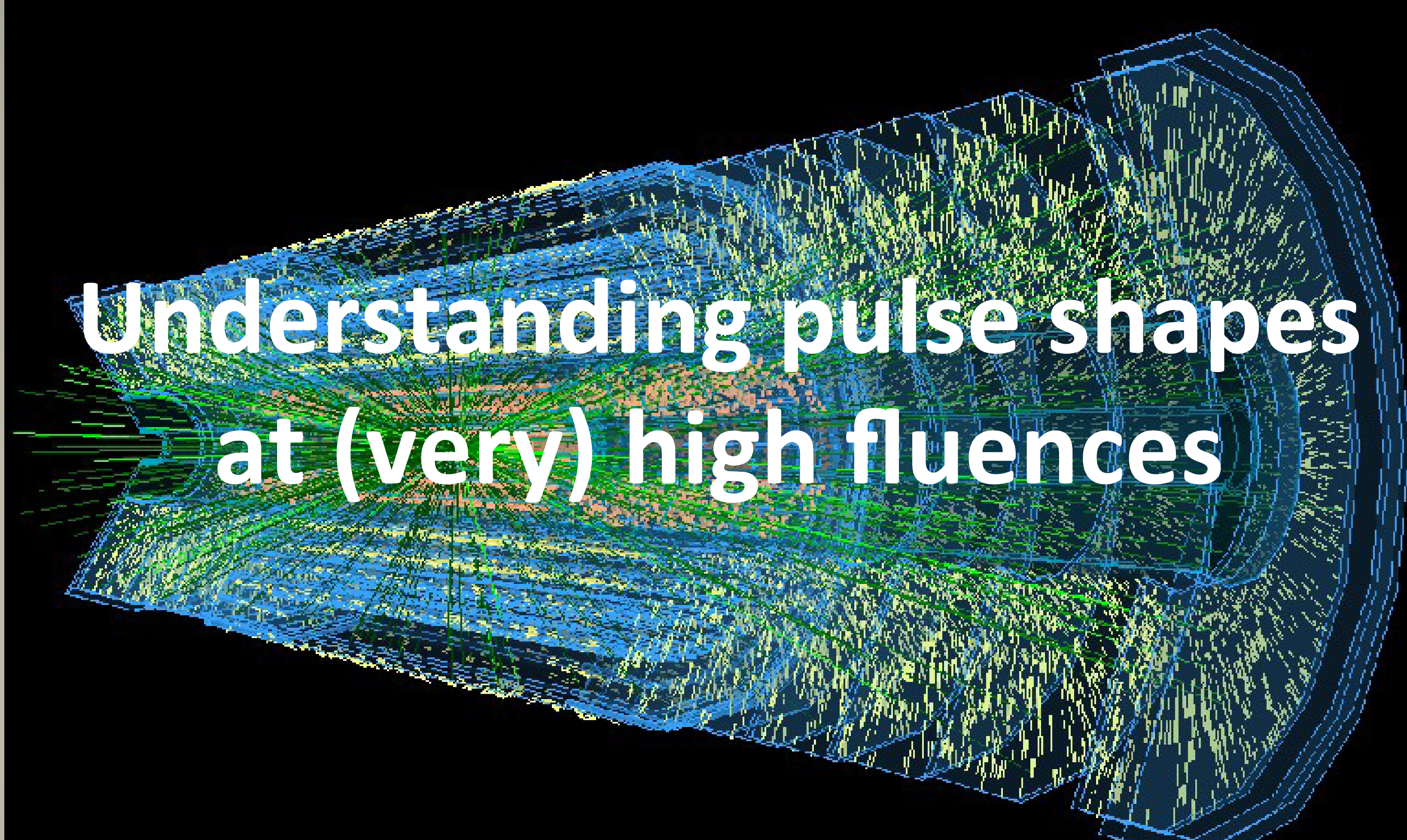

Understanding pulse shapes at (very) high fluences

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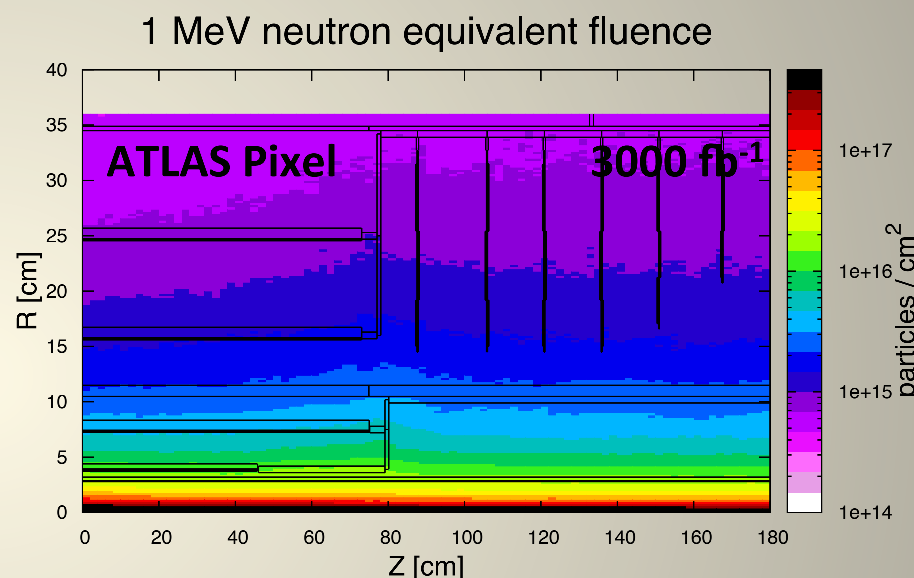
University of Ljubljana & Jožef Stefan Institute

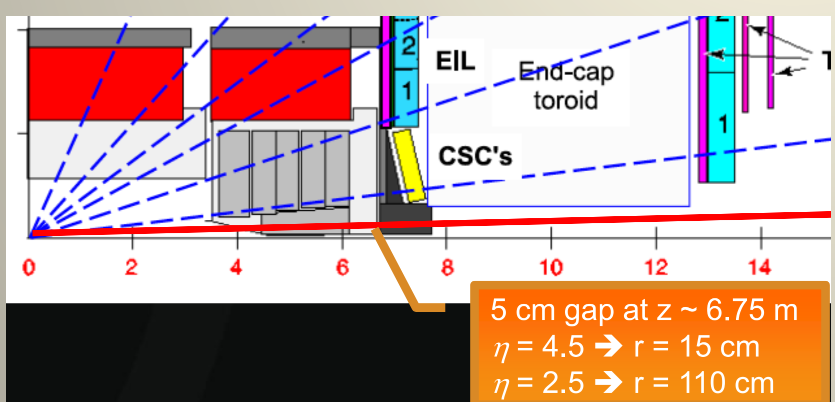
2nd TCT Workshop

Ljubljana, October 17th, 2016

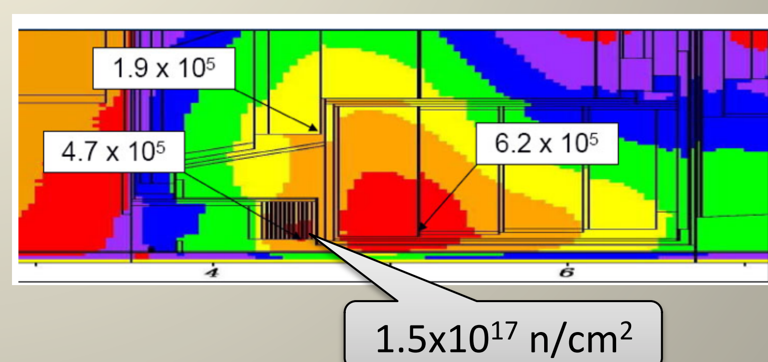
Why the 10^{17} Ballpark ?

- 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)
    - n$\times10^{16}$ 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 ?



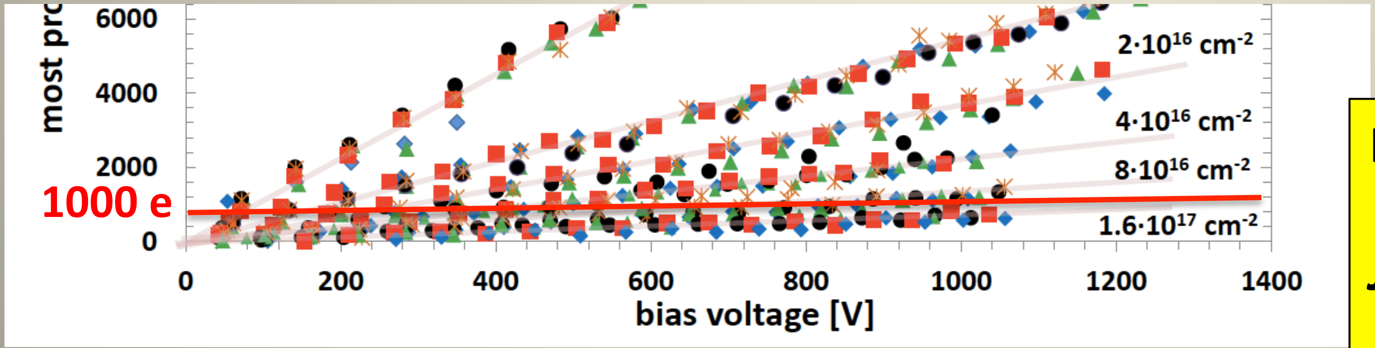


ATLAS FCAL 3000 fb^{-1}



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

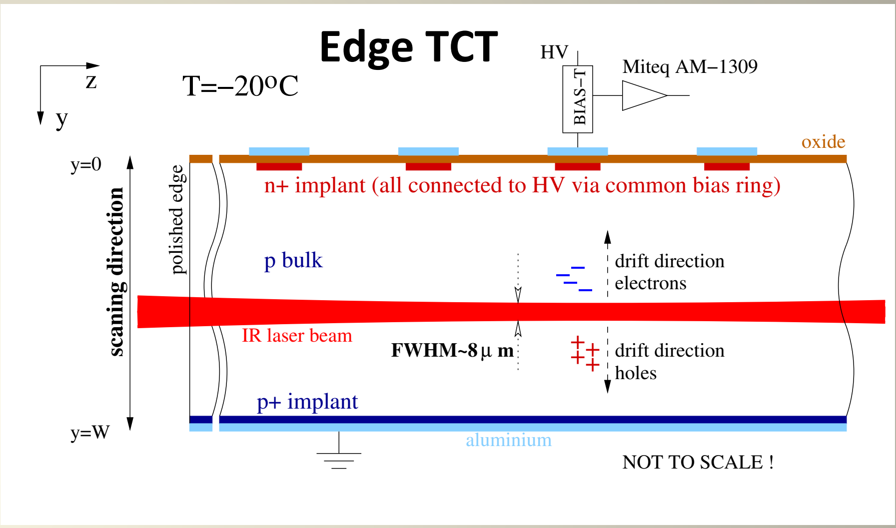
- Linear extrapolation from low fluence data
  - Current: I_{leak} = 4 A/cm^3 @20°C
    - 2 mA for 300 µm thick 1 cm^2 detector @ -20°C
  - Depletion: N_{eff} ≈ 1.5x10^{15} cm^{-3}
    - *FDV* ≈ 100 kV
  - Trapping τ_{eff} ≈ 1/40 ns = 25 ps
    - $Q \approx Q_0/d\ v_{sat}\tau_{eff}$ ≈ 80 e/µm 200 µm/ns 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



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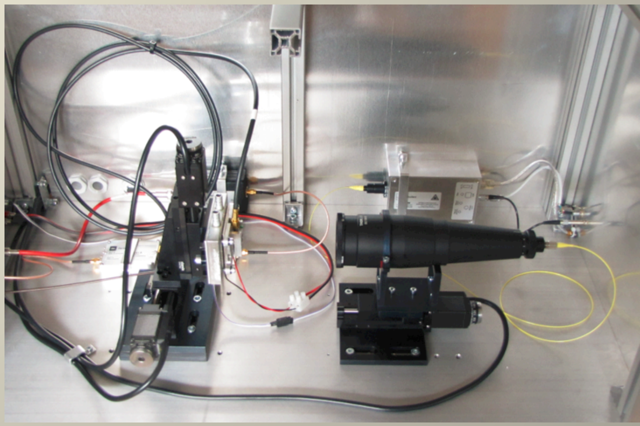
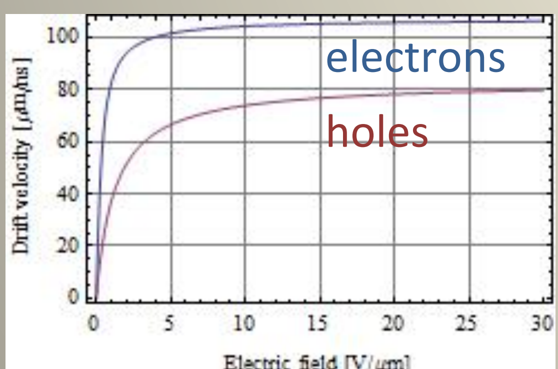
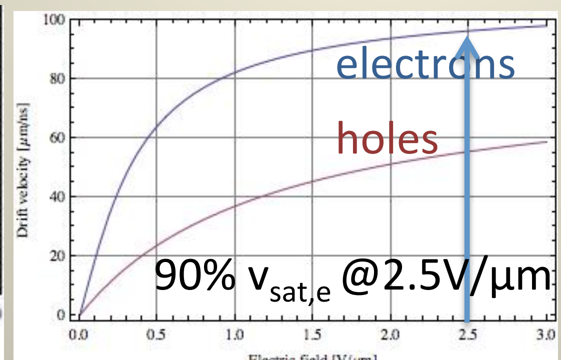


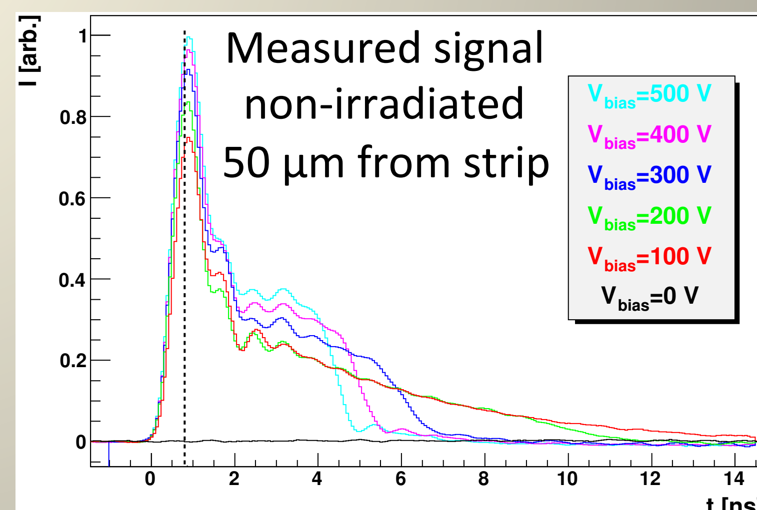
Measured signal

- Induced current signal given by Ramo's theorem
  - Transfer function of electronics convolutes induced current signal
  - Carriers might reach detector end
  - Velocity depends on *E*
    - *v* saturates for *E* >> 1V/µm

$$I(t=0) = q\vec{v}\cdot\vec{E}_w =$$
$$= N_{e-h}e_0\cdot\left(v_e e^{-t/\tau_e} + v_h e^{-t/\tau_h}\right)/d$$







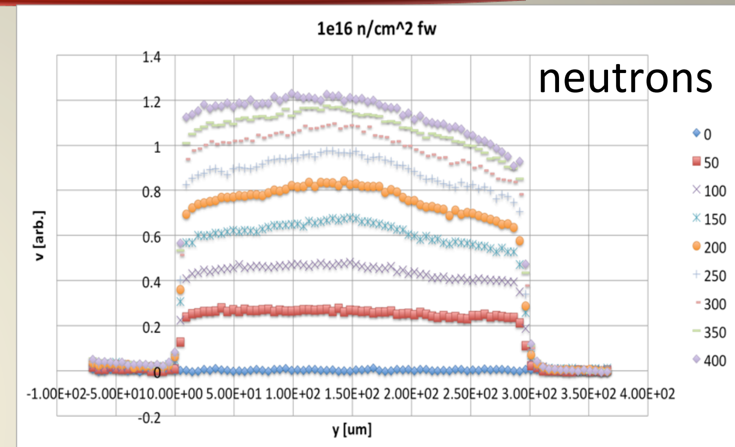
Mobility Considerations FW bias

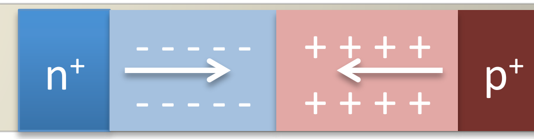
- For forward bias can extract *v(E)* up to a scale factor
- Observe less saturation than predicted
- Model with

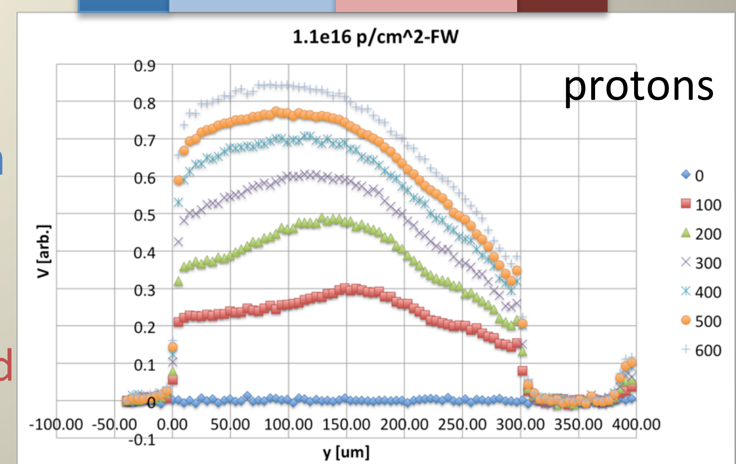
$$v_{sum}(E) = \frac{\mu_{0,e} E}{1 + \frac{\mu_{0,e} E}{v_{e,sat}}} + \frac{\mu_{0,h} E}{1 + \frac{\mu_{0,h} E}{v_{h,sat}}}$$

  - 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 $\phi_n \geq 5 \times 10^{15}$ and $\phi_p \geq 3 \times 10^{15}$

    n.b. FW profiles less uniform for lower fluences and for protons, but departures from average field still small

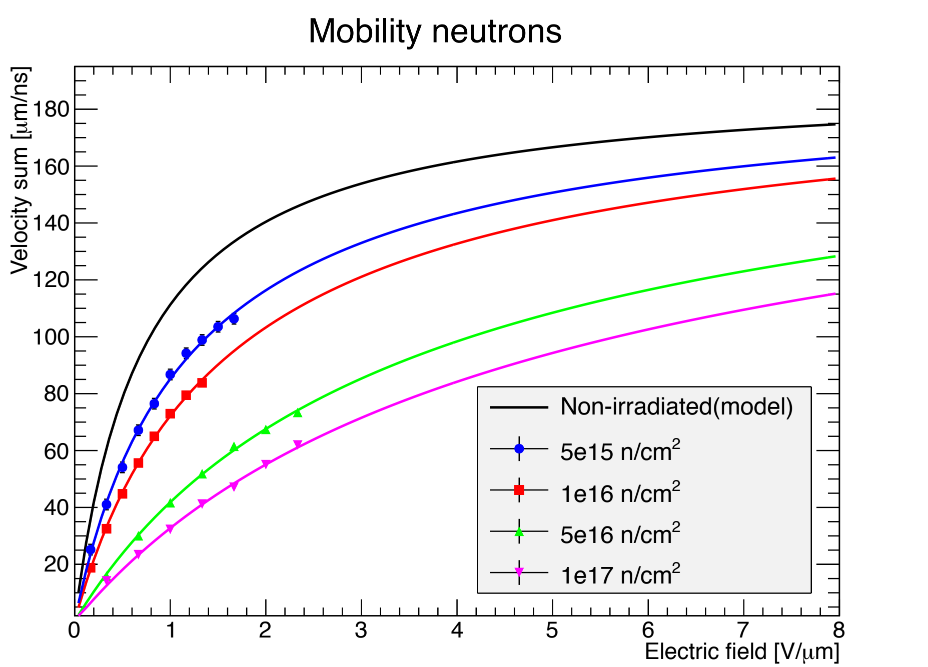


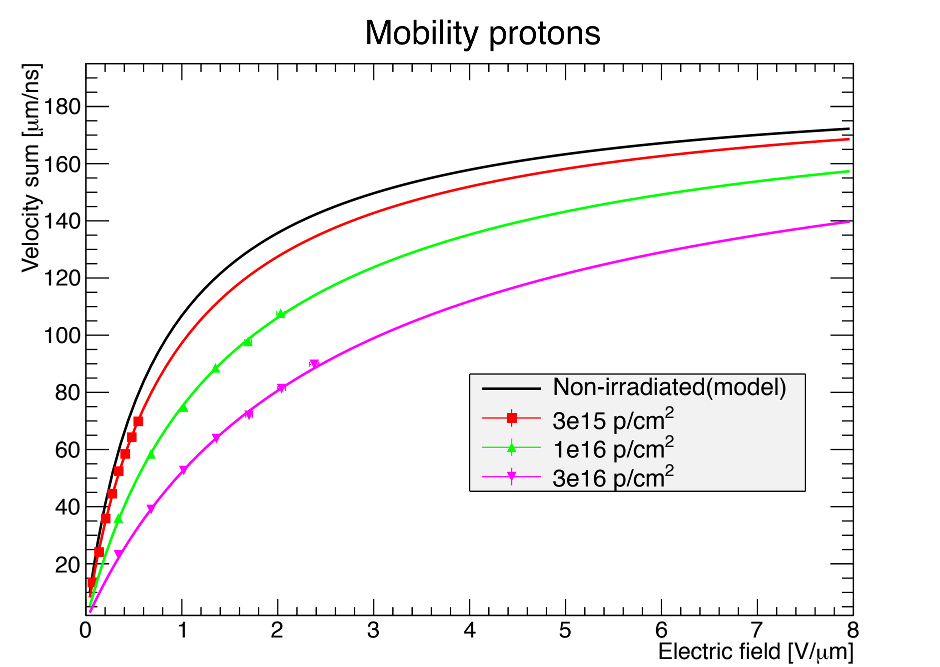




Mobility Fits

- 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		

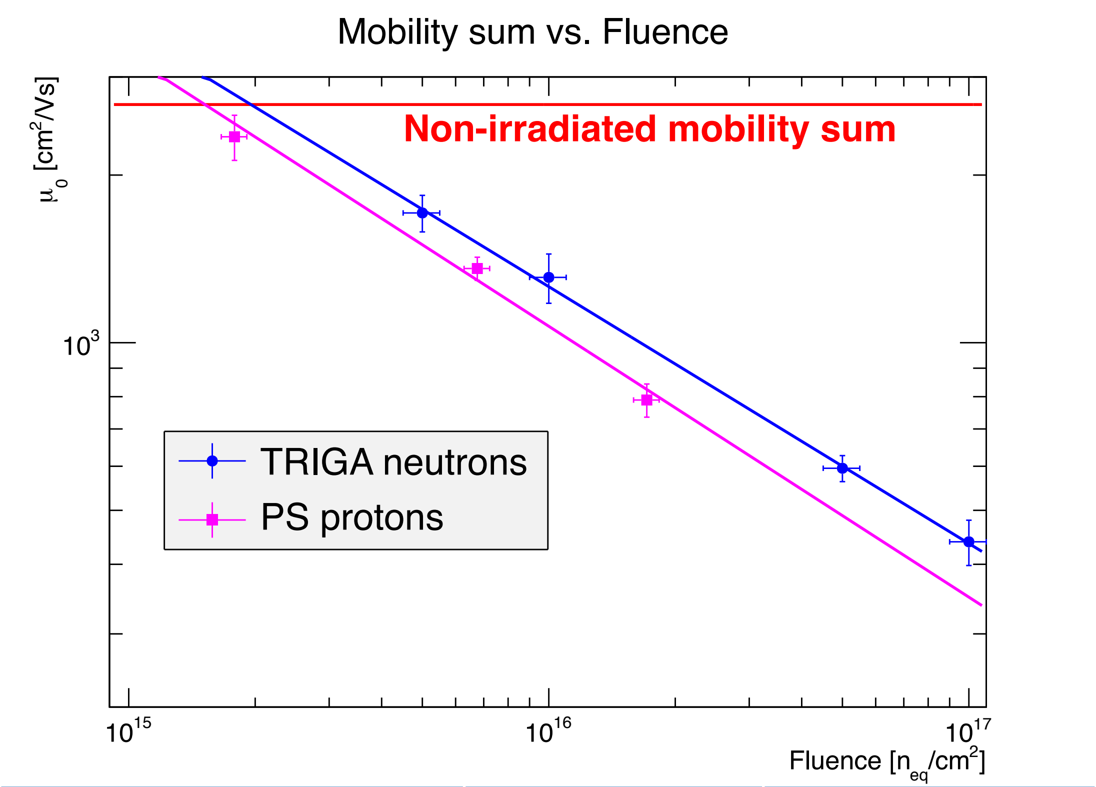
T=-20°C

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 ?

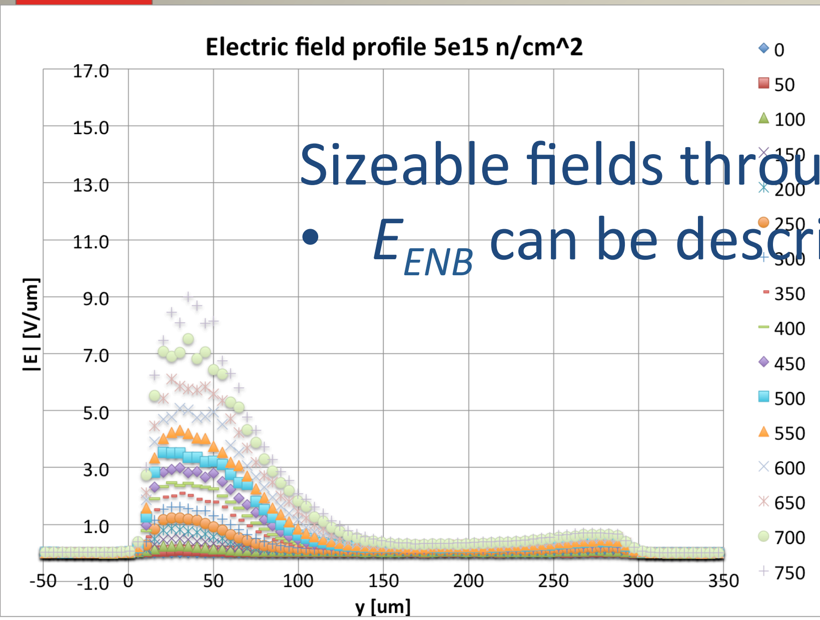


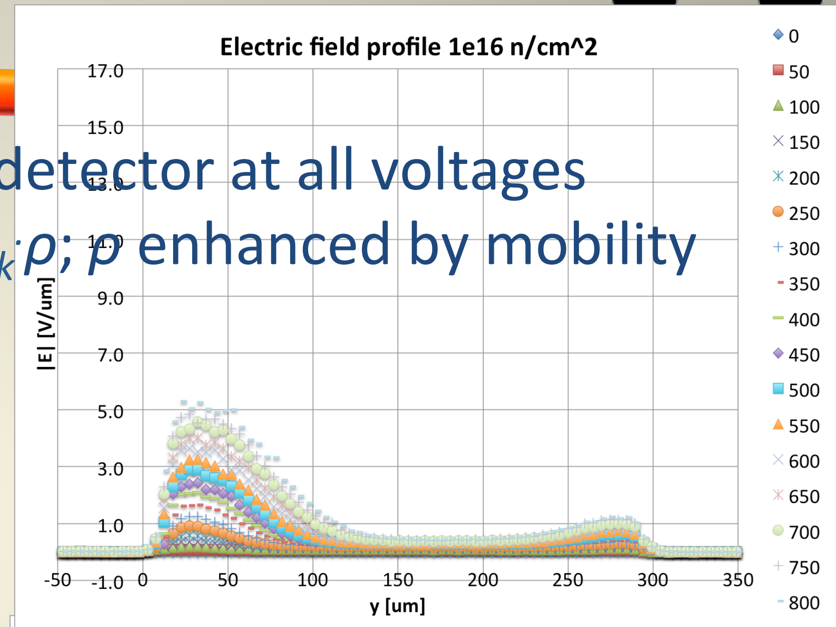
Irradiation particle	a	σ_a
Reactor neutrons	-0.46	0.04
PS protons	-0.49	0.05

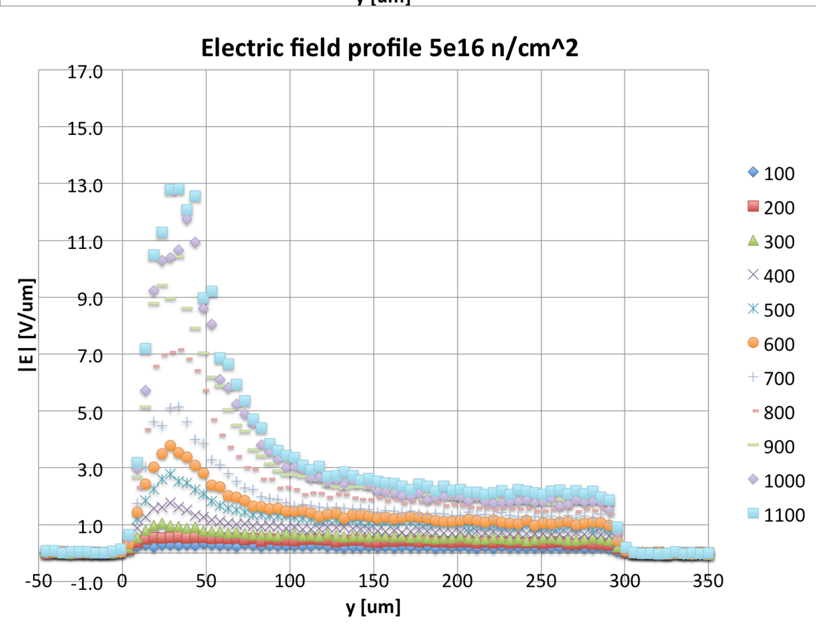
Field Profiles Neutrons

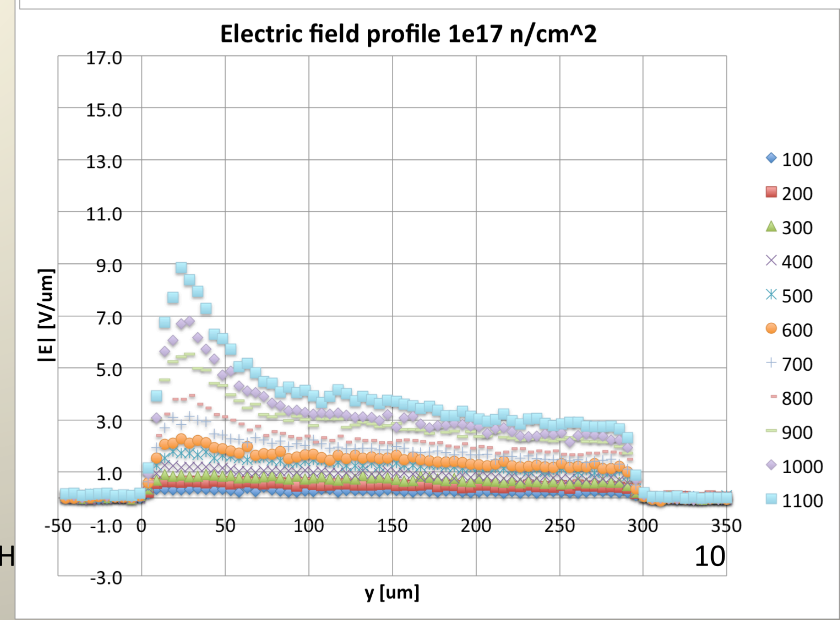
Sizeable fields through whole detector at all voltages

- E_{ENB} can be described as $j_{leak} \cdot \rho$; ρ enhanced by mobility

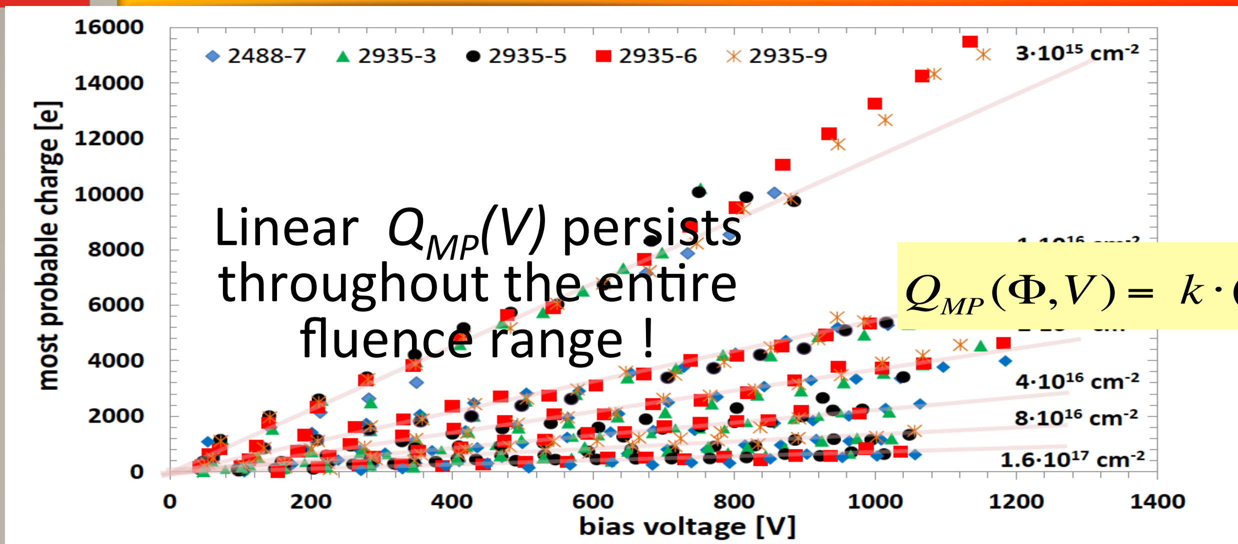








Magic revisited

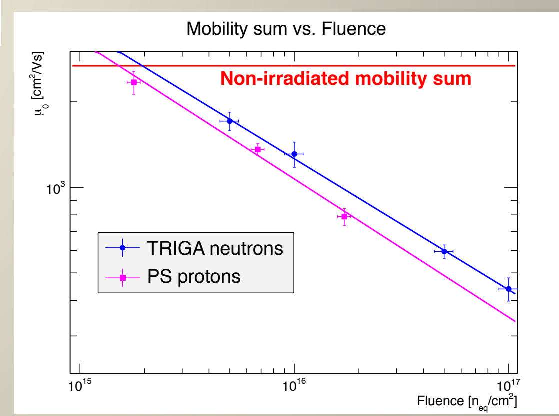


Linear $Q_{MP}(V)$ persists throughout the entire fluence range !

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

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

$$b = -0.683$$

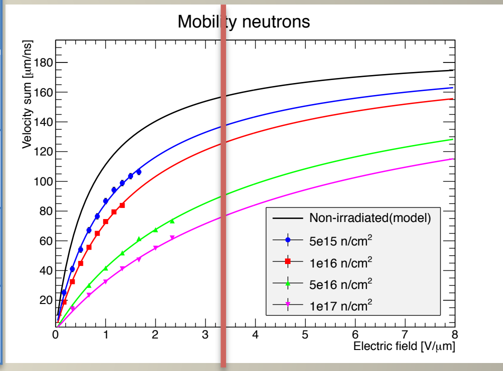


- *Q=k.V* most natural when linear *v(E)*
  - not to *E*~3 V/µm, especially at low *Φ*
  - far from saturation, too
- Fluence dependence as $\Phi^{-2/3}$
  - but mobility already decreases as $\Phi^{-1/2}$
- Small margin left for trapping increase, certainly not linear

Trapping Considerations

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

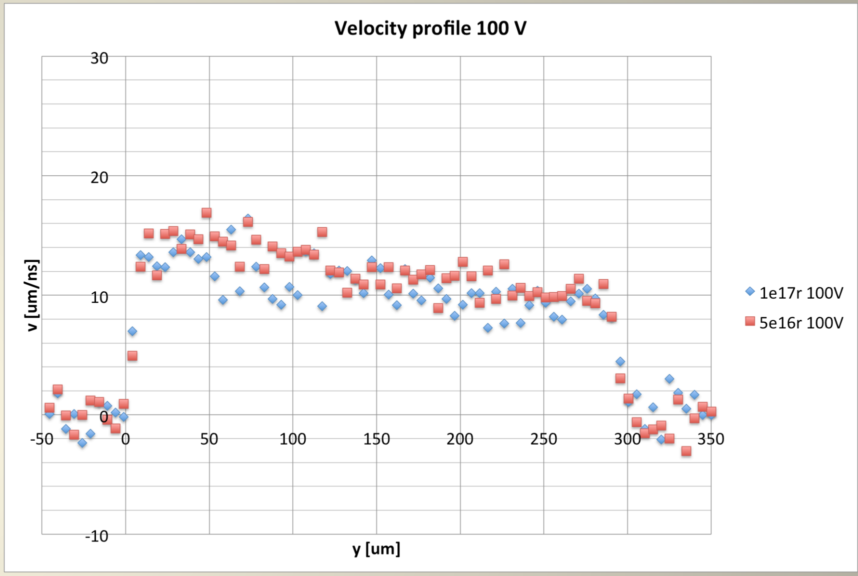
Φ [1e15]	**5**	**10**	**50**	**100**
v_{sum}(3.3 V/µm)	137	126	90	77
$CCD_{1000\ V}$ [µm]	110	70	23	14
$\tau \approx CCD/v$ [ps]	800	560	260	180
τ_{ext} [ps]	400	200	40	20



- Implies factor of 6-9 less trapping at highest fluences
  - 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)
  - not good when CM (more signal at same τ)

Another try

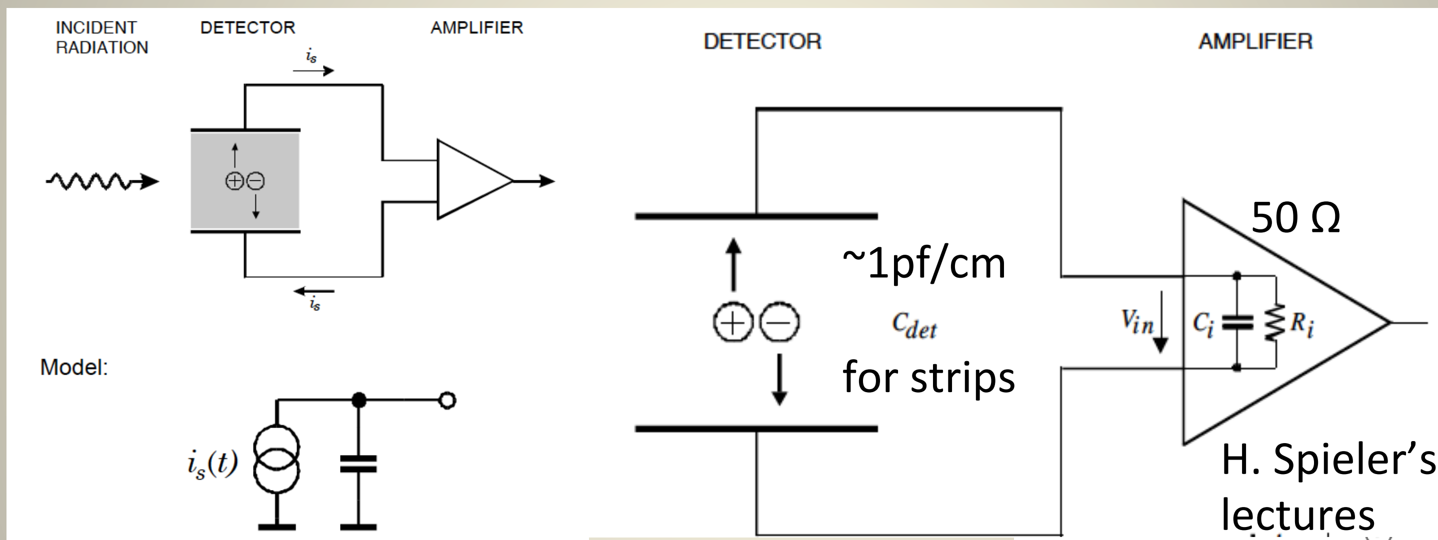
- Focus on cases with small and linear *v(E)* -> *v(E)* = *v*
  - 100 V at 5×10^{16} and 10^{17} look promising – flat field
  - also the integral of *E(x)* yields 63/100 and 76/100 V
- Can assume linear *v(E)* in whole detector
  - assume same ratio as for low fluences
  - less trapping compared to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



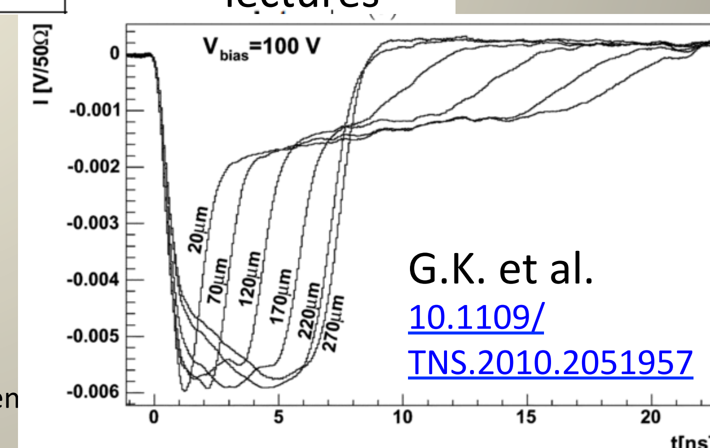
Φ	τ_e[ps]	τ_h[ps]
5e16	145	110
1e17	122	93

Textbook Waveforms

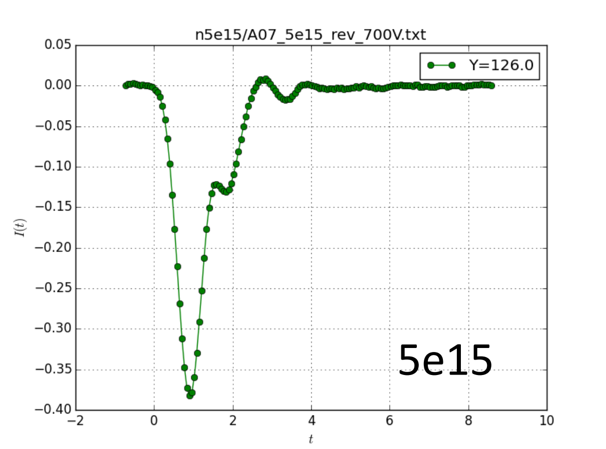
- You think of your system like this

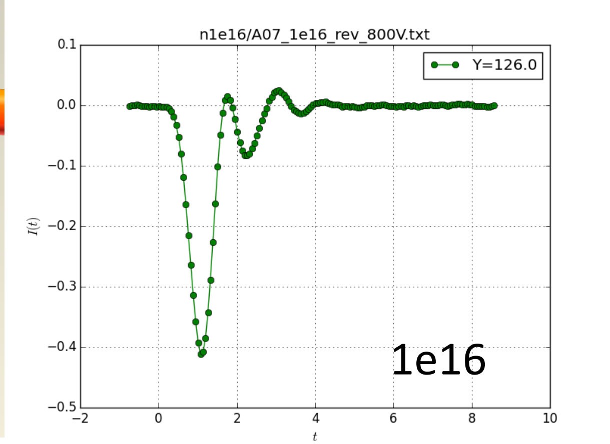


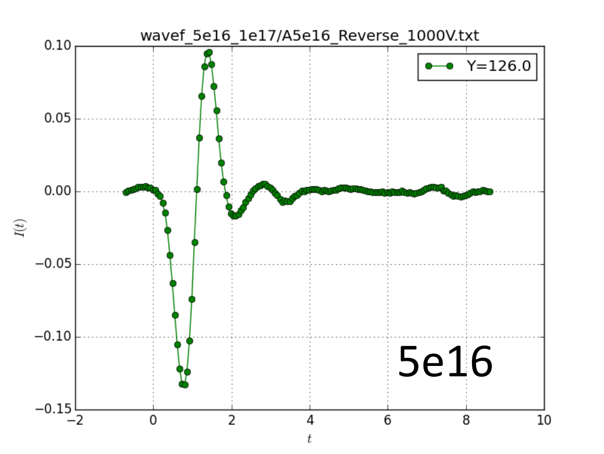
- *H(ω) = 1/(1+iωRC)*; *RC* ~ 0.1 ns; υ_{cutoff} ~ 1.5 GHz
  - *ω >> 1/RC* -> integrator
  - *ω << 1/RC* -> current amplifier ✔

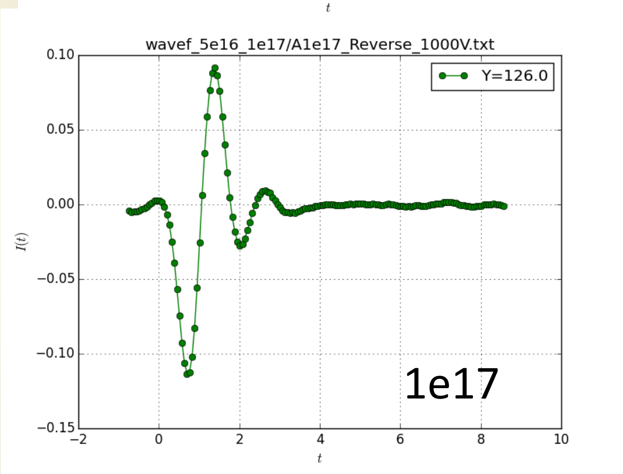


TCT Waveforms @ High Fluence





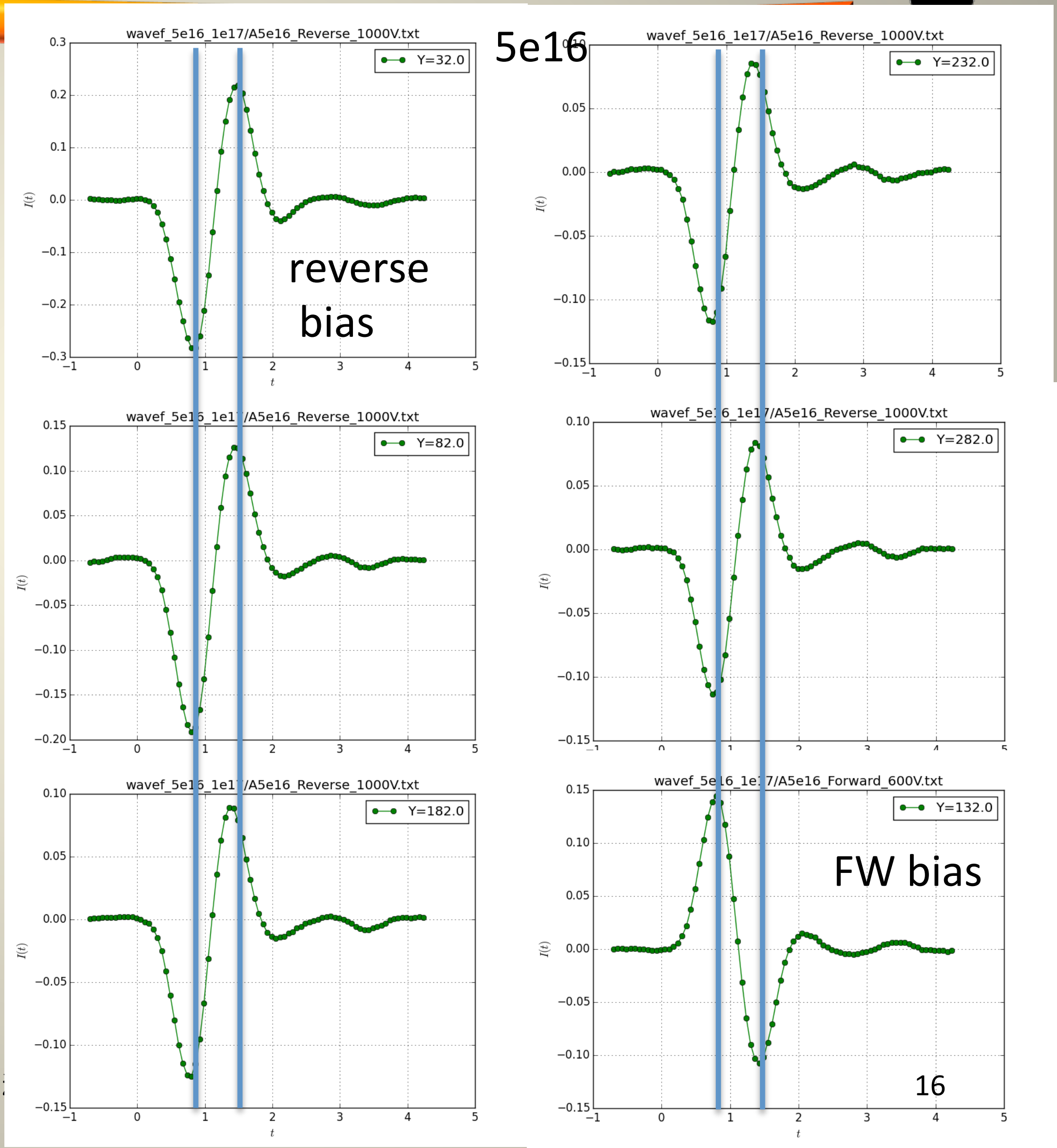




- Nothing like textbook behaviour !
  - damped oscillations, influenced by trapping time ?

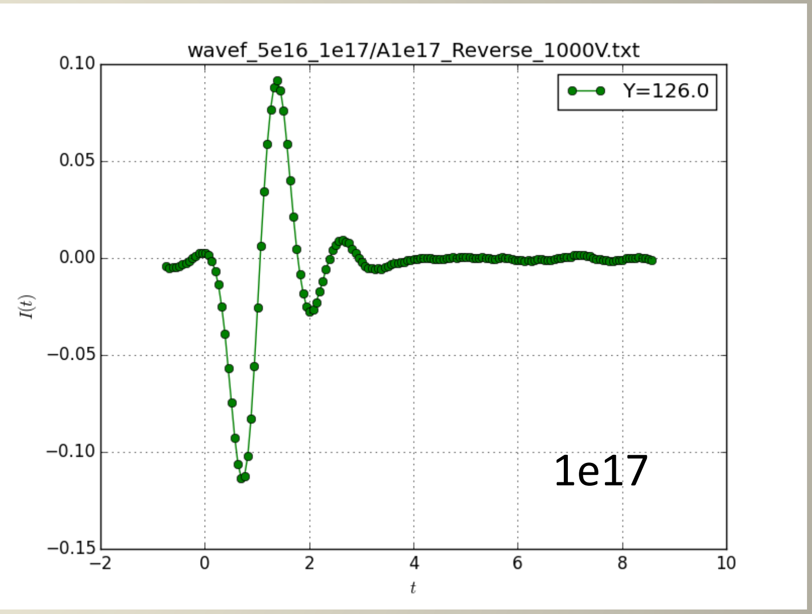
WF – position dependence ?

- 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 !?



Transfer function

- Waveforms at y=100 µm, 1000 V, 1e10^{17}
  - $E \approx$ 3 V/µm, *CCD* implies signal within ~15 µm or 0.2 ns
    - the rest you see is the transfer function of the system
- Observed features
  - damped oscillations with t_0 ~ 1.5 ns, τ ~ 1 ns
  - definitely under-critical
    - $\omega=2\pi/t_0=4$ ns^{-1} ~4β; $\omega \sim \omega_0$
  - simple *RLC* hard to imagine with *R*=50 Ω and *C* ~ 1 pF
    - *L~30-60* nH from $\omega_0^2=1/LC$; $\beta=R/2L$



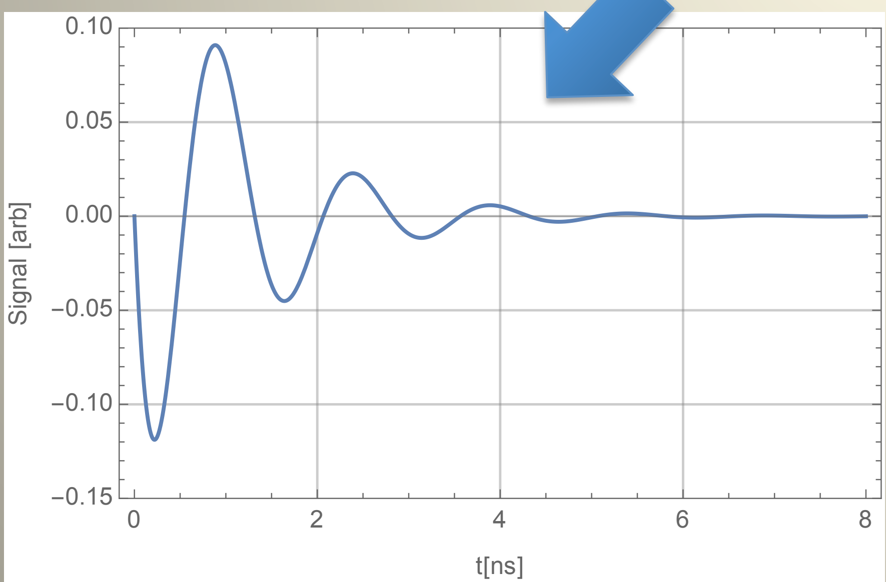
Transfer function

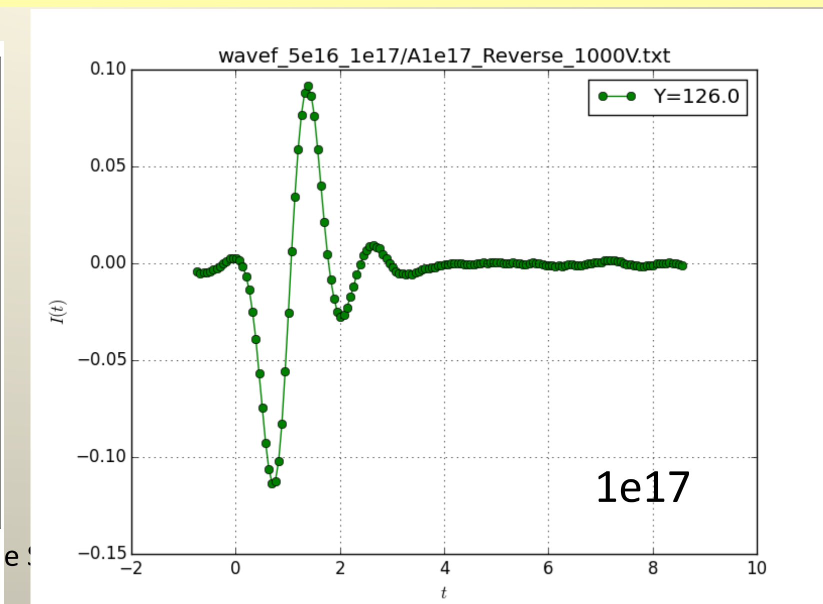
- Construct *H(t)* with observed features
  - t_0 = 1.5 ns, τ = 1.1 ns
- Signal
  - τ = 0.2 ns

$$H(t) = e^{-\beta t}\cos\omega t$$

$$I(t) = \int_0^t I_0 e^{-t'/\tau} H(t-t')\,dt'$$

$$I(t) = A\{(\beta - 1/\tau)[e^{-t/\tau} - e^{-\beta t}\cos\omega t] + \omega e^{-\beta t}\sin\omega t\}$$





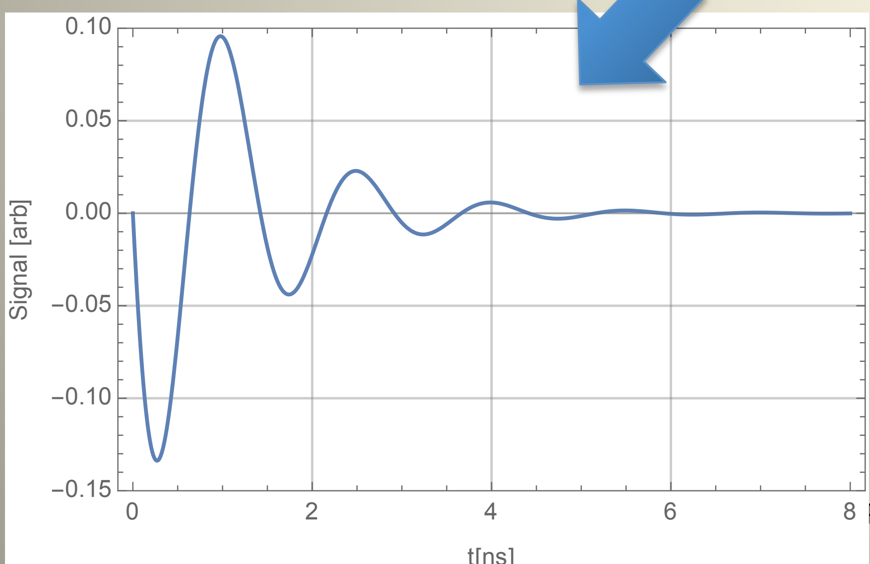
At 5e16

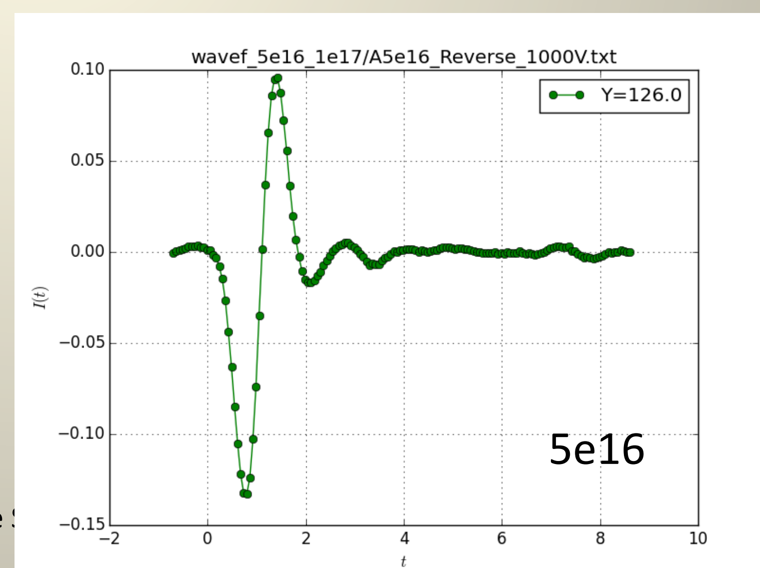
- Same *H(t)*
  - $t_0 = 1.5$ ns, $\tau = 1.1$ ns
- Signal
  - $\tau = 0.4$ ns

$$H(t) = e^{-\beta t}\cos\omega t$$

$$I(t) = \int_0^t I_0 e^{-t'/\tau} H(t-t')\,dt'$$

$$I(t) = A\{(\beta - 1/\tau)[e^{-t/\tau} - e^{-\beta t}\cos\omega t] + \omega e^{-\beta t}\sin\omega t\}$$

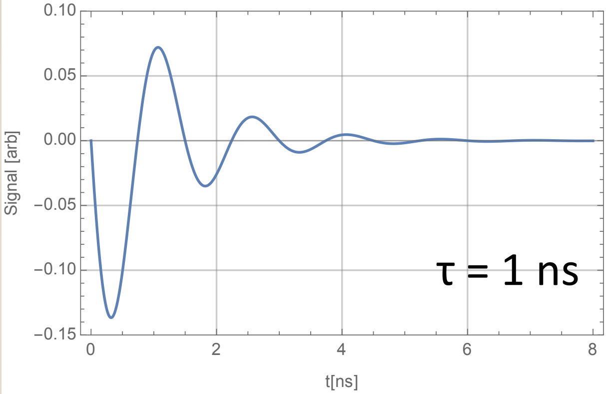




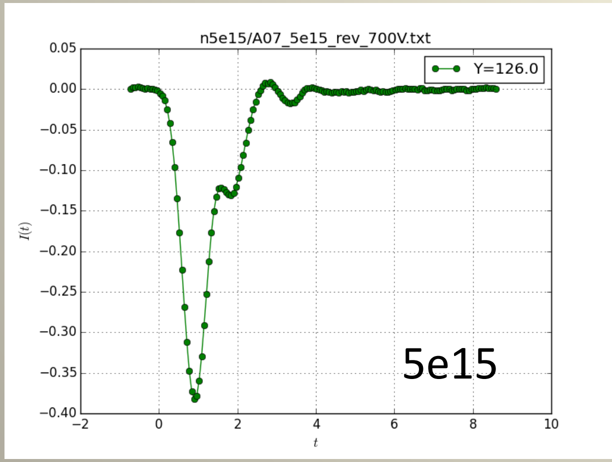
At 5e15 and 1e16

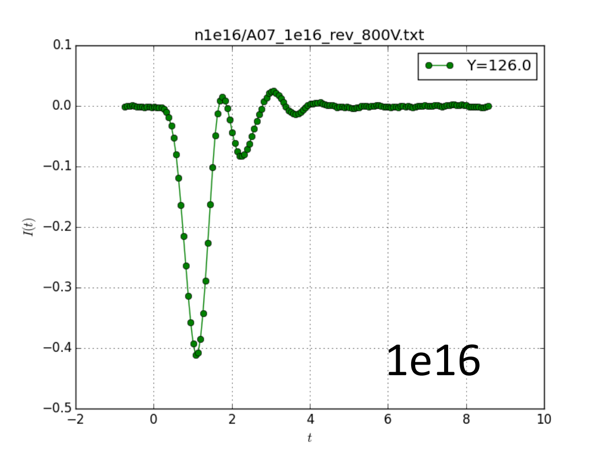
- No way to reproduce signal, although basic features of *H(t)* still there

$$I(t) = A\{(\beta - 1/\tau)[e^{-t/\tau} - e^{-\beta t}\cos\omega t] + \omega e^{-\beta t}\sin\omega t\}$$



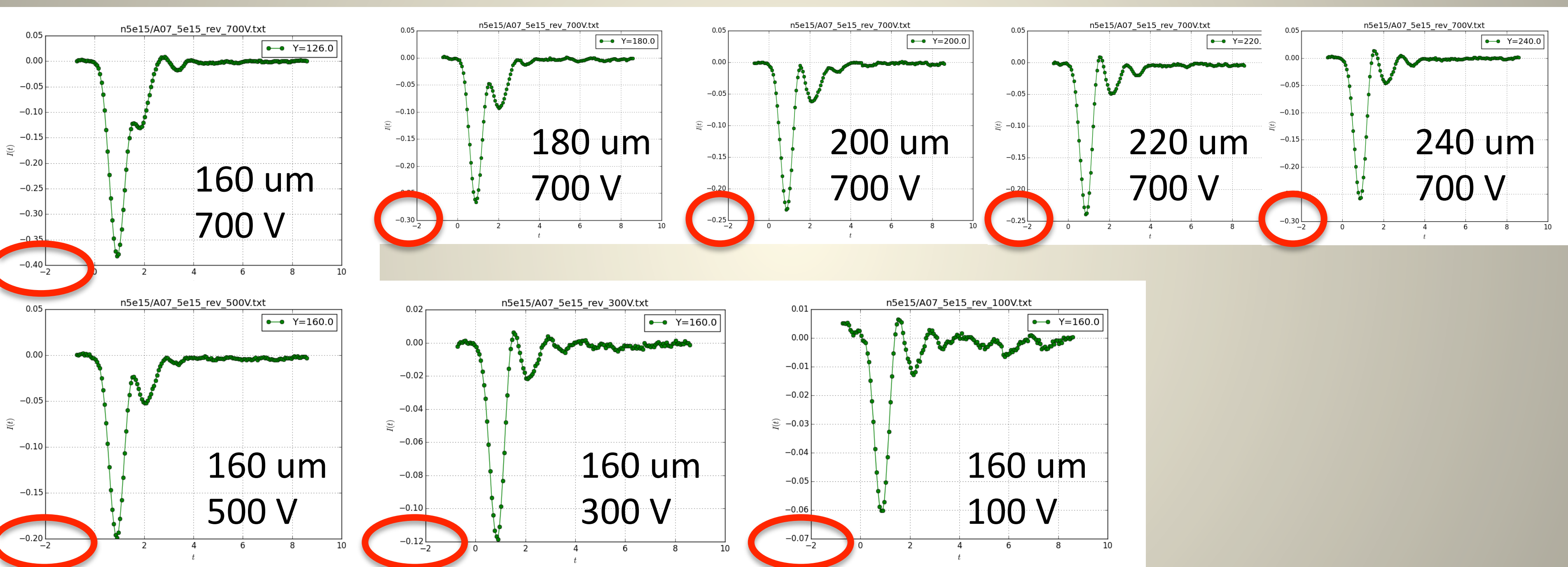
- border ? CM ?





5e15: position, voltage

- border (CM@strip) ? – further away
- CM ? – lower *V*



- qualitatively makes sense
  - still no hope fitting with same *H(t)* and *τ* ?
- not the same run as 5e16, 1e17 -> did *H(t)* change ?

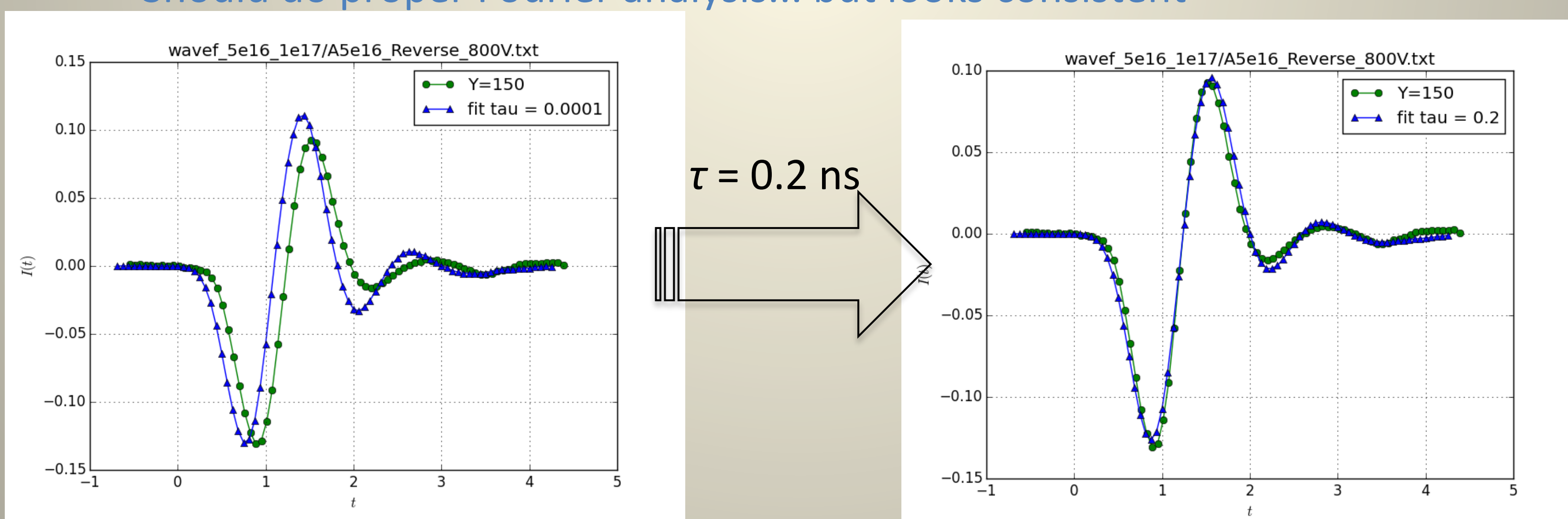
Summary

- TCT waveforms studied for Si detectors irradiated
  - with neutrons from 5e10^{15} to 10^{17} n_{eq}/cm^2
- Prior knowledge on el. field, mobility and trapping taken into account
  - expected trapping times O(100 ps) @1e17
- Transfer function constructed from observed characteristics @1E17
  - no reasonable equivalent *RLC* found (so far ?)
- Trapping convoluted with *H(t)* reasonably matches *WF* at 1e17 and 5e16
- No match for 5e15 and 1e16
  - position/voltage dependent *WF* (CM ?)
  - different *H(t)* ?

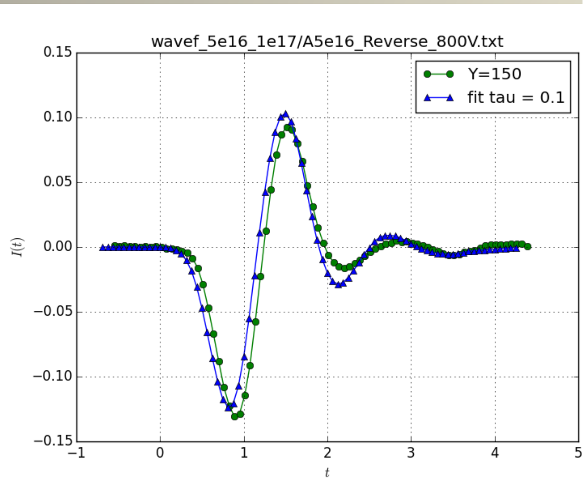
Backup Slides

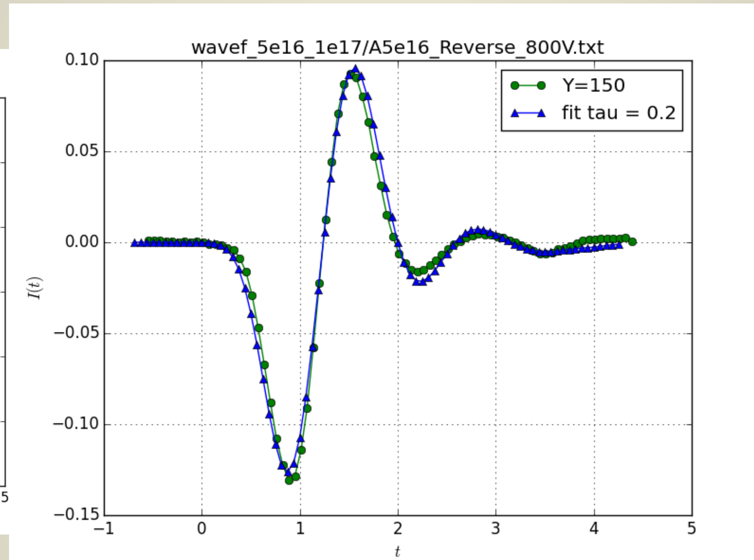
Waveforms –direct method

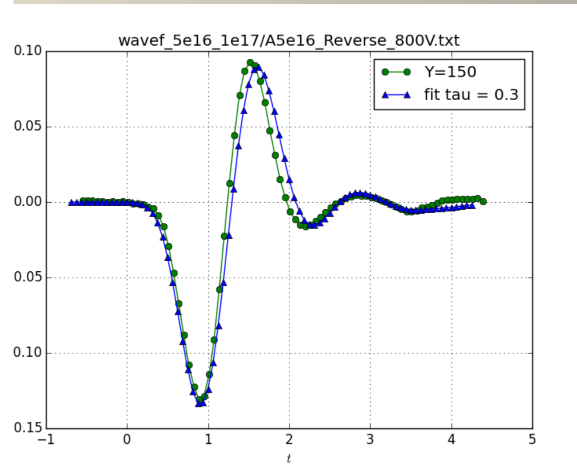
- Waveforms at y=100 µm, 800 V, 5x10^{16} and 10^{17}
  - $E \approx 3$ V/µm, *CCD* implies signal within ~15 µm or ~0.2 ns
    - the rest you see is the transfer function of the system
- Still distinct signals from the two fluences
  - treat 10^{17} waveform as transfer function of the system
    - 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 $e^{-t/\tau(1e17)}$!
  - Should do proper Fourier analysis... but looks consistent



Waveforms: How sensitive ?







- $\Delta\tau$ = 0.2 ns certainly best fit, 0.1 too narrow, 0.3 too broad
- precision ~50 ps