The 8th International Conference on MPGDs

Simulating Timing Performance of Resistive Detectors with Garfield++

Djunes Janssens

On behalf of the CERN EP-DT-GDD team

djunes.janssens@cern.ch

October 14th, 2024

EP R&D

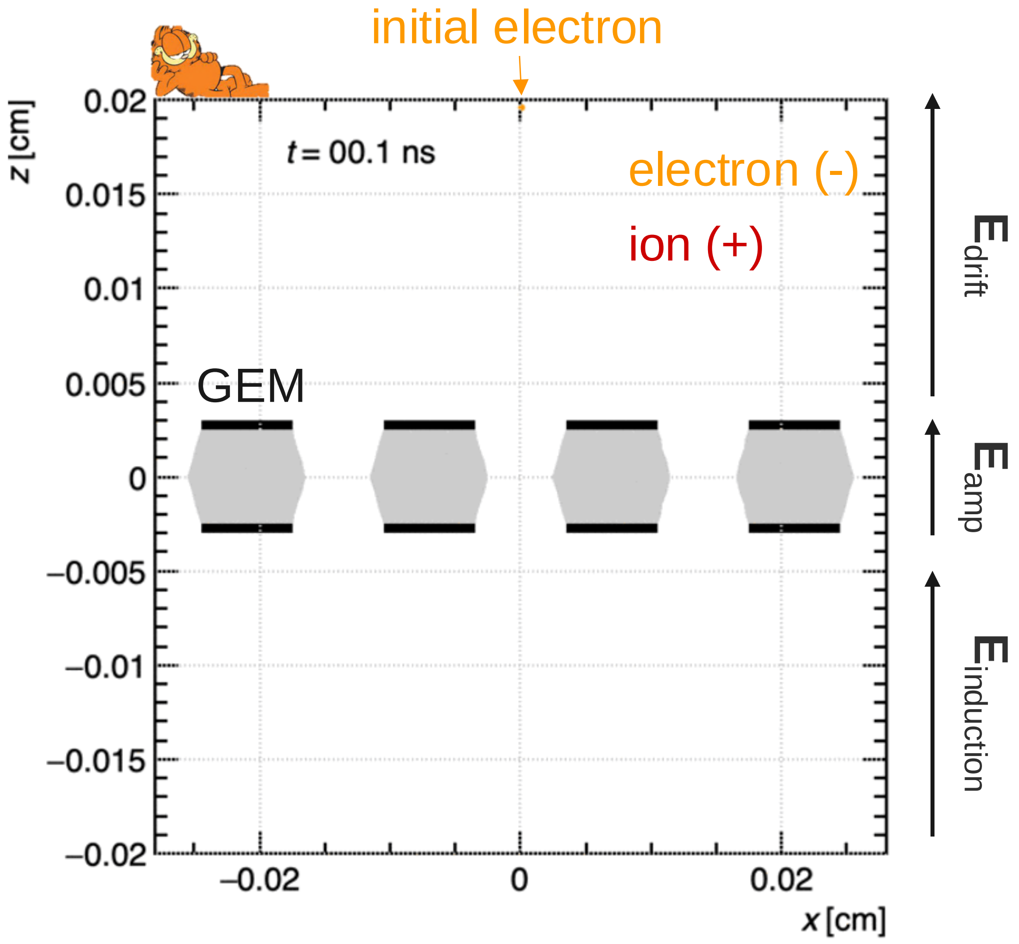
USTC HEFEI 2024

Introduction

We aim to provide a brief overview of the simulation methods and tools available for conducting time resolution studies on resistive particle detectors using Garfield++.

<u>Outline:</u>

- **Time resolution studies of non-resistive detectors**
  - Electric field and avalanche dynamics
  - Signal induction
  - Capacitive coupling
- **Resistive detectors**
  - Extension of the Ramo-Shockley theorem for conductive media
  - Resistive PICOSEC Micromegas
  - Noise from resistive elements
- **Summary**

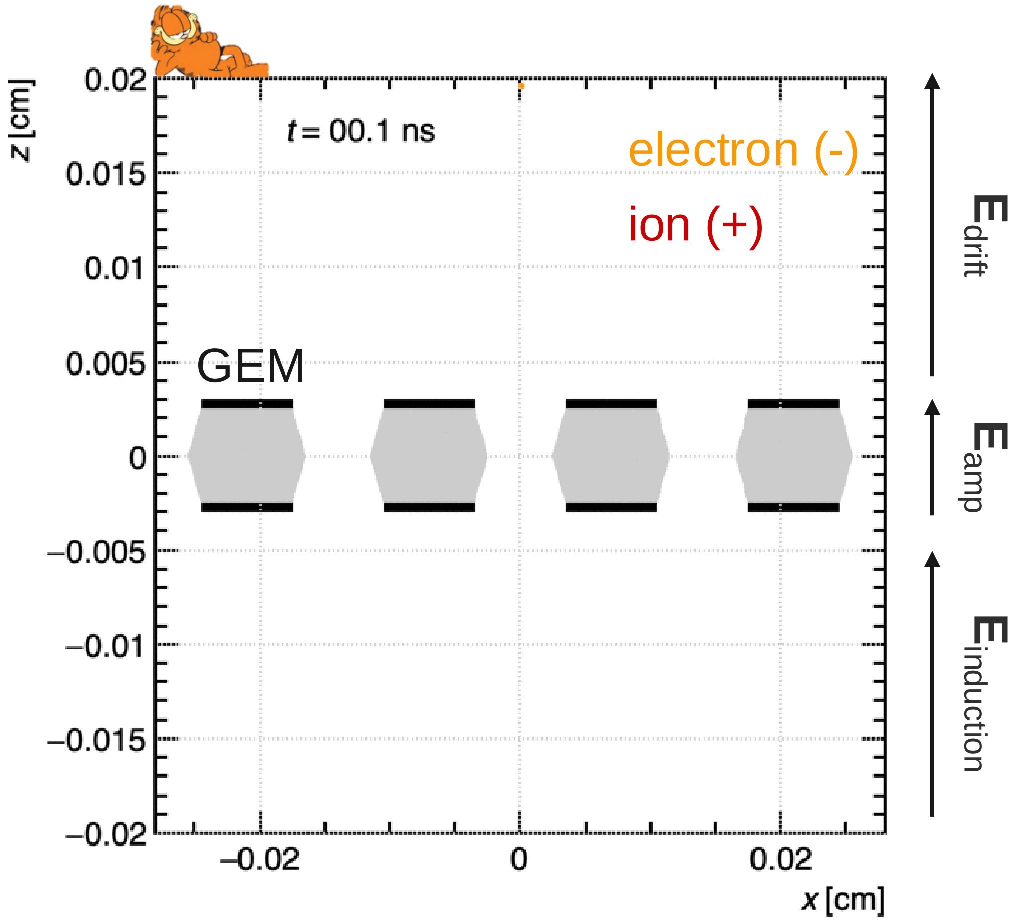


Introduction

We aim to provide a brief overview of the simulation methods and tools available for conducting time resolution studies on resistive particle detectors using Garfield++.

<u>Outline:</u>

- **Time resolution studies of non-resistive detectors**
    - Electric field and avalanche dynamics
    - Signal induction
    - Capacitive coupling
- **Resistive detectors**
    - Extension of the Ramo-Shockley theorem for conductive media
    - Resistive PICOSEC Micromegas
    - Noise from resistive elements
- **Summary**

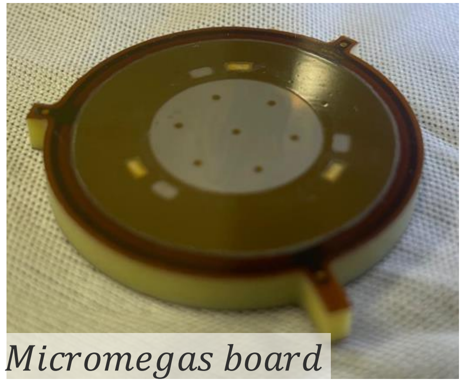


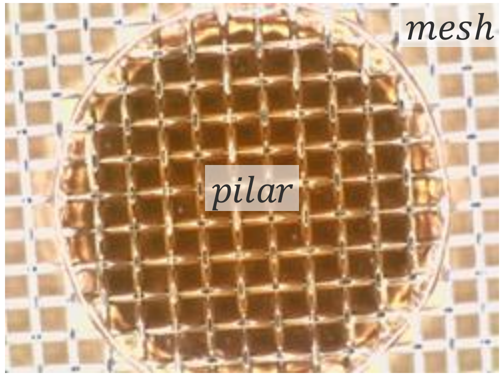
Example: simulating a PICOSEC Micromegas

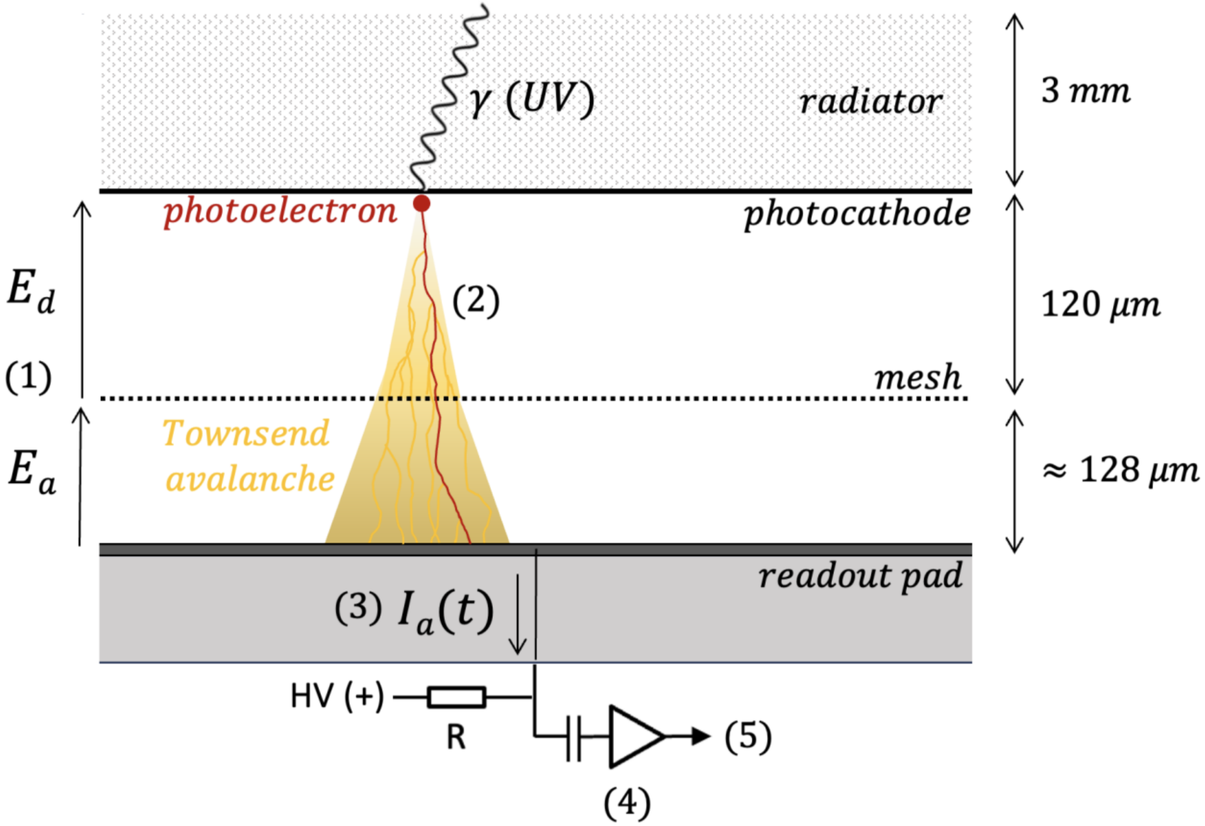
As an example of a (non-resistive) timing MPGD, let us consider the PICOSEC Micromegas.

To get the timing resolution, we need to:

1. Compute the electric field for a woven mesh
2. Simulate the tracks of electrons and ions
3. Calculate the induced signal on the anode
4. Incorporate the response of the electronics
5. Perform post-processing (e.g., CFD, slew rate correction, etc.)





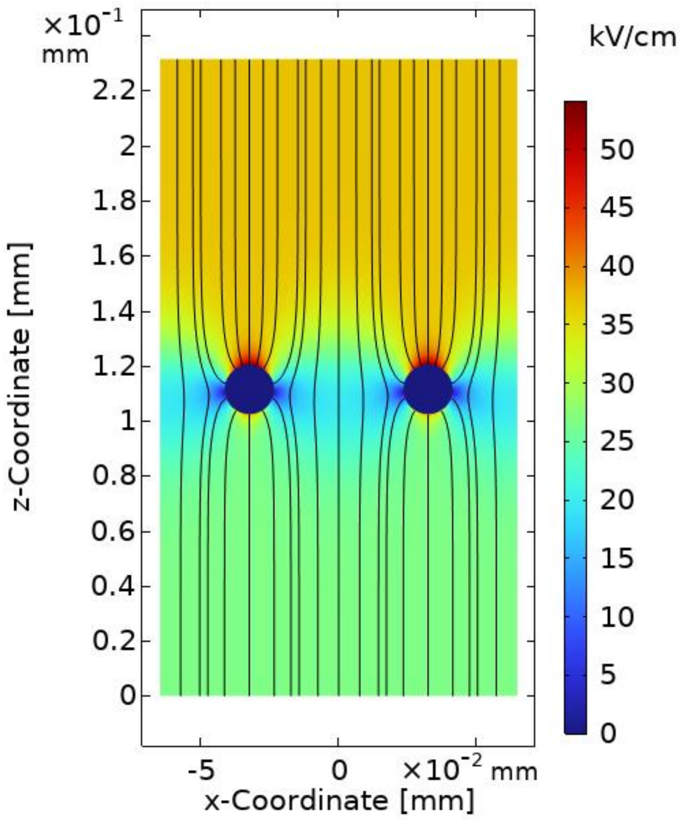


Electric fields and microscopic electron transport

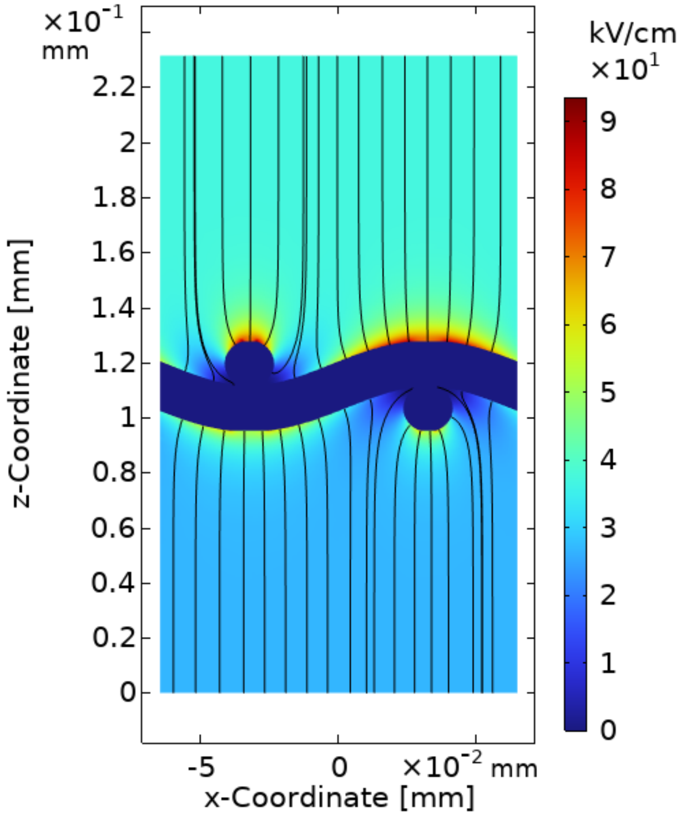
Electric field calculations

Using the finite element method (e.g., COMSOL), the applied electric field and weighting potentials for all three electrodes can be calculated. In this case, a standard calendared woven mesh was used:

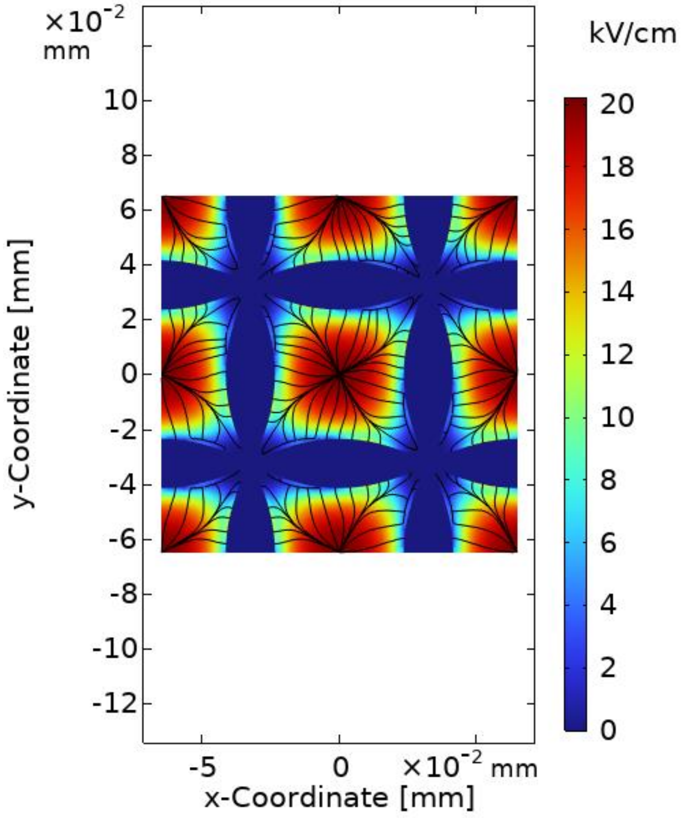
Electric field strength (y = 0 µm)



Electric field strength (y = 32.5 µm)



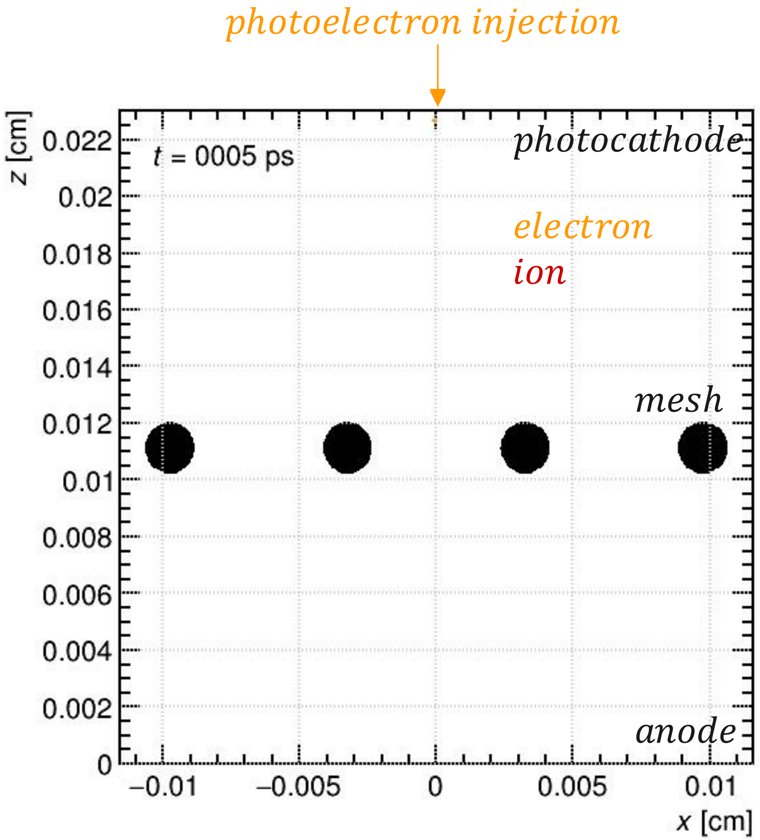
Electric field strength (z = 111.38 µm)

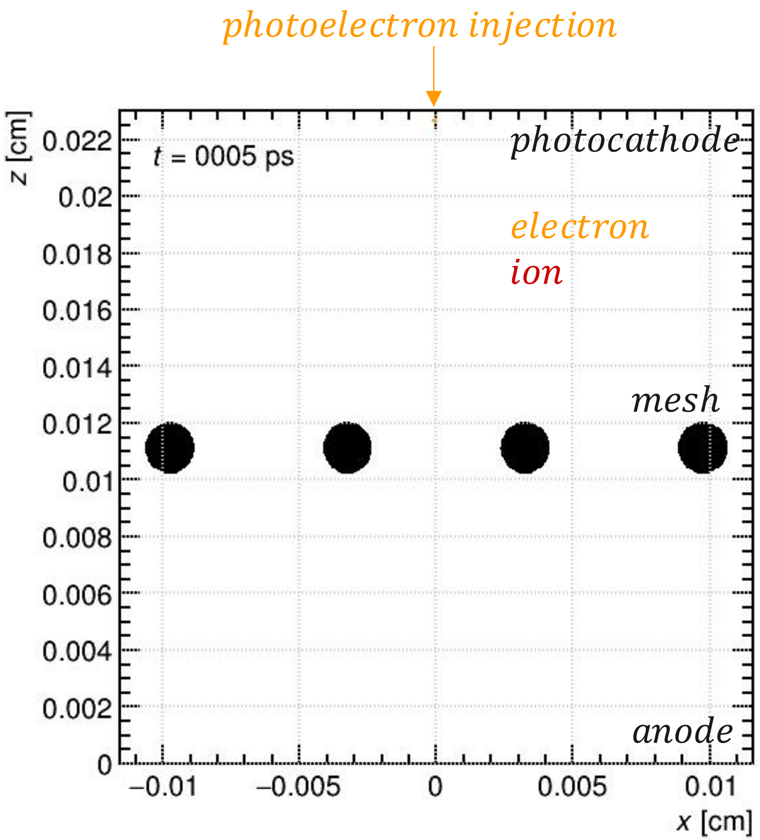


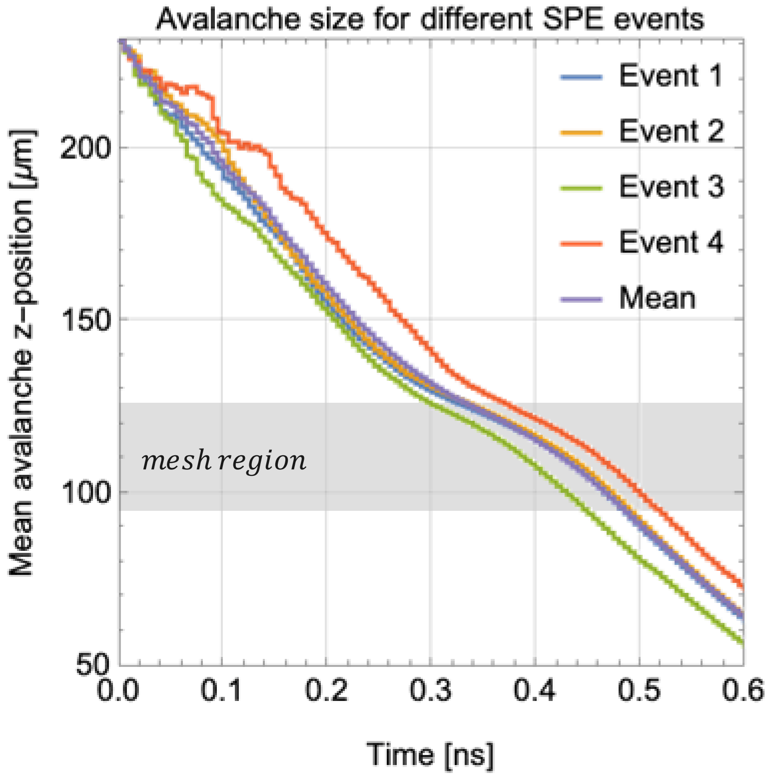
Avalanche development

By using microscopic tracking for the electrons, from collision to collision, their trajectories through the detector and interactions with surrounding gas atoms and molecules can be calculated.

The time of arrival at the mesh is sensitive to initial avalanche fluctuations, affecting when signal formation begins.



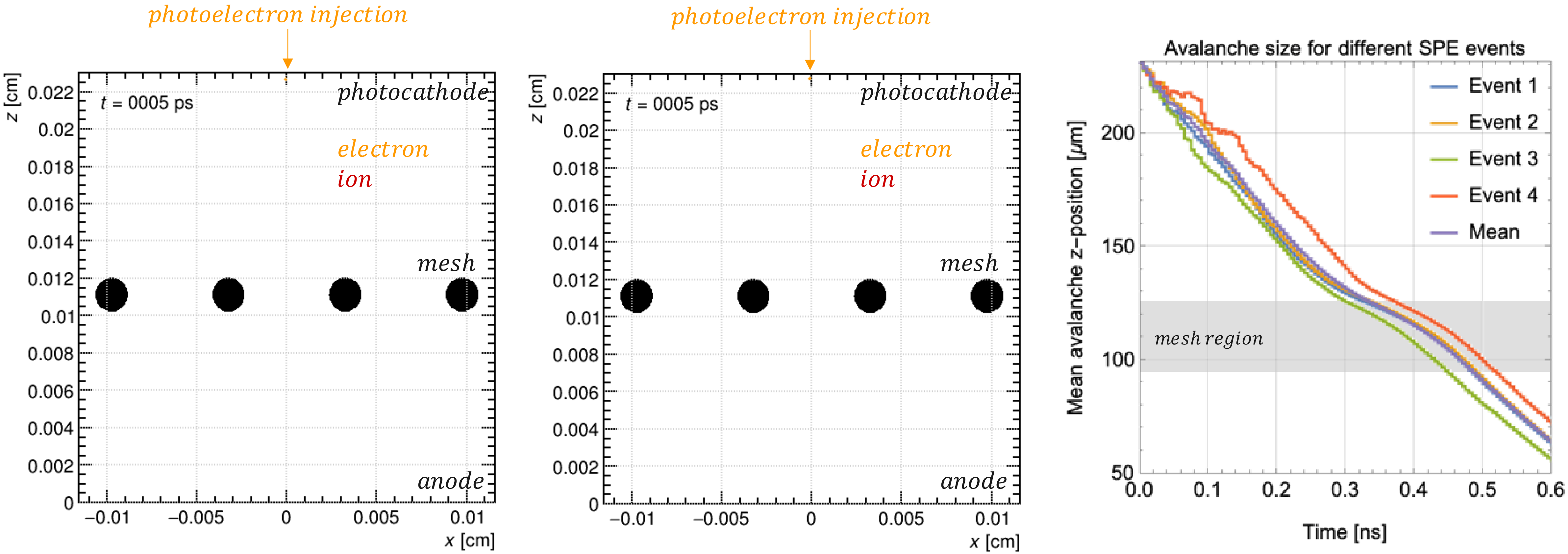




Avalanche development

By using microscopic tracking for the electrons, from collision to collision, their trajectories through the detector and interactions with surrounding gas atoms and molecules can be calculated.

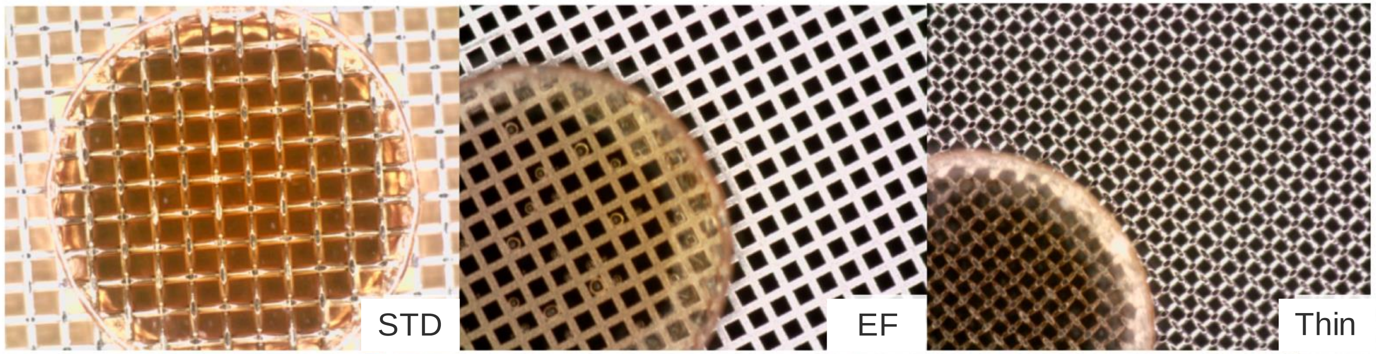
The time of arrival at the mesh is sensitive to initial avalanche fluctuations, affecting when signal formation begins.



Transparency of the mesh

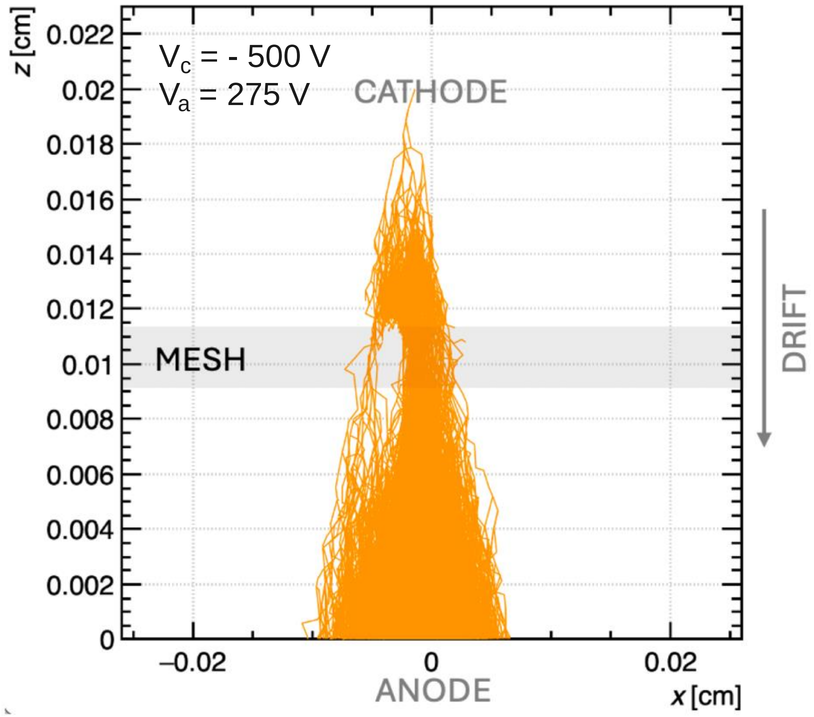
Given the established precision of Garfield++ as a Monte Carlo tool for predicting the transparency of Micromegas meshes, a study was conducted using Garfield++ for two new candidate meshes for PICOSEC.

→ In this field configuration, they have a reduced transparency when compared to the standard mesh.



type	hole diameter [um]	wire ϕ [pm]	open area [%]	transparency [%]
STD	44.0	19.0	49	12.04
EF	30.4	19.6	37	9.45
Thin	19.9	15.1	32	3.97

Simulated drift lines of electrons

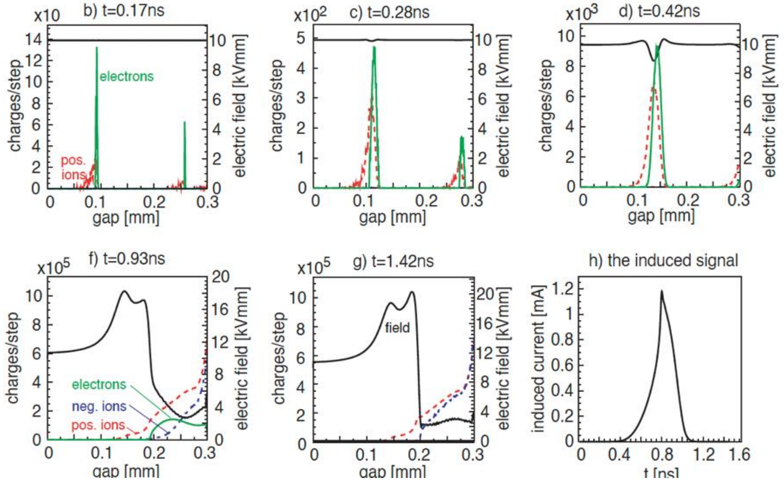


F. Kuger. PhD dissertation, arXiv:1708.01624 [physics.ins-det].
M. L. V. Fernández, CERN-STUDENTS-Note-2024-096.

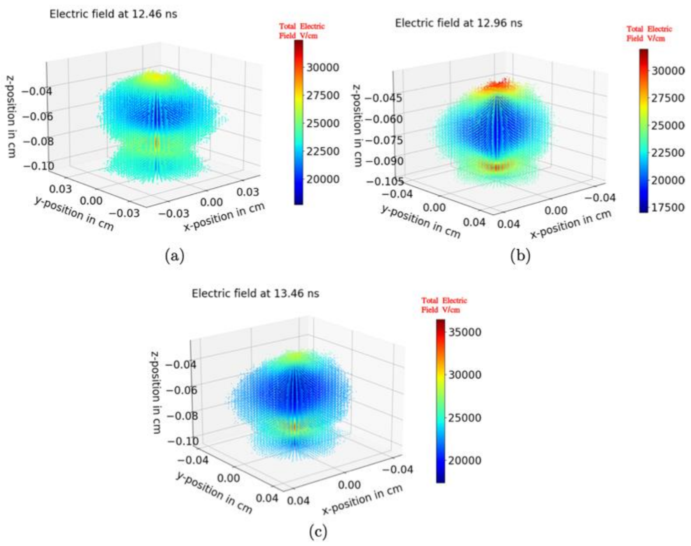
What about space-charge effects?

Garfield++ provides an accurate description of amplification in the proportional regime, where all electrons and ions can be treated independently. However, in timing detectors with large avalanche sizes, space-charge effects may play a significant role.

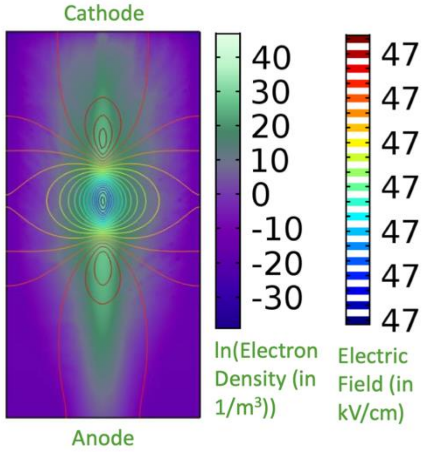
Although this challenging topic requires further development within WG4, some models are already available:



C. Lippmann, W. Riegler, NIM-A 517 (2004) 54–76
See also presentation of Dario Stocco.



See presentation of Supratik Mukhopadhyay and Thursday's presentation given by Maxim Titov.
Also: arXiv:2211.06361v1 [physics.ins-det]



A gaussian distribution of primary electrons is used as the seed to initiate the avalanche.

RD51–NOTE-2011-005, by Paulo Fonte
RD-51 Open Lectures by Filippo Resnati.
Also: Jaydeep Datta's presentation.

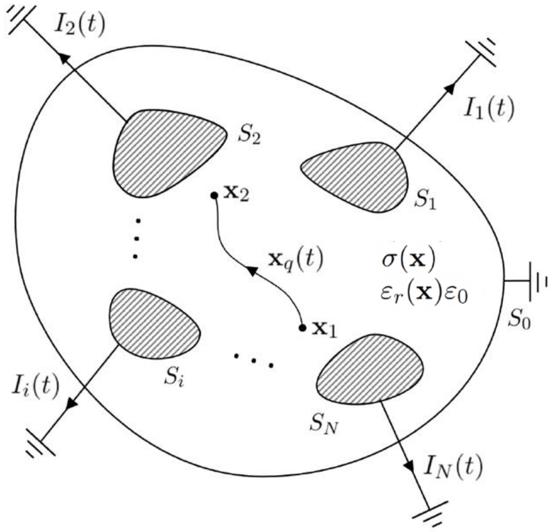
Signal induction

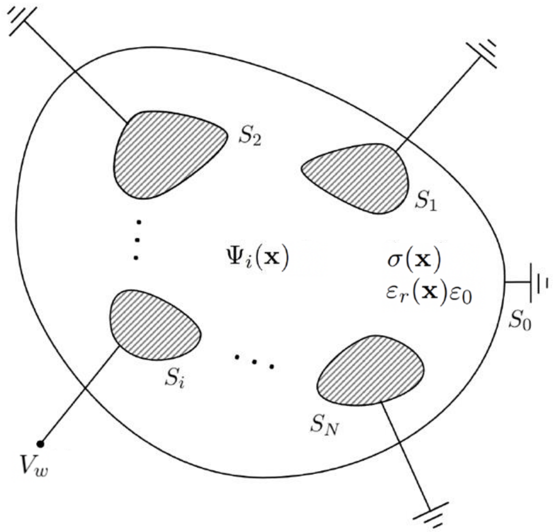
Ramo-Shockley theorem

Using this framework, the induced current on the electrode, sourced by a point charge q, can be calculated using its calculated weighting potential.

$$I_i(t) = -\frac{q}{V_w}\mathbf{E}_i(\mathbf{x}_q(t)) \cdot \dot{\mathbf{x}}_q(t) \quad \text{, where} \quad \mathbf{E}_i(\mathbf{x}) = -\nabla\Psi_i(\mathbf{x})$$

Due to the linearity of Maxwell’s equations, the contributions of each charge can be summed up independently.

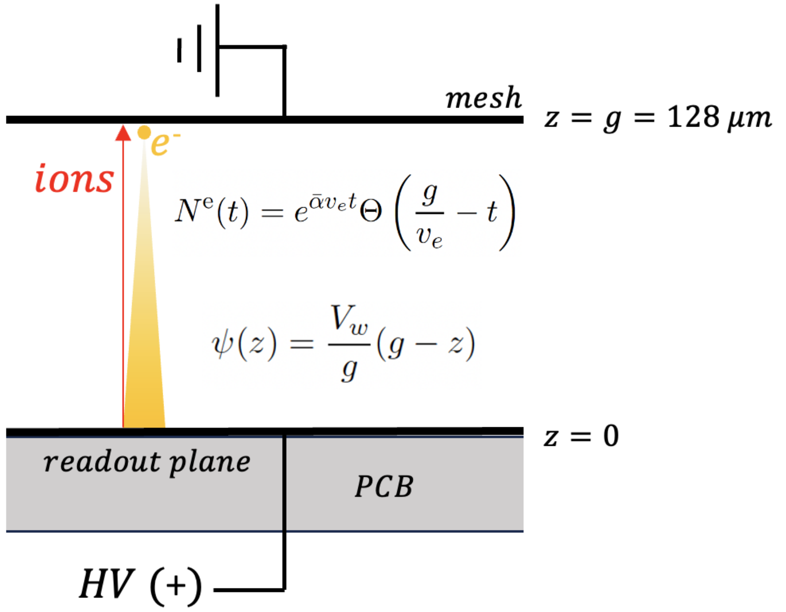


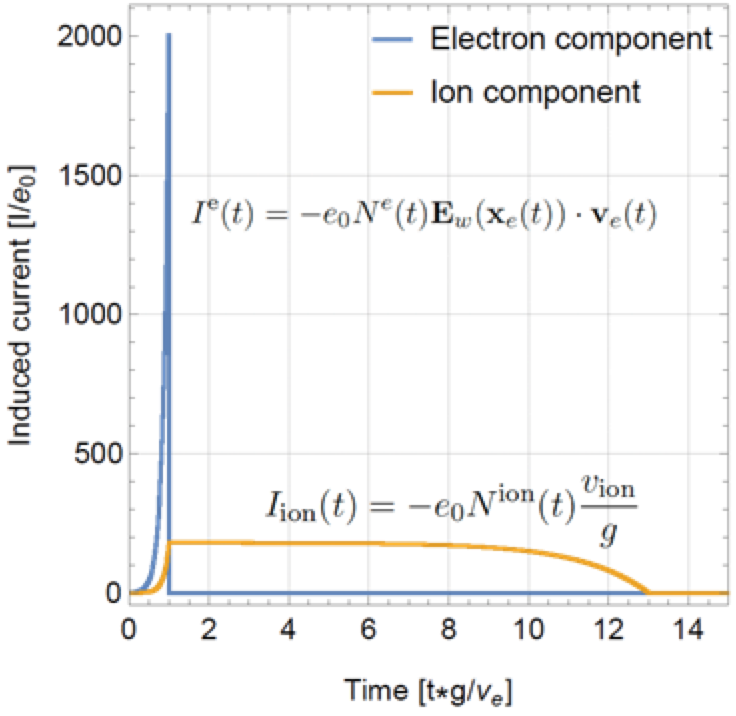


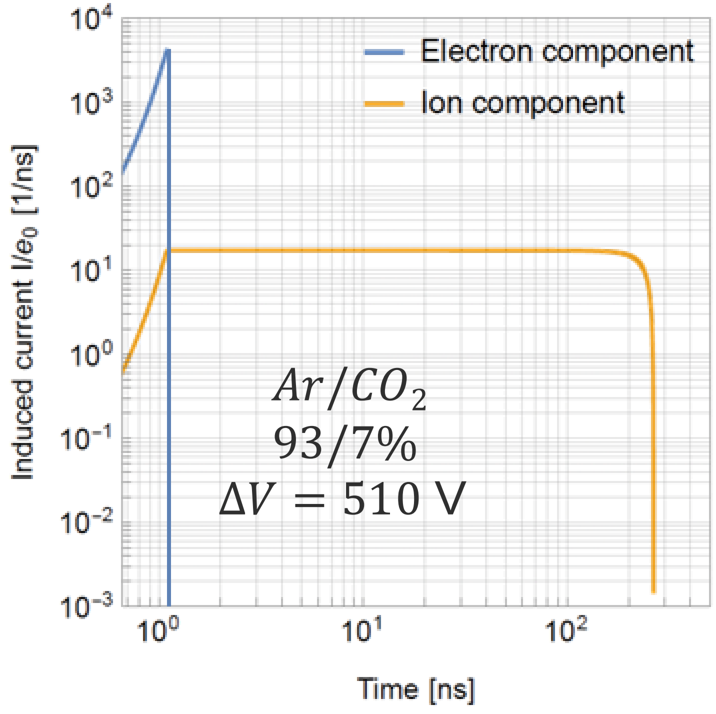
S. Ramo, PROC. IRE 27, 584 (1939).
W. Shockley, Journal of Applied Physics. 9 (10): 635 (1938).

Induced signal in anode (toy model)

Let us consider a Townsend avalanche inside the amplification gap of a Micromegas detector that induces a signal on the anode plane.



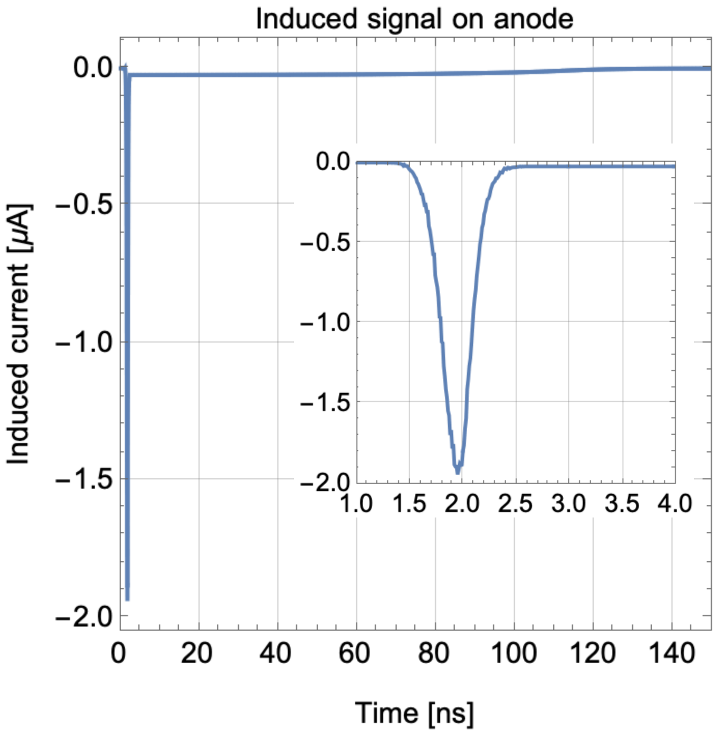




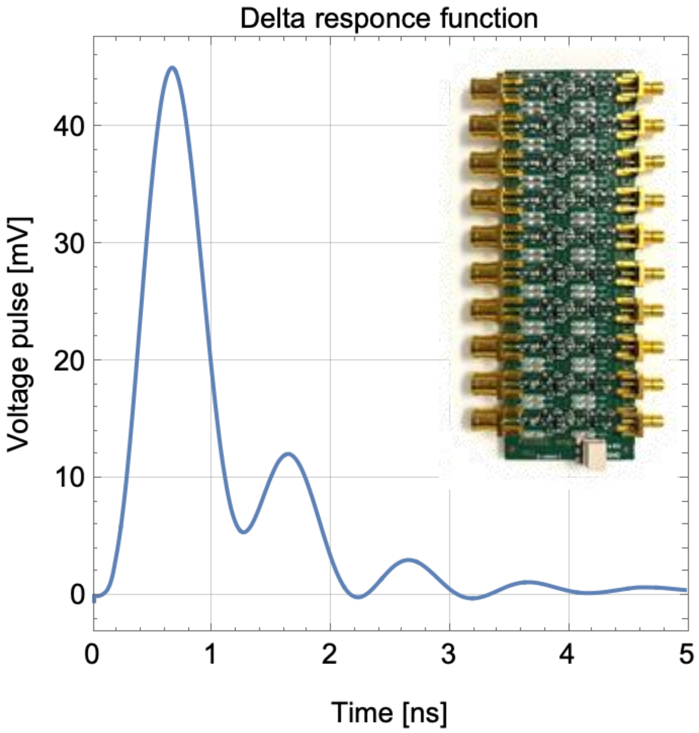
Similar to the electric field, the weighting potential that includes the woven mesh can be obtained using the FEM.

Including amplifier response

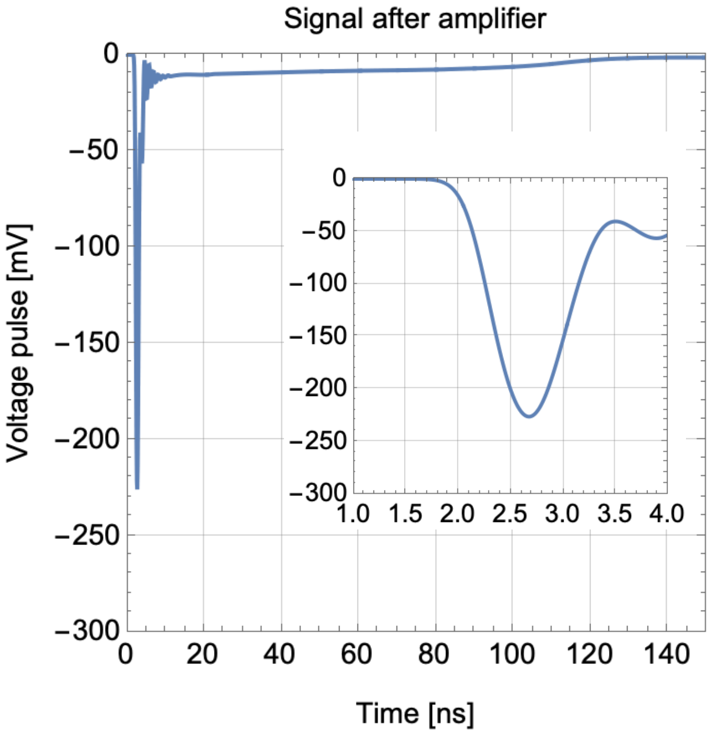
Using the weighting potential of the pad, the induced current on the electrode can be calculated for each simulated event. This current can then be convolved with the delta response function of the RF amplifier in Garfield++.



*



=



PICOSEC amplifier design: A. Utrobičić, et al., JINST 18 (2023) C07012.
Based on the RF pulse amplifier: C. Hoarau, et al., JINST 16 (2021) T04005.
Delta response function is courtesy of Marinko Kovačić and LTSpice.

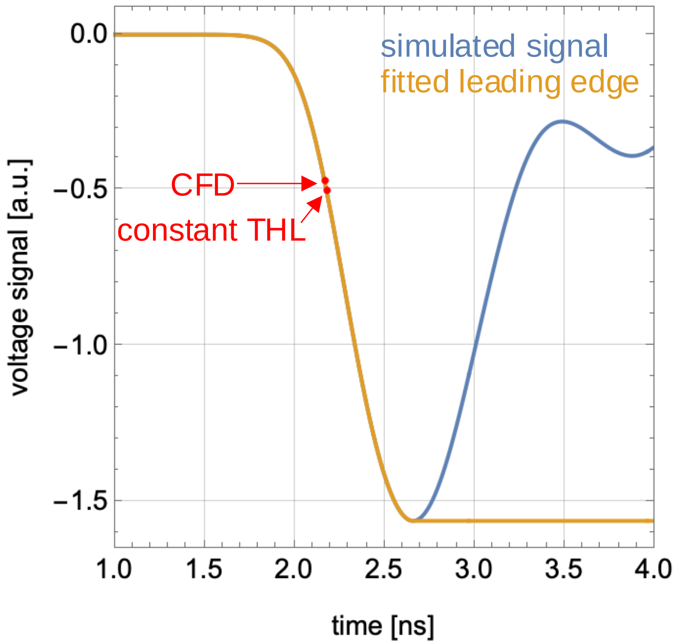
Correcting for the signal arrival time

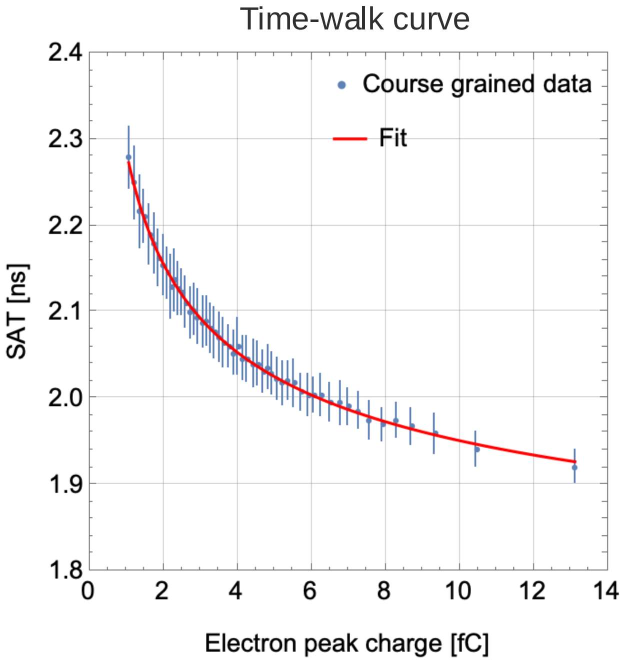
The resulting signals can be analyzed. We fit the leading edge of each signal to determine the signal arrival time (SAT) using either a constant threshold level (THL) or constant fraction discrimination (CFD). We fit the time walk:

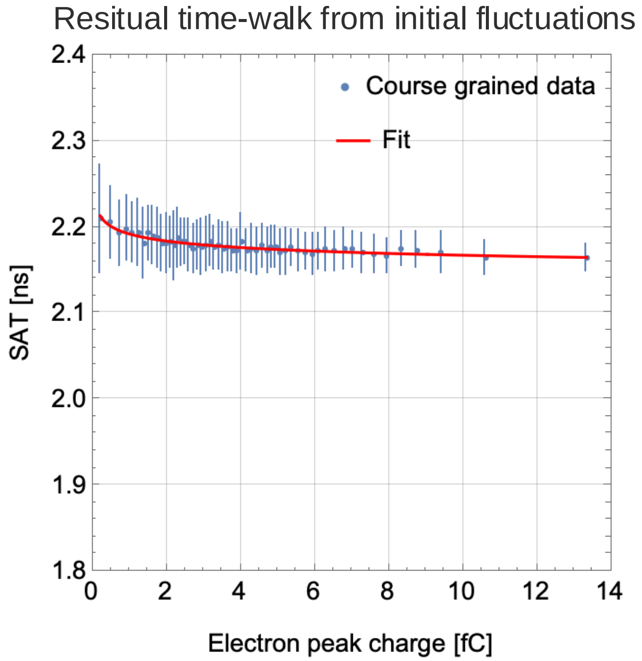
$$\langle \mathrm{SAT}(\tilde{q}) \rangle = \frac{c_1}{\tilde{q}^{c_2}} + c_3,$$

where c_i are the to be estimated parameters.

electron peak charge







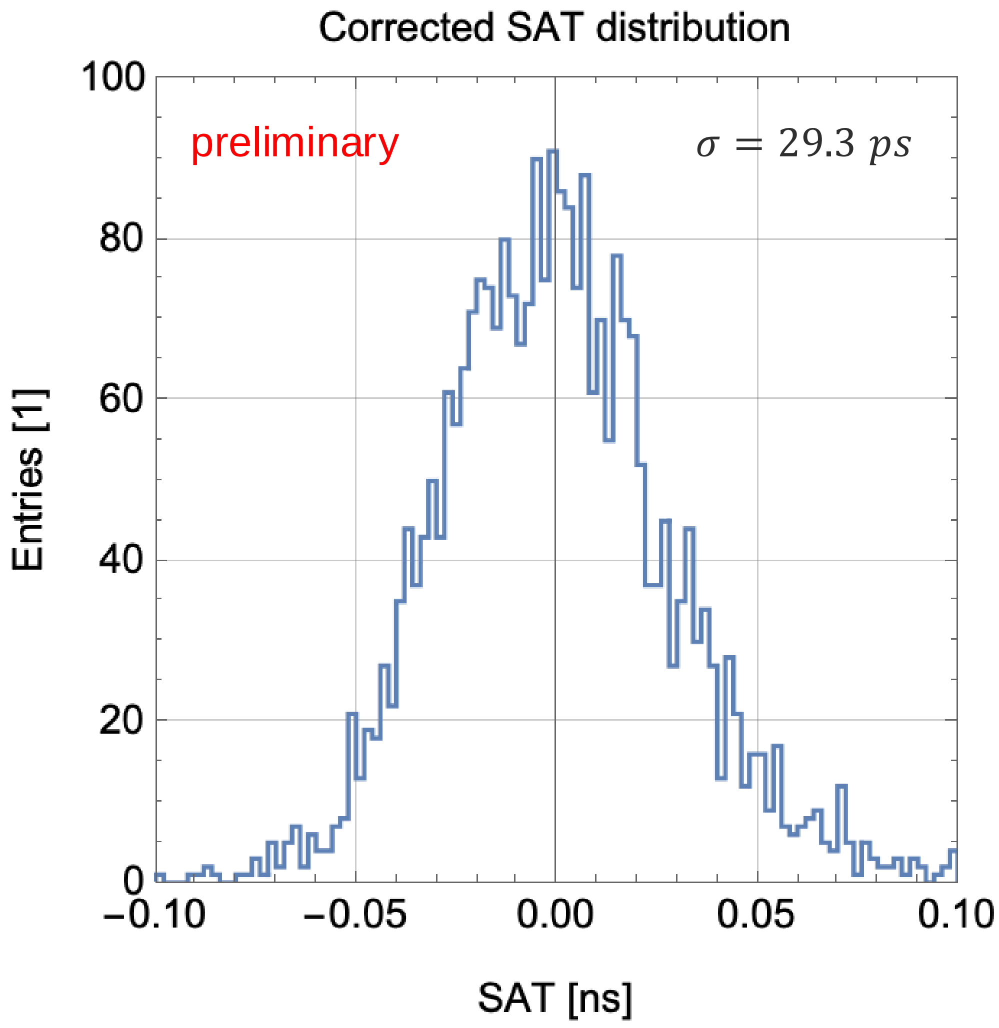
Fit parametrisation taken from: J. Bortfeldt et al., NIM-A **903** (2018) 317.
For more detailed PICOSEC simulation work: J. Bortfeldt et al., NIM-A **993** (2021) 165049.

Signal arrival time distribution

Correcting the SAT with the fitted curves:

$$\mathrm{SAT}_{corr,i} = \mathrm{SAT}_i - \langle \mathrm{SAT}(\tilde{q}_i) \rangle ,$$

for events $i \in \{1,2, \ldots, N\}$, we get the final SAT distribution. This in turn provides us with the timing resolution or our detector.



What about:

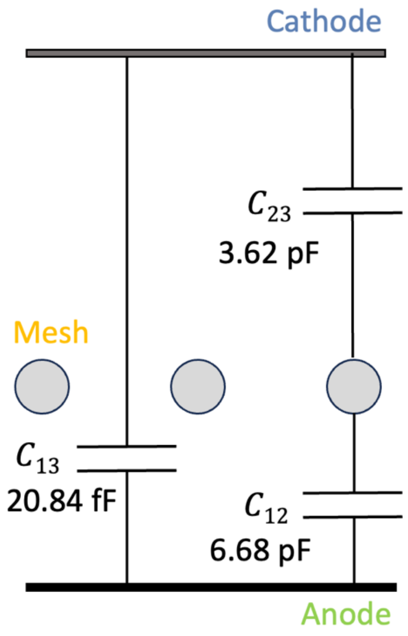
- Capacitive coupling between electrodes?
- Resistive elements?
- Noise of the detector?

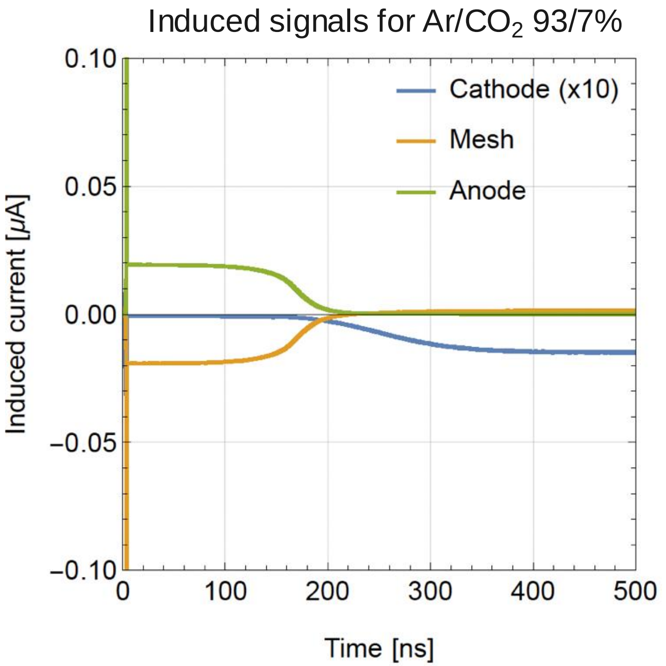
Capacitive-coupling between electrodes

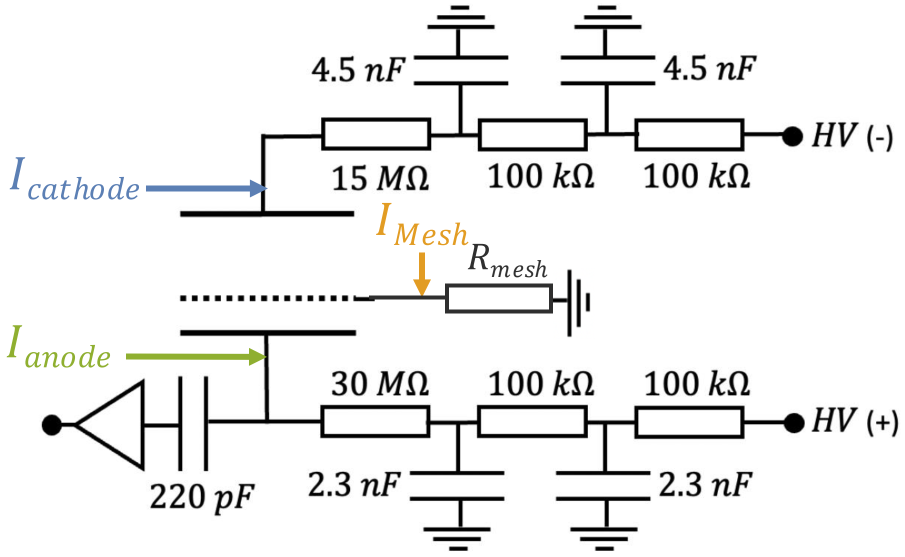
Capacitive-coupling between electrodes

The Maxwell capacitance matrix was calculated numerically to include the capacitive coupling between electrodes.

To the equivalent circuit of the detector, the amplifier model and filter boxes were added.

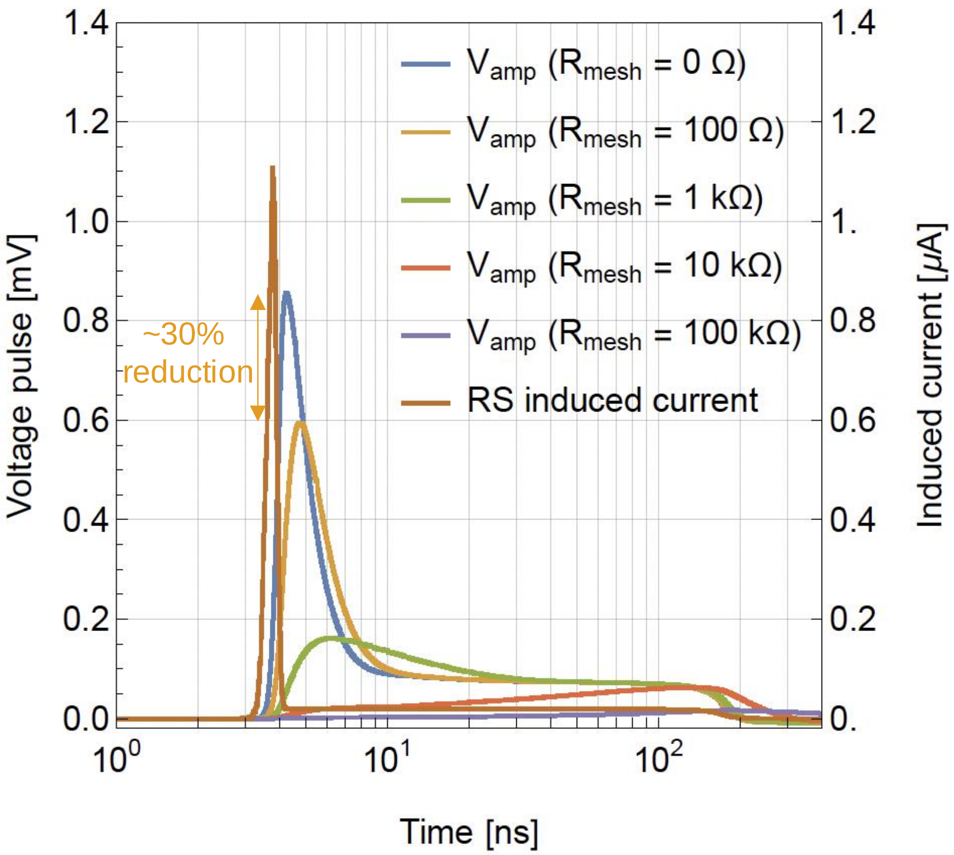


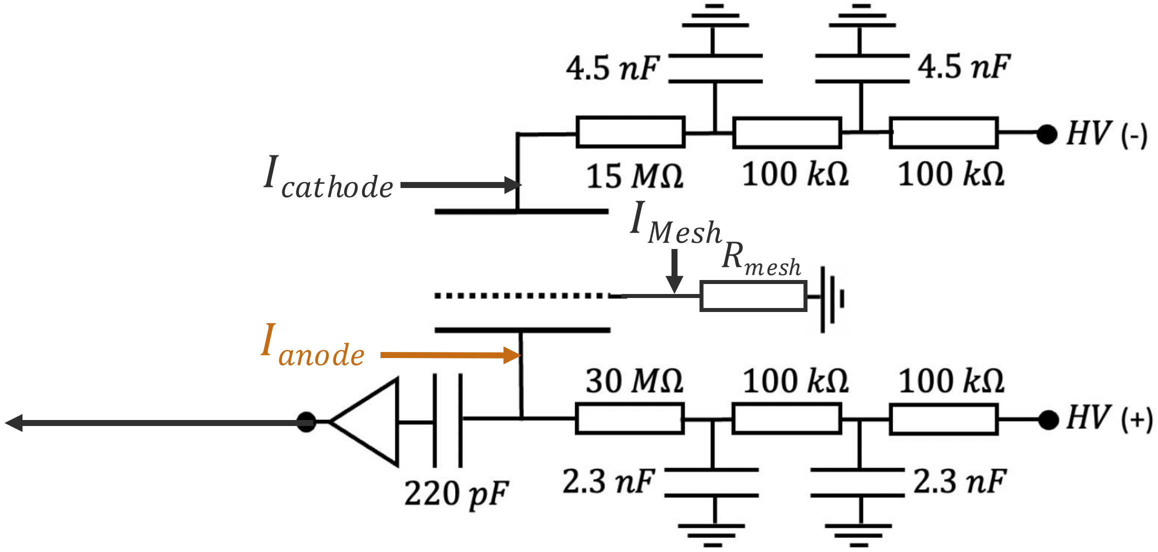




Capacitive-coupling between electrodes

The capacitive coupling is more exacerbated when introducing a non-zero resistance between the mesh connection and ground, resulting in the mesh's current being, in part, coupled out through the anode.

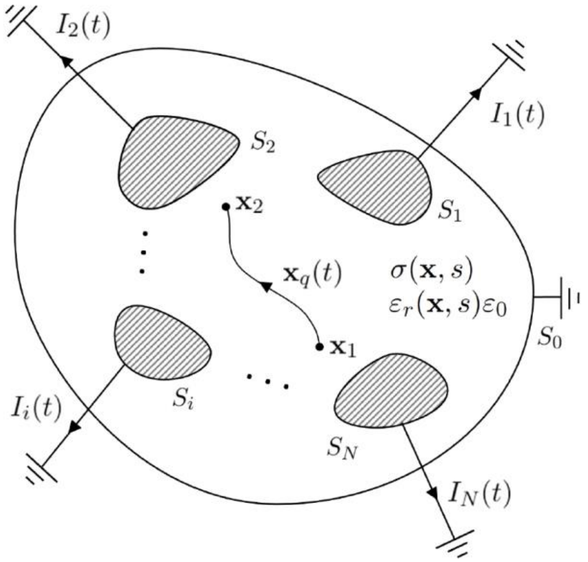


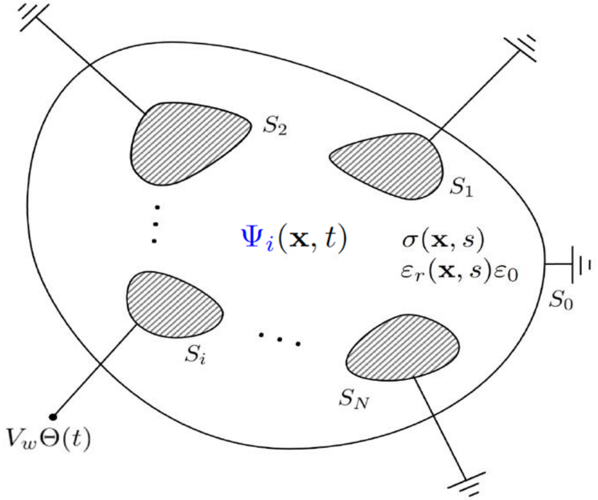


For a result on the ion tail length: D. Janssens,"Ion mobility in a Micromegas detector: a puzzle between measurement and simulation", RD51 Collaboration Meeting.
Also: Daniele D'Ago's presentation of today: https://indi.to/PsCwX.

Signal formation with resistive elements

Ramo-Shockley theorem extension for conducting media





In detectors with resistive elements, the signal shape depends on both charge movement in the drift medium and the time-dependent reaction of resistive materials.

$$I_i(t) = -\frac{q}{V_w}\int_0^t \mathbf{H}_i\left[\mathbf{x}_q\left(t'\right), t - t'\right] \cdot \dot{\mathbf{x}}_q\left(t'\right)\, dt'$$

$$\mathbf{H}_i(\mathbf{x}, t) := -\nabla \frac{\partial \Psi_i(\mathbf{x}, t)\Theta(t)}{\partial t}$$

The dynamic weigting potential $\psi_i(\mathbf{x}, t)$ can be calculated:

- Remove the drifting charges
- Put the electrode at potential Vw at time t = 0
- Grounding all other electrodes

E. Gatti et al., Nucl. Instrum. Meth. in Physics Research 193 (1982) 651.
W. Riegler, Nucl. Instrum. Meth. A 535 (2004), 287-293.
W. Riegler, Nucl. Instrum. Meth. A 940 (2019) 453-461.

Ramo-Shockley theorem extension for conducting media

The time-dependent weighting potential is comprised of a static prompt and dynamic delayed component:

$$\psi_i(\mathbf{x},t) \doteq \psi_i^p(\mathbf{x}) + \psi_i^d(\mathbf{x},t) \quad \text{where} \quad \psi_i^d(\mathbf{x},0) = 0$$

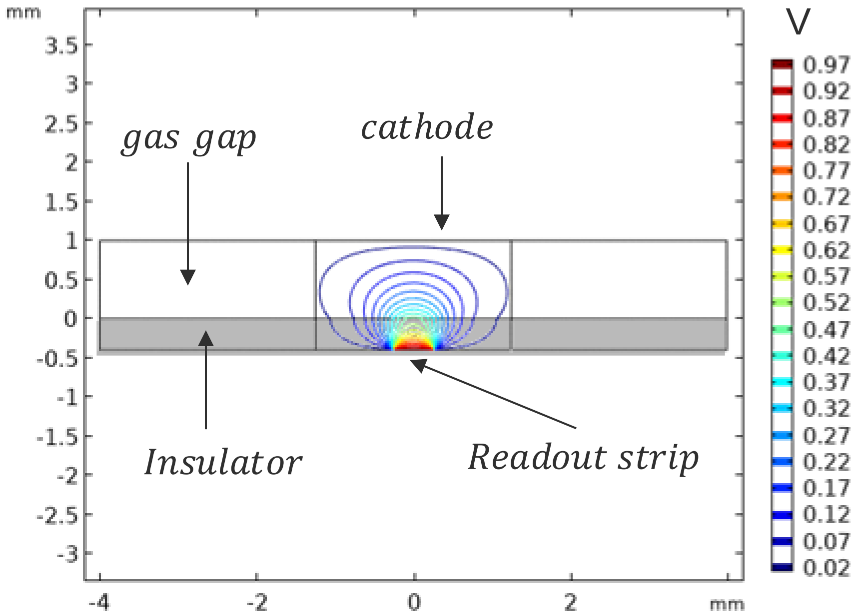
.

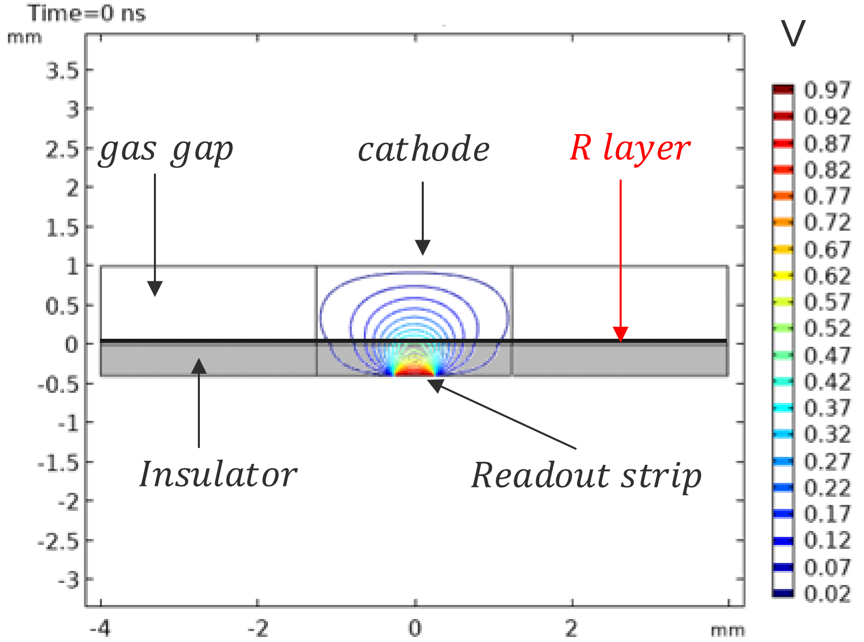
The current induced by a point charge q following $x_q(t)$ is given by:

$$I_i(t) = -\frac{q}{V_w}\mathbf{E}_i^p(\mathbf{x}_q(t)) \cdot \dot{\mathbf{x}}_q(t) - \frac{q}{V_w}\int_0^t dt'\, \mathbf{H}_i^d\left[\mathbf{x}_q\left(t'\right), t-t'\right] \cdot \dot{\mathbf{x}}_q\left(t'\right)$$

Direct induction

Reaction from resistive material

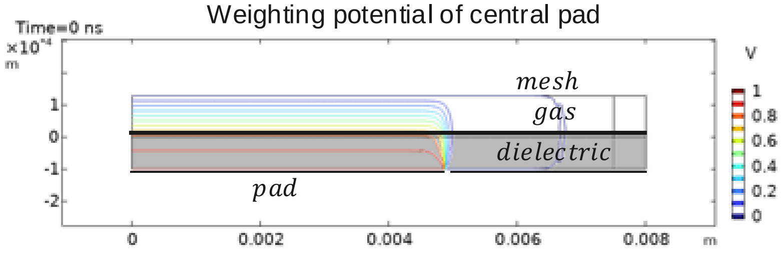


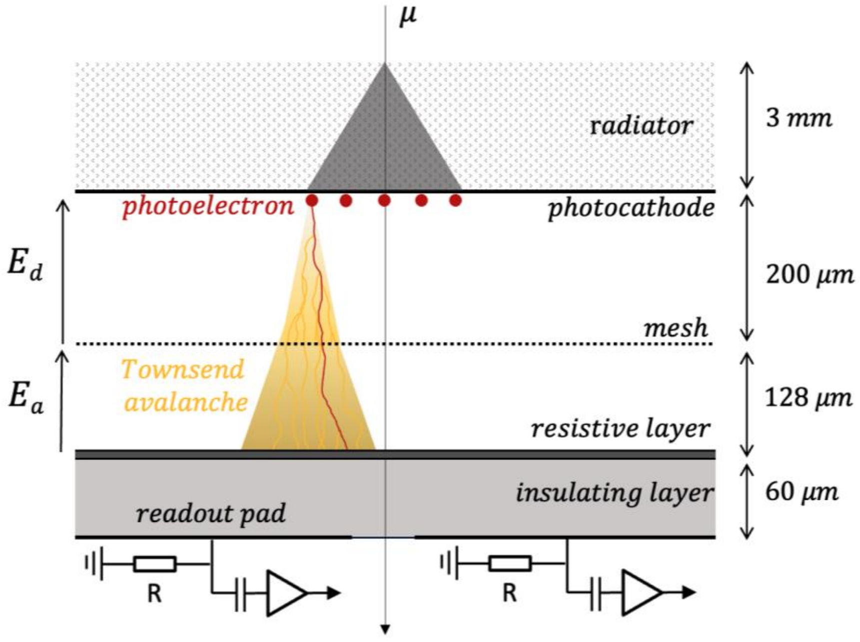


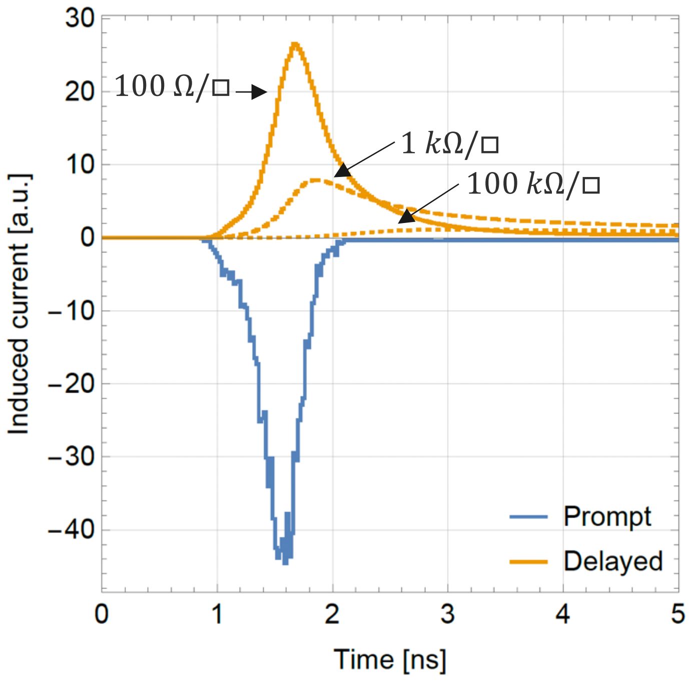
Resistive PICOSEC Micromegas

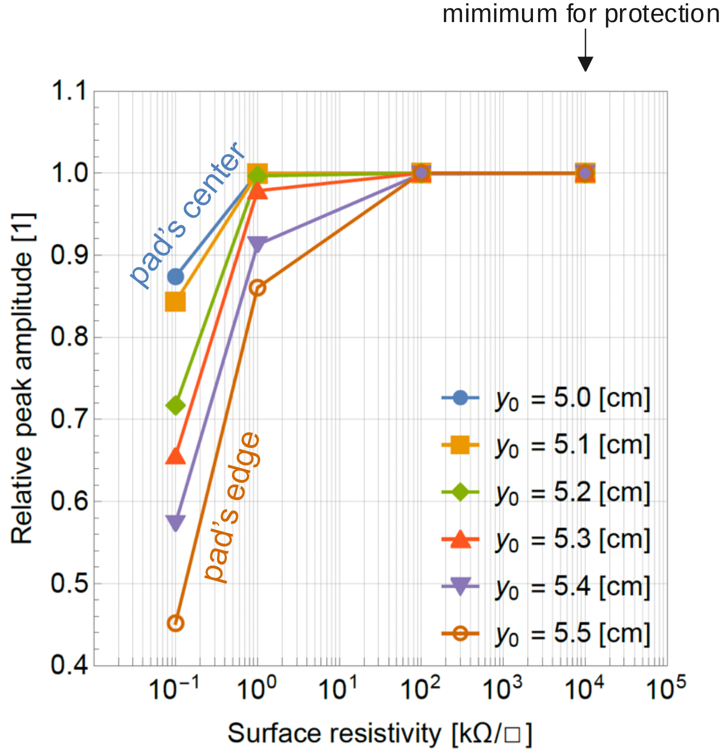
Given a surface resistivity of ≥100 kΩ/□, the leading edge of the signal is virtually unaffected by the reaction of the resistive layer.

However, the dielectric layer does reduce the signal amplitude by ~ 20%.









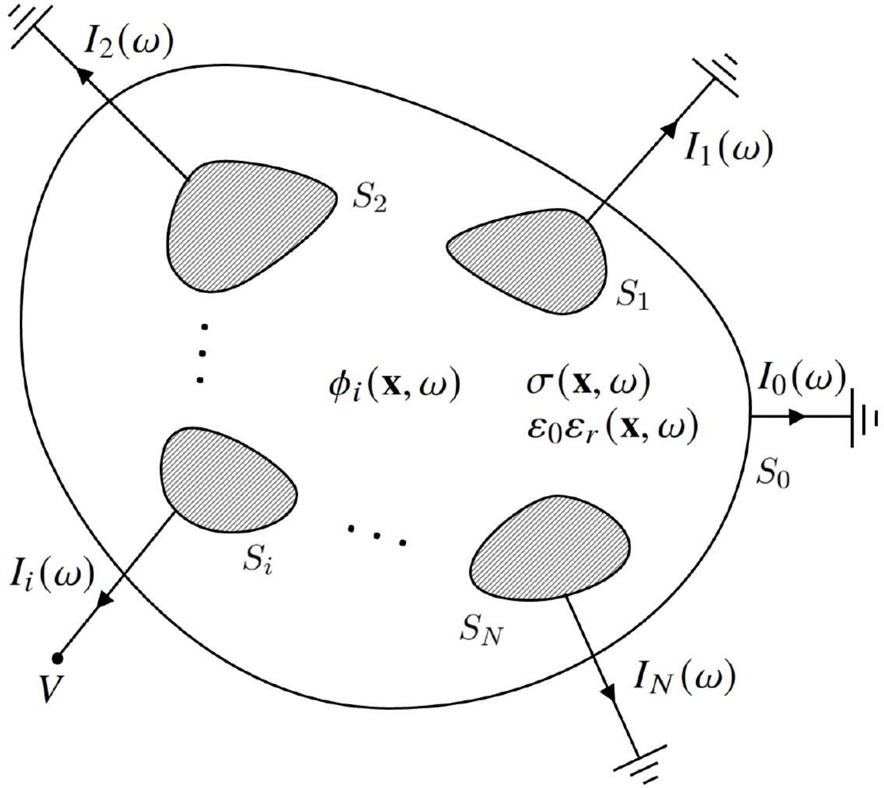
Rate capability simulation: D. Janssens' presentation (tomorrow): https://indi.to/Fvpkh.
D. Janssens, PhD dissertation, https://cds.cern.ch/record/2890572.

Noise in detectors containing resistive elements

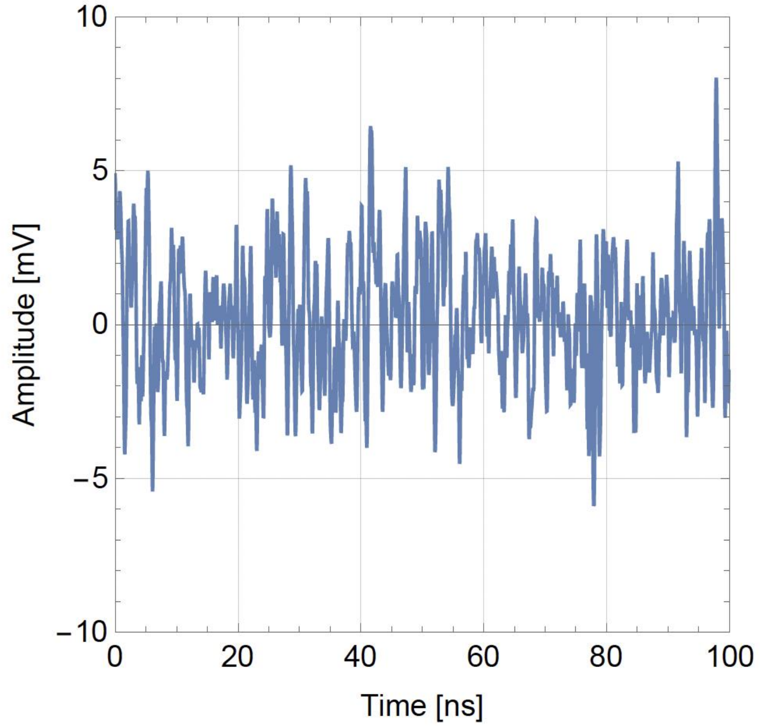
Noise in detectors containing resistive elements

There are many physical processes that generate noise in electric circuits. One of the most significant sources is noise from structures containing resistive materials, such as a DLC layer.

The self-impedance Z(iω) of the terminal will contribute to the detector's noise power spectrum.



$$w(\omega) = 4kbTRe[1/Z(i\omega)]$$

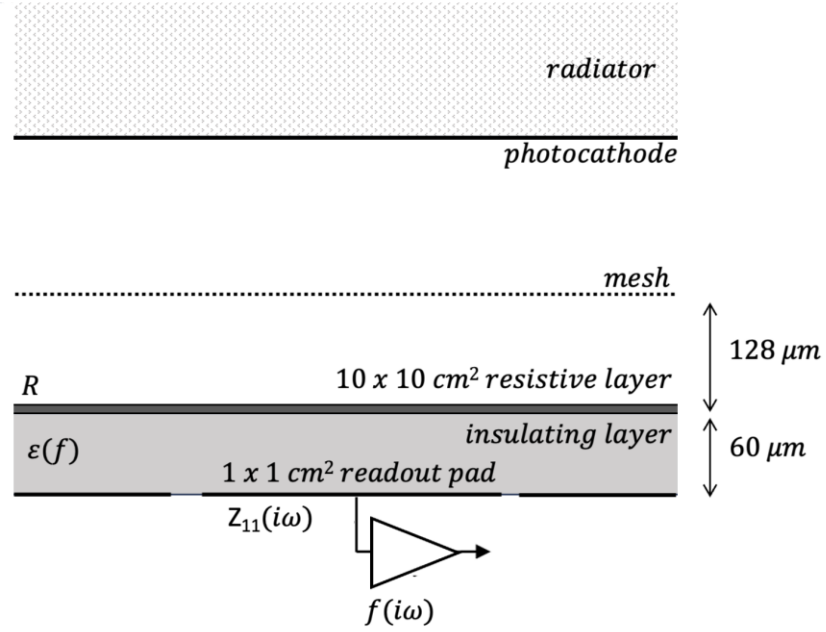


H. Nyquist, Physical Review 32 (1928) 110.168.
J.B. Johnson, Physical Review 32 (1928) 97.169.
D. Janssens and W. Riegler, NIM-A 1064 (2024) 169374.

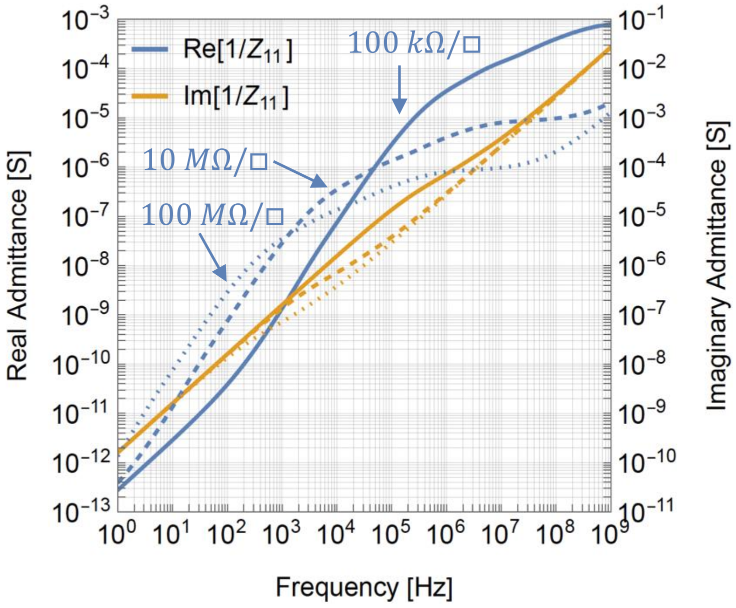
Noise in detectors containing resistive elements

We can calculate the self-impedance of the pad $Z_{11}(i\omega)$, located below a resistive layer, in the frequency domain using a finite element method approach. With this information, the equivalent noise charge can be determined.

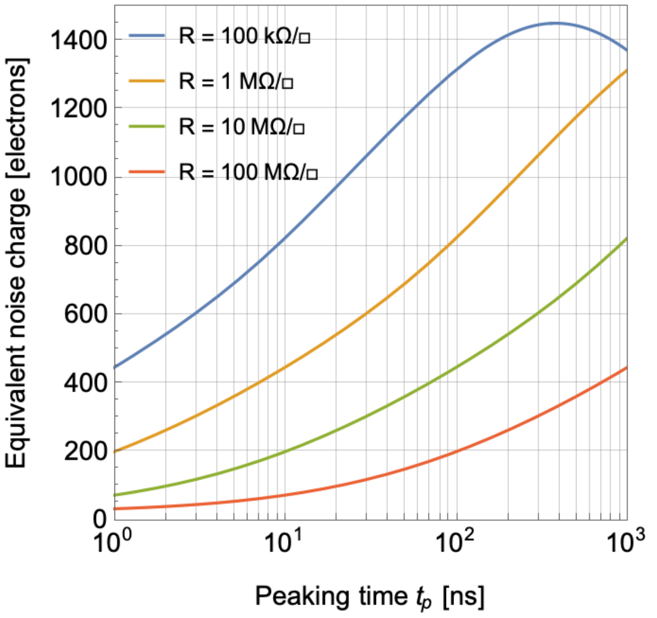
$$\mathrm{ENC}^2 = \left(\frac{\sigma_v}{g}\right)^2 = \frac{2k_bT}{\pi}\int_0^\infty \mathrm{Re}\left[\frac{1}{Z_{11}(i\omega)}\right]|f(i\omega)|^2 d\omega\,.$$



Simulated self-impedance of the central 1 x1 cm^2 pad



Simulated ENC for a pad electrode in a resistive MM



Summary

We aimed to provide a brief overview of the simulation methods and tools available for conducting time resolution studies on resistive particle detectors using Garfield++.

- **Charge Transport:** The microscopic approach for electron transport allows for a precise description of the initial fluctuations of the avalanche, which is vital for timing and provides great flexibility to investigate different contributions.

  This approach enabled the PICOSEC collaboration to estimate the transparency of various meshes.
- **Signal Formation:** Using the (extended) Ramo-Shockley theorem, the induced signal can be obtained for electrodes made with resistive materials. For the resistive PICOSEC, a surface resistivity of ≥100 kΩ/□ preserves the leading edge.
- **Time-Walk:** After correcting for the (residual) time-walk, the final signal arrival time (SAT) distribution can be obtained.
- **Thermal Noise:** A finite element method-based approach can be used to find the noise contribution from resistive elements.

<u>Outlook</u>**:**

- Modeling **large avalanche sizes** present a challenging but relevant issue that can benefit from contemporary computing methods.

Thank you for your attention!