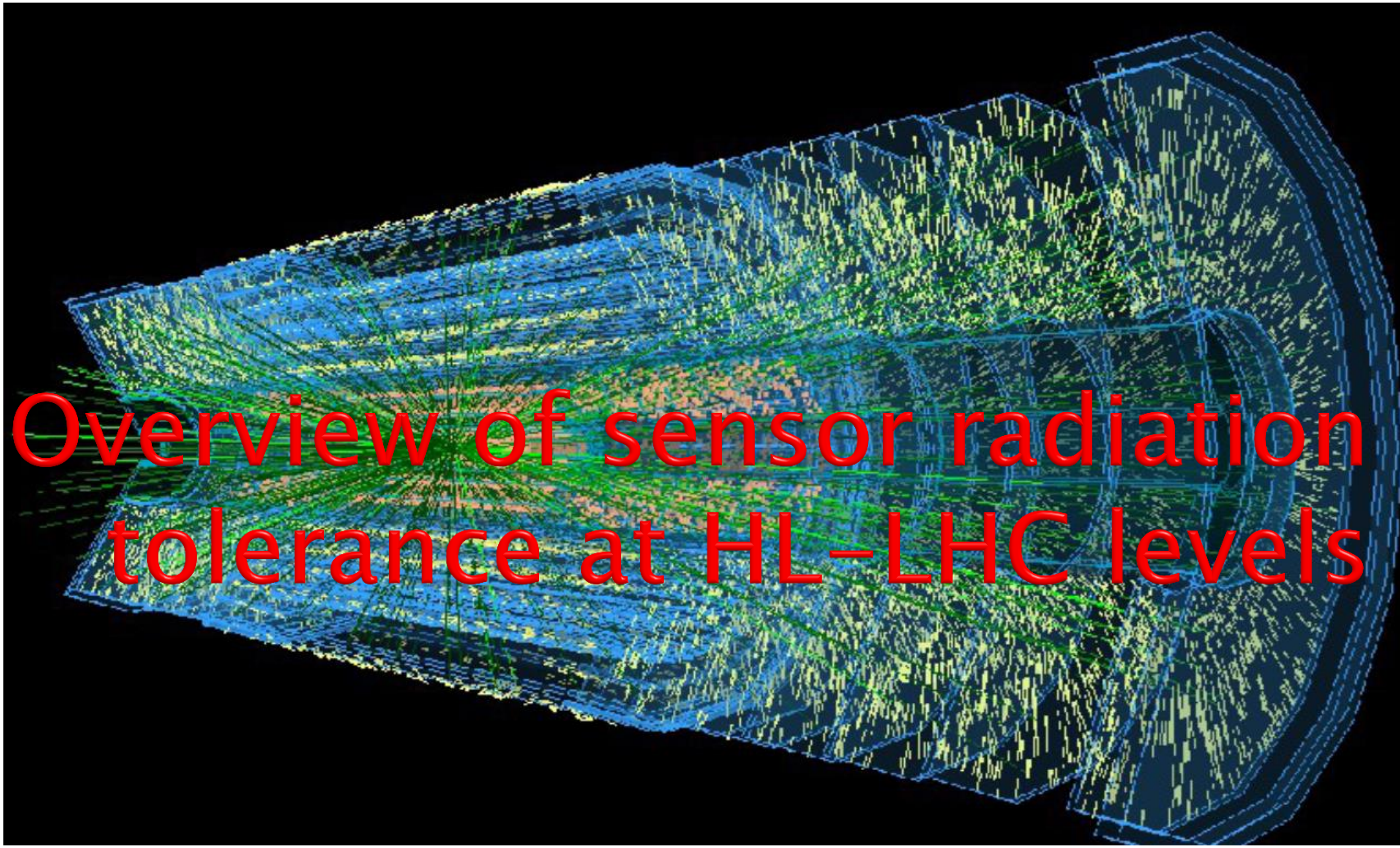
Overview of sensor radiation tolerance at HL-LHC levels



G. Kramberger
Jožef Stefan Institute

Radiation tolerance at HL-LHC levels is too broad for one talk.

The emphasis will be on charge collection as it mainly determines the detection efficiency and position resolution and steers all other main device parameters…

surface effects, SiO_2-Si interface and lots of details will be left out

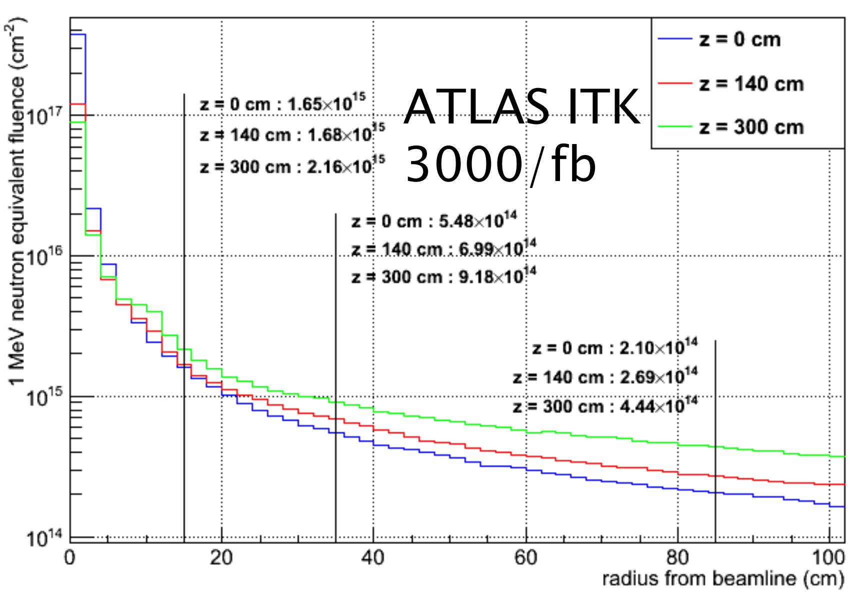
I am "slightly" biased to ATLAS studies… apologies

Introduction

- Position sensitive silicon detectors are an indispensable ingredient of any collider experiment mostly as tracking detectors, but also for calorimetry
- Physics requirements in terms of integrated luminosity and the resulting particle fluences are ever escalating
  - for LHC 10^{15} n_{eq}/cm^2 considered extremely difficult
    - design was 730/fb @14TeV…
  - **HL-LHC takes it to nx10^{16} (vertex) or even 10^{17} (FW calo)**
    - 4000/fb @14TeV
  - **FCC is dreaming of towards 10^{18} for the tracker**
    - 30/ab @100TeV
- Ratio ~1:20:600 !

"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)

"Can silicon operate beyond 10^{15}neutrons cm^{-2}?" Nucl. Instr. & Meth. A 501 (2003), p 138



Instrumentation for ITER (fusion reactor) required radiation hardness comparable to HL-LHC

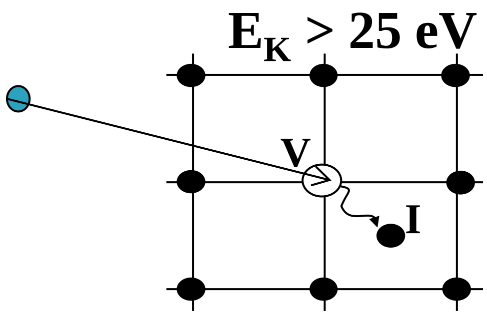
Luis F. Delgado-Aparicio, Burning-plasma diagnostics: photon & particle detector development needs, 31th RD50 Workshop

About 20x planned for LHC

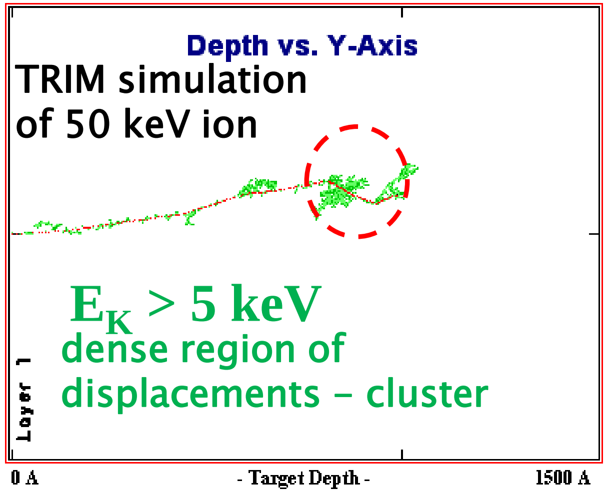
TID up to 10 MGy

Generation of bulk damage – defects

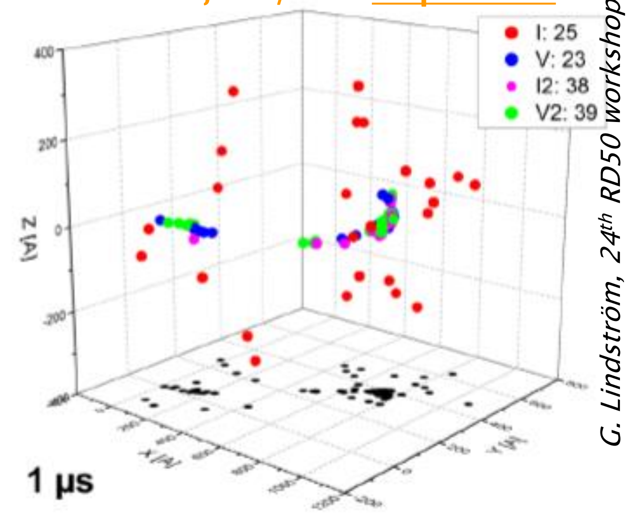
Imping particle hits the lattice atom and knocks it out of the lattice site



point defects: Frekel pair
(Vacancy-Interstitial pair)

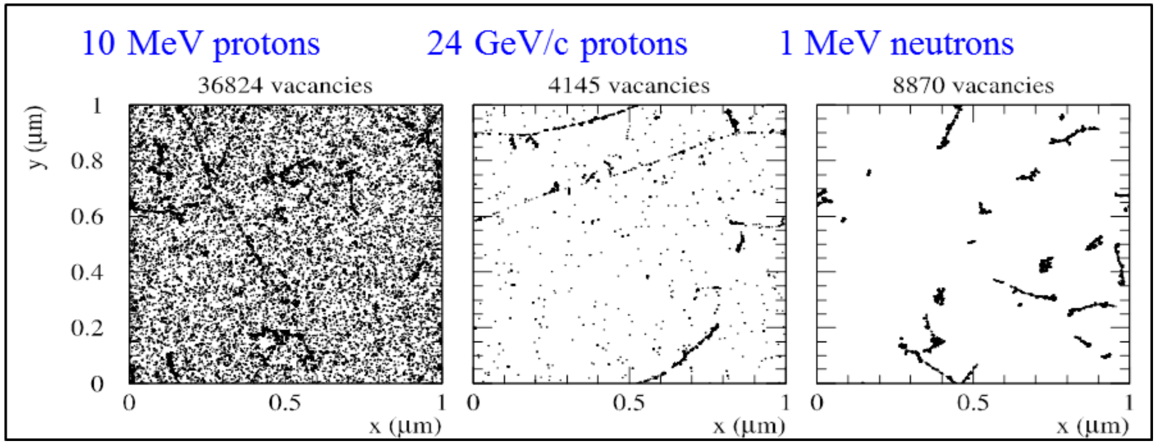


V,Is migrate and react with other V,I or/and impurities.



Simulation:
Initial distribution of vacancies in $(1\mu m)^3$ after 10^{14} particles/cm^2

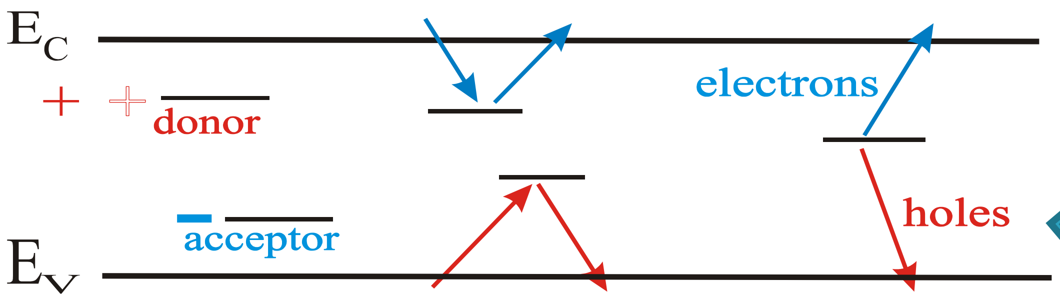
1. Different particles can create different damage at the same NIEL
2. In different materials the damage can manifest differently



M. Huhtinen, *NIMA* 491(2002) 194

How do the defects manifest?

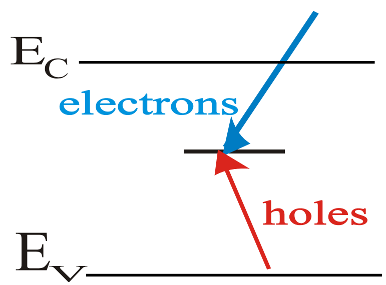
Influence of defects on the device properties – depleted region



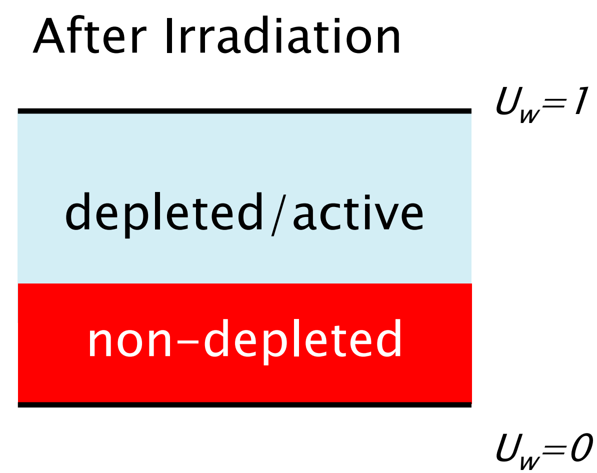
charged defects
⇒ N_{eff}, V_{dep}
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

generation
⇒ **leakage current**
Levels close to midgap most effective



Non-depleted region: decrease of recombination time and increase of resistivity



How do the defects manifest?

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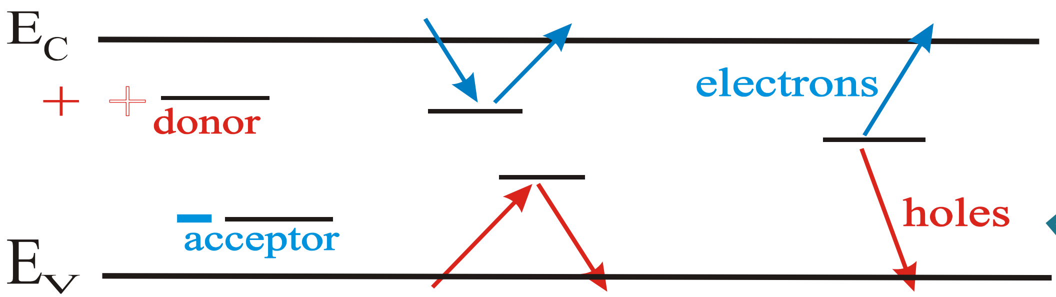

charged defects
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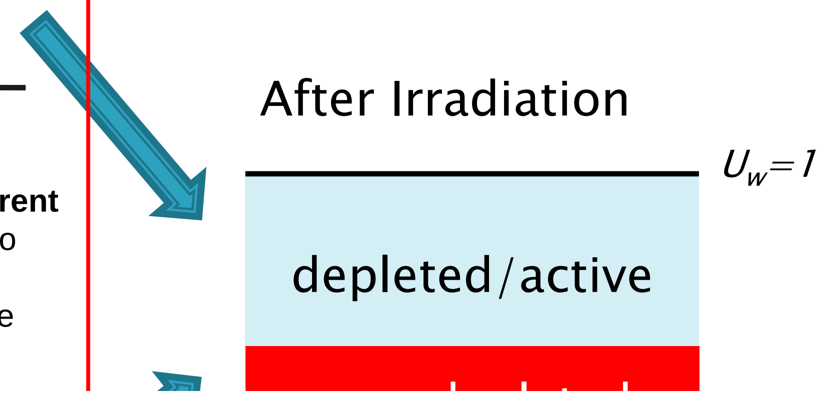
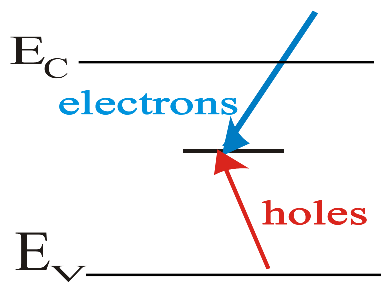
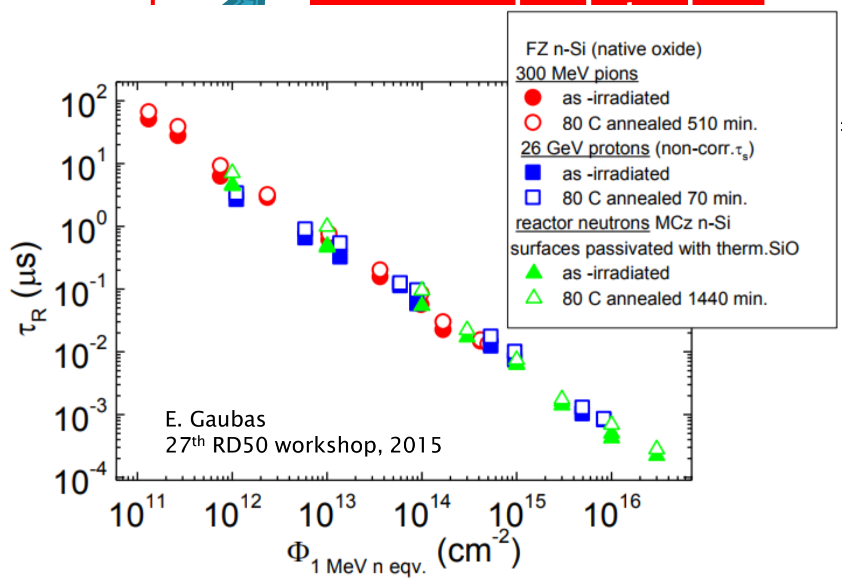




Un-depleted region: decrease recombination time and increase of re



Summary on defects with strong impact on device performance (n-type silicon) after irradiation

Point defects

- $E_i^{BD} = E_c - 0.225$ eV
- $\sigma_n^{BD} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{I} = E_c - 0.545$ eV
  - $\sigma_n^{I} = 1.7\cdot10^{-15}$ cm^2
  - $\sigma p^{I} = 9\cdot10^{-14}$ cm^2

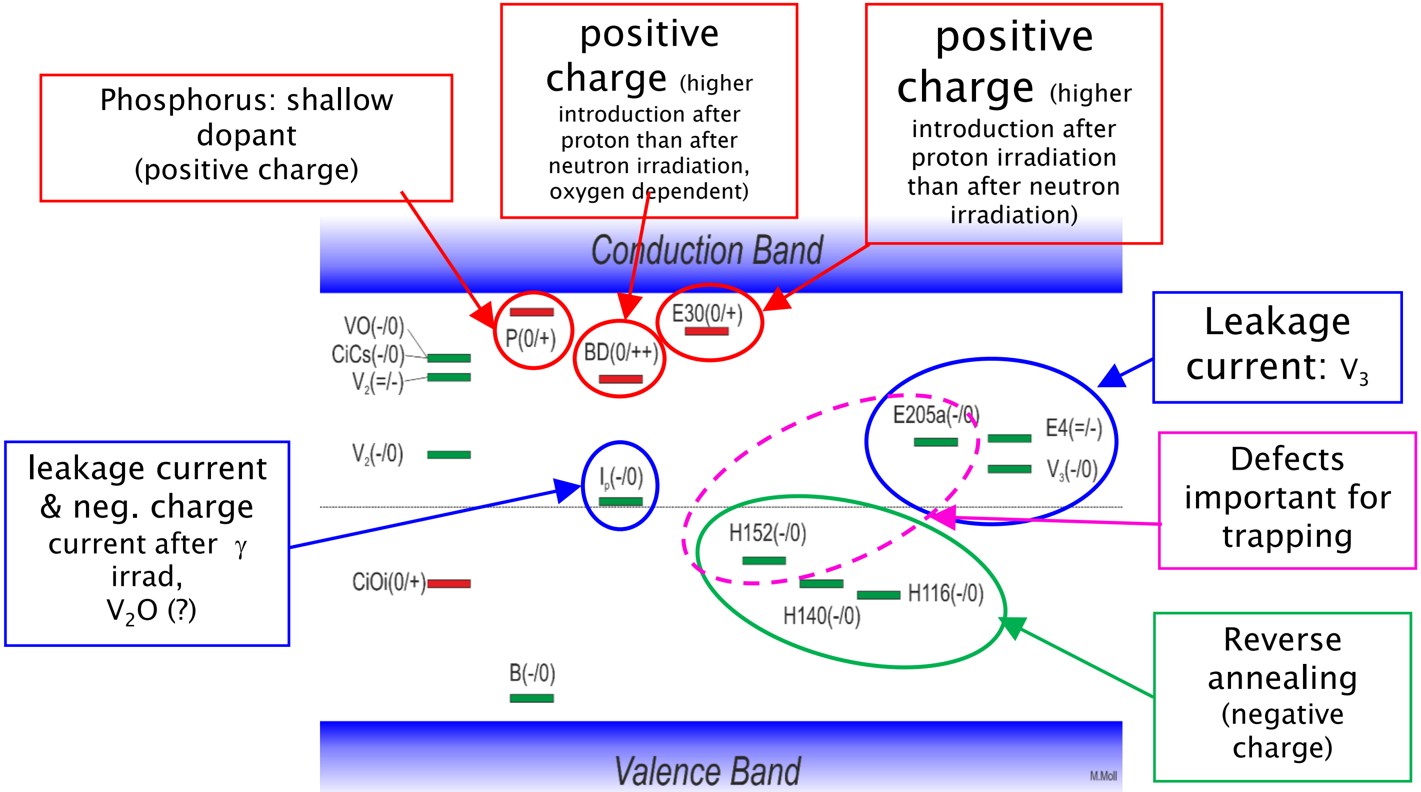
Cluster related centers

- $E_i^{116K} = E_v + 0.33$eV
- $\sigma_p^{116K} = 4\cdot10^{-14}$ cm^2

- $E_i^{140K} = E_v + 0.36$eV
- $\sigma_p^{140K} = 2.5\cdot10^{-15}$ cm^2

- $E_i^{152K} = E_v + 0.42$eV
- $\sigma_p^{152K} = 2.3\cdot10^{-14}$ cm^2

- $E_i^{30K} = E_c - 0.1$eV
- $\sigma_n^{30K} = 2.3\cdot10^{-14}$ cm^2



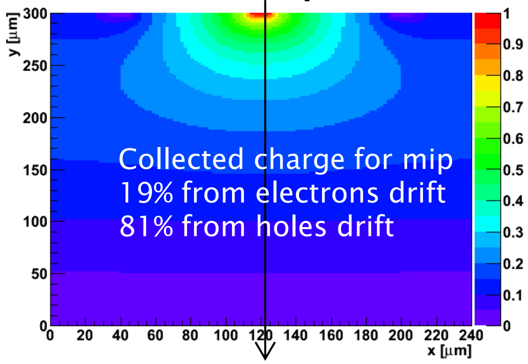
- Converging on consistent set of defects observed after p, π, n, γ and e irradiation.
- Defect introduction rates are depending on particle type and particle energy and for some point defects on the impurity content of the material – defect engineering works!

A lot of effort invested to get the picture …

…difficult to simulate devices by including all of them

Radiation hard detector design (I)

ATLAS strip



S. Ramo, Proceedings of I.R.E. 27 (1939) 584.

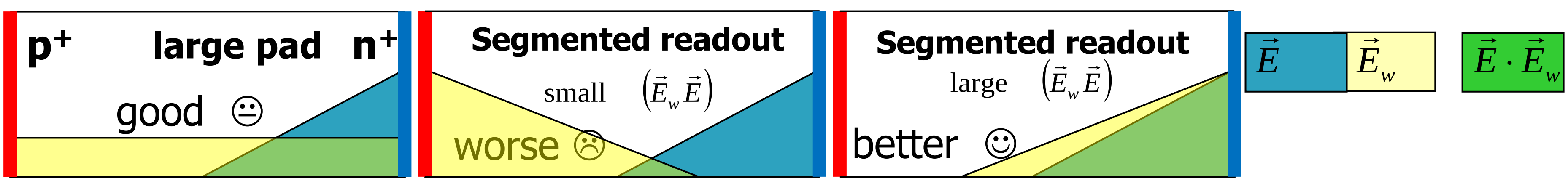
Charge collection (highly geometry dependent) is given by:

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

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

All terms of equation are influenced by radiation!

1.) Choice of readout side – always where the field is high unless you can over-deplete!



even worse: p^+ readout (holes)

even better: n^+ readout (electrons)

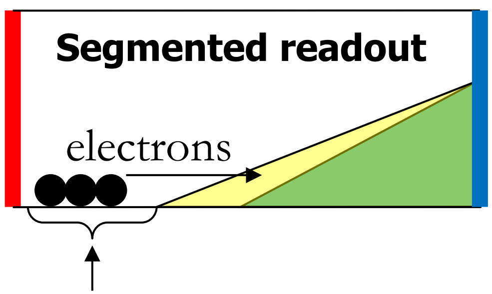
2.) collect particle with smaller μ·τ product – i.e. electrons

n^+ – n (LHC choice for innermost Si detectors)

n^+ – p (HL-LHC – single sided processing – more cost efficient)

Radiation hard detector design (II)

2.) Optimize geometry trapping dominated environment $\tau_{eff} << t_{drift}$ thin planar sensors perform better than thick at the same voltage



Carriers in this region would be trapped before reaching high E_w

Why thin:

-reduction of trapping at the expense of less charge generated

-smaller clusters (easier reconstruction)

-less leakage current

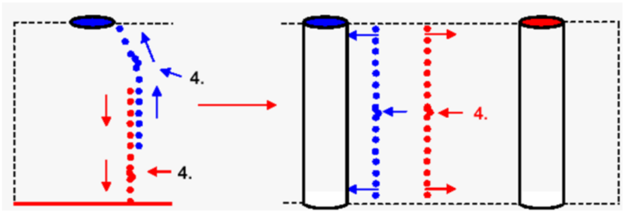
-larger average fields reached (multiplication)

-less effect of irradiation on drift velocity

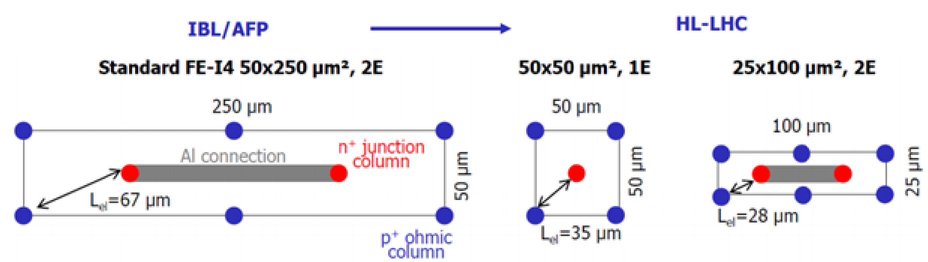
3.) Separate generation path from drift 3D detectors

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

3D detectors



steadily becoming mature technology – used in ATLAS – IBL

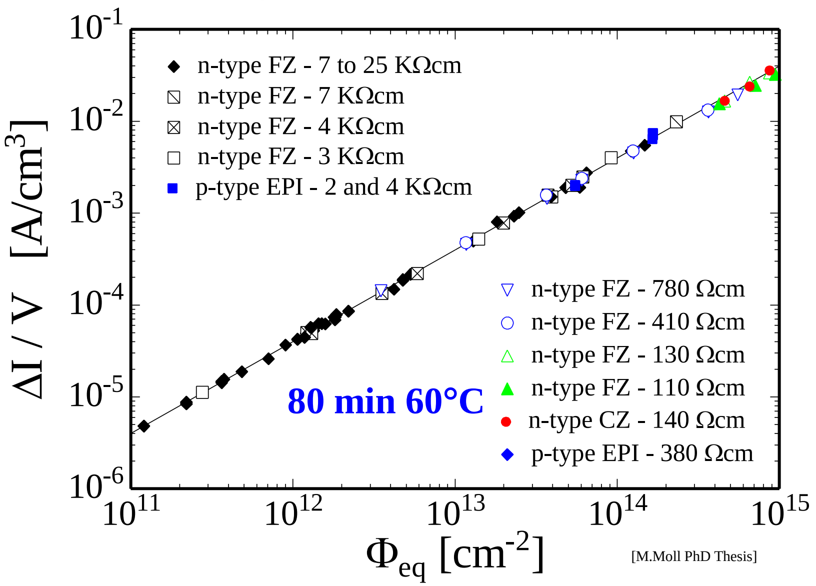


see talks in 3D session

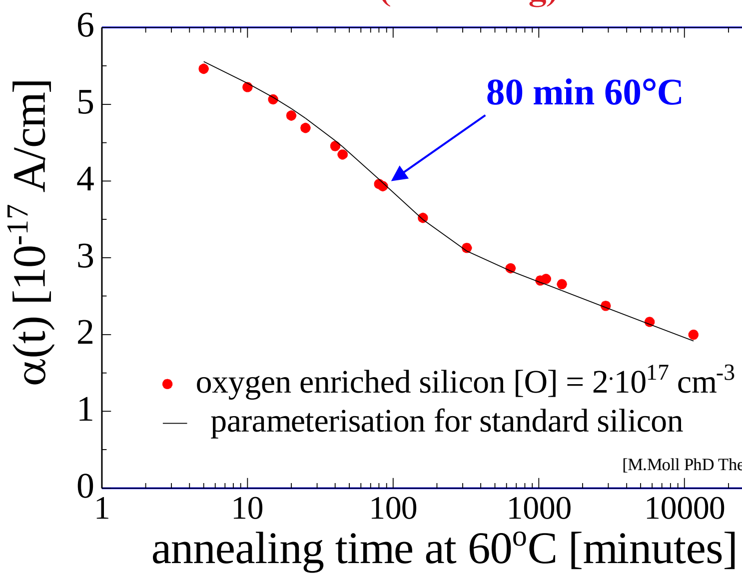
Leakage current

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

.... with particle fluence:



.... with time (annealing):



- Damage parameter α (slope in figure)

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

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

$$I \propto \exp\left(-\frac{E_a}{2k_B T}\right)$$

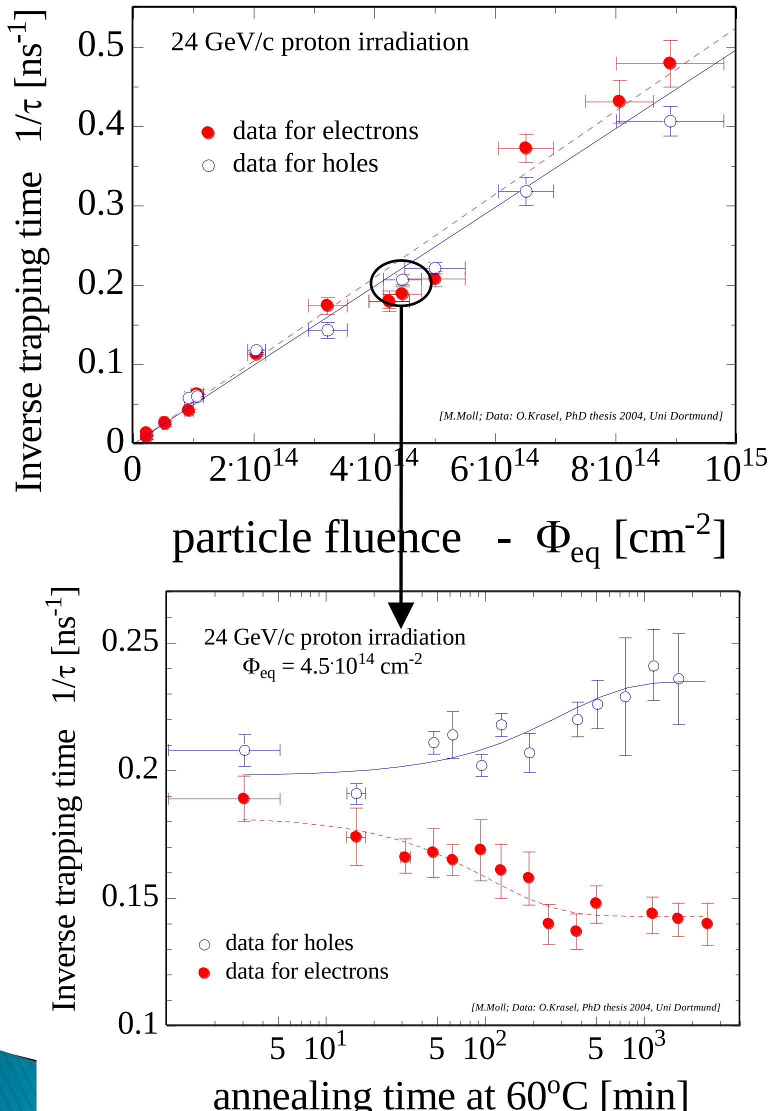
Consequence:

Cool detectors during operation!

Example: $I(-10°C) \sim 1/16\ I(20°C)$

Charge Trapping

T.J. Brodbeck et al., Nucl. Instr. and Meth. A455 (2000) 645.
J. Weber et al., IEEE Trans. NS 54(6) (2007) 2701.
A. Bates and M. Moll, Nucl. Instr. and Meth. A 555 (2005) 113-124.
O. Krasel et al., IEEE Trans. NS 51(1) (2004) 3055.
G. Kramberger et al., Nucl. Instr. and Meth. A 481 (2002) 297-305.
T. Lari et al., Nucl. Instr. and Meth. A 518 (2004) 349.
V. Cindro et al., Nucl. Instr. and Meth. A599 (2009) 65.



β(-10°C, t=min Vfd) [10^{-16} cm²/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

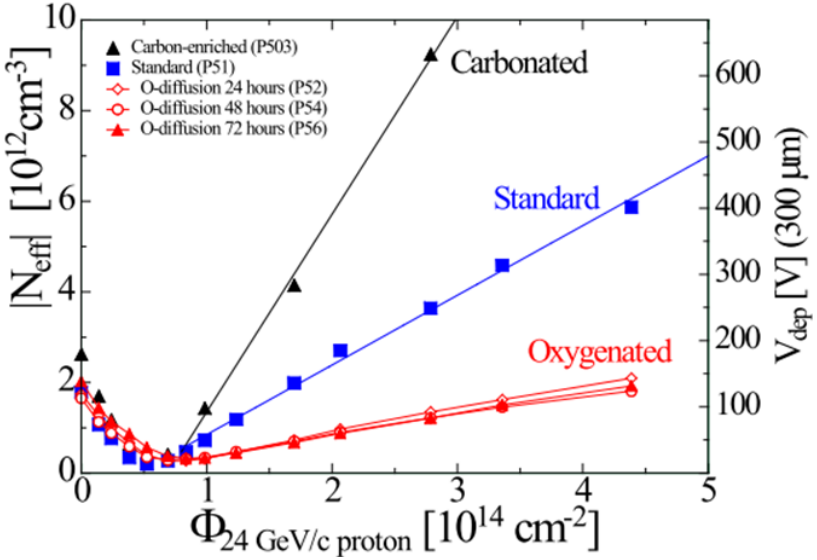
$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t)\,\Phi_{eq}$$

The $\beta_{e,h}$ was so far found independent on material;
- resistivity
- [O], [C]
- type (p,n)
- wafer production (FZ, Cz, epitaxial)
- **$\beta_{e,h}$ ~ 0 for ^{60}Co irradiated samples – trapping is related to cluster damage**
- … but only limited fluence range could be investigated directly

The trapping probability:
- gets smaller with time for electrons
- gets larger with time for holes

Electric field and V_{fd} as a main driver (@LHC)

- The main concern was the increase of effective doping concertation and related full depletion voltage (seen as crucial parameter)

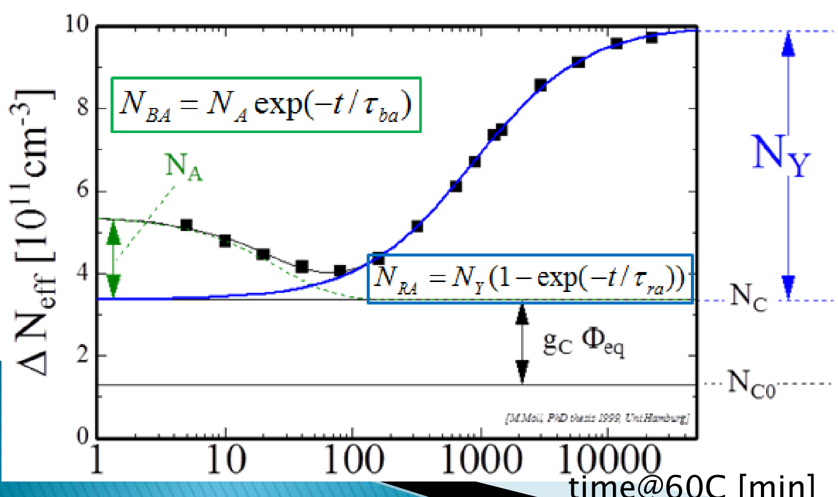


G. Lindstroem for RD48, Nucl. Instr. and Meth. A 466 (2001) 33.

Radiation induces mostly negative space charge. Its introduction rate was in focus:

$$N_{eff,0} - N_{eff} = N_c[1-\exp(-c\cdot\Phi_{eq})] + g_c\cdot\Phi_{eq} + N_{BA} + N_{RA}$$

Initial dopant removal
(studied only for n-type
$N_c = N_{eff,0}$ for charge hadrons,
$N_c < N_{eff,0}$ for neutron)

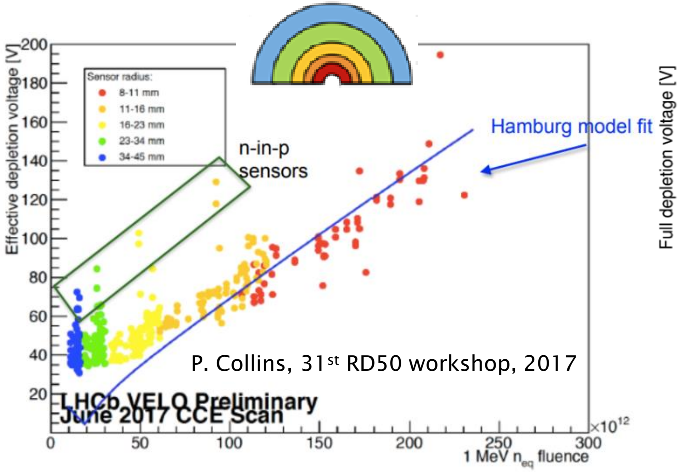


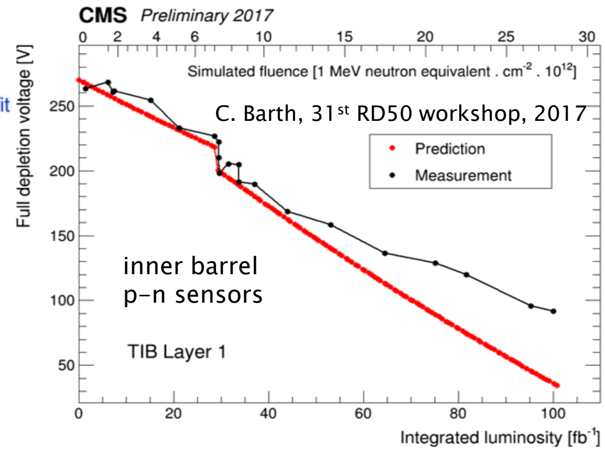
↓ g_c~0.02 cm^{-2} ↑ g_c~−0.007 cm^{-1}	neutrons	Fast charged hadrons
STFZ n,p	↓	↓
DOFZ n,p	↓	↓
MCz-n	↓	↑
MCz-p	↓	↓↑
Epi(Cz)- n	↓	↑
Epi(Cz) -p	↓	↑

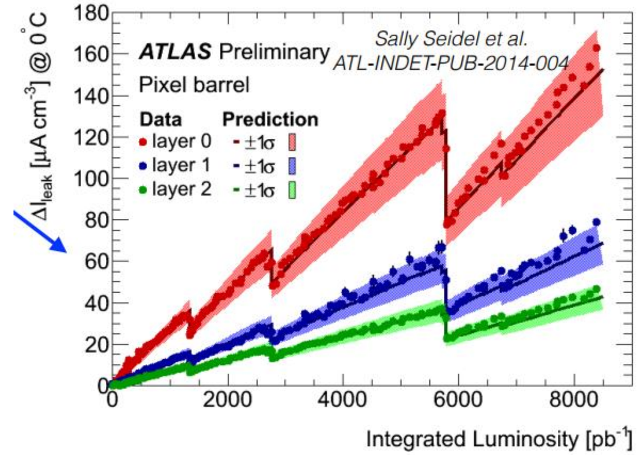
http://cdsweb.cern.ch/record/1291631/files/LHCC-SR-003.pdf (RD50 Status report)

Expectations LHC->HL-LHC

Hamburg model was confirmed at LHC, mixed irradiations (damage compensation), CERN scenario for thin sensors







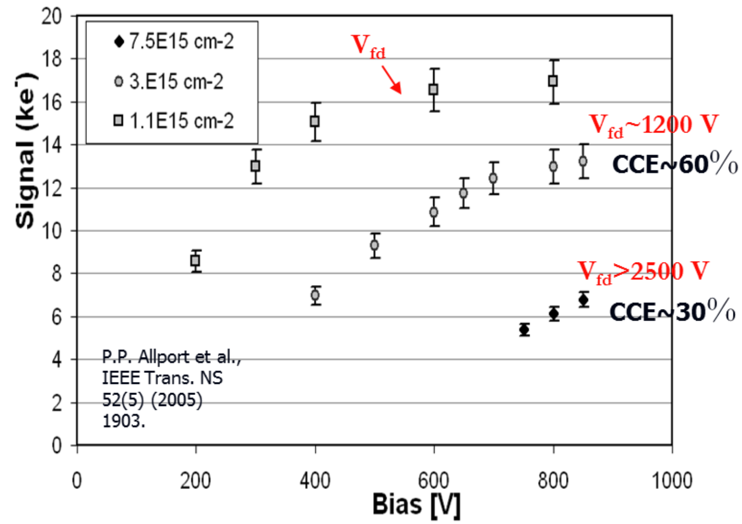
In general Hamburg models works fine at LHC, however…

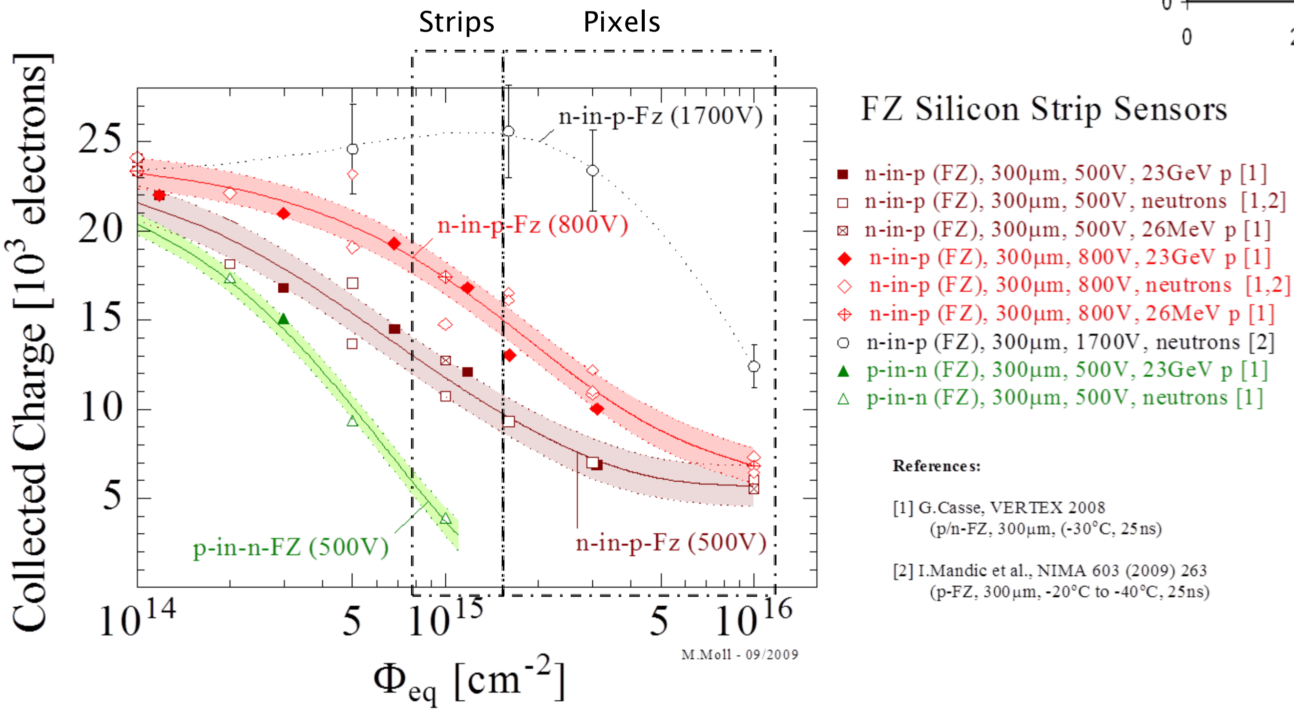
- Linear extrapolation from low fluence data for standard float zone detectors ($2\cdot10^{16}$ cm^{-2})
  - Current: I_{leak} = 0.8 A/cm^3 @20°C
    - 0.4 mA/cm^2 for 300 μm thick detector @ -20°C
  - Depletion: $N_{eff} \approx 4\times10^{14}$ cm^{-3}
    - $FDV \approx$ 30 kV
  - Trapping $\tau_{eff} \approx$ 1/8 ns = 125 ps
    - $Q \approx Q_0/d\, v_{sat} \tau_{eff} \approx$ 80 e/μm 200 μm/ns 1/8 ns = 2000 e in very high electric field (>>1 V/μm)
- Looks much like Mission Impossible…., but

But the reality for strips is …

- n^+–p work sufficiently well
- bias-voltage increase is the main tool that we have to improve CCE
- irradiation particle type matters, but it is not crucial
- choice of material becomes less relevant at high bias voltages and fluences

n^+–p historical plot

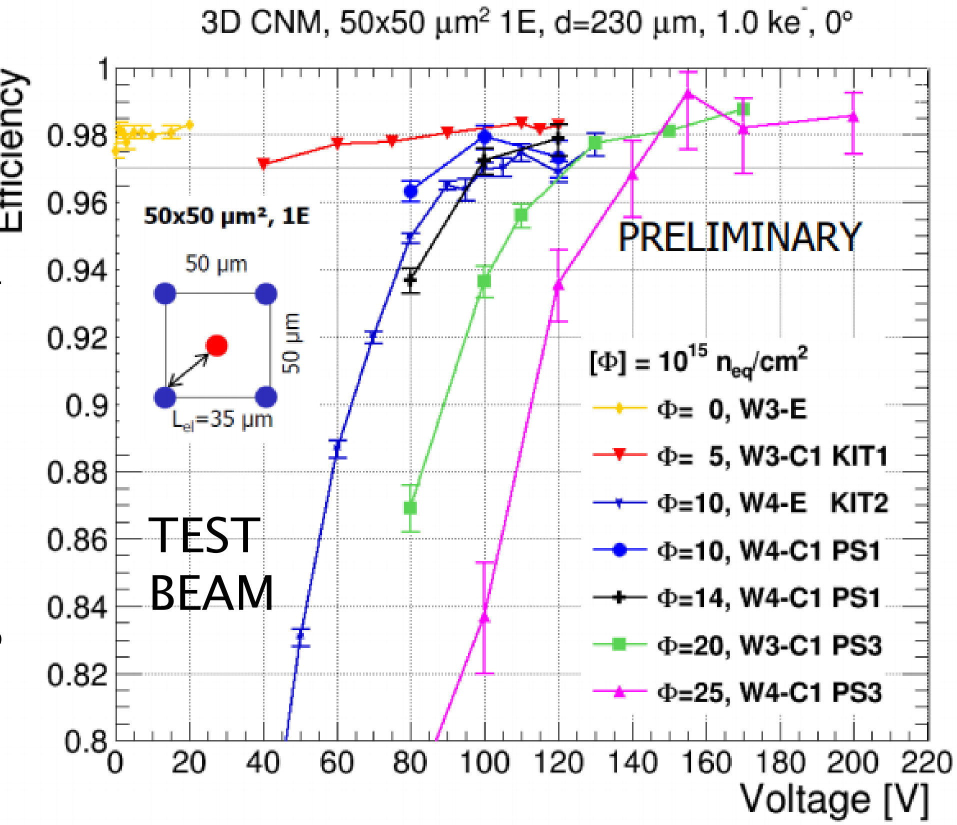




There will be many presentations that will show that in much more detail:

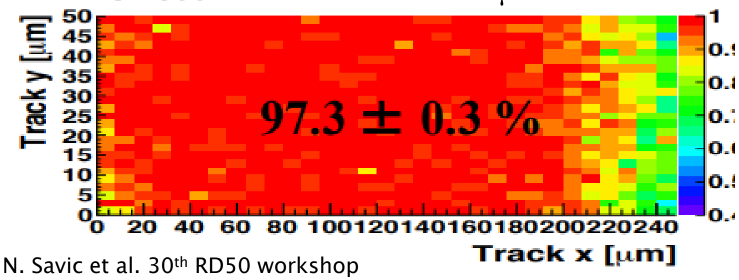
See talks:
- *A. Dierlamm, The CMS Outer Tracker for HL-LHC*
- *L. Wick-Fuchs, Annealing studies of irradiated p-type sensors designed for the upgrade of ATLAS Phase-II Strip Tracker*
- *A. Blue, Test beam evaluation of heavily irradiated silicon strip modules for ATLAS Phase – II Strip Tracker Upgrade*
- *V. Cindro, Measurement of charge collection in irradiated miniature sensors for the upgrade of ATLAS Phase-II Strip tracker*

But the reality for pixels is …

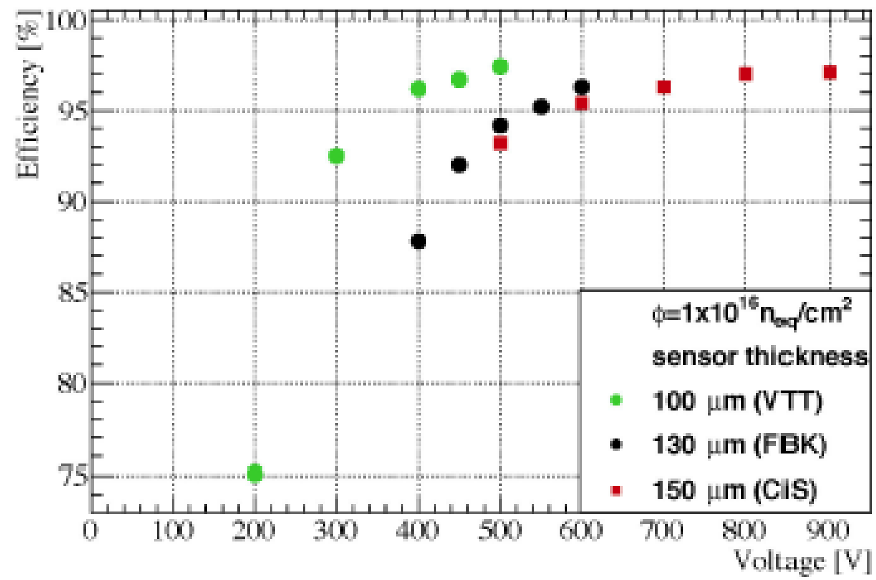


see. J. Lange et al. 31st RD50 workshop

VTT-100 µm, 10^{16} cm^{-2}
U= 500 V FEI4-250x50 µm^2



see. N. Savic et al. 30th RD50 workshop



Latest run of CNM RD53 chip compatible 3D detector
Ideal combination : n$^+$-p detector with small column width

F. Hügging, 26th Vertex conference , Las Caldas, 2017

see J. Lange – Superior radiation hardness of 3D pixel sensors up to HL-LHC fluences and beyond

more in pixel session

Why is the nature so kind to us?

There are several reasons why the projections didn't materialize and why silicon still outperforms all other materials for tracking applications – the nature was kind to us:

- high voltage operation (rather obvious, but far from trivial)
- smaller trapping
- active bulk
- charge multiplication

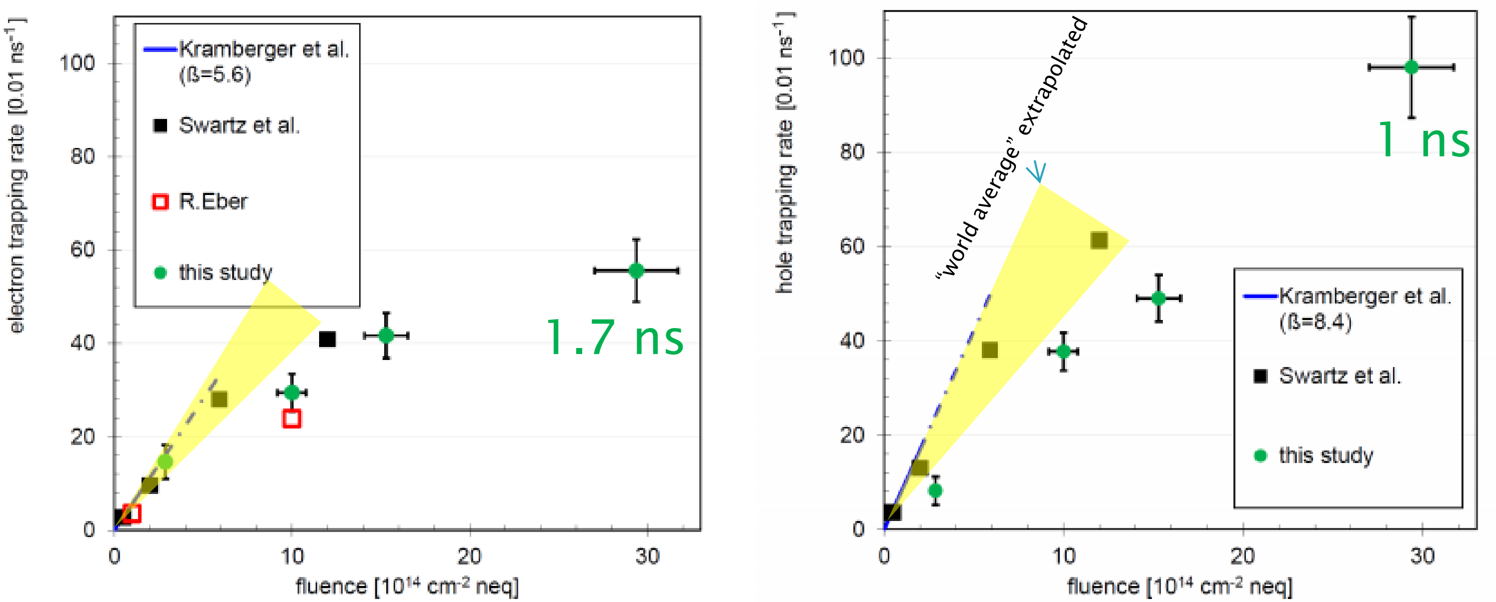
What was forgotten during LHC RD?

- initial dopant removal
  - new detector technologies with much higher N_{eff} (LGAD, HV-CMOS detectors)
  - thin LGAD change of paradigm – as large as possible N_{eff} increase with radiation
- mobility changes with radiation

Trapping at high fluences

- Trapping gets smaller than extrapolated – nothing is linear everywhere
  - defect formation is not linear (2nd order processes?)
  - required high voltage application may influence (de)trapping times
  - may depend on position in the detector

W. Adam et al 2016 JINST 11 P04023 (CMS collaboration)

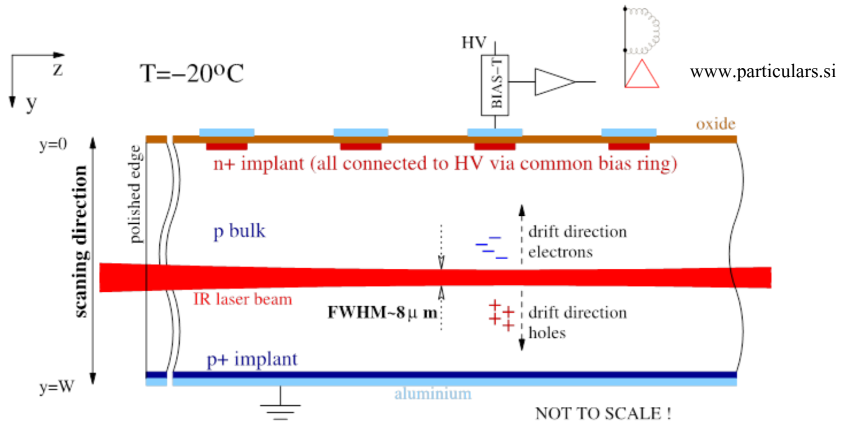


- At fluences 10^{16}–10^{17} cm^{-2} around 6–9x smaller trapping than etrapolatex from LHC fluences $\beta_{e,h}<10^{-16}$ cm^2/ns (*M. Mikuž et al., 26th Vertex, Las Caldas, 2017*)

Electric field (importance of active bulk)

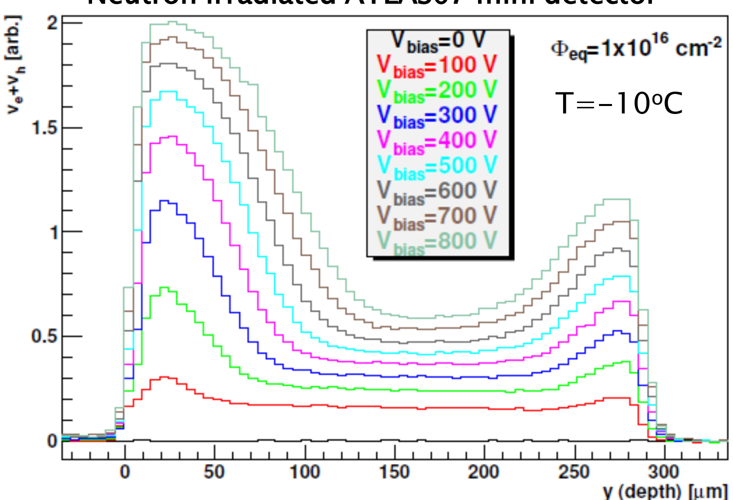
Edge-TCT allows for studies of velocity/charge collection profiles in heavily irradiated sensors

- Generation current accumulates, increasing *p* and *n* in opposite directions through SCR – "double junction" – dynamic configuration
- *e* and *h* trap, contributing to space charge

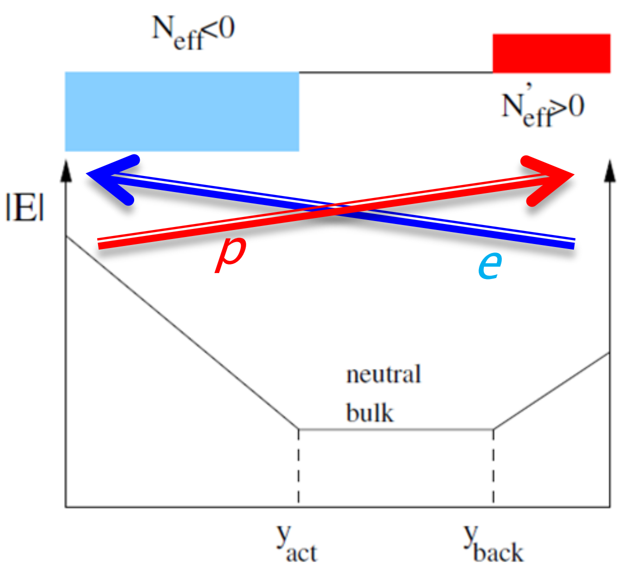


G. Kramberger et al., IEEE TNS, VOL. 57, NO. 4 (2010) 2294.

Neutron irradiated ATLAS07 mini detector



G. Kramberger et al., JINST 9 P10016(2014).

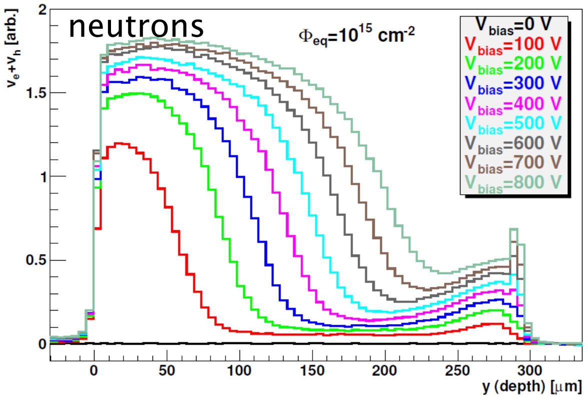


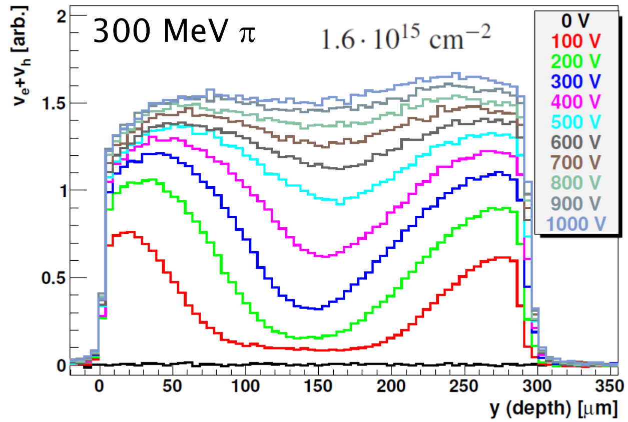
Full depletion voltage doesn't determine active field region at high fluences.

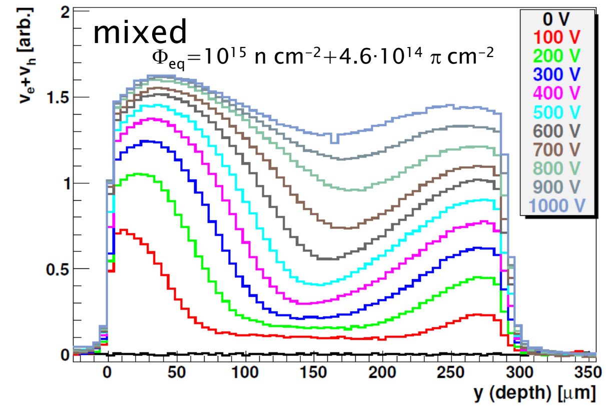
- ➢ whole detector volume is active (velocity in the saddle-30% of v_{sat})
- ➢ the high field region penetrates deeper in the detector than predicted

Electric field (different particles)

ATLAS 07 detector prototypes n⁺-p (75 μm pitch, 300 μm thick, V_{fd}=180 V)

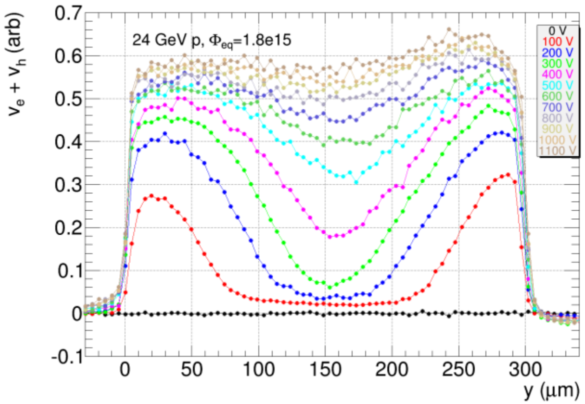


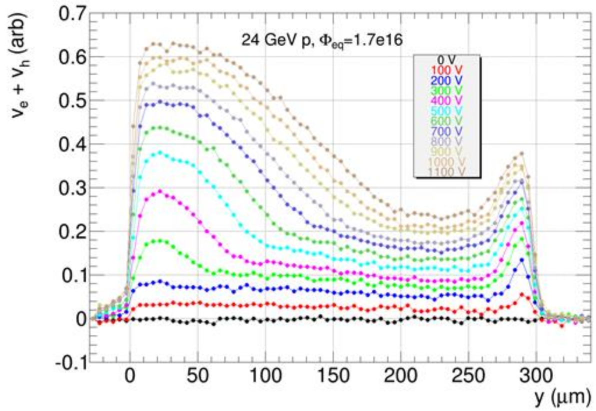




G. Kramberger et al., JINST 9 P10016(2014).

ATLAS 12 detector prototypes n⁺-p (75 pitch, 300 μm thick, V_{fd}=320 V)

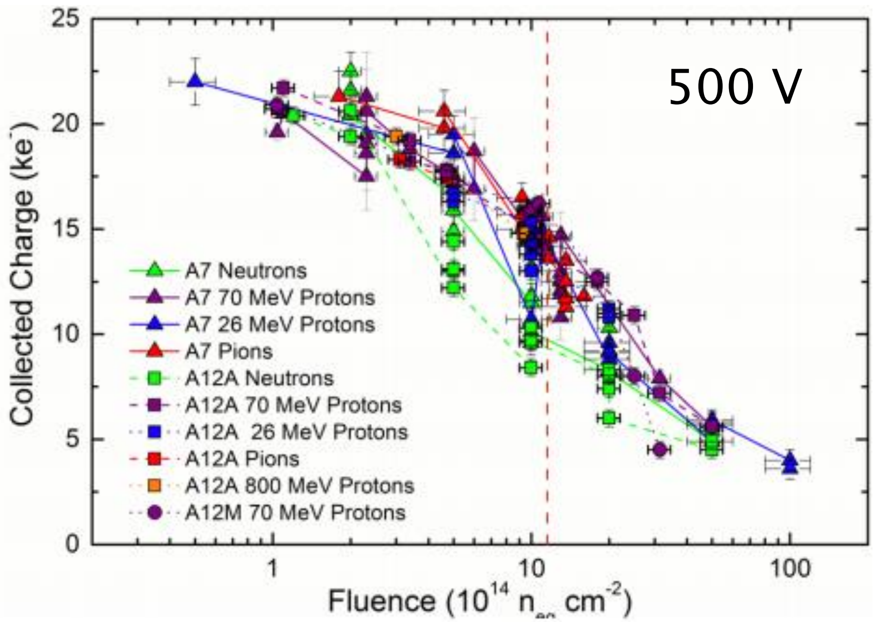


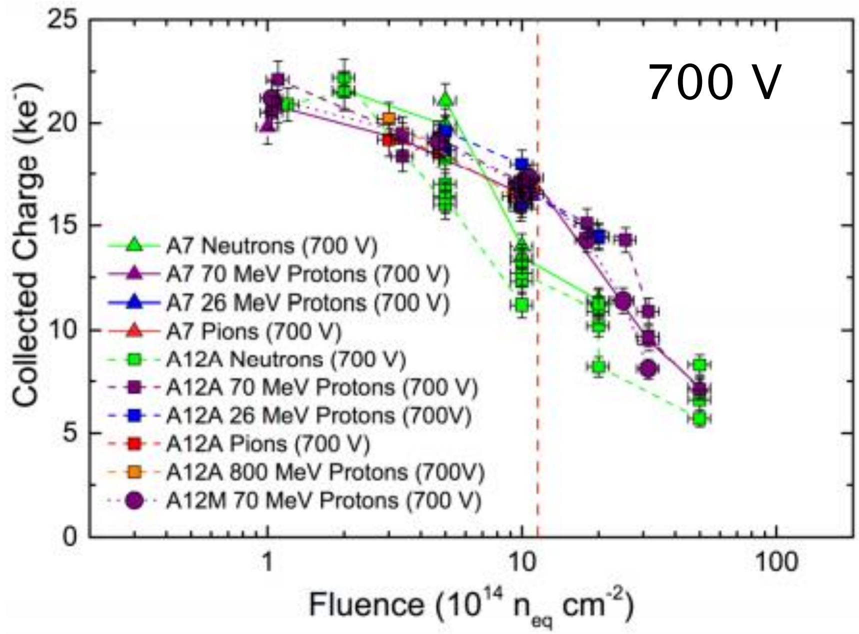


- neutron irradiated samples around 10^{15} cm^{-2}
  - very much as expected from predictions (Hamburg model like) – very low field in the bulk
  - damage parameters agree with predictions (g_c=0.018 cm^{-2})

- 300 MeV pions/24 GeV protons irradiated samples
  - almost symmetrical field in the bulk around Φ_{eq}=5-20·10^{15} cm^{-2} (full active detector at 500 V)
  - at very high fluences the velocity profiles become much more similar to neutron irradiated samples
  - point defects seem to be the ones responsible for the symmetrical field (role of oxygen ?)
- Mixed irradiation – between both

http://cds.cern.ch/record/2257755/files/ATLAS-TDR-025.pdf?version=3

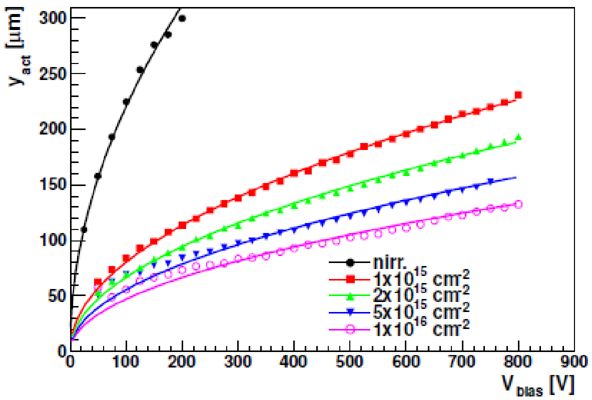




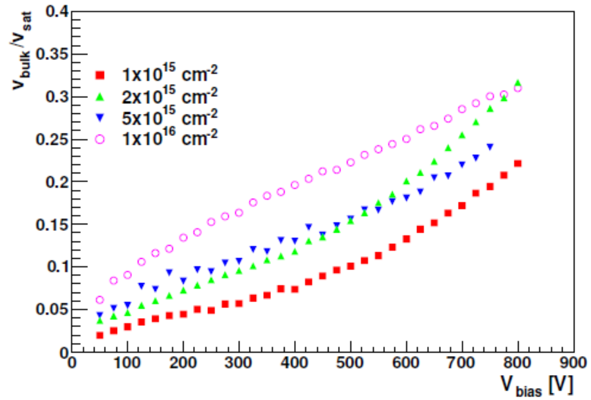
Technical Design Report for the ATLAS Inner Tracker Strip Detector

Electric field model parameter–neutrons

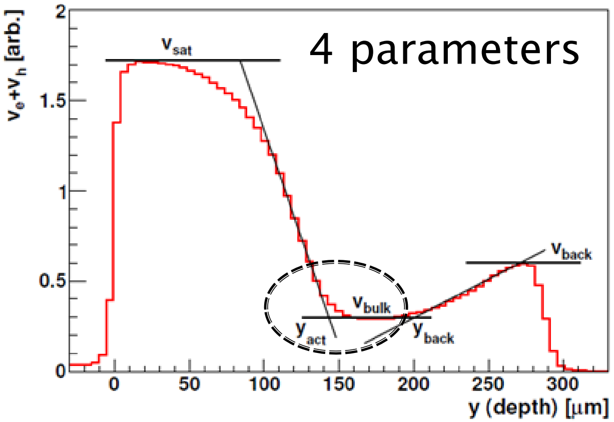
active region y_{act}

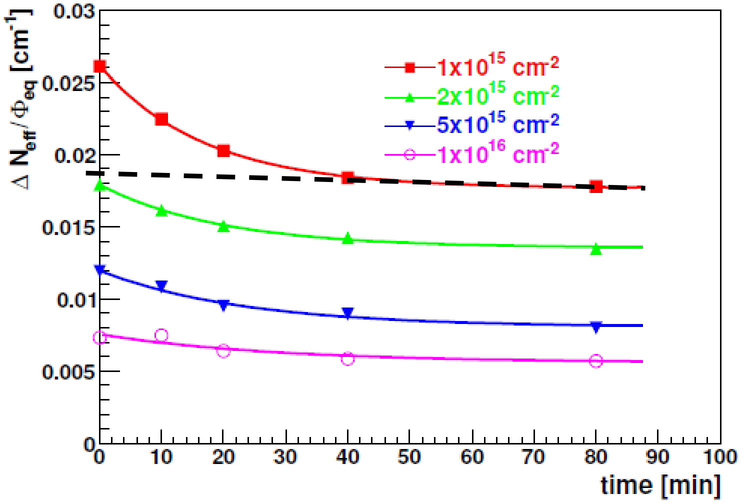


velocity in the bulk

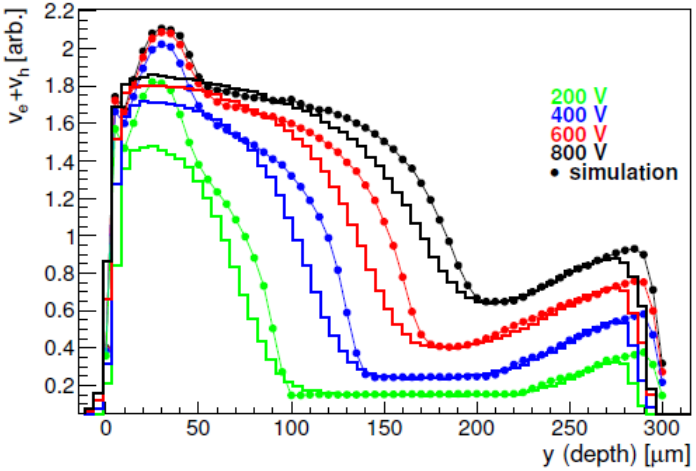


depth of "second/back" active region





model fed to the simulator



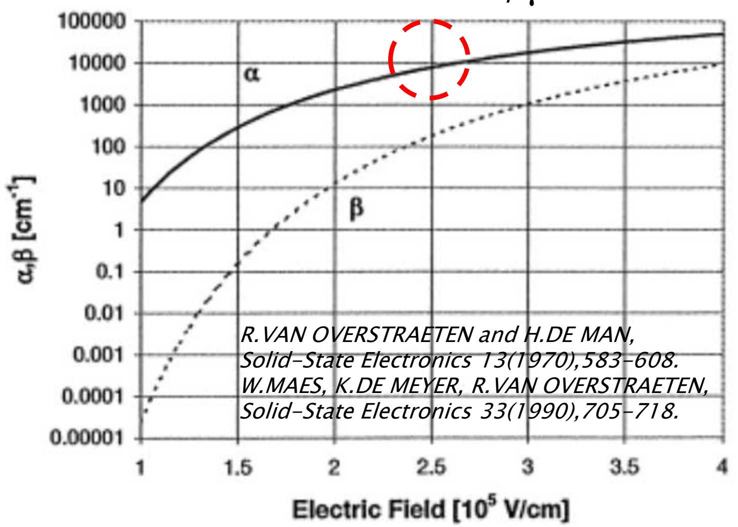
- introduction rate of negative space charge gets smaller with fluences (not linear) than extrapolated
- bulk velocities are high
- high fields at the ohmic contact extend well inside the detector

Charge multiplication

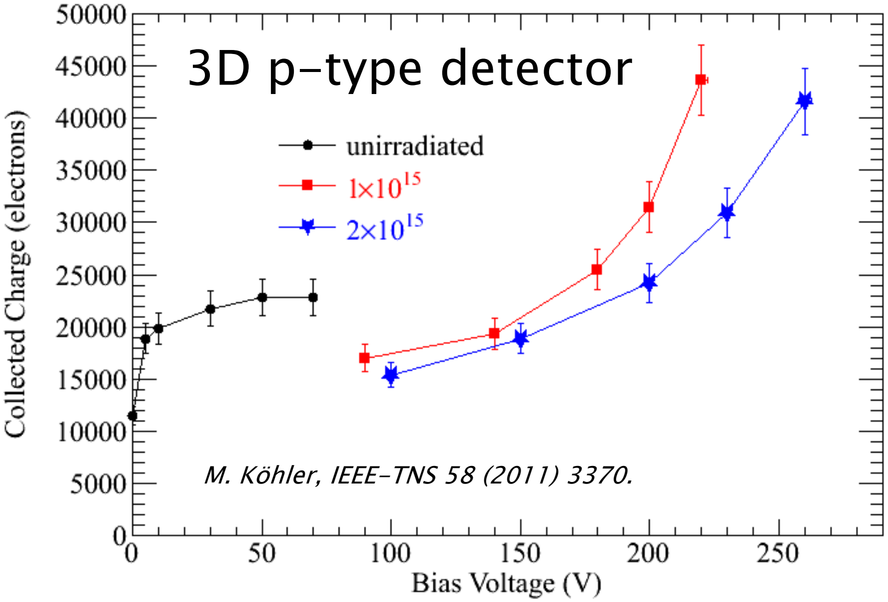
High Φ_{eq} → large N_{eff} high V → High E → Impact ionization

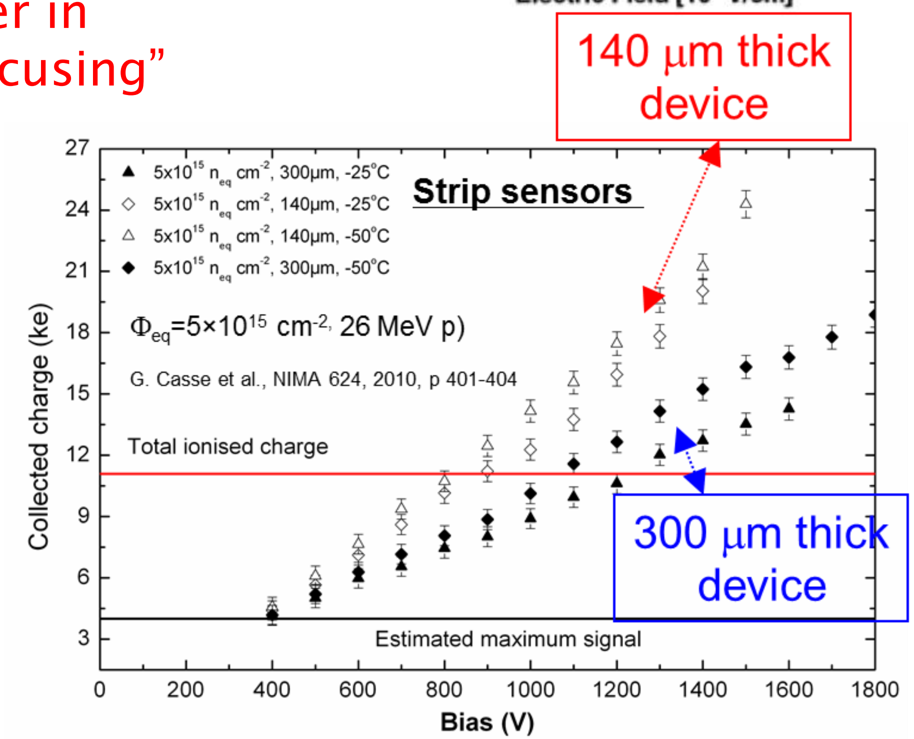
$$dN_e = N_e \cdot \alpha \cdot dx$$

Electrons undergo multiplication in electric fields >15-25 V/µm

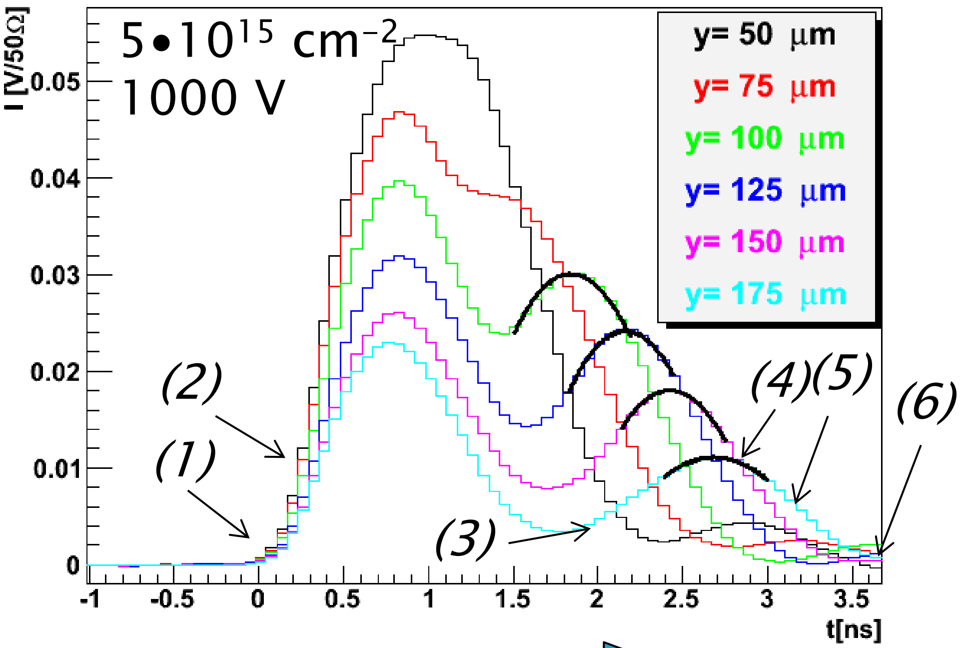


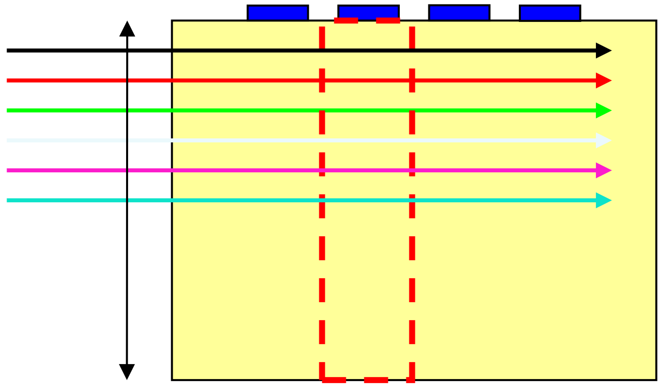
CCE > 1 observed for all types – larger in segmented detectors due to "field focusing"



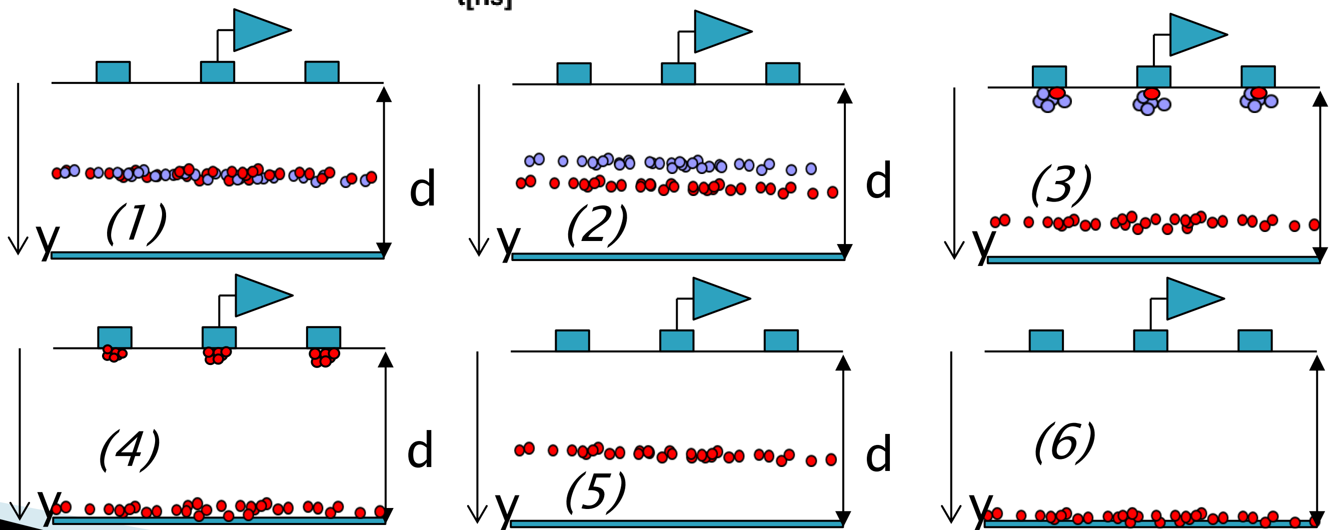


Charge multiplication





Micron n-p "baby" strip detector of ATLAS geom.

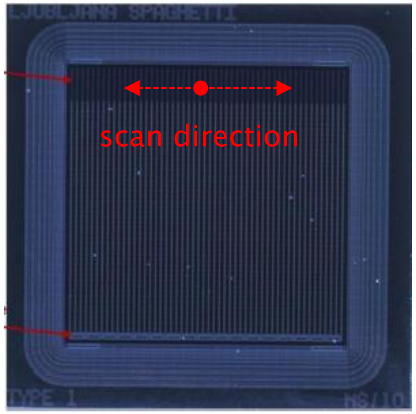


Charge multiplication

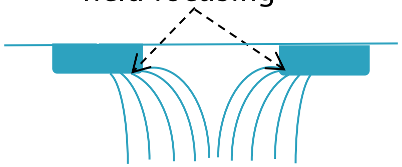
Micron diodes

no metallization

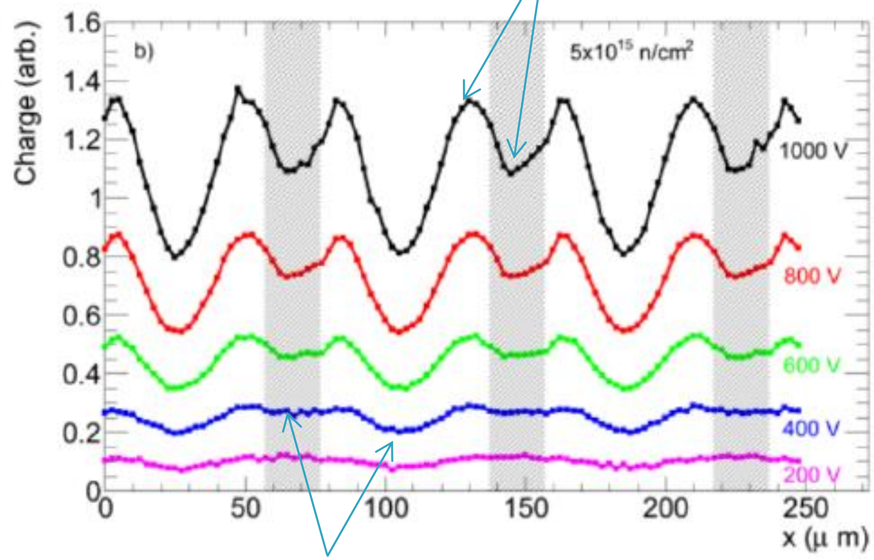
strips ganged together



field focusing



difference in gain



difference in trapping
longer drift paths/smaller fields

Charge multiplication due to deep defects:

- moderate gain of few times can be reached (higher in thin sensors – *see H. Sadrozinski's talk*)
- there is no steep rise in collected charge (gain is present even if CCE<1) – trapped holes quench the field – field stabilization (high gain more holes trapped – smaller field) – moderate dependence on voltage

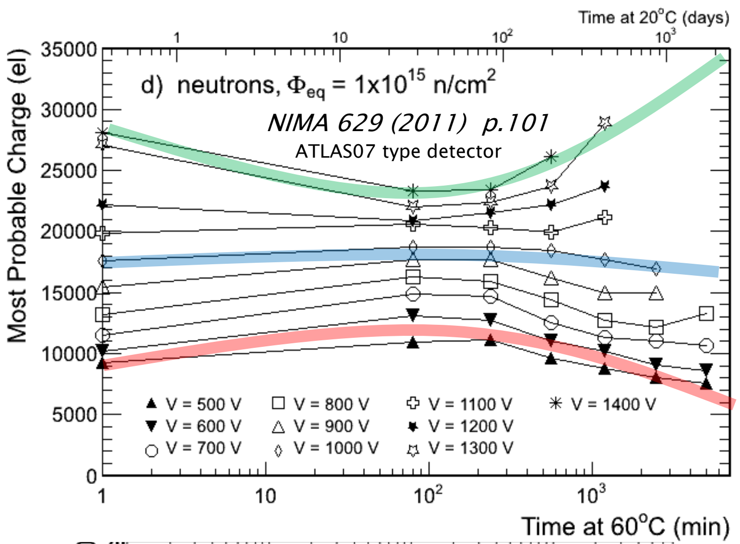
Charge multiplication is difficult to master/control:

- it is geometry/process dependent – field focusing effect (mostly seen in strips/pixels, more difficult in pads of standard thickness)
- difficult to fully parametrize field and simulate it
- long term time stability of multiplication

Annealing at HL-LHC fluences

Annealing has a smaller role than at LHC for several reasons:

- n-side readout (high field always at the segmented side, beneficial annealing of electron trapping probability)
- at high fluences – bulk becomes active and stays so also after annealing
- multiplication can increase due to additional acceptors being formed during "reverse annealing" *(seen in edge-TCT – JINST 6 (2011) P06007)*

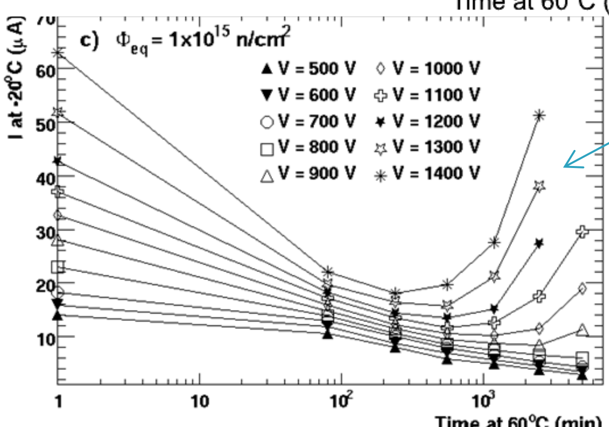


Typical behavior for CC at high voltages with pronounced CM
~20% decrease during beneficial annealing and then increase

see V. Cindro, Measurement of charge collection in irradiated miniature sensors for the upgrade of ATLAS Phase-II Strip tracker

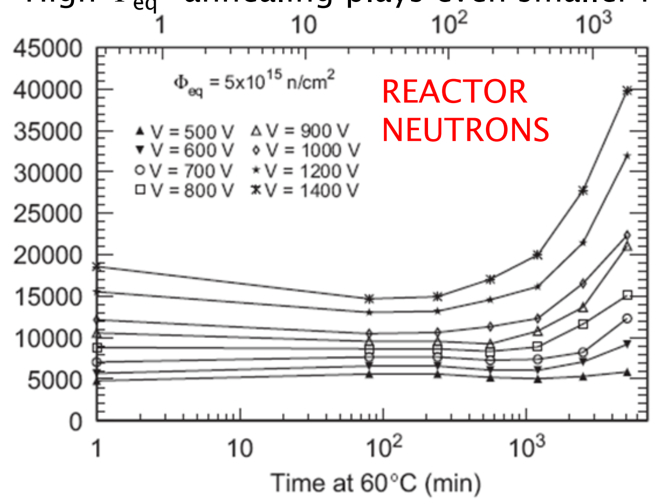
In the intermediate voltages CC remains constant

Typical behavior for CC at low voltages
~20% increase during beneficial annealing and then decrease



CM clearly seen in current

High Φ_{eq} – annealing plays even smaller role



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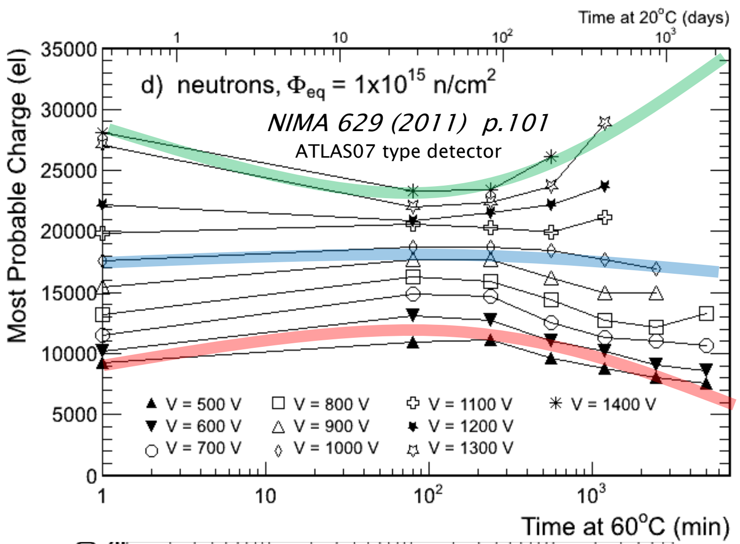

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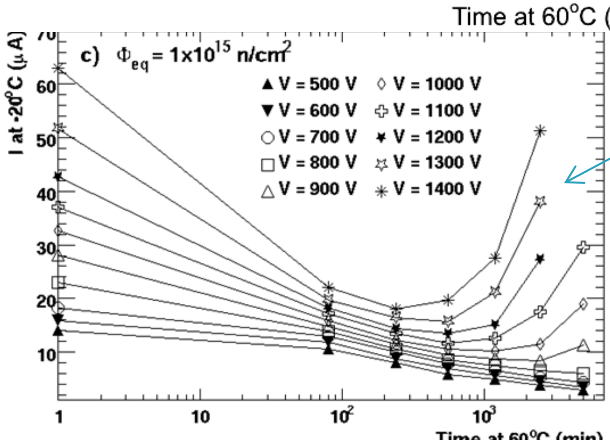

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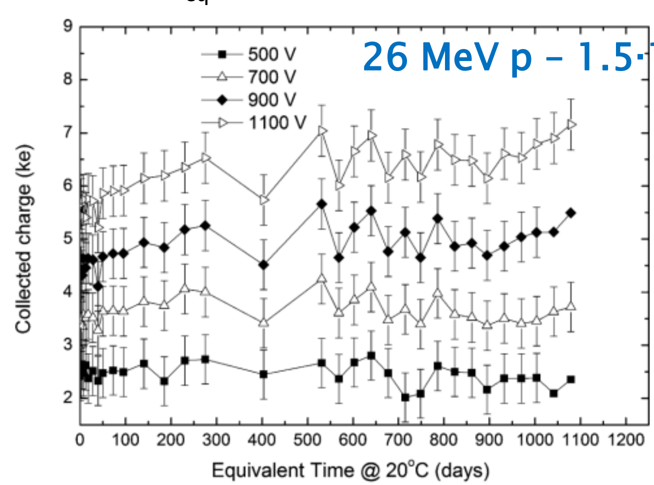
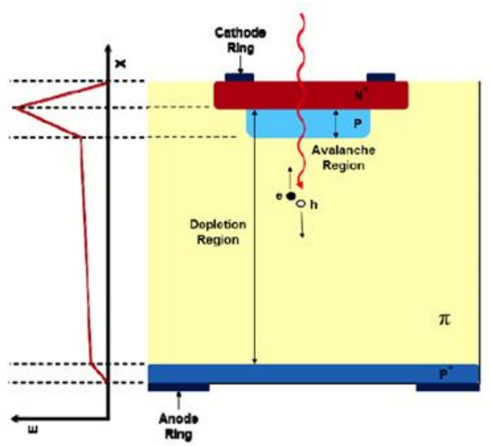


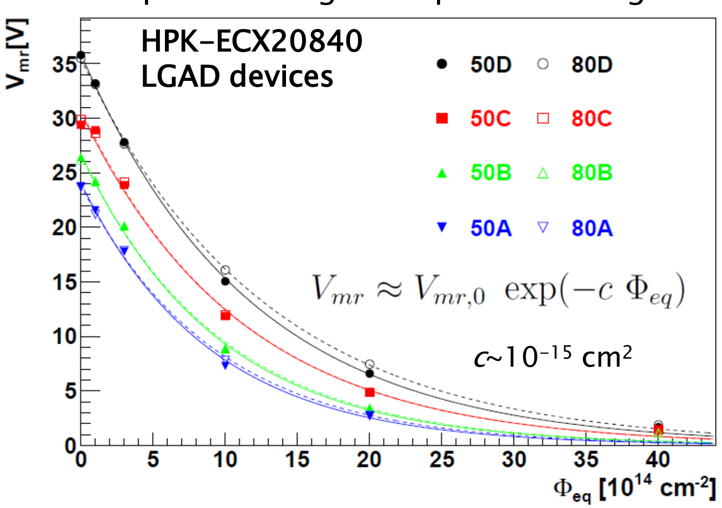
G. Casse, IEEE-TNS Vol.59 (2012) 419.

Initial acceptor removal (LGAD, HVCMOS)

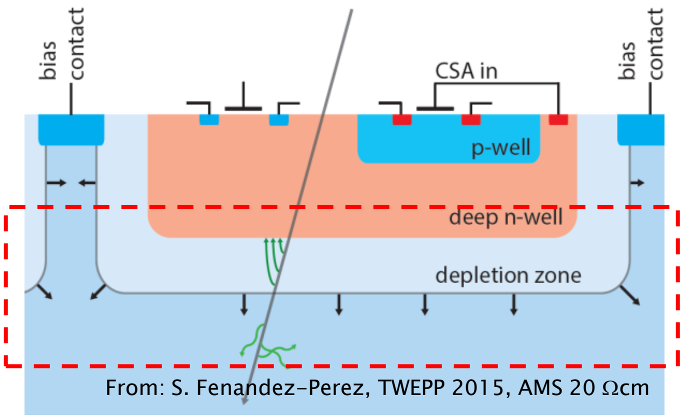
- Radiation hardness of the LGAD – loss of gain due to loss of active acceptors in the gain layer (so called acceptor removal) – (see Thursday morning session)

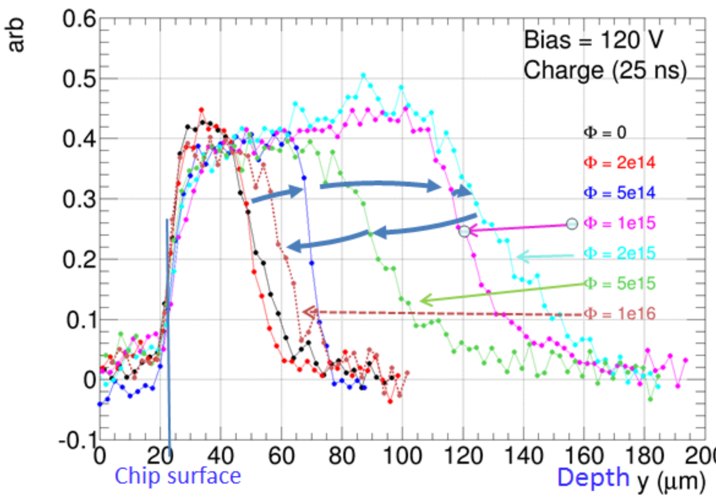


multiplication region depletion voltage



- Radiation hardness of HVCMOS – increase of active zone by irradiation for low resistivity substrates (see Tuesday afternoon session)





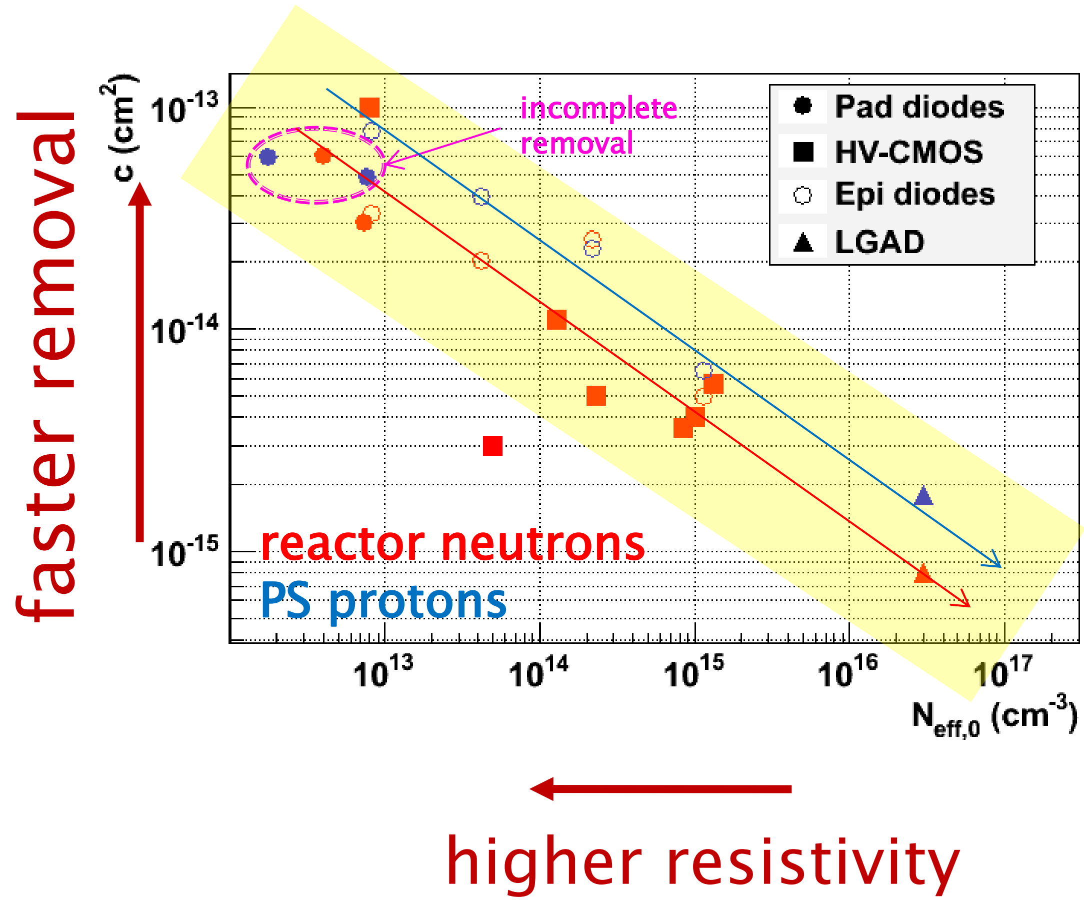
Acceptor removal constant

$$N_A = N_{A,0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))$$

$$dN_A = -\sum_i c_i \cdot N_A \, d\Phi \quad , \quad c = \sum_i c_i([O],[C],[B])$$

R. Wunstorf et al, NIMA 377 (1996) 228.
J. Adey, PhD Thesis, Univeristy of Exceter, 2004
J. Adey et al., Physica B 340-342 (2003) 505-508

main mechanism: I + Bs → Bi



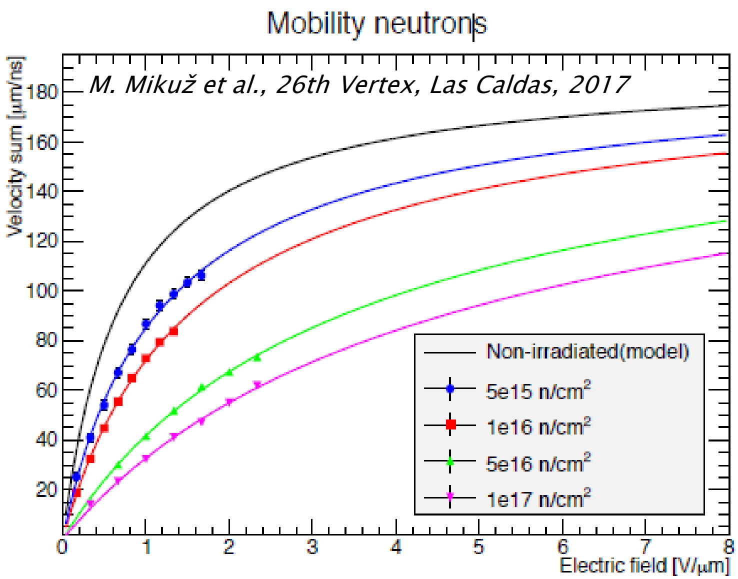
- The relation $c(\Phi_{eq})$ not yet understood – Why?
- $N_c = N_{A,0}$ –> complete removal observed at lower resistivity
- faster removal for charged hadrons at the same equivalent fluence
- B (w. C-spray) and Ga-doping (w/o C-spray) are investigated to reduce removal rate

Epi diodes: *P. Dias de Almeida*, 30th RD50 Workshop, 2017
LGAD: *G. Kramberger, JINST Vol. 10 (2015) P07006*
Pad diodes*: G. Kramberger, 26th RD50 workshop, Santander, 2015*

HV-CMOS: *A. Affolder et al.*, JINST 11 P04007 2016
I. Mandić et al., JINST 12 P02021 2017
E. Cavallaro et al., JINST 12 C01074 2017
B. Hiti et al., JINST 12 P10020 2017

Mobility after heavy irradiation

Edge-TCT allows also for determination of mobility after extreme fluences



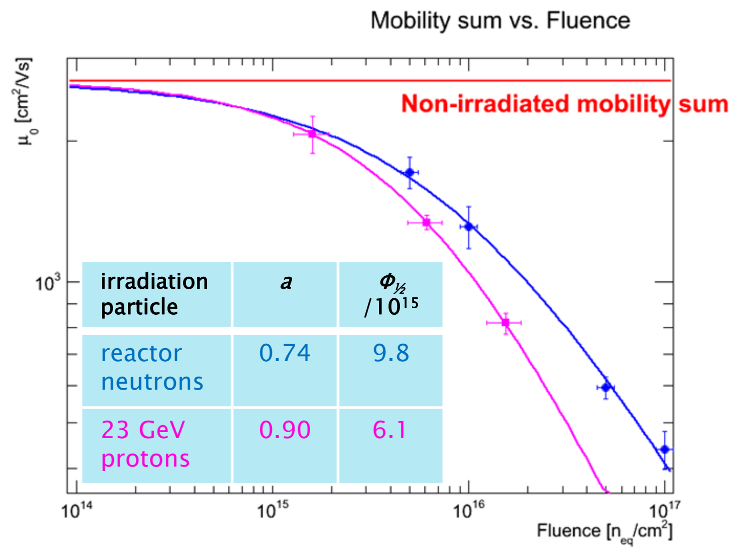
- Mobility governed by hard scattering on acoustic phonons and traps

$$\frac{1}{\tau} = \frac{1}{\tau_{ph}} + \frac{1}{\tau_{trap}}$$

- Fit mobility dependence on fluence with a power law

$$\mu_{0,sum}(\Phi) = \frac{\mu_{0,sum,phonon}}{1 + \left(\frac{\Phi}{\Phi_{1/2}}\right)^{a}}$$

- Fits perfectly, value of *a* close to linear
- At same NIEL, mobility decrease worse for protons
  - NIEL violation ? Large errors ?

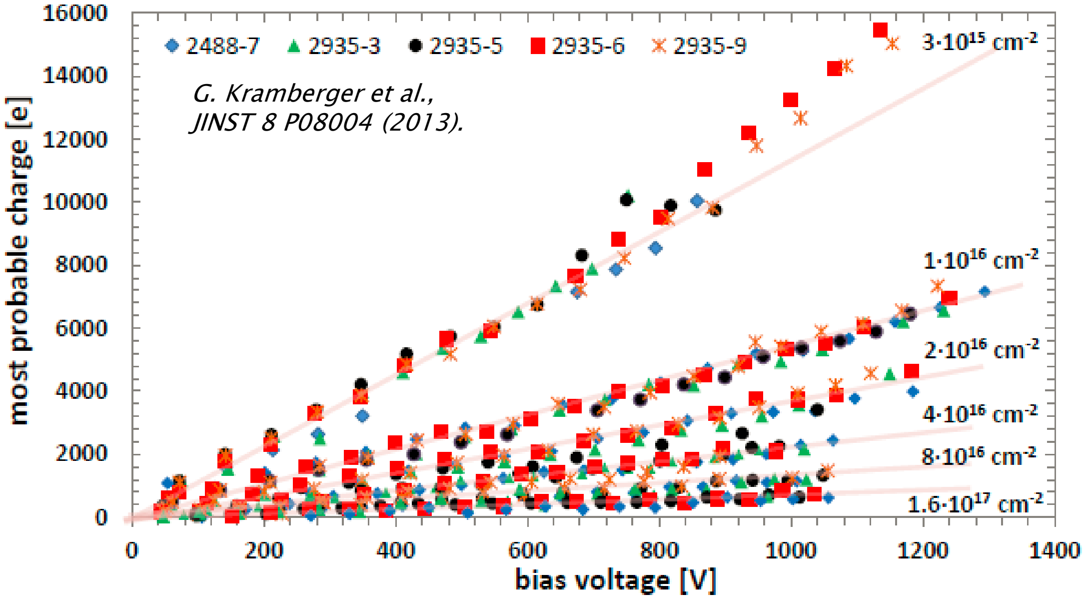


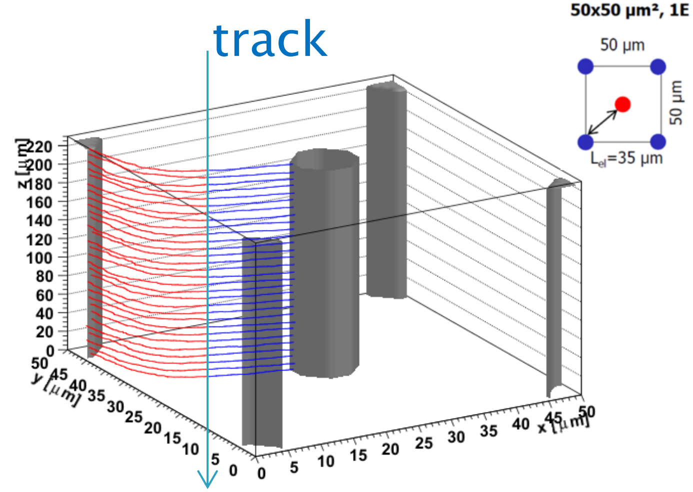
irradiation particle	*a*	$\Phi_{1/2}$ /10^{15}
reactor neutrons	0.74	9.8
23 GeV protons	0.90	6.1

Same reduction of electron and hole low field mobility assumed:

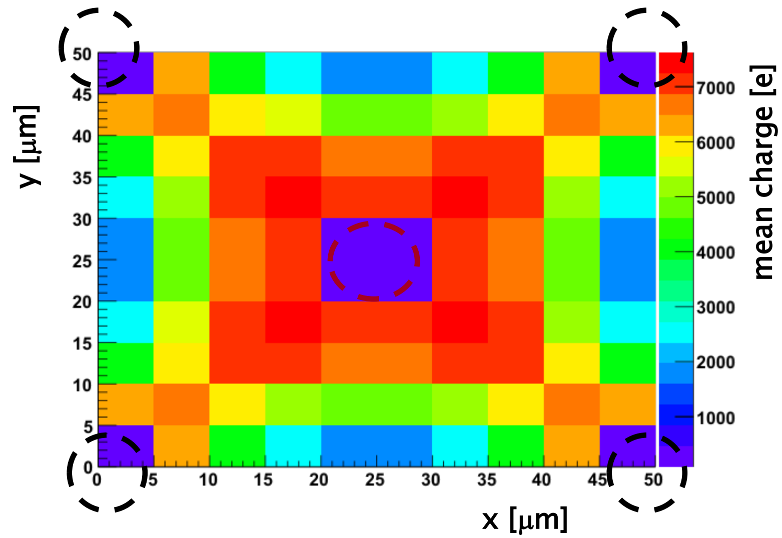
- Large decrease of mobility, therefore larger E required to saturate velocity – a strong argument for thin detectors
- Somewhat larger decrease for protons than for neutrons

Charge collection at $\Phi_{eq}>10^{17}cm^{-2}$ –FCC





mean charge
$1\cdot10^{17}$ cm^{-2},200 V, 0°, ,–20°C



the mip signal is above 3000e in most of the cell

- Collected charge at Φ_{eq}~$1.6\cdot10^{17}cm^{-2}$ of around 1000e – measured for minimum ionizing particle
- Simulation of sensors with RD53 configuration with known data
  - 9x longer trapping times as extracted from TCT (obtained from above and Edge-TCT)
  - reduced low field mobility for highly irradiated sensors
  - introduction rate of effective acceptors as extracted from the measurements at 10^{16} cm^{-2}

Conclusions

- a lot of effort was invested in studying radiation effects in silicon over the years
  - linking damage effects to "microscopically" identified defects
  - understanding the defect engineering (role of [O], [C] changing dopants – Ga)
  - improving the design and exploiting operation conditions
- the nature has been kind to us and silicon detectors are far more resilient than initially predicted and can be successfully operated for tracking at HL-LHC
  - moderate trapping
  - active bulk
  - charge multiplication
  - high voltage design
- the paramount difficulties successfully surmounted from LHC to HL-LHC awaken aspirations for Si at FCC

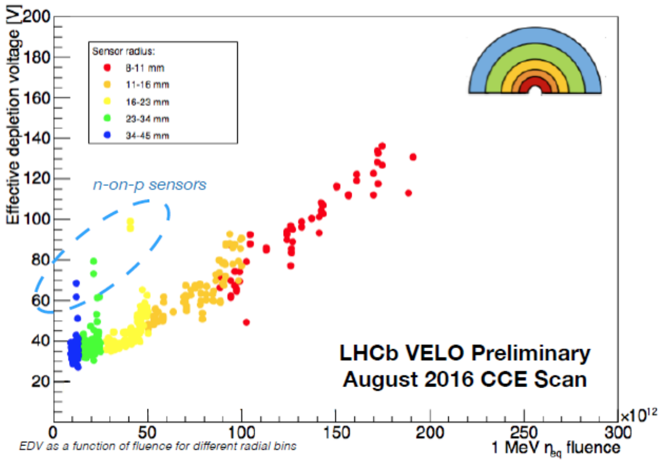
NOTHING IS IMPOSSIBLE, THE WORD ITSELF SAYS "I'M POSSIBLE"!
- AUDREY HEPBURN

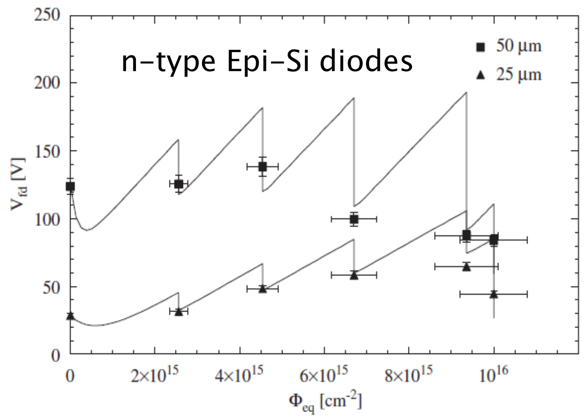
Backup

RD50

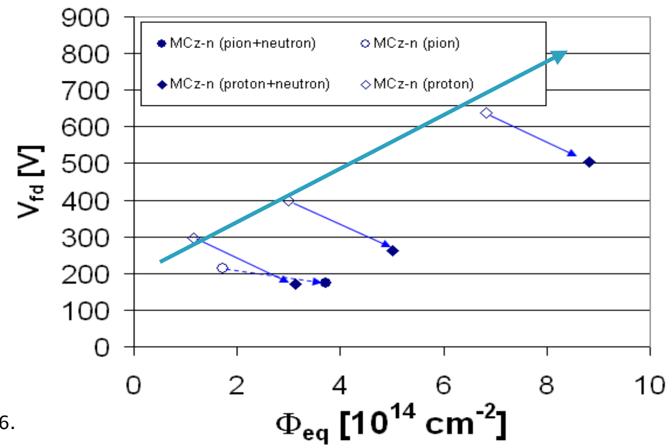
Expectations LHC->HL-LHC

Hamburg model was confirmed at LHC, mixed irradiations (damage compensation), CERN scenario for thin sensors





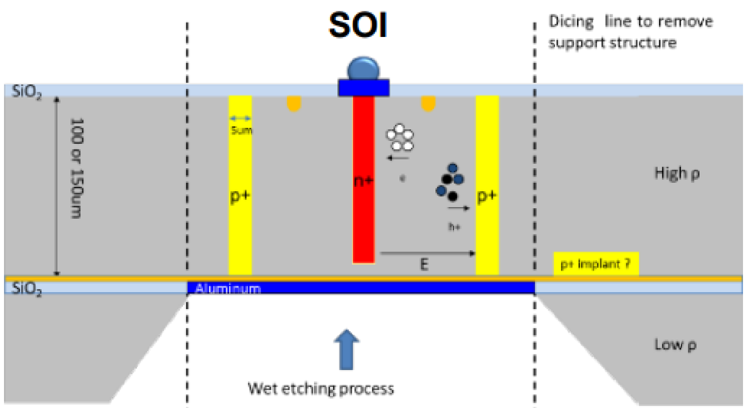
G. Lindstroem et al., Nucl. Instr. and Meth. A 568 (2006) 66.

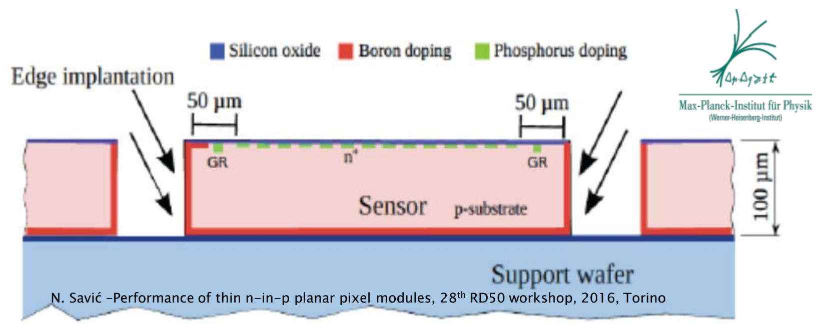


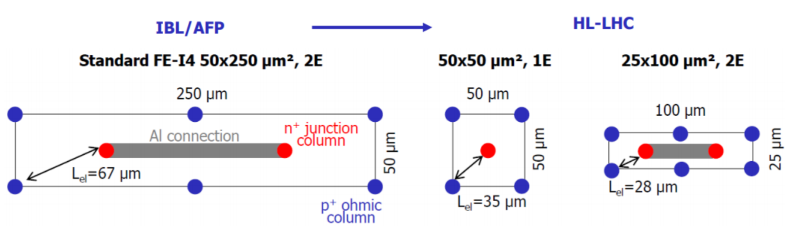
- Linear extrapolation from low fluence data for standard float zone detectors (2e16 cm−2)
  - Current: I_{leak} = 0.8 A/cm³ @20°C
    - 0.4 mA/cm² for 300 µm thick detector @ −20°C
  - Depletion: $N_{eff} \approx 4\mathrm{x}10^{14}$ cm^{-3}
    - $FDV \approx$ 30 kV
  - Trapping $\tau_{eff} \approx$ 1/8 ns = 125 ps
    - $Q \approx Q_0/d\, v_{sat}\tau_{eff} \approx$ 80 e/µm 200 µm/ns 1/8 ns = 2000 e in very high electric field (>>1 V/µm)
- Looks much like Mission Impossible…., but

Proper design

- **Expense of n^+–n overcome by turning to n^+–p**
  - shallow dopant benefit hardly noticeable
  - no inversion, if that matters…
- Improved design of the sensors with respect to the electrode geometry
  - 3D sensors (decoupling the collection and generation distance)
  - thin detectors







Why thin:
-less material
-smaller clusters (easier reconstruction)
-less leakage current
-larger average fields reached (multiplication)
-more favorable weighting field (bulk is highly resistive)
-reduced trapping in high electric field compensates for less depletion

History teaches us … never say never

- **1984:** Preparations for LHC/SSC (20y ahead of construction)

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

Detector Element	Luminosity 10^{30}	10^{31}	10^{32}	10^{33}
Vertex Detection	Yes	Hard	Maybe	No
Central Tracking	Yes	Yes	Yes	Hard

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

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

- **2003:** Preparations for HL-LHC (20y ahead)

C. Da Via, S. Watts "Can silicon operate beyond 10^{15}neutrons cm^{-2}?" Nucl. Instr. & Meth. A 501 (2003), p 138

at that time a lot was known about radiation hardness of sensors thanks to RD2, RD48 collaborations, but the projection of the damage parameters to HL-LHC made the use of silicon extremely challenging.

- **2017:** Preparations for FCC (>20y ahead)

Is silicon good enough also for FCC? – don't rule it out at least in some parts

What are the reasons for such a high radiation tolerance which surpasses all other known materials?