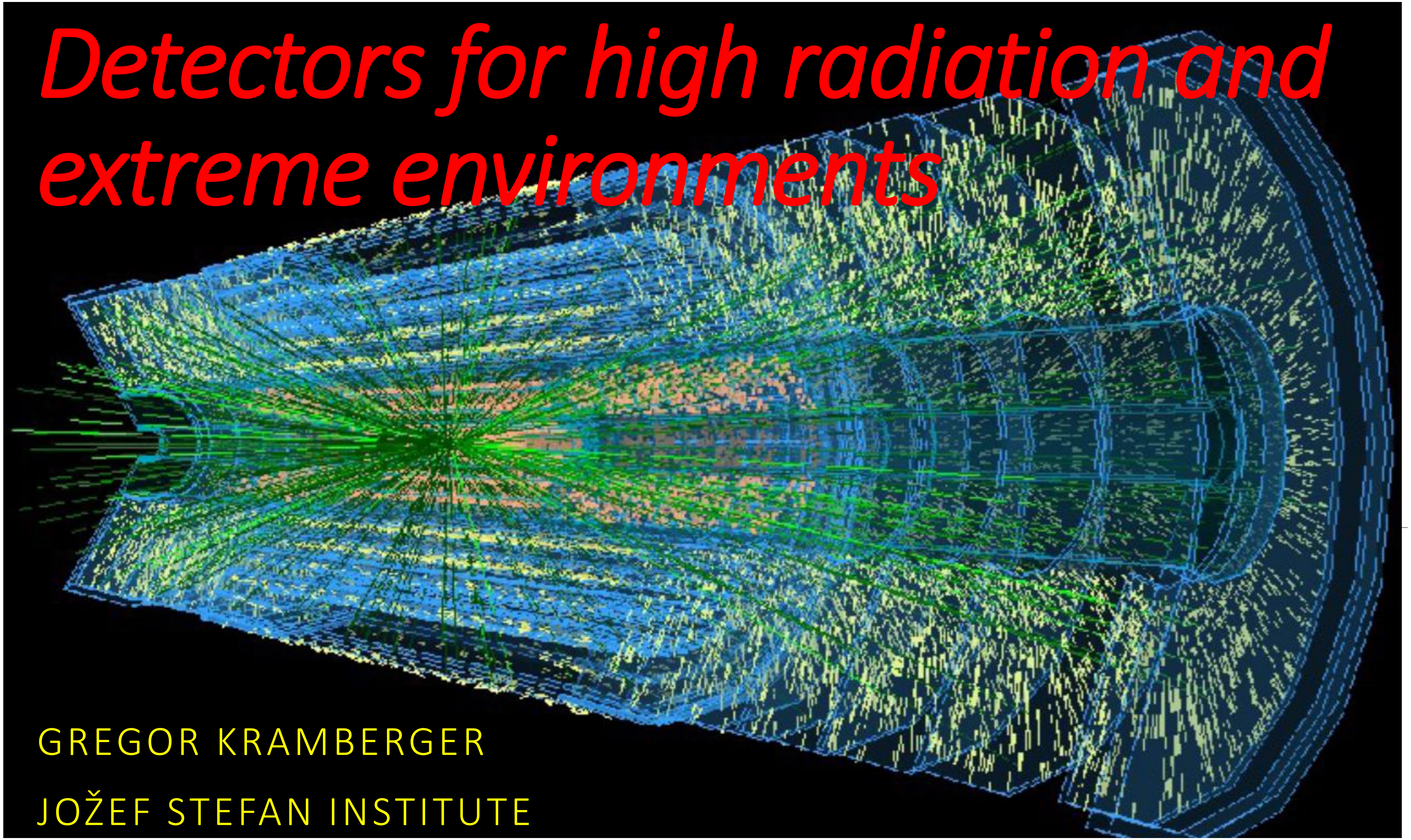
Detectors for high radiation and extreme environments



GREGOR KRAMBERGER

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Slovenian
Research
Agency
arrs

Introduction

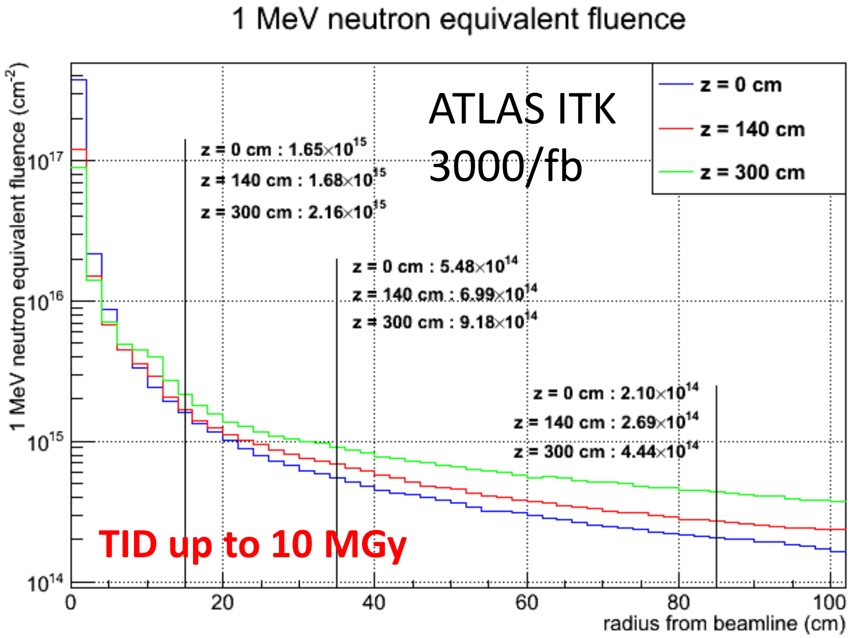
Position sensitive silicon detectors are an indispensable ingredient of any collider experiment mostly as tracking detectors, but also for calorimetry (becoming the main user of silicon – CMS-HGCAL)

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…
- ~x20 **HL-LHC takes it to nx10^{16} n_{eq}/cm^2 (vertex) or even 10^{17} n_{eq}/cm^2 (FW calo)**
  - 4000/fb @14TeV
- ~x600 **FCC is dreaming of towards 10^{18} n_{eq}/cm^2 for the tracker**
  - 30/ab @100TeV

"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)

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



ATLAS ITK
3000/fb

TID up to 10 MGy

Apart from particle physics similar conditions in:

- ➢Beam monitors (therapy beam monitoring, physics experiments)
- ➢Instrumentation for ITER (fusion reactor) required radiation hardness comparable or even larger than that of HL-LHC

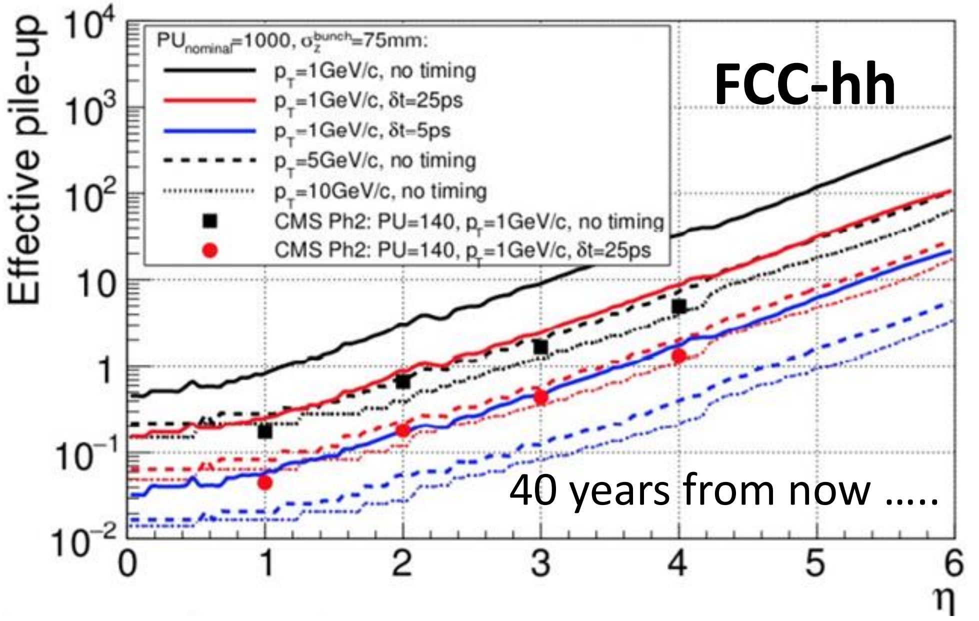
Luis F. Delgado-Aparicio, Burning-plasma diagnostics: photon & particle detector development needs, 31th RD50 Workshop

"Extreme" starts at fluences ~10^{16} cm^{-2}

What should future sensors do?

- We don’t only require excellent position resolution and detection efficiency even at the harshest conditions, **but also excellent timing resolution (4D tracking) as well** *(see Nicolo’s talk on Tuesday)*
  - much better/simpler pattern recognition, ghost rate reduction
  - better and faster tracks/physics reconstruction, better tracking algorithms
  - less CPU power (improved cost and energy efficiency)
  - effectively more luminosity
- In addition we want:
  - Very small material budget
  - Low power consumption

Effective pile up – number of vertices compatible with reconstructed tracks
Eff. pile-up = 1: Indication for unambiguous primary vertex identification



FCC-hh

40 years from now …..

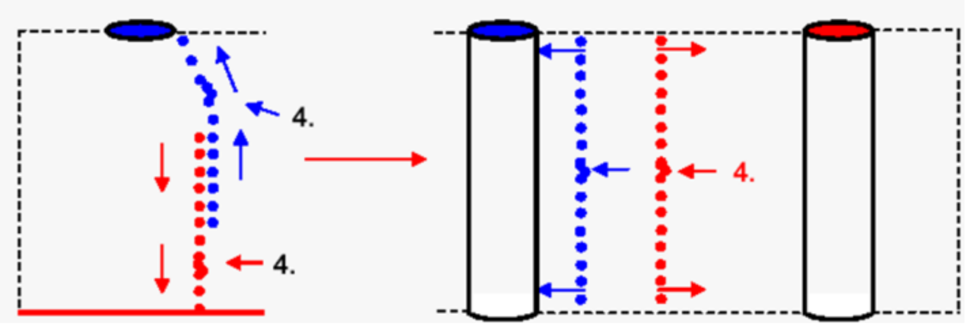
Sensor design – a key to radiation hardness

Charge collection (highly geometry dependent) is given by:

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

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

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



Planar detectors:

- n^+-p
- thin sensors
- defect engineered ([O],[C])
- **GAIN**

3D detectors

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

2.) “collect” carriers with larger $\mu\cdot\tau_{eff}$ product – i.e. electrons, n^+-p readout

3.) Optimize geometry for trapping dominated environment $\tau_{eff} << t_{drift}$

thin planar sensors perform better than thick at the same voltage

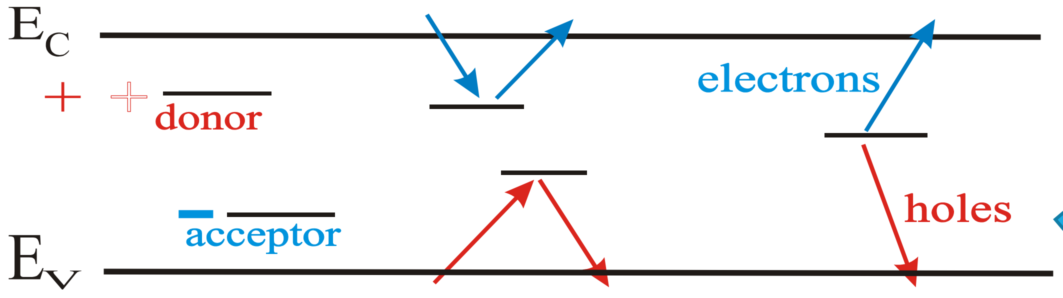
4.) Separate generation path from drift 3D detectors

5.) GAIN (LGADs, irradiated silicon)

Optimize S/N not only S (charge)!

Radiation damage

Influence of defects on the device properties – depleted region



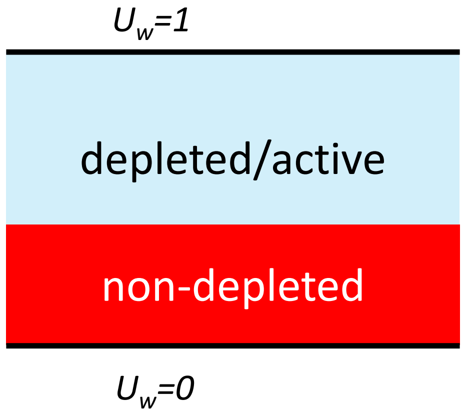
charged defects
⇒ **N_{eff} , V_{dep}**
e.g. donors in upper and acceptors in lower half of band gap

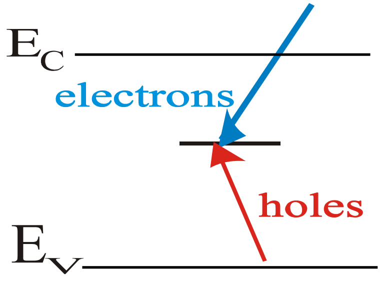
Trapping (e and h)
⇒ **CCE**
shallow defects do not contribute at room temperature due to fast detrapping

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

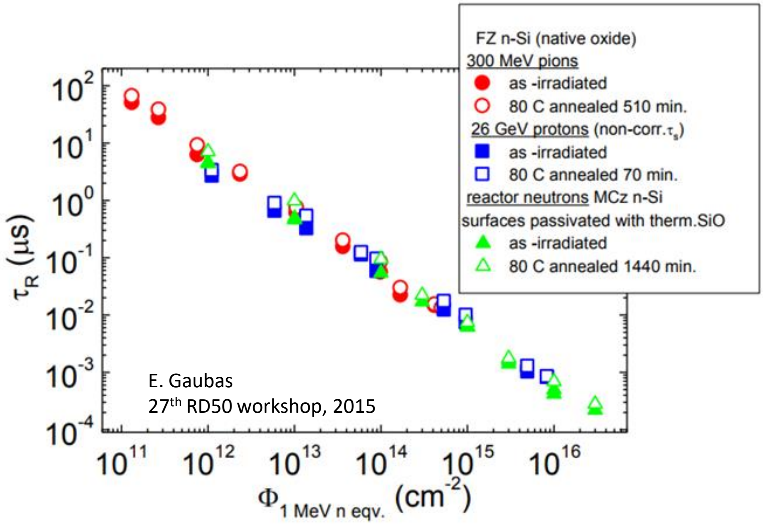
Remember that manifestation of the energy levels in a semiconductor is very dependent on temperature.
The damage is measured in 1 MeV n equivalent fluence (holds for generation)

After Irradiation





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

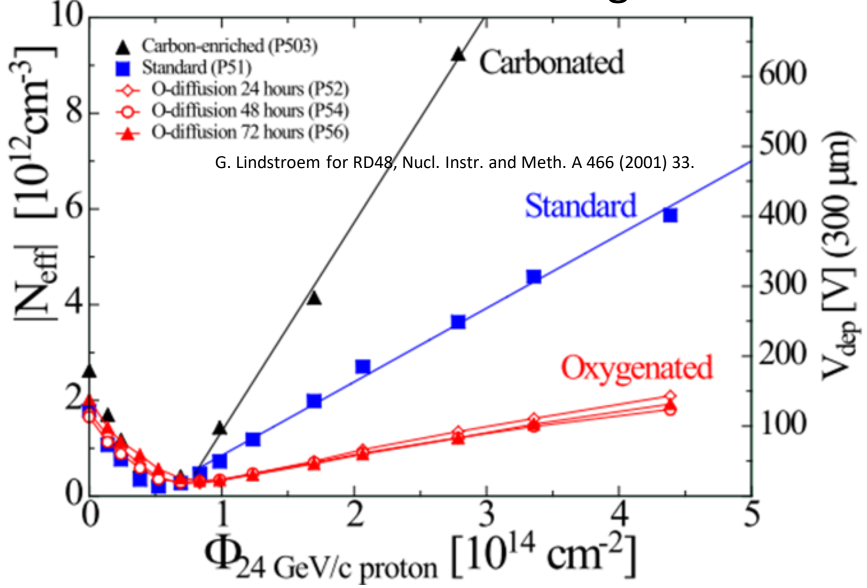


E. Gaubas
27th RD50 workshop, 2015

Radiation damage – good old LHC times

Radiation induces mostly negative space charge.

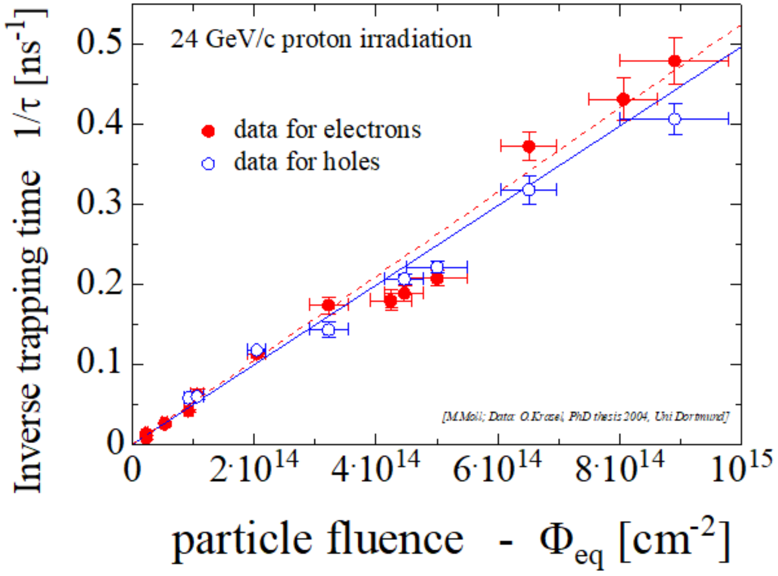
$$|N_{eff}| = \underbrace{g_c \cdot \Phi_{eq}}_{\text{stable damage}} + N_{BA}(t) + N_{RA}(t)$$



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

Huge effort invested in RD48 and RD50 to understand the damage on microscopic level.

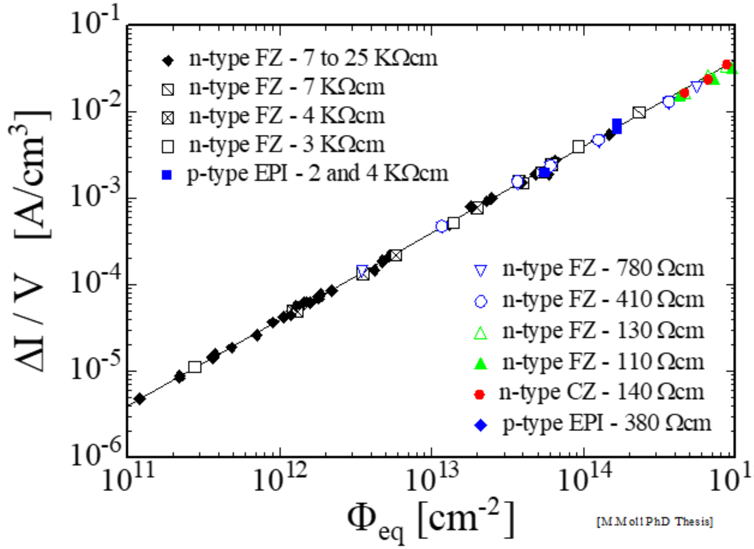
$$\frac{1}{\tau_{eff,e,h}} = \beta_{e,h}(T,t)\,\Phi_{eq}$$



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

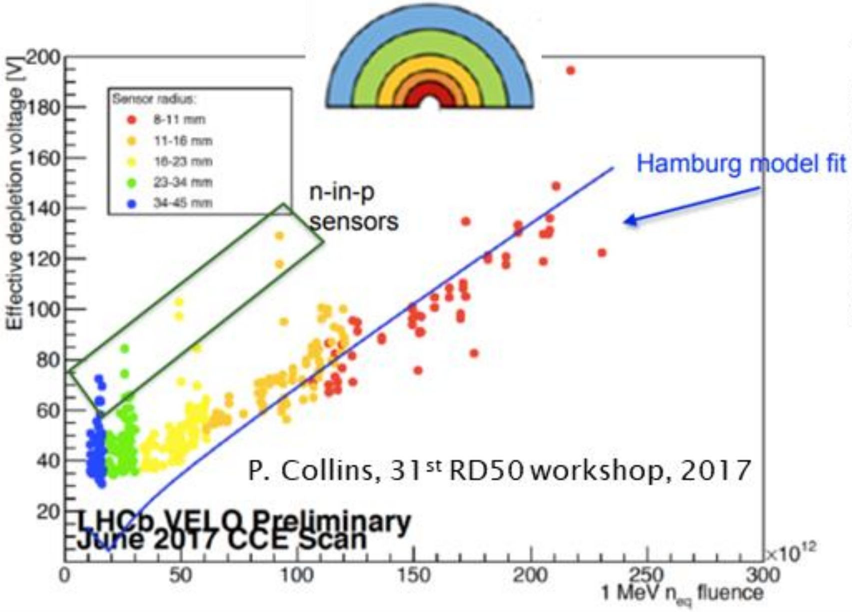
$$\boxed{\alpha = \frac{\Delta I}{V \cdot \Phi_{eq}}}$$



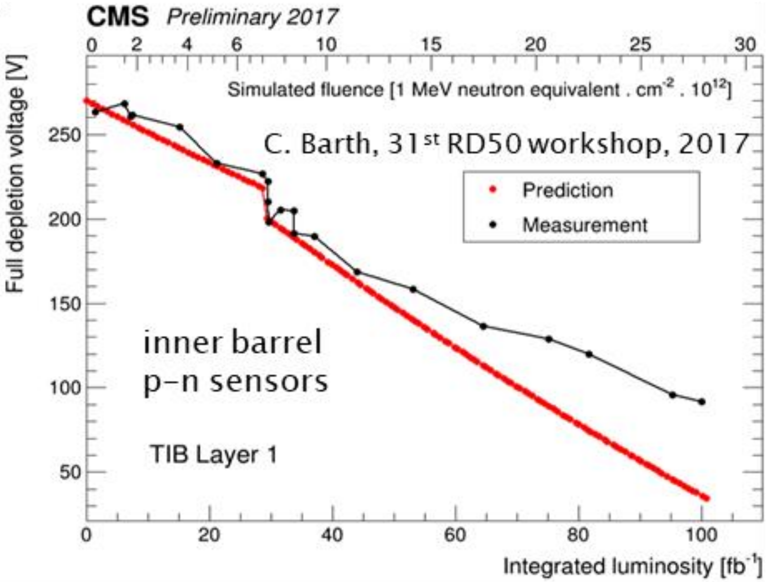
Two tools to reduce it:
- cooling – 2x every 7°C
- annealing

Expectations LHC->HL-LHC

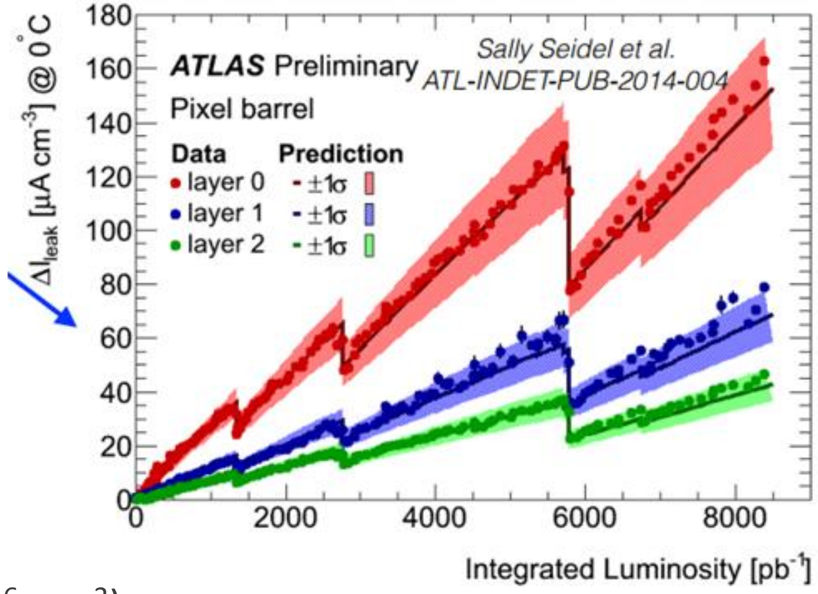
In general Hamburg models works fine at LHC – good agreement for leakage current, Neff and CCE, but



P. Collins, 31st RD50 workshop, 2017



C. Barth, 31st RD50 workshop, 2017



Sally Seidel et al. ATL-INDET-PUB-2014-004

Linear extrapolation from low fluence data for standard float zone detectors ($2 \cdot 10^{16}$ 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: $N_{eff} \approx 4\text{x}10^{14}$ 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 …

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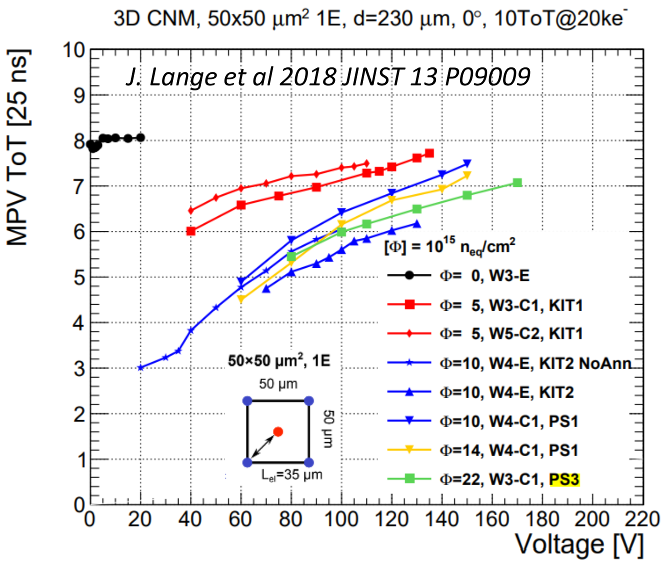
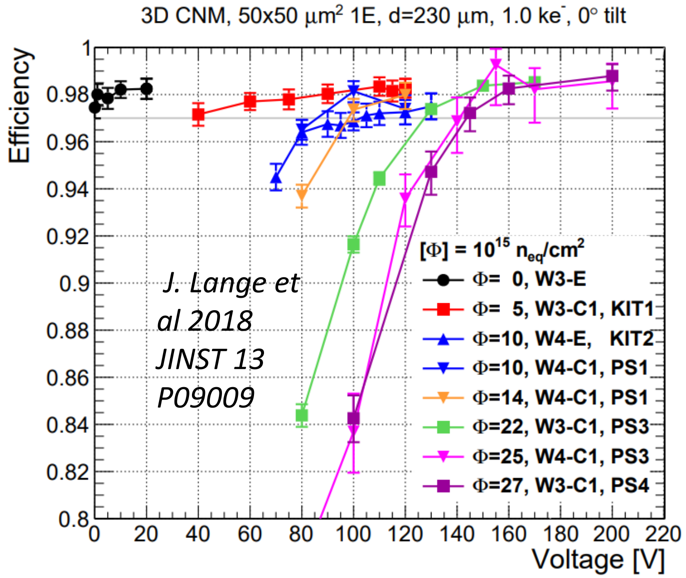
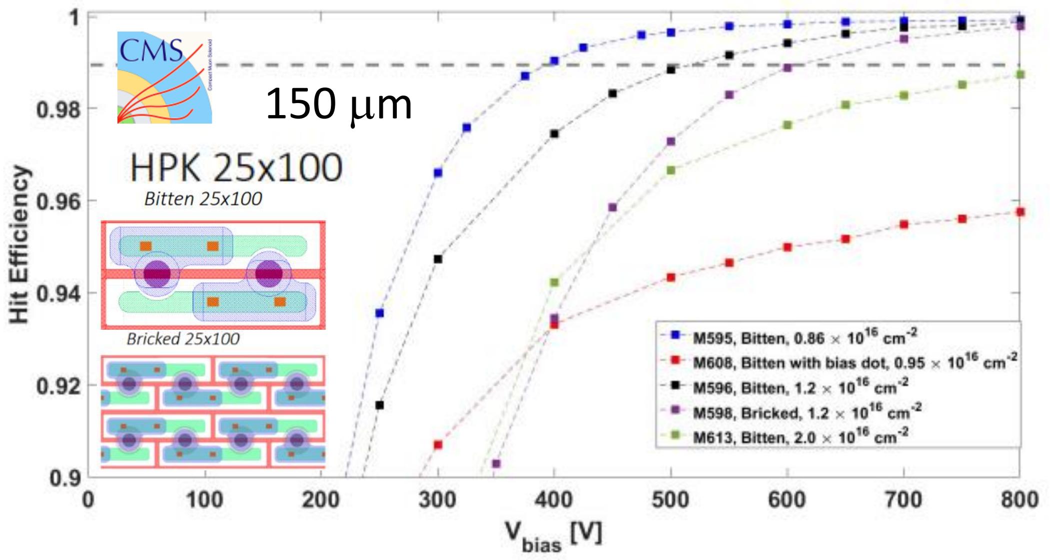
Silicon sensors performance at very high fluences







There are several reasons why the grim projections didn't materialize – the nature was kind to us:

- **trapping probabilities saturate**
- **the electric field is present in the entire device – "active bulk"**
- **charge multiplication**

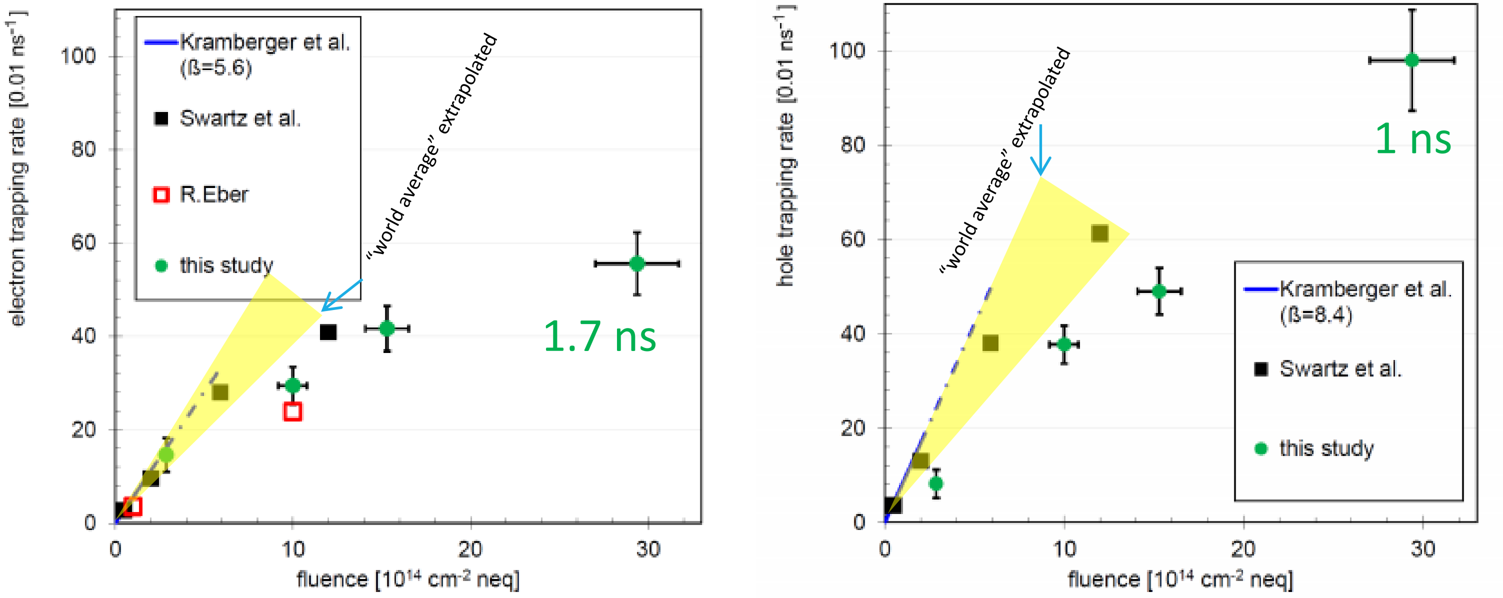
it took us a decade to gain understanding about those effects and we are still learning …

Trapping at high fluences

Trapping gets smaller than extrapolated – nothing is linear everywhere

- defect formation is not linear (2nd order processes?)
- high electric field in a device may influence (de)trapping times which become position dependent

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



$\lambda=\lambda_e+\lambda_h= v_e\tau_e+v_h\tau_h$
$\lambda\sim 250$ μm for
saturated drift
velocities at 3e15 cm^{-2}

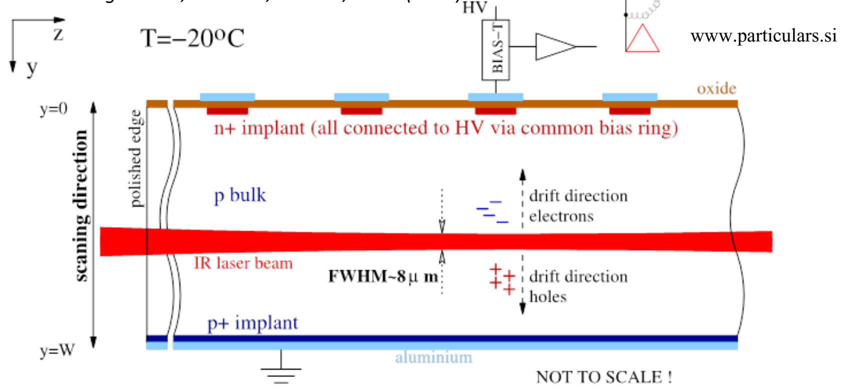
At already 3e15 cm^{-2} the trapping seems to be 3x smaller than projected from lower fluences.
The main obstacle is a direct measurement on the trapping probability with TCT which works only up to few 10^{14} cm^{-2}.

Active bulk

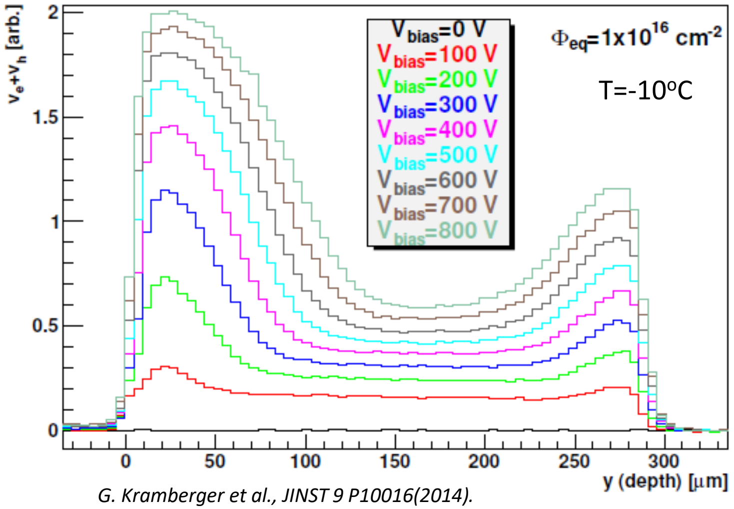
Edge-TCT allows for studies of velocity/charge collection profiles in heavily irradiated sensors

- generation current accumulates, increasing *p* and *n* in opposite directions through SCR – “double junction” – dynamic configuration dependent on temperature annealing time …
- *electron* and *hole* traps, contributing to space charge

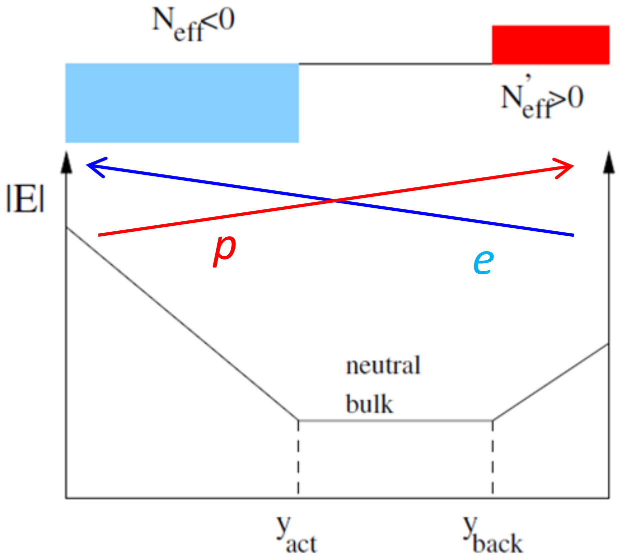
G. Kramberger et al., IEEE TNS, VOL. 57, NO. 4 (2010) 2294.



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.

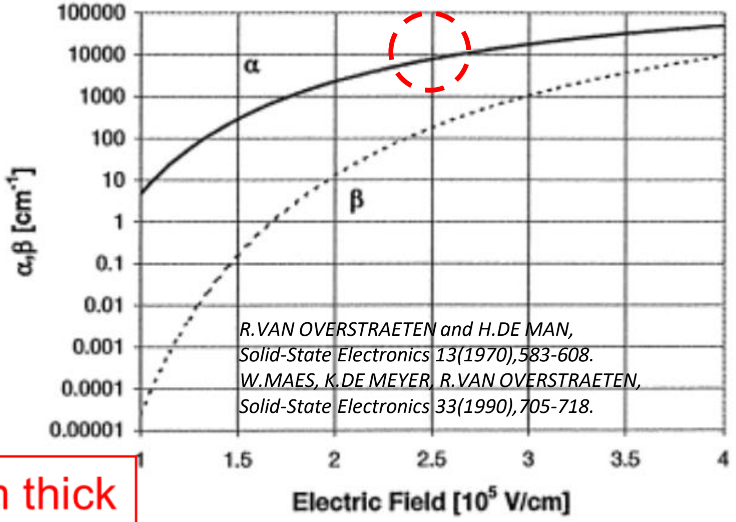
- ➢ whole detector volume is active (velocity in the saddle - 30% of v_{sat})
- ➢ the high field region penetrates deeper in the detector than predicted (saturation of g_c?)

Charge multiplication

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

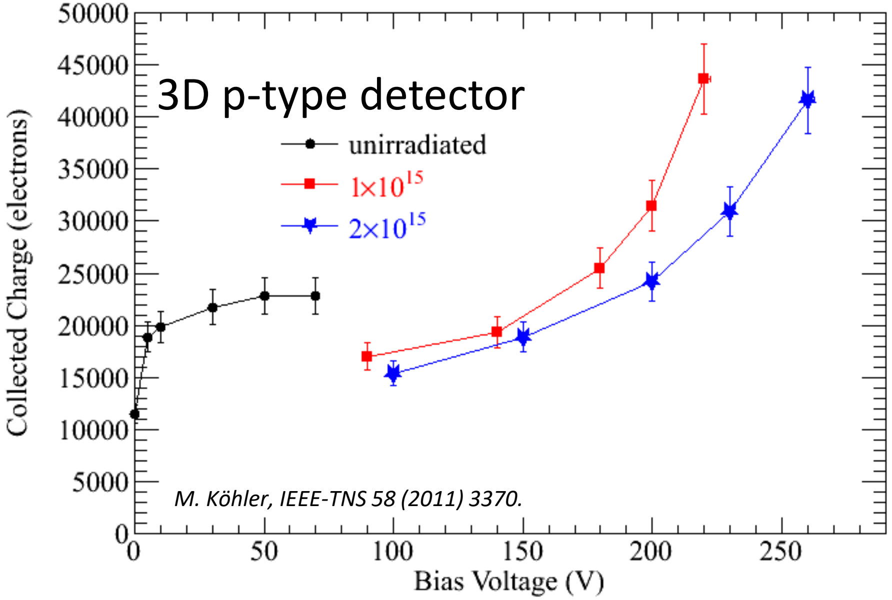
$$dN_e = N_e \cdot \alpha \cdot dx$$

Electrons undergo multiplication in electric fields >25 V/μm

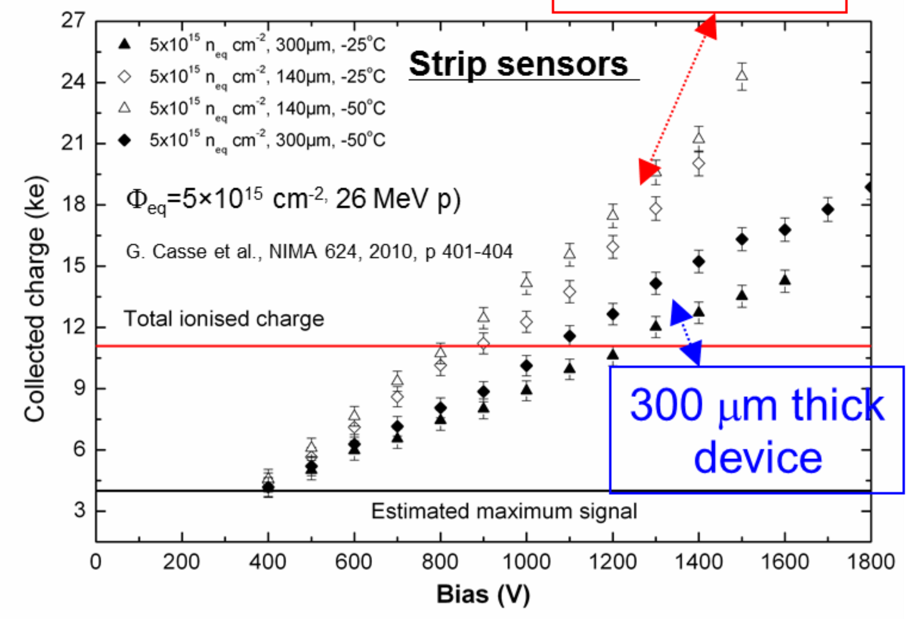


R.VAN OVERSTRAETEN and H.DE MAN, Solid-State Electronics 13(1970),583-608.
W.MAES, K.DE MEYER, R.VAN OVERSTRAETEN, Solid-State Electronics 33(1990),705-718.

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



M. Köhler, IEEE-TNS 58 (2011) 3370.



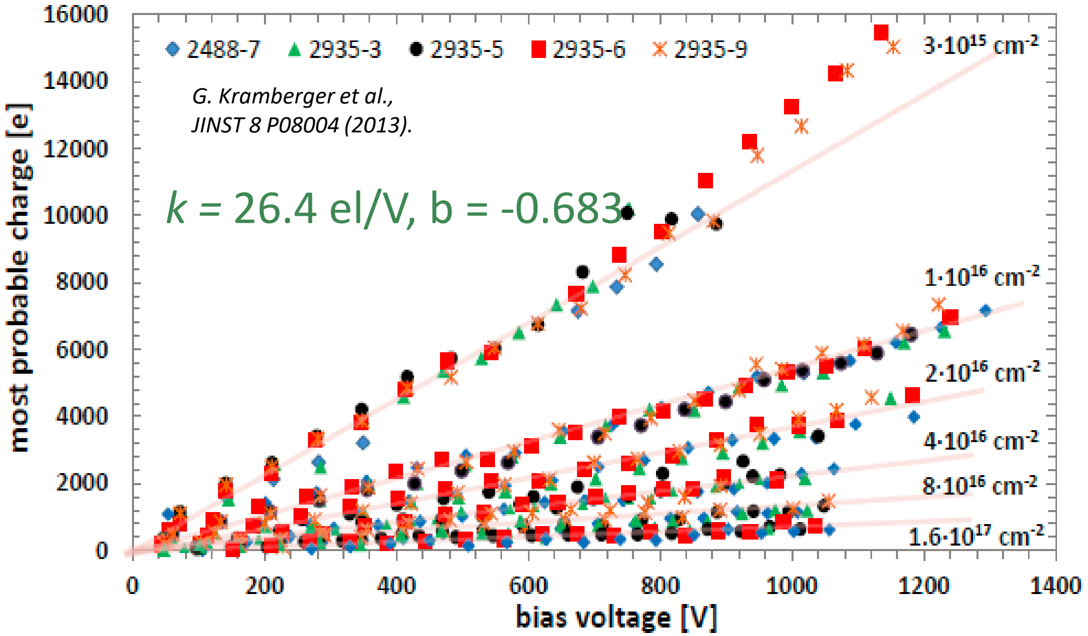
G. Casse et al., NIMA 624, 2010, p 401-404

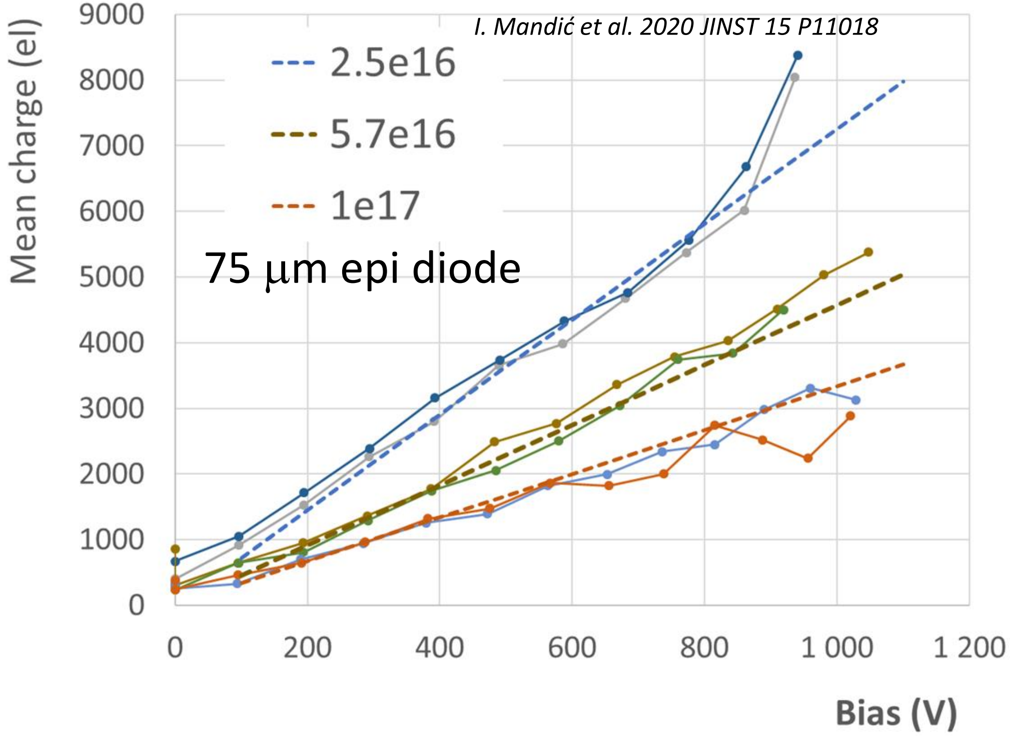
140 μm thick device

300 μm thick device

That behaviour was the trigger for CNM to start LGADs. Implementation of the gain by the process.

Performance at FCC-hh levels ~10^{17} cm^{-2}





Decrease of mobility and saturation of the trapping:

$$\lambda=\lambda_e+\lambda_h= v_e\tau_e+v_h\tau_h \sim (\mu_e\beta_e+\mu_h\beta_h)\cdot V/D\cdot \Phi_{eq}^{\;b}$$

$$\lambda<<D \quad -> \quad Q=\lambda\rho=k\cdot\Phi^b\cdot V$$

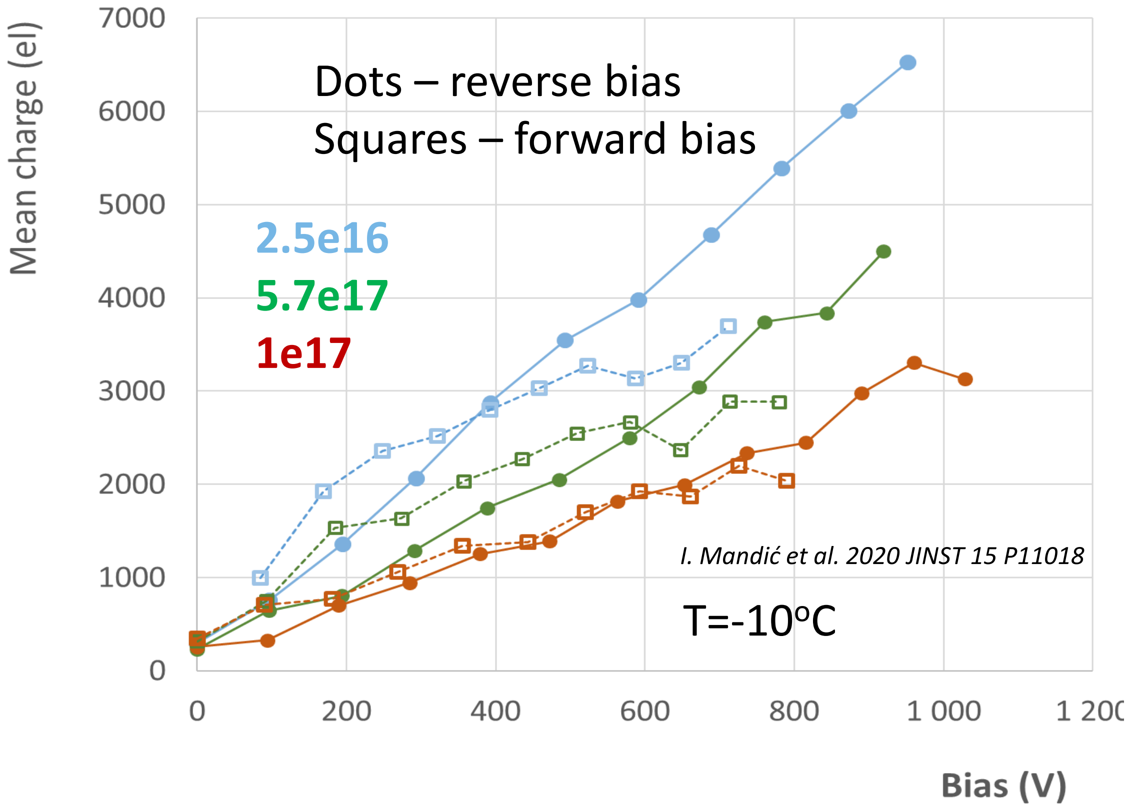
$$\mathbf{Q=k\cdot\Phi^b\cdot V}$$

$$Q_{mean\_75um}=k\cdot\Phi^b\cdot V$$

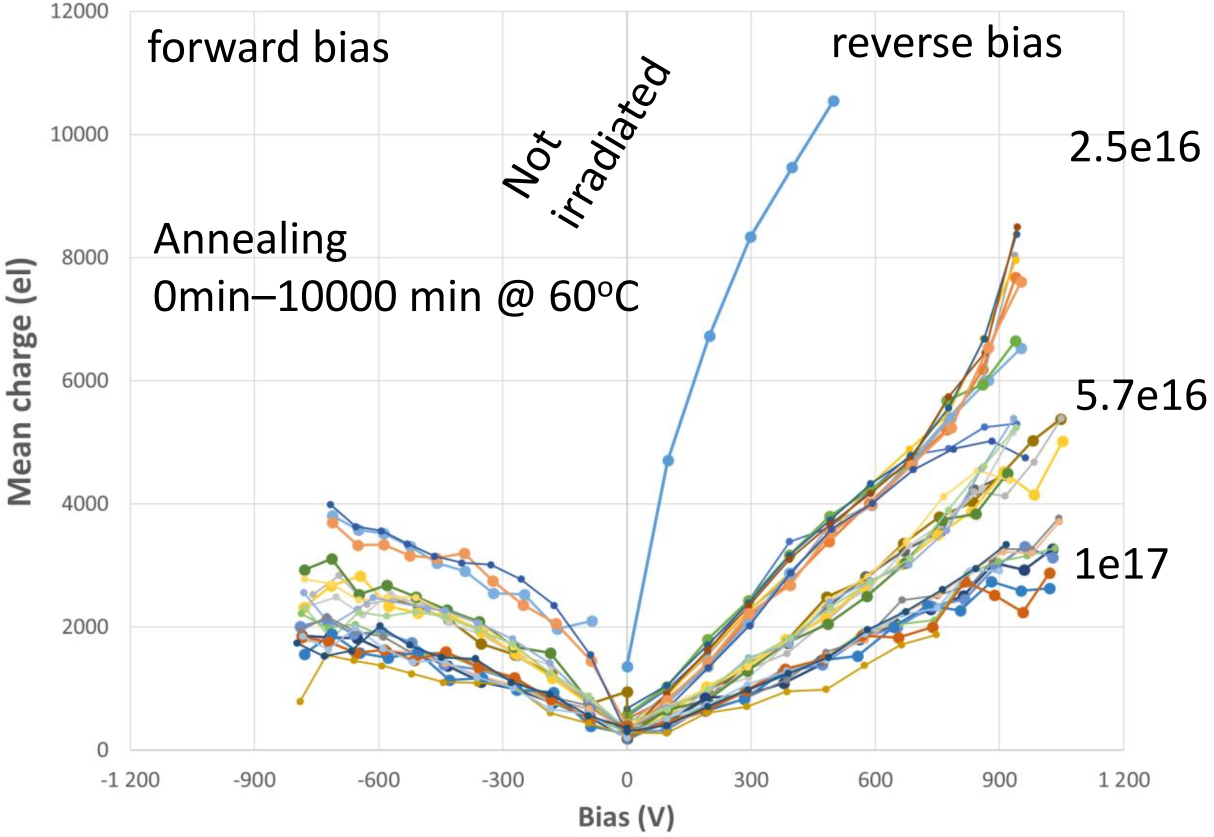
k = 44 el/V, b = -0.56,
(Φ in 1e15 n/cm^2, V in volts)

Signals of several 1000 e!

Forward bias vs Reverse Bias



All measurements, different annealing times

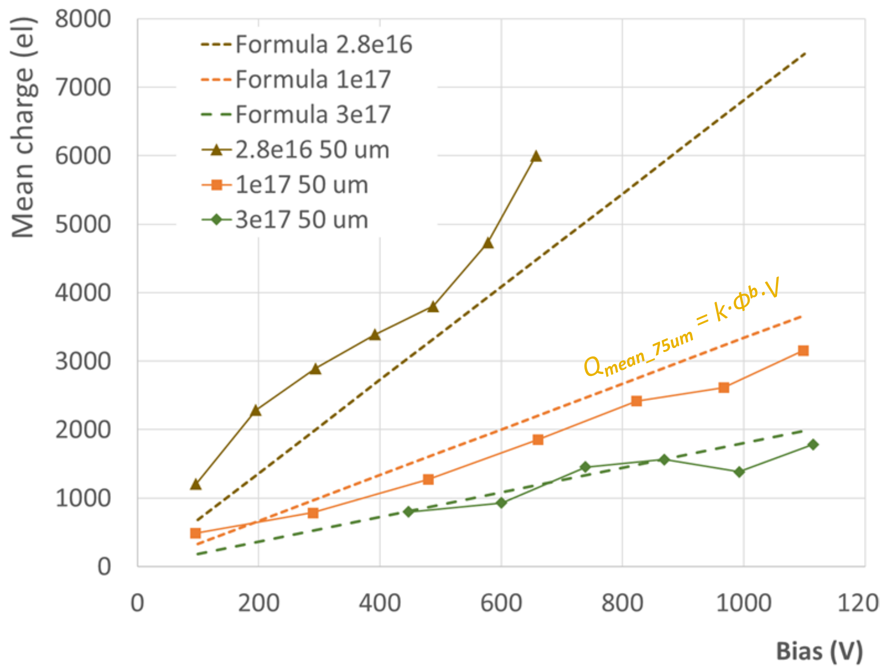


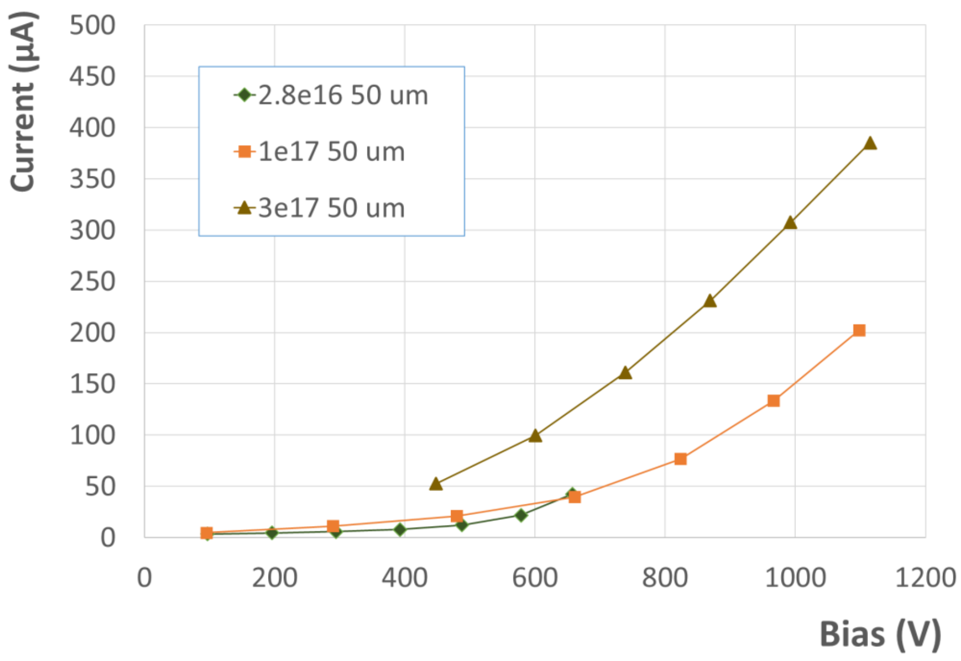
- ➢ the difference in collected charge for forward and reverse bias voltage disappears at high fluences
- ➢ lower current in reverse bias → can go to higher bias voltages and outperforms forward biased samples
- ➢ Annealing of detectors has no effect on operation -> the space charge region is very small

In a certain sense the silicon is becoming easier to work with …. much less parameters to control.

- 50 µm epitaxial LGAD – not LGAD anymore at extreme fluences (see https://indico.cern.ch/event/719814/contributions/3022499)
- Collected charge compatible with 75 µm – devices (small difference in thickness)

more on extreme fluences from Valentina





- The sensors can stand the 1100 V (<22 V/µm>) and are operational – at lower fluences they break down much earlier! Clearly impact ionization heavily affected by high fluences -> **its understanding is one of the main goals for future R&D**
- Does **Single Event Burnout** (destructive breakdown of thin sensors due to high energy deposits) affect the performance in the same way as at low fluences (*see G. Medin's talk in this session*)

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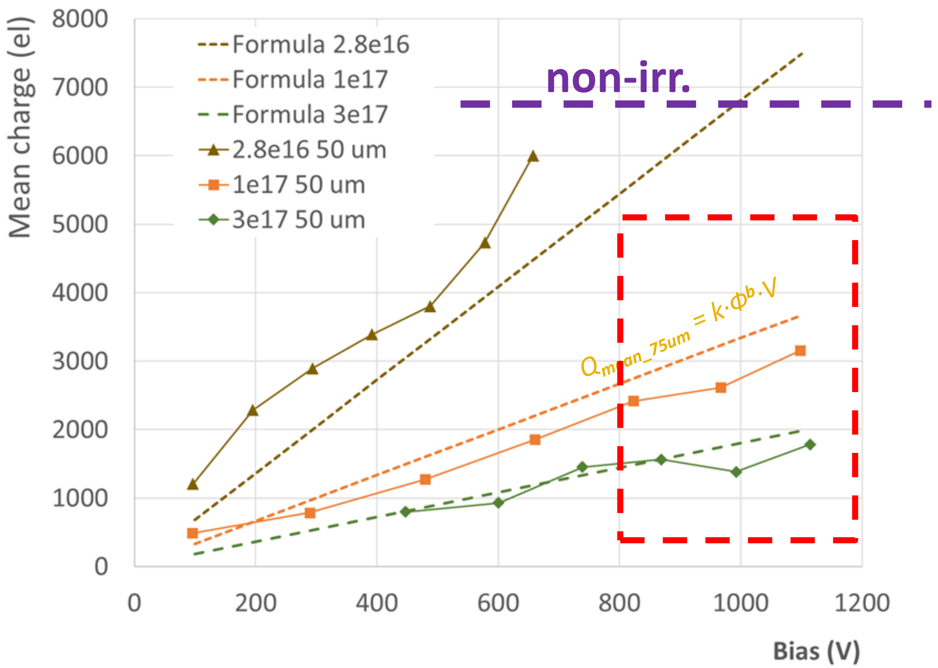

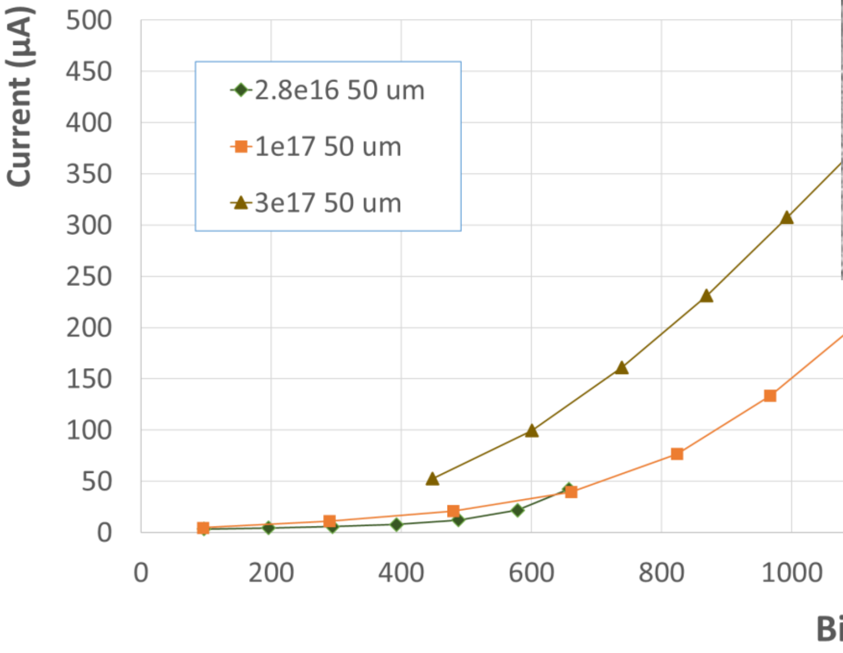

burn mark in the CNM sensor after ATLAS TB in 2018 after the test beam – dimensions are few tens μm ("crater" photo taken by CNM)

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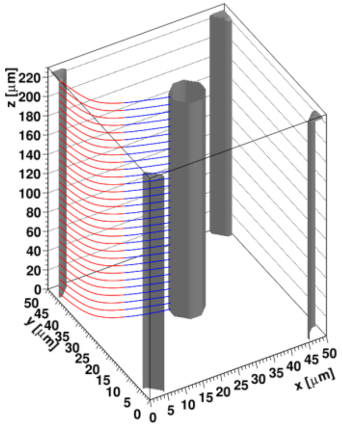
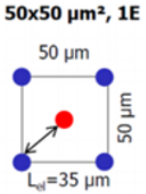
Operation of 3D sensors at ~10^{17} cm^{-2}

Simulation with known damage parameters



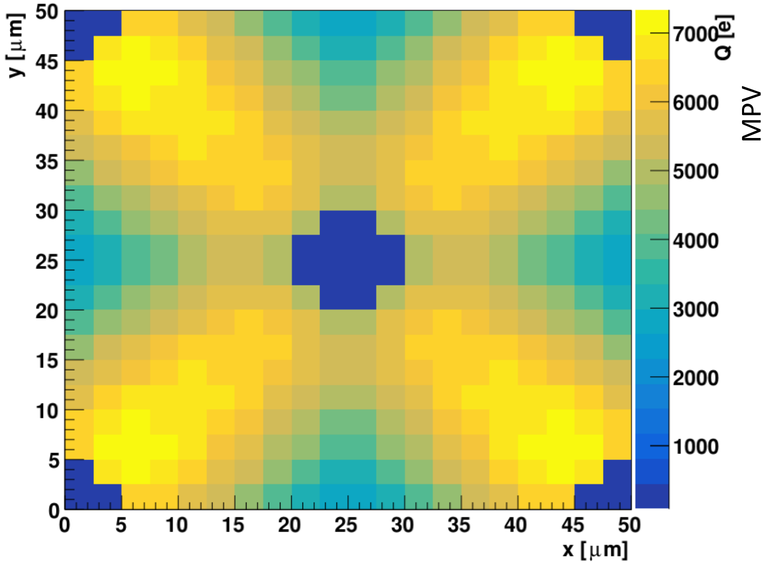


$\Phi_{eq}=10^{17}$ cm^{-2}

200 V, -20°C, 0°

$N_{eff}=1.5\cdot 10^{14}$ cm^{-3}

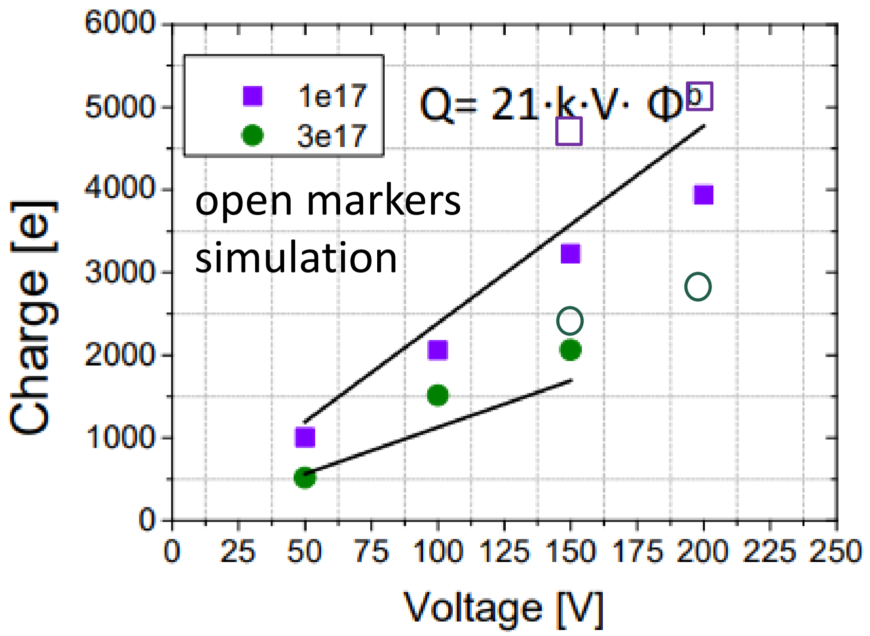
$\tau_{eff,e}=\tau_{eff,h}=100$ ps



KDetSim.org

Measurements of 3D - Strip sensors irradiated to FCC-hh fluences using TCT/Alibava/CCE setups

M. Manna et al., NIMA 979 (2020) 164458.
M. Manna et al., 35th RD50 workshop,2019



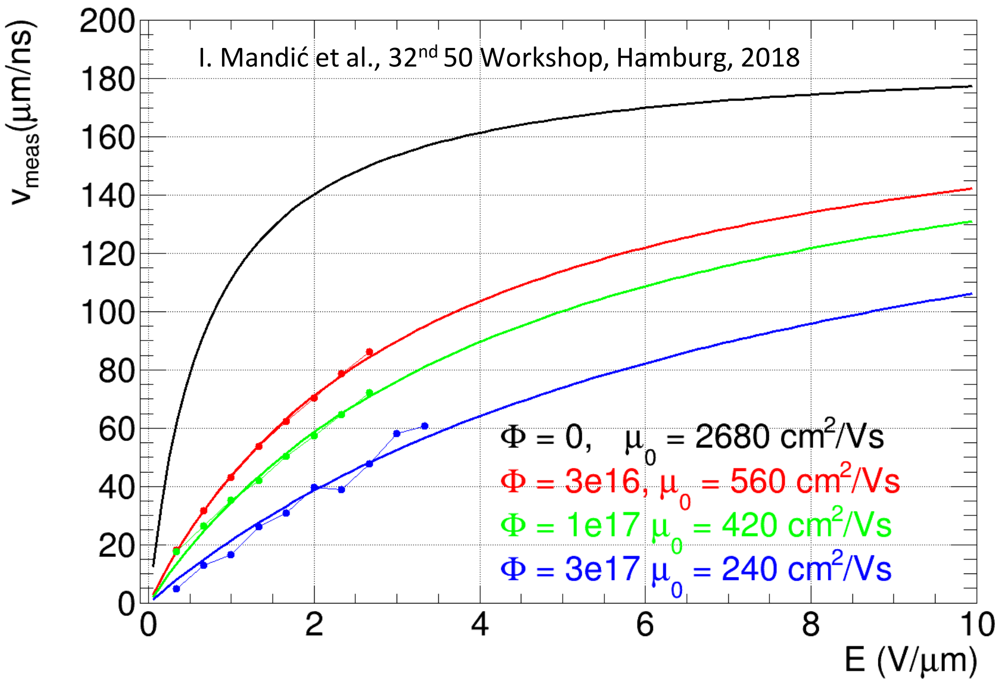
open markers simulation

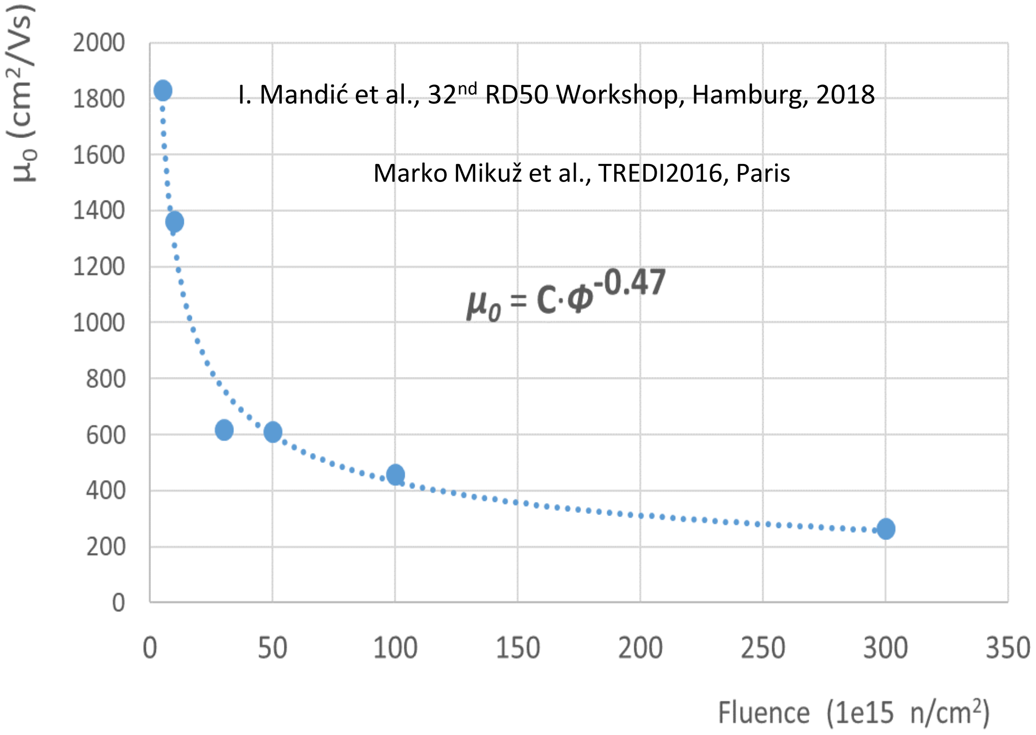
Signals around few 1000 e !

- Simulation and measurements are roughly compatible
- It seems that for 3D sensors the radiation damage at $\Phi_{eq}>10^{17}$ cm^{-2} is not too severe!
- A great benefit of much smaller voltages required – avoiding the danger of operation close to the breakdown.

Mobility at extreme fluences

Edge-TCT measurements in forward bias allow extraction of mobility – actually sum of mobilities





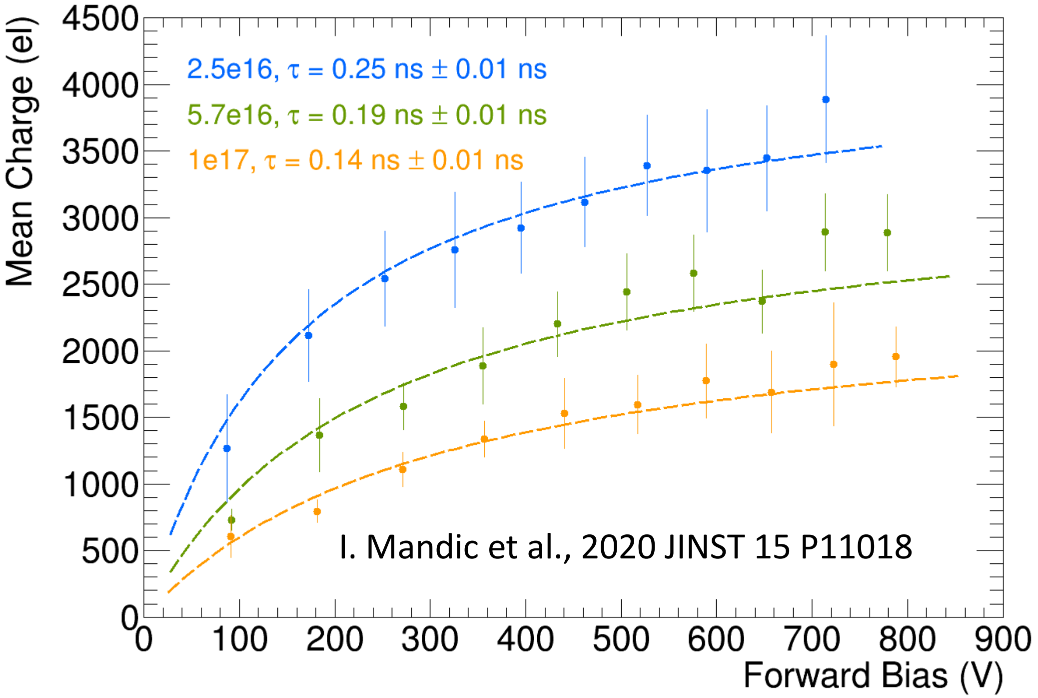
Silicon becomes much "slower" at lower fields, but the saturation velocity is assumed to be the same:

- Larger bias voltages required (linear dependence of collected charge on bias voltage)
- Higher resistivity due to lower mobility

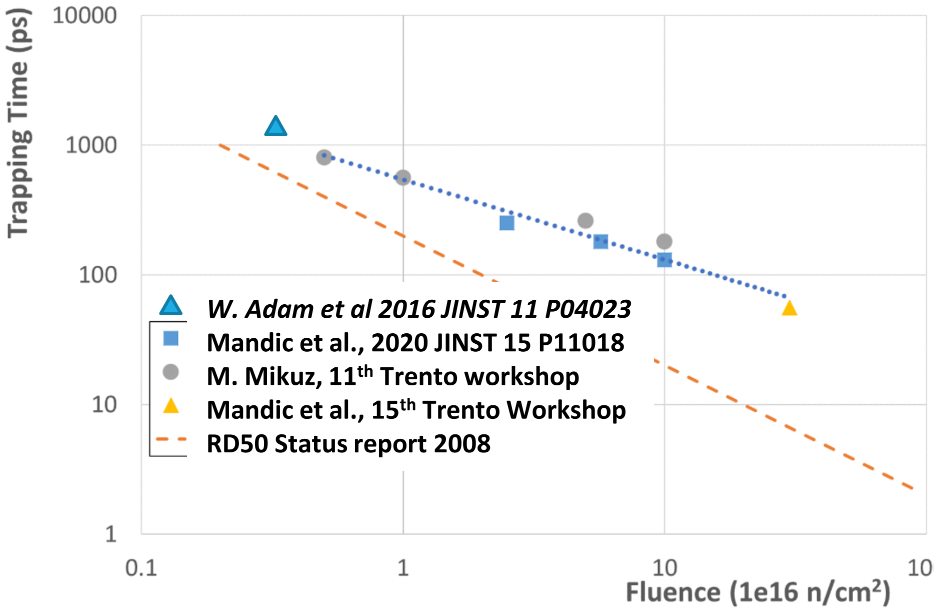
Trapping times at extreme fluences

Trapping time estimated from fit of Charge vs. fluence

- forward bias, use approximation: $E = V/D$
- fluence dependent mobility $\mu_0 = \mu_0(\Phi)$



I. Mandic et al., 2020 JINST 15 P11018



Extrapolation: $\tau[\mathrm{ps}] = 200\cdot\Phi^{-1}$

This work: $\tau[\mathrm{ps}] = 540\cdot\Phi^{-0.62}$ (Φ in [1e16 n/cm²])

value close to the one obtained under reverse bias from charge collection dependence on bias voltage

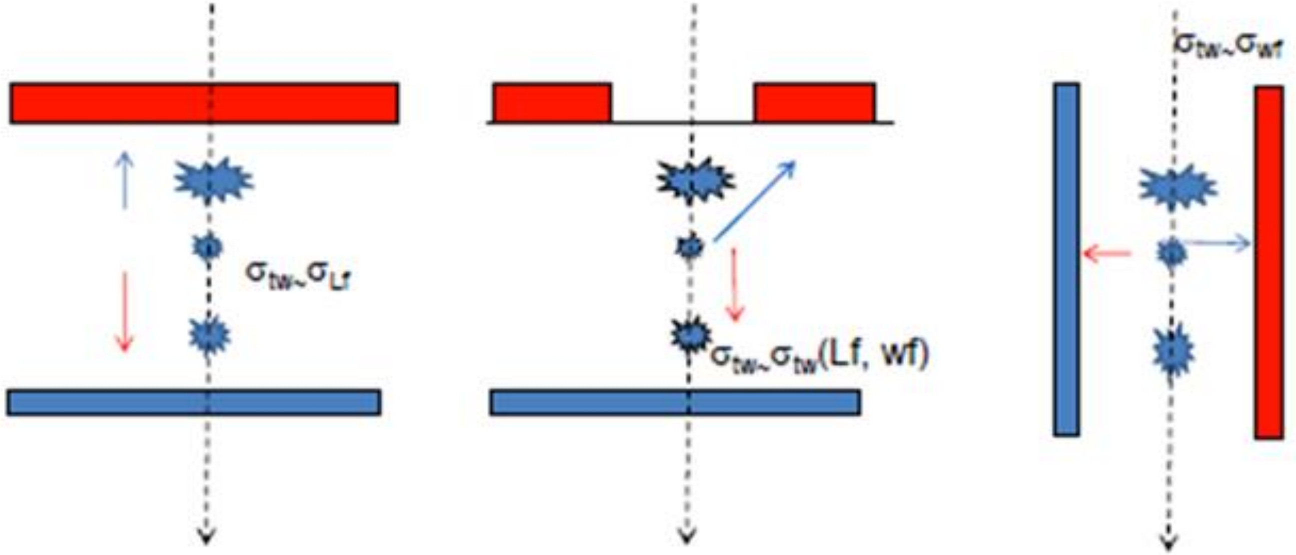
… but our life is more complicating in 4D

The problem at any silicon detector is that the signal is small, but our requirements are even more demanding – we want to measure the precise timing with them, < 30 ps

$$\boxed{\sigma_j = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|} \approx \frac{\sigma_n}{\left|\frac{S}{\tau_p}\right|} = \frac{\tau_p}{S/N}}$$

$$\boxed{\sigma_{tw}^2 = \sigma_{wf}^2 + \sigma_{lf}^2} + \cancel{\sigma_Q^2}$$

CFD or ToA/ToT compensation



Effectively the time resolution is usually dominated by one component:

- ➢ Landau fluctuations in LGADs
- ➢ Weighting field/distortion in 3D

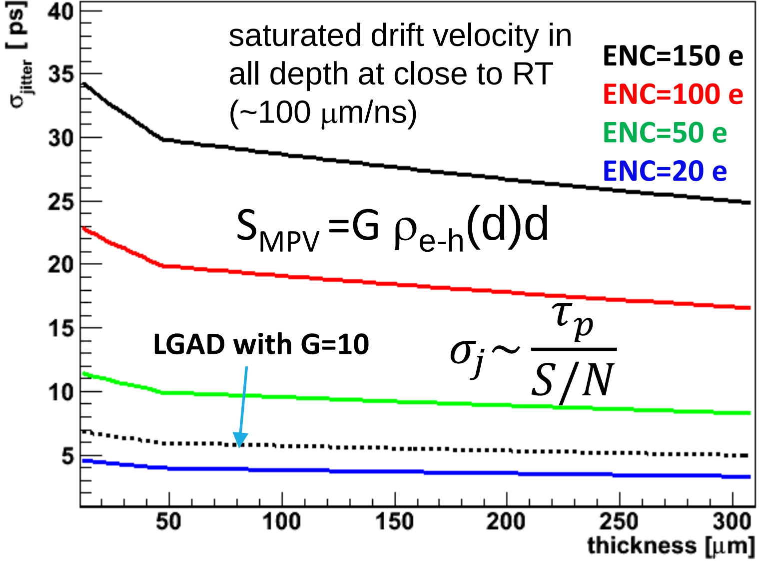
Planar sensors at extreme fluences

**NA62, NIM A958 (2020) 162127*
***ATLAS HGTD TDR*

In order for the planar sensors to fulfil the requirement high gain in very thin sensors would be required!

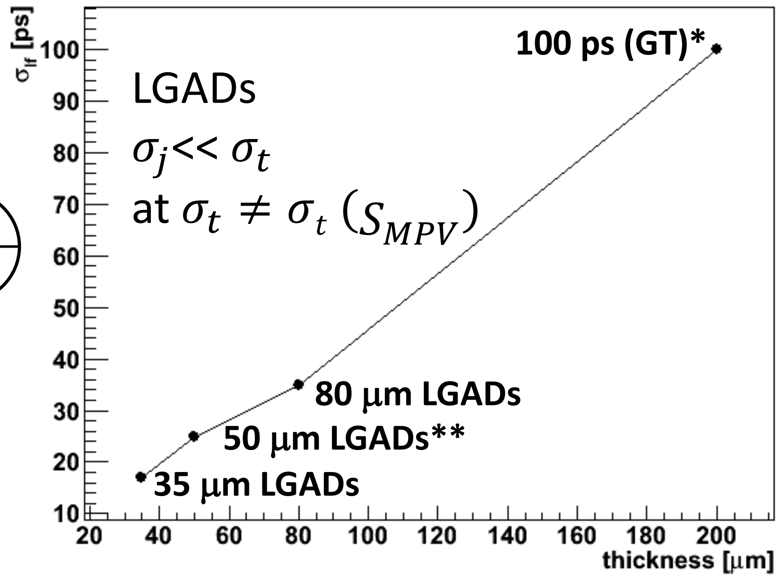
(see V. Sola's talk)

σ_j - Jitter (τ_p= $t_{collection}$)



$\oplus$

σ_{lf} - Landau fluctuations

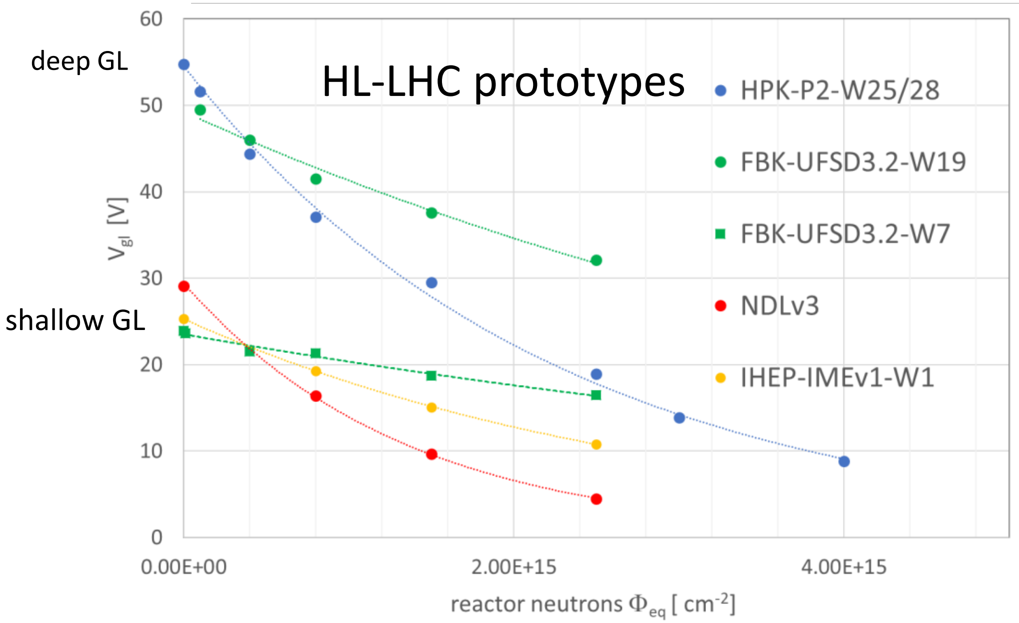


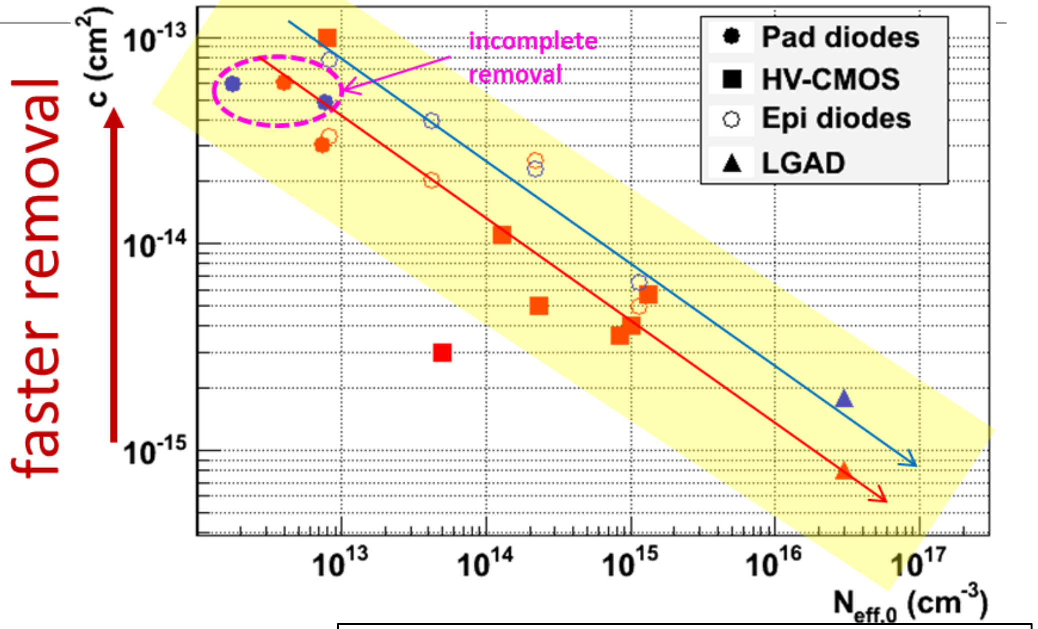
$\oplus$ **σ_{wf}** (segmentation pitch/thickness) $\approx$ **~10 ps** is (almost?) impossible in Si planar technology

~1000 e in 50 μm detector at 1000 V
$t_{collection}$~dominated by trapping ~0.5 ns

We need gain or/and extremely low noise – very difficult to see how now!
(speed requires power and that is hardly not a option)

Solving the problem of acceptor removal





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

higher resistivity

- Acceptor removal is a problem for LGADs – reduction of gain
  - can we introduce/find mechanism to suppress the acceptor removal so that increase of required bias would used to compensate impact ionization
  - C-infusion in GL improves the situation, but the use is still limited to 3e15 cm^{-2}
  - Can we replace B with something else that is much more resilient (RD50 projects Al, In…) – we know Ga is not any better.

- Can we rely on deep levels that will give rise to the gain (see V. Sola’s talk) after the gain layer doping is lost at extreme fluences
  - lots of unknowns simply because all the silicon parameters is difficult to measure
  - The problem with deep defects is that their occupation is a strong function of free carrier concentration – quenching of gain

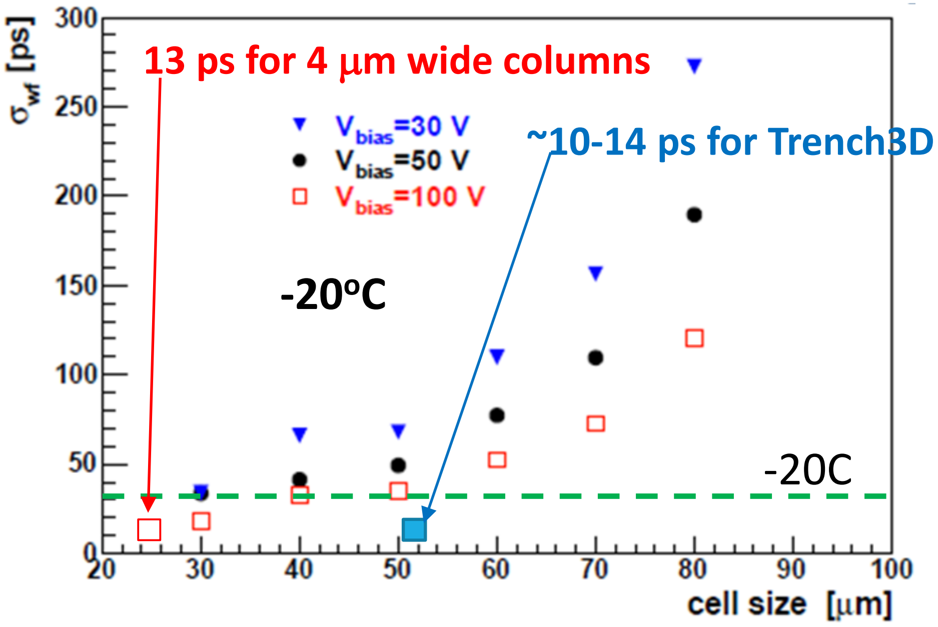
3D – detectors

see Nicolo Cartiglia's talk

There are two approaches taken so far:

- Column 3D detectors (different patterns)
- Trench 3D detectors *(web.infn.it/timespot/)*

Inclined tracks – cell size/thickness problem !

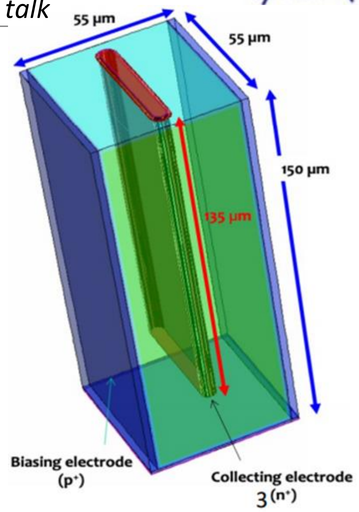


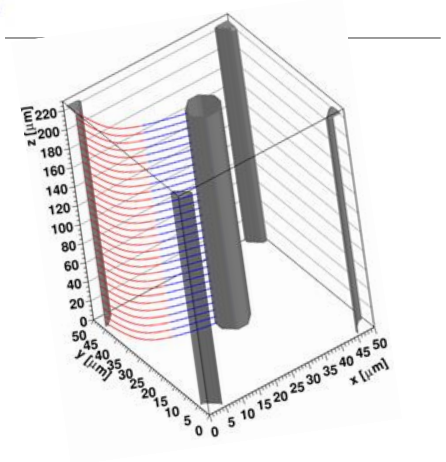
13 ps for 4 µm wide columns

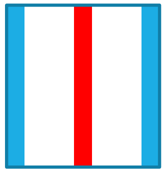
~10-14 ps for Trench3D

-20°C

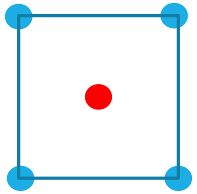
-20C







not fully efficient for all φ at θ≠0



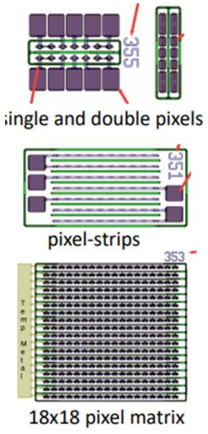
fully efficient at θ≠0

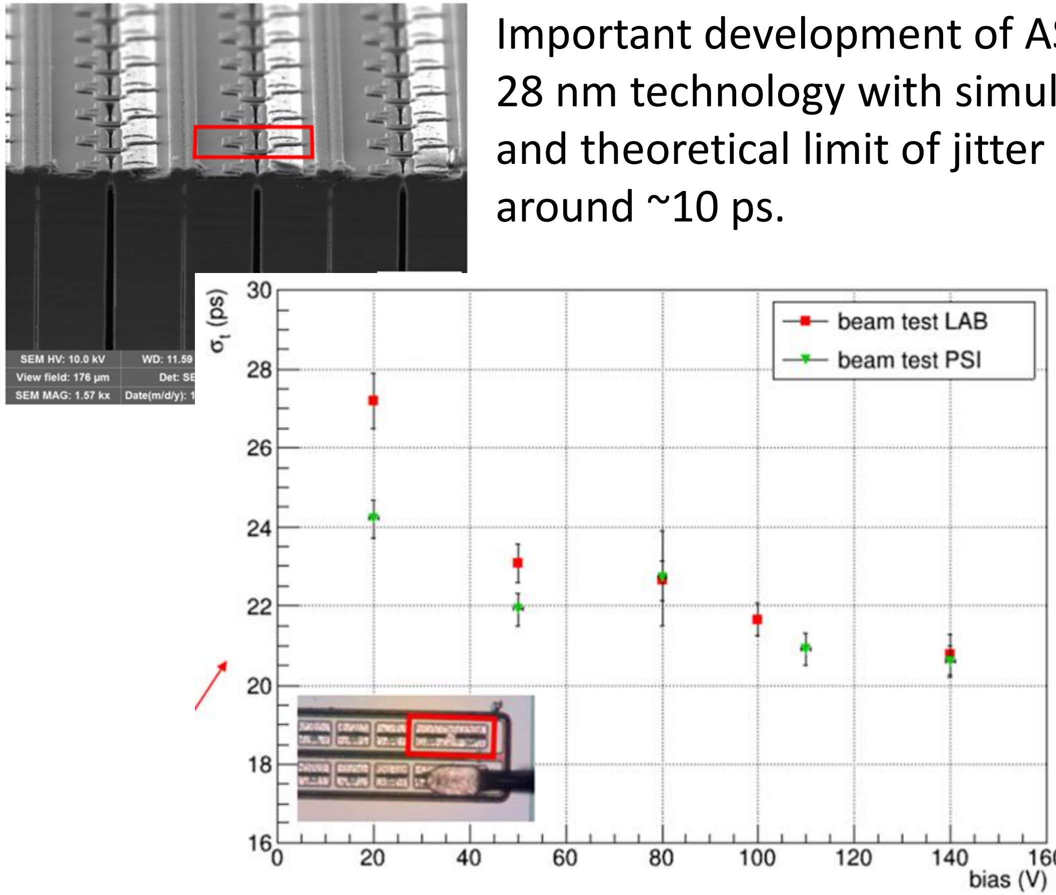
	Trench 3D	**Column 3D**
σ_{wf}	✓ (theoretical limit)	X (requires smaller cell)
Capacitance (σ_j)	X	✓ (a factor of ~2 better)
Fill factor	X (not for all φ at θ≠0)	✓
rise time(speed)	✓ (shorter drift)	X

3D – detectors

- **55x55 µm²** pixels
- **150 µm** active thickness
- Collection electrode **135 µm** deep

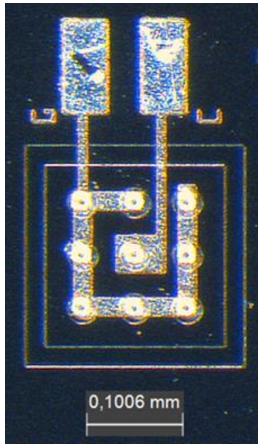
TimeSPOT

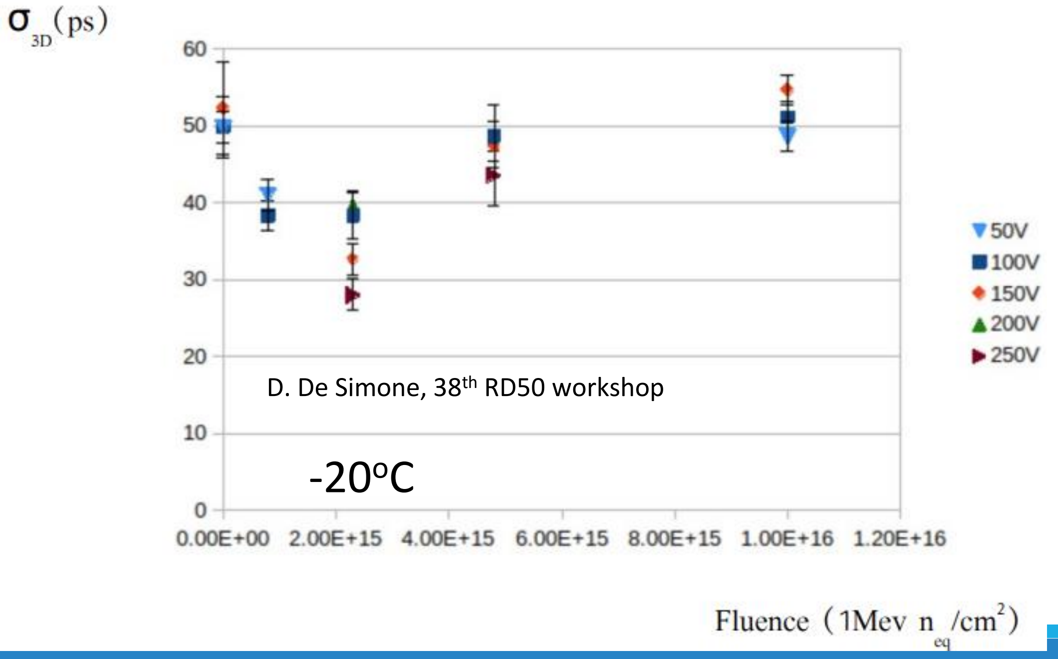




Important development of ASIC in 28 nm technology with simulated and theoretical limit of jitter around ~10 ps.

50x50 μm² pixel
285 μm thick
CNM – 3D detector



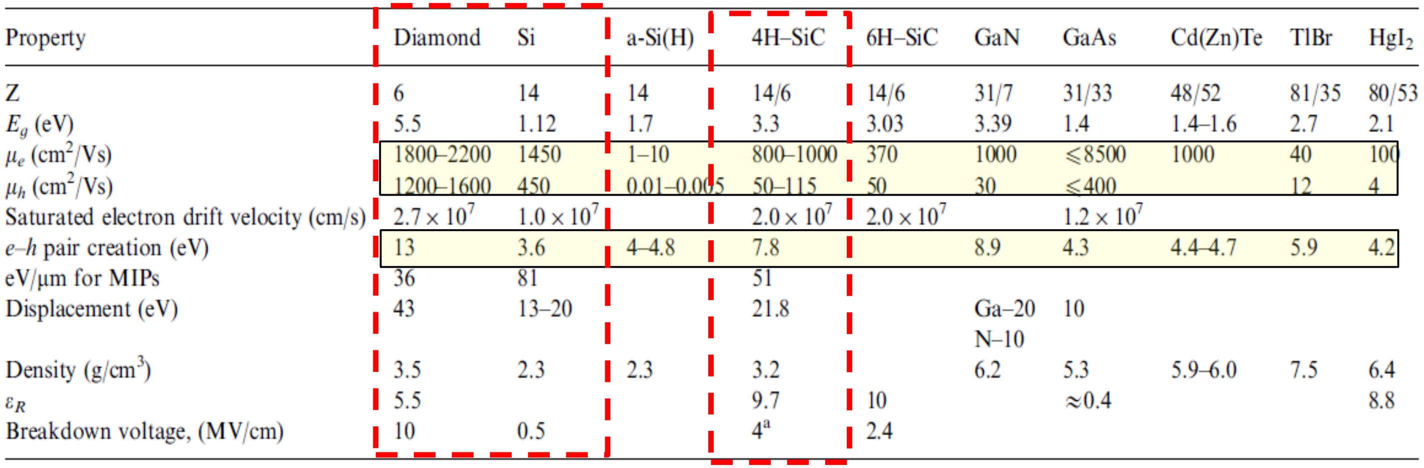


D. De Simone, 38th RD50 workshop

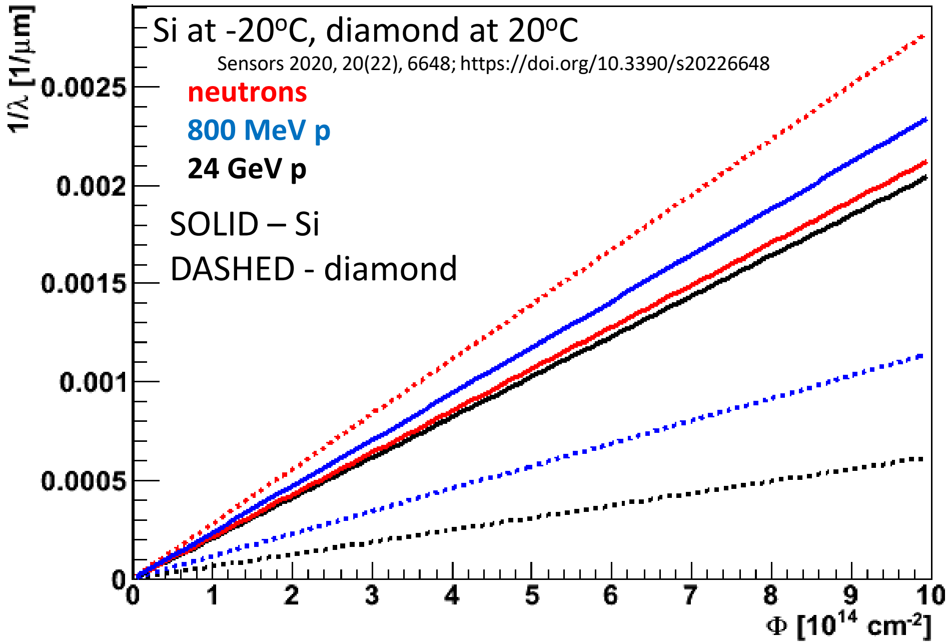
-20°C

What about other materials?

- For extreme fluences and tracking (4D) applications diamond and SiC are next to silicon regarding the required speed
- SiC was tested in early days of RD50 and was shown not to outperform silicon, but progress has been made recently
- Radiation hardness of diamond is on par with silicon in λ(Φ):
  - Less generated charge by factor of three requires thicker material
  - thicker material adversely affects the timing applications
  - Impact ionization is difficult to achieve (similar impact ionization for e and h) and requires extreme fields



Property	Diamond	Si	a-Si(H)	4H–SiC	6H–SiC	GaN	GaAs	Cd(Zn)Te	TlBr	HgI_2
Z	6	14	14	14/6	14/6	31/7	31/33	48/52	81/35	80/53
E_g (eV)	5.5	1.12	1.7	3.3	3.03	3.39	1.4	1.4–1.6	2.7	2.1
μ_e (cm^2/Vs)	1800–2200	1450	1–10	800–1000	370	1000	⩽8500	1000	40	100
μ_h (cm^2/Vs)	1200–1600	450	0.01–0.005	50–115	50	30	⩽400		12	4
Saturated electron drift velocity (cm/s)	2.7×10^7	1.0×10^7		2.0×10^7	2.0×10^7		1.2×10^7			
e–h pair creation (eV)	13	3.6	4–4.8	7.8		8.9	4.3	4.4–4.7	5.9	4.2
eV/μm for MIPs	36	81		51						
Displacement (eV)	43	13–20		21.8		Ga–20 N–10	10			
Density (g/cm^3)	3.5	2.3	2.3	3.2		6.2	5.3	5.9–6.0	7.5	6.4
ε_R	5.5			9.7	10		≈0.4			8.8
Breakdown voltage, (MV/cm)	10	0.5		4^a	2.4					



Diamond sensors at extreme fluences

$$\frac{ccd}{t} = \sum_{i=e,h} \frac{\lambda_i}{t} \left[1 - \frac{\lambda_i}{t} \left(1 - \exp\left(-\frac{t}{\lambda_i} \right) \right) \right]$$

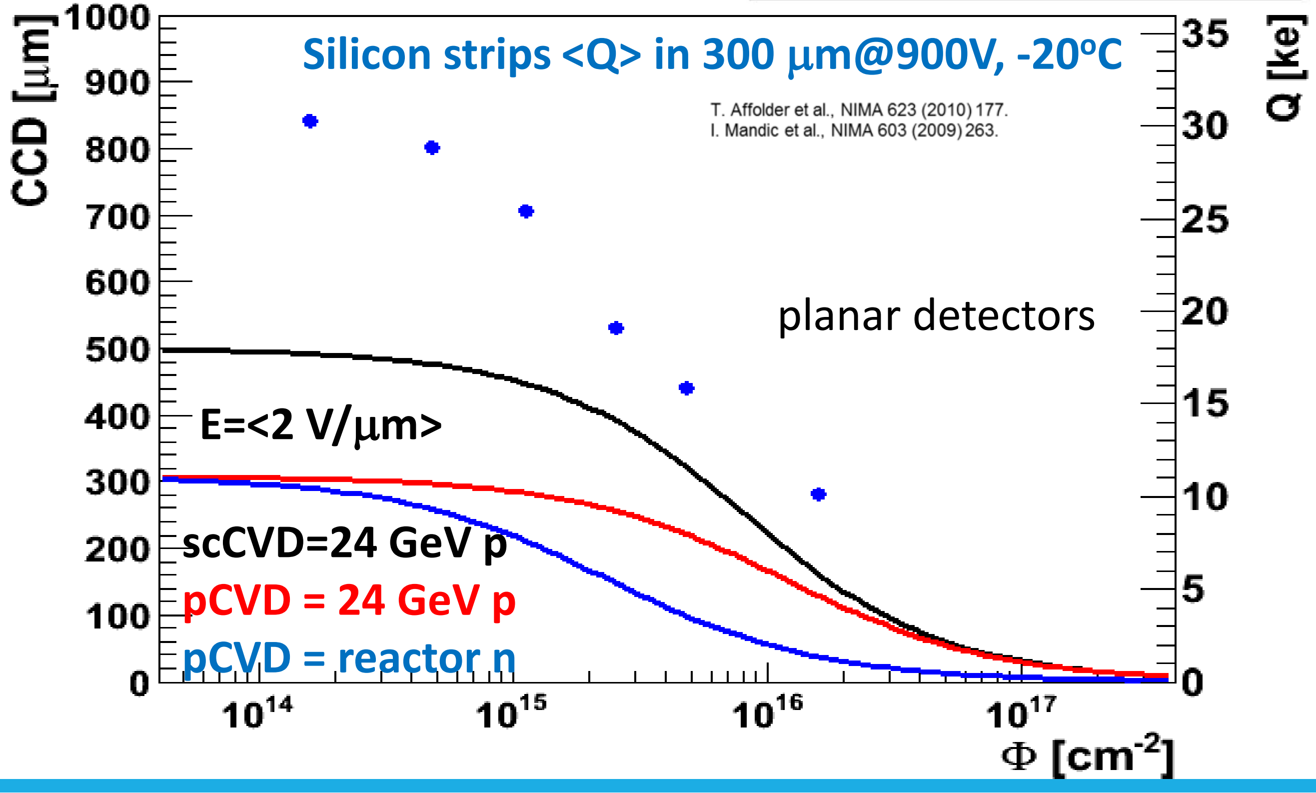
$$n = n_0 + k'\phi$$

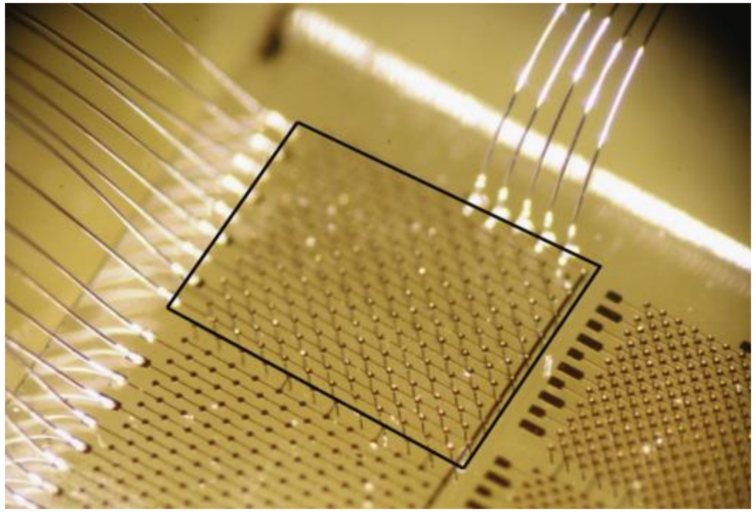
$$\frac{1}{\lambda} = \frac{1}{\lambda_0} + k\phi$$

t	thickness
n	number of traps
n_0	initial traps in material
ϕ	fluence
λ	schubweg
λ_0	initial schubweg
k	damage constant

RD42 - Nucl. Instr. & Methods A924 (2019) p. 241

Particle species	κ
24 GeV protons	1.0
800 MeV protons	1.67 ± 0.09
70 MeV protons	2.48 ± 0.25
Fast neutrons	4.5 ± 0.4





F.Bachmair et al., Nucl. Instr. and Meth. A786 (2015) 97.

3D diamond detectors are a very promising detectors considering lower capacitance, very narrow electrodes, no leakage current, but scalability, cost, availability …

Conclusions

- Silicon is far more resilient material than we imagined and will likely remain the material of choice
  - the damage exhibits saturation and is not as severe as projected from lower “LHC” fluences
  - gain due to radiation induced space charge
  - “active bulk”
- Small cell size 3D devices were shown to work with ASICs up to ~3e16 cm^{-2} and planar pixel detectors up to 2e16 cm^{-2}
- Measurements of charge show few 1000 e even as high as 3e17 cm^{-2} although for timing applications the required performance will be extremely difficult to achieve – it is still early days … clearly matching electronics will be at least equal if not much bigger challenge
- It is crucial to understand all the fundamental properties of heavily irradiated silicon – main R&D for the future (mobilities, trapping, recombination, impact ionization ….)
- New ideas will be important and may become possible and/or mature over the years:
  - “Marriage” of LGADs and 3D (either by trench filling, careful substrate selection with small interelectrode distance allowing charge multiplication without special processing of gain layer)
  - “Marriage” of CMOS and 3D.

NOTHING IS
IMPOSSIBLE,
THE WORD
ITSELF SAYS
“I’M POSSIBLE”!
- AUDREY HEPBURN