MC for the GBP. Updates

The Geant4 & Allpix2 for the experiments with alpha source

Università degli Studi di Padova

Summary of the MC needs

- LUXE
  - Dose for the electronics placed nearby the gamma beam horizontal plane
  - Hadronic interactions on the profile reconstruction
  - Best distance between the I and II station (min/max distance d_1, d_2)
  - ~~Check that 10um W foil in gamma spectrometer is included in lxsim~~ [yes]
  - Check that 200um Kapton - Al window at the beam pipe exit window in accounted
  - Thermal stress on the detectors and on the beam pipe exit window (200um Kapton/Al)
    - Not a problem for the Kapton (link1) (link2)

- Test beam (~~ELBE~~ -> LNF Frascati on May 2022)
  - Geometry of the setup
  - Characteristics of the test beam
  - Estimating the expected signal with Geant4+Allpix2
  - Dose received for each beam configuration (intensity, spatial distribution)

- Padova experiments with the alpha source and sapphire 110/150 um
  - Energy loss in air/metallization/sapphire, spatial distribution of energy depositions in DUT
  - Model the charge propagation in sapphire using CCE data and Allpix2

Geant4 – Alpha source and 110 um sapphire pad

Alpha source. Characteristics

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

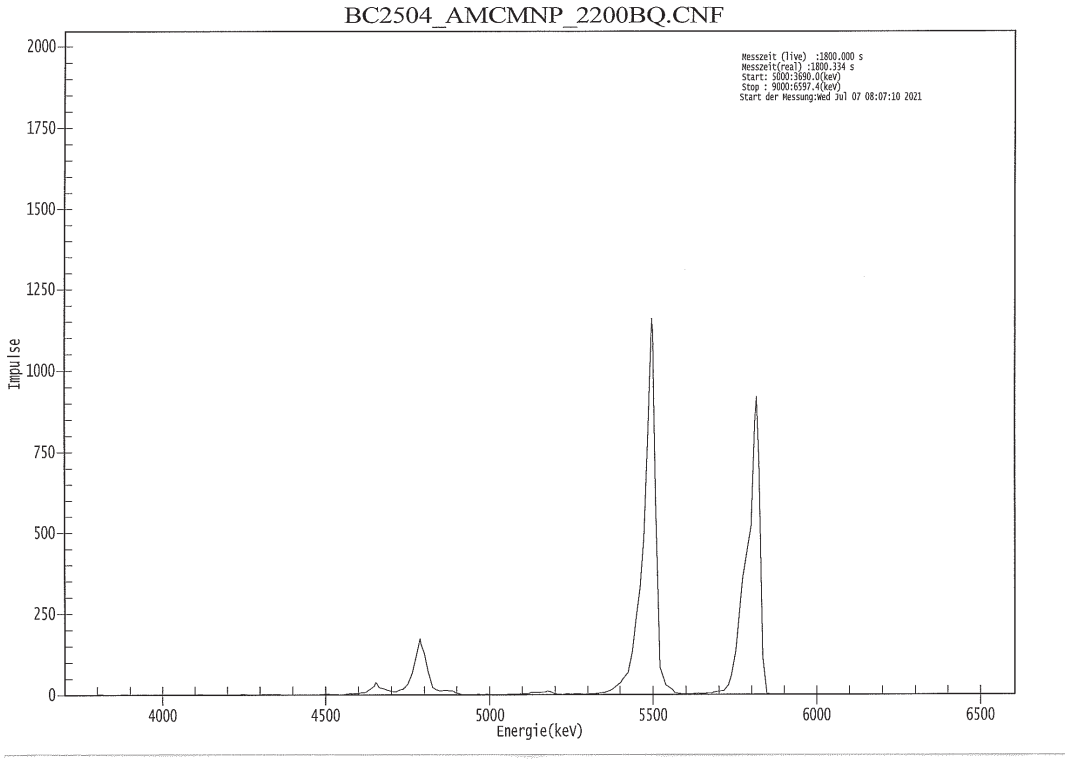
- Source composition:
  1. 241Am - 1000 Bq
  2. 244Cm - 1000 Bq
  3. 273Np – 200 Bq
- Date of experiment: 16/02/22
  - 205 days later

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

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

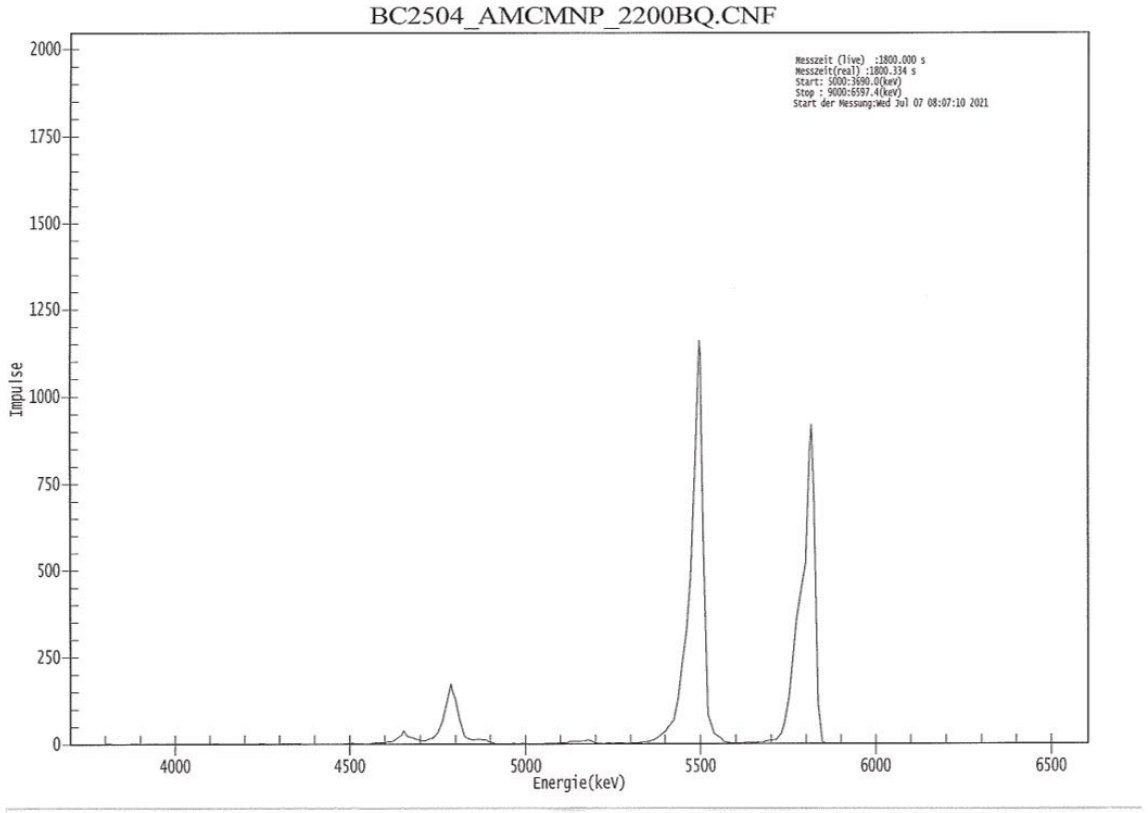
Simulated an acquisition of 1800 sec in Geant4 using 3.9 x 10^6 events

Alpha source energy spectrum (from vendor)

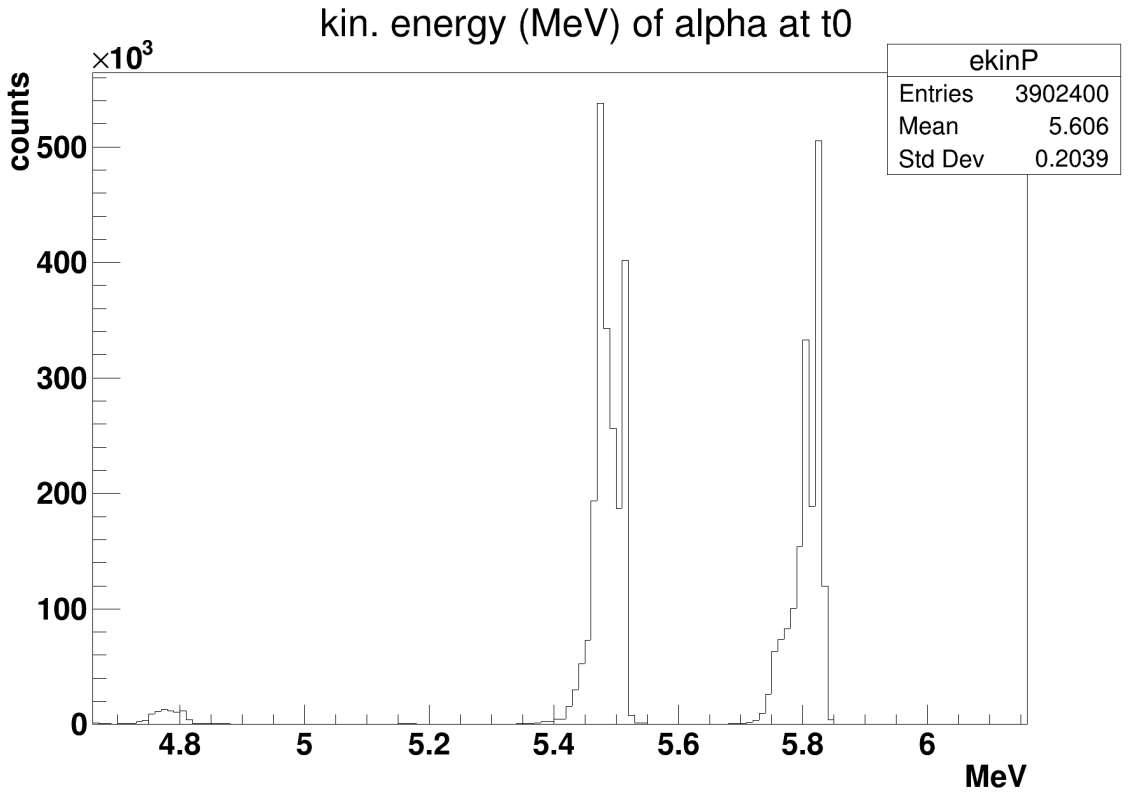


Alpha source in the sim.

Source spectrum (measured)



Source implementation in Geant4



Alpha source is implemented using a Geant4-GPS

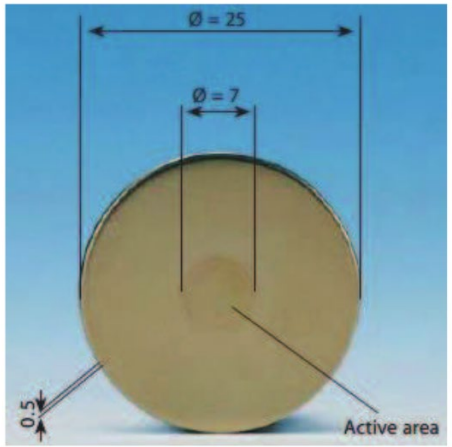
Number of events: 3902400

Average energy: 5.606 MeV

Alpha source in the sim.

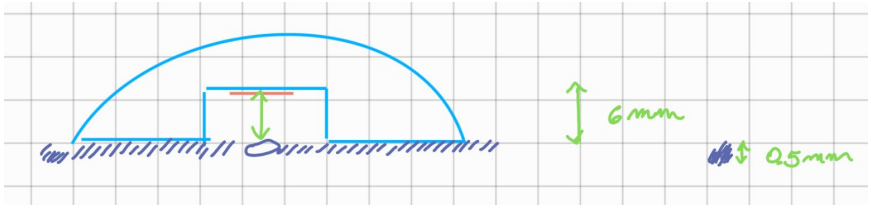
- Alpha source is enclosed in a plastic container with cylindric shape.
- The active alpha-emitting area is a circle of diameter d1 = 7 mm, deposited in a disk of diameter d2 = 25 mm, with thickness dz = 0.5 mm.
- The source enclosure is such that there is a 6 mm gap between the active area and the device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

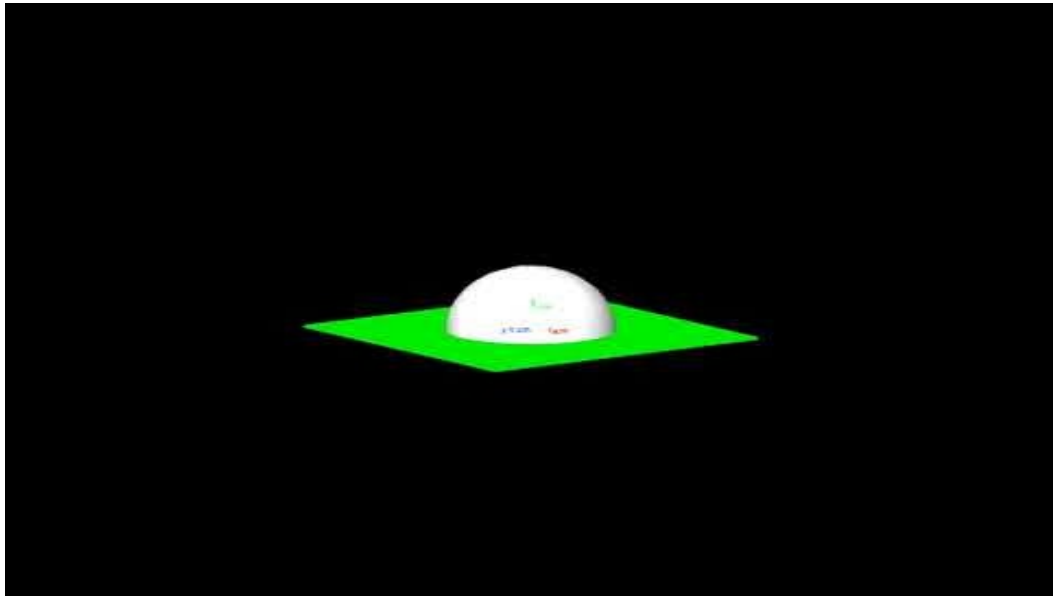
DRAWING



Geometry -> alpha are emitted in a cone with semi-aperture 28.3 deg.

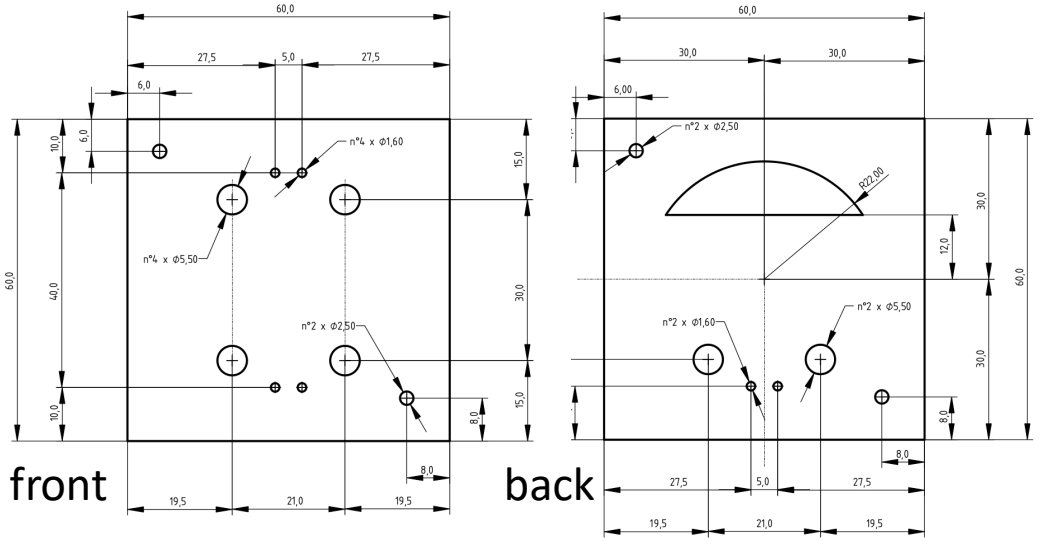
The geometry is shown here ->

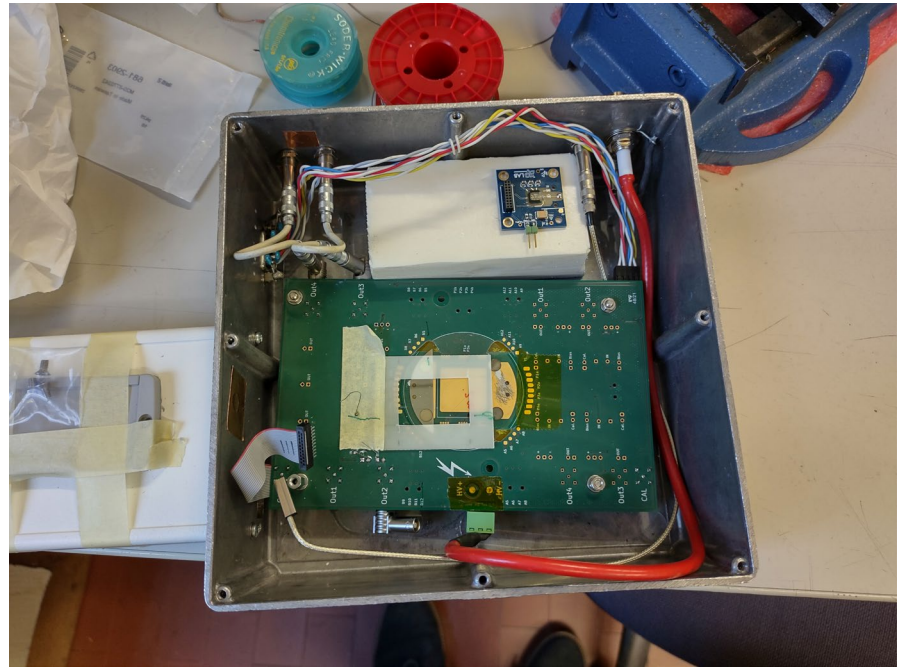




Sapphire pad

- 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

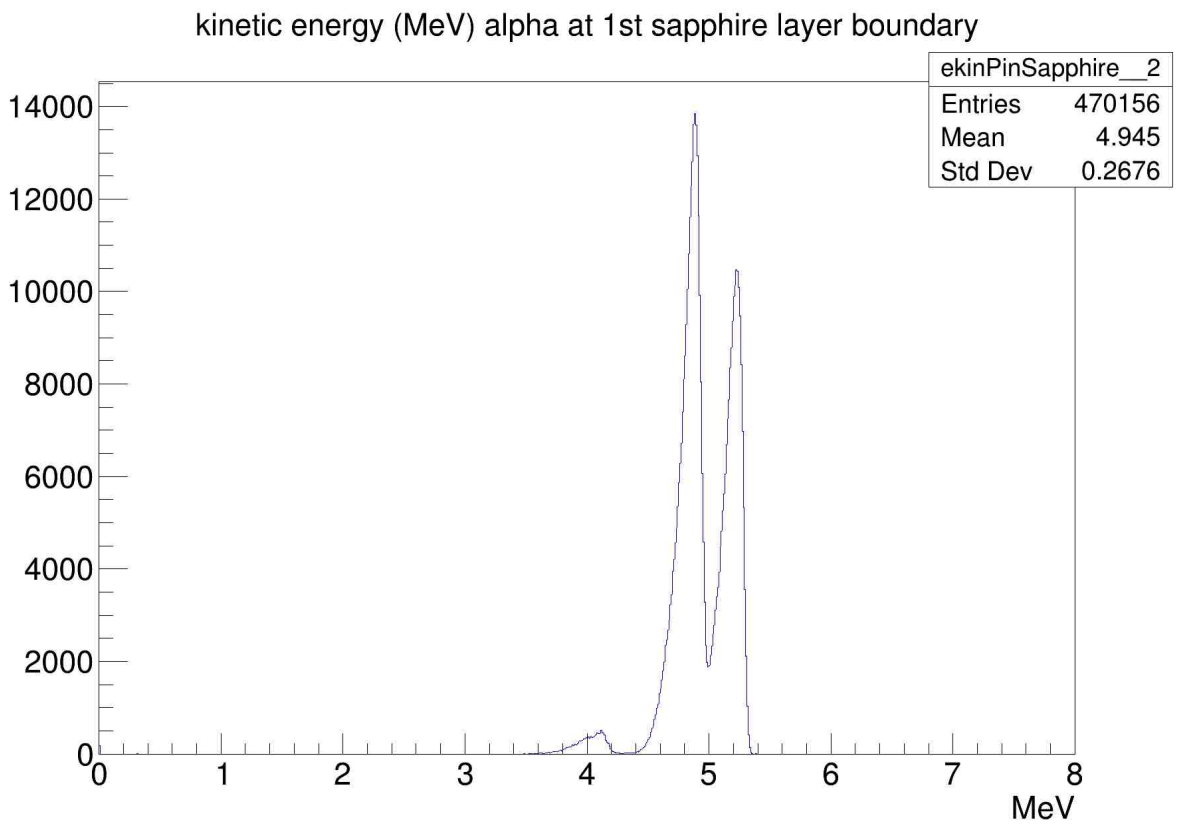


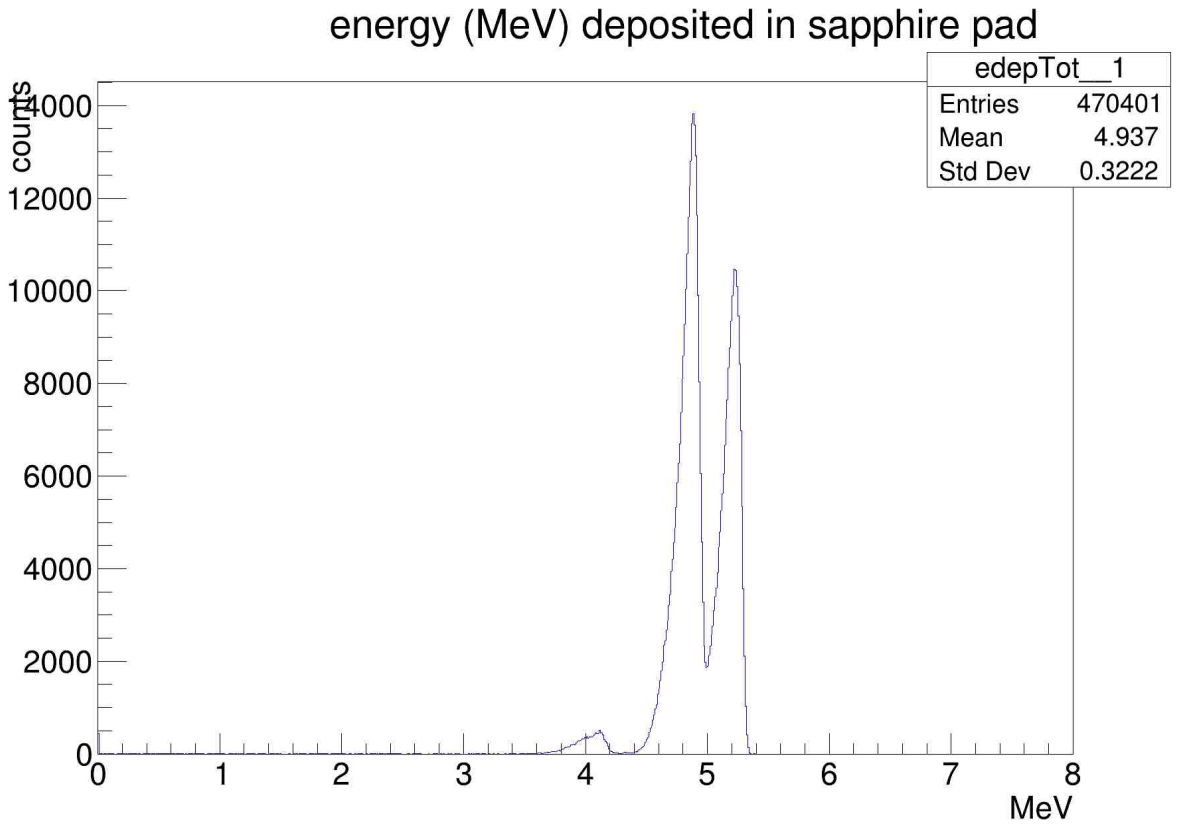


Results 110 um

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

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





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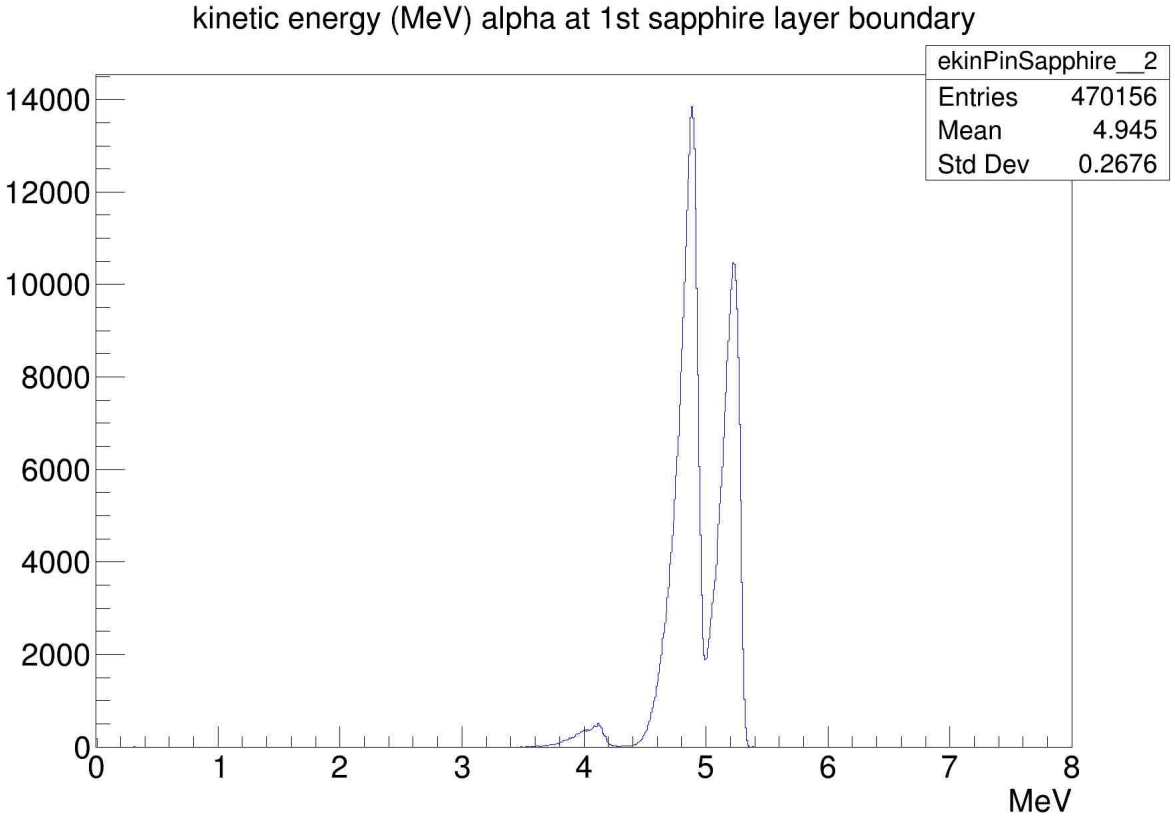


The average energy loss of alpha particles in the 6.5 mm air + 100 nm metallization is

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

Results 110 um

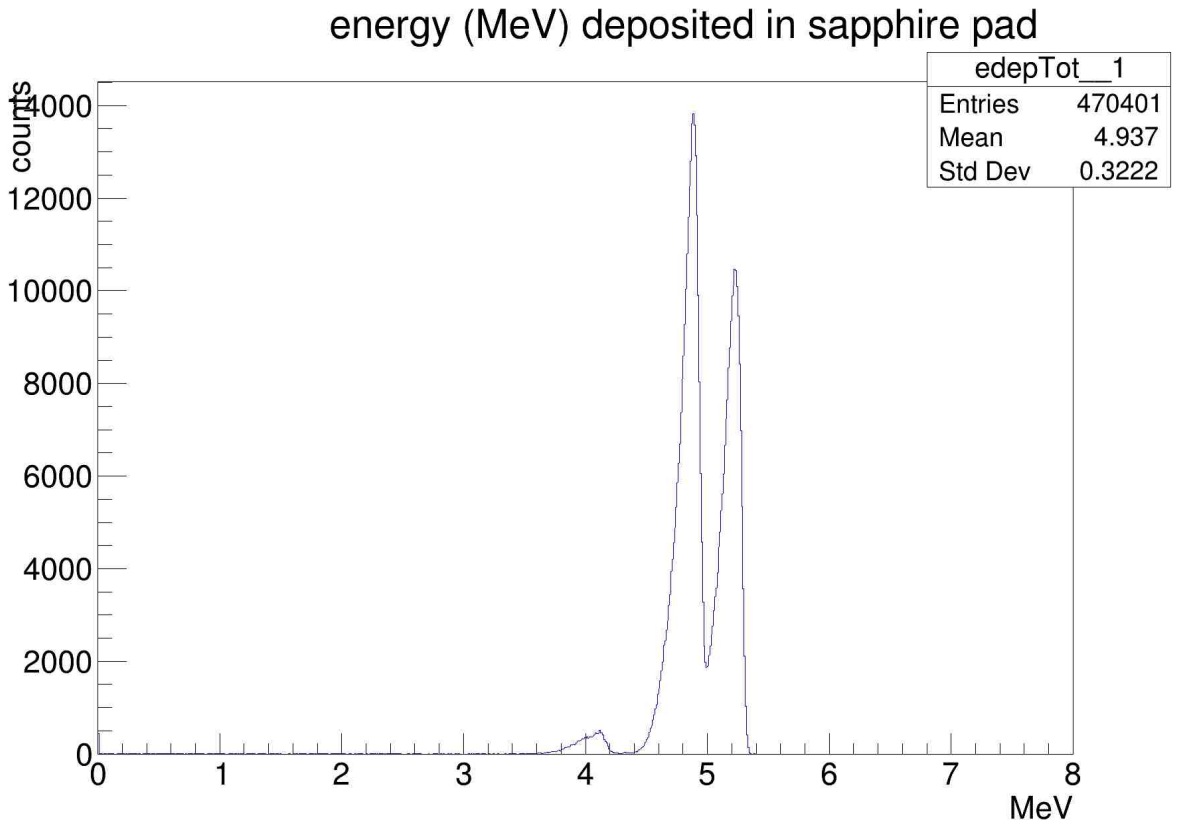
Let us focus on the 110-um pad detector. The conclusions hold also for the other one.

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.

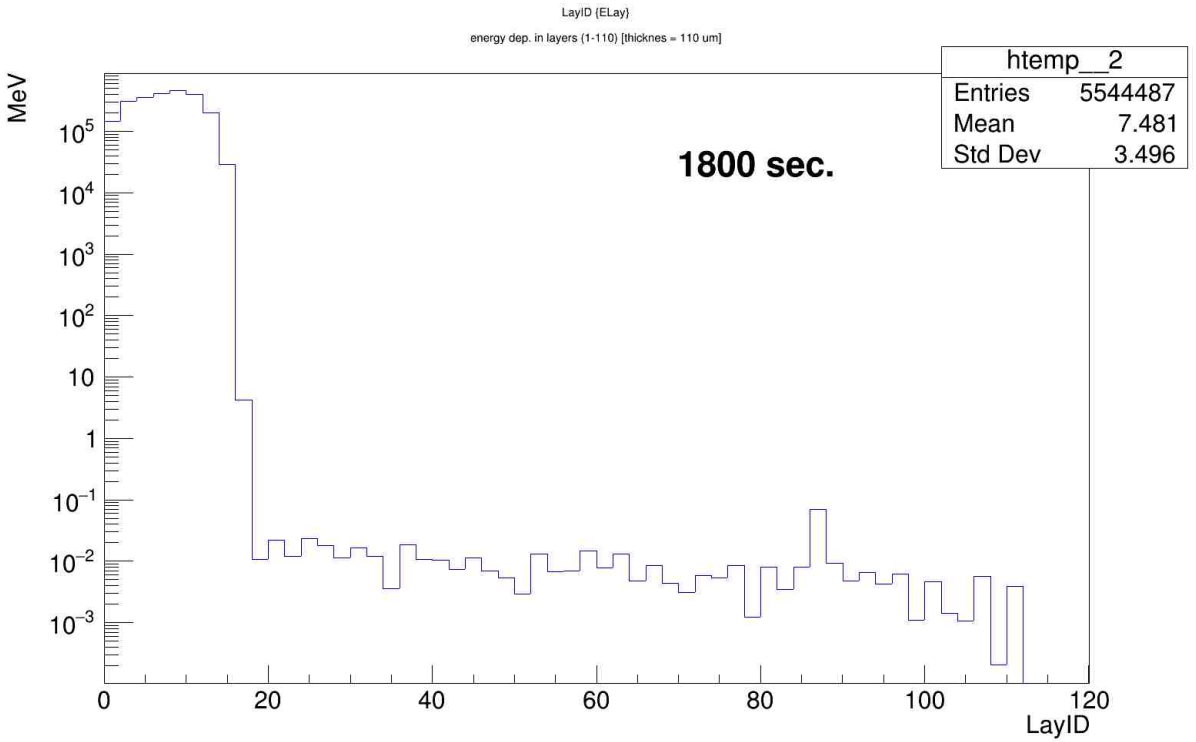
Simulation are made using the FTFP_BERT physics list (the standard hadronic list)

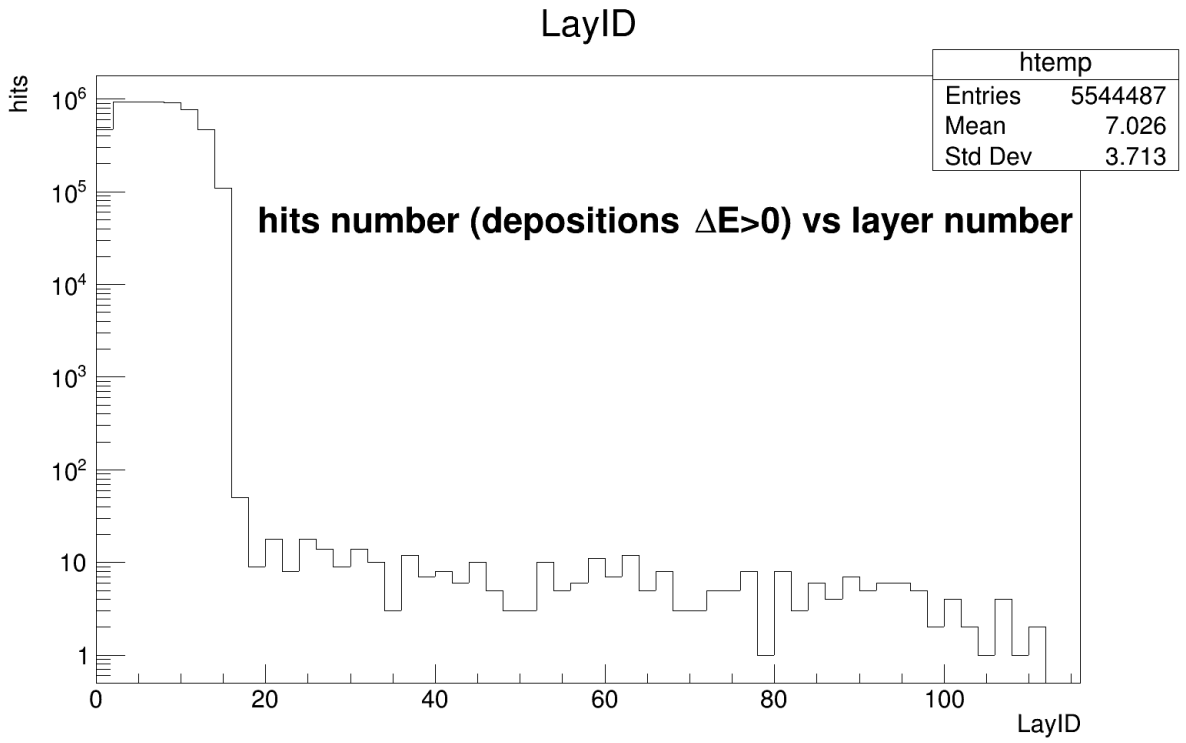


Results 110 um

The average energy deposited in the sapphire is 4.937 MeV.

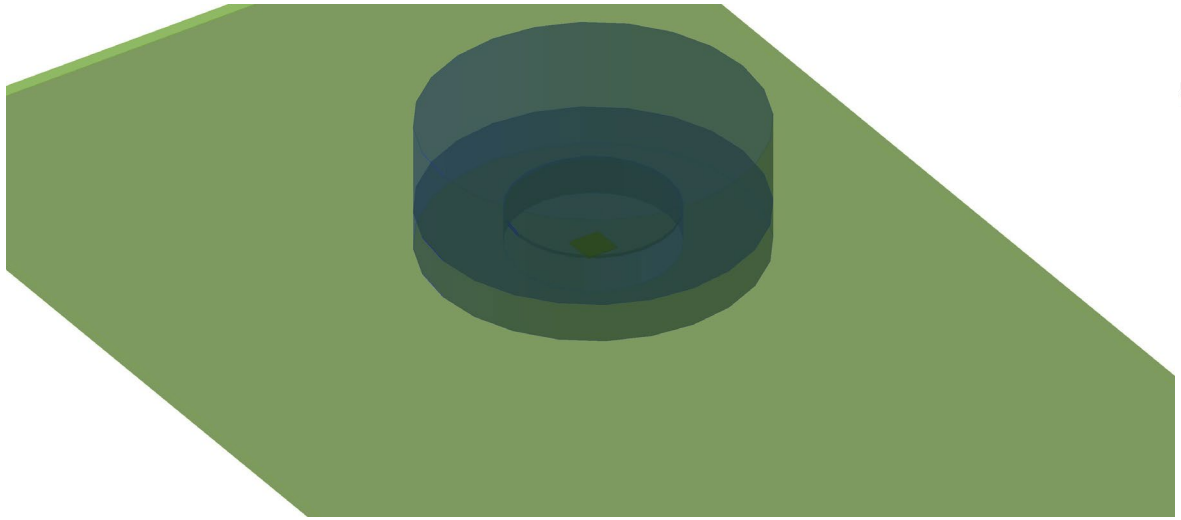
Most of the energy is deposited within the first 20 um of sapphire, leaving only an O(10) hits for deeper layers
(therefore no major differences are expected rear metallization is implemented)

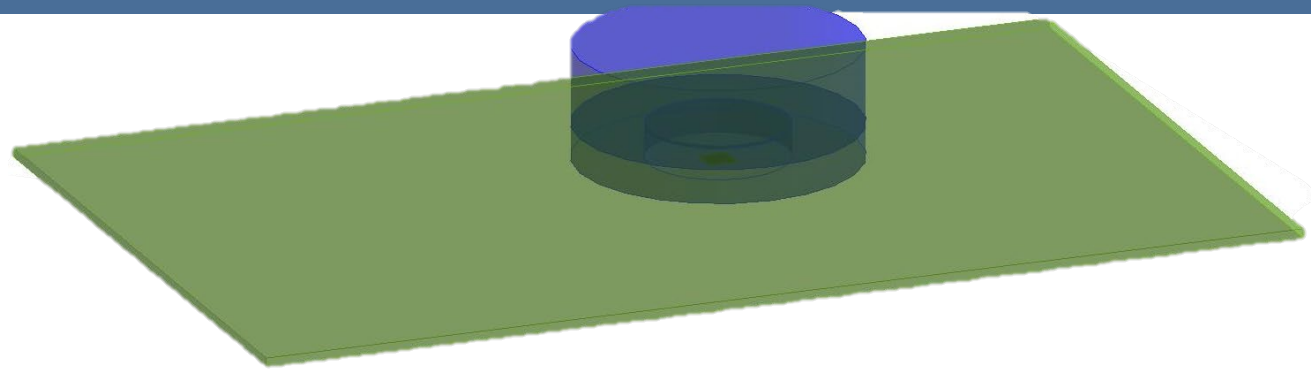




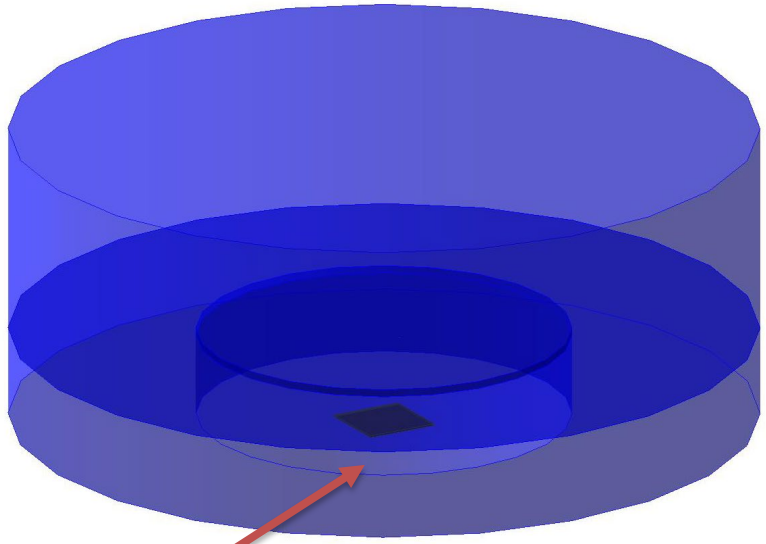
Allpix2 – Alpha source and 110 um sapphire pad

Geometry





Alpha source enclosure



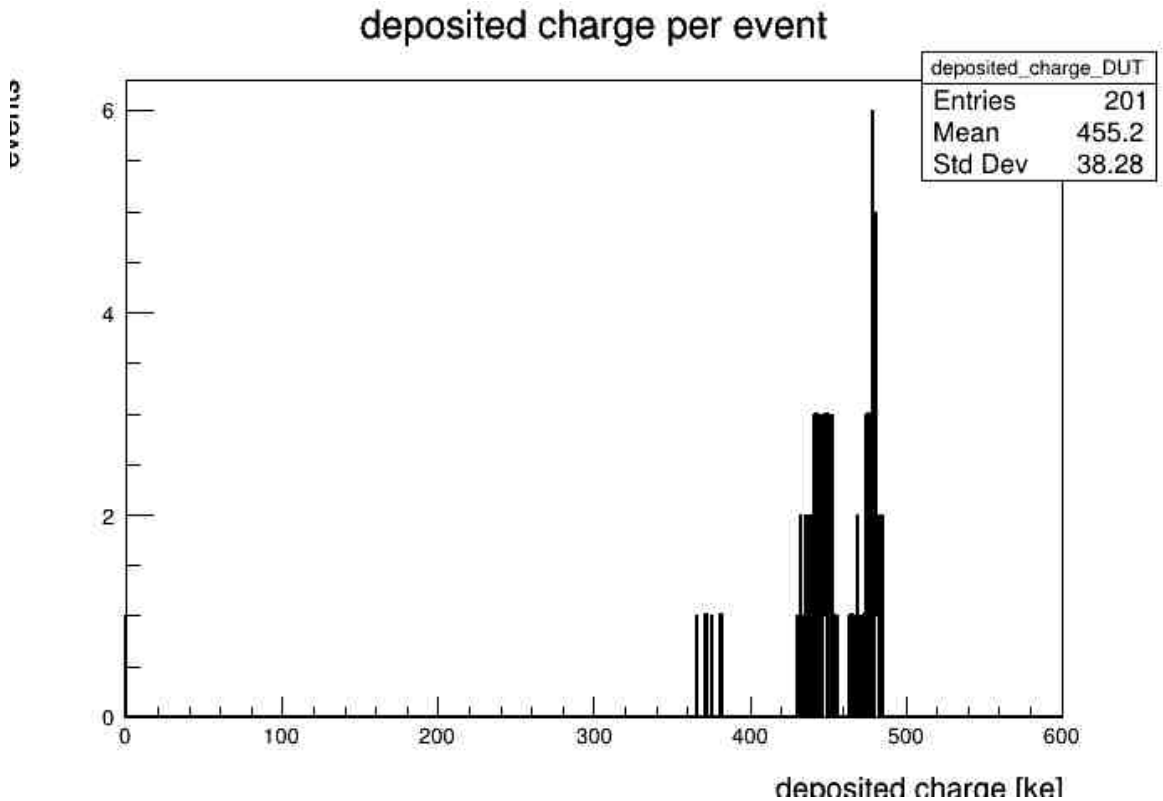
DUT – 110/150 um sapphire pad

There is a bug with Allpix2 for which the application crash if a macroscopic (\sim mm) pixel is used. Therefore the DUT – pad – is implemented using a pixel array of 100x100 pixels.

Predefined geometry objects allow for square-shaped sensors only, the pad is implemented using a square with the same area of the circular pad.

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 27 eV average energy for pair creation (see slide 10)
- There is the Fano factor (0.115) responsible for gaussian fluctuations over the average pairs number.



Literature on sapphire 1/2

- 1504.04023 - Investigation of a direction sensitive sapphire detector stack at the 5 GeV electron beam at DESY-II
  - Experimental setup with 5GeV e- and 10mmx10mmx525um thick optical-grade sapphire detectors. 'Biasing' voltage fixed to 950V.
  - Particles cross the 10mm sapphire producing 22ke
  - Measured CCE varies from sample to sample, on average CCE=10%
  - The model used accounts for:
    - Immediate recombination of charge carriers after production (f_0 \sim 50%)
    - Charge trapping (\tau_e > 1ns, \tau_h < 1ns)
    - Electric field modifications due to trapped charges (polarization field)
  - Conclusions
    - low hole mobility -> electron contributions to charge transport is dominant
    - A fraction of charge carriers (\sim 50%) recombines immediately after creation
    - Charge collection is done only by one type of carriers (electrons)
    - Polarization effect observed

Literature on sapphire 2/2*

- “Electronic Charge Transport in Sapphire Studied by Optical-Pump THz-Probe Spectroscopy”
  - Temperature dependence of electron mobility studied over wide temperature range (from ambient to cryogenic temperatures) using optical spectroscopy
  - Impurities play a big role in affecting electron mobility
  - Room-temperature electron mobility \mu \sim 600 cm^2/V/s , up to 30’000 at 40K for high purity sapphire while 4’000 if impurities are present

- …

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

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

- 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

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

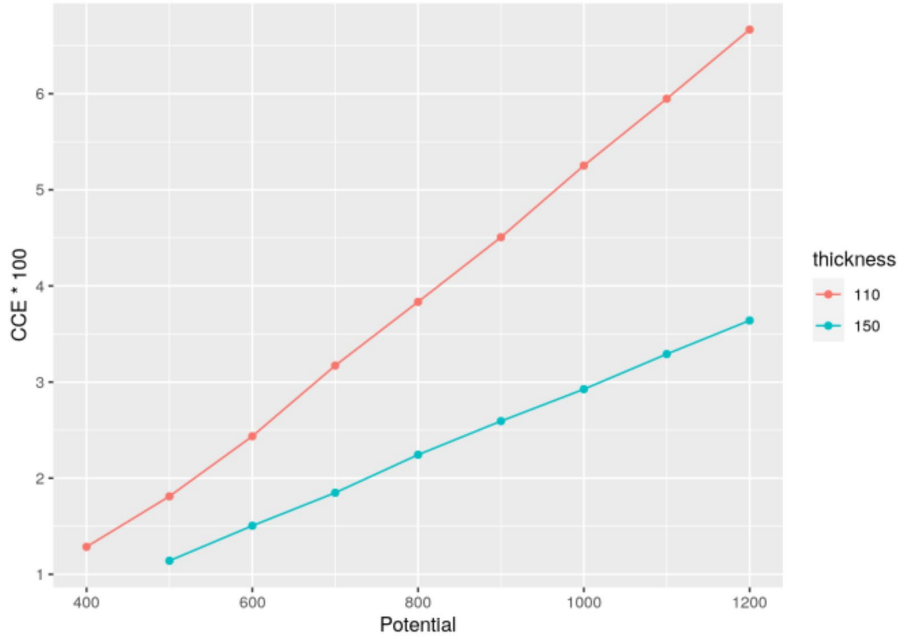
- Extended Canali

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

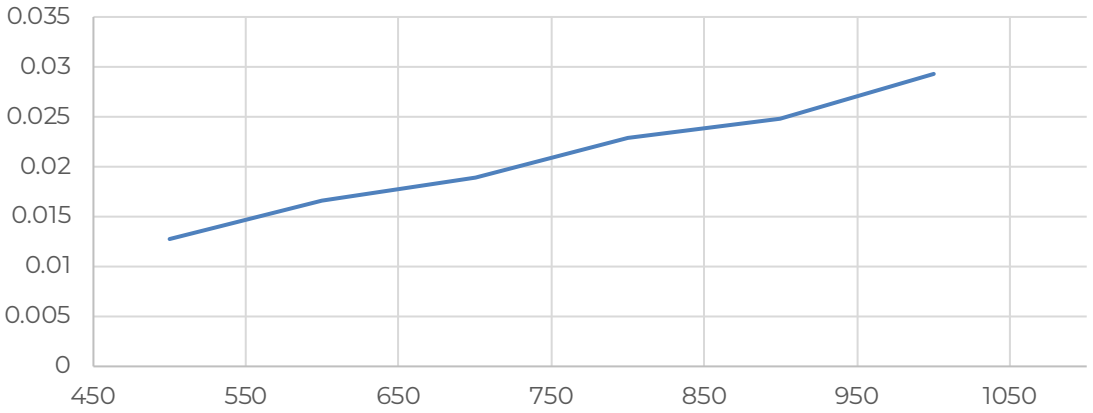
Preliminary conclusions

a. If a constant uniform E-field is used, no suitable built-in model can reproduce the observed CCE behaviour.
b. Custom model with fixed \mu (600 cm2/V/s), \tau (e: 5.8 ns) and constant E-field doesn't agree with the experimental data.
c. Custom model with fixed \mu, \tau and linear E-field agrees better with data. However the CCE is not well described yet.

Experimental data from [M.Morandin slides]



CCE model (c)



Preliminary conclusions

a. Polarisation field is important (in the simulation it is accounted by E-field z-dependence).
b. Hole are not propagated but they might have a role too in this setup.

backup

Conclusions – result b)

- Holes aren't propagated
- Electron mobility value fixed to 600 cm2/V/s
- Electron lifetime: 5.78 ns
- Electric field with parabolic dependence from z-coordinate:
  field_function = "[0]*(z-[1])*(z-[1]) + [2]"
  field_parameters =
  [0] -0.0001V/um/um/um
  [1] 102.5um
  [2] 4.54V/um
  ([2] varies, it is given by V_bias/110 um)