Validating the MC template against Padova α-particles experiments with 110/150 um pads

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Overview

Experimental setup

Alfa particles (5MeV) emitted with 2168Hz rate.
Distance 6.5mm between source and DUT.
Measure time for each V_{bias} ‘30m

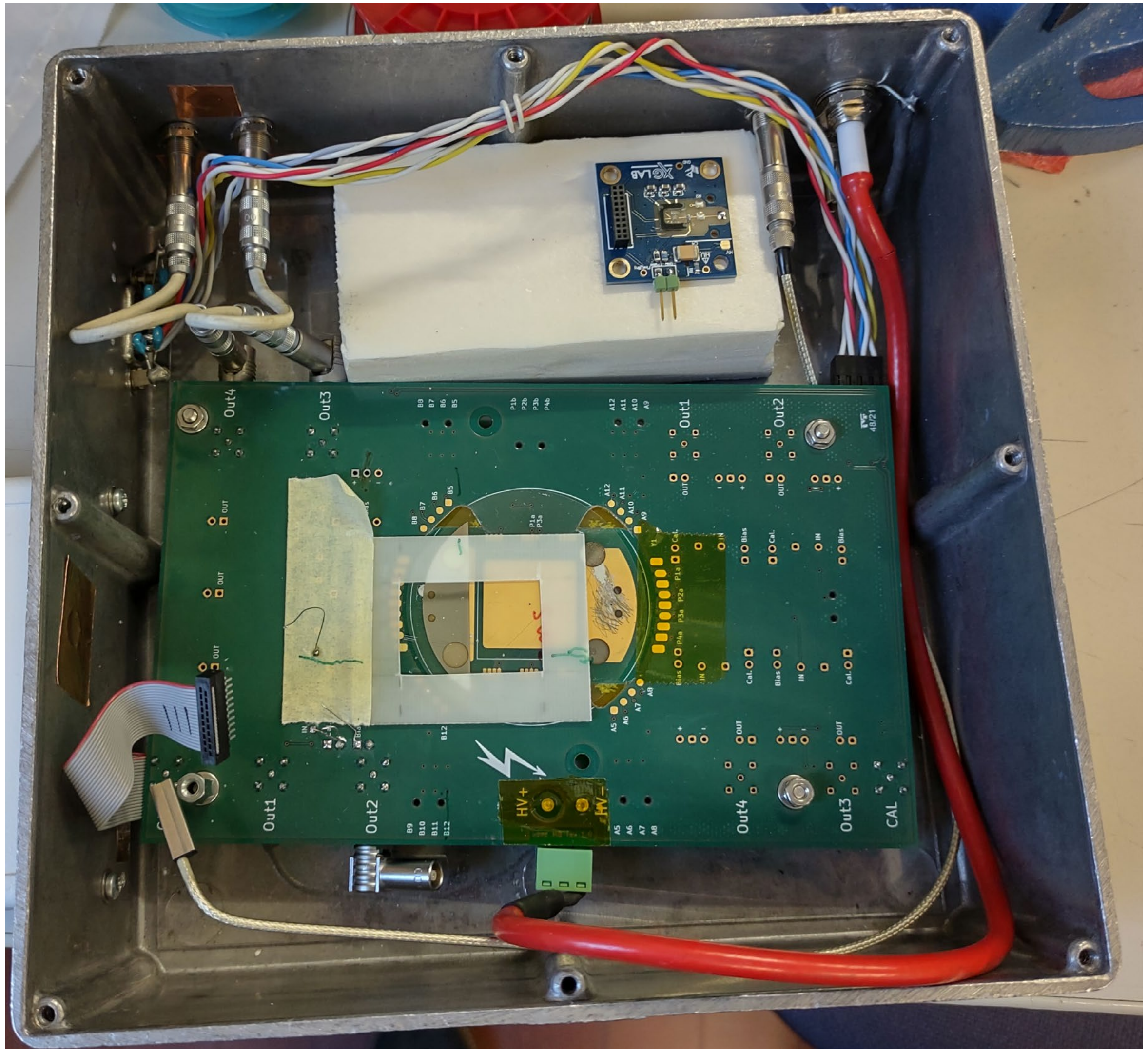
Objective

Reproduce the observed CCE(V)

Strategy

- Setup a Geant4 simulation to determine initial charge distribution

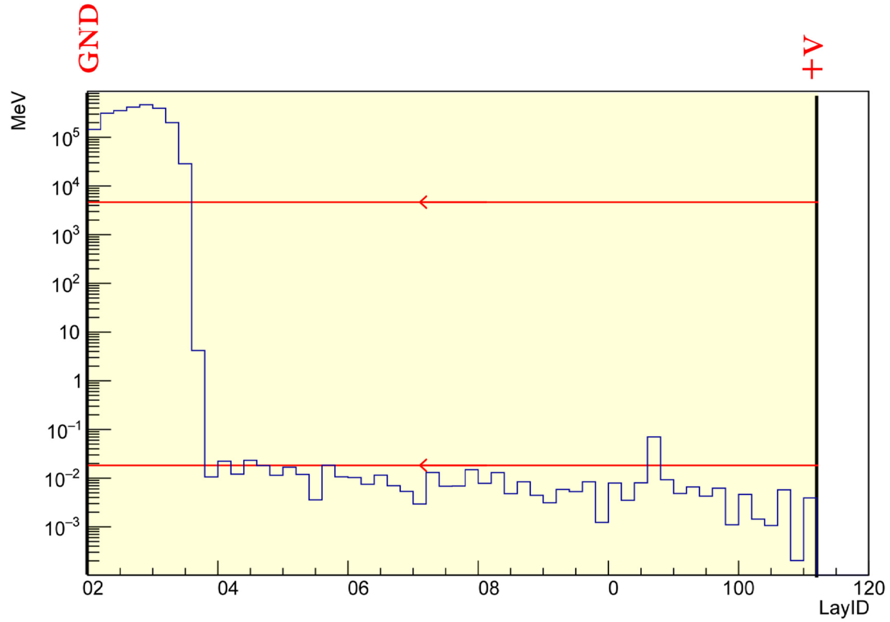
- Setup a set of Allpix2 simulations with:
  1. Ad-hoc charge transport model where charge carriers have constant uniform mobilities;
  2. Electric field assigned:
     a. Uniform E=V/d
     b. Two regions field
  3. (Mobility x lifetime) fixed from fit parameters
     a. DESY-II
     b. Padova’s



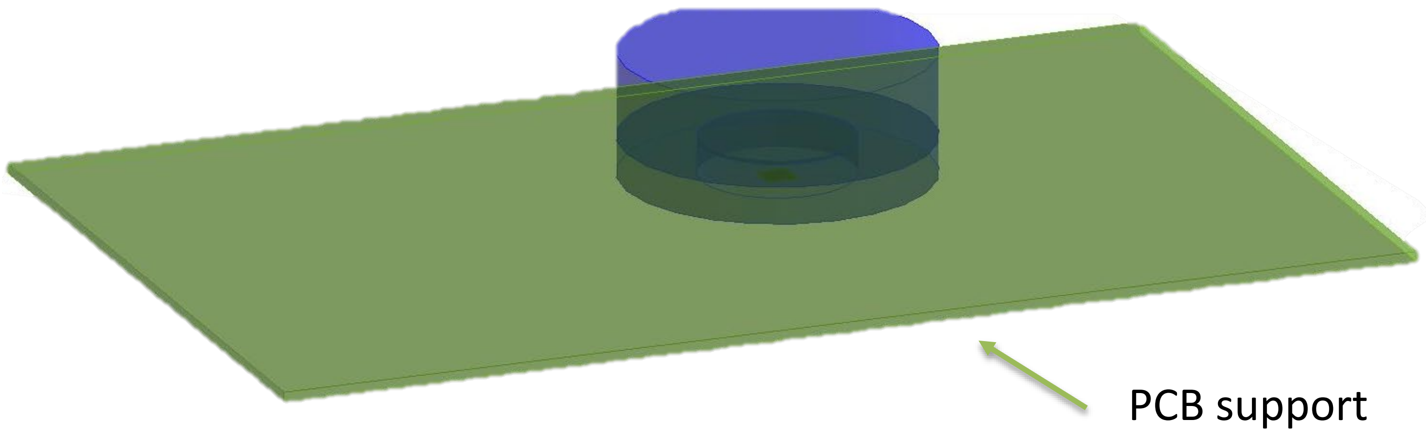
Geant4 simulation

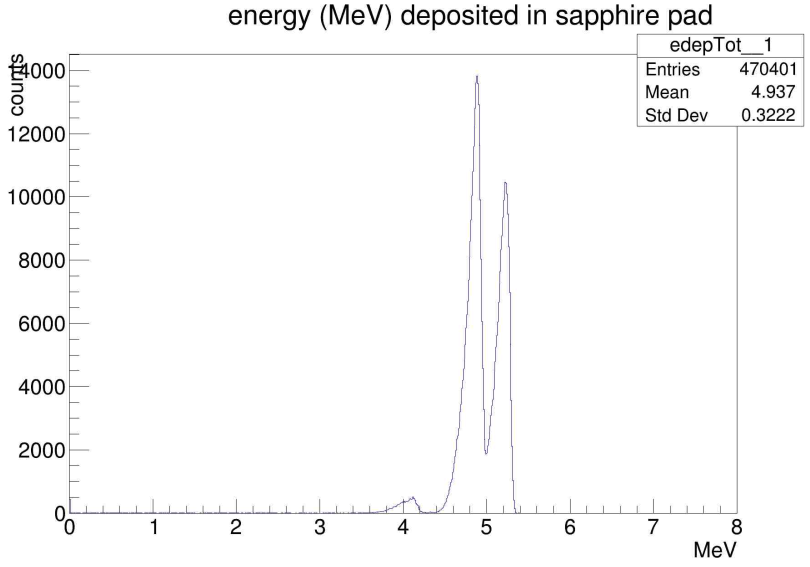
Observations from the Geant4 sim.

a. Alfa tracks entering DUT with 65Hz rate.
b. Alfa particles stop within the first 20um of sapphire. Each track generates 5MeV/27eV = 180k pairs
c. The integration time (<50us) is such that charge from a single track (T=16ms) is relevant to the signal*.



Geometry





Allpix² and experimental points

Allpix² simulation strategy

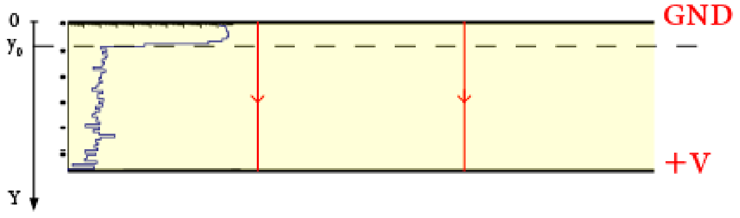
1. Set (μτ) product using fit values
2. Set electric field with constant value E=V/d
3. Run CCE vs. V and compare with datapoints

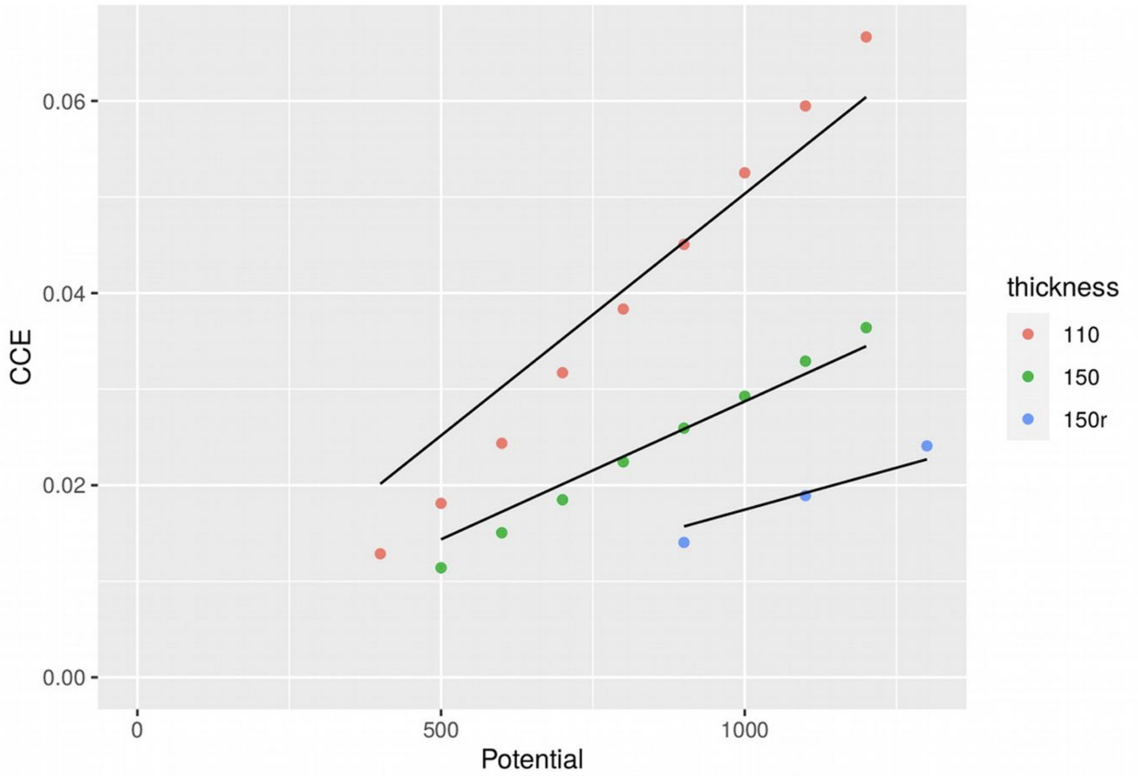
II. If no agreement is found, try with the electric field like

$$E(z) = \begin{cases} E_0 & 0 \leq y \leq y_0 \\ E_1 & y_0 < y \leq d \end{cases}$$

$$E0 \equiv f \cdot E_1 \qquad f \in [0, 1]$$

$$\int_0^d dy\, E(z) \;=\; -\int_0^{+V} dV \;=\; V$$

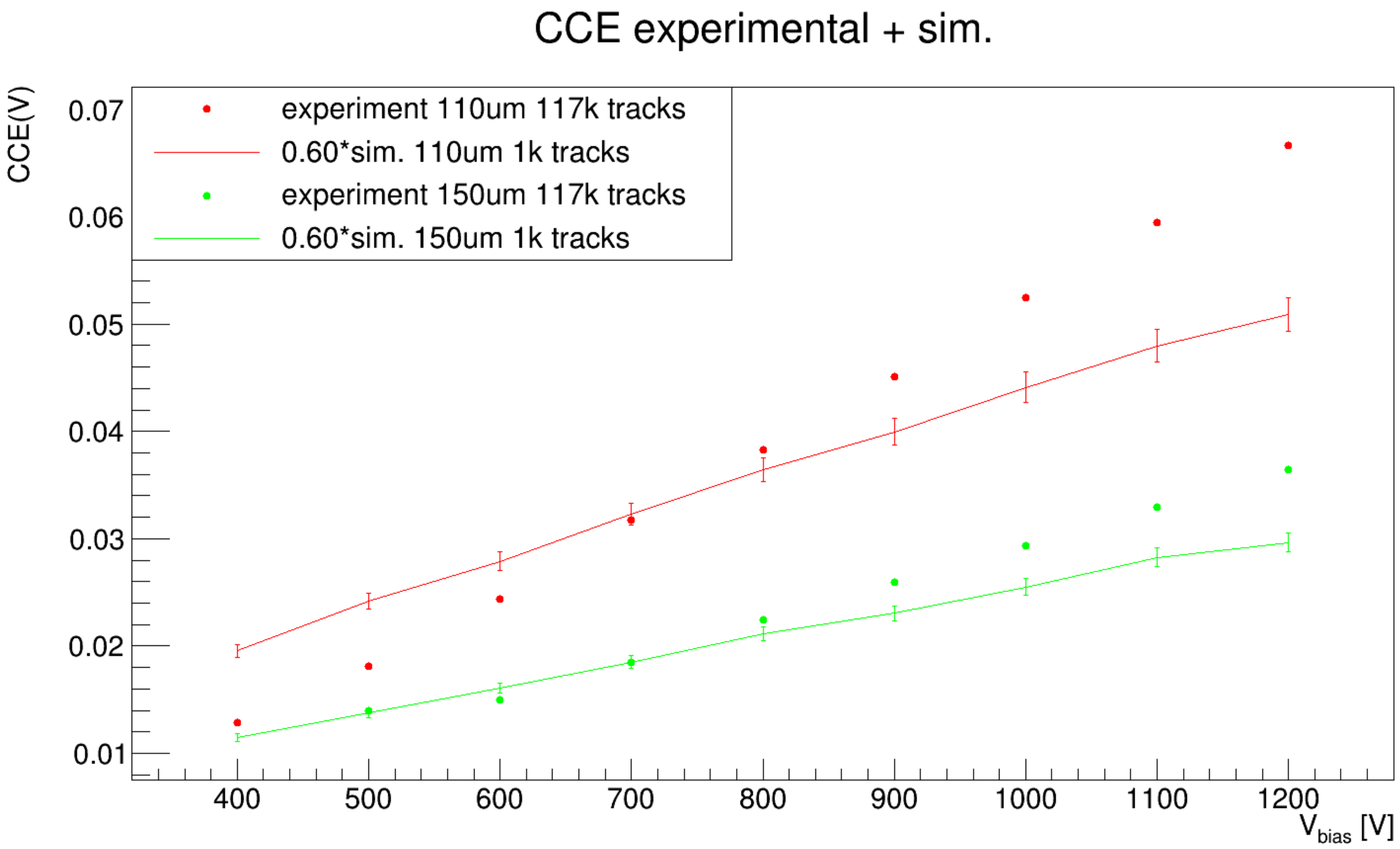




Experimental points do not align as foreseen by the Hecht equation, which holds under the hypotheses:

1. Planar detector
2. Transport properties and electric field uniform in the whole volume of the sensor
3. Free charge in stationary conditions is negligible and its generation, due to alpha absorption, is instantaneous
4. Diffusion and detrapping are negligible

Sapphire parameters from fit



110um/150um samples

- 100000 events (1h sim. Time) corresponding to 1050 tracks in the detector
- Parameters used:

$$\mu_e = 600\ \mathrm{cm}^2/\mathrm{V/s}$$
$$(\mu\tau)_e = 8.25 \cdot 10^{-9}\ \mathrm{cm}^2/\mathrm{V}$$
$$(\mu\tau)_h = 5.65 \cdot 10^{-9}\ \mathrm{cm}^2/\mathrm{V}$$

- Uniform electric field:

$$E(V) = \frac{V}{110}\ \mathrm{V/um}$$

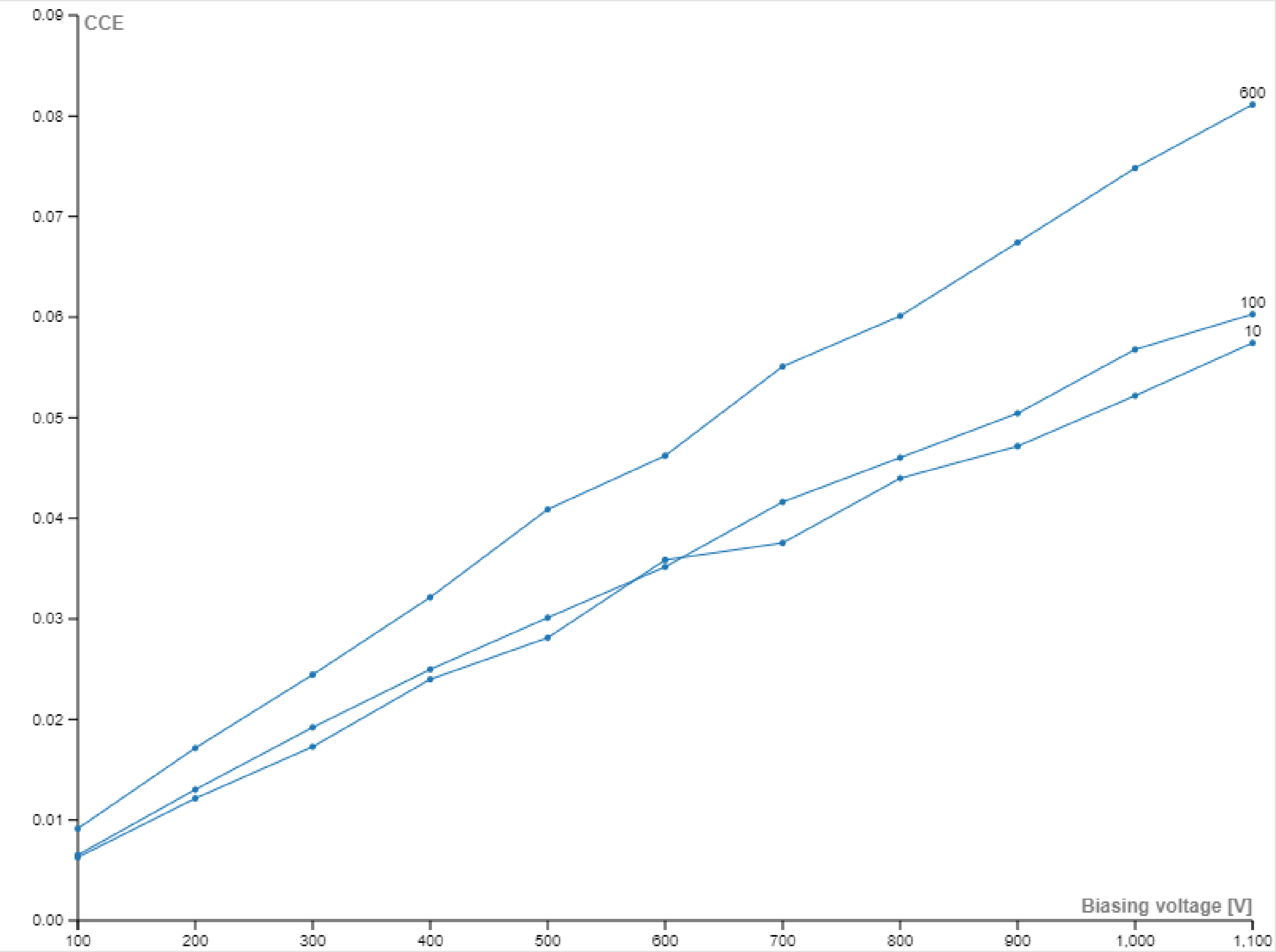
Comment

Simulated CCE(V) is not reproduced.

Possible causes

- Different parameters?
- E-field approximation inadequate?

Uniform field issue



Sim. settings

a. 110um sample

b. Uniform E-field

Open question

Simulations with 1k tracks and fixed ($\mu\tau$) product shows dependence of the CCE(V) from the mobility.

Why?

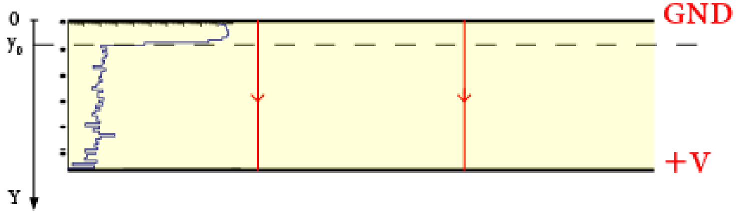
(this was not observed in DESY-II validation using MIPs.)

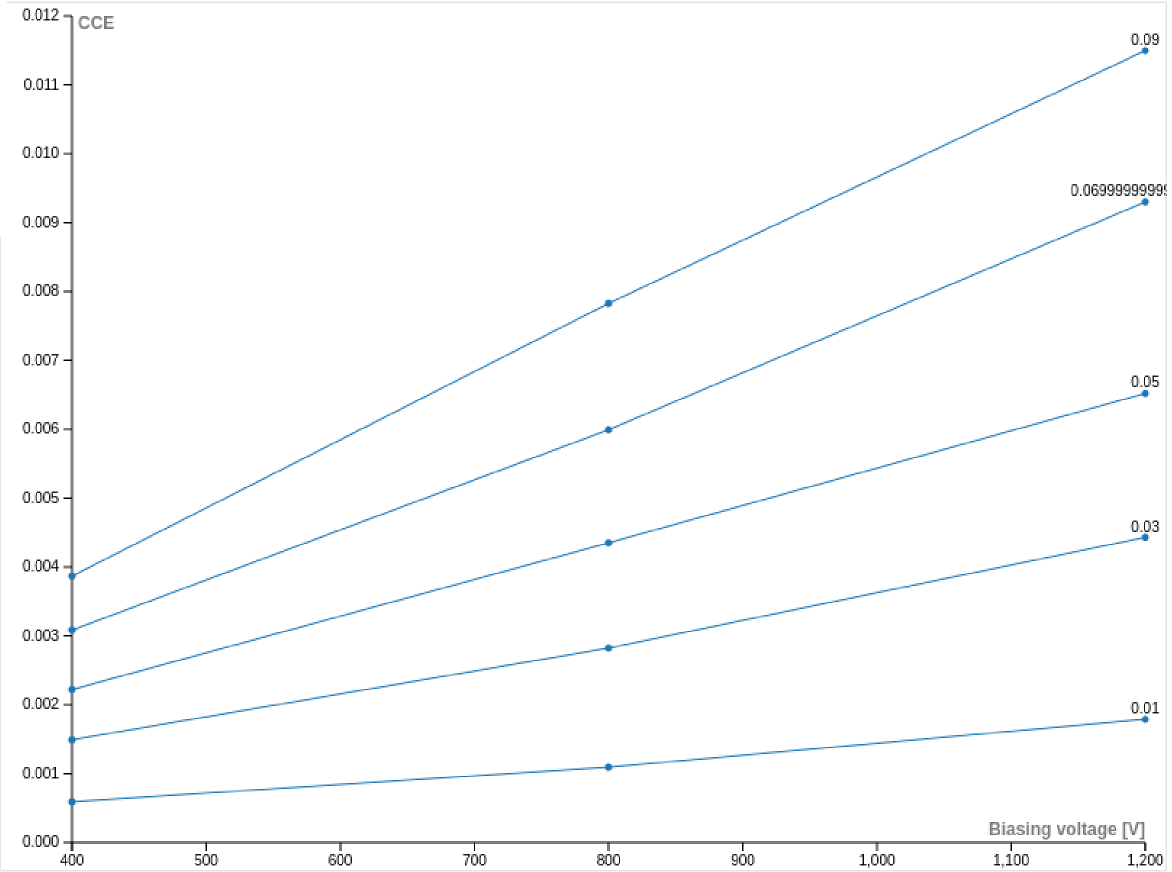
Attempt II. Using 2-regions electric field

$$E(z) = \begin{cases} E_0 & 0 \leq y \leq y_0 \\ E_1 & y_0 < y \leq d \end{cases}$$

$$E0 \equiv f \cdot E_1 \qquad f \in [0,\, 1]$$

$$\int_0^d dy\, E(z) \;=\; -\int_0^{+V} dV \;=\; V$$





The **f** fraction is a free parameter of the simulation:

- Scanned f values, with fixed (μτ) product, in the range [0.001, 1.0] the latter corresponding to uniform field.

Conclusions 1/2

Decreasing the field - as one may expect from a 'screening effect' of the external electric field in the region where alpha-sourced charge is accumulated- results in decreasing the slope of the CCE(V). Therefore, this model doesn't go in the right direction.
On the other hand, the opposite effect (f>1) may improve the agreement with datapoints.

Conclusions 2/2

If we use an uniform electric field (E=V/d) and the desy-ii \mu\tau products for electron/hole, the simulated charge is much bigger than the one measured.

Open questions

a. Polarisation effects and the internal field
b. Surface recombination
c. De-trapping

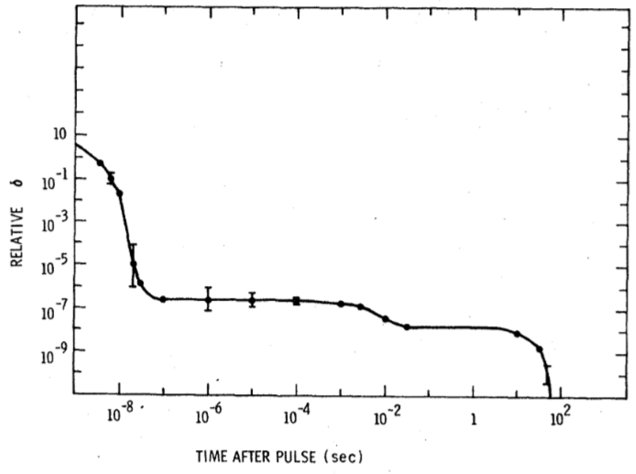


FIG. 1. Log–log plot of the relative conductivity vs time for a typical sapphire sample at 300 °K. The applied field and the number of excess carriers are kept low enough so that all conductivity decays depicted are due to first-order trapping kinetics. The excitation pulse is 3×10^{-9} sec wide. The error bars reflect the experimental error in taking the derivative of charge collection data in the given time ranges.

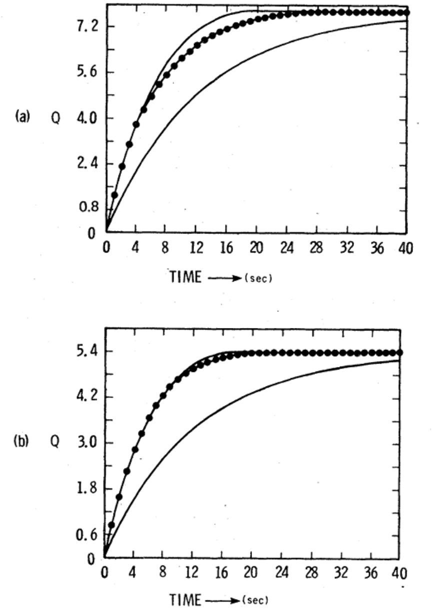
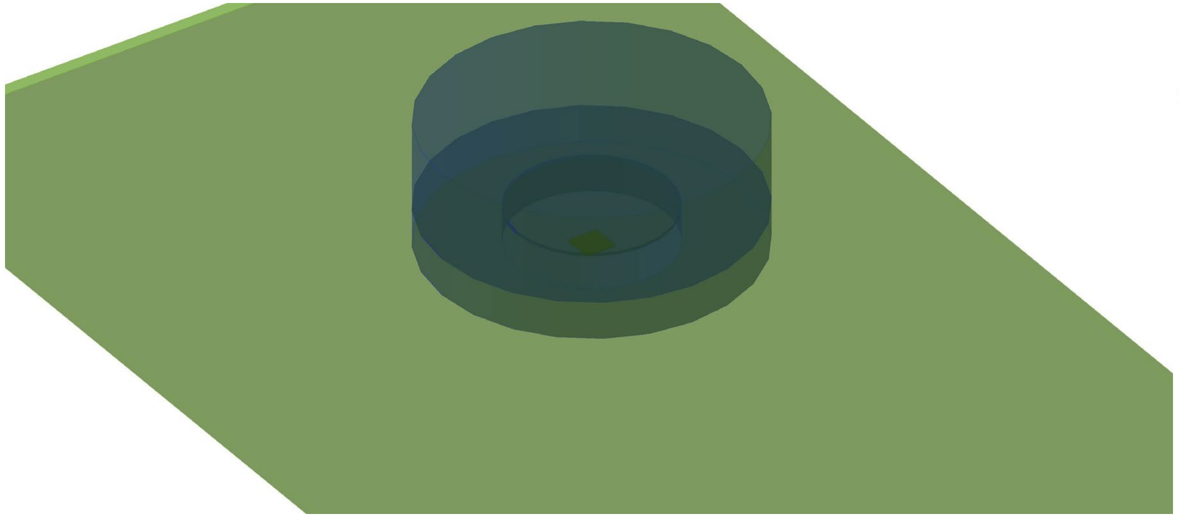
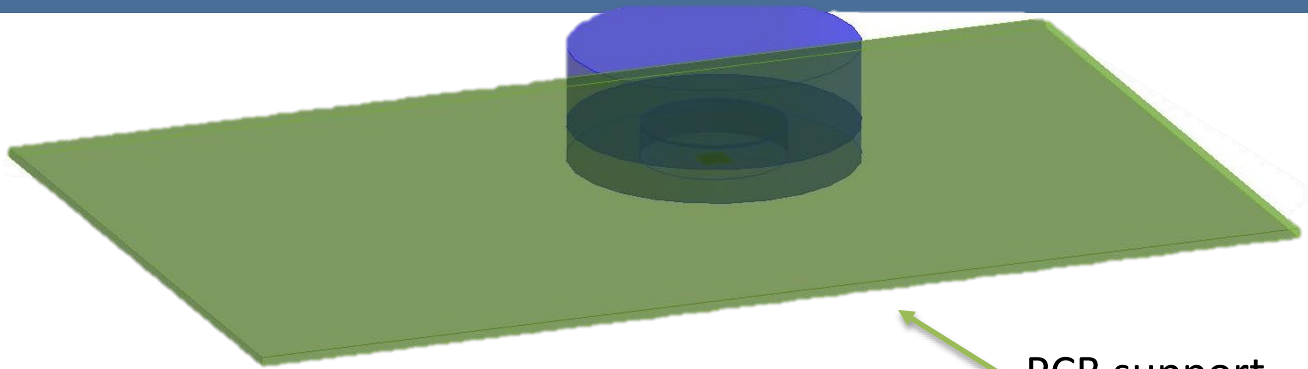


FIG. 3. Integrated photocurrent at 10^5 V/cm in the regime where sweepout of the carriers dominates the carrier lifetime. The curve designated by the circles is the data points. The lower curve is taken from data at much lower fields where the bulk lifetime of the carriers dominates the photocurrent. The upper solid line is a fit to the data employing the measured lifetime and the best-fit sweepout time. The experimental setup is described in the text, but this data show the special case where the concentration of electron–hole pairs was not uniform throughout the bulk of the sample, but was enhanced near one electrode by a layer of high-Z metal. Curve (a) was for a negative polarity at the high-density electrode, and curve (b) was for a positive polarity. Each curve was normalized to the same x-ray flux.

Backup

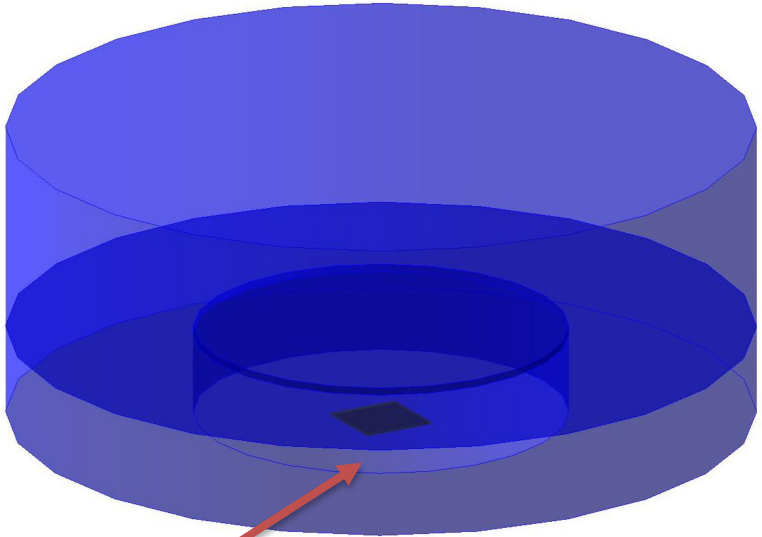
Geometry

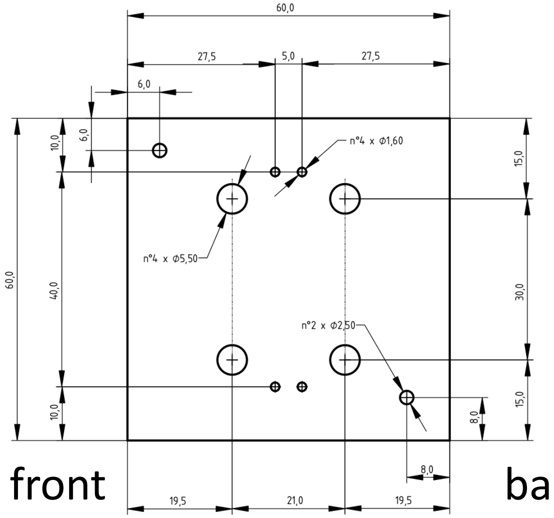




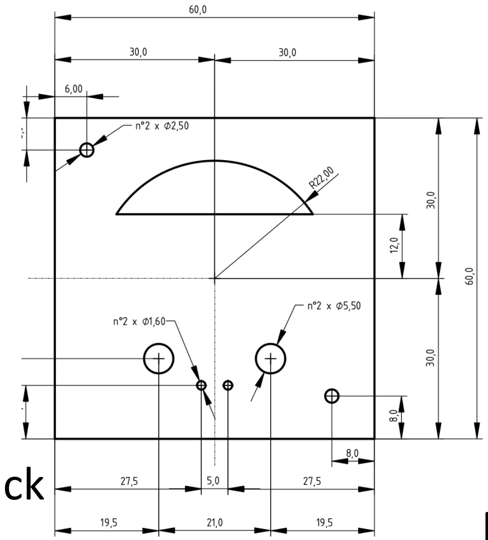
PCB support

Alpha source enclosure





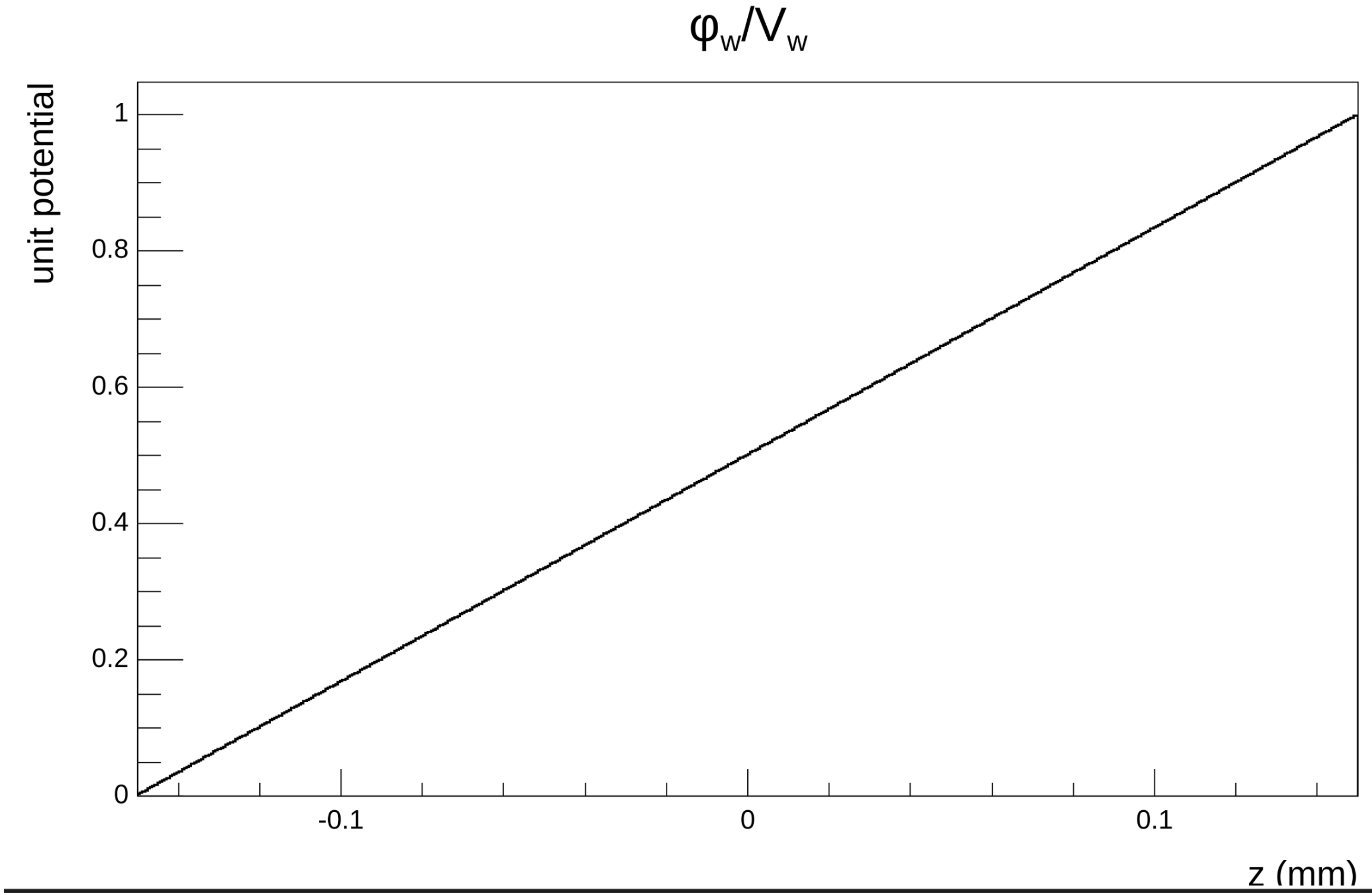
front



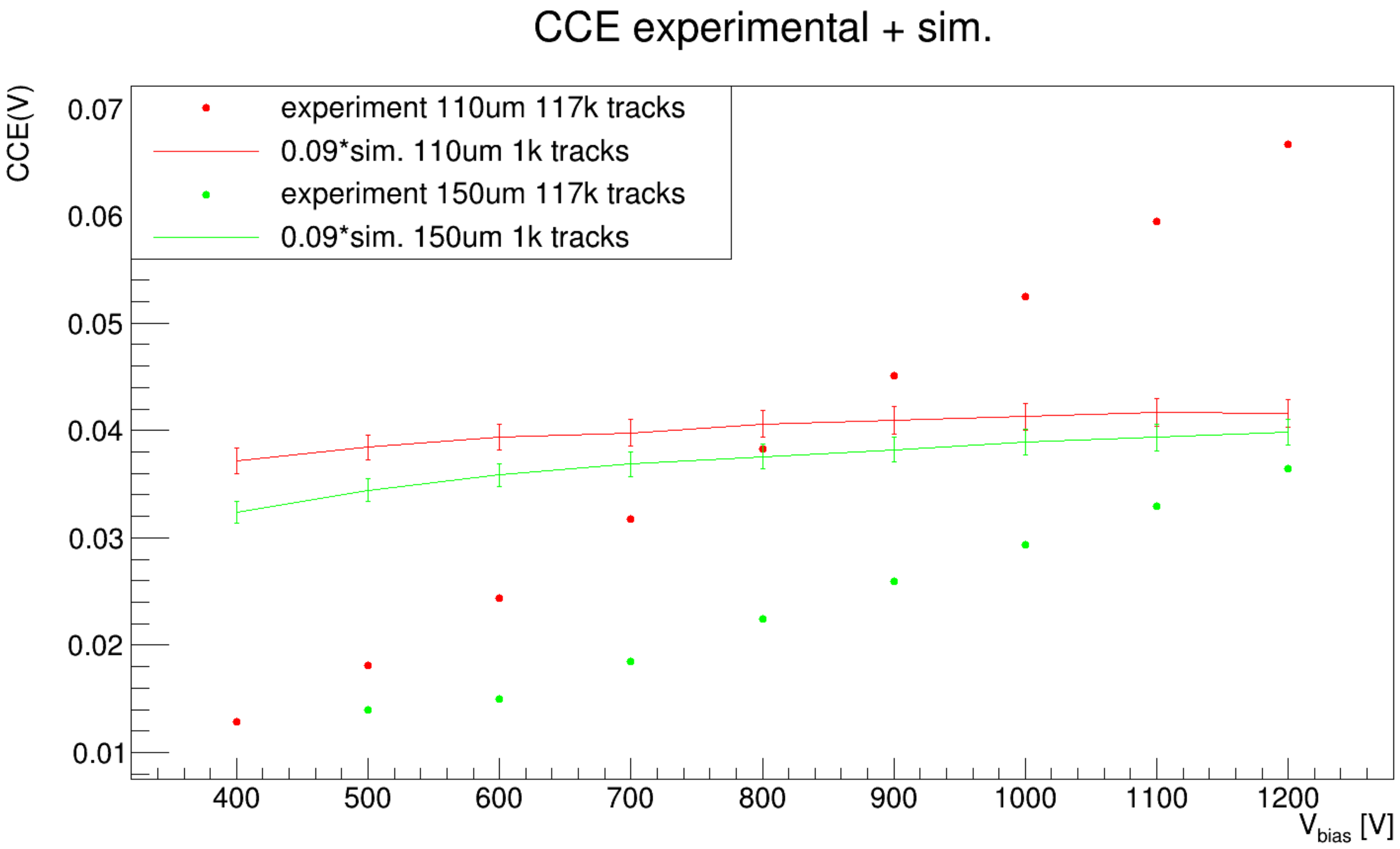
back

DUT – 110/150 um sapphire pad

Weighting field



Sapphire parameters from [1]



110um/150um samples

- 100000 events (1h sim. Time) corresponding to 1050 tracks in the detector
- Parameters used:

$$\mu_e = 600\ \mathrm{cm}^2/\mathrm{V/s}$$
$$(\mu\tau)_e = 79.1 \cdot 10^{-8}\ \mathrm{cm}^2/\mathrm{V}$$
$$(\mu\tau)_h = 4.2 \cdot 10^{-8}\ \mathrm{cm}^2/\mathrm{V}$$

- Uniform electric field:

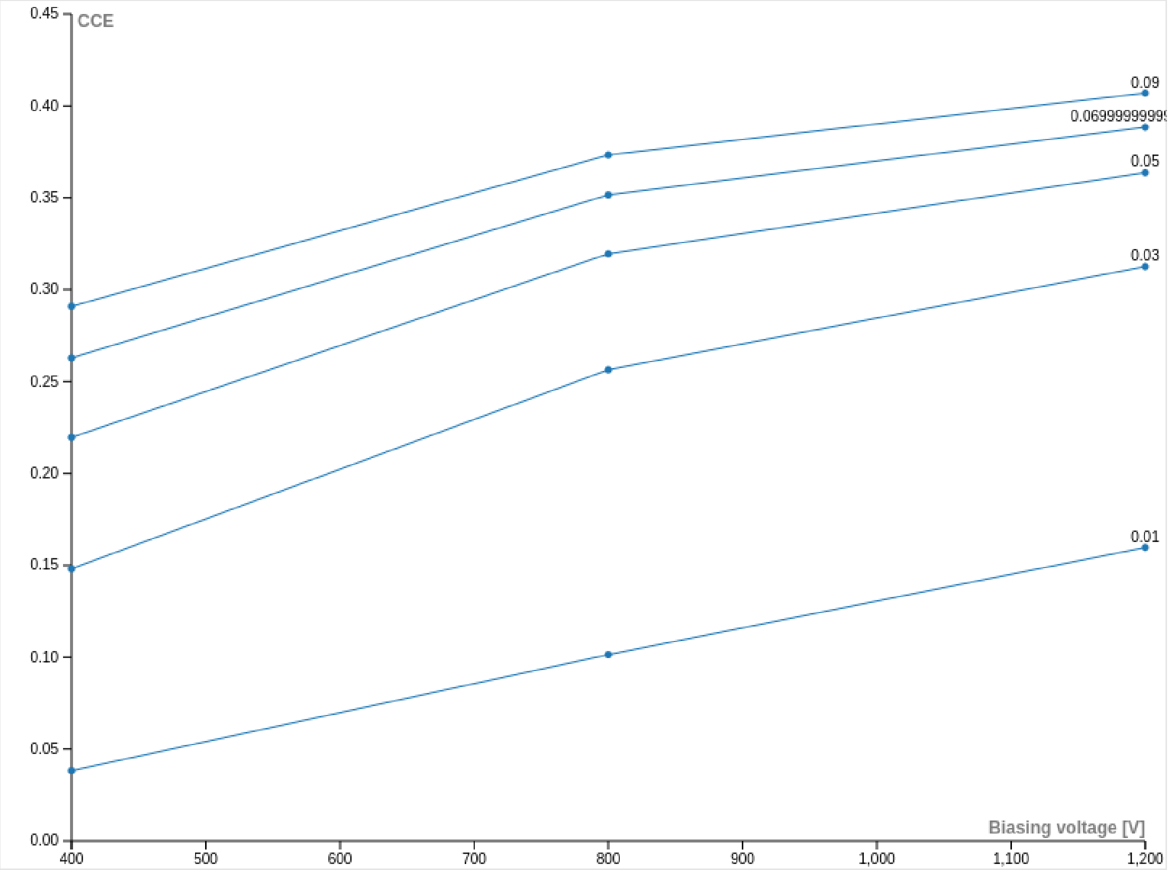
$$E(V) = \frac{V}{110}\ \mathrm{V/um}$$

Comment

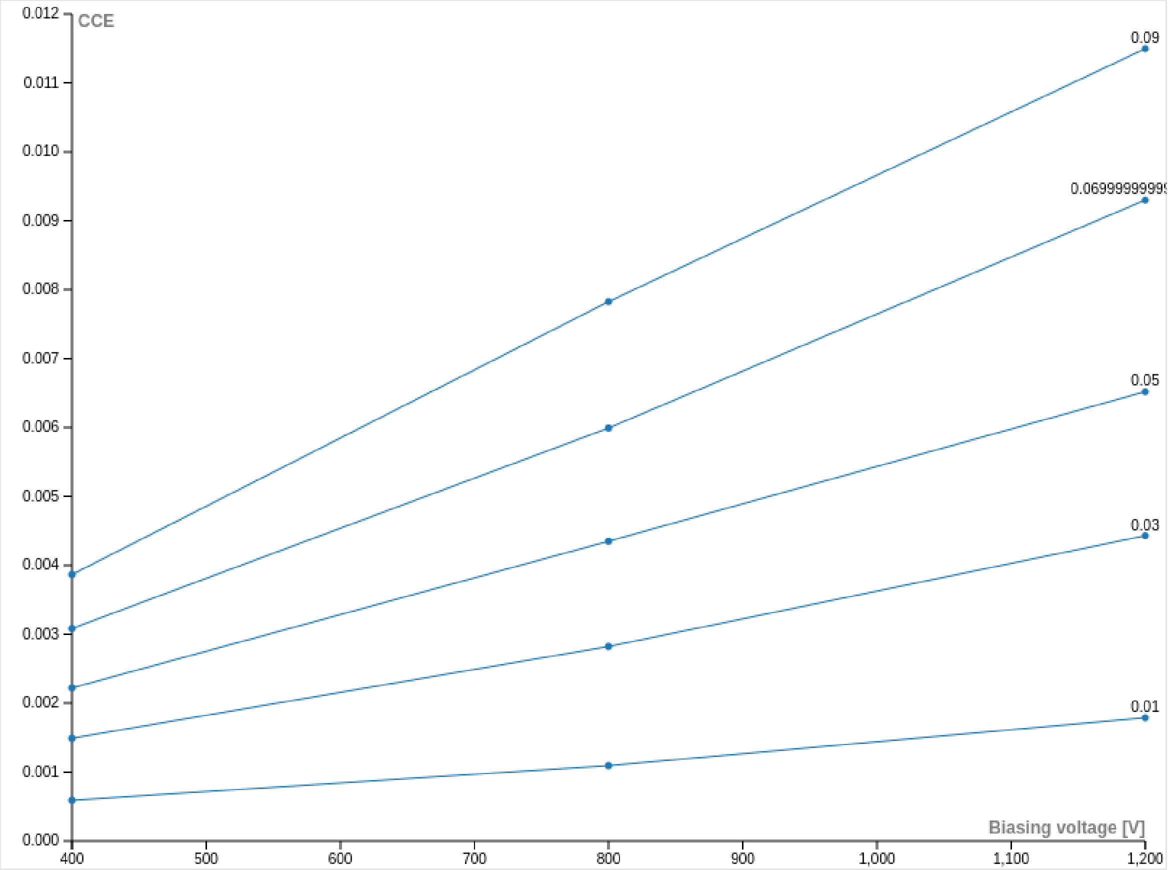
DESY-II parameters (plate1) are inadequate if used in this model with uniform e-field, predicting a very high >30% CCE.

Scanning

Desy pars 110um



Padova pars 110um



Backup
Geant4 110um

Alpha source. Characteristics

- Source activity (27/7/21): **2200 Bq**

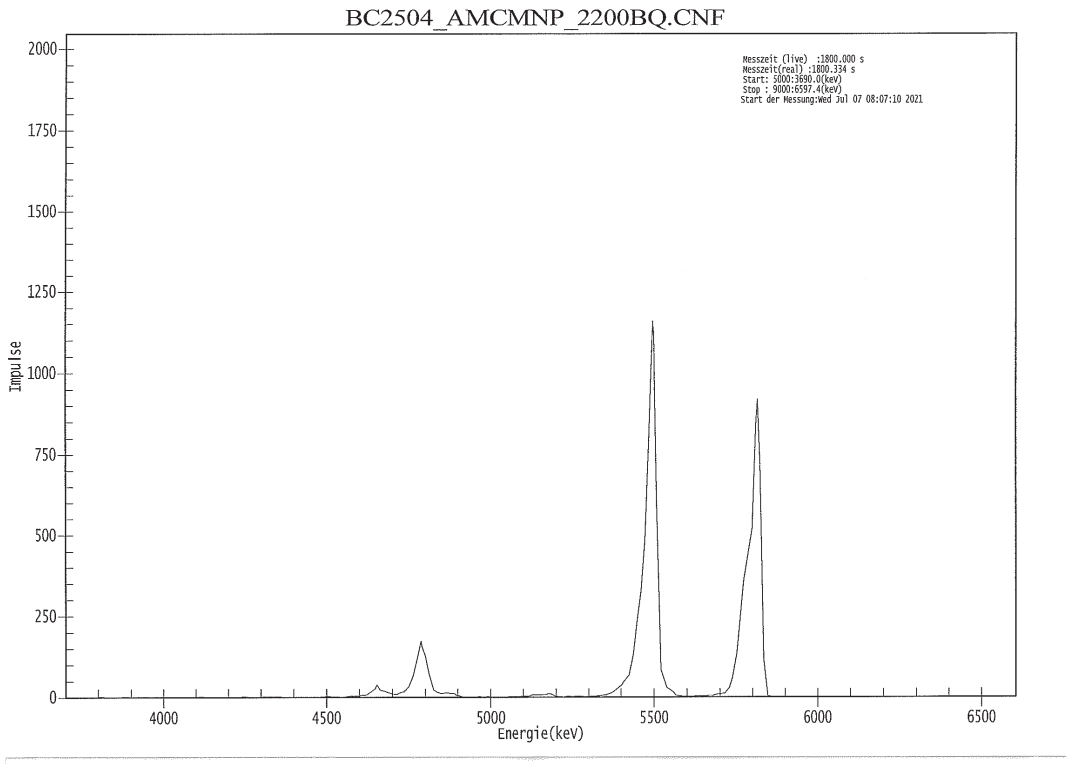
- Source composition:
    1. 241Am - 1000 Bq
    2. 244Cm - 1000 Bq
    3. 273Np – 200 Bq
- Date of experiment: 16/02/22
  - 205 days later

- Activity at the 16/02/22: **2168.17 Bq**

--> Decays in 30': **3.9 x 10^6**

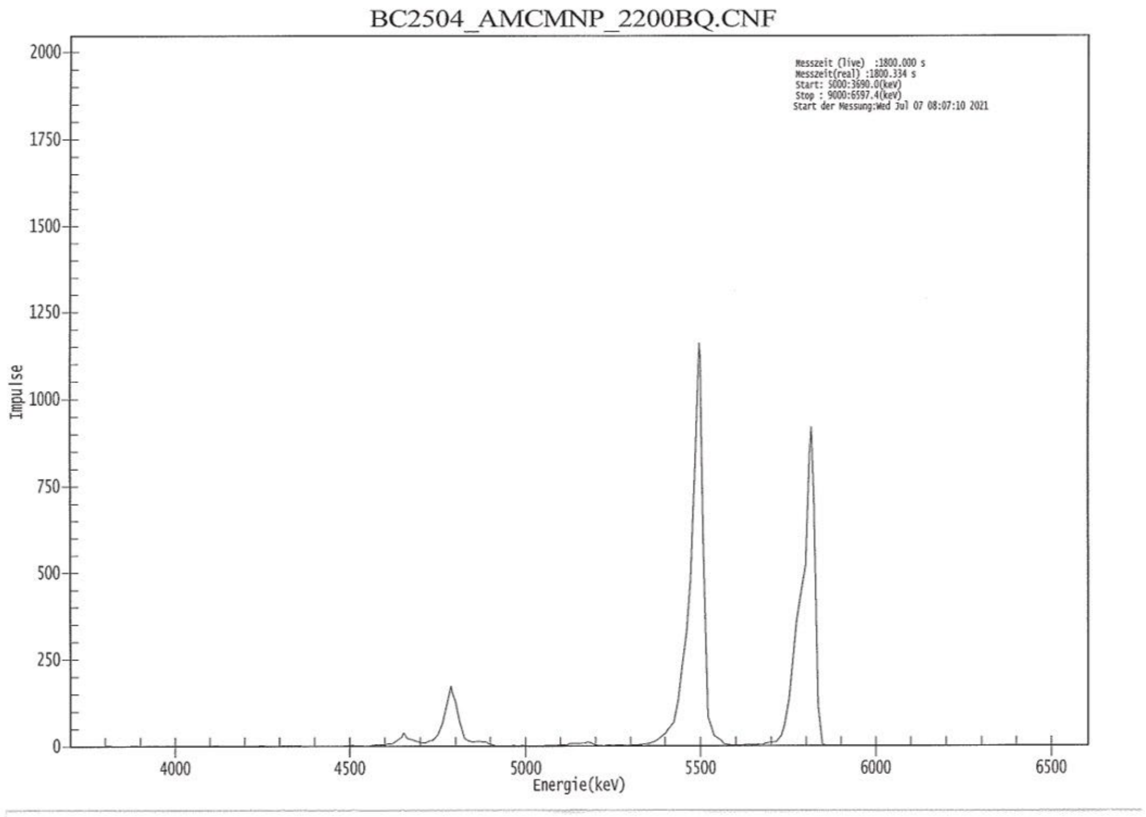
Simulated an acquisition of 1800 sec in Geant4 using 3.9 x 10^6 events

Alpha source energy spectrum (from vendor)

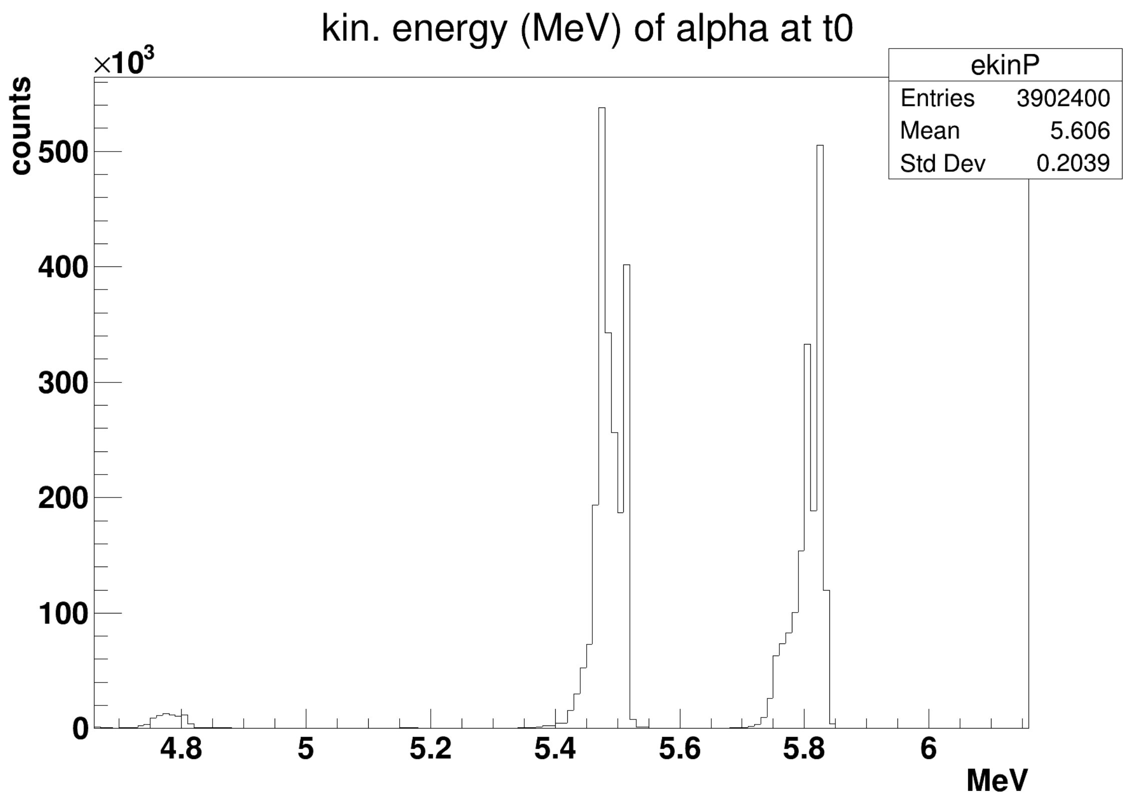


Alpha source in the sim.

Source spectrum (measured)



Source implementation in Geant4



Alpha source is implemented using a Geant4-GPS

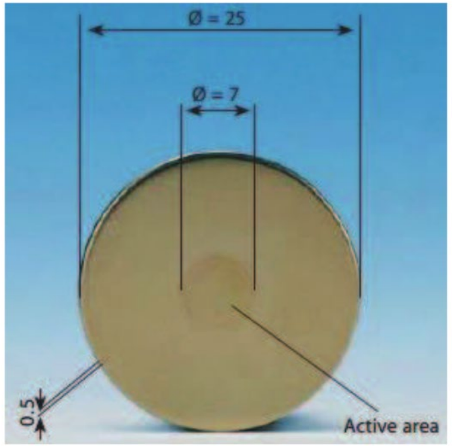
Number of events: 3902400

Average energy: 5.606 MeV

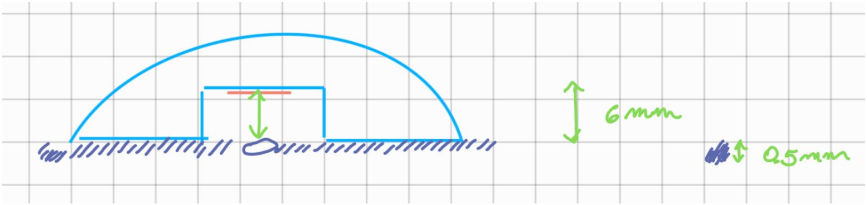
Alpha source in the sim.

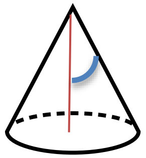
- Alpha source is enclosed in a plastic container with cylindric shape.
- The active alpha-emitting area is a circle of diameter d1 = 7 mm, deposited in a disk of diameter d2 = 25 mm, with thickness dz = 0.5 mm.
- The source enclosure is such that there is a 6 mm gap between the active area and the device under test.
- A further 0.5 mm distance between the plastic container and the sapphire pad is present, to avoid damaging the wire bondings

DRAWING



Geometry -> alpha are emitted in a cone with semi-aperture





28.3 deg

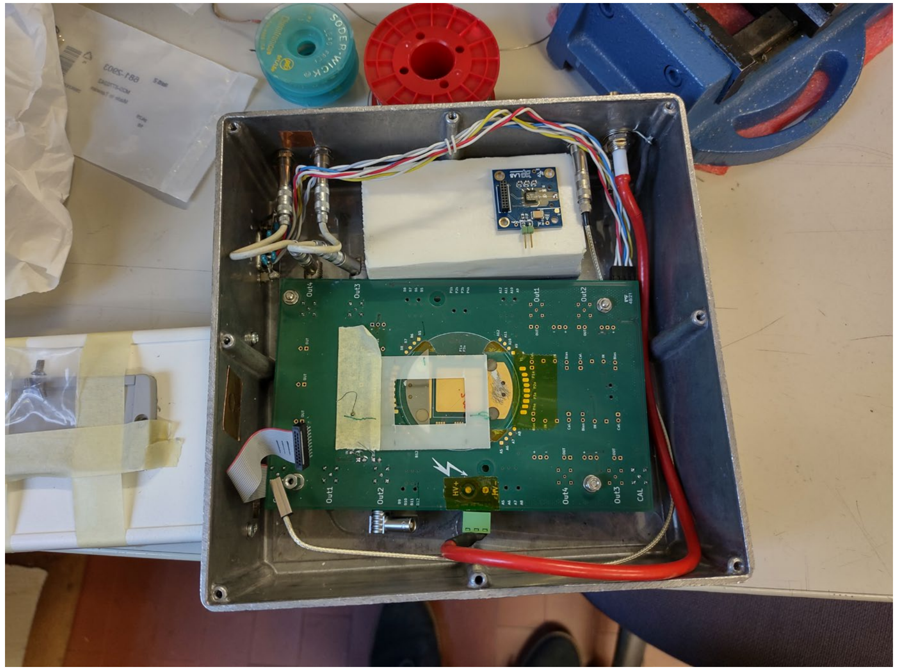
Sapphire pad

- Sapphire pad is implemented with a disk
  -diameter 5.50 mm
  -thickness 110/150 um

- Upper metallization is made of
  50 nm Ti + 50 nm Ag

- Lower metallization is not implemented (see later)

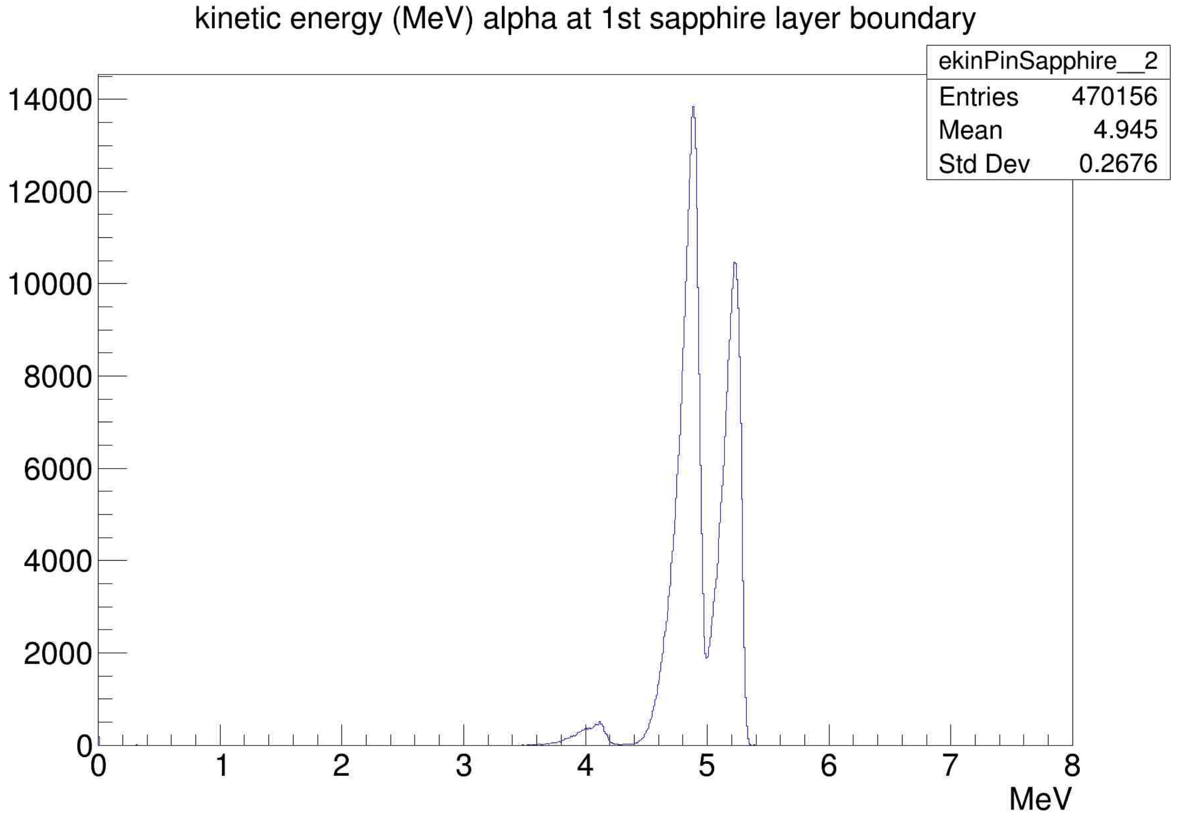
- 110 um sapphire pad is virtually segmented in 110 layers to study dE/dz



Energy deposition (110um)

Let us focus on the 110-um pad detector. The conclusions hold also for the other one.

In the Fig. Below there is the kinetic energy of alpha particles reaching the first sapphire layer (left) and the spectrum of energy depositions in the sapphire (right)



The average energy loss of alpha particles in the 6.5 mm air + 100 nm metallization is

\DeltaE_k = (5.606 - 4.945) MeV = 0.661 MeV

Energy deposition (110um)

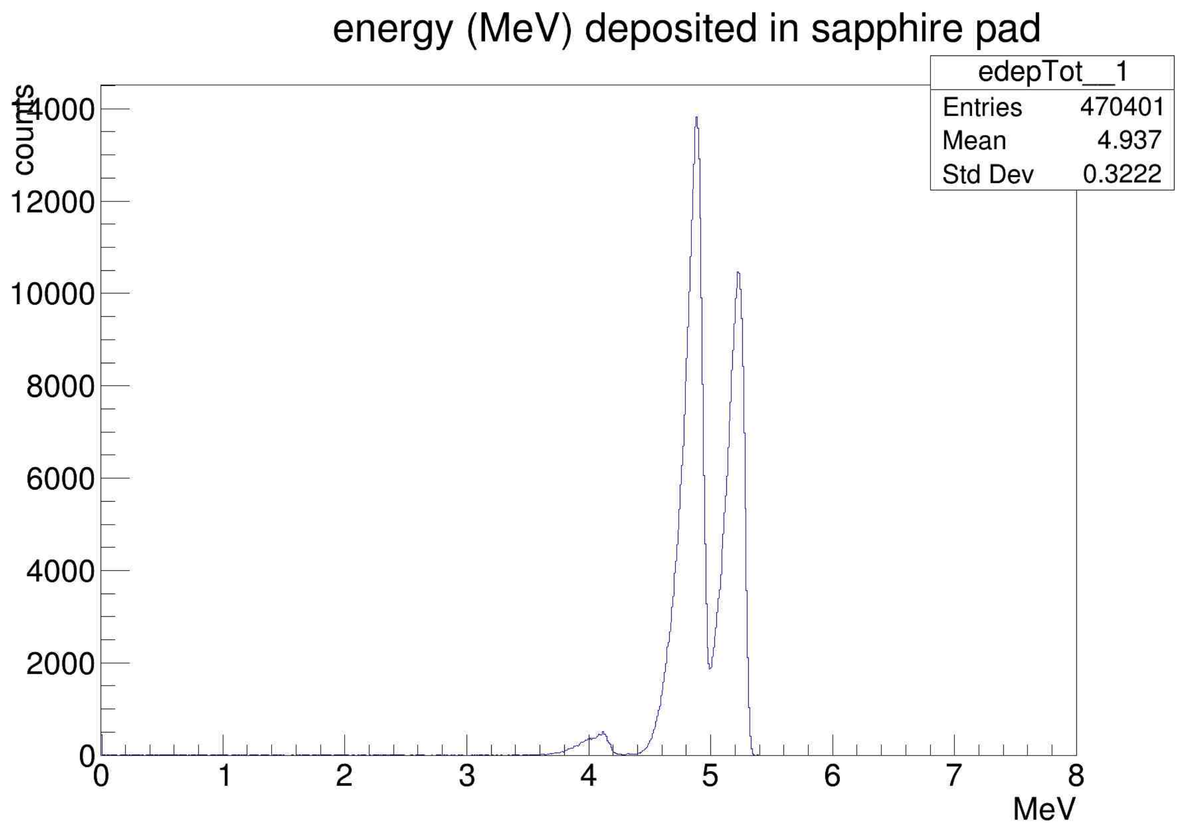
Let us focus on the 110-um pad detector. The conclusions hold also for the other one.

In the Fig. Below there is the kinetic energy of alpha particles reaching the first sapphire layer (left) and the spectrum of energy depositions in the sapphire (right)

The average kinetic energy of alpha entering the sapphire is 4.945 MeV

The average energy deposited in the sapphire is 4.937 MeV.

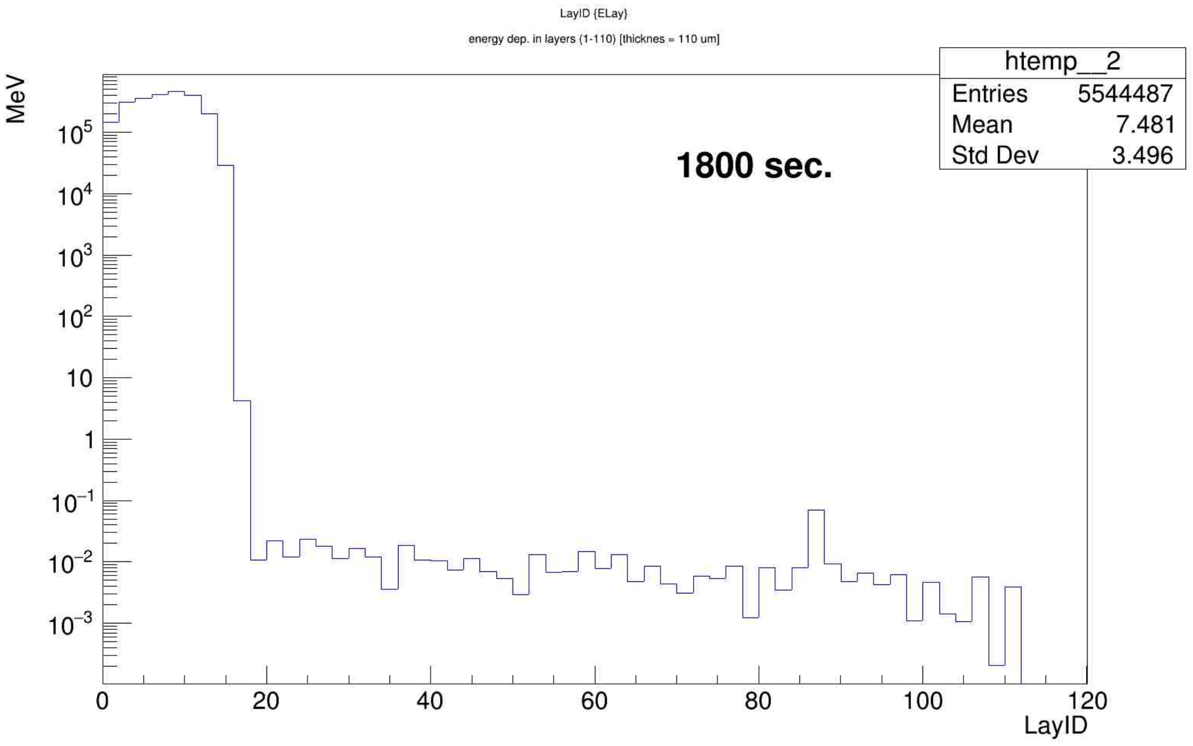
Simulation are made using the FTFP_BERT physics list (the standard hadronic list)

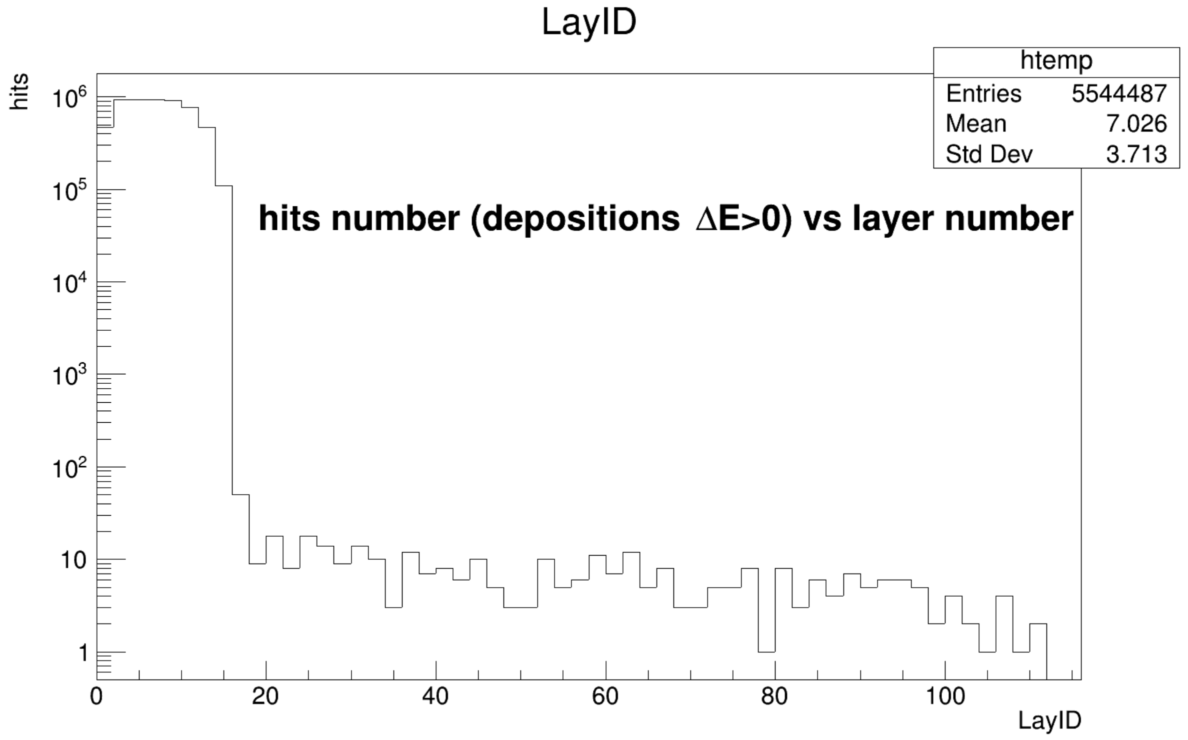


Energy deposition (110um)

The average energy deposited in the sapphire is 4.937 MeV.

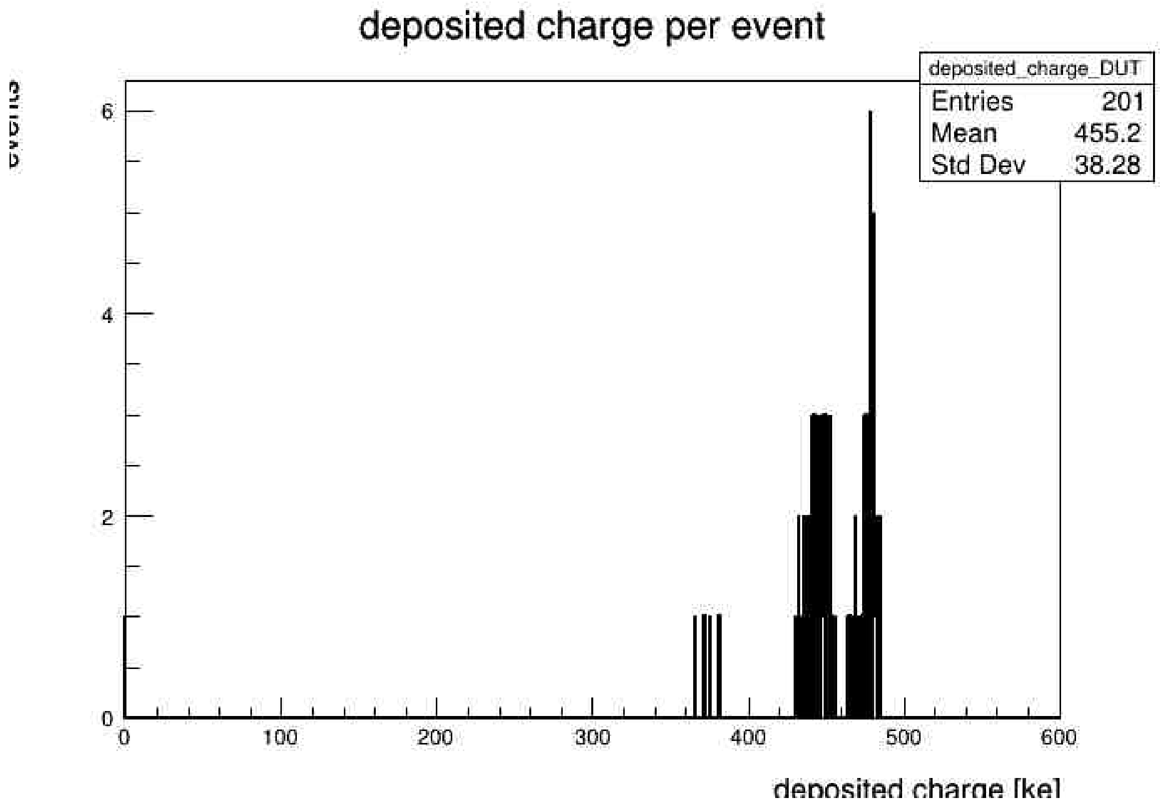
Most of the energy is deposited within the first 20 um of sapphire, leaving only an O(10) hits for deeper layers
(therefore no major differences are expected rear metallization is implemented)





Deposited charge

- The DepositionGeant4 reproduces the same results of the Geant4 simulation: the number of electron/hole produced is obtained from the deposited energy dividing for the 27eV average energy for pair creation
- There is the Fano factor (0.115) responsible for gaussian fluctuations over the average pairs number.



Models in Allpix2

Built-in Allpix2 models parametrize the mobility as function of the electric field E and/or the doping concentration N.

- Jacoboni-Canali model

$$\mu(E) = \frac{v_m}{E_c} \frac{1}{(1 + (E/E_c)^{\beta})^{1/\beta}}, \tag{6.1}$$

- Hamburg model

$$\begin{aligned} \mu_e^{-1}(E) &= 1/\mu_{0,e} + E/v_{sat} \\ \mu_h^{-1}(E) &= 1/\mu_{0,h} && \text{for} \quad E < E_0 \\ &= 1/\mu_{0,h} + b \cdot (E - E_0) + c \cdot (E - E_0)^2 && \text{for} \quad E \geq E_0 \end{aligned} \tag{6.3}$$

- Masetti model

$$\begin{aligned} \mu_e(N) &= \mu_{0,e} + \frac{\mu_{max,e} - \mu_{0,e}}{1 + (N/C_{r,e})^{\alpha_e}} - \frac{\mu_{1,e}}{(1 + (C_{s,e}/N)^{\beta_e})} \\ \mu_h(N) &= \mu_{0,h} + \frac{\mu_{max,h}}{1 + (N/C_{r,h})^{\alpha_h}} - \frac{\mu_{1,h}}{(1 + (C_{s,h}/N)^{\beta_h})} + e^{P_c/N} \end{aligned} \tag{6.5}$$

- Arora model

$$\begin{aligned} \mu_e(N) &= \mu_{min,e} + \mu_{0,e}/\left(1 + (N/N_{ref,e})^{\alpha}\right) \\ \mu_h(N) &= \mu_{min,h} + \mu_{0,h}/\left(1 + (N/N_{ref,h})^{\alpha}\right) \end{aligned} \tag{6.6}$$

- Extended Canali

$$\mu(E, N) = \frac{\mu_m(N)}{\left(1 + (\mu_m(N) \cdot E/v_m)^{\beta}\right)^{1/\beta}} \tag{6.7}$$

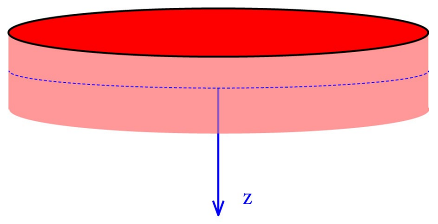
- Custom model – const. uniform mobility

Summary of the simulation strategy

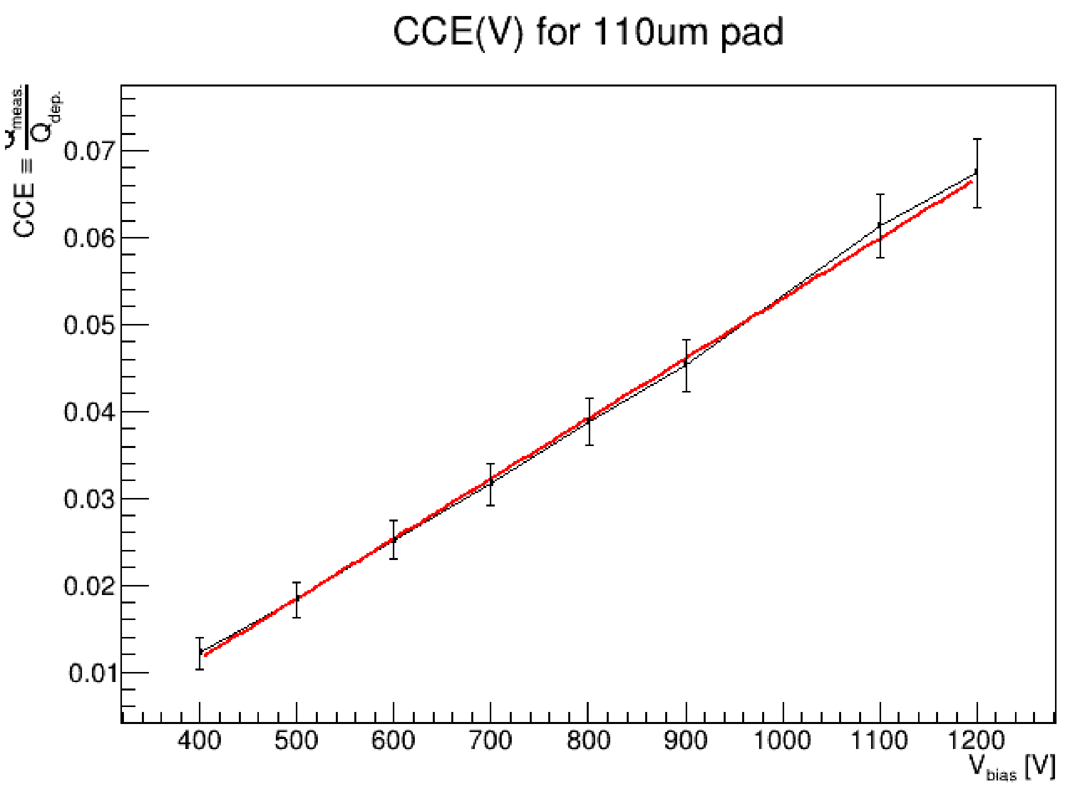
- Three models have been used. Model-dependent parameters are varied and simulation outcomes are compared with experimental data (CCE) for the 110/150 um DUT.
- All model neglect hole propagation, focussing on the electron propagation only.
- (Toy) Model 1
  - Fixed uniform electron mobility (no saturation speed)
  - Fixed uniform electron lifetime
  - Fixed uniform electric field along z
- Model 2
  - Fixed uniform electron mobility & lifetime
  - Linear electric field along z $E_z(z) = E_0 - E_1\,(z - z_0)$
- Model 3
  - Fixed uniform electron mobility & lifetime
  - Electric field along z with the form (6)

$$E_z(z) = E_0 - E_1\,(z - z_0) - E_2\, w(\mathrm{V_{bias}})\, e^{-\frac{(z-z_0)^2}{2\sigma^2}} \quad (6)$$

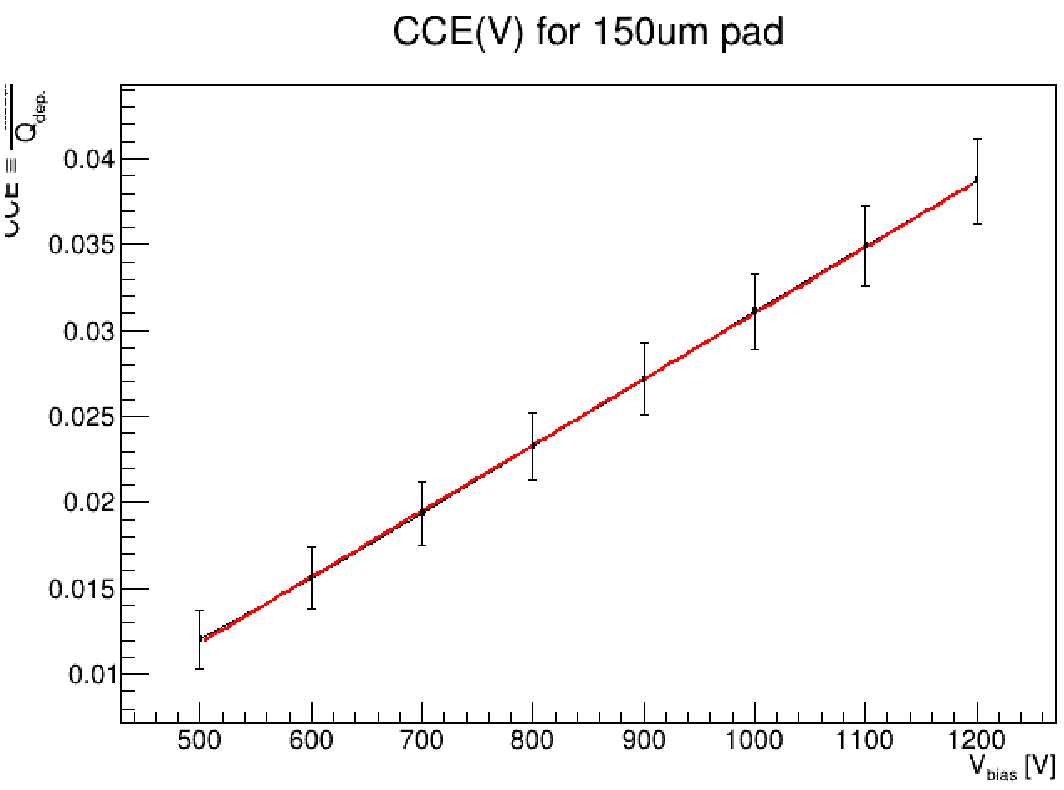
$$w(\mathrm{V_{bias}}) \equiv \frac{V_{\mathrm{bias}} - 1200\,V}{500\,V - 1200\,V} \quad (7)$$



Hecht with linear electric field




```
root [1] fit110()
 FCN=0.437789 FROM HESSE     STATUS=OK             16 CALLS        1760 TOTAL
                     EDM=5.11523e-06    STRATEGY= 1      ERROR MATRIX ACCURATE
  EXT PARAMETER                                   STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  p0           8.06842e-09   1.43563e-09   2.40803e-14   1.24240e+06
   2  p1          -4.19089e+06   2.12094e+07   9.99186e-01   3.02237e-09
   3  p2           1.10000e-02     fixed
   4  p3           4.19420e-02   1.11303e-01   3.84359e-05  -2.27460e-03
(int) 0
```




```
root [1] fit150()
 FCN=0.0250893 FROM HESSE     STATUS=NOT POSDEF     16 CALLS        137 TOTAL
                     EDM=1.7533e-08    STRATEGY= 1      ERR MATRIX NOT POS-DEF
  EXT PARAMETER                APPROXIMATE        STEP         FIRST
  NO.   NAME      VALUE            ERROR          SIZE      DERIVATIVE
   1  p0           8.50391e-09   6.86839e-10   4.77519e-15   1.60594e+05
   2  p1          -1.75392e+06   2.29618e+06   4.18167e-01  -1.78013e-10
   3  p2           1.50000e-02     fixed
   4  p3           1.43160e-02   1.10767e-01   2.26320e-05  -2.48039e-05
```