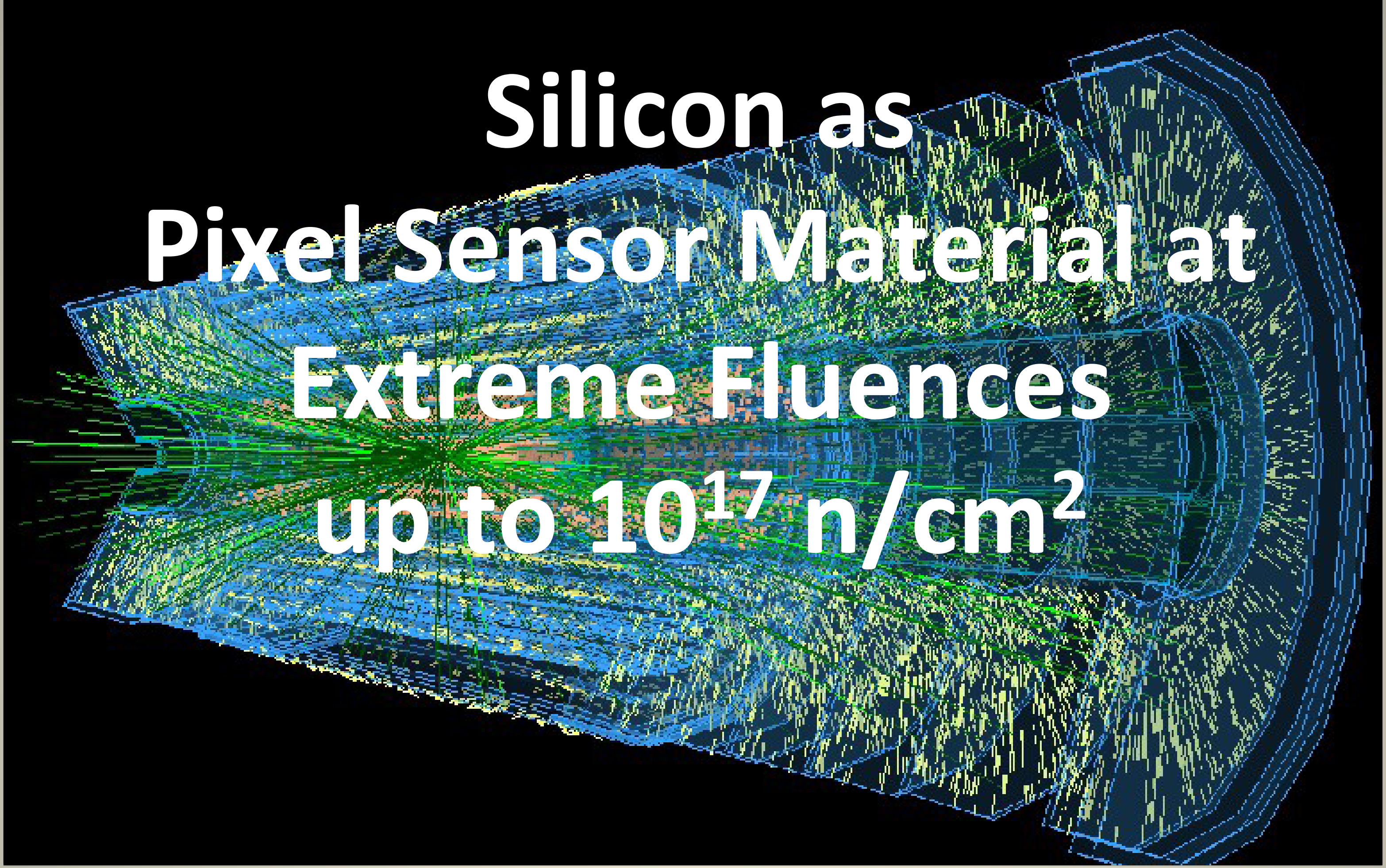
Silicon as Pixel Sensor Material at Extreme Fluences up to 10^{17} n/cm^2



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Pixel 2014, Niagara Falls
September 4th, 2014

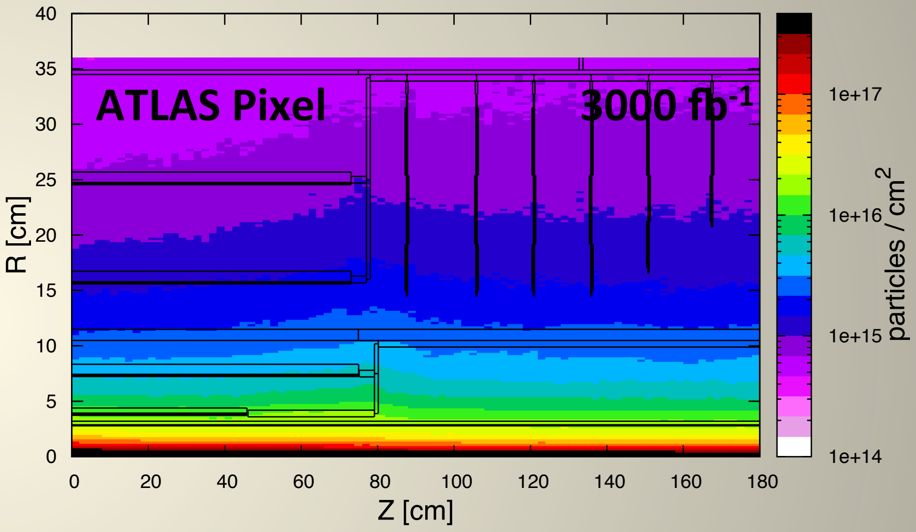
The Ljubljana Team

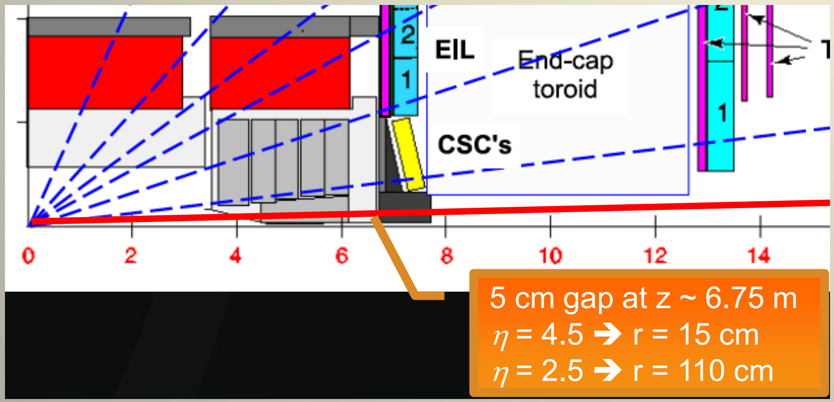
- Those who did all the work:
  - Vladimir Cindro
  - Gregor Kramberger
  - Igor Mandić
  - Marko Zavrtanik
- A big thanks to them !

Why the 10^{17} Ballpark ?

- Run1 at LHC finished, 2&3 in sight
  - Designed for 730 fb^{-1} of 14 TeV pp collisions, ~30 fb^{-1} in Run1
  - Will probably get ~½ of planned
- HL-LHC in advanced planning
  - 3000 fb^{-1} i.e. ~10xLHC
  - ~10^{16} n_{eq}/cm^2 for pixels (pions)
  - n$\times 10^{16}$ n_{eq}/cm^2 for vFW pixels (π & n)
  - ~10^{17} n_{eq}/cm^2 for FCAL (neutrons)
- Can (tracking) sensors survive in these extreme environments ?

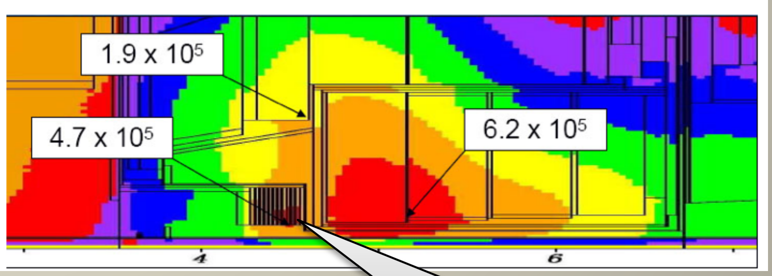
1 MeV neutron equivalent fluence





5 cm gap at z ~ 6.75 m
η = 4.5 ➔ r = 15 cm
η = 2.5 ➔ r = 110 cm

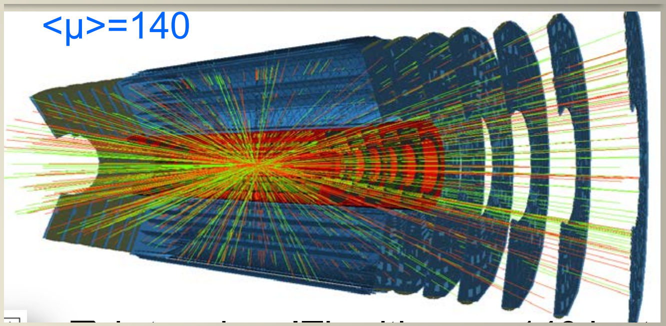
ATLAS FCAL **3000 fb^{-1}**

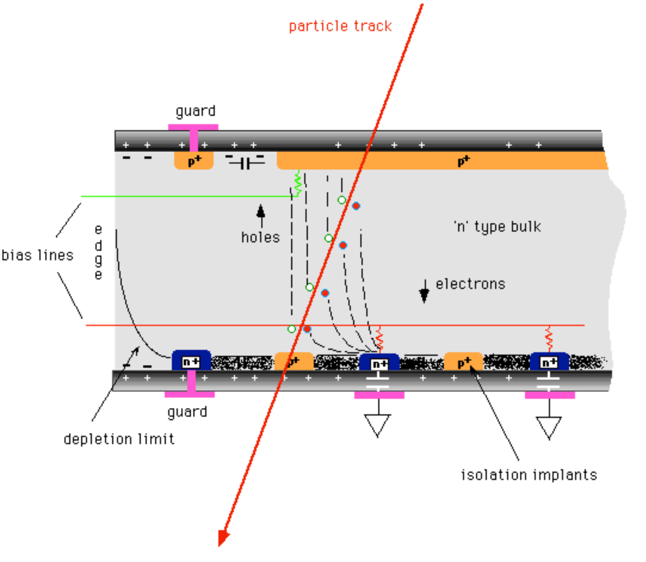


1.5×10^{17} n/cm^2

Tracking sensors

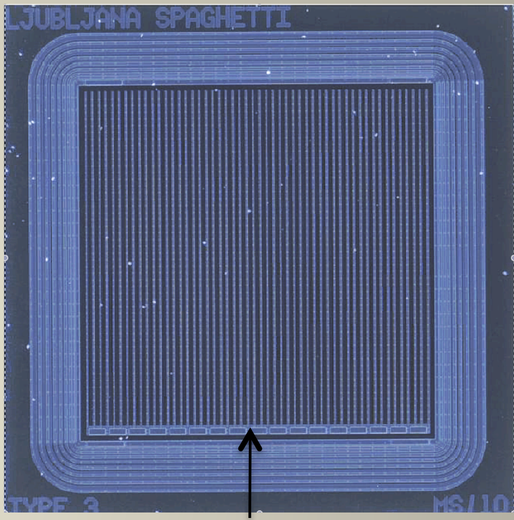
- Convert charged particle ionization into measurable electrical signal
- Sensor segmentation provides position info
  - 2-D: strips, 3-D: pixels
  - Resolution *d/√(12)* (binary) or better (analogue - charge division)
- Tracking: many layers, keep occupancy < 1 %
- Considerations
  - Signal to (electronics) noise, threshold
    - Radiation hardness
  - Manufacturability
    - Large scale production
  - Engineering (electrical, thermal, mechanical)
    - Material budget
  - Price
- Paradigm might change for FCAL
  - Jet reco: multiple hits/segment, no real tracking...





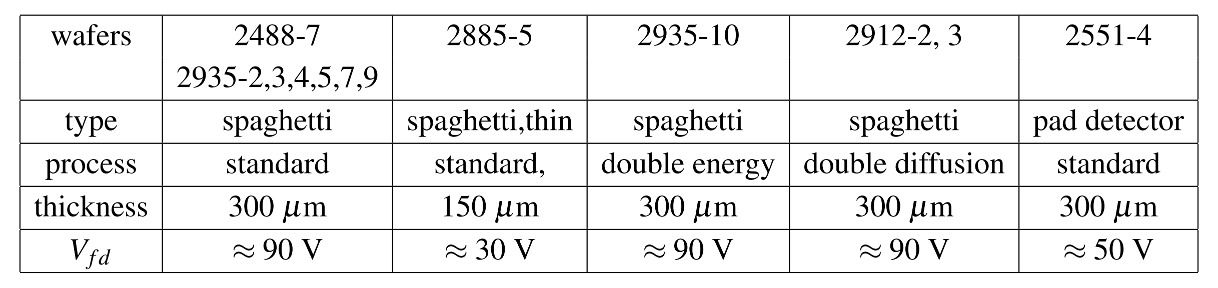
How far can we go with Si?

- Special run of “spaghetti” diodes to address this
  - All strips connected to one readout
  - Strip electric field, equal weighting field (~pad)
  - Different implants (double diffusion, energy)
- Irradiated with reactor neutrons in steps
  - 3, 10×10^{15} –> 5 samples annealed
  - 2, 4, 8×10^{16}, 1.6×10^{17} n_{eq}/cm^2 – 6 standard samples
- *I(V)*, *Q_{MP}(V)* and noise on ^{90}Sr set-up at -25°C
  - Trigger purity allows measurements at low *S/N*

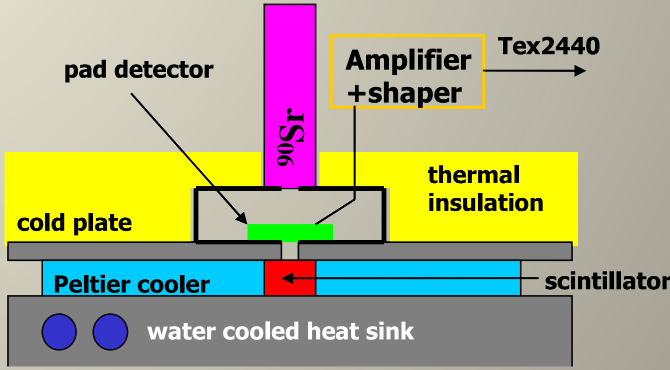


ganged strips

Published in : **G. Kramberger et al., *JINST 8 P08004 (2013)*.**

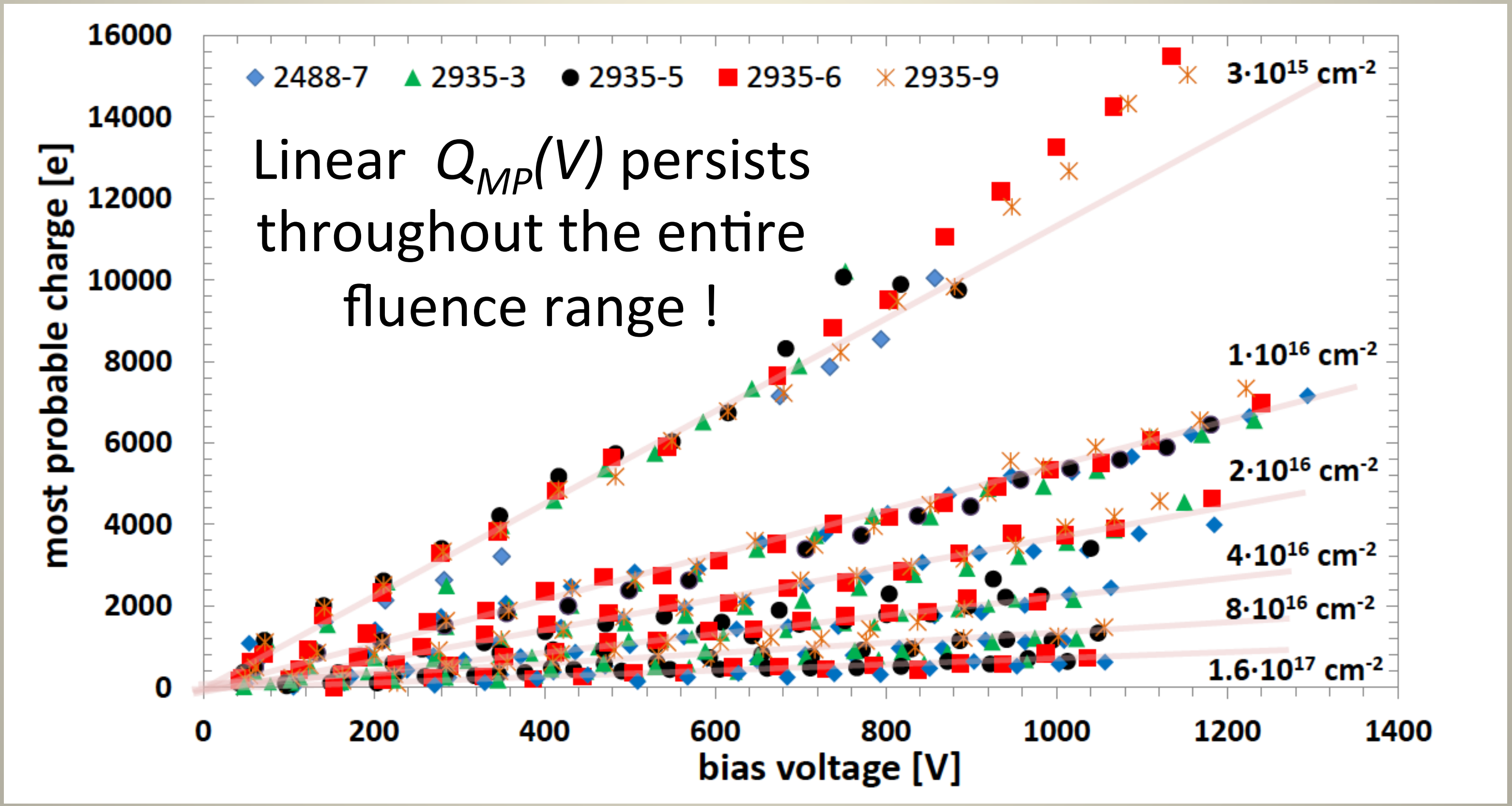


wafers	2488-7 2935-2,3,4,5,7,9	2885-5	2935-10	2912-2, 3	2551-4
type	spaghetti	spaghetti,thin	spaghetti	spaghetti	pad detector
process	standard	standard,	double energy	double diffusion	standard
thickness	300 μm	150 μm	300 μm	300 μm	300 μm
V_{fd}	≈ 90 V	≈ 30 V	≈ 90 V	≈ 90 V	≈ 50 V



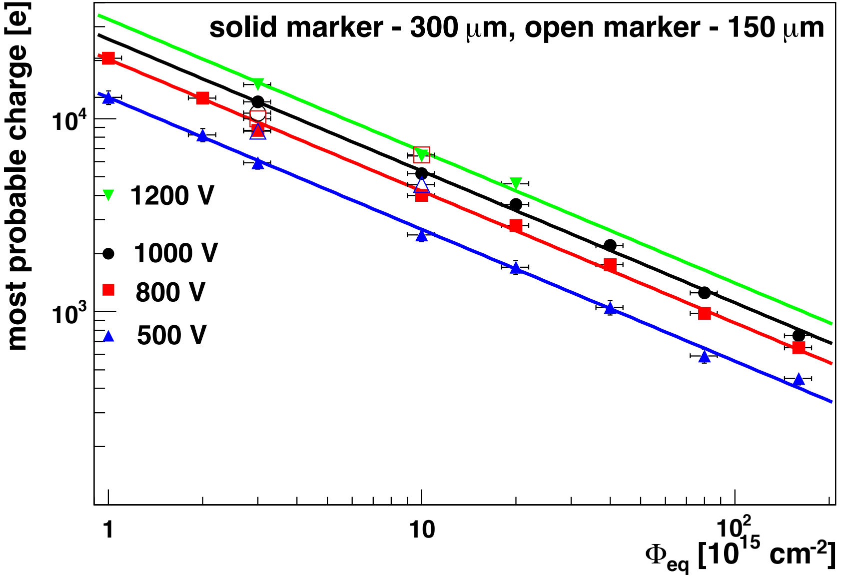
Silicon is still alive!

- Up to 1.6x10^{17} n$_{eq}$/cm^2, steps 1, 2, 4, 8x10^{16}
  - Annealing 80 mins @ 60°C between steps



Linear $Q_{MP}(V)$ persists throughout the entire fluence range !

The Magic Formula



- Linear relationship $Q_{MP}(V)$
  - Same slope in log(Q_{MP}) vs. log(Φ) for any V
  - Magic formula

$$Q_{MP}(\Phi,V) = k\cdot\left(\Phi/10^{15}\,\mathrm{n_{eq}}/\mathrm{cm}^2\right)^{b}\cdot V$$

$$k = 26.4\ \mathrm{e_0/V}$$
$$b = -0.683$$

- "Magic" – no underlying physics… in fact lots of it
  - Mix of depletion, trapping and charge multiplication

Note on Weighting Field

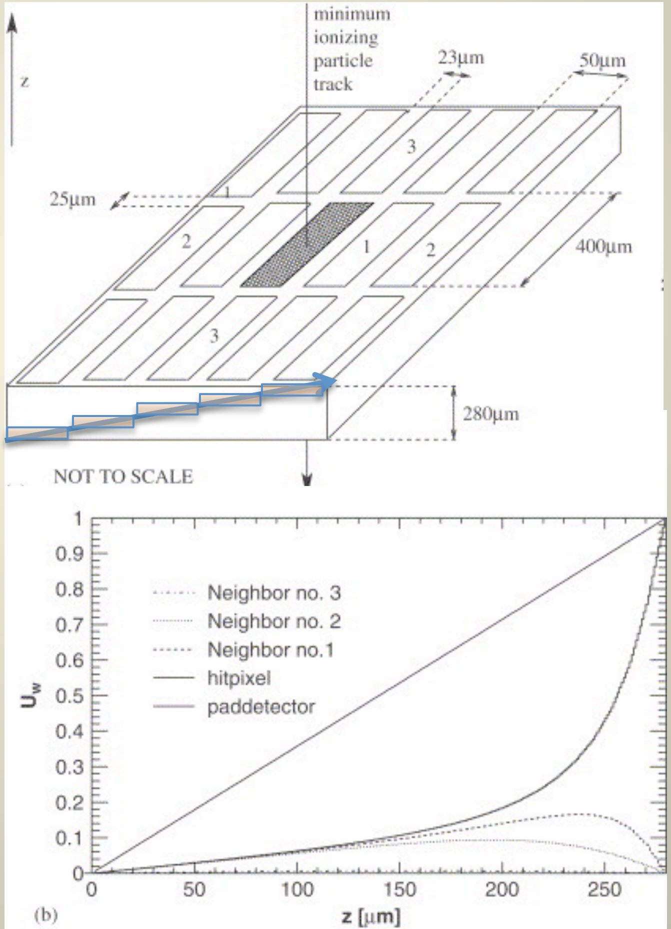
- Weighting field sharply peaked at pixels (3-D!)
- Will affect signal when *$v.\tau_{eff} << d$*
  - $v_{sat}\tau_e \approx 30\mu m$ @10^{16}

➢ Thin detectors

❖ Inclined tracks
  - Skewed distributions
  - Algorithms ?
  - ✓ Thin = binary !

❖ Non-homogeneous detectors ?

G. Kramberger, D. Contarato, NIM A560(2006)98.



Top 25% yield 80% of signal, top 10% give 50%

U_w	x	Δx
0.0	0	
0.1	145	145
0.2	208	63
0.3	234	26
0.4	247	14
0.5	256	9
0.6	263	7
0.7	268	5
0.8	272	4
0.9	276	4
1.0	280	4

Can we explain the signal ?

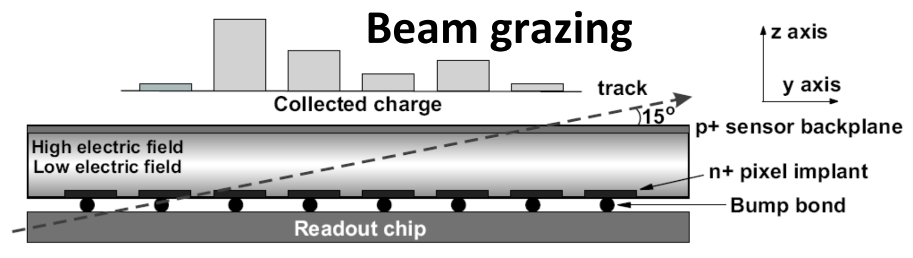
- Extensive efforts have been going on to model irradiated silicon from “first principles”
  - Trap parameters -> models (semi-analytic, TCAD)
- The problem, nicely formulated by Michael Moll

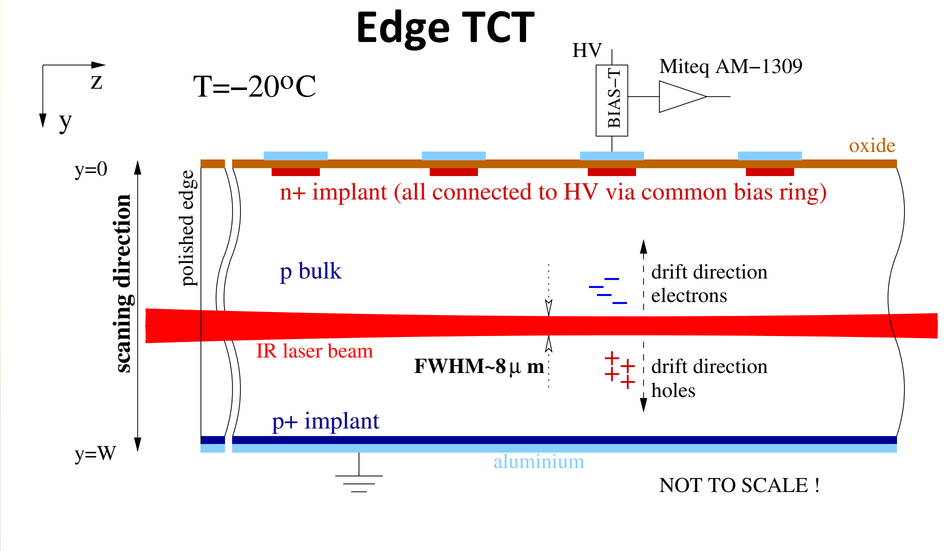
  “There is no shortage of traps in irradiated silicon…”
- Signal governed by Ramo theorem
  - E_w depends solely on geometry, can be calculated
  - E problematic for modeling
- Can we measure it ?

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

Edge TCT

- Inspired by beam grazing technique introduced by R. Horisberger to study *CCE* in pixel detectors
- Edge-TCT
  - Replace small angle beam by edge-on IR laser perpendicular to strips, detector edge polished
  - Focus laser under the strip to be measured, move detector to scan,
  - Measure induced signal with fast amplifier with sub-ns rise-time (TCT)
  - 8 µm FWHM under the chosen strip, fast (40 ps) and powerful laser
    - Caveat – injecting charge under all strips effectively results in constant weighting (albeit not electric !) field





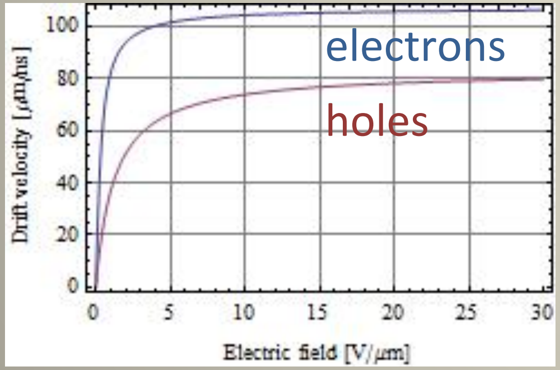
Electric Field Measurement

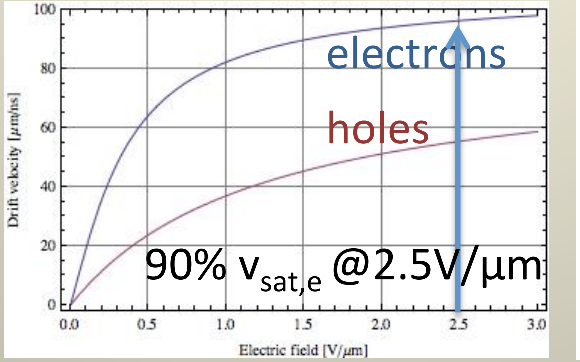
- Initial signal proportional to velocity sum at given detector depth
- Caveats for field extraction
  - Transfer function of electronics smears out signal, snapshot taken at ~600 ps
    - Problematic with heavy trapping
    - Electrons with v_{sat} hit electrode in 500 ps
  - Mobility depends on *E*
    - *v* saturates for *E* >> 1V/µm

$$I(t=0) = q\vec{v}\cdot\vec{E}_w =$$

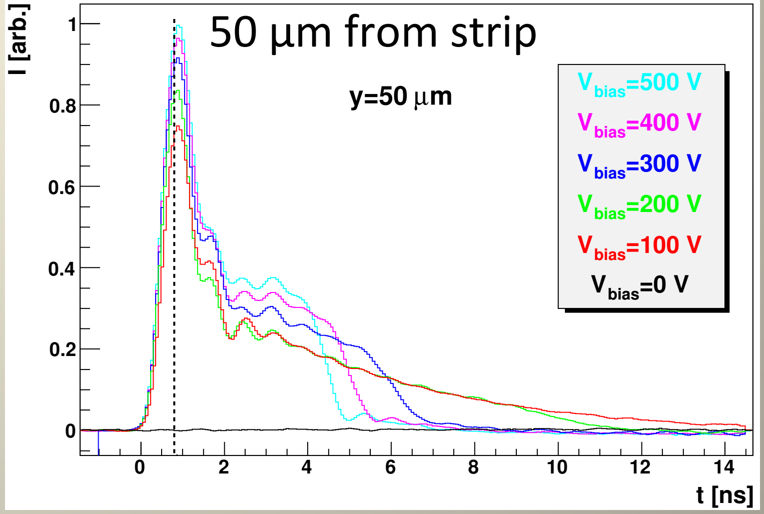
$$= N_{e-h}e_0\cdot(v_e+v_h)/d =$$

$$= N_{e-h}e_0\cdot(\mu_e+\mu_h)\cdot E(x)/d$$



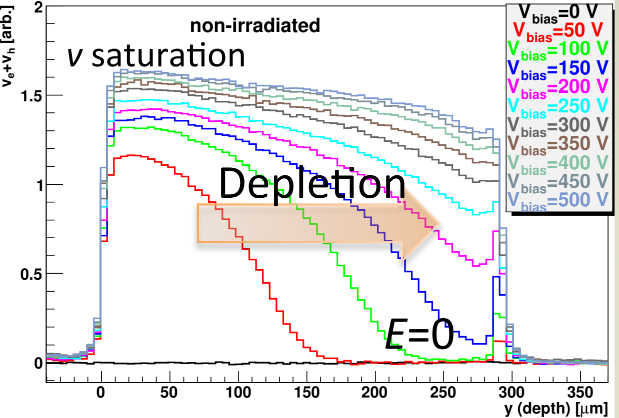


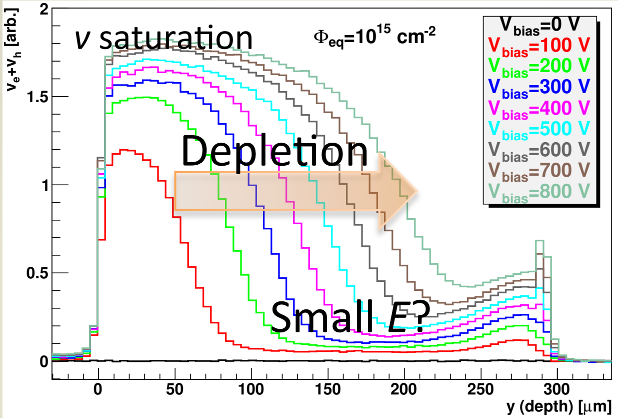
Non-irradiated

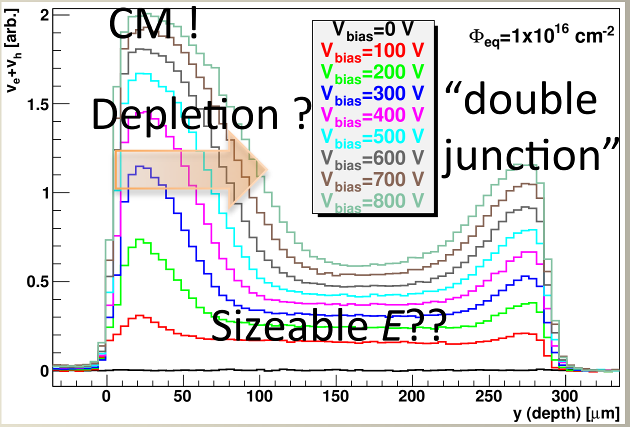


Selected Results

- Hamamatsu n$^+$ strip (mini-)sensors, FZ p-type, irradiated with neutrons



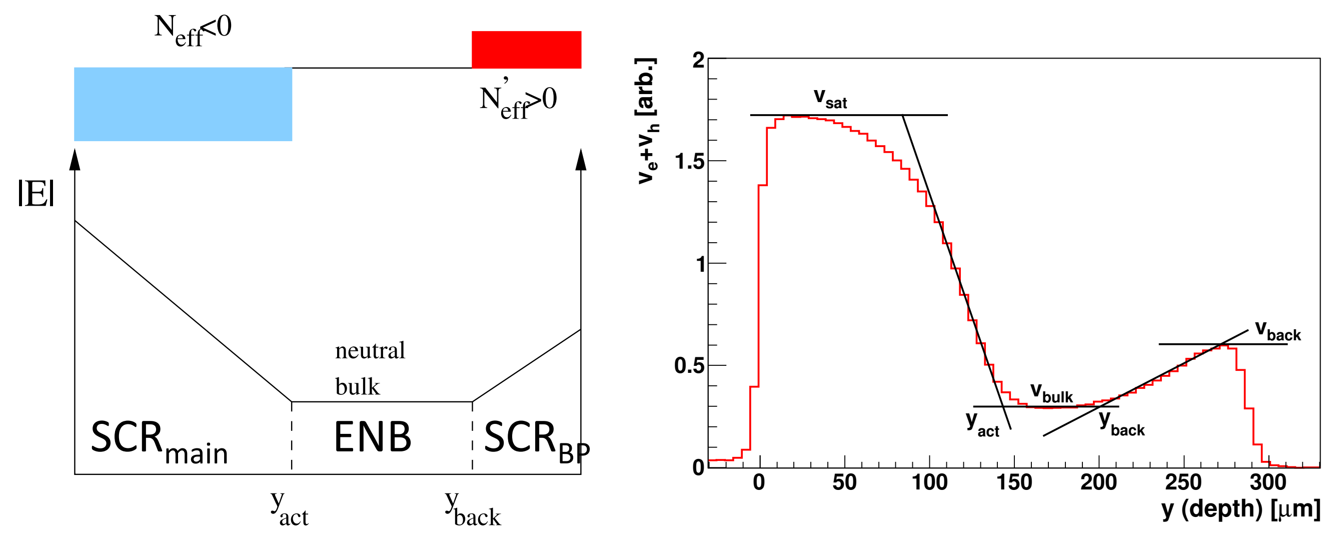




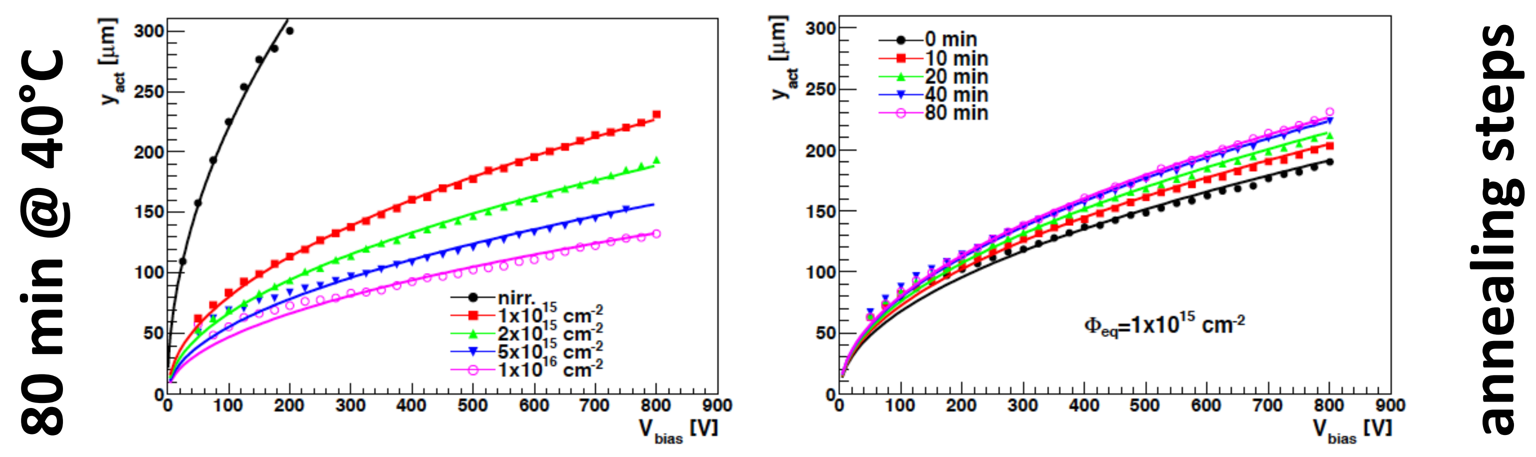
- Very instructive regarding qualitative electric field shape
  - Non-irradiated "by the book" for abrupt junction n$^+$p diode
    - SCR and ENB nicely separated, small double junction near backplane
  - Medium fluence ($\Phi=10^{15}$ neutrons): some surprise
    - Smaller space charge than expected in SCR, some field in "ENB"
  - Large fluence ($\Phi=10^{16}$): full of surprises
    - Still lower space charge, sizeable field in "ENB"
    - CM additional trouble for interpretation at large *V*
- Can we bring these observations to quantitative level ?

Field Modeling: Regions

- Detectors exhibit three distinct regions
  - Space Charge Region at main junction, negative SC
  - SCR at backplane, positive SC
  - Electrically Neutral Bulk in-between
    - Remember: *E*=const => no space charge
- Determine extent of each region by geometrical fits



Main Junction SCR

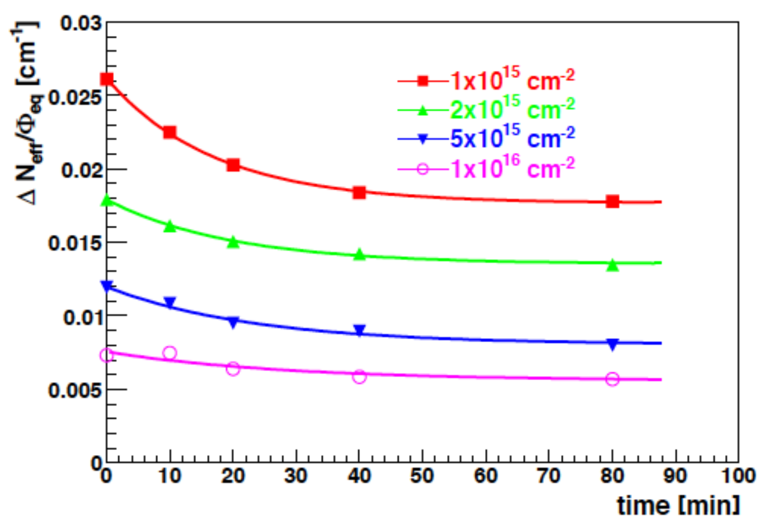


80 min @ 40°C

annealing steps

- Turn y_{act} into N_{eff}
  - assuming constant SC, and no *V* drop in ENB and SCR_{BP}

$$y_{act} = \sqrt{\frac{2\,\varepsilon_{Si}\,V_{bias}}{e_0\,N_{eff}}}$$

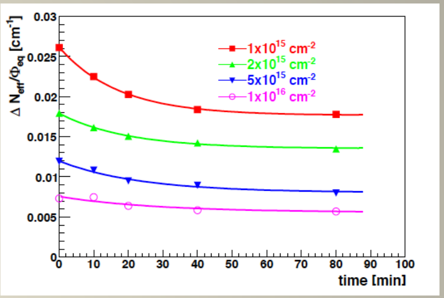


Main SCR - Description

- Fit (early stage) annealing data by

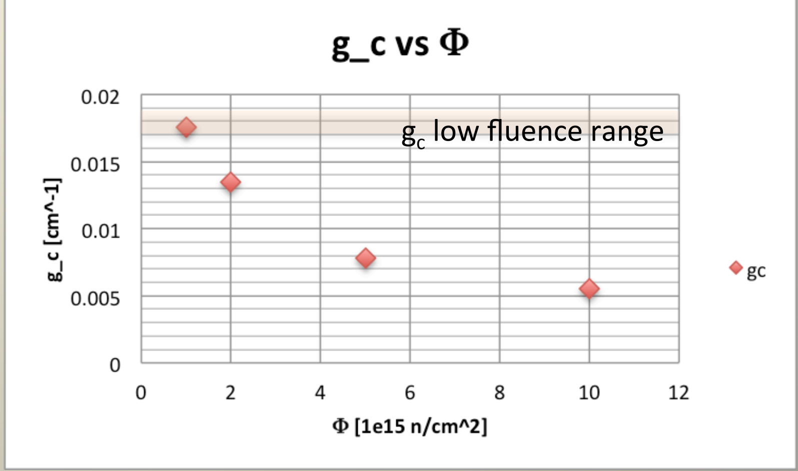
$$\frac{\Delta N_{eff}}{\Phi_{eq}} = \frac{N_{eff}-N_{eff,0}}{\Phi_{eq}} \approx g_c + g_{ba}\exp(-t/\tau_{ba})$$

  - rescale g_{ba} by $\Phi_{total} / \Phi_{last\ step}$



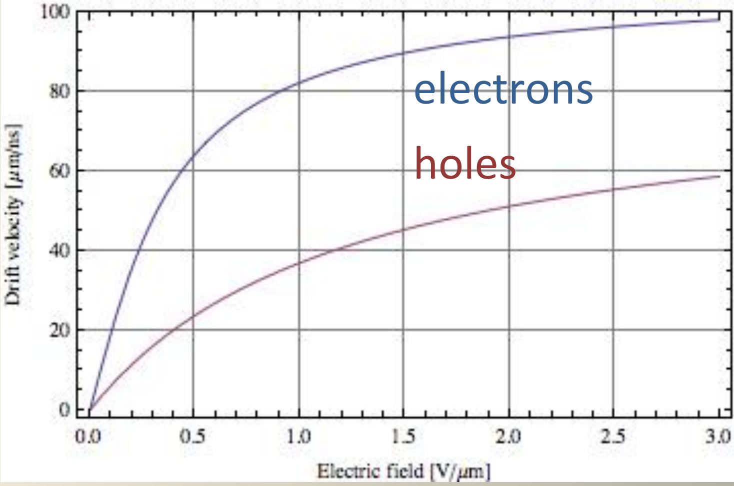
- Clear non-linearity of stable acceptor generation
- Mechanism unknown, but there is plenty of dynamics going on in (heavily) irradiated semiconductors
- Whatsoever happens here, it is good for us !

F_eq 1e15 cm^-2	g_c cm^-1	g_ba cm^-1	t_ba min
1	0.0176	0.0085	17.20
2	0.0135	0.0088	20.50
5	0.0078	0.0069	26.25
10	0.0055	0.0040	27.80



Field Modeling: Field Value

$$I(t\approx 600\text{ps},y)\propto v_e+v_h=(\mu_e+\mu_h)\cdot E(y)$$



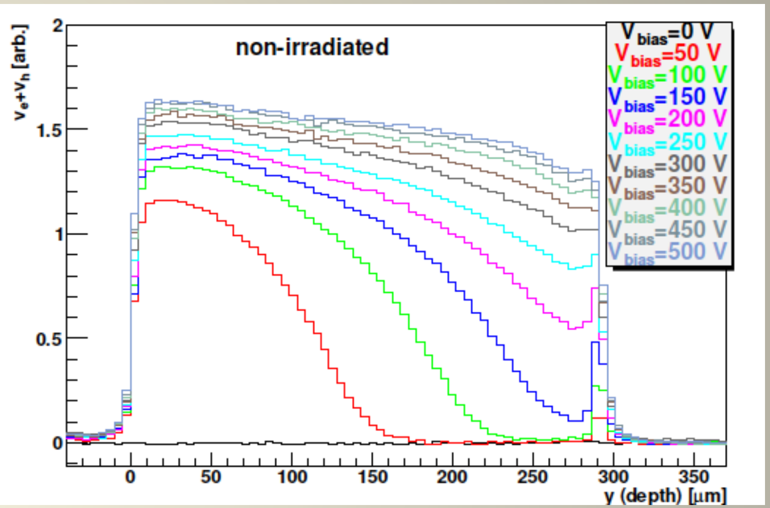
- Invert to get *E(y)* ? Caveat:
  - *μ=μ(E),* need *scale* of *E* to invert
- Scale from $\int E(y)dy=V$? Not really:
  - Poorly known large field at electrode contributes sizably to the integral
- Measured "*I(t)*" is in fact a convolution of the induced signal with electronics transfer function *H(t)*

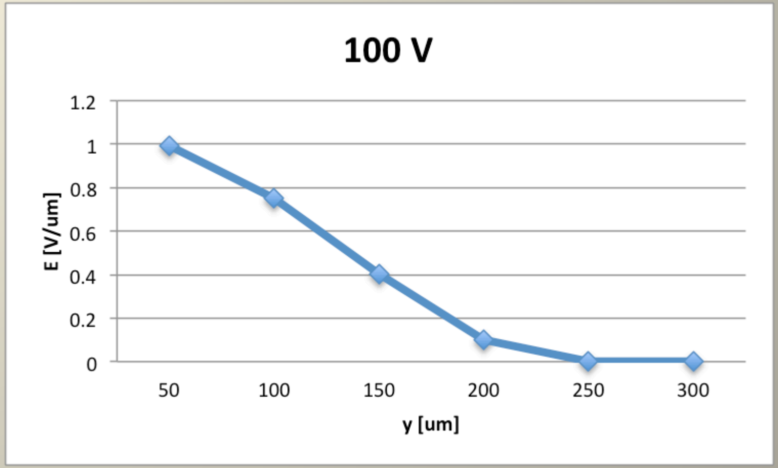
$$I(t)\propto\int_0^t(\mu_e+\mu_h)\cdot E(y(t'))H(t-t')dt'$$

- Further *I(t)* plagued by
  - Inhomogeneity of *E(y)* close to *y*
  - Trapping reducing *I(t)*
  - Charge multiplication boosting *I(t)*

Case We Know: Non-Irradiated

- Assume abrupt junction, constant SC
- No trapping, no CM
- At 500 V
  - 180 V (*FDV*) to linear *E*
  - 320 V to constant *E*
  - $E = (1.1 + 1.2\times(w-y))$ V/µm
  - 2.1 V/µm @ y=50 µm
- In $v_{sum}(y)$: 1.62(a.u.) translates to 131 µm/ns
- Can invert $E(v_{sum})$

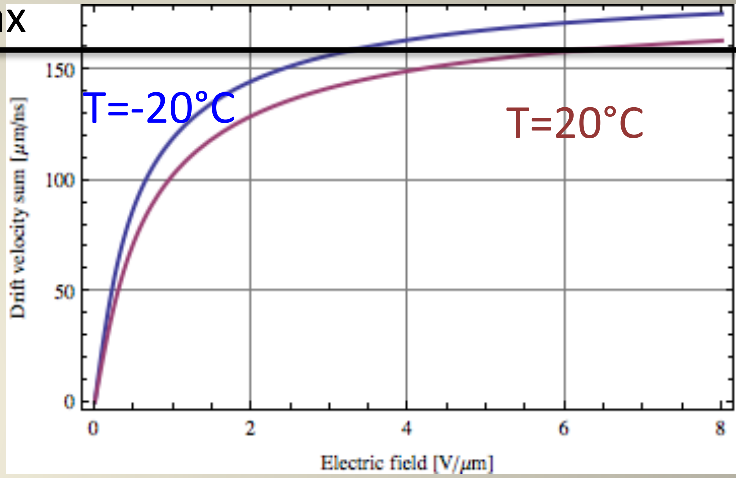


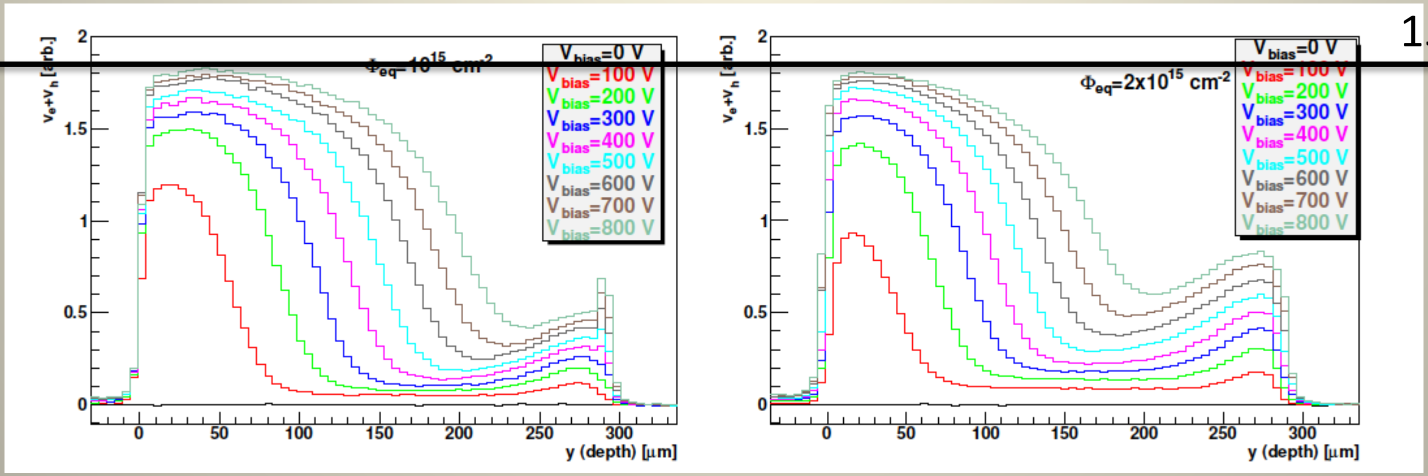


Can we scale to irradiated Si ?

- Keep scale for v_{sum}
- Trivial: use *v(E)* for -20°C instead of 20°C
  - big effect at high v_{sum}
- Not so obvious: keep same laser input
  - expect ~10%, in fact looks even better

plot max

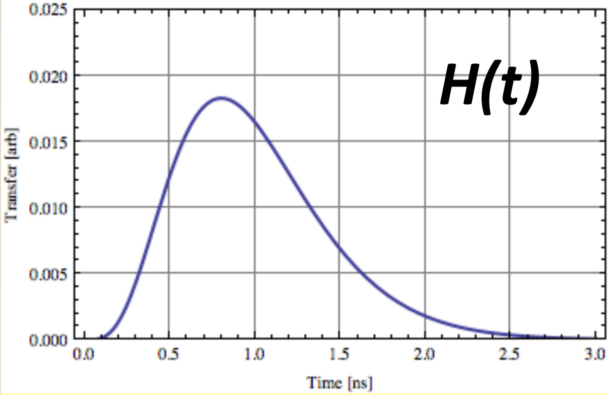




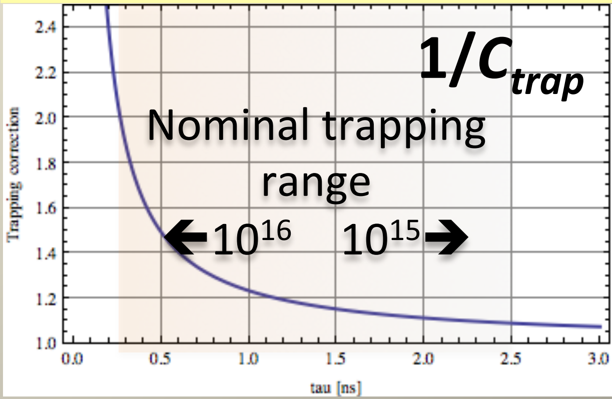
150 µm/ns
2.3 V/µm

Trapping

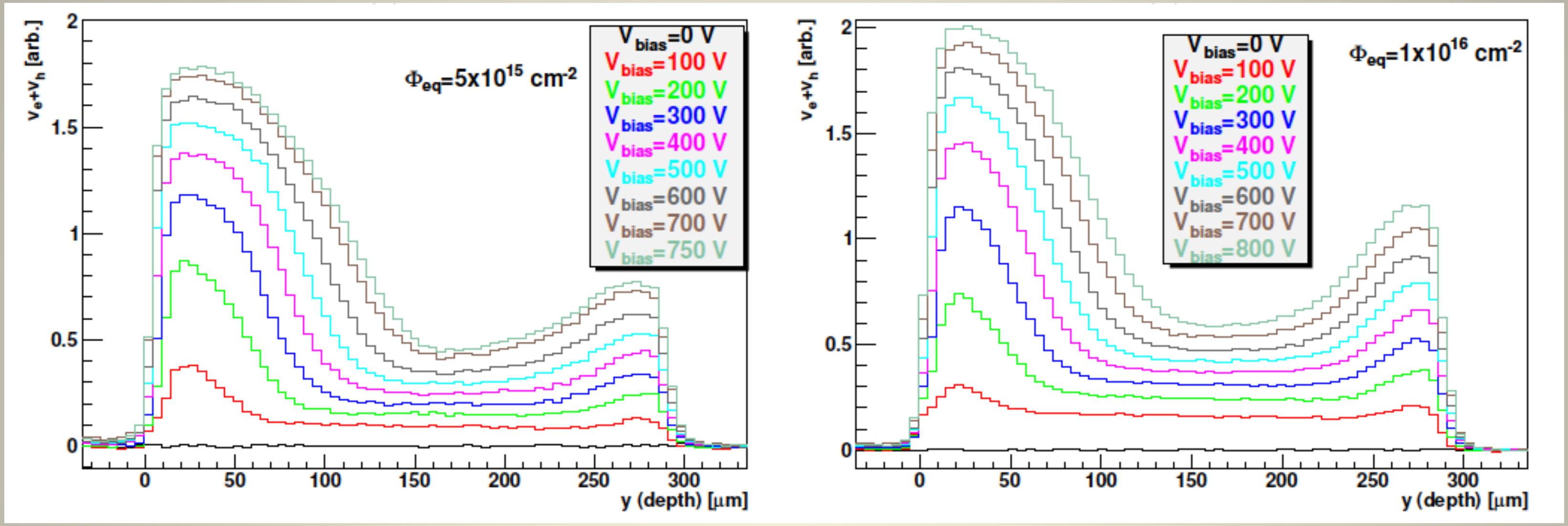
- Naïve trapping – reduce $I(t)$ by $e^{-t/\tau}$
  - Independent of E, so v_{sum} just scaled up
  - But $\tau << t$ at 10^{16} - no signal ??
- Have to invoke transfer function $H(t)$
  - Reproduce $I(t)$ for non-irradiated
  - Model as CR-RC^4 with t_{sh} = 0.8 ns
- Trapping correction with $H(t)$
- Correction calculated for nominal trapping times $\tau_e = \tau_h = 1/\beta\Phi$ with $\beta = 4\times10^{-16}$ cm^{-2}s^{-1}
- v_{sum} scale boosted by +10% -> ×2
  - For 10^{16} scale exceeds physical limit !



$$C_{trap}(t) = \int_0^t e^{-t'/\tau} H(t-t')\,dt'$$

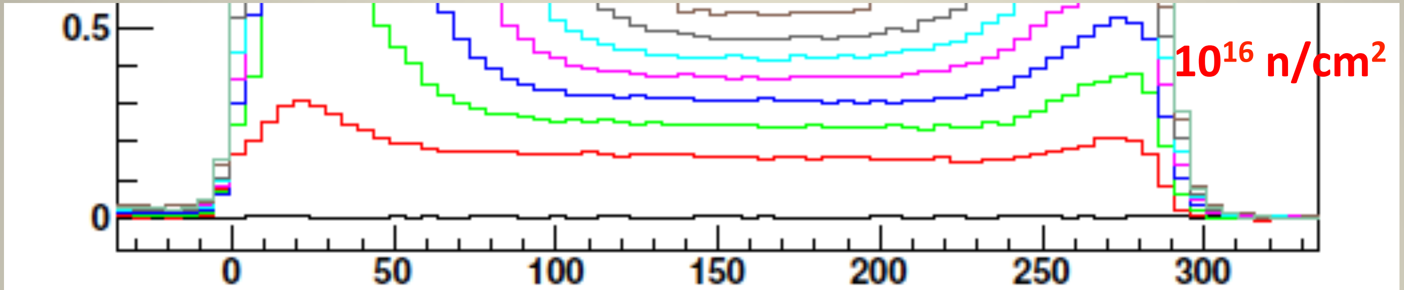


Charge Multiplication



- At 5x10^{15} and 10^{16} no clear saturation in v_{sum} observed
- Taking nominal trapping correction both v_{sum} exceed $v_{sum,sat}$ = 190 μm/ns (2.35 a.u.×C_{trap})
- Clear sign of charge multiplication close to electrode
- Difficult to model, so give up modeling this region

ENB Description

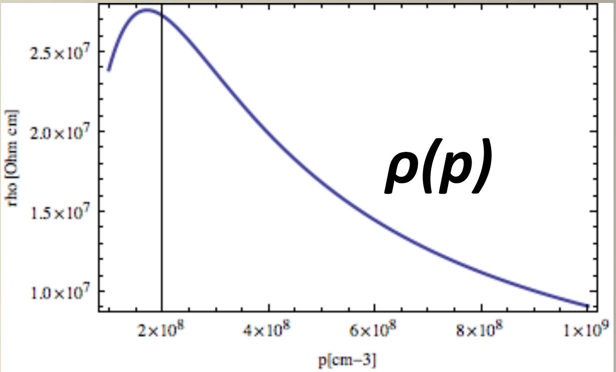


10^{16} n/cm^2

- Si @ 10^{16} full of defects, so how do we get Electrically Neutral Bulk ?
  - Honestly, I do not know, but at low V there is a large region with constant v_{sum} thus constant E
  - Constant E implies no (net) space charge
  - Generation current is known to generate linear space charge dependence due to charging up traps
    - Thus no generation current ?
    - Thermal quasi-equilibrium, implying $np = n_i^2$ so ENB ??

ENB Sanity Check

- Usually *E=0* assumed in ENB
  - No signal due to charge recombination
- Heavily irradiated Si
  - Large I_{leak}, high resistivity ρ
  - Need sizable E to transport I_{leak} across ENB
- Model 10^{16} @ 100 V
  - g_c from SCR fit, ρ close to max
  - I_{leak} generated in SCR transported through ENB by $j=E_{ENB}/\rho$
  - Linear rise of E_{SCR}
  - V divided between SCR and ENB in a self-consistent way (quadratic equation)



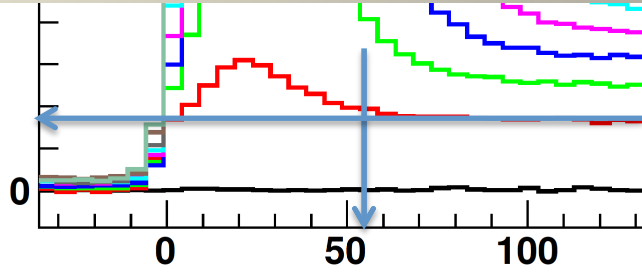
- Result

  w_{SCR} = 56 µm

  E_{ENB} = 0.053 V/µm

Too good for coincidence !

But what about trapping ?

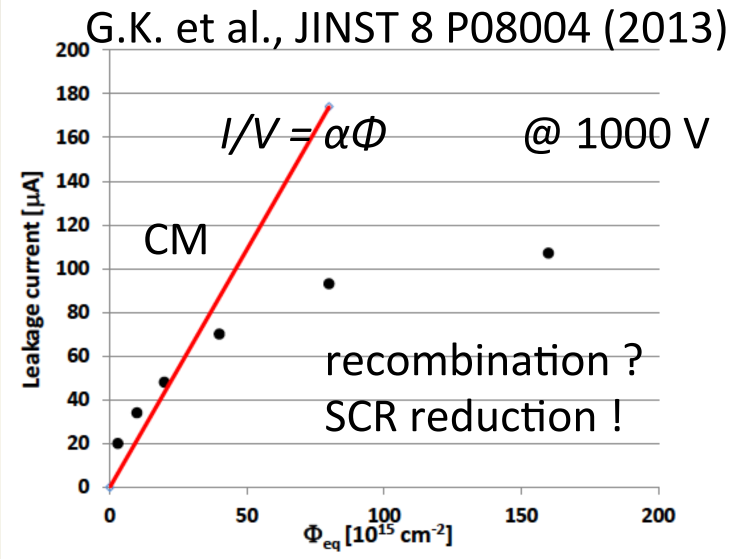


ENB Result Implications

- ENB not contributing to I_{leak}
  - Significant I_{leak} reduction
  - Observed in 10^{17} exercise

➢ Very important for detector operation (noise, power) !

- Trapping would require v_{sum} -> E larger by ~2
  - Significant trapping reduction required
  - Hints presented by RD50
- Can we measure trapping directly ?


G.K. et al., JINST 8 P08004 (2013)

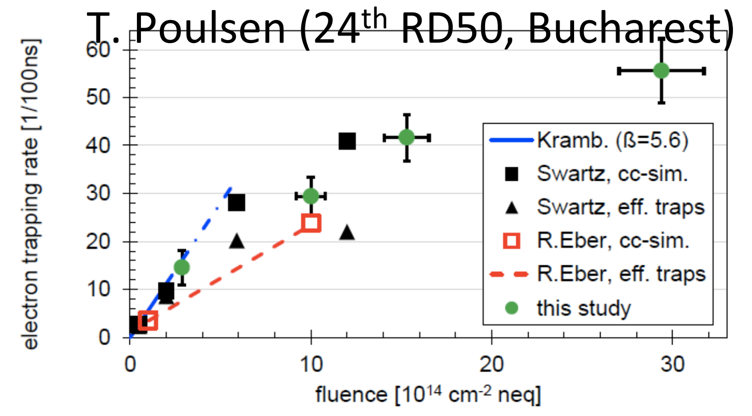
$I/V = \alpha\Phi$

@ 1000 V

CM

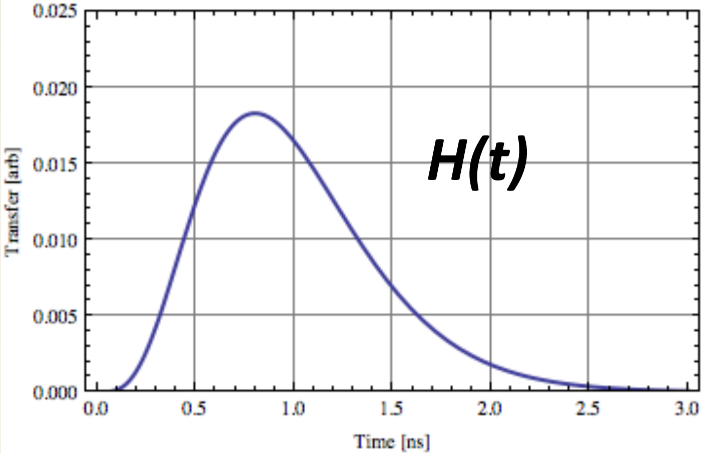
recombination ?

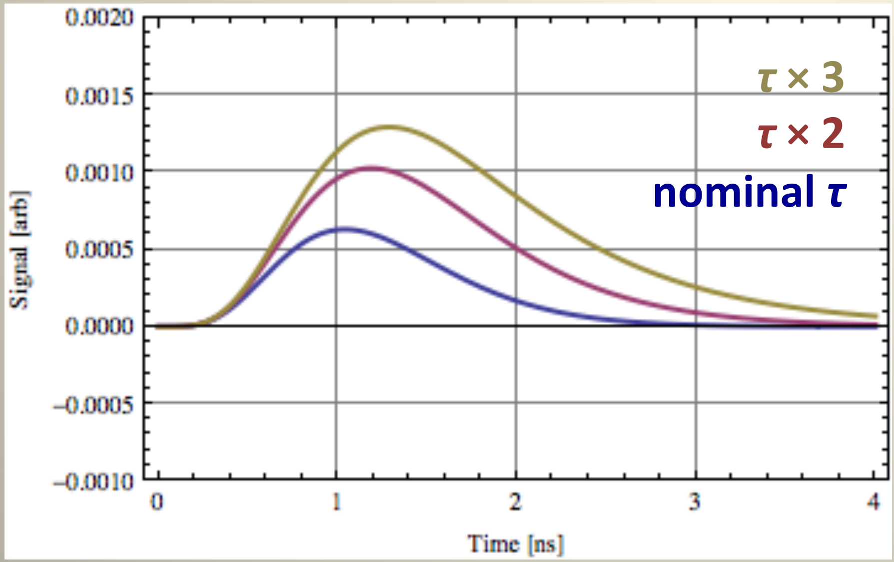
SCR reduction !

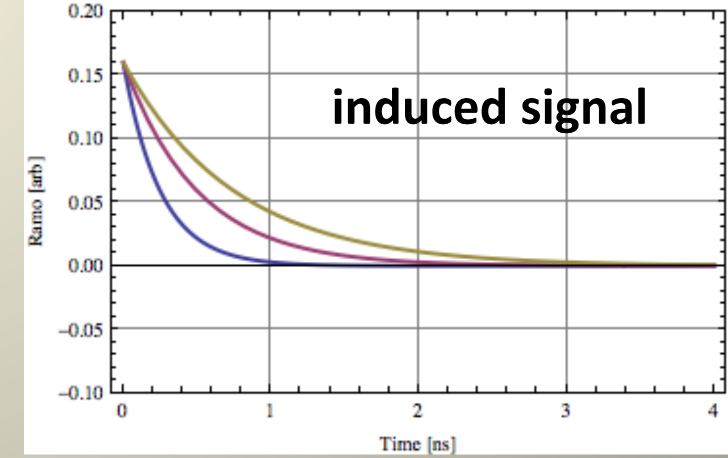

T. Poulsen (24^{th} RD50, Bucharest)

Signal Modeling

- Method: extract trapping from *I(t)* quenching by trapping
- Modeling in Mathematica
  - Input: shaping CR-RC^4, t_{sh} = 0.8 ns, nominal trapping, reduced trapping by ×2, 3
  - *v(E)*, *E* = 0.05 V/µm irrelevant for *I(t)* shape
  - Calculate *I(t)*, convolute with shaping *H(t)*

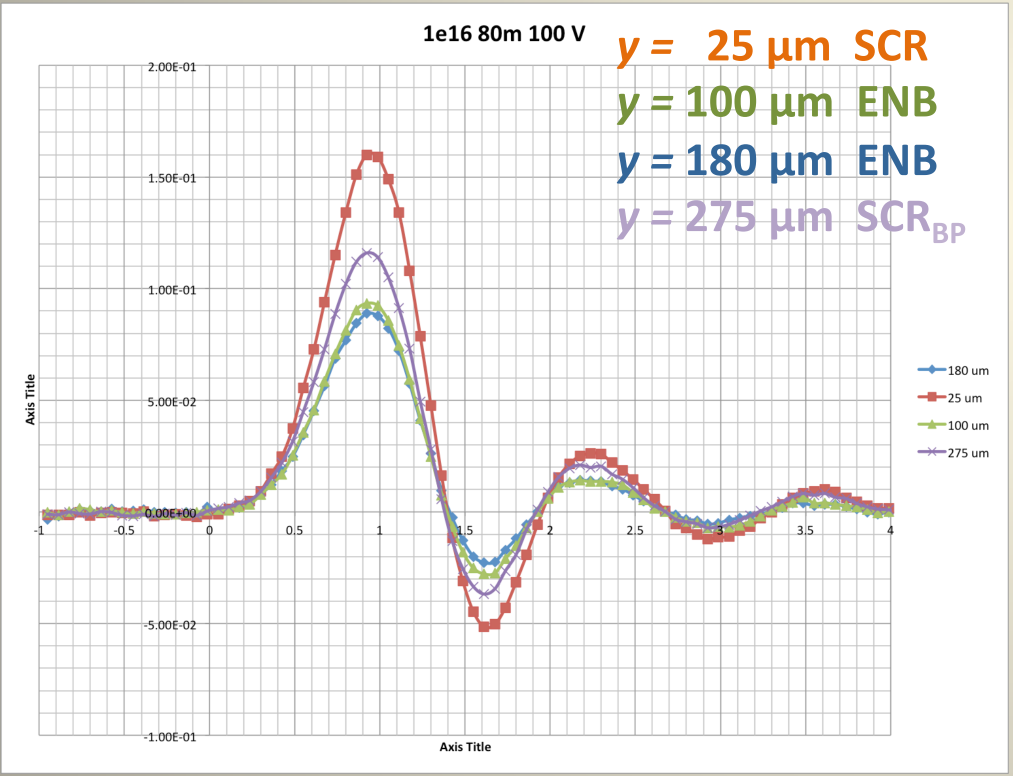






Reality

- Measured *I(t)* in E-TCT 10^{16} @ 100 V



y = 25 µm SCR

y = 100 µm ENB

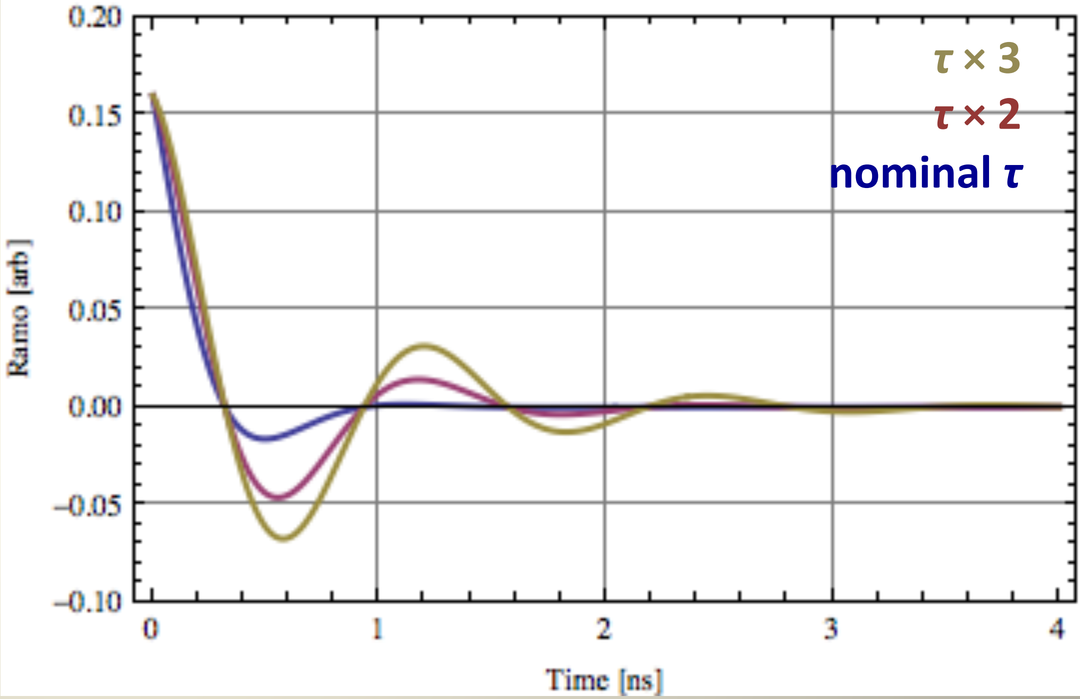
y = 180 µm ENB

y = 275 µm SCR_{BP}

- Not really what we hoped for
- Oscillatory behaviour with period 5/4 ns
- Remarkable: same form in ENB and SCR

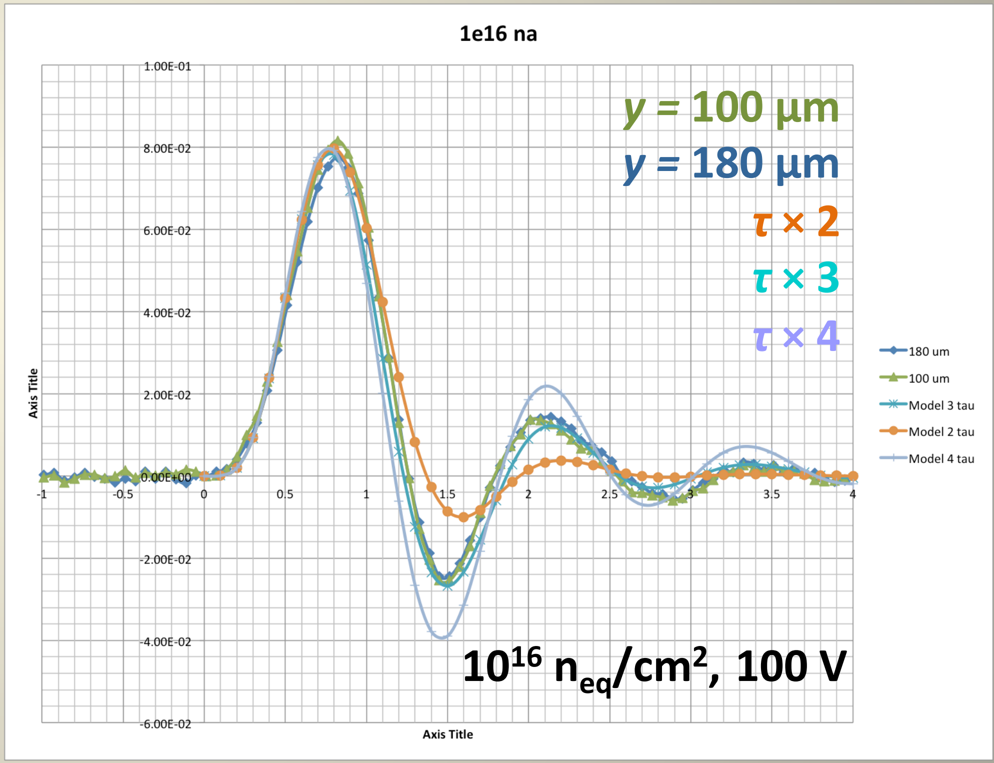
Fudge

- Put oscillations with observed frequency on top of induced signal, damped solely by trapping
  - Reflections close to detector induce oscillations before actual H(t) ?!
  - Don’t ask about underlying physics details…
- Then convolute with H(t)



Fudged Signal Facing Reality

- Compare with $\tau = 2, 3$, 4 x nominal
  - Nominal τ ruled out anyway
- ✓ Good agreement
- ✓ 3x longer τ looks like a clear winner
  - Definitely not 2 or 4
  - Implies ~20% trapping correction to v_{sum}



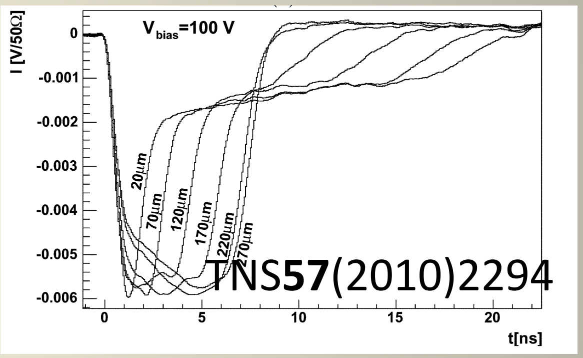
10^{16} n_{eq}/cm^2, 100 V

Conclusions

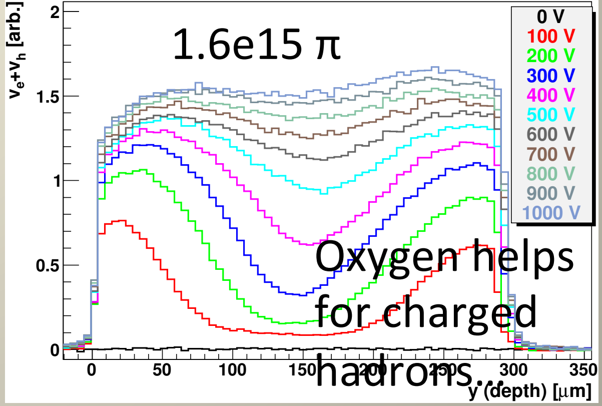
- We irradiated Si with neutrons up to 1.6x10^{17} n_{eq}/cm^2 and provide a "magic" formula for Q(V) above 10^{15} n_{eq}/cm^2
- Based on E-TCT, we present a simple model for neutron irradiated silicon detector with 3 distinct regions
- We observe
  - Reduced acceptor introduction in SCR
  - No current generation in ENB
  - Reduced trapping by factor of ~3 at 10^{16} n_{eq}/cm^2
- All this is highly beneficial for Si operation at HL_LHC
- But...

To-Do List

- Produce *E(y)* plots
- Solidify trapping time extraction
  - Get rid of oscillations ?
    - Had it much better in 2009…
  - Better modeling ?
    - *S(ω)* for reflections ?
- Get E-TCT up to 10^{17} n_{eq}/cm^2
  - Does the model survive ?
- Field model applies to neutrons only
  - Pion-induced field completely different: ~parabolic *E*
- Conduct PS proton campaign



TNS**57**(2010)2294

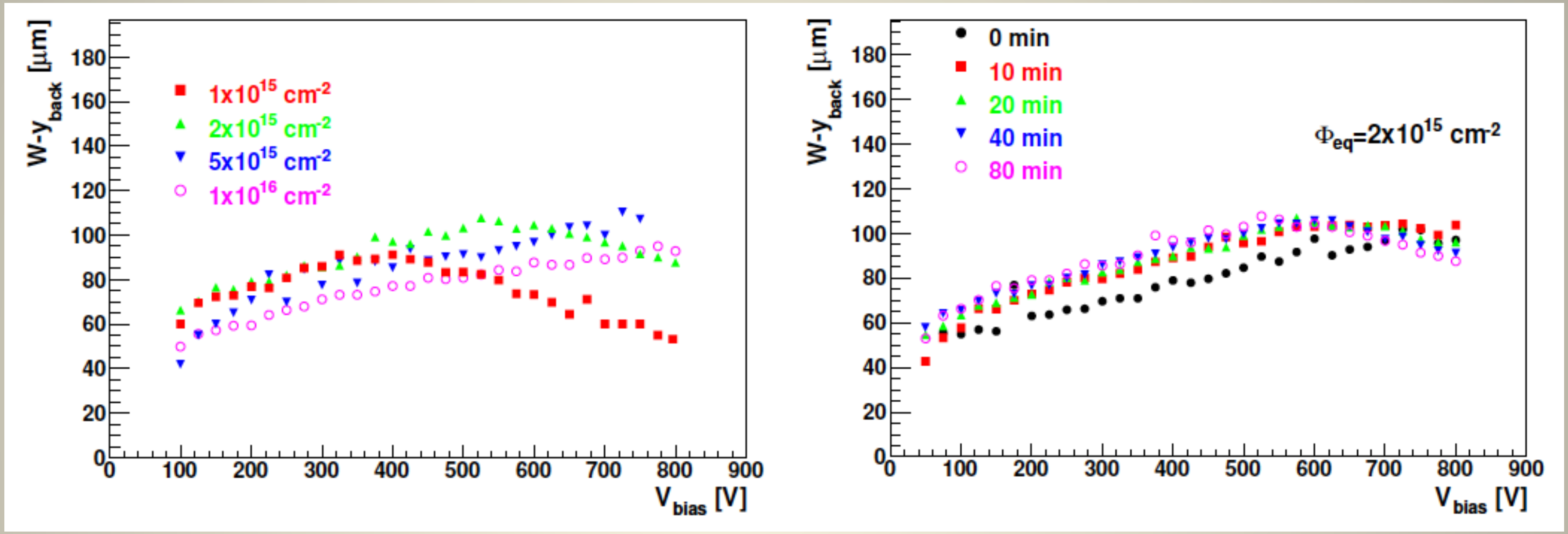


1.6e15 π

Oxygen helps for charged hadrons…

Backup Slides

Backplane SCR



- SCR at backplane with positive SC
  - Width ~1/5 of detector, quasi-independent on fluence
  - Moderate increase with V
  - No real annealing effect
- Trapping induced or just hole diffusion out of BP ?
- Not clear whether it contributes to I_{leak} (is $np = n_i^2$?)

Silicon – material of choice

- For LHC, initially very little Si was envisaged for tracking
  - 2/3 layers in barrel only for ATLAS LOI
  - Majority MSGC, some GaAs, diamond
  - Radiation hardness, price
- During project execution Si remained the only tracking sensor
  - Except TRT in outer ATLAS tracking
    - Still ~70 m^2 of Si
  - CMS all-Si with ~200 m^2 of active sensors
- These trackers perform extremely well at LHC
- Can performance be extended by an order of magnitude in radiation fluence ?

ATLAS LOI

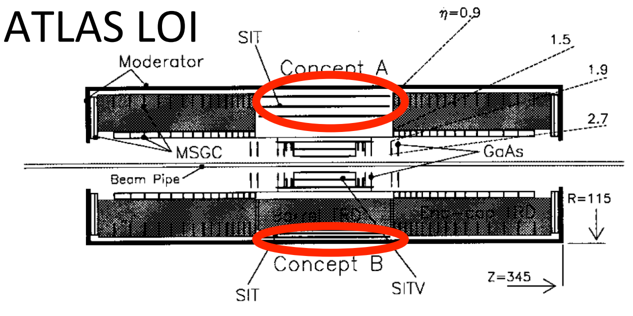
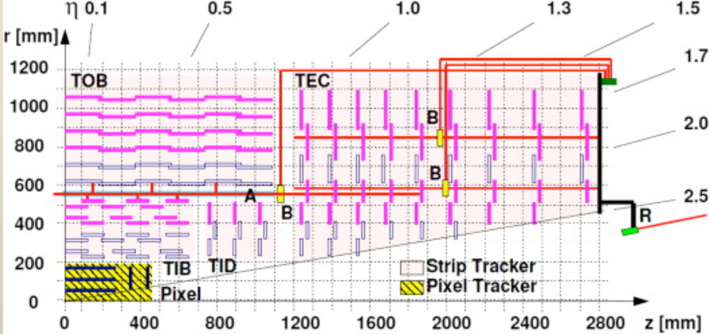


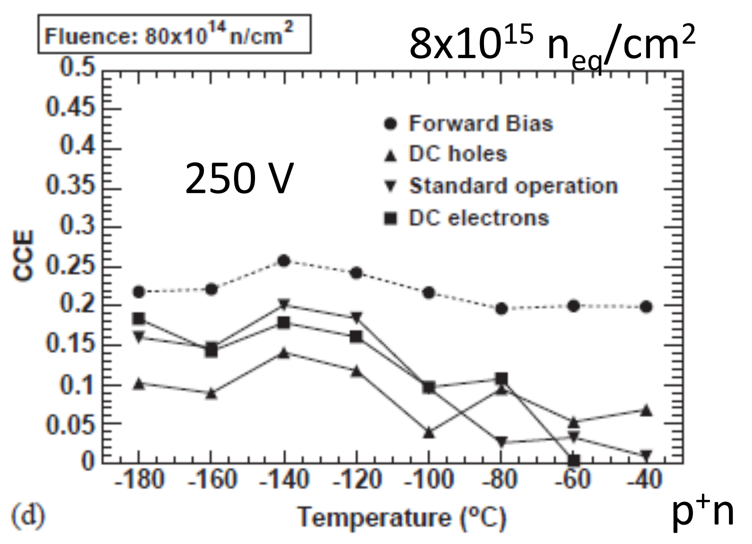
Figure 3.1: *Layout of the Inner Detector with two design concepts; concept A above and B below the beam line (dimensions in cm)*

CMS Tracker



Past Experience

- Extensive R&D for >20 years
  - RD-20, -48, -50
- Three effects of radiation
  - ☆ Leakage current
  - ✪ Space charge
  - ☠ Trapping
- All sorts of tricks applied
  - New materials
  - Low temperature
  - Field manipulation
  - Forward bias
  - …



$8\text{x}10^{15}\ n_{eq}/cm^2$

250 V

p^+n

I. Mandić et al. NIM A533 (2004) 442

☠ 10 years ago trapping (and space charge) appeared detrimental for operation beyond ~$10^{15}\ n_{eq}/cm^2$

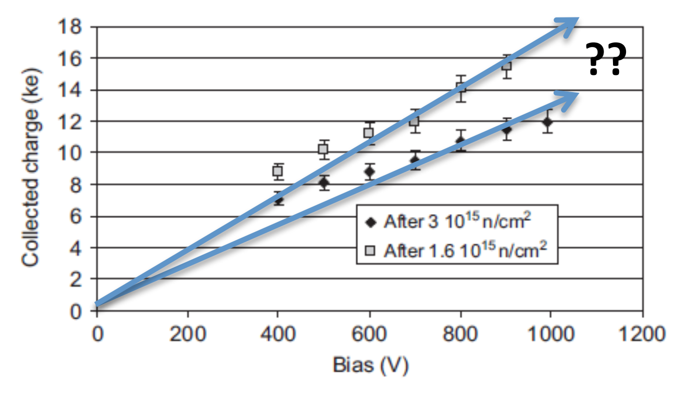
New Hope

- Collection of electrons on n^+ read-out strips proved essential for detector operation beyond 10^{15} n_{eq}/cm^2
  - Junction grows from n^+ side
  - Electrons move faster
  - Electrons trap less

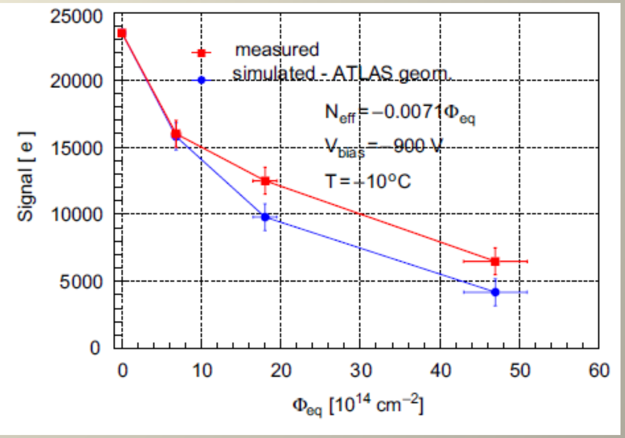
☺ *CCE of ≥ 50 % @* $3x10^{15}$ n_{eq}/cm^2

- CCE quasi-linear with V, no saturation ?!

- Severely inconsistent with simulations based on measured trapping and acceptor introduction at low fluences
  - Trapping, space charge not linear with fluence ?



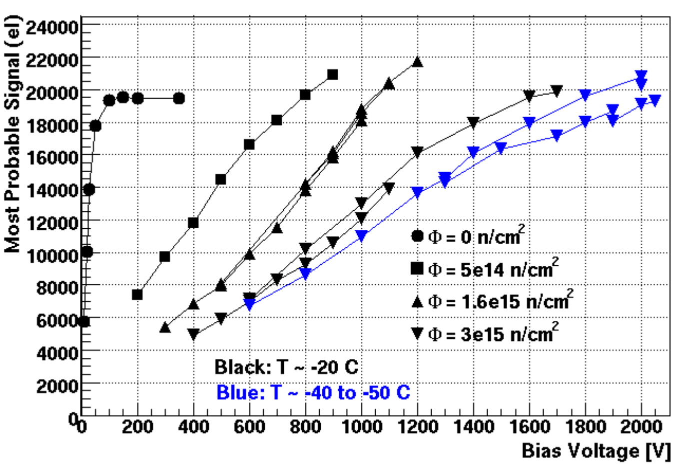
G. Casse et al. NIM A581(2007)318



G. Kramberger et al. NIM A579(2007)762

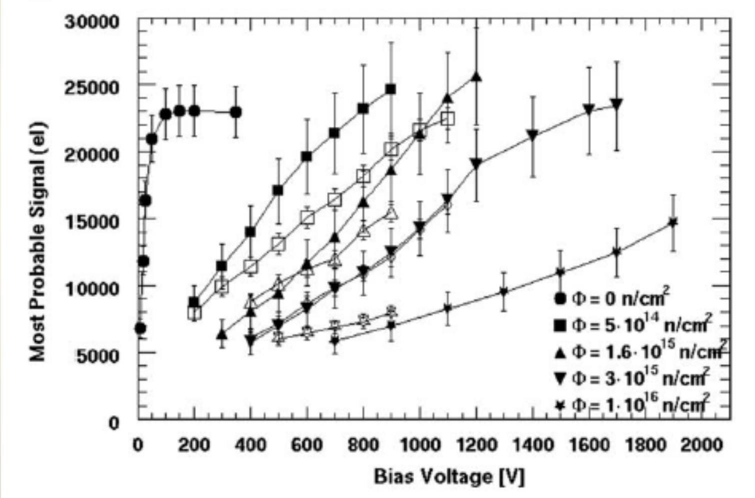
Anno Mirabilis 2008

- In 2008 evidence for even higher *CCE* ≥100 % obtained with n^+p strips using SCT128A (25 ns)



Measurement of charge collection in p-type microstrip sensors with SCT128 chip

I. Mandić et al., 12th RD50 Workshop , June 2008

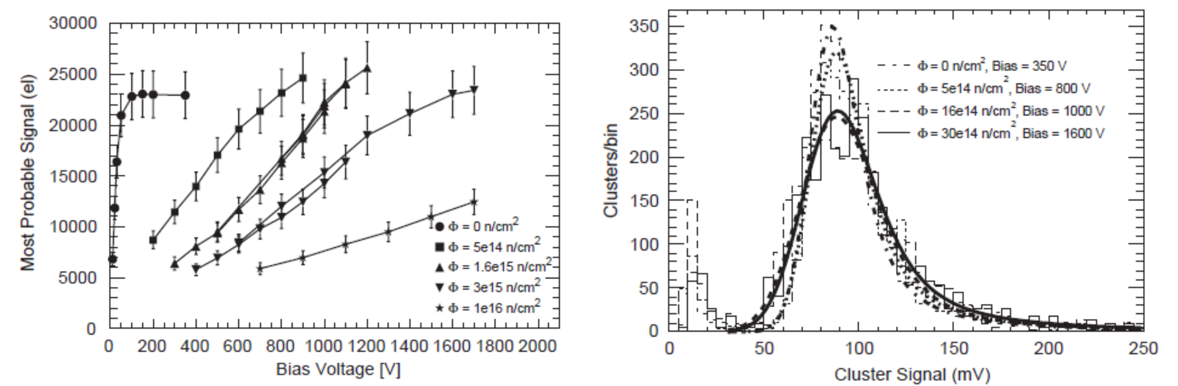


Observation of full charge collection efficiency in heavily irradiated n^+p strip detectors irradiated up to 3×10^{15} n_{eq}/cm^2

I. Mandić, et al., RESMDD08, October 2008

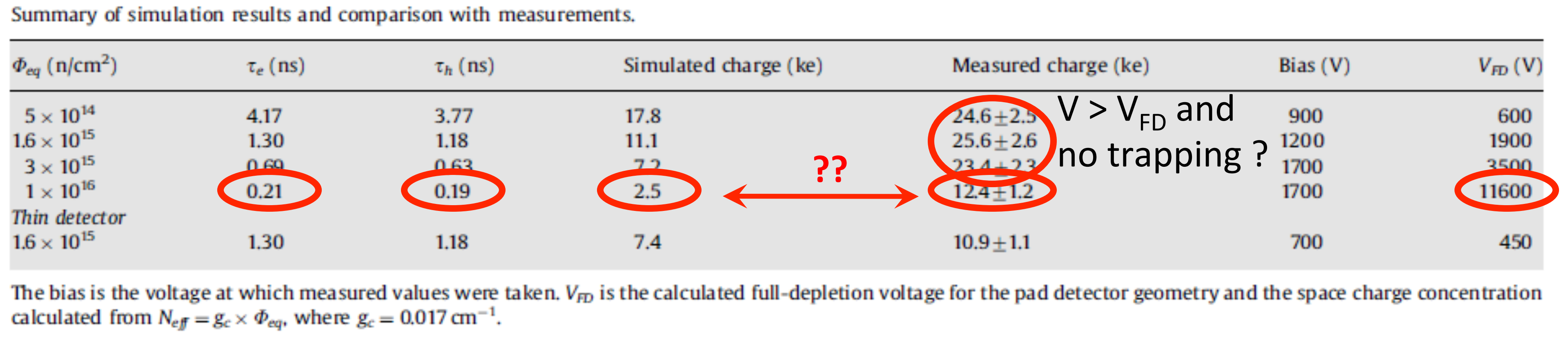
NIMA(2009) , doi:10.1016/j.nima.2009.08.004

What’s going on ?



Measurement of anomalously high charge collection efficiency in n⁺p strip detectors irradiated by up to 10^{16} n_{eq}/cm^2,
I.Mandić et al. NIM A603(2009)263

CCE results clearly incompatible with simulation based on N_{eff} and trapping data from lower fluences !



Summary of simulation results and comparison with measurements.

Φ_{eq} (n/cm^2)	τ_e (ns)	τ_h (ns)	Simulated charge (ke)	Measured charge (ke)	Bias (V)	V_{FD} (V)
5×10^{14}	4.17	3.77	17.8	24.6±2.5	900	600
1.6×10^{15}	1.30	1.18	11.1	25.6±2.6	1200	1900
3×10^{15}	0.69	0.63	7.2	23.4±2.3	1700	3500
1×10^{16}	0.21	0.19	2.5	12.4±1.2	1700	11600
Thin detector						
1.6×10^{15}	1.30	1.18	7.4	10.9±1.1	700	450

The bias is the voltage at which measured values were taken. V_{FD} is the calculated full-depletion voltage for the pad detector geometry and the space charge concentration calculated from $N_{eff} = g_c \times \Phi_{eq}$, where $g_c = 0.017\ \mathrm{cm}^{-1}$.

??

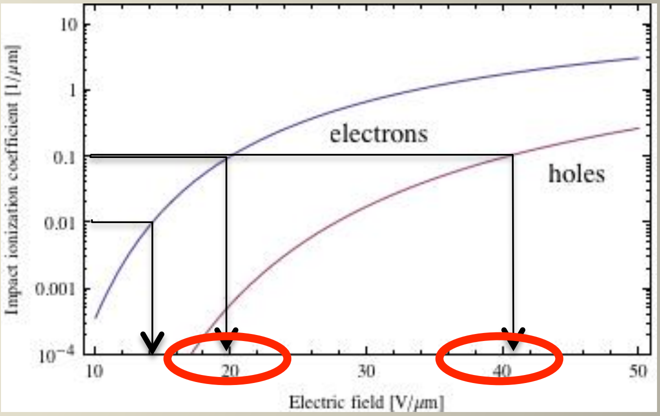
V > V_{FD} and no trapping ?

Charge Multiplication

- Multiplication is textbook physics
  - e.g. S.M. Sze, Physics of Semiconductor Devices, Wiley, New York, 1981
    - Ch 1.6.4 High-Field Property
      - Velocity saturation, impact ionization
    - Ch 2.5.3 Avalanche Multiplication
      - Junction break-down
- Measured impact ionization
  - Electrons create 1 pair in 10 µm at *E*~20 V/µm (100 µm at 14 V/µm), holes need *E*~40 V/µm
  - Holes need ~1 mm for pair creation at *E*~20 V/µm
    - Neglect hole multiplication in signal creation altogether
    - Need to invoke hole multiplication for junction breakdown
- $\alpha_e >> \alpha_h$ - Nature gentle to us (in silicon)
  - Large range in *E* where electrons multiply without inducing breakdown
  - But beware of (too) high electric fields !

$$\alpha_{e,h}(E) = \alpha_{e,h}^{\infty} e^{-b_{e,h}/E}$$

A. G. Chynoweth, Phys. Rev. 109, 1537(1958).



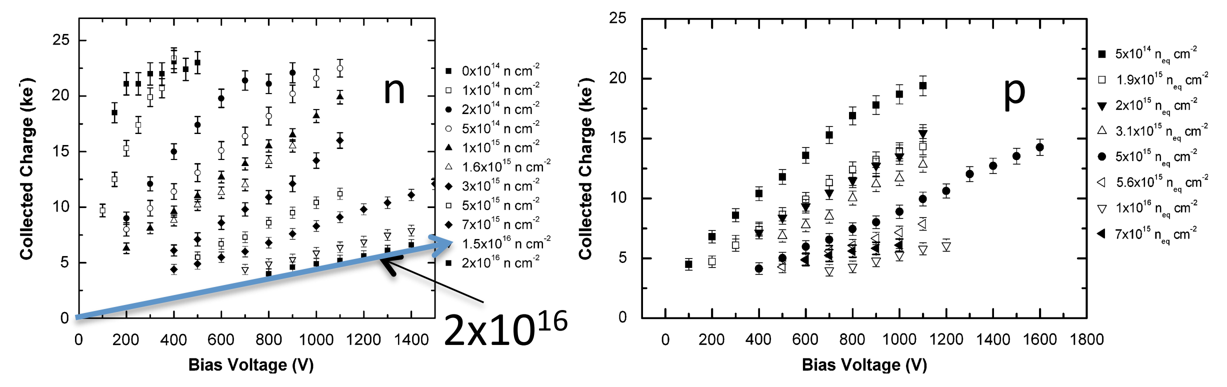
R.VAN OVERSTRAETEN and H.DE MAN, Solid-State Electronics 13(1970),583-608.
W.MAES, K.DE MEYER, R.VAN OVERSTRAETEN, Solid-State Electronics 33(1990),705-718.

$$\int_0^w dx\, \alpha_e(x) e^{-\int_0^x (\alpha_e(x')-\alpha_h(x'))\,dx'} = 1$$

Breakdown condition, can swap α_e with α_h

Multiplication observed

- *E* = 20(14) V/µm needs field peaking
  - Homogeneous *E*: V≈6000(4000) V for *d*=300 µm
  - Space charge, electrode shape sharpen up *E*
  - To get multiplication: $V >> E/\alpha_e$ = 200(1400) V
    - Clear advantage of high *E* in limited region (APD's !)
- Observed in
  - Strip sensors
- Later in
  - Pad detectors
  - 3-D
  - Pixels

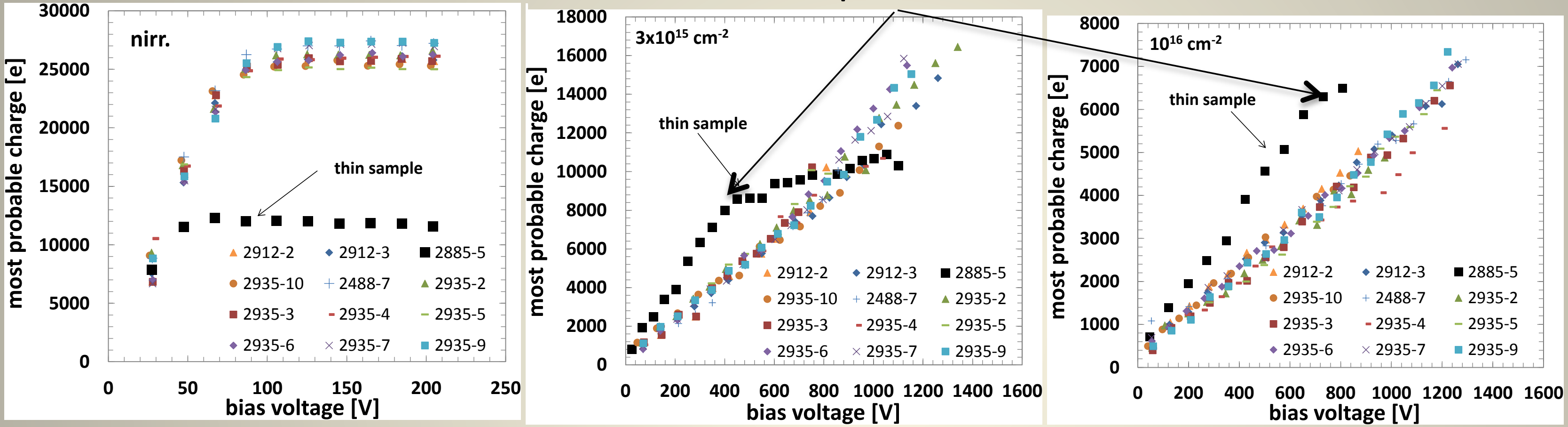


$2\text{x}10^{16}$

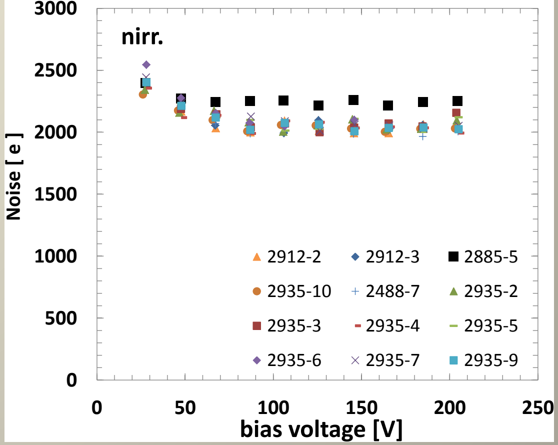
G. Casse et al. NIM A 636(2011)56

Over 0, $3x10^{15}$ & $1x10^{16}$ …

Depletion ?

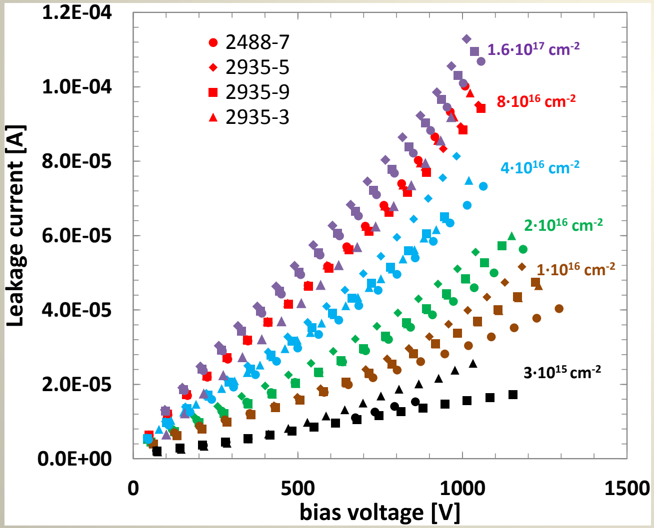


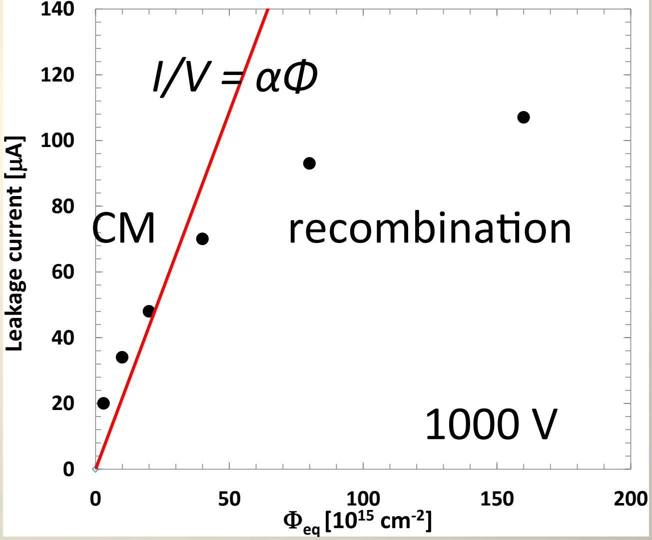
- No influence of different processing
  - At least no systematic one…
- Hint of “depletion” for the thin detector
- 25 ns shaper not optimized for noise
  - Noise ~2000 e before irradiation



Have we won ?

- Well, the signal is there… but what about current & noise ?
  - If signal gets multiplied (M_S) so does the current
    - In fact even more due to de-trapping ($M_I > M_S$)



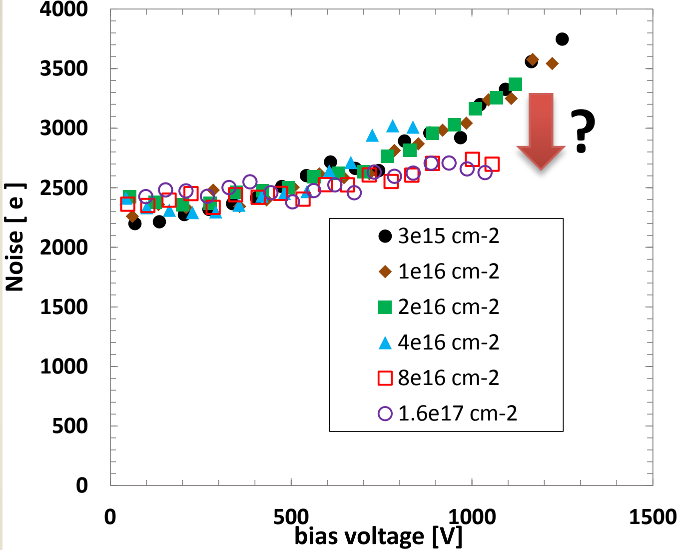


…true, until above $2\text{x}10^{16}$ recombination kicks in !

- Current starts to saturate

Noise ?

- Noise results in interplay of sensor and electronics
  - Sensors contribute through C_{det} to voltage and I_{leak} to current (Shot) noise, added in quadrature
  - In fast electronics voltage noise tends to dominate
- When CM present, noise enhanced by excess noise factor *F*; *F(M=1) =1, F(M>>1)≈2*
  - R. J. McINTYRE, IEEE TED13(1966)164 for details
- Impossible to tell apart contributions of CM and recombination
  - CM decrease at highest fluences ?

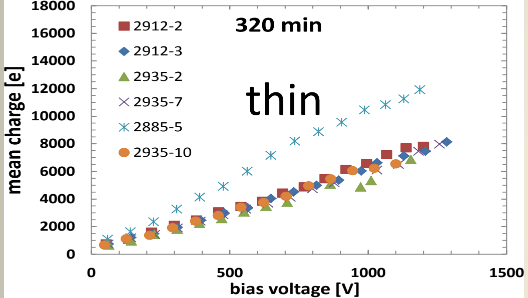


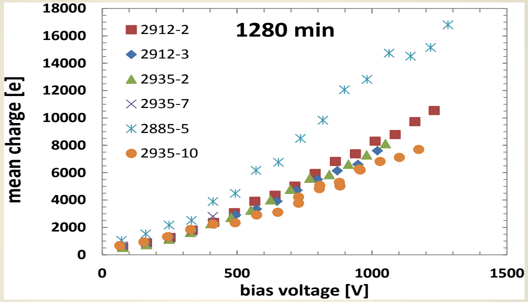
$$ENC_{MI} = \sqrt{2e_0 I_{gen}\tau}\cdot\sqrt{F}\cdot M_I$$

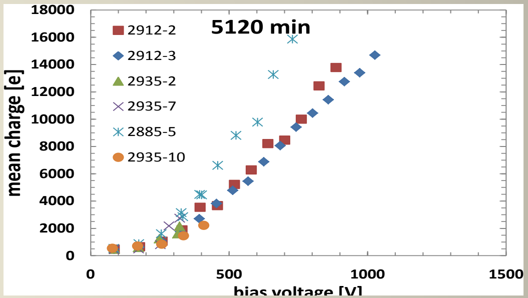
Annealing

- 6 samples with different processing after 10^{16} n_{eq}/cm^2
  - Steps: 80, 320, 640, 1280, 2560, 5120 min @ 60°C

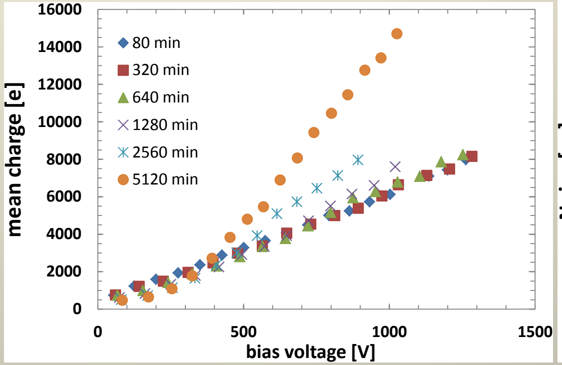
CCE

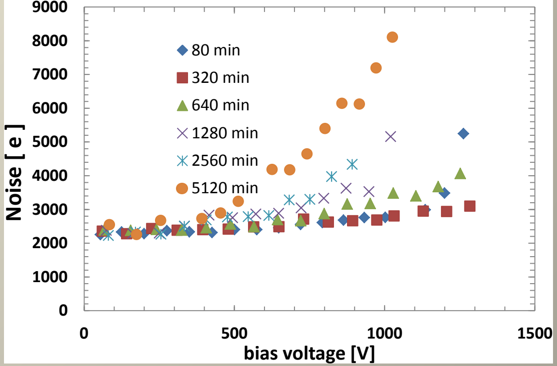






- All samples exhibit similar annealing
  - As already observed, reverse annealing enhances CM
- Gain offset by increased noise
- Could still be beneficial for small structures e.g pixels





Thin detectors

- Seen to provide more signal after heavy irradiation at “low” *V*
  - Less charge sharing for inclined tracks
- But beware:
  - Less ionization signal, more fluctuations
    - Bichsel, *Rev.Mod.Phys.60(1988)663*; PDG
  - Additional fluctuations from trapping, CM
    - Rely on Central Limit Theorem ?
  - Best measure *MPV-> S/N-> spectrum* on actual device in test beam
- Efficiency vs. noise occupancy as function of threshold - ultimate info for (binary) tracking

$$FWHM \geq 4\xi = 2K\cdot(Z/A)\cdot(x/\beta^2)\ \text{MeV}$$