Extraction of electric field of non-irradiated microstrip detectors using the edge-TCT technique

Instituto de Física de Cantabria

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(Work developed at the Solid State Detector-SSD lab at CERN)

Contents

Motivation for this study

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▪ In the framework of the **LHC upgrades** and **RD50** collaboration, we want to have a **tool to measure the E-field profile** inside a heavily irradiated microstrip detector. This knowledge is key to improve current designs and develop more radiation hard devices. The tool now exists (2010) and is called edge-TCT.

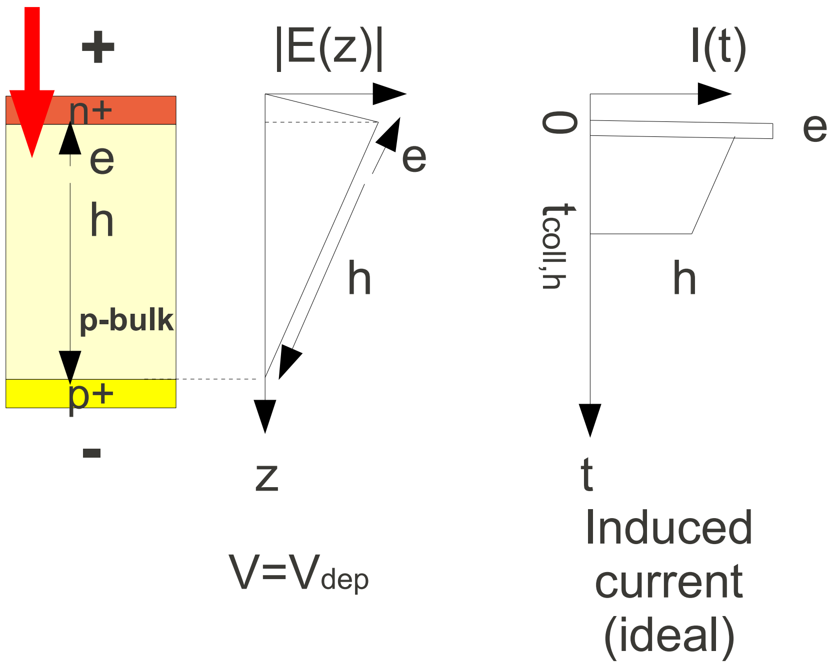
▪ **Device simulation community** also benefits of such tool, to validate, tune or discard some of the employed models. Better description of existing devices, more accurate predictions, better new devices.

▪ For **irradiated detectors**, knowledge of E-field is very helpful to calculate the trapping. Measurements this technique can address:

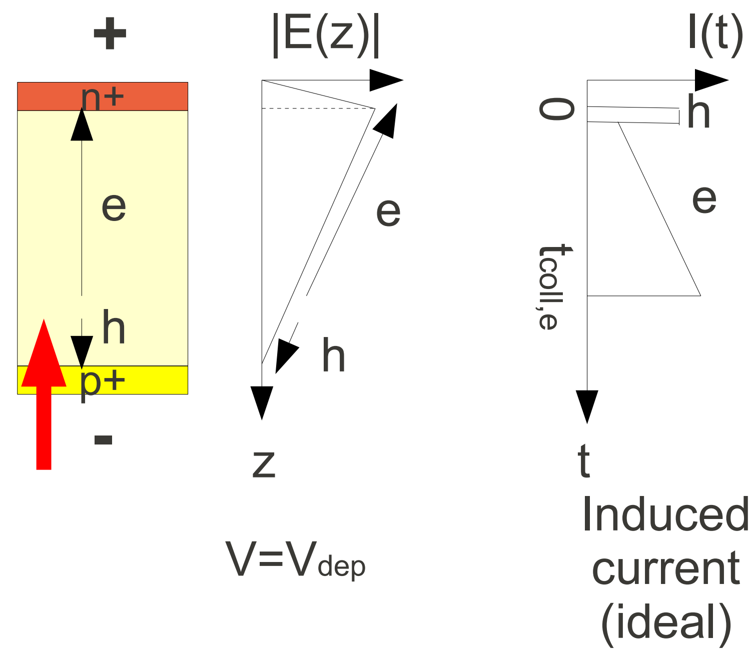
Double Junctions
Evolution of E-field with annealing
Description of E-field for devices exhibiting multiplication
. . .

Transient Current Techniques

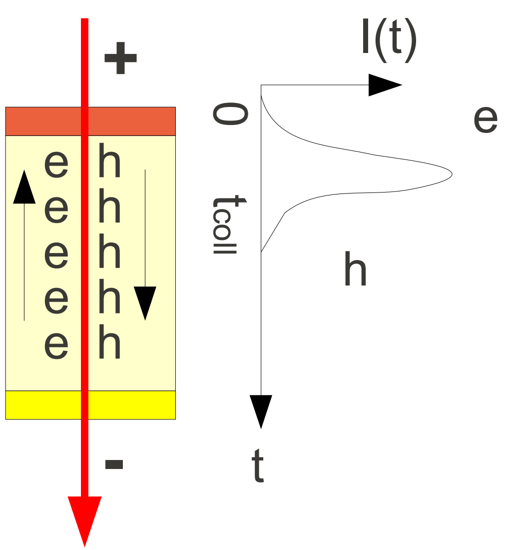
Top Red TCT (h injection)



Bottom Red TCT (e injection)



IR TCT

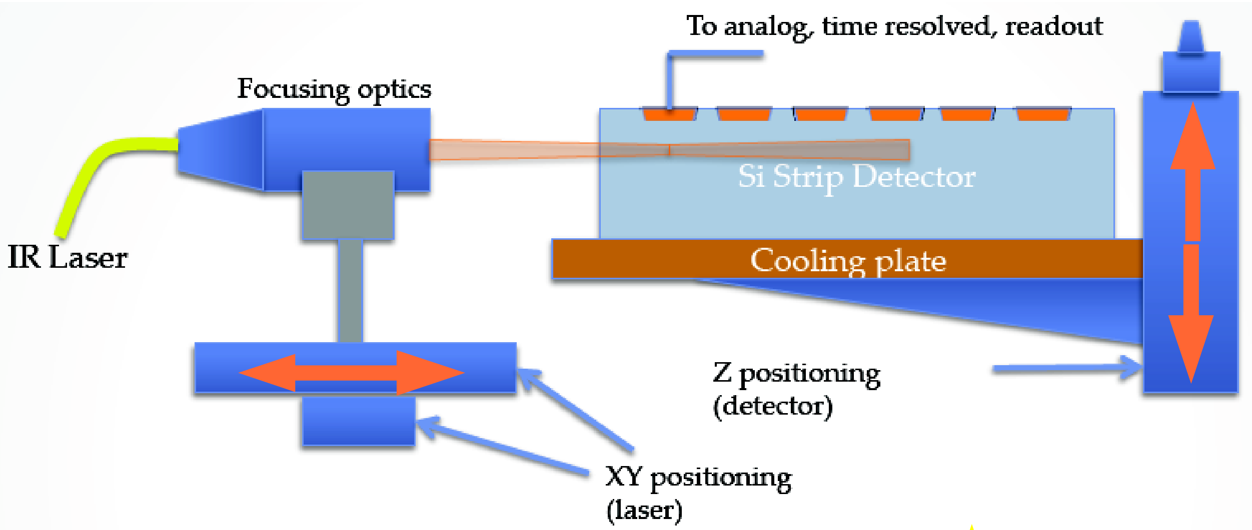


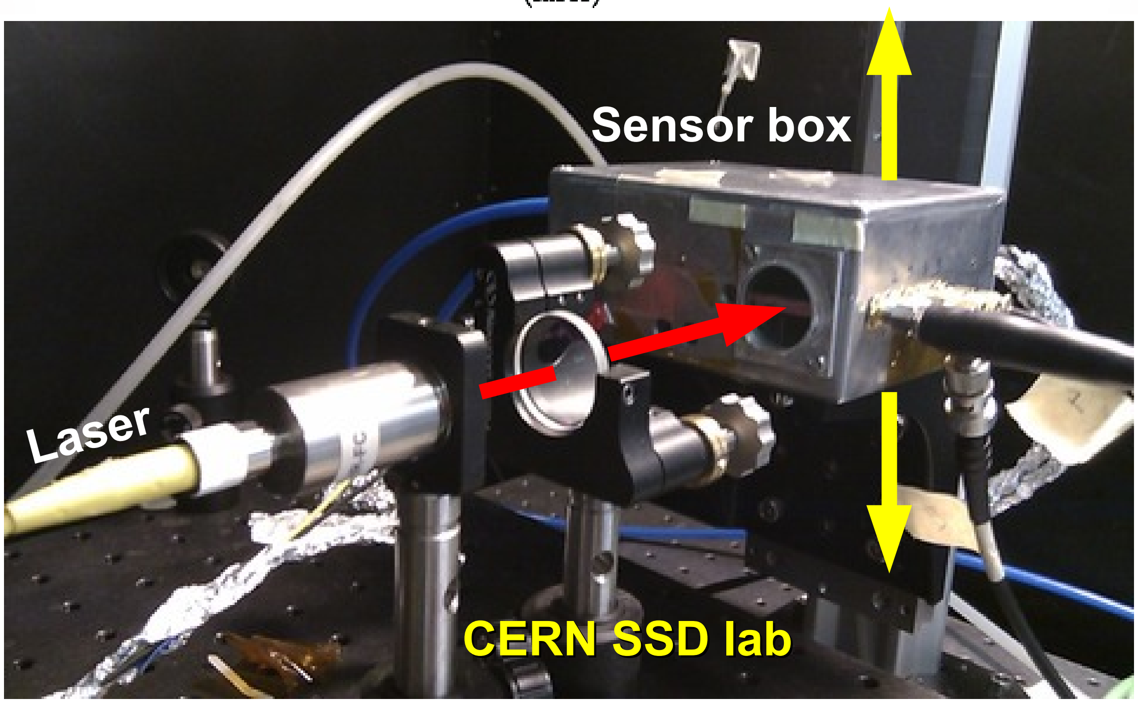
- TCT is a direct application of Ramo's theorem (diode):

$$\begin{cases} I(t) \propto v_{drift}(t)\dfrac{1}{d} \\ v_{drift}(t) \propto E(z(t)) \end{cases}$$

- Red TCT offers a "**picture**" of the electric field the carriers "see" along the drift. However for heavily irradiated detectors, charge is trapped before crossing the whole bulk, and then we see a **"cropped"** picture of the field. **Edge-TCT** is a **solution** for that.

Edge-TCT technique





- Transient Current technique developed by Ljubljana group [1]. It allows to extract sensor properties (vdrift ⇒**E-field**, CCE) **as a function of depth.**

- Charge carriers created at **selected depth** in the bulk

- **Spatial resolution** given by laser width (vertical, σ=8 μm). Measurements averaged over strip width (horizontal). Best on **segmented devices**

- **SSD setup: 5th strip** AC readout. Bias Ring grounded, Backside biased.

Setup Featuring:

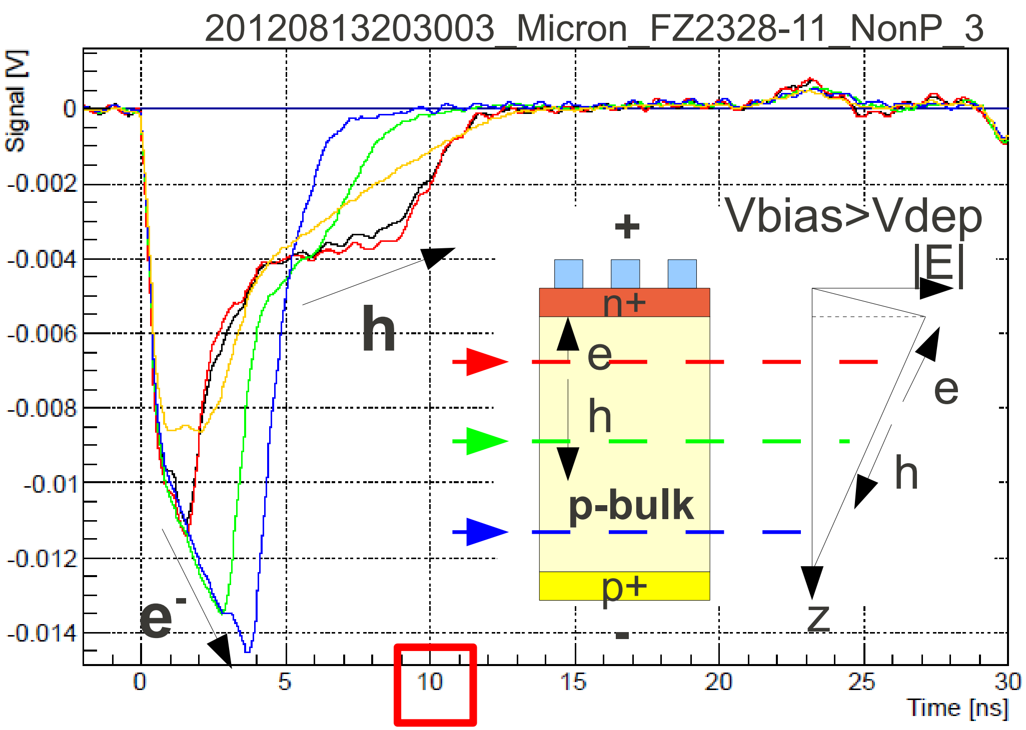
→ 80 ps FWHM laser 1060 nm
→ XYZ motion
→ T controlled meas. [-20,80]C
→ In-situ annealing

- DAQ by CERN SSD (N. Pacifico, M. Gabrysch, I. Dolenc)

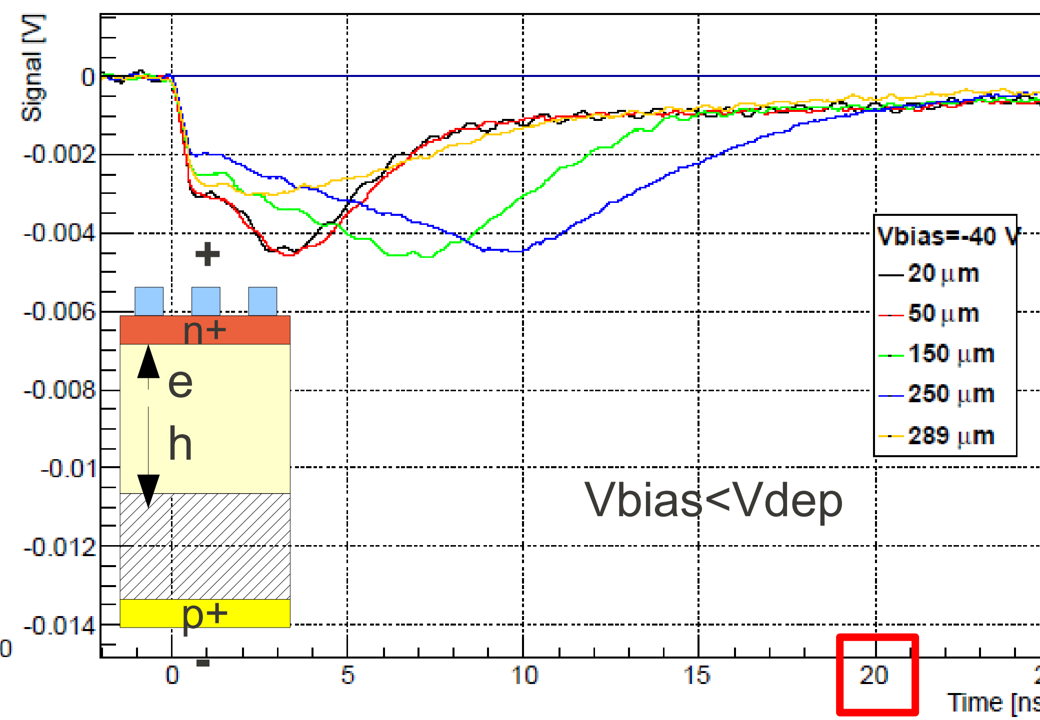
[1] ETCT method: G. Kramberger et al., IEE TNS, VOL. 57, NO. 4, August 2010, p. 2294

Typical edge-TCT measurement

• Time resolved current transients for various laser injection depths. Contribution from e and h can be resolved.



Drift



Drift and diffusion

• Note: All measurements presented in this work correspond to AC-coupled **“baby” sensors** from 2 different producers: Micron, VTT.

• Thanks to **F. Manolescu & I. McGill** from **CERN bonding lab**

Measurement of drift velocity:

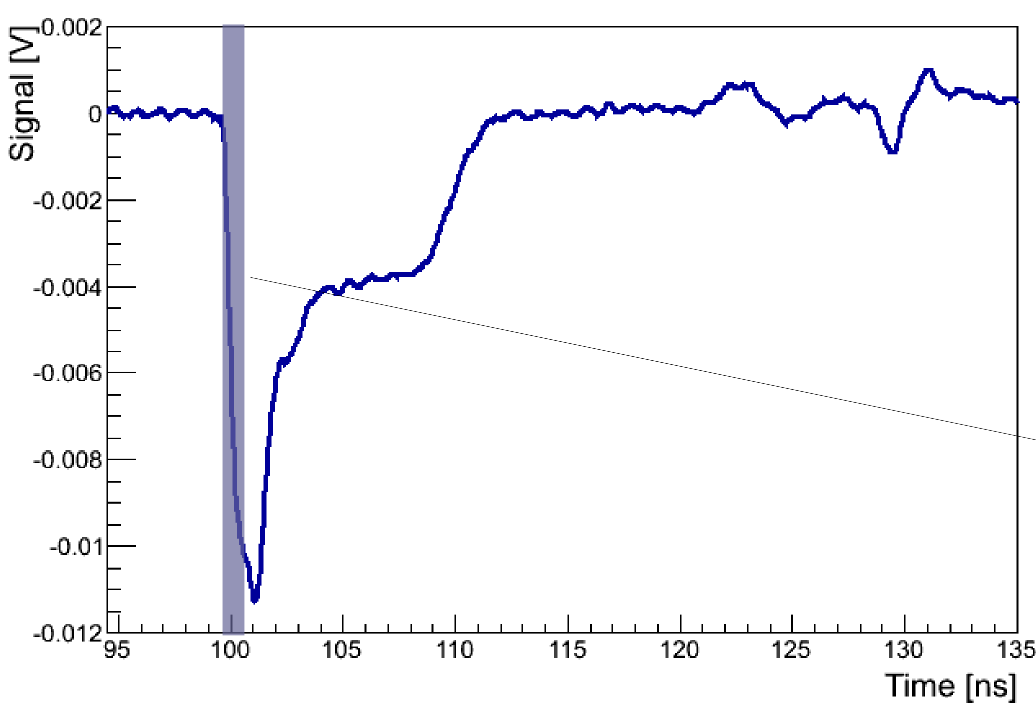
- edge-TCT provides a **measurement** of the instantaneous “trapping-free” drift velocity ve+vh, **for each injection position** along the thickness of the detector.

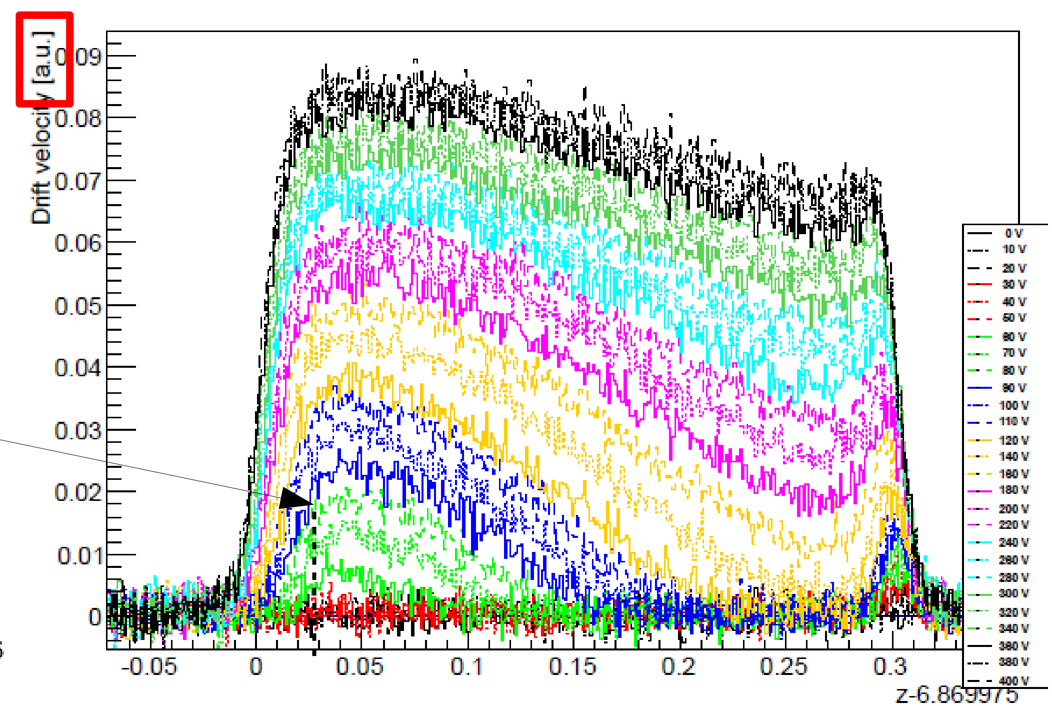
$$I_{e,h}(t,z)=Ae_0N_{e,h}\underbrace{\left[\exp\left(\frac{-t}{\tau_{e,h}}\right)\right]}\frac{v_e(z,t)+v_h(z,t)}{d} \Rightarrow v_e(z,t\approx 0)+v_h(z,t\approx 0)=\frac{d\cdot I_{e,h}(t\approx 0;z)}{Ae_0N_{e,h}(z)}$$

Trapping term (important for irradiated detectors)
Vdrift calculation allows t~0 (not possible in TCT)

A=Amplification, e_0=elementary charge
Ne,h=Number of injected e-h pairs
τ = trapping time, $v_{e,h}$= drift velocity,
d= thickness

- **Unknowns**: Ne,h and integration time (what is t~0?) [see backup]
  Vdrift can be measured **except for a constant**





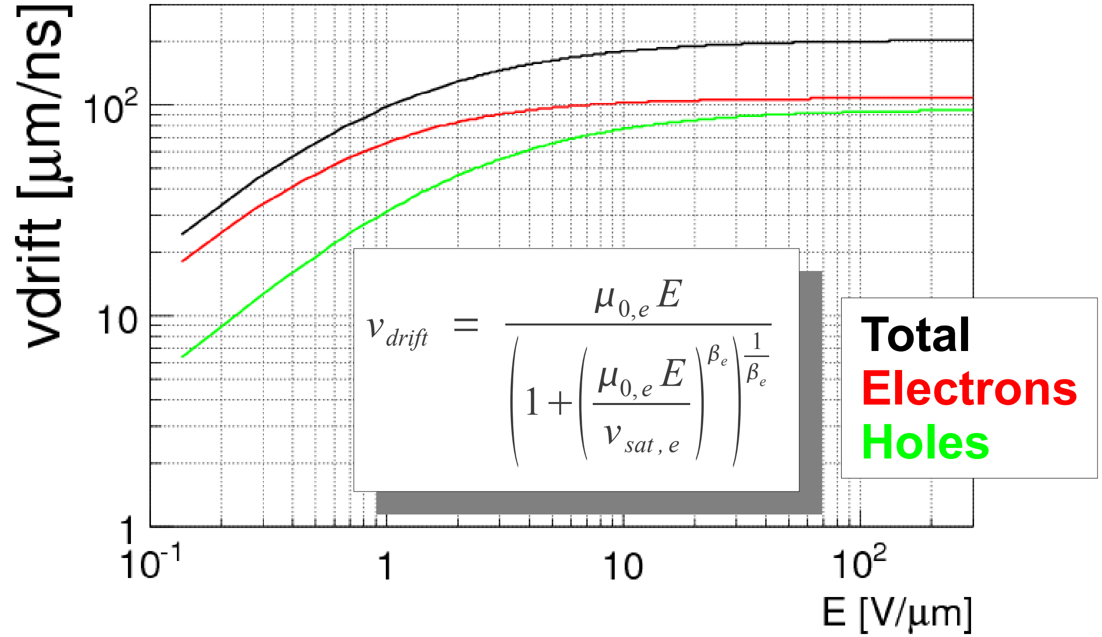
Main difficulties extracting E-field from vdrift measurements

- Even if we know the exact drift velocity, we will still have:

  - **Non-linear** dependence of vdrift on E-field

  - Dependence on **T**

  - **vdrift saturates** at high E-fields. In this regime it is not possible to calculate E-field



E-field → vdrift **Easy**
Vdrift → E-field **Fit**

- We propose **2 methods** to calculate the “missing” **proportionality factor** in edge-TCT and thus calculate the E-field:

  Method 1: Assume E-field of a strip ≡ E-field of a diode (true when far from electrodes).
  1.1: Scales measured vdrift by diodes drift velocity at detector half-thickness.

  Method 2: Uses a different “observable”, the collection time, to extract a first estimation of E-field, therefore a vdrift.
  2.1 Go back to 1.1

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Method 1: diode approximation

1) Far from electrodes, E-field assumed to match diode's field: $E(z)=a+bz$

2) Conditions for the field:

$$V_{bias}=\int_0^w E(z)\,dz=\int_0^w (a+bz)\,dz \Rightarrow a$$

$E(z=w)=0 \Rightarrow b$ parameter

w = depletion width

$$E(z) = \underbrace{\frac{V_{bias}}{w}}_{a'} - \underbrace{2\frac{V_{bias}}{w^2}}_{b'}\cdot\left(z-\frac{w}{2}\right)$$

3) If we fix parameter a' in the fit, the V_{bias} condition is fulfilled by construction. Note that the field in the middle of the detector is:

$$E\left(z=\frac{w}{2}\right)=\frac{V_{bias}}{w}$$

4) Assume this field is accurate in the middle of the detector. Calculate the proportionally factor at z=w/2, and scale for other z values.

Limitation: not true if vdrift is saturated !!

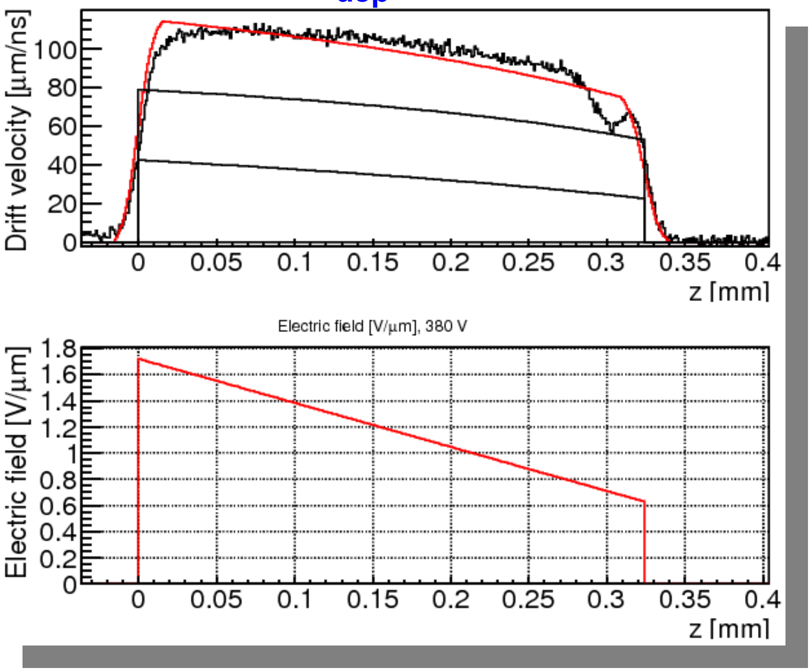
$$k = \frac{v_{diode}\left(z=\frac{w}{2}\right)}{v_{meas}\left(z=\frac{w}{2}\right)}$$

5) Extract E-field from fit to (scaled) measured vdrift

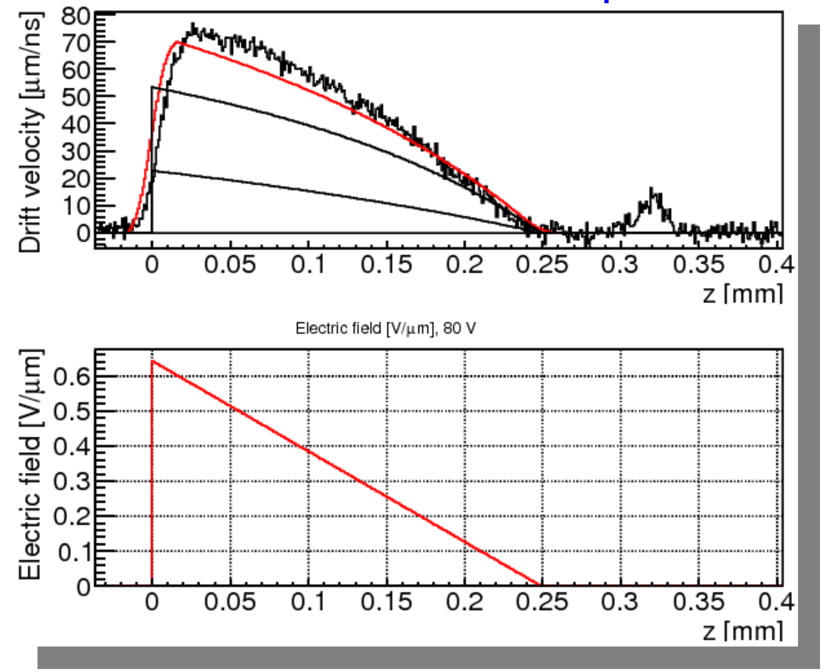
$$\chi^2 = \sum_0^d \left[k\times v_{drift,meas}-\left(\frac{\mu_{0,e}E}{\left(1+\left(\frac{\mu_{0,e}E}{v_{sat,e}}\right)^{\beta_e}\right)^{\frac{1}{\beta_e}}}+\frac{\mu_{0,h}E}{\left(1+\left(\frac{\mu_{0,h}E}{v_{sat,h}}\right)^{\beta_h}\right)^{\frac{1}{\beta_h}}}\right)\right]^2$$

MCZ 320 μm, N-bulk, Vdep=130V

$V > V_{dep}$

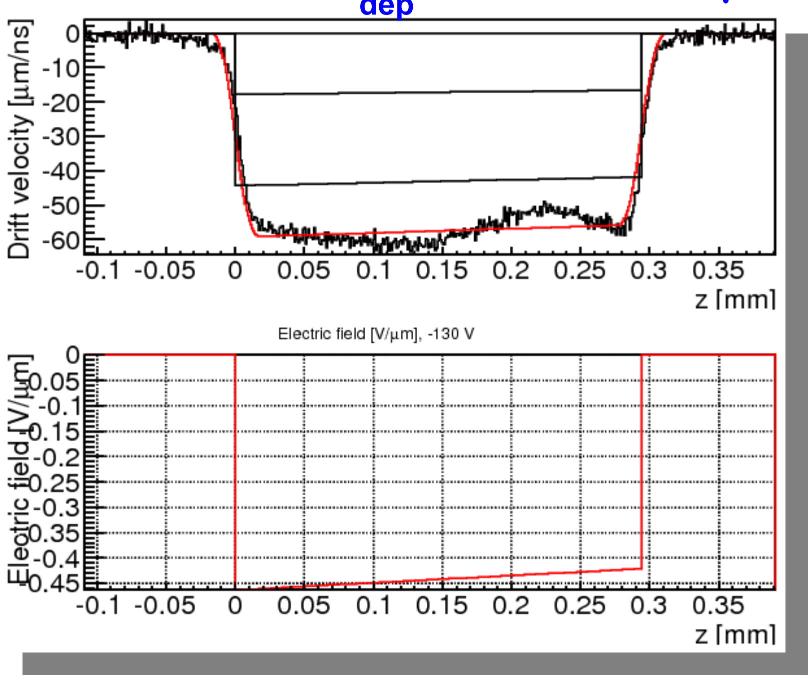


$V < V_{dep}$

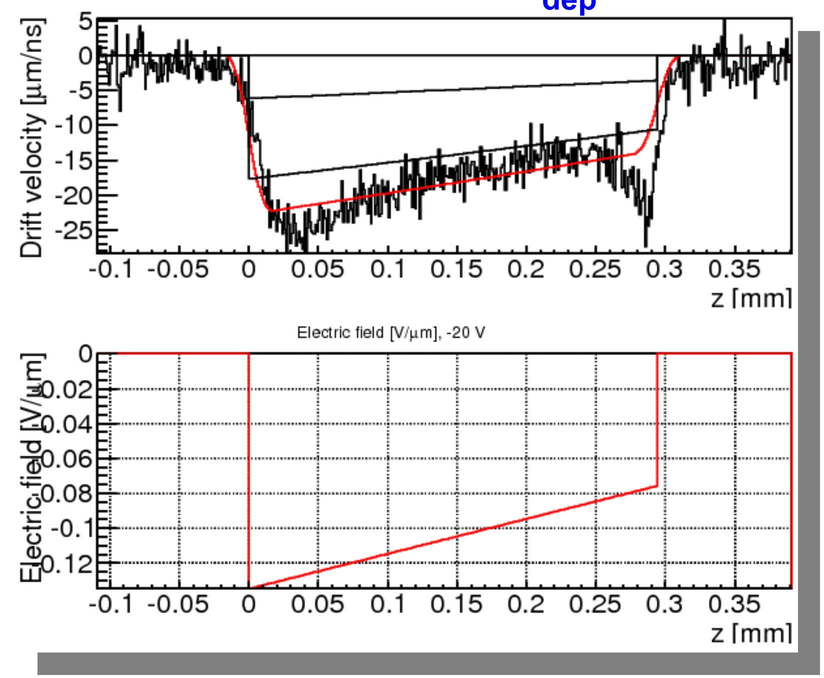


FZ 300 μm, P-bulk, Vdep=45 V

$V > V_{dep}$



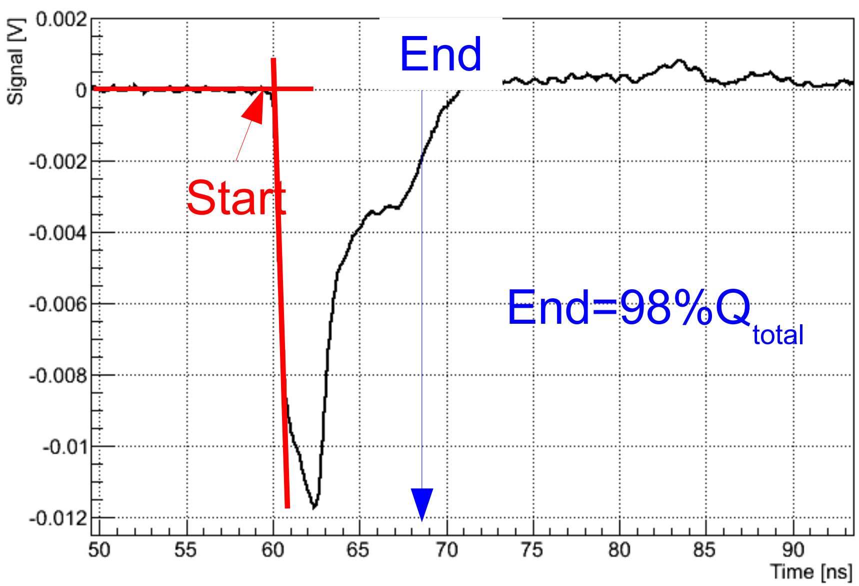
$V < V_{dep}$



Method 2: E-field from collection time

- In edge-TCT we can **measure** the collection time as a function of depth ($t_{coll}(z)$). Different collection times at different injection depths.

- The collection time is **measured** as the time lapse between rise edge and falling edge of current pulse.

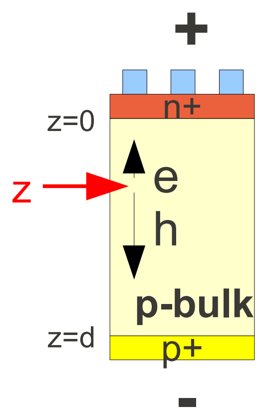


- The collection time can be **calculated** as the longest of the drifting times of the 2 types of carriers:

$$t_{collection}(z) = \mathrm{Max}\left(t_e(z)\,,\,t_h(z)\right)$$

$$t_{e(h)}(z) = \int_z^{0(d)} \frac{1}{v_{e(h)}(z')}\,dz'$$

$$v_e = \frac{\mu_{0,e}E}{\left(1+\left(\frac{\mu_{0,e}E}{v_{sat,e}}\right)^{\beta_e}\right)^{\frac{1}{\beta_e}}} \quad ; \quad E(z) = a' + b'\left(z - \frac{w}{2}\right)$$

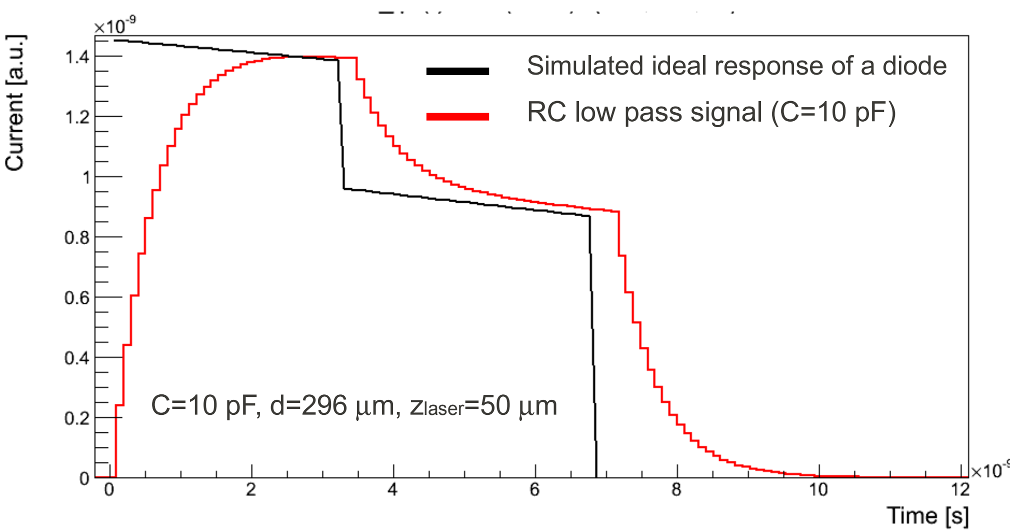


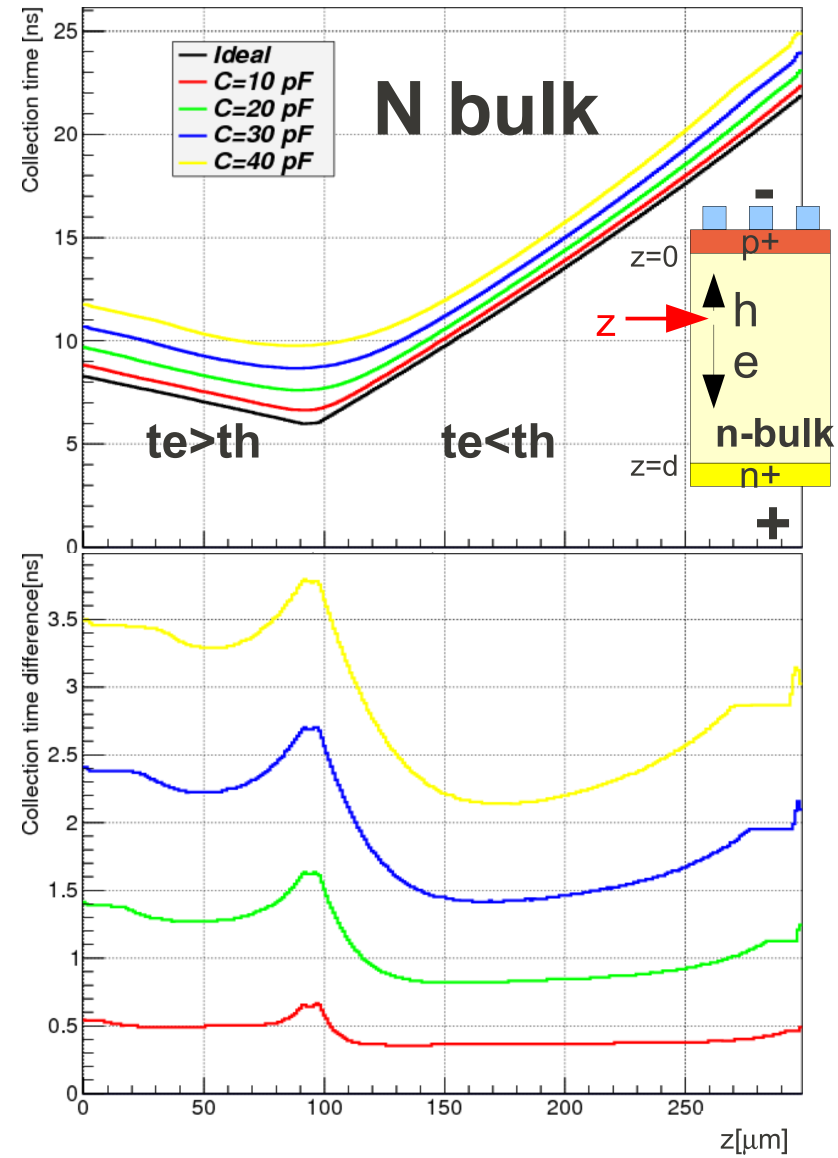
- This method does not need the **measured vdrift** at all.

$$\chi^2 = \sum_{z=0}^{d}\left[t_{coll,meas}(z) - t_{collection}\right]^2$$

Degradation of timing information due to detector RC

- edge-TCT equivalent circuit behaves like an amplifying low pass filter





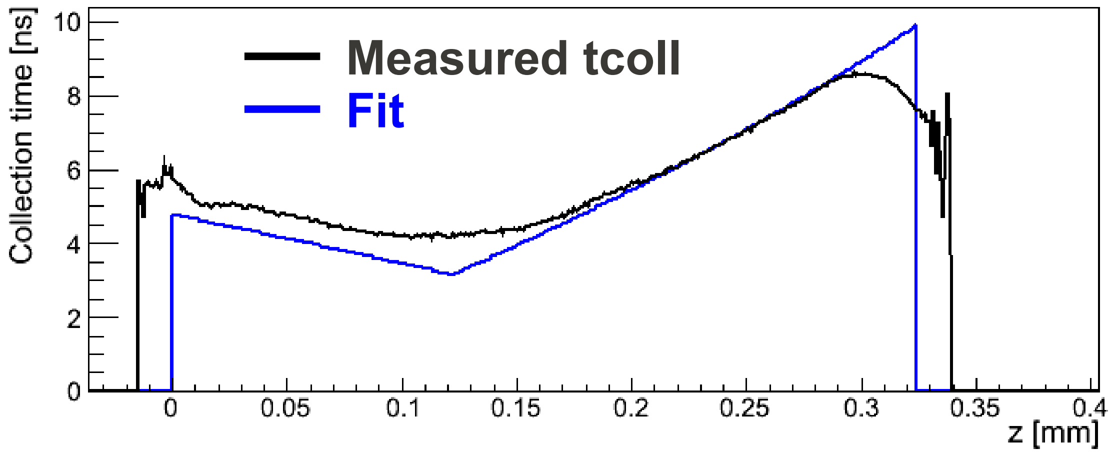
- N-bulk simulation using overdepleted diode, no diffusion considered

- **Below C=10 pF**, the contribution of RC to the collection time is <u>below 1 ns.</u>

- For our detectors, measured total capacitances [*see backup*] < 3 pF. Bias due to RC< 1 ns.

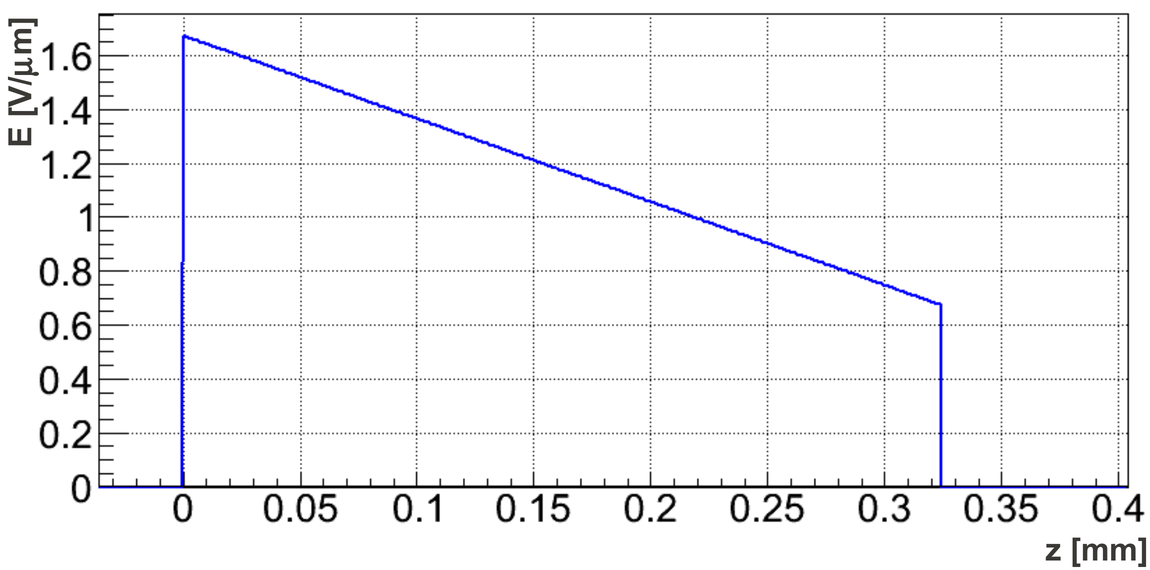
Method 2 (collection time): fit procedure

1) Fit collection time using diode field.



Border effects not modelled
Fit extends to sensor boundaries

We get: $E=E_{coll}(z)$ [1st estimation].



Method 2" for non-irradiated detectors (cont.)

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2) Calculate drift velocity for $E_{coll}(z)$:

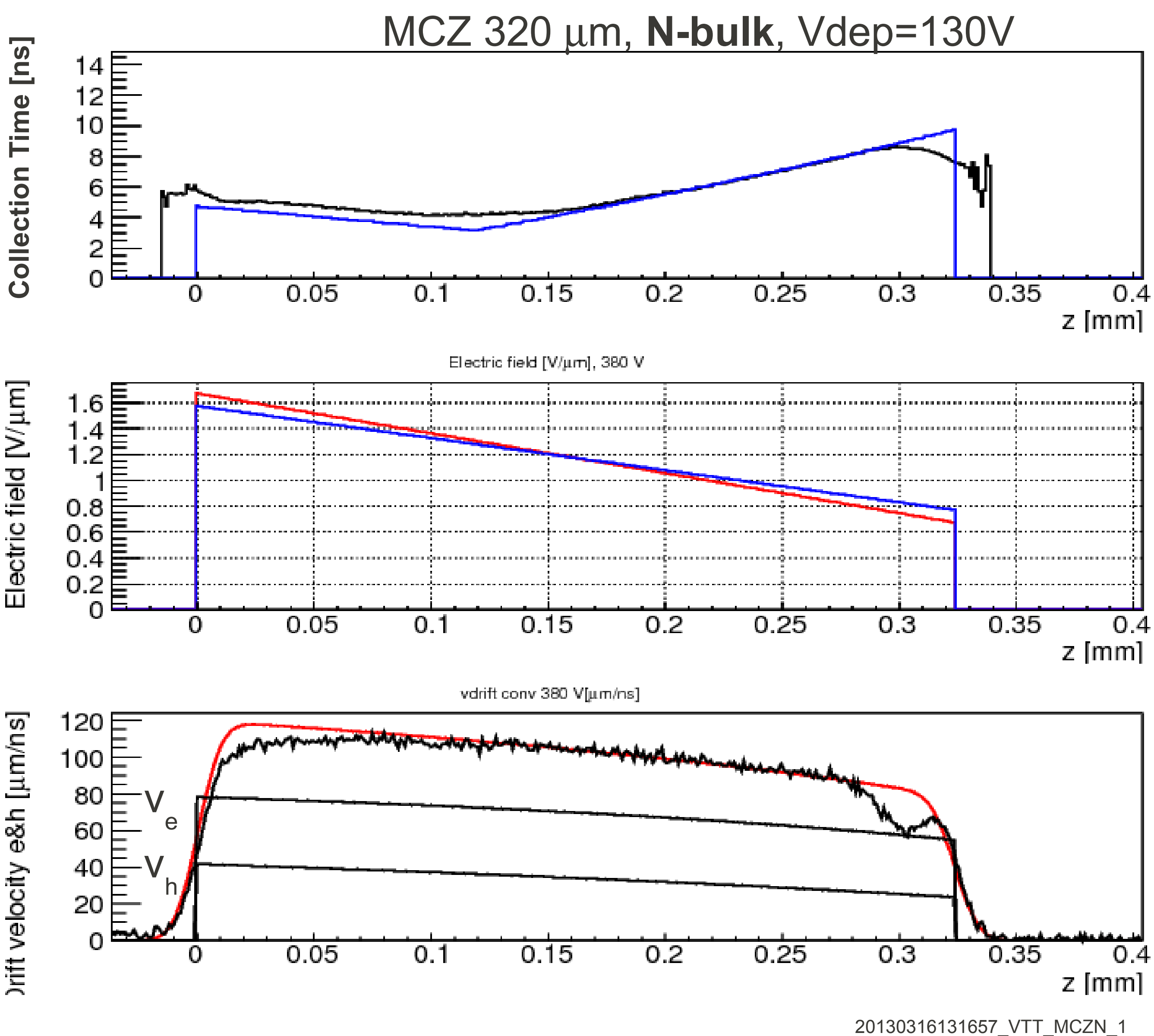
$$v_{drift,coll} = \frac{\mu_{0,e} E_{coll}}{\left(1 + \left(\frac{\mu_{0,e} E_{coll}}{v_{sat,e}}\right)^{\beta_e}\right)^{\frac{1}{\beta_e}}}$$

Scale **measured** drift velocity to calculated v_{drift}

$$k = \frac{v_{drift,coll}\left(z = \frac{w}{2}\right)}{v_{meas}\left(z = \frac{w}{2}\right)}$$

3) Fit $k \times v_{meas}$ and extract E-field from drift veloity fit $E_{vdrift}(z)$

Measured and fitted collection time (**VTT-Helsinki**)



Measured collection time

Collection time fit

Fit not good at sensor boundaries

Blue: E_{coll} (E-field from t_{coll} fit)

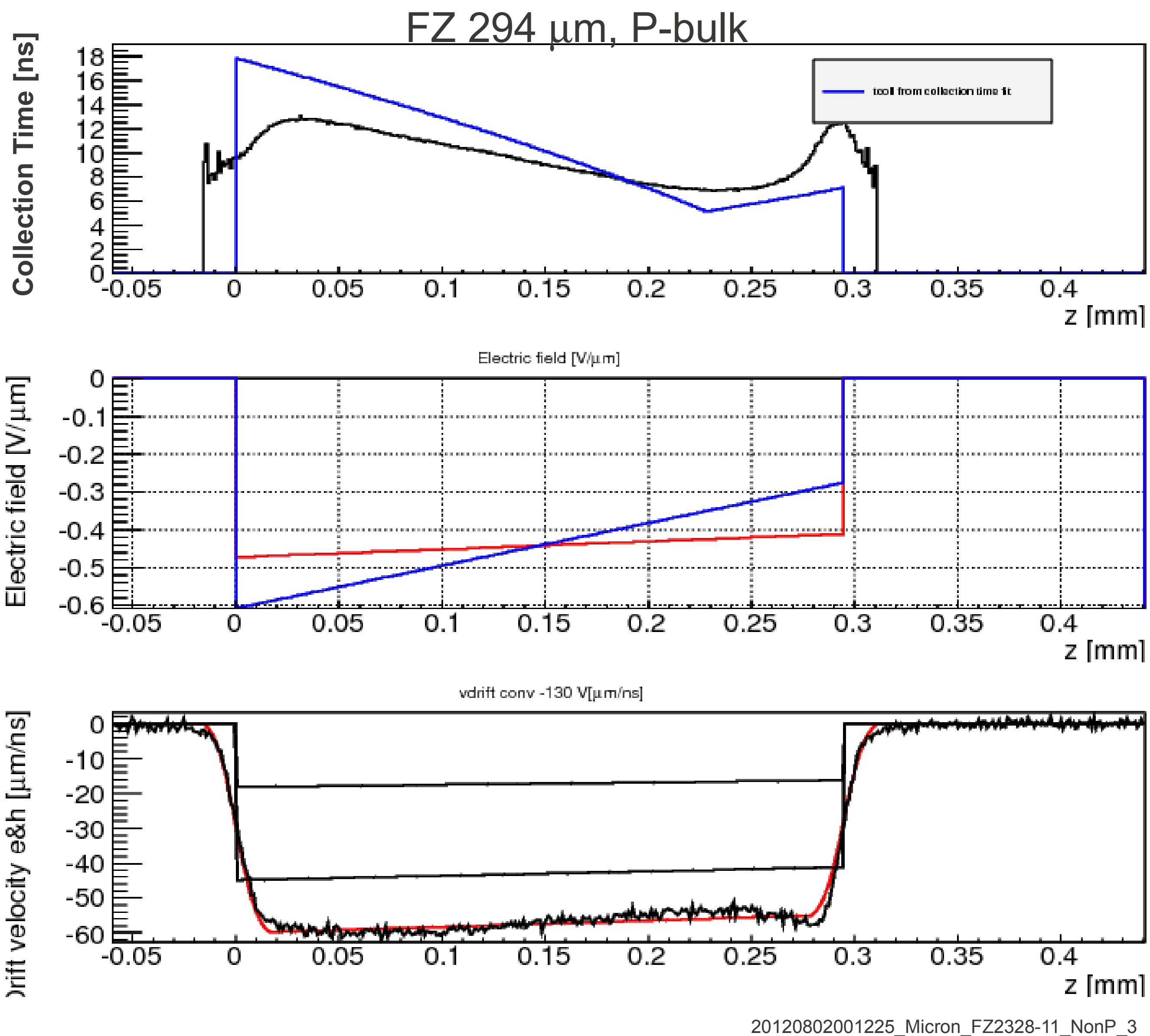
Red: E_{vdrift} (E-field from v_{drfitl} fit)

Scaled v_{drift}

Vdrift fit, using E_{coll} as starting parameter

Good fit at boundaries

Measured and fitted collection time (Micron-P)



Magnitude of the collection time reproduced, but worse agreement than with VTT-N

~20% difference in the electric filed estimated from collection time and from vdrift

Good vdrift fit!!

Comparison of E-field from vdrift both methods

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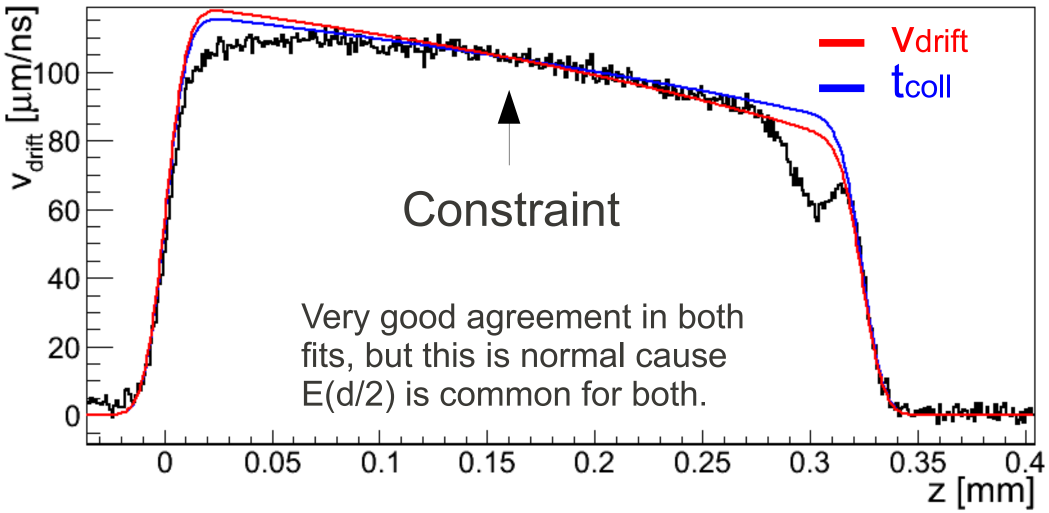
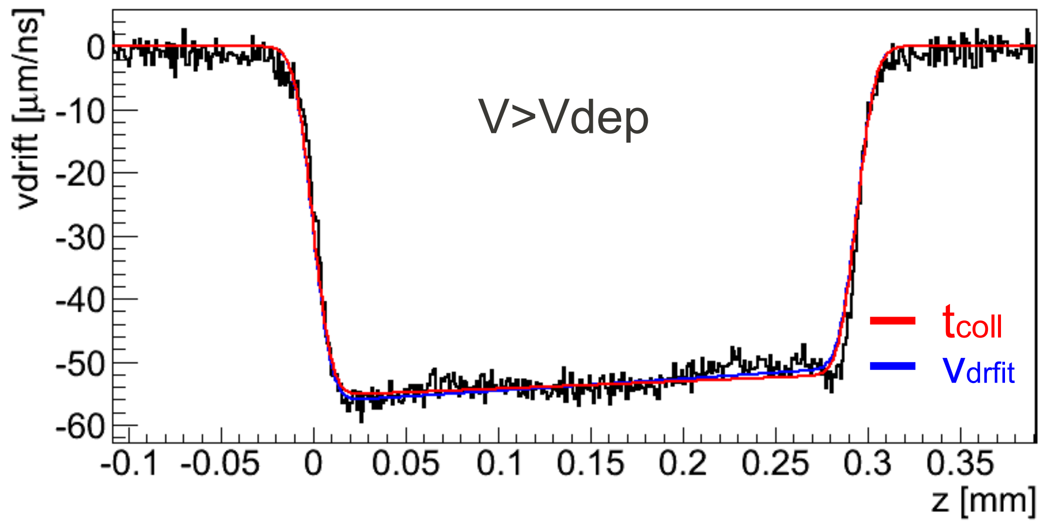
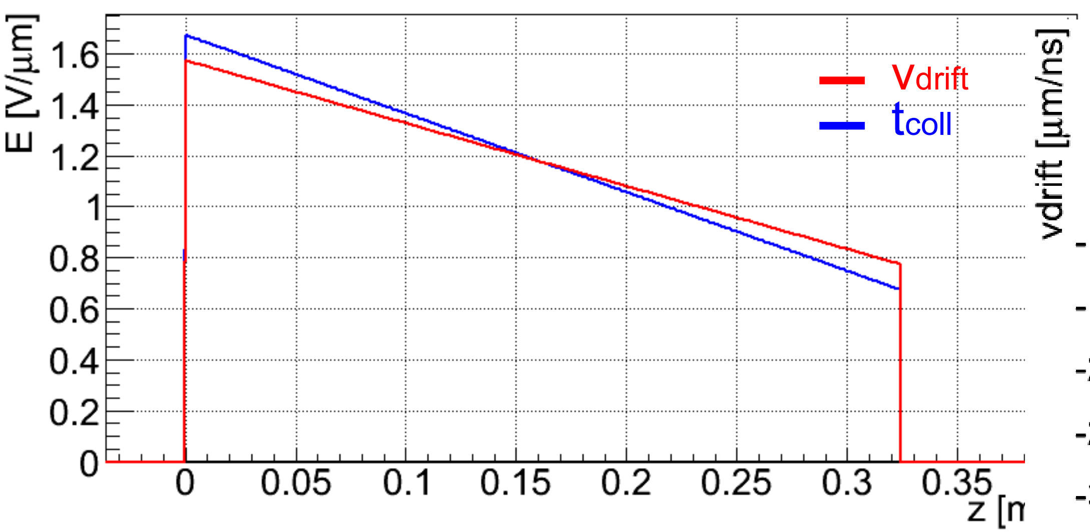
MCZ 320 μm, **N-bulk**, Vdep=130V

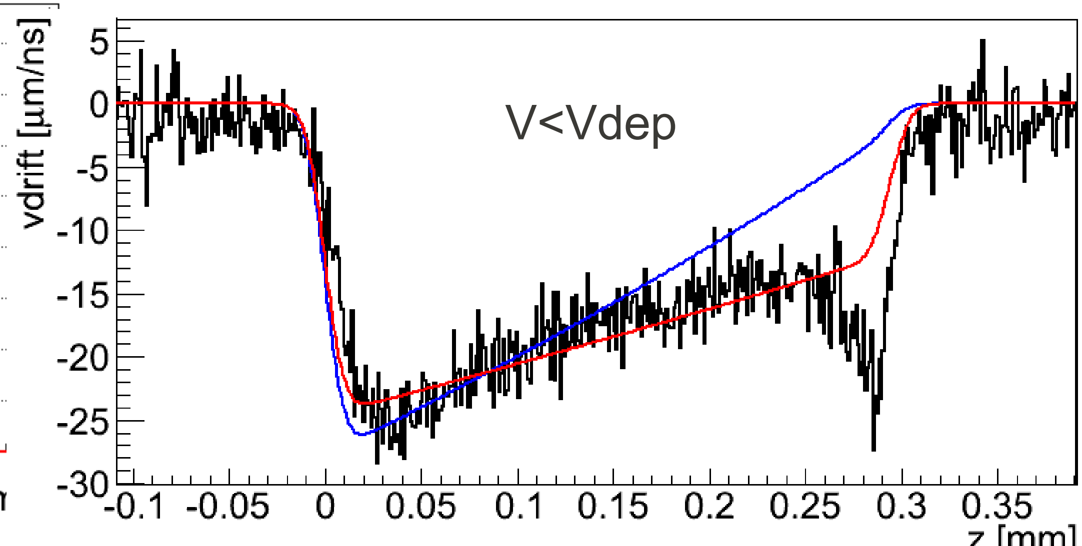


Micron FZ 294 μm, P-bulk





20120802001225_Micron_FZ2328-11_NonP_3



Very good agreement for V>Vdep, slightly worse for underdepleted (diffusion not simulated)

Conclusions

▪ Standard TCT measurements provide information on the detector's E-field. If trapping is important, edge-TCT is more suitable.

▪ Edge-TCT provides information of a segmented detector across its thickness (0<z<d)

Drift velocity is measured except for a proportional factor

Proposed 2 methods to calculate this constant and to extract the E-field

1) Assumes diode field, scales vdrift at detector half-thickness
2) Uses collection time to estimate E-field.

Both methods yield very similar description of the sensor. In general, 1st method is more suitable since it applies for any Vbias and is simpler.

▪ The methods presented give a polynomial description of the E-field (very easy to handle in simulation programs)

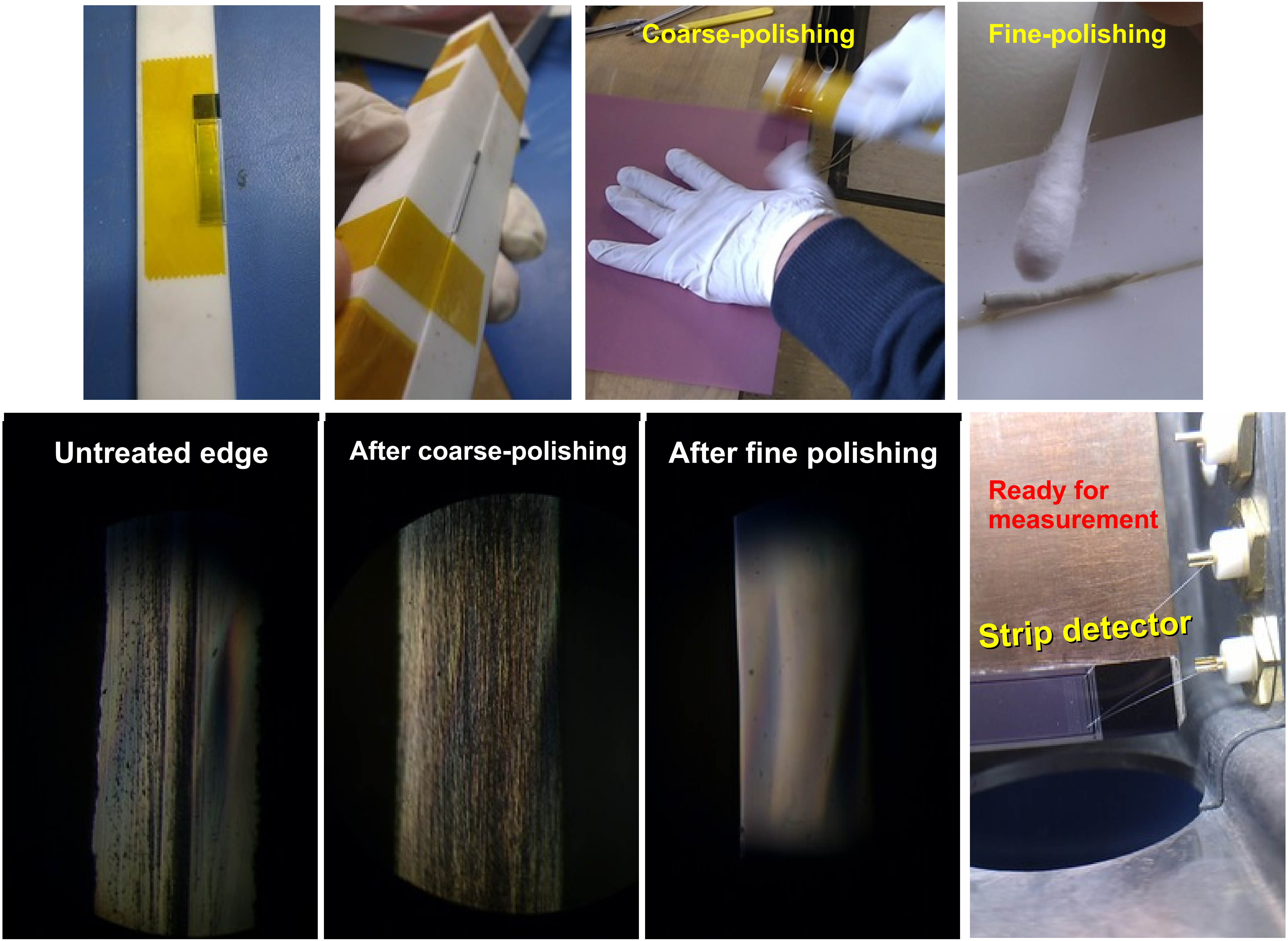
▪ This study is the 1st step towards the goal of extracting E-field (and trapping) in irradiated detectors.

Next

▪ Apply method to irradiated detectors where we have double junction near the electrodes and neutral bulk. First step: using parabolic E-field.

▪ Once E-field is known, calculate trapping time, possibly as a function of thickness (and/or field?)

BACKUP


Coarse-polishing
Fine-polishing
Untreated edge
After coarse-polishing
After fine polishing
Ready for measurement
Strip detector

Uncertainties on the measured drift velocity:

• edge-TCT provides a **profile** of the instantaneous “trapping-free” drift velocity ve+vh

$$I_{e,h}(t,z)=A e_0 N_{e,h}\left[\exp\left(\frac{-t}{\tau_{e,h}}\right)\right]\frac{v_e(z,t)+v_h(z,t)}{d} \quad\Rightarrow\quad v_e(z,t\approx 0)+v_h(z,t\approx 0) = \frac{d\cdot I_{e,h}(t\approx 0;z)}{A e_0 N_{e,h}(z)}$$

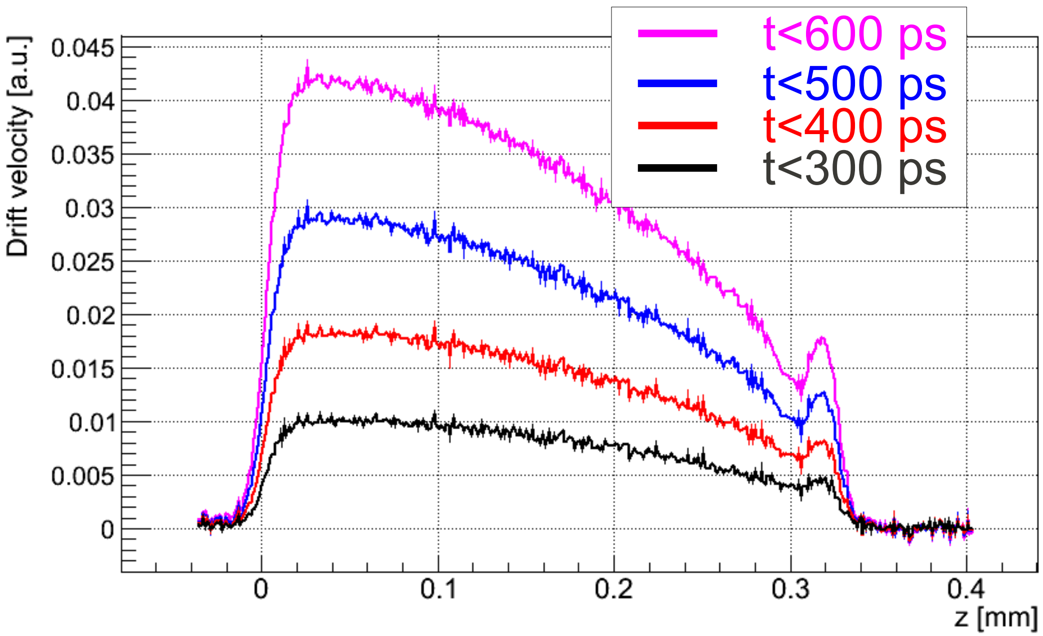
Two unknowns:

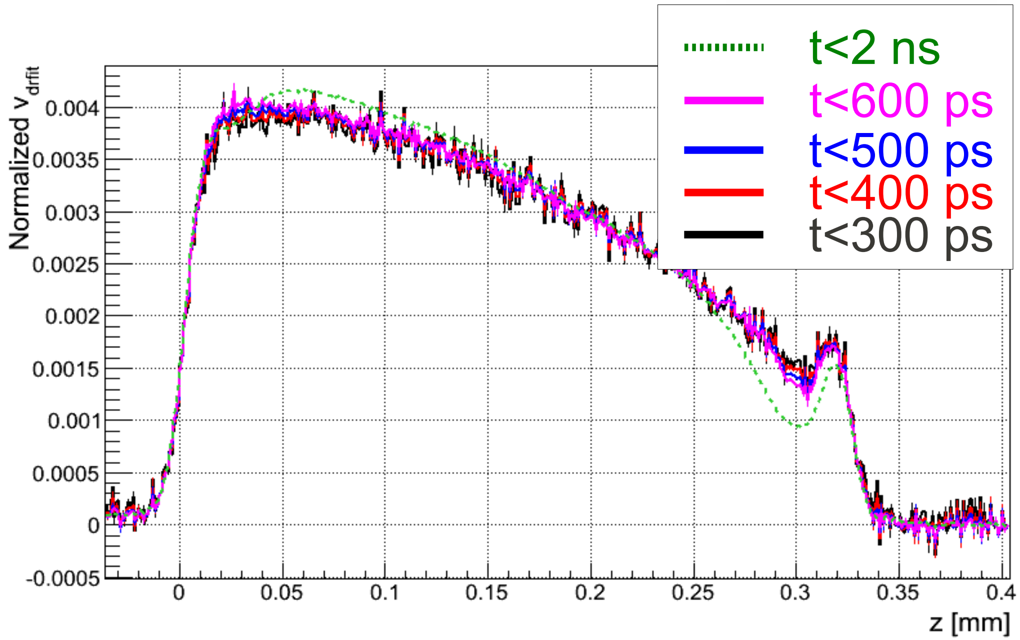
1) Number of e-h pairs $N_{e,h}(z)$ → for non-irrad detectors we can calculate it from the charge collected (see backup).

2) BUT how is I(t~0;z) defined?? I use an average of I(t) over 400 ps:

$$v_{drift}(z_i)=\frac{d}{Ae_0 N_{e,h}}\cdot\frac{1}{N_{400}}\sum_{j=0}^{400\,ps} I(t_j, z_i)$$

Drift velocity for different t~0 definitions





Absolute vdrift ([a.u.]) for different averaging times

Normalized vdrift ([a.u.]) for different averaging times

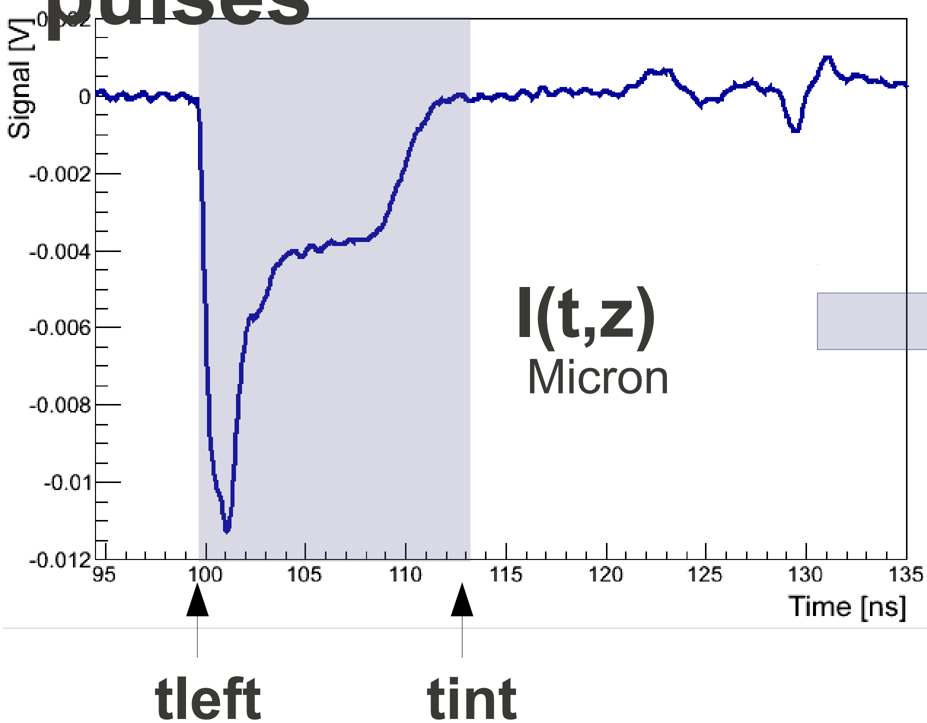
Even if the relative information in the range [300-600] ps is the same, the **absolute** value of vdrift is different.

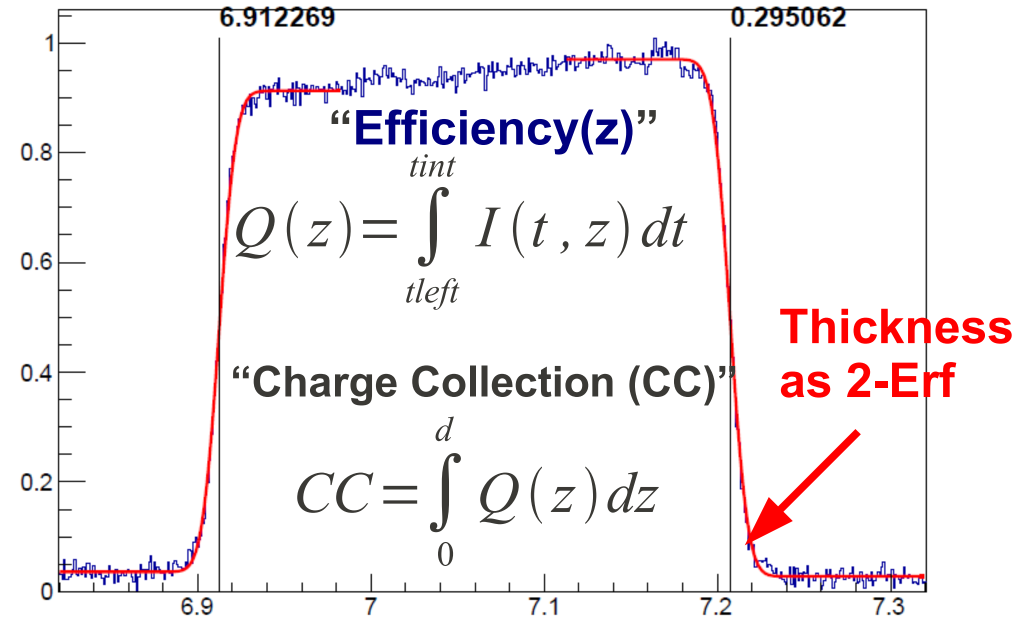
Different averaging times, will lead to **different absolute values of vdrift** and therefore of E-field.

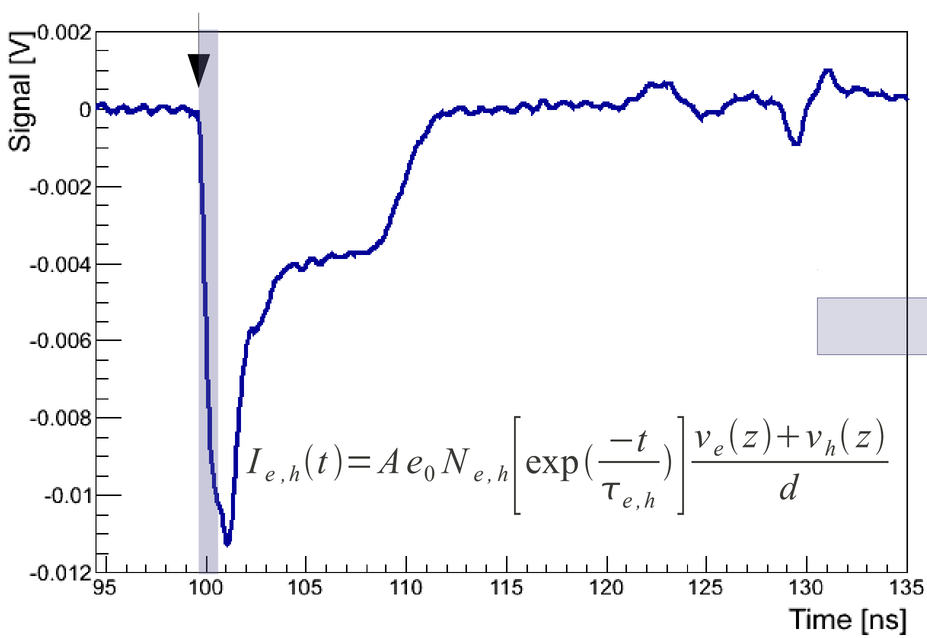
$\Downarrow$

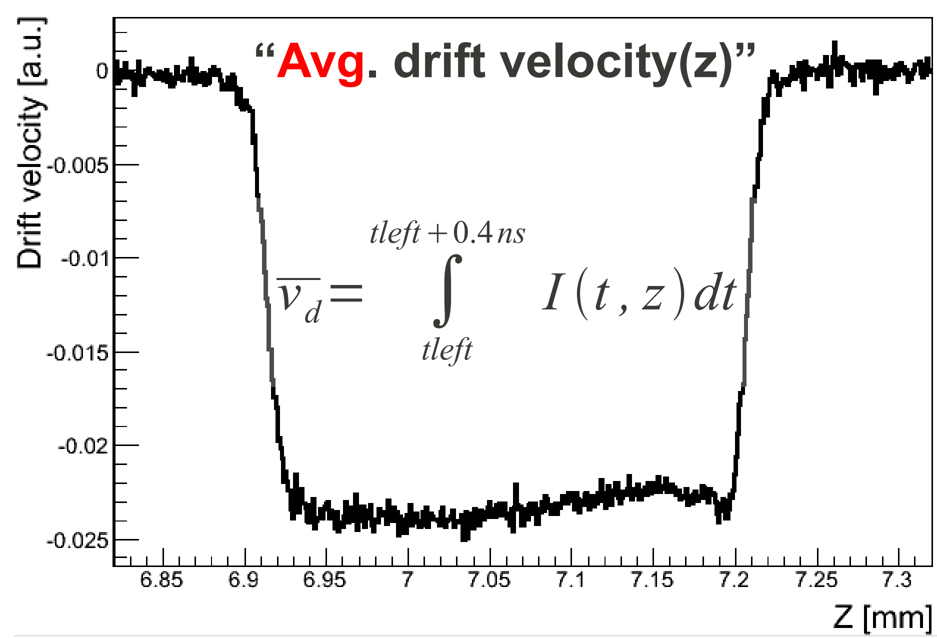
So to extract the E-field we need a method not based in v_{drift}

Analysis of edge-TCT pulses

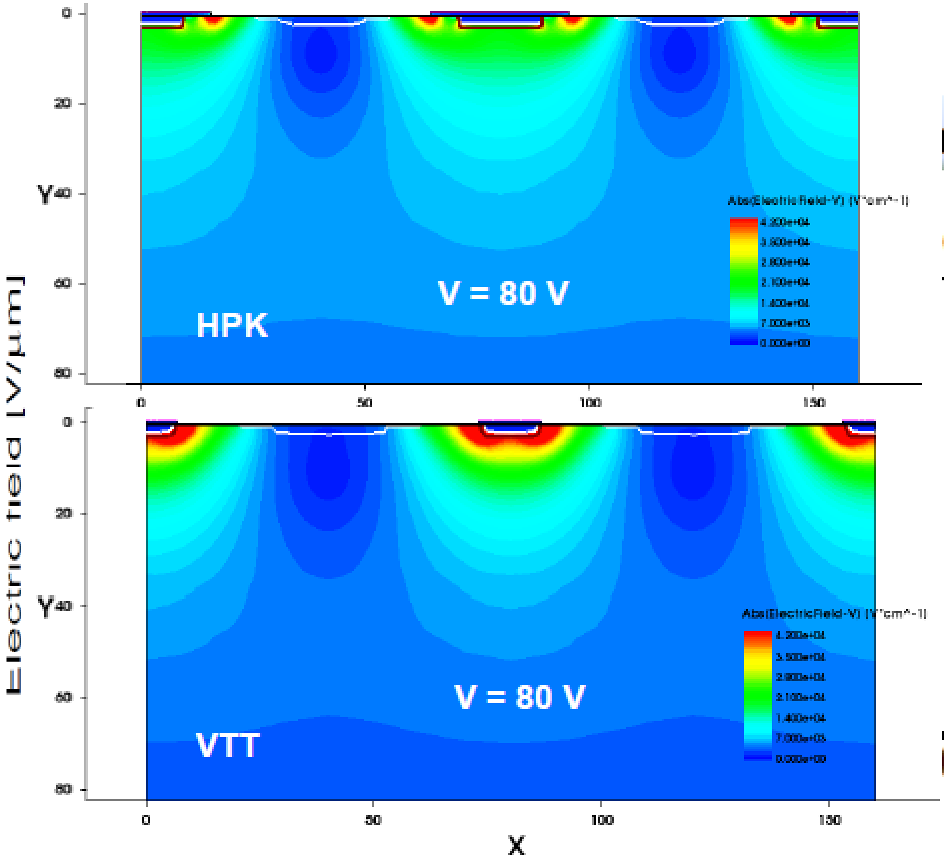


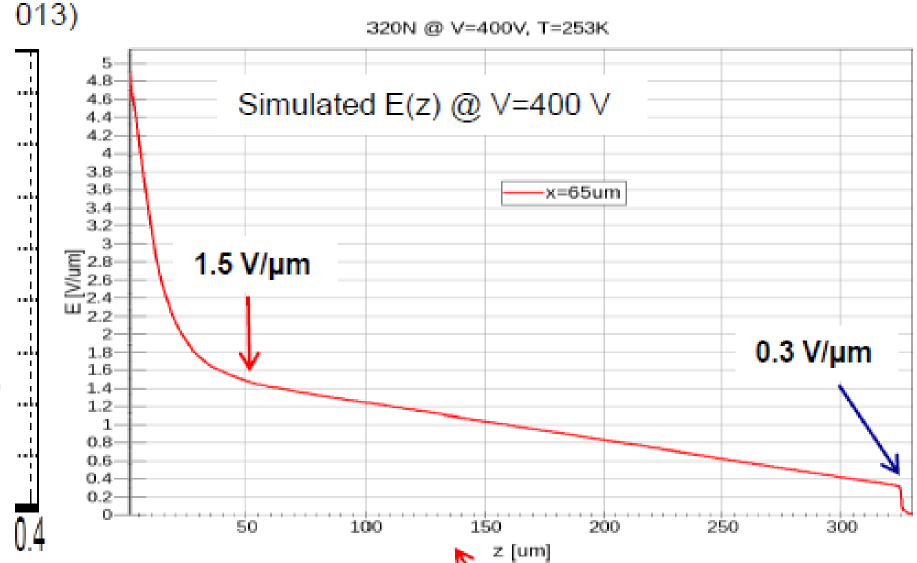


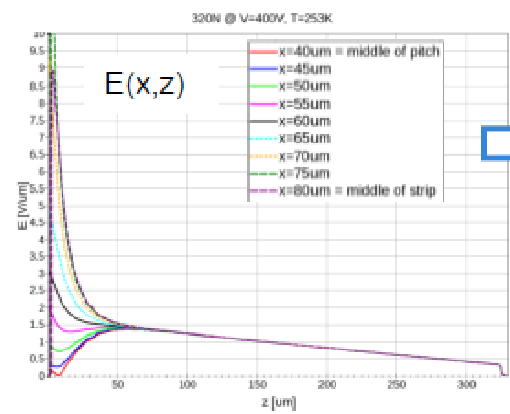


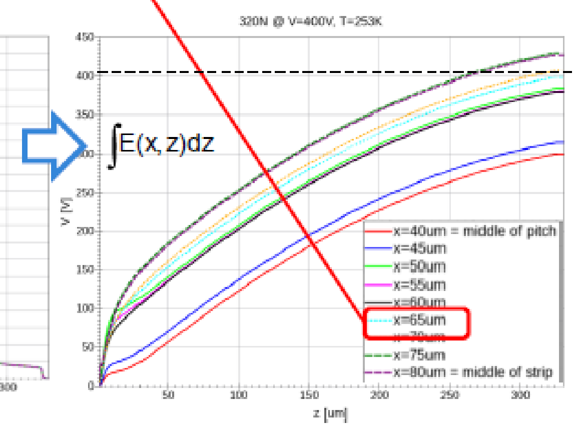


detector E(z)









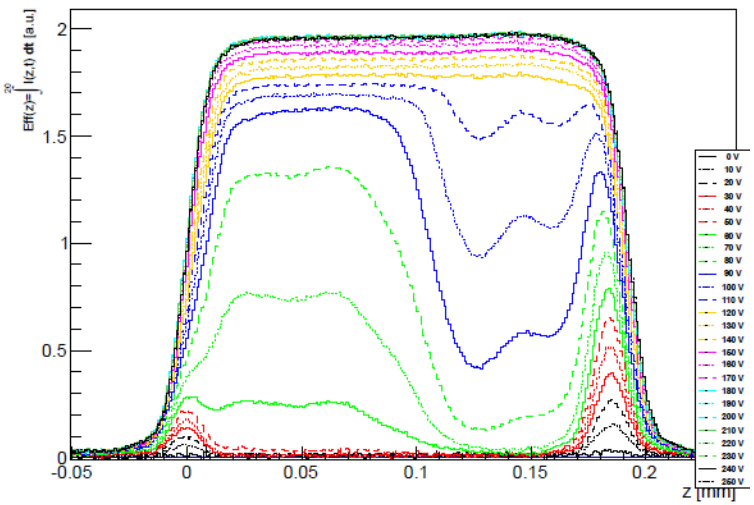
- ❑ E(z) is calculated from fits with linear approx.
- ❑ Calculated E(z) is compared with simulated E(z,x=65 μm) since it reproduces the applied voltage most accurately
- ❑ Simulation matches the calculated value at z = 50 μm, but has a steeper slope

Calculating vdrift normalization   Method #1: Ne,h from Q(z)

vdrift known from edge-TCT up to a normalization constant.

- Ne,h pairs can be extracted from Q(z), at V>depletion: Q(z)~Ae_0N

$$Q(z)=Ae_0N(z)\underbrace{\int_0^{tint}\frac{(v_e(t)+v_h(t))}{d}dt}_{\substack{=1\ \text{depleted}\\ <1\ \text{non-depleted, and function of (z,V)}}} \Rightarrow \quad Q(z)=Ae_0N(z)$$



- Take average of N(z): $\overline{N}=\frac{1}{N_d}\sum_0^d N(z_i)$

- Calculate "normalized averaged" drift velocity:
  - … normalized to $\overline{N}$
  - … averaged for 400 ps

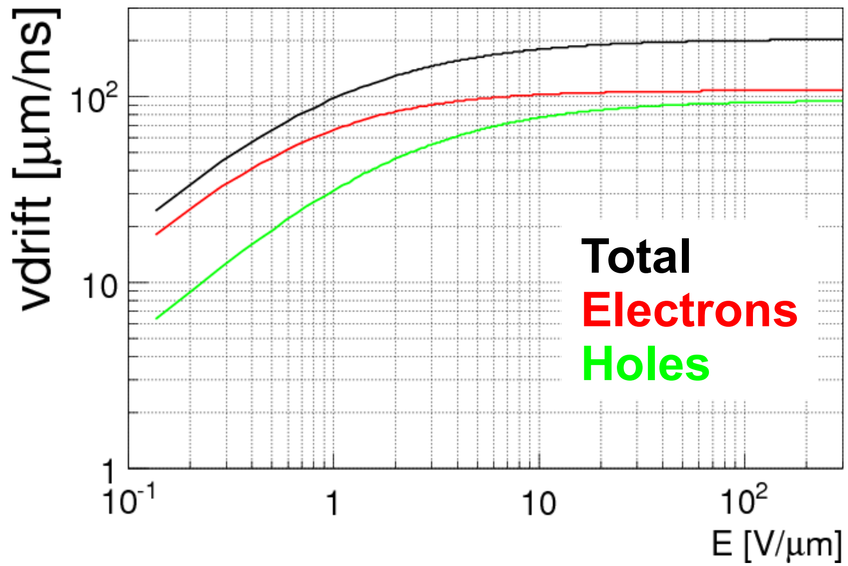
$$v_{drift}(z_i)=\underbrace{\frac{d}{Ae_0\overline{N}}}_{\text{Normalized}}\underbrace{\frac{1}{N_{400}}\sum_{j=0}^{400\,ps} I(t_j,z_i)}_{\text{Averaged}}$$

Equivalent to drift velocity due to 1 pair e-h

Fit of v_{drift} with border effects

- We minimize a χ^2 function that depends on polynomial coefficients of the E-field

$$\chi^2 = \sum_0^d \left[k \times v_{drift,meas} - \left(\frac{\mu_{0,e} E}{\left(1 + \left(\frac{\mu_{0,e} E}{v_{sat,e}}\right)^{\beta_e}\right)^{\frac{1}{\beta_e}}} + \frac{\mu_{0,h} E}{\left(1 + \left(\frac{\mu_{0,h} E}{v_{sat,h}}\right)^{\beta_h}\right)^{\frac{1}{\beta_h}}} \right) \right]^2$$

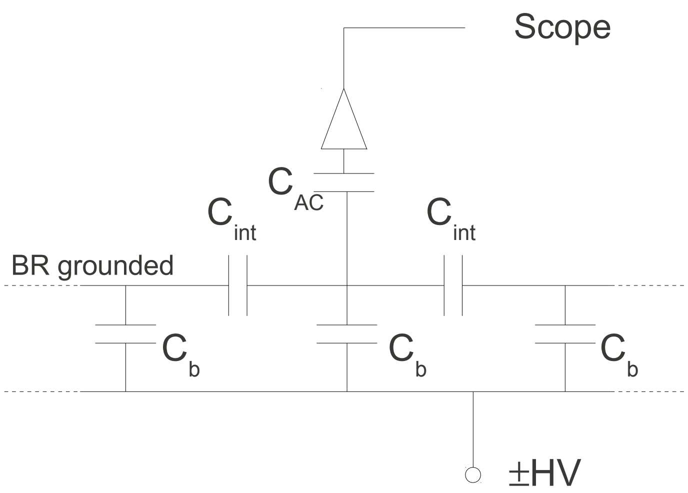


- Laser beam has a width of ~ 8 μm. At the sensor boundaries, the beam is not fully inside the detector and the measured drift velocity falls to zero softly (no sharp edges)

$$v_{drift}(c) = \int_{c-\sigma}^{c+\sigma} v_{drift}(z)\, G(z-c)\, dz$$

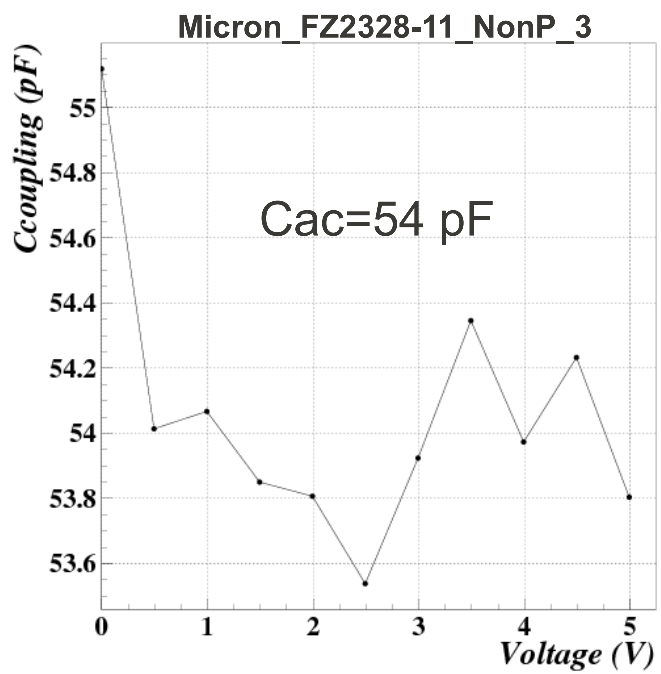
Question: How much capacitance is seen by the amplifier in edge-TCT?

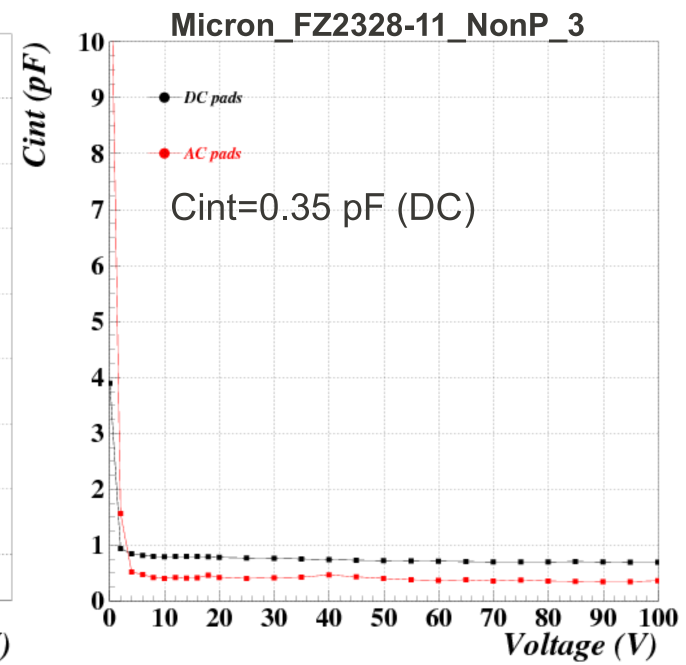
edge-TCT: 5th strip connected to amplifier, Bias Ring is grounded, backplane biased



$$C_{strip} = C_b + \frac{2 \cdot C_b C_{int}}{C_b + C_{int}}$$

$$C_{tot} = \frac{C_{AC} C_{strip}}{C_{AC} + C_{strip}}$$



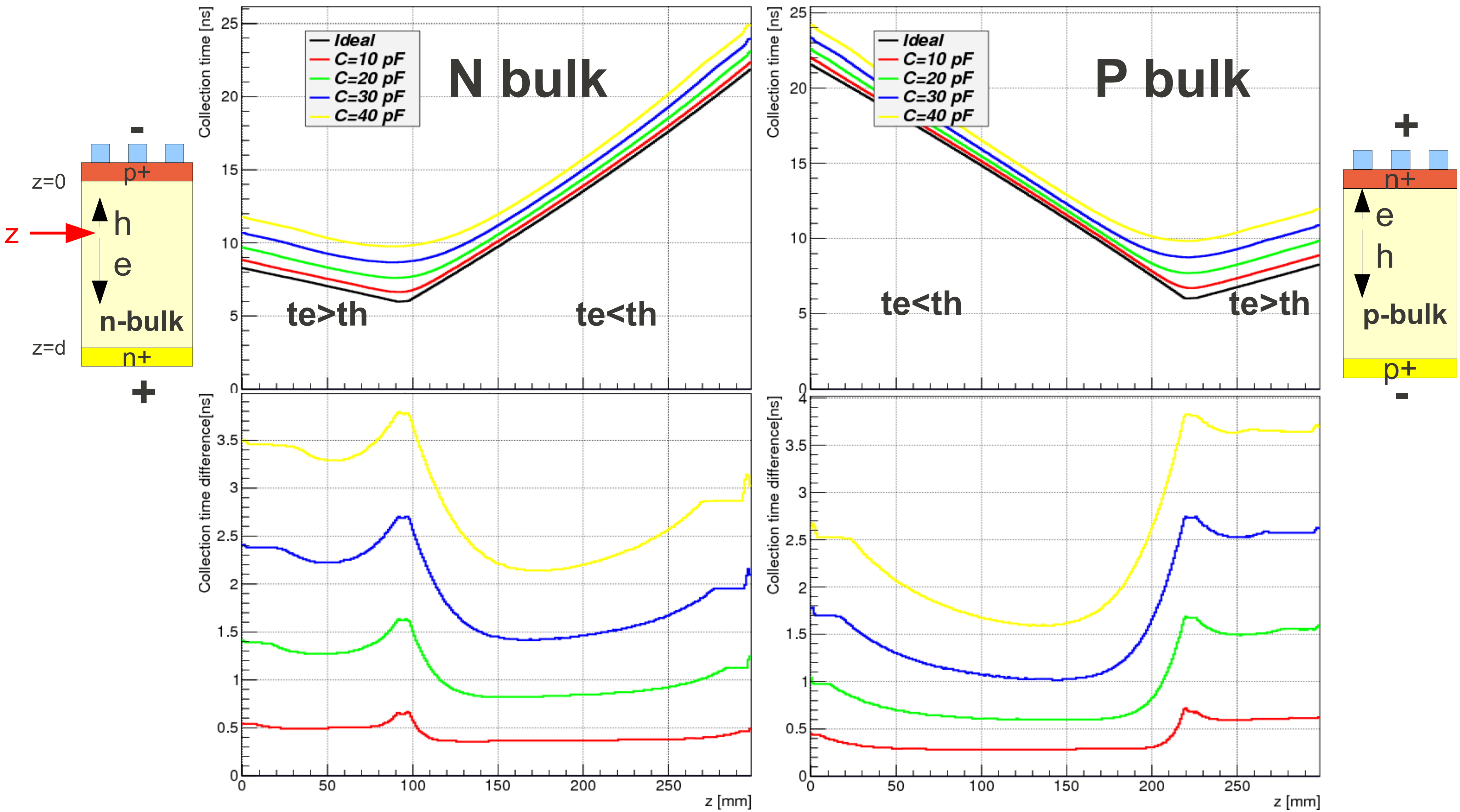


Micron: **Ctot=0.62 pF** Cb=0.3 ; Cint=0.35 ; Cac=54 pF
VTT: **Ctot=0.48 pF** Cb=0.18 ; Cint=1.04 ; Cac=32 pF
Badd: **Ctot=2.254 pF**

Conclusion: RC smearing should not be important for depleted sensors

Question: how much RC degrades the timing information?

Simulated effect of RC low pass filter



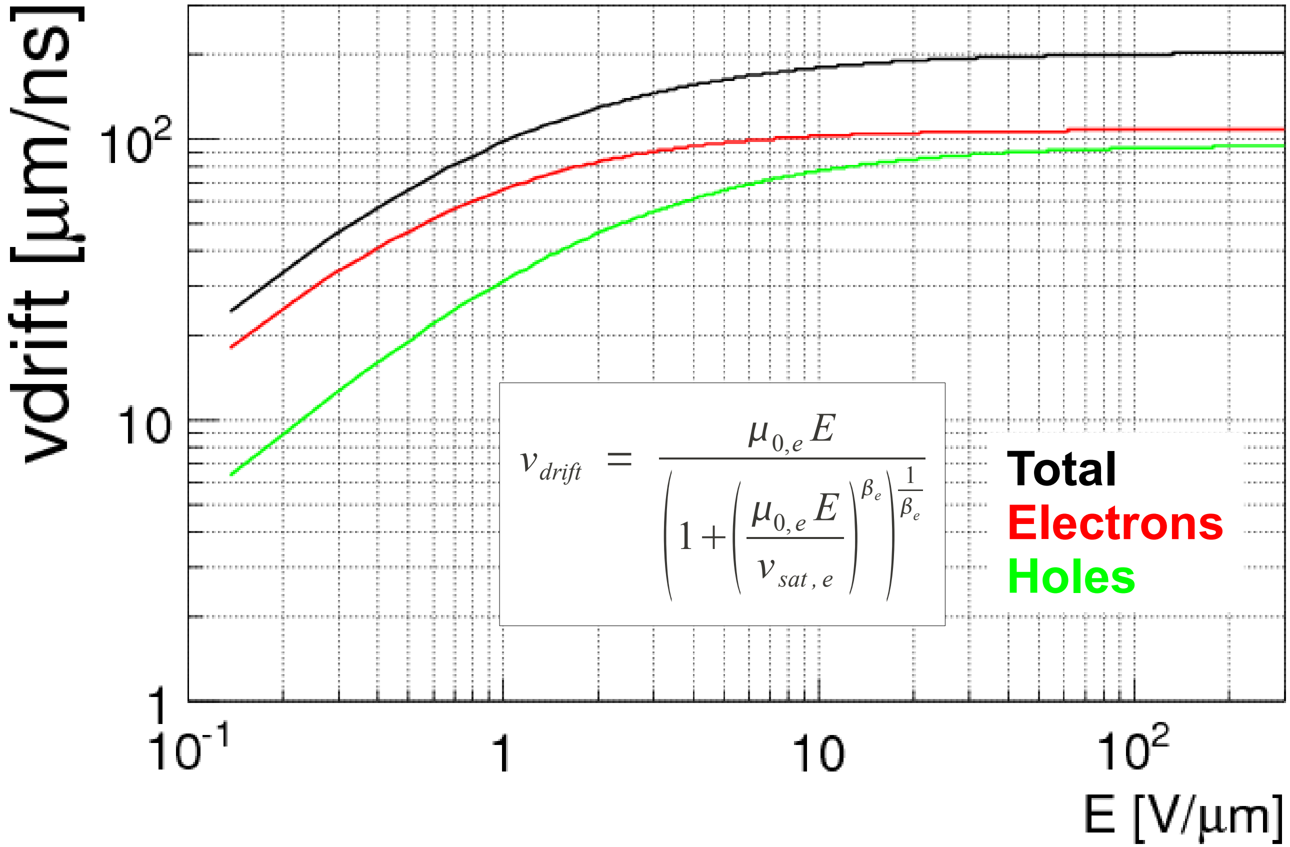
- Simulation using overdepleted diode, no diffusion considered
- **Below C=10 pF**, the contribution of RC to the collection time is <u>below the experimental error</u>.
- Higher spread with electrons.

Correlations in vdrift fits

If we use a polynomial for the electric field, then we cannot extract the vdrift normalization using only the Vbias equation, since the parameters would be all correlated

$$\left(V_{bias} - \int_0^d E(z)\,dz\right)^2 = \left(Vbias - k\int_0^d (p_0 + p_1 z + p_2 z^2)\,dz\right)^2$$

k is 100 % correlated to p0,p1,p2,...


vdrift [µm/ns]
10^2
10
1
10^{-1}
1
10
10^2
E [V/µm]
$v_{drift} = \frac{\mu_{0,e} E}{\left(1+\left(\frac{\mu_{0,e} E}{v_{sat,e}}\right)^{\beta_e}\right)^{\frac{1}{\beta_e}}}$
Total
Electrons
Holes