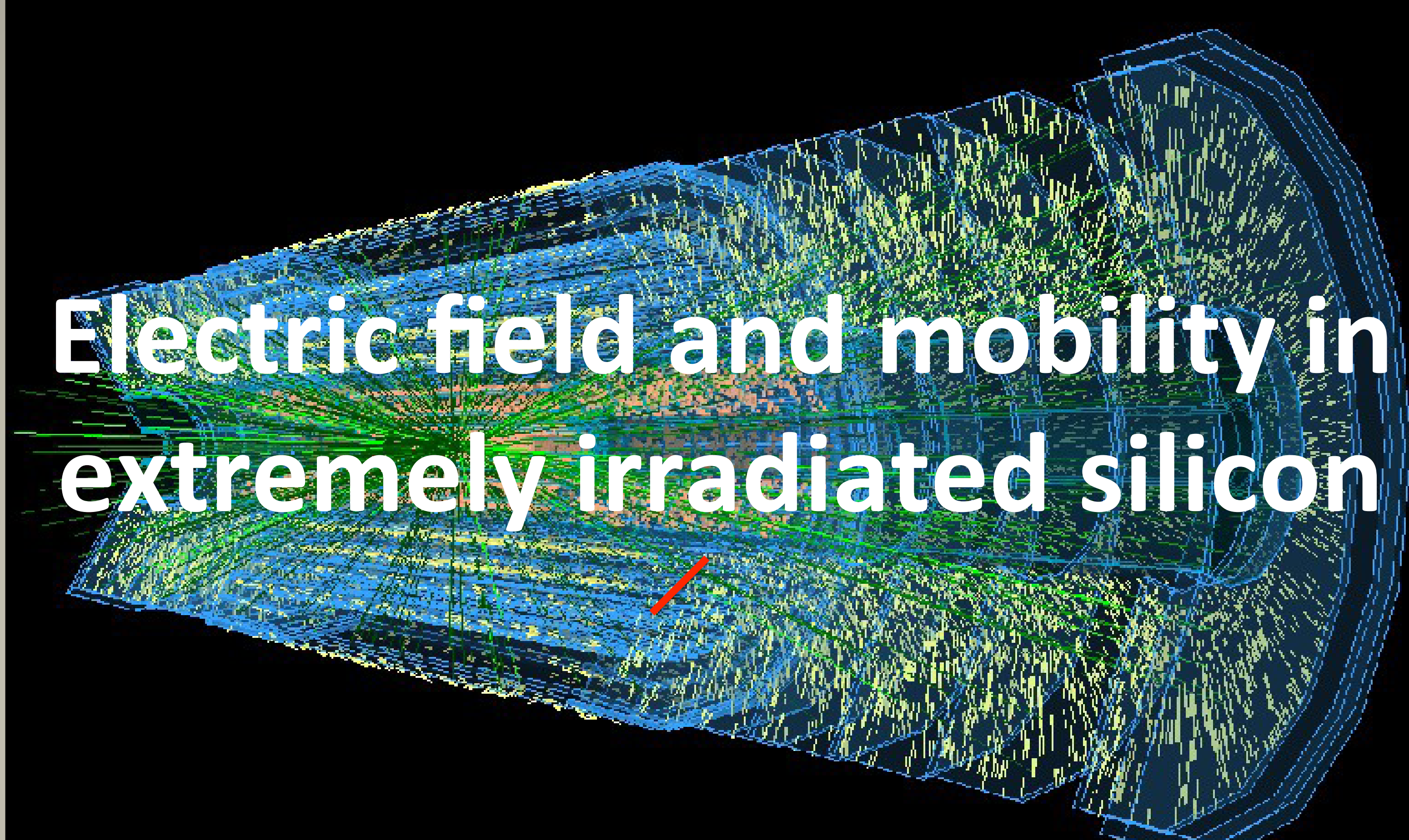

Electric field and mobility in extremely irradiated silicon

Marko Mikuž, G. Kramberger, V. Cindro, I. Mandić, M. Zavrtanik

University of Ljubljana & Jožef Stefan Institute

RD-50, CERN

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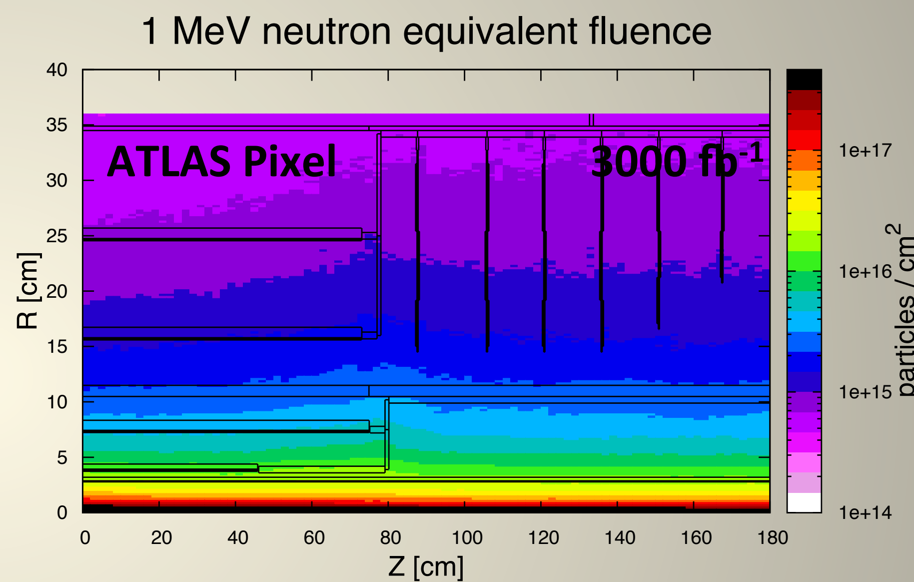
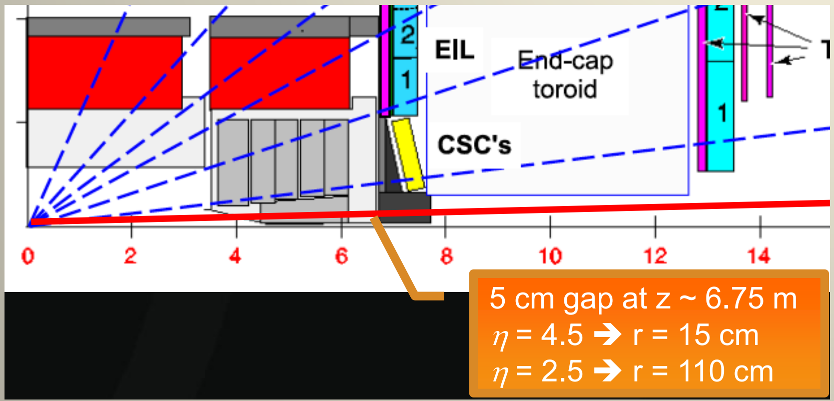
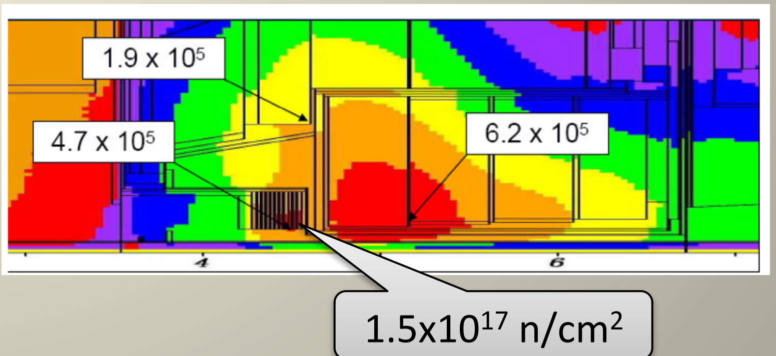
Why the 10^{17} Ballpark ?

- 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)
  - nx10^{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 ?



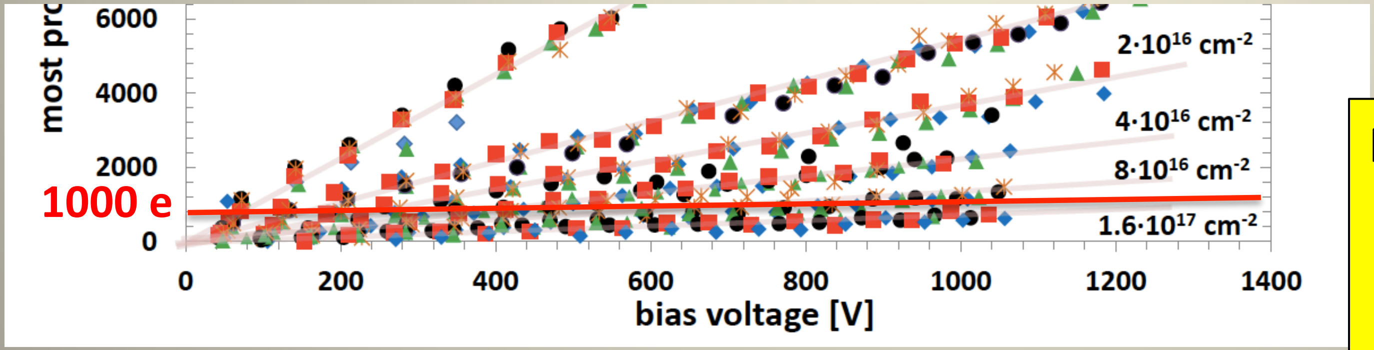


ATLAS FCAL **3000 fb^{-1}**



Expectations for 10^{17} n_{eq}/cm^2

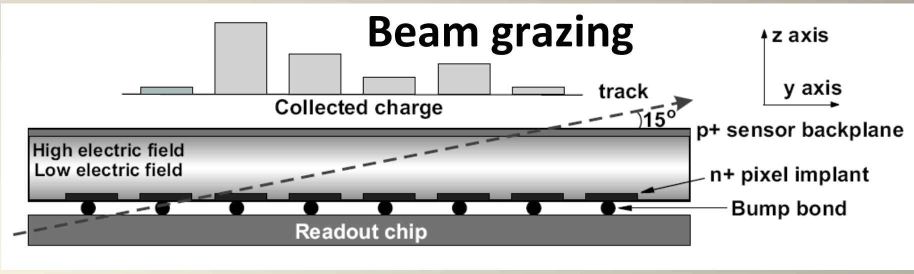
- Current: I_{leak} = 4 A/cm^3 @20°C
  - 2 mA for 300 μm thick 1 cm^2 detector @ -20°C
- Depletion: $N_{eff} \approx 1.5 \times 10^{15}$ cm^{-3}
  - *FDV* ≈ 100 kV
- Trapping $\tau_{eff} \approx$ 1/40 ns = 25 ps
  - $Q \approx Q_0/d\ v_{sat}\tau_{eff} \approx$ 80 e/μm 200 μm/ns 1/40 ns = 400 e in very high electric field (>1 V/μm)
- Observed signal not at all compatible with expectations

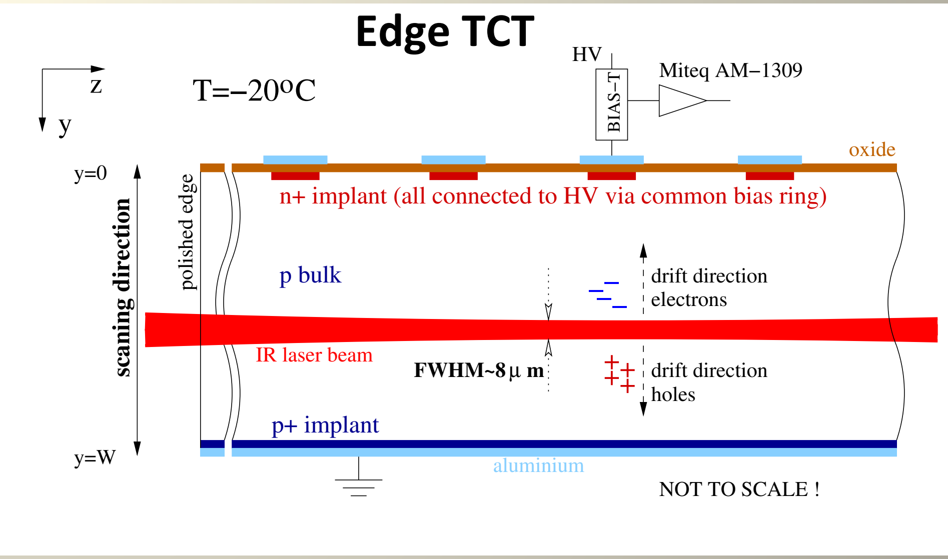


From:
G. Kramberger et al.,
JINST 9 P10016(2014).

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

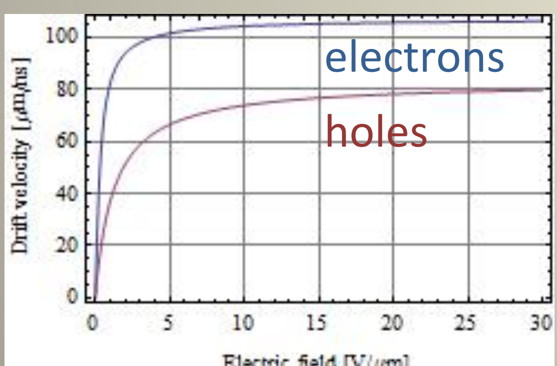


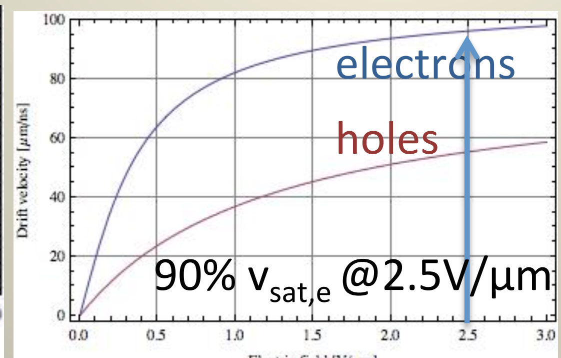


Electric Field Measurement

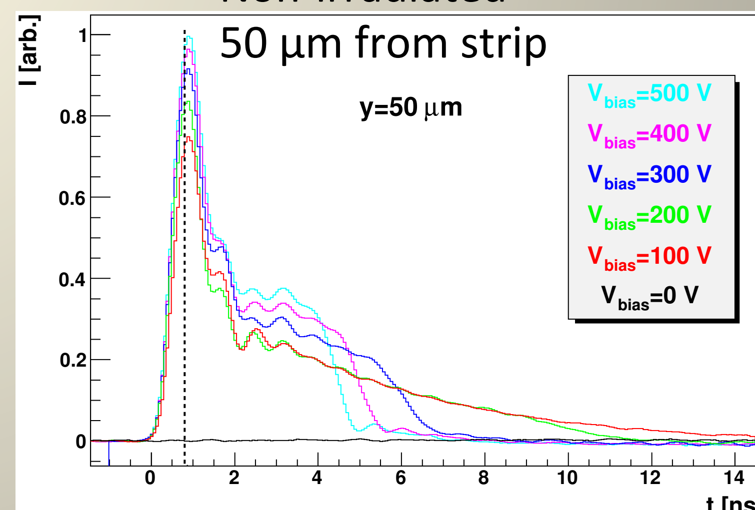
- Initial signal proportional to velocity sum at given detector depth
- Caveats for field extraction
  - Transfer function of electronics smears out signal, snapshot taken at ~600 ps
    - Problematic with heavy trapping
    - Electrons with v_{sat} hit electrode in 500 ps
  - Mobility depends on *E*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

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



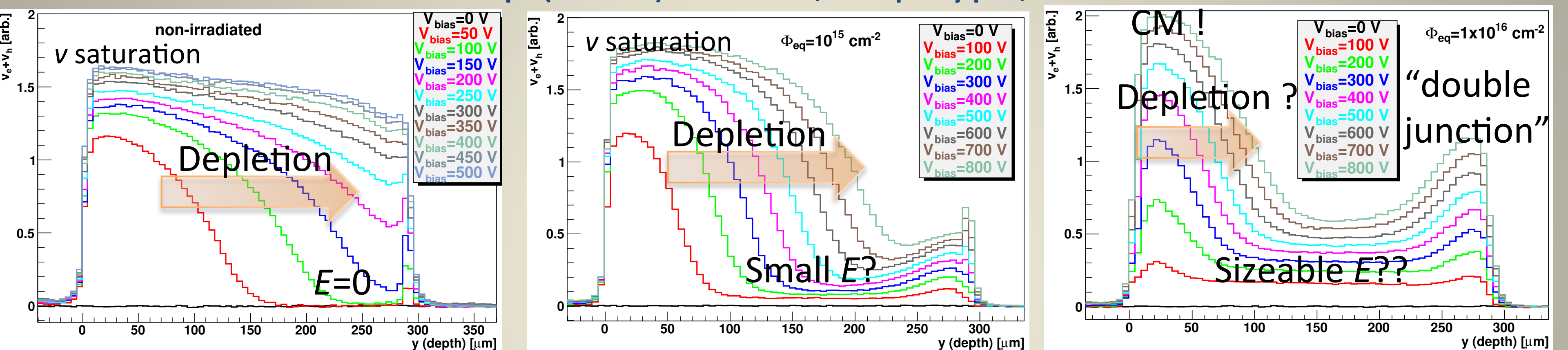


Non-irradiated



Selected Results

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



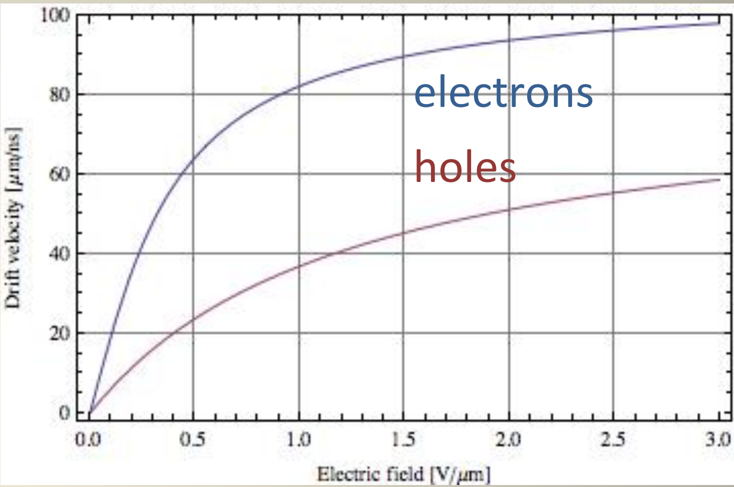
- Very instructive regarding qualitative electric field shape
  - Non-irradiated "by the book" for abrupt junction n$^+$p diode
    - SCR and ENB nicely separated, small double junction near backplane
  - Medium fluence ($\Phi=10^{15}$ neutrons): some surprise
    - Smaller space charge than expected 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 ?

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

Field Modeling: Field Value

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

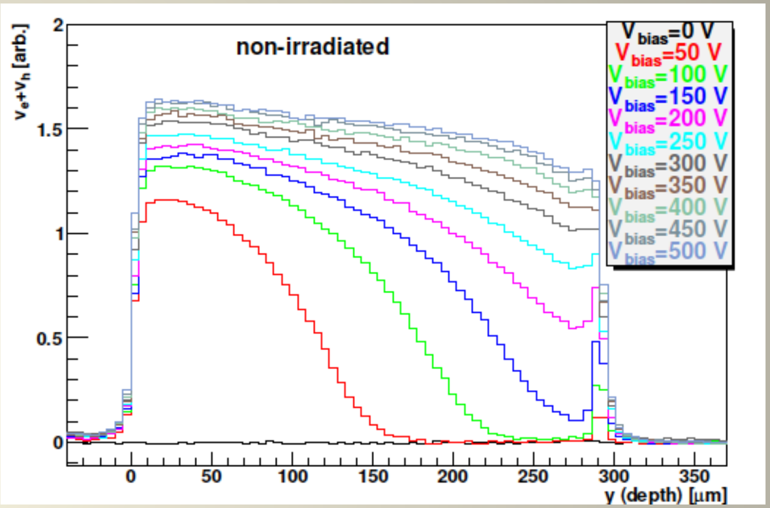
- Invert to get *E(y)* ? Caveat:
  - *μ=μ(E),* need *scale* of *E* to invert
- Scale from $\int E(y)dy = V$? Not really:
  - Poorly known large field at electrode contributes sizably to the integral
- Measured "*I(t)*" is in fact a convolution of the induced signal with electronics transfer function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

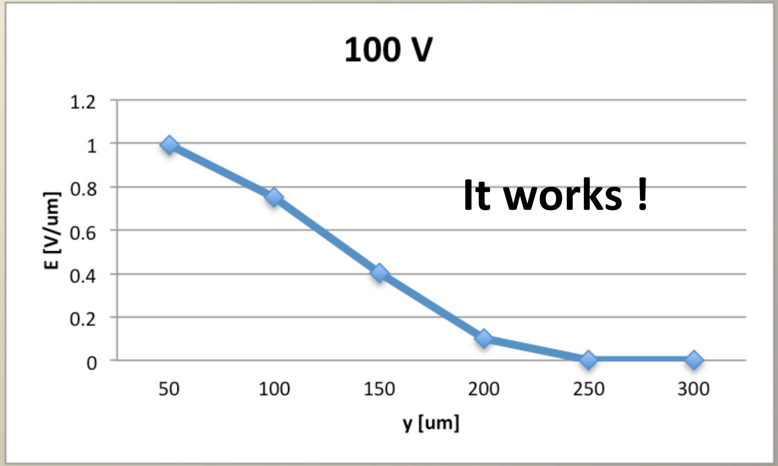


$$I(t) \propto \int_0^t (\mu_e + \mu_h) \cdot E(y(t'))H(t-t')dt'$$

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*
  - $E = (1.1 + 1.2\times(w\text{-}y))$ V/µm
  - 2.1 V/µm @ y=50 µm
- In $v_{sum}(y)$: 1.62(a.u.) translates to 131 µm/ns
- Can invert $E(v_{sum})$

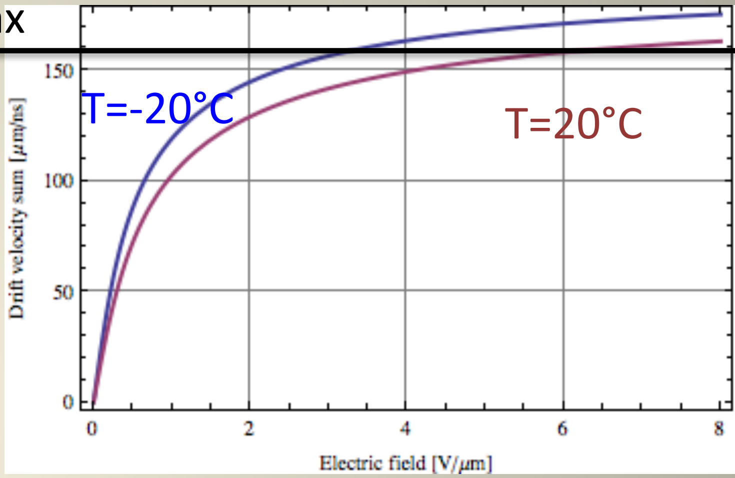


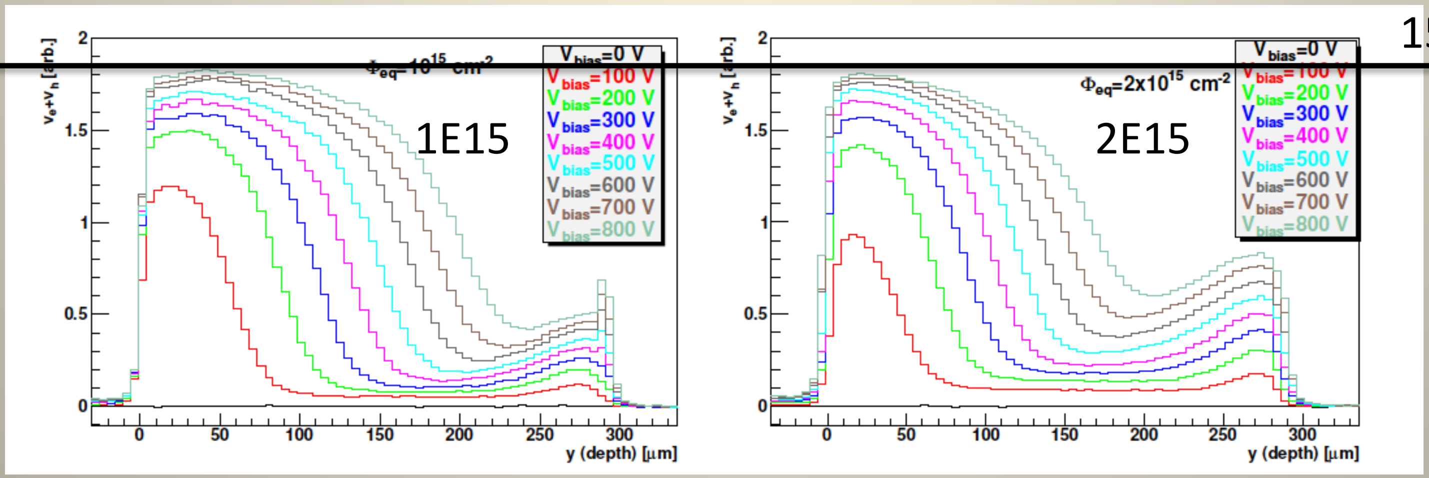


Can We Scale to Irradiated Si ?

- 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: assume to keep same laser input
  - expect ~10%, in fact looks even better

plot max

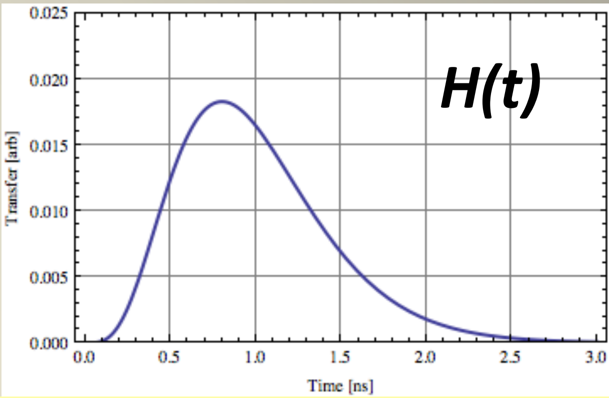




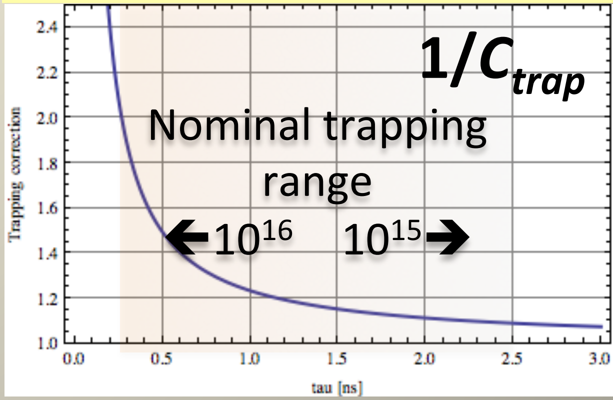
150 μm/ns
2.3 V/μm

Trapping

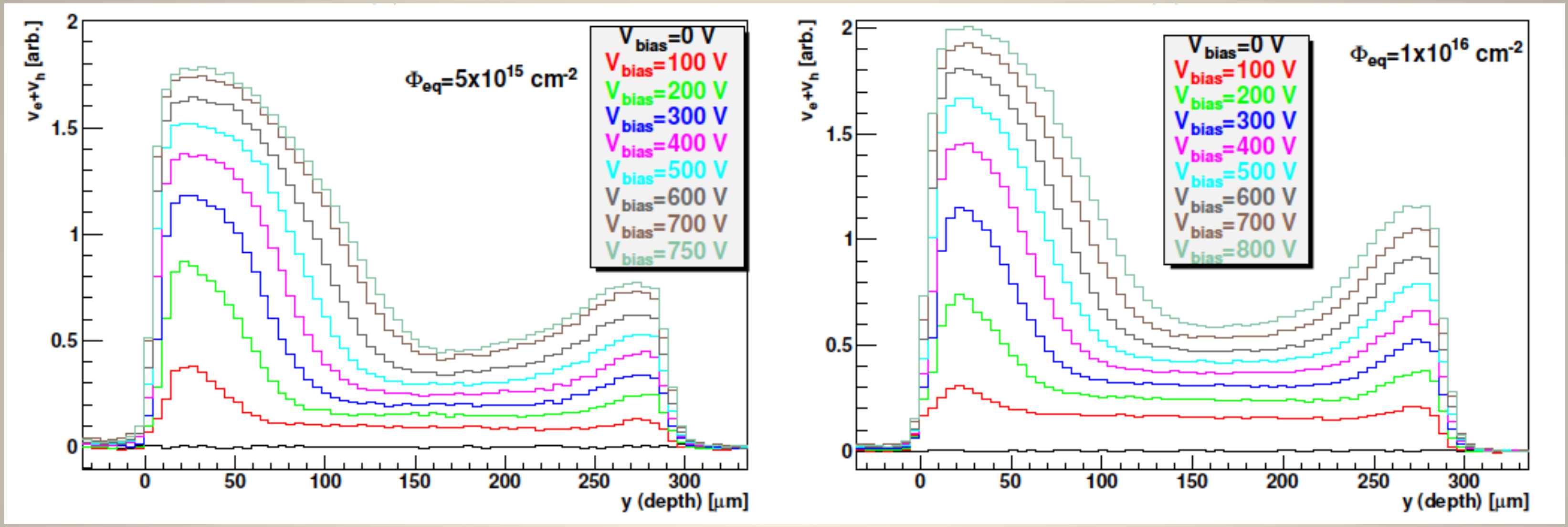
- Naïve trapping – reduce *I(t)* by $e^{-t/\tau}$
  - Independent of *E*, so v_{sum} just scaled up
  - But $\tau << t$ at 10^{16} - no signal ??
- Have to invoke transfer function *H(t)*
  - Reproduce *I(t)* for non-irradiated
  - Model as CR-RC^4 with t_{sh} = 0.8 ns
- Trapping correction with *H(t)*
- 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 !



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



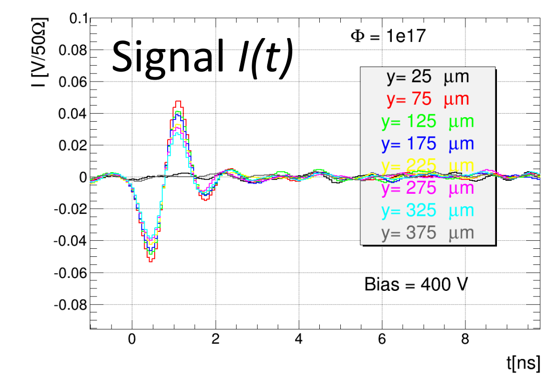
Charge Multiplication

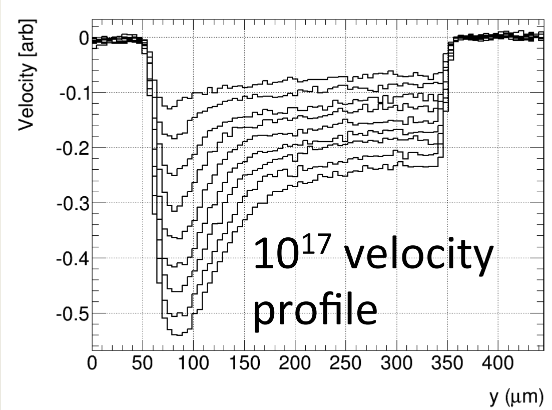


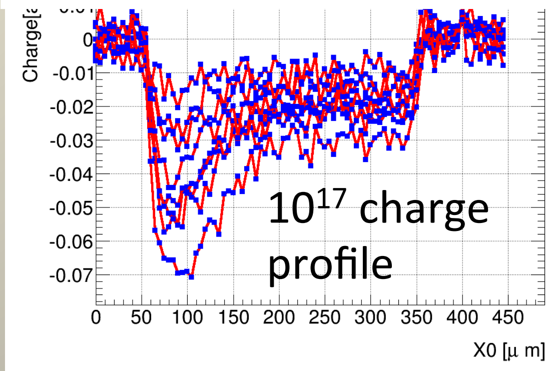
- At $5\text{x}10^{15}$ and 10^{16} no clear saturation in v_{sum} observed
- Taking nominal trapping correction both v_{sum} exceed $v_{sum,sat}$ = 190 μm/ns (2.35 a.u.×C_{trap})
- Clear sign of charge multiplication close to electrode
- Difficult to model, so give up modeling this region

Fresh from the Oven

- Recently added $5x10^{16}$ and 10^{17} n_{eq}/cm^2 measurements of the same detector
  - 10^{16} of this fluence fully annealed, the rest 80 min @ 60°C
- Persisting problem – signal oscillations
  - period ~5/4 ns
  - LC ? signal generation ? amplifier ?
- Nevertheless, velocity (slope) and charge (integral) yield consistent results
  - should be, as $Q \approx Q_0/d\ v_{sum}\tau_{eff}$
- Cannot use *I(t)* to measure trapping...

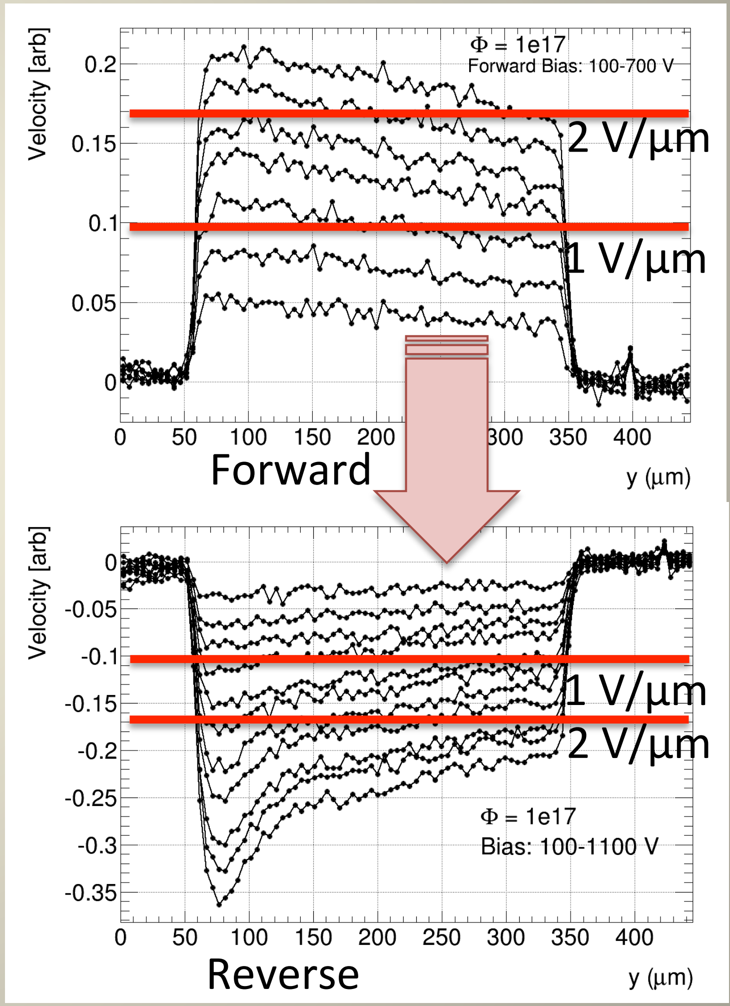






Field Value Revisited

- Had to tune up laser power for measurements
  - lost velocity normalization
- Solution: concurrent forward bias v_{sum} measurements
  - clean ohmic behaviour with some linear field dependence
    - constant (positive) space charge
  - can use $\int E(y)dy = \bar{E}d = V$ to pin down field scale
    - corrections from *v(E)* non-linearity small
  - Use same scale for reverse bias
- FW measurements up to 700 V
  - know *E* scale up to 2.33 V/µm
  - can reveal *v(E)* dependence

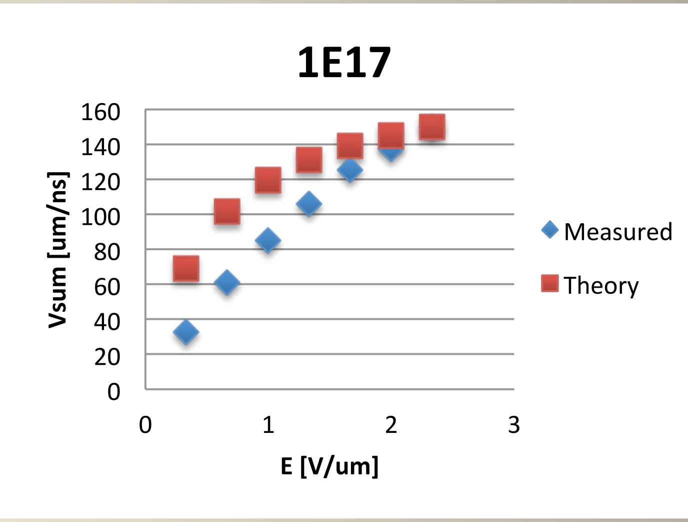


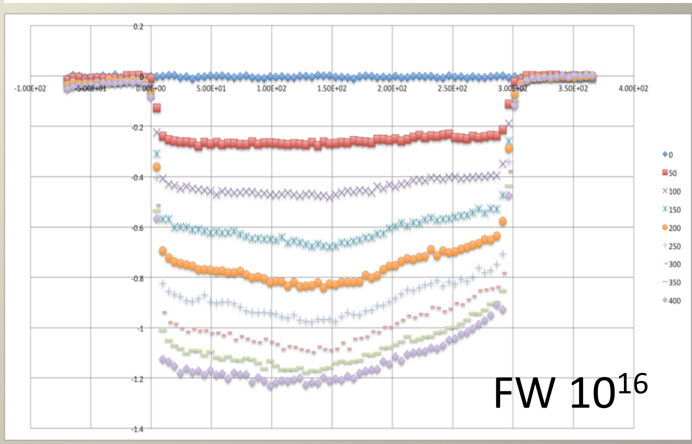
Mobility Considerations

- Can extract *v(E)* up to a scale factor
- Observe less saturation than predicted
- Model with

$$v_{sum}(E) = \frac{\mu_{0,sum} E}{1 + \mu_{0,sum} E / v_{sum,sat}}$$

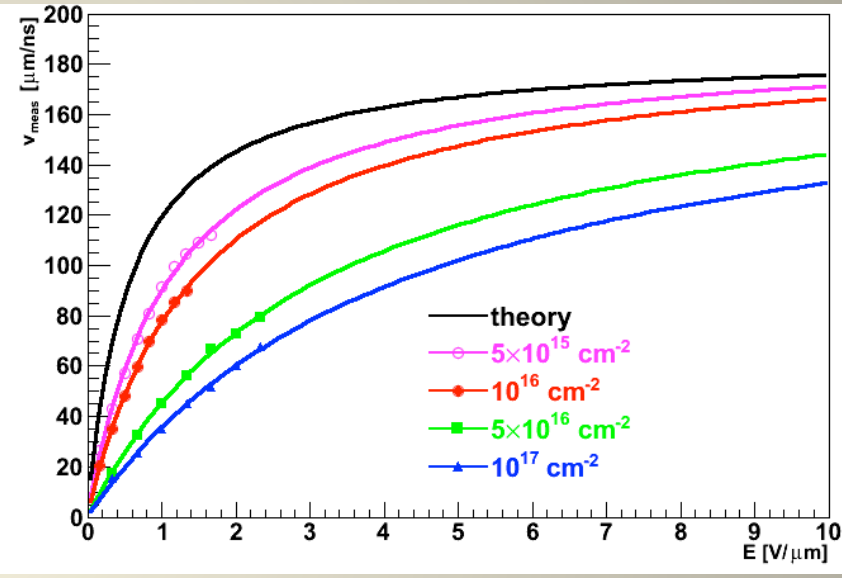
  - keep saturation velocity sum at $v_{sum,sat}$ = 190 µm/ns
  - float zero field mobility sum
  - fit *v(E)* for 5, 10, 50, 100x10^{15}
    - n.b. FW profiles worse for lower fluences, but departures from average field still small





Mobility Results

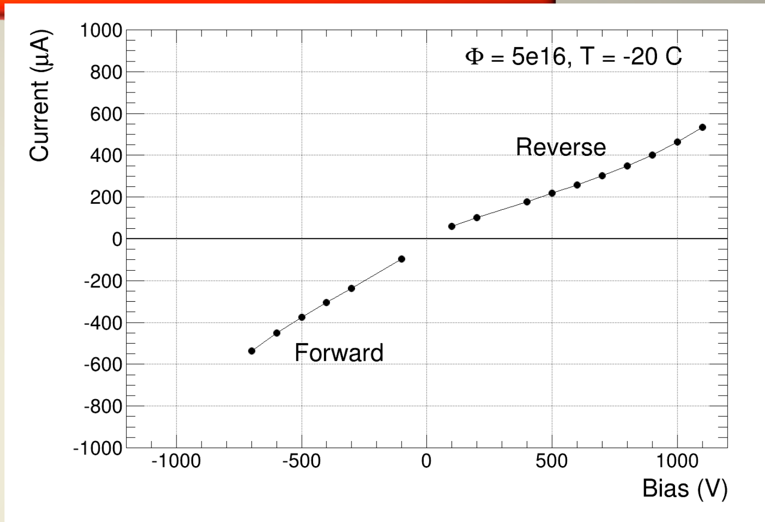
- Data follow the model perfectly
  - although *E* range limited, $v_{sum,max}$ still > 1/3 of $v_{sum,sat}$
- Monotonic decrease of zero field mobility with fluence observed
  - factor of 6 at 10^{17} n_{eq}/cm^2
  - need 6x higher *E* to saturate *v* !

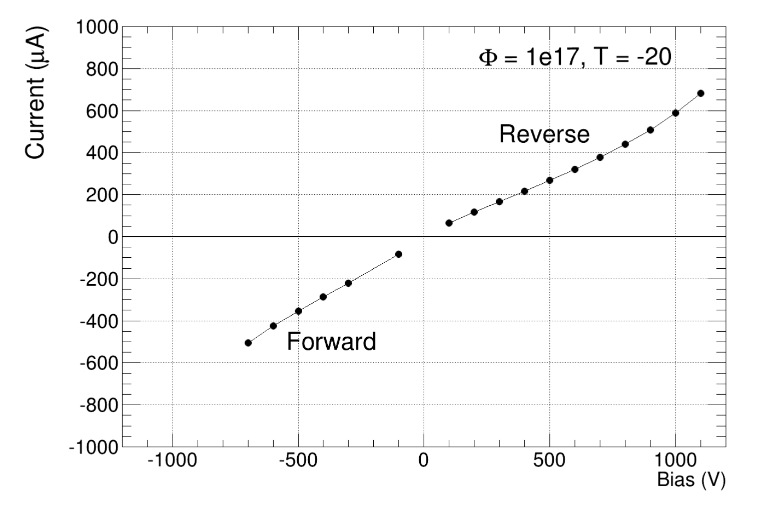


Φ	$\mu_{0,sum}$
[10^{15} n_{eq}/cm^2]	[cm^2/Vs]
non-irr (model)	2680
5	T=-20°C 1710
10	1300
50	590
100	430

Current Characteristics

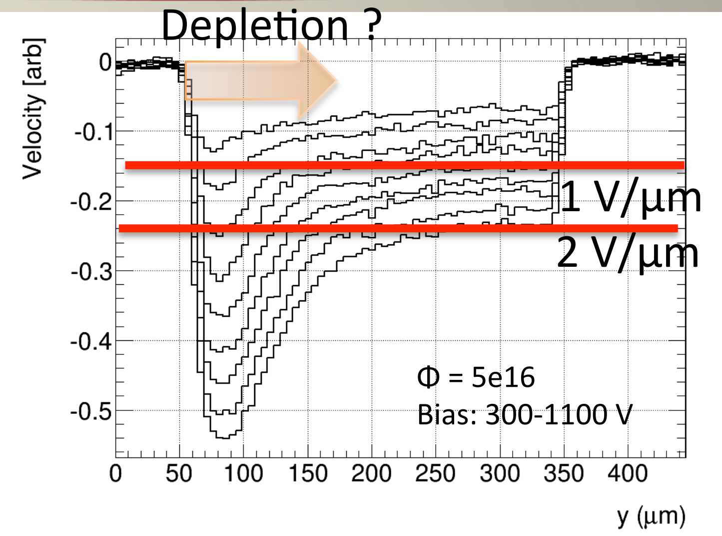
- Smooth behaviour in both directions
  - Highly resistive Si limits FW injection
- Reverse current smaller than predicted by an order of magnitude
- Both currents rising with bias

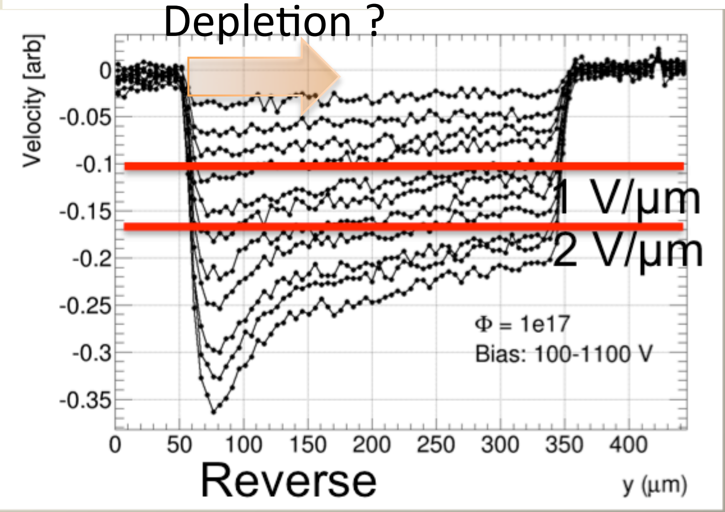




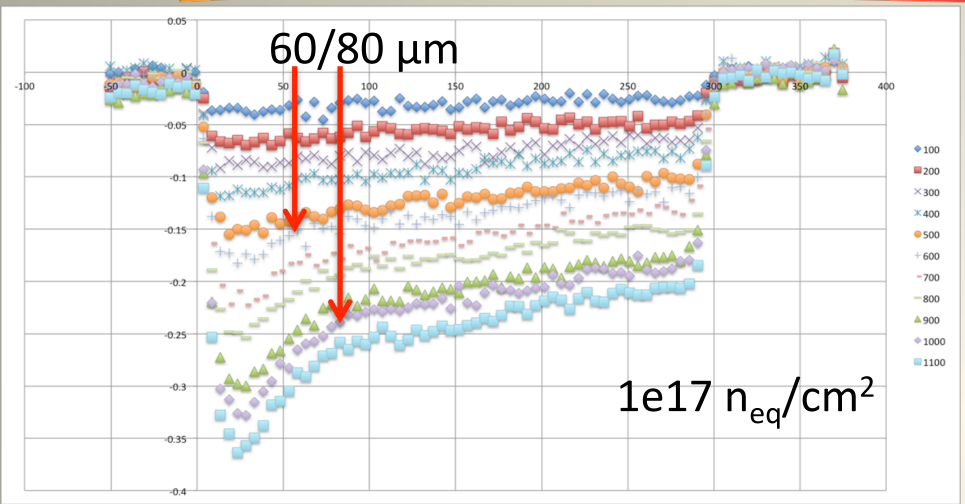
Reverse Bias Field Profile

- Two distinct regions at high biases
  - Large region from backplane with (small) slope in the field
    - constant (small, negative) space-charge
    - *E = j.ρ* at junction ? like "ENB" ?
    - indication of thermal (quasi)equilibrium: $np = n_i^2$?
    - thus no current generation ?
  - Small region at junction building up with bias
    - depleted space-charge region ?
    - source of generation current ?





SCR Consistency

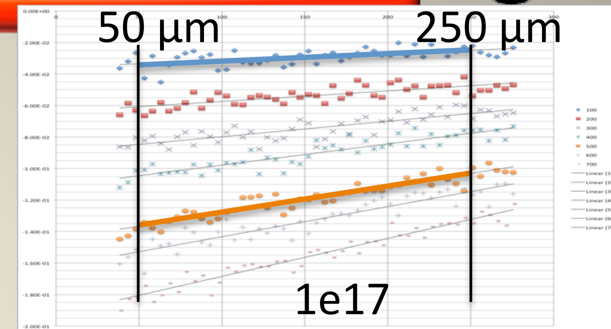


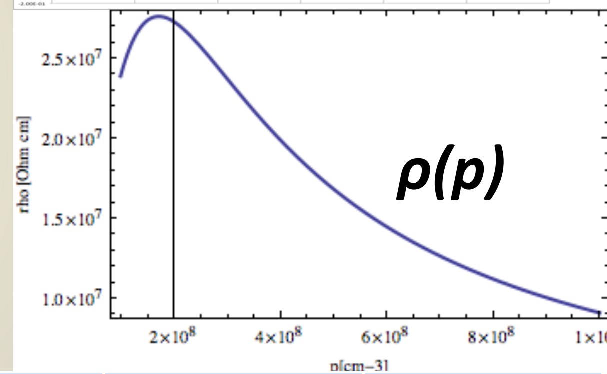
- Hard to estimate SCR extent, especially at lower bias and highest fluence
- A crude estimate
  - $5x10^{16}$ n_{eq}/cm^2 :
    ~80 µm @ 600 V; ~120 µm @ 1000 V
  - 10^{17} n_{eq}/cm^2 :
    ~60 µm @ 600 V; ~80 µm @ 1000 V

- Predicted/measured currents
  - $5x10^{16}$ n_{eq}/cm^2: 300/300 µA @ 600 V; 400/500 µA @ 1000 V
  - 10^{17} n_{eq}/cm^2: 400/300 µA @ 600 V; 500/600 µA @ 1000 V
- Reasonable agreement with current generated exclusively in SCR
  - n.b. - current "saturation" observed @1000V in *JINST 8 P08004 (2013)*
- Acceptor introduction rates: $g_c \approx 6/4x10^{-4}$ cm^{-1}
  - substantial part (up to 80 %) of voltage drop "spent" in "ENB"

“ENB” Consistency

- Space charge in “ENB” rising with bias, e.g. for 10^{17} n_{eq}/cm^2
  - 1.6×10^{11}@ 100 V, $9.2\times10^{11}cm^{-3}$ @ 500V
  - c.f. ~$4\times10^{13}cm^{-3}$ in SCR
  - negative space charge, like in SCR
- Resistivity from $\rho = j/E$ @ 100 V
  - maximum $\rho(p) \approx 2.8\times10^7$ Ωcm using nominal mobilities @ p ~ 2×10^8 cm^{-3}
    - all measured values exceed this limit
  - compatible with measured mobility sum and p~$\mathcal{O}$ (10^9) cm^{-3}





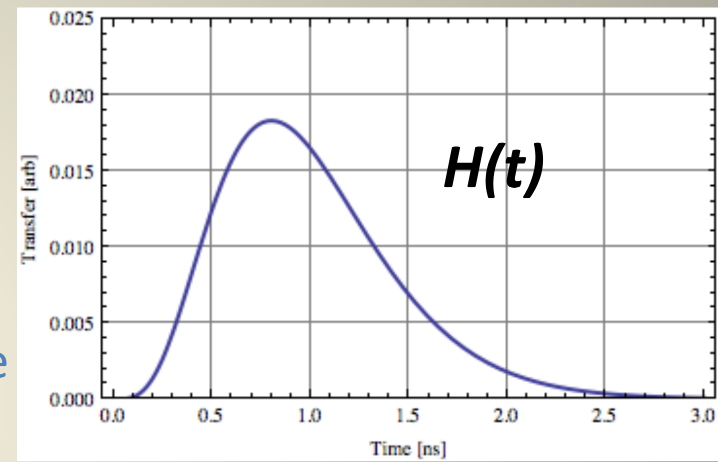
Φ	**ρ**	**p**
[n_{eq}/cm^2]	[10^7 Ωcm]	[10^9 cm^{-3}]
1e16	3.3	0.5
5e16	3.0	1.5
1e17	2.8	2.1

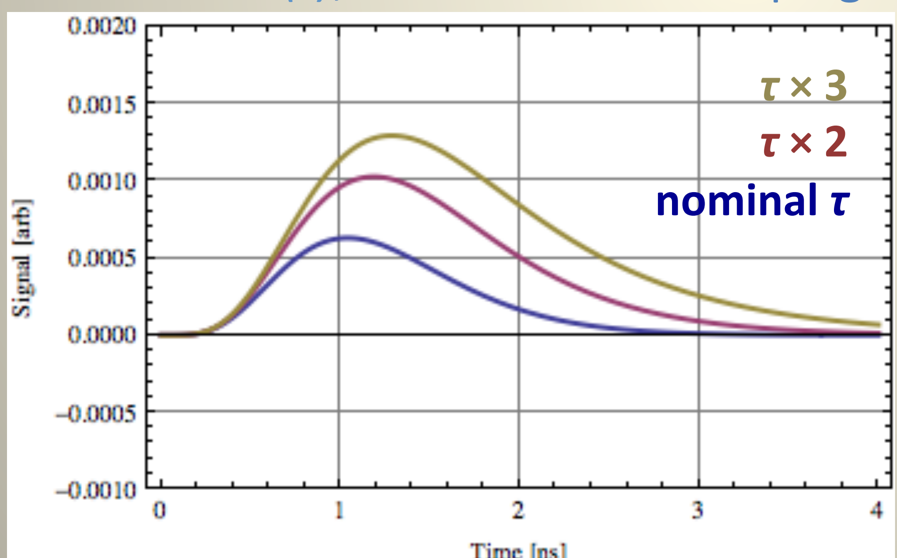
Summary

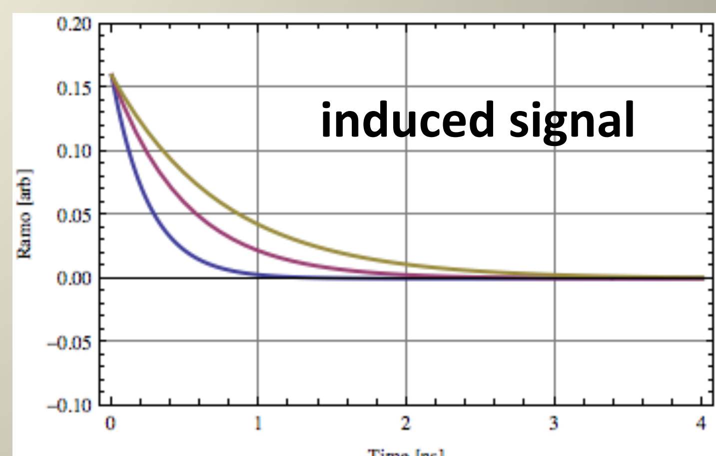
- Electric field profiling performed for Si detectors irradiated with neutrons from 10^{15} to 10^{17} n_{eq}/cm^2
- Mobility changes observed and interpreted as reduction of zero field mobility with fluence
- Simplistic Si detector picture with a SCR and "ENB" yields consistent results
  - significant reduction of g_c in SCR
  - reduced I_{leak} generated in SCR
  - electric field O(1 V/μm) in "ENB" mainly due to current transport from SCR through high resistivity Si
- To do: charged hadrons ? (reduced) trapping ?

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)*

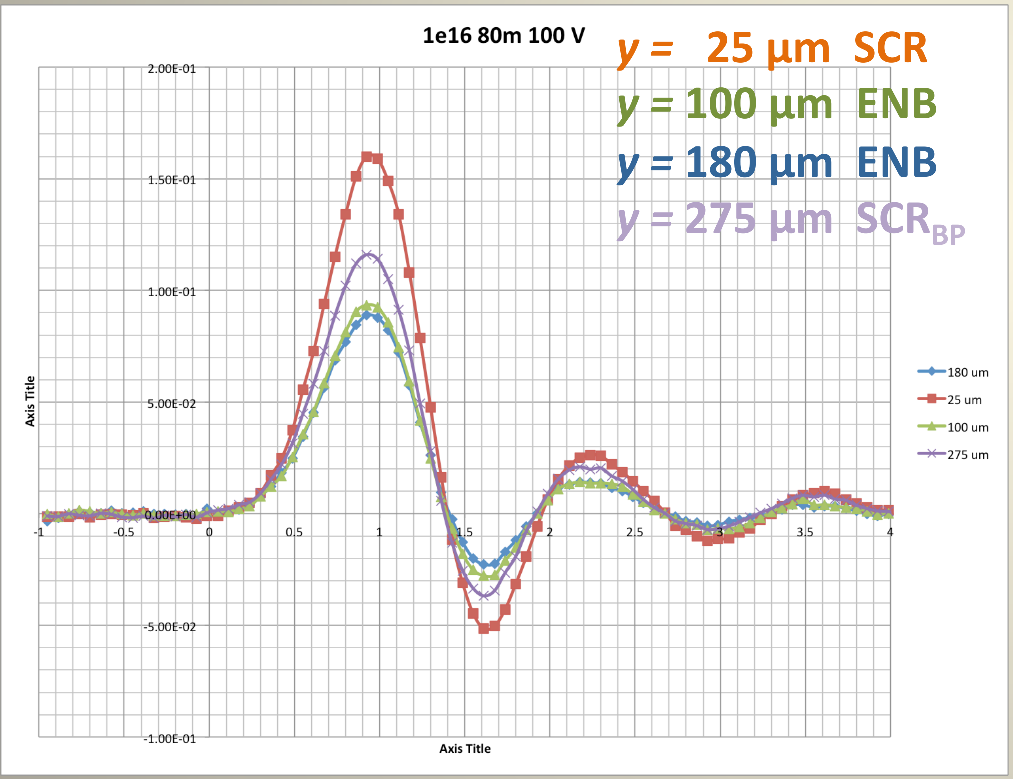






Reality

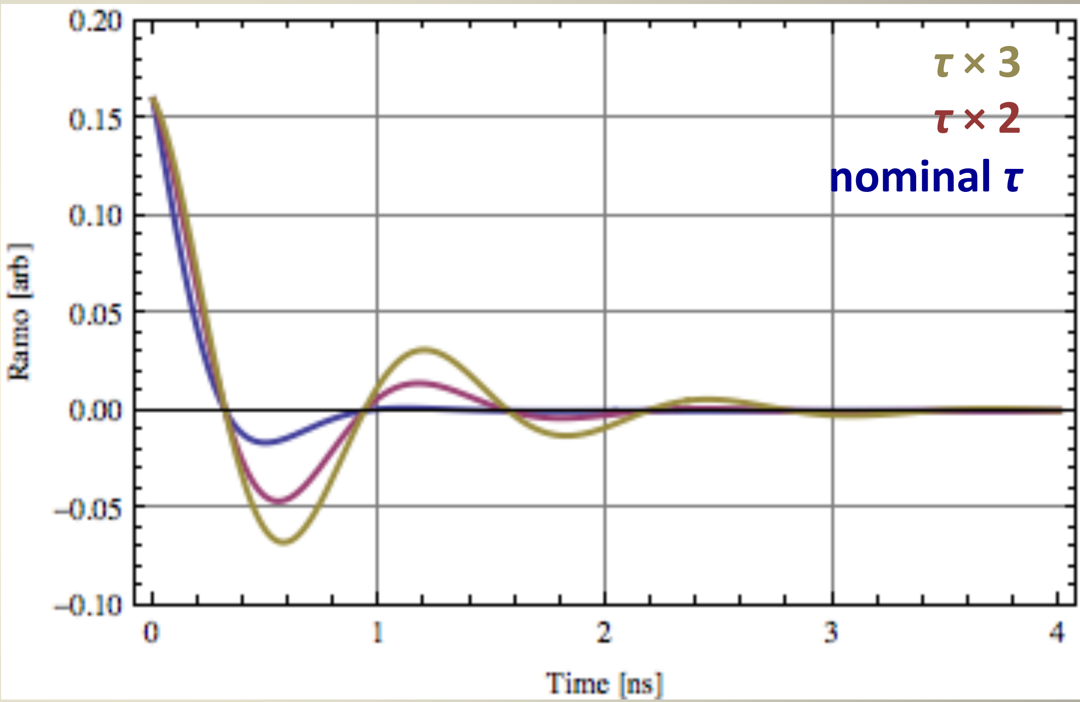
- Measured *I(t)* in E-TCT 10^{16} @ 100 V



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

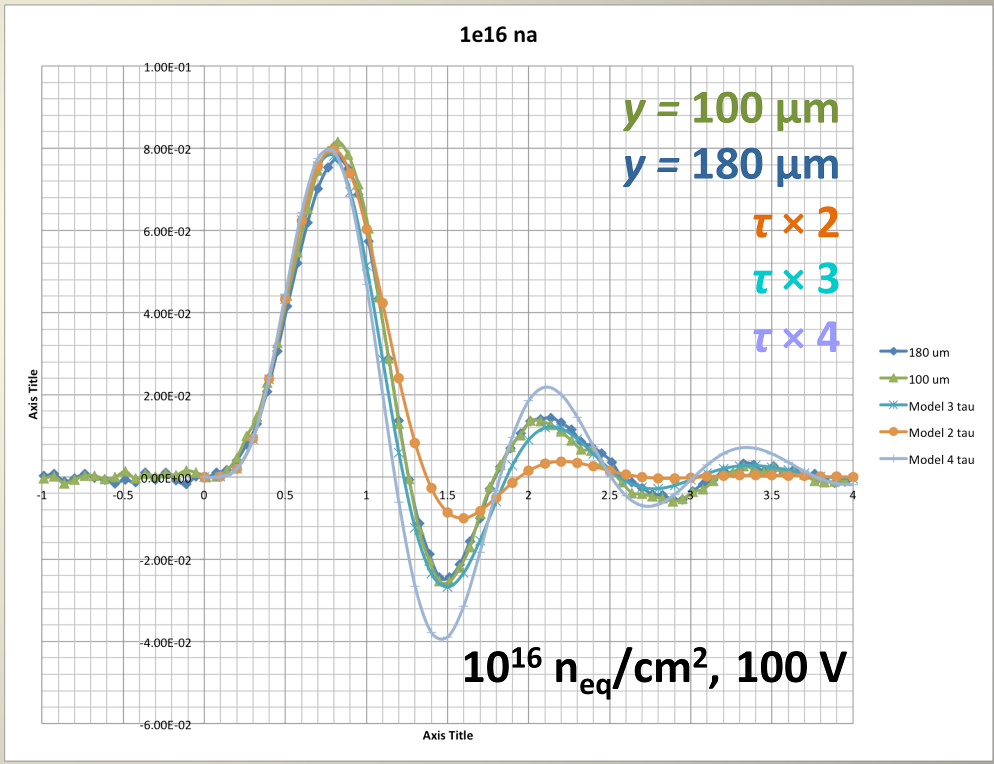
Fudge

- 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

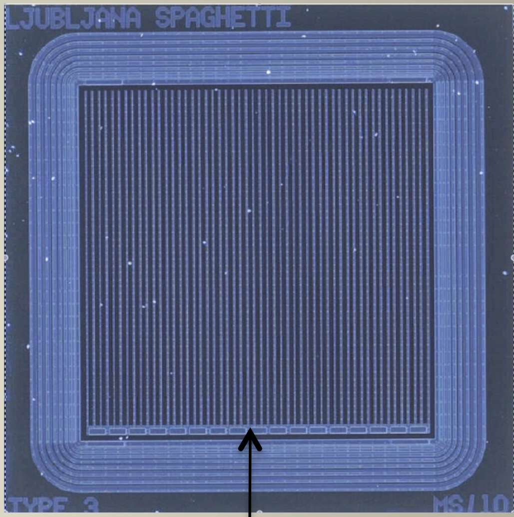
- Compare with τ = 2, 3, 4 x nominal
  - Nominal τ ruled out anyway
- ✓ Good agreement
- ✓ 3x longer τ looks like a clear winner
  - Definitely not 2 or 4
  - Implies ~20% trapping correction to v_{sum}



Backup Slides

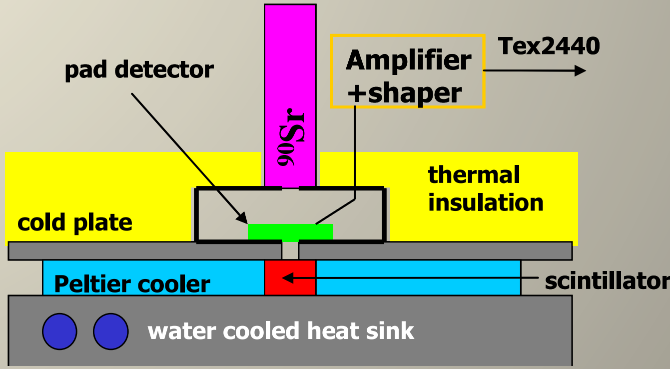
How far can we go with Si?

- 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, 10x10^{15} –> 5 samples annealed
  - 2, 4, 8x10^{16}, 1.6x10^{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*



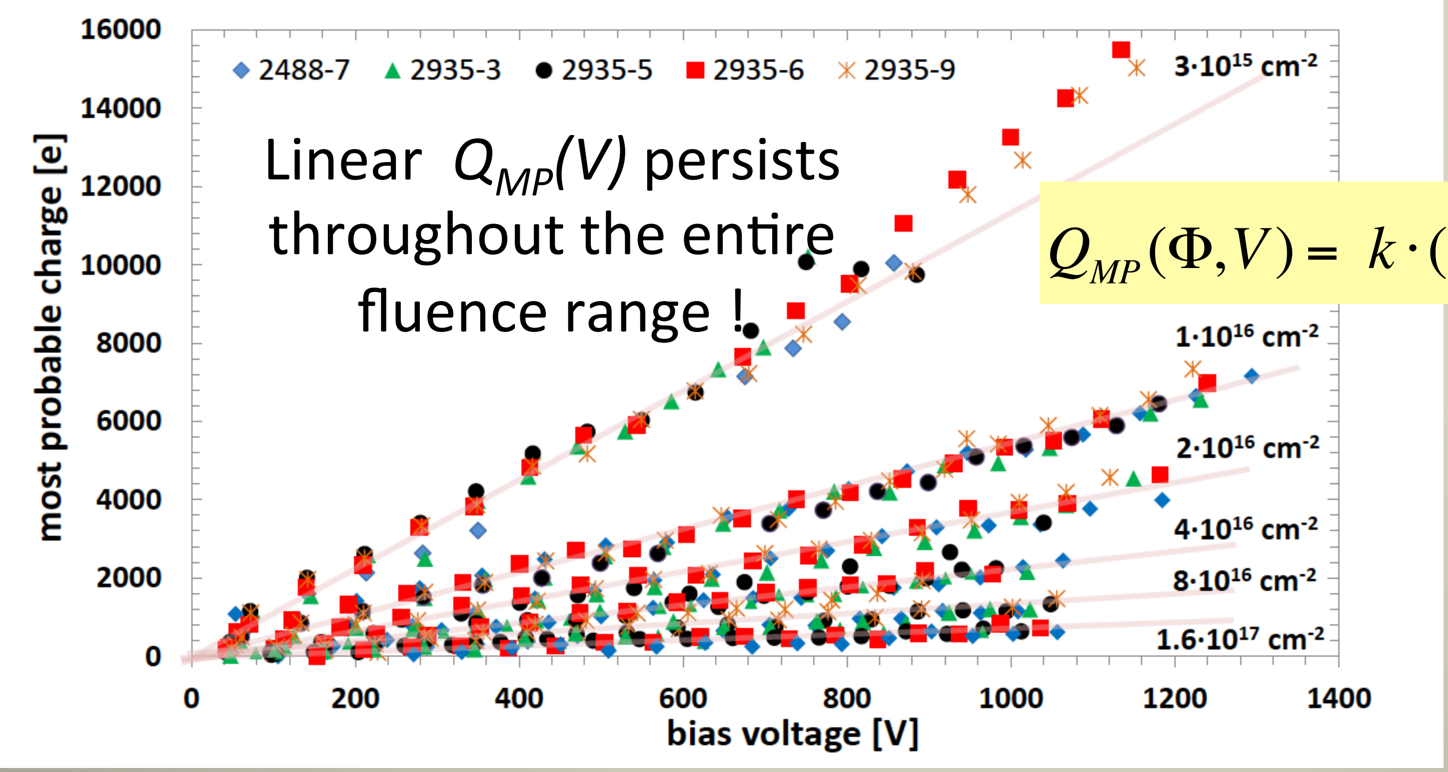
Published in : **G. Kramberger et al., *JINST 8 P08004 (2013)*.**

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



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



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

$$k = 26.4\ \mathrm{e_0/V}$$

$$b = -0.683$$

How to 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

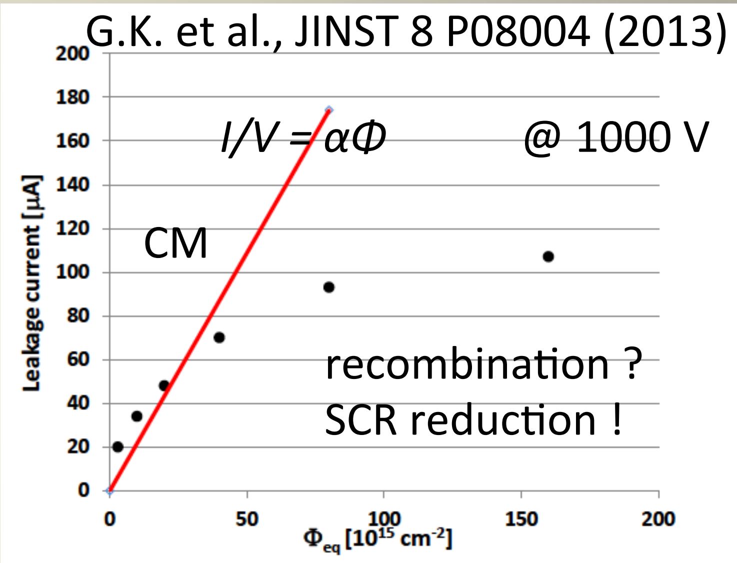
  “There is no shortage of traps in irradiated silicon…”
- Signal governed by Ramo theorem
  - E_w depends solely on geometry, can be calculated
  - 1E15 E problematic for modeling
- Can we measure it ?

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

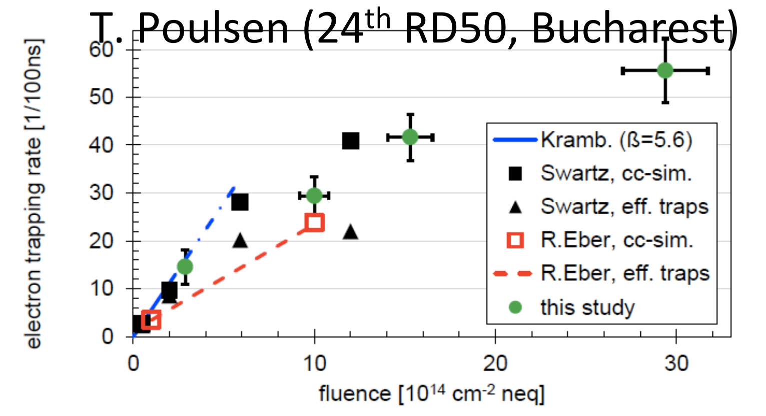
$$= q \cdot \mu(E) \cdot \vec{E} \cdot \vec{E}_w$$

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 ?

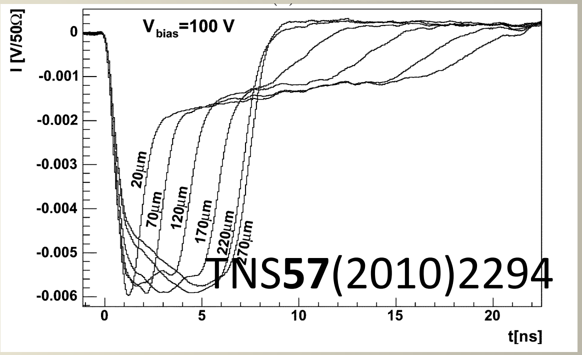


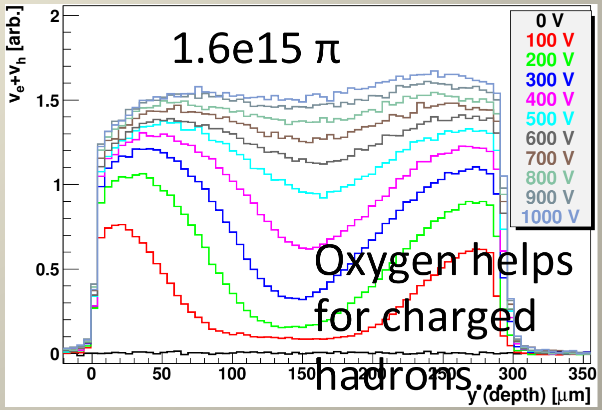
Conclusions

- We irradiated Si with neutrons up to $1.6\text{x}10^{17}$ 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





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 ?

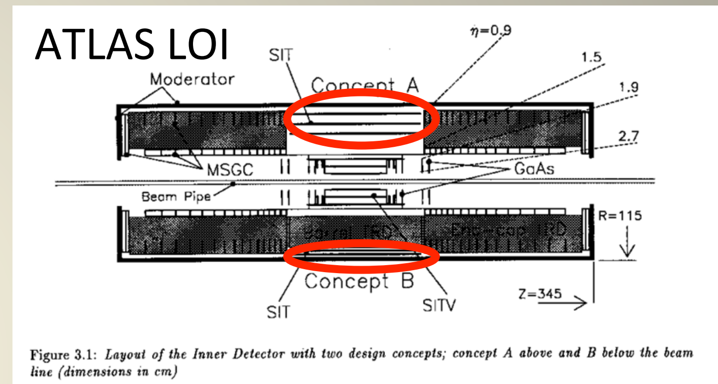


Figure 3.1: Layout of the Inner Detector with two design concepts; concept A above and B below the beam line (dimensions in cm)

CMS Tracker