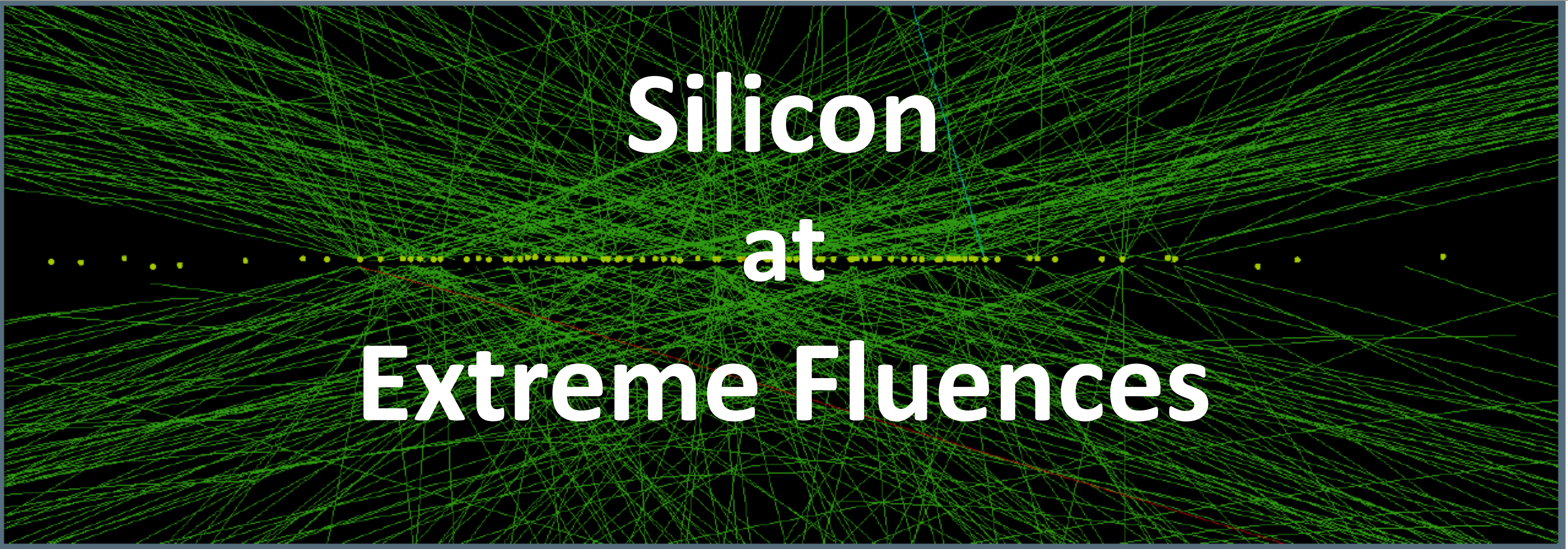


Silicon at Extreme Fluences

M.Mikuž

University of Ljubljana & Jožef Stefan Institute

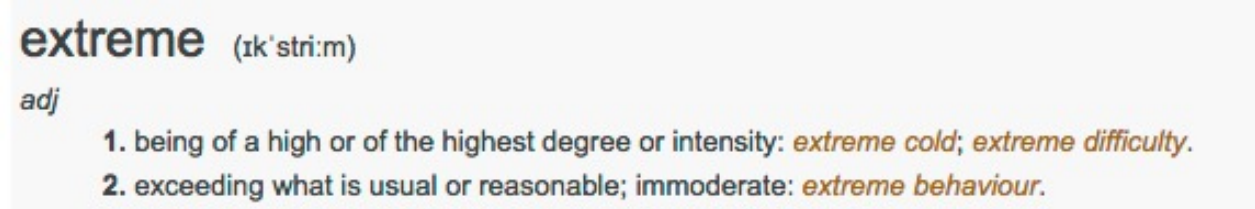
ECFA Detector R&D Roadmap

TF3 Solid State Detectors

Zoom, April 23rd, 2021

Extreme ?

- What is extreme ?

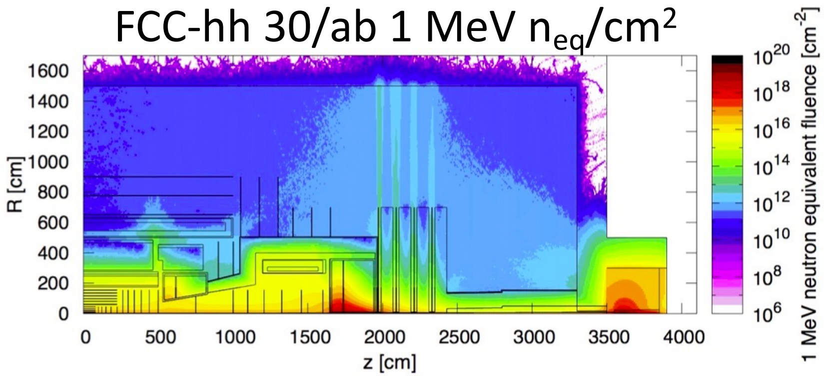


extreme (ɪkˈstriːm)

adj

1. being of a high or of the highest degree or intensity: *extreme cold*; *extreme difficulty*.
2. exceeding what is usual or reasonable; immoderate: *extreme behaviour*.

- A rather subjective measure
  - for LHC 10^{15} n_{eq}/cm^2 was considered extreme
    - design was 730/fb @14TeV…
  - HL-LHC takes it to nx10^{16} (vertex) or even 10^{17} (FW calo)
    - 4000/fb @14TeV
  - FCC-hh is *specifying* towards 10^{18} for the tracker (*M. Aleksa: FCC-hh req's*)
    - 30/ab @100TeV
    - 300 MGy TID in addition (not addressed)
  - Ratio 1:20:600 !
    - well, you *need* ~7^2≈50 in HL/FCC lumi…
- What is the limit of tracking sensors ?
  - TRIGA, NPP and ITER are 10^{21} ⟷10^{24}



FCC-hh 30/ab 1 MeV n_{eq}/cm^2

Central tracker:

- first IB layer (2.5 cm): ~5-6 10^{17} cm^{-2}
- external part: ~5 10^{15} cm^{-2}

Forward calorimeters:

~5 10^{18} cm^{-2} for both the EM and the HAD-calo

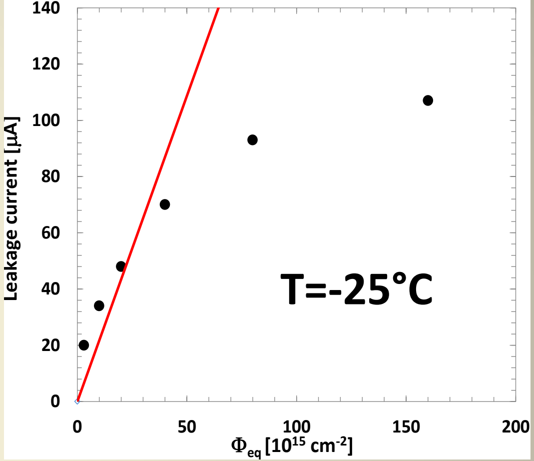
Expectations for $10^{17}\ n_{eq}/cm^2$

- For a ~yearly replacement of FCC-hh inner tracker !
- Linear extrapolation from low fluence data
  - Current: I_{leak} = 4 A/cm^3 @20°C
    - 2 mA/cm^2 (2W @ 1 kV) for 300 µm thick detector @ -20°C
  - Depletion: $N_{eff} \approx 1.5\text{x}10^{15}$ 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)

- Looks much like *Mission Impossible* (part n...)

CCE measurements up to 1.6x10^{17} n$_{eq}$/cm^2

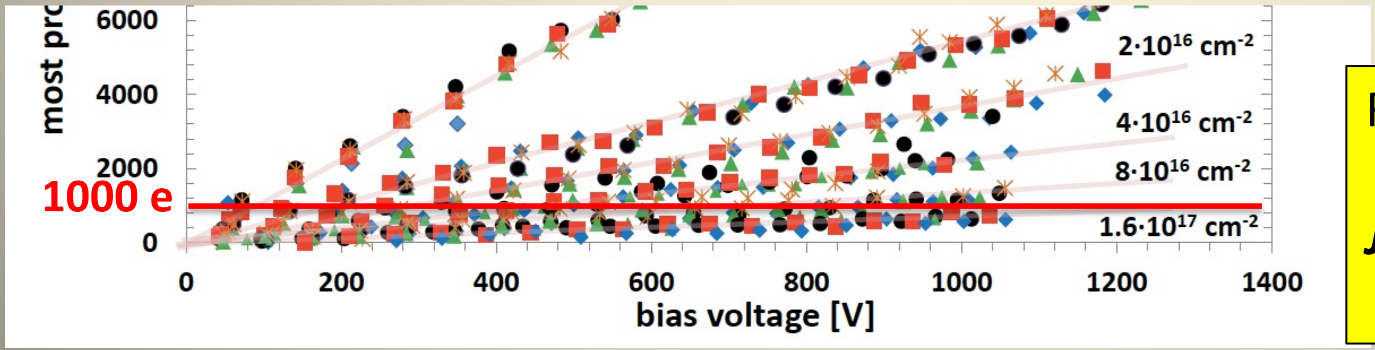
- n$^+$p ”spaghetti” strips, 300 µm
- Observed signal not at all compatible with expectations
  - Above 3x10^{15} linear *CCE(V$_{bias}$)*
  - Power law scaling with fluence, *b* ≈ -⅔
  - Leakage current “saturating”



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

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

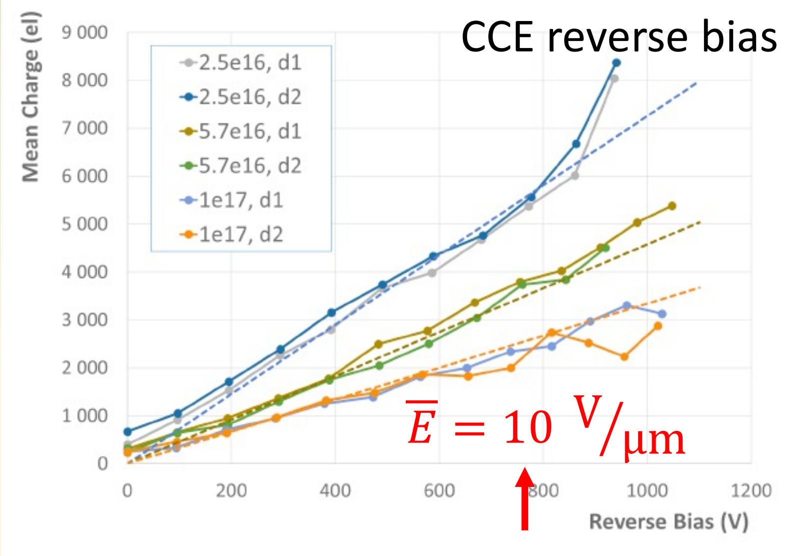
$$b = -0.683$$



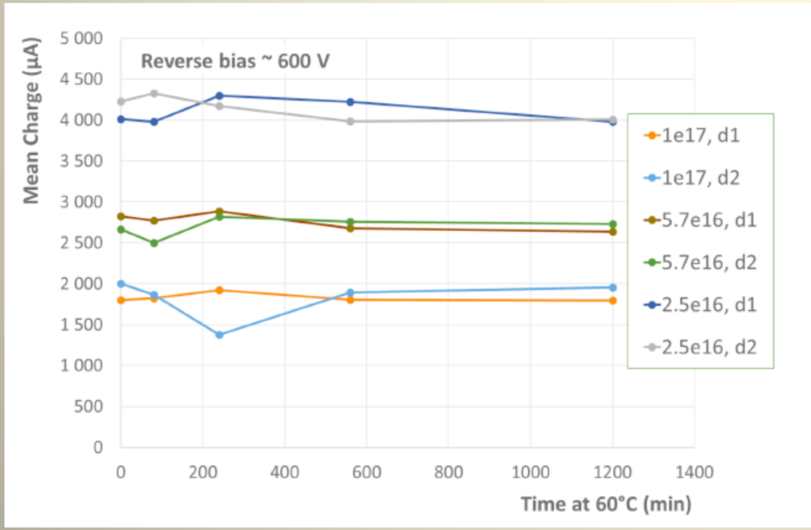
From:
G. Kramberger et al., *JINST 8 P08004 (2013)*.

More measurements on thin detectors

- 75 µm epi detectors from CNM on low-resistivity substrate
- Irradiated to 0.25, 0.57 and 1.0x10^{17} n_{eq}/cm^2
- *CCE* in reverse and FW
- Annealing 1200 min @ 60°C


CCE reverse bias

$\overline{E} = 10\ ^{\mathrm{V}}/_{\mathrm{\mu m}}$



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

$$k_{75} = 44\ \mathrm{e_0/V}$$

$$b_{75} = -0.56$$

Thinner is better!

From:
I.Mandić et al.,
JINST 15 P11018 (2020).

Linear *CCE(V)* ??

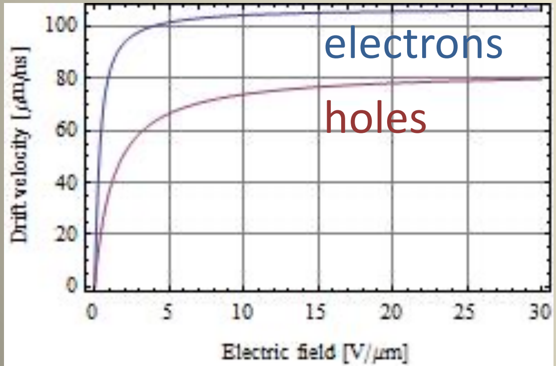
- What could be linear
  - SCR governed *CCE(V)* after irradiation (√*V*), highly resistive ENB (√*V)*, without trapping
  - Trapping dominated with non-saturated drift velocity
- What is *not* linear
  - velocity saturation
  - charge multiplication
  - double junction
  - field in ENB
  - ...
- Just a nice coincidence or some physics behind ?
  - look *into* silicon to search for an answer

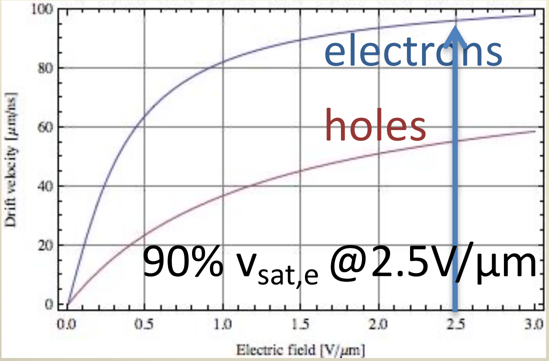
➢ Using edge-TCT to probe silicon

Electric Field Measurement

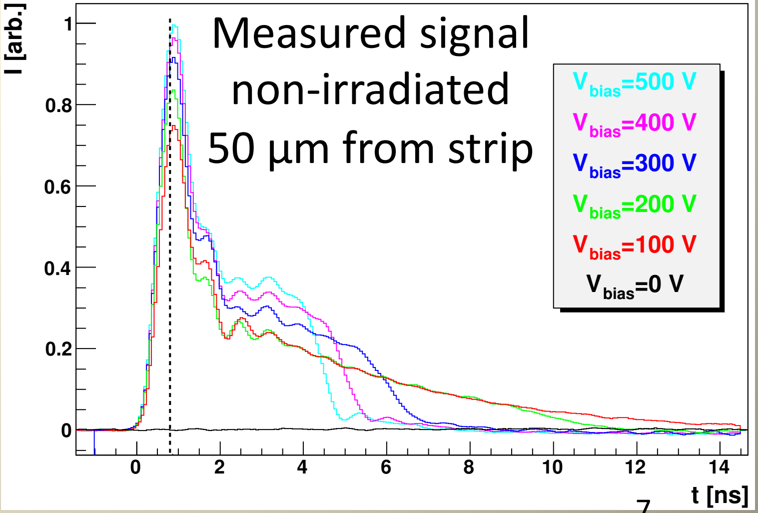
- Initial signal proportional to velocity sum at given detector depth
- Caveats for field extraction
  - Transfer function of electronics smears out signal, snapshot taken at ~600 ps
    - Problematic with heavy trapping
    - Electrons with v_{sat} hit electrode in 500 ps
  - Mobility depends on *E*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

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





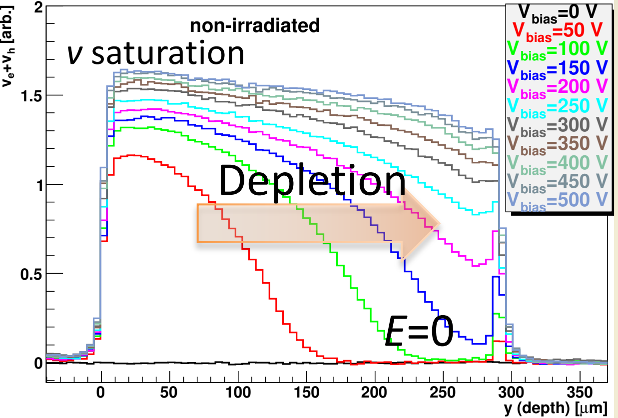
90% $v_{sat,e}$ @2.5V/µm

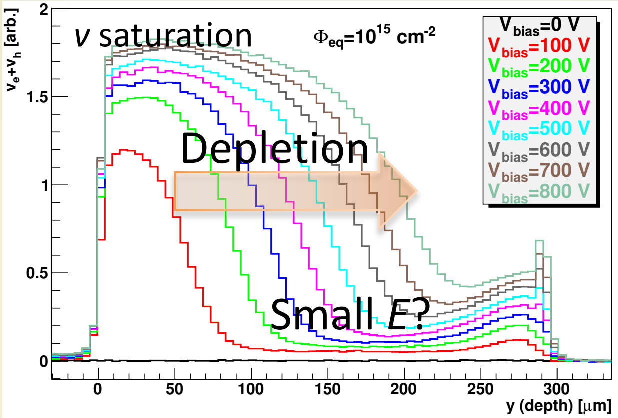


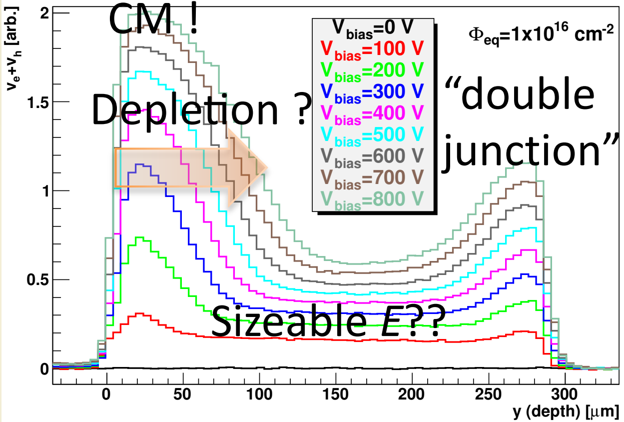
Measured signal
non-irradiated
50 µm from strip

Selected Results from Neutrons

- Hamamatsu ATL07 n^+ mini-strip, FZ p-type, neutron irradiated at JSI TRIGA reactor
  - In steps up to 10^{16} n_{eq}/cm^2





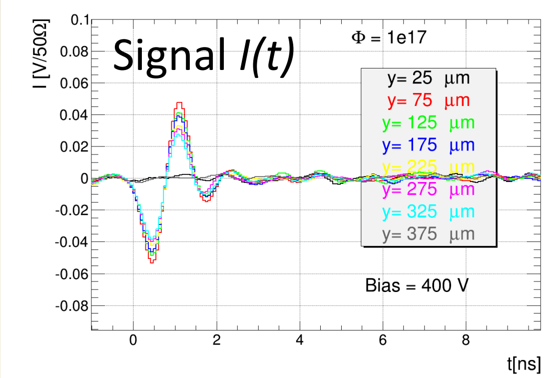


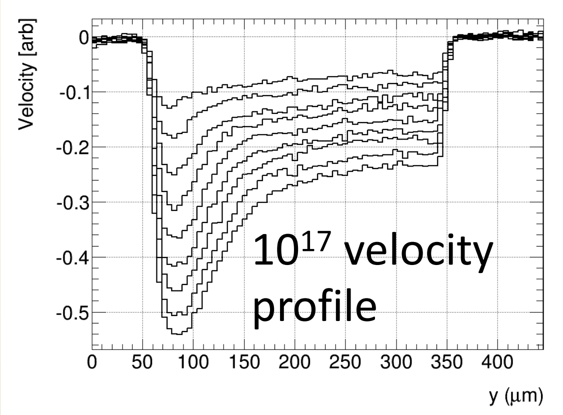
- Very instructive regarding qualitative electric field shape
  - Non-irradiated "by the book" for abrupt junction n^+p diode
    - SCR and ENB nicely separated, small double junction near backplane
  - Medium fluence ($\Phi=10^{15}$ neutrons): some surprise
    - Smaller space charge than expected in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

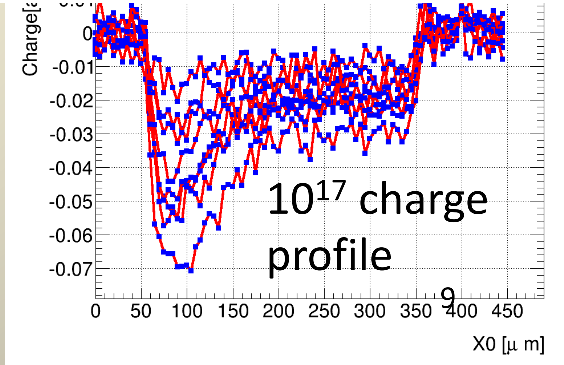
Published in :
G. Kramberger et al.,
JINST 9 P10016(2014).

Extending the Reach

- In 2014 added 5×10^{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
- Intrinsic feature – signal oscillations
  - – period ~5/4 ns
  - – LRC (C~2pf => L~20 nH ~ 1cm of wire)
- Velocity (slope) and charge (integral) yield consistent results
- should be, as $Q \approx Q_0 \, v_{sum} \tau_{eff} / d$

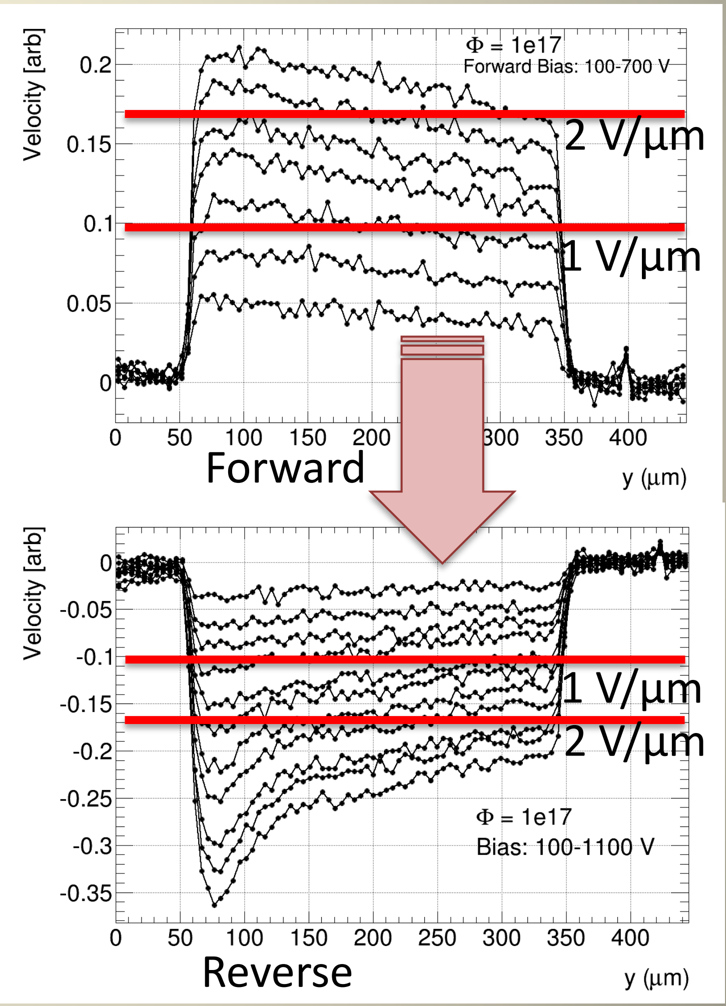






Absolute Field Measurement

- Solution: *concurrent* forward bias v_{sum} measurements
  - 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

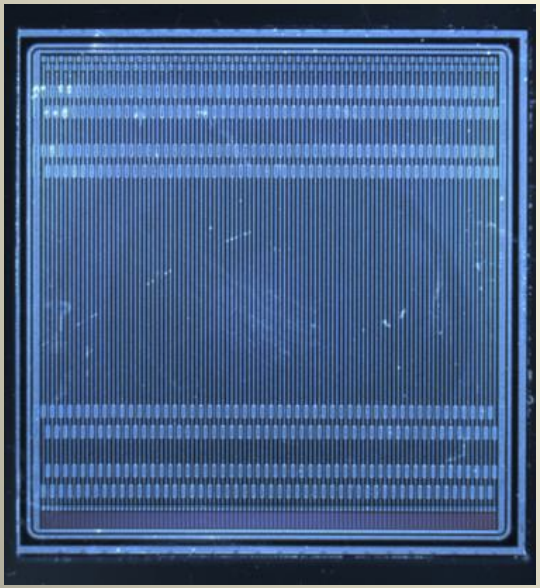


Proton Irradiations

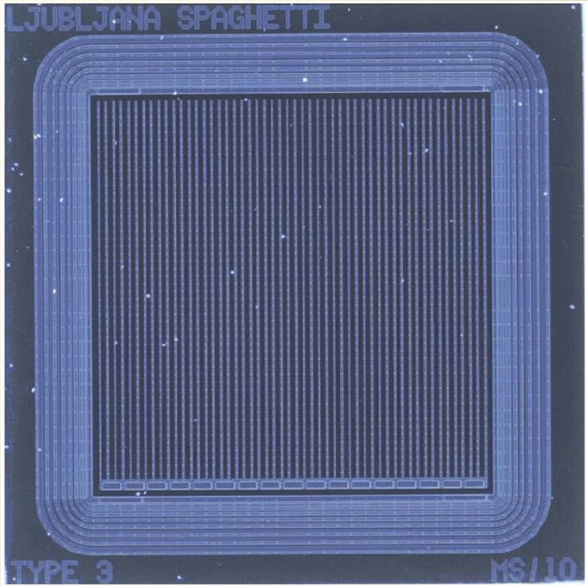
- 5 sample pairs of ATL12 mini-strips irradiated at CERN PS during summer 2015
  - got 0.5, 1.0, 2.9, 11, 28e15 protons/cm^2, no scanning
  - NIEL hardness factor 0.62
  - thanks to CERN IRRAD team
    - took **41 PS days** to reach the highest fluence
- Covers HL-LHC tracker range well
  - does really not look practical for 10^{17}++
- 2 samples per fluence investigated by E-TCT for all fluences
  - concurrent forward and reverse bias measurements

Additional irradiations

- 3e17 n_{eq}/cm^2, JSI reactor neutrons
  - A12 mini, 7x8 mm^2, 75 µm pitch, 300 µm thick
    - Also to 3e16, 1e17
  - Spaghetti: 4x4 mm2, n-on-p, strip pitch 80 um, 300 um thick, strips connected together at side
    - 1.6e17 received previously, 4.6e17 total



A12

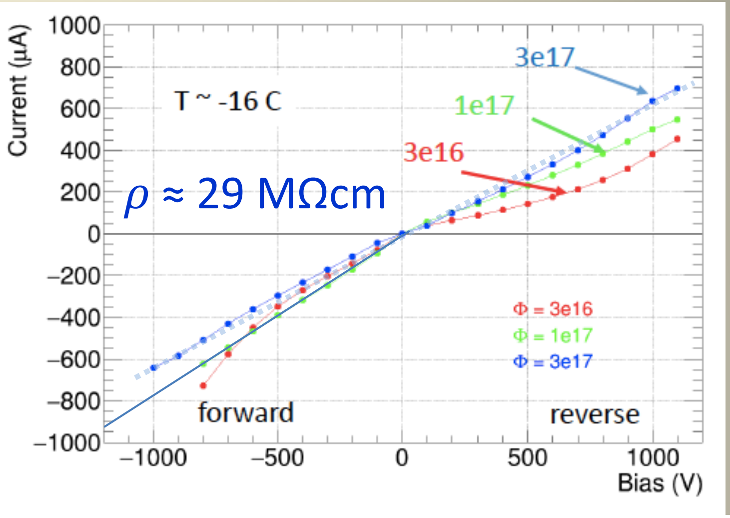


Spaghetti

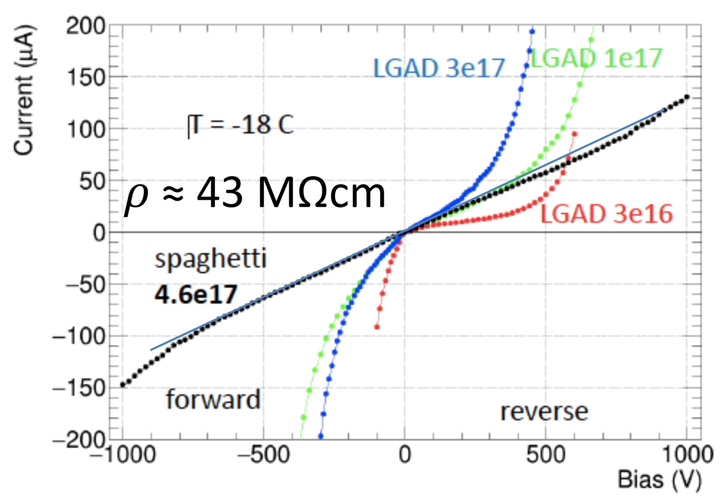
Basic measurements

- *I-V* for 3&4.6e17 looks very linear with little difference between reverse/FW bias
  - No breakdown, as observed in LGAD's
- *I* @1000 V does not scale linearly with fluence !
  - Not governed by generation current ?

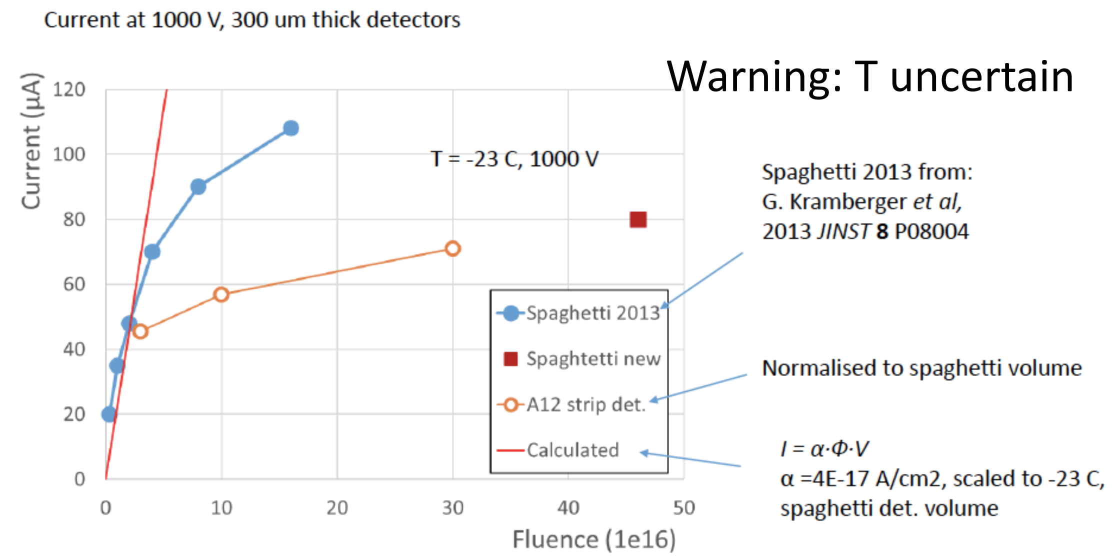
- Tried to measure 4.6e17 spaghetti *CCE* with ^{90}Sr
  - No signal above background observed up to 320 V
  - Magic formula predicts 120e for 4.6e17 @320 V



$\rho \approx 29$ MΩcm



$\rho \approx 43$ MΩcm



Warning: T uncertain

Spaghetti 2013 from:
G. Kramberger *et al*,
2013 *JINST* **8** P08004

Normalised to spaghetti volume

$I = \alpha \cdot \Phi \cdot V$
α =4E-17 A/cm2, scaled to -23 C,
spaghetti det. volume

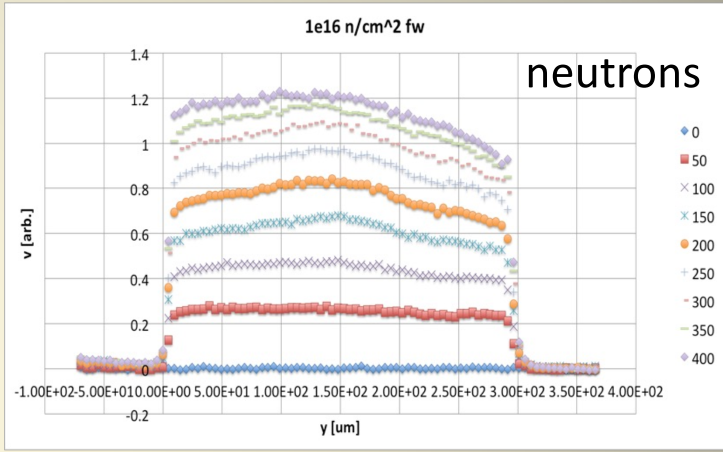
Mobility Considerations FW bias

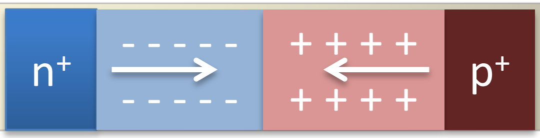
- For forward bias can extract *v(E)* up to a scale factor
- Observe less saturation than predicted
- Model with

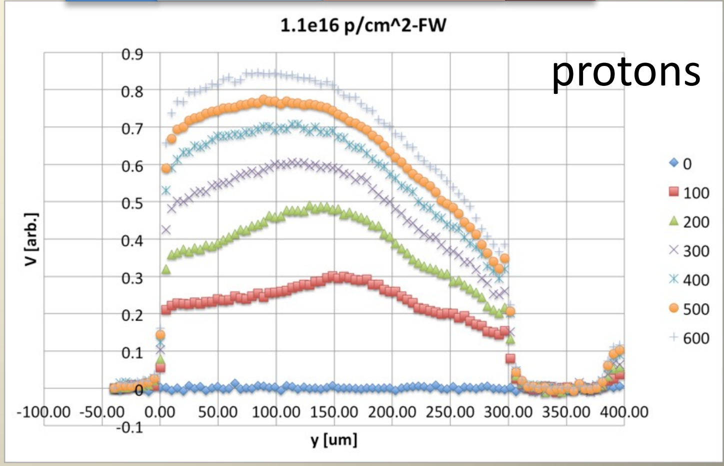
$$v_{sum}(E) = \frac{\mu_{0,e}E}{1+\mu_{0,e}E \big/ v_{e,sat}} + \frac{\mu_{0,h}E}{1+\mu_{0,h}E \big/ v_{h,sat}}$$

  - keep saturation velocities at nominal values @-20°C ($v_{e,sat}$ = 107 µm/ns; $v_{h,sat}$ = 83 µm/ns)
  - float (common) zero field mobility degradation
  - fit *v(E)* for $\phi_n \geq 5\text{x}10^{15}$ and $\phi_p \geq 3\text{x}10^{15}$

n.b. FW profiles less uniform for lower fluences & protons; departures from average field still small, corrections *O(%)*

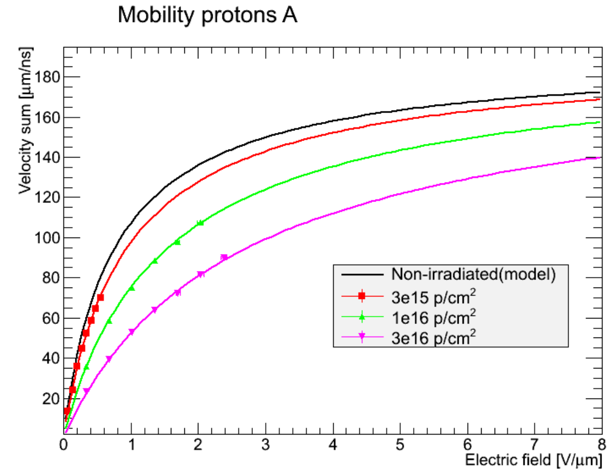


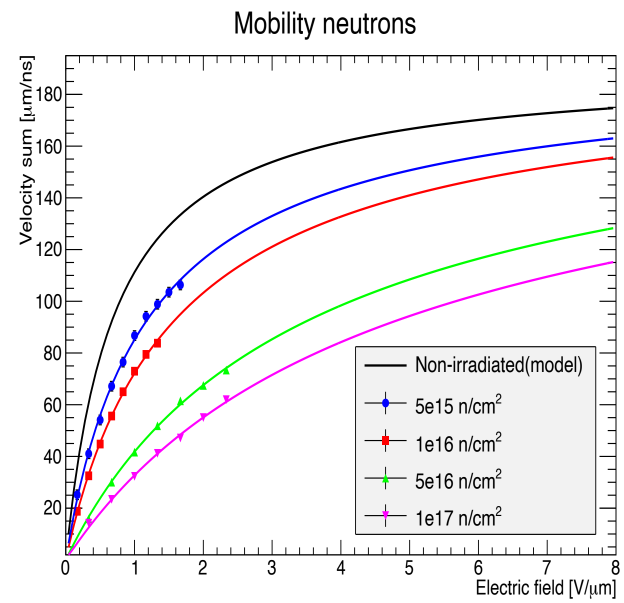


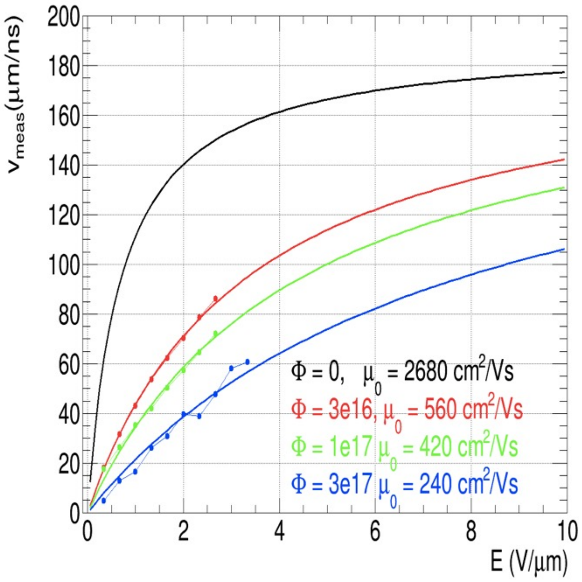


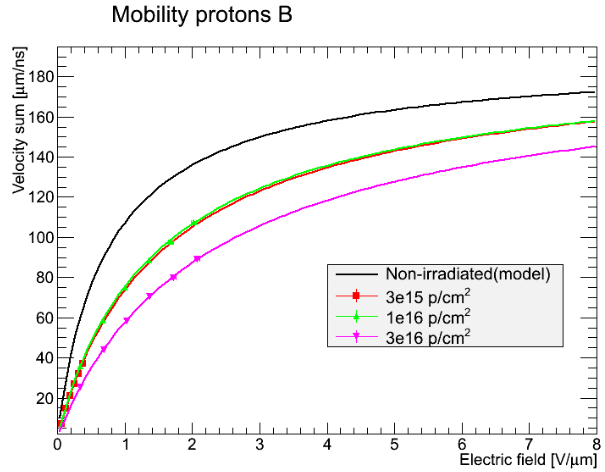
Mobility Fits

- Data fits model almost perfectly
  - μ_0 degradation the only free parameter, scale fixed by $v_{sum,sat}$
  - At 3e17 E range too limited ($v(E)$ linear), regard result as upper limit


Mobility protons A


Mobility neutrons




Mobility protons B

Mobility Results

- Fit to $v_e + v_h$ with common mobility degradation factor
  - factor of 2 at 10^{16} n_{eq}/cm^2, 6 at 10^{17} n_{eq}/cm^2, >10 at $3x10^{17}$ n_{eq}/cm^2
  - need 2x/6x/>10 higher *E* to saturate *v* !
  - ☠ correspondingly higher *E* for charge multiplication !

Φn	**$\mu_{0,sum}$**	**Φp**	**$\mu_{0,sum}$**
[10^{15} n_{eq}/cm^2]	[cm^2/Vs]	[10^{15} n_{eq}/cm^2]	[cm^2/Vs]
non-irr (model)	2680		
5	1661 ± 134	1.6	2063± 188
10	1238 ± 131	6.1	1337± 47
30	560	15.4	817± 42
50	555 ± 32		
100	407 ± 40		
100	420	**T=-20°C**	
300	<240		

Mobility Analysis

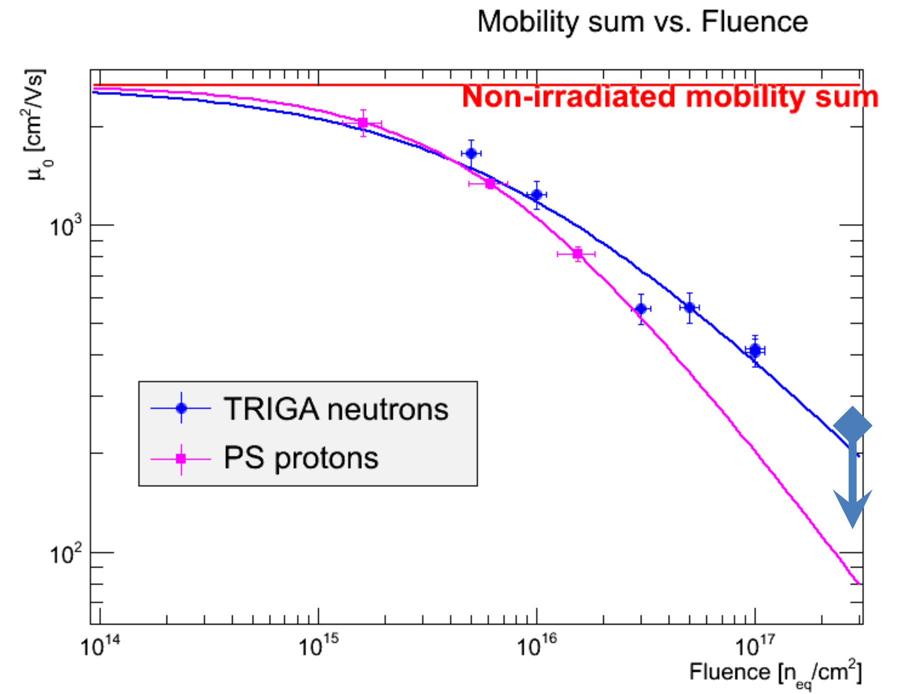
- Mobility governed by hard scattering on acoustic phonons and traps

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

- Fit mobility dependence on fluence with a power law

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

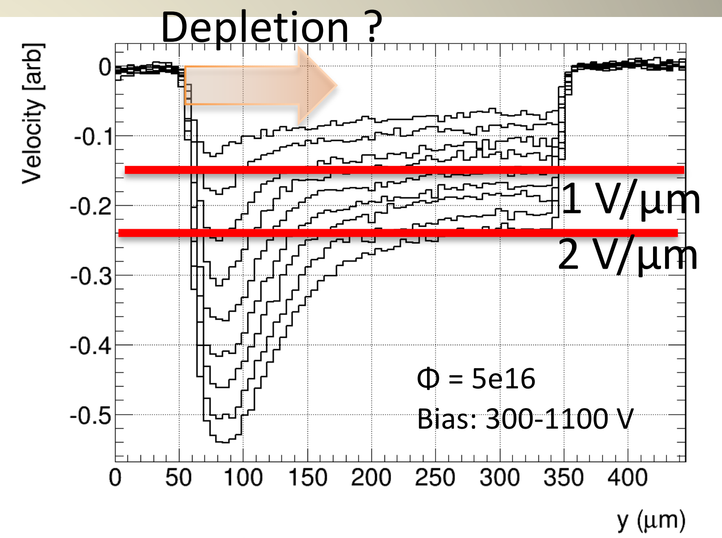
- Fits perfectly, value of *a* close to linear
  - 10% error assumed for all neutron data
- At same NIEL, mobility decrease worse for protons
  - NIEL violation ? Large errors ?

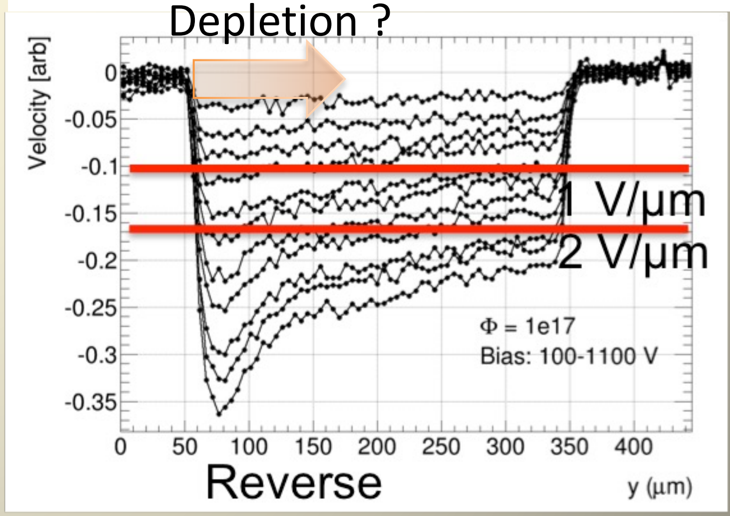


Irradiation particle	a	σ_a	$\Phi_{1/2}/10^{15}$	$\sigma_{\Phi 1/2}/10^{15}$
Reactor neutrons	-0.68	0.08	6.9	1.7
PS protons	-0.90	0.19	6.1	1.0

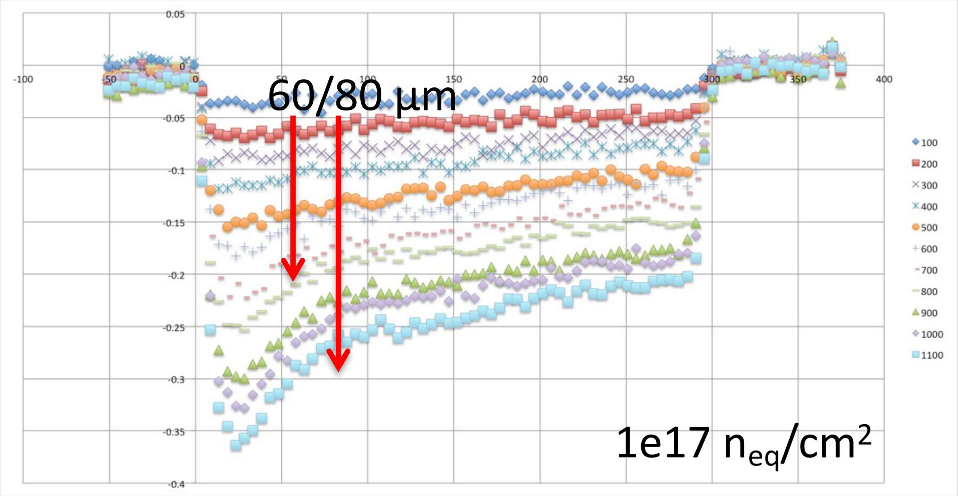
Reverse Bias Field Profile

- Two distinct regions at high biases
  - Large region from backplane with (small) slope in the field
    - constant (small, negative) space-charge
    - $E = j.\rho$ 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 ?





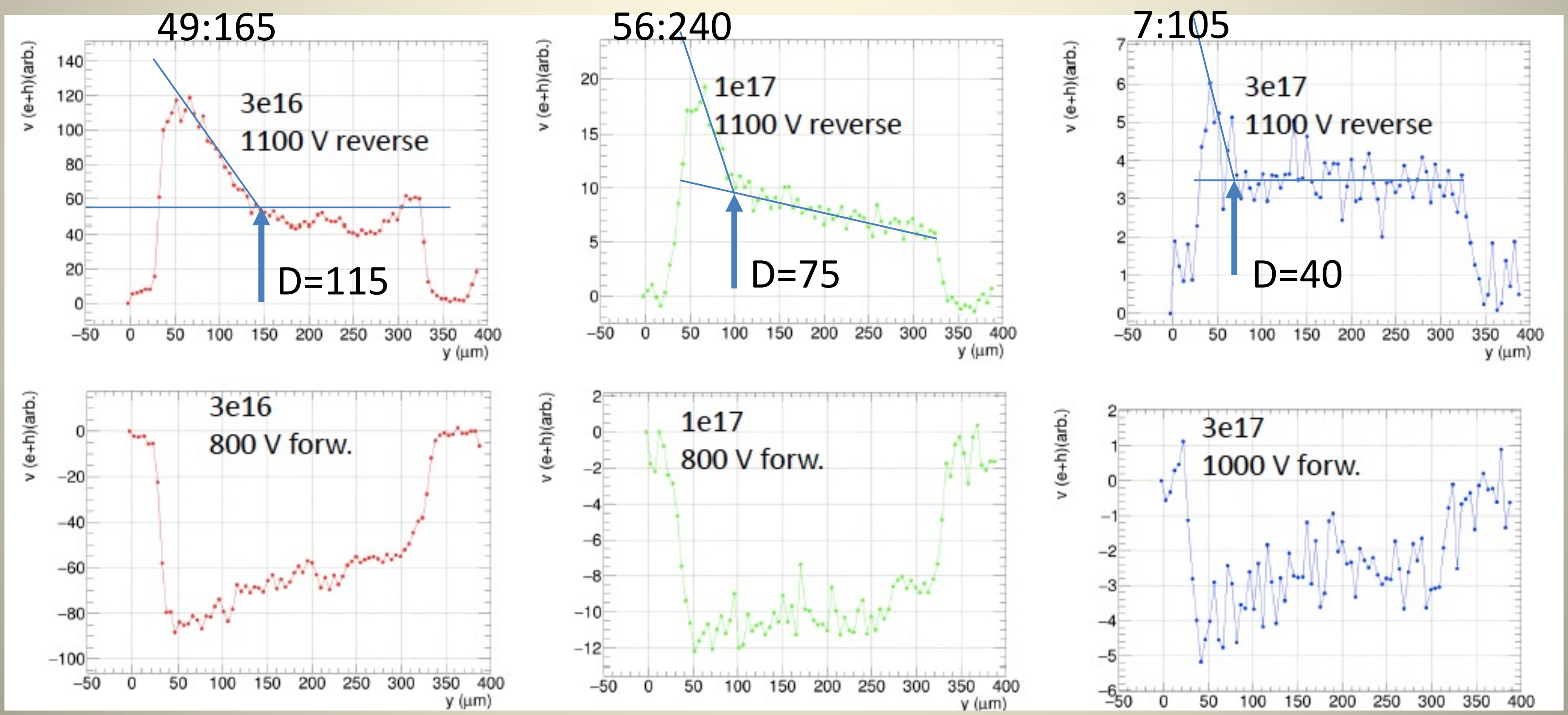
SCR Consistency



- Hard to estimate SCR extent, especially at lower bias and highest fluence
- A crude estimate
  - 5×10^{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
  - 5×10^{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
  - Not compatible with linear *I-V* at 3 & 4.6e17 – pure resistor ?
- Reasonable agreement with current generated exclusively in SCR
  - n.b. - current “saturation” observed @1000V in *JINST 8 P08004 (2013)*
- Acceptor introduction rates: $g_c \approx 6/4\times10^{-4}$ cm^{-1}
  - substantial part (up to 80 %) of voltage drop “spent” in “ENB”
  - matches well data in ***JINST 9 P10016(2014)*** (up to 10^{16})

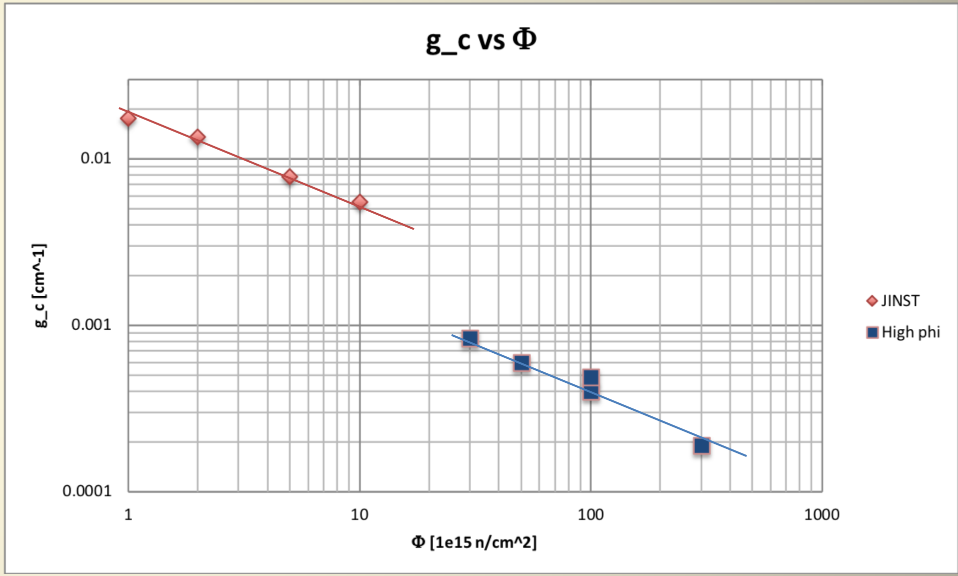
ATL12 up to 3e17

- Estimate of SCR width 115 -> 75 -> 40 µm
- V_{drop} in SCR only 23 -> 19 -> 6 % of 1100 V



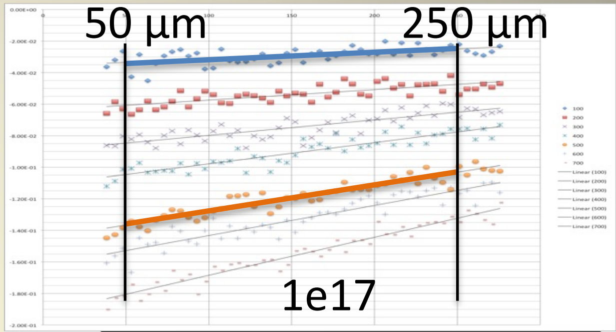
Acceptor introduction in SCR

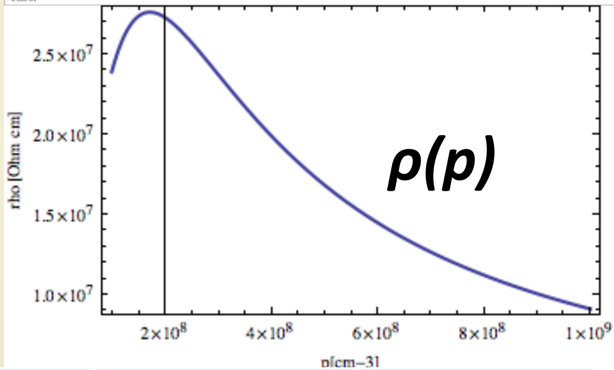
- Stable acceptor introduction rate g_c drops by nearly two orders of magnitude from low fluences to $3x10^{17}$
  - Observed up to 10^{16} in *JINST 9 P10016(2014)*
  - Looks like a power law
    - g_c in JINST not taking into account voltage drop out of SCR – higher values of g_c



“ENB” Consistency

- Space charge in “ENB” rising with bias, e.g. for 10^{17} n_{eq}/cm^2
  - 1.6×10^{11}@ 100 V, $9.2 \times 10^{11} cm^{-3}$ @ 500V
  - c.f. ~$4 \times 10^{13} cm^{-3}$ in SCR
  - negative space charge, like in SCR
- Resistivity from $\rho = j/E$ @ 100 V
  - maximum $\rho(p) \approx 2.8 \times 10^7$ Ωcm using nominal mobilities @ $p \sim 2 \times 10^8$ cm^{-3}
    - all measured values exceed this limit
  - compatible with measured mobility sum and $p \sim \mathcal{O}(10^9)$ cm^{-3}
  - Compatible also with ρ from *I-V* for 3 & 4.6e17





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

Trapping analysis

- From *I.Mandić et al., JINST 15 P11018 (2020)*
  - FW bias CCE estimated by

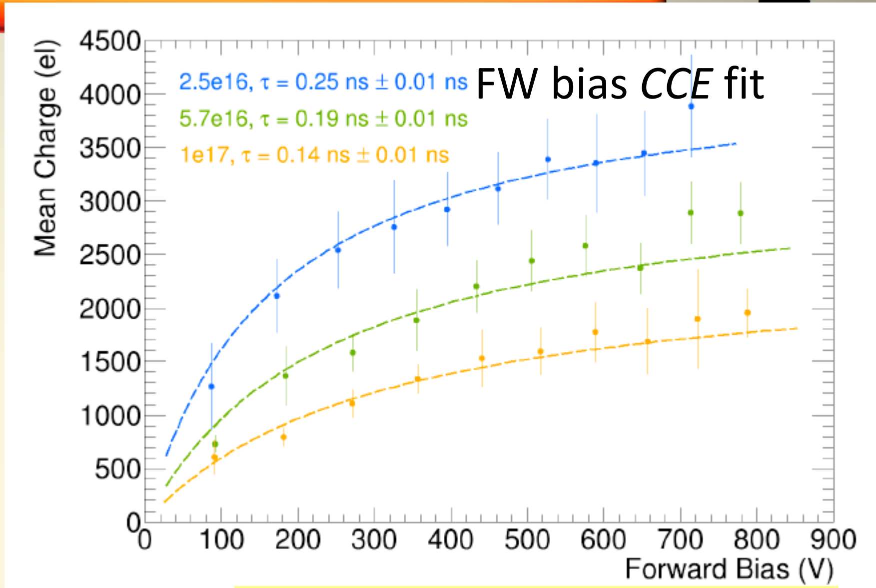
$$Q = \frac{\Delta Q}{\Delta x} \cdot v \cdot \tau$$

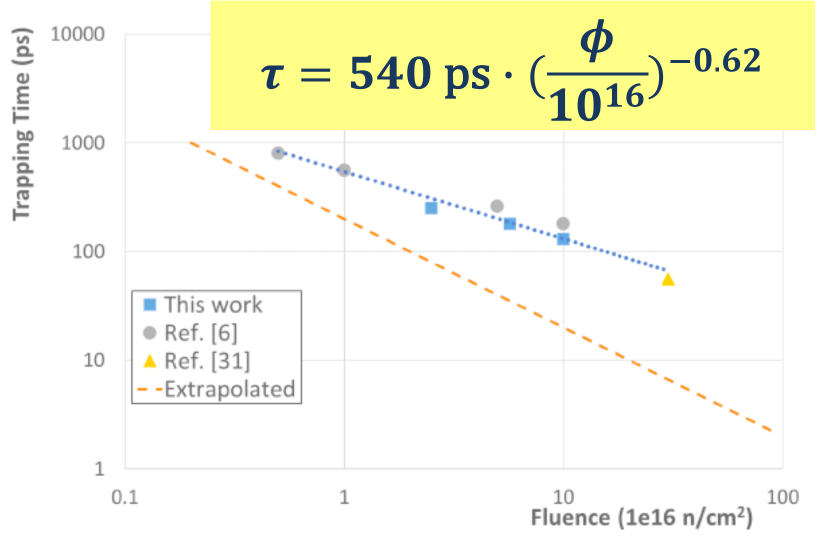
    - *v(E)* with fluence dependent *μ*
    - constant *E=V/D* (FW)

😀 Order of magnitude smaller than extrapolated !

😀 Agrees with estimates from reverse bias CCE (backup)

- Trapping independent of bias, seen in wave-froms





$$\tau = 540\ \mathrm{ps} \cdot \left(\frac{\phi}{10^{16}}\right)^{-0.62}$$

Summary

- Measurements performed on Si detectors irradiated to extreme fluences
  - Neutrons from 10^{15} to 4.6×10^{17} n_{eq}/cm^2 , PS protons from 5×10^{14} to 3×10^{16} p/cm^2
  - Velocity vs. electric field impact observed and interpreted as reduction of zero field mobility
    - Zero field mobility follows power law with $|a| \leq 1$, $\Phi_{\frac{1}{2}} \approx 10^{16}$ n/cm^2
    - Protons degrade mobility more than neutrons
    - Induces resistivity increase in-line with measured *I-V*
    - Exhibits adverse effect on charge multiplication !
  - Simple field profile for very high neutron fluences
    - Diminishing SCR and highly resistive ENB
    - Effective acceptor introduction rates reduced by factor ~100 wrt low fluences
    - Current much lower than anticipated. Generated in SCR only ? Ohmic at highest fluences…
  - Trapping estimates for very high neutron fluences
      - from charge collection in FW and reverse bias
      - from waveforms
    - All estimates point to severe non-linearity of trapping with fluence, 10x lower at 10^{17}
    - Trapping appears independent of electric field
- Conclusion: ***Low fluence extrapolations do not work at all !***

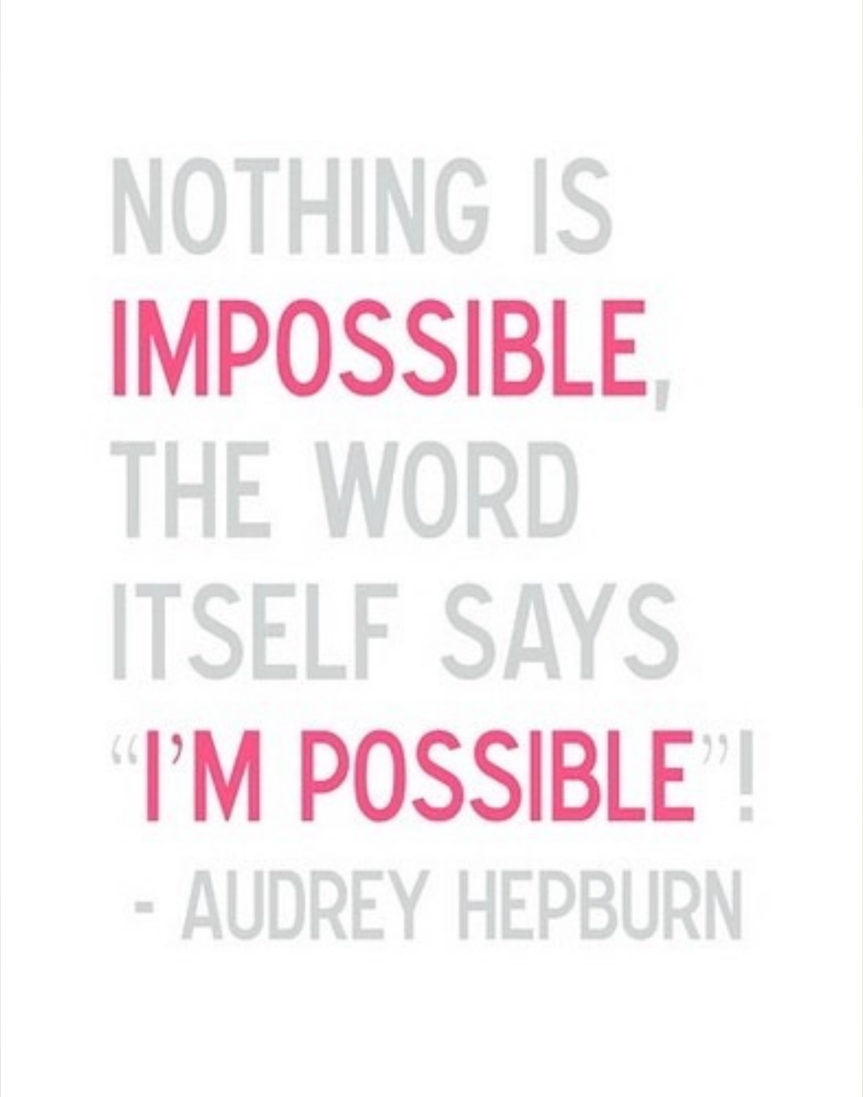
… go out and ***measure*** to get anything working at ***extreme*** fluences !!!

Implications for TF3

- Basic bulk silicon properties in the fluence range to master are the prerequisite to any inner tracking detector design for FCC-hh
- They need to be ***measured***
  - Only pioneering consistency checks done so far
- Need resources far beyond current ones
  - Facilities
  - Measurement techniques
  - People

  at least for the first ~5 of the 20 years
- New RD or additional RD50 research line essential for achieving the goal
  - EU funding would help to rise funds at national level

Conclusion

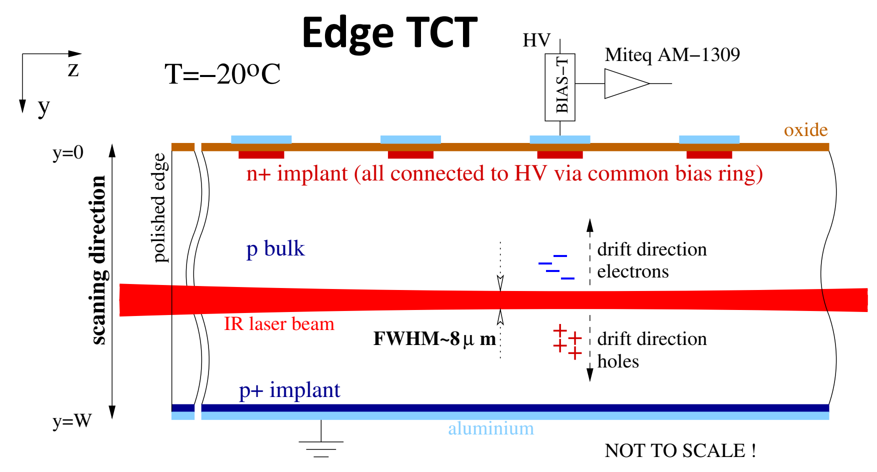


NOTHING IS
IMPOSSIBLE,
THE WORD
ITSELF SAYS
"I'M POSSIBLE"!
- AUDREY HEPBURN

Backup Slides

Edge TCT

- Edge-TCT
  - Generate charges 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 (Transient Current Technique)
  - Laser beam width 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



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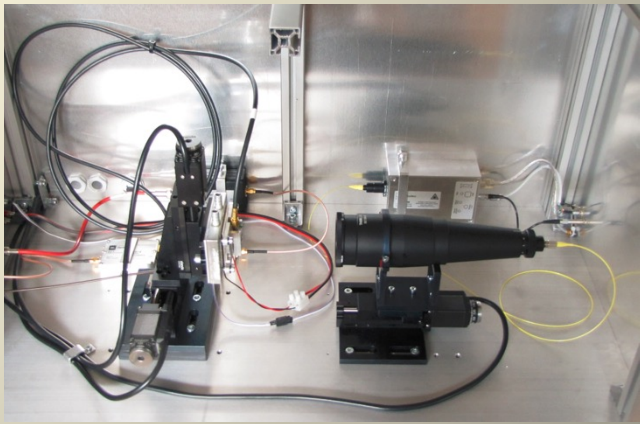
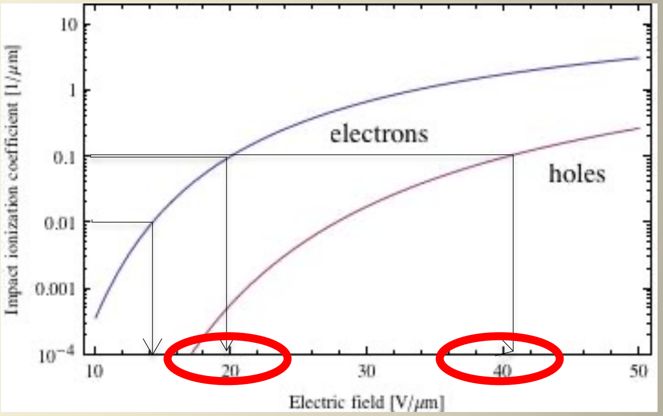


Charge Multiplication

- 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).

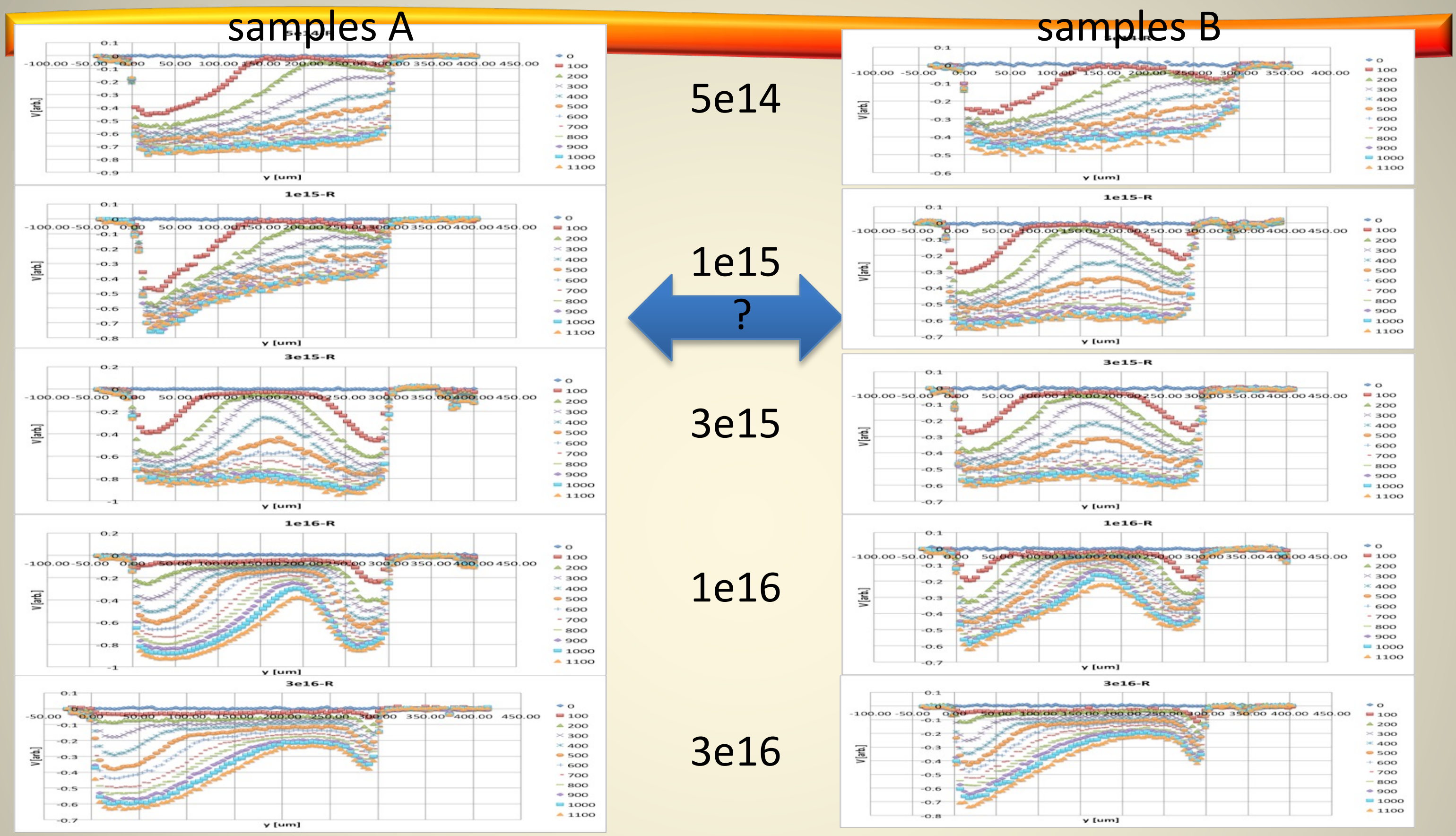


R.VAN OVERSTRAETEN and H.DE MAN, Solid-State Electronics 13(1970),583-608.
W.MAES, K.DE MEYER, R.VAN OVERSTRAETEN, Solid-State Electronics 33(1990),705-718.

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

Breakdown condition, can swap α_e with α_h

Reverse velocity profiles



samples A

samples B

5e14

1e15

?

3e15

1e16

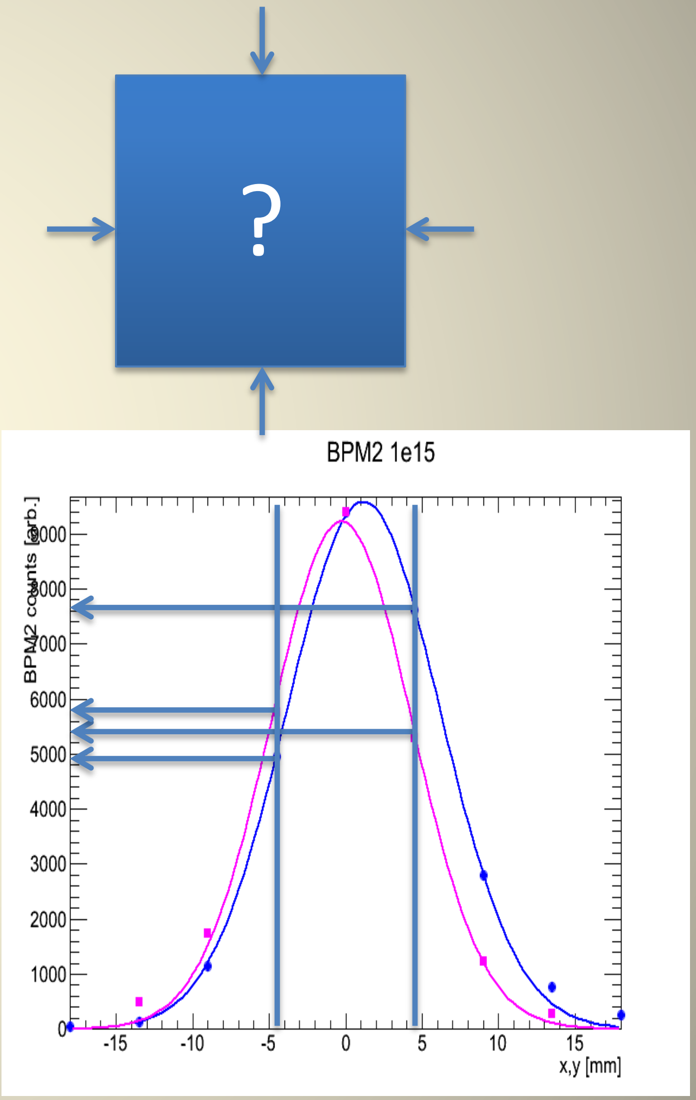
3e16

- 🙃 Something's fishy... never repeat experiments ?!
  - 😀 Explained by PS beam profile variation on sample edges

Proton irradiations - details

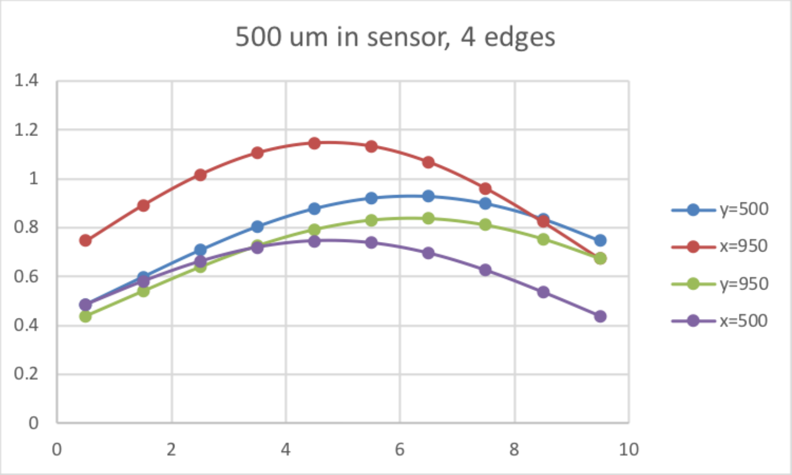
- Samples irradiated in PS in pairs
  - in series in same sample holder
- Same leakage current in both samples

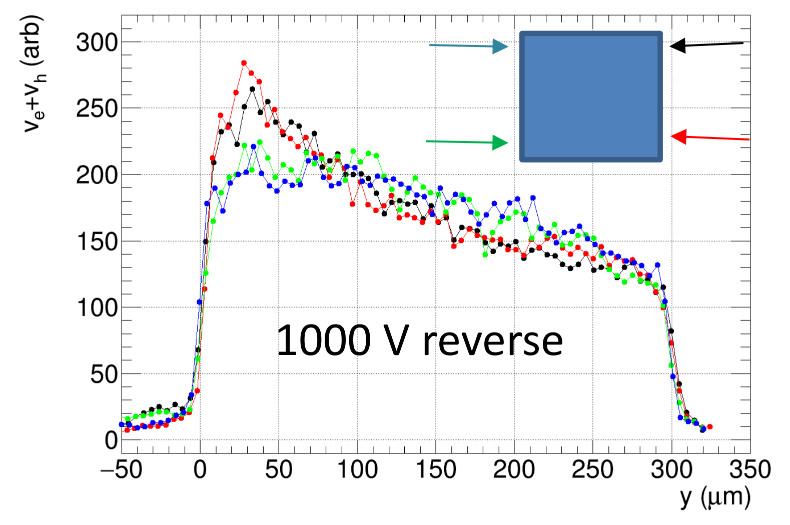
  ⇒same *average* fluence received
- Beam profile asymmetric
  - monitored by BPM2
- Which side did we pick up ?



Protons revisited

- BPM2 results for the 1e15 sample, 0.5 mm in sensor
- 10x10 mm^2 average to peak: 0.7
  - Values rescaled
- Mid-side to average:
  - 1.17, 0.88, 0.82, 0.74
    - Must be the larger difference
  - ➢ Correct fluences by -10 %
  - ➢ Assign 20 % error
- ➢ Re-measured one sample from both sides, match with BPM2 data – still in progress
  - ➢ Looks like explaining the issue





Mobility Comparison

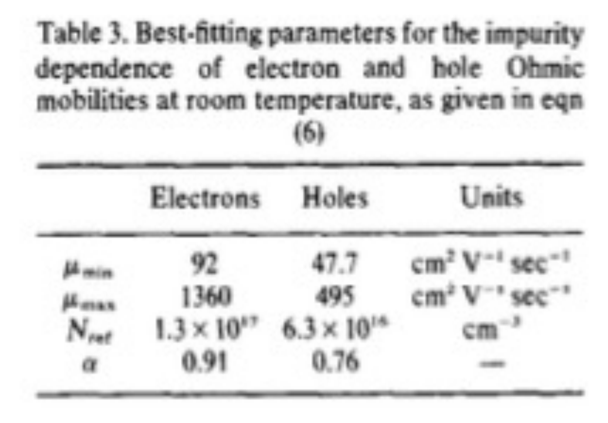


Table 3. Best-fitting parameters for the impurity dependence of electron and hole Ohmic mobilities at room temperature, as given in eqn (6)

	Electrons	Holes	Units
μ_{min}	92	47.7	$cm^2 V^{-1} sec^{-1}$
μ_{max}	1360	495	$cm^2 V^{-1} sec^{-1}$
N_{ref}	1.3×10^{17}	6.3×10^{16}	cm^{-3}
α	0.91	0.76	—

- Dependence on *shallow* dopant concentration
  - Measured in the roaring 60’s
- Characteristic trap concentration N~10^{17} cm^{-3}
  - looks out of reach for typical g=O(10^{-2})
- But g refers to $N_{eff} = |N_a - N_d|$
- While N is more like $N_a + N_d$
  - *x-sections for deep and shallow ?*
- Power law looks compatible: $a \leq 1$

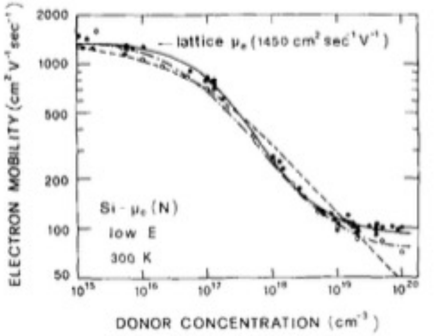


Fig. 5. Electron mobility, μ_e, in silicon at 300 K as a function of impurity concentration. Open and closed circles are the experimental results reported by Irvin[55] and of Mousty *et al.*[56], respectively. The continuous line is the phenomenological best fit (eqn (6)) of Baccarani and Ostoia[53] the broken line the best fit (eqn (7)) of Hilsum[54] the dot-dashed line (eqn (8)) of Scharfetter and Gummel[57] (see Tables 3 and 4).

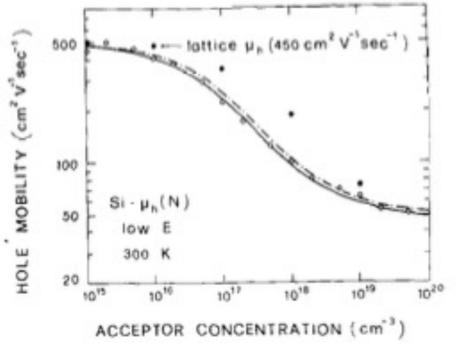
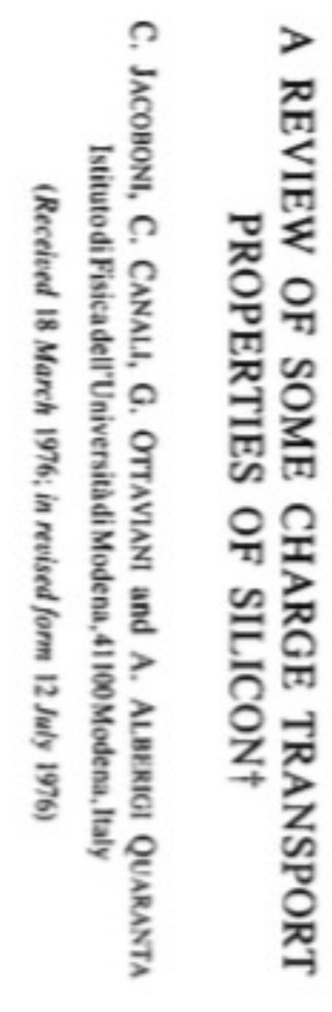


Fig. 6. Hole mobility, μ_h, in silicon at 300 K as a function of impurity concentration. Open circles are experimental results reported by Irvin[55]. Continuous and dot-dashed lines represent the best fitting curves of Caughey and Thomas[58] (eqn (6)) and of Scharfetter and Gummel[57] (eqn (8)), respectively (see Tables 3 and 4).



A REVIEW OF SOME CHARGE TRANSPORT PROPERTIES OF SILICON†

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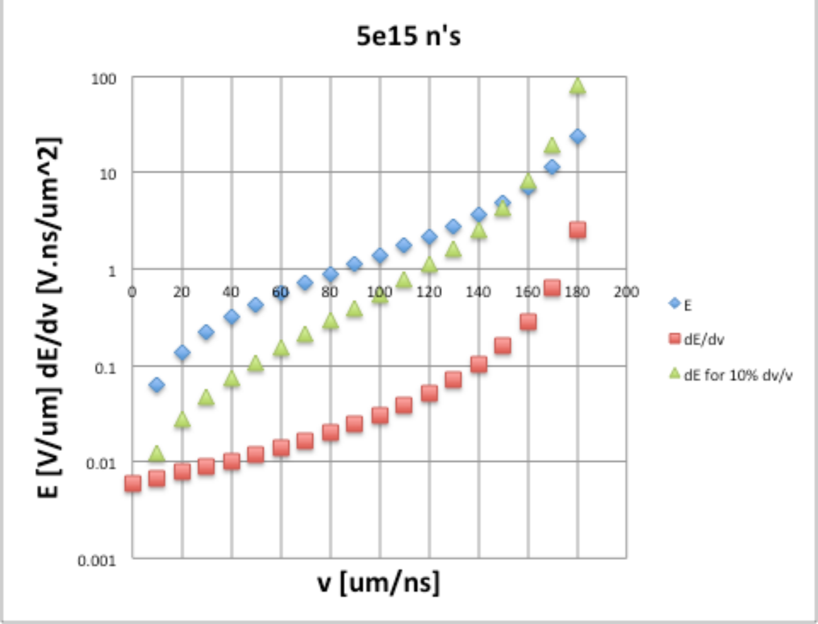
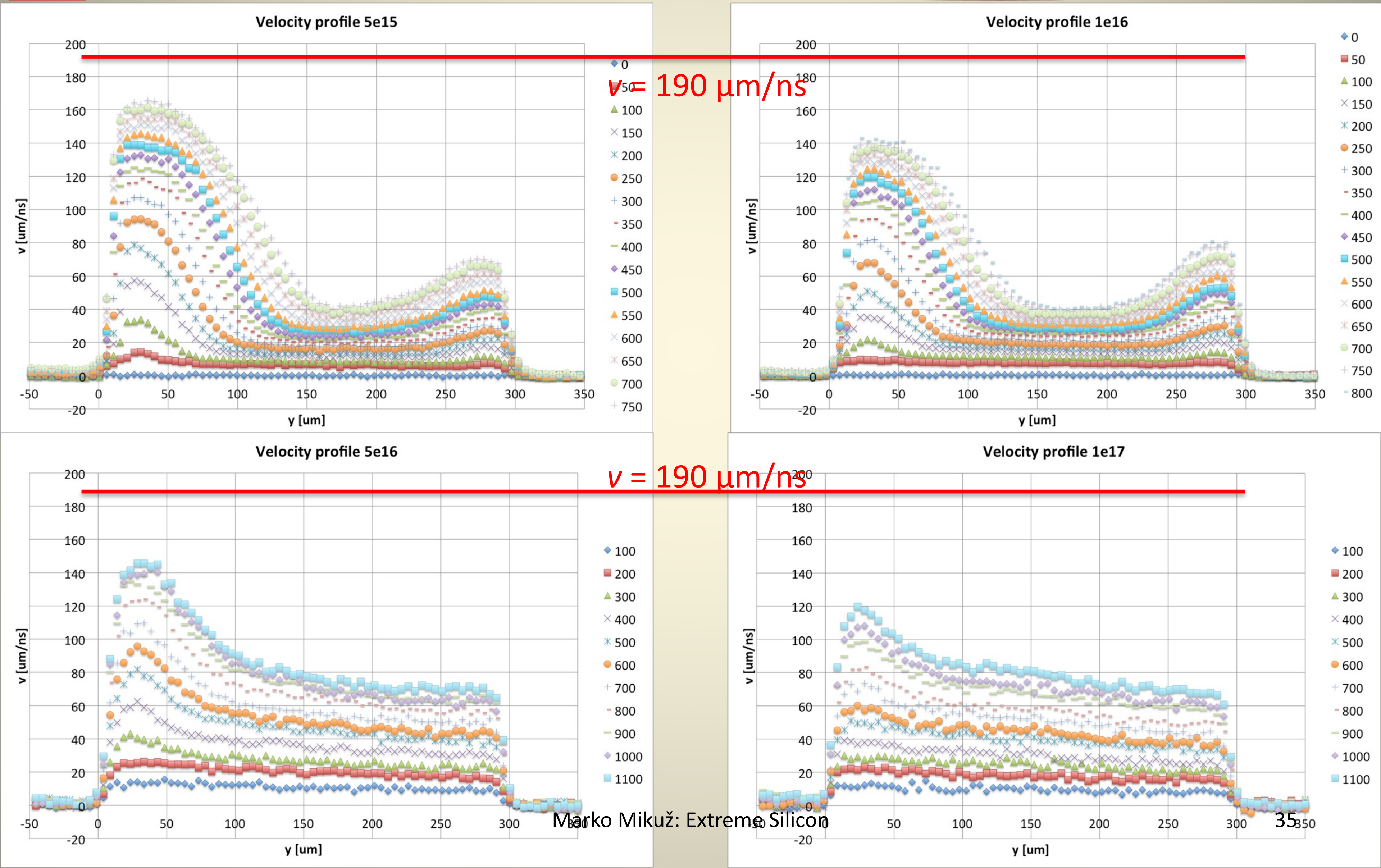
Velocity and Field Profiles

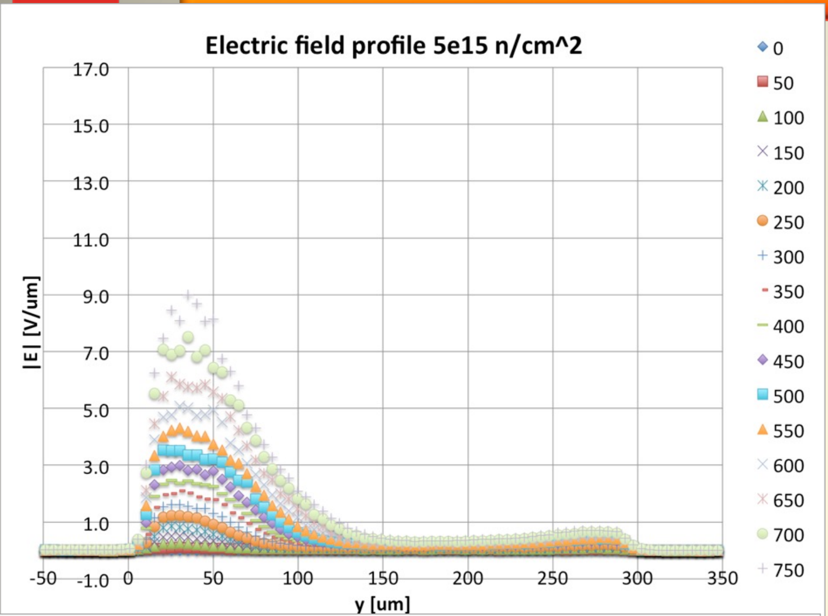
- Knowing *v(E)* can set scale to velocity profiles
  - assumption: same scale on FW and reverse bias
    - protons: for 5x10^{14} and 10^{15} use same scale, fixed by average field for 5x10^{14} at 1100 V (no good FW data)
- Invert *E(v)* to get electric field profiles
  - big errors when approaching v_{sat} i.e. at high *E*
    - exaggerated by CM in high field regions
    - $v > v_{sat}$ not physical, but can be faked by CM

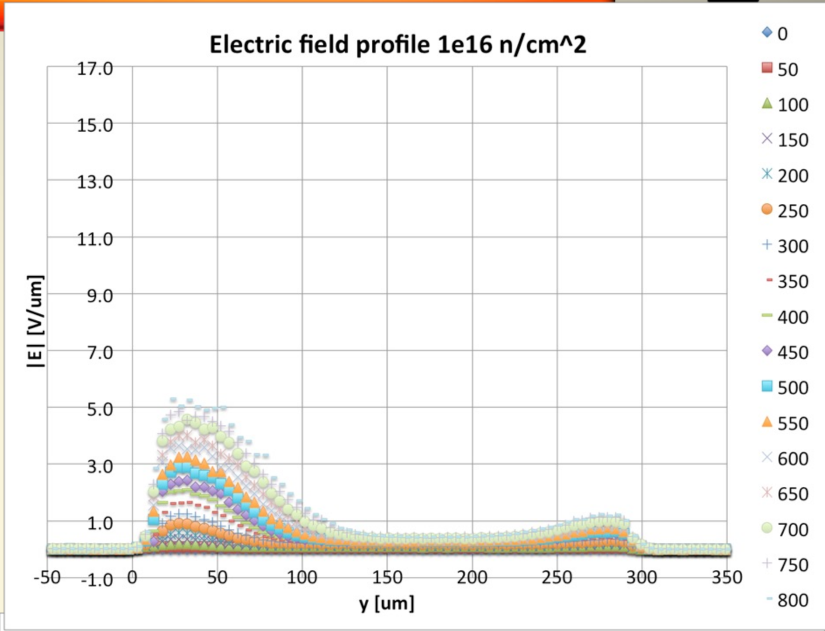


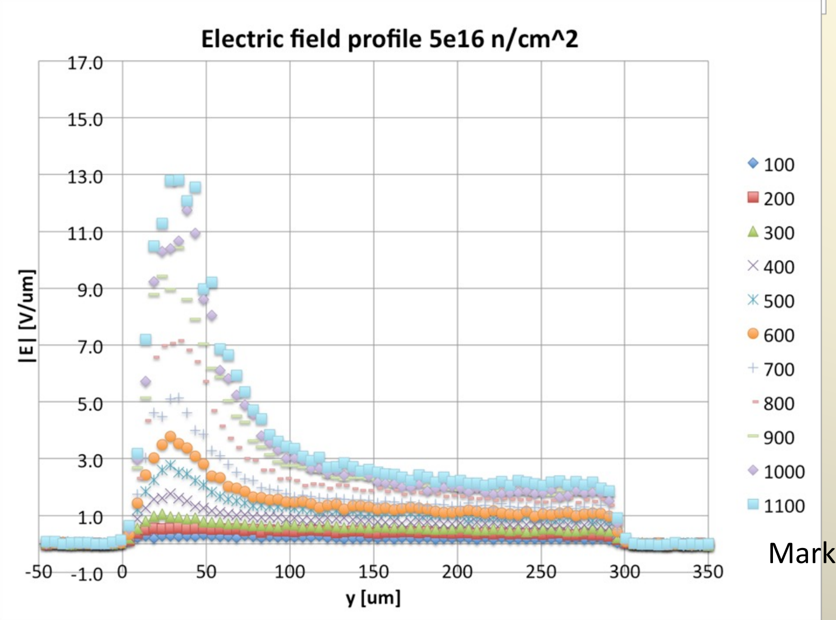
Velocity Profiles Neutrons

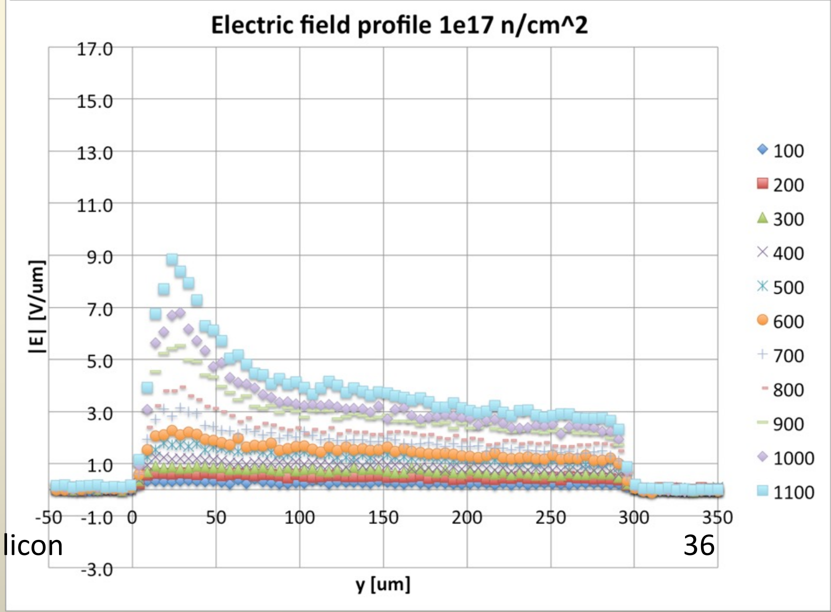


Field Profiles Neutrons


Electric field profile 5e15 n/cm^2

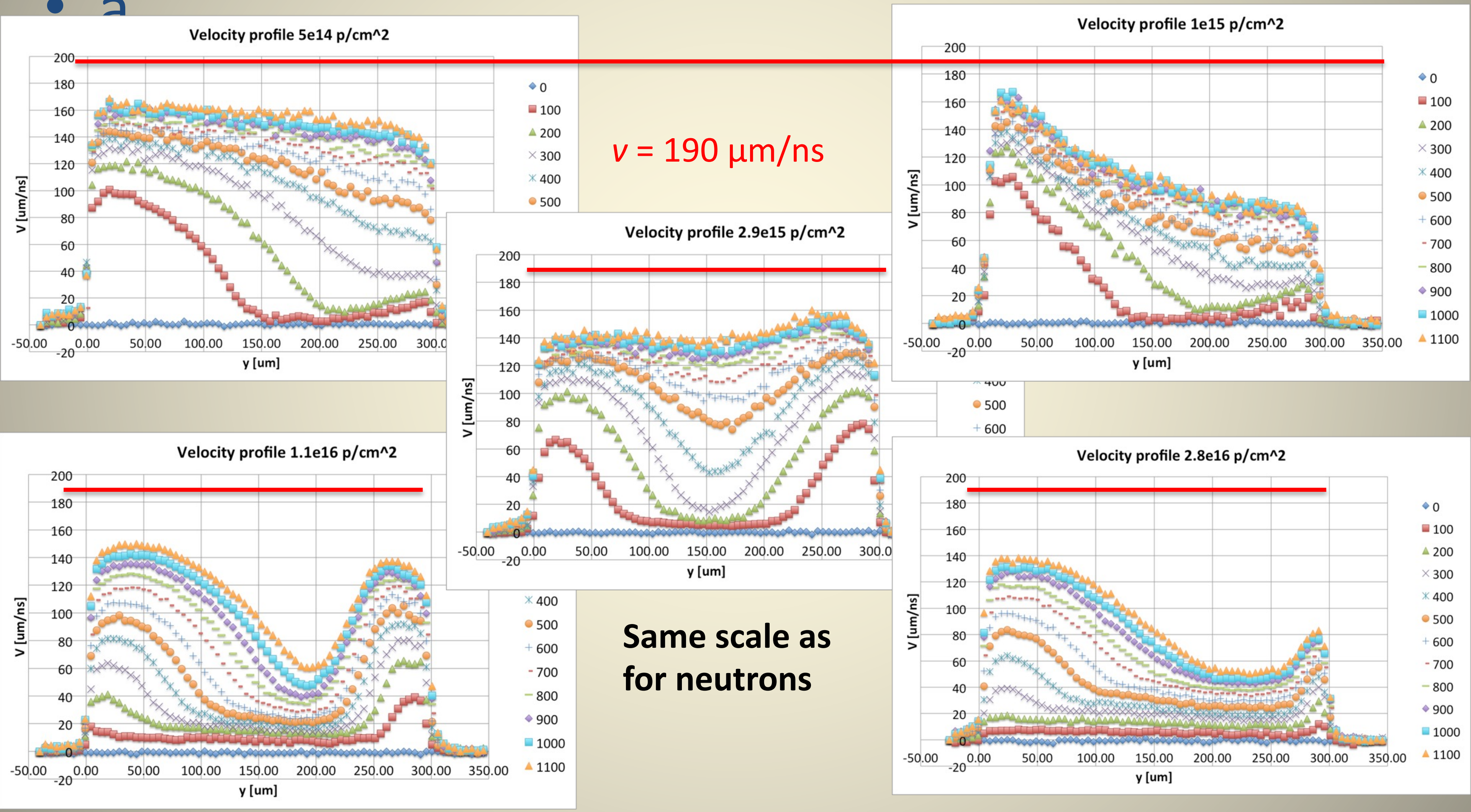

Electric field profile 1e16 n/cm^2


Electric field profile 5e16 n/cm^2


Electric field profile 1e17 n/cm^2

Velocity Profiles Protons

- a



Velocity profile 5e14 p/cm^2

Velocity profile 1e15 p/cm^2

Velocity profile 2.9e15 p/cm^2

Velocity profile 1.1e16 p/cm^2

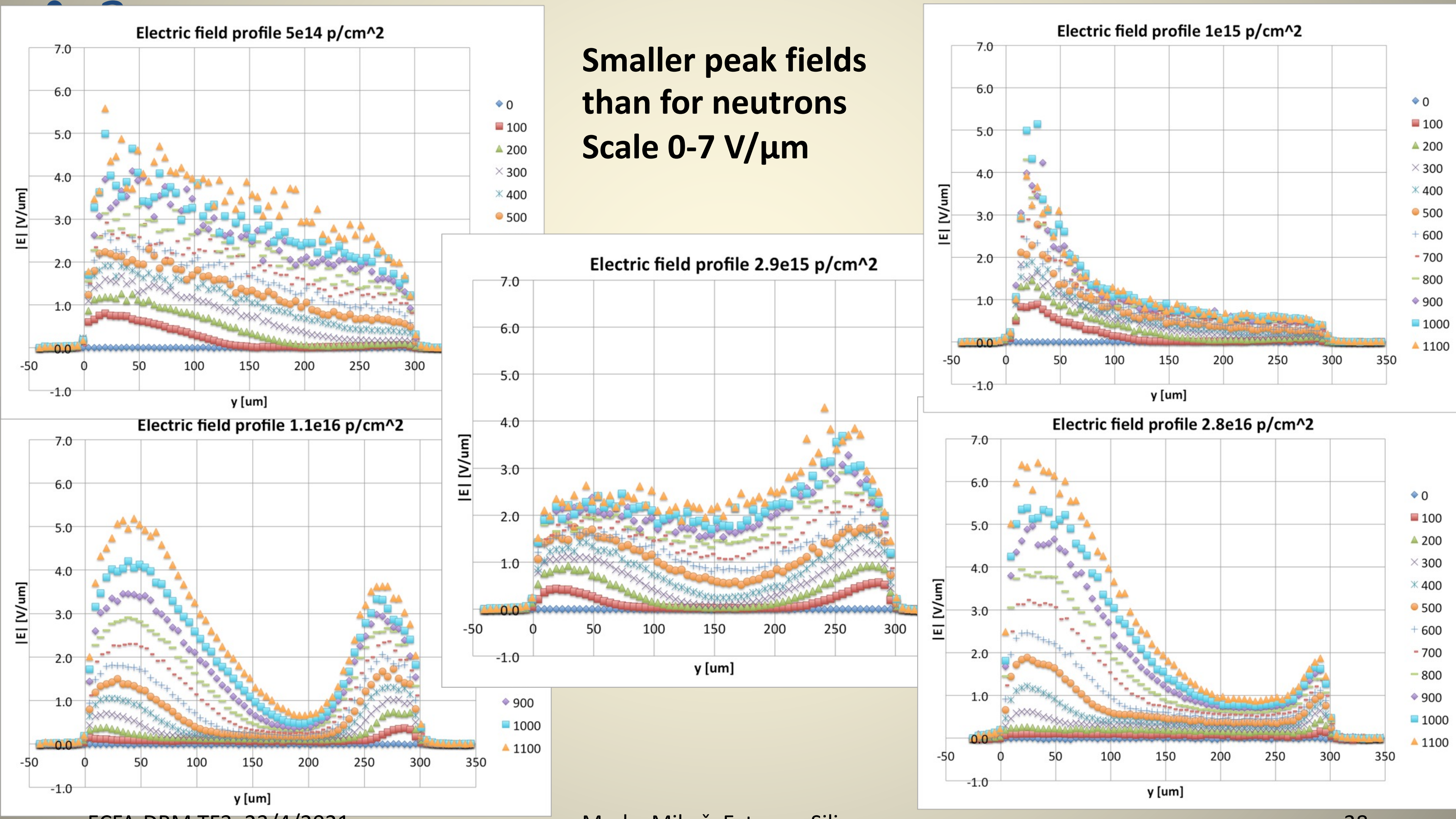
Velocity profile 2.8e16 p/cm^2

v = 190 µm/ns

Same scale as for neutrons

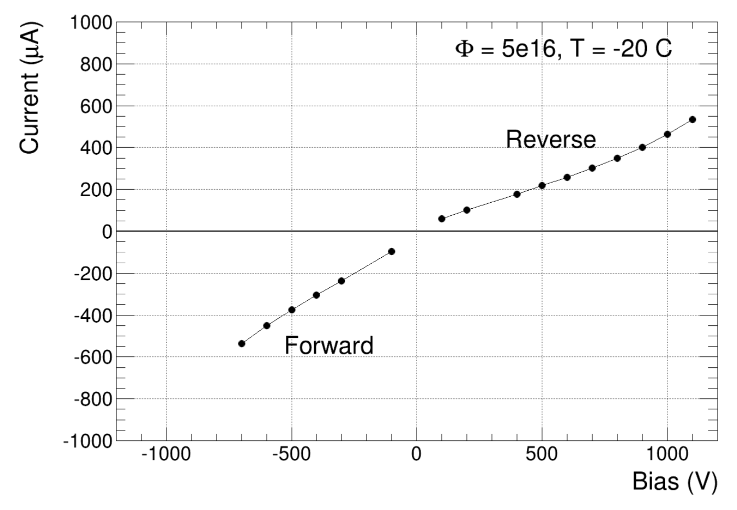
Field Profiles Protons

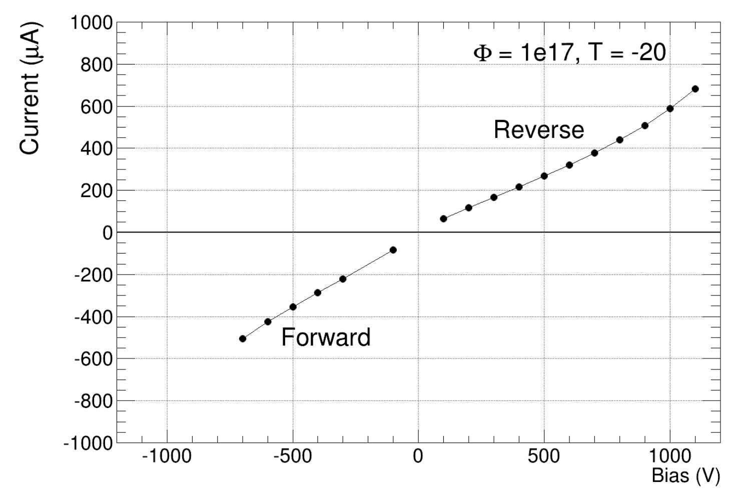
Smaller peak fields than for neutrons
Scale 0-7 V/µm



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 ~linear with bias
  - Slopes FW/reverse more compatible at higher fluences
- Consistent with recent measurements at highest fluences





Trapping Considerations

- Extrapolation from low fluence data with $\beta_{e,h}$(-20°C)=4.4,5.8x10^{-16} cm^2/ns; $1/\tau = \beta \Phi$

Φ [1e15]	**5**	**10**	**50**	**100**
τ [ps]	400	200	40	20
$mfp@v_{sat}$ [µm]	95	48	9.5	4.8
MPV [e_0]	7600	3800	760	380
MPV@1000 V	8900	5500	1800	1150
$CCD_{1000\ V}$ [µm]	110	70	23	14

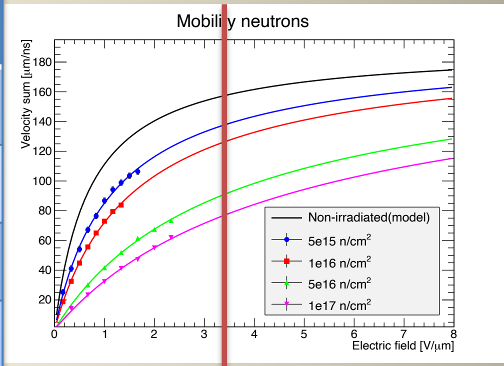
From "magic formula"
JINST 9 P10016(2014)

- Measured data exceeds (by far) linear extrapolation of trapping
  - n.b.1: *E*~3 V/µm by far not enough to saturate velocity
  - n.b.2: little sign of CM at highest fluences

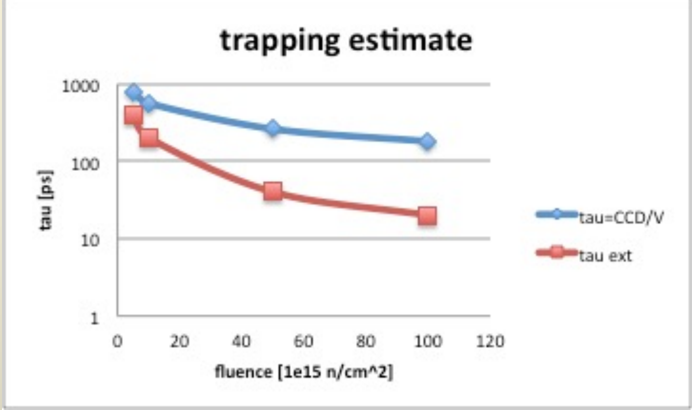
More Considerations

- More realistic: take v_{sum} at average $E = 3.3$ V/µm

Φ [1e15]	5	10	50	100
$v_{sum}(3.3$ V/µm)	137	126	90	77
$CCD_{1000\ \mathrm{V}}$ [µm]	110	70	23	14
$\tau \approx CCD/v$ [ps]	800	560	260	180
τ_{ext} [ps]	400	200	40	20

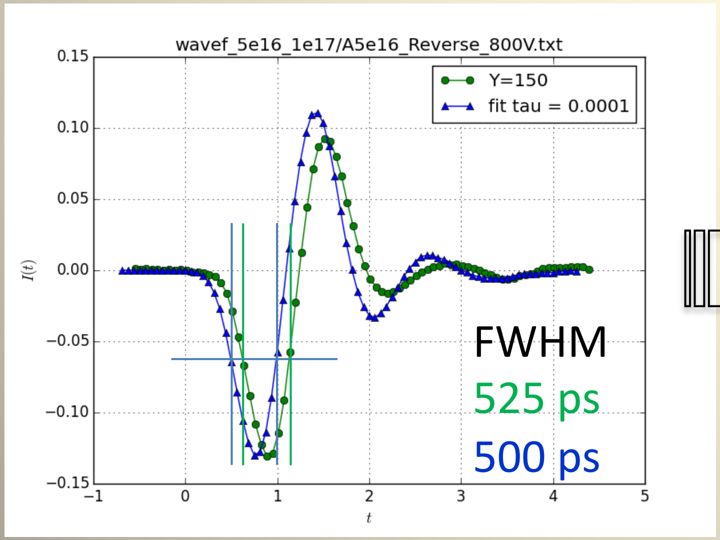


- Implies factor of 6-9 less trapping at highest fluences
  - lowest fluence still x2 from extrapolation
  - weak dependence on fluence as anticipated
  - CM would effectively shorten trapping times
  - not good when large *E* variations (*v(E)* saturates)
  - not good when *CCD* ≈ thickness (less signal at same *τ*)

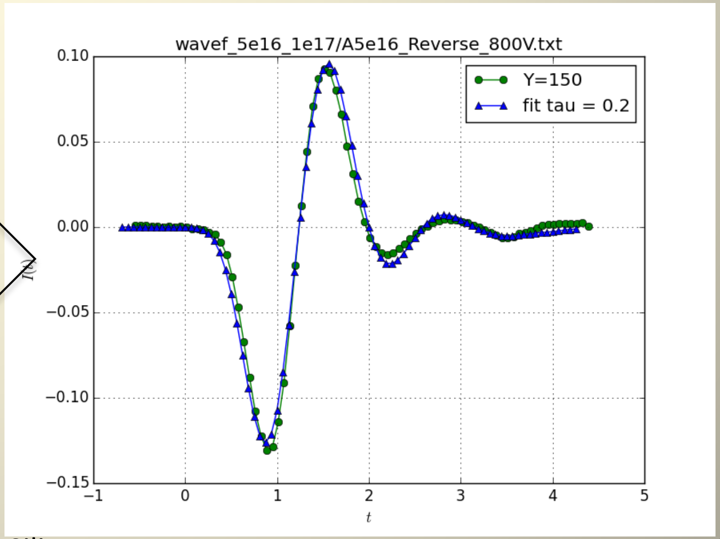


Exploiting TCT Waveforms

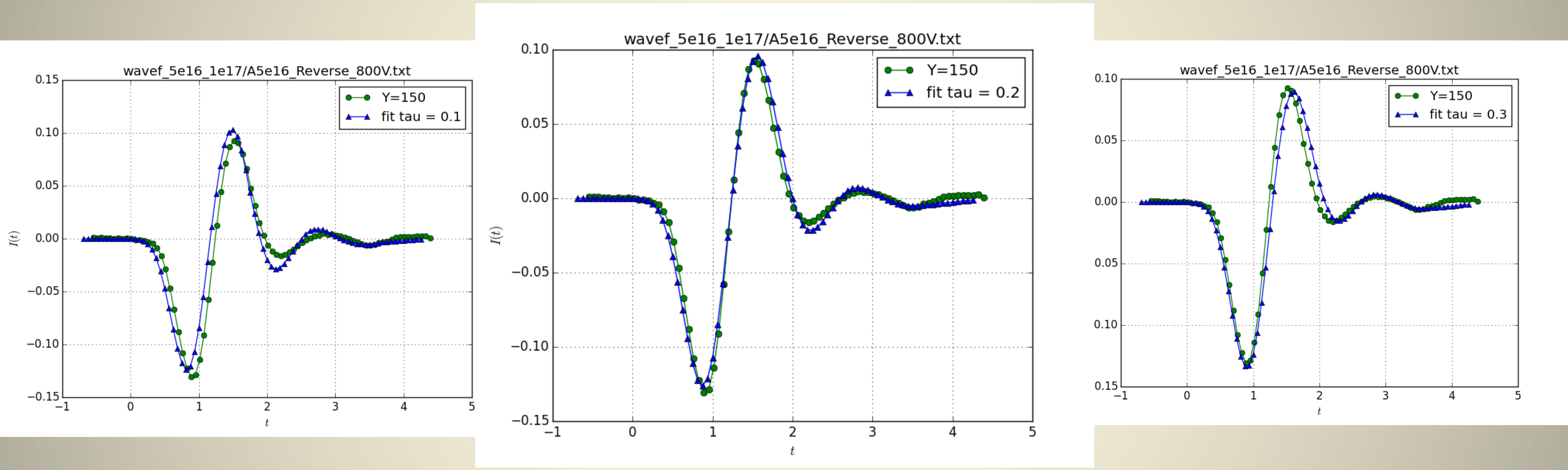
- Waveforms at *y*=100 μm, 800 V, 5x10^{16} and 10^{17}
  - *E* ≈ 3 V/μm, *CCD/2* implies signal within ~10 μm or <0.2 ns
    - the rest you see is the transfer function of the system
- Still distinct signals from the two fluences
  - treat 10^{17} waveform as transfer function of the system
    - convolute with $e^{-t/\tau}$ to match 5x10^{16} response
    - τ = 0.2 ns provides a good match
- In fact, measure ~$\Delta\tau$, as “transfer” already convoluted with $e^{-t/\tau(1e17)}$!



τ = 0.2 ns



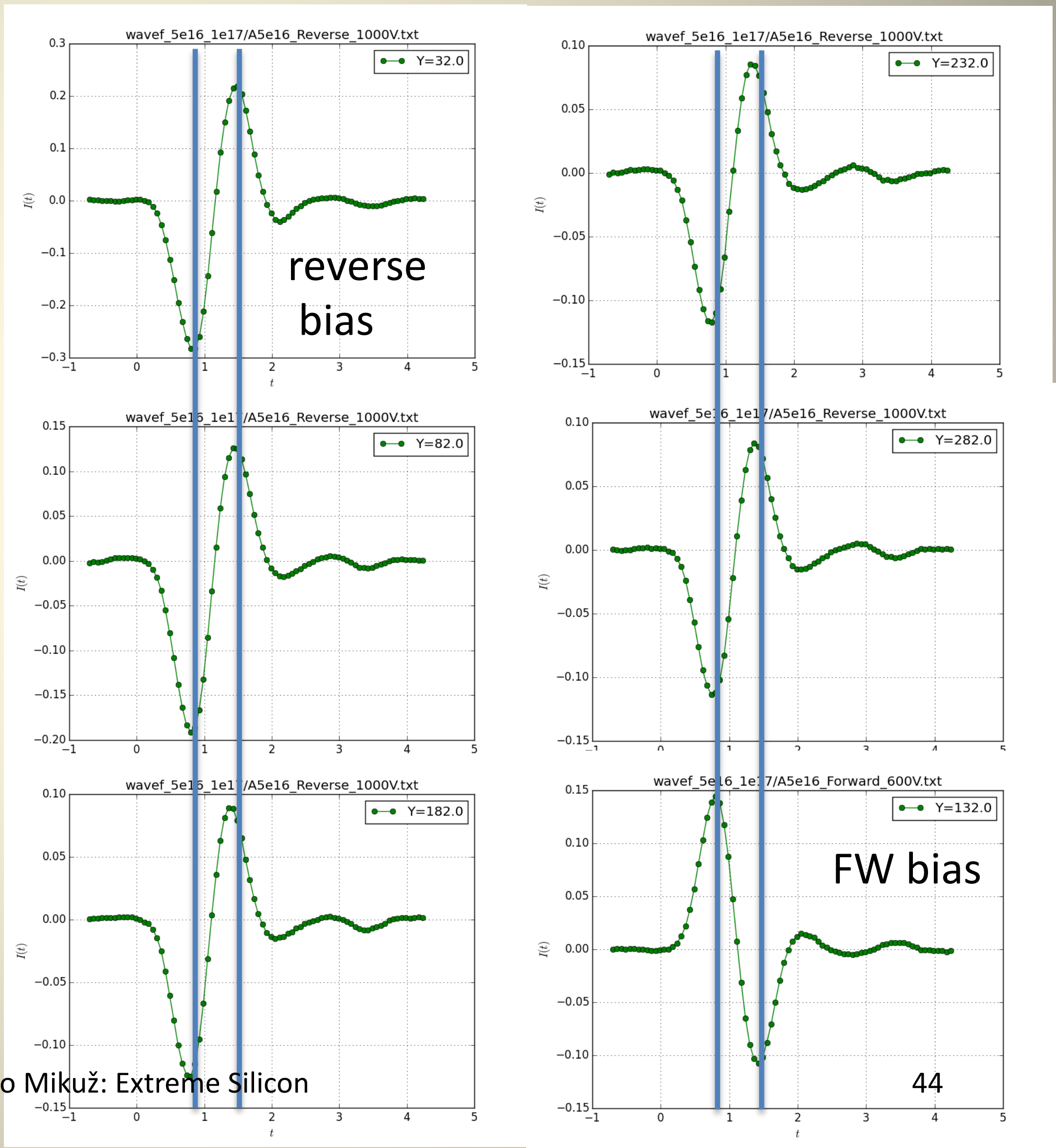
Waveforms: How sensitive ?



- *Δτ* = 0.2 ns certainly best fit, 0.1 too narrow, 0.3 too broad
- precision ~50 ps

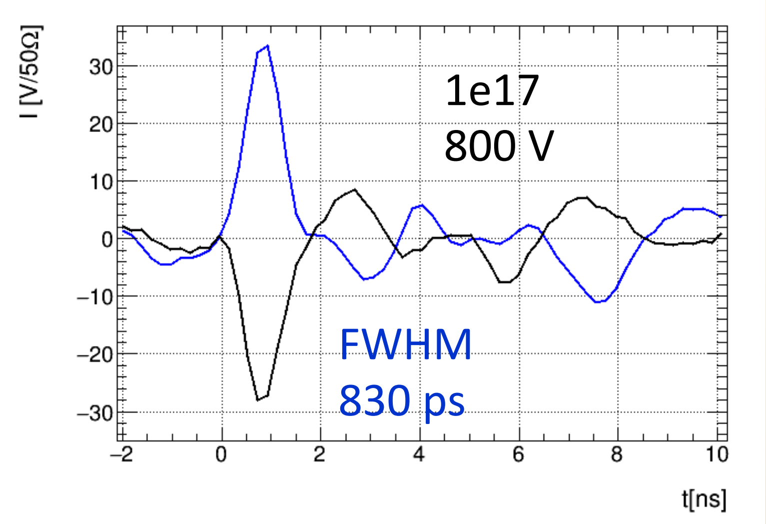
Trapping – position dependence ?

- Waveforms plotted every 50 um in detector depth for reverse bias at 1000 V
- Forward bias in middle of detector added at 600 V
- Very little, if any, wf dependence on position observed
- Trapping not position (even not bias) dependent !?



Trapping @3e17

- Moved to another setup – different waveforms
  - Widths of reverse and FW similar
  - With decreases 1->3e17
  - Irregular waveforms with small signal @3e17
  - Hard to state something more quantitative



Blue
Reverse

Black
FW