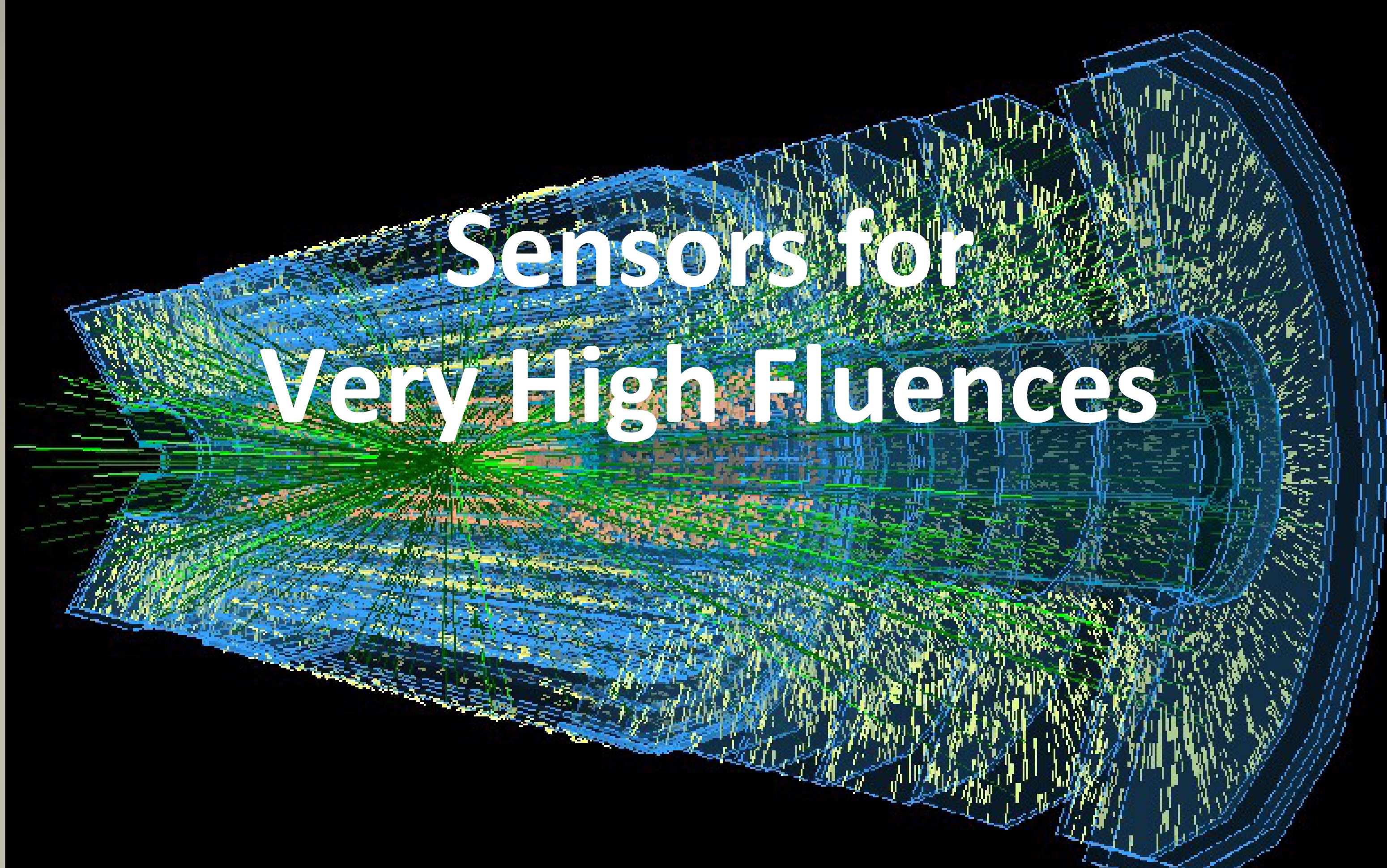
Sensors for Very High Fluences



Marko Mikuž

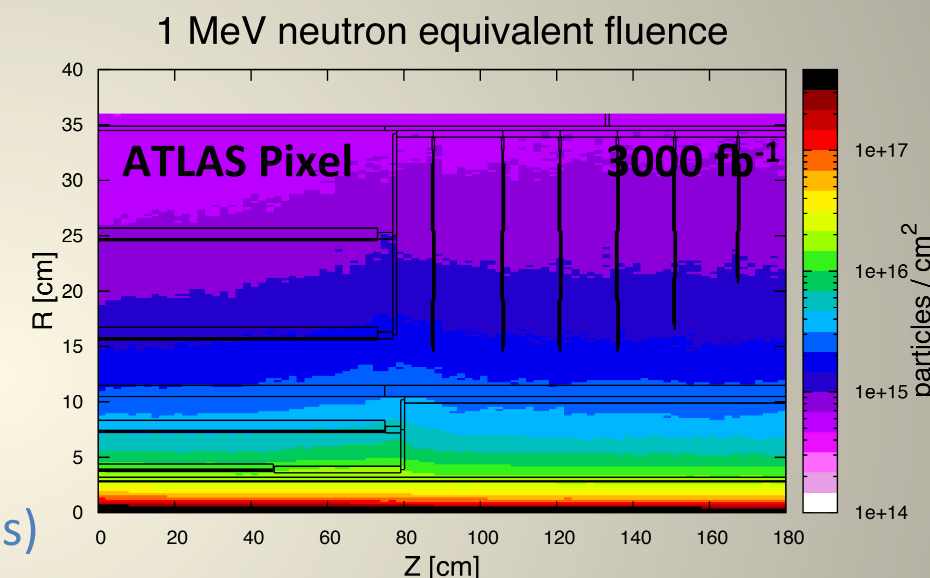
University of Ljubljana & Jožef Stefan Institute

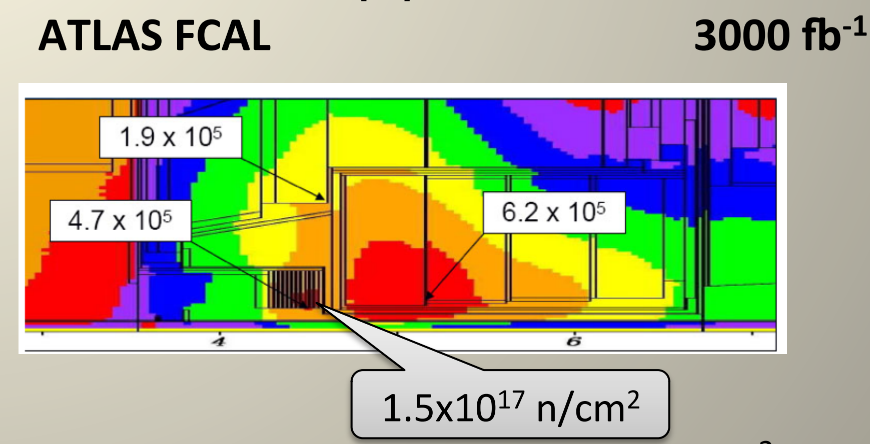
9th STD, Hiroshima

September 2nd, 2013

The Name of the Game

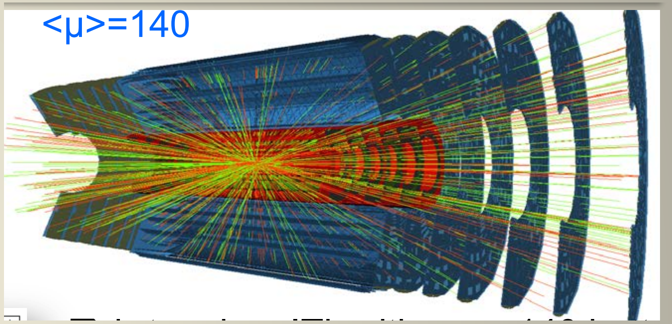
- We just gloriously finished Run I at LHC, a big challenge by itself
  - Designed for 730 fb^{-1} of 14 TeV pp collisions, ~30 fb^{-1} in Run I
  - Will probably get ~½ of planned
- HL-LHC in advanced planning
  - 3000 fb^{-1} i.e. ~10xLHC
  - ~10^{16} n_{eq}/cm^2 for pixels (pions)
  - ~10^{17} n_{eq}/cm^2 for FCAL (neutrons)
- Can (tracking) sensors survive in these extreme environments ?
  - The same question had been asked for SSC&LHC ~25 y ago
  - The answer was (is) never straightforward

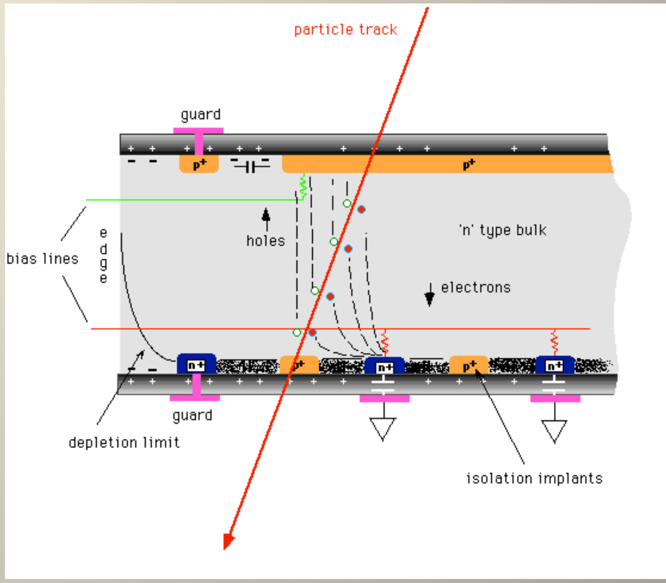




Tracking sensors

- 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





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

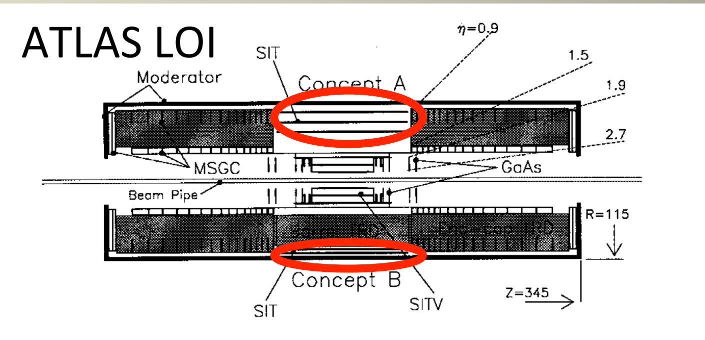
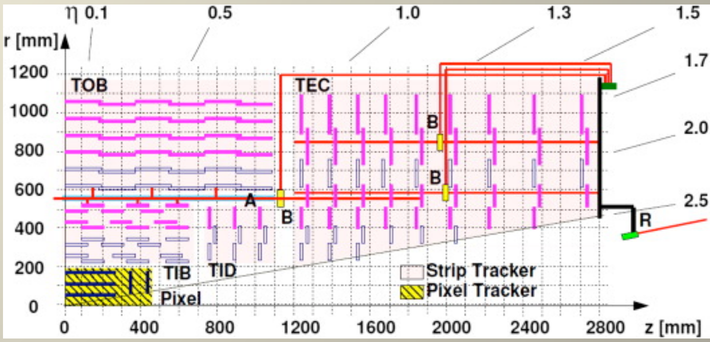


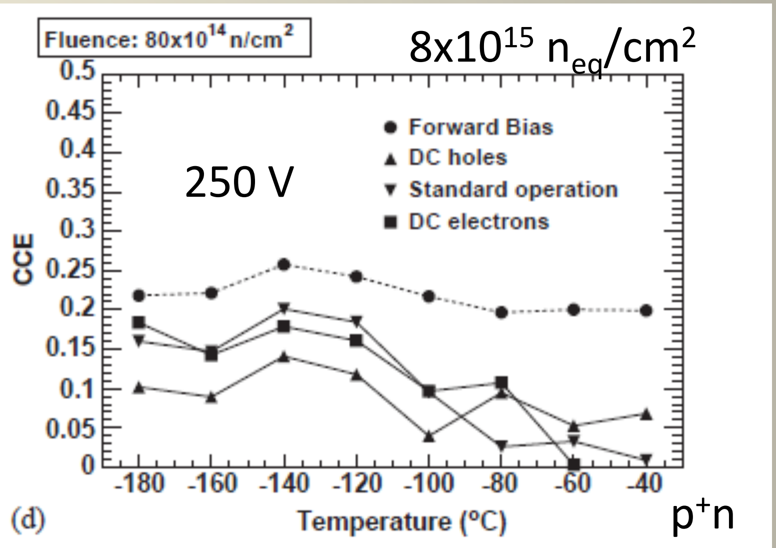
Figure 3.1: *Layout of the Inner Detector with two design concepts; concept A above and B below the beam line (dimensions in cm)*

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
  - …



I. Mandić et al. NIM A533 (2004) 442

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

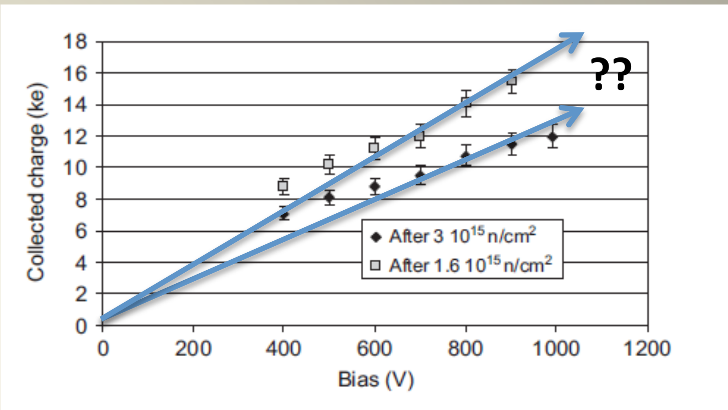
New Hope

- 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

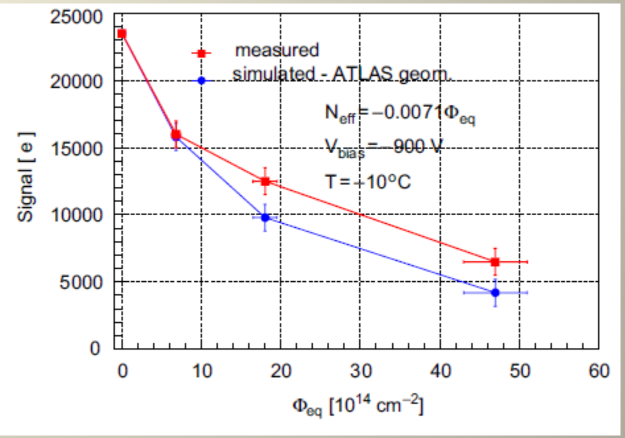
☺ *CCE* of ≥ 50 % @ 3×10^{15} n_{eq}/cm^2

- 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 ?



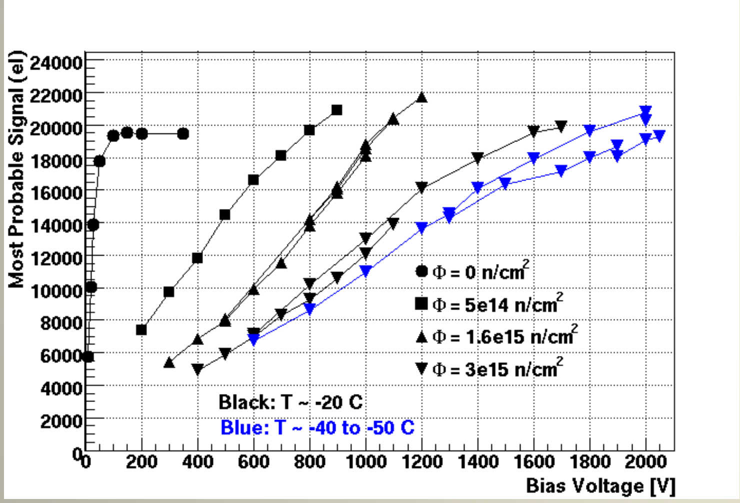
G. Casse et al. NIM A581(2007)318

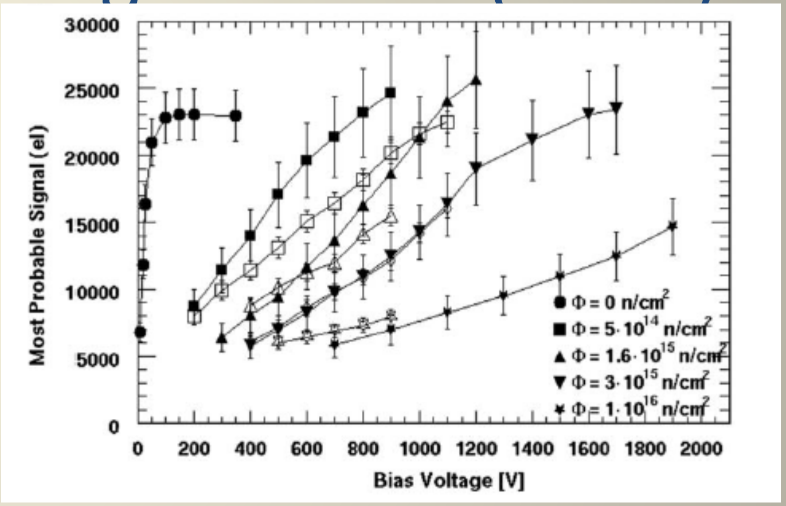


G. Kramberger et al. NIM A579(2007)762

Anno Mirabilis 2008

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

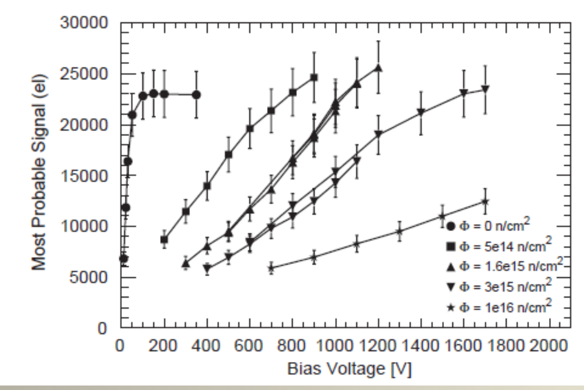


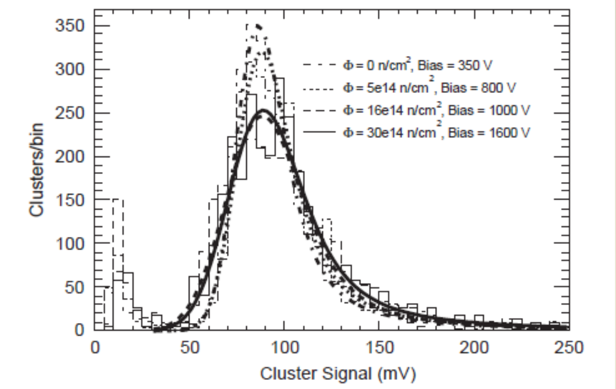


Measurement of charge collection in p-type microstrip sensors with SCT128 chip
I. Mandić et al., 12th RD50 Workshop , June 2008

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/cm²)	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 $g_c = 0.017\ \text{cm}^{-1}$.

$V > V_{FD}$ and no trapping ?

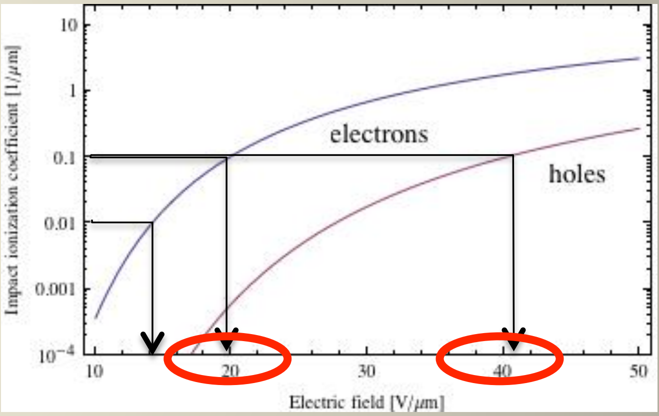
??

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).



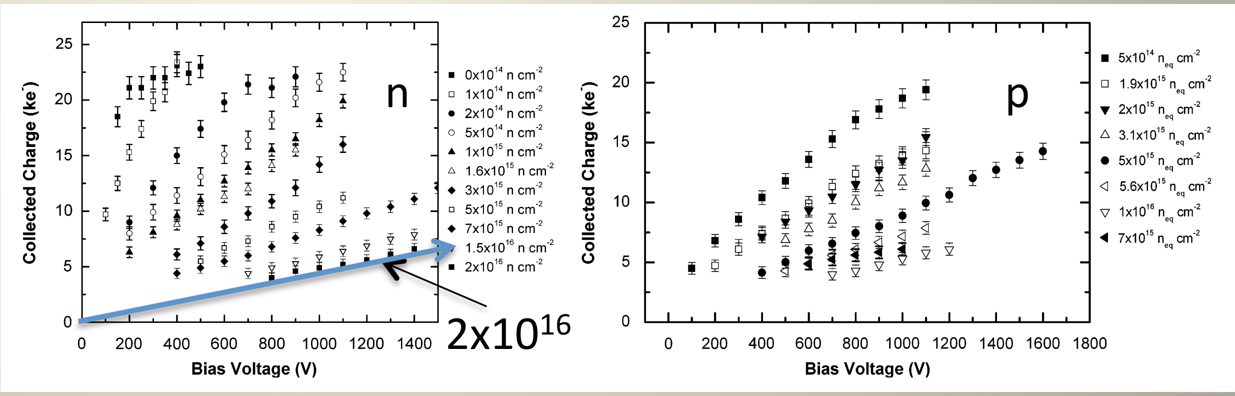
R.VAN OVERSTRAETEN and H.DE MAN, Solid-State Electronics 13(1970),583-608.
W.MAES, K.DE MEYER, R.VAN OVERSTRAETEN, Solid-State Electronics 33(1990),705-718.

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

Breakdown condition, can swap α_e with α_h

Multiplication observed

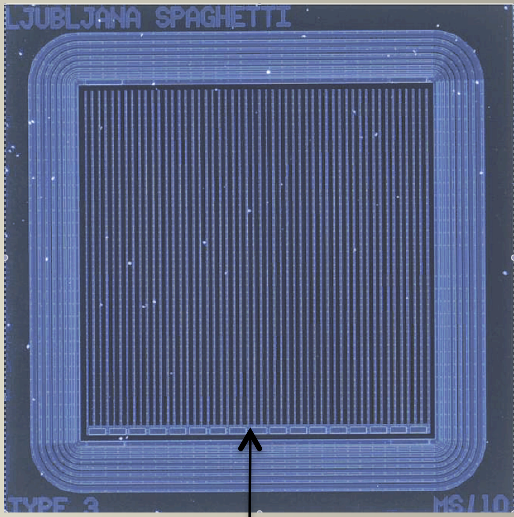
- *E* = 20(14) V/μm needs field peaking
  - Homogeneous *E*: V≈6000(4000) V for *d*=300 μm
  - Space charge, electrode shape sharpen up *E*
  - To get multiplication: $V \gg E/\alpha_e$ = 200(1400) V
    - Clear advantage of high *E* in limited region (APD's !)
- Observed in
  - Strip sensors
- Later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



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

How far can we go ?

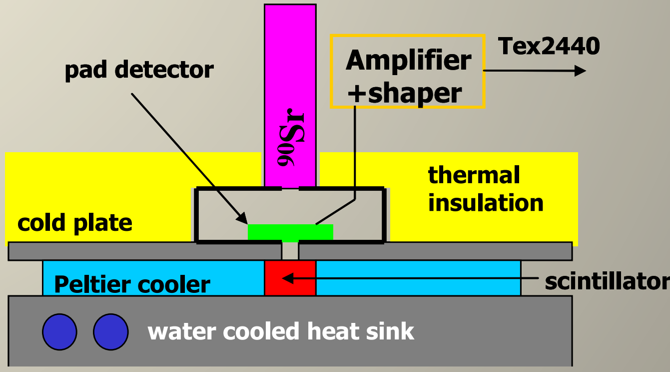
- Special run of “spaghetti” diodes to address this
  - All strips connected to one readout
  - Strip electric field, equal weighting field (~pad)
  - Different implants (double diffusion, energy)
- Irradiated with reactor neutrons in steps
  - 3, 10x10^{15} –> 5 samples annealed
  - 2, 4, 8x10^{16}, 1.6x10^{17} n_{eq}/cm^2 – 6 standard samples
- *I(V), CCE(V)* and noise on ^{90}Sr set-up at -25°C
  - Trigger purity allows measurements at low *S/N*



ganged strips

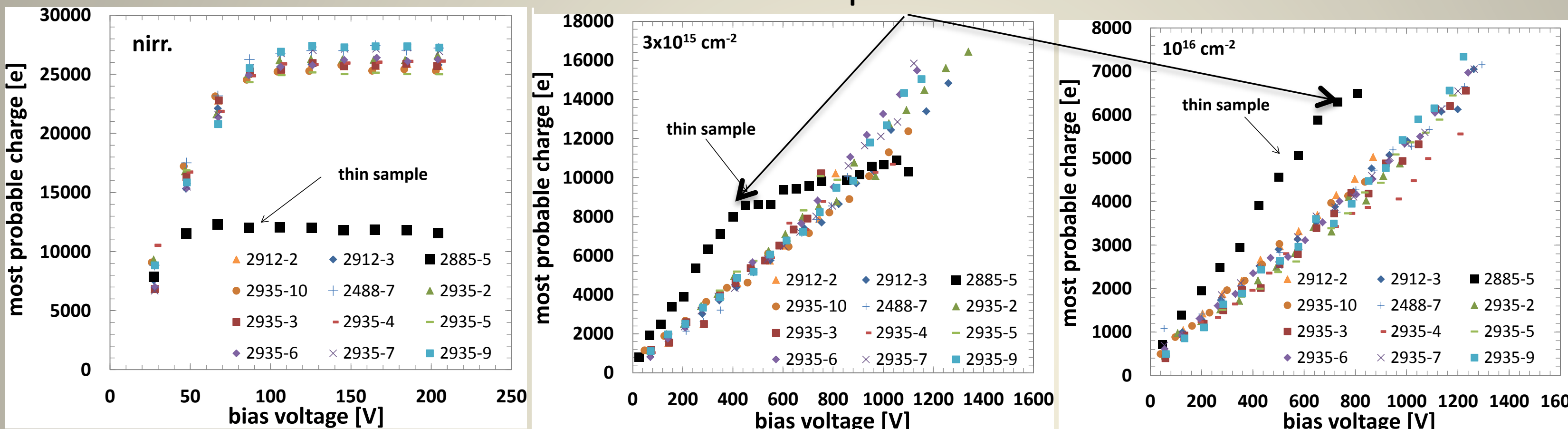
Published in : G. Kramberger et al., *JINST 8 P08004 (2013)*.

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}	$\approx$ 90 V	$\approx$ 30 V	$\approx$ 90 V	$\approx$ 90 V	$\approx$ 50 V

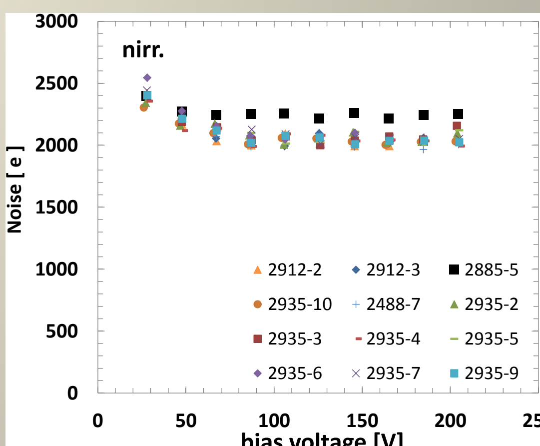


Over 0, 3×10^{15} & 1×10^{16} …

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

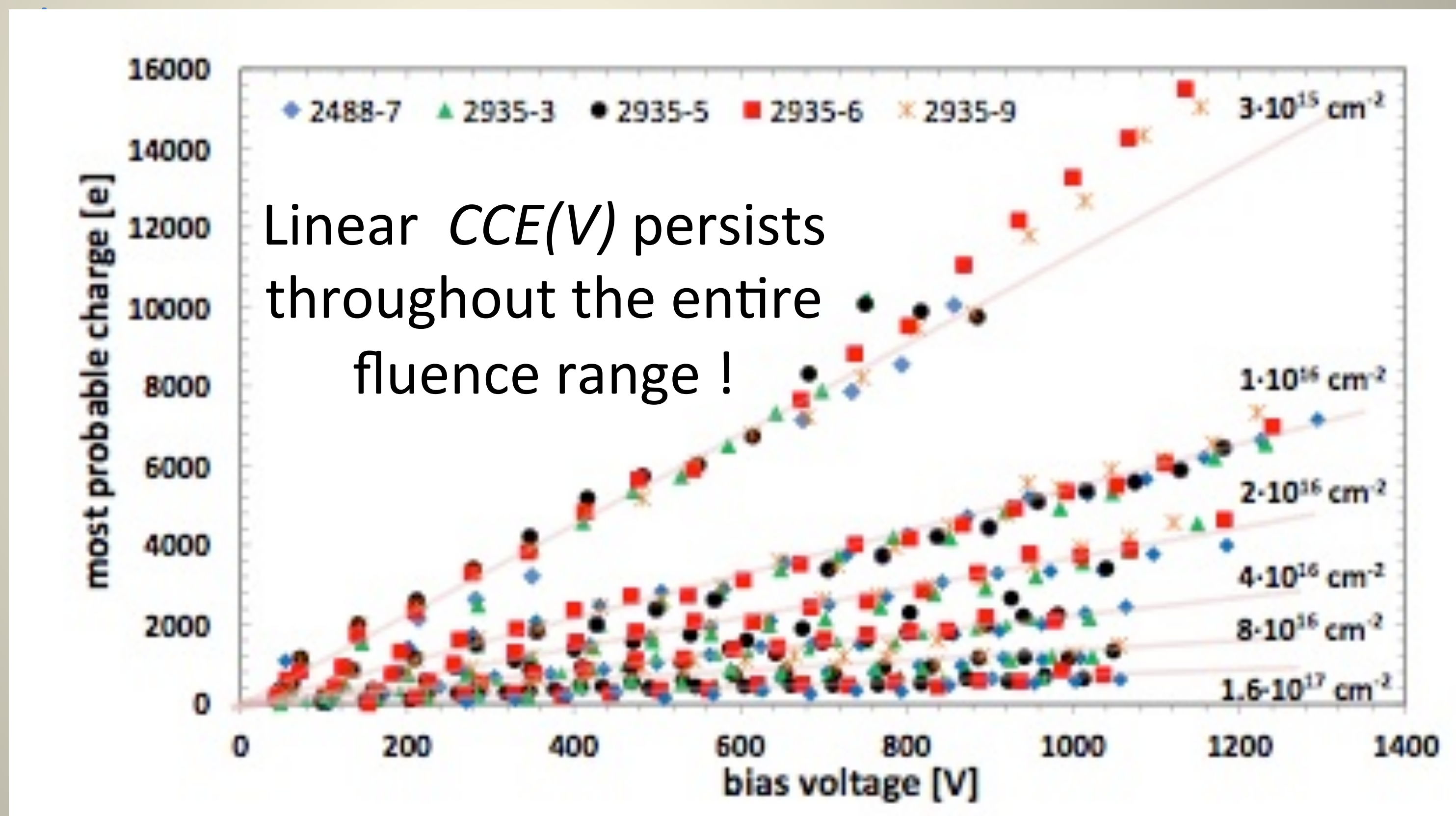


… into unchartered land

- Up to 1.6x10^{17} n_{eq}/cm^2
  - Steps 1, 2, 4, 8x10^{16}
  - Annealing 80 mins @ 60°C between …

… and

Silicon is still alive !

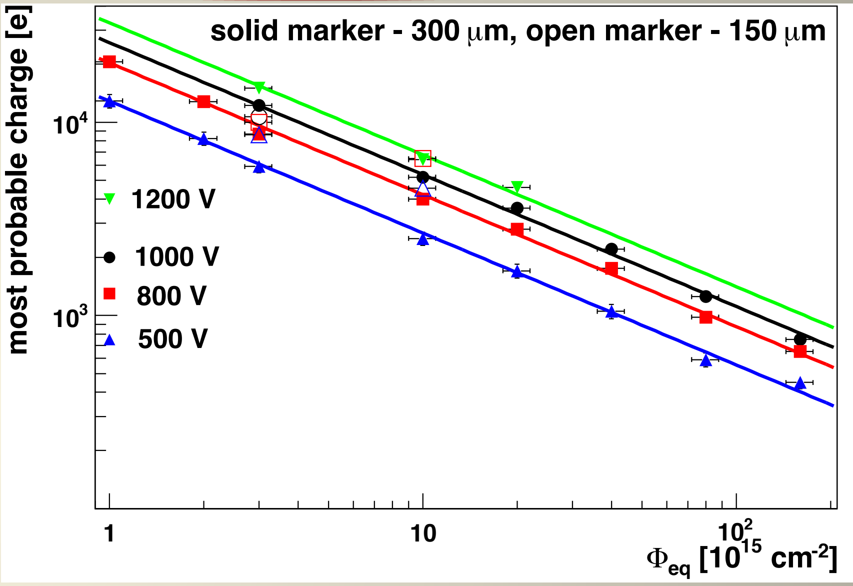


The magic formula

- Linear relationship *CCE(V)*
  - Same slope in log(*CCE*) *vs.* log(*Φ*) for any *V*
  - Magic formula

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

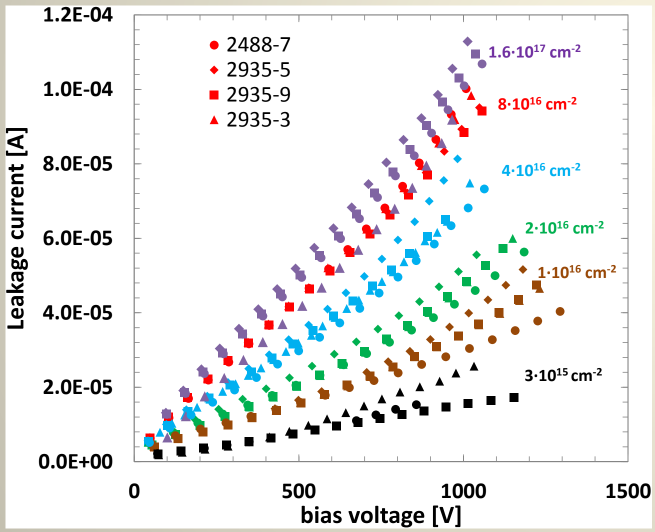
$$k = 26.4\ \mathrm{e_0/V}$$
$$b = -0.683$$

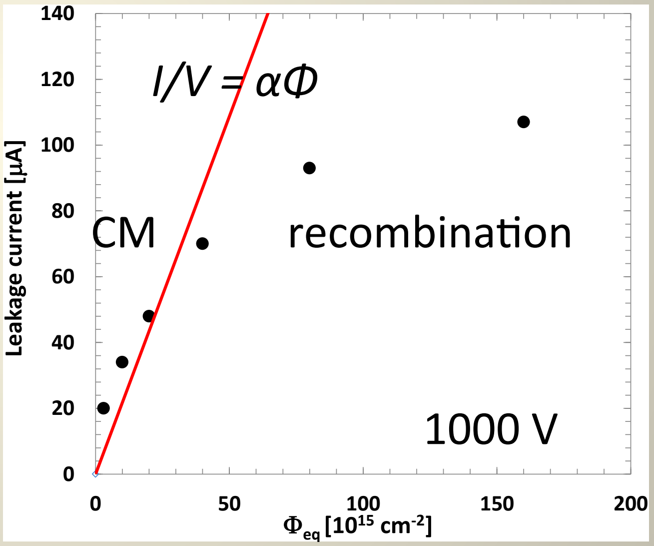


- "Magic" – no underlying physics… in fact lots of it
  - Mix of depletion, trapping and charge multiplication

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 ($M_I > M_S$)



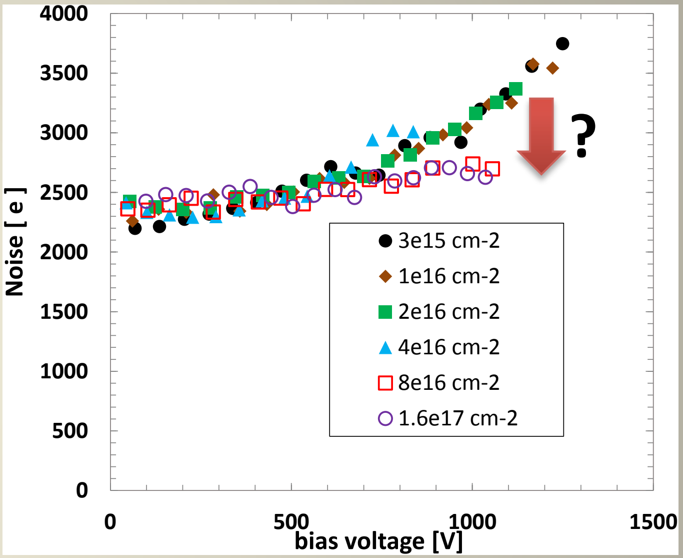


…true, until above $2x10^{16}$ recombination kicks in !

– 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 ?

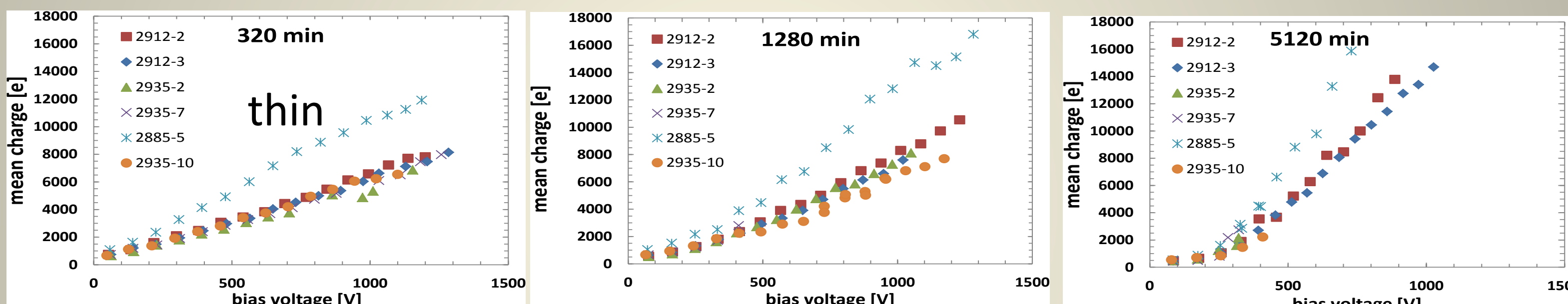


$$ENC_{MI} = \sqrt{2e_0 I_{gen} \tau} \cdot \sqrt{F} \cdot M_I$$

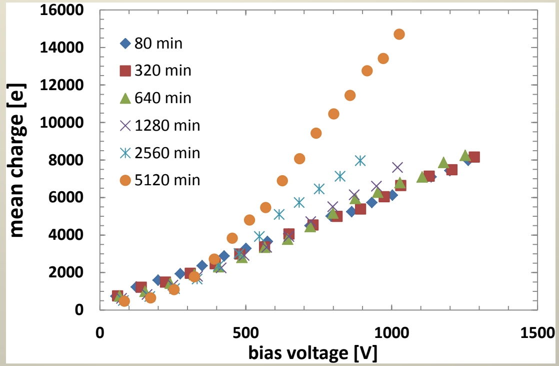
Annealing

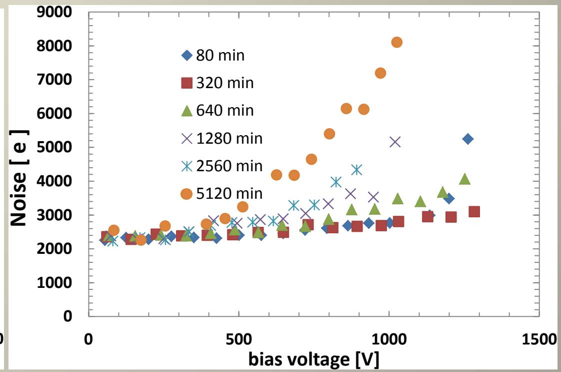
- 6 samples with different processing after 10^{16} n_{eq}/cm^2
  - Steps: 80, 320, 640, 1280, 2560, 5120 min @ 60°C

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

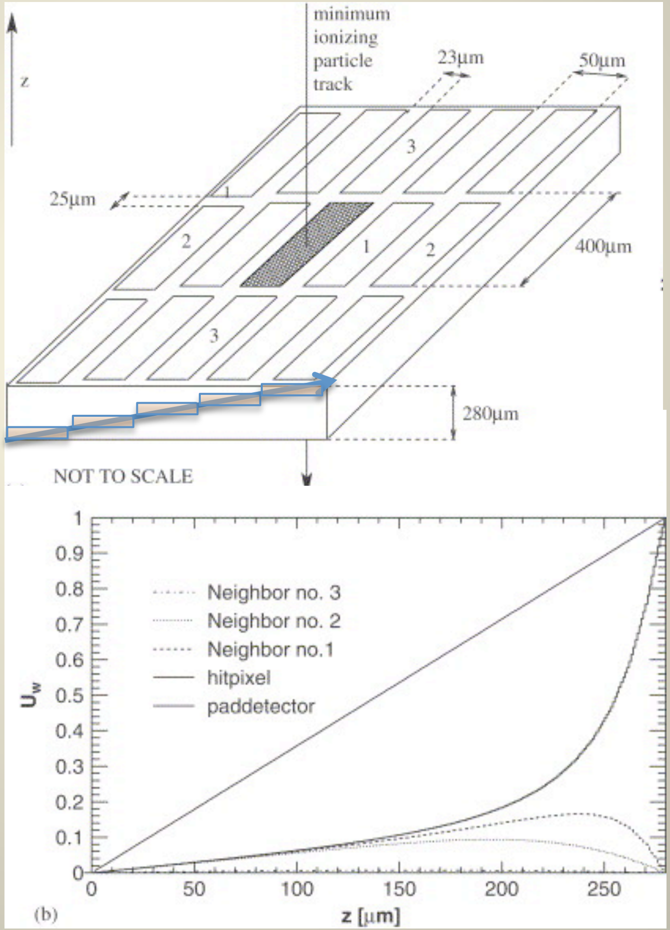




Weighting field

- Weighting field sharply peaked at strips, 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.



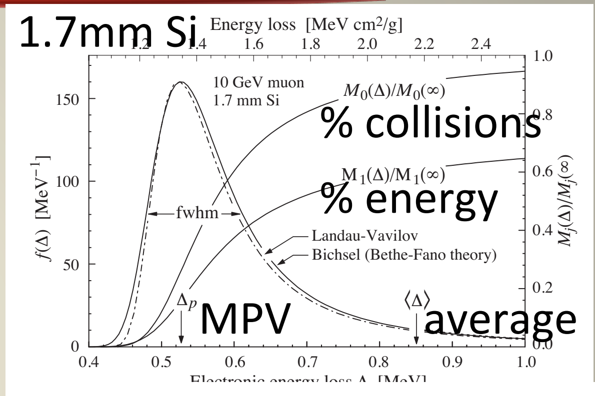
Top 25% yield 80% of signal, top 10% give 50%

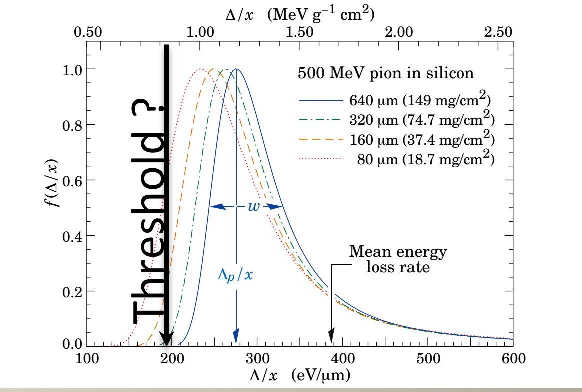
U_w	x	Δx
0.0	0	
0.1	145	145
0.2	208	63
0.3	234	26
0.4	247	14
0.5	256	9
0.6	263	7
0.7	268	5
0.8	272	4
0.9	276	4
1.0	280	4

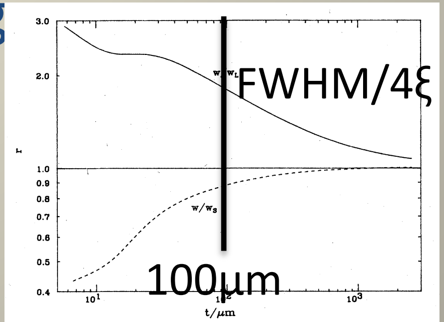
Thin detectors

- 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

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







Can we explain the signal ?

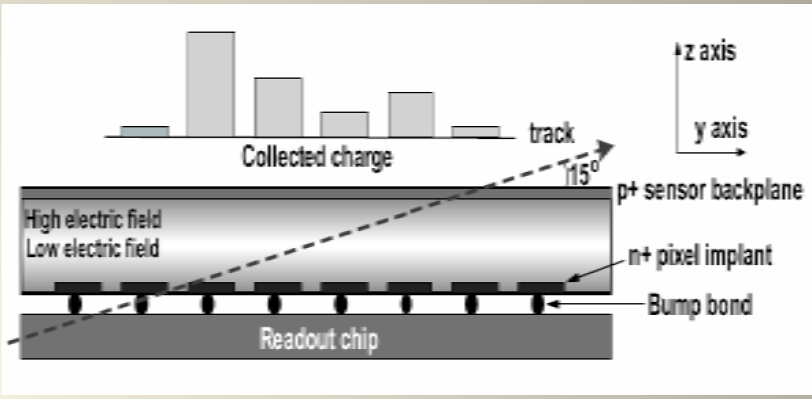
- Extensive efforts have been going on to model irradiated silicon from “first principles”
  - Trap parameters -> models (semi-analytic, TCAD)
- The problem, nicely formulated by Michael Moll

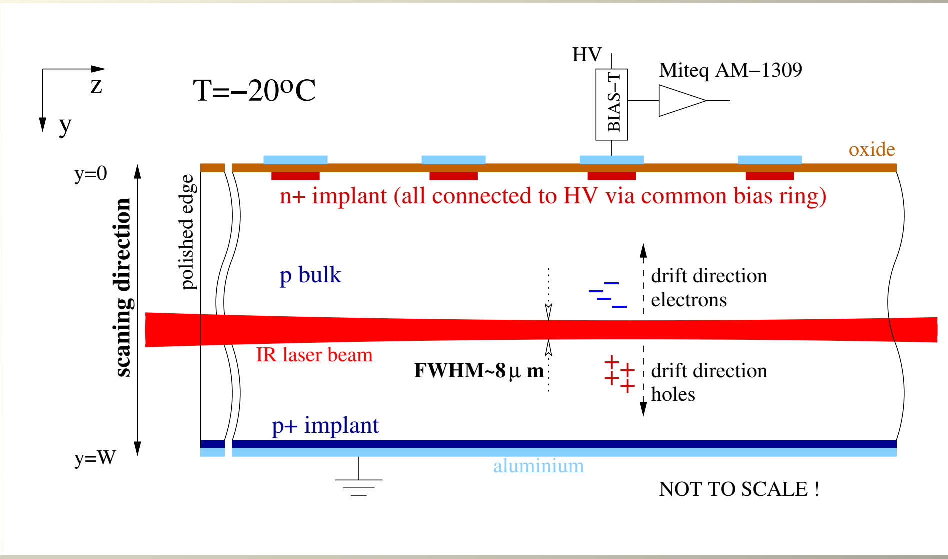
  “There is no shortage of traps in irradiated silicon…”
- Signal governed by Ramo theorem
  - E_w depends on geometry, can be calculated
  - E problematic for modeling
- Can we measure it ?

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

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

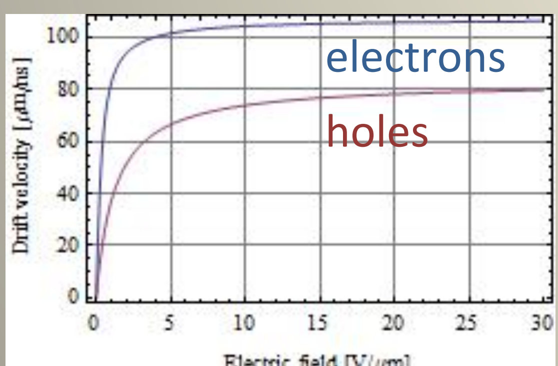


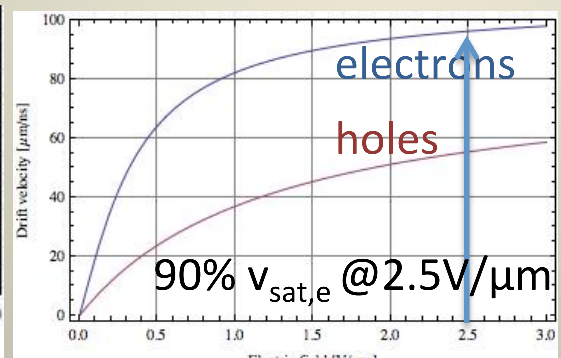


Electric field measurement

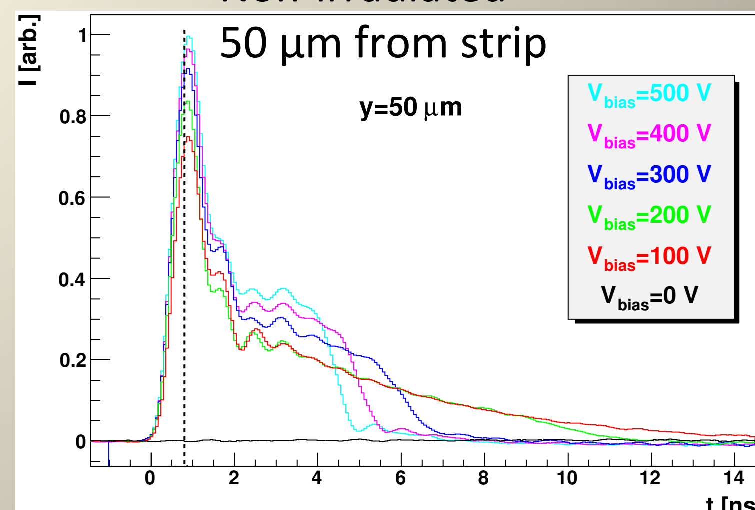
- Initial signal proportional to velocity sum at given detector depth
- Caveats for field extraction
  - Transfer function of electronics smears out signal, snapshot taken at ~600 ps
    - Problematic with heavy trapping
    - Electrons with v_{sat} hit electrode in 500 ps
  - Mobility depends on E
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

$$I(t=0) = q\vec{v}\cdot\vec{E}_w =$$
$$= N_{e-h}e_0\cdot(v_e+v_h)/d =$$
$$= N_{e-h}e_0\cdot(\mu_e+\mu_h)\cdot E(x)/d$$



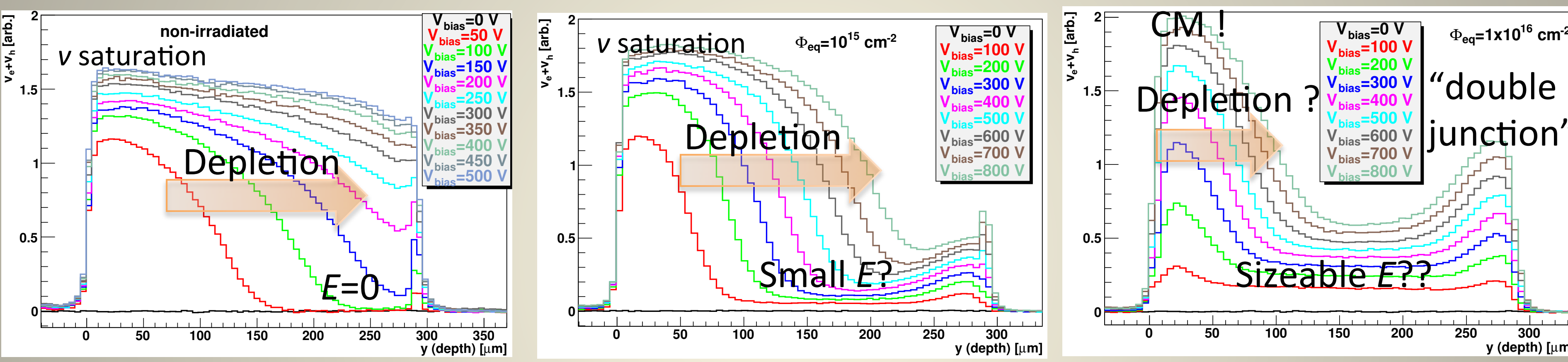


Non-irradiated



Selected results

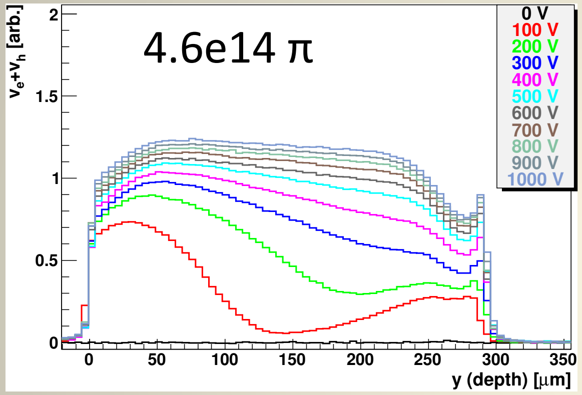
- Hamamatsu n⁺ strip (mini-)sensors, FZ p-type, irradiated with neutrons

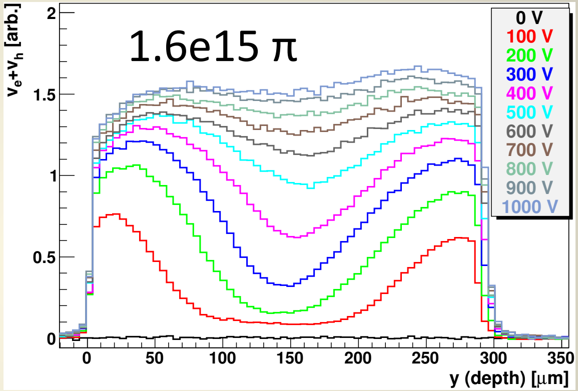


- Instructive qualitatively, but (not yet ?) quantitative in terms of *E*
  - Non-irradiated "by the book" for abrupt junction n⁺p diode
    - SCR and ENB nicely separated, small double junction near backplane
  - Medium fluence ($\Phi=10^{15}$ neutrons): some surprise
    - Smaller space charge than 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*

Mixed irradiations

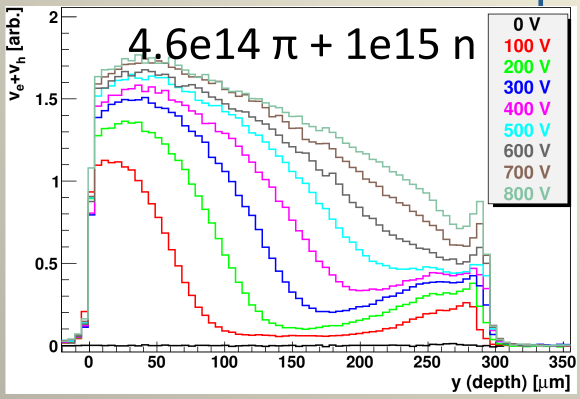
- First PSI pions, $\Phi=4.6\times10^{14}$, 1.6×10^{15} n_{eq}/cm^2

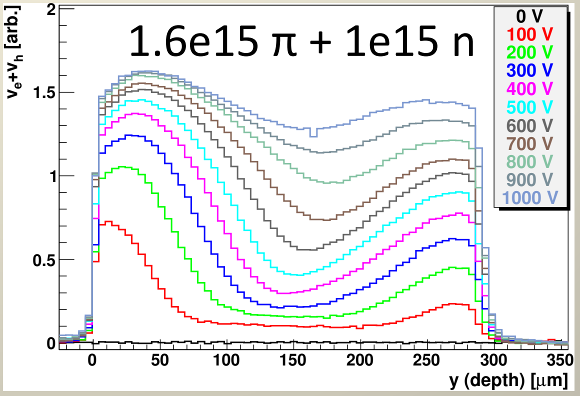




Oxygen helps for charged hadrons…

- Topped by 10^{15} n_{eq}/cm^2 neutrons





…but neutrons introduce acceptors providing negative space charge

Conclusions

- In recent years we learned how to exploit charge multiplication to enhance signal in silicon detectors
- This offers the possibility to operate silicon sensors at fluences not imaginable a decade ago
- Success of operation depends critically on details in sensor design, electronics and environment
- New techniques enable better understanding of sensor operation and further optimization