Simulating and improving the compact ion-counting track structure detector

Annual Loma Linda Imaging Workshop 20.07.2022

Irina Kempf irina.kempf@uzh.ch
PhD student at University of Zurich, Switzerland

Universität Zürich[UZH]

Disclosures

This work was supported by the Swiss Federal Nuclear Safety Inspectorate (ENSI, contract CRT00512).

Overview

Nanodosimetry Introduction

Detector Principle

Simulations

Ongoing Challenges

ETH zürich Universität Zürich UZH

Radiotherapy Overview

Cell survival curves

Prescription dose based on data obtained with **photons**

Relative biological effectiveness (RBE)

RBE-weighted dose for other treatment modalities

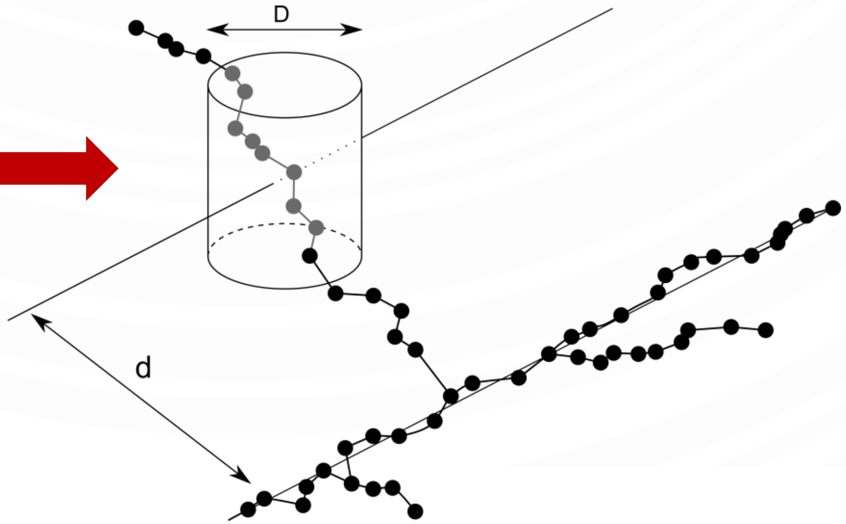
Measurable physical quantity

Biological damage

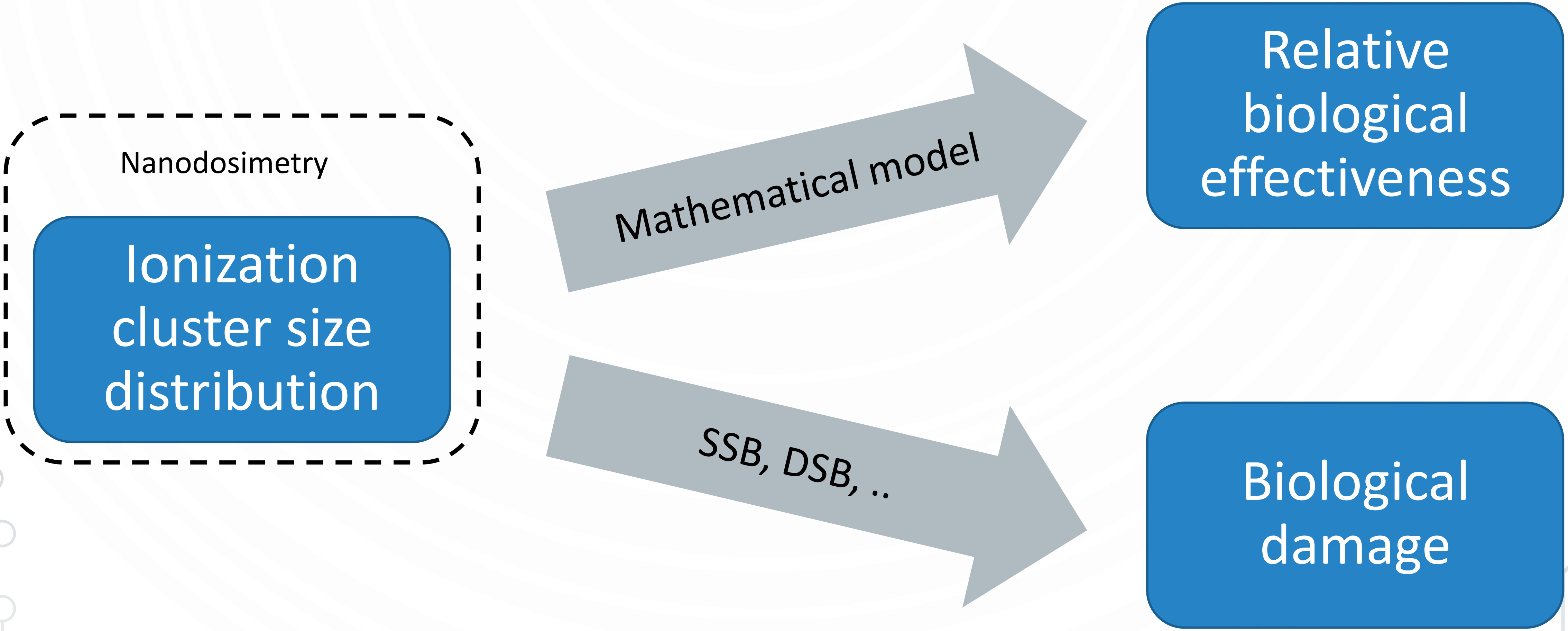
Which Physical Quantity?

Ionizing particle passing through matter → Ionizations in nanometric volume ≙ DNA → Biological damage

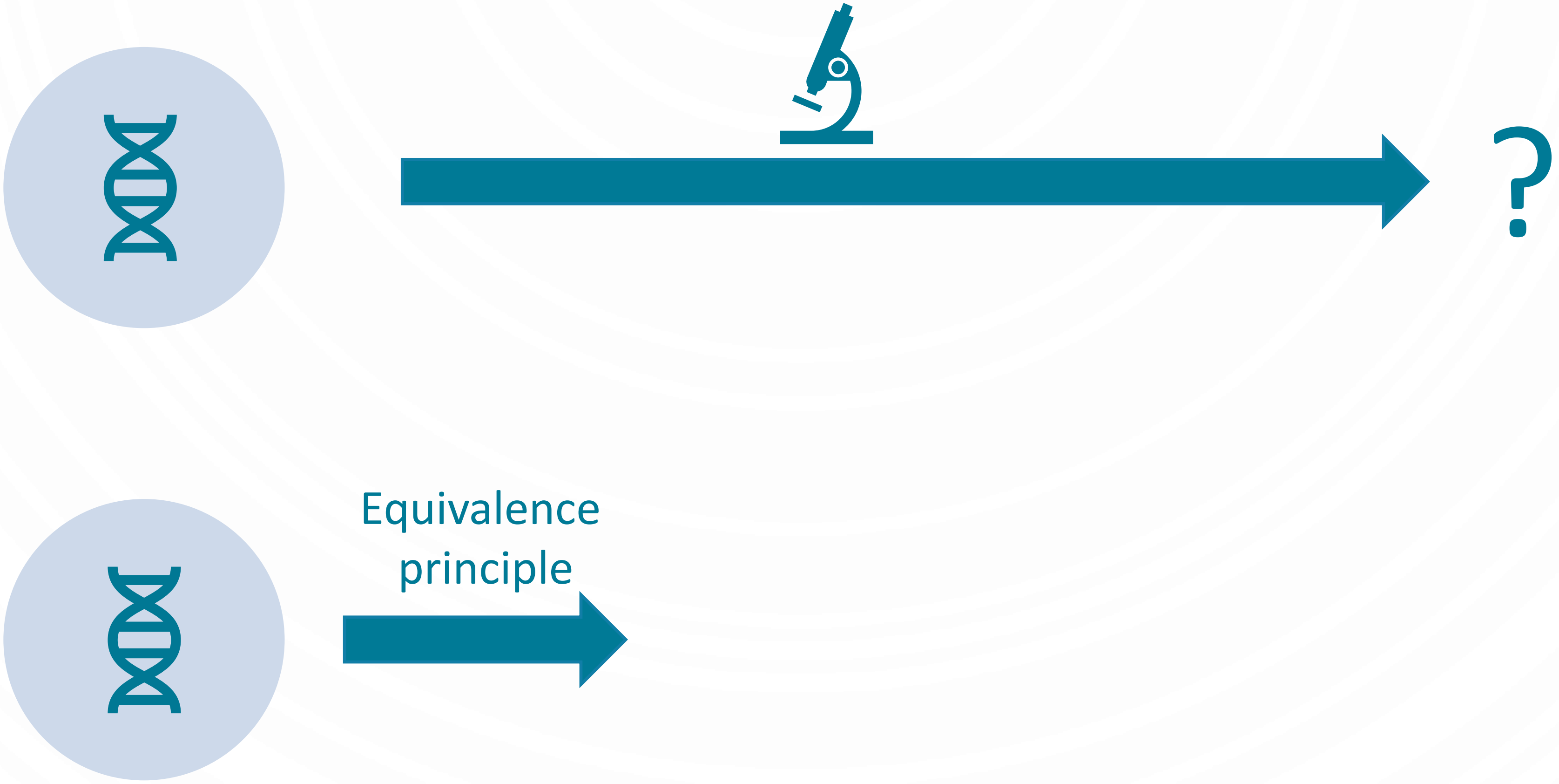
SSB?
DSB?
..?



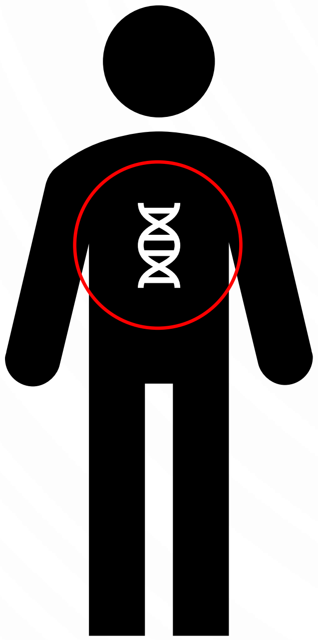
Nanodosimetry



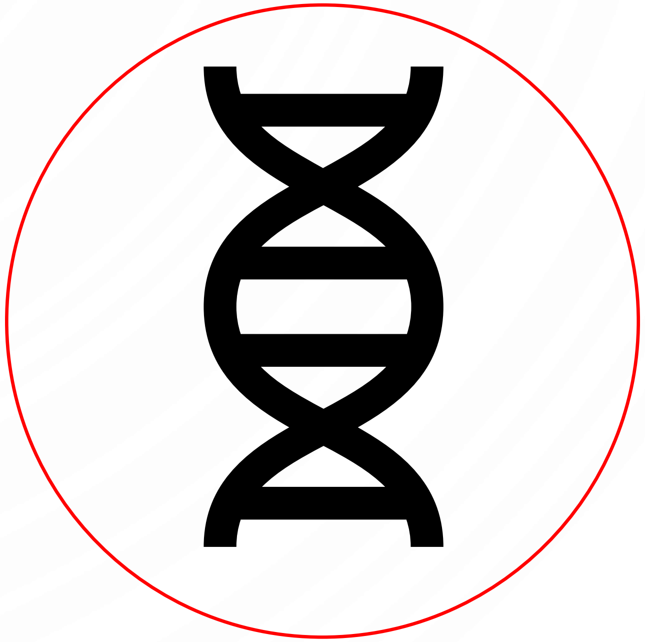
How can we observe on a nanometric scale?



Equivalence principle



Spatial ionisation distribution scales linearly with **density**



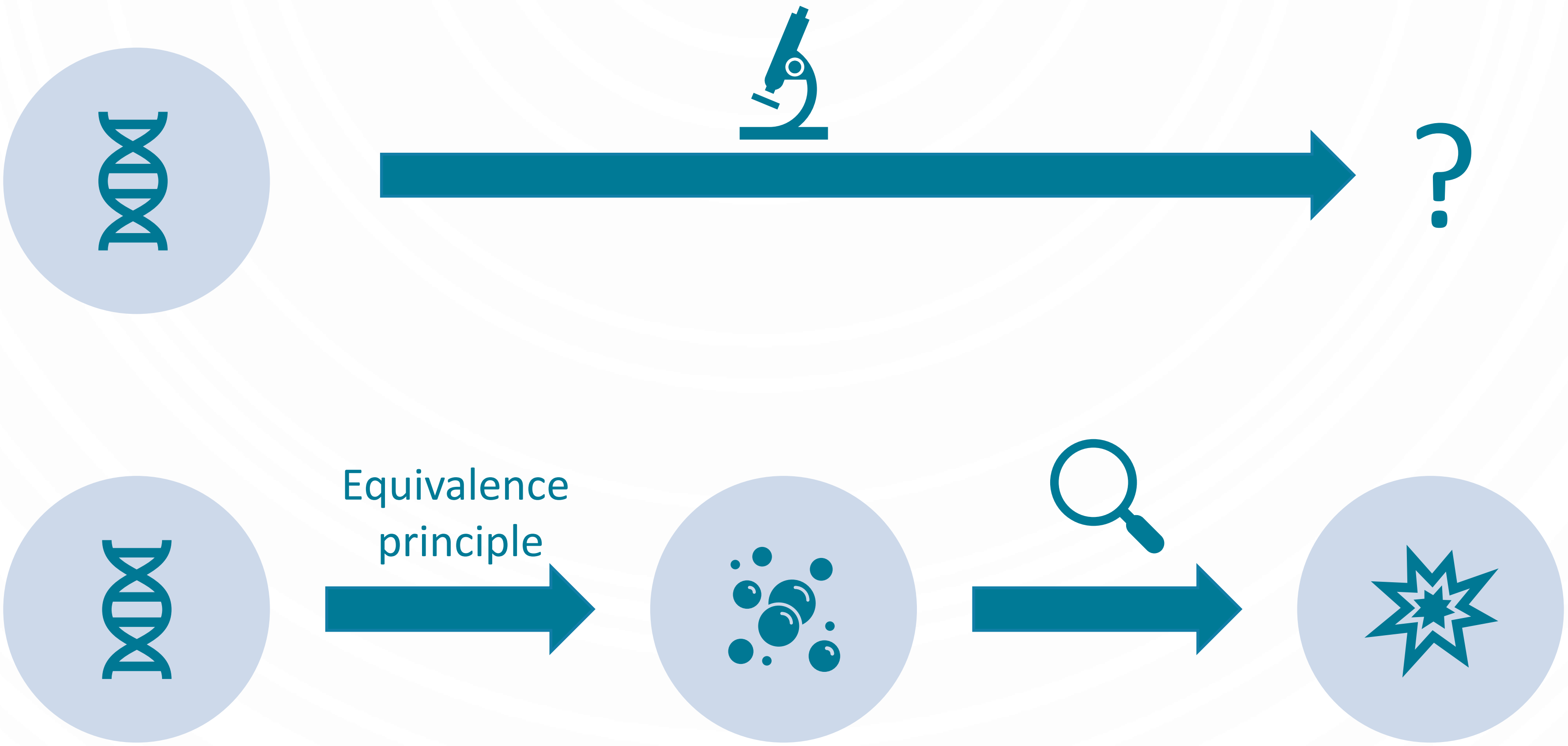
Microscopic volume

Liquid water

Macroscopic volume

Low pressure gas

How can we observe on a nanometric scale?



History

TIDe imaging detector

(**T**rack **I**maging **De**tector)

Developed by Vladimir Bashkirov and Reinhard Schulte at Loma Linda University

Further developed by Margeritha Casiraghi at Loma Linda University, PSI and Gaseous Detector Development Laboratory CERN.

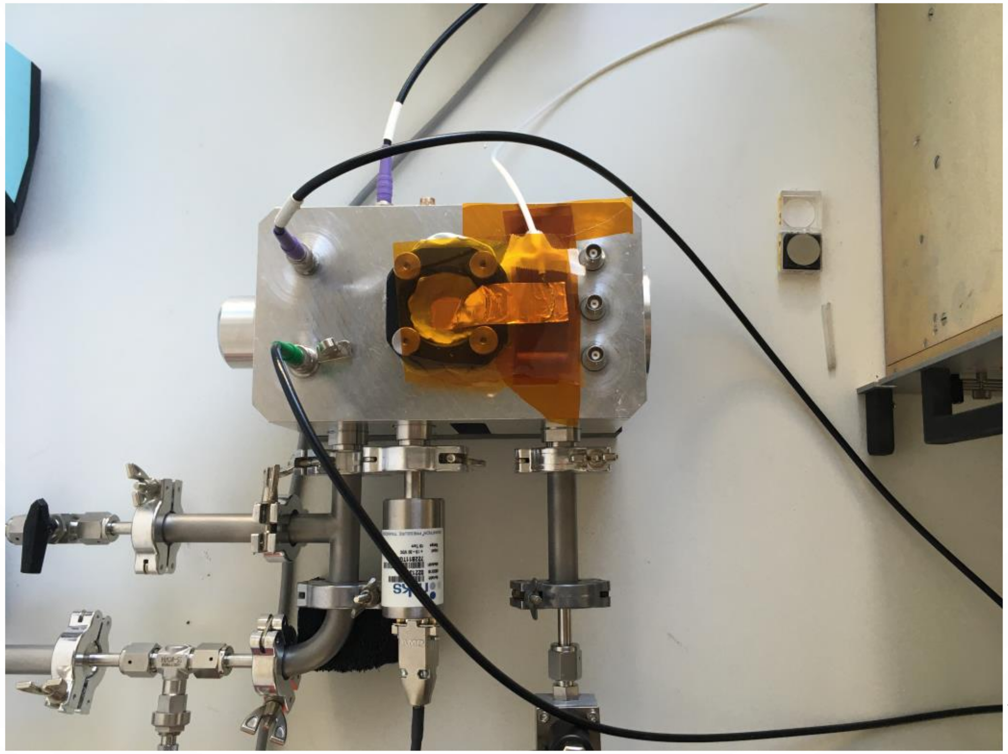
FIRE detector

(**F**requency of **I**on **Re**gistration)

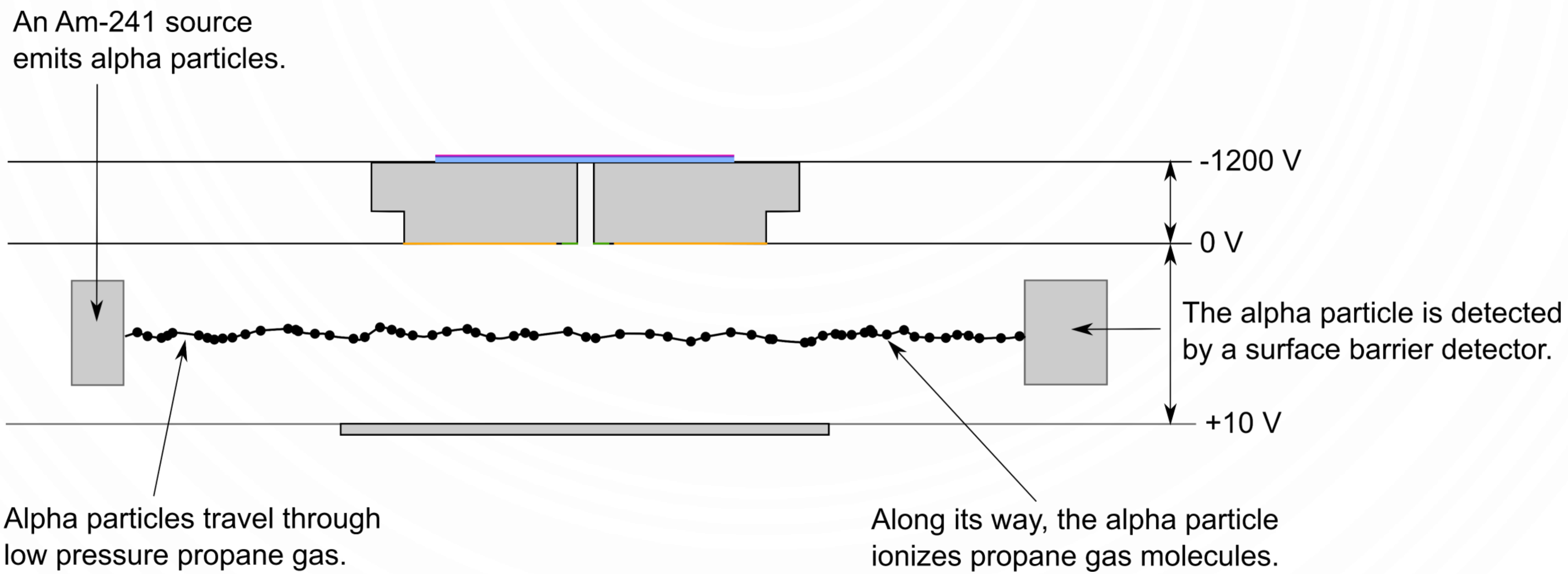
Continued development by Fabiano Vasi during his PhD

Further development of FIRE detector during PhD of Irina Kempf

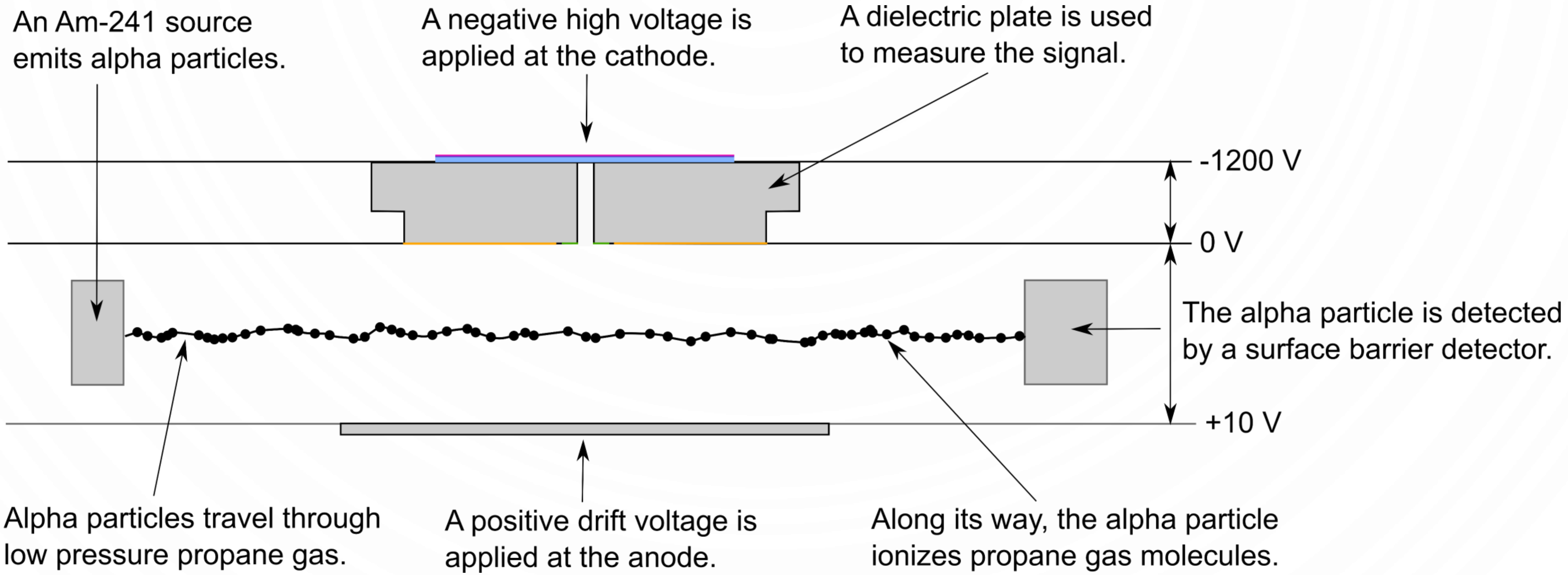
How does the nanodosimetric detector work?



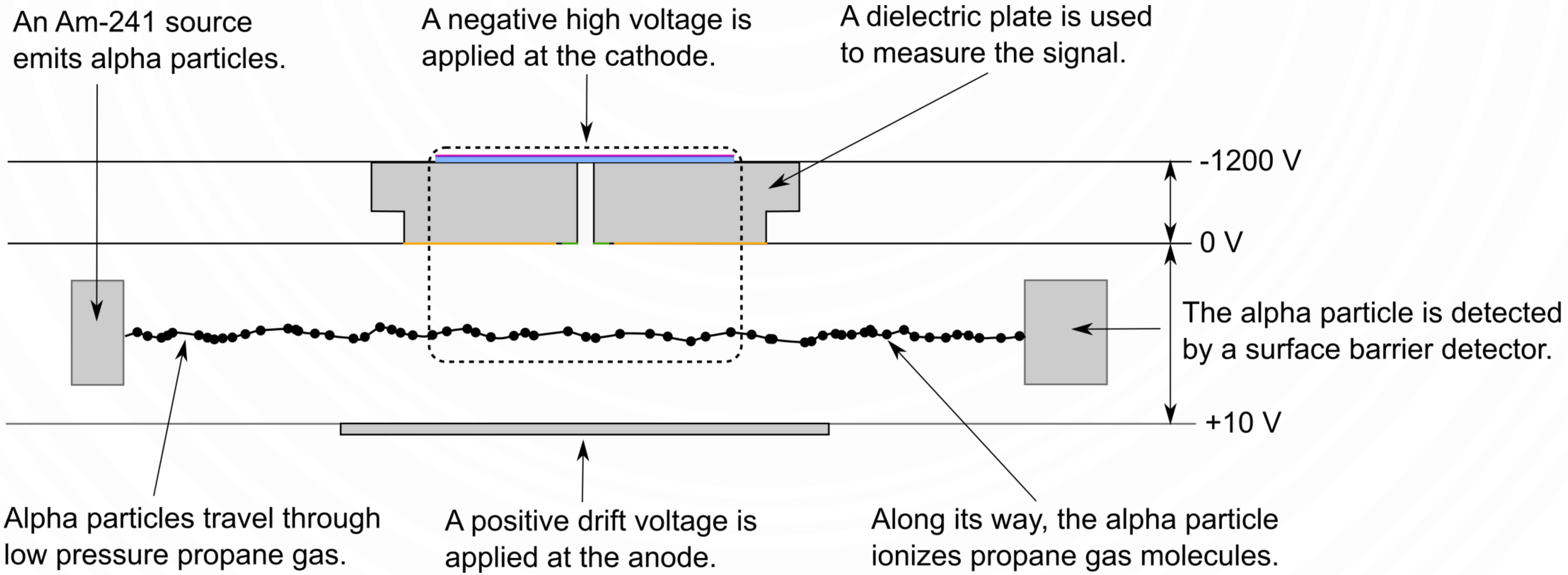
What is inside the chamber?



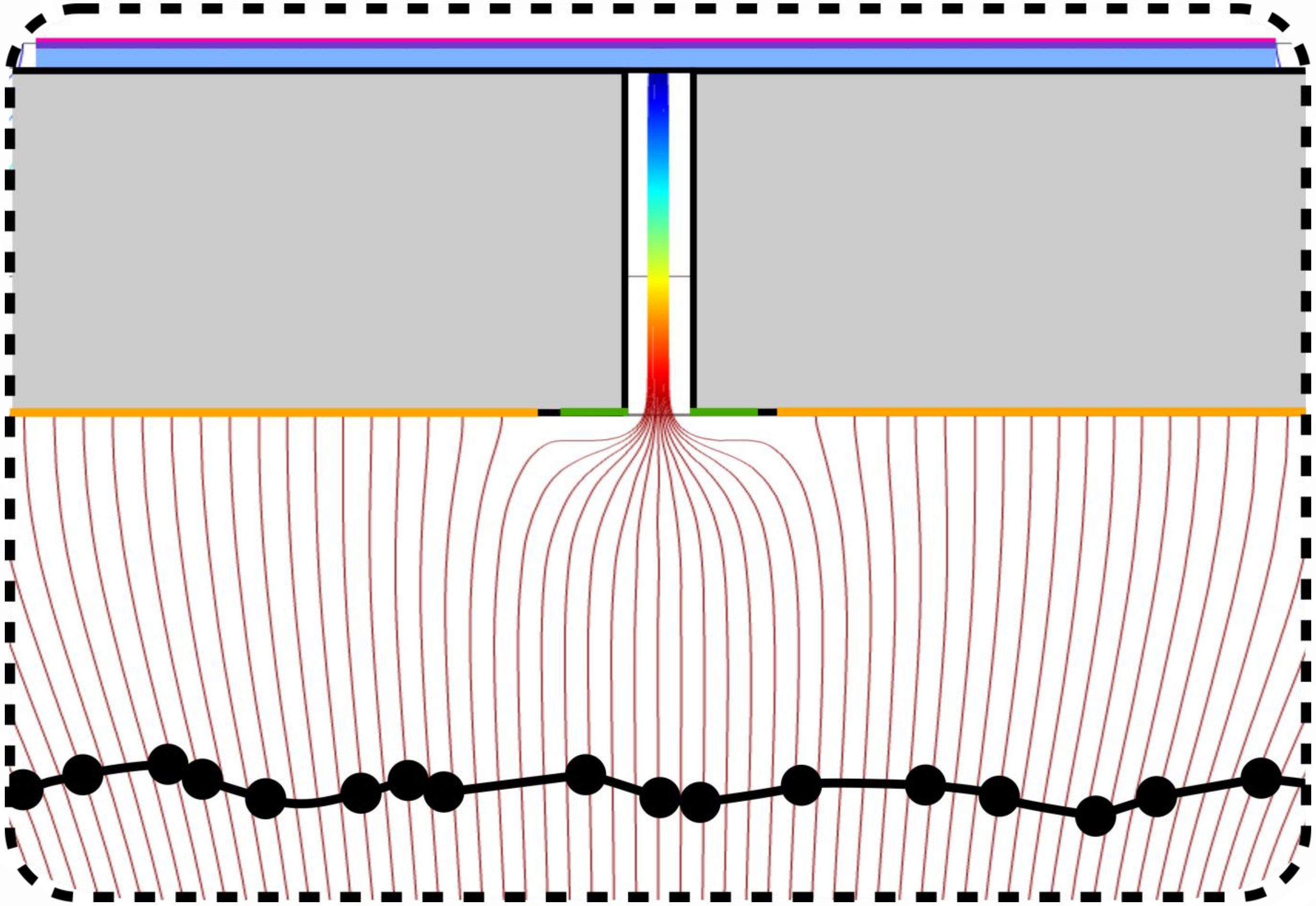
What is inside the chamber?



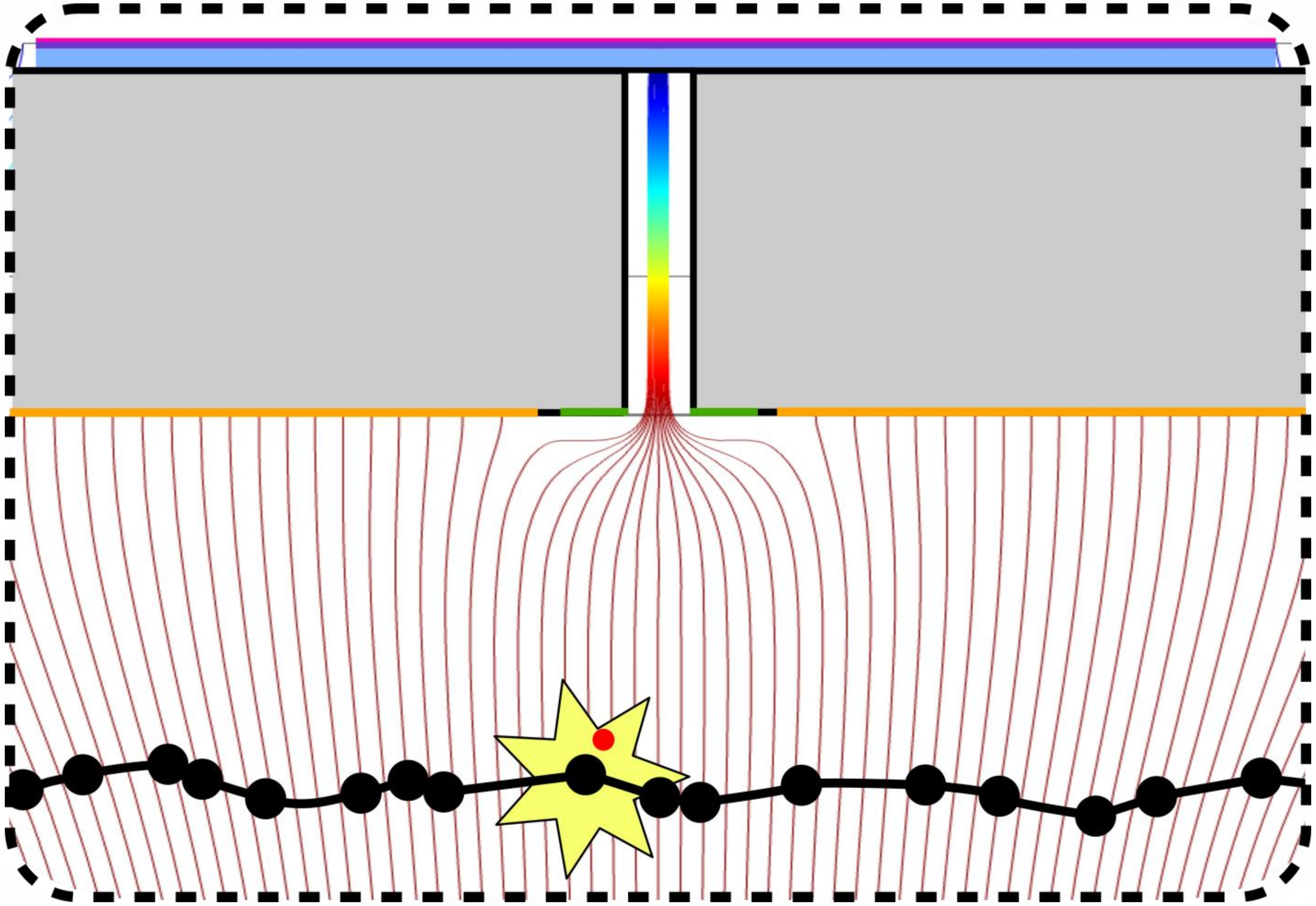
What is inside the chamber?



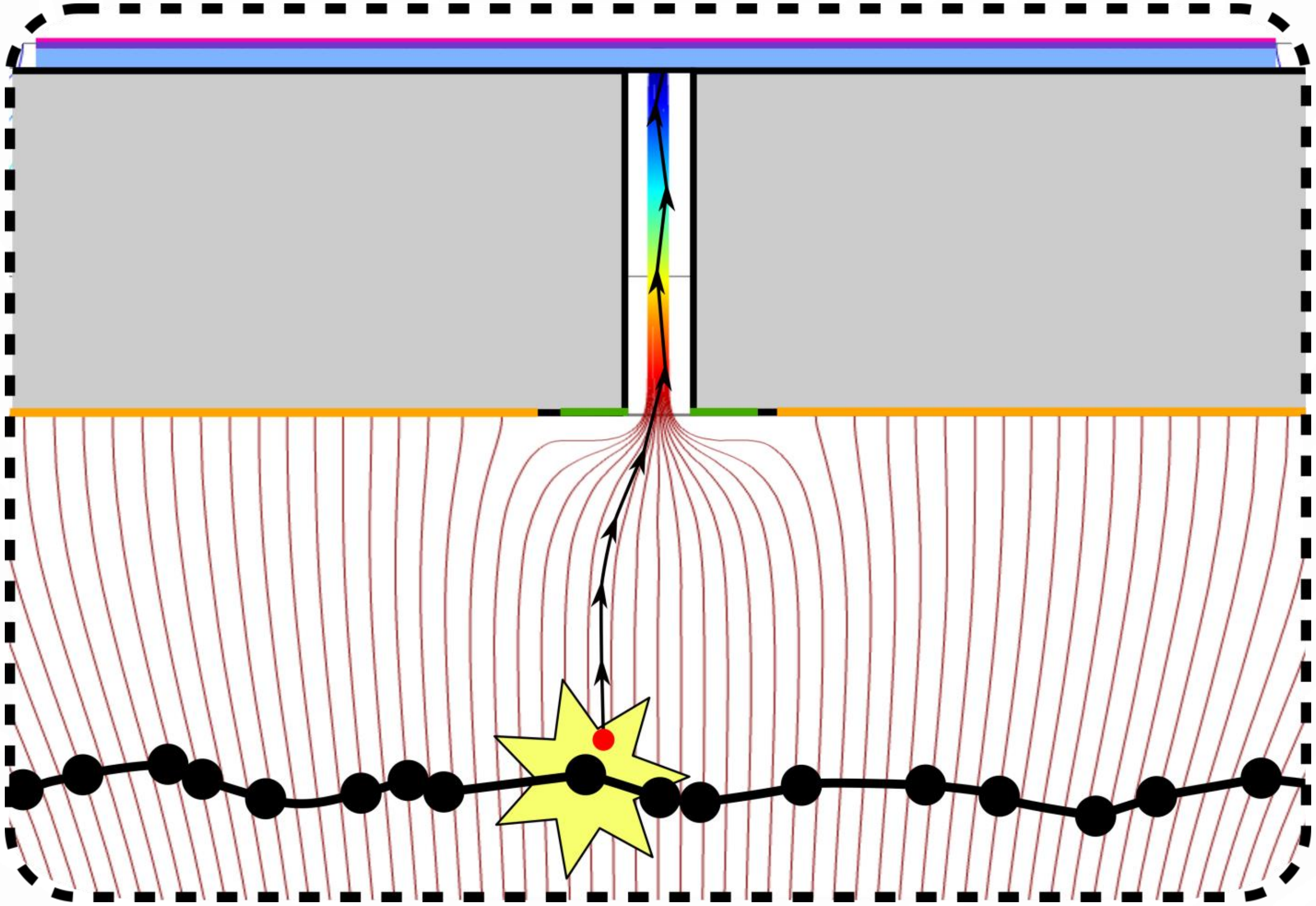
How is the signal produced?



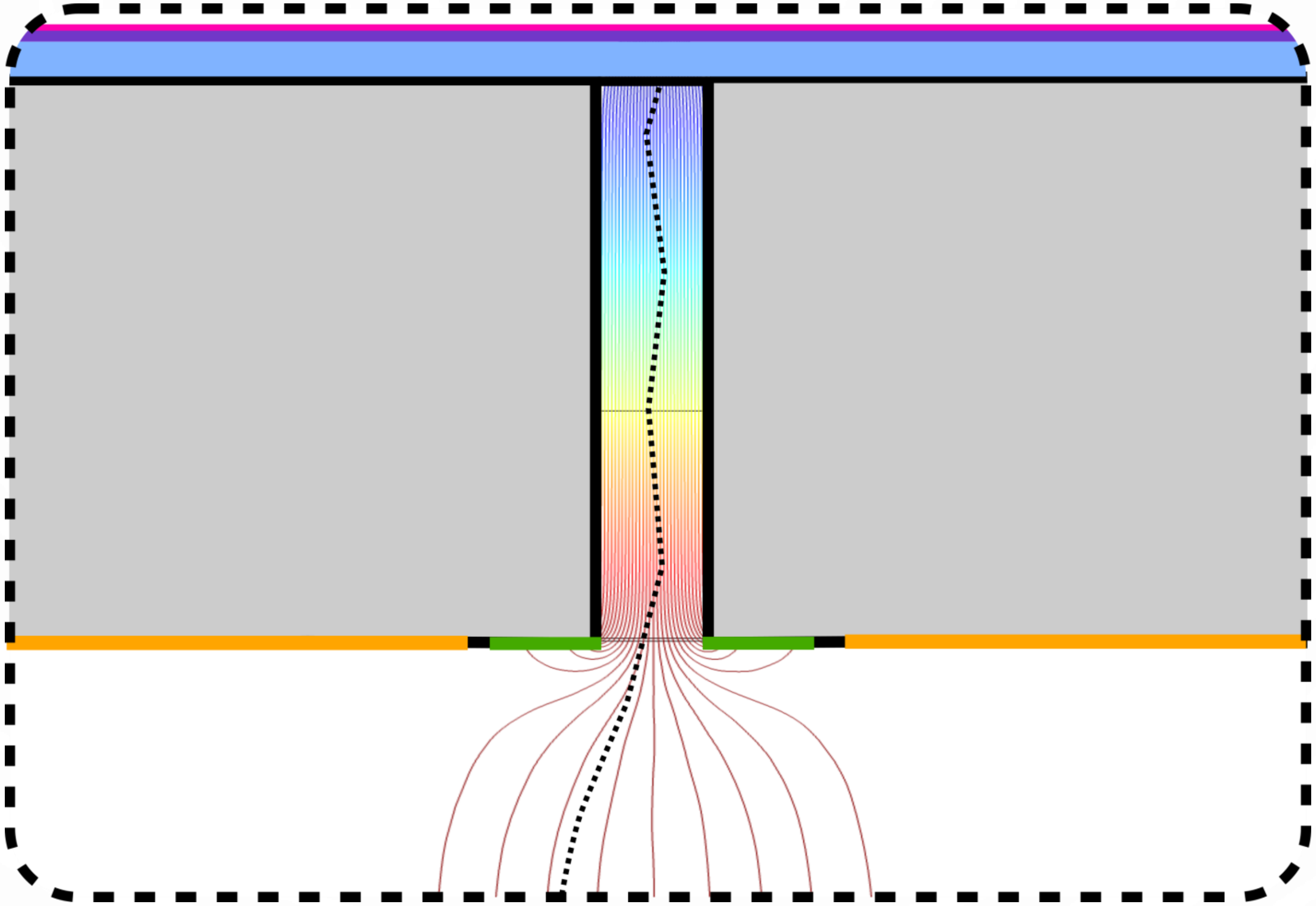
How is the signal produced?



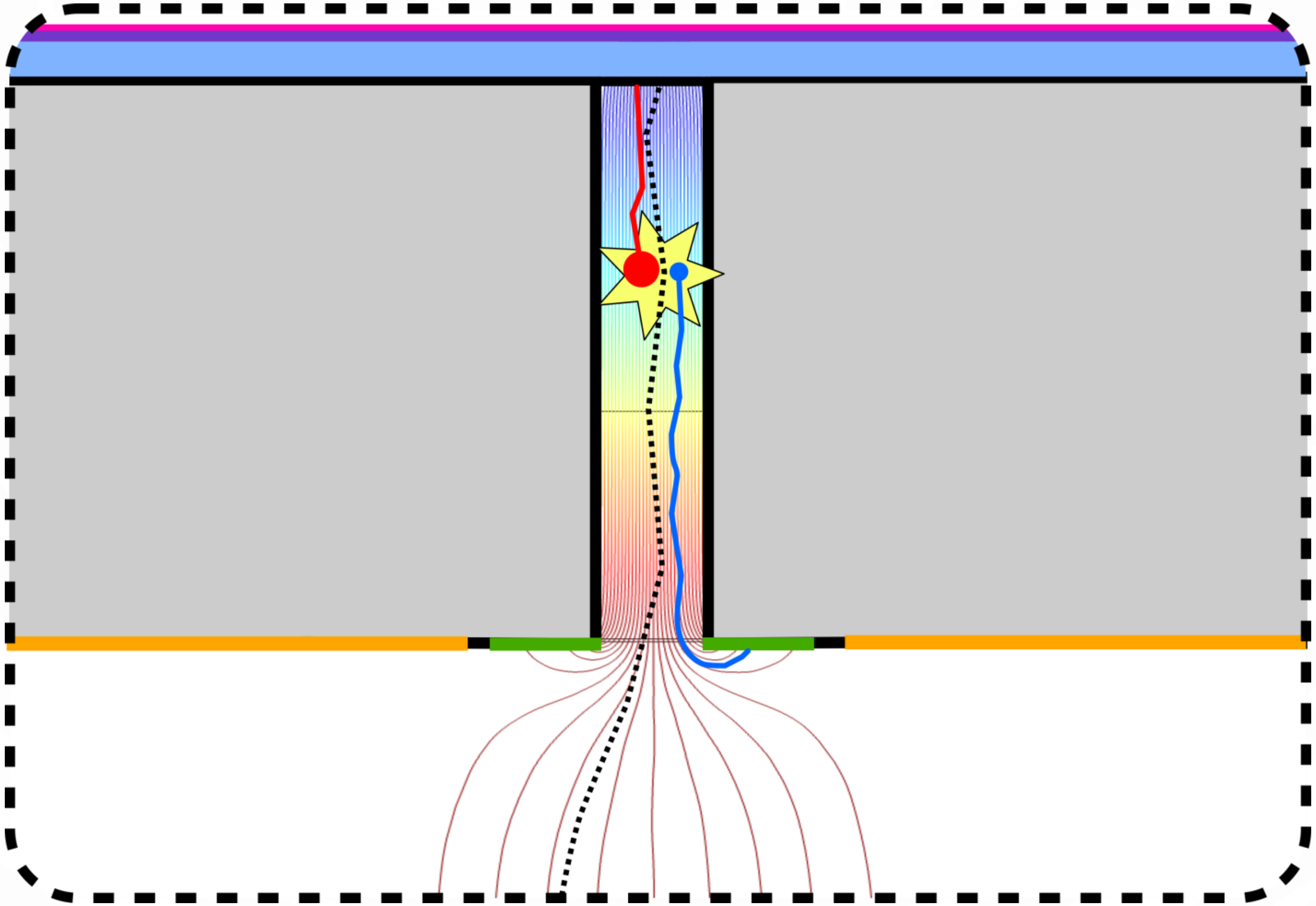
How is the signal produced?



How is the signal produced?



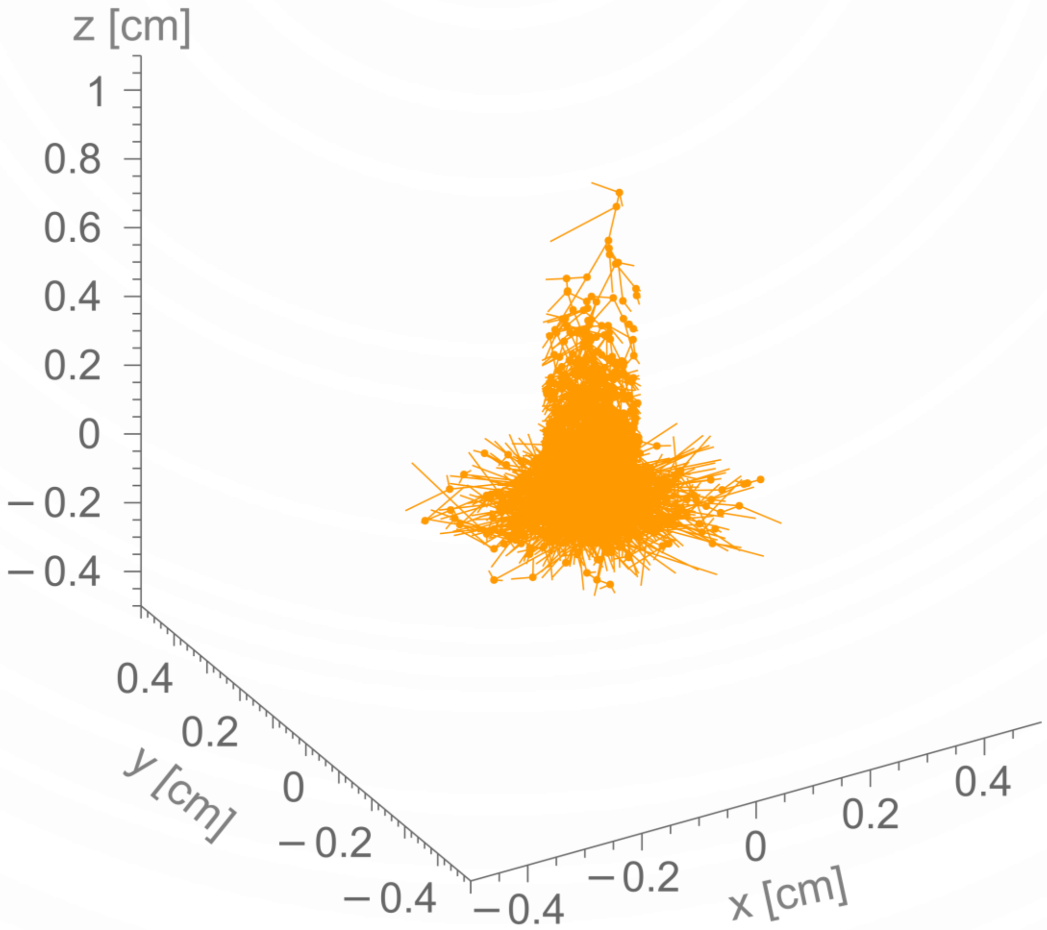
How is the signal produced?



How is the signal produced? Electron Avalanche

3D view of Monte Carlo simulation of Electron Avalanche

Electric fields calculated with COMSOL Multiphysics, MC Simulation based on Garfield++ (CERN).



Simulations

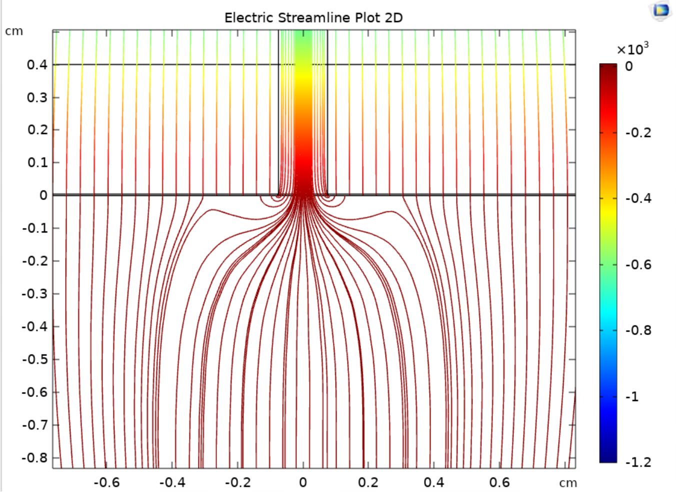
Simulation Overview

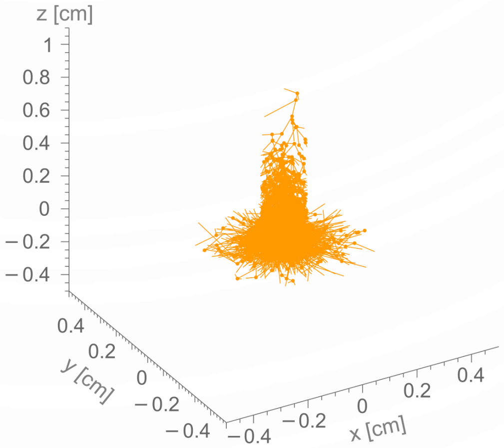
COMSOL Multiphysics → (Electric Field, Mesh) → Garfield++ (CERN)

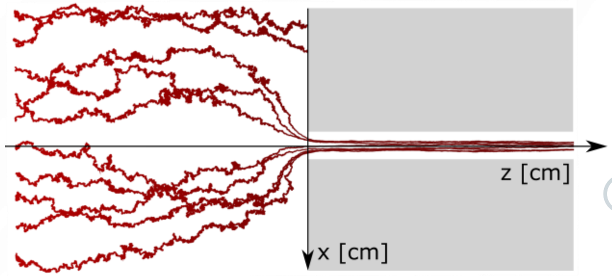
COMSOL Multiphysics → Simulation of electrostatic Fields

Garfield++ (CERN) → Electron avalanche simulations

Garfield++ (CERN) → Ion drift simulations







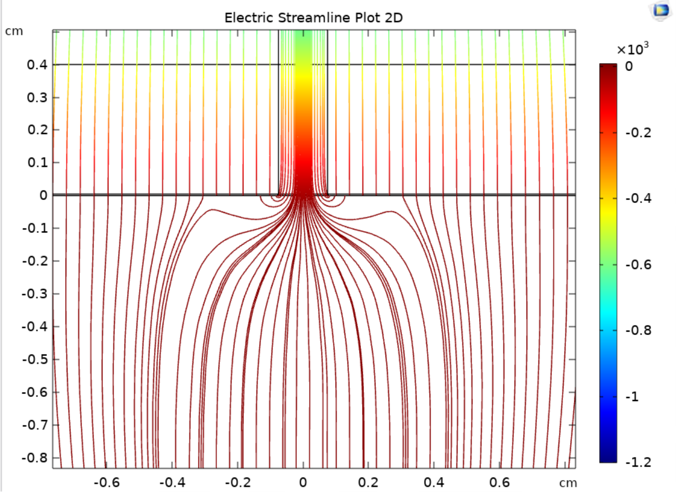
Simulation Overview

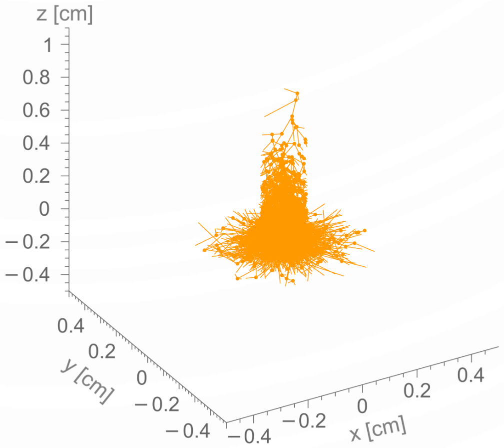
COMSOL Multiphysics → (Electric Field, Mesh) → Garfield++ (CERN)

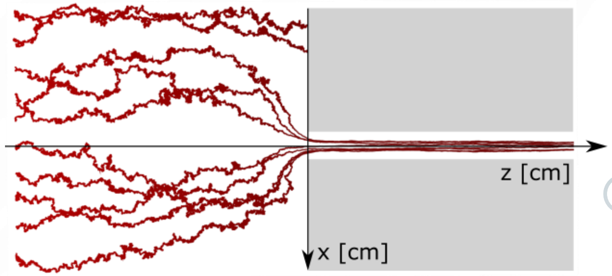
COMSOL Multiphysics → Simulation of electrostatic Fields

Garfield++ (CERN) → Electron avalanche simulations

Garfield++ (CERN) → Ion drift simulations

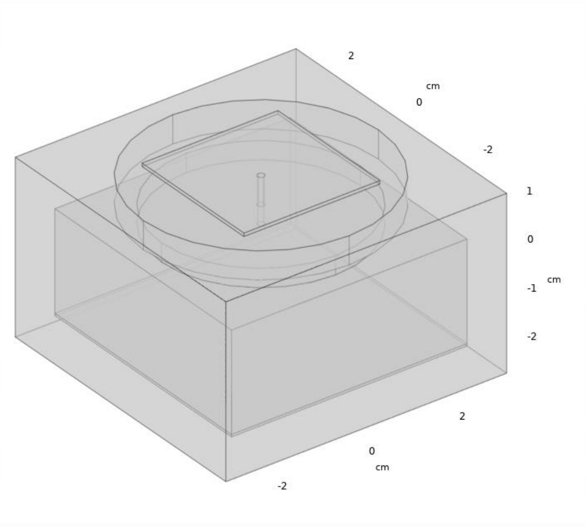






Electric Field Calculations with COMSOL

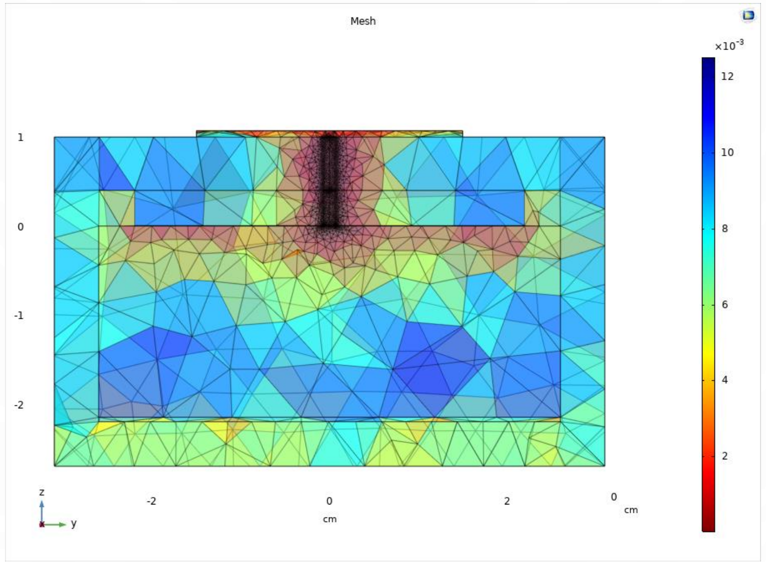
Create 3D model of detector



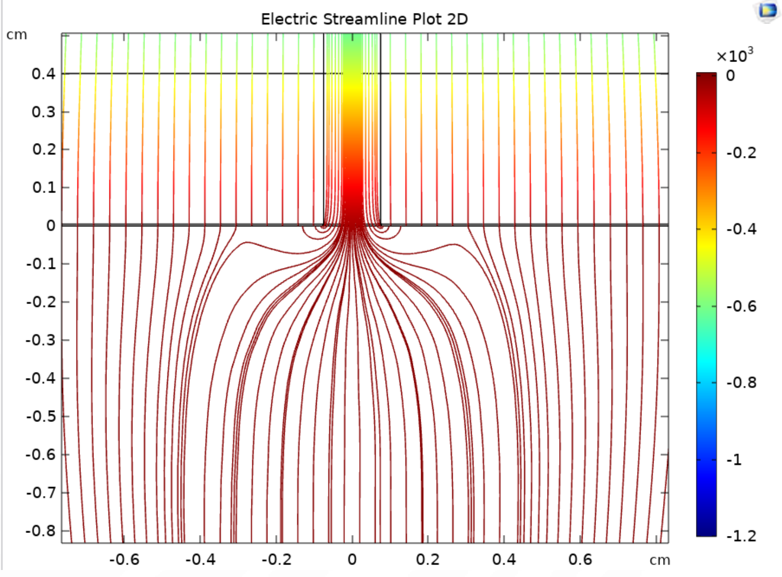
Input Parameters

Name	Expression
GEM_radius_hole	0.075
GEM_Rim_Hole	0.002
GEM_thickness_total	2

Create meshing



Calculate electric field



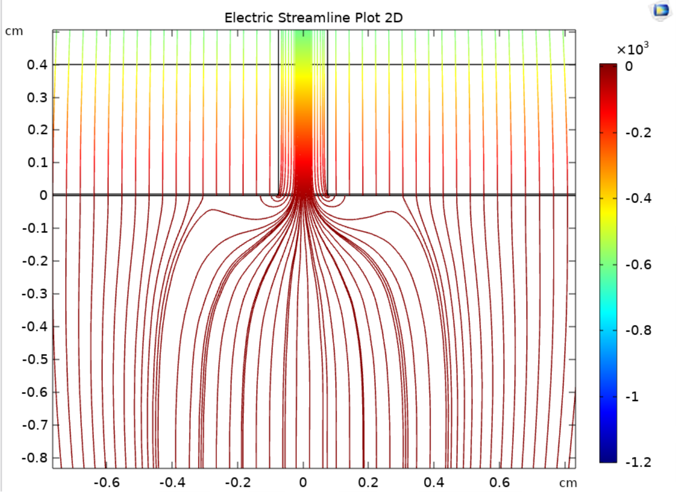
Simulation Overview

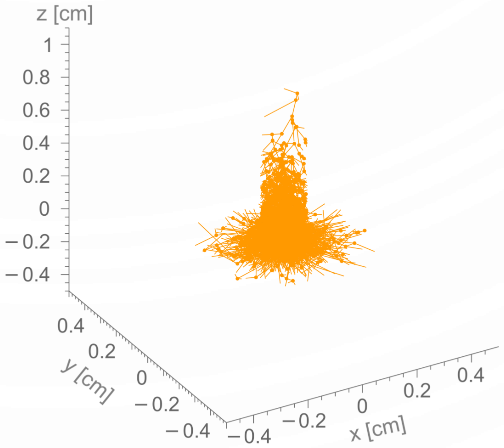
COMSOL Multiphysics → Electric Field Mesh → Garfield++ (CERN)

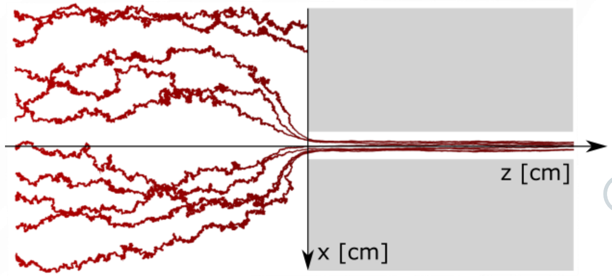
COMSOL Multiphysics → Simulation of electrostatic Fields

Garfield++ (CERN) → Electron avalanche simulations

Garfield++ (CERN) → Ion drift simulations







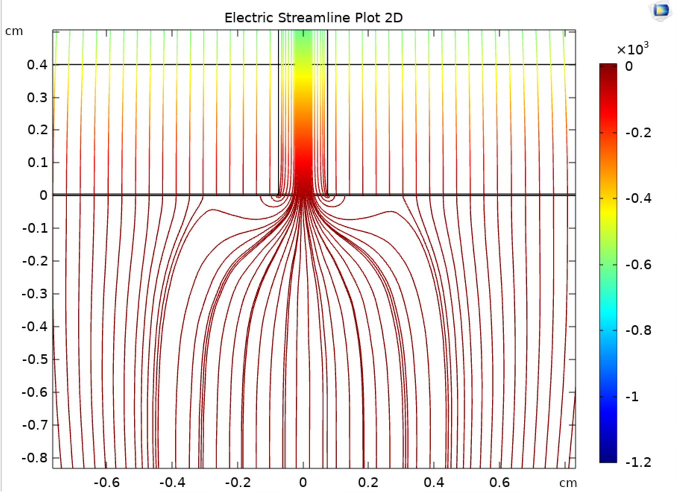
Simulation Overview

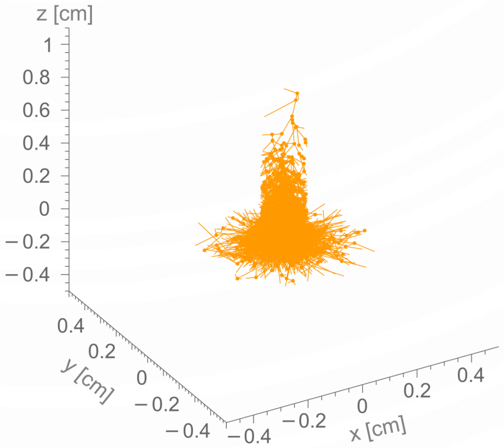
COMSOL Multiphysics → (Electric Field, Mesh) → Garfield++ (CERN)

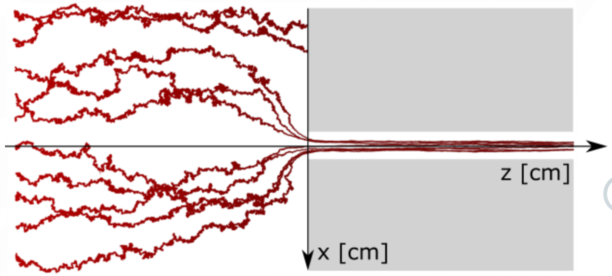
COMSOL Multiphysics → Simulation of electrostatic Fields

Garfield++ (CERN) → Electron avalanche simulations

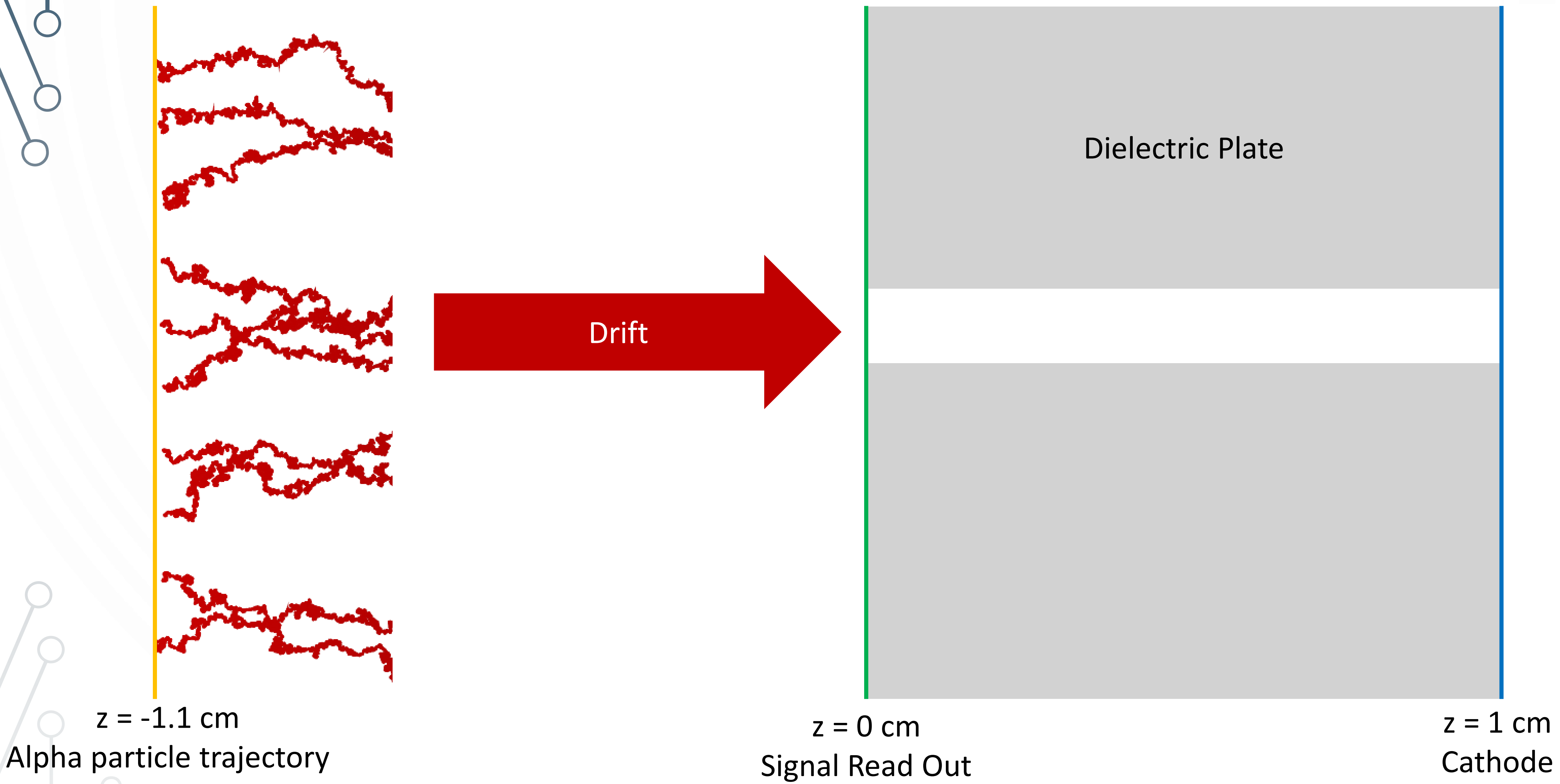
Garfield++ (CERN) → Ion drift simulations



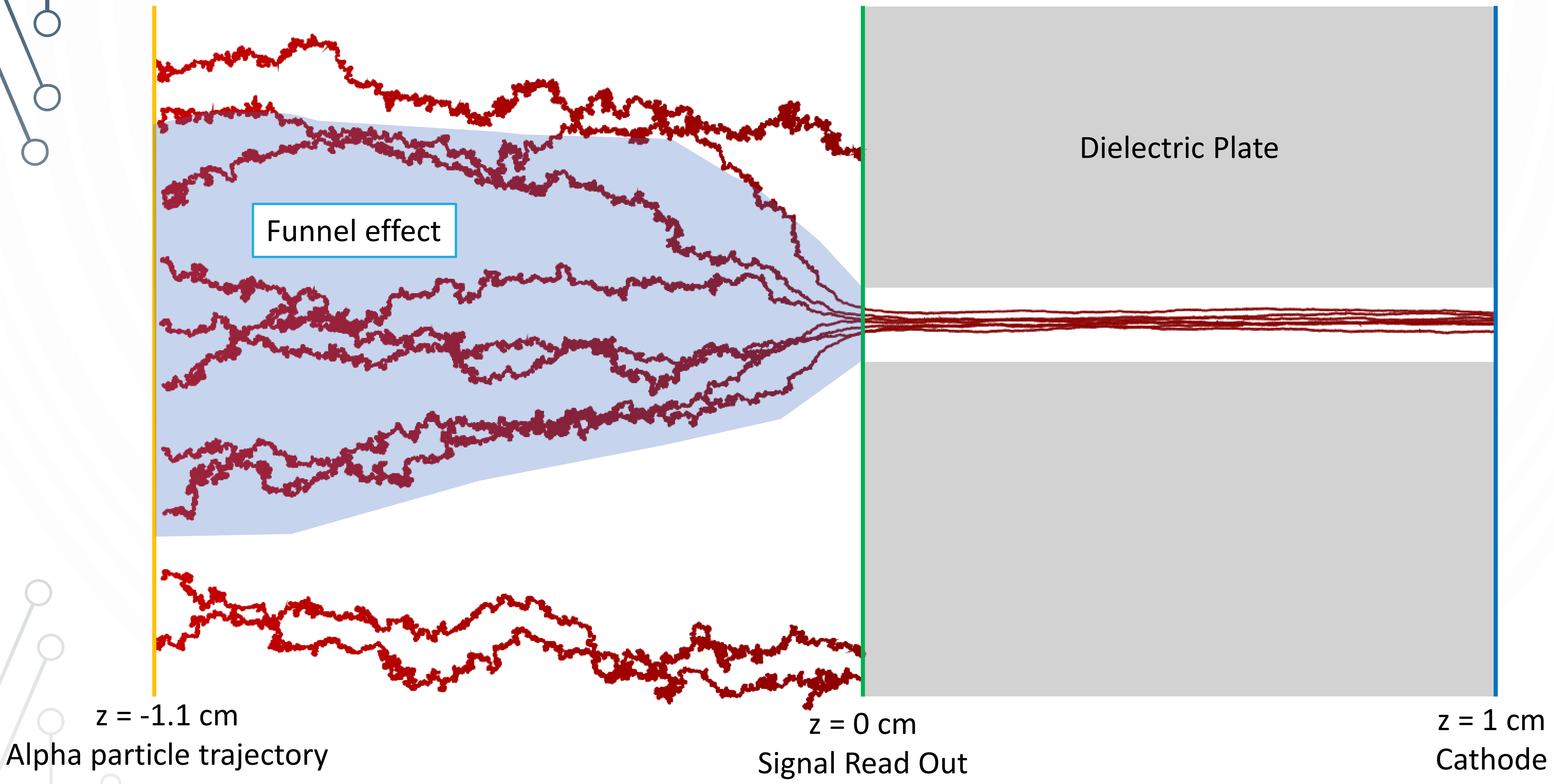




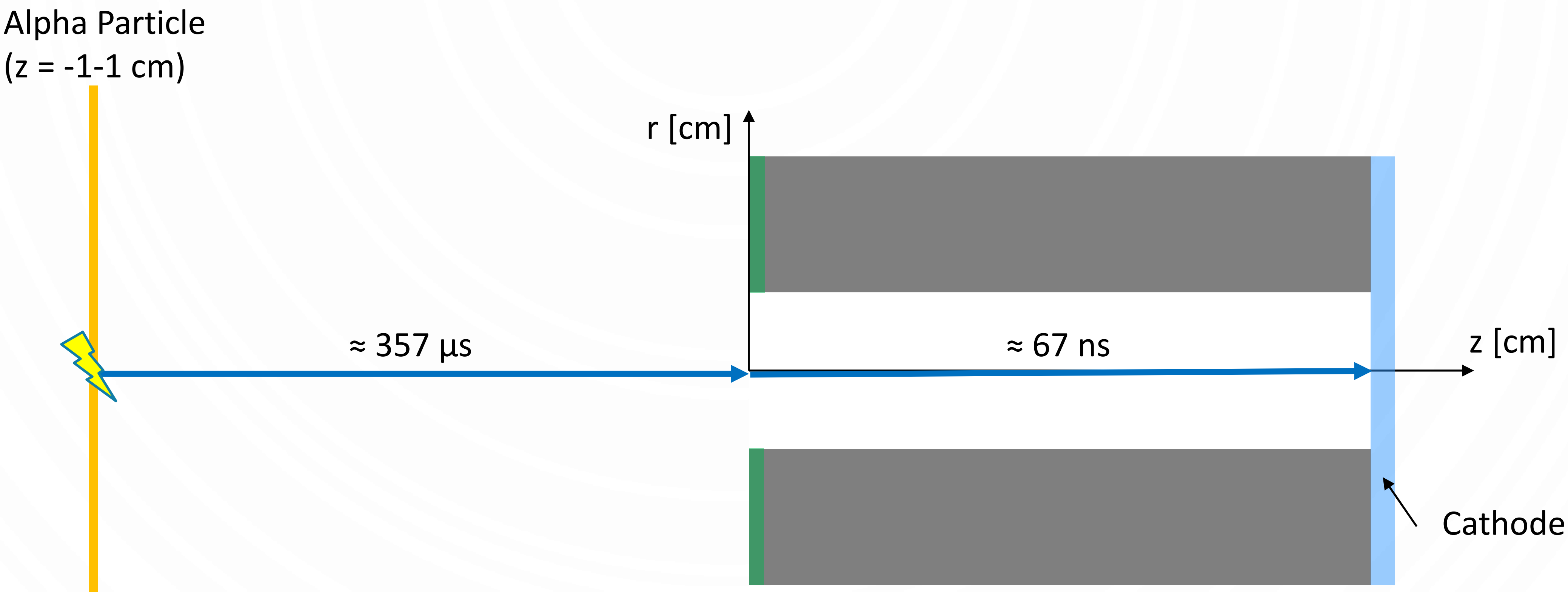
Ion Drift Simulations

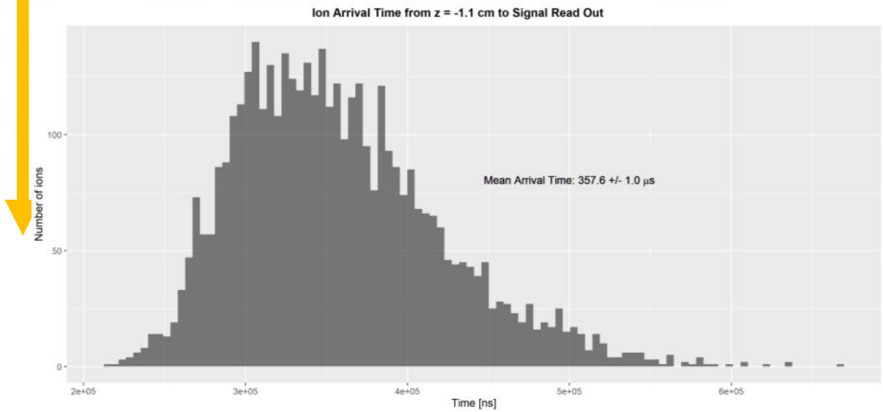


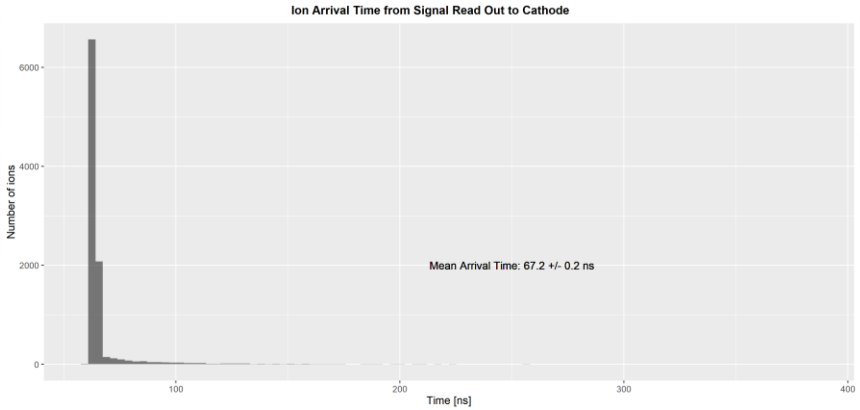
Ion Drift Simulations



How long is ion drifting within hole?







Problem: Mobility data for propane gas

- Garfield++ requires mobility data
- There is no dataset for propane mobility at low pressures & for our electric field.

We must assume a mobility value.

We can not interpret ion arrival time simulation results.

The ion funnel effect is independent of the mobility.

```
# ------------------------------------------------------------------
# Mobility of CO2+ ions in CO2 measured for T=303 K
# Accuracy: 4 %
# Data from Atomic Data and Nuclear Data Tables 60, 37-95 (1995)
# L.A.Viehland and E.A.Mason
# Electric Field in Td (E/N) (multiply by 250 for V
# ------------------------------------------------------------------
  50   1.26
  60   1.25
  70   1.25
  80   1.24
 100   1.21
 120   1.19
 140   1.16
 170   1.12
 200   1.08
 250   1.03
 300   1.00
 350   0.96
 400   0.94
 500   0.89
 600   0.85
 800   0.79
1000   0.75
1200   0.72
```

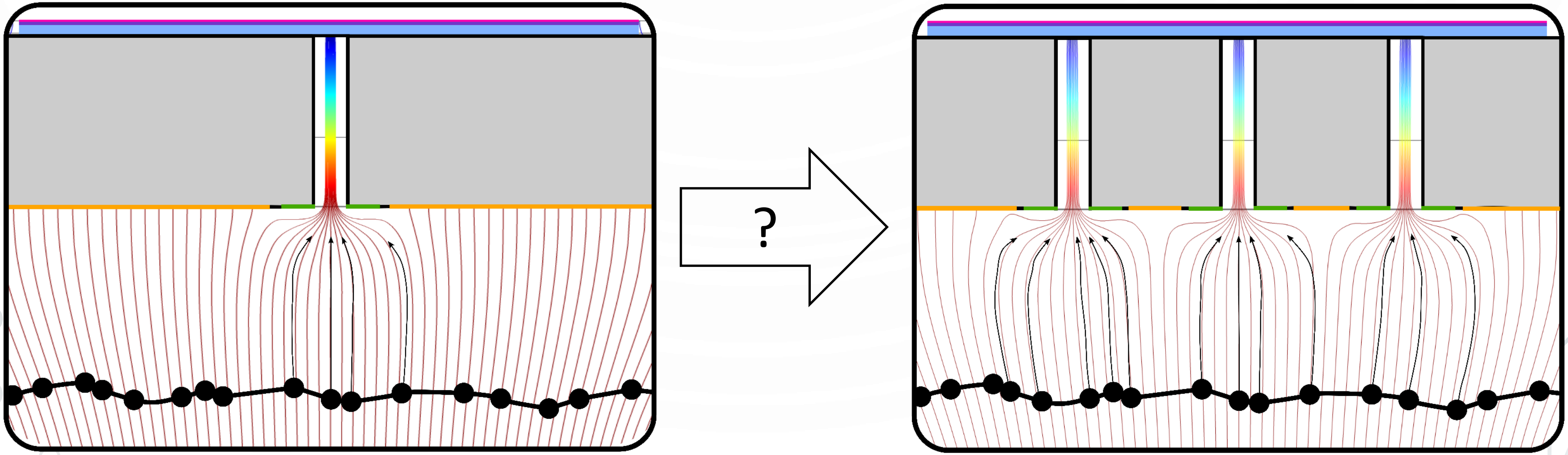
(Reduced mobilities)

$$K_0 = \frac{p\,[Torr]}{760}\frac{273}{T\,[K]}K$$

Multi-hole detector design

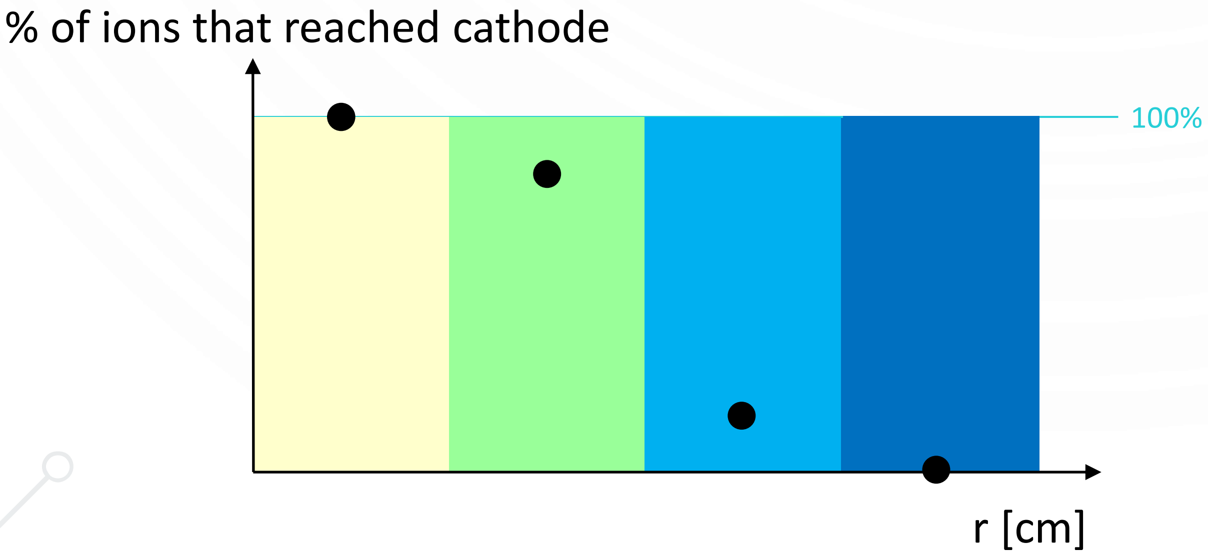
Current: The FIRE detector measures the frequency of ion registration with a single hole.
Future: Analyze ionization tracks with multi-hole detector.

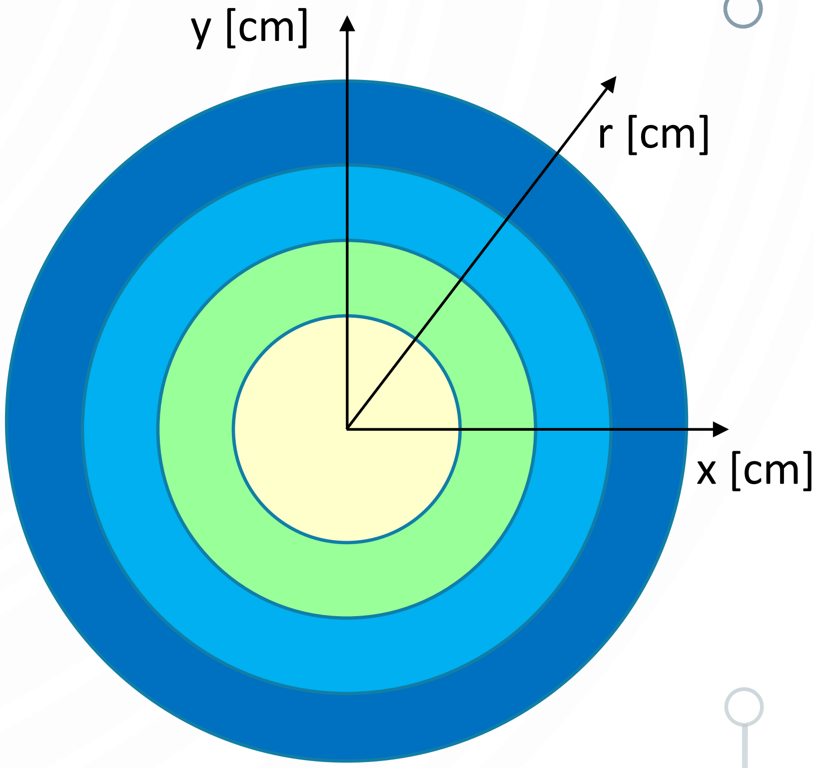
→ How should a multi-hole detector be designed?



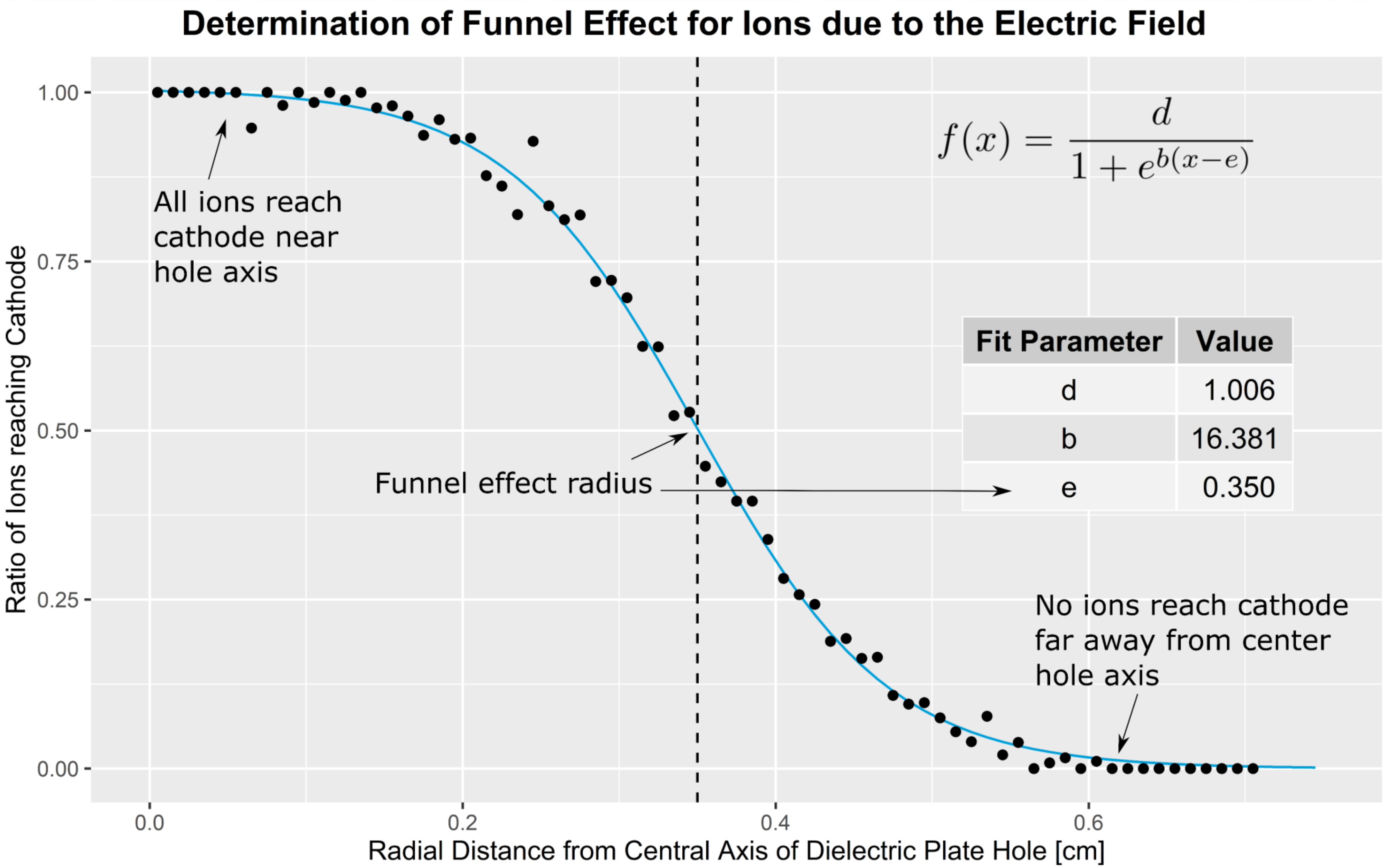
Funnel size

- Setup is radially symmetric
- For each annulus calculate:
  - «How many ions that started within this annulus reached the cathode?»
- Plot as a function of radius





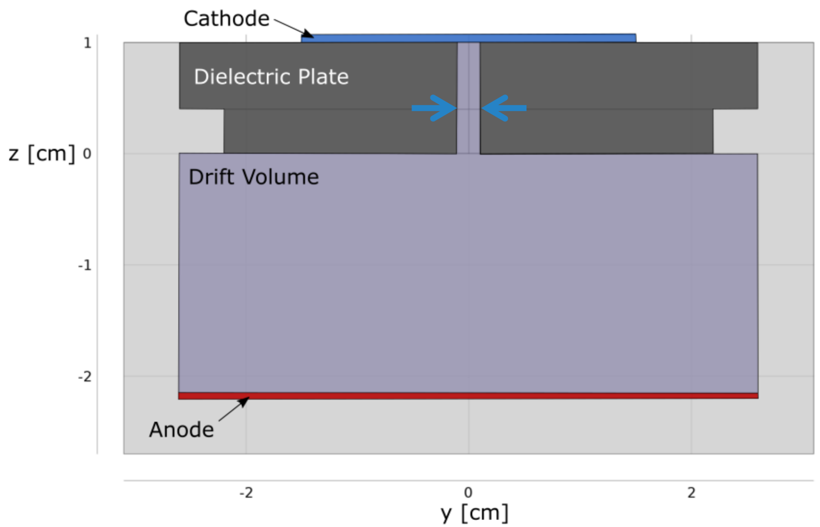
Funnel size – Logistic fit to simulation data

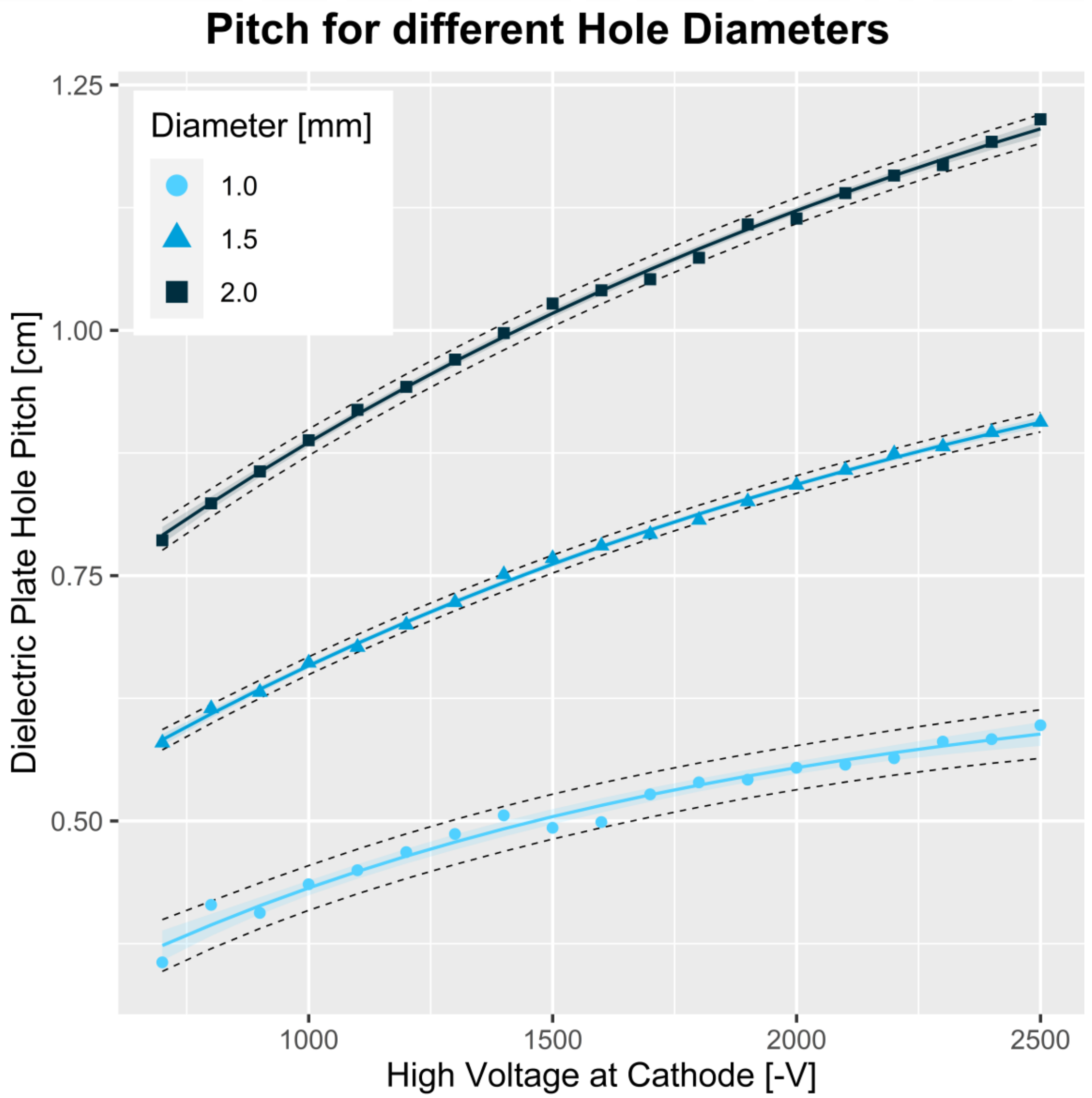


Hole diameter

Funnel effect is proportional to hole radius.

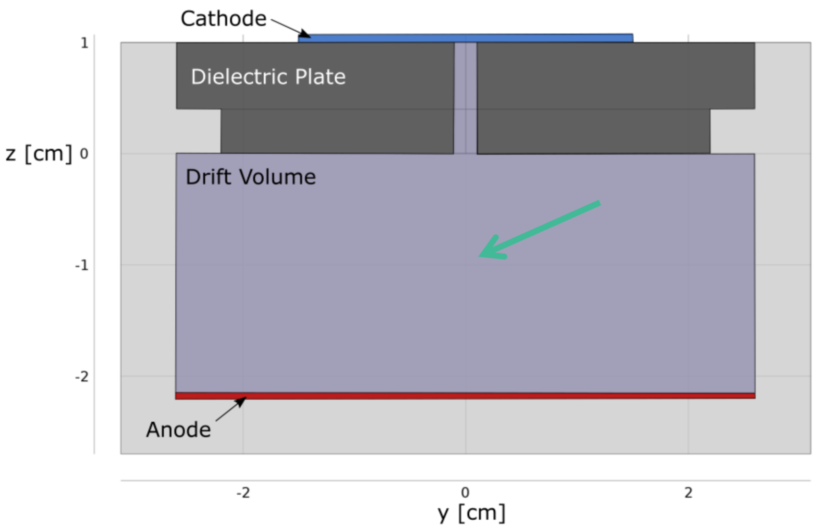
Larger diameter → larger funnel effect

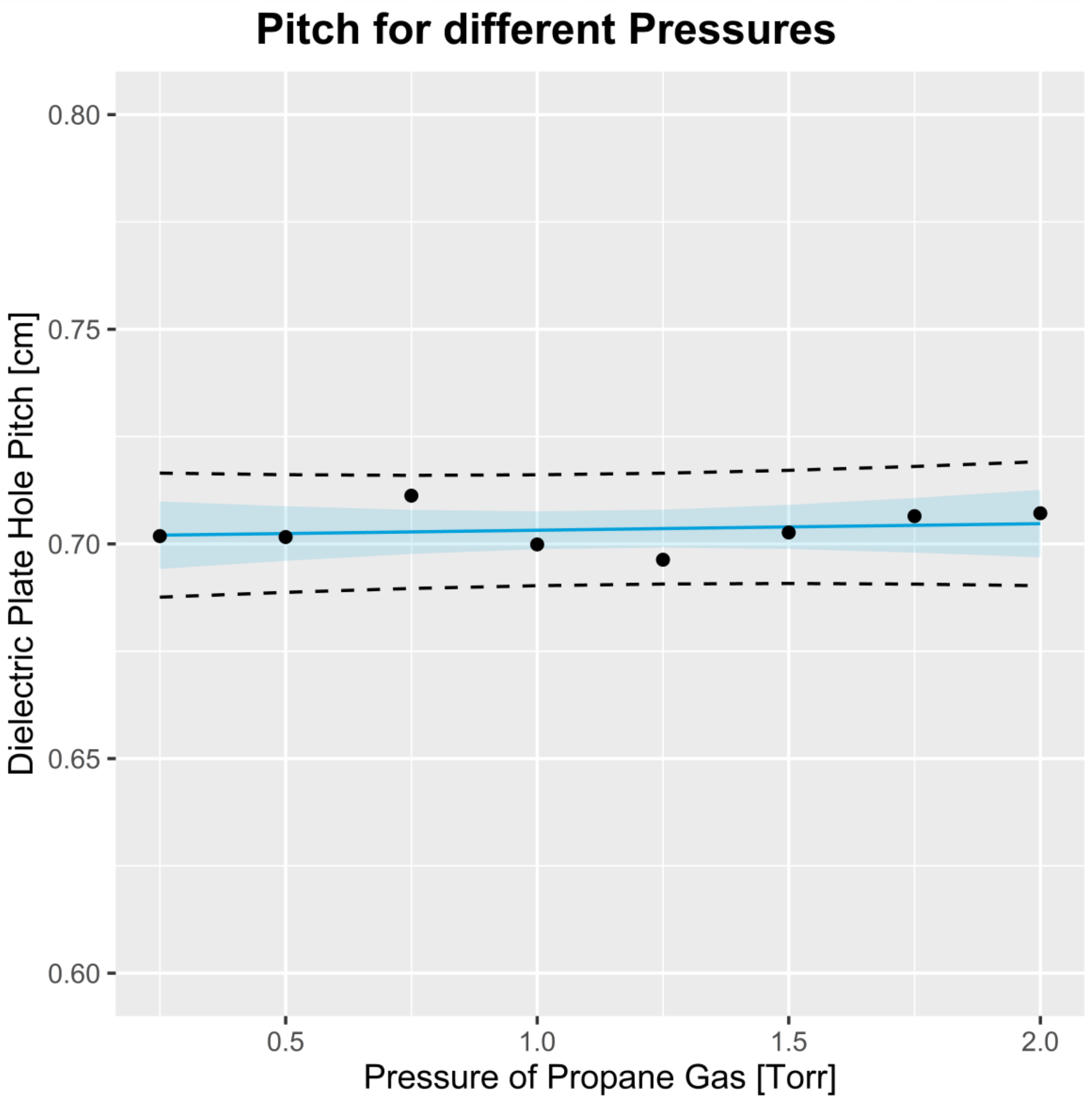




Propane gas pressure

Dielectric plate hole pitch does not depend on gas pressure.



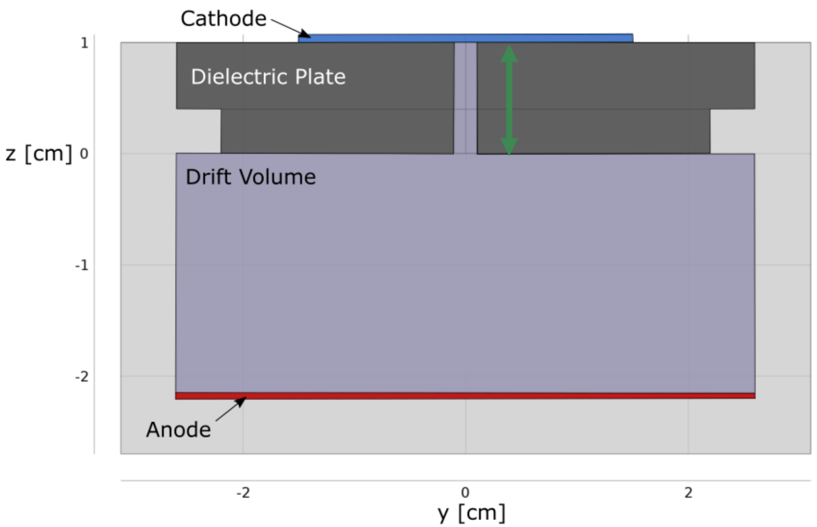


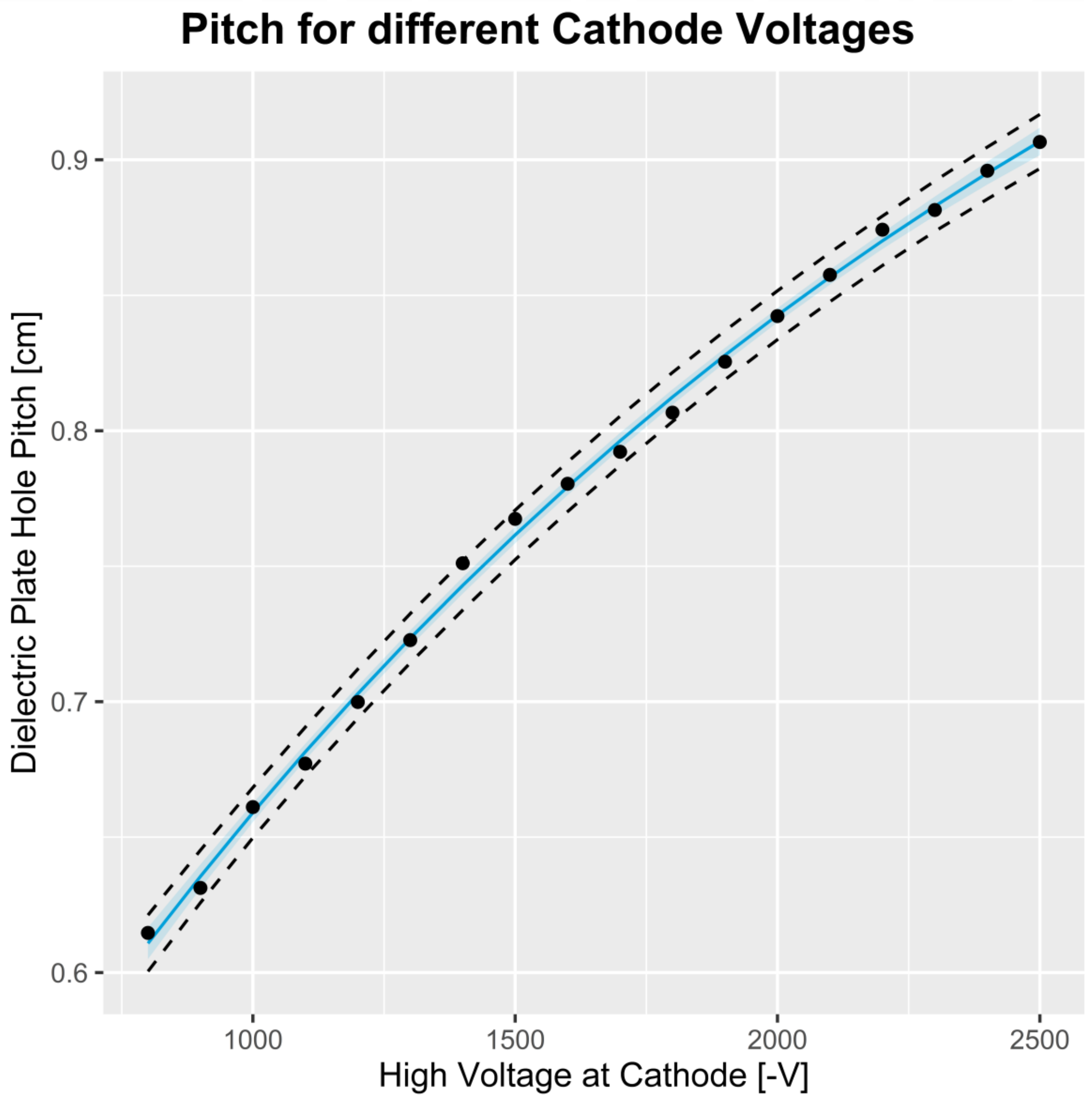
Cathode voltage

Higher cathode voltage

→ Larger funnel effect

→ Larger pitch needed



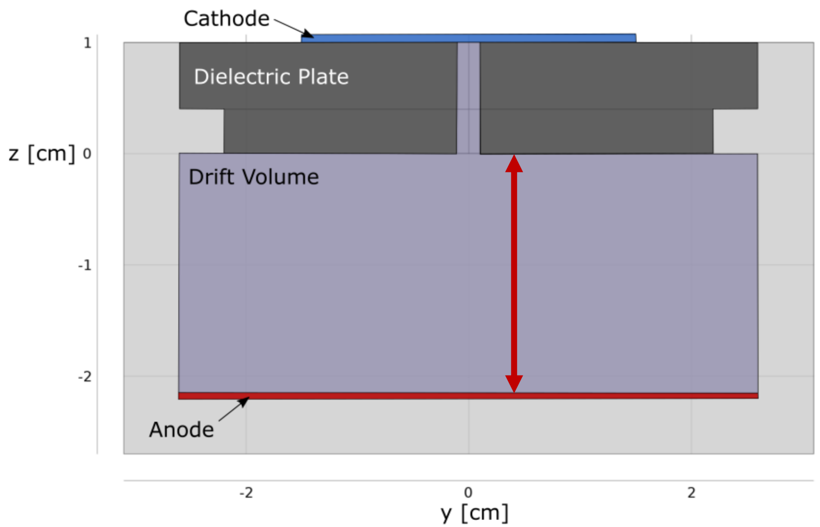


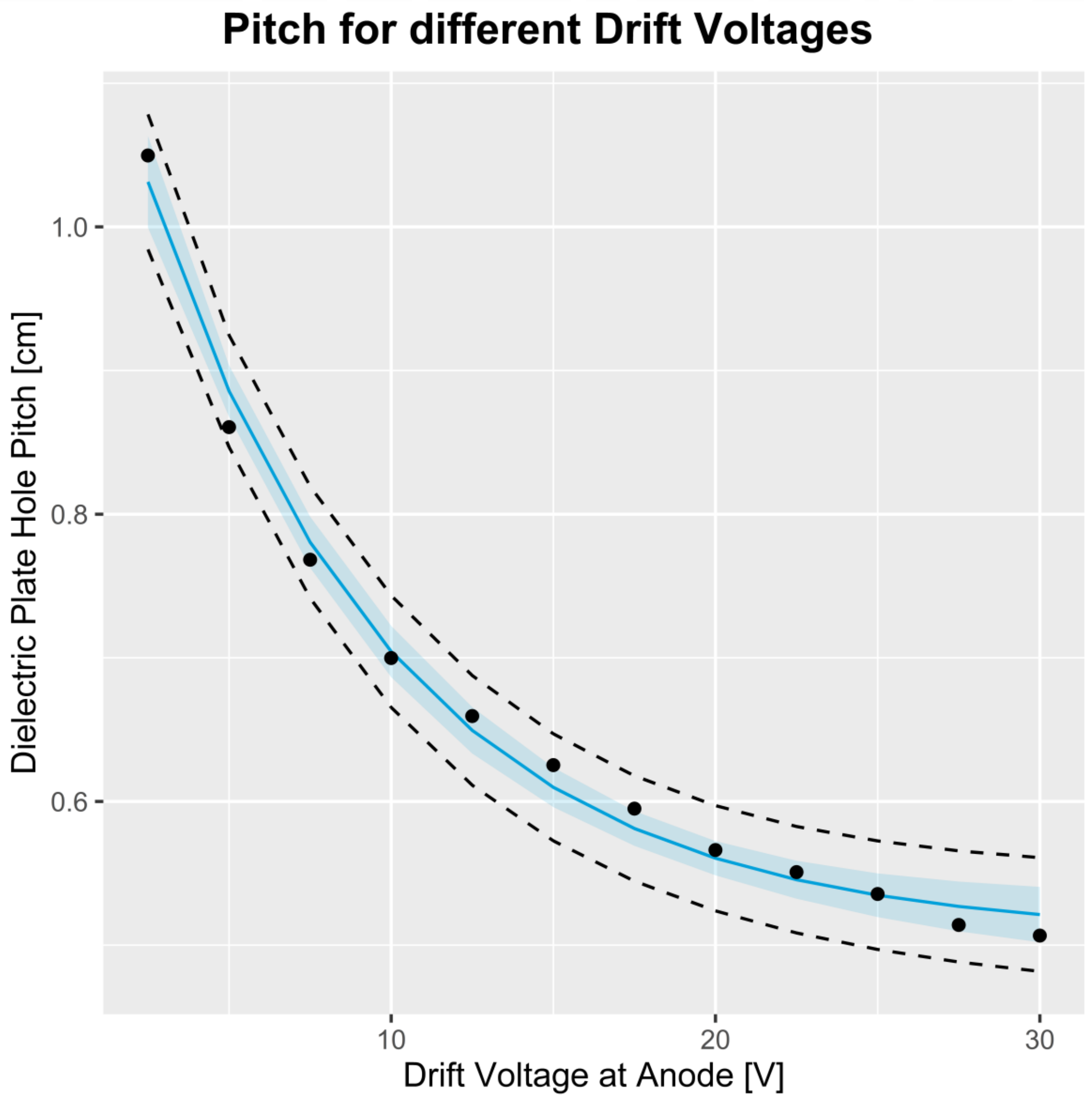
Drift voltage

Higher drift voltage

→ Smaller funnel effect

→ Smaller pitch needed

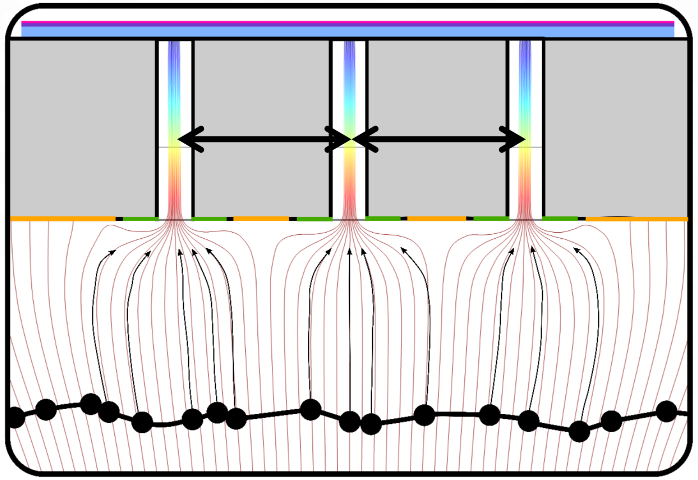


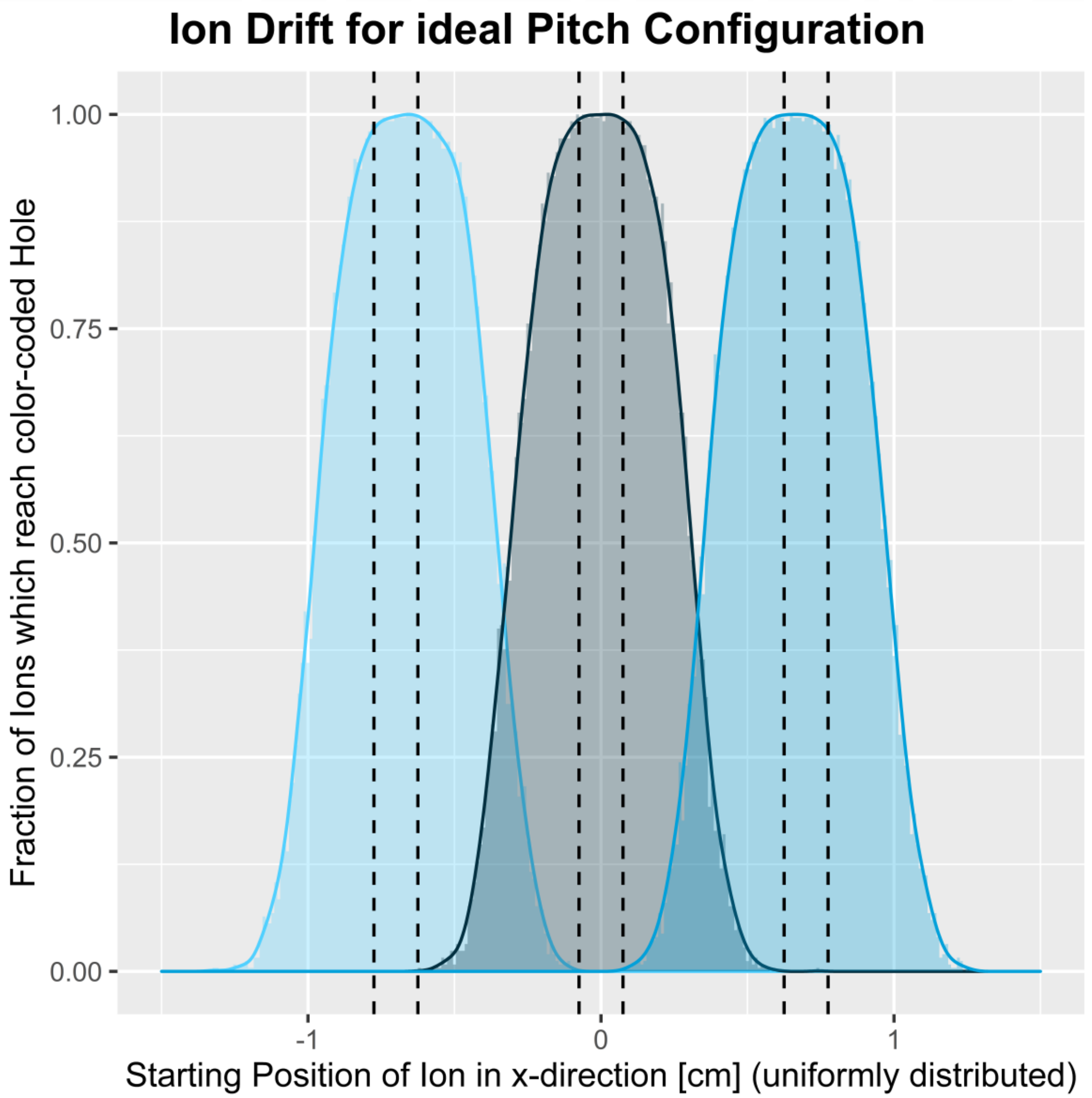


Ideal pitch configuration

Ideal pitch can be calculated for any:

- Hole diameter
- Pressure
- Electric field configuration

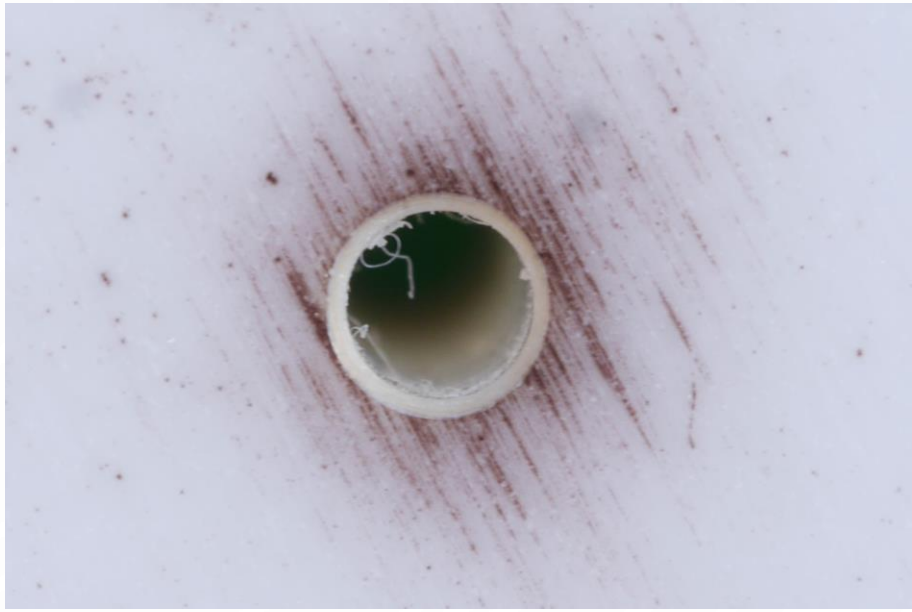




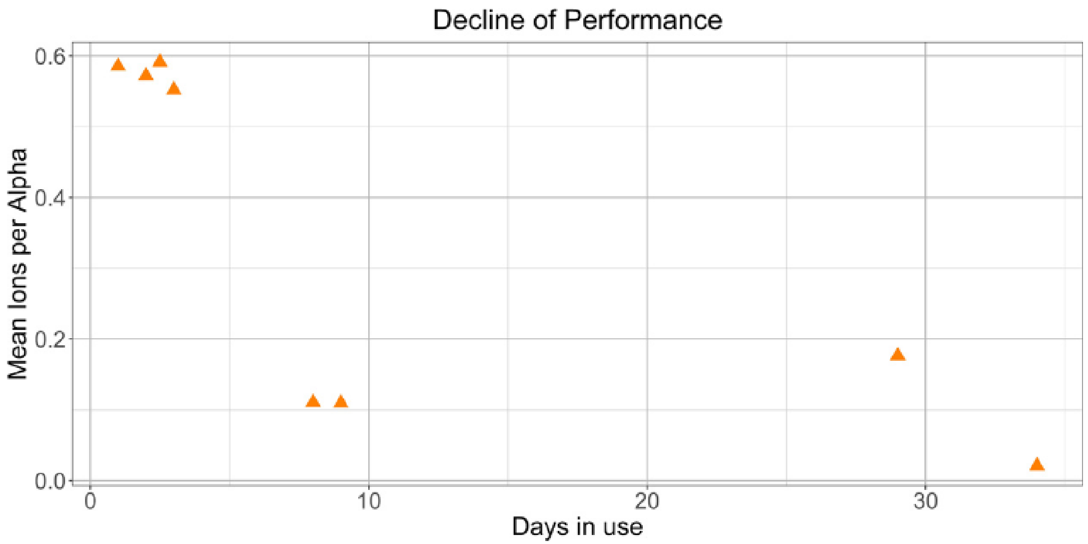
Ongoing challenges with the detector

Ongoing detector challenges

- Low detection efficiency
  - Testing new materials for dielectric plate & cathodes (low bulk resistivities)

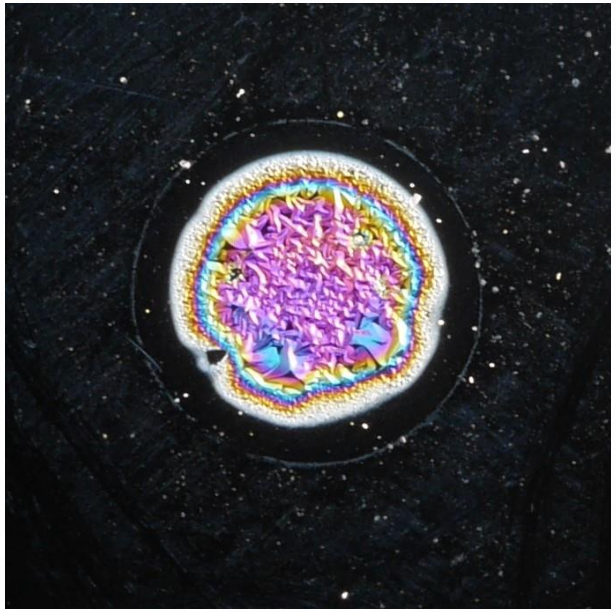


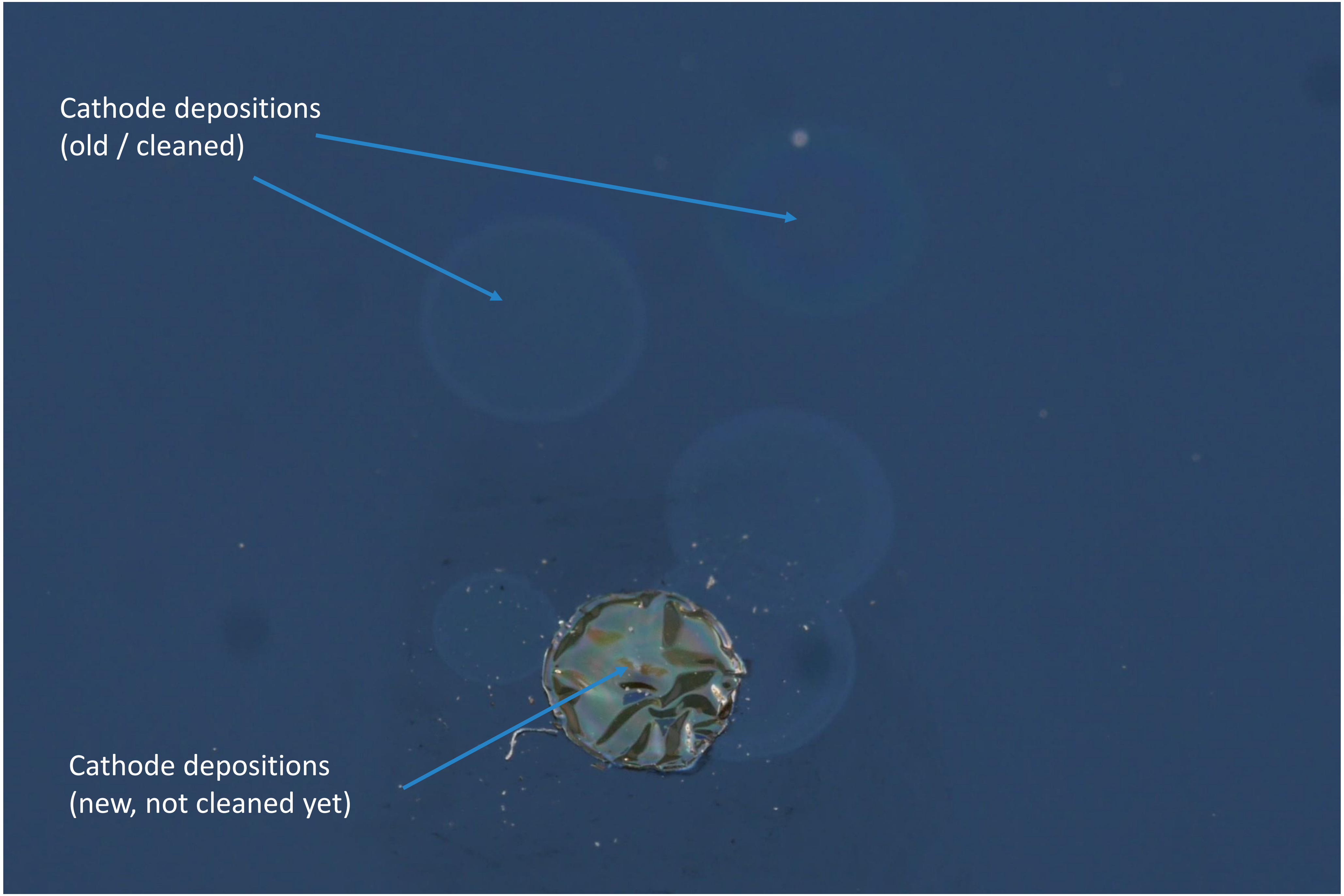
- Ceramic dielectric plate
  - Showed promising results at first (ICSD distribution visible)
  - Detector efficiency decreased from 80% to <1%, probably due to aging effects.



Ongoing detector challenges

- Depositions on glass cathode
  - We note that overtime detection efficiency decreases.
  - If we exchange the glass cathode (or clean it), effciency is increased again.
  - Part of the depositions can be cleaned with medical gasoline.
  - Residual imprints remain on the material

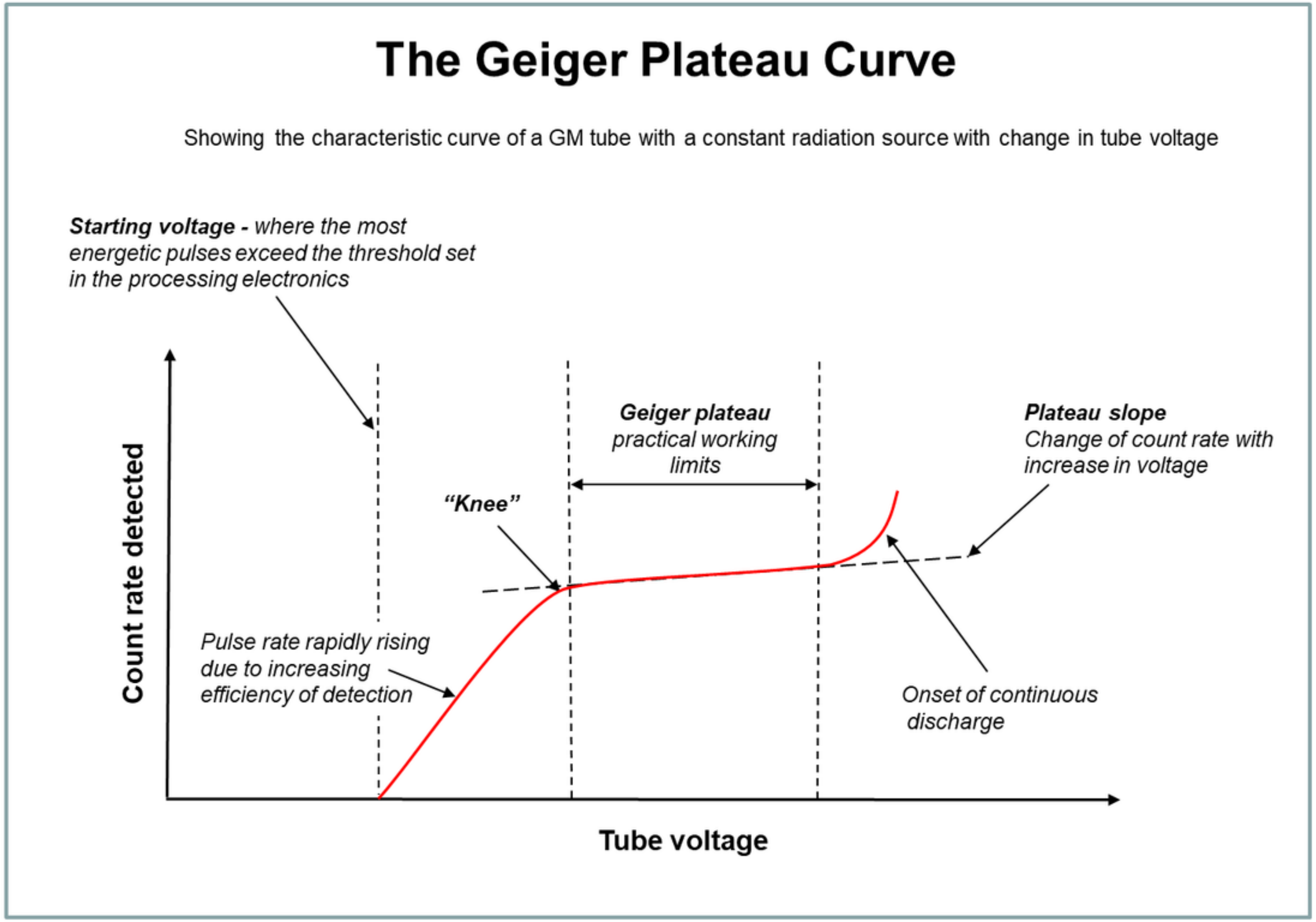




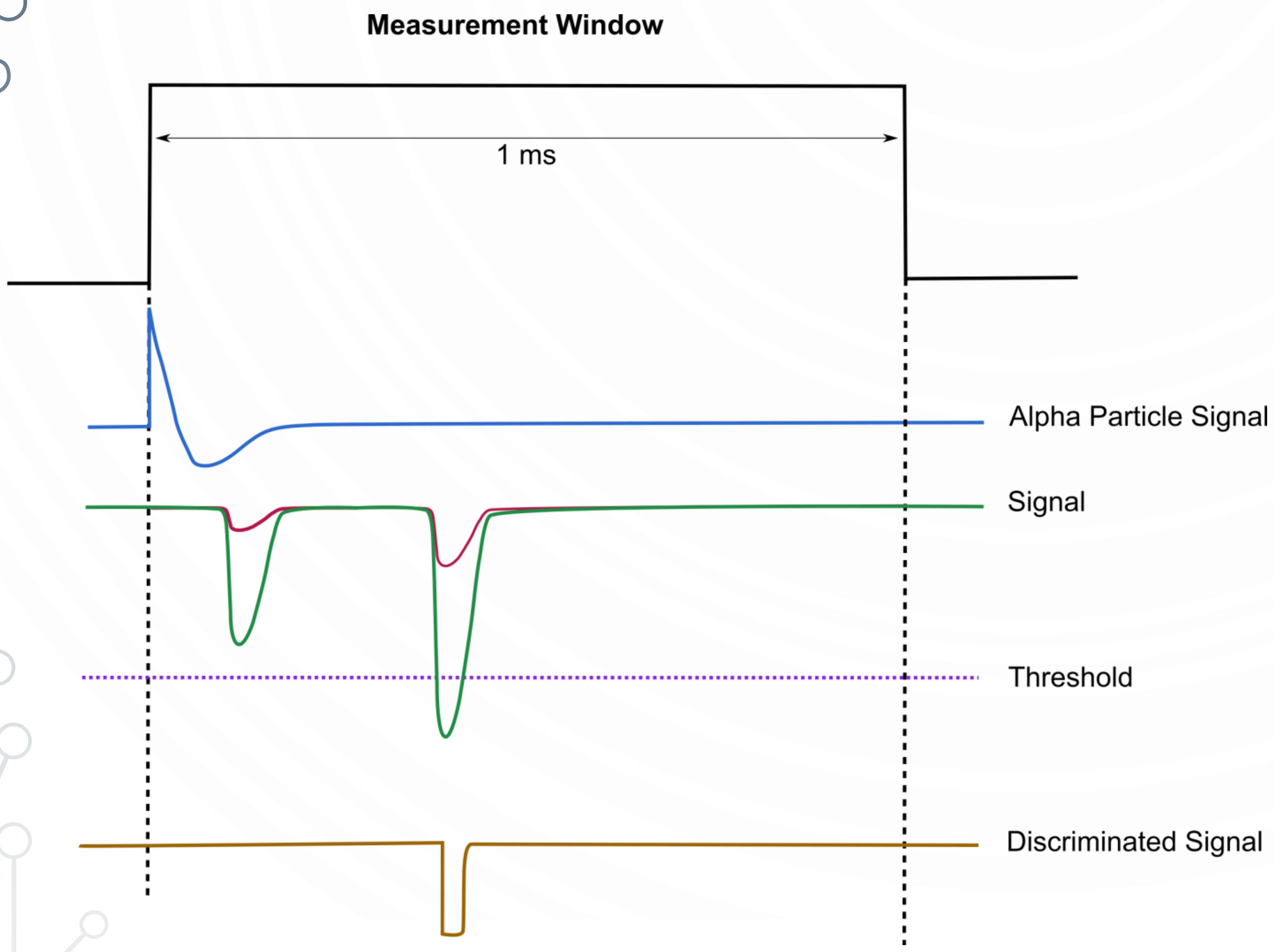
Cathode depositions
(old / cleaned)
Cathode depositions
(new, not cleaned yet)

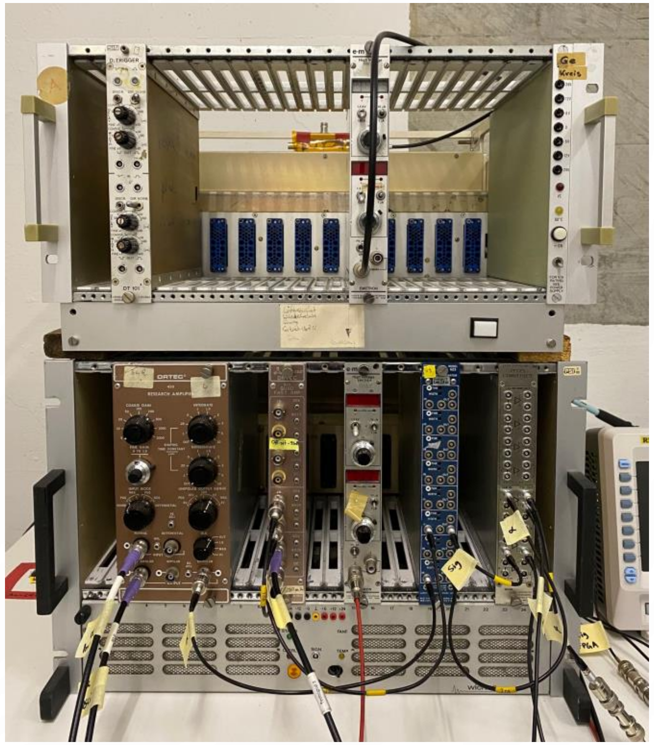
Which region are we in?

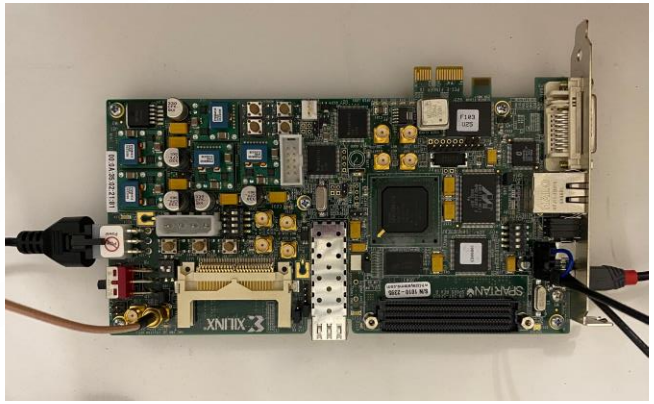
- Large unamplified signals
  - Streamer? Discharge?
- Fast deterioration of materials
- Rapid increase in depositions



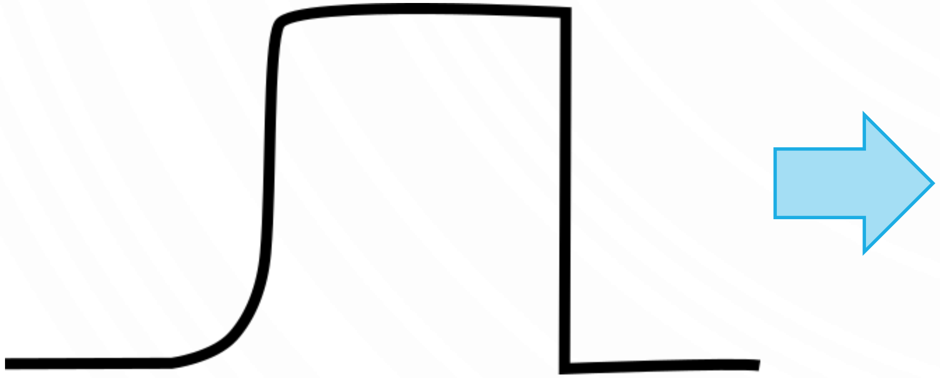
Current data acquisition system: FPGA

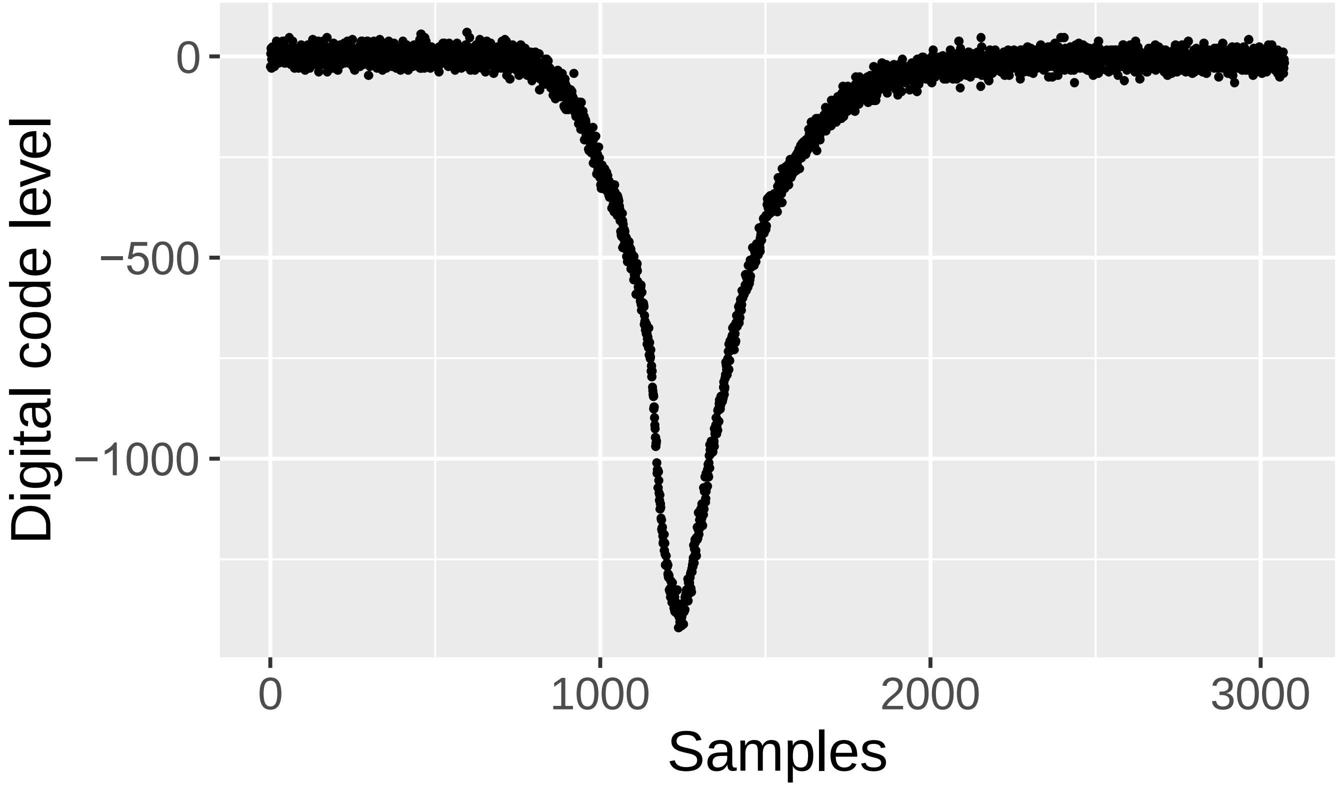






New data acquisition system: ADC



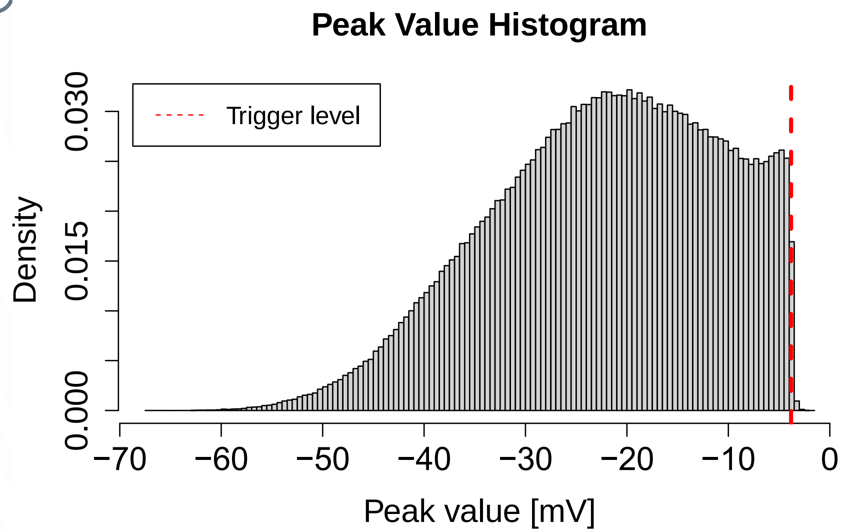


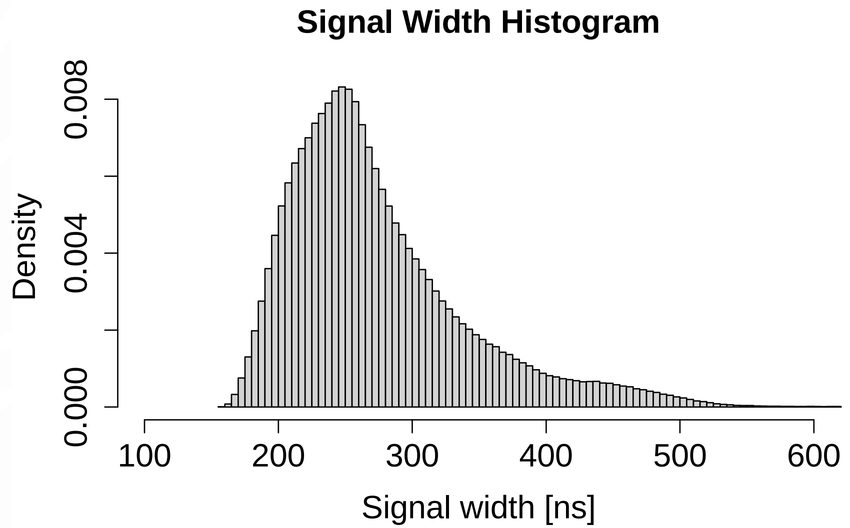
New data acquisition system

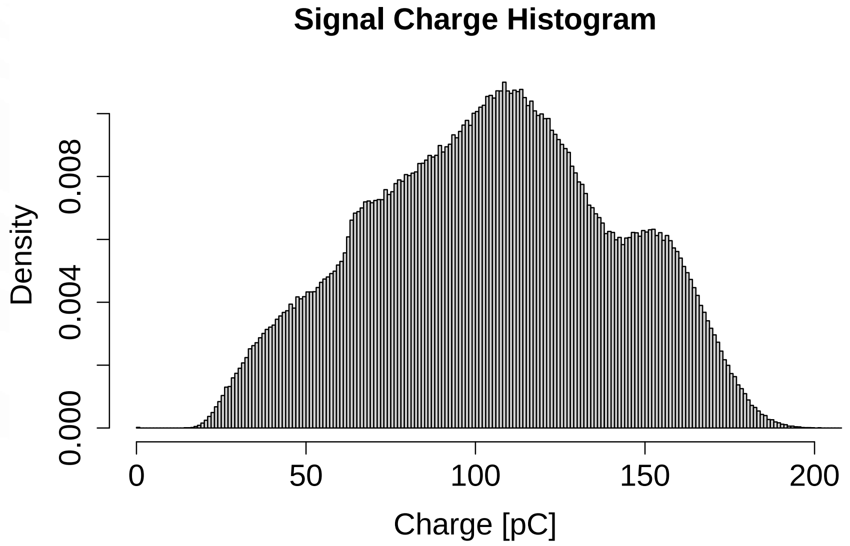
- Currently: We only register when a pulse occurs relative to the trigger (detection of alpha particles), but have no other information about the signal.
- Future: By using an ADC, we will get access to raw data of all pulses, allowing us to monitor pulse height, widht, area etc.
- ADQ14DC-4C-VG-USB by Teledyne SP Devices

Source: Teledyne SP Devices ADQ14DC-4C-VG-USB [4]

Signal properties can now be studied



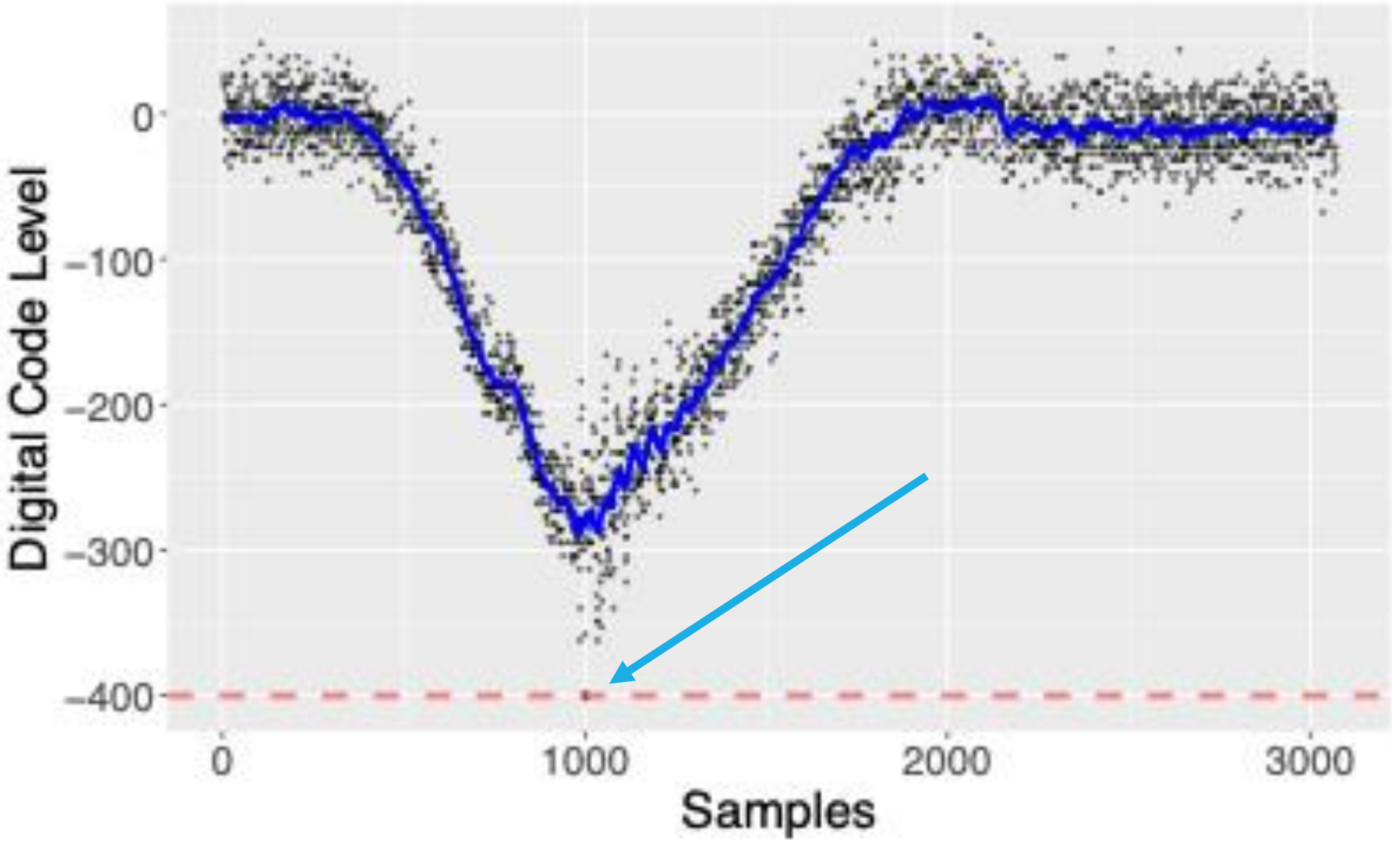




Ongoing Challenges with ADQ

Noise

- New signal amplification needed
  - Risk of signal shape distortion
- Filter noise within recorded data



Thank you for your attention!

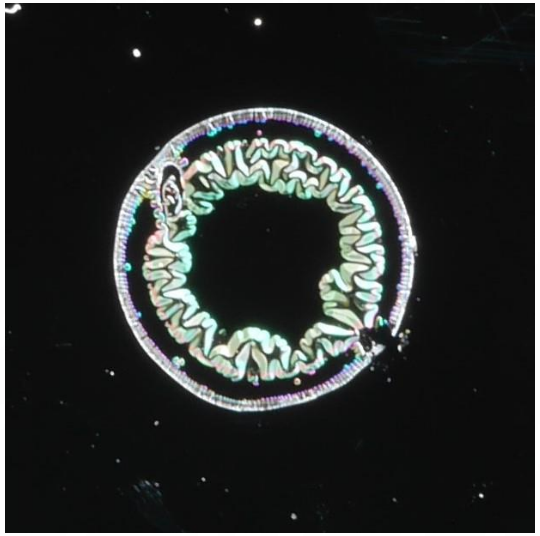
Contact information & Sources

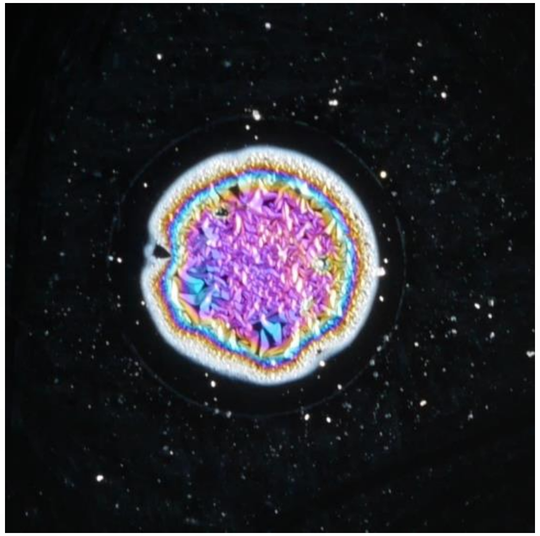
Irina Kempf – PhD student at University of Zurich

Email: irina.kempf@uzh.ch

[1] Vasi, F., Kempf, I., Besserer, J., & Schneider, U. (2021). FIRE: A compact nanodosimeter detector based on ion amplification in gas. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, *999*(January), 165116. https://doi.org/10.1016/j.nima.2021.165116

[2] I. Kempf, T. Stäuble and U. Schneider, Electrostatic field simulations and dynamic Monte Carlo simulations of a nanodosimetric detector, Nuclear Inst. and Methods in Physics Research, A (2022), doi: https://doi.org/10.1016/j.nima.2022.166374





Depositions on glass cathode