Radiation effects on position sensitive semiconductor detectors

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Purpose of the lecture is to understand the concepts rather than list numerous results.

In spite of 2h it is not possible to cover everything and I apology if some topics were left uncovered --- that does not mean they are not important!

Based on my personal experience too much equations and numbers confuse listeners and make them fall asleep. Avoiding them makes the lectures less "scientific", but maybe more enjoyable. However it is not possible to be completely without …

It is impossible to start without any background. So the important numbers from yesterday…

- Silicon detectors are essentially "solid state ionization cells":
- Important numbers
  - ☐ signal of mip in 300 μm ~ 23000 e
  - ☐ Saturated velocity of: electrons ~110 μm/ns , ~80 μm/ns (drift time >= 4ns)
  - ☐ N_{eff} of orders 10^{12} cm^{-3} -> in 300 μm 10^{12} cm^{-3} corresponds to 70 V
  - ☐ Required S/N>8 (more conservative 10)

Outline

Some overlap
with other lectures

Basics on Silicon Sensors and Detector Systems P. Giubilato

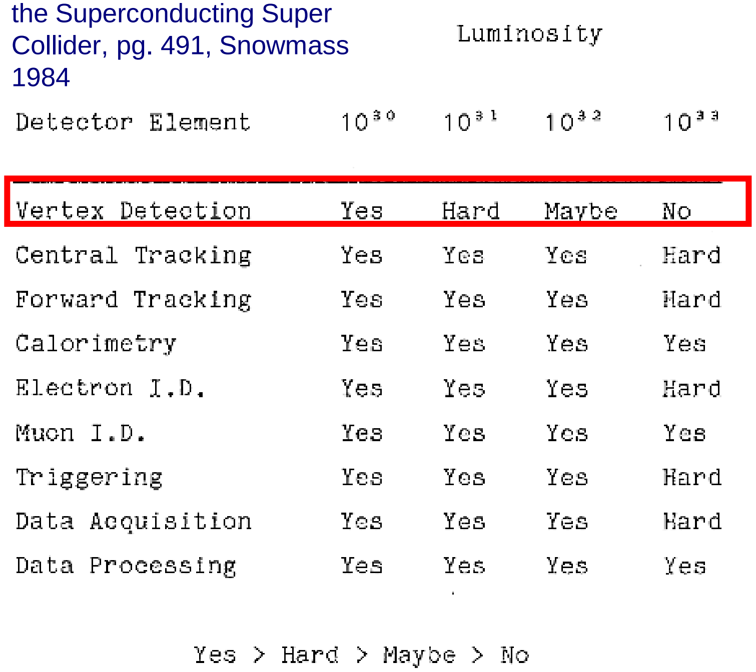
Microscopic damage in semiconductor detectors M.Bruzzi

- Motivation and basics
  - LHC …. HL-LHC, but also other fields
  - What are the challenges?
- Radiation damage
  - Fluence, dose, NIEL
  - Macroscopic effects on detector performance
  - Influence of radiation to signal and noise
- Radiation damage effects in silicon (material studies/engineering)
  - Leakage current
  - Effective doping concentration and electric field for different silicon materials: FZ, MCZ, DOFZ
  - Trapping of the charge
- Radiation effects in segmented detectors
  - p-in-n, n-in-n and n-in-p sensors
  - 3D sensors and thin devices
- Operation at very high fluences – recent highlights
  - Active bulk
  - Charge multiplication
  - Diamond detectors
- Conclusions

At all points shown how to get more radiation hard detectors

First considerations about radiation hardness for HEP - SSC

(Detectors and Experiments for the Superconducting Super Collider, pg. 491, Snowmass 1984



	Luminosity			
Detector Element	10^{30}	10^{31}	10^{32}	10^{33}
Vertex Detection	Yes	Hard	Maybe	No
Central Tracking	Yes	Yes	Yes	Hard
Forward Tracking	Yes	Yes	Yes	Hard
Calorimetry	Yes	Yes	Yes	Yes
Electron I.D.	Yes	Yes	Yes	Hard
Muon I.D.	Yes	Yes	Yes	Yes
Triggering	Yes	Yes	Yes	Hard
Data Acquisition	Yes	Yes	Yes	Hard
Data Processing	Yes	Yes	Yes	Yes

Yes > Hard > Maybe > No

“Silicon strip detectors (near the beam pipe) appear to be limited to…≤ 10^{32}….the 10^{32} limit could be optimistic.” (PSSC Summary Report pg. 130, 1984)

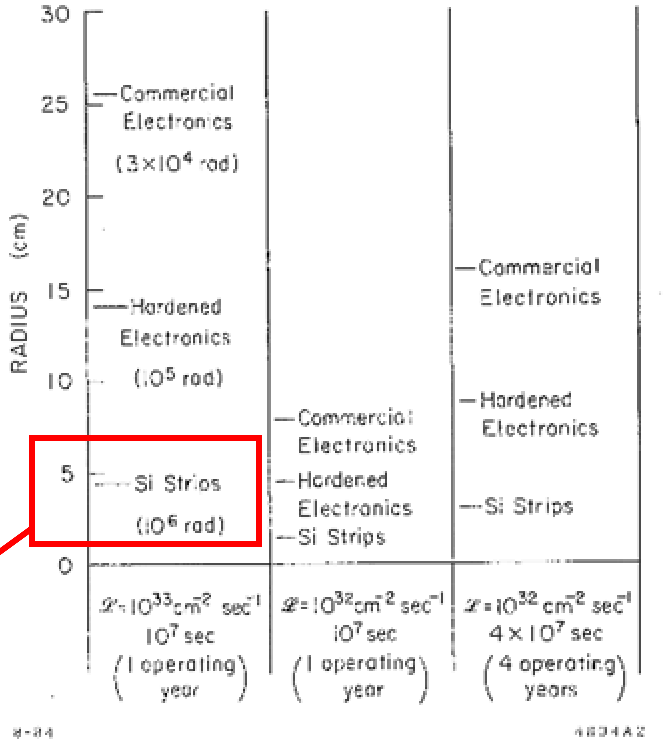


Fig. 1 Minimum component radii for radiation damage at luminosities of 10^{32} and 10^{33} cm^{-2} sec^{-1}.

T. Kondo et al, Radiation Damage Test of Silicon Microstrip Detectors, pg. 612, Snowmass 1984

And we are we know now …

LEP → HERA , Tevatron → LHC → HL-LHC

e^+e^- $1.5 \cdot 10^{31}$ $\mathrm{cm^{-2}\,s^{-1}}$ ep $7 \cdot 10^{31}$ $\mathrm{cm^{-2}\,s^{-1}}$ $\bar{p}p$ $1.4 \cdot 10^{32}$ $\mathrm{cm^{-2}\,s^{-1}}$ pp $\sim 10^{34}$ $\mathrm{cm^{-2}\,s^{-1}}$ pp 10^{35} $\mathrm{cm^{-2}\,s^{-1}}$?

90’ 2020

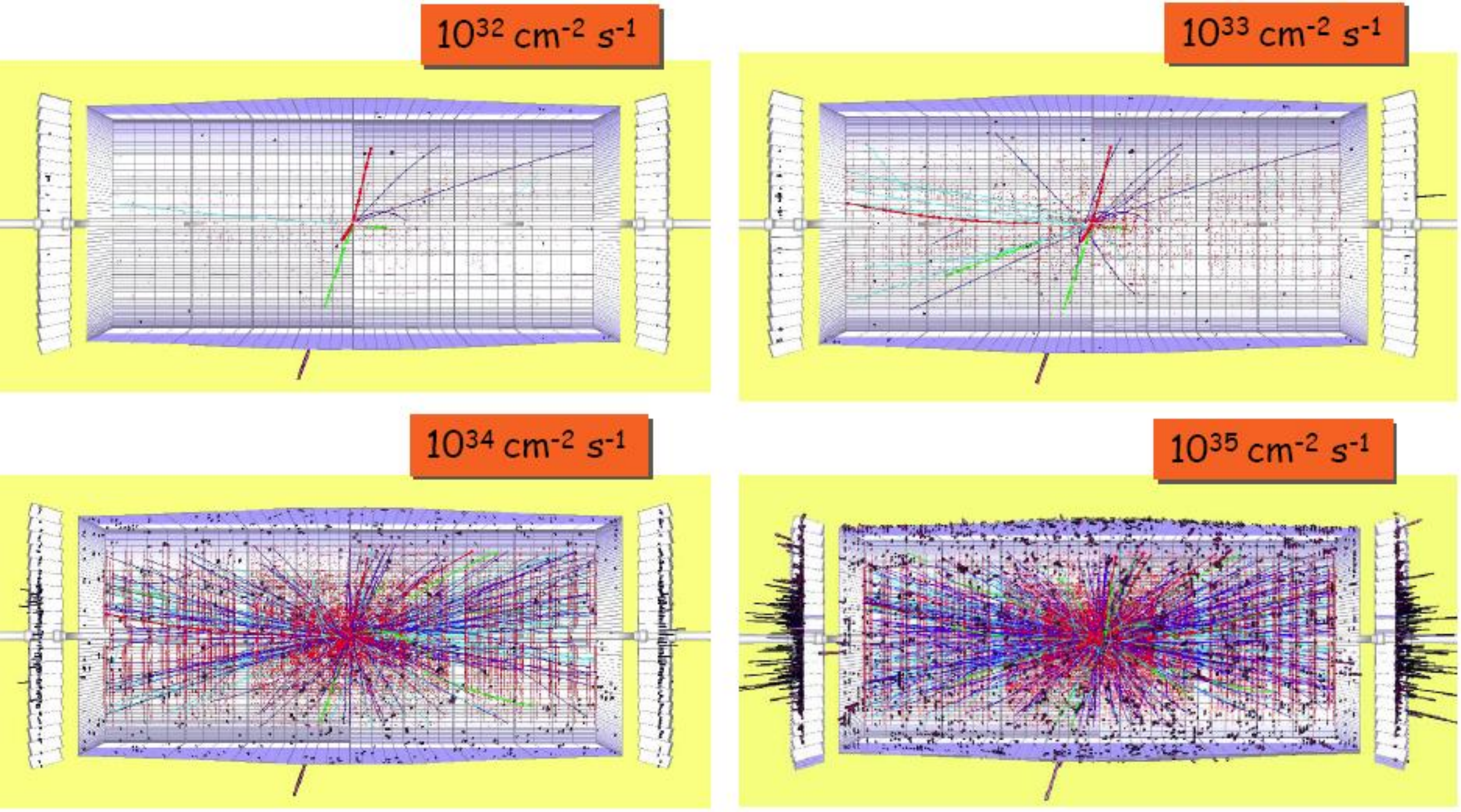
high collision rates -> more particles hitting the detectors -> larger damage
(at LHC ~20 collisions every 50 ns at present)

Amount of particles that hit the detectors is called fluence: $\Phi = \int \phi(t)\, dt$

But we are not alone …

medicine – smaller damage
space – smaller damage
fusion reactors – larger damage

The challenge: HL-LHC - visually



LHC luminosity

SLHC luminosity ~200-400 interactions/bx

Motivation for R&D on Radiation Tolerant Detectors HL-LHC

- **LHC upgrade**

⇨**LHC (2009)** **L = 10^{34}cm^{-2}s^{-1}**

10 years

500 fb^{-1}

ϕ(r=4cm) ~ $3\cdot10^{15}$cm^{-2}

× 5

⇨**HL-LHC (>2020)** **L = 10^{35}cm^{-2}s^{-1}**

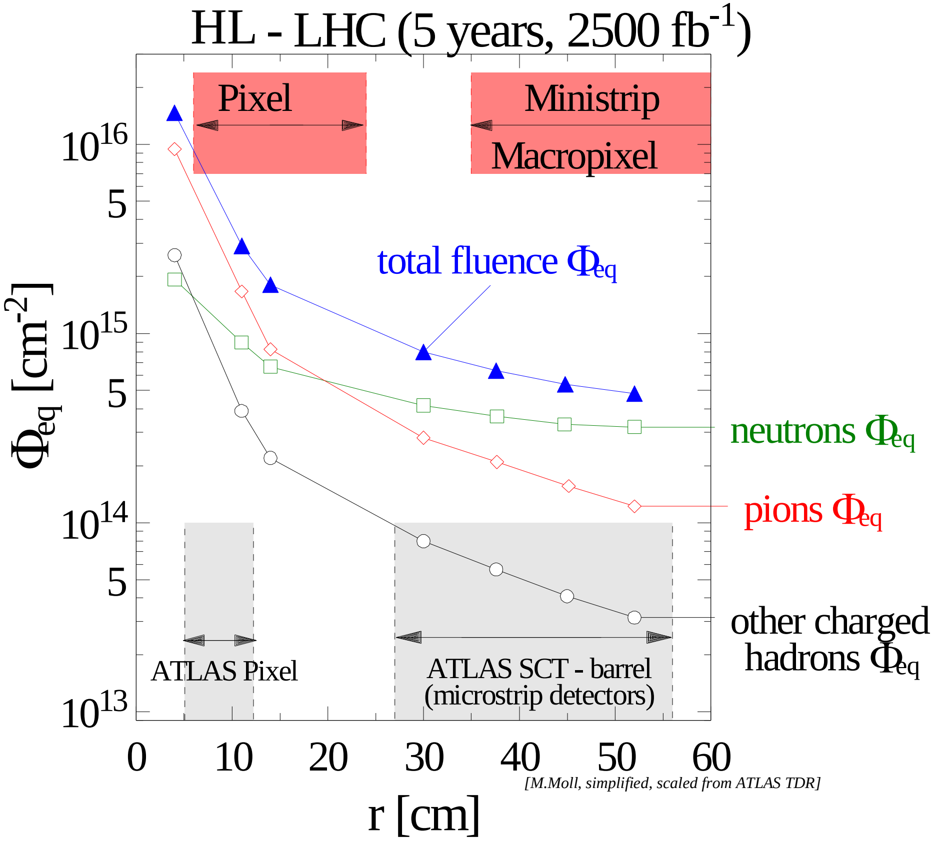
3000 fb^{-1}

ϕ(r=4cm) ~ $1.6\cdot10^{16}$cm^{-2}

- **LHC (Replacement of components)**

e.g. - LHCb Velo detectors
- ATLAS IBL

HL - LHC (5 years, 2500 fb^{-1})



[M.Moll, simplified, scaled from ATLAS TDR]

HL-LHC compared to LHC:

- Higher radiation levels ⇨ Higher radiation tolerance needed!
- Higher multiplicity ⇨ Higher granularity needed!

⇨ Need for new detectors & detector technologies

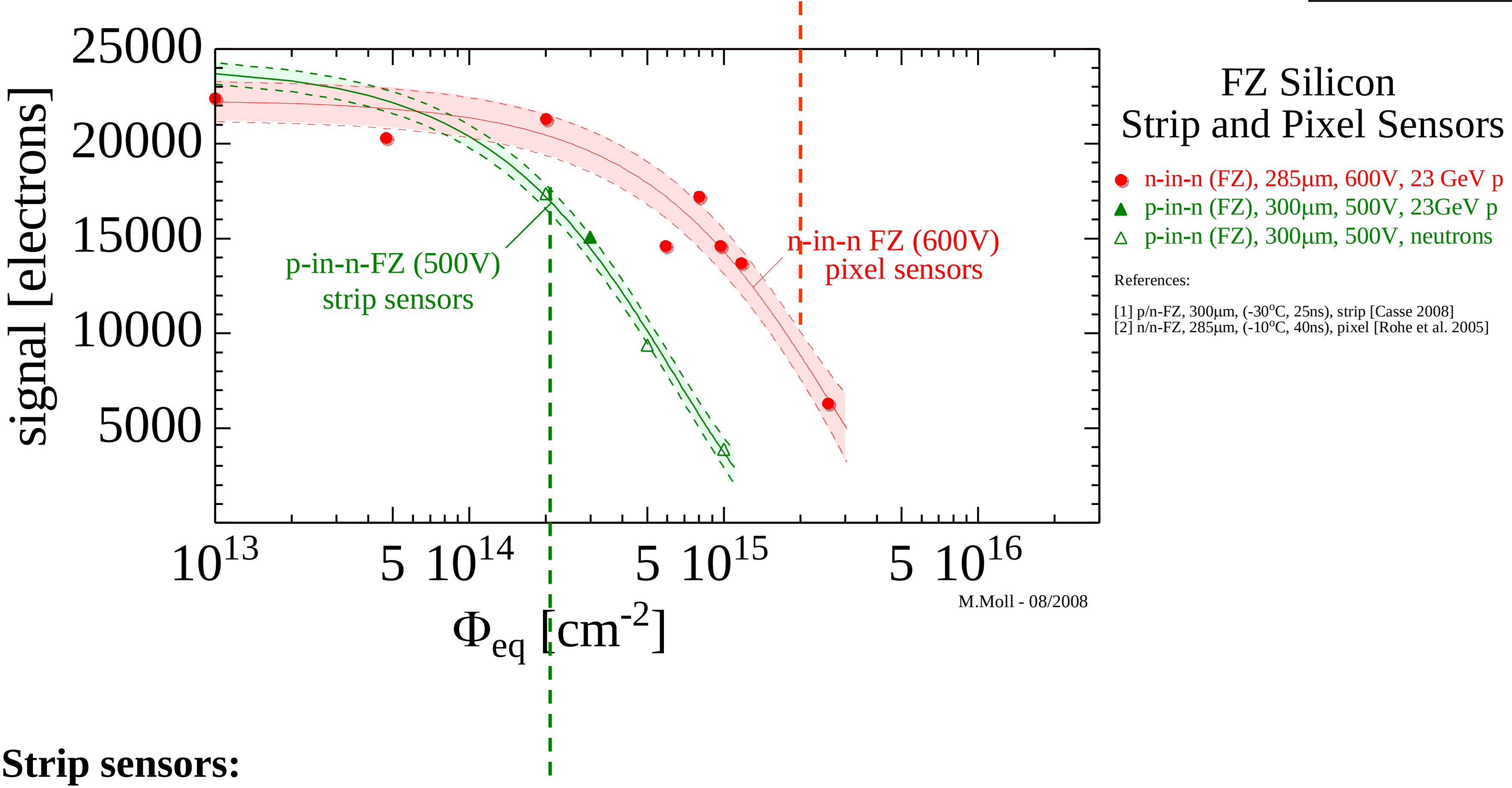
⇔

Power Consumption ?
Cooling ?
Connectivity
Low mass ?
Costs ?

Signal degradation for LHC Silicon Sensors

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

Pixel sensors:
max. cumulated fluence for LHC

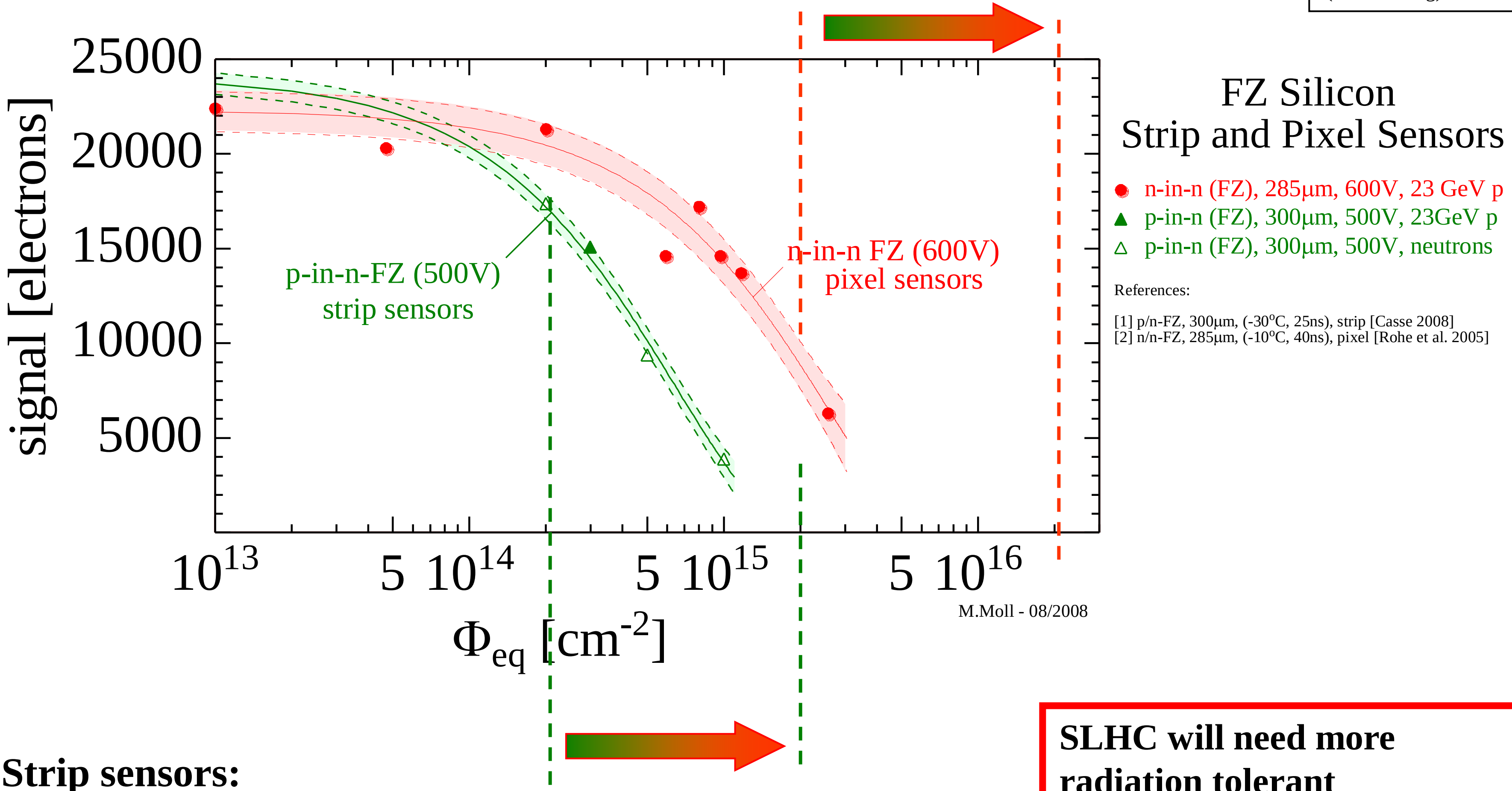


Strip sensors:
max. cumulated fluence for LHC

Signal degradation for LHC Silicon Sensors

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

Pixel sensors:
max. cumulated fluence for LHC and SLHC



Strip sensors:
max. cumulated fluence for LHC and SLHC

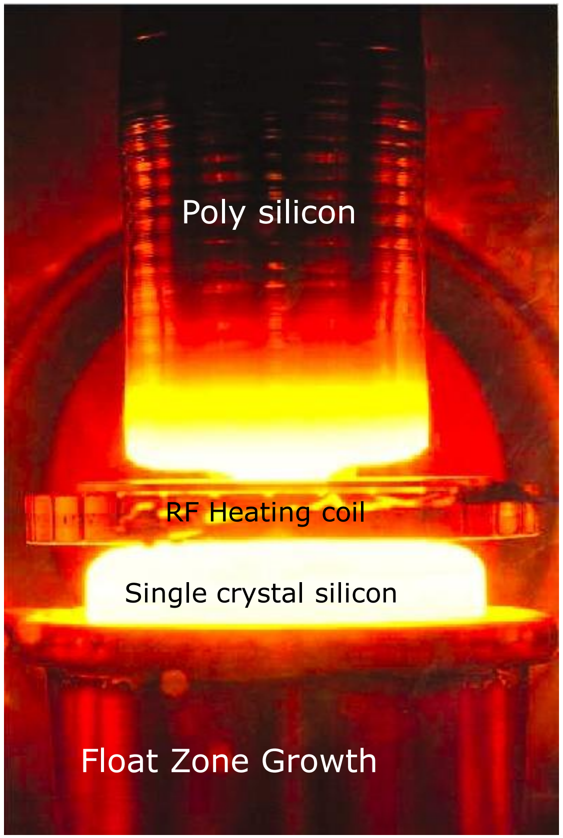
SLHC will need more radiation tolerant tracking detector concepts!

PART 2

Radiation damage and its impact

Silicon Growth Processes

Float zone Silicon (FZ)



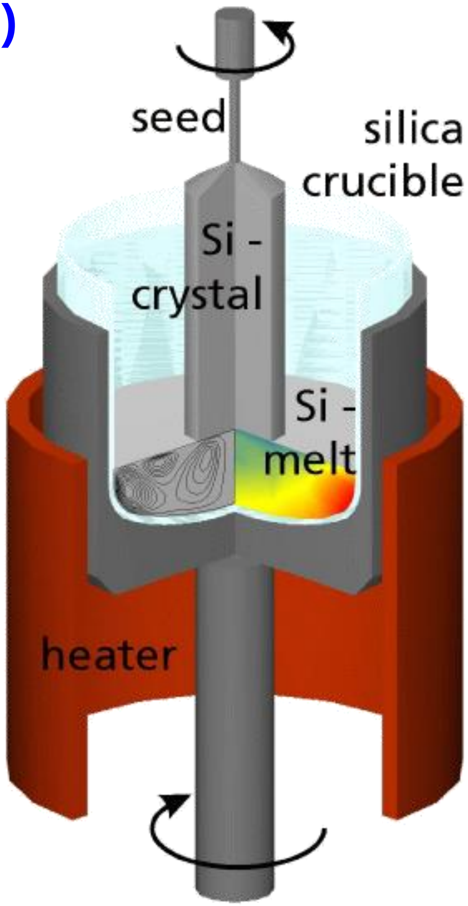
Float Zone Growth

- Basically all silicon tracking detectors made out of **FZ** silicon [O$_i$]< 5 × 10^{16} cm^{-3}
- Some pixel sensors: Diffusion Oxygenated FZ (**DOFZ**)silicon [O$_i$]~ 1-2 × 10^{17} cm^{-3}

Czochralski Silicon (CZ)

- The growth method used by the IC industry.
- Difficult to produce very high resistivity
- [O$_i$] ~ 5 × 10^{17} cm^{-3}

Czochralski Growth



Epitaxial Silicon (EPI)

- Chemical-Vapor Deposition (CVD) of Si
- up to 150 μm thick layers produced
- growth rate about 1μm/min

Types of radiation damage

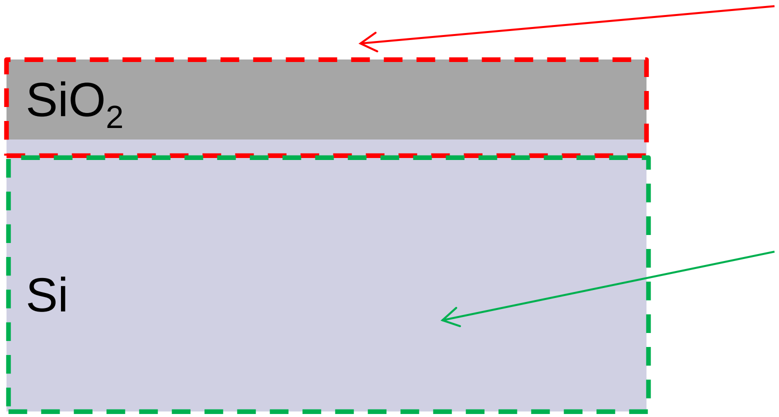
Two types of radiation damage in detector materials:

- **Bulk (Crystal) damage** due to **Non Ionizing Energy Loss (NIEL)**

  - displacement damage, built up of crystal defects –

- **Surface damage** due to **Ionizing Energy Loss (IEL)**

  - accumulation of charge in the oxide (SiO_2), traps at Si/SiO_2 interface –



Region affected by ionizing energy loss - surface damage

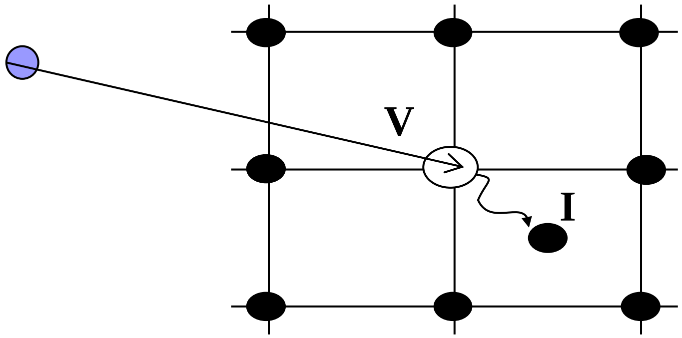
Region affected by non-ionizing energy loss - bulk damage

Generation of bulk damage (I)

Imping particle hits the lattice atom and knocks it out of the lattice site.

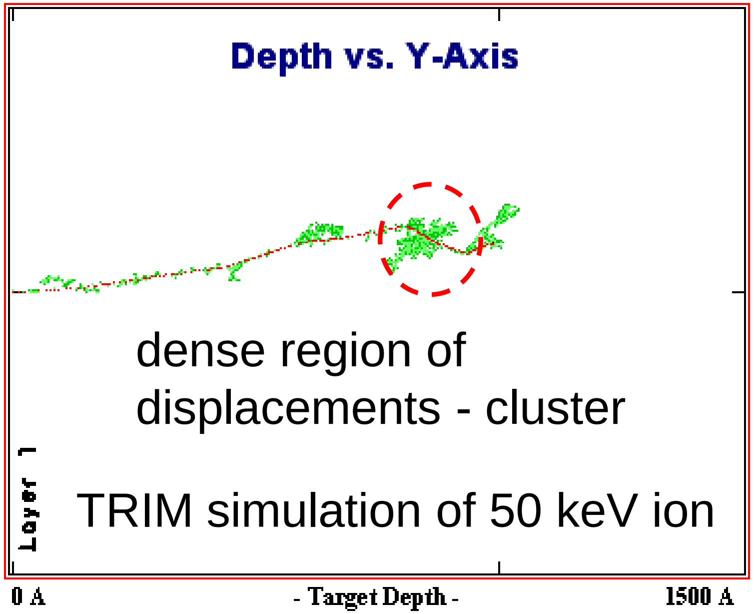
- energy of E_k>25 eV is required for formation of a Frenkel pair (point defects)
- for E_k>5 keV than knocked off atom displaces further lattice atoms (cluster defects)

$E_K > 25$ eV



Frekel pair – (Vacancy-Interstitial pair)

$E_K > 5$ keV



dense region of displacements - cluster

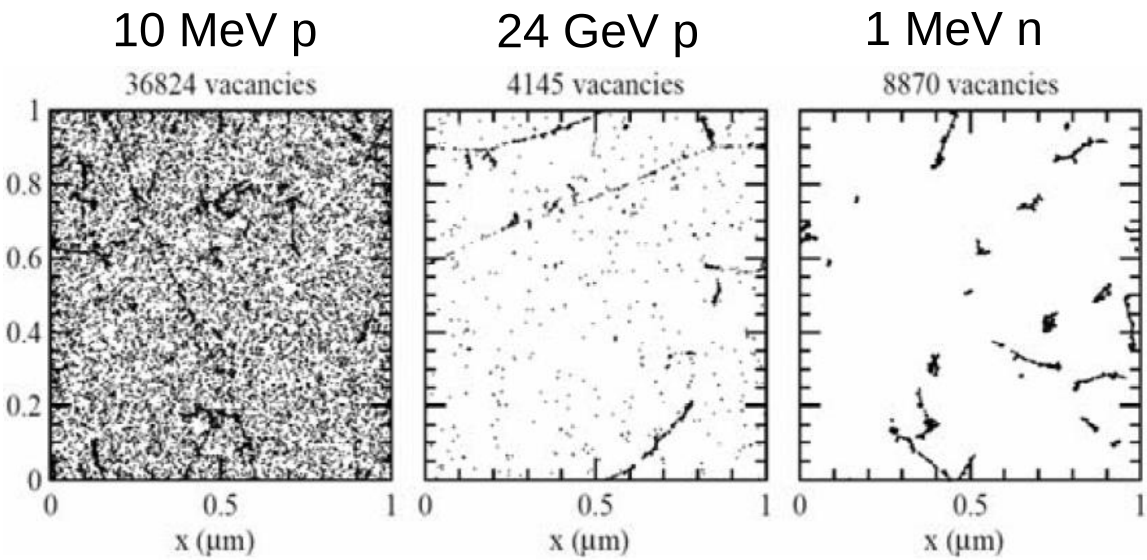
TRIM simulation of 50 keV ion

Vacancies and Interstitial migrate in the crystal and react with other V,I or impurities.

Generation of bulk damage (II)

How much clusters/point defects are produced by impinging particle depends on particle type and energy.

- reactor neutrons – more clusters , less point defects
- 24 GeV protons – both in similar share
- 10 MeV protons – more point defects less clusters
- γ with < 8 MeV – only point defects



Generation of bulk damage (III)

How do we then compare the fluences of different particles?

NIEL hypothesis – the damage effects in silicon depend only on the non-ionizing energy loss regardless of the particle type and energy.

It is wrong (not extremely) for some radiation damage effects, but correct for leakage current. Still serves as a reference point.

One can normalize different particle fluences to the equivalent fluence of 1 MeV neutrons – equivalent fluence.

$$\Phi_{eq} = \kappa_x \Phi_x$$

κ_p = 0.62 (24 GeV protons)
κ_p = 1.85 (26 MeV protons)
κ_π = 1.14 (300 MeV pions)
κ_n = 0.92 (reactor neutrons >100 keV)

Effects of bulk damage to detector operation

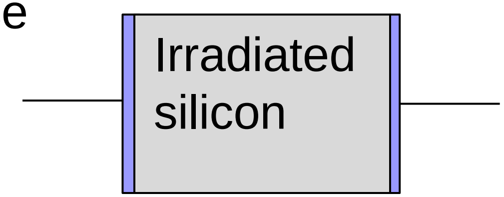
I. Increase of **leakage current** (increase of shot noise, thermal runaway)

II. Change of **effective doping concentration**
(higher depletion voltage, under- depletion)

III Increase of **charge carrier trapping** (loss of charge)

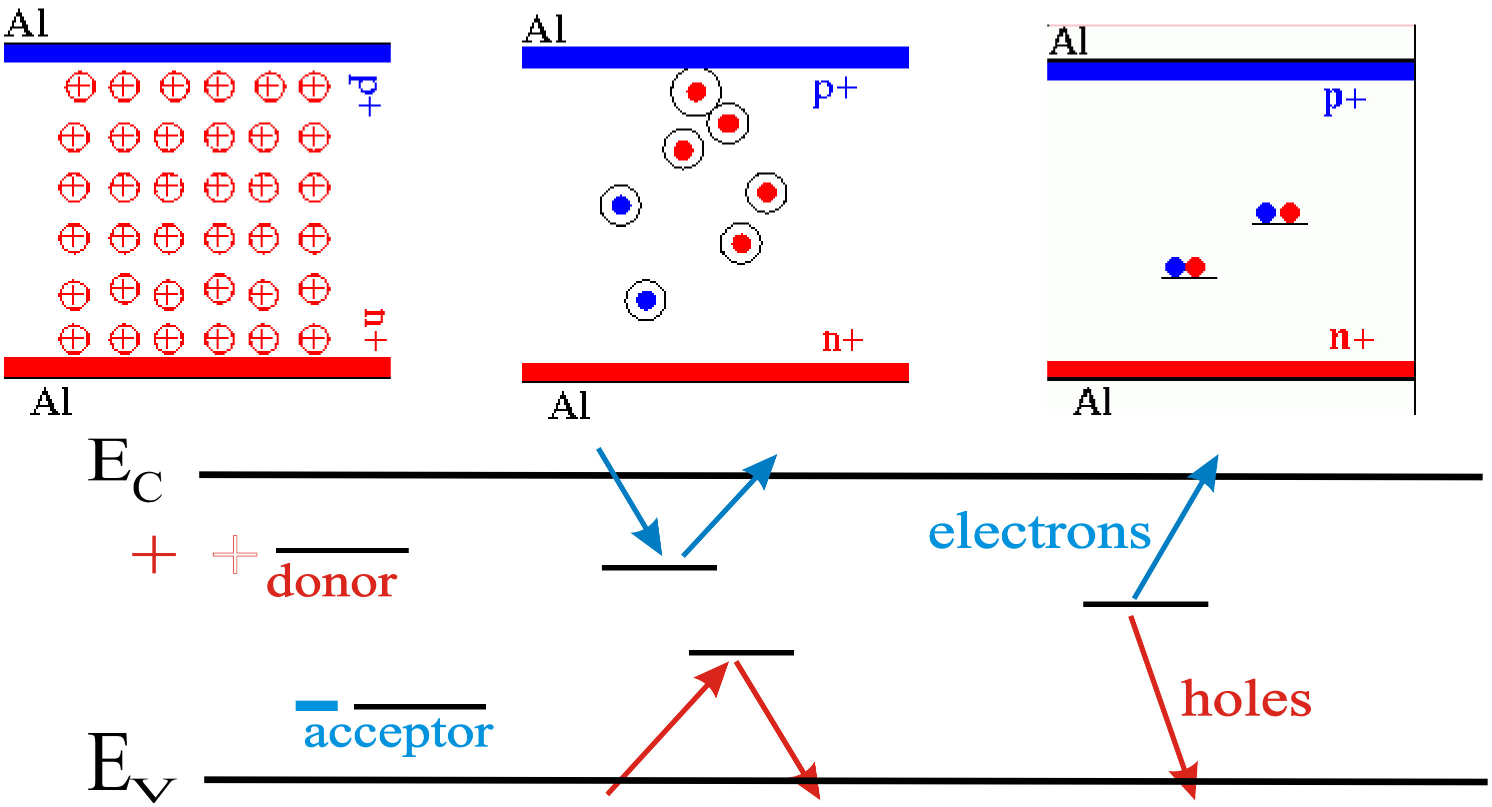
IV. Increase of silicon **resistivity**

The resistivity of silicon bulk increases with fluence -deep defects push Fermi level close to mid-gap and the material becomes highly resistive. The upper limit is set by intrinsic silicon.



Irradiated silicon

Effects of bulk damage to detector operation



charged defects

⇒ N_{eff} , V_{dep}

e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)

⇒ CCE

shallow defects do not contribute at room temperature due to fast detrapping

generation

⇒ leakage current, N_{eff}

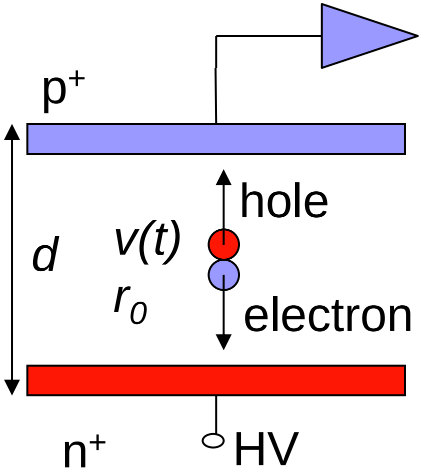
Levels close to mid-gap most effective

Signal in semiconductor detector (pad)

$$I(t) = q\ \vec{E}_w \cdot \vec{v}(t)$$

$$Q = \int_{t=0}^{t} I\,dt = q \int_{t=0}^{t} \vec{v}\vec{E}_w\,dt = q \int_{\vec{r}_0}^{\vec{r}(t)} \vec{E}_w\,d\vec{r}$$

$$\boxed{\begin{aligned} Q &= q[U_w(\vec{r}) - U_w(\vec{r}_0)] \\ Q_{e-h} &= Q_e + Q_h \end{aligned}}$$



Weighting field

$\nabla^2 U_w = 0,\ \vec{E}_w = -\nabla U_w$

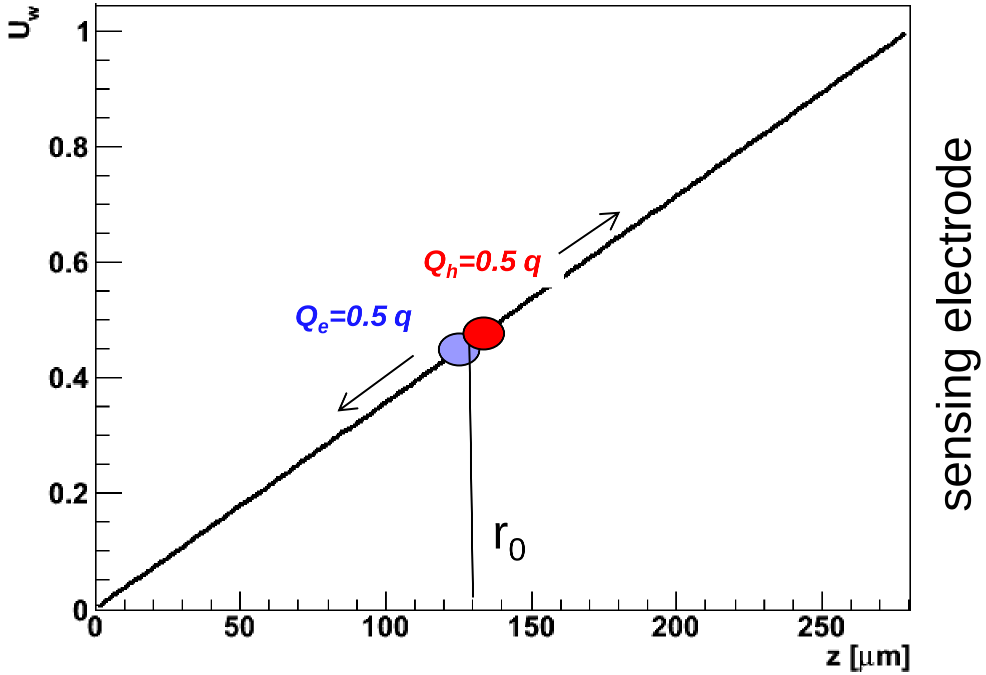
$U_w = 1$ ⟶ sensing electrode

$U_w = 0$ ⟶ all other electrodes

$$Q_{e-h} = e_0 \cdot \left(1 - \frac{r_0}{d}\right) + e_0 \frac{r_0}{d} = e_0$$

What if the drift is not completed?

- Ballistic deficit – short integration
- Charge trapping

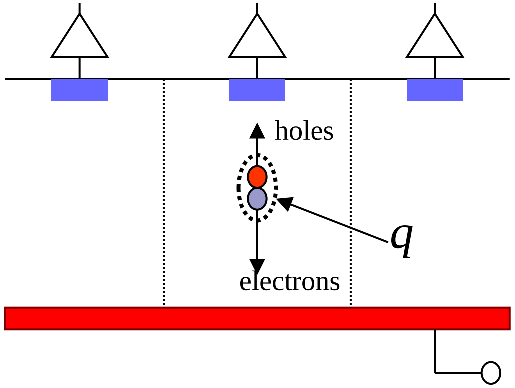


Signal in semiconductor detector (strip)

$$I(t) = q \; \vec{E}_w \cdot \vec{v}(t)$$

$$Q = \int_{t=0}^{t} I dt = q \int_{t=0}^{t} \vec{v}\vec{E}_w dt = q \int_{\vec{r}_0}^{\vec{r}(t)} \vec{E}_w d\vec{r}$$

$$\boxed{\begin{array}{l} Q = q[U_w(\vec{r}) - U_w(\vec{r}_0)] \\ Q_{e-h} = Q_e + Q_h \end{array}}$$

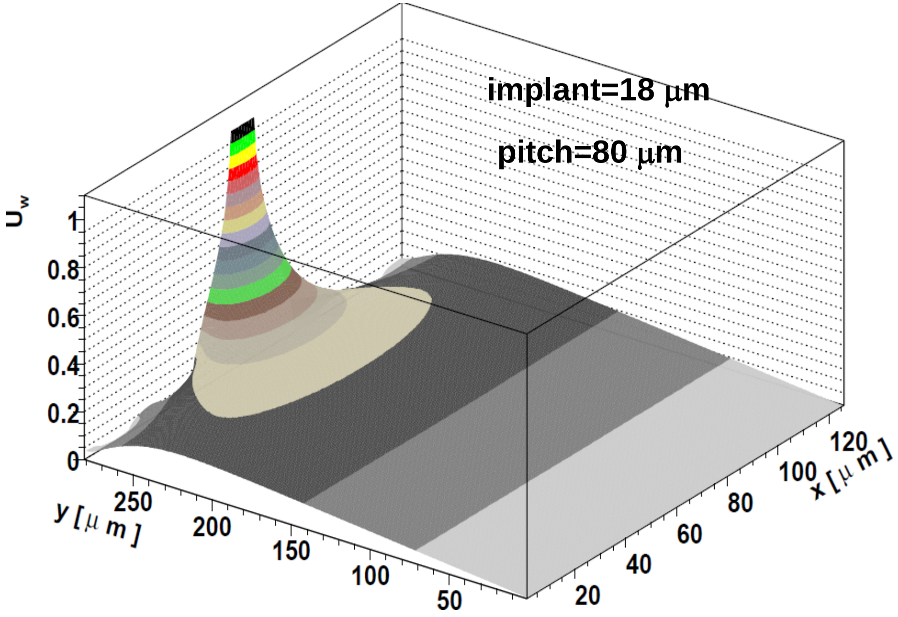


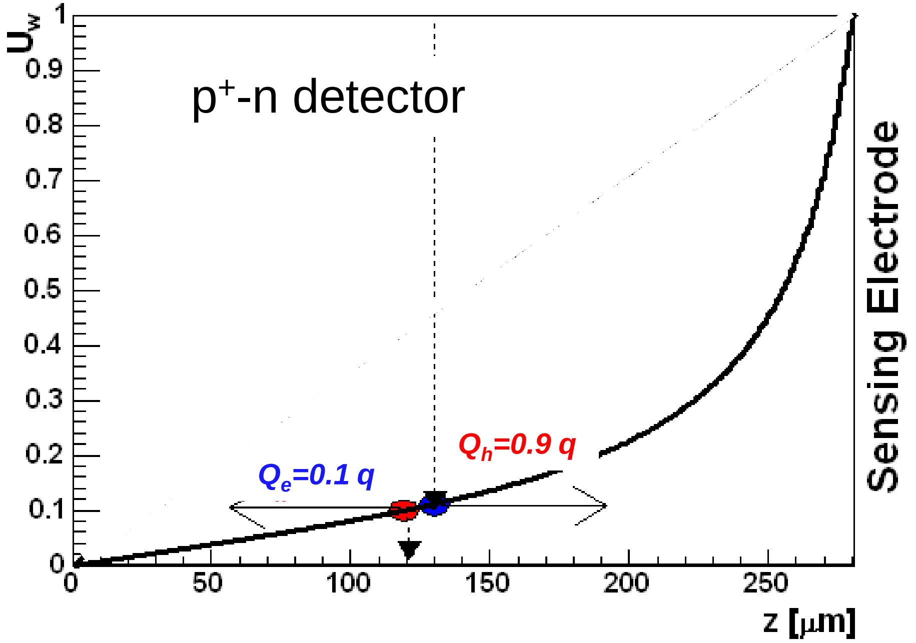
Weighting field

$$\nabla^2 U_w = 0$$

$U_w = 1$ → sensing electrode

$U_w = 0$ → all other electrodes





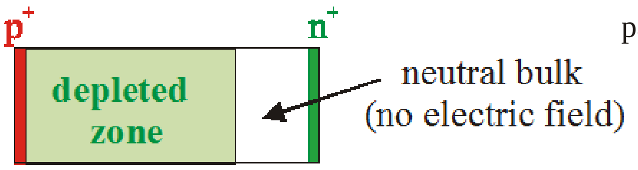
Signal in semiconductor detectors (electric field)

We are really interested in the electric field:

$$\boxed{\vec{E} = -\nabla U(\vec{r}) \quad , \quad \nabla^2 U(\vec{r}) = -\frac{e_0 N_{eff}(\vec{r})}{\varepsilon\varepsilon_0}}$$

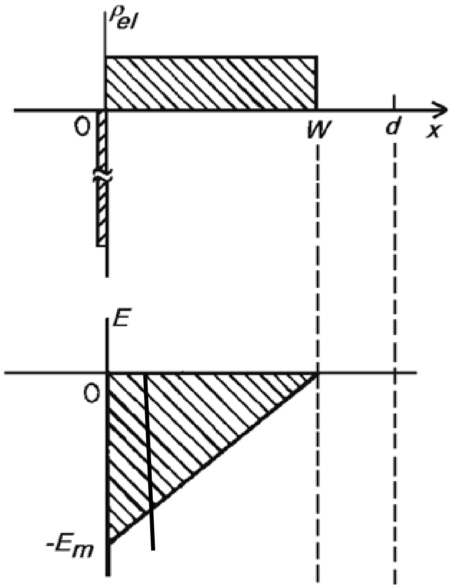
SIMPLEST CASE OF ALL : 1D , N_{eff}=const.

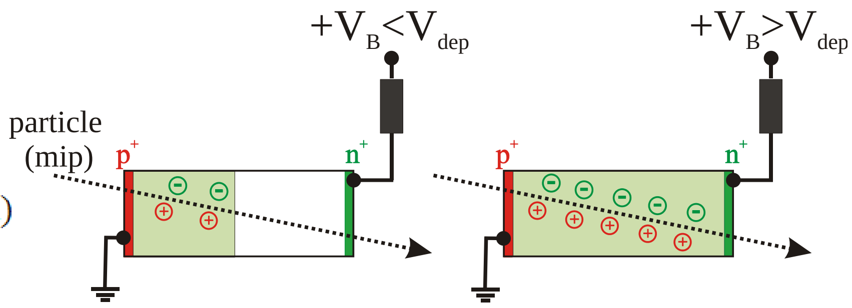
Positive space charge,
N_{eff} =[P]
(ionized Phosphorus
atoms)



Electrical charge density

Electrical field strength





Full charge collection only for $V_B>V_{dep}$!

depletion voltage

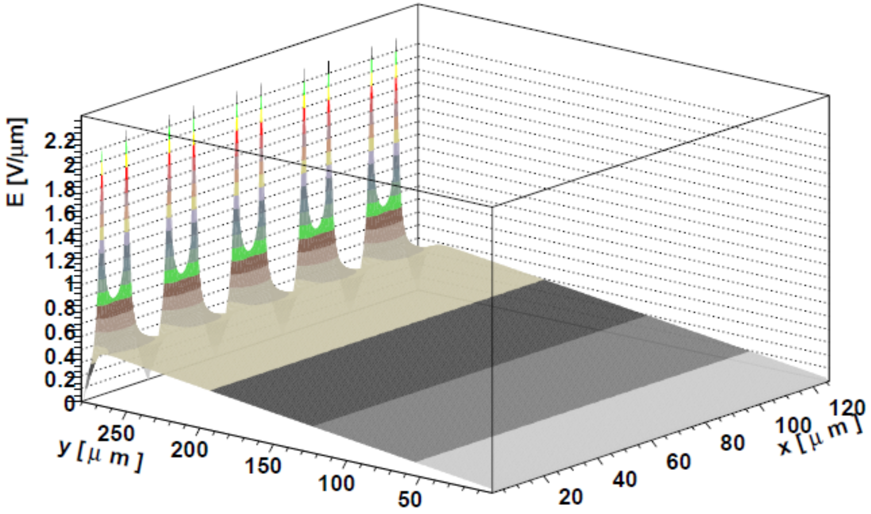
$$\boxed{V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2}$$

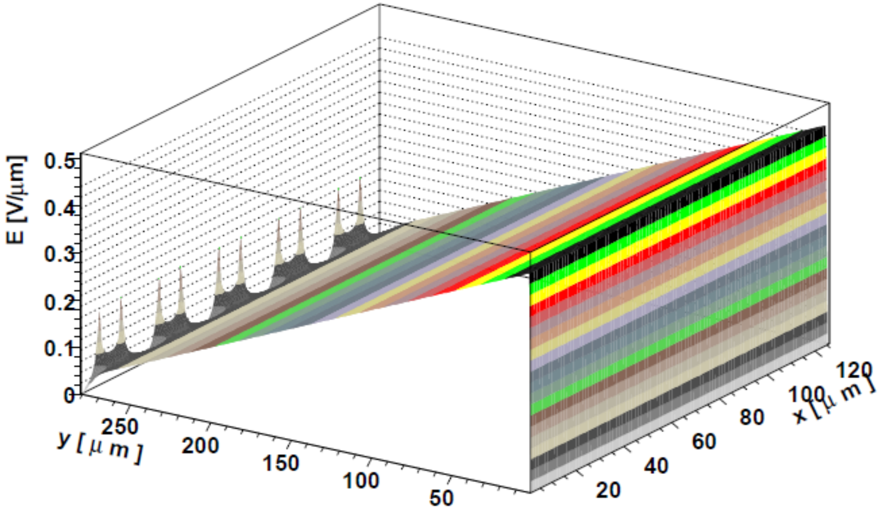
effective space charge density

Signal in semiconductor detectors (electric field)

A MORE COMPLICATED CASE : 2D , N_{eff}=const.

e.g. : 280 μm thick detector, 25 μm strip pitch, 10 μm strip width

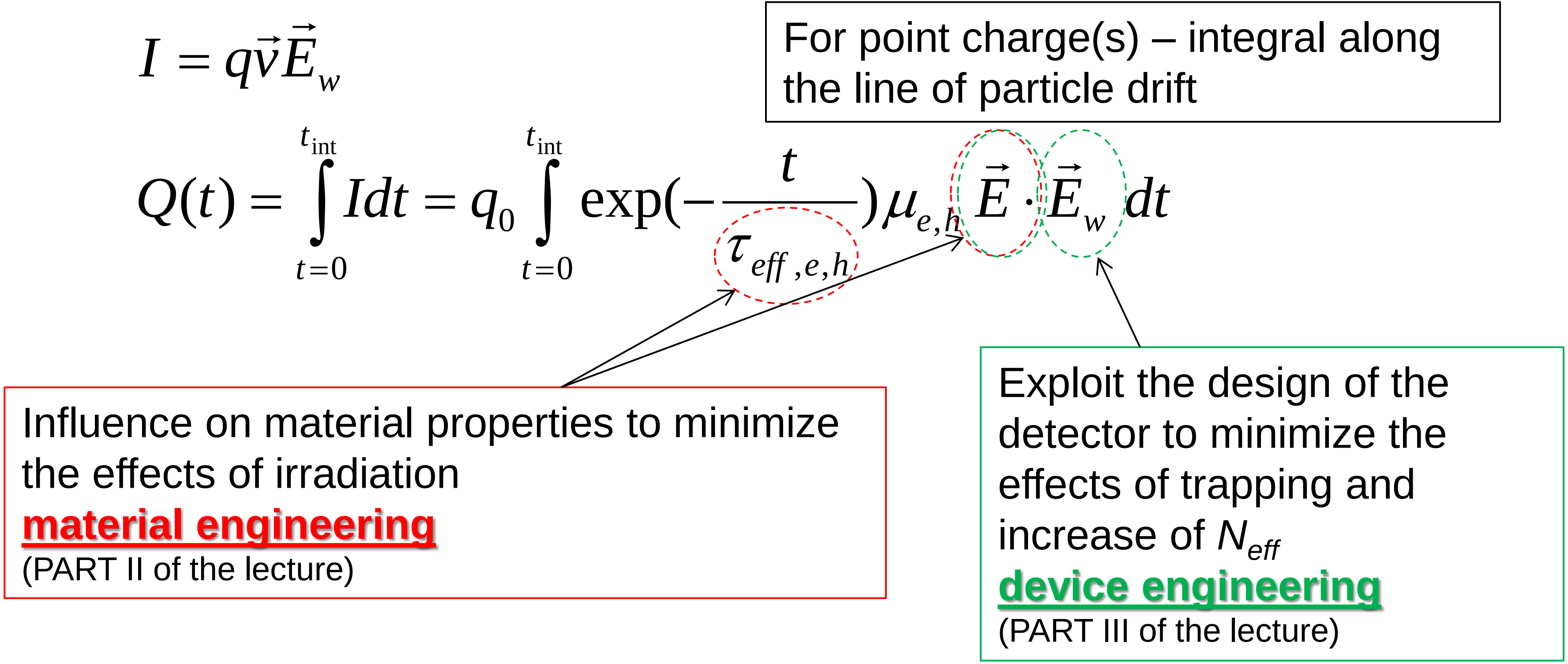




N_{eff} determines the electric field in the detector!

Signal in semiconductor detector - trapping

In irradiated detector there comes the trapping term. Each individual charge drifts until it is trapped – the probability that it will drift over certain distance decreases exponentially (for $v_d << v_{th}$):



$$I = q\vec{v}\vec{E}_w$$

For point charge(s) – integral along the line of particle drift

$$Q(t) = \int_{t=0}^{t_{\text{int}}} I\,dt = q_0 \int_{t=0}^{t_{\text{int}}} \exp\left(-\frac{t}{\tau_{eff,e,h}}\right)\mu_{e,h}\,\vec{E}\cdot\vec{E}_w\,dt$$

Influence on material properties to minimize the effects of irradiation
material engineering
(PART II of the lecture)

Exploit the design of the detector to minimize the effects of trapping and increase of N_{eff}
device engineering
(PART III of the lecture)

Everything is much simpler in pad detector – suitable for material studies.

Noise in semiconductor detectors

Remember we look for high Signal/noise ratio (most important quantity)

$$ENC^2 = ENC_S{}^2 + ENC_P{}^2$$

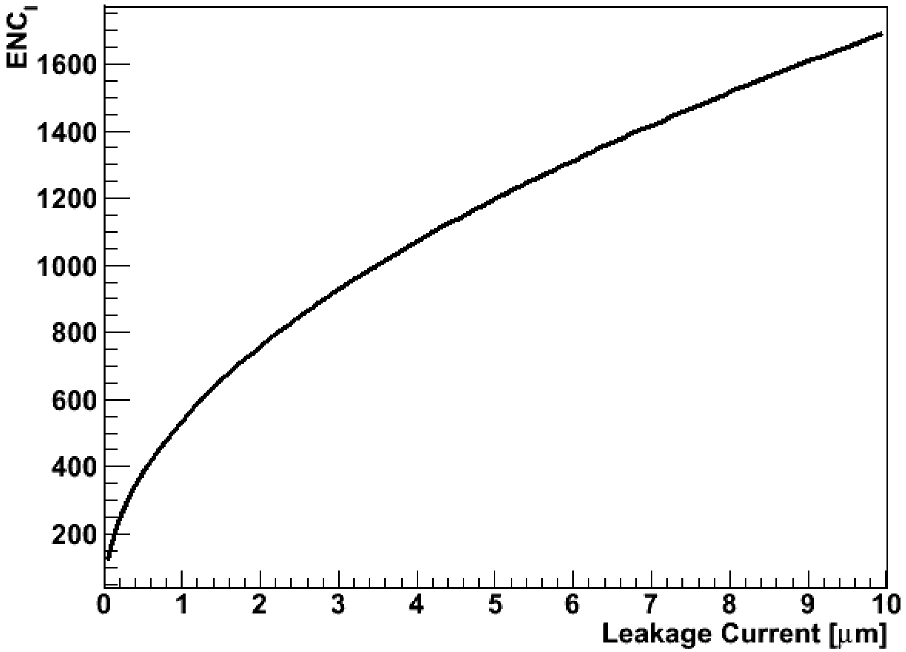
$$ENC_S = a + b \cdot C$$

Inter-strip capacitance can change due to interface states/traps, but at typical frequencies of 1 GHz the impact is questionable.

$$ENC_p{}^2 = ENC_I{}^2 + \ldots$$

$$ENC_I = \frac{e}{2e_0}\sqrt{e_0 I_{leak} t_{\mathrm{int}}}$$

a and b should be optimized for the readout, to render *ENC*$_p$ less important.



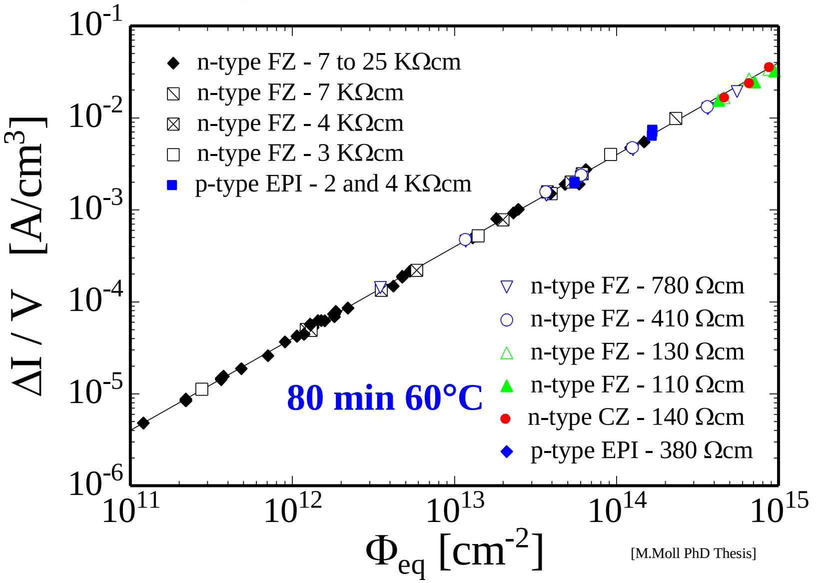
PART 3

Radiation damage effects in silicon (material studies/engineering)

Leakage current

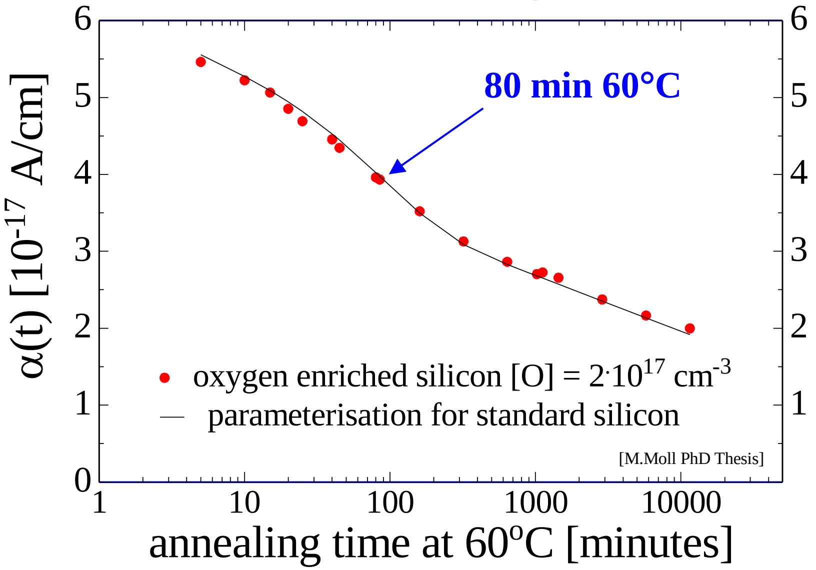
- ***Change of Leakage Current (after hadron irradiation) -> increase of noise***

…. with particle fluence:



[M.Moll PhD Thesis]

…. with time (annealing):



[M.Moll PhD Thesis]

- **Damage parameter α (slope in figure)**

$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$

Leakage current
per unit volume
and particle fluence

- **α is constant over several orders of fluence and independent of impurity concentration in Si**
  ⇨ **can be used for fluence measurement**

- **Leakage current decreasing in time (depending on temperature)**
- **Strong temperature dependence**

$$I \propto \exp\left(-\left.E_g\middle/2k_B T\right.\right)$$

Consequence:

Cool detectors during operation!
Example: *I*(-10°C) ~1/16 *I*(20°C)

Effective doping concentration - N_{eff}

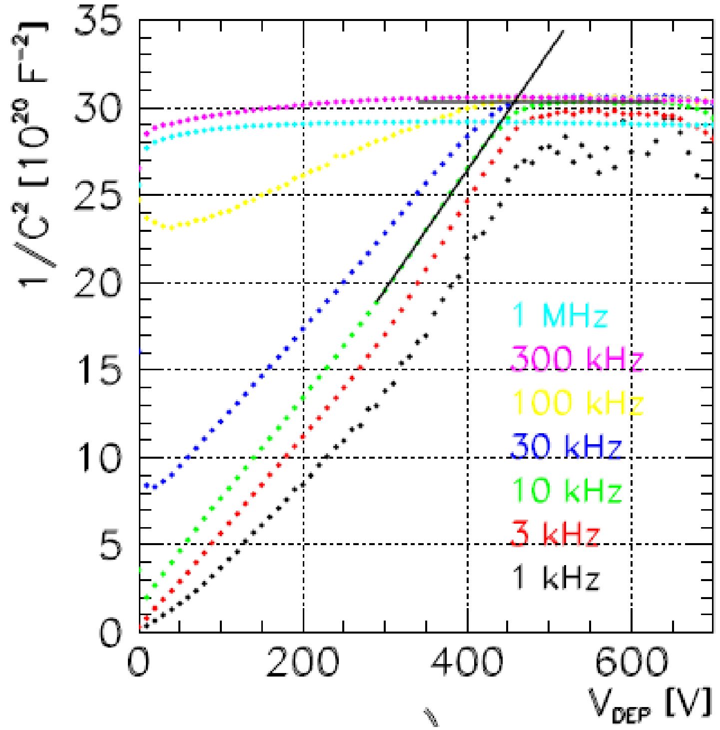
How do we measure Neff and V_{dep}?

Capacitance measurement

V_{dep} from looking at C_{geom}

$$C_{\det}(V) = \varepsilon\varepsilon_0 \frac{S}{w(V)} \rightarrow C_{\det}(V_{dep}) = C_{geom} = \varepsilon\varepsilon_0 \frac{S}{d}$$

$$\boxed{V_{dep} = \frac{q_0}{\varepsilon\varepsilon_0}\cdot\left|N_{eff}\right|\cdot d^2}$$



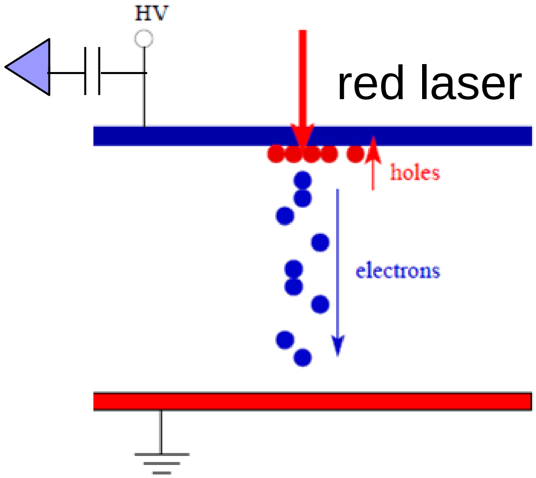
The capacitance measurement has been the workhorse of radiation damage studies for decades.

C-V becomes unreliable at high fluences:

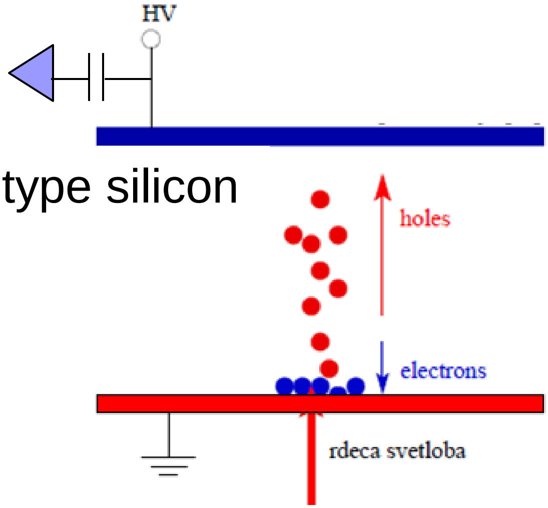
- Undepleted bulk becomes highly resistive
- Charging and discharging the traps is frequency and temperature dependent

Transient current technique and space charge

$$I_{e,h}(t) = e_0 \cdot N_{e,h} \cdot \exp(-t/\tau_{eff,e,h}) \cdot \frac{v_{e,h}(t)}{d} \approx \frac{e_0 \cdot N_{e,h} \cdot \mu_{e,h}}{d} \cdot \exp(-t/\tau_{eff,e,h}) \cdot E(t)$$

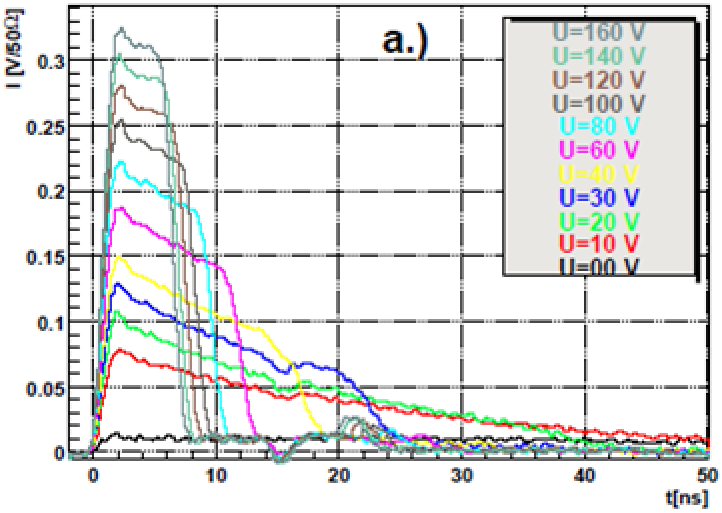


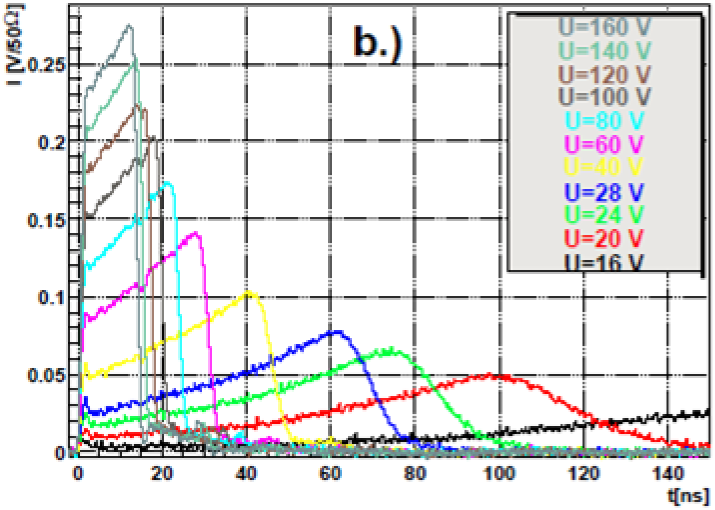
red laser pulse



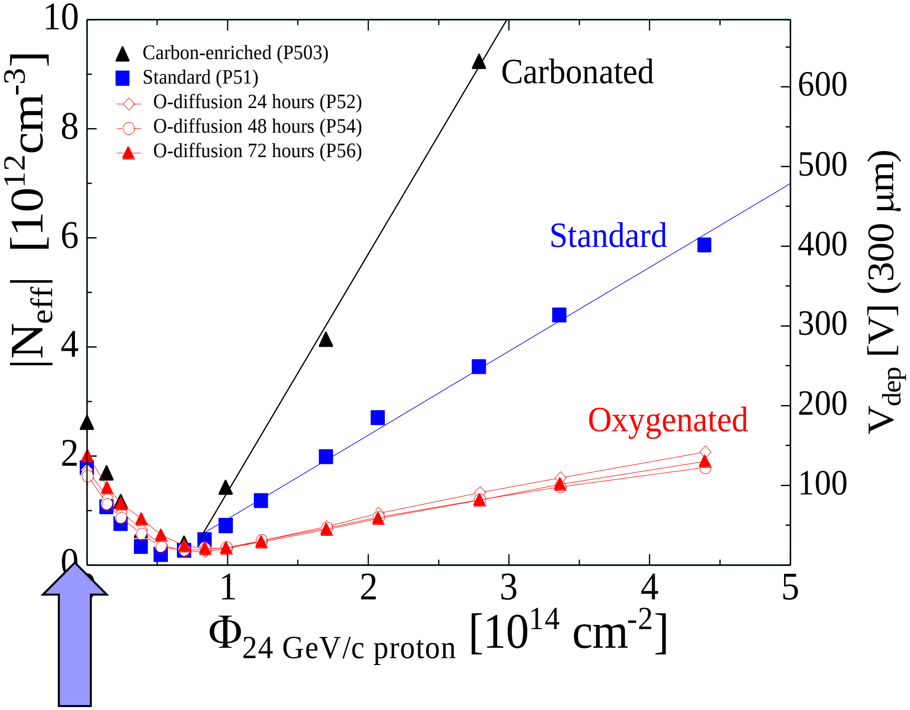
n-type silicon

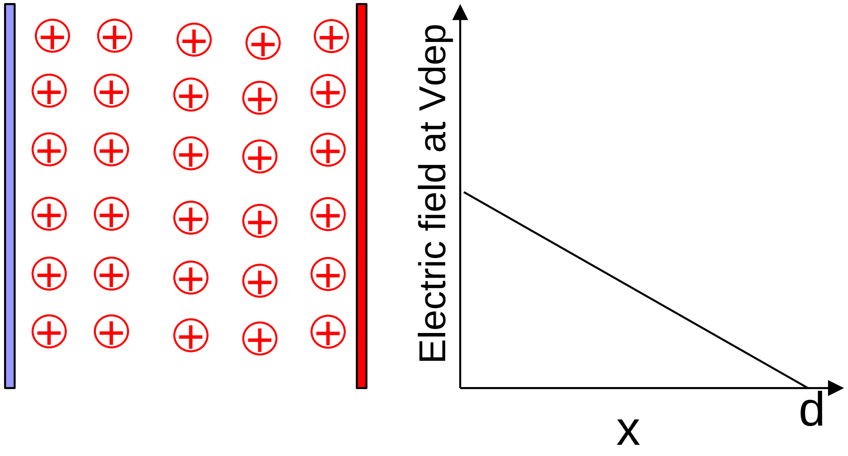
Non-irradiated sensor





Evolution of V_{dep} with fluence …

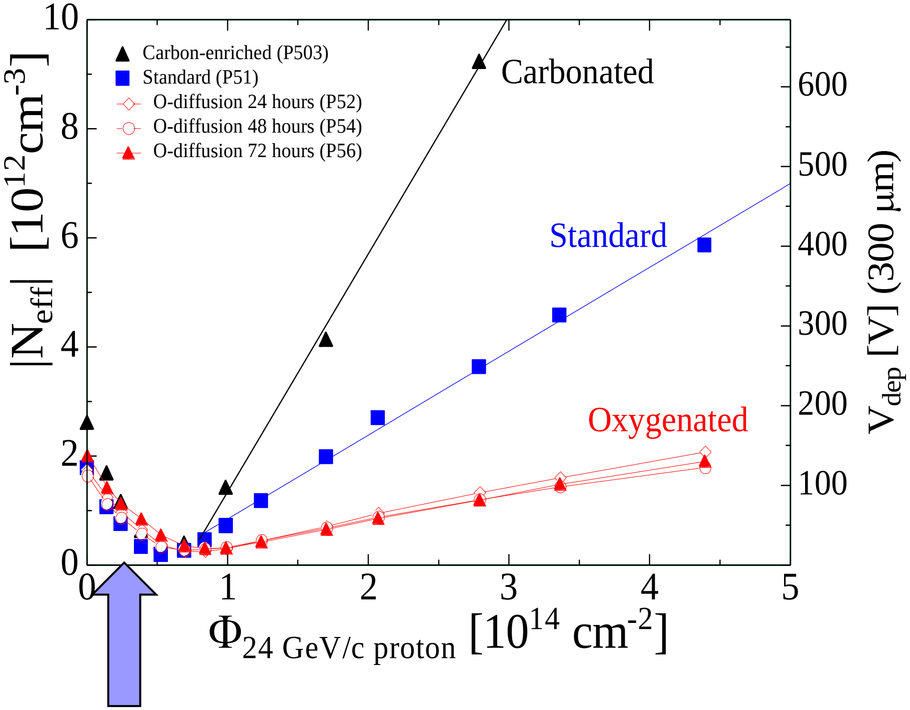


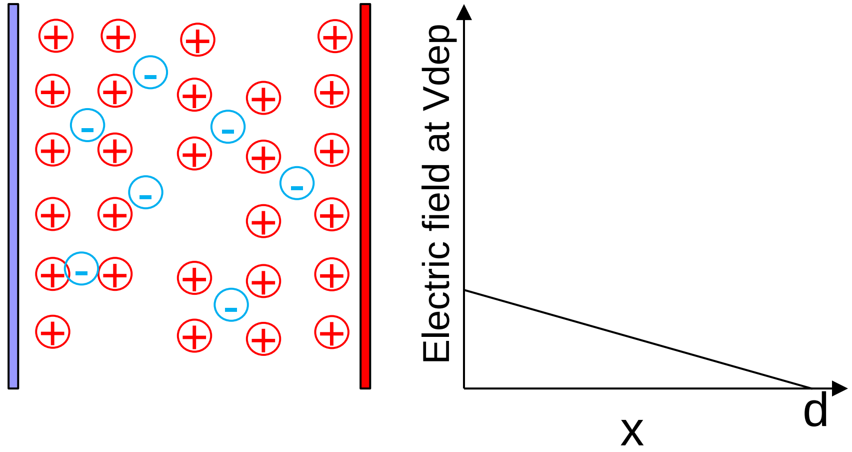


RD48: Comparison of different materials with respect to oxygen/carbon concentration. Idea! Oxygen/Carbon may influence defect formation and reduce N_{eff} after irradiation.

The material used was produced by using a so called Float-zone silicon, which ensures the silicon with least impurities and defects.

Evolution of V_{dep} with fluence …

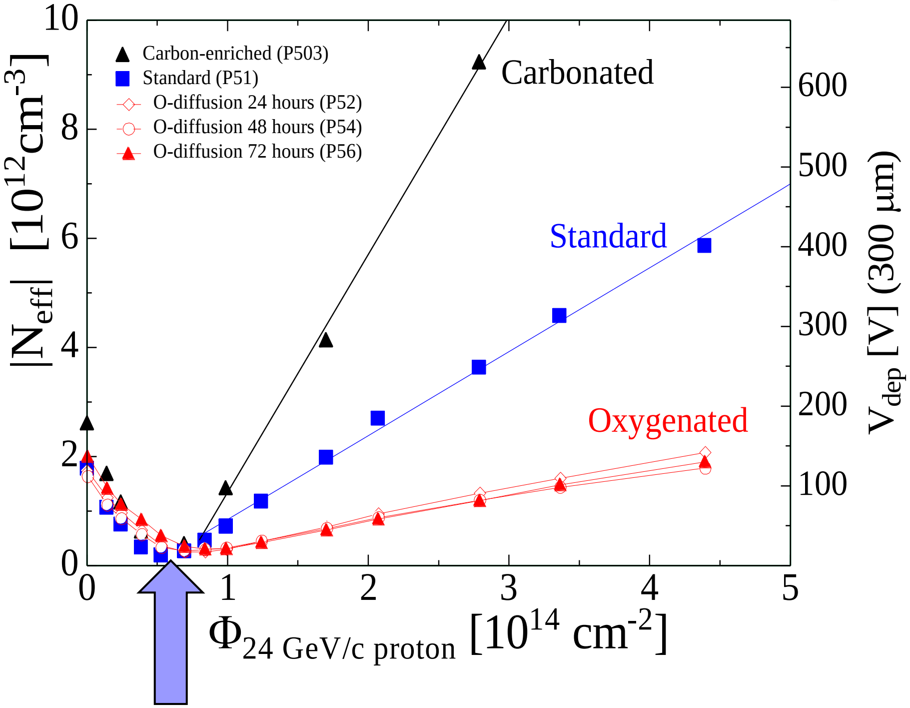


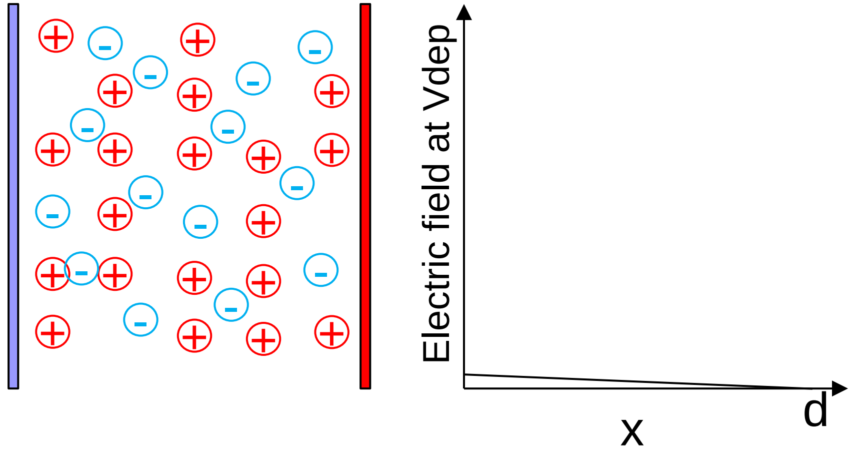


Not only the effective acceptors are introduced by irradiation, but also the initial donors are removed.

Initial acceptors – boron - are removed also for p-type material.

Evolution of V_{dep} with fluence …

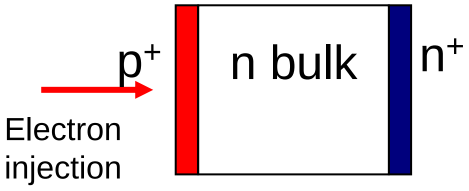


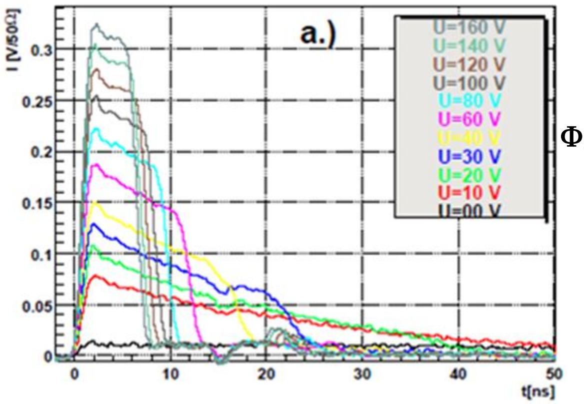


Inversion of the detector type (Φ_{eq}=1-5·10^{13} cm^{-2})

Detector of n-type turns effectively into p-type detector. This has a major consequence on detector operation. Using detector with higher initial dopant concentration shifts the inversion point towards higher fluences.

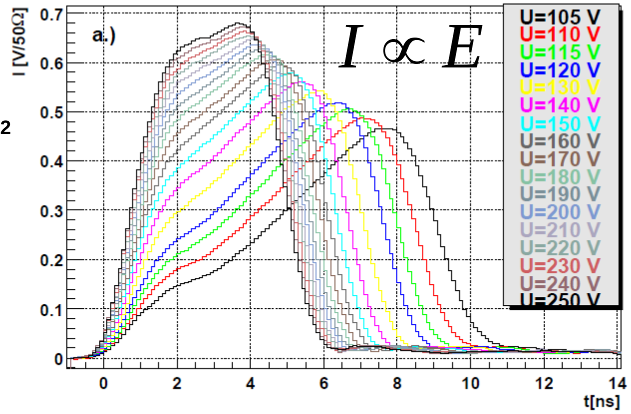
Evolution of V_{dep} with fluence



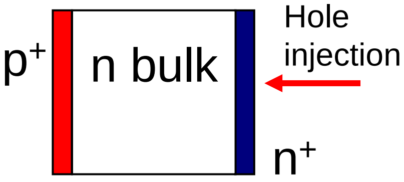


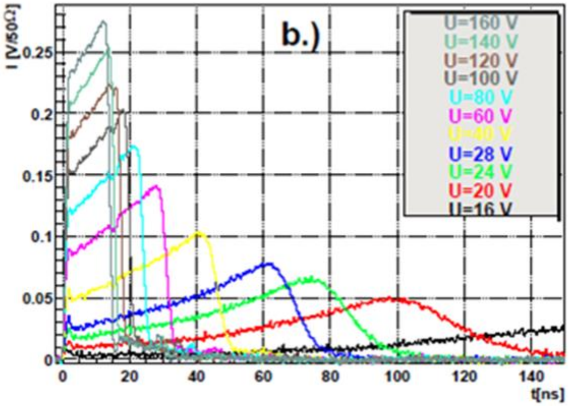
V_{dep}=20 V

Φ_{eq}=5·10^{13} cm^{-2}

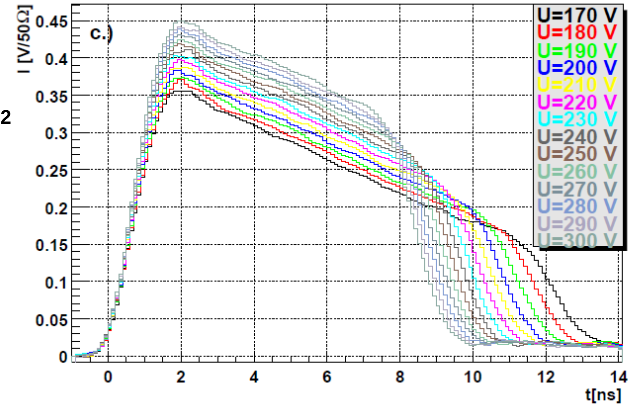


V_{dep}=70 V



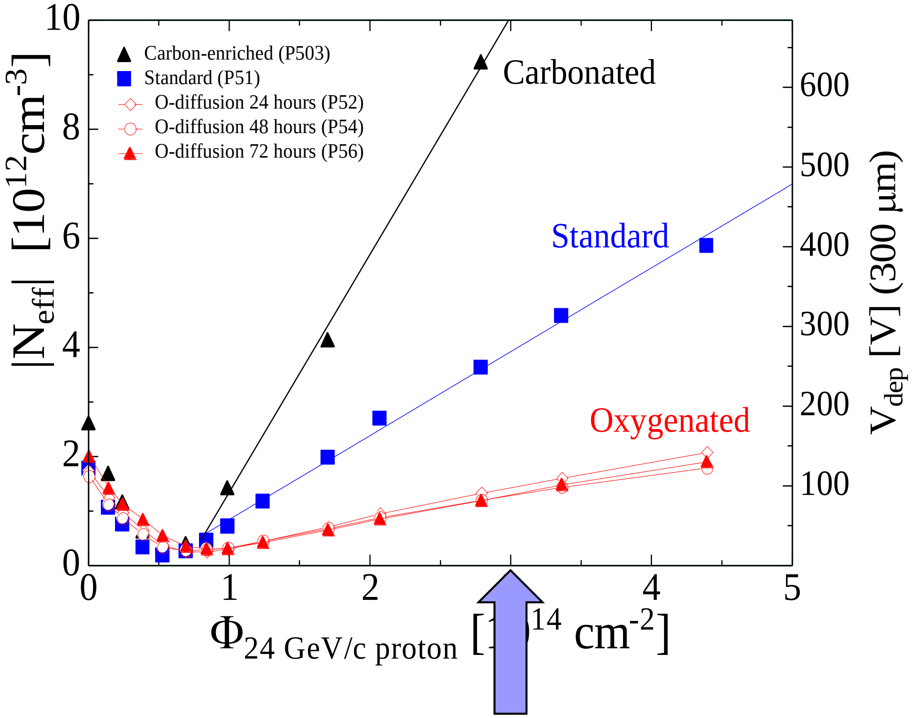


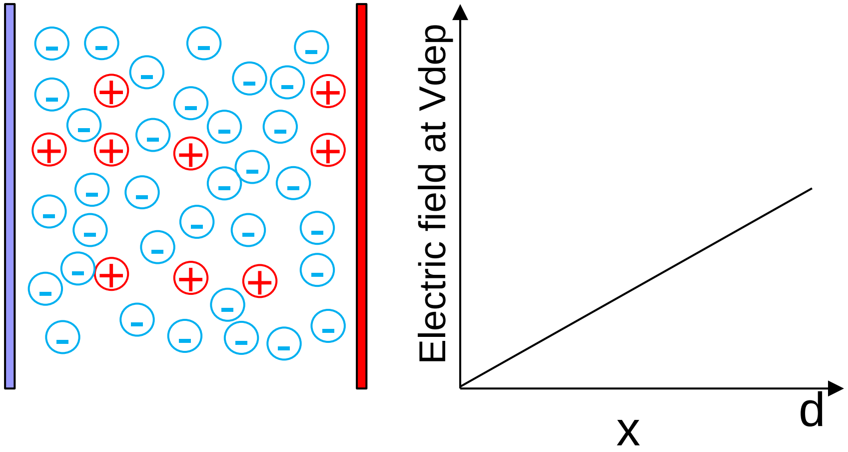
Φ_{eq}=5·10^{13} cm^{-2}



Remember – the shape of *I* gives you the shape of *E*

Evolution of V_{dep} with fluence …





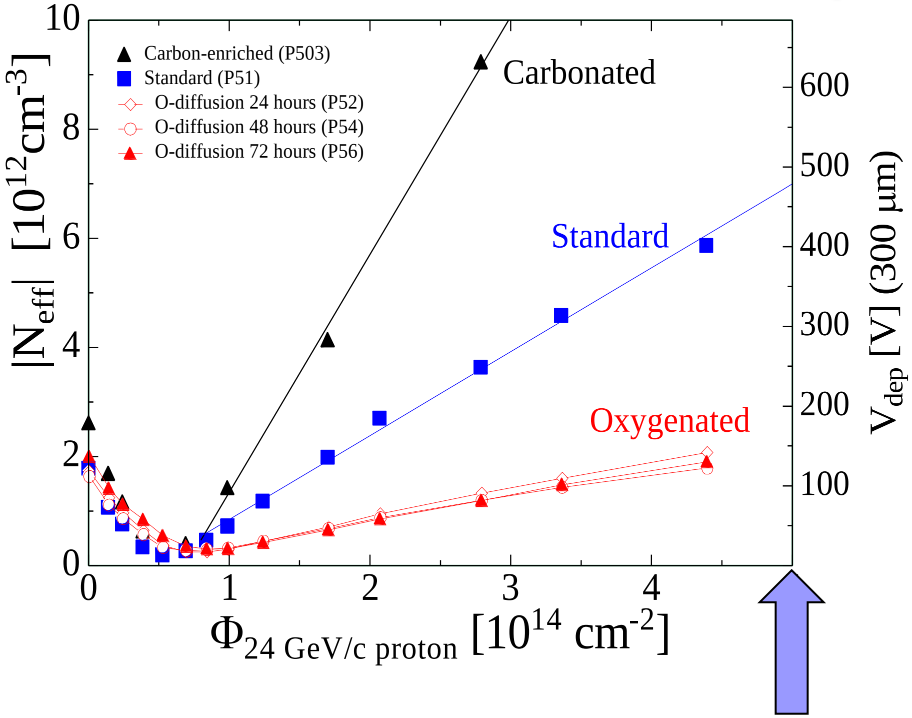
The increse of Vdep i.e. |Neff| is almost linear with fluence.
The donor removal is almost complete.

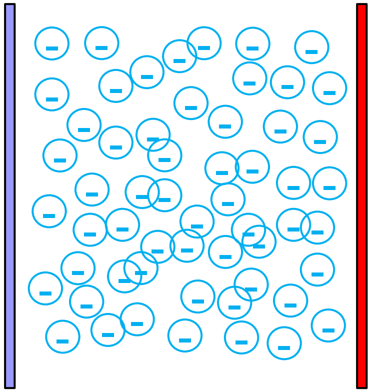
$$N_{eff} \sim g_{eff}\Phi_{eq}$$

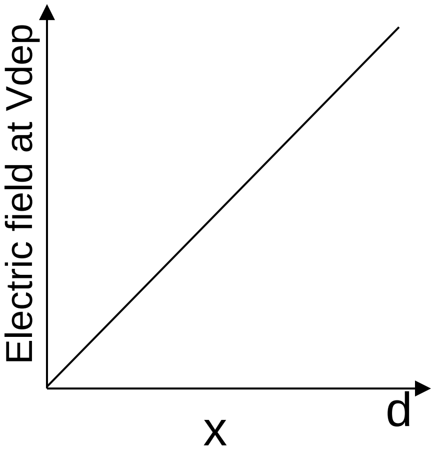
$g_{eff}\sim 0.0055\ cm^{-1}$ oxygeneted

$g_{eff}\sim 0.017\ cm^{-1}$ standard

Evolution of V_{dep} with fluence …

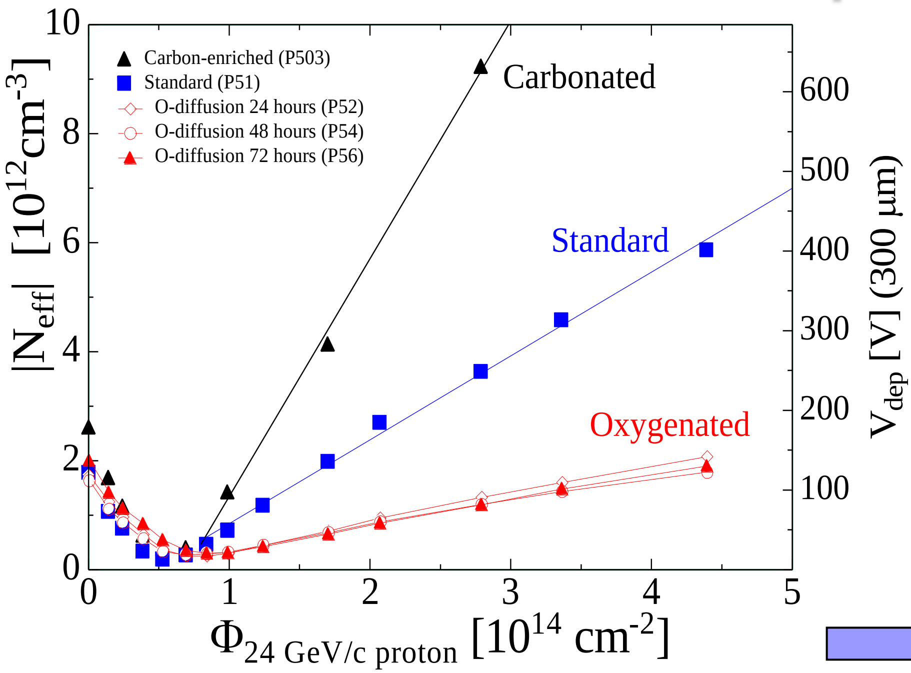


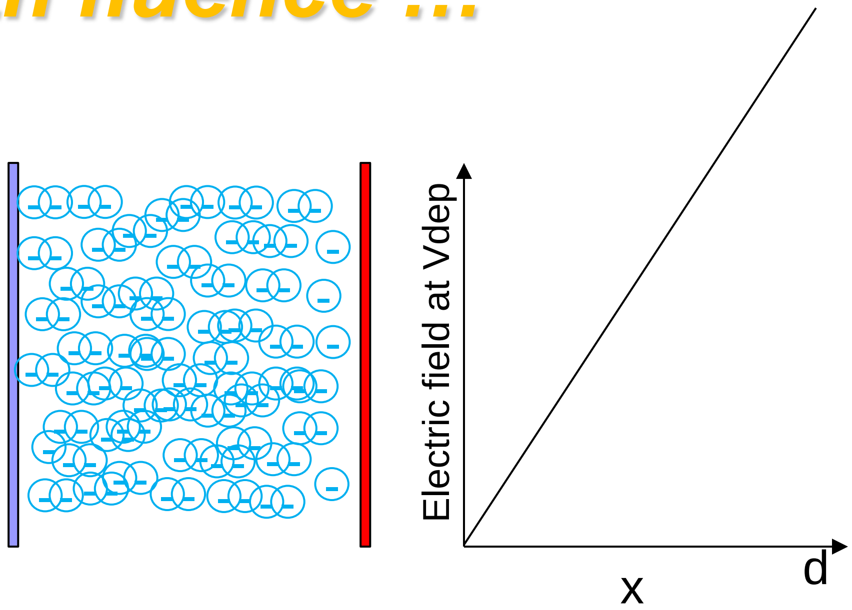




Standard float-zone n-type silicon detector would be at the limit of the power supply (500 V for ATLAS SCT), however V_{dep} is not enough – low field require some over depletion to avoid ballistic deficit and reduce trapping.

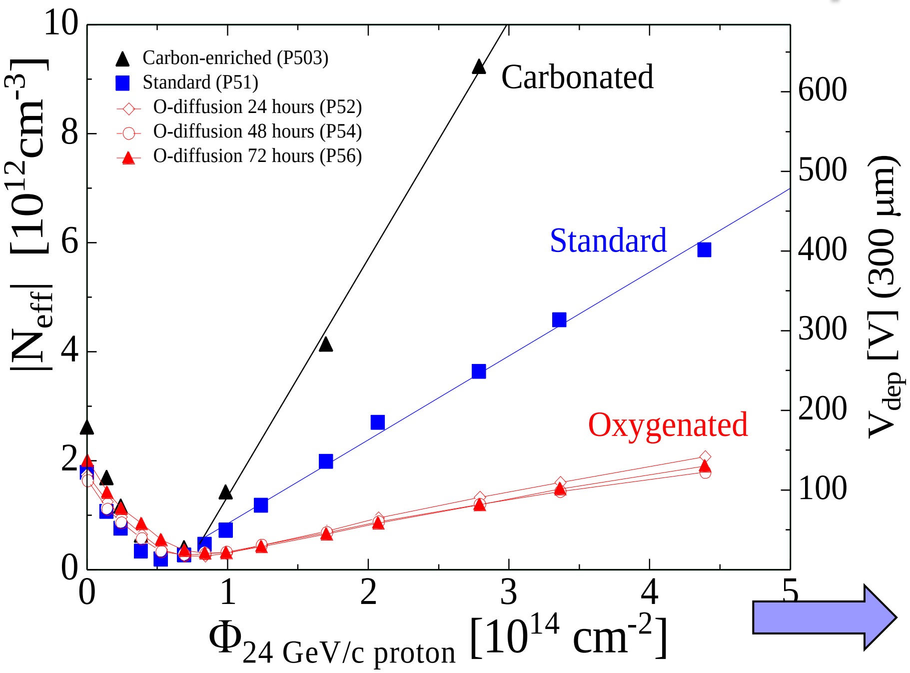
Evolution of V_{dep} with fluence …

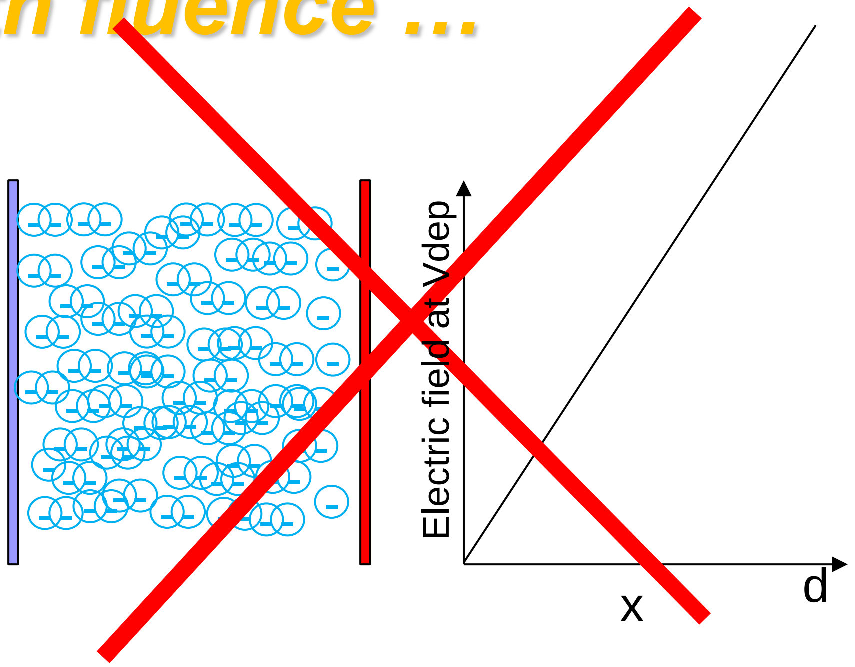




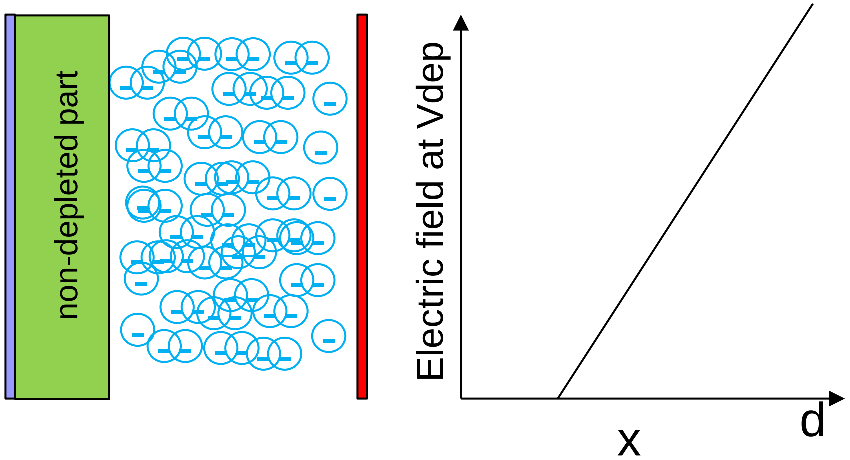
With further fluence the detector break down voltage or power supply limit becomes smaller than V_{dep}

Evolution of V_{dep} with fluence …



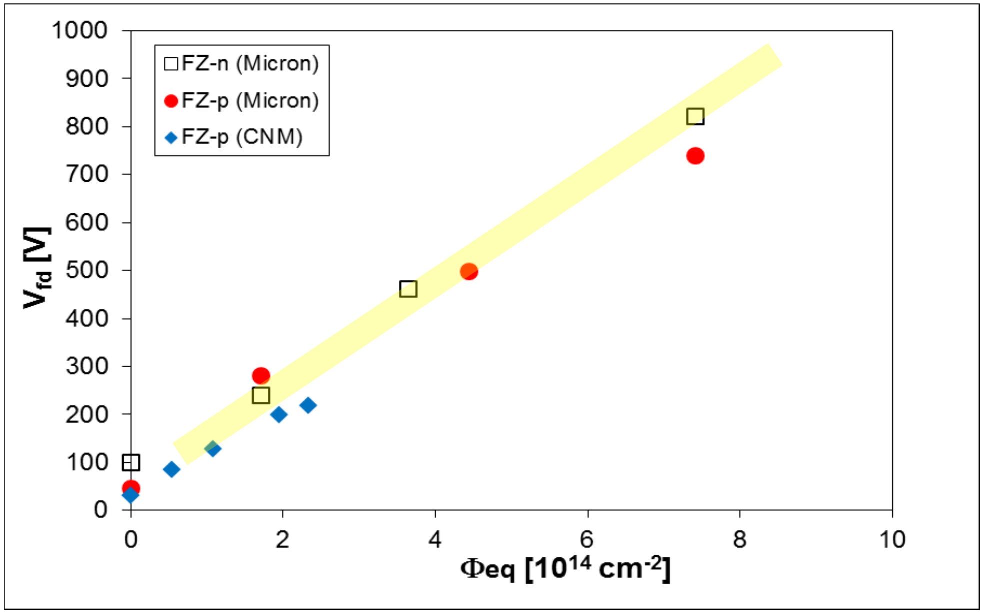


Reduce the voltage = not fully depleted detector



Detector is not fully efficient and has to run partially depleted. Huge problem for n-type detectors.

What about the p-type material?



p-type FZ material:

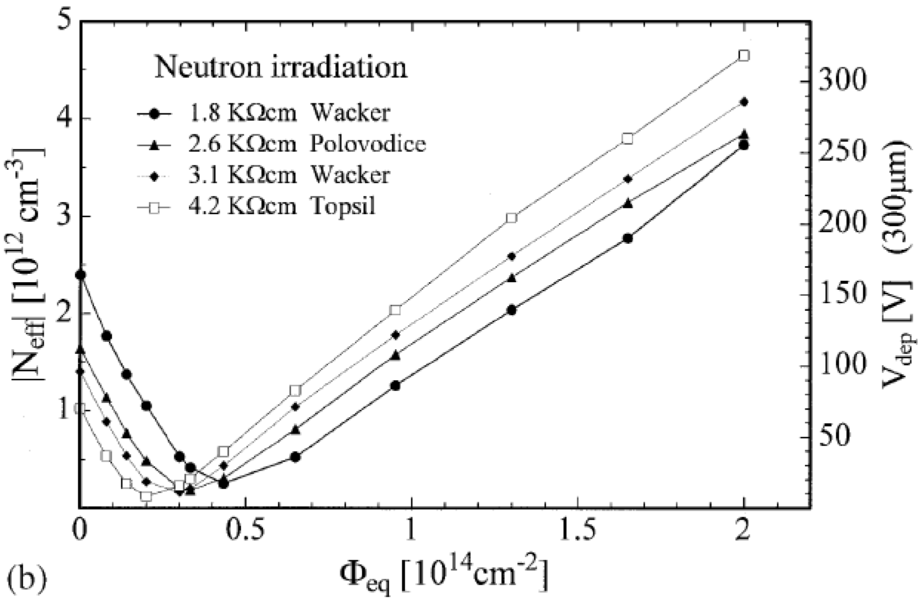
- No inversion (material stays always effectively p-type)
- There is some initial acceptor removal, but is not so well studied
- The rate with which the negative space charge is introduced is comparable to n-type detectors

As will be explained later p-type material is more suitable (cheaper) for building detector for very harsh radiation environments.

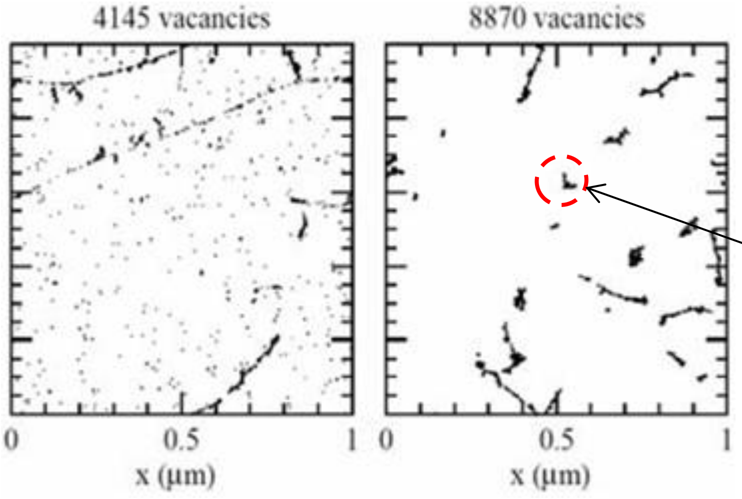
Neutron irradiations

The neutron irradiations show:

- incomplete donor removal – not all initial donors are removed
- no influence of any impurity – after neutron irradiations all materials behave the same – similar to the standard material irradiated with protons.



24 GeV protons neutrons



Cluster with several hundred V has a volume of $r\sim100A \rightarrow Volume\sim10^{-18}$ cm $^{-3}$

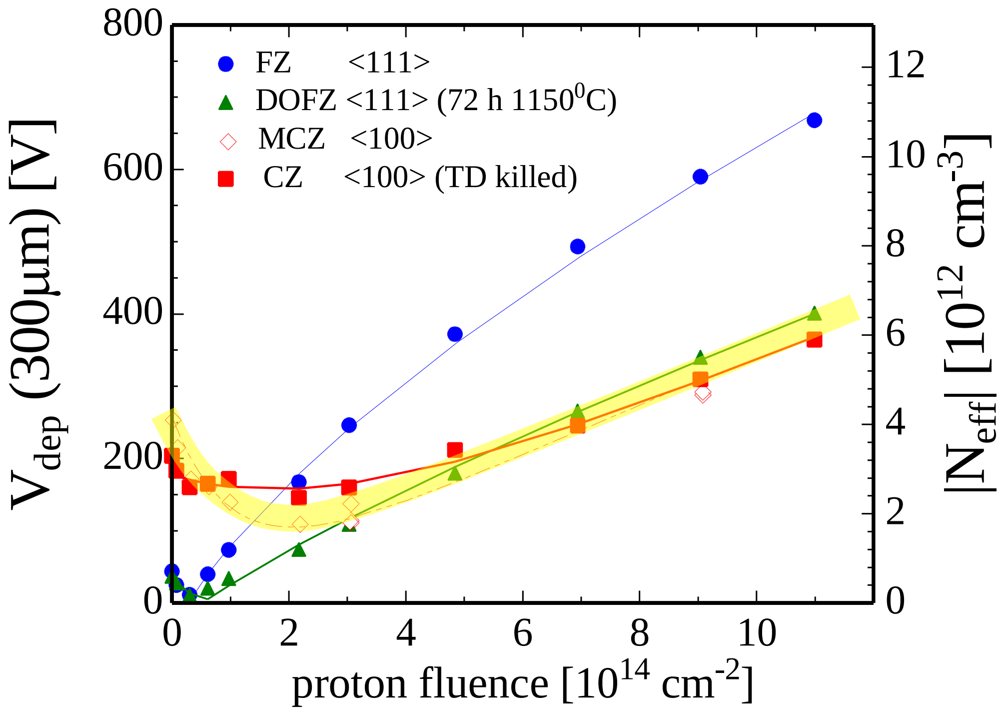
concentration of [O]=10^{17}-10^{18} cm^{-3}

Approximately few O atoms per cluster = the density of O is simply to small to have an effect!

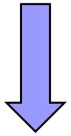
Add more oxygen…

If the oxygen has such a positive role why not taking the material with most oxygen – Czochralski (only recently available with high enough resistivity)

[O]~10^{18} cm^{-3}

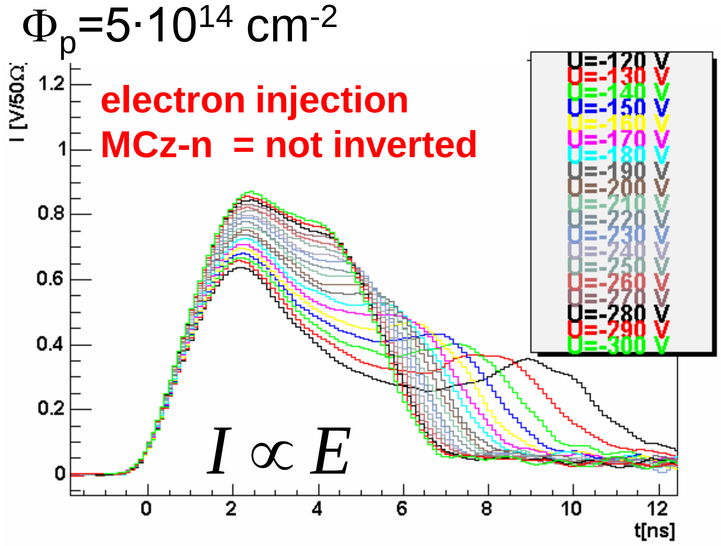


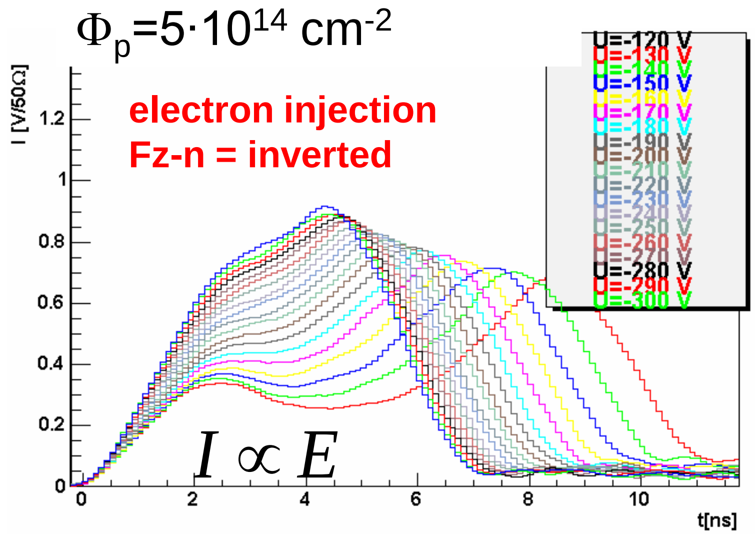
The material seem not to invert – that means it stays effectively n-type after irradiation with charged hadrons – radiation introduces effective donors



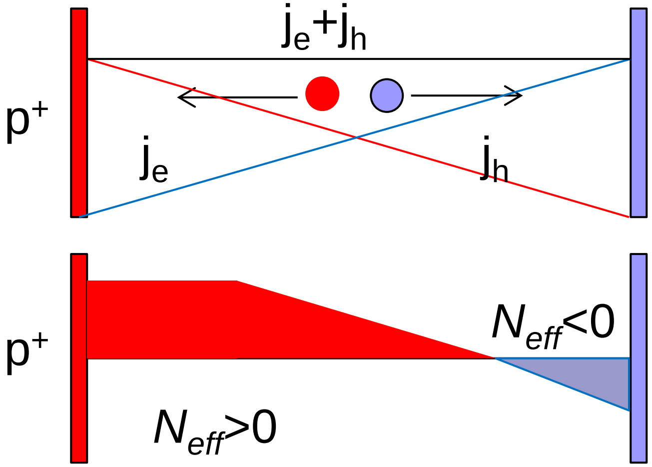
But the rate of increase is about the same as for diffusion oxygenated float zone detector. Coincidence ?

Double junction – polarization effects





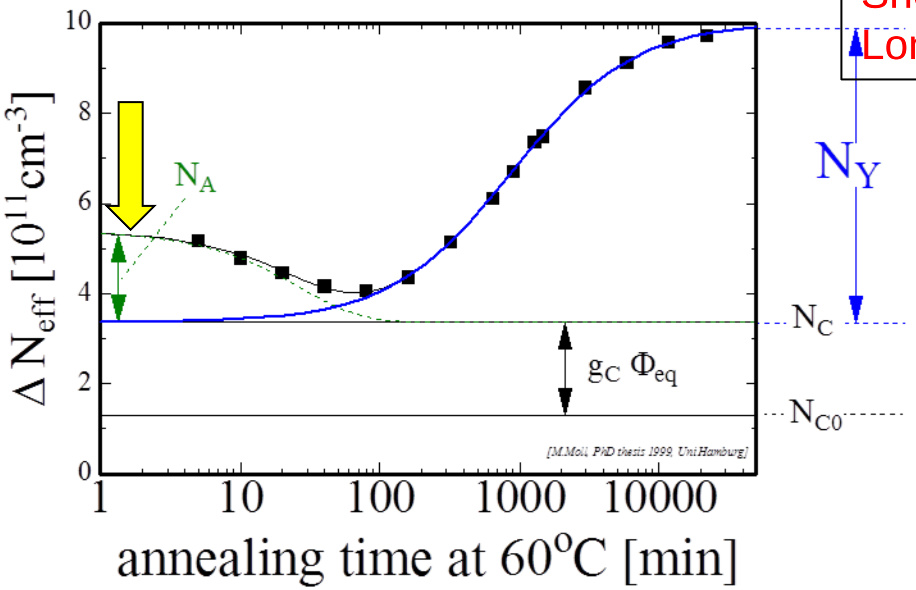
Induced current has a non-monotonic shape – sign of different space charge

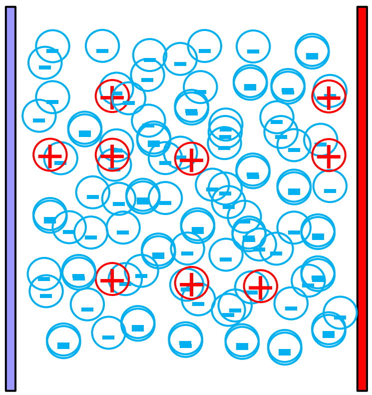


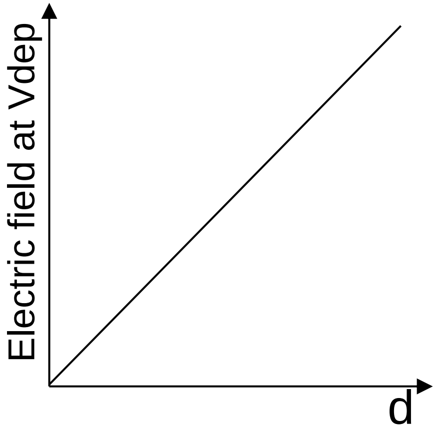
- This effect is present in all detector types
- It gets more pronounced at high fluences
- It is more pronounced for charged hadron irradiated detectors and oxygen rich material – point defects dominant?
- It gets more pronounced at low temperatures

Evolution with time - Hamburg model

Short term : reduction of negative space charge
Long term: introduction of negative space charge







- **Short term:** “Beneficial annealing”-N_A
- **Long term:** “Reverse annealing”-N_Y
  - time constant depends on temperature:
    - ~ 500 years (-10°C)
    - ~ 500 days (20°C)
    - ~ 21 hours (60°C)
  - **Consequence:** Detectors must be cooled even when the experiment is not running!

$$\Delta N_{eff} = N_{eff,0} - N_{eff}$$

$$\Delta N_{eff} = N_A(t,\Phi_{eq}) + N_c + N_Y(t,\Phi_{eq})$$

$$\Delta N_{eff} = N_a \exp(-t/\tau_{ba}) + N_c + N_Y(1-\exp(-t/\tau_{ra}))$$

x

Evolution with time - Hamburg model

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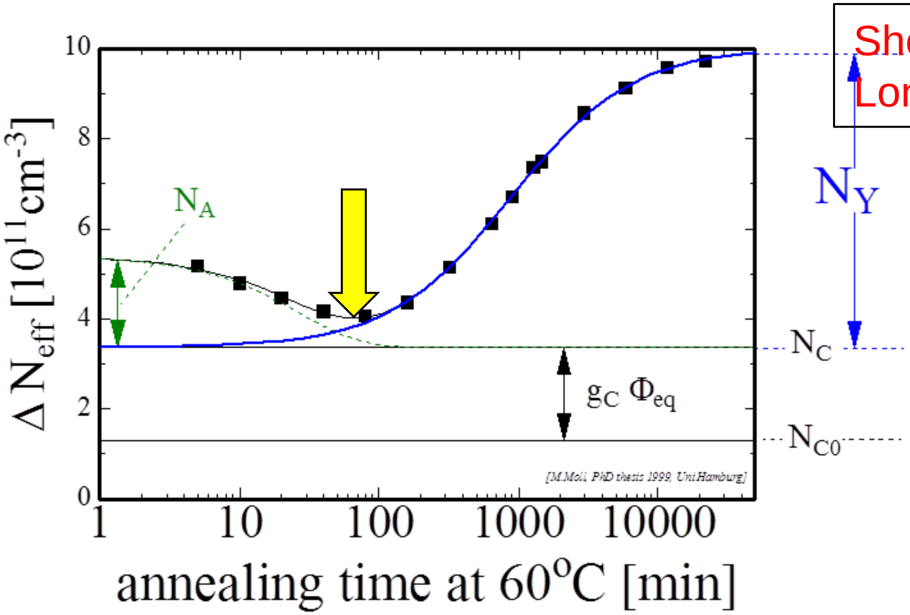
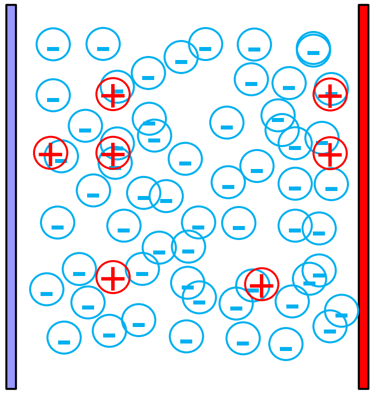
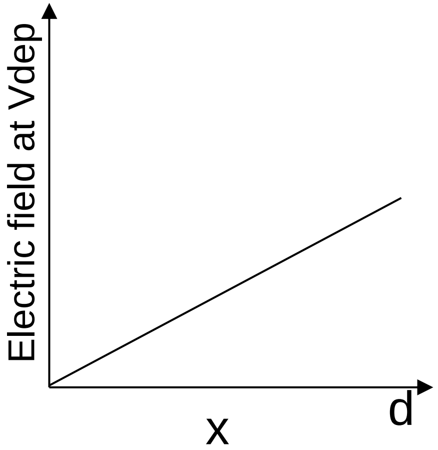
Long term: introduction of negative space charge



[M.Moll, PhD thesis 1999, Uni Hamburg]





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Evolution with time - Hamburg model

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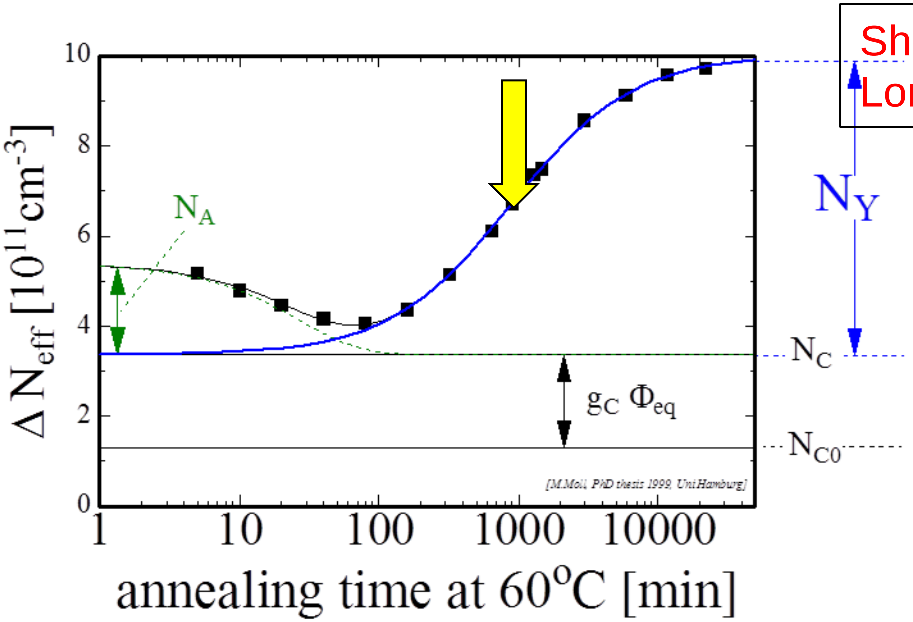

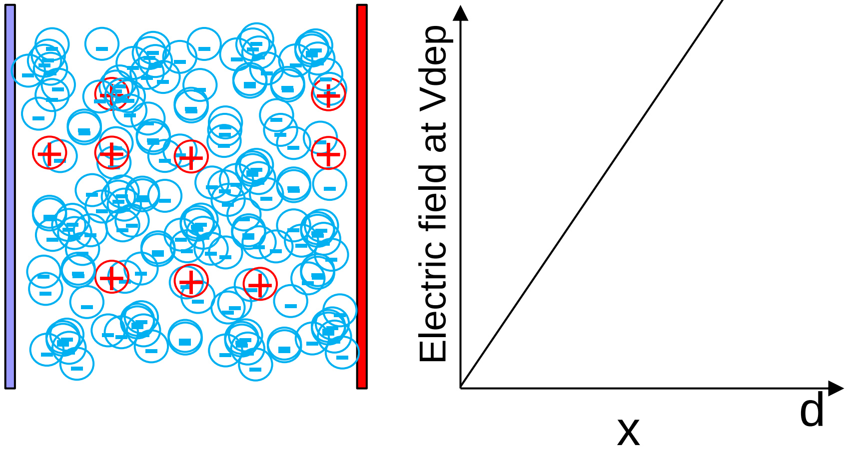

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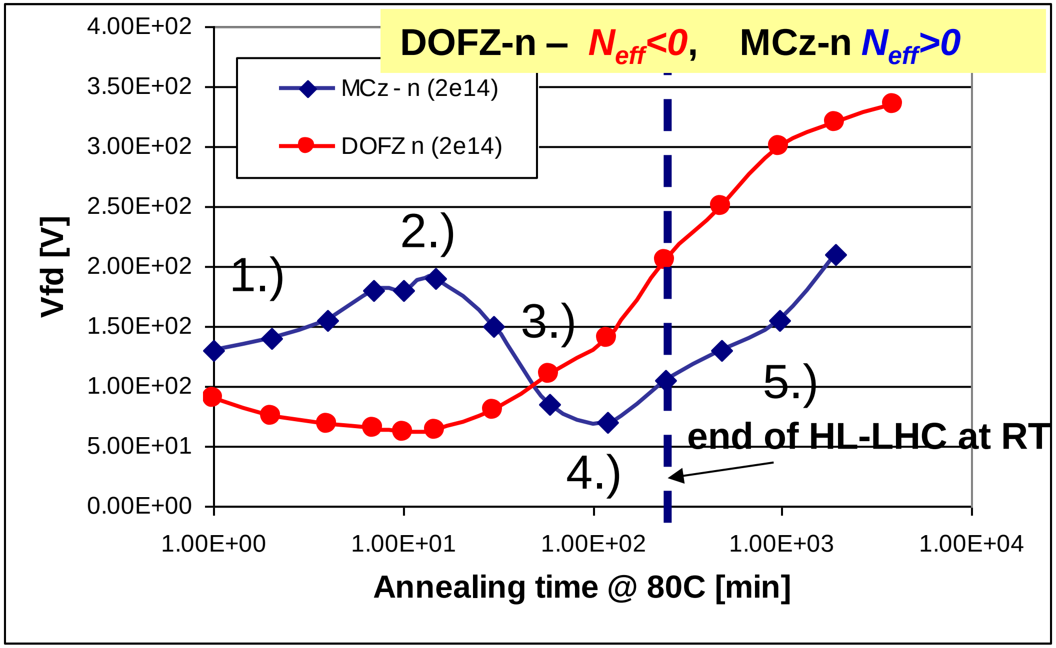
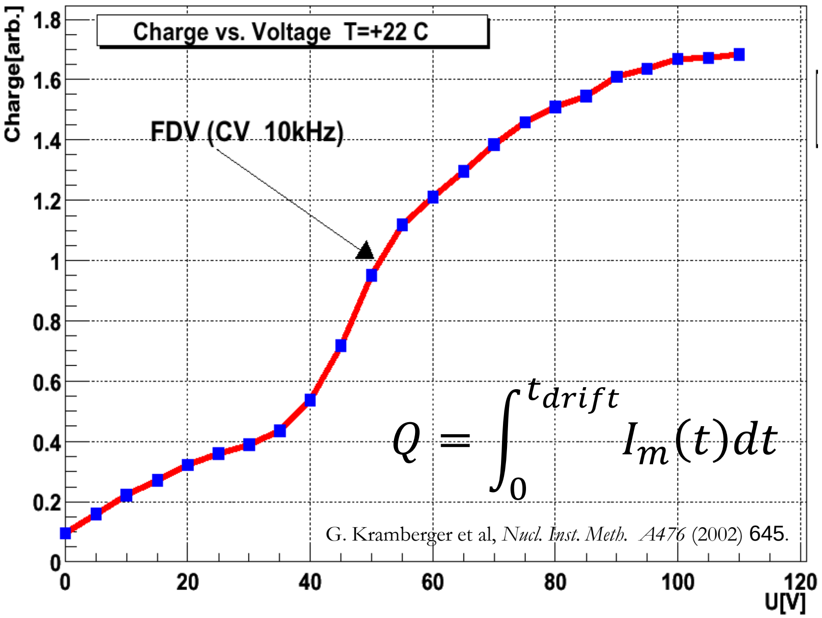
Annealing behavior of MCz-n, FZ-n detectors

Finger print of positive space charge seen in annealing

1. decay of acceptors -> increase of V_{fd}
2. local maximum of V_{fd} (plateau)
3. generation of acceptors -> decrease of V_{fd}
4. inversion of space charge at late stages, **but V_{fd} never really goes to ~0 (double junction)**
5. further generation of acceptors increase of V_{fd}



Trapping of drifting charge



$$Q = \int_0^{t_{drift}} I_m(t)dt$$

G. Kramberger et al, *Nucl. Inst. Meth. A476* (2002) 645.

higher voltages(i.e. higher field)

$\Downarrow$

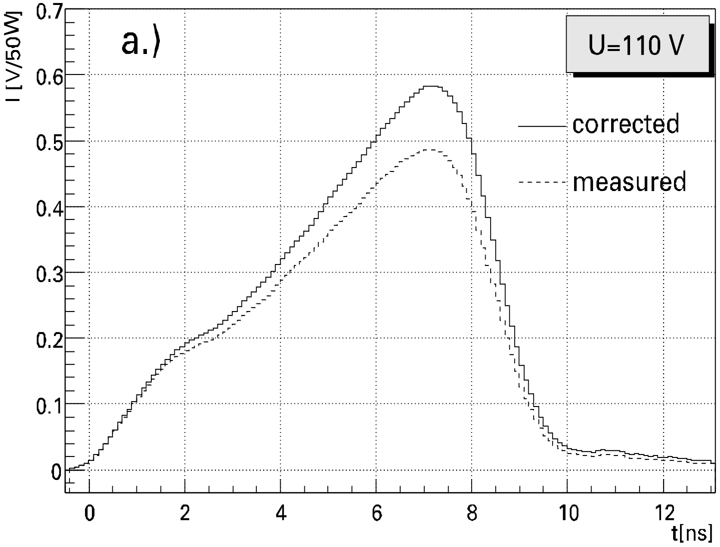
shorter drift

$\Downarrow$

less charge trapped

$\Downarrow$

increase of charge($V>V_{dep}$)



$$\underbrace{I_m(t) = \left[e_0 \, N_{e,h} \frac{1}{D} v_{e,h}(t) \right] \exp\left(\frac{-t}{\tau_{eff,e,h}}\right)}$$

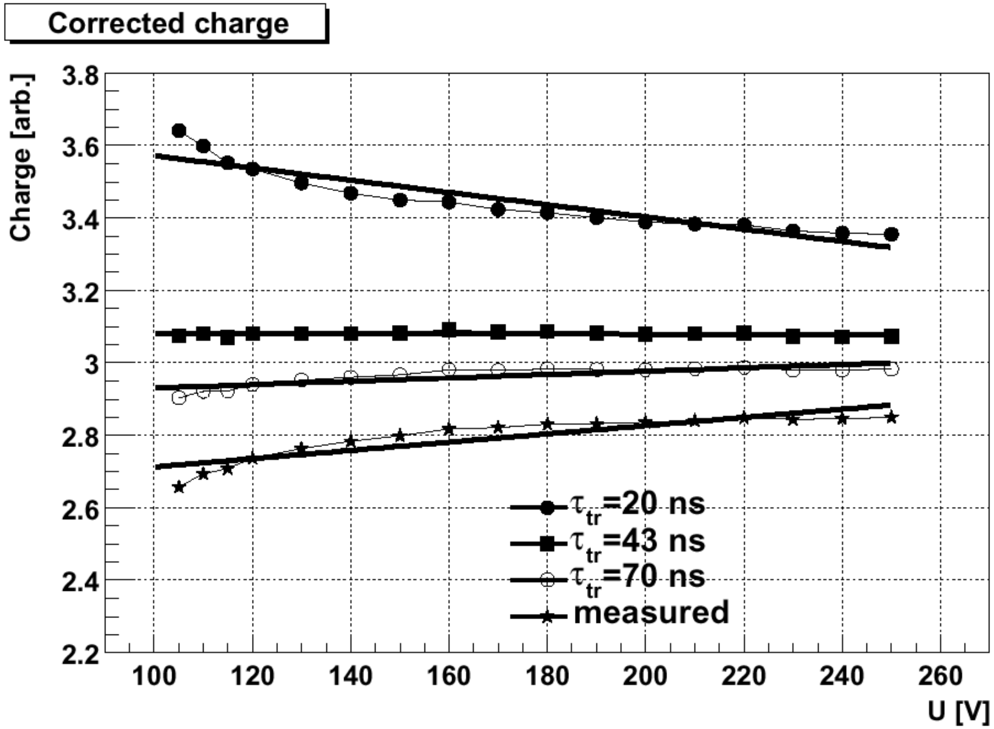
$$\downarrow \textit{correction}$$

$$I_c(t) = I_m(t) \exp\left(\frac{t}{\tau_{tr}}\right)$$

in the way that

Q=constant for $V>V_{dep}$

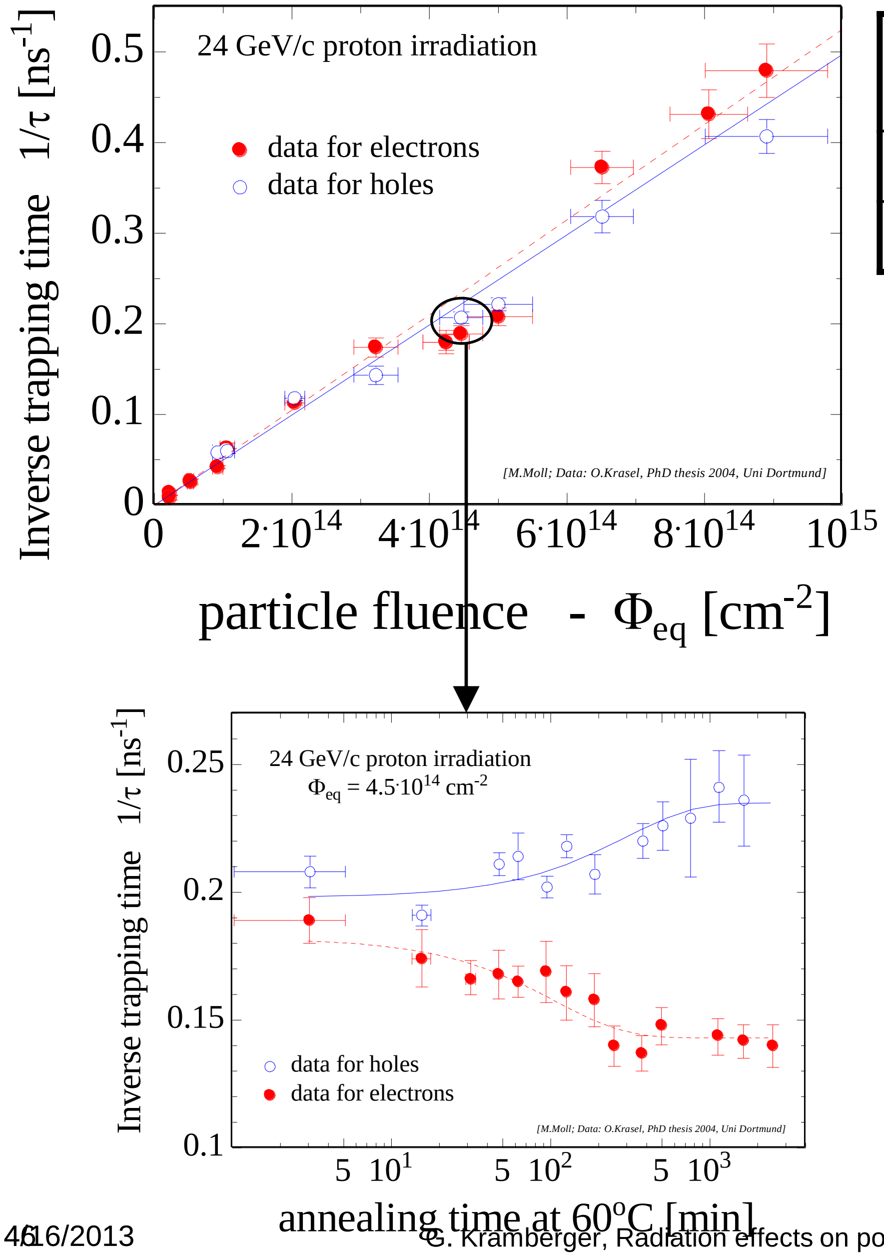
τ_{eff} = τ_{tr} that gives equal current integral above V_{FD} (compensate the trapping)



$\tau_{tr} > \tau_{eff}$ - lower voltages are under weighted

$\tau_{tr} < \tau_{eff}$ - lower voltages are over-weighted

Trapping of drifting charge



β(-10°C, t=min Vfd) [10^{-16} cm^2/ns]	24 GeV protons 200 MeV/c pions (average)	reactor neutrons
Electrons	5.3 ± 0.7	3.5 ± 0.6
Holes	6.6 ± 0.8	4.7 ± 1

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

The $\beta_{e,h}$ was so far found independent on material;

- resistivity
- [O], [C]
- type (p,n)
- wafer production (FZ, Cz, epitaxial)
- somewhat lower trapping at $\Phi_{eq} > 10^{15}$ cm^{-2}
- **$\beta_{e,h}$ ~ 0 for ^{60}Co irradiated samples**

The trapping probability:

- gets smaller with time for electrons
- gets larger with time for holes

PART 4

Radiation effects in segmented detectors

Can we design a detector where the effects of the irradiation are mitigated?

Drift equation for the mip signal

$$I = q\vec{v}\vec{E}_w \longleftarrow$$ drift current of a single carrier

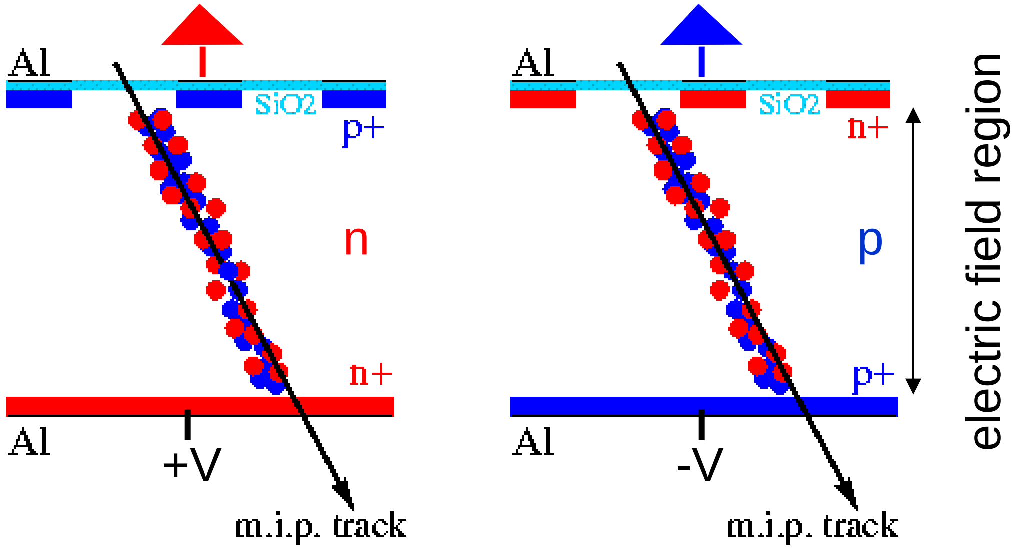
$$Q(t) = \sum_{e-h\ pairs} \int_{t=0}^{t_{\text{int}}} I dt = \sum_{e-h\ pairs} q \int_{t=0}^{t_{\text{int}}} \exp\left(-\frac{t}{\tau_{eff,e,h}}\right) \mu_{e,h} \vec{E} \cdot \vec{E}_w dt$$

geometry factor peaked at electrodes

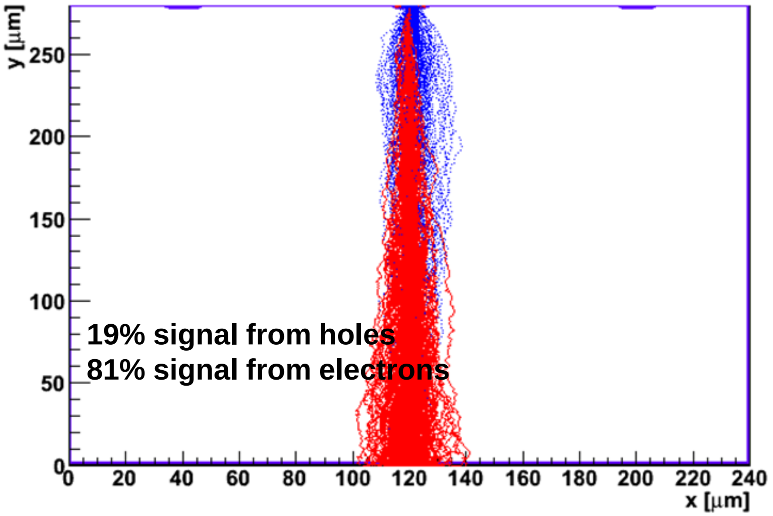
- trapping term ($\tau_{eff,e} \sim \tau_{eff,h}$)
- drift velocity ($\mu_e \sim 3\mu_h$)

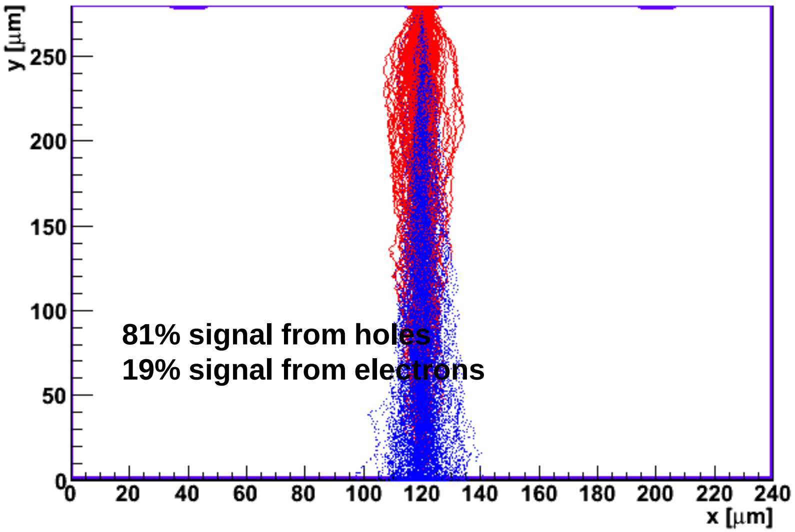
- electrons get less trapped
- they should drift to the strips/pixels and contribute most to Q (n^+ readout for silicon)

Remember: in segmented detector one carrier type always contributes more than the other – U_w determines the difference.



Influence of geometry on charge collection


19% signal from holes
81% signal from electrons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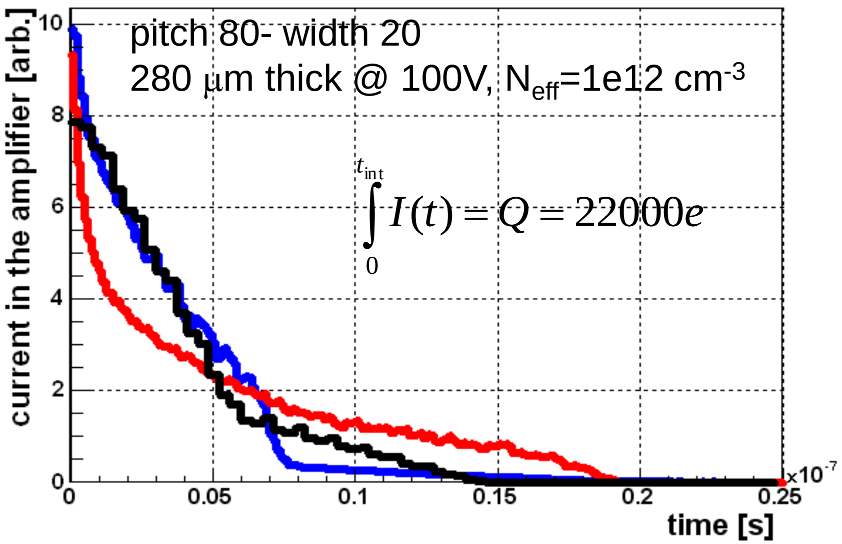
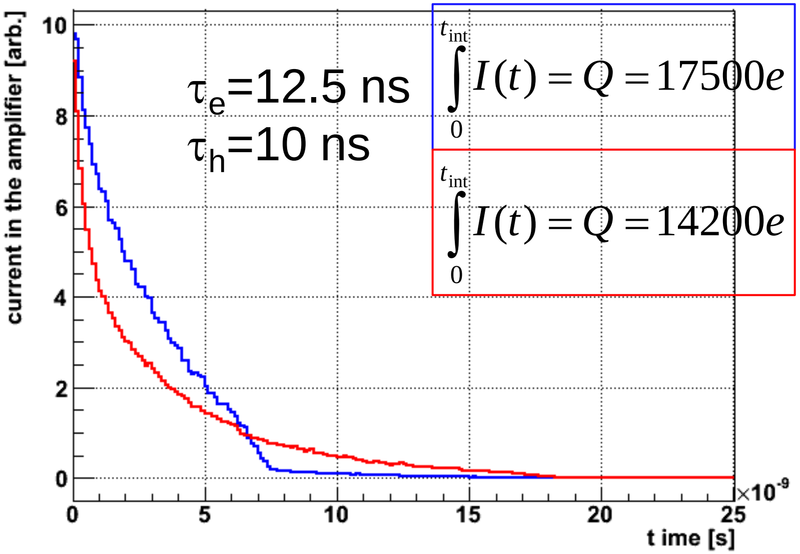

pitch 80- width 20
280 µm thick @ 100V, N_{eff}=1e12 cm^{-3}

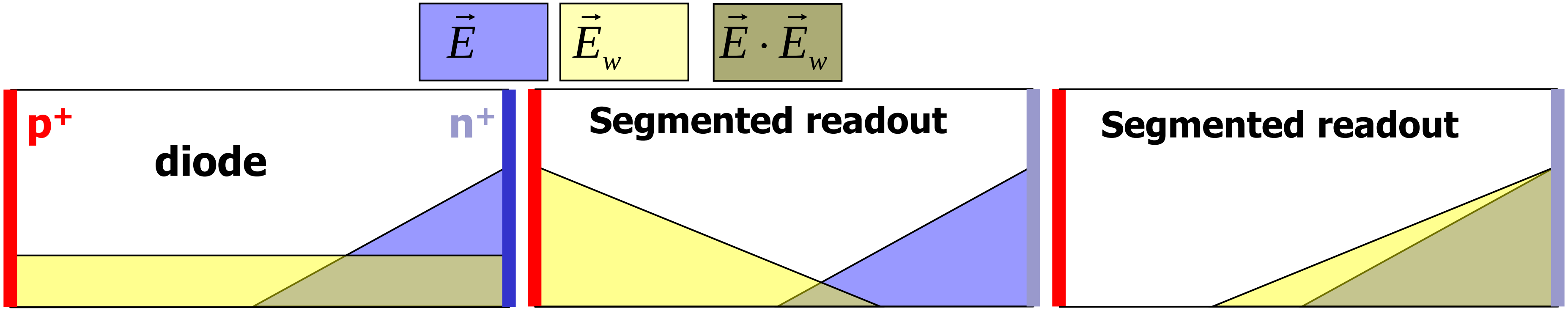
$$\int_0^{t_{int}} I(t) = Q = 22000e$$


τ_e=12.5 ns
τ_h=10 ns

$$\int_0^{t_{int}} I(t) = Q = 17500e$$

$$\int_0^{t_{int}} I(t) = Q = 14200e$$

Device engineering – n+ readout



good 😐

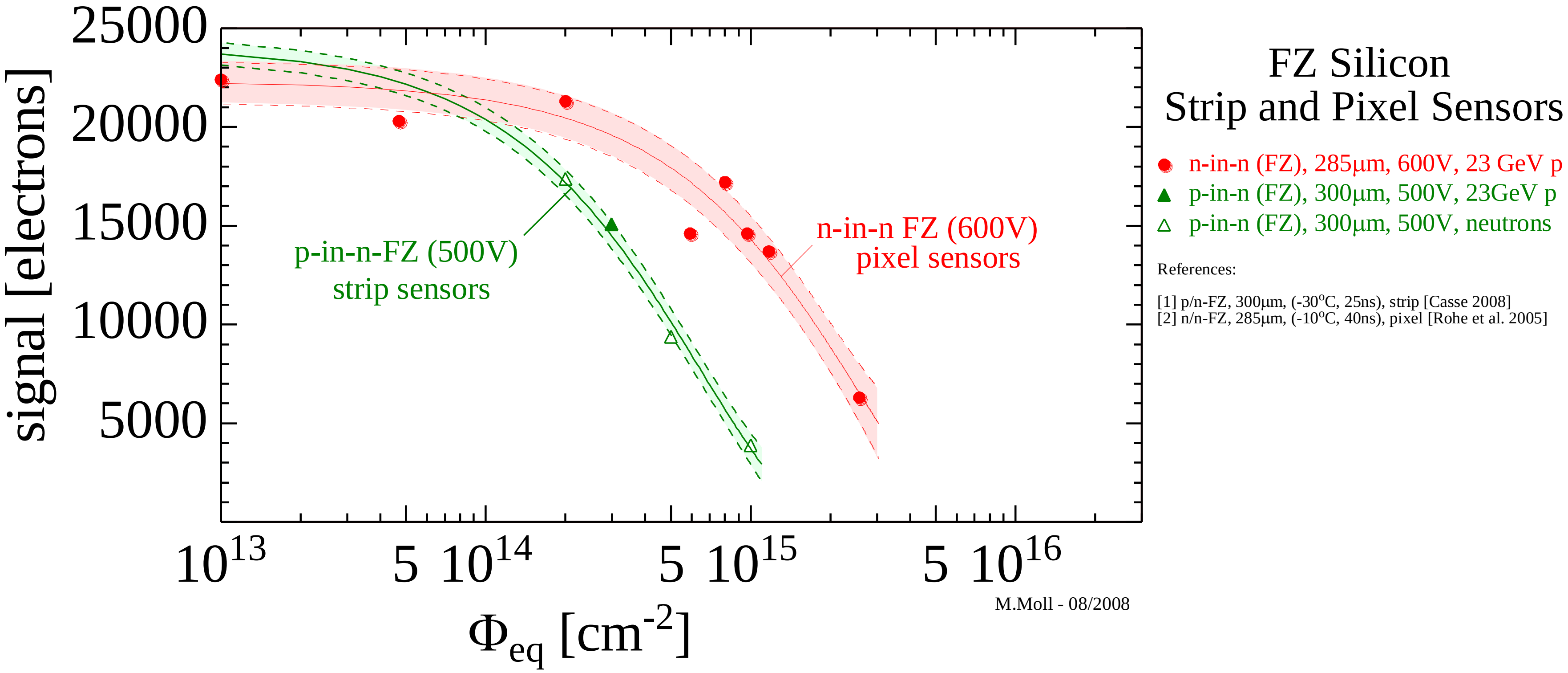
worse ☹
even worse: p^+ readout
(p^+-n detector)

better ☺
even better: n^+ readout
(n^+-p, n^+-n detector)

How to get maximum signal?

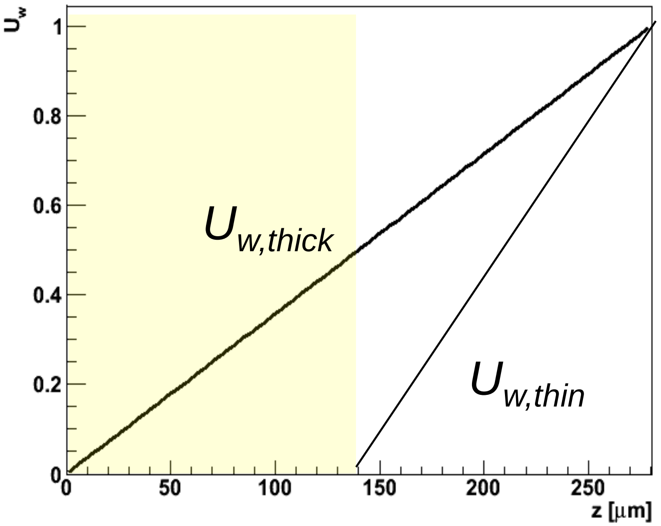
- use of n^+-n or n^+-p device (electron collection) with pitch<<thickness
- implant width close to pitch (depends on FE elec. – inter-electrode capacitance)
- for a given cell size of a pixel detector $\boxed{\frac{pitch_x}{pitch_y} \to 0,\infty}$

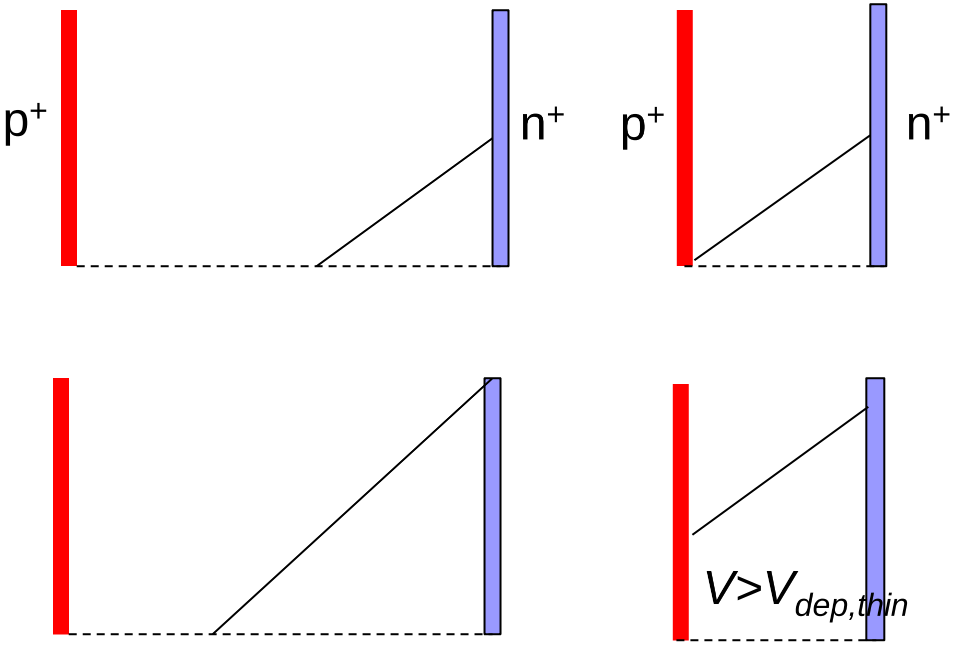
The difference between n+ or p+ readout is obvious!



Device engineering – thin detectors

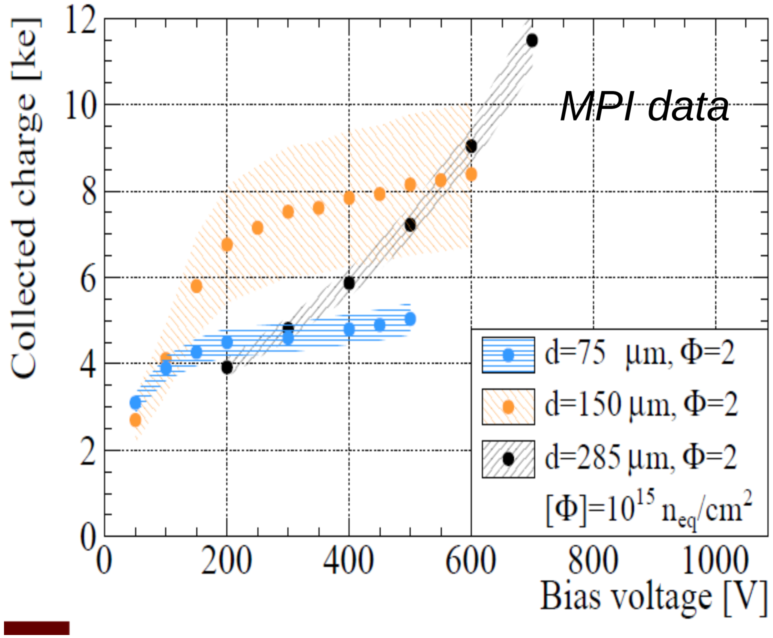
- If bias is too small to deplete thin detector: benefit due to weighting field!
- If bias is larger the if it better to have larger field and less trapping than larger deposited charge.



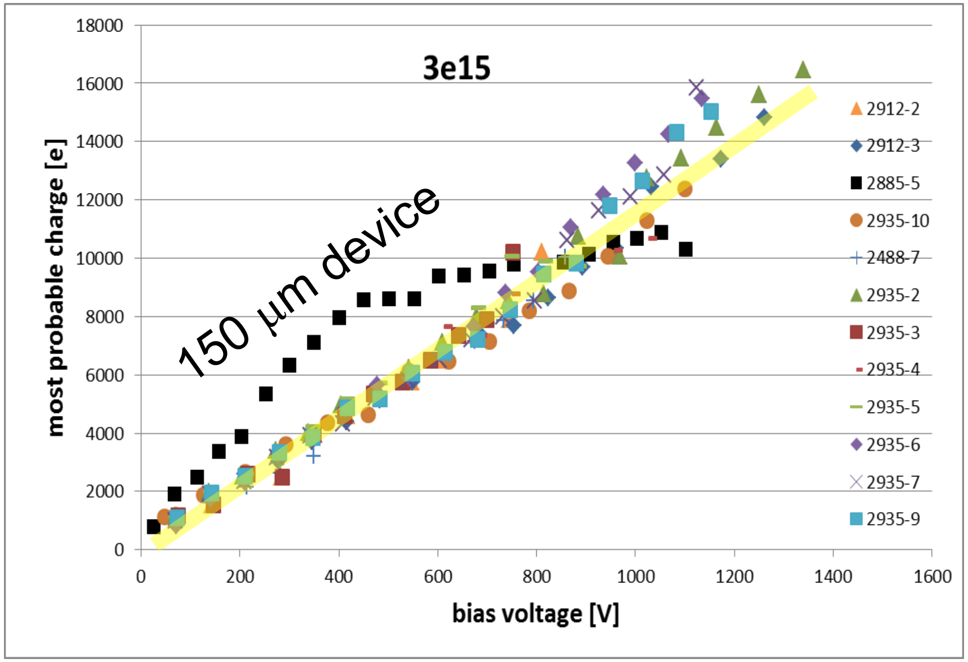


Device engineering – thin detectors

250x150 μm^2 pixel detector

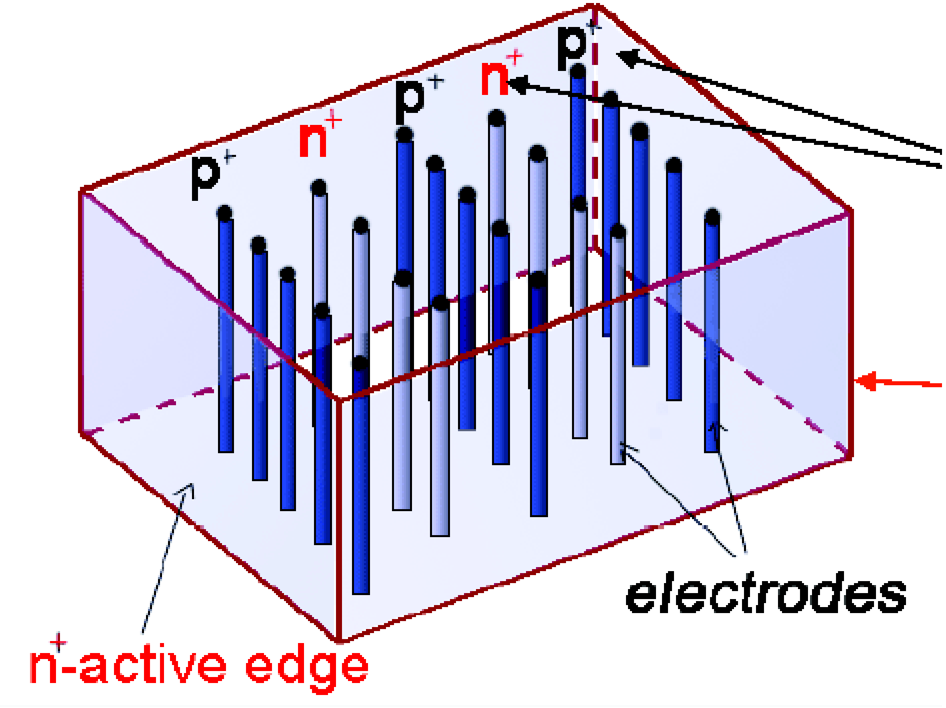


pad detectors



Examples of the thin vs. thick detector operation!
NOTE: before irradiation and up to certain (large) fluence thick detector outperforms thin!

3D n^+-p pixel detectors



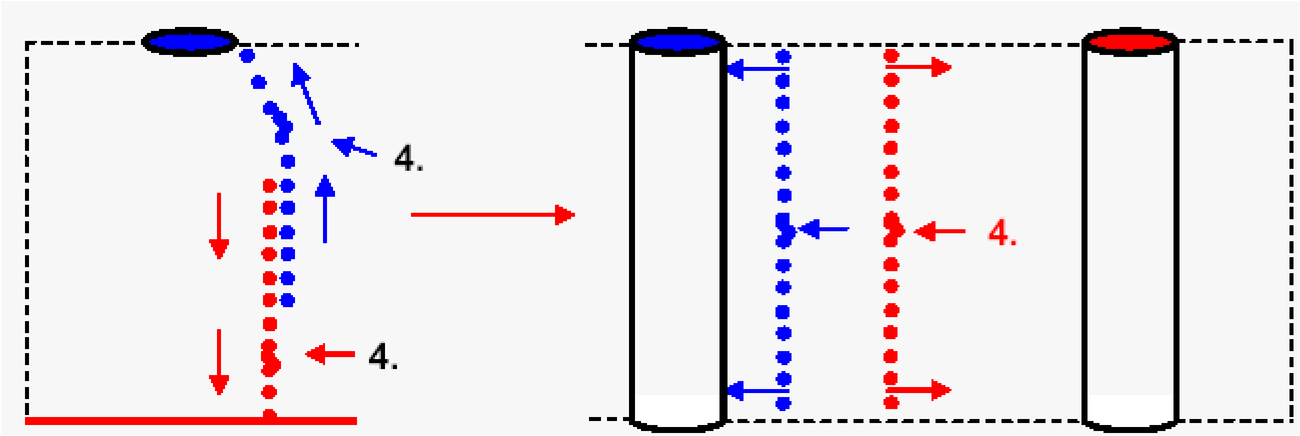
Combine traditional VLSI processing and MEMS (Micro Electro Mechanical Systems) technology.

Both electrode types are processed inside the detector bulk instead of being implanted on the wafer's surface.

The edge is an electrode. Dead volume at the Edge < 5 microns! Essential for forward physics experiments and material budget

S.I. Parker, C.J. Kenny, J. Segal, Nucl. Instr. and Meth. A395 (1997) 328.

3D n^+-p pixel detectors



Pros.

- Better charge collection efficiency
- Faster charge collection (depends on inter-column spacing)
- Reduced full depletion voltage and by that the power
- Larger freedom for choosing electrode configuration

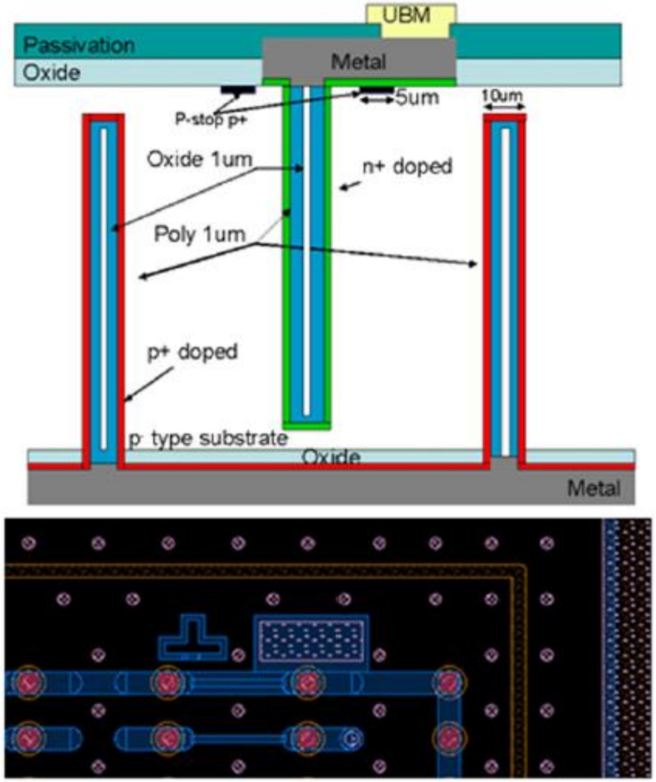
Cons.

- Columns are dead area (aspect ratio ~30:1)
- Spatially non-homogenous CCE (efficiency=function of position)
- Much higher electrode capacitance (hence noise), particularly if small spacing is desired – small drift length
- Availability on large scale
- Time-scale and cost

3D sensors:

- used in IBL, excellent up to $\Phi_{eq} = 5\cdot10^{15}$ n/cm^2, promising results also for HL-LHC,
- operation at lower voltage in innermost HL-LHC tracking layer(s)

➔ More in other presentations at this conference!

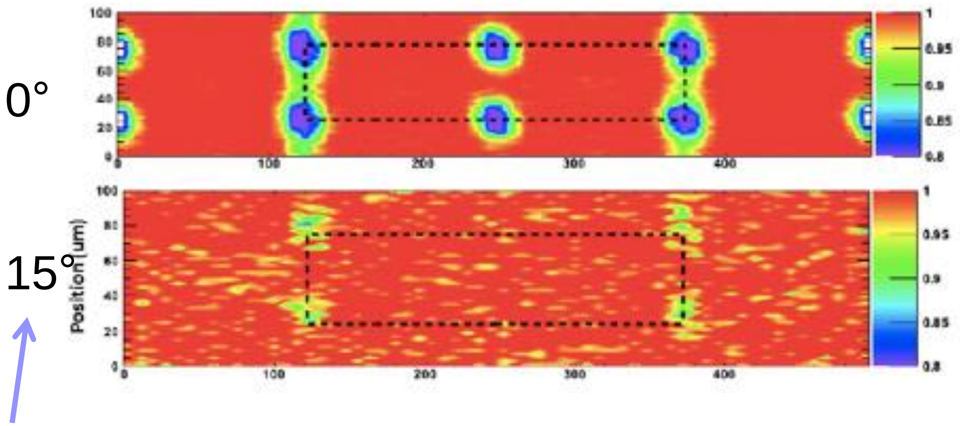


CNM 3D sensor

[G. Pellegrini, et al., NIMA 592 (2008) 38].

Work of ATLAS 3D Sensor R&D Collaboration:

Test beam, CNM, sensors,
$\Phi_{eq} = 5\cdot10^{15}$ n/cm^2, Bias voltage = 160 V
Track efficiency > 98%



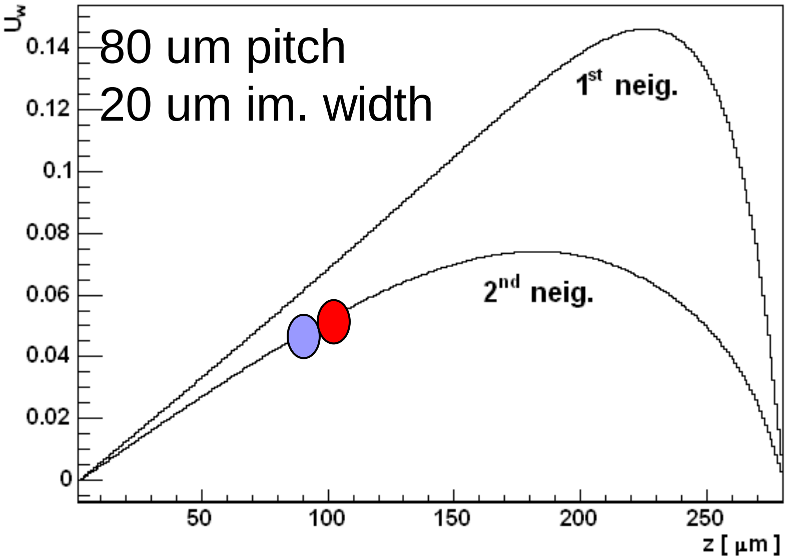
Track incidence angle

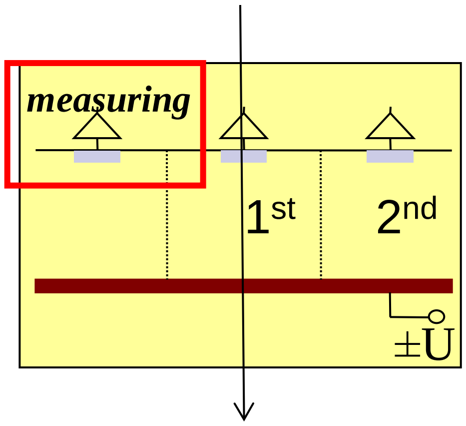
[S. Grinstein, NIMA 699 (2013) 61–66]
[S. Tsiskaradze, 19th RD50 workshop]

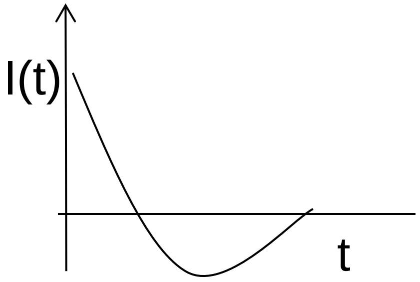
Trapping induced charge sharing

If drift of the carriers is not completed – the charge is induced in the neighbors:

- ➢ E field is not present in entire detector
- ➢ Large trapping





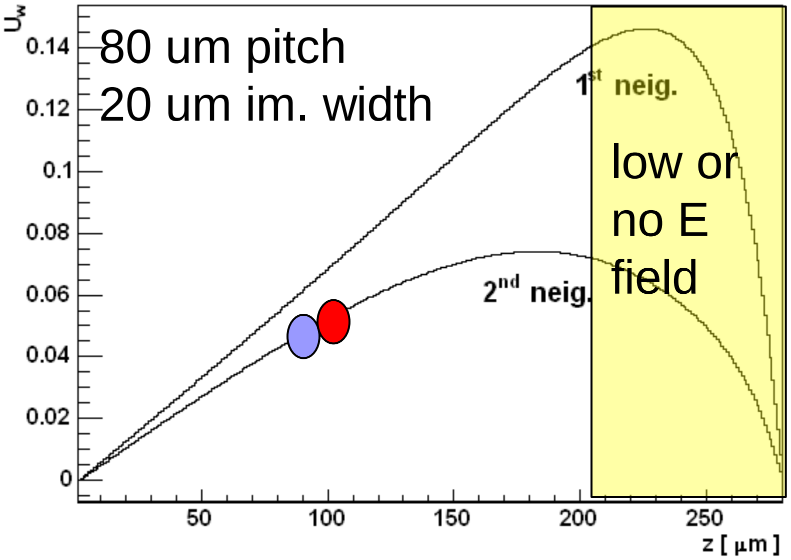


Electric field present whole volume and no trapping – the charges complete the drift. The bipolar induced current gives no net induced charge.

Trapping induced charge sharing

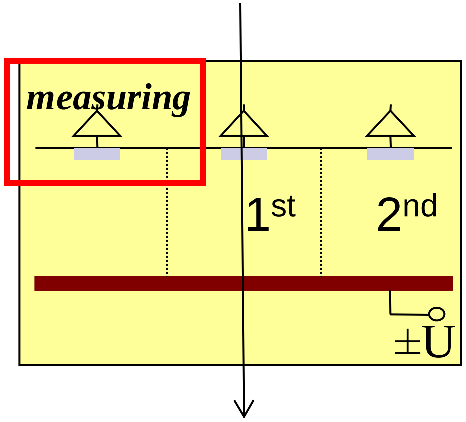
If drift of the carriers is not completed – the charge is induced in the neighbors:

- E field is not present in entire detector
- Large trapping



80 um pitch
20 um im. width

low or no E field



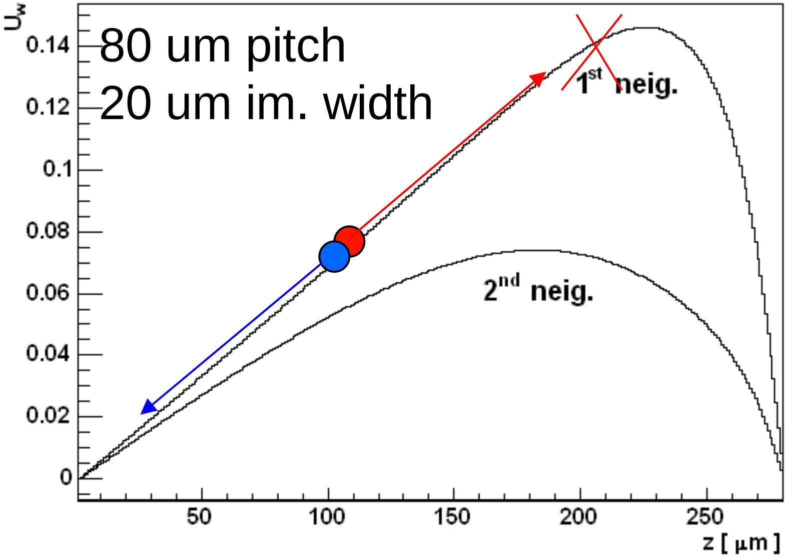
Electric field not present in the whole volume? Charges induced in the neighbors (e.g. 13% on the first, 7% on the second ones).

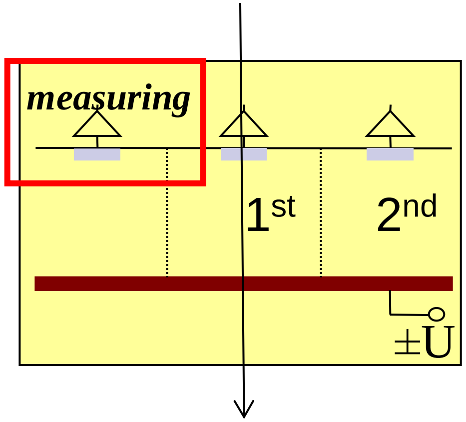
Large number of strips with relatively small signal – wide clusters – this is where the charge was induced if $E_w \cdot E$ is small for the hit strip.

Trapping induced charge sharing

If drift of the carriers is not completed – the charge is induced in the neighbors:

- ➢ E field is not present in entire detector
- ➢ Large trapping

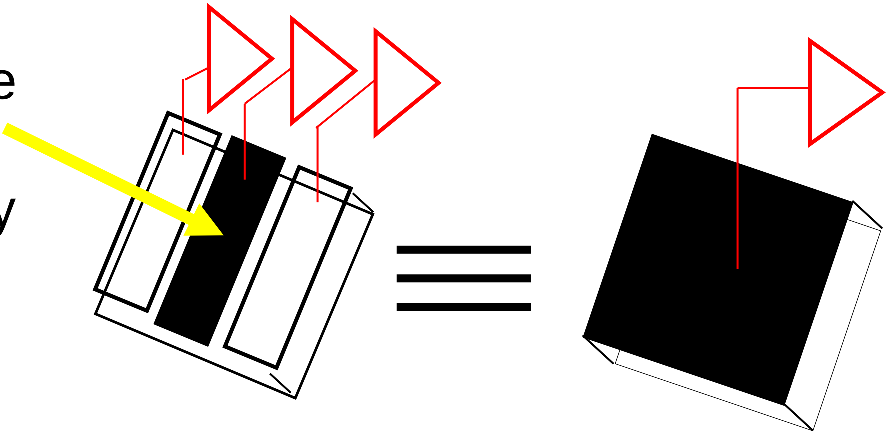


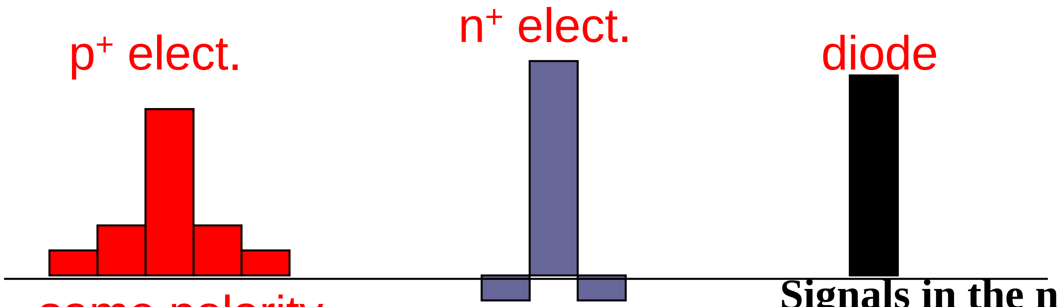


Electric field present in the whole volume, but large trapping. The bipolar induced charge doesn't give zero net charge.

There is a big difference between n^+-p and p^+-n !

electrode hit in the center by ionizing particle





same polarity ↓ wider clusters

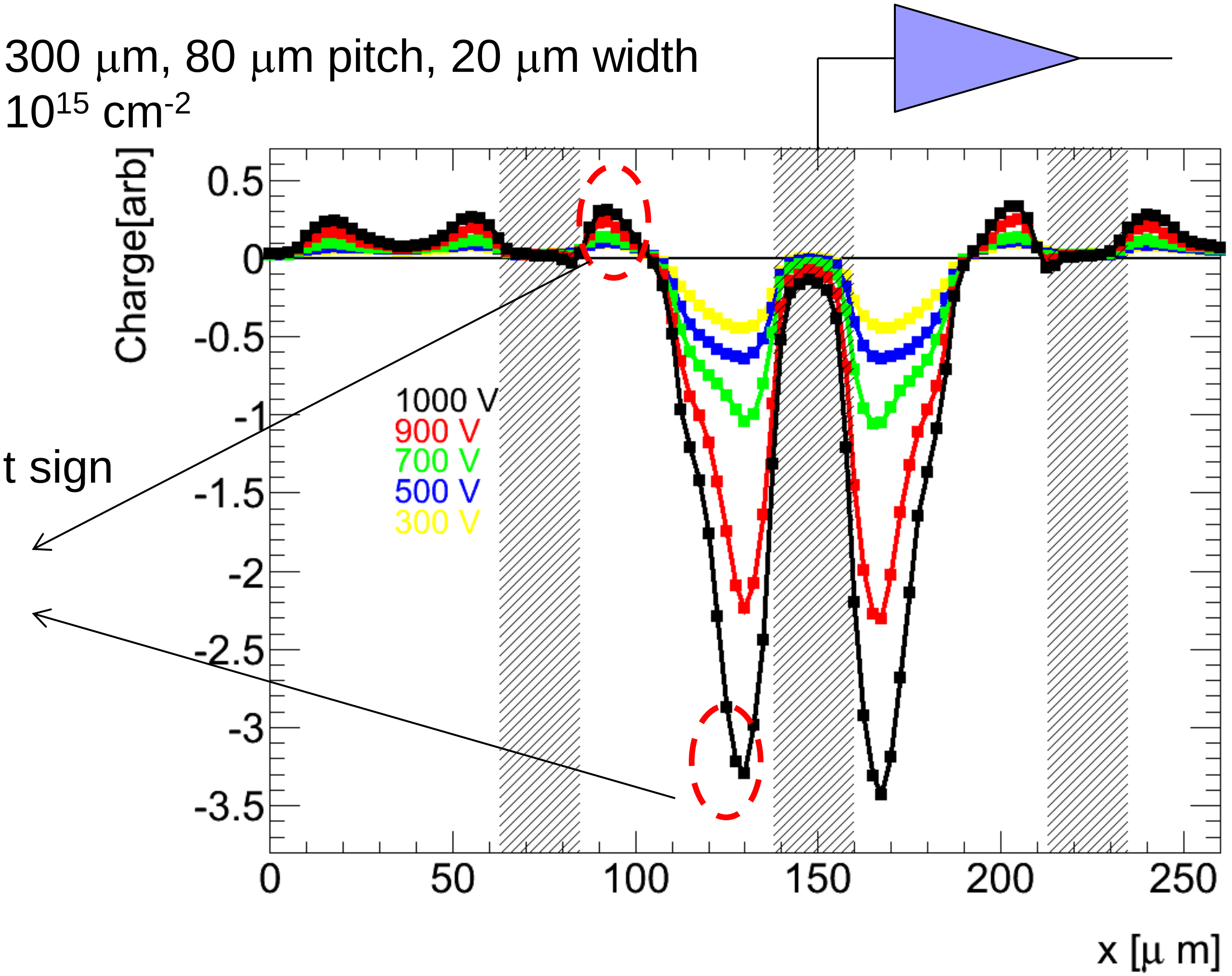
opposite polarity ↓ larger signals

Signals in the neighbors few % of the hit strip

Depends strongly on fluence position of the hit and electrode geometry!

Trapping induced charge sharing – infra red TCT

300 μm, 80 μm pitch, 20 μm width
10^{15} cm^{-2}



different sign

Laser scan over the detector surface (8μm FWHM beam width – 1064 nm) : induced charge in the central strip vs. laser position.

PART 5

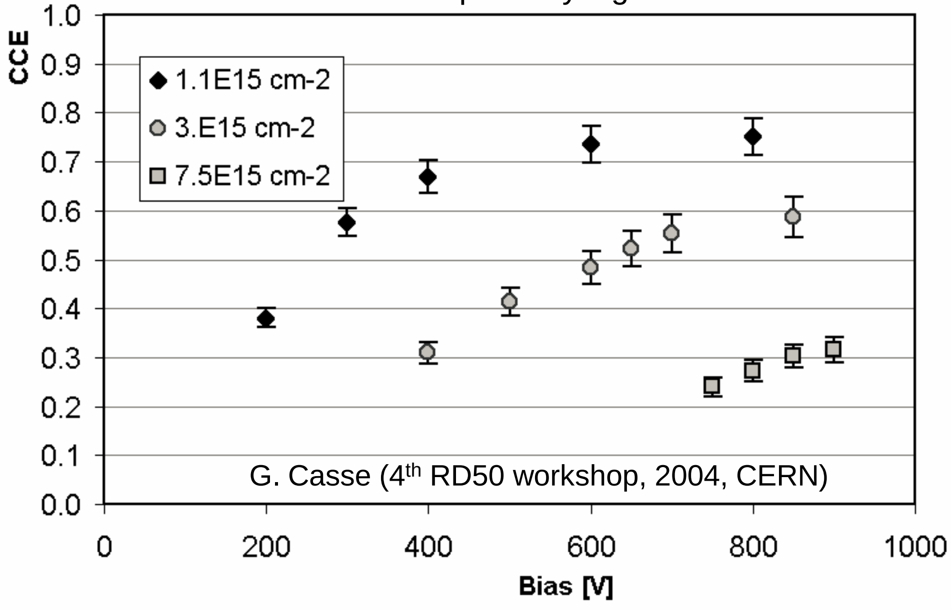
Operation at very high fluences

recent highlights and challenges

What about operation above 10^{15} cm^{-2}?

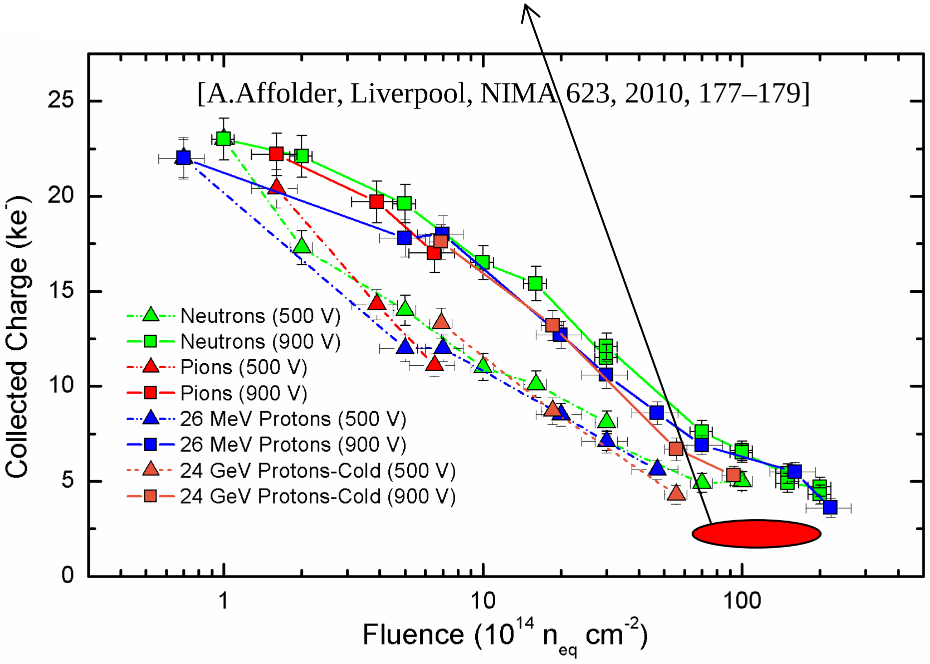
- CCE measurements show excellent results – much better than predicted?
- Problems to understand why:
  - ☐ V_{dep} – CV doesn’t work
  - ☐ Time resolved TCT does not work, trapping to severe

1st observation of unexpectedly high CCE



G. Casse (4th RD50 workshop, 2004, CERN)

Expected signal 2-3x too low!

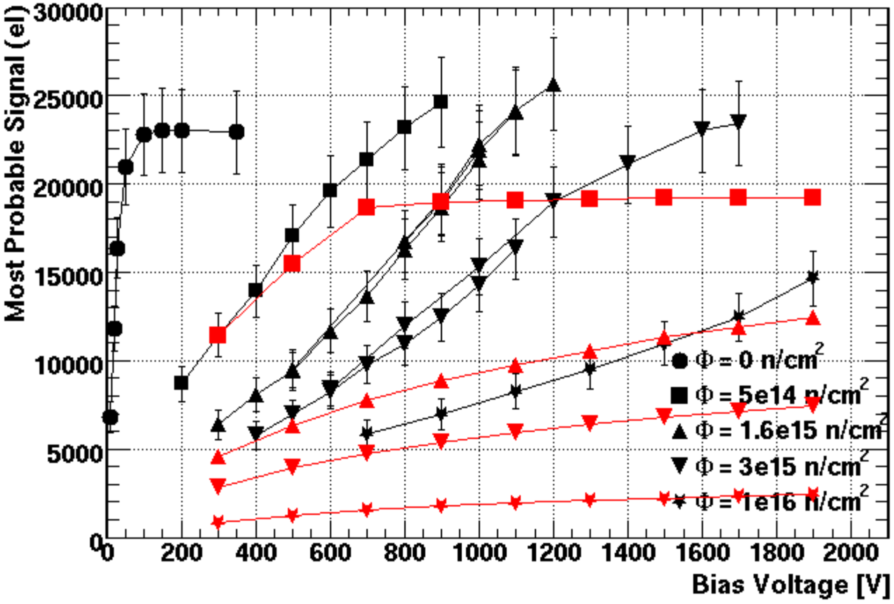


[A.Affolder, Liverpool, NIMA 623, 2010, 177–179]

SIMULATION BASED ON MEASURED DAMAGE PARAMETERS FAILS COMPLETELY!
Even if trapping is off - the active region assumed by depletion is not enough to reproduce the signal!

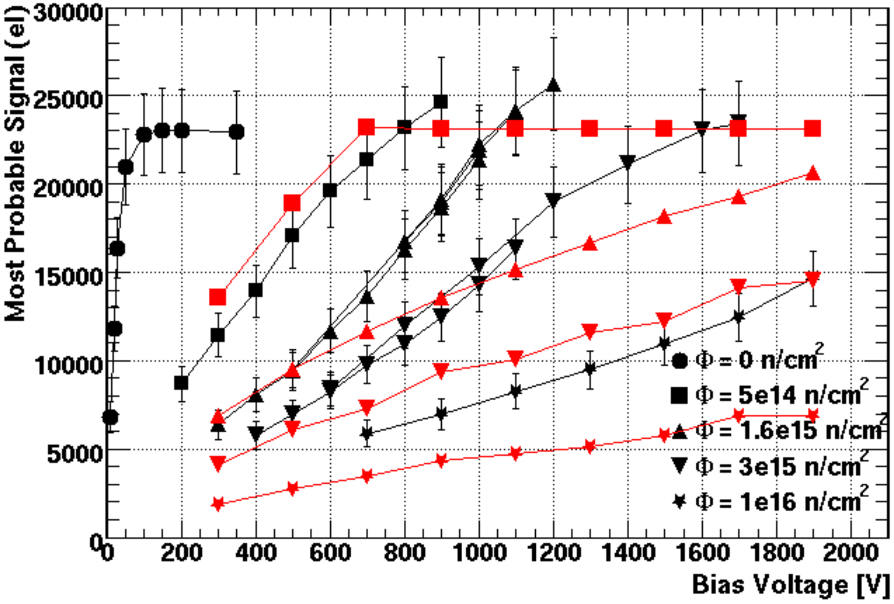
Black: measured, Red: simulation

$\beta_e = 3.2\cdot10^{-16}$ cm^2/ns
$\beta_h = 3.5\cdot10^{-16}$ cm^2/ns



Black: measured, Red: simulation

No trapping, only N_{eff}:

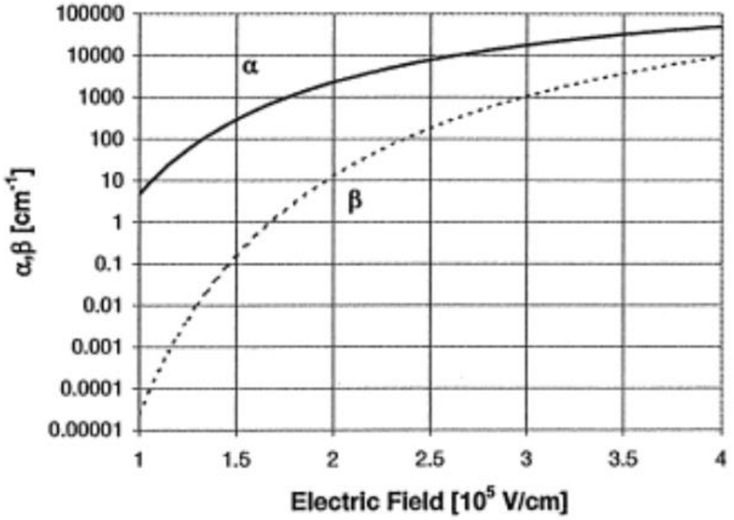


NOTE:

- Very high voltage applied
- CCE >=1

Charge multiplication

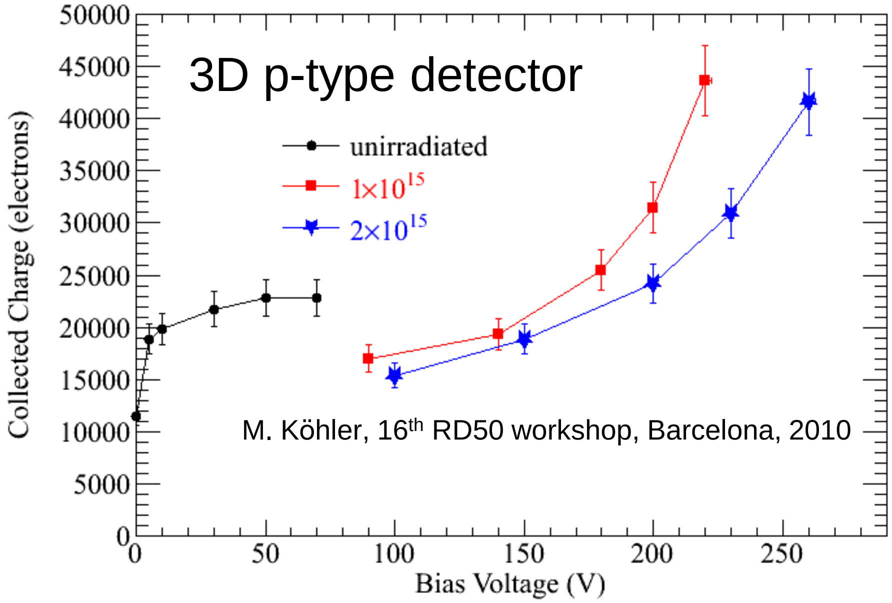
High Φ → large N_{eff} high V → High E → Impact ionization



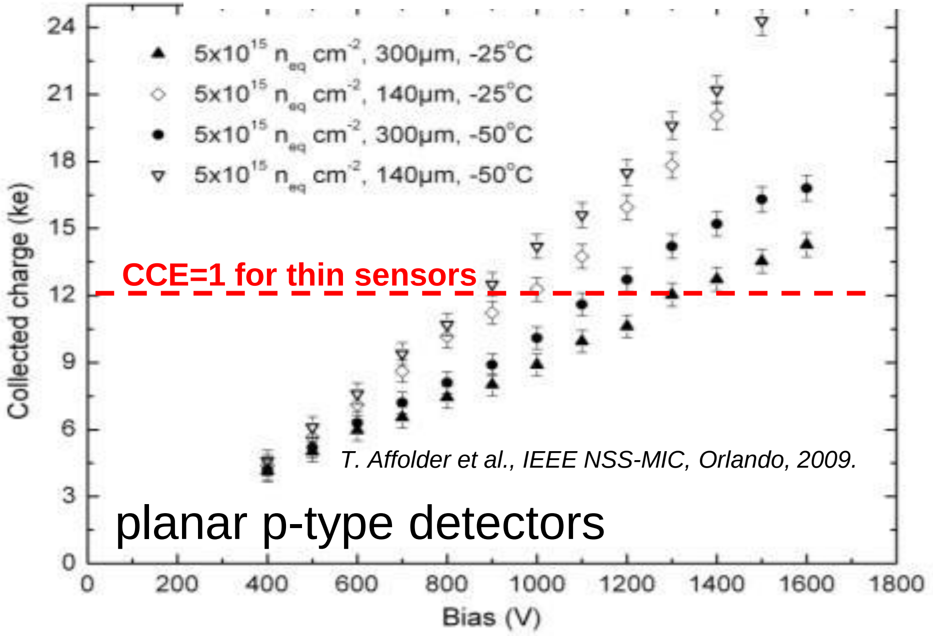
$$dN_e = N_e \cdot \alpha \cdot dx$$

Electrons undergo multiplication in electric fields >10-15 V/µm

CCE > 1 observed for all types – larger in segmented detectors due to "field focusing"


3D p-type detector

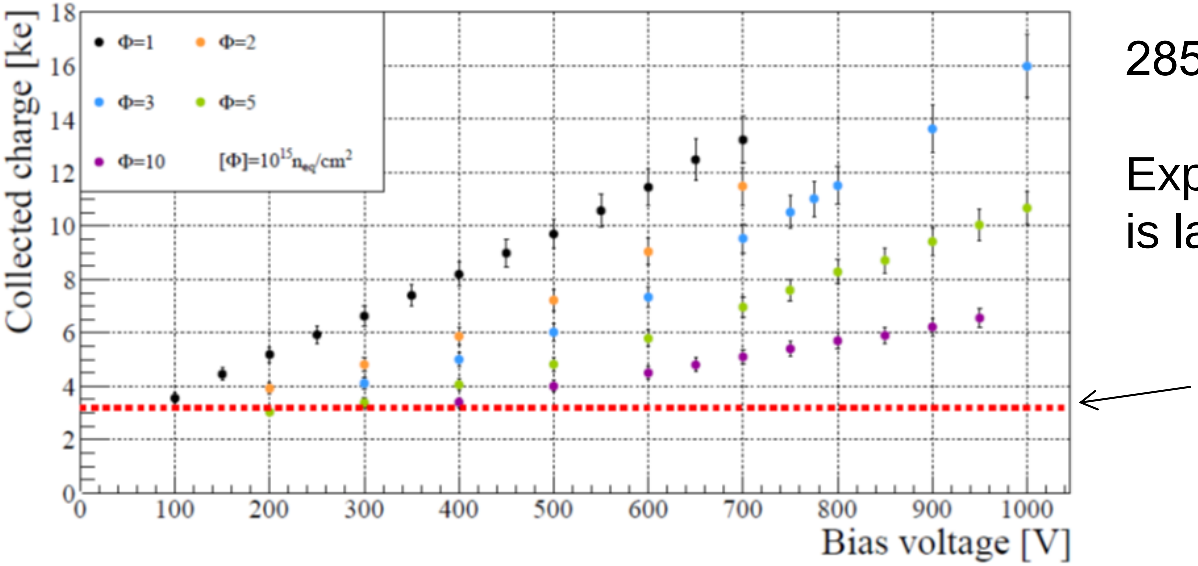
M. Köhler, 16th RD50 workshop, Barcelona, 2010


CCE=1 for thin sensors

T. Affolder et al., IEEE NSS-MIC, Orlando, 2009.

planar p-type detectors

Charge multiplication



threshold

285 μm thick n-in-p FZ pixels

Expected charge of ~2.5-3 ke is largely surpased at 10^{16} cm^{-2}

Both planar and 3D detectors are capable of surviving HL-LHC fluences in terms of signal!

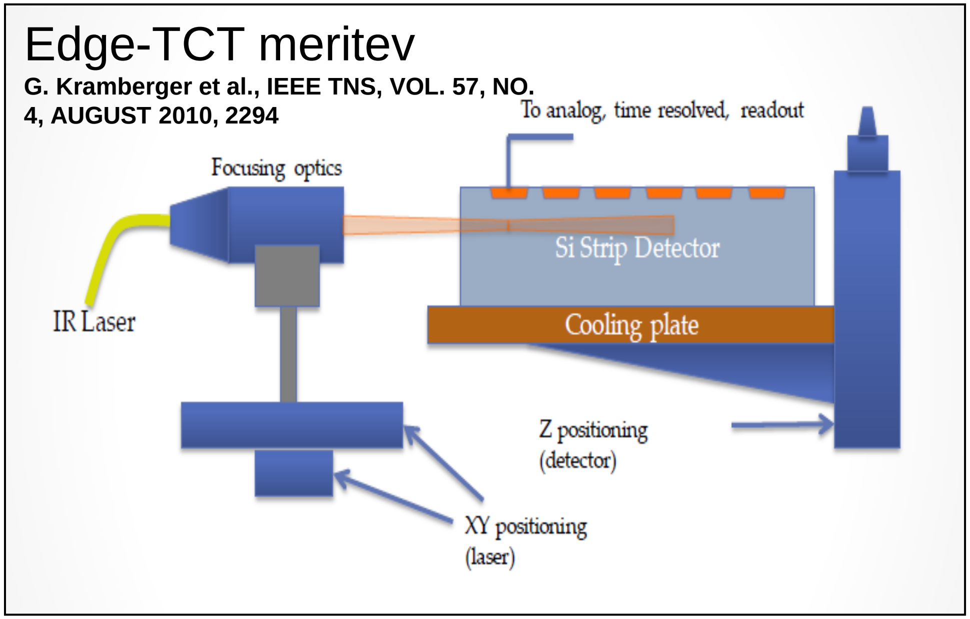
Answers to be provided:

- How to see it in the induced current?
- How to measure the field?

Edge-TCT

- Classical TCT: information of the field from I(t)

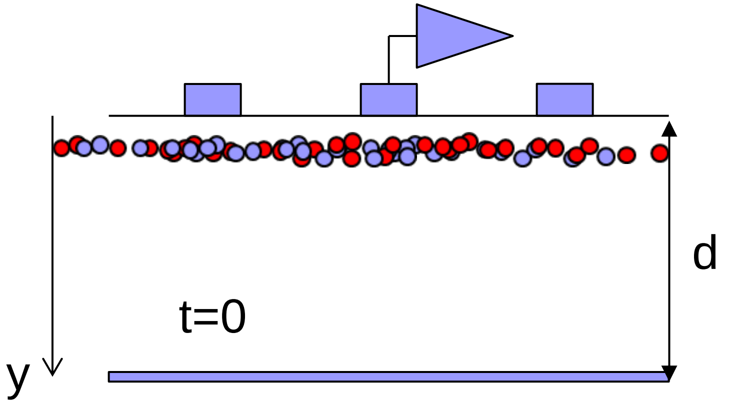
  Edge-TCT: information of the field from I(depth)
- A narrow 8 μm beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip



Edge-TCT meritev

G. Kramberger et al., IEEE TNS, VOL. 57, NO. 4, AUGUST 2010, 2294

$$I(y,t)=\frac{e_0 N_{e,h}}{d}\cdot\left[v_e(y)\exp(-t/\tau_e)+v_h(y)\exp(-t/\tau_h)\right]$$



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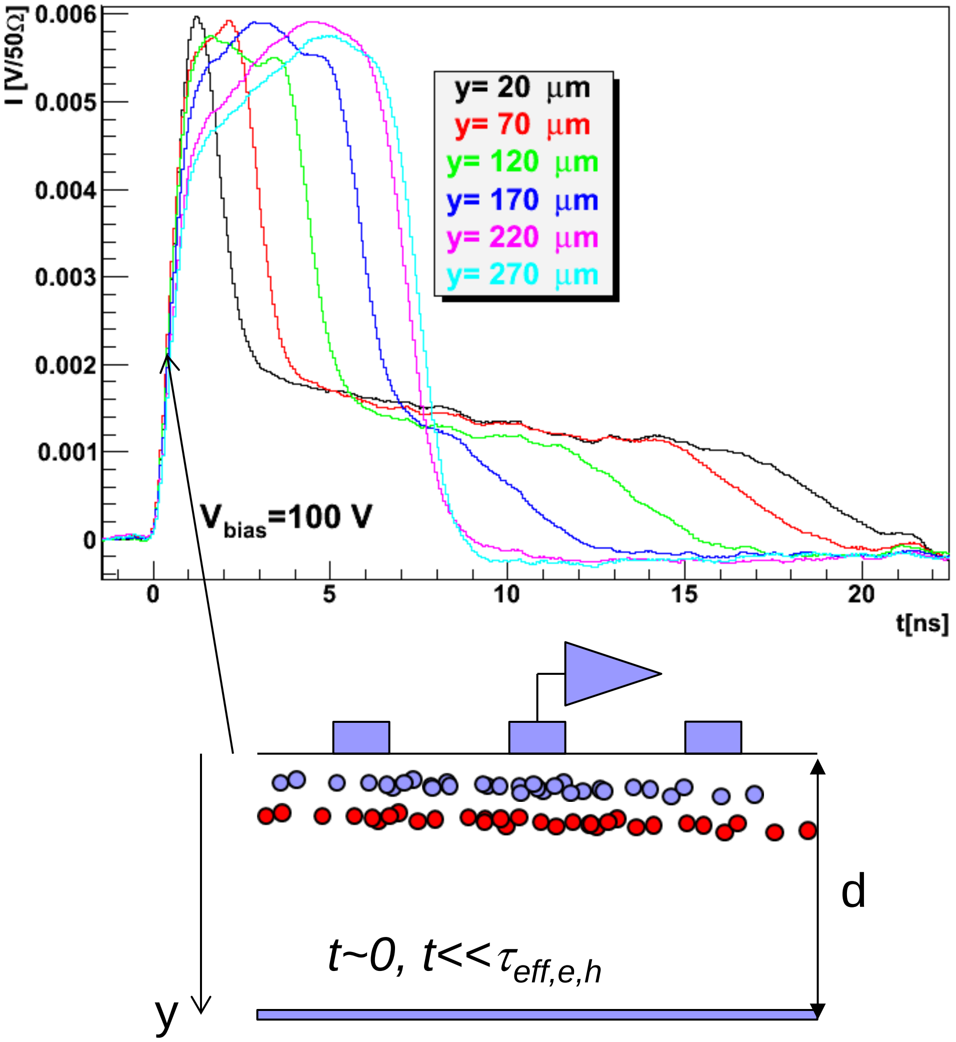
  Edge-TCT: information of the field from I(depth)
- A narrow 8 μm beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip

VELOCITY PROFILE:

$$I(y,t\sim 0)=e_0\,N_{e,h}\cdot\frac{v_e(y)+v_h(y)}{d}$$

$$v_e(y)+v_h(y)\propto I(y,t\sim 0)$$

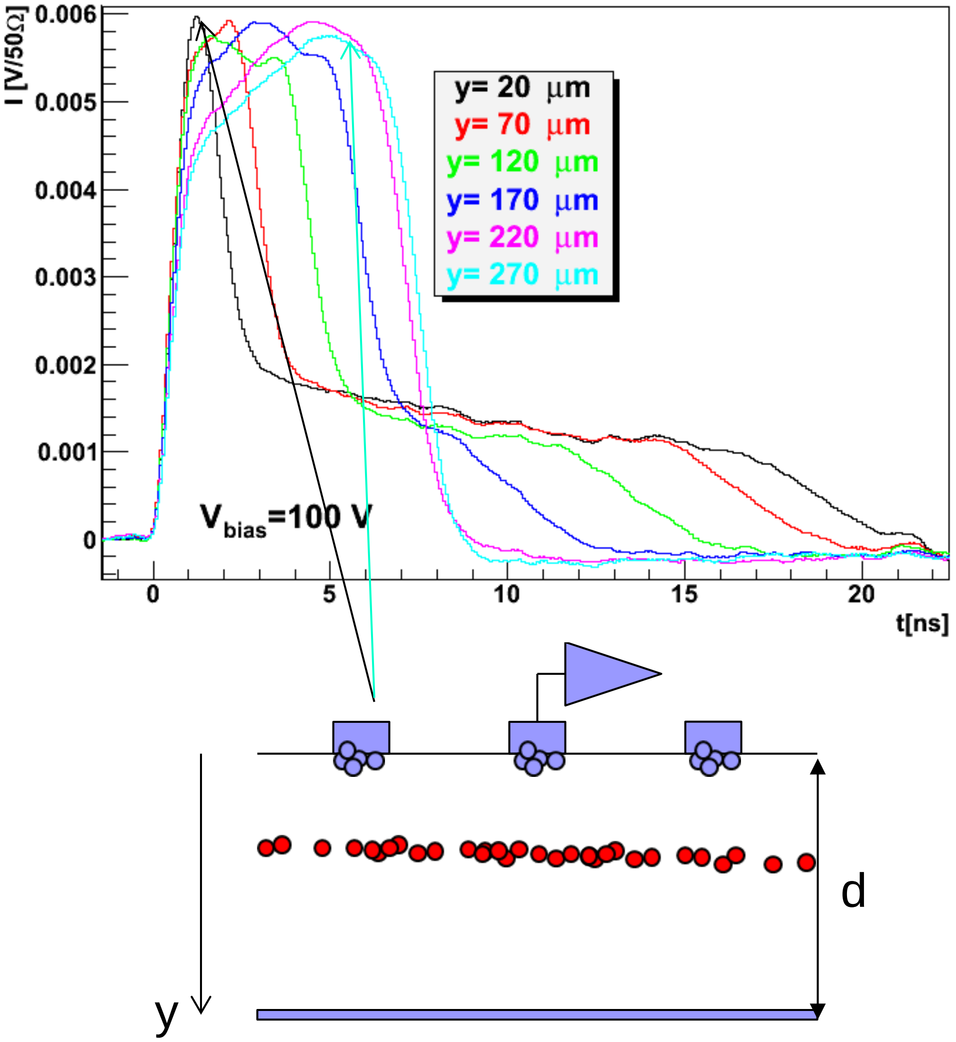


Edge-TCT

- Classical TCT: information of the field from I(t)

  Edge-TCT: information of the field from I(depth)
- A narrow 8 μm beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip

Electrons finish their drift.



Edge-TCT

- Classical TCT: information of the field from I(t)

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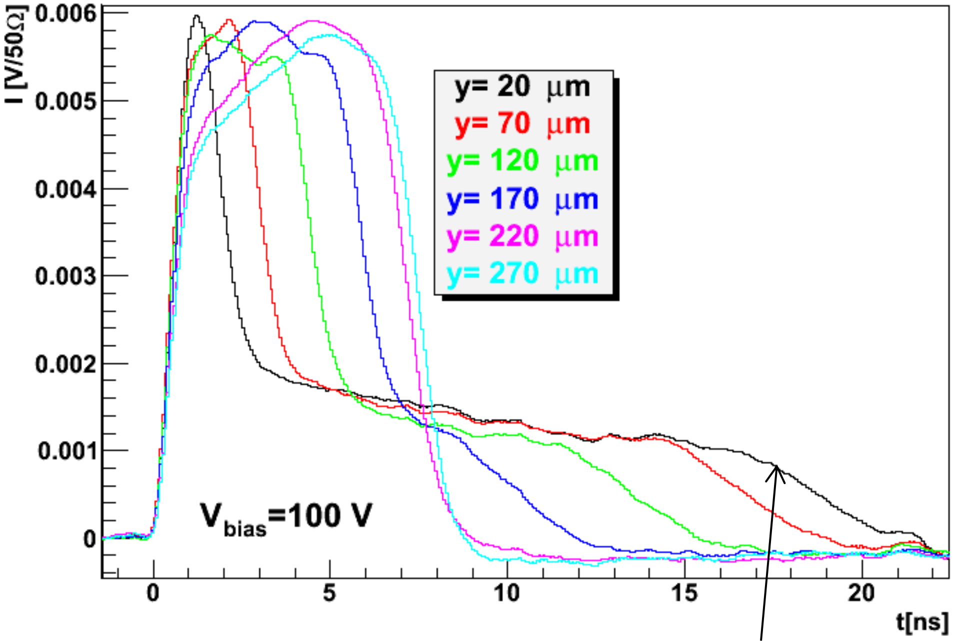
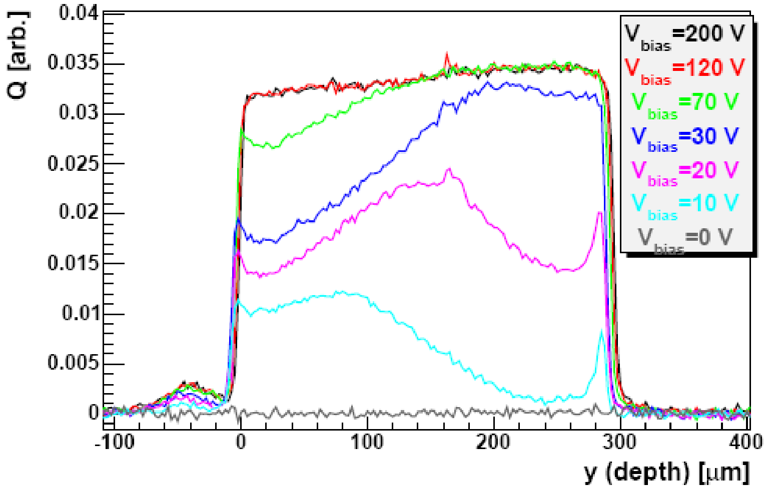
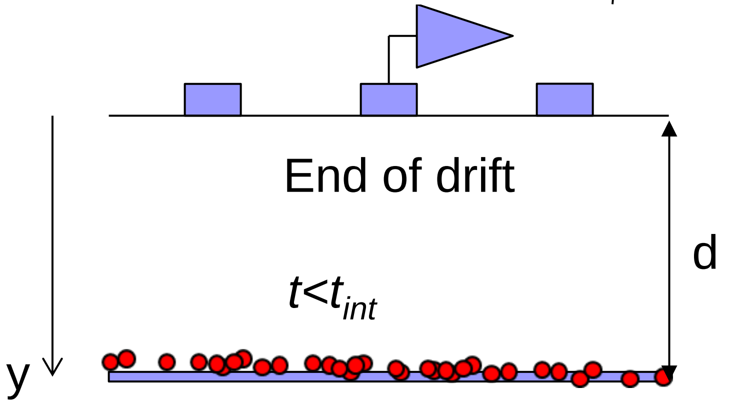
- A narrow 8 μm beam is used to generate e-h pairs at known depth
- Measured current is average over the width of the strip

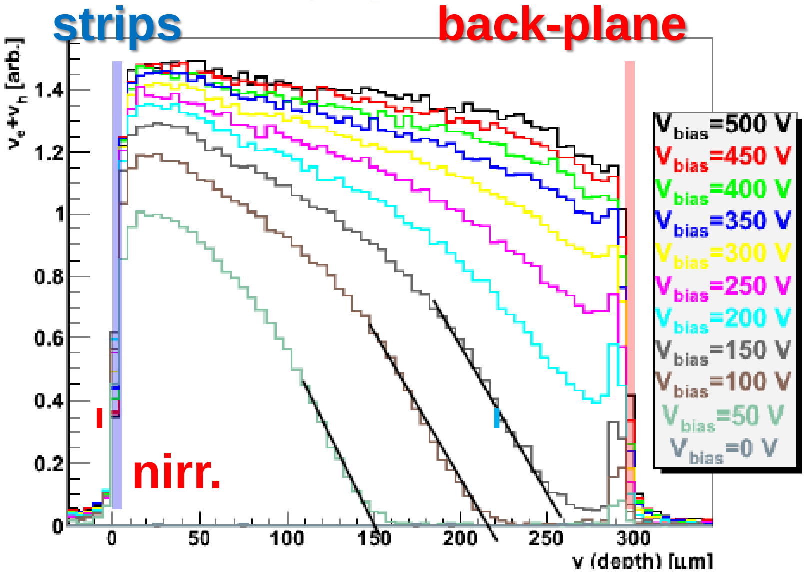


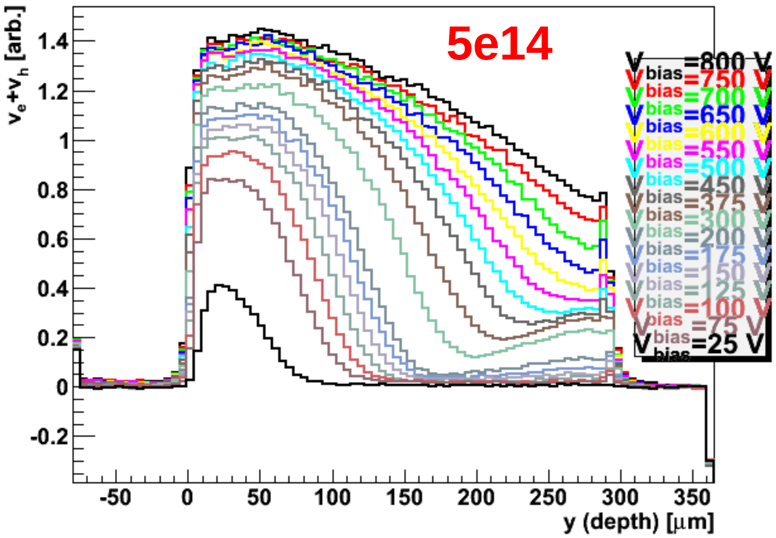


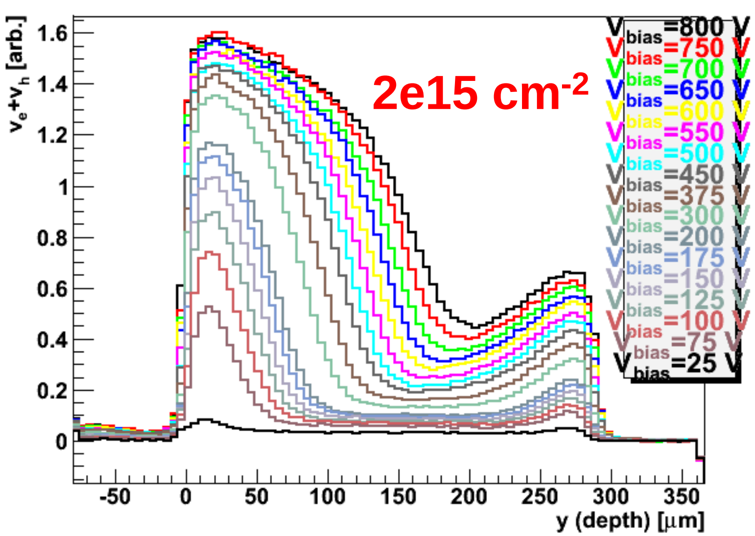


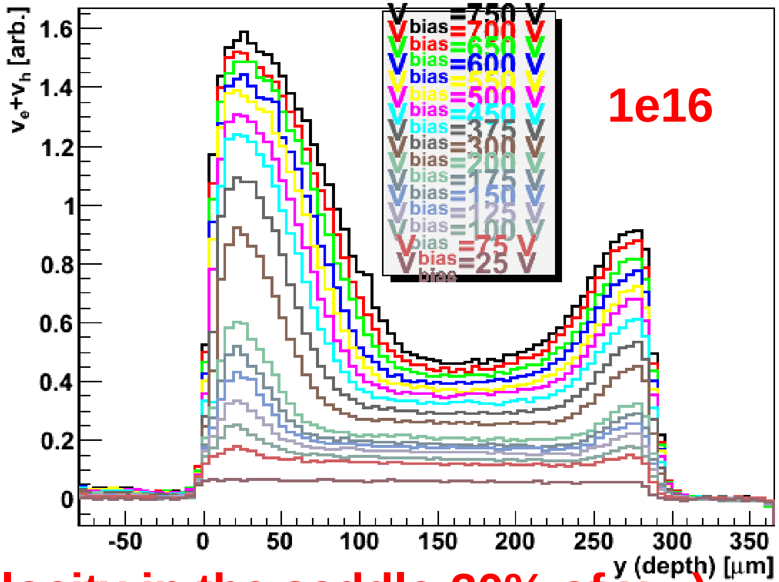
$$Q(y) = \int_{t=0}^{t_{\text{int}}} I(y,t)\, dt$$

Velocity profiles





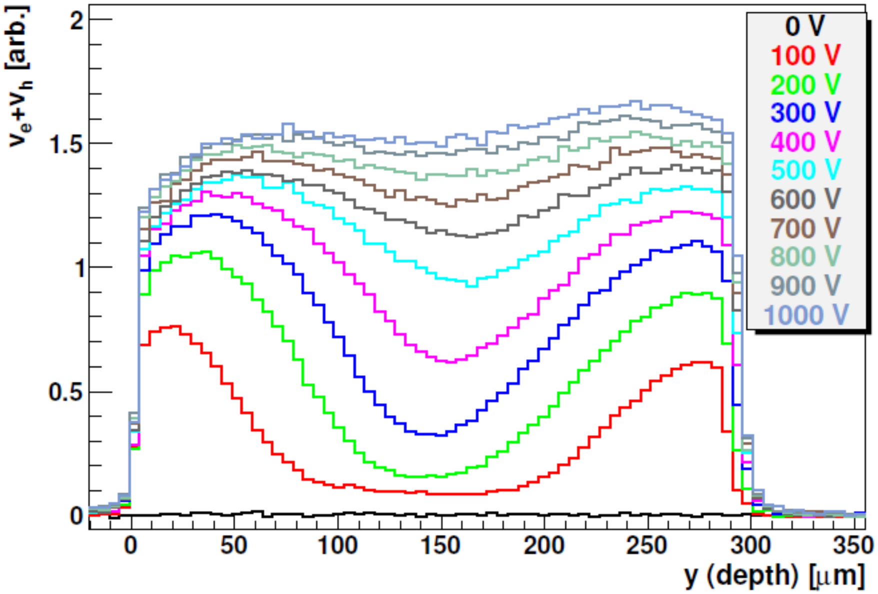


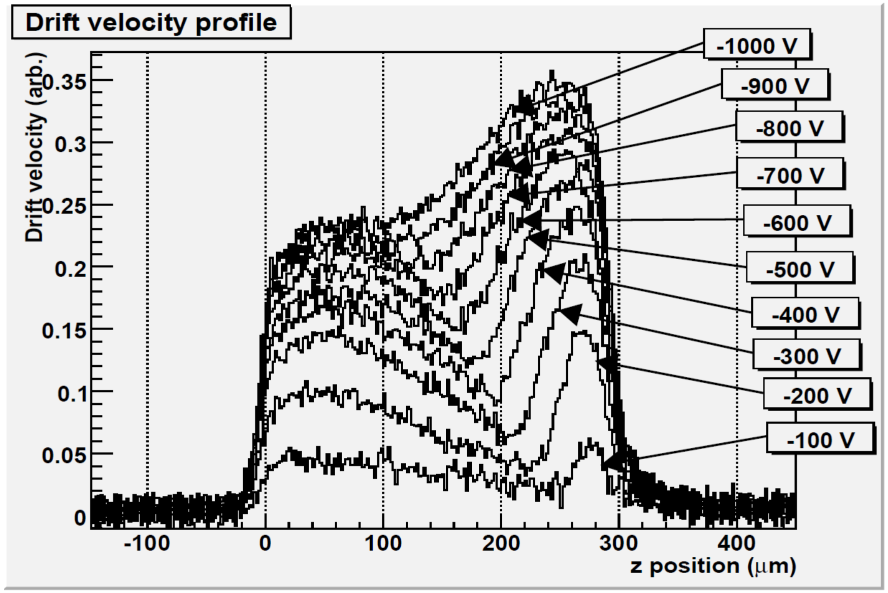


- **whole detector volume is active (velocity in the saddle-30% of v_{sat})**
- **the high field region penetrates deeper in the detector than predicted**

Velocity profiles

N. Pacifico et al., presented at RESMDD 10





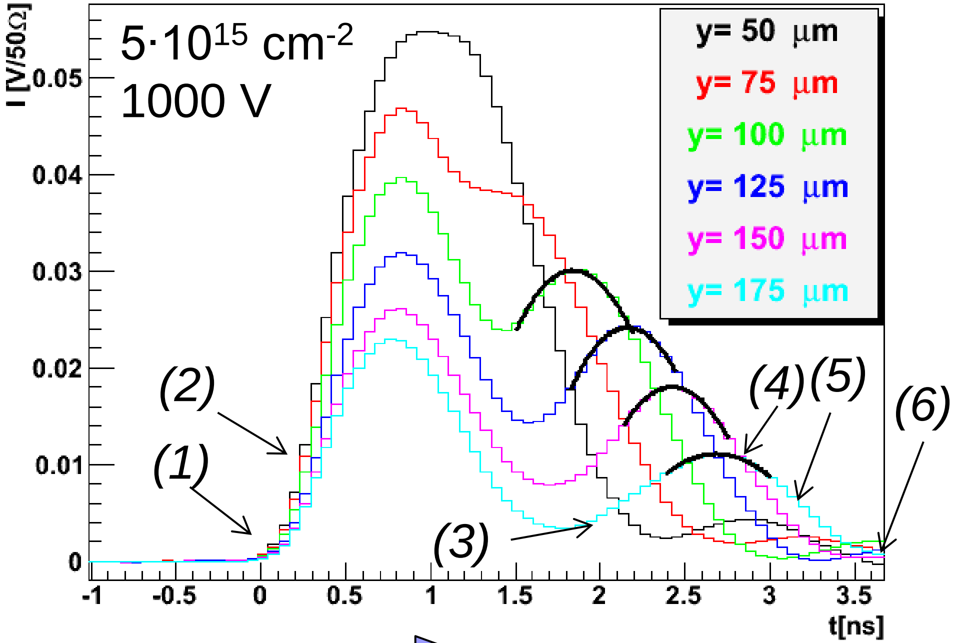
FZ-p detector irradiated to
$\Phi_{eq}=1.6\cdot10^{15}$ cm^{-2} 300 MeV pions

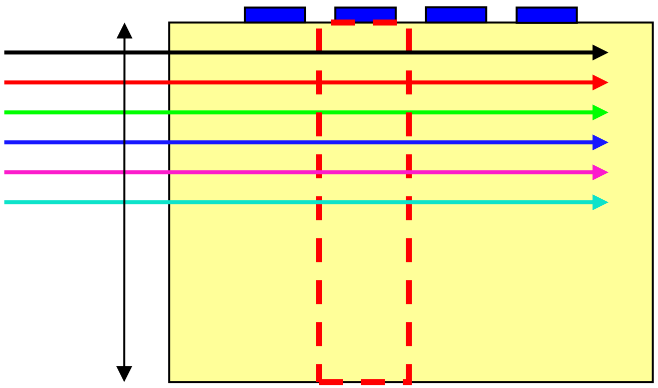
- Almost symmetrical electric field.
- Elmost saturated drift velocity in the sensor at already 500V

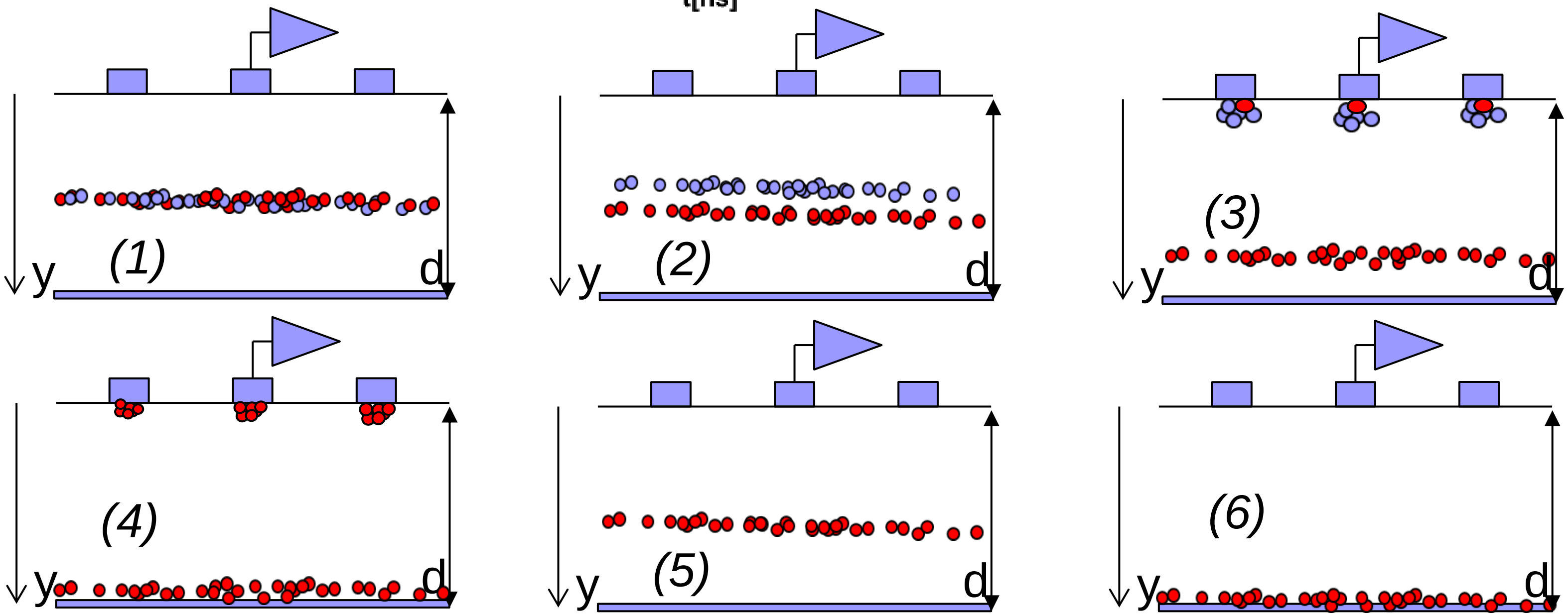
MCz-n detector irradiated to
$\Phi_{eq}=3\cdot10^{15}$ cm^{-2} neutrons

- symmetrical electric field.
- dominant p^+ side at small/moderate voltages

Charge multiplication





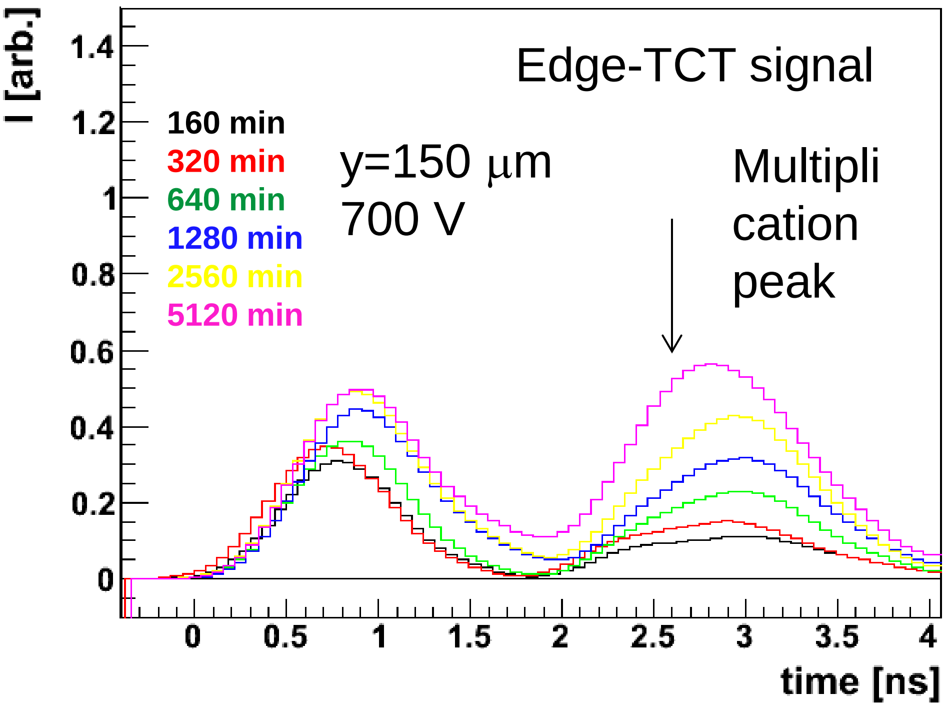


Charge multiplication and annealing

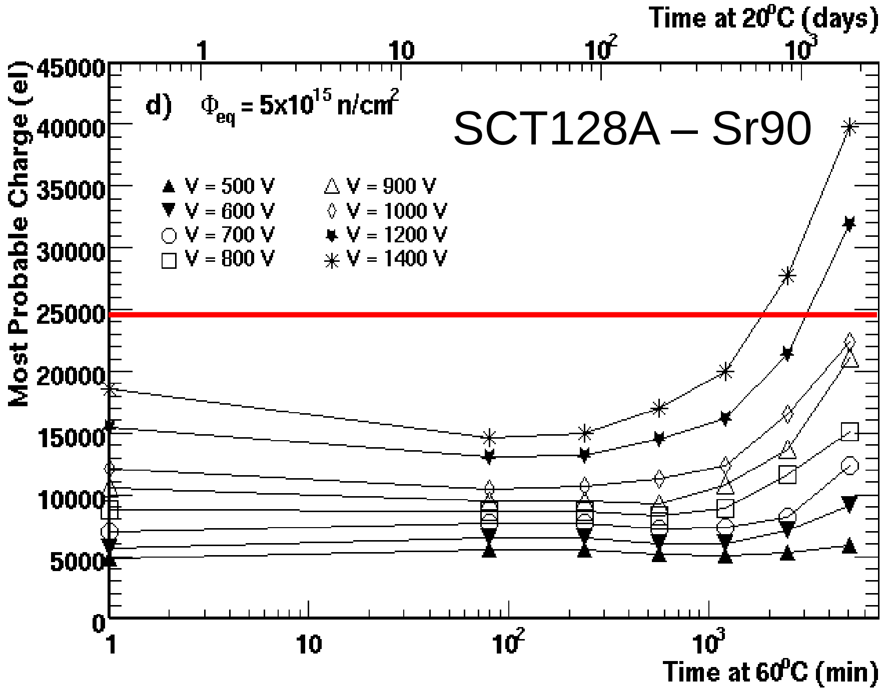
Long term annealing seem not be a problem

- ☐ Electric field present in the whole detector
- ☐ Electric field is high at the strips
- ☐ Effective trapping times beneficially anneal
- ☐ Additional acceptors even increase multiplication at high voltages

Micron; FZ n-p, neutrons 5e15 cm^{-2}



HPK FZ n-p, neutrons 5e15 cm^{-2}



Multiplication current and noise

- increase of current correlated with increase of signal – thermally generated carriers are multiplied
- current increase results in the increase of noise according to

excess factor

shot noise with multiplication →

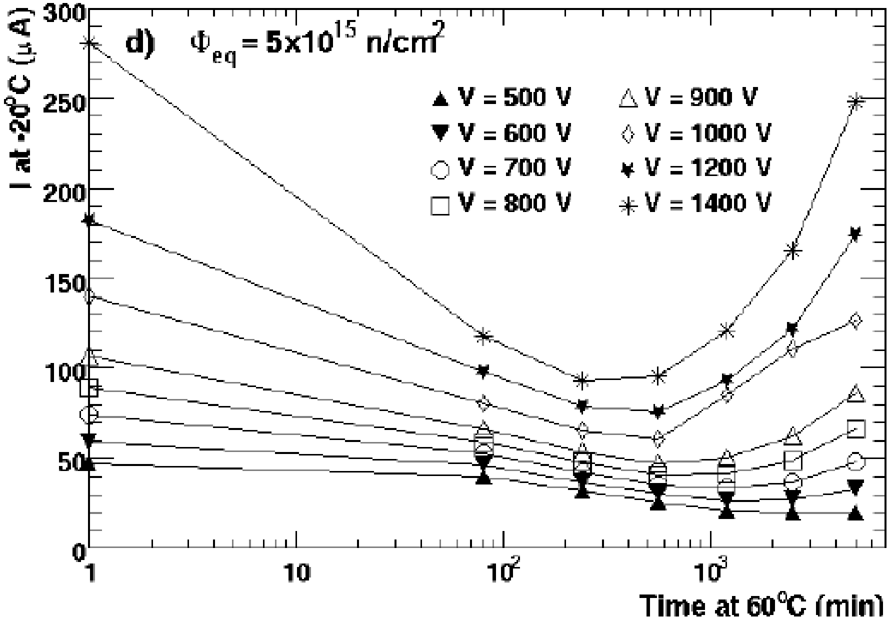
$$ENC_{MI} = ENC_I \cdot \sqrt{F} \cdot M_I$$

current multiplication

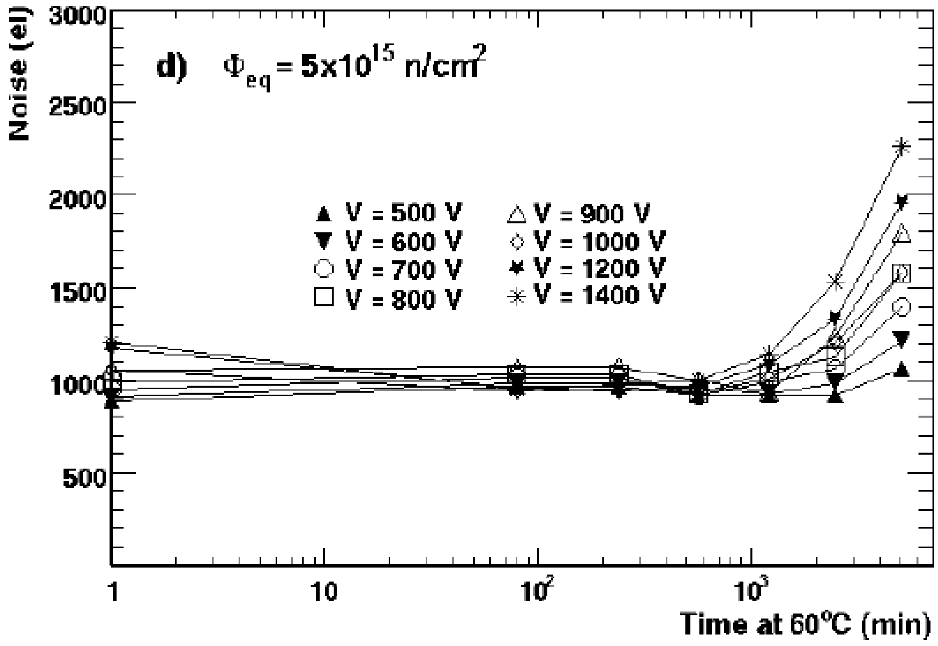
Noise without multiplication for the generation current I

Gain in S/N expected for small electrodes where the series noise dominates!

HPK FZ n-p, neutrons 5e15 cm^{-2}



Current larger than expected for full volume already at low voltages.



SCT128A – Sr90

Conclusions – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (internal electric field modifications, “type inversion”, reverse annealing, loss of active volume, …) (can be influenced by defect engineering!)
  - Increase of **Leakage Current** (same for all silicon materials)
  - Increase of **Charge Trapping** (same for all silicon materials)

Signal to Noise ratio is quantity to watch (material + geometry + electronics)

- **Approaches to obtain radiation tolerant devices:**
  - **Material Engineering:** - explore and develop new silicon materials (oxygenated Si)
    - use of other semiconductors (Diamond)
  - **Device Engineering:** - look for other sensor geometries
    - 3D, thin sensors, n-in-p, n-in-n, …

- **Excellent radiation hardness of silicon detectors at HL-LHC fluences**
  - **active bulk** **-** velocity in the saddle can be >30% of the saturated one
  - **active region** **-** penetrates deeper in the bulk than extrapolated
  - **Charge multiplication** **-** increase of N_{eff} leads to impact ionization at high bias
    - the leakage current and noise also increase – improvement in S/N requires optimization of geometry
    - long term annealing seem not to be harmful

Acknowledgements & References

- **Most references to particular works given on the slides**

- **Some additional material taken from the following presentations:**
  - ***RD50 presentations: http://www.cern.ch/rd50/***
  - ***Anthony Affolder: Presentations on the RD50 Workshop in June 2009 (ATLAS fluence levels)***
  - ***Frank Hartmann: Presentation at the VCI conference in February 2010 (Diamond results)***

- **Books containing chapters about radiation damage in silicon sensors**
  - ***Helmuth Spieler, "Semiconductor Detector Systems", Oxford University Press 2005***
  - ***Frank Hartmann, "Evolution of silicon sensor technology in particle physics", Springer 2009***
  - ***L.Rossi, P.Fischer, T.Rohe, N.Wermes "Pixel Detectors", Springer, 2006***
  - ***Gerhard Lutz, "Semiconductor radiation detectors", Springer 1999***

- **Research collaborations and web sites**
  - ***CERN RD50 collaboration (http://www.cern.ch/rd50) - Radiation Tolerant Silicon Sensors***
  - ***CERN RD39 collaboration – Cryogenic operation of Silicon Sensors***
  - ***CERN RD42 collaboration – Diamond detectors***
  - ***Inter-Experiment Working Group on Radiation Damage in Silicon Detectors (CERN)***
  - ***ATLAS IBL, ATLAS and CMS upgrade groups***