Comparing Si and Diamond for SLHC

Folklore up to a few years ago:

Diamond: radiation hard up to 10^{16} n/cm^2
Si radiation hard up to 10^{14} n/cm^2

Diamond available soon as large
single crystal wafers
allowing MIP detection

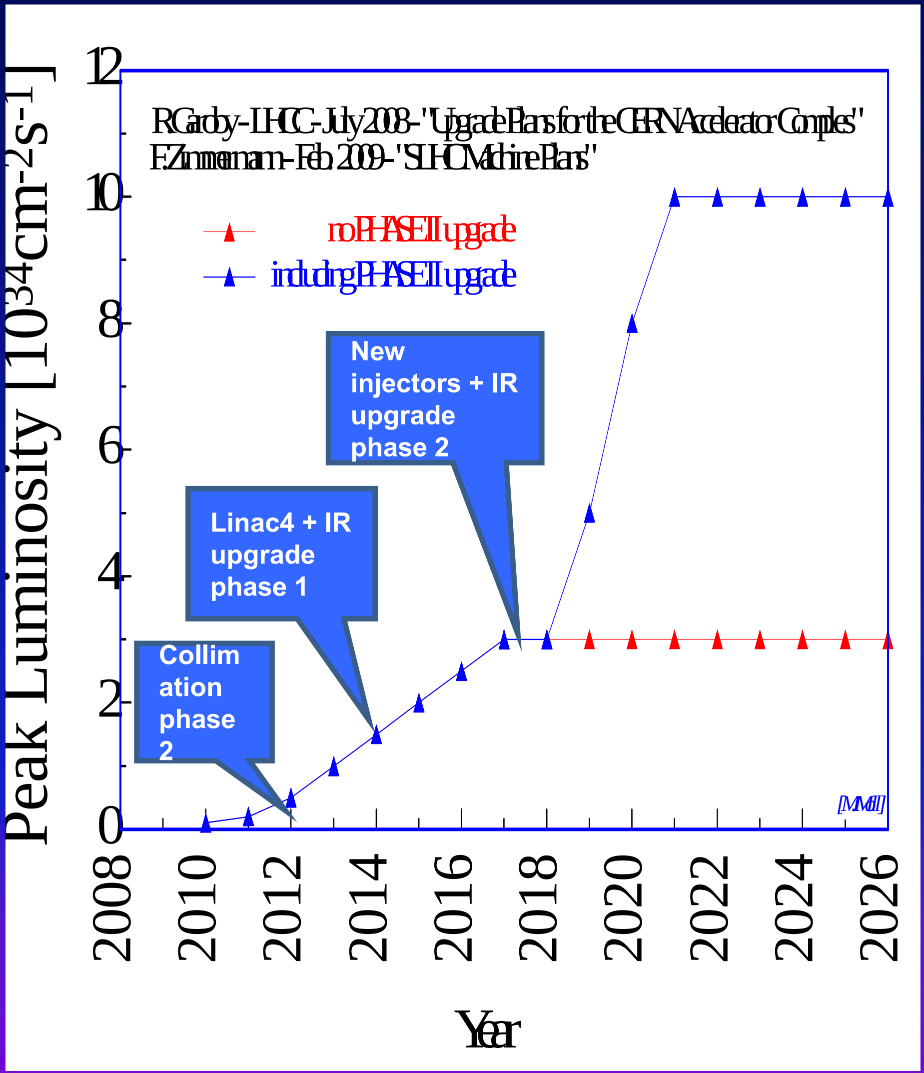
Comparing Si and Diamond for SLHC

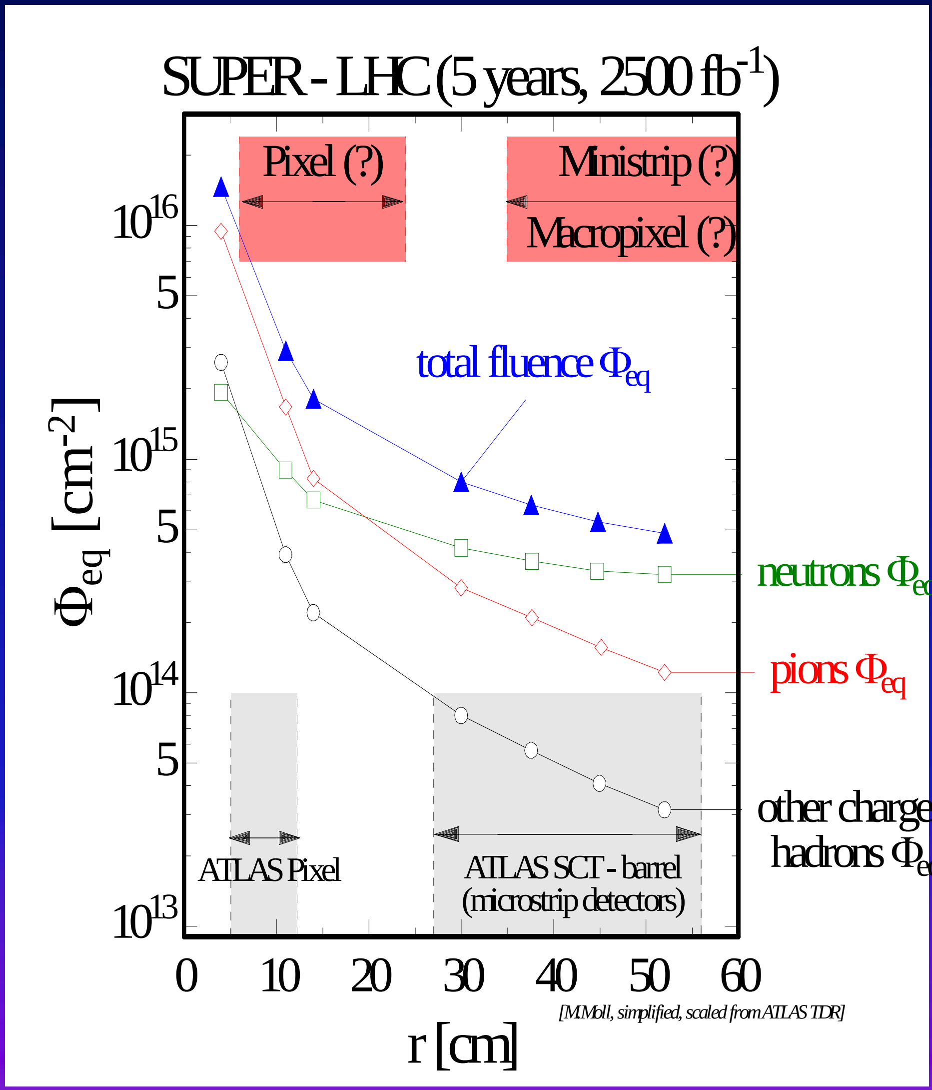
Folklore in 2010:

Si usable up to a few 10^{16} n/cm2
(albeit large leakage current, i.e. needs strong cooling)

Diamond single crystals in large quantities at reasonable prices still difficult and not so radiation hard
(but small leakage current, no cooling)

Why 10^16 needed?

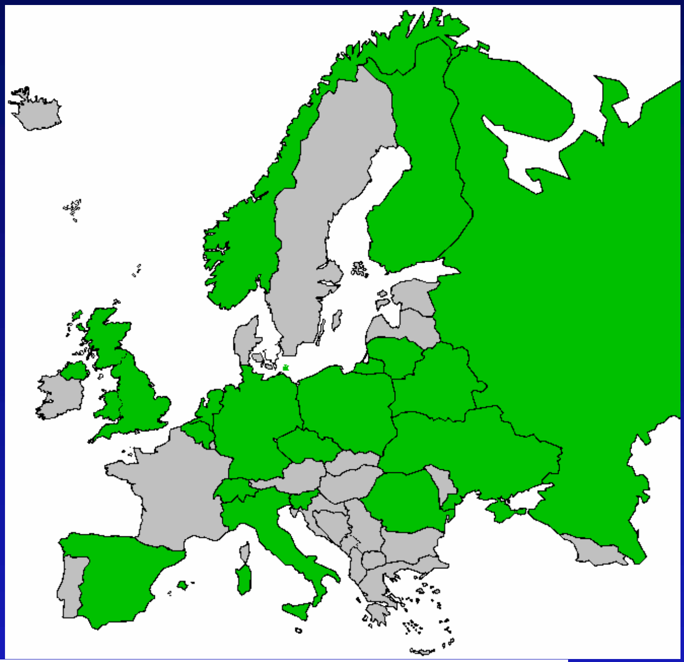




From M. Moll, CERN, RD50

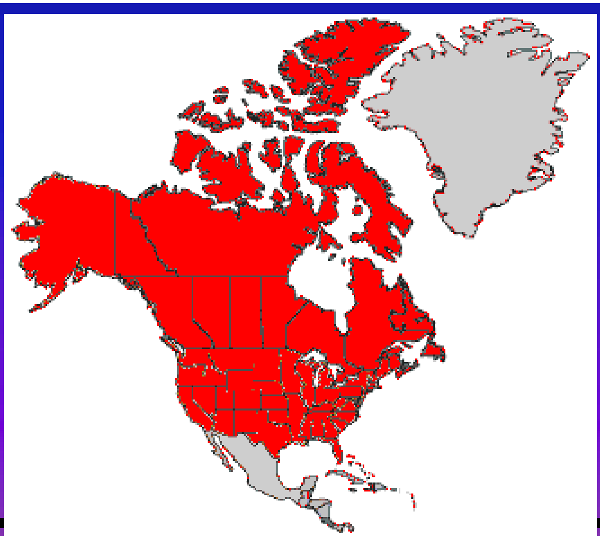
RD50 Collaboration on radiation hardness

247 Members from 47 Institutes



38 European institutes

Belarus (Minsk), **Belgium** (Louvain), **Czech Republic** (Prague (3x)), **Finland** (Helsinki, Lappeenranta), **Germany** (Dortmund, Erfurt, Freiburg, Hamburg, Karlsruhe, Munich), **Italy** (Bari, Florence, Padova, Perugia, Pisa, Trento), **Lithuania** (Vilnius), **Netherlands** (NIKHEF), **Norway** (Oslo (2x)), **Poland** (Warsaw(2x)), **Romania** (Bucharest (2x)), **Russia** (Moscow, St.Petersburg), **Slovenia** (Ljubljana), **Spain** (Barcelona, Valencia), **Switzerland** (CERN, PSI), **Ukraine** (Kiev), **United Kingdom** (Glasgow, Lancaster, Liverpool)



8 North-American institutes

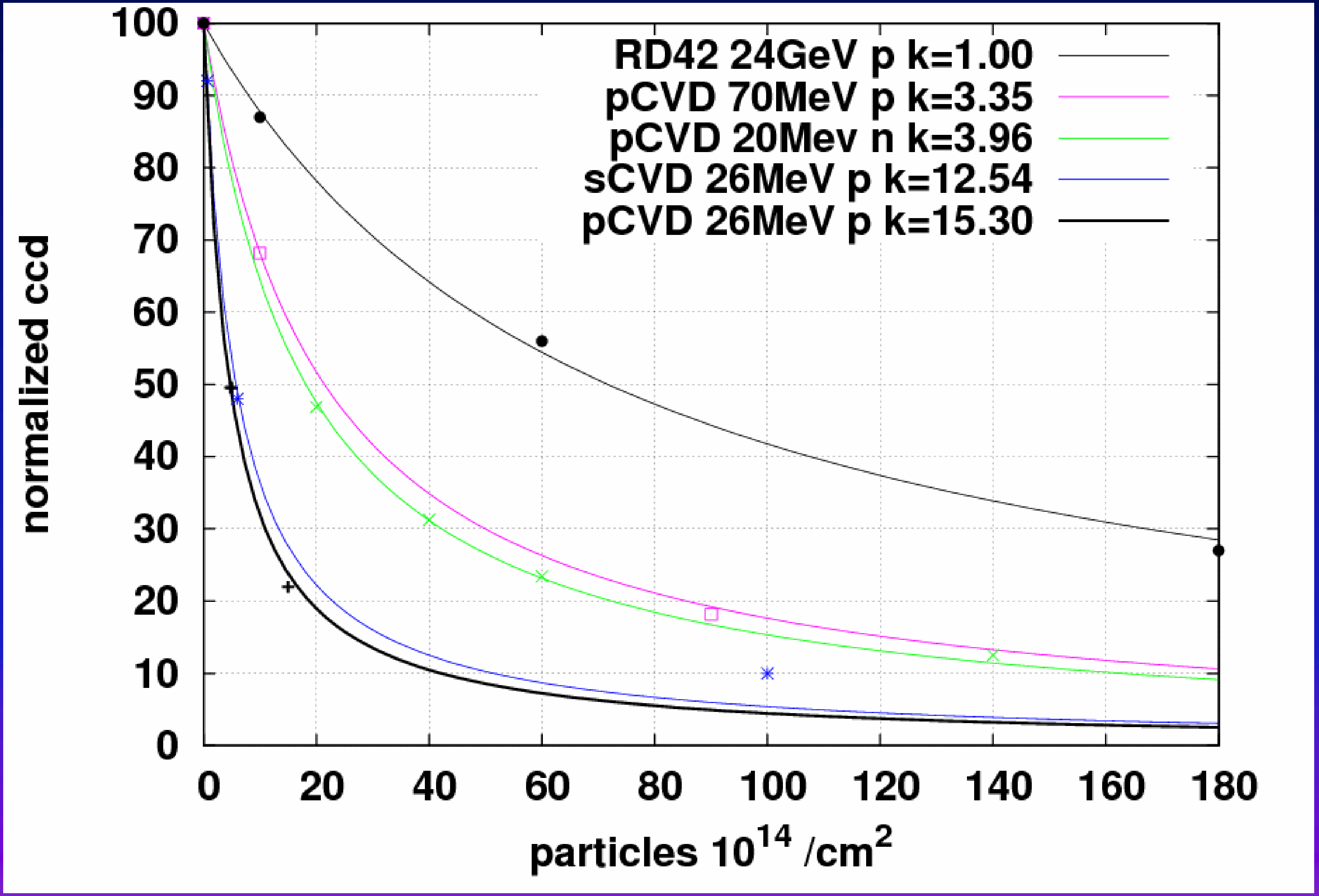
Canada (Montreal), **USA** (BNL, Fermilab, New Mexico, Purdue, Rochester, Santa Cruz, Syracuse)

1 Middle East institute

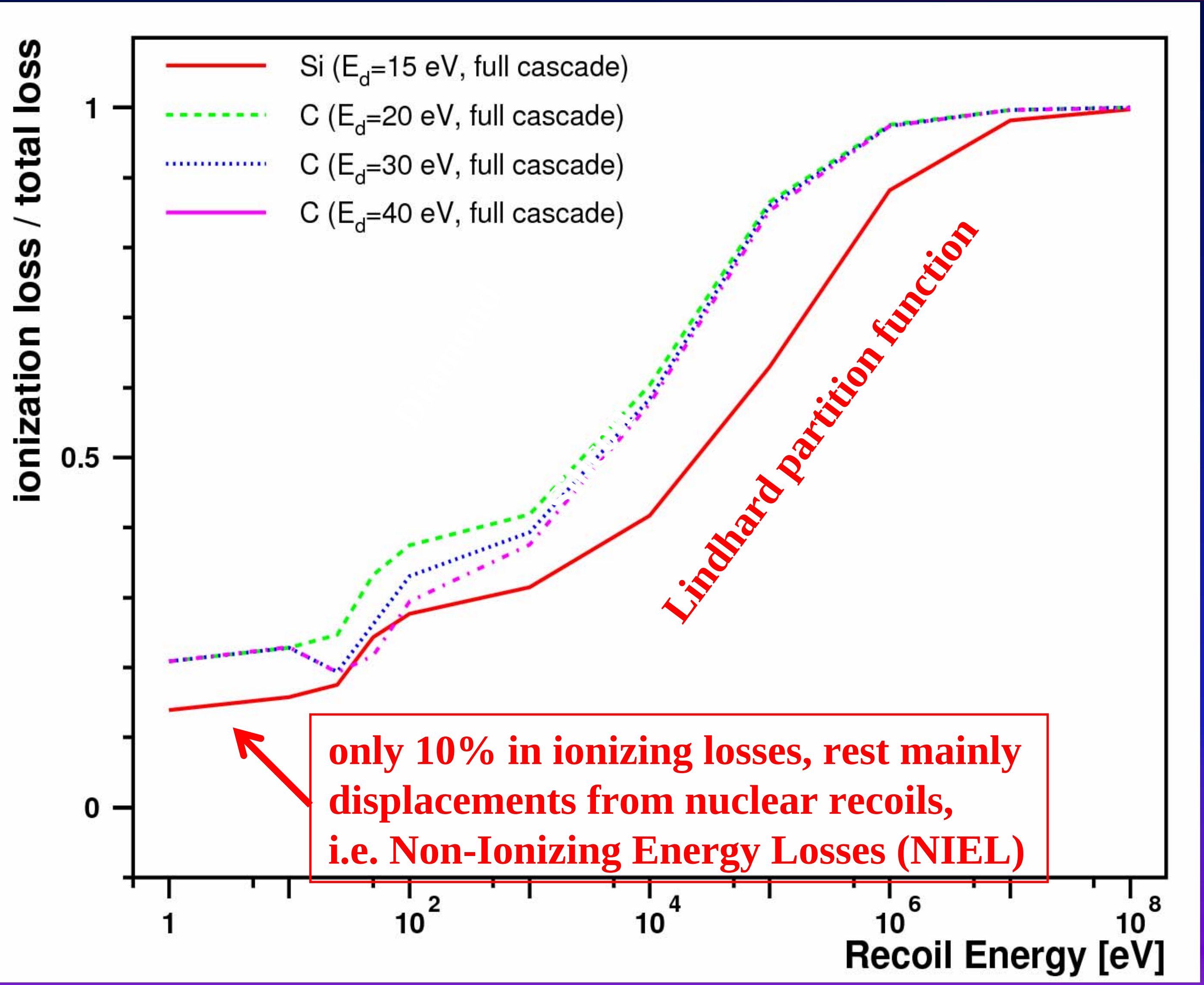
Israel (Tel Aviv)

Detailed member list: http://cern.ch/rd50

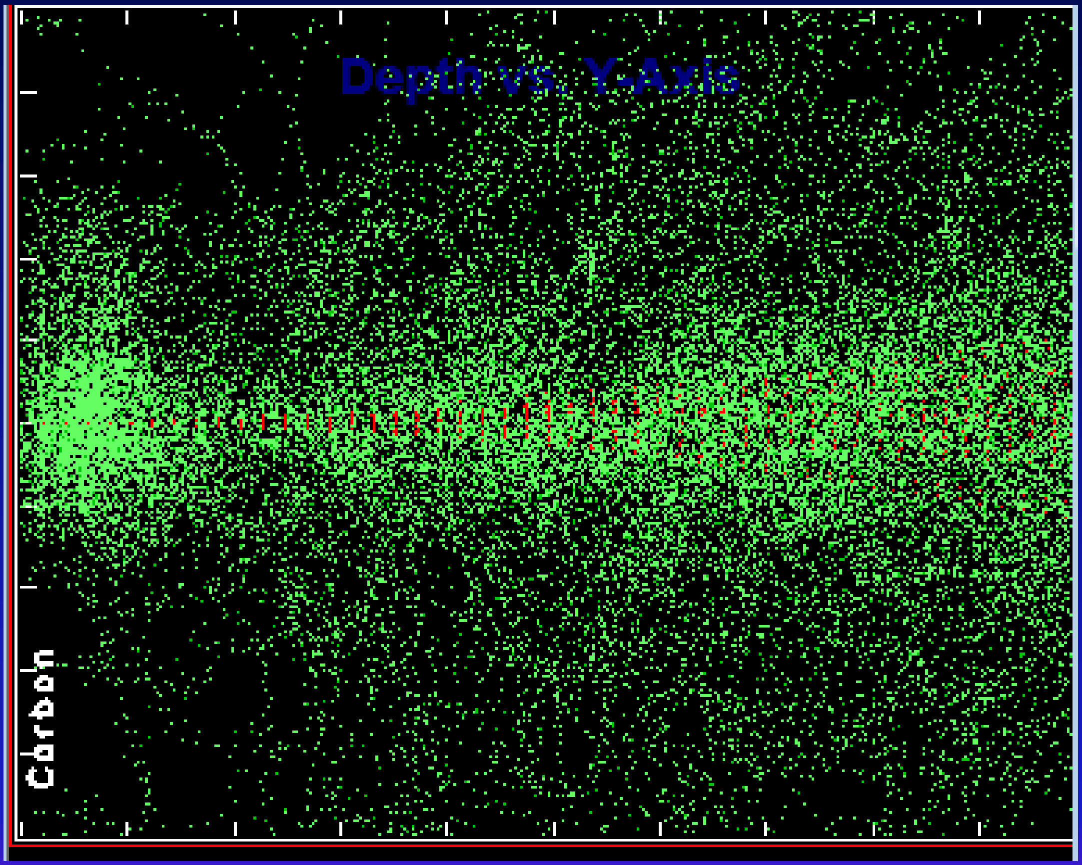
Diamond radiation hardness decreases at low energies



NIEL mainly by low energy impinging particles



Radiation damage by nuclear recoils in Si and C



Displacement defects calculated with SRIM.COM

Z	Ions	NIEL
14	417	4.2
13	910	9.06
12	1384	12.47
11	1021	8.86
10	1225	8.45
9	265	1.41
8	493	2.09
7	398	1.31
6	909	2.36
5	270	0.55
4	383	0.66
3	662	0.67
2	11152	4.4
1	46107	0.9
Total	6559	57.38

Mg, Al important recoils in Si

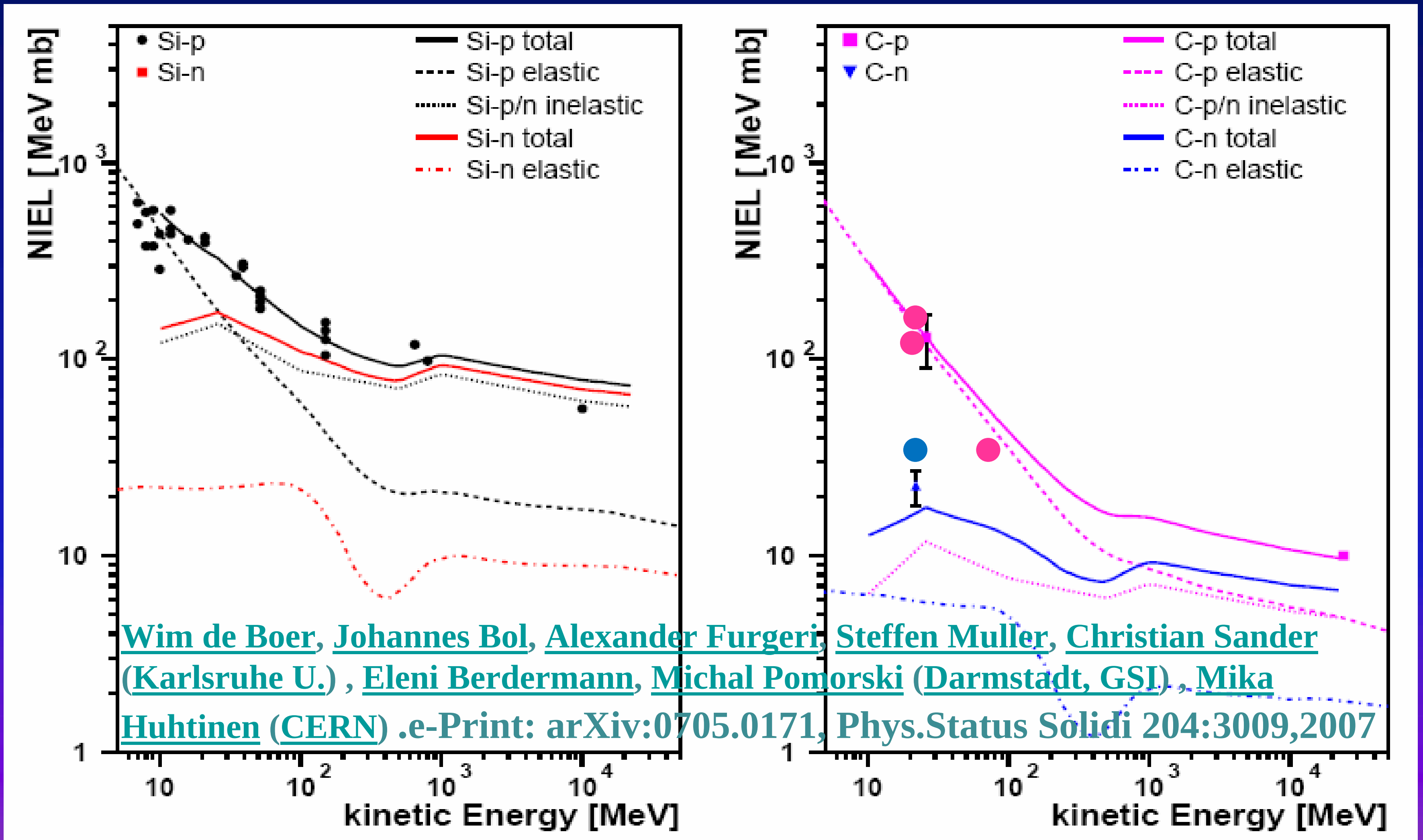
10 GeV protons

Z	Ion	NIEL
6	698	0.8
5	869	0.77
4	584	0.44
3	1133	0.55
2	10625	2.01
1	30465	0.24
Total	44374	4.81

only He important recoil in C

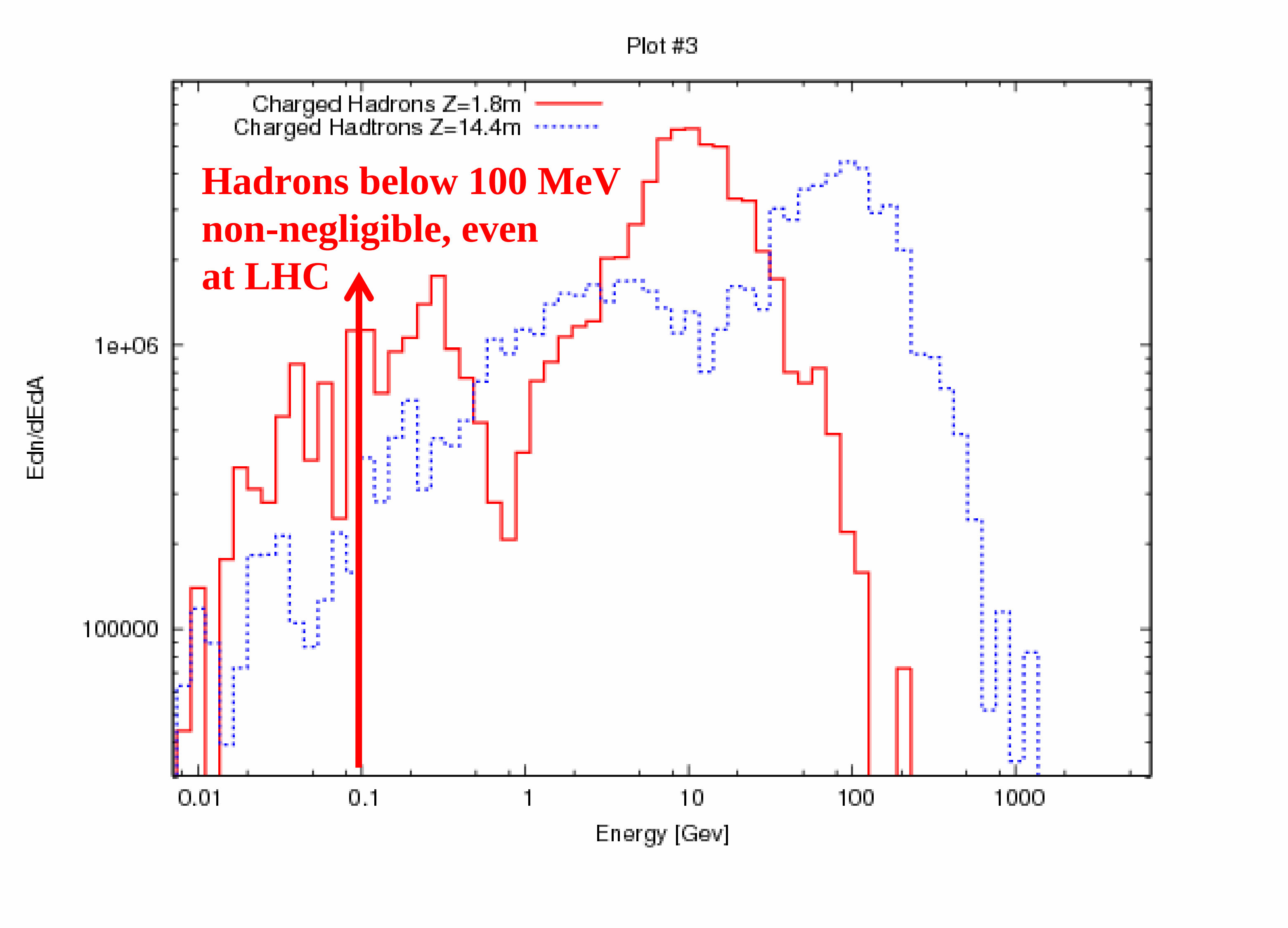
Comparison with NIEL cross sections

NIEL in Silicon **NIEL in Diamond**

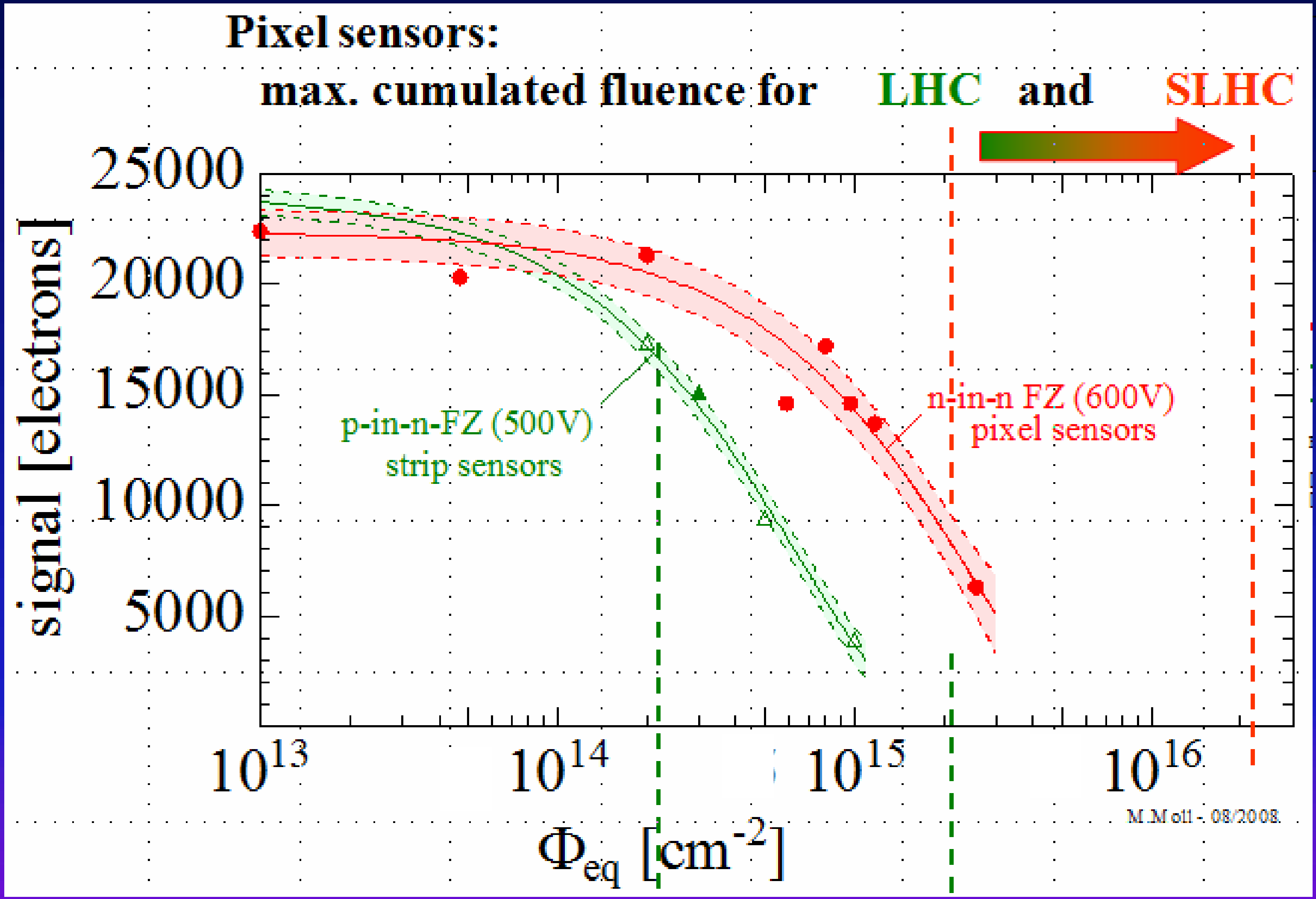


Wim de Boer, Johannes Bol, Alexander Furgeri, Steffen Muller, Christian Sander (Karlsruhe U.) , Eleni Berdermann, Michal Pomorski (Darmstadt, GSI) , Mika Huhtinen (CERN) .e-Print: arXiv:0705.0171, Phys.Status Solidi 204:3009,2007

Hadron spectra at the LHC

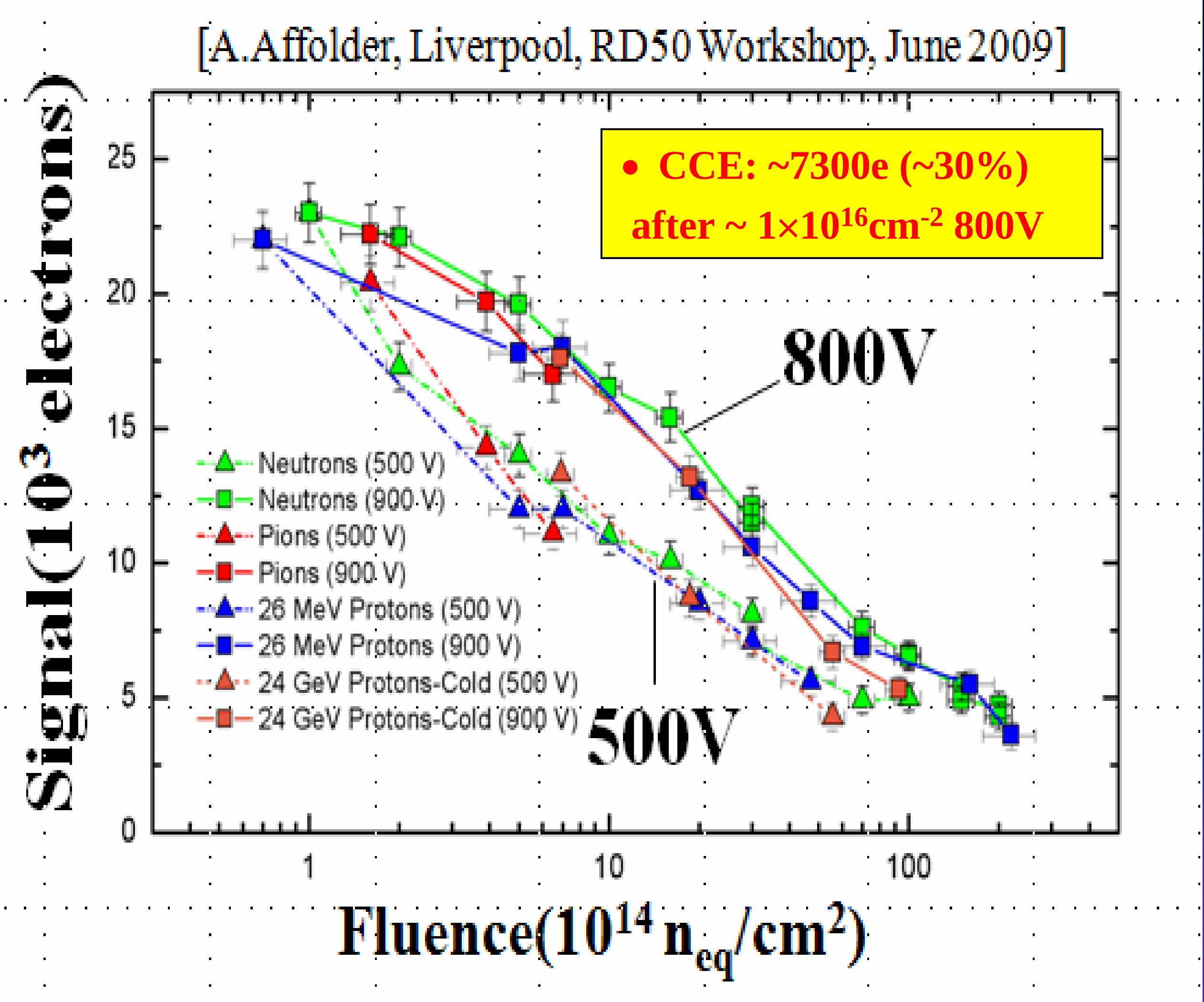


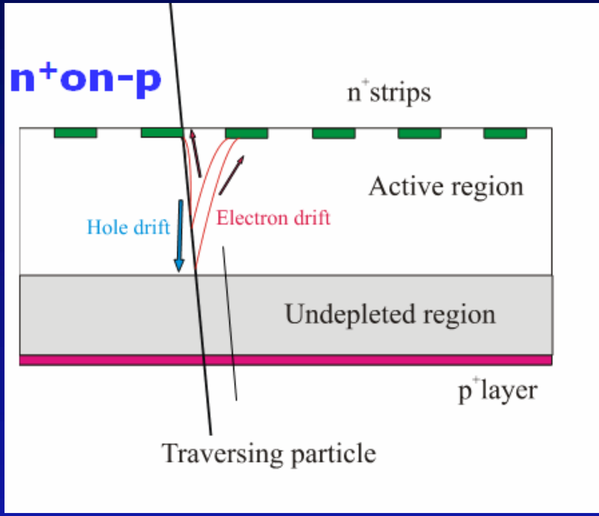
Expected Signal degradation for LHC Silicon Sensors

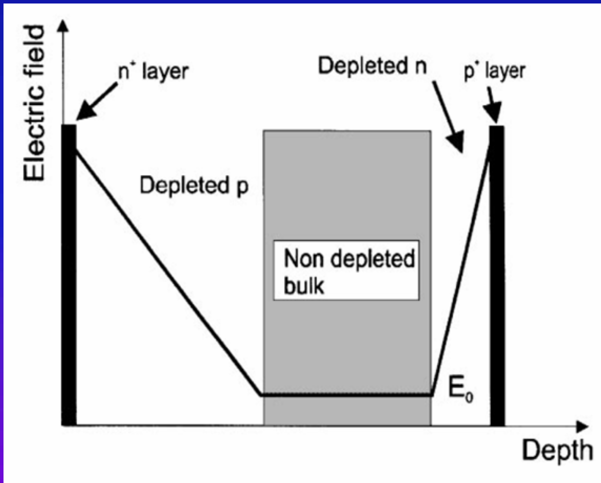


Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

Observed charge after 10^{16} n/cm2 much larger than expected!

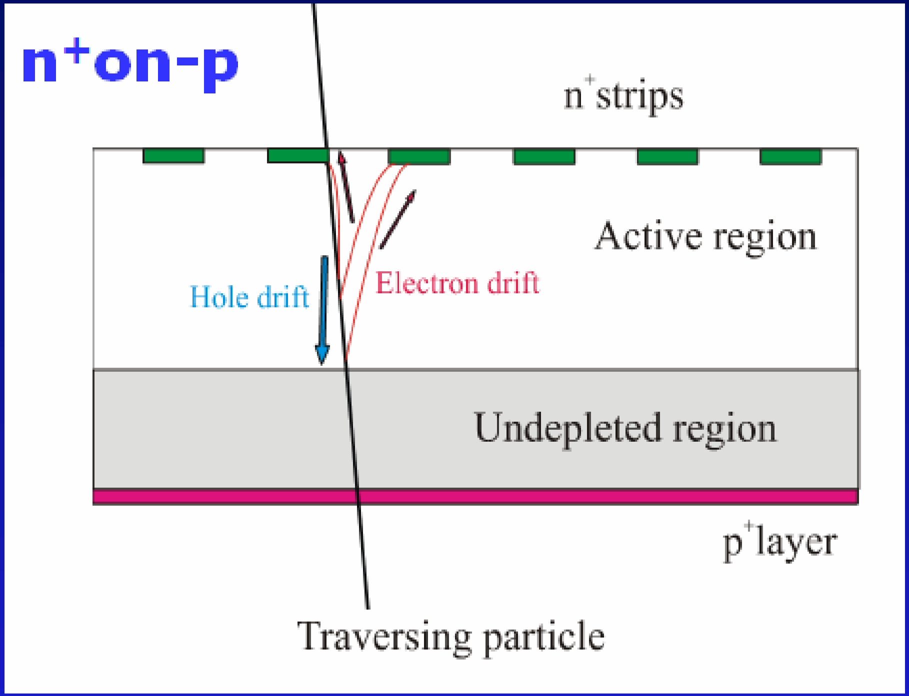






Use n-in-p detectors for high fluences

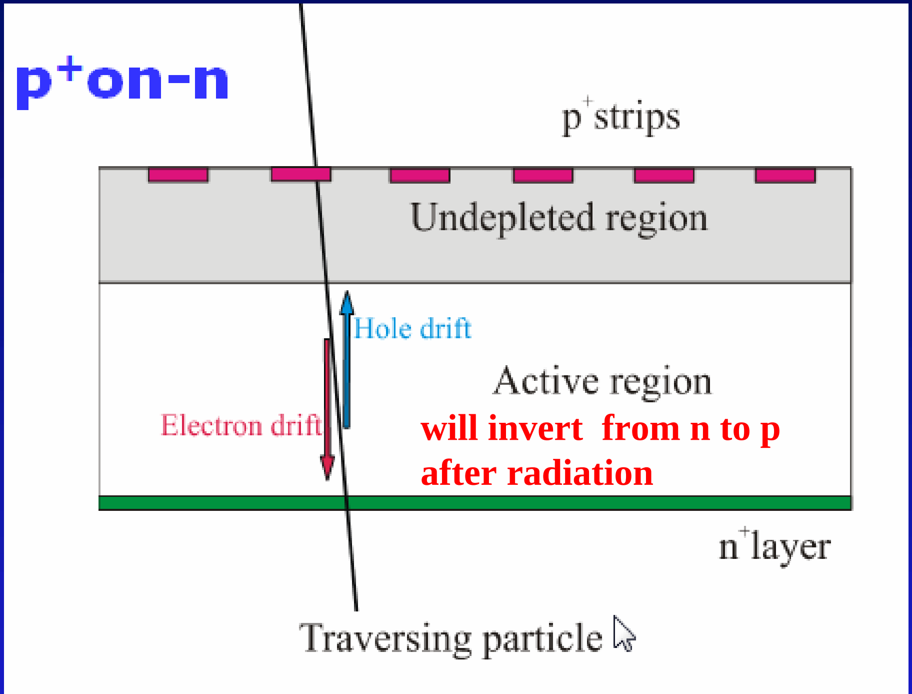
Future SLHC strip detectors ??



non-inverted, under-depleted:

- Limited loss in CCE
- Less degradation with under-depletion

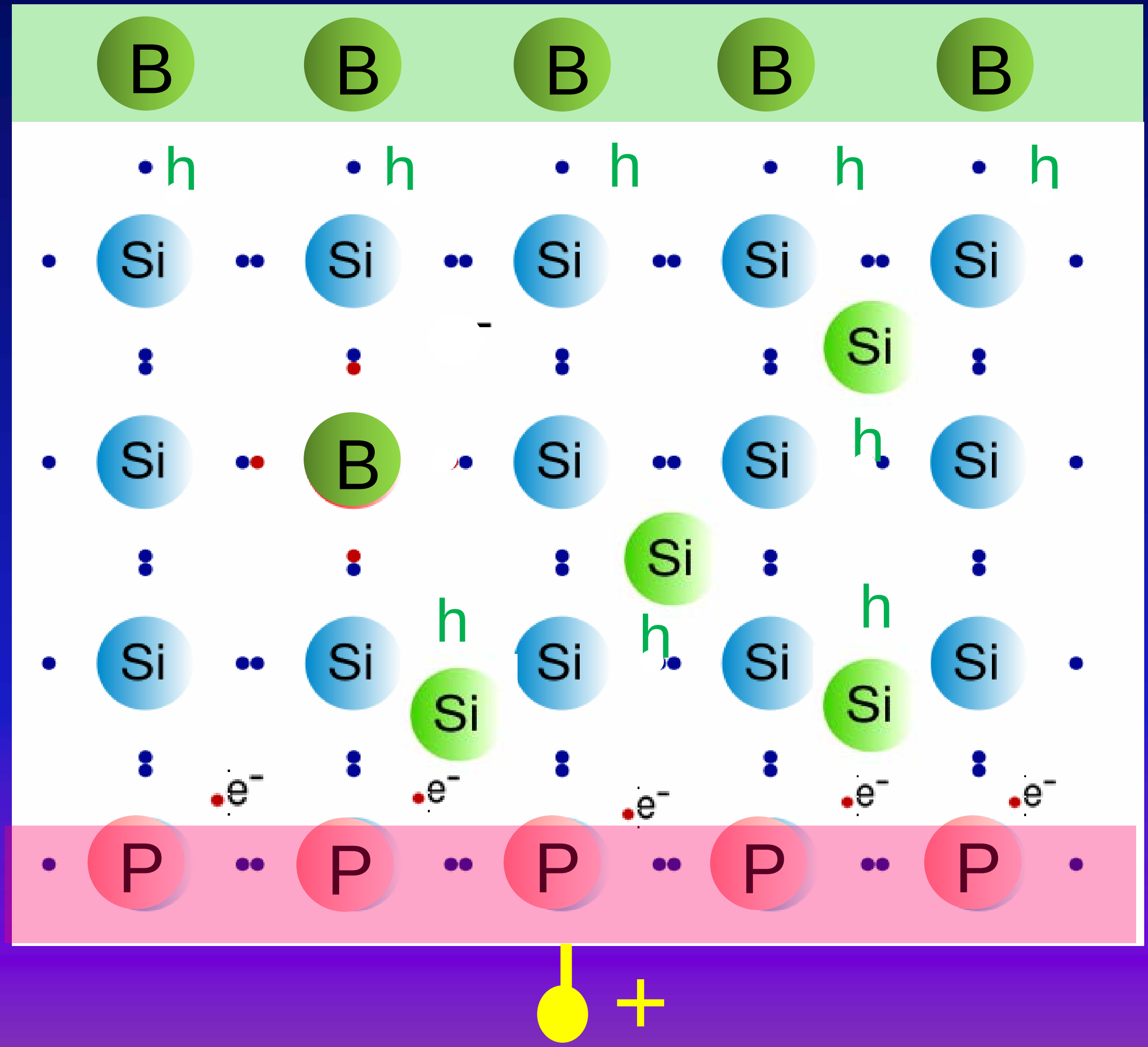
Present LHC strip detectors



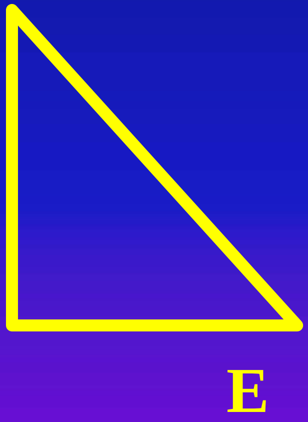
inverted to "p-type", under-depleted:

- Charge spread – degraded resolution
- Charge loss – reduced CCE

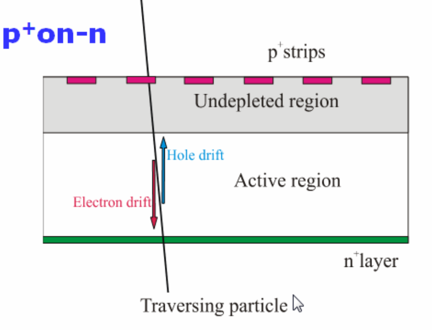
Radiation damage introduces acceptors

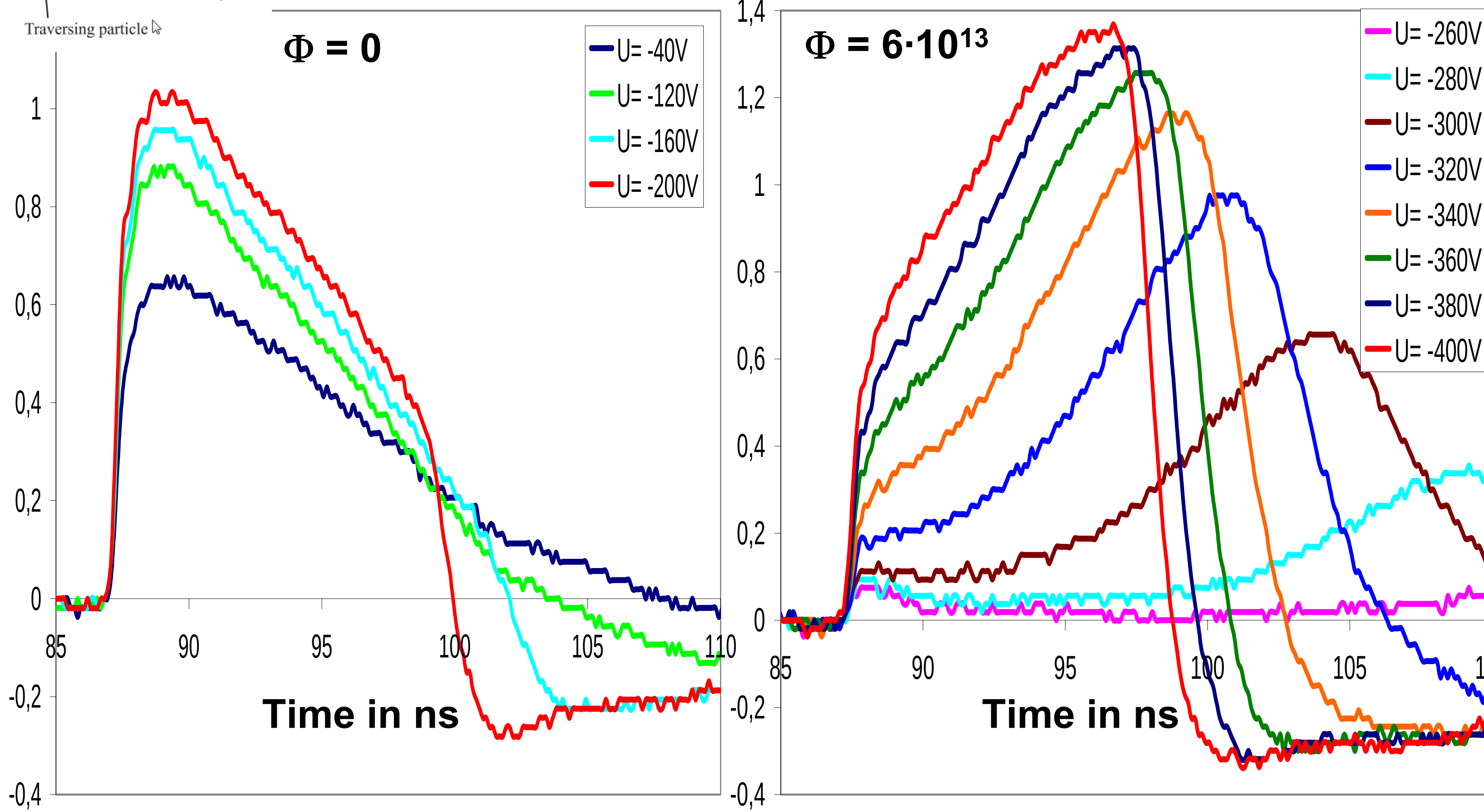


After high fluences the acceptor concentration becomes so high, that the detector cannot be depleted anymore and results in strong negative space charge, i.e. high E-field.

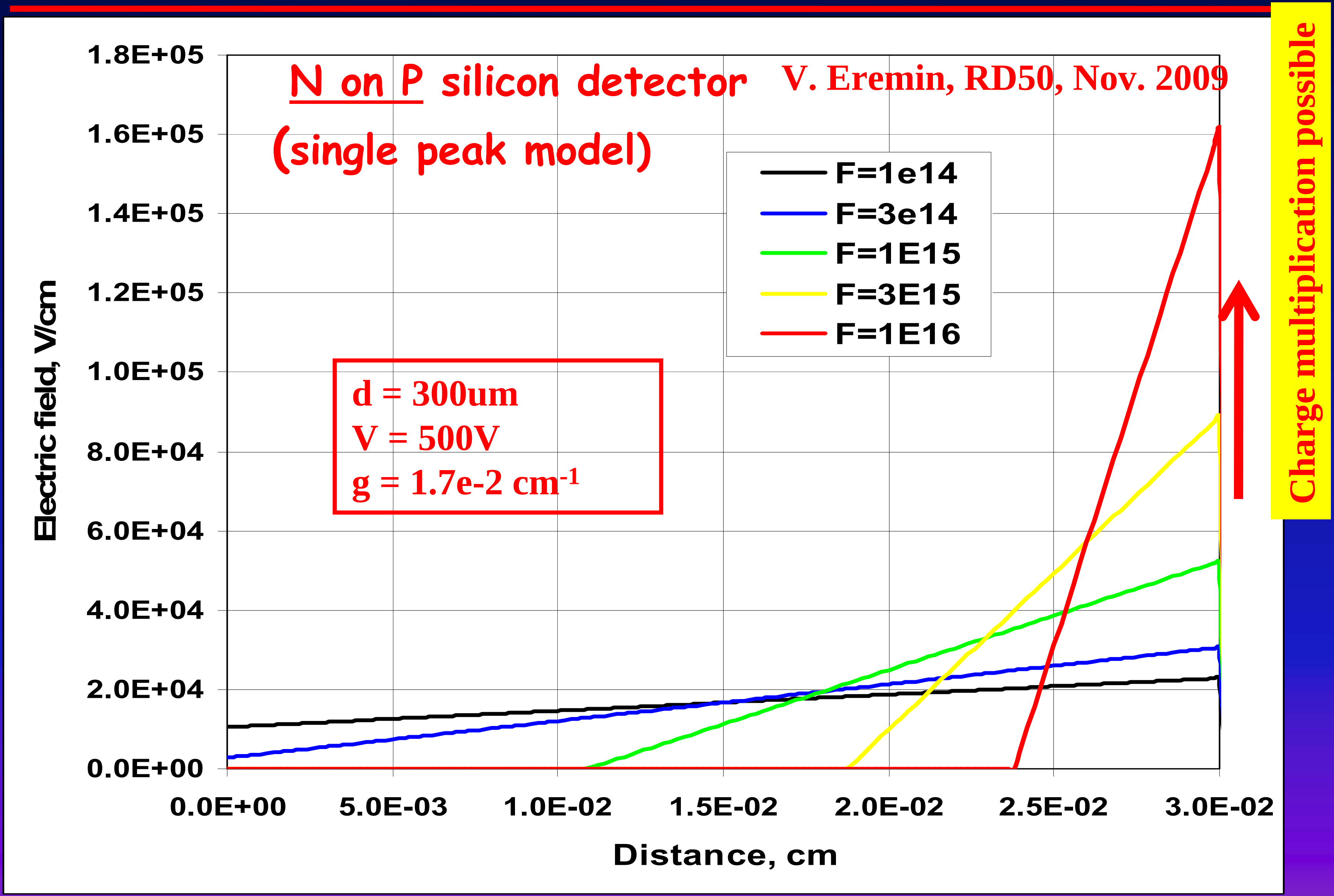


Drift of ionized cloud reveals electric field (TCT measurement)





Electric field evolution with fluence



How does charge multiplication work?

Avalanche in Silicon:

holes produced by impact ionization in high field near strip drift back in volume,

recombine with electron and emitted

photon generates „Auger“ electrons, which drift to electrode and process repeats, so charge multiplication is obtained.

A large enough hole current reduces field on hit strip, thus stopping avalanche

Applications of avalanche mechanism: Zener diodes, Si-photomultipliers, ….

Evidence for charge multiplication

1) Collected charge larger than in unirradiated sensor

2)Second peak in TCT after electrons reach strip

3) TCT signal not saturated at high voltages, as expected
in saturated drift region is reached

4) TCT signal delayed if holes are produced at strip
receiving electrons

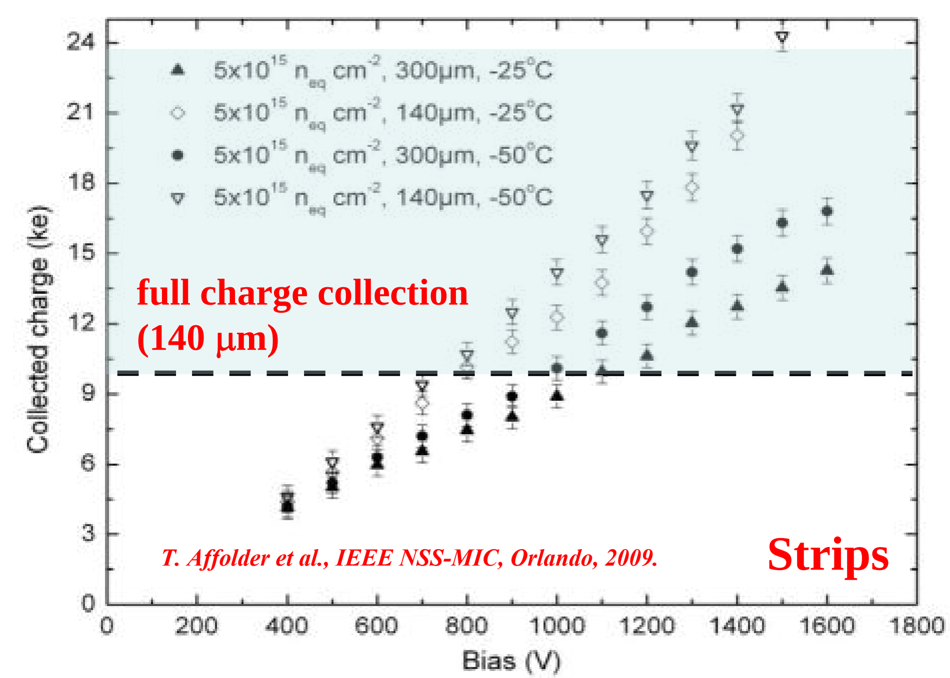
5) TCT signal and leakage current BOTH increases with bias voltage

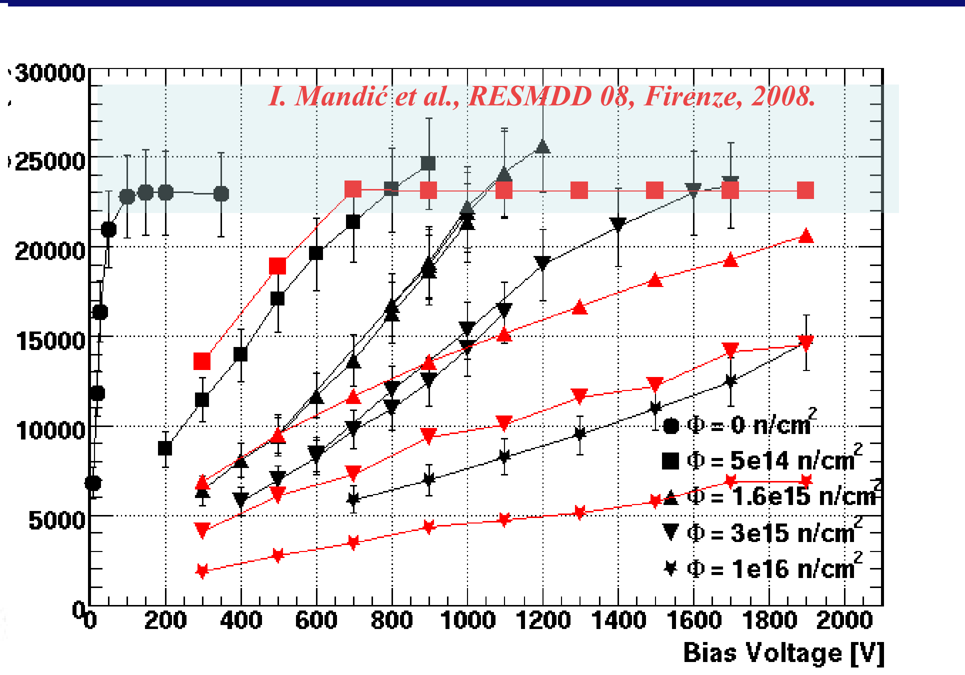
6) Lorentz angle may change sign, if holes are produced sufficiently strongly

Evidence for 1) by Affolder, for 2-5 shown by G. Kramberger and M. Milovanovic (Ljubljana) at RD50 meeting, CERN, Nov. 2009. Following plots taken from them! First hint for 5) measured in Karlsruhe (Diplomarbeit M. Schneider)

Charge collection above 100%

- 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!**

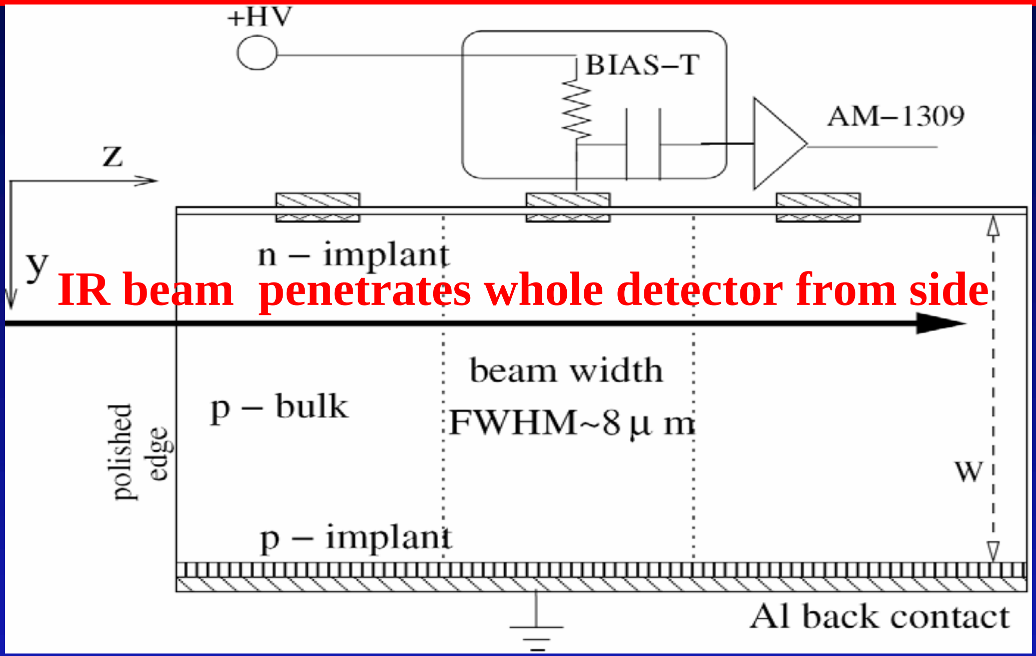




- We need a new tool to identify electric field and multiplication effects! Ideal tool for investigation of electric field and charge multiplication in silicon detectors (paticularly heavily irradiated) is Edge-TCT!

The work presented in this work is submitted to IEEE-TNS. Kramberger, RD50, Nov. 2009

"Edge-TCT"



Advantages:

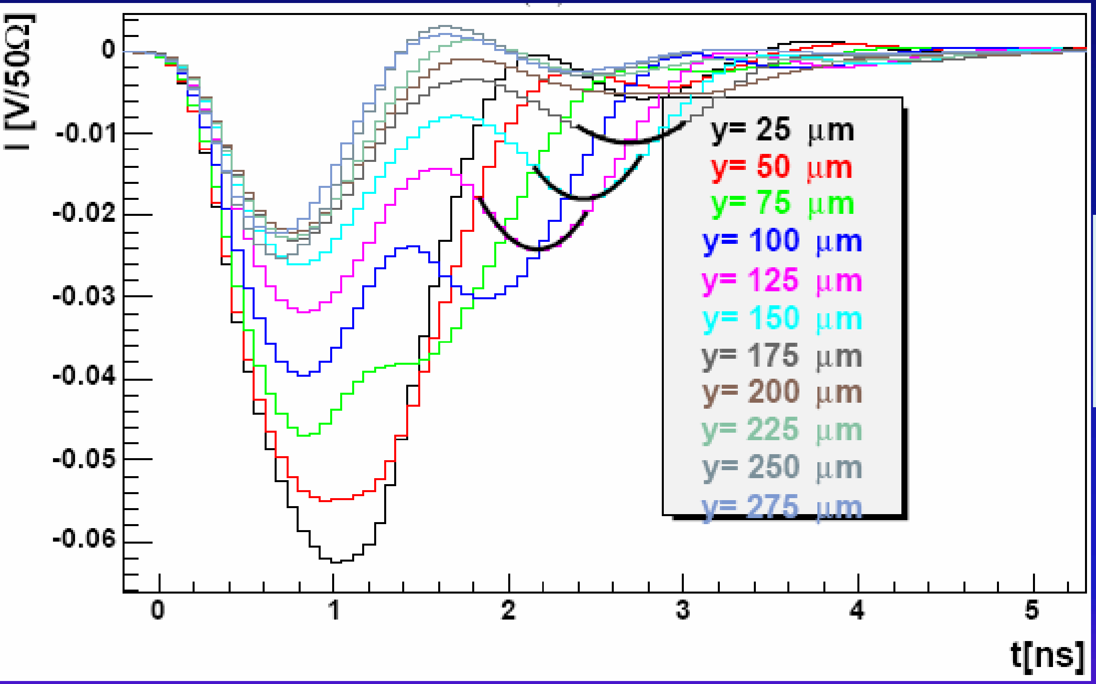
- Position of e-h generation can be controlled by moving tables
- the amount of injected e-h pairs can be controlled by tuning the laser power
- easier mounting and handling
- not only charge but also induced current is measured – a lot more information is obtained

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

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:

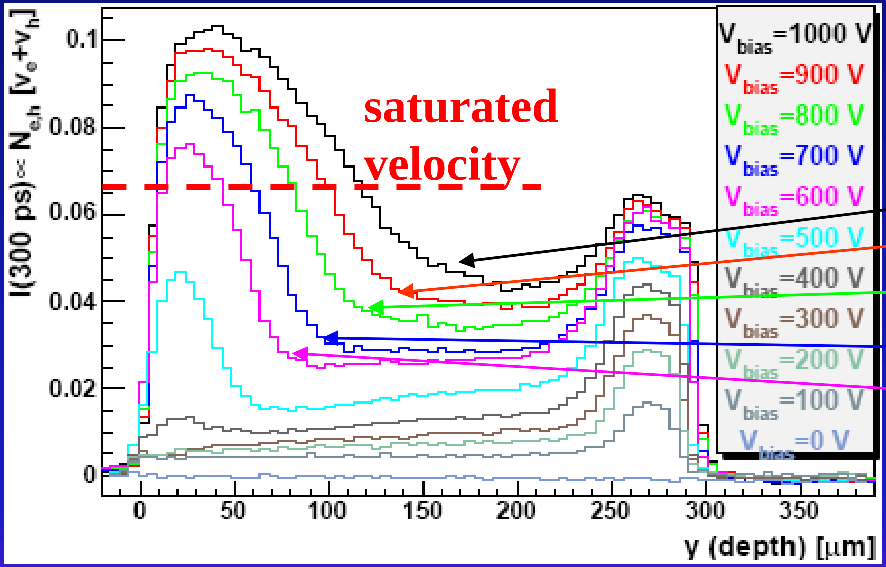
$$\frac{I(y=175\mu\mathrm{m}, t_{p2}=2.69\,\mathrm{ns})}{I(y=125\mu\mathrm{m}, t_{p2}=2.16\,\mathrm{ns})} \approx \exp\left(-\frac{\Delta t_{p2}}{\tau_{eff,e}}\right) \rightarrow \tau_{eff,e} = 670\,ps$$

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

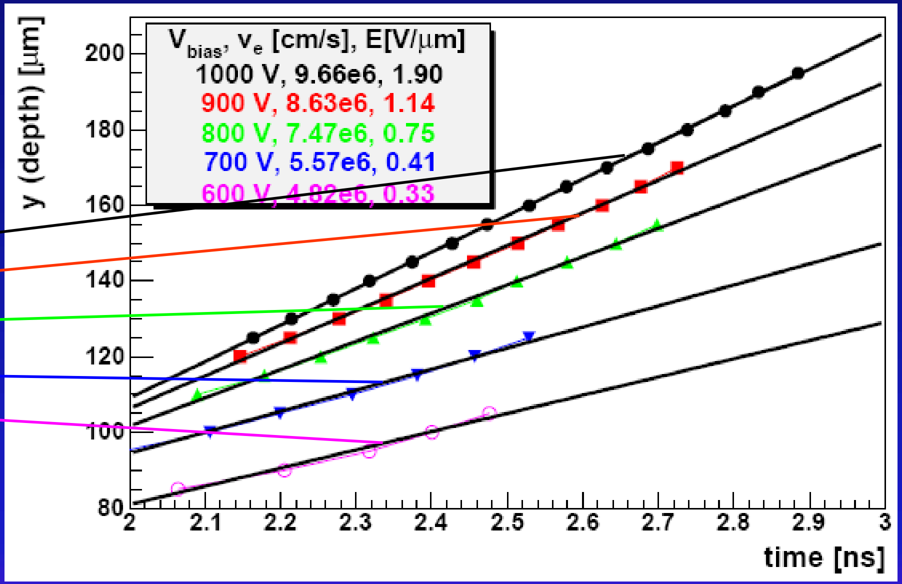
From short decay of I(y=25 µm) one can conclude that $\tau_{eff,h}$ is short (in 700 ps holes drift 50-60 µm. At y<100 µm the field is present)

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

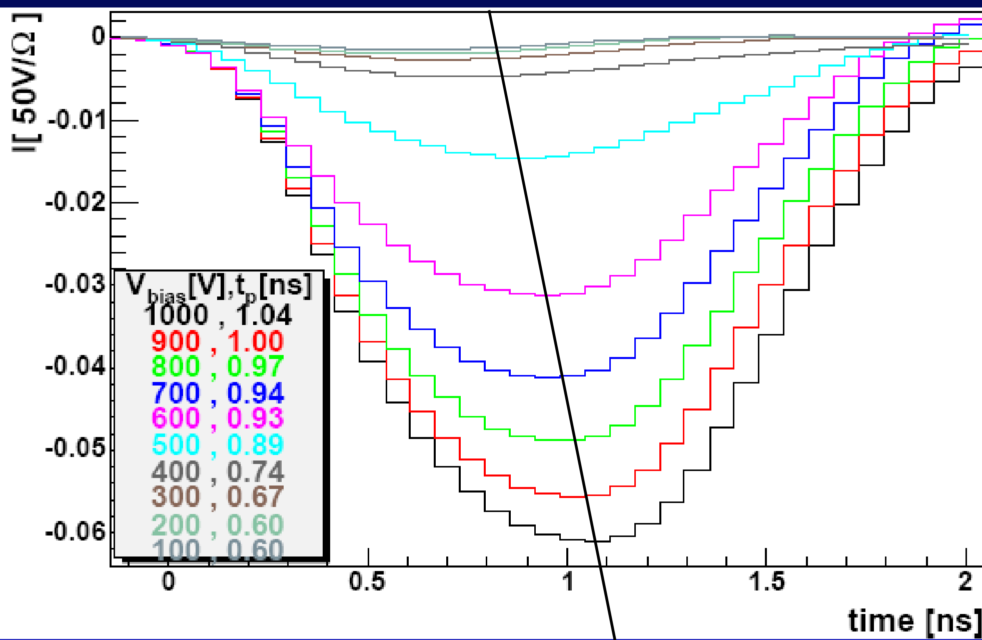


Arrival of electrons used for DPM



- 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*!

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

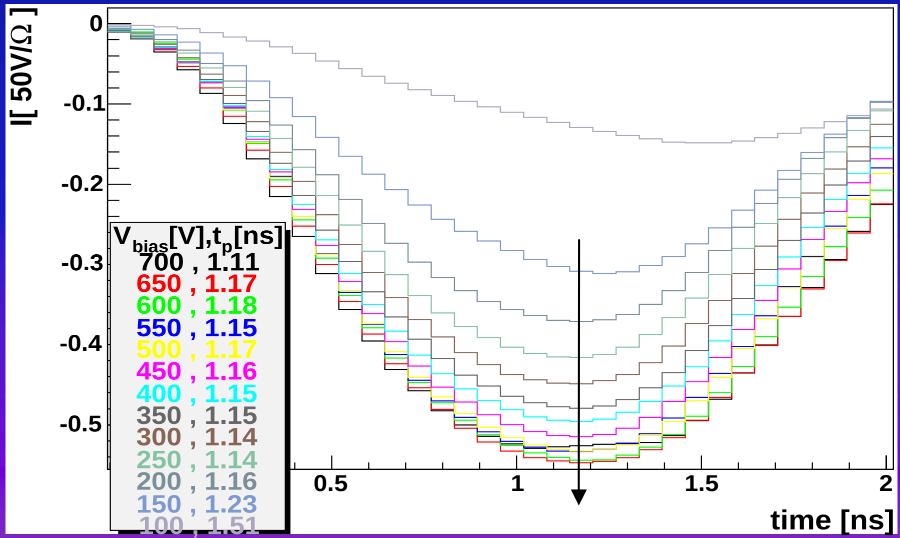


The shift of the signal is of the same order as:

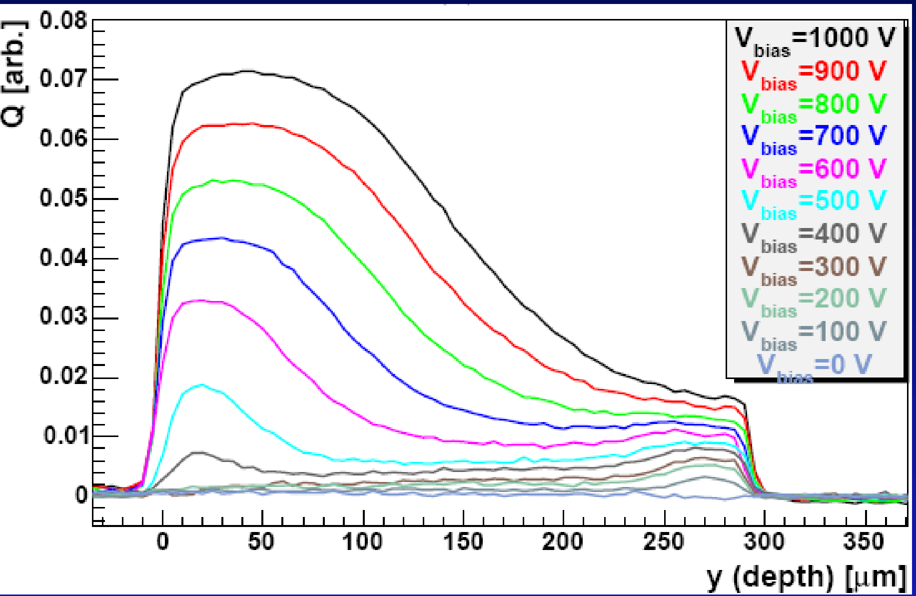
$v_{sat,e} \cdot t_{shift} = 30\ \mu m$

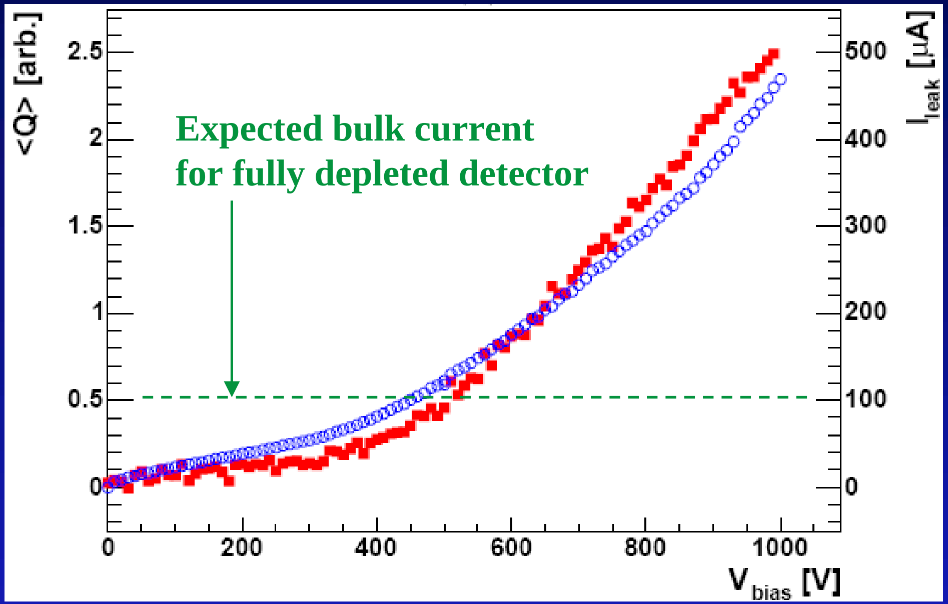
the time needed for electrons to get to the strips!

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



Charge collection profile and Q_{mip} correlation with current



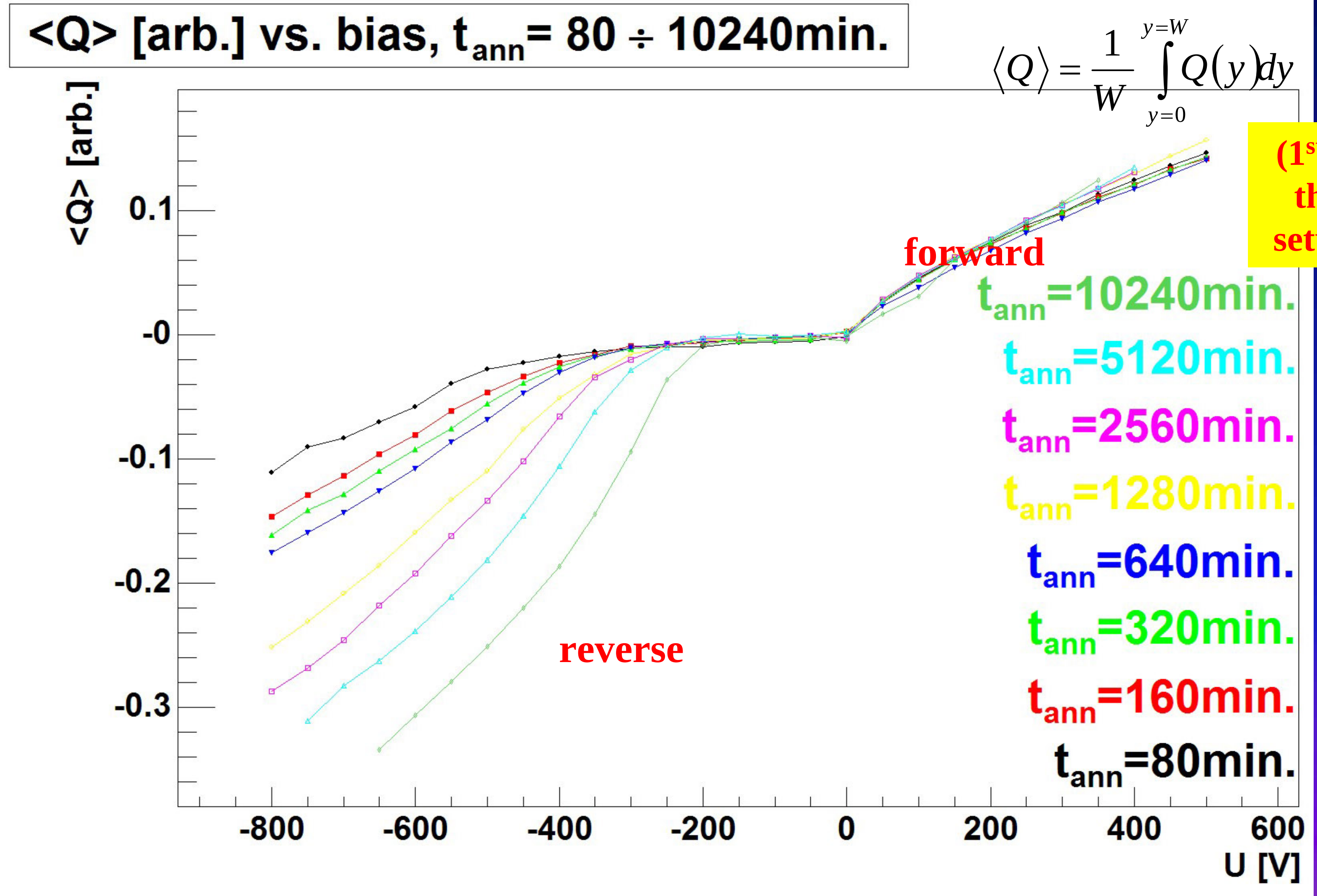


High bias voltage significantly improves charge collection!

Leakage current and <Q> are correlated!

<Q> vs. bias

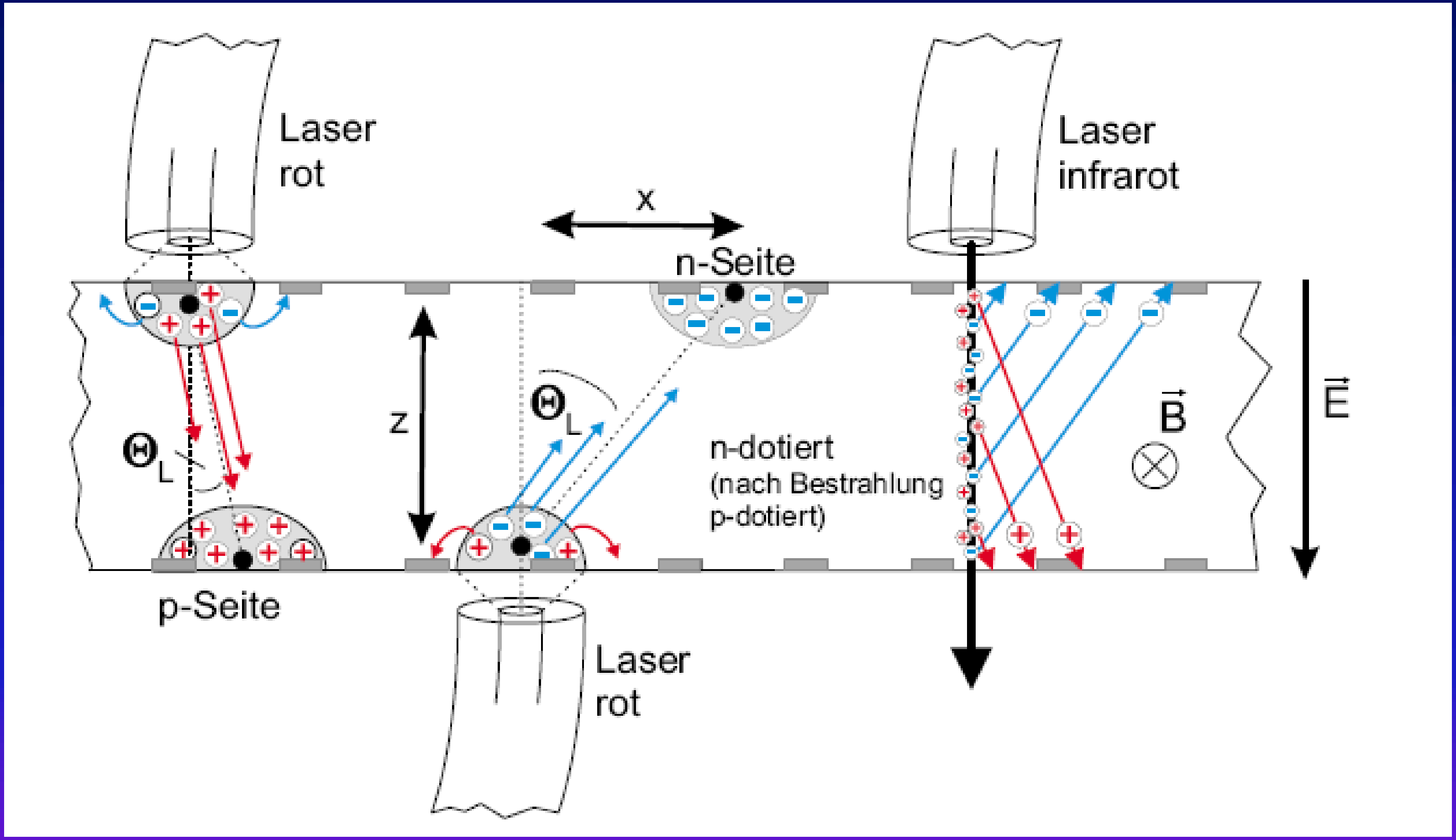
Detector: Micron, FZ-Si p-type micro-strip, $\Phi=5\times10^{15}$ cm^{-2}, T=-20°C



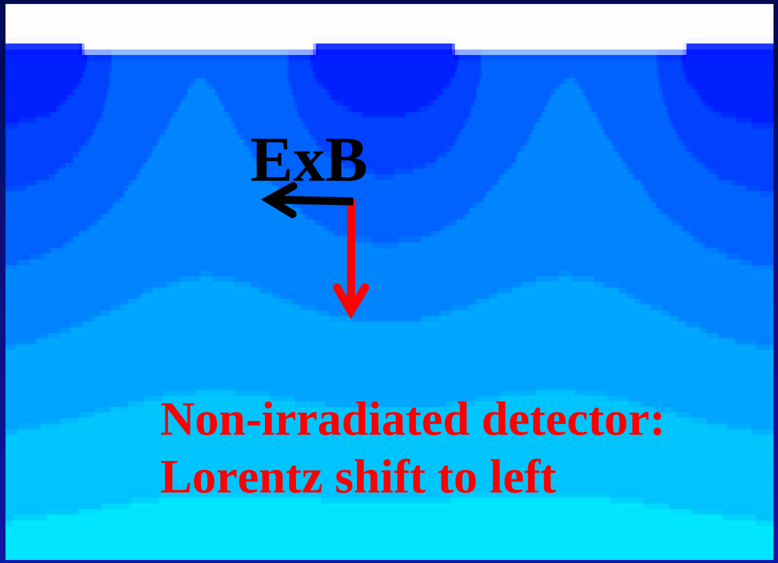
$$\langle Q \rangle = \frac{1}{W} \int_{y=0}^{y=W} Q(y)\,dy$$

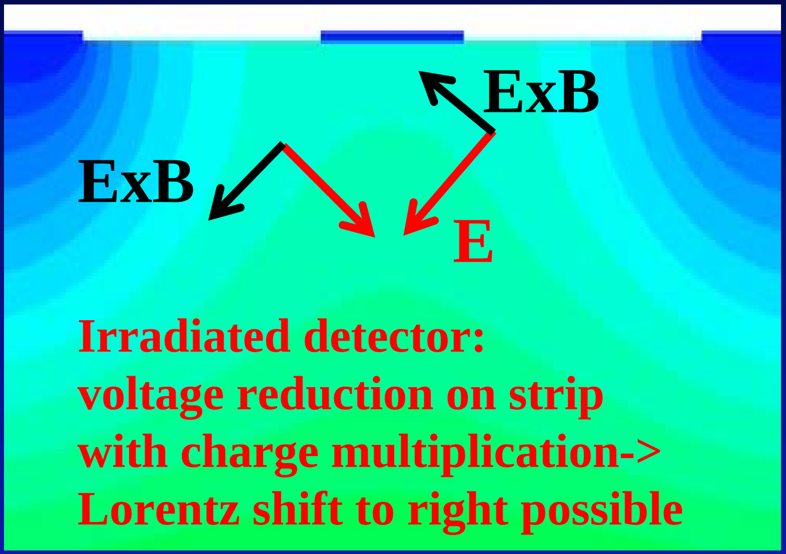
(1st proof that this is not a setup artifact)

Principle of Lorentz angle measurements



Lorentz shift becomes negative in irradiated sensors





Preliminary

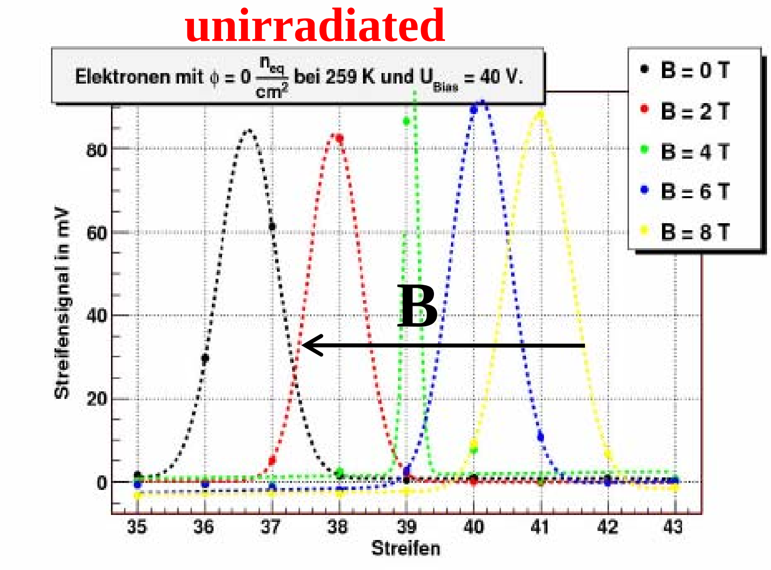
The hole current reduces field on hit strip, which creates horizontal electric field components from neighbouring strips.

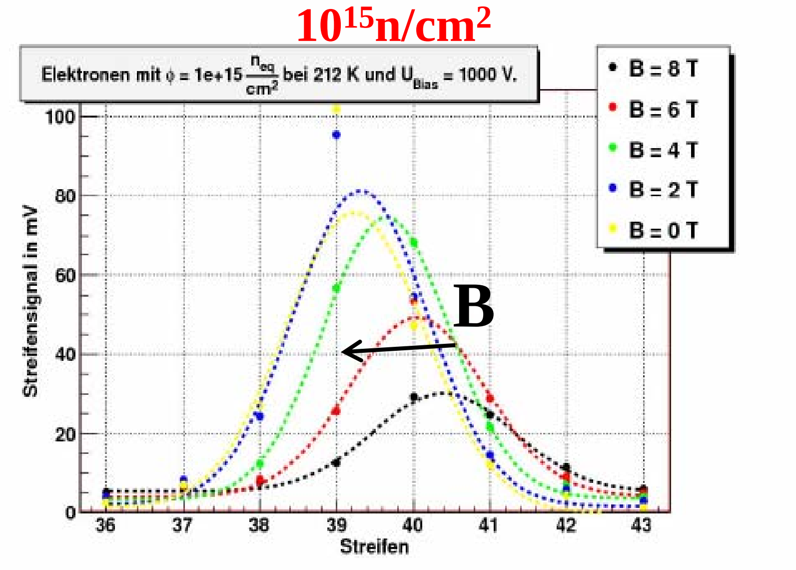
In a magnetic field this can enhance charge multiplication on one side of strip,

thus pulling charge sharing to „wrong“ side, i.e. effectively a negative Lorentz shift,

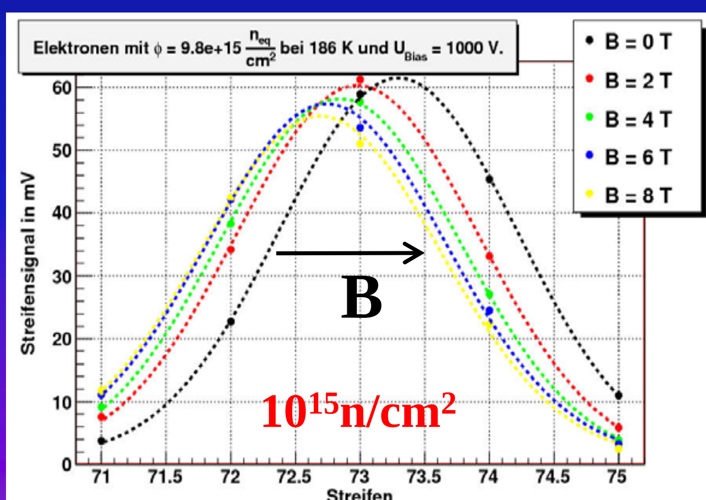
Observed Lorentz shifts

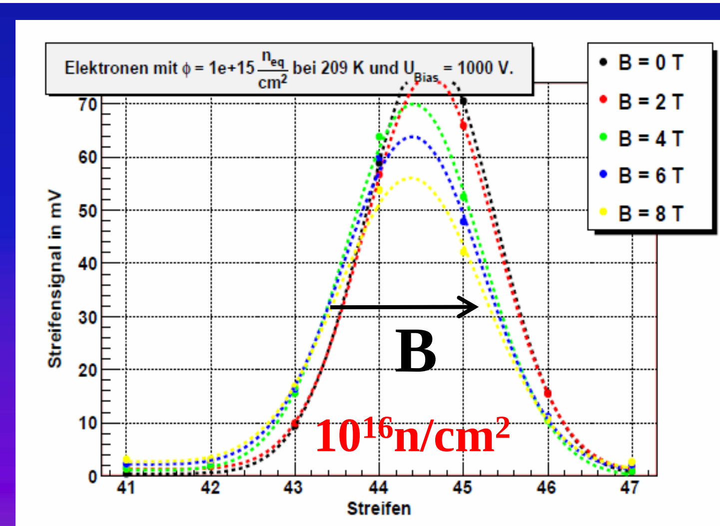
Red laser





IR laser





Preliminary

Future

Quantization of the charge multiplication and its dependence on voltage, fluence and annealing

Building a new device model

What is optimum design ?

Can one really operate Si detectors in charge multiplication mode??

PROGRAMS TO INVESTIGATE OPTIMUM DESIGN, STABILITY AND S/N UNDERWAY.

MANY INTERESTING RESULTS EXPECTED TO COME