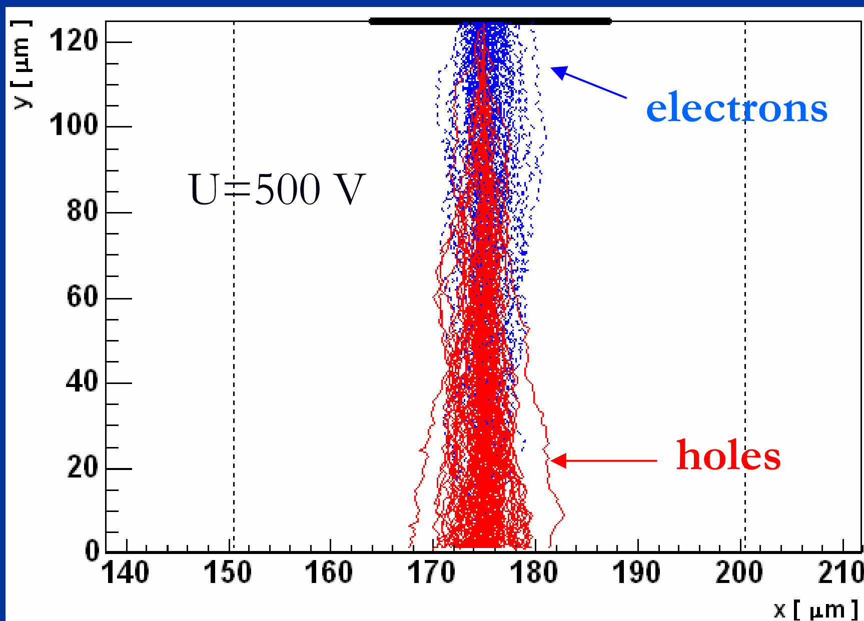
The geometry of the pixel was 400x50 $\mu m^2$ – the difference to 200x50 $\mu m^2$ should be small!
Implant width = 0.8 ·pitch

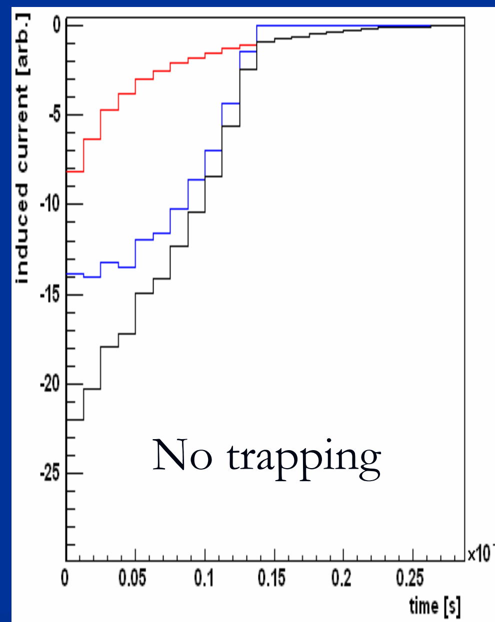
<u>Software:</u>

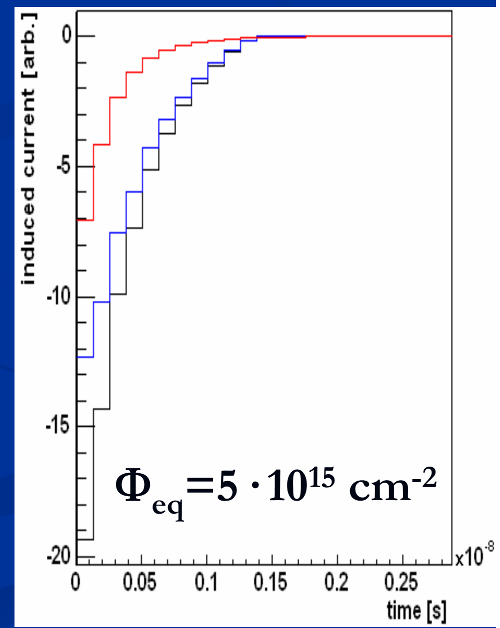
- Calculation of the weighting and electric field (ISE-TCAD 3D, custom made software 2D)
- Simulation of drift and calculation of induced current done by custom made software

Assumptions:

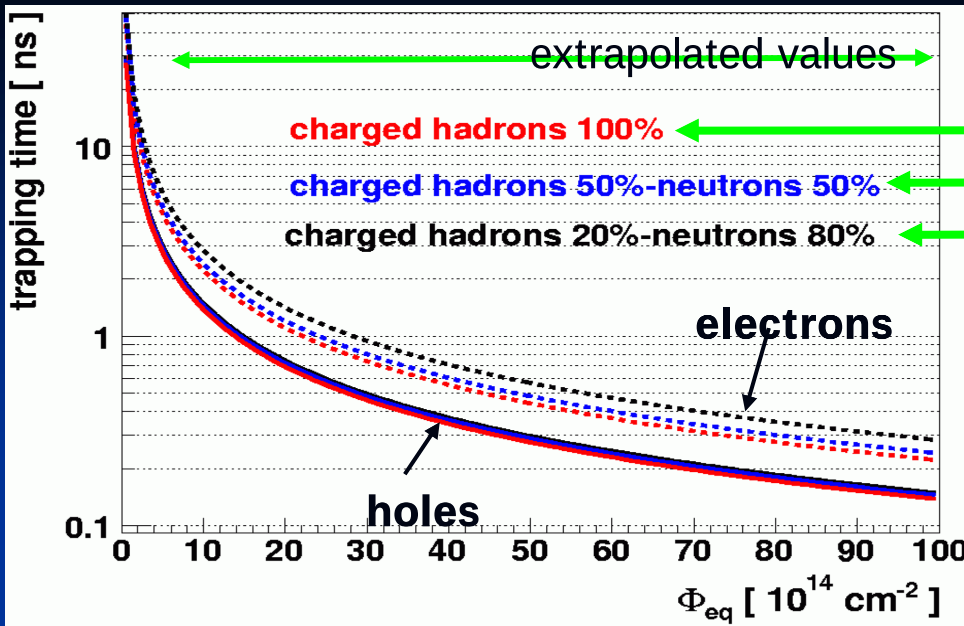
- The damage originates from charged hadrons and $N_{eff}$=-0.0071 $cm^{-1}$ $\Phi_{eq}$ (except for epi-Si)
- T=-10°C, detectors are annealed to the minimum of $V_{fd}$



# Trapping times – input to simulation




r~4cm

r~20cm

r~60cm

$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t)\,\Phi_{eq}$$

$\beta_{e,h} \rightarrow \frac{2}{3}\beta_{e,h}$ at high fluences

for higher fluences

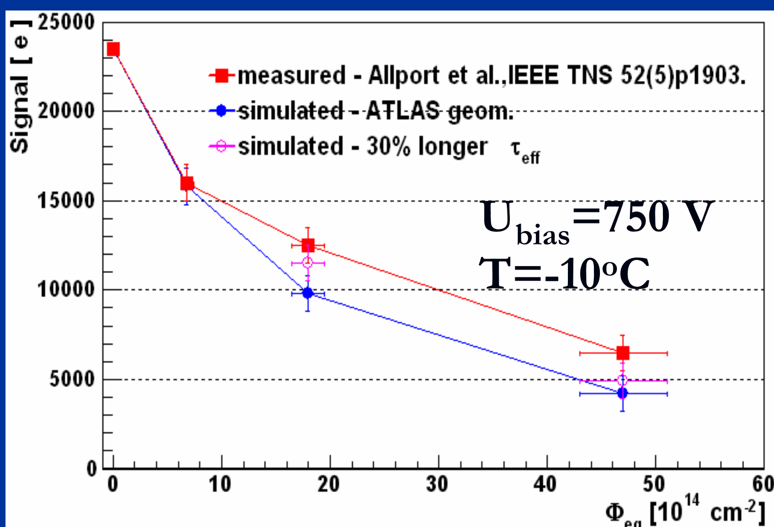
$$v_{sat} \cdot \tau_{eff,e,h} \leq 40\,\mu\text{m}$$

$$\frac{300\,\mu\text{m}}{v_{sat}} \approx 3\text{ ns}$$

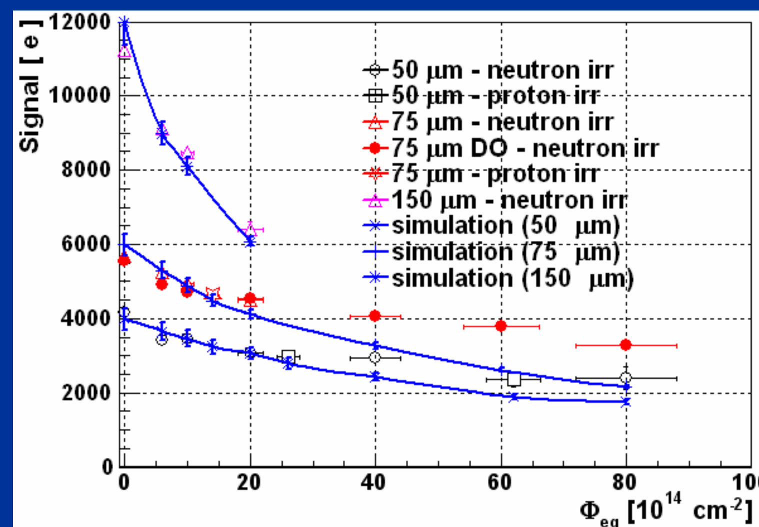
$\beta_e = 3.9 \cdot 10^{-16}\,\text{cm}^2/\text{ns}$

$\beta_e = 4.3 \cdot 10^{-16}\,\text{cm}^2/\text{ns}$

reason

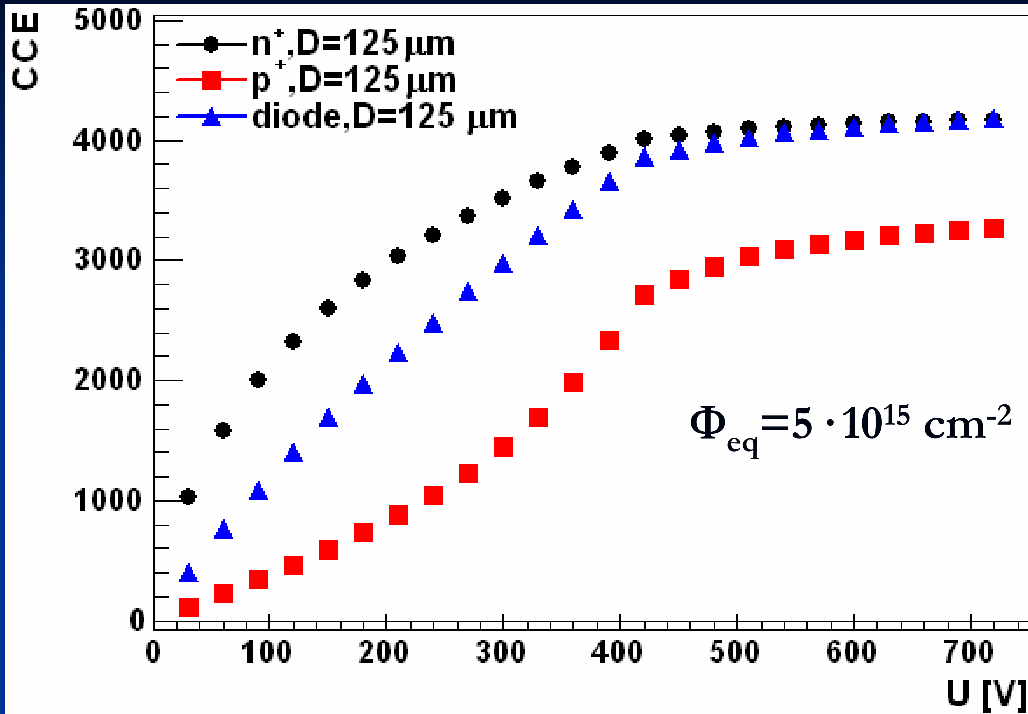



Simulation of p irr. $n^+$-p detectors !




Fully depleted epi-Si diodes well above $V_{fd}$ !

# QV plots – different detector types




The difference between p and n readout is large!

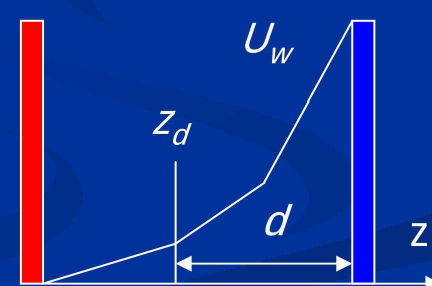
- Track along the center of the pixel!
- Around 4200e are expected at 450V
- No significant rise of signal above $V_{fd}$ ;E is already so high that velocity is saturated almost everywhere
- Safer operation of $n^+$ devices at lower voltages

$$Q_{track} \propto d(1-U_w(z_d))$$

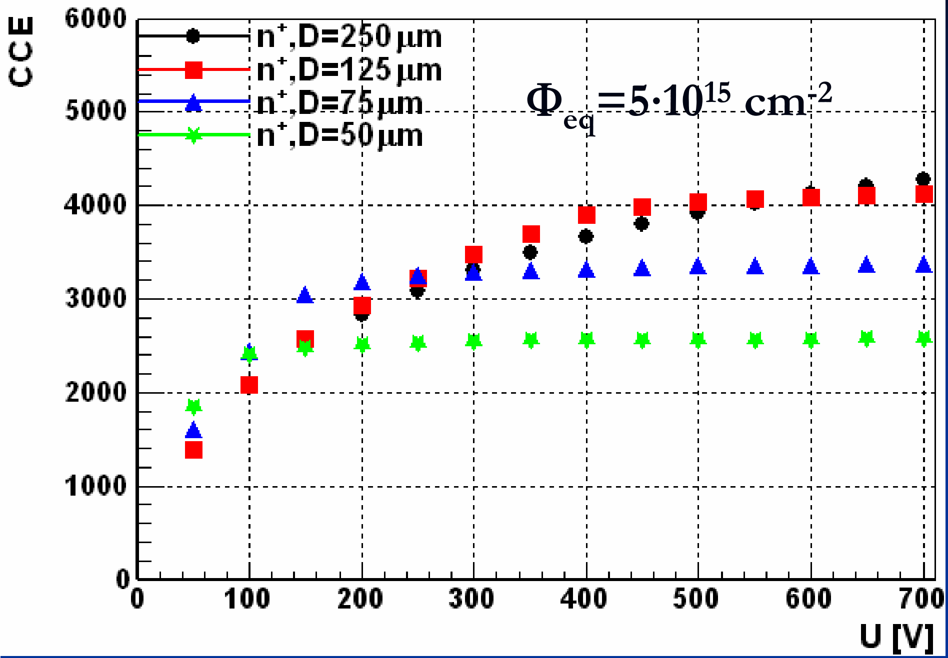
$$diode \Rightarrow Q_{track} \propto d\cdot d \propto U$$

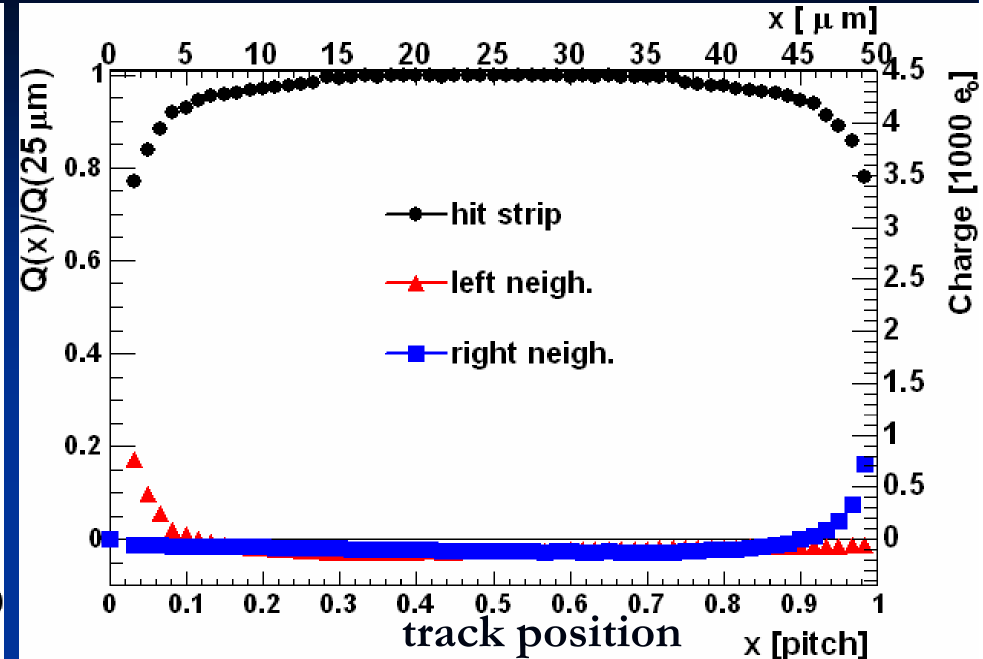
$$n^+ \Rightarrow Q_{track} \propto d \propto \sqrt{U}$$

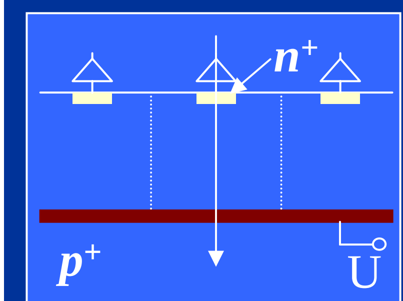
$p^+ \Rightarrow$ Increase when bias approaches $V_{fd}$



# QV plots – different detector thicknesses



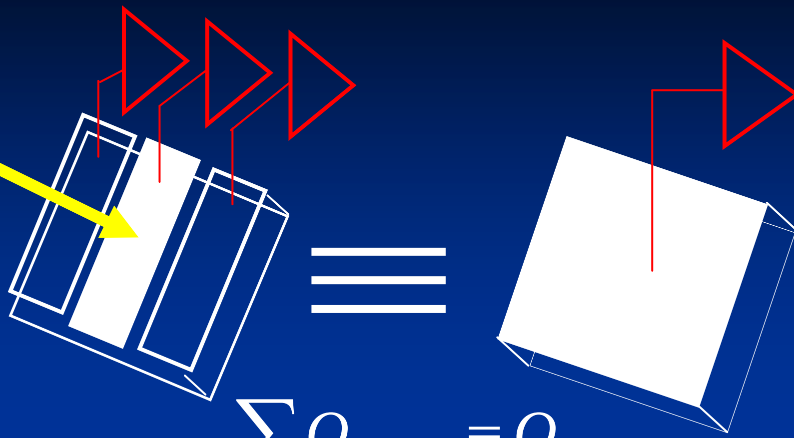




- Similar Q-V characteristics up to full depletion!
- Thinner sensors are beneficial at lower voltages – the more voltage you can apply the more beneficial are thicker detectors

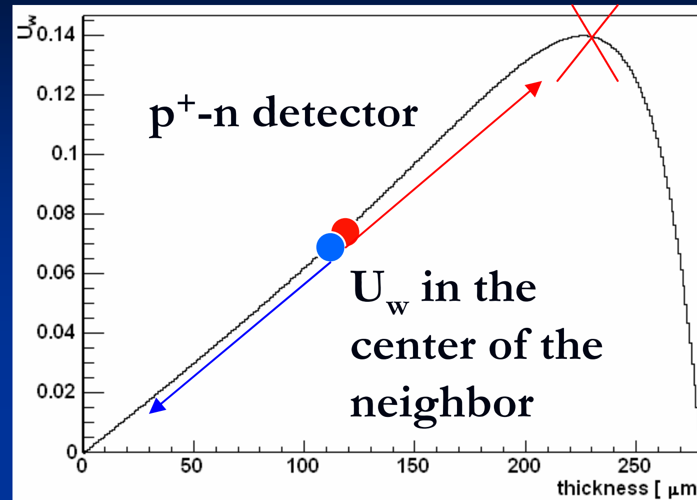
- Less than 5% difference when averaged over the whole pixel in x!
- Small charge sharing
- Negative signals on neighbors are relatively small due to high voltage!

# Trapping induced charge sharing

electrode hit in the center by ionizing particle



$$\sum_{\substack{\text{all electrodes} \\ (\text{pitch}-\text{implant width})\to 0}} Q_i \equiv Q_{diode}$$





same polarity

$Q_{hit} < Q_{diode}$

↓

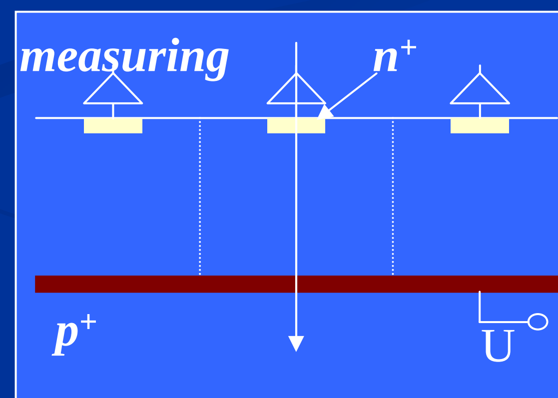
wider clusters

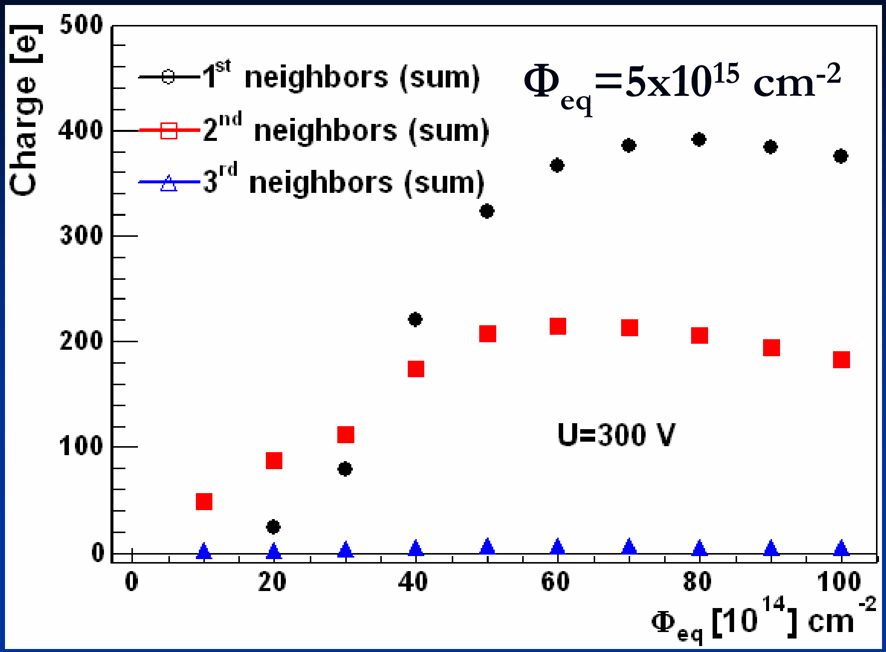
opposite polarity

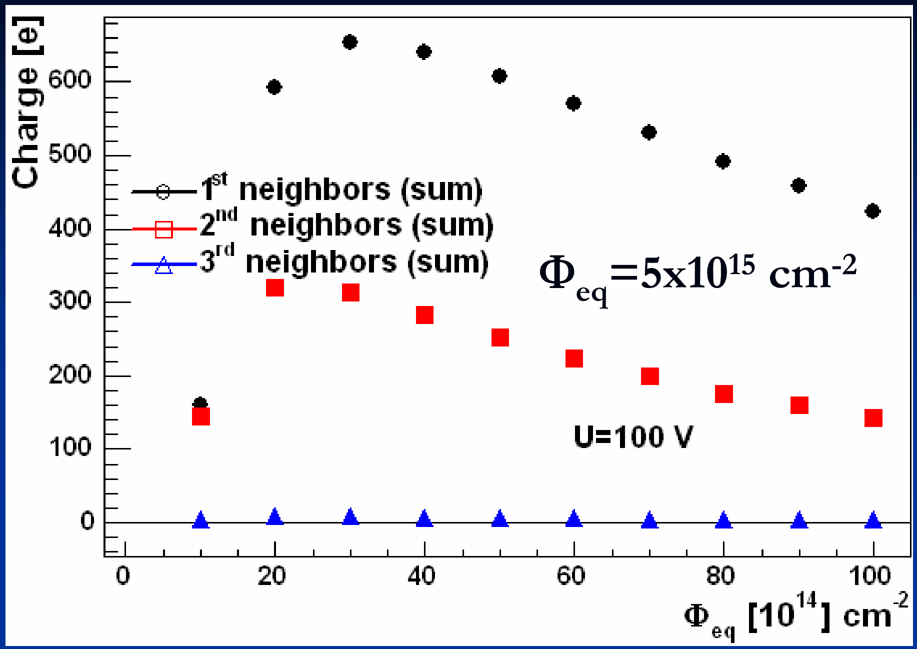
$Q_{hit} > Q_{diode}$

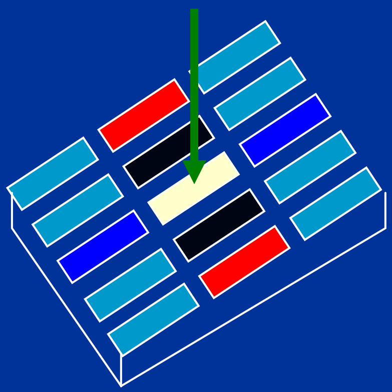
↓

larger signals



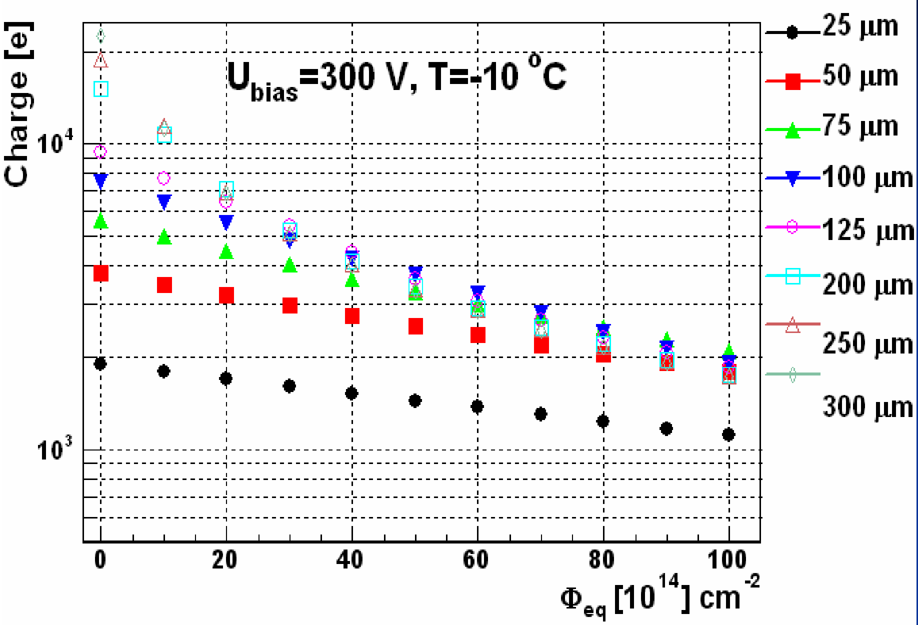


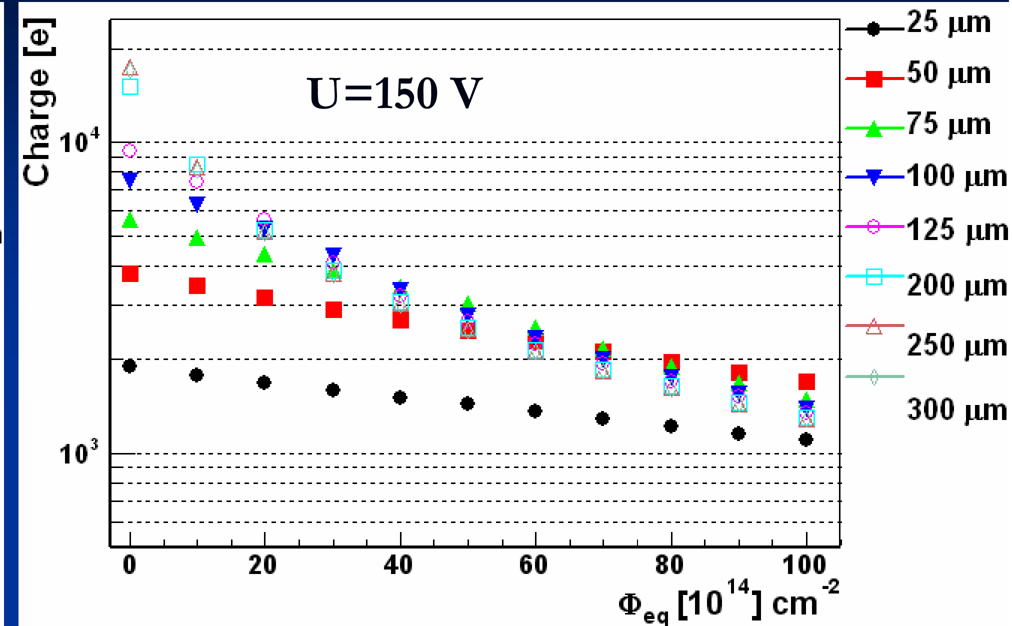



- Around 20% of the charge is induced in the neighbors
- The charge is lost due to thresholds applied and opposite sign
- The amount of induced charge in the neighbors:
  - ↑ with larger trapping
  - ↑ with larger depletion depth
  - ↓ with faster drift

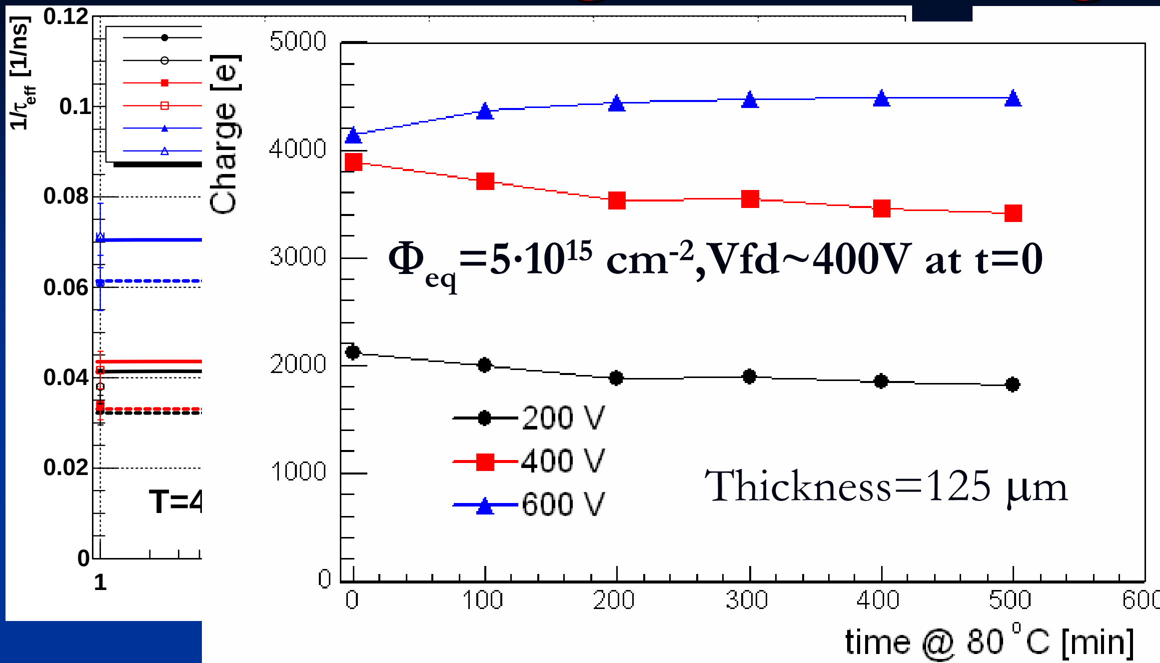
# Are thinner detectors beneficial?

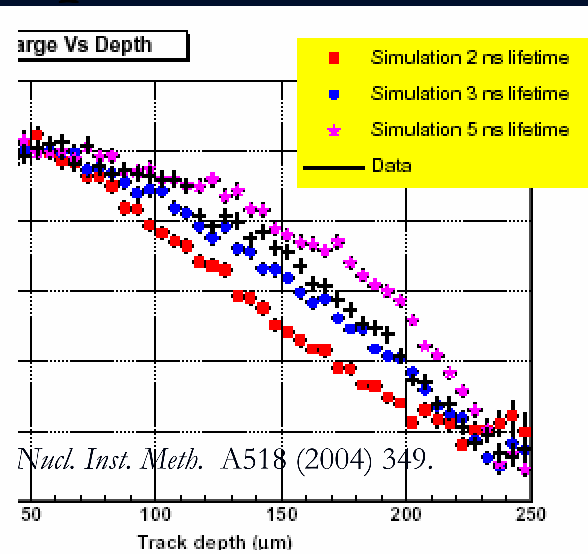



- The thick detectors don’t perform significantly worse at high fluences!
- the thicker the detector the larger contribution of electrons
- the high weighting field region is depleted already at moderate voltages which makes the detector similar to fully depleted thin detector
- the break even point between thick and thin detector depends on voltage applied.

# Is long term annealing important?




| | aling | τ (ns) | β ($10^{-16}$ cm$^2$ s$^{-1}$) |
|---|---|---|---|
| | at 60°C | 5.5±1.1 | 1.7±0.4 |
| | ... h at 60°C | 3.4±0.5 | 2.7±0.4 |
| I | 25 h at 60°C | 4.1±0.6 | 2.2±0.3 |
| T3 | 25 h at 60°C | 4.8±1.5 | 1.9±0.6 |
| T2 | Minimum $V_{fd}$ | 2.3±0.8 | 4.0±1.4 |

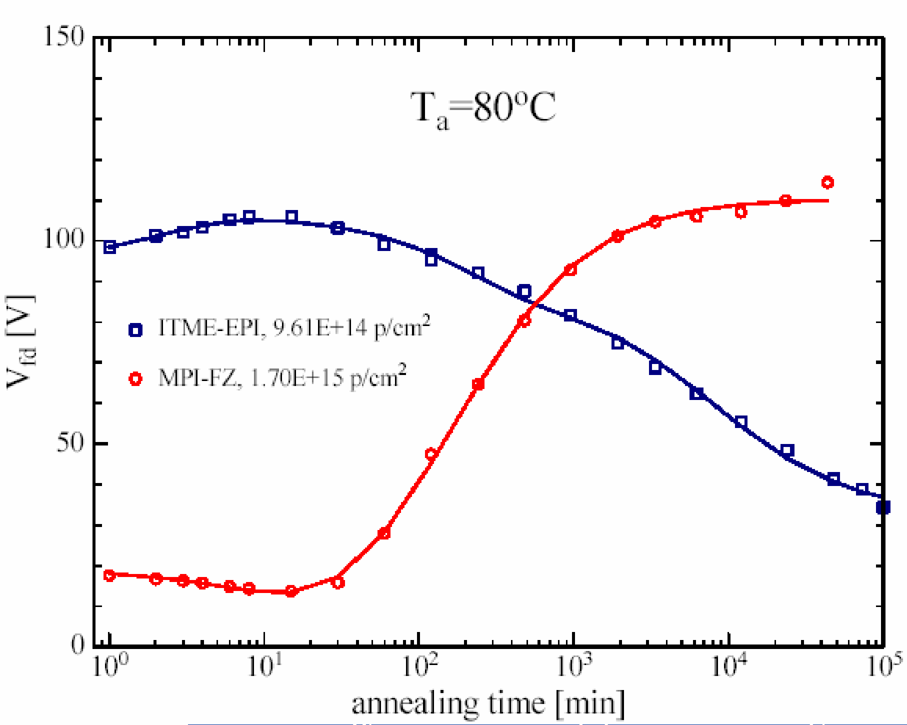
The reverse annealing seem not to be such a a big problem as for $p^+$-n detectors:

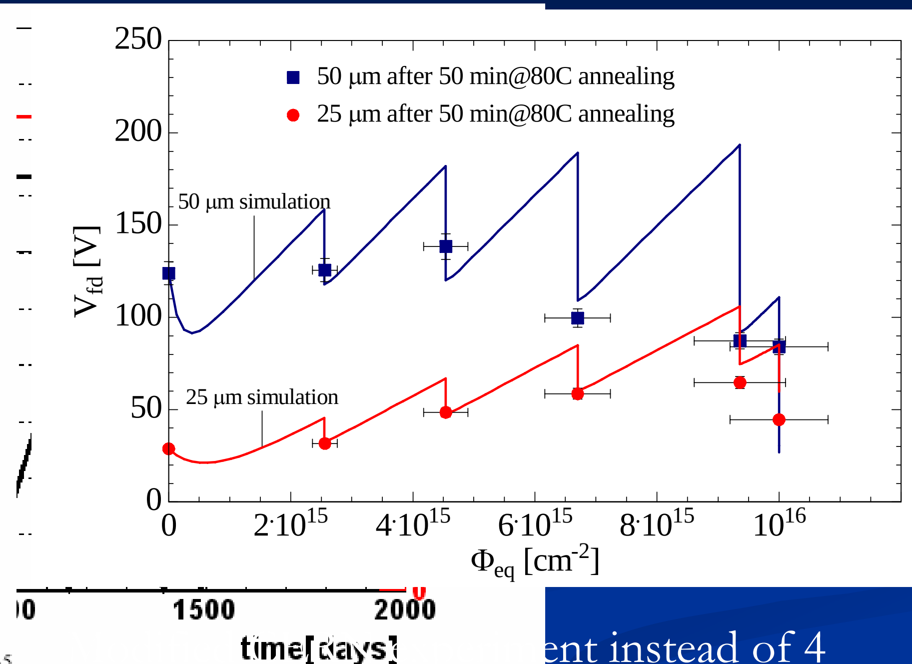
- the $\tau_{eff,e}$ renders the non-collecting side less important at high fluences
- $\tau_{eff,e}$ anneals with time and compensates the increase of $V_{fd}$ (average of know measurements is 40%)
- The un-depleted bulk is almost intrinsic – E field in the bulk is not zero

$$\frac{I_{leak}}{S} = \frac{1}{\rho} \cdot E \qquad \mathbf{E \sim 40V/cm}$$

## Is there a chance to have detectors depleted all the time and anneal the $\tau_{eff}$?

Epi-Si (n-type): with charged hadrons stable donors are introduced that can be compensated with acceptors from reverse annealing




Sta

$g_c$=0.0053 cm$^{-1}$ (DOFZ - acceptors)

Reverse annealing: $g_{y1}$=0.015 cm$^{-1}$ $g_{y2}$=0.068 cm$^{-1}$ (epi-Si , acceptors, 2 components)

$g_y$=0.048 cm$^{-1}$ (DOFZ - acceptors)

…ent instead of 4 min@80°C, 50 min @80°C is applied between steps!

Very good agreement with prediction!

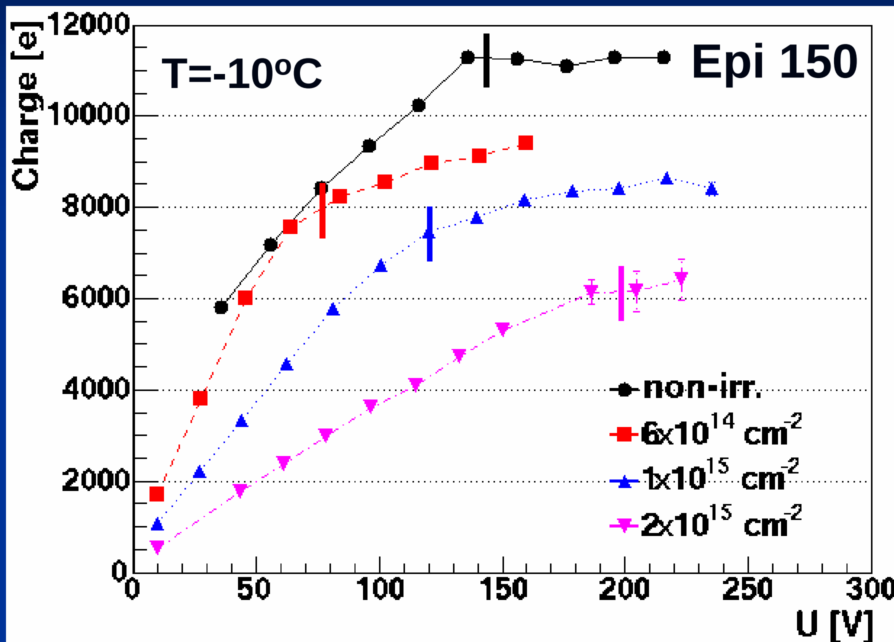
Scenario: T=266 K during operation T=295K, 290K, 286K, 283K during next years for the nonoperational periods!

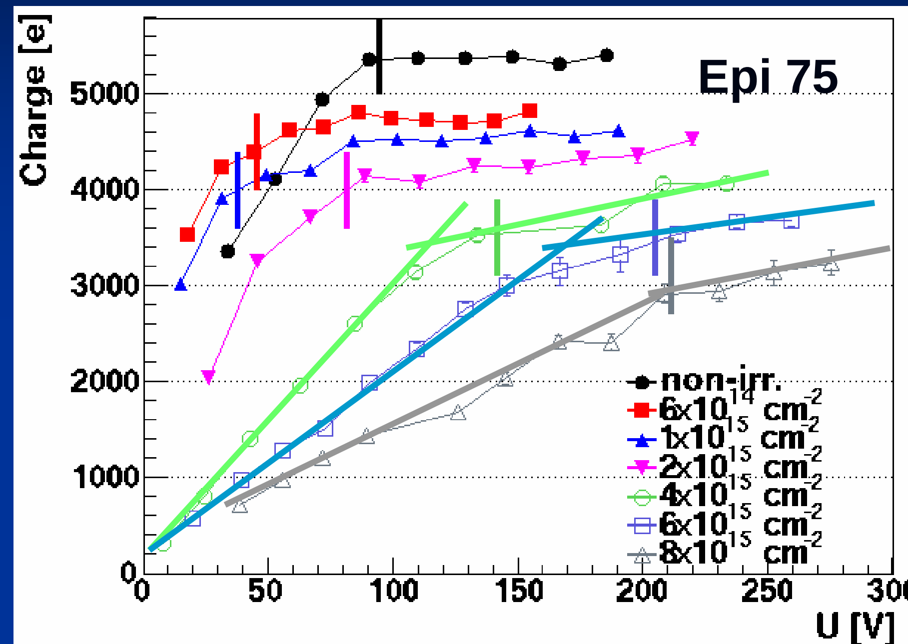
Keeping detectors are 300V Q>3000 e can be achieved!

Low operation voltage -> low power

Low leakage current -> low shot noise

# How about measurements?

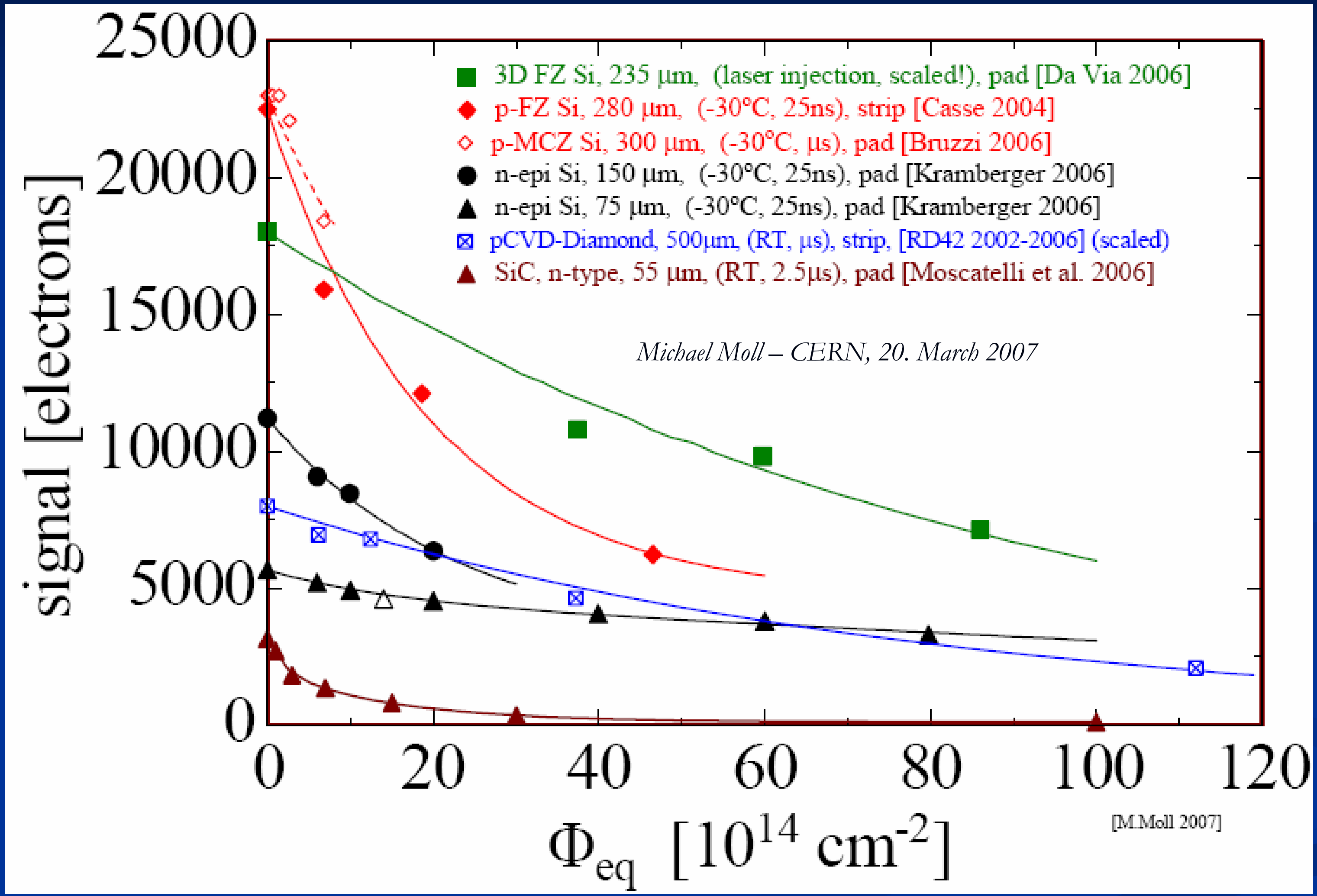



75 μm diodes perform superbly in term of noise (no break downs) also at very high fluences!

- Epi-si detectors processed by CiS (75 mm, 150Ωcm) and IRST (150 mm, 500Ωcm)
- Neutron irradiated and measured after 10 days at RT with LHC speed electronics!
- The $V_{fd}$ is denoted by line – nice correlation with kink in CCE!

# Summary of CCE results



# Conclusions

- Detectors of around 100-150 μm are good compromise between the signal and voltage needed to get it. With better electronics even less.
- In the ideal case we can get to >3000 e after $10^{16}$ $cm^{-2}$
- If possible the material should be chosen for which the annealing of detectors is beneficial
- Significant signals are induced in the neighbors due to charge trapping!

# How wrong is assumption of linear field.

The electric field in irradiated detectors deviates from linear ("double junction" field)!

- At $\Phi_{eq}$>few $10^{15}$ $cm^{-2}$ it is important to have E field present close to electrodes; e.g. even under-depleted detector can have larger Q than fully depleted one at given voltage
- The "ideal case" of "$N_{eff}$=0" isn't much better-> the difference get even smaller with $\Phi_{eq}$