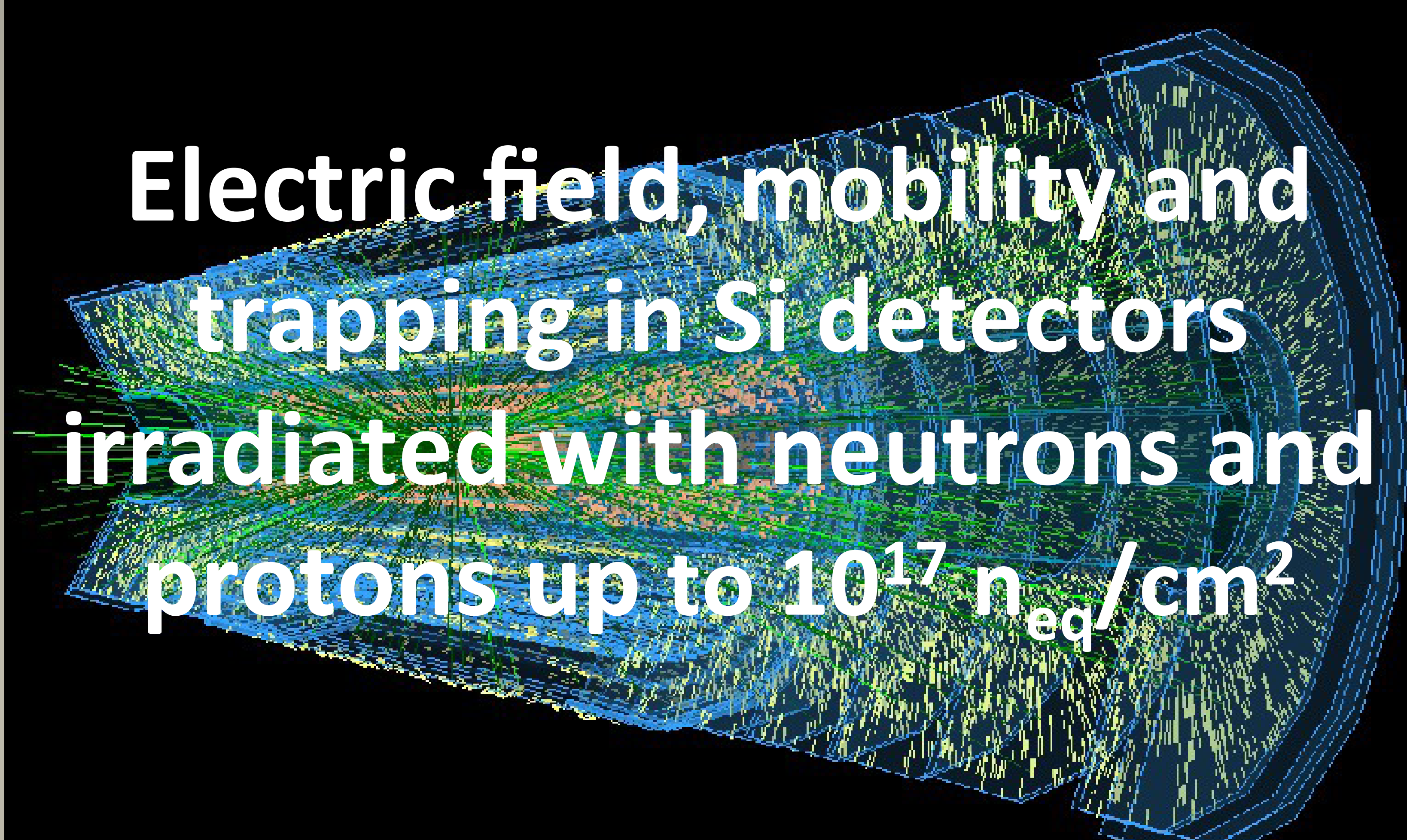

Electric field, mobility and trapping in Si detectors irradiated with neutrons and protons up to $10^{17}\ n_{eq}/cm^2$

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University of Ljubljana & Jožef Stefan Institute

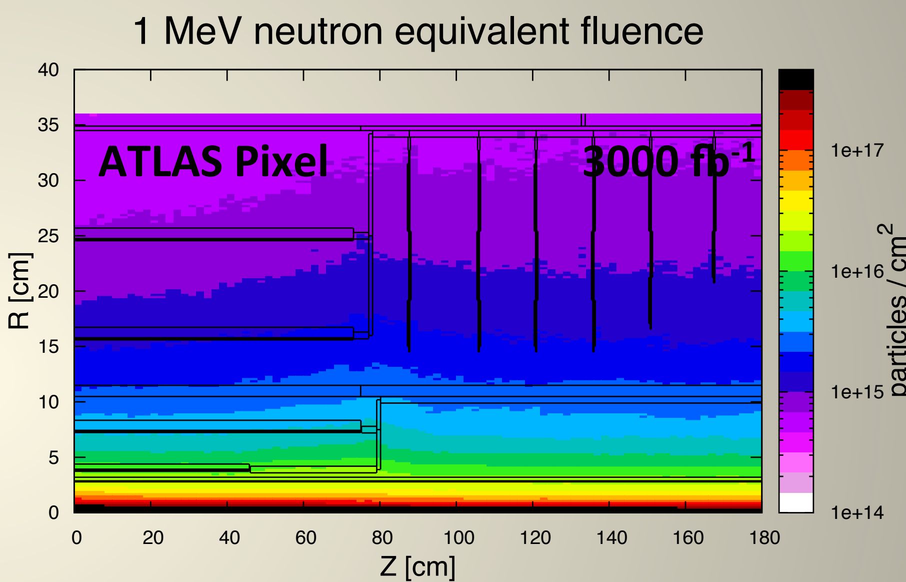
11th "Trento" Workshop on

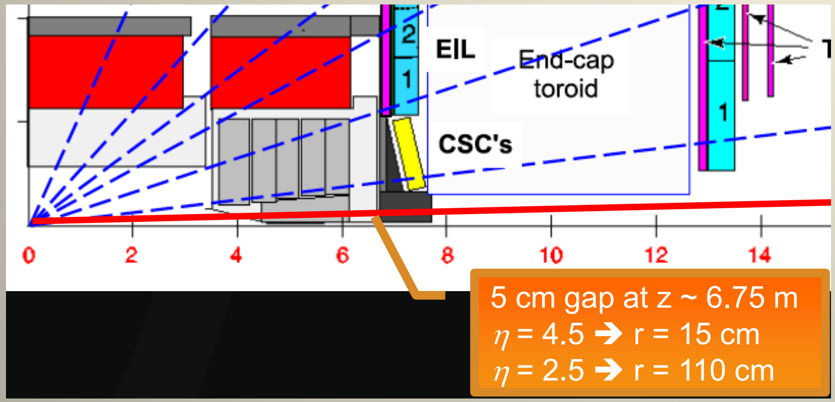
Advanced Silicon Radiation Detectors

Paris, February 22nd, 2016

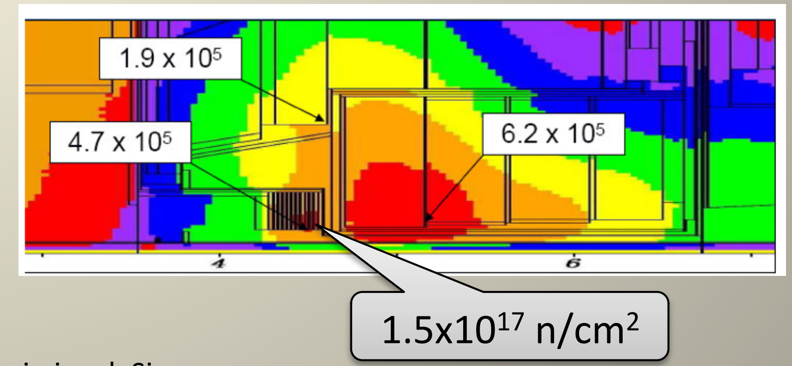
Why the 10^{17} Ballpark ?

- Run1 at LHC finished, 2 under way
  - LHC trackers designed for 730 fb^{-1} of 14 TeV pp collisions, ~35 fb^{-1} up to now
  - Will probably get ~½ of planned
- HL-LHC in advanced planning
  - 3000 fb^{-1} i.e. ~10xLHC
    - ~10^{15} n_{eq}/cm^2 for strips (neutrons&pions)
    - ~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 ?



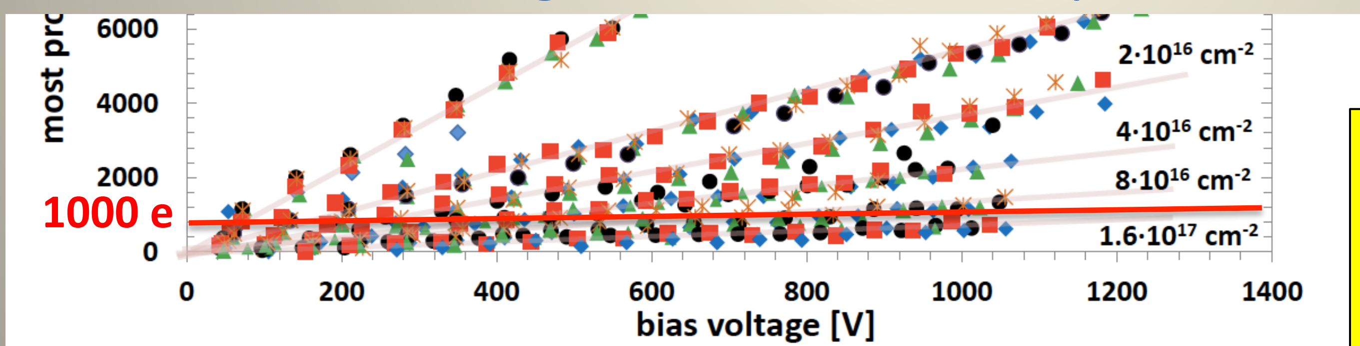


ATLAS FCAL **3000 fb^{-1}**



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

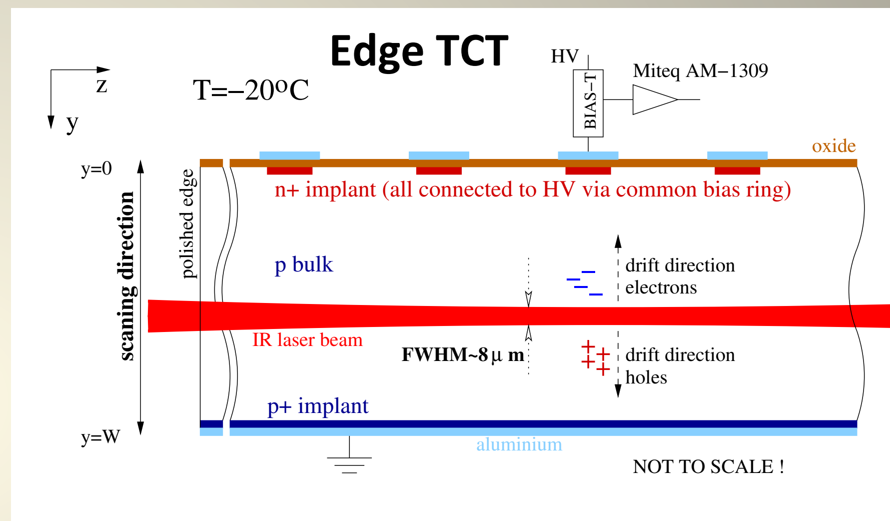
- Linear extrapolation from low fluence data
  - Current: I_{leak} = 4 A/cm^3 @20°C
    - 2 mA for 300 μm thick 1 cm^2 detector @ -20°C
  - Depletion: $N_{eff} \approx 1.5\times10^{15}$ cm^{-3}
    - *FDV* ≈ 100 kV
  - Trapping $\tau_{eff} \approx$ 1/40 ns = 25 ps
    - $Q \approx Q_0/d\ v_{sat}\tau_{eff} \approx$ 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



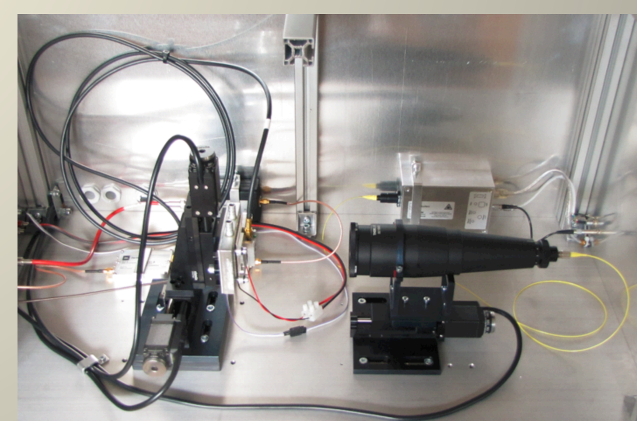
From:
G. Kramberger et al., *JINST 8 P08004 (2013).*

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



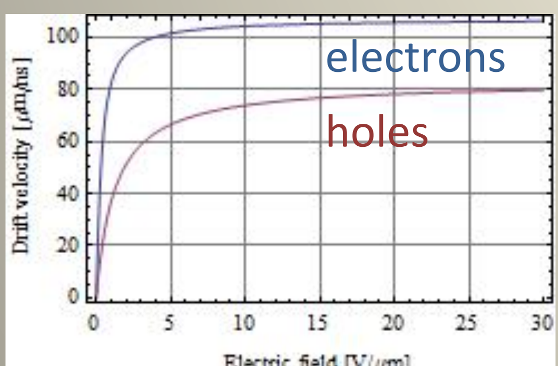
www.particulars.si

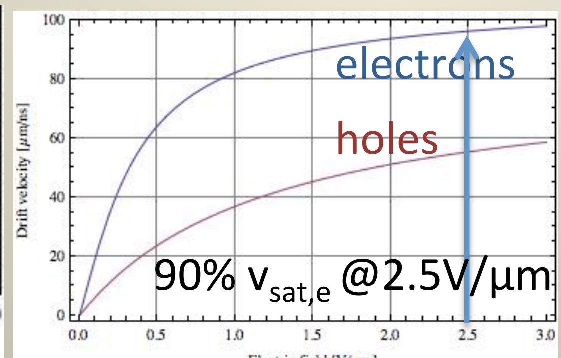


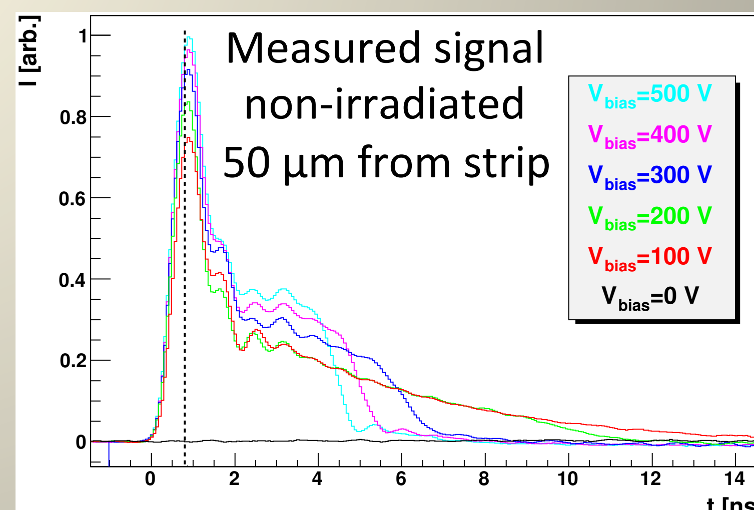
Electric Field Measurement

- 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

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

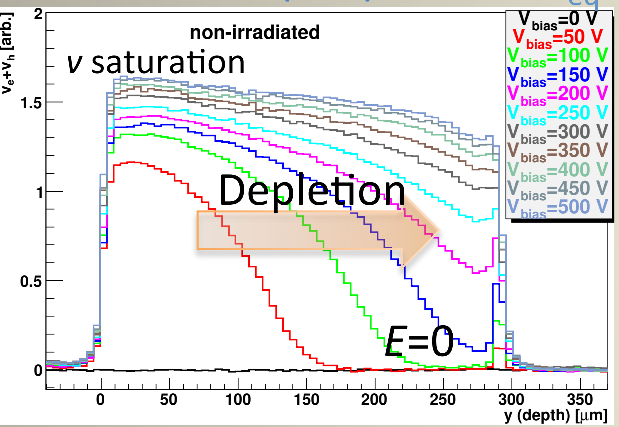


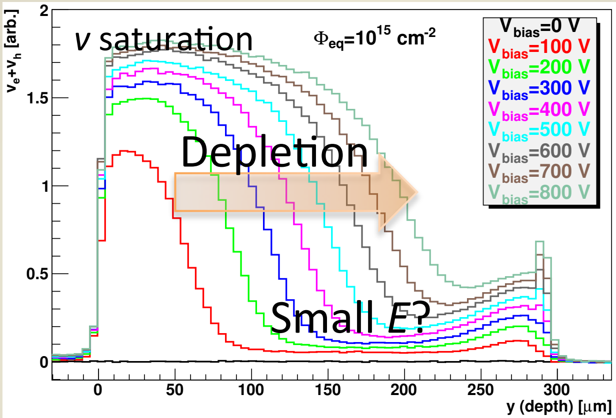


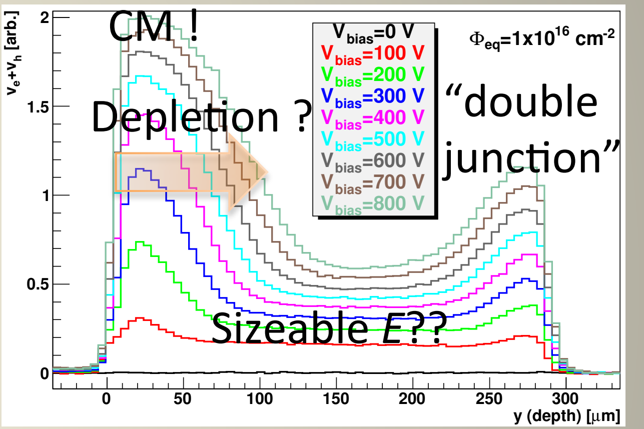


Selected Results from Neutrons

- 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*
- Can we bring these observations to *quantitative* level ?

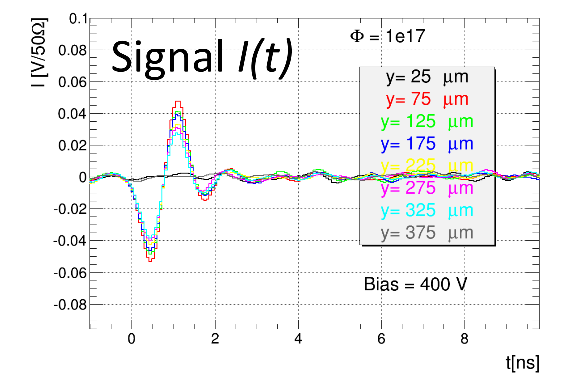
Published in :
G. Kramberger et al.,
JINST 9 P10016(2014).

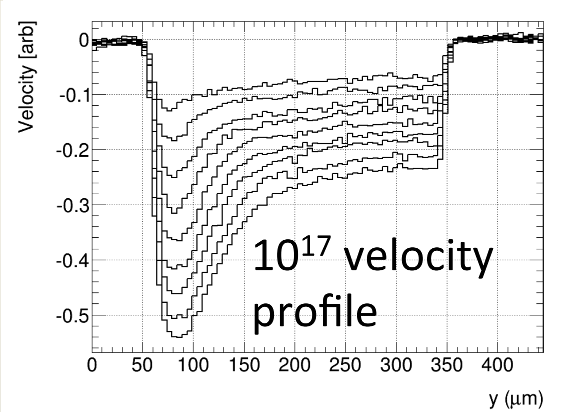
Extending the Reach

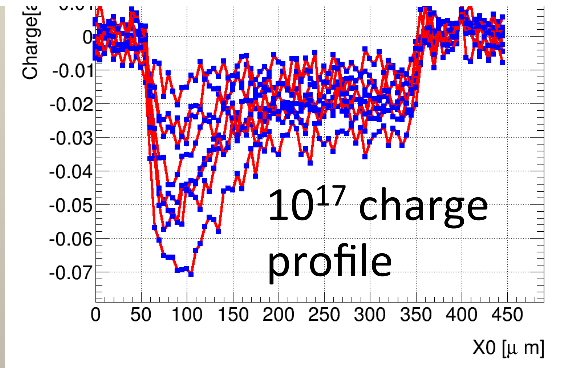
- In 2014 added 5x10^{16} and 10^{17} n_{eq}/cm^2 measurements of the same detector
  - 10^{16} of this fluence fully annealed, the rest 80 min @ 60°C
- Intrinsic feature – signal oscillations
  - period ~5/4 ns
  - CLR ? (C~2pf => L~20 nH ~ 1cm of wire)
  - velocity (slope) and charge (integral) yield consistent results
  - should be, as $Q \approx Q_0 \, v_{sum} \tau_{eff} / d$

☹Cannot use *I(t)* to measure trapping...

☑ ... shall be revised

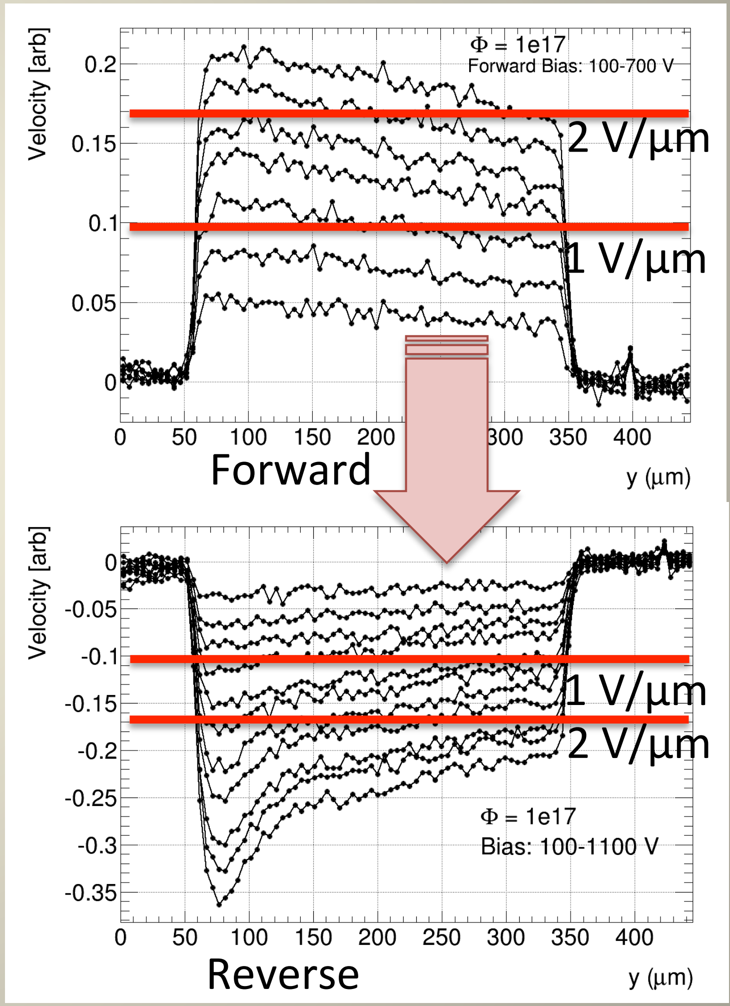






Field Measurement Mastered

- 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
- Can 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
  - NIEL hardness factor 0.62
  - thanks to CERN IRRAD team
- Covers HL-LHC tracker range well
- Samples back in September, one of the pair investigated by E-TCT for all fluences
  - concurrent forward and reverse bias measurements

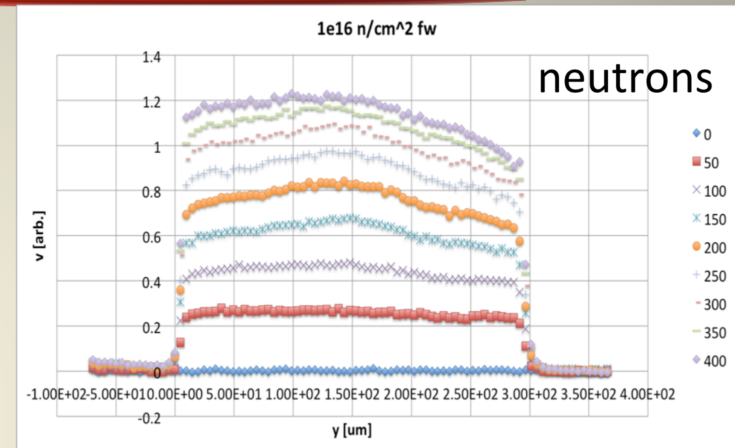
Mobility Considerations FW bias

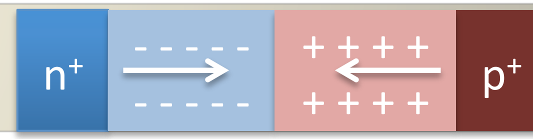
- For forward bias can extract *v(E)* up to a scale factor
- Observe less saturation than predicted
- Model with

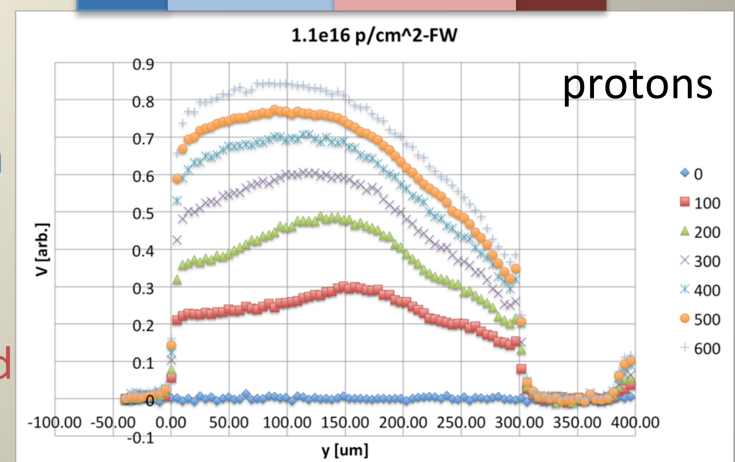
$$v_{sum}(E) = \frac{\mu_{0,e}E}{1+\frac{\mu_{0,e}E}{v_{e,sat}}} + \frac{\mu_{0,h}E}{1+\frac{\mu_{0,h}E}{v_{h,sat}}}$$

  - 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 and for protons, but departures from average field still small

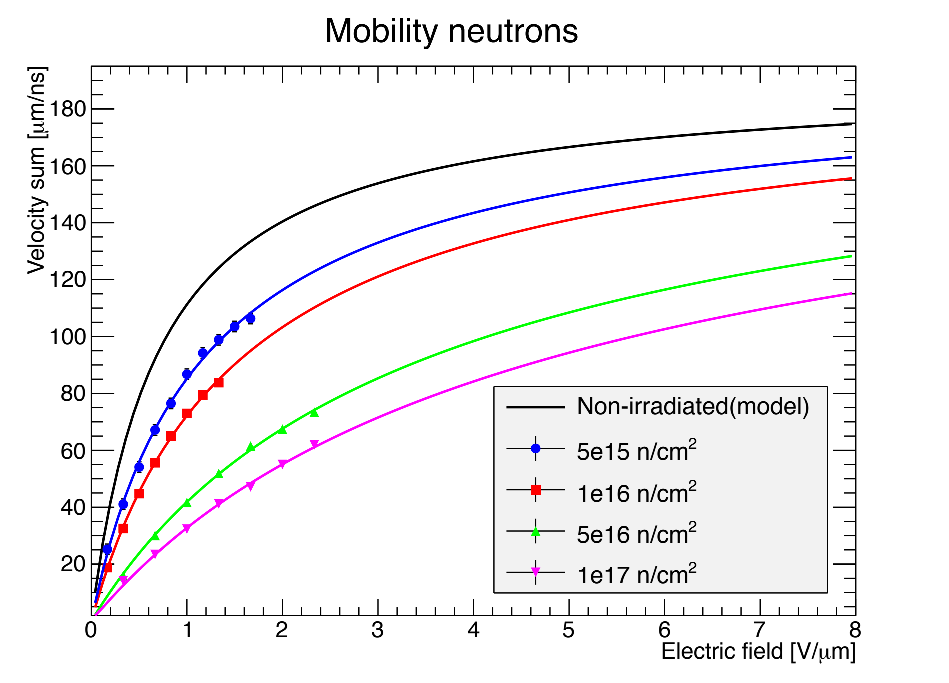


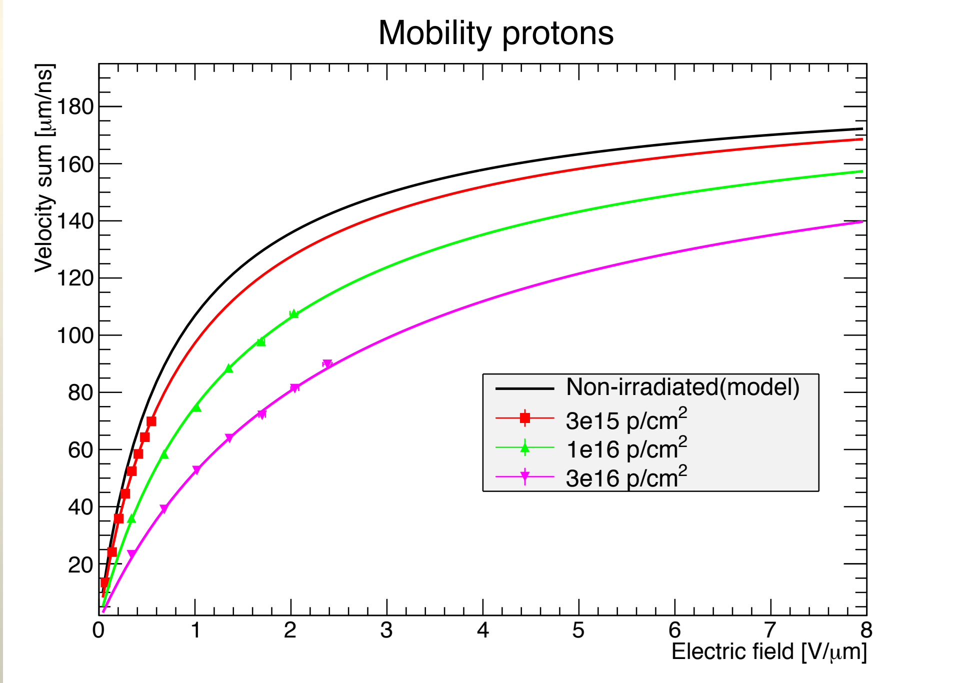




Mobility Fits

- Data follow the model perfectly
  - μ_0 degradation the only free parameter, scale fixed by $v_{sum,sat}$
  - although E range limited, $v_{sum,max}$ still > 1/3 of $v_{sum,sat}$





Mobility Results

- Fit to $v_e + v_h$ with common mobility degradation factor
  - factor of 2 at 10^{16} n_{eq}/cm^2
  - factor of 6 at 10^{17} n_{eq}/cm^2
  - need 2x/6x higher *E* to saturate *v* !

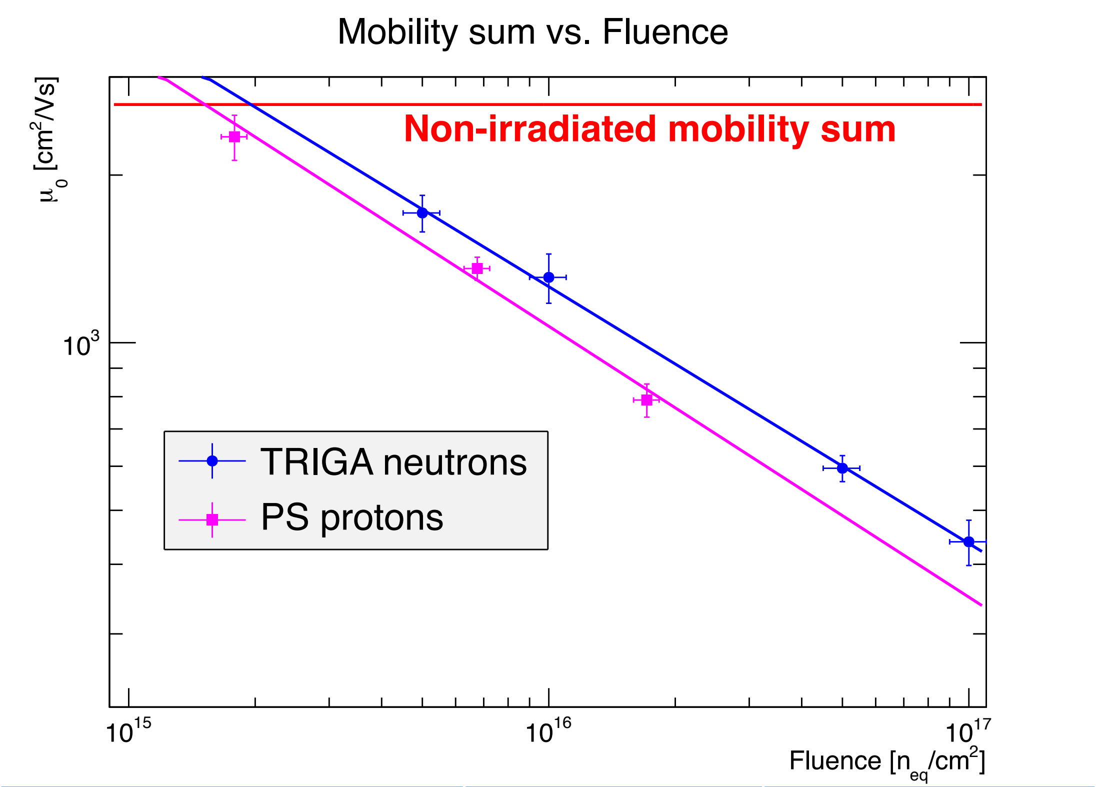
Φn	$\mu_{0,sum}$	Φp	$\mu_{0,sum}$
[10^{15} n_{eq}/cm^2]	[cm^2/Vs]	[10^{15} n_{eq}/cm^2]	[cm^2/Vs]
non-irr (model)	2680		
5	1661 ± 134	1.8	2165± 212
10	1238 ± 131	6.8	1319± 67
50	555 ± 32	17	750± 54
100	407 ± 40	T=-20°C	

Mobility Analysis

- Fit mobility dependence on fluence with a power law

$$\mu_{0,sum}(\Phi) = C\Phi^{a}$$

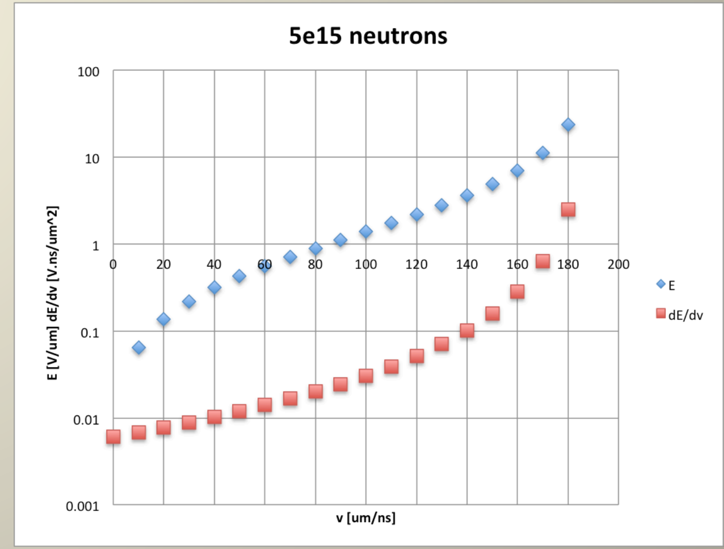
- Fits perfectly with $a \approx -1/2$ indicating a single scattering process in this fluence range
  - ~same a for neutrons and protons
- Below ~10^{15} n_{eq}/cm^2 the process gets obscured by acoustic phonon scattering
- At same equivalent fluence, mobility decrease ~20 % worse for protons
  - NIEL violation
- Is $a \approx -1/2$ accidental ?



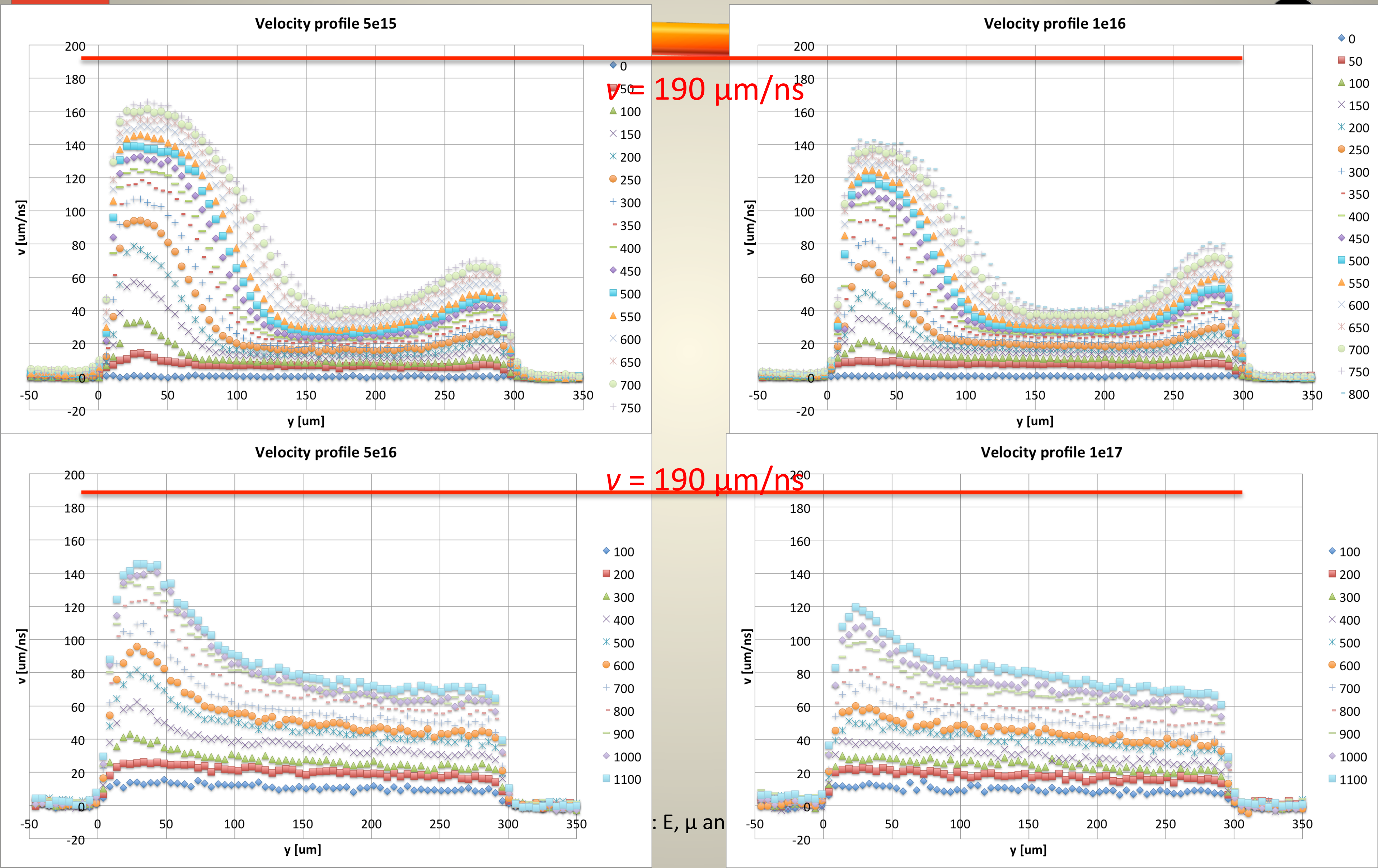
Irradiation particle	a	σ_a
Reactor neutrons	-0.46	0.04
PS protons	-0.49	0.05

Velocity and Field Profiles

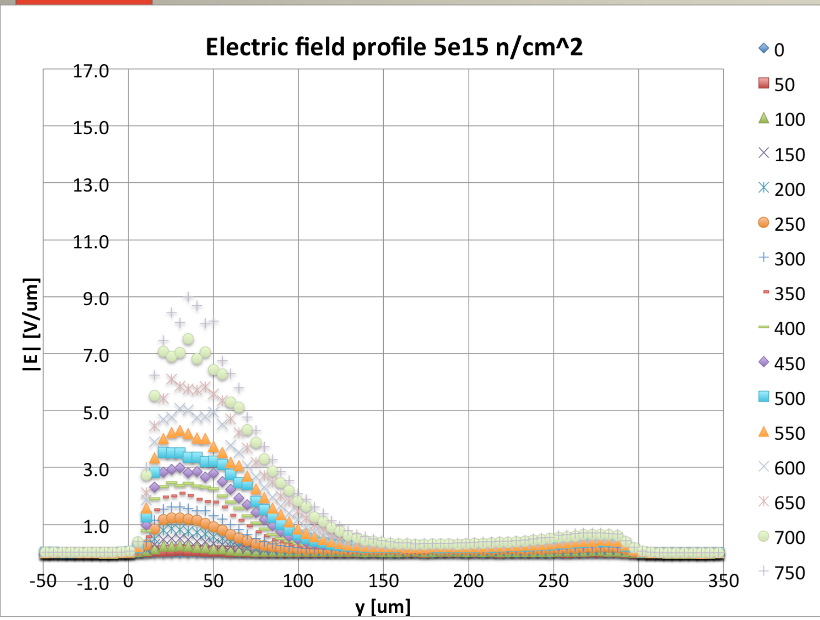
- Knowing *v(E)* can set scale to velocity profiles
  - assumption: same scale on FW and reverse bias
    - protons: for 5×10^{14} and 10^{15} use same scale, fixed by average field for 5×10^{14} at 1100 V (no good FW data)
- Invert *E(v)* to get electric field profiles
  - big errors when approaching 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

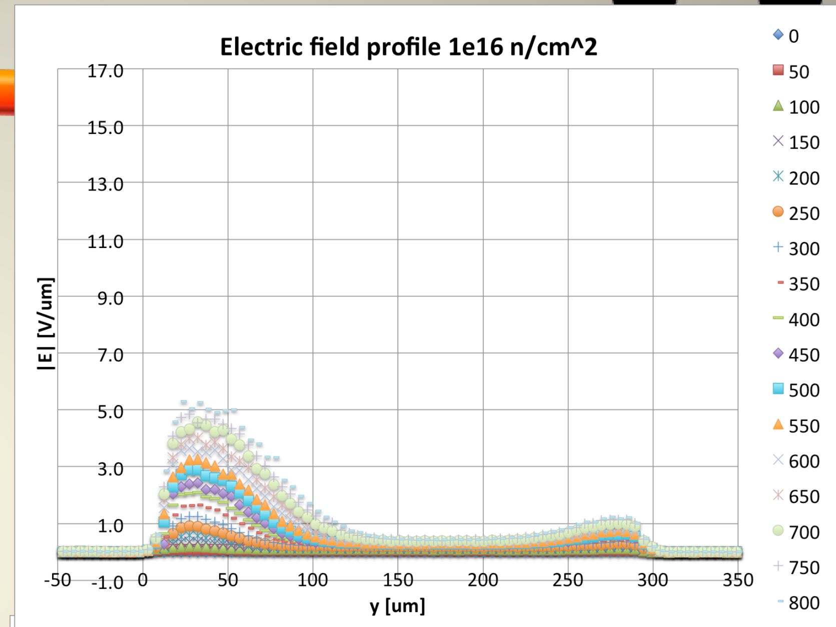


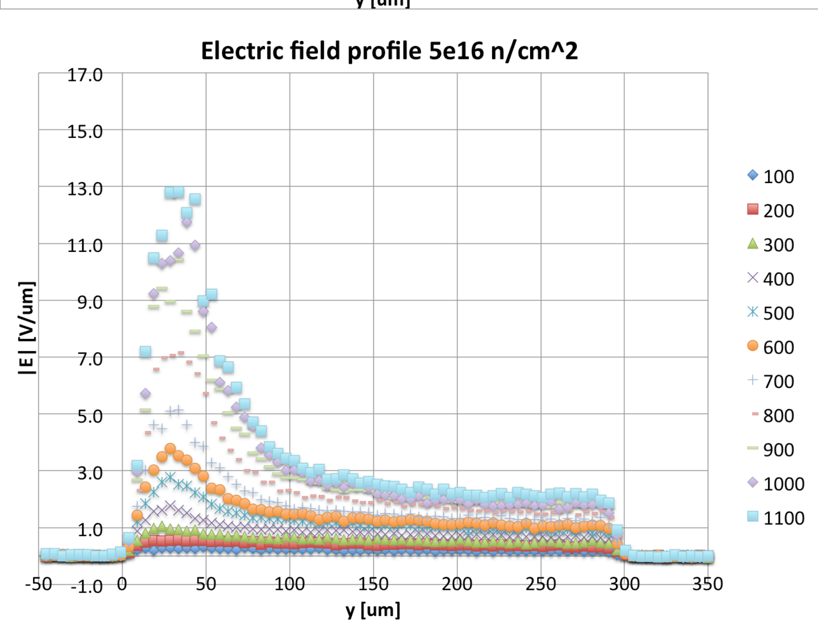
Velocity Profiles Neutrons

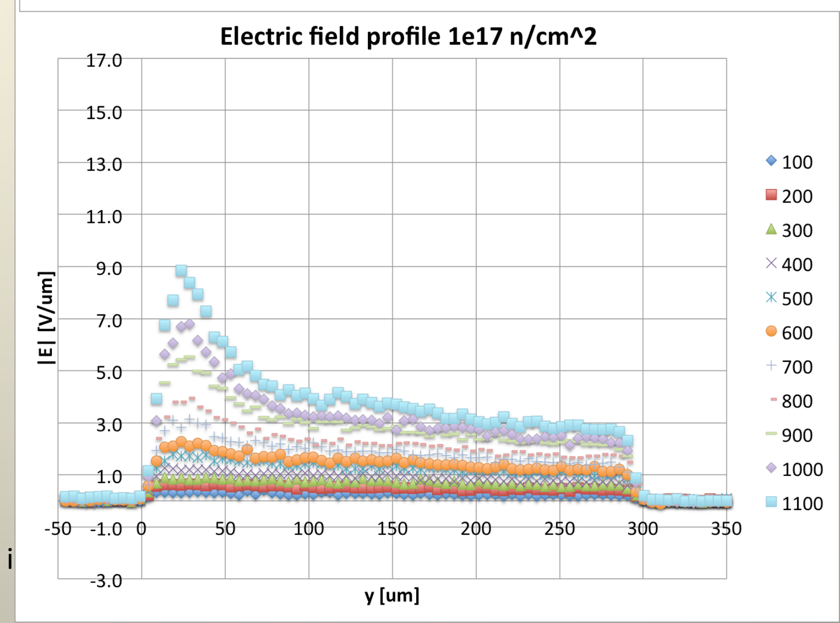


Field Profiles Neutrons

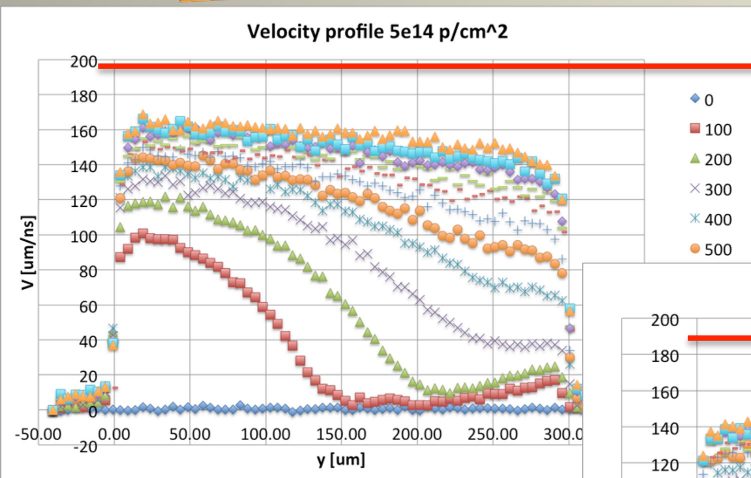


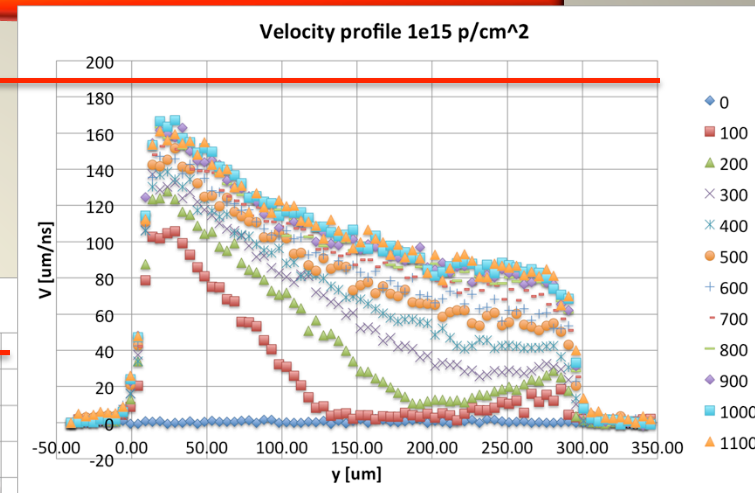




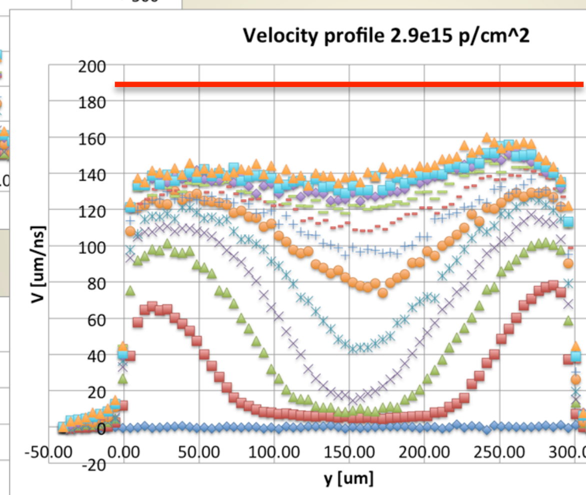


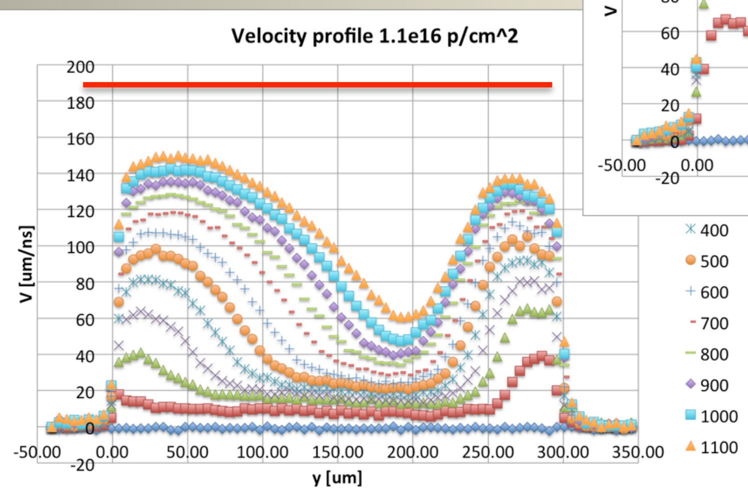
Velocity Profiles Protons



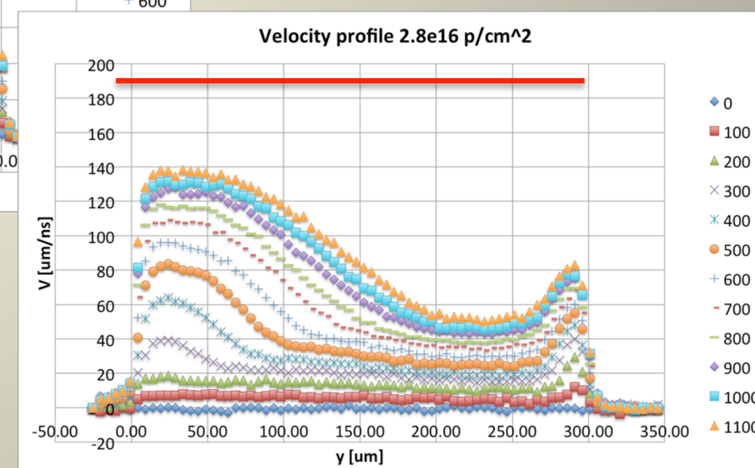


v = 190 μm/ns

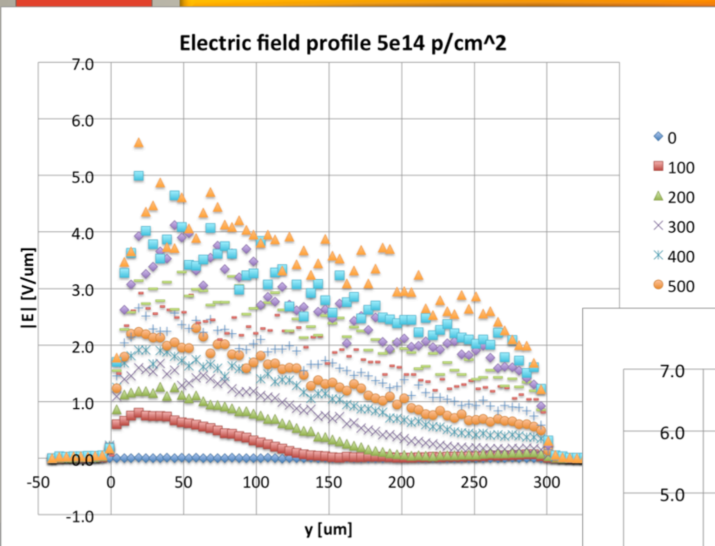




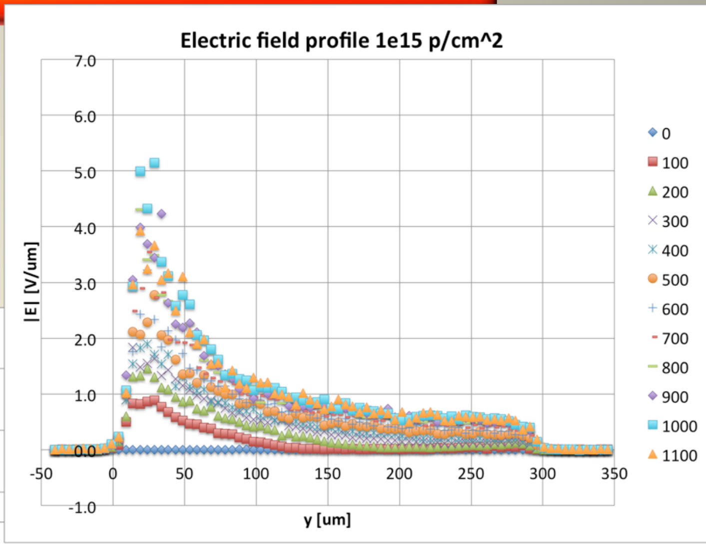
Same scale as for neutrons

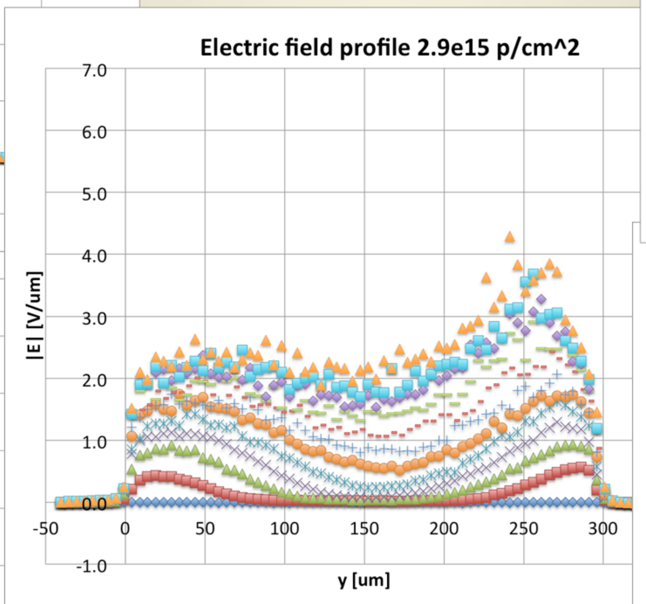


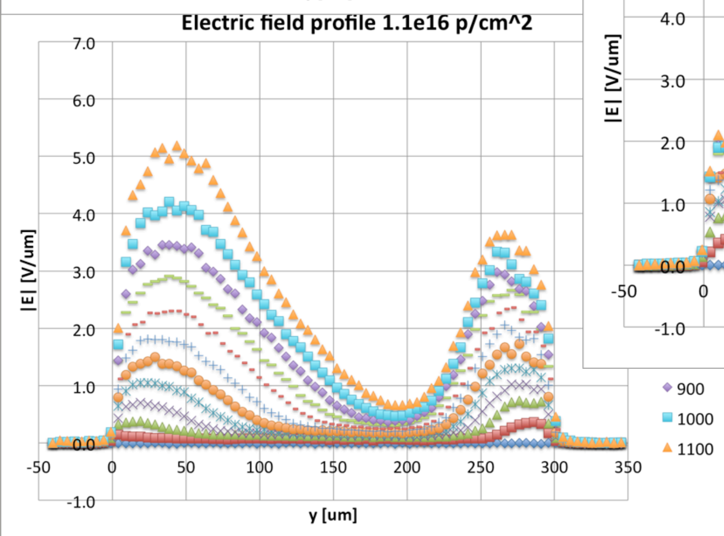
Field Profiles Protons

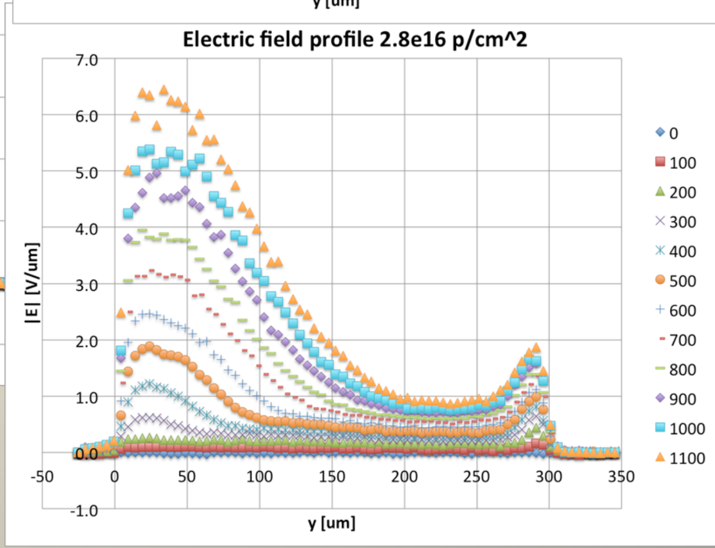


Smaller peak fields than for neutrons
Scale 0-7 V/µm



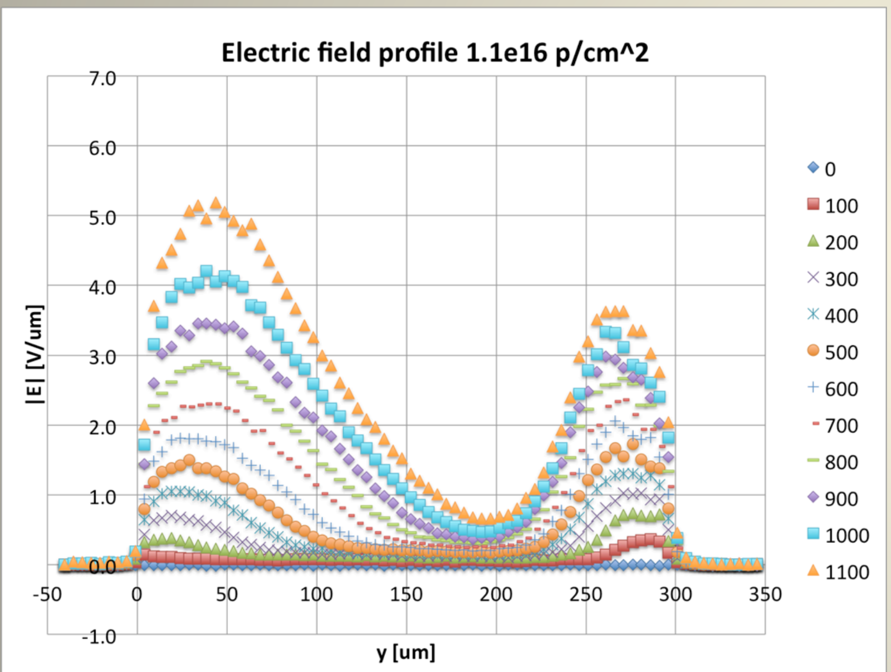


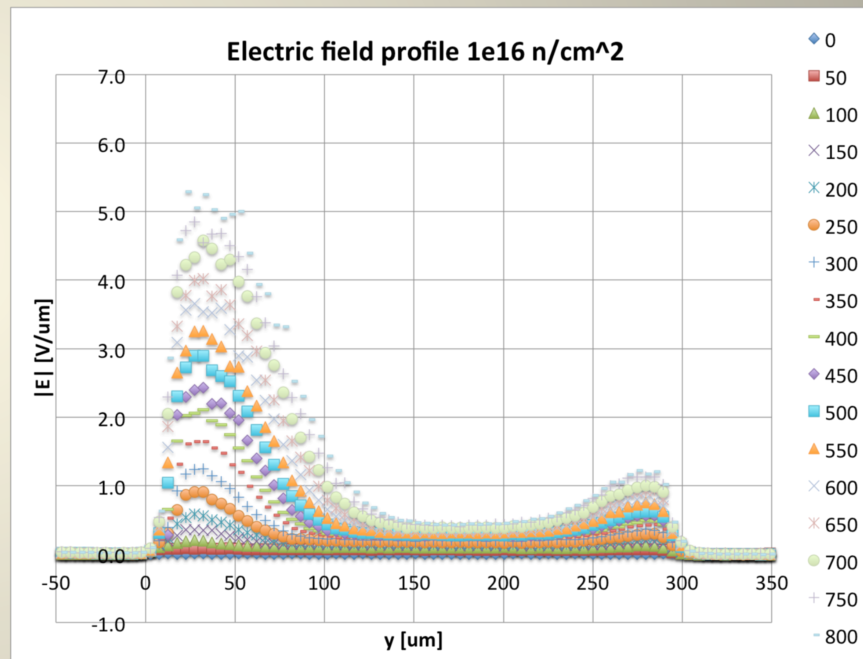




Protons <-> Neutrons ~10^{16}

- Field profiles compared

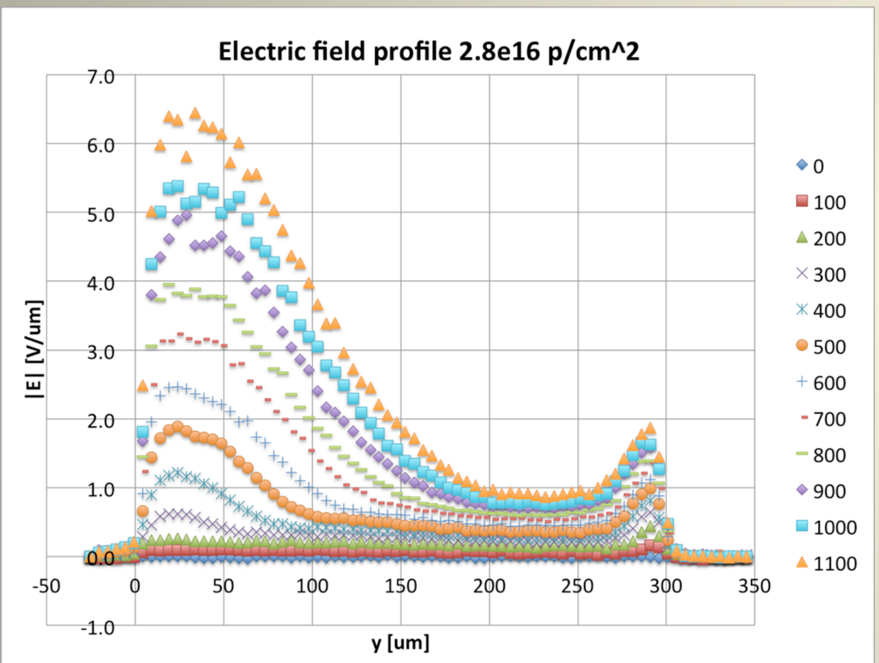


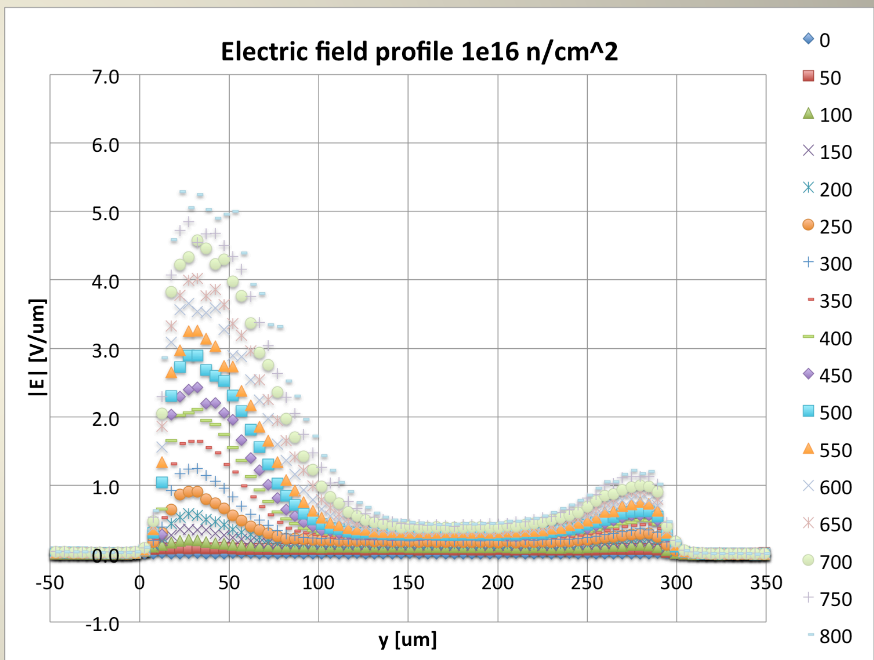


- Protons with more “double junction”, flatter field, less peaked at junction

Protons 2.8x10^{16} p/cm^2

- Field profile, compared to 10^{16} neutrons





- Looks more neutron-like, with deeper SCR

Trapping Considerations

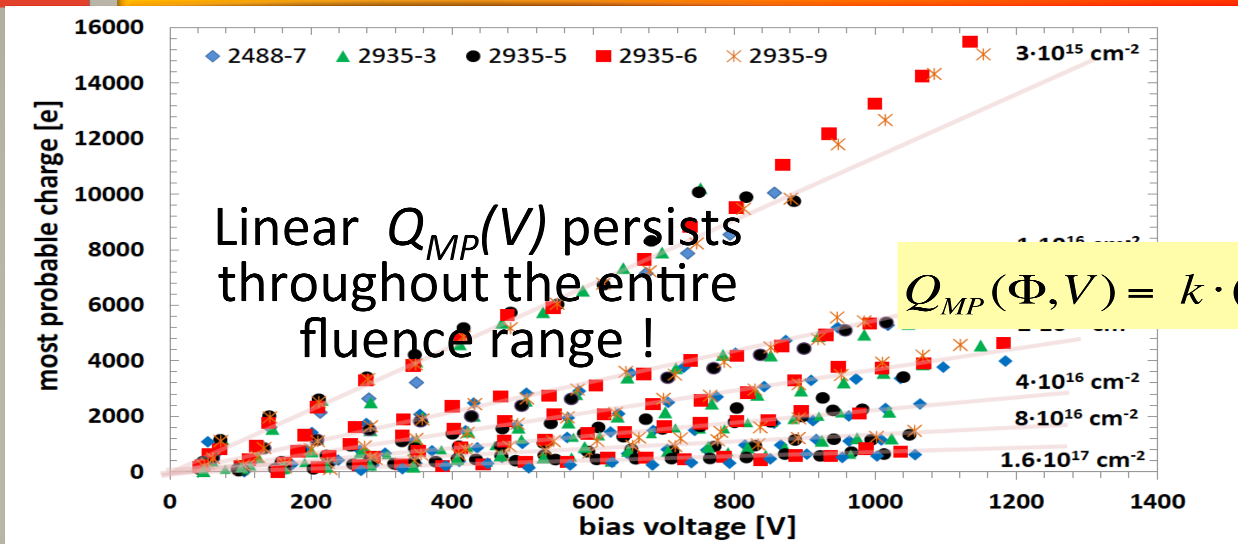
- Extrapolation from low fluence data with $\beta_{e,h}$(-20°C)=4.4,5.8x10^{-16} cm^2/ns; $1/\tau=\beta\Phi$

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 fluence

Magic revisited

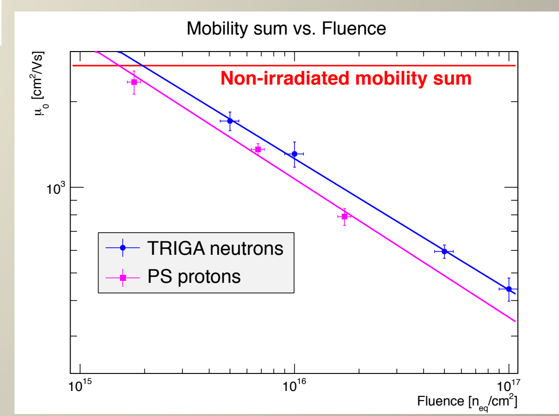


Linear $Q_{MP}(V)$ persists throughout the entire fluence range !

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

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

$$b = -0.683$$

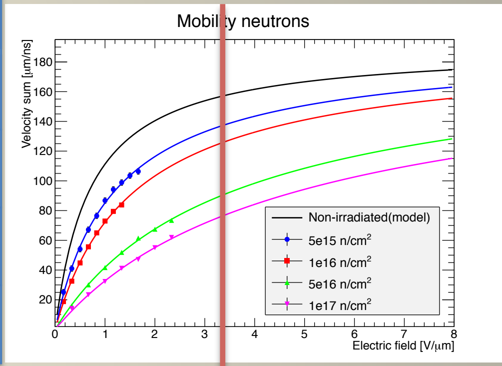


- *Q=k.V* most natural when linear *v(E)*
  - not to *E*~3 V/µm, especially at low Φ
  - far from saturation, too
- Fluence dependence as $\Phi^{-2/3}$
  - but mobility already decreases as $\Phi^{-1/2}$
- Small margin left for trapping increase, certainly not linear

More Considerations

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

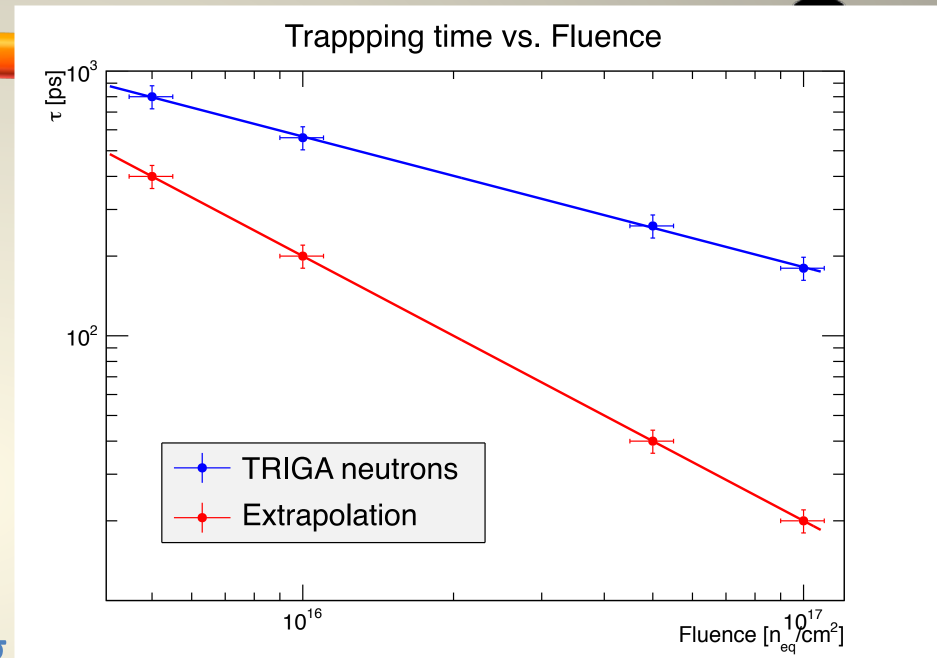
Φ [1e15]	5	10	50	100
v_{sum}(3.3 V/µm)	137	126	90	77
$CCD_{1000\ V}$ [µm]	110	70	23	14
$\tau \approx CCD/v$ [ps]	800	560	260	180
τ_{ext} [ps]	400	200	40	20

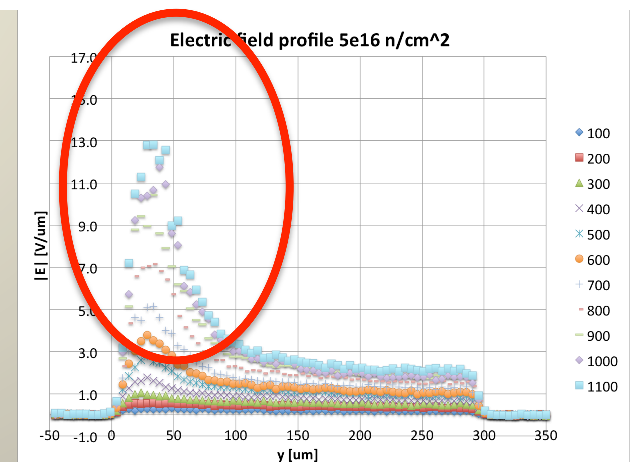


- Implies factor of 6-9 less trapping at highest fluences
  - lowest fluence still x2 from extrapolation
  - weak dependence on fluence as anticipated by "-1/6" power law
  - not good when large E variations (damped by $v(E)$)
  - not good when CCD ≈ thickness (less signal at same τ)

Result ?

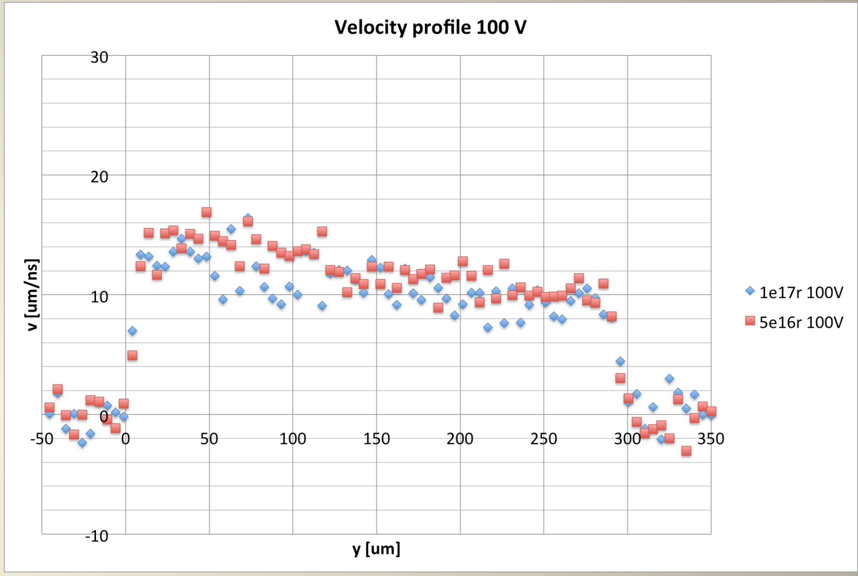
- Victory ? Wrong... two effects
  - saturating v(E) -> less signal, effectively more trapping
  - charge multiplication -> more signal, less trapping
- Old story revisited, no handle on 1st few 10 microns where a lot can happen





Another try

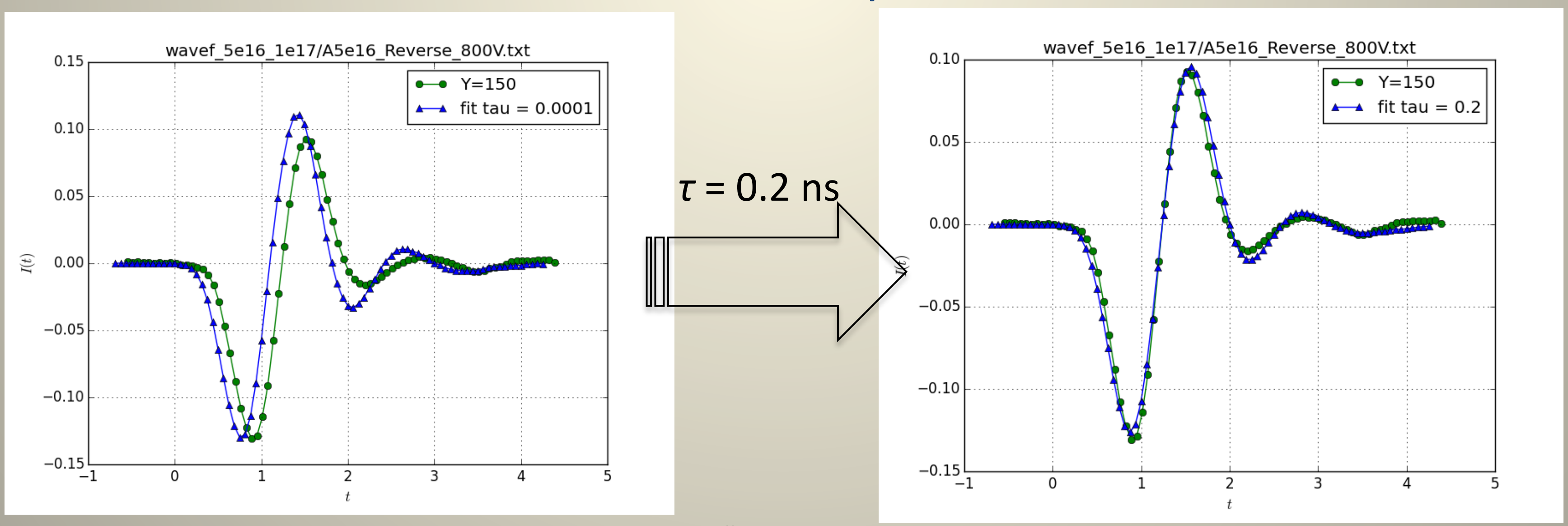
- Focus on cases with small and linear *v(E)* -> $v(\overline{E}) = \overline{v}$
  - 100 V at 5x10^{16} and 10^{17} look promising – flat field
  - also the integral of *E(x)* yields 63/100 and 76/100 V
- Can assume linear *v(E)* in whole detector
  - assume same ratio as for low fluences
  - less trapping compared to linear extrapolation by factors of 3.2 and 5.4



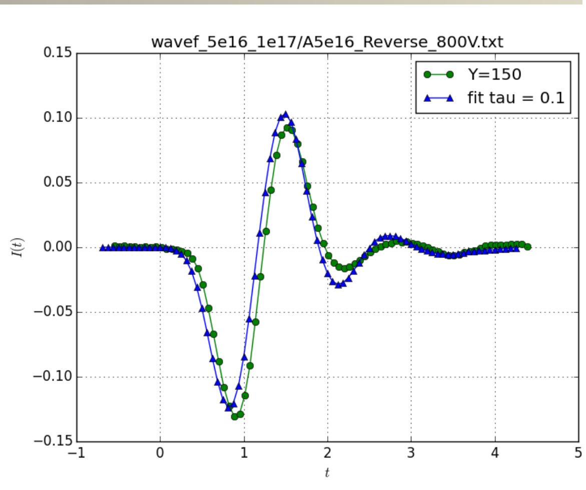
Φ	τ_e[ps]	τ_h[ps]
5e16	147	81
1e17	81	62

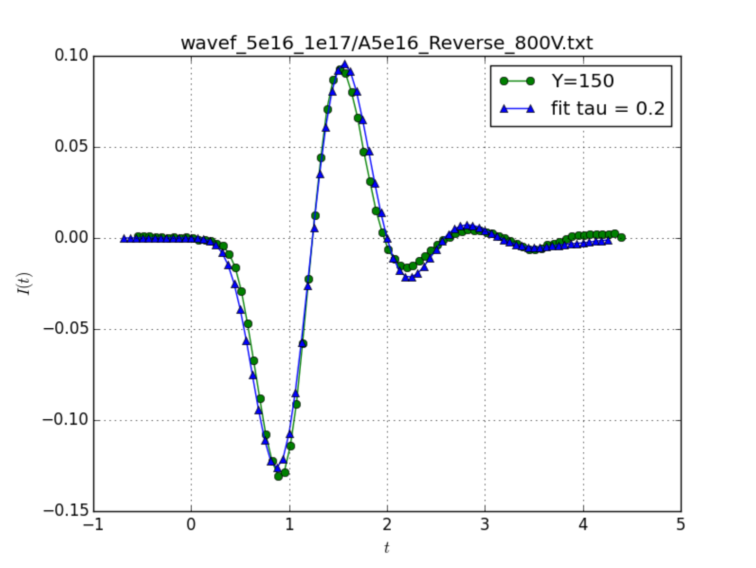
Exploiting TCT Waveforms

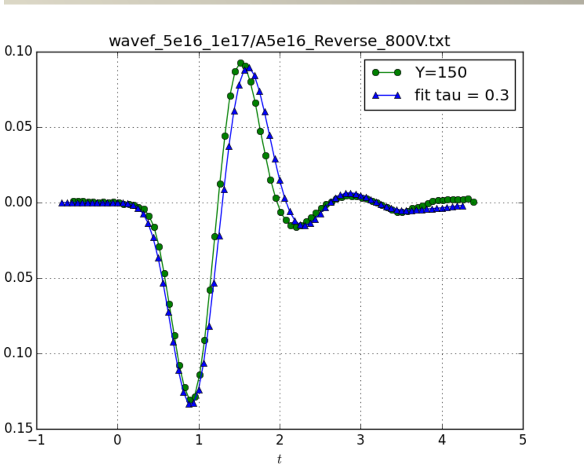
- Waveforms at y=100 µm, 800 V, 5×10^{16} and 10^{17}
  - $E \approx 3$ V/µm, *CCD/2* implies signal within ~10 µm or <0.2 ns
    - the rest you see is the transfer function of the system
- Still distinct signals from the two fluences
  - treat 10^{17} waveform as transfer function of the system
   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



Waveforms: How sensitive ?



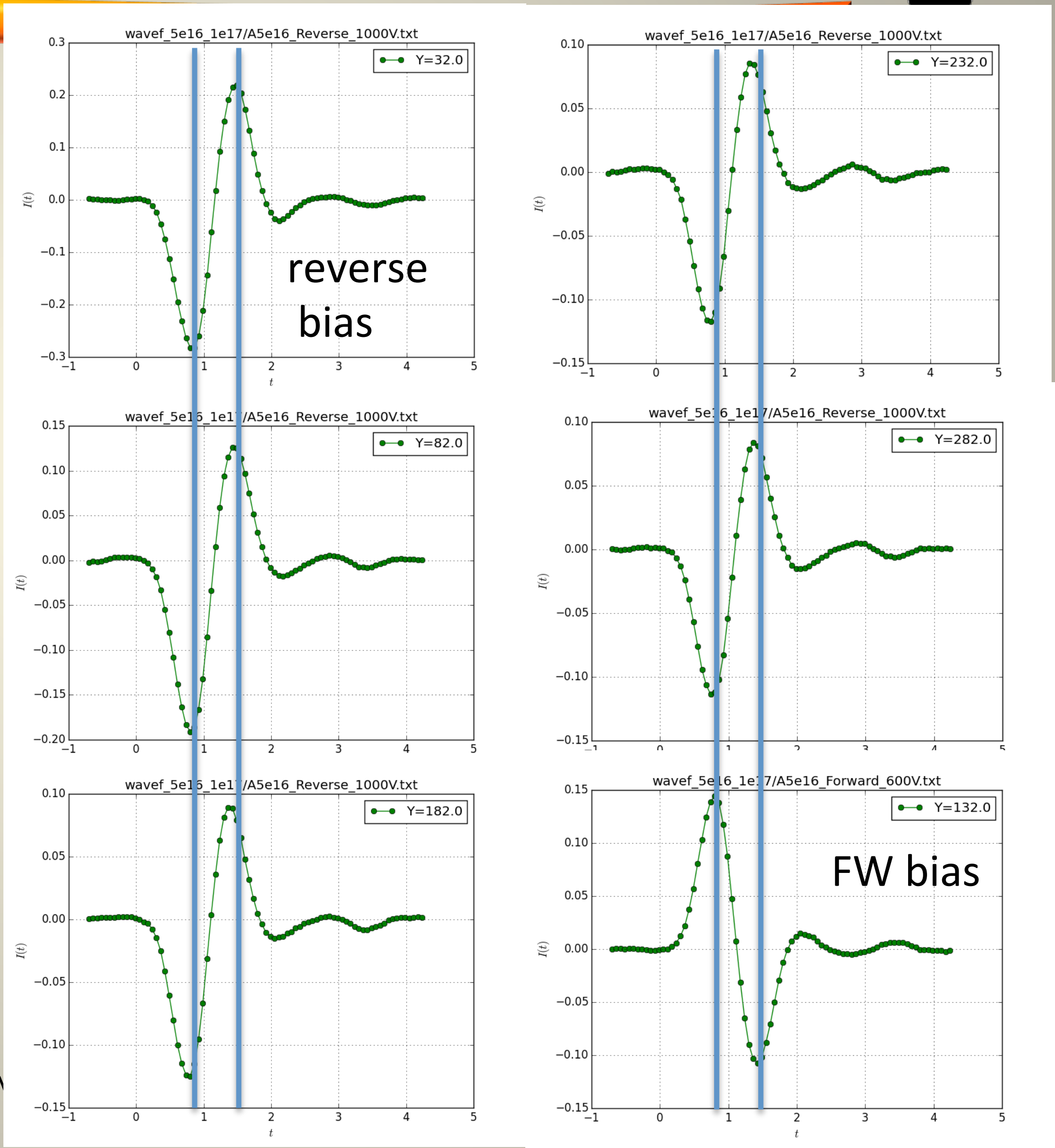




- *Δτ* = 0.2 ns certainly best fit, 0.1 too narrow, 0.3 too broad
- precision ~50 ps

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 !?



Summary

- Velocity profiling performed for Si detectors irradiated
  - with neutrons from 10^{15} to 10^{17} n_{eq}/cm^2
  - with protons from $5x10^{14}$ to $3x10^{16}$ p/cm^2
- Velocity vs. electric field fluence impact observed and interpreted as reduction of zero field mobility
  - Zero field mobility follows power law with $a \approx -1/2$
  - Protons degrade mobility by ~20 % more
- Absolute velocities and field maps provided
  - With caveats at high electric fields
- Trapping estimates for very high neutron fluences
  - from charge collection
  - from waveforms
  - all estimates point to severe non-linearity of trapping with fluence
- To do:
  - CCE for protons
  - 2^{nd} proton irradiated set
  - Sensible error estimates

Backup Slides