Sapphire CCE with Alpha particles

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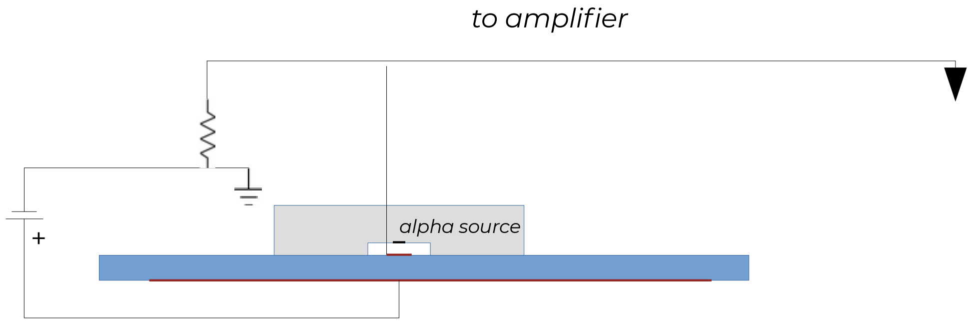
Setup and CCE measurement

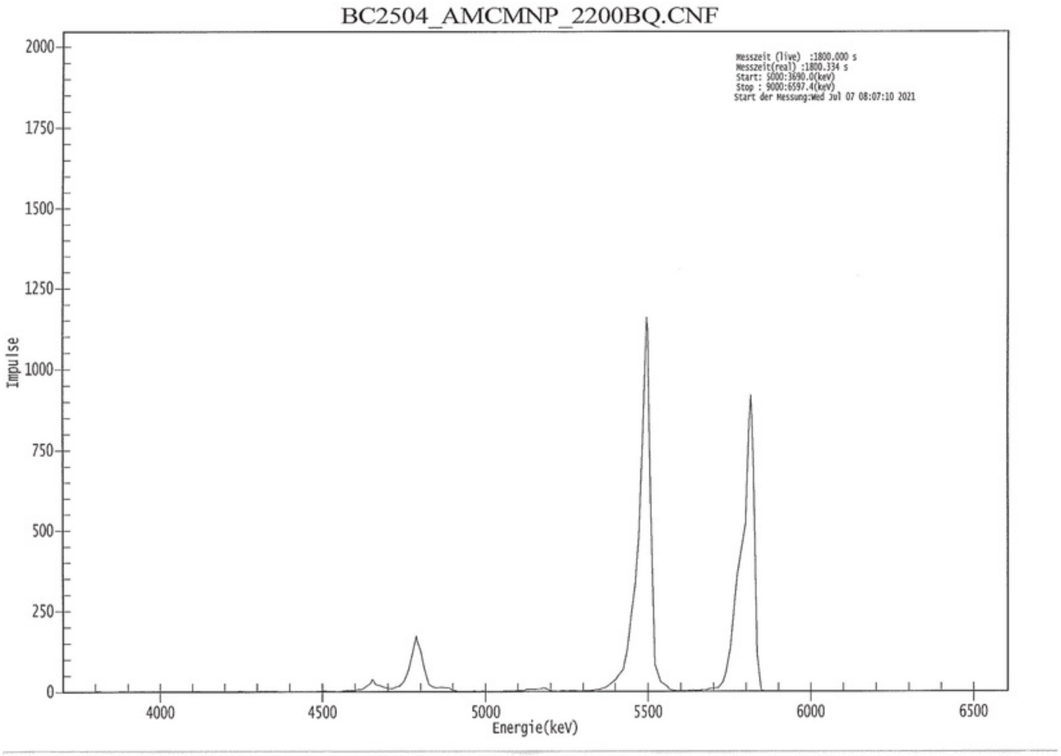


- Sapphire
  - 110 um (Wuppertal)
  - 150 um (Univ. Wafer)
- low noise HV power supply
  - HV up to 1200 V
- new home-made charge amplifier
  - RMS noise ~ 31 mV ~ 0.13 fC (800 e-)
- 6.5 mm nominal air gap from source to sapphire
  - 7 mm used for calculations to keep into account also the ~ 100 nm of Ti-Ag deposition

- *CCE* is obtained by measuring the collected charge and estimating the free charge originated in the sapphire by ionization:
  - $CCE = Q_s / Q_i$
- $Q_i = E_\alpha / 27$ eV $\times q_e =$ 4.94 MeV / 27 eV $\times$ 1.6 e^{-19} C = 29.3 fC
  - we only consider the electrons contributions to the signal, due to much lower ions mobility
- $Q_s = V_{ADC} / G_a = V_{ADC}$ / 245 mV/fC
- most important contribution to CCE systematic error comes from estimate of E_α and, especially G_a

Alpha source

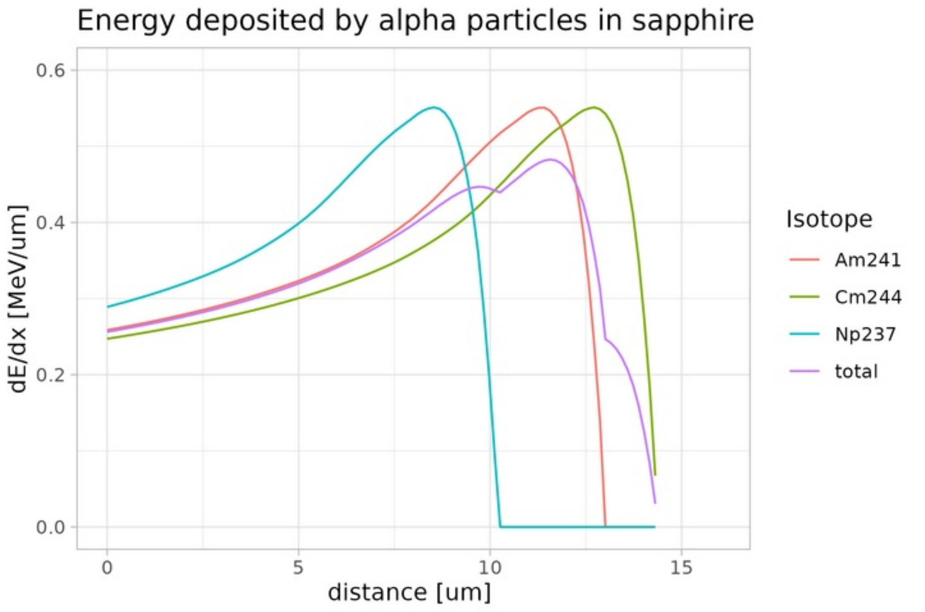
- ^{241}Am (1000 Bq)
  - 5.486 MeV (85%)
  - 5.443 MeV (13%)
  - 5.388 MeV (2%)
- ^{244}Cm (1000 Bq)
  - 5.765 MeV (23%)
  - 5.806 MeV (77%)
- ^{237}Np (200 Bq)
  - 4766 MeV (9%)
  - 4771 MeV (23%)
  - 4788 MeV (48%)
- Tolerance on activity: +/- 30%
- Active diameter: 7 mm



Energy realeased in Sapphire

- from the range tables one can compute the energy loss in air and in sapphire

Ek	Ek_in	Range	Isotope	activity
5.48	4.85	12.96	Am241	1,000.00
5.80	5.20	14.32	Cm244	1,000.00
4.78	4.08	10.15	Np237	200.00



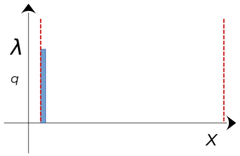
The model

One obtains In the two simplest cases of ionization charge

- produced at $x = 0$, i.e.:

$$Q_i = q_i(0) \quad \rightarrow \quad Q_c(x_0) = Q_i e^{-\frac{x_0}{kD}}$$

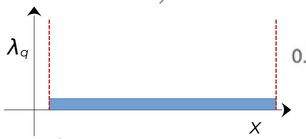
$$CCE = k(1 - e^{-1/k})$$



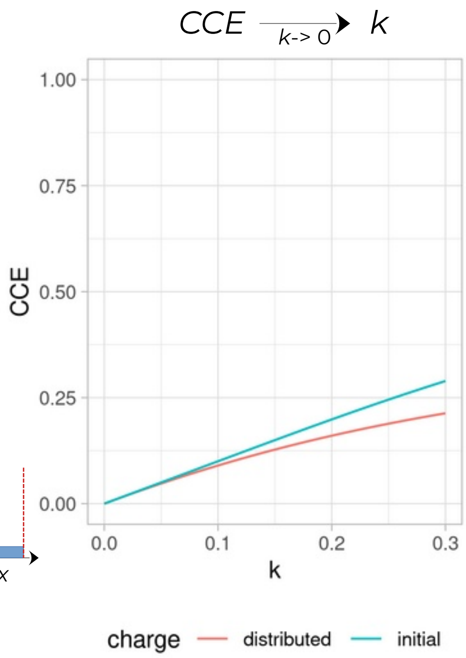
- uniformly distributed over D, i.e.:

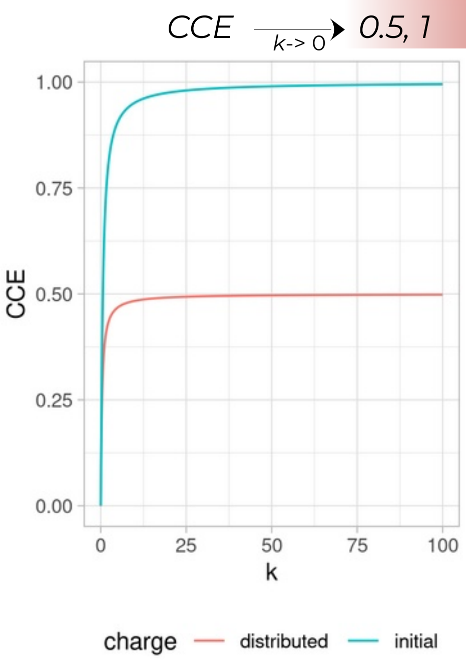
$$\lambda_{q_i}(x) = Q_i/D \quad \rightarrow \quad Q_c(x_0) = Q_i k(1 - e^{-x_0/kD}))$$

$$CCE = k(1 - k(1 - e^{-1/k})$$



Since $k = \frac{v_d \tau}{D} = \frac{\mu E \tau}{D} = \frac{\mu \tau V}{D^2}$, where E and V are the bias electric field and related potential, one can derive $\mu\tau$ by measuring how the CCE increases with V.





Results: mu x tau

- Points do not align on a straight line from the origin as foreseen by the Hecht equation

$\mu\tau = 0.609\ \mu\text{m}^2/\text{V}$ for 110 μm sapphire

$\mu\tau = 0.646\ \mu\text{m}^2/\text{V}$ for 150 μm sapphire

$\mu\tau = 0.393\ \mu\text{m}^2/\text{V}$ for 150 μm sapphire reversed voltage

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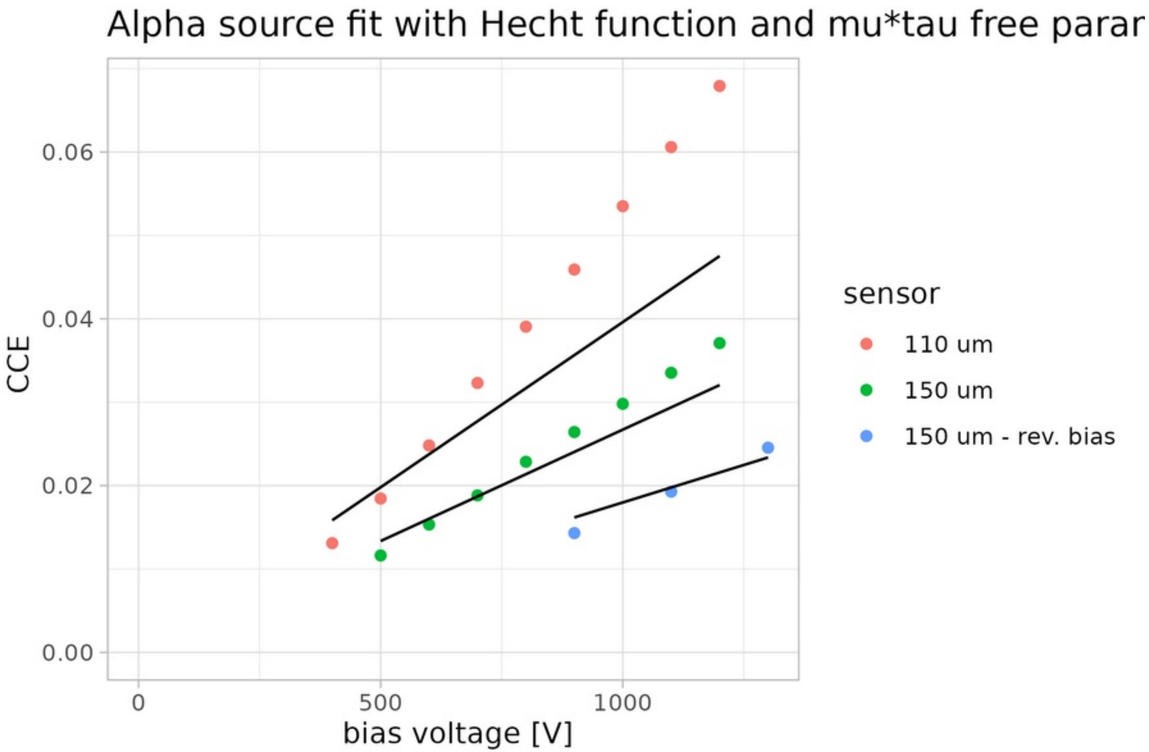
$$k = \mu\tau V / d^2 \sim 0.05 \quad @V = 1000\ \text{V}$$



Results: mu x tau

- Fitting for:

$$CCE = CCE_0 + k\left(1 - \exp\left(-1/k\right)\right)$$

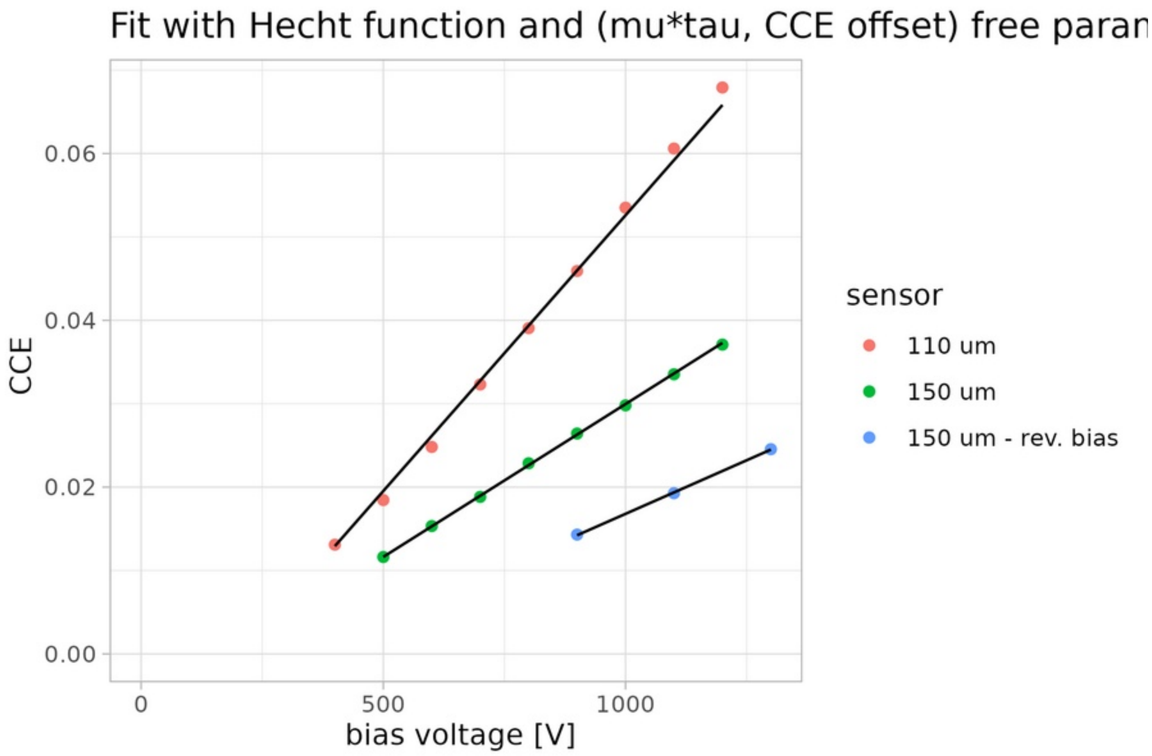
- one obtains:

$\mu\tau = 0.825\ \mu\mathrm{m}^2/\mathrm{V}$
$CCE_0 = -1.57\,\%$
for 110 um sapphire

$\mu\tau = 0.804\ \mu\mathrm{m}^2/\mathrm{V}$
$CCE_0 = -0.64\,\%$
for 150 um sapphire

$\mu\tau = 0.565\ \mu\mathrm{m}^2/\mathrm{V}$
$CCE_0 = -0.86\,\%$
for 150 um sapphire - reversed bias

with $\mu \sim 600\ \mathrm{cm}^2/\mathrm{Vs}$:
$\tau \sim 13\,\mathrm{ps}$



The model for two regions

The fact that ionizatin charge is released only in one region of the sensor can induce the initial non-linear effect shown in the measurements. If we have two regions with thicknesses D_1 and D_2 and possibly different values of $k_{1,2} = (\mu\tau)_{1,2} V/D^2_{1,2}$, then, using x_1 and x_2 as local coordinates:

$$CCE = \frac{1}{DQ_i}\left[\int_0^{D_1} Q_{c1}(x_1)dx_1 + \int_0^{D_2} Q_{c2}(x_2)dx_2\right]$$

and, if we assume that ioinization charge is uniformly produced only in the first region:

$$CCE = \frac{1}{DQ_i}\left[D_1 Q_i k_1(1 - k_1(1 - e^{-1/k_1})) + D_2 Q_{c2}(0) k_2(1 - e^{-1/k_2})\right]$$

But since $Q_{c2}(0) = Q_{c1}(D_1) = Q_i k_1(1 - e^{-1/k1})$:

$$CCE = \frac{1}{DQ_1}\left(D_1 Q_i k_1(1 - k_1(1 - e^{-1/k_1})) + Q_i k_1(1 - e^{-1/k1}) D_2 k_2(1 - e^{-1/k_2})\right)$$

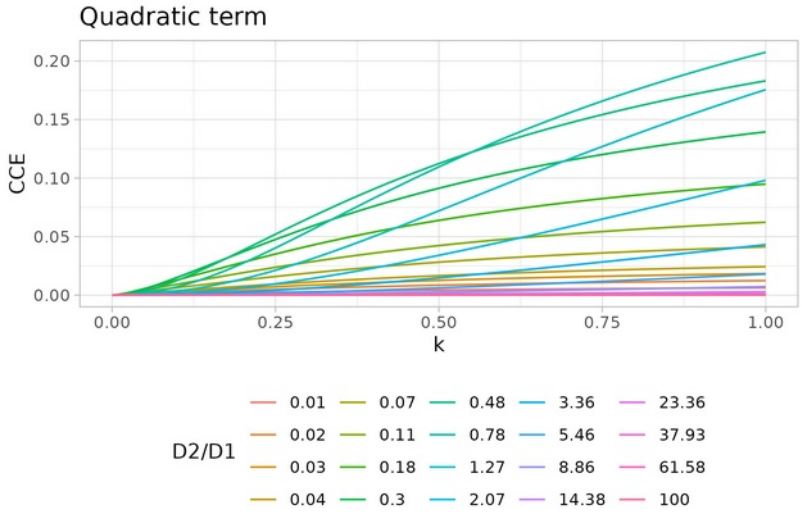
$$= \frac{D_1}{D} k_1(1 - k_1(1 - e^{-1/k_1})) + \frac{D_2}{D} k_1(1 - e^{-1/k1}) k_2(1 - e^{-1/k_2})$$

The model for two regions

If $\mu\tau$ is the same in the two regions and we assume $r_{2/1} = D_2/D_1$ and therefore $k_2/k_1 = D_1^2/D_2^2 = 1/r_{2/1}^2$

$$CCE = \frac{1}{1+r_{2/1}}\left[k_1(1-k_1(1-e^{-1/k_1})) + r_{2/1}\left(k_1(1-e^{-1/k_1})\right)\left(\frac{k_1}{r_{2/1}^2}(1-e^{-r_{2/1}^2/k_1})\right)\right]$$

The second term is quadratic and can induce the non-linearity as shown in the plot where the curves represents different values of $R_{2/1}$



The model (VI)

However, when summing the two terms, the effect disappears as shown in the plot on the l.h.s..

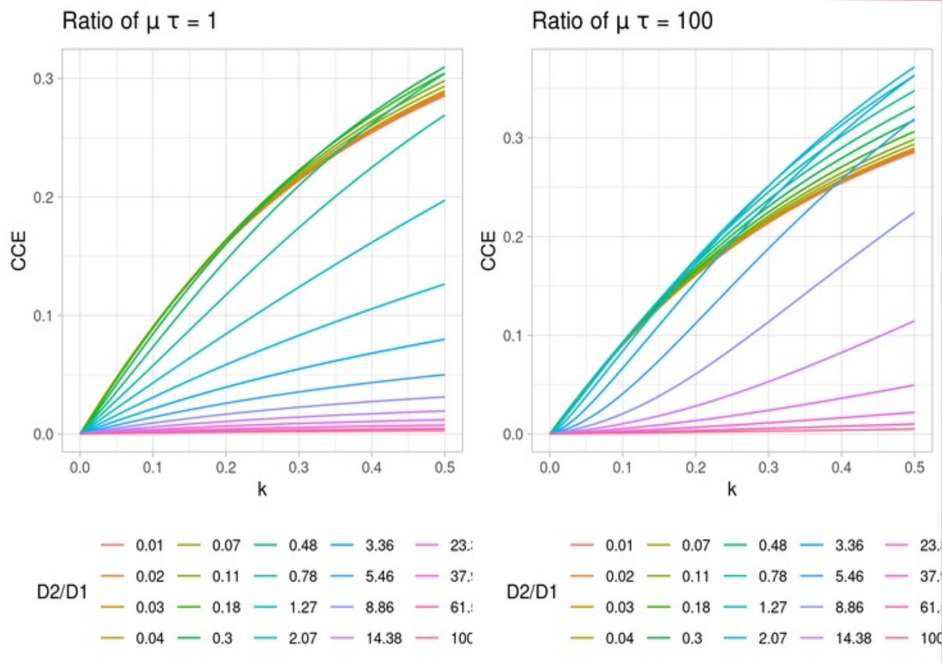
To recover it, the fist term has to be dumped, something that can happen if:

$$f_{\mu\tau} = \frac{(\mu\tau)_2}{(\mu\tau)_1} \gg 1$$

as it is the case when the lifeteime or the effective field are reduced in the region where there is a high ionization density.

The plot on the r.h.s is obtained with $f_{\mu\tau} = 100$

The non-linearity is evident for $D_2/D_1 \sim 5-20$, which indeed corresponds to what happens with the Alpha particle ionization in a 100-150 μm thick sapphire sensor



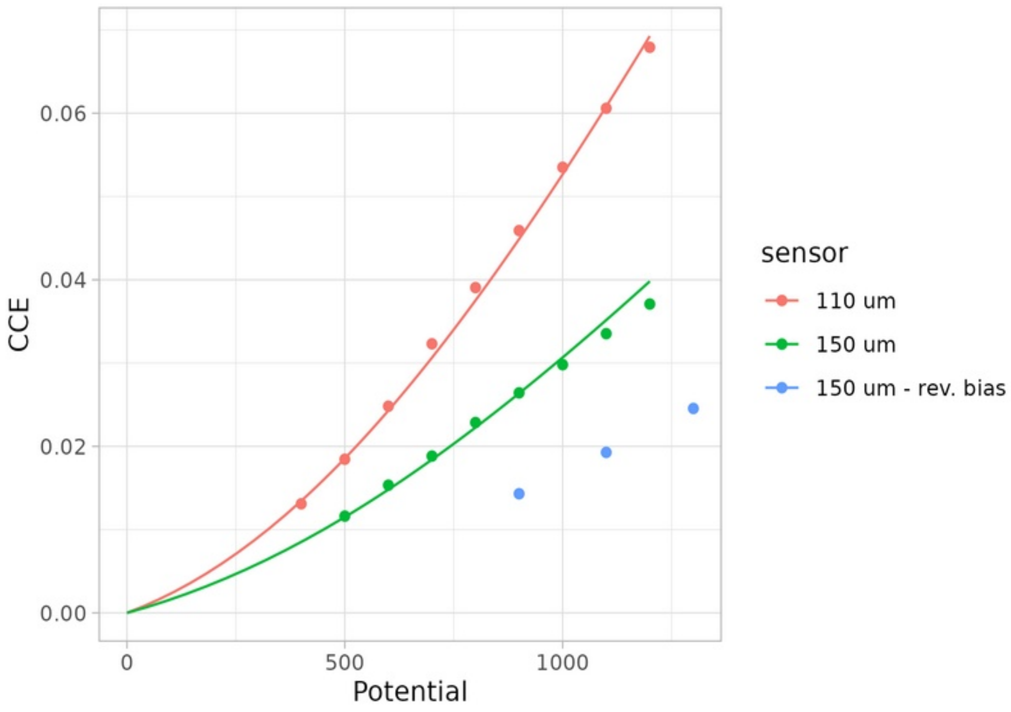
Comparison with the data

- a fit shows that the preferred values are:
  - $D_1 \sim 6$ µm
  - $\mu\tau_1/\mu\tau_2 \sim 10^{-2}$
- for this combination, fitting only for $\mu\tau_2$ gives for both sensor:
  - $\mu\tau_2 = 1.35$ µm²/V for both sensors
- this simple model shows that to obtain a shape consistent with the data, there should be a strong reduction of the mean free path

  $\lambda = \mu\tau_1 V/D_1$

  in the first region.

  This is what is expected as a result of the very high charge density produced by the Alpha particle (plasma effect)
- the thickness of the region is however not consistent with the average range of the Alpha particles in sapphire



Three regions model

- if one try to better reproduce the ionization profile with two regions of different charge density, then the fit converges for a total thickness of ~ (6+4) = 10 μm
- in this case the fit produce:
  - $\mu\tau_2$ = 1.56 μm²/V for both sensors
- in this case to make further progress on would need to model the dependence of the mean free path reduction as a function of the charge density
- in conclusion, using a simple model with three regions with diverse ionization charge density and the free mean path reproduce a shape of the CCE dependency that is in agreement with the data as long as the reduction of the free mean path is of the order of 100.