EP R&D SEMINAR

Signal formation in detectors with resistive elements

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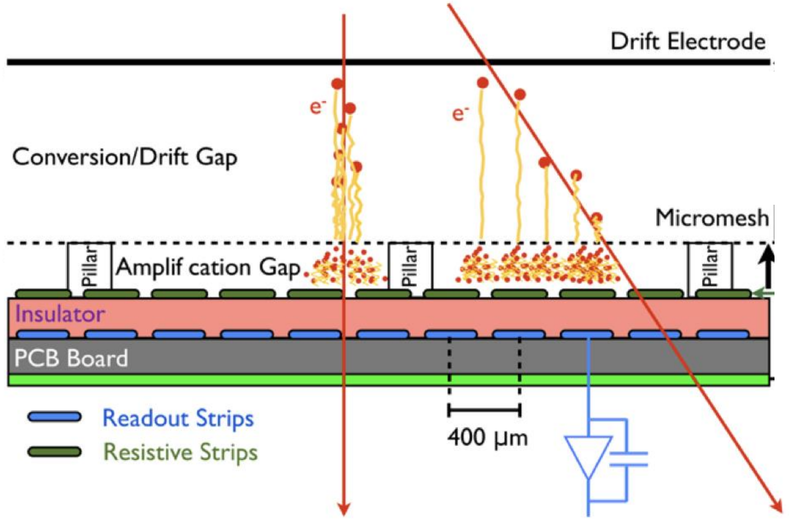
Introduction

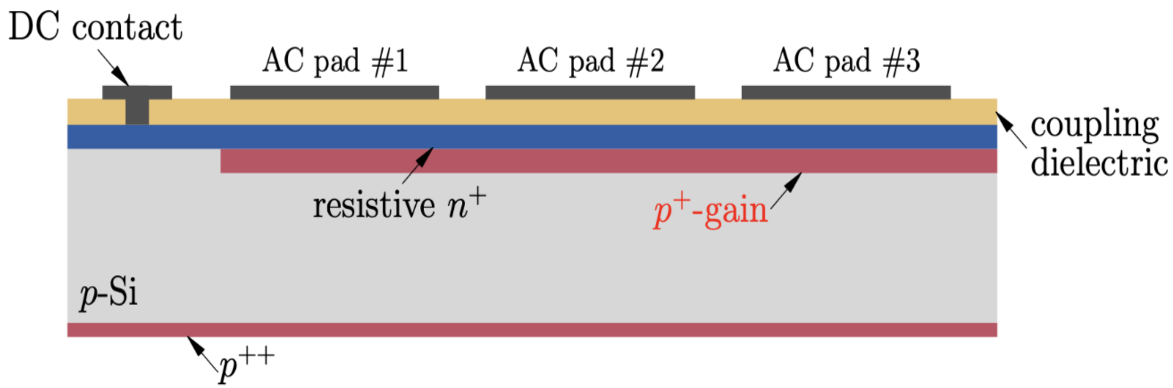
Novel detector structures are proposed regularly, mixing old and new ideas, with detectors containing resistive elements widening the landscape of possible configurations.

The use of these technologies in experiments makes it necessary to understand and characterize its the response for the design and optimization of the next generation of particle detectors and their application.

Resistive-strips micromegas



AC-Coupled LGAD



T. Alexopoulos et al., Nucl. Instrum. Meth. A 640 (2011) 110.
M. Tornago, R. Arcidiacono, N. Cartiglia et al., Nucl. Instrum. Meth. A **1003** (2021).

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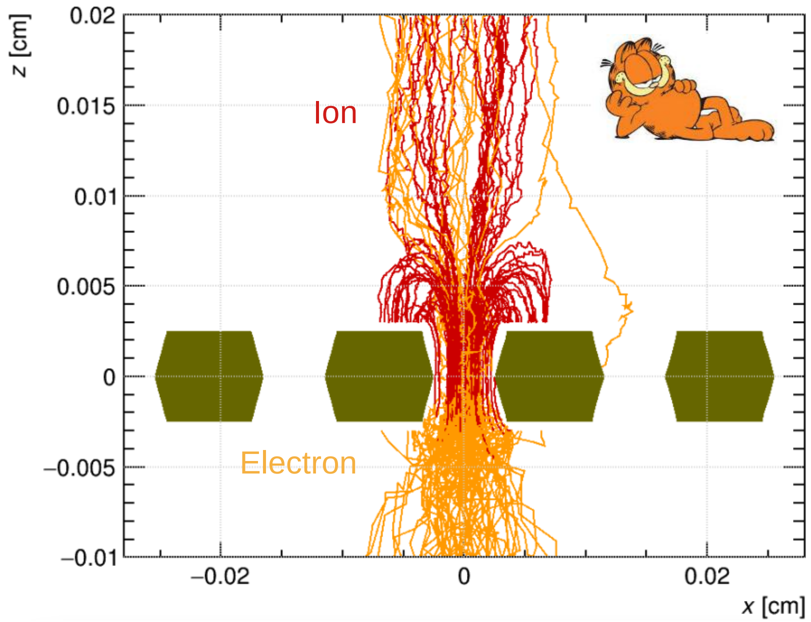
Overview

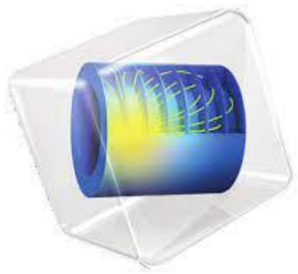
We want to use Garfield++ and COMSOL to model the signal formation in detectors with resistive elements by applying an extended form of the Ramo-Shockley theorem.

Outline:

- Ramo-Shockley theorem extension for conductive media
- Overview of the numerical approach
- Examples of signals induced in various detectors
- Summary

Drift lines of a GEM in Garfield++





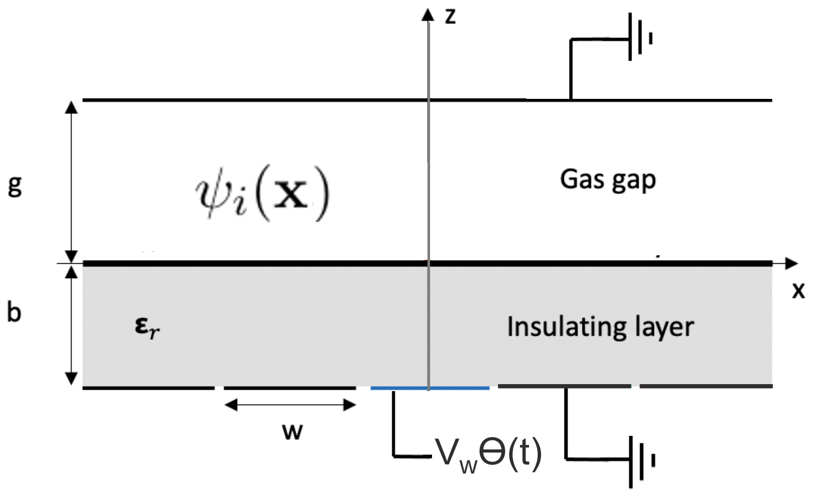
Garfield++: https://garfieldpp.web.cern.ch/garfieldpp/
H. Schindler's dissertation: Microscopic simulation of particle detectors
COMSOL Multiphysics: https://www.comsol.ch

Ramo-Shockley theorem

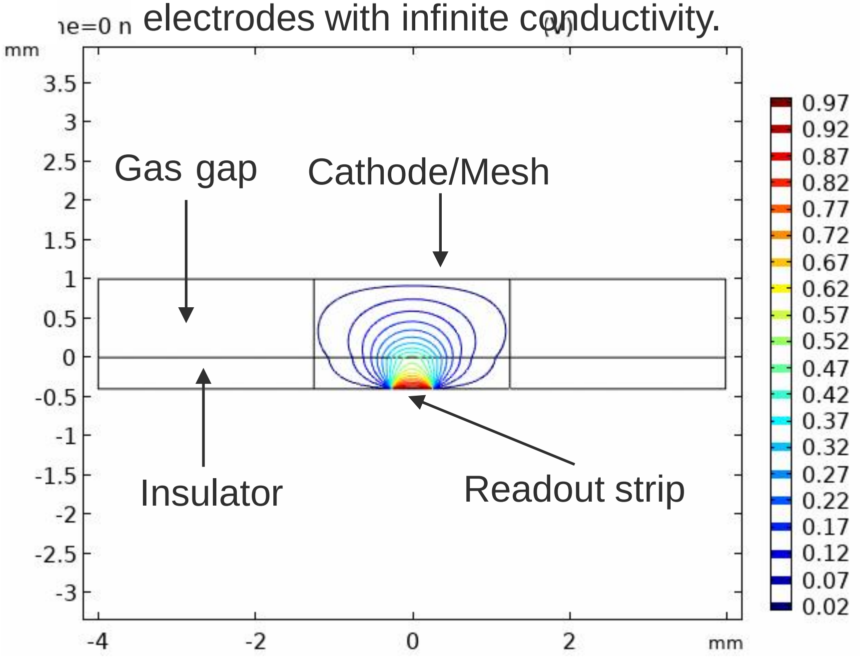
The Ramo-Shockley theorem allows the current induced by an externally impressed charge density on any electrode to be calculated by the usage of a so-called weighting potential $\psi(\mathbf{x})$.

This static $\psi_i(\mathbf{x})$ can be calculated for an electrode i by:

- Remove the drifting charges
- Put the electrode at potential V_w
- Grounding all other electrodes



Weighting potential for only perfect insulators and electrodes with infinite conductivity.

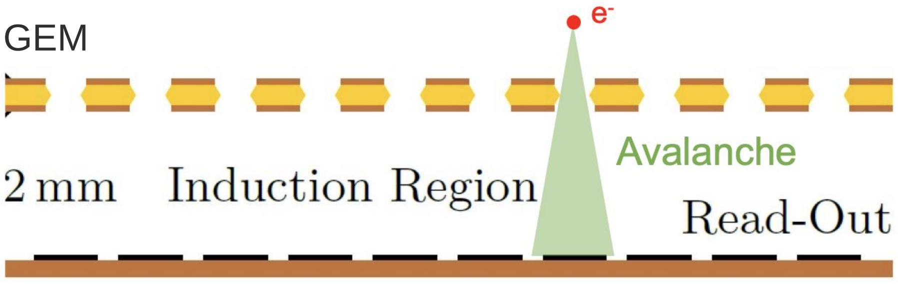


S. Ramo, PROC. IRE 27, 584 (1939).
W. Shockley, Journal of Applied Physics. 9 (10): 635 (1938).

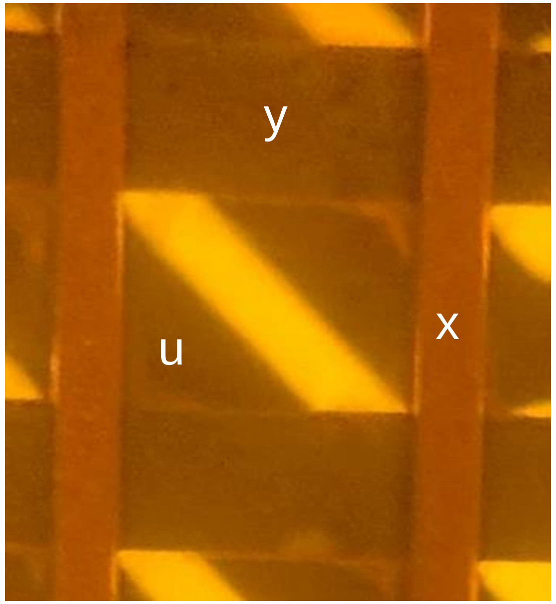
Ramo-Shockley theorem

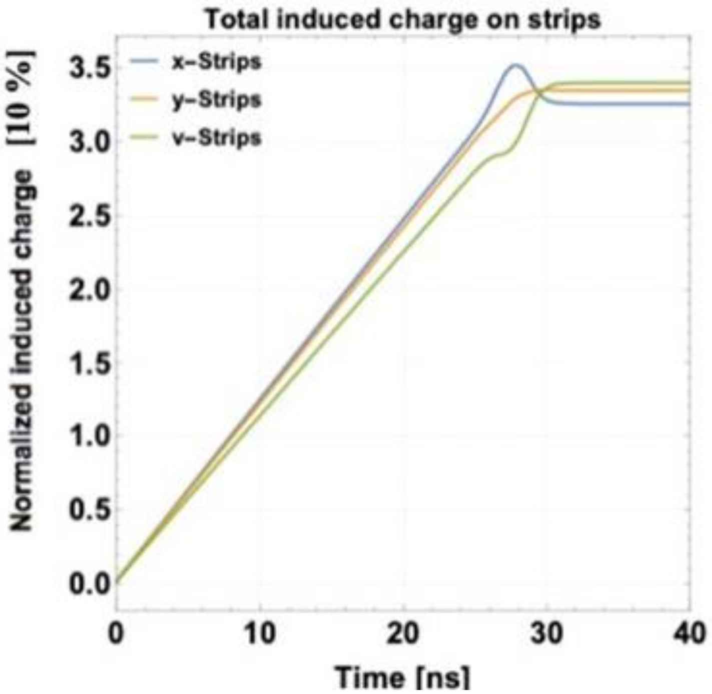
Using this framework, the induced current sourced by a point charge q can, for example, be calculated in a single GEM geometry with x- and y-strips. This is done by first calculating the weighting potential of the strips.

$$I_i(t) = -\frac{q}{V_w}\nabla\psi_i[\mathbf{x}_q(t)]\dot{\mathbf{x}}_q(t)$$



XYU Readout image





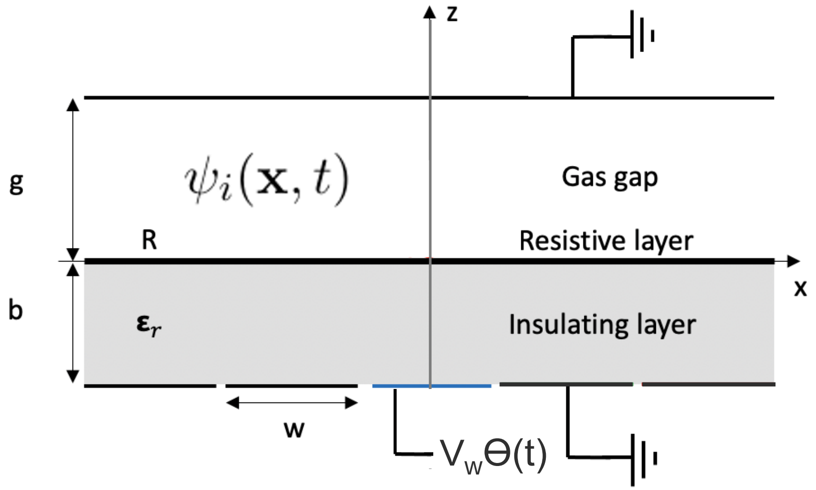
This XYU-Readout design is a project in progress with F. Sauli and K. J. Flöthner.
First results will be presented tomorrow by K. J. Flöthner :
https://indico.cern.ch/event/1138814/contributions/4917313/

Ramo-Shockley theorem extension for conducting media

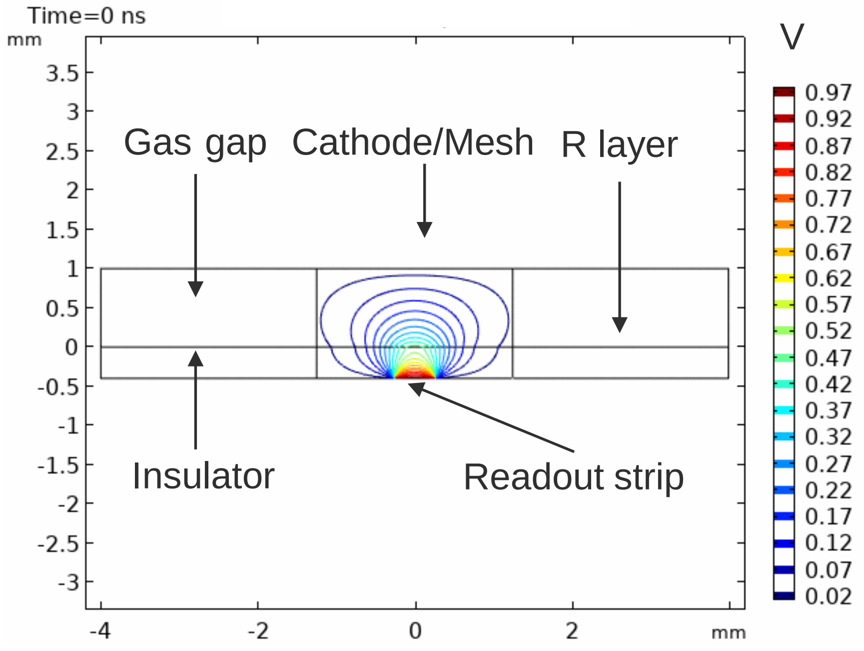
For detectors with resistive elements, the time dependence of the signals is not fully given by the movement of the charges in the drift medium but also by the time-dependent reaction of the resistive materials.

This dynamic $\psi_i(\mathbf{x}, t)$ can be calculated for an electrode i by:

- Remove the drifting charge carriers
- On the electrode apply a step voltage pulse at time t = 0
- Grounding all other electrodes

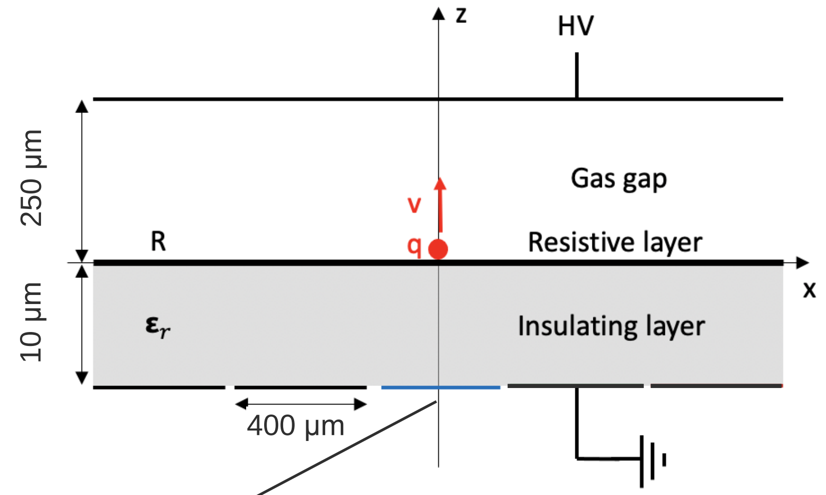


Weighting potential for a resistive layer separating the gas gap and insulating layer.



W. Riegler, Nucl. Instrum. Meth. A 535 (2004), 287-293.
W. Riegler, Signals in Particle Detectors, CERN's Academic Training Lecture Regular Programme (2019): https://indico.cern.ch/event/843083/

Ramo-Shockley theorem extension for conducting media



The time-dependent weighting potential is comprised of a static *prompt* and a 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 particle q is given by:

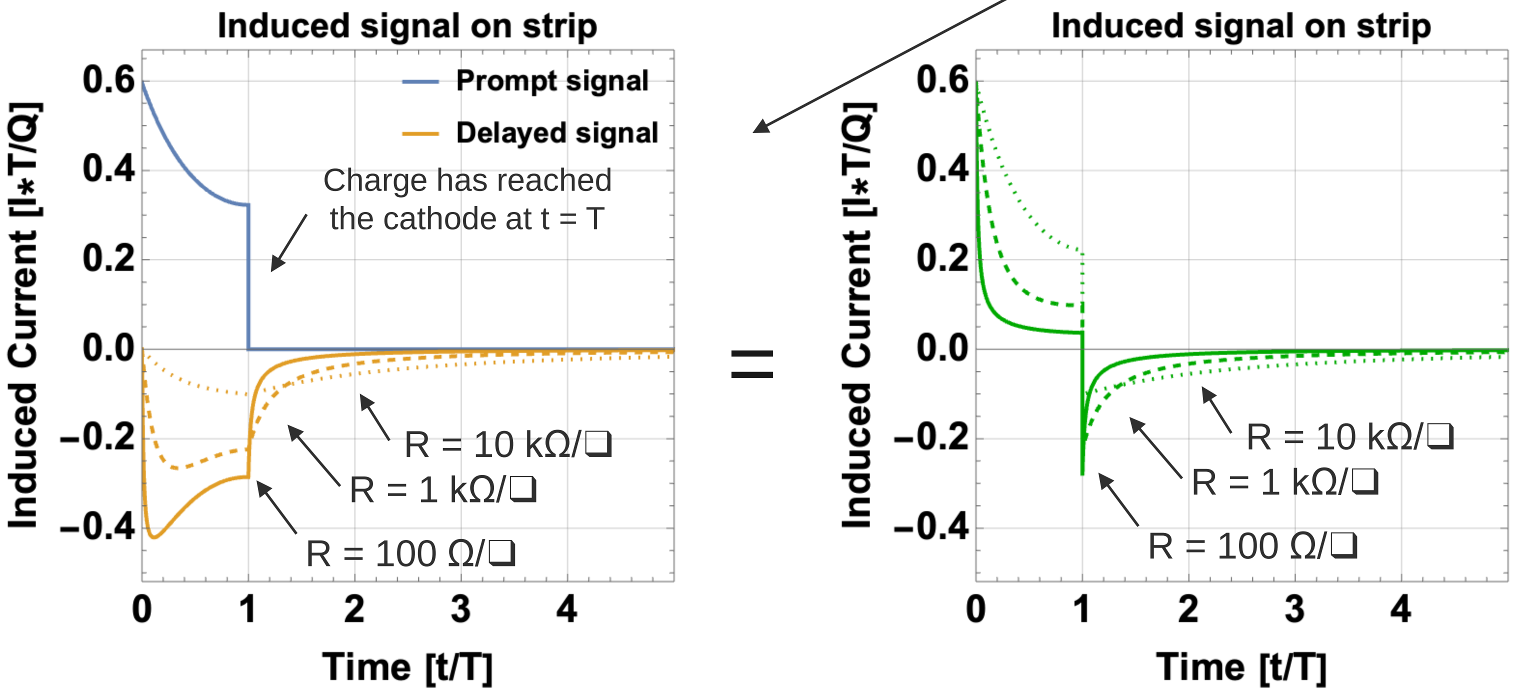
$$I_i(t) = -\frac{q}{V_w} \int_0^t dt' \, \mathbf{H}_i \left[\mathbf{x}_q(t'), t - t' \right] \cdot \dot{\mathbf{x}}_q(t')$$

$$\mathbf{H}_i(\mathbf{x}, t) \doteq -\nabla \frac{\partial \psi_i(\mathbf{x}, t)}{\partial t}$$

$$= -\nabla \psi_i^p(\mathbf{x}) \delta(t) - \nabla \frac{\partial \psi_i^d(\mathbf{x}, t)}{\partial t} \Theta(t)$$

Direct induction

Reaction from resistive material

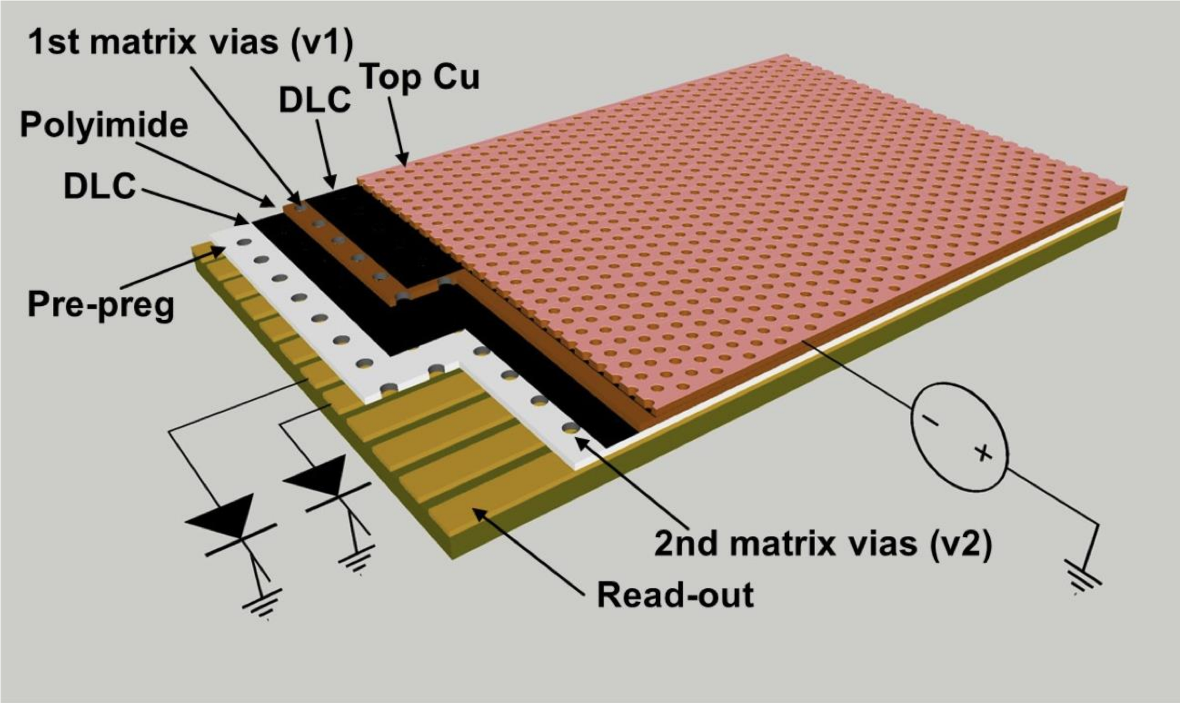


Examples of systems of which the weighting potential is analytically obtainable see W. Riegler, JINST **11** (2016) no.11, P11002.
Further reading: W. Riegler, P. Windischhofer, Nucl. Instrum. Meth. A 980 (2020)

Overview of the numerical methodology

These weighting potentials can only be obtained analytically for a small subset of the larger group of existing detectors; thus, a numerical method is used.

Sketch of the Double-Resistive layout µRWELL:



COMSOL® :

Numerically obtain the dynamic weighting potential.

Garfield++:

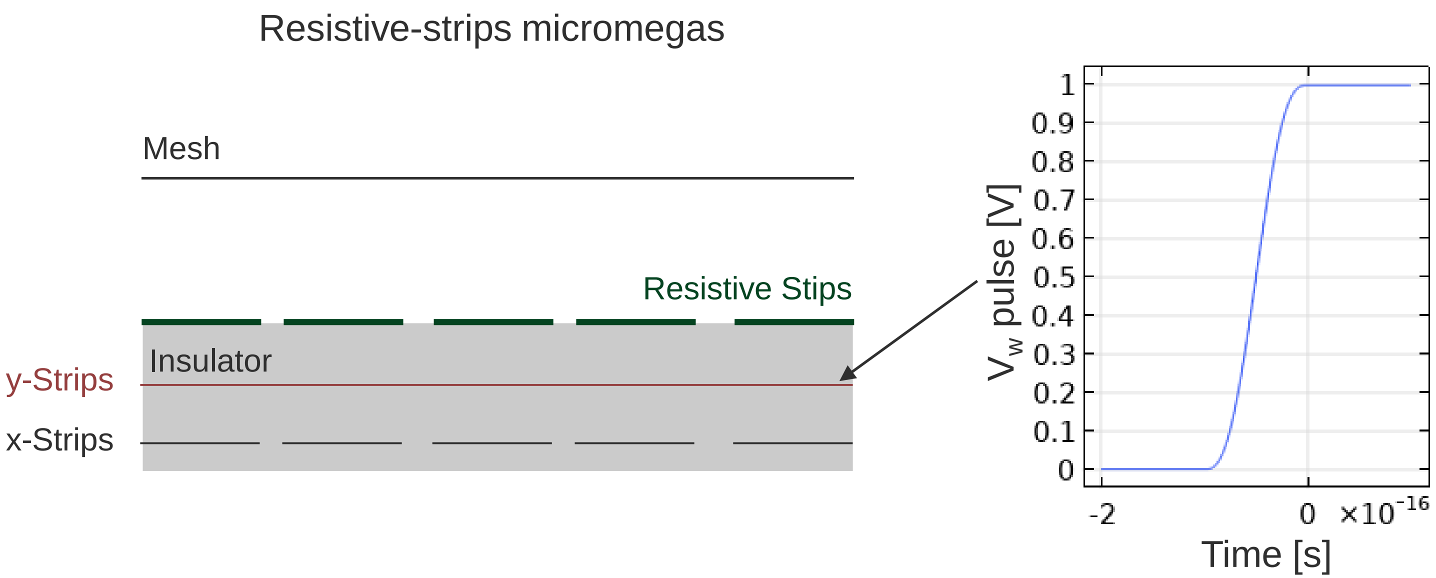
Detailed microscopic simulation of particle detectors based on ionization measurements in gases or semiconductors.

Garfield++: https://garfieldpp.web.cern.ch/garfieldpp/
COMSOL Multiphysics: https://www.comsol.ch /
G. Bencivenni et al., JINST 14 P05014 (2019).

Overview of the numerical methodology

COMSOL is a finite element solver capable of solving the electrodynamics field equations using the Electric Currents module and time solver.

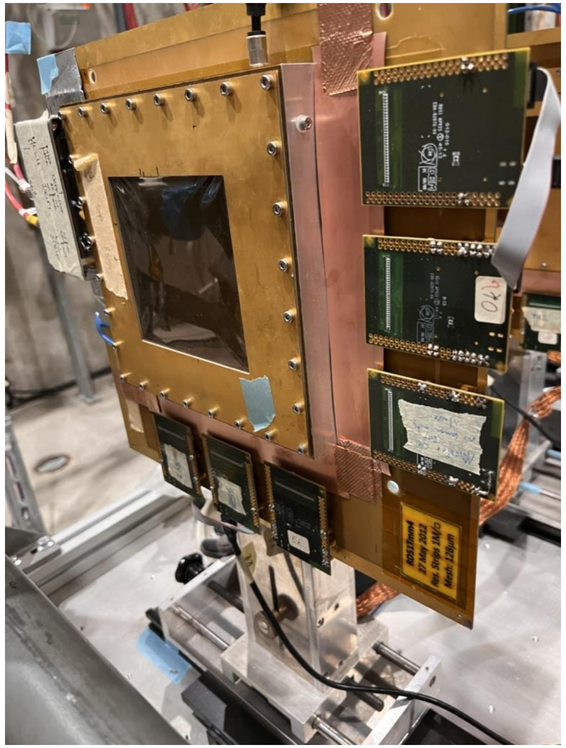
The ramping time of the step function for the V_w pulse is taken is taken smaller than the reaction time of the resistive material.



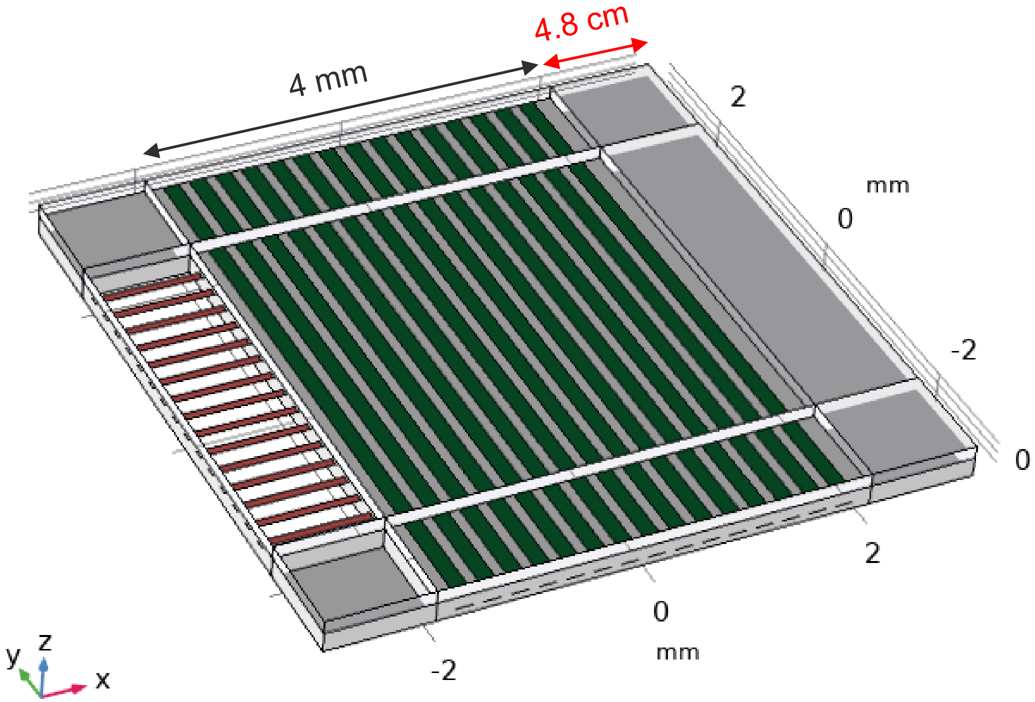
Overview of the numerical methodology

Coordinate mapping allows to modelling large area detectors such as a Resistive-strips micromegas.

Image taken at the May-June 2022 SPS test beam



COMSOL model of the geometry

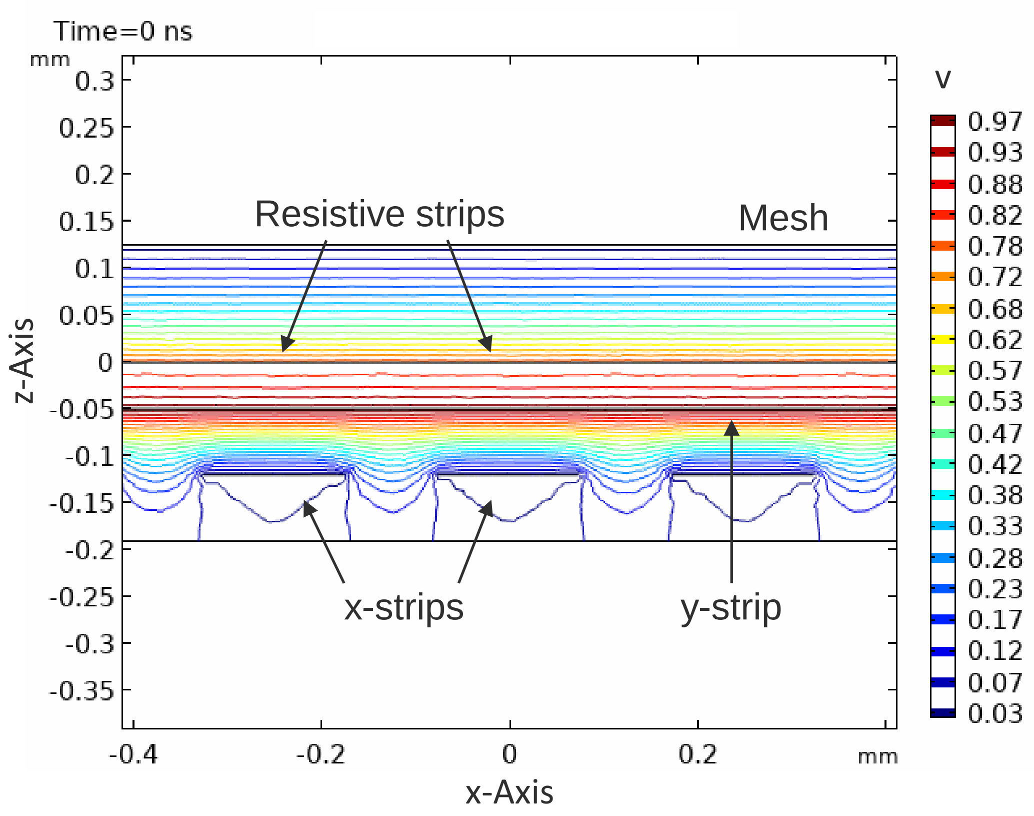


T. Alexopoulos et al., Nucl. Instrum. Meth. A 640 (2011) 110.
M. Byszewski1 and J. Wotschack, JINST 7 C02060 (2011).
COMSOL coordinate mapping: link.

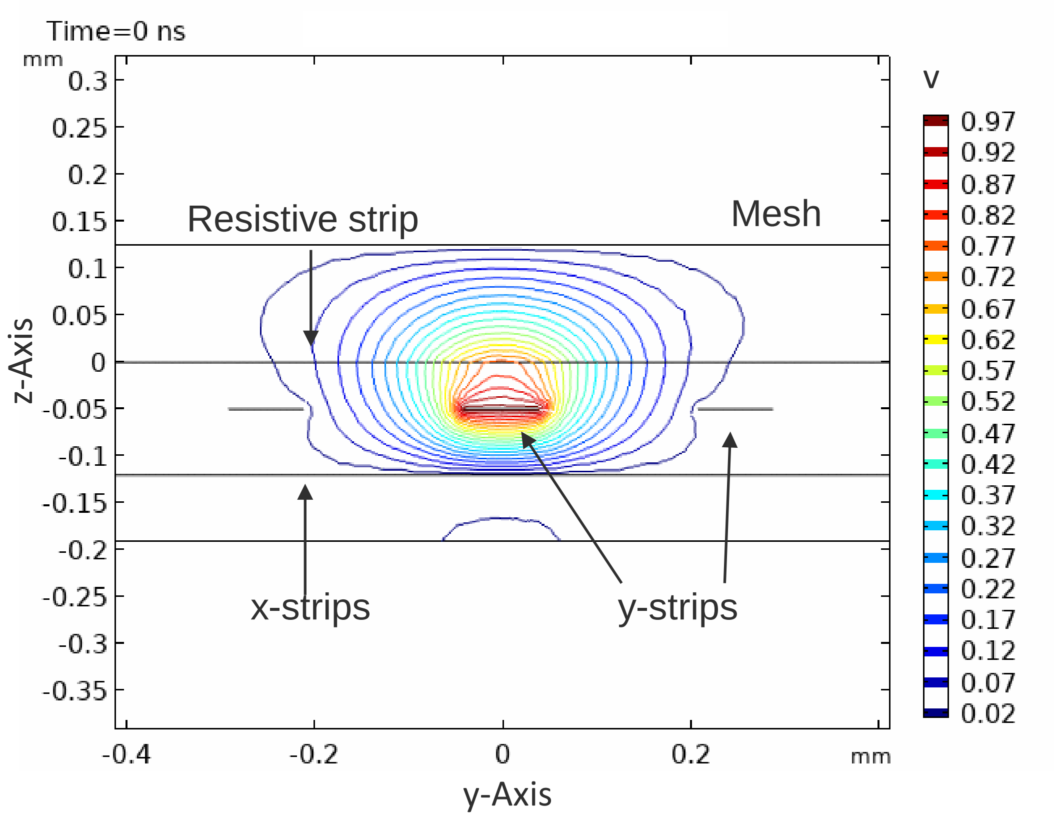
Overview of the numerical methodology

The resulting solutions are imported into Garfield++ as a finite collection of time sliced potential maps using its *ComponentComsol* class.

Weighting potential of a y-strip at y = 0.



Weighting potential of a y-strip at x = 0.

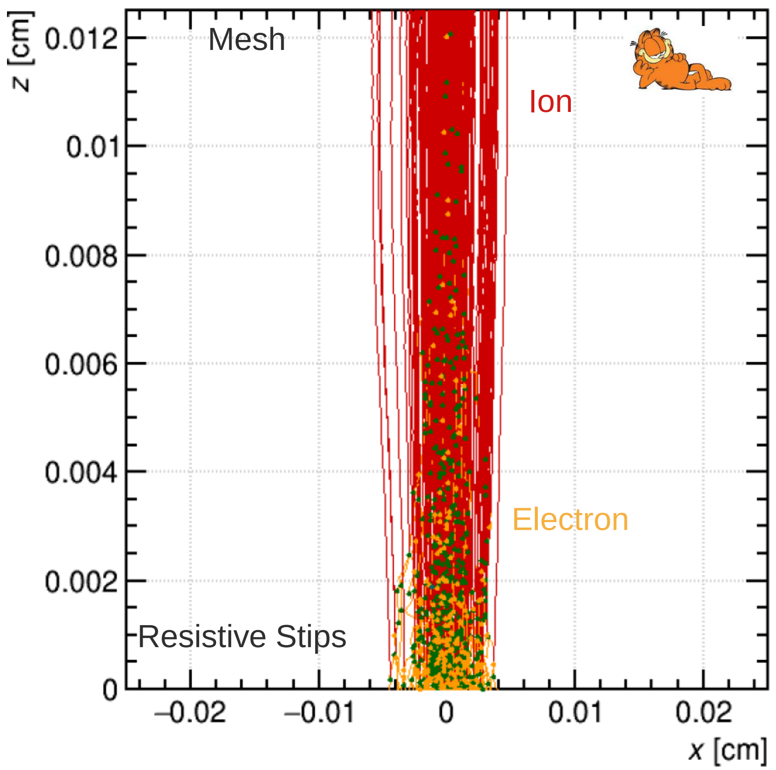


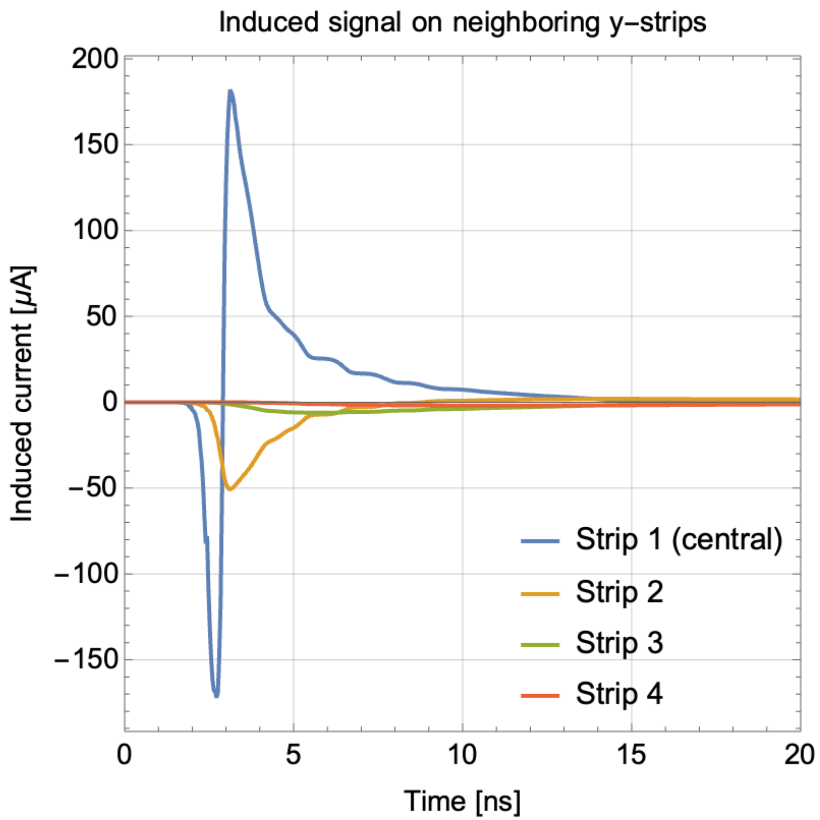
There is a tutorial on the Garfield++ webpage on the importing of field maps of COMSOL:
https://garfieldpp.web.cern.ch/garfieldpp/examples/comsol/

Overview of the numerical methodology

Given the trajectories of all charge carriers in your geometry, the induced current on the readout can be calculated.

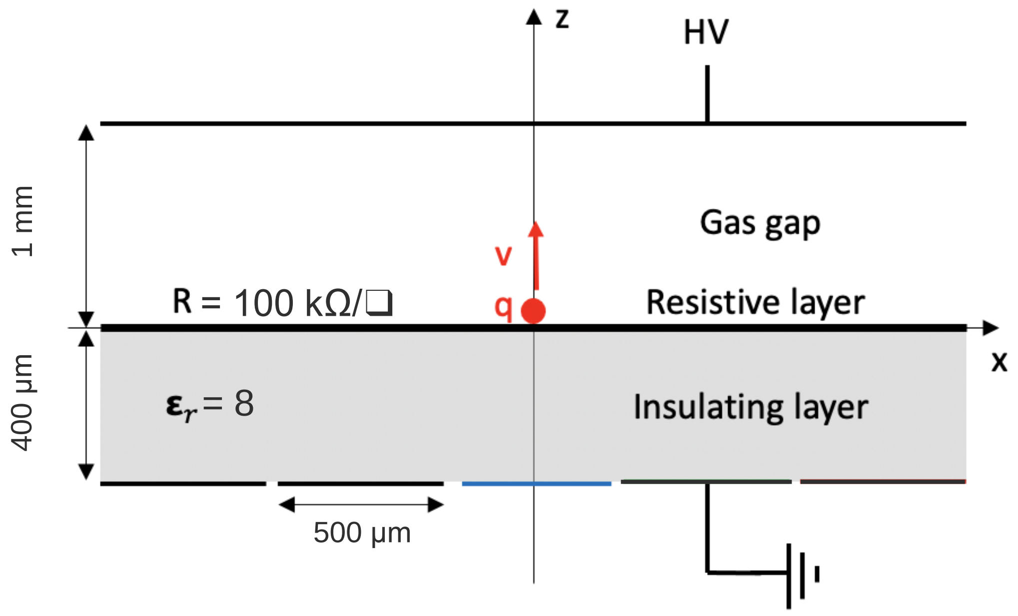
Drift lines in the induction gap as modelled by Garfield++

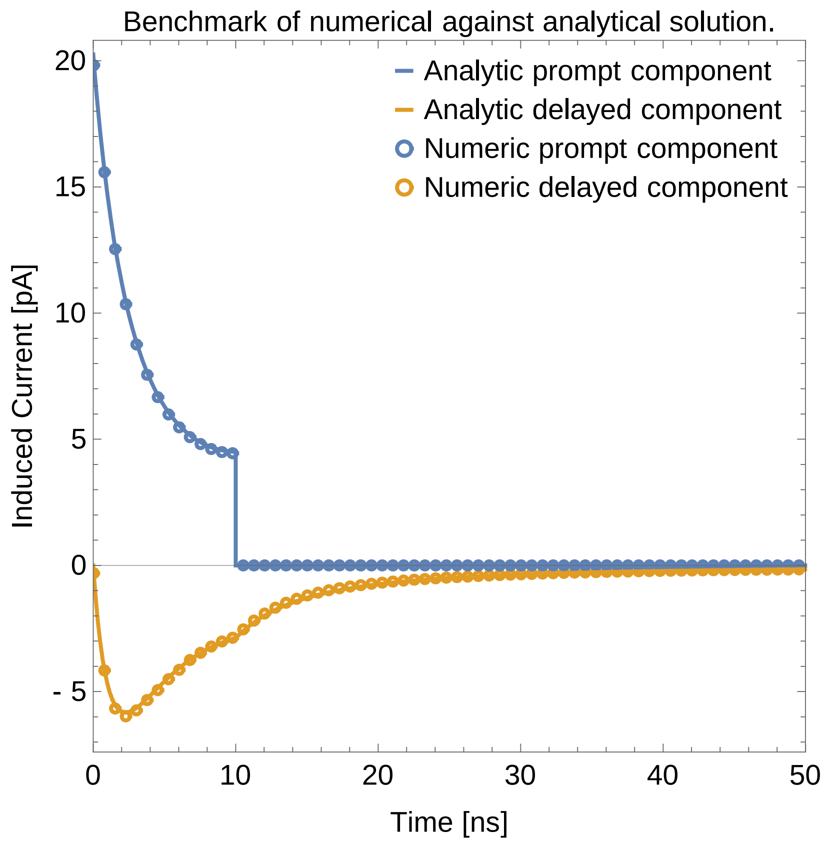




Overview of the numerical methodology

With the assurance of the accuracy of the methodology based on toy model examples which enjoy an analytic solution, we are deploying it to characterize the signals obtained from a wide variety of resistive particle detectors.



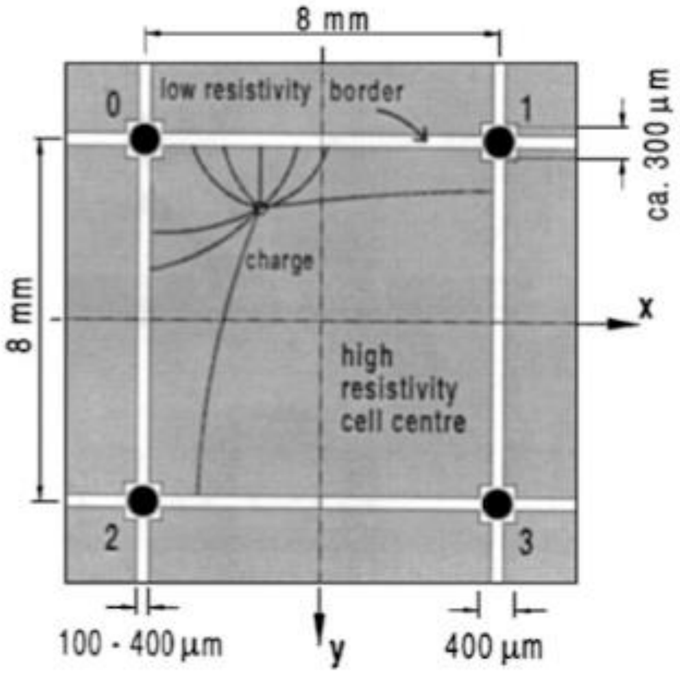


Examples of systems of which the weighting potential is analytically obtainable see W. Riegler, JINST **11** (2016) no.11, P11002.

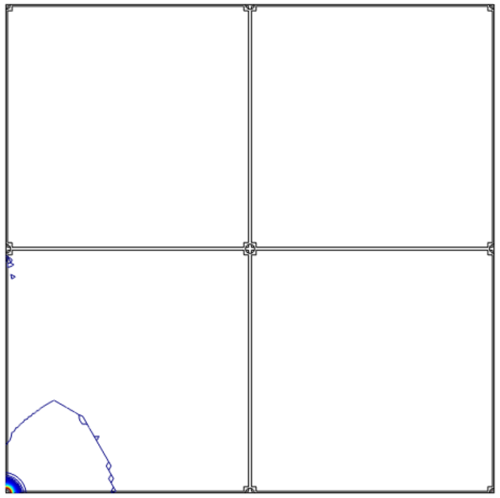
Signal formation in a MicroCAT detector

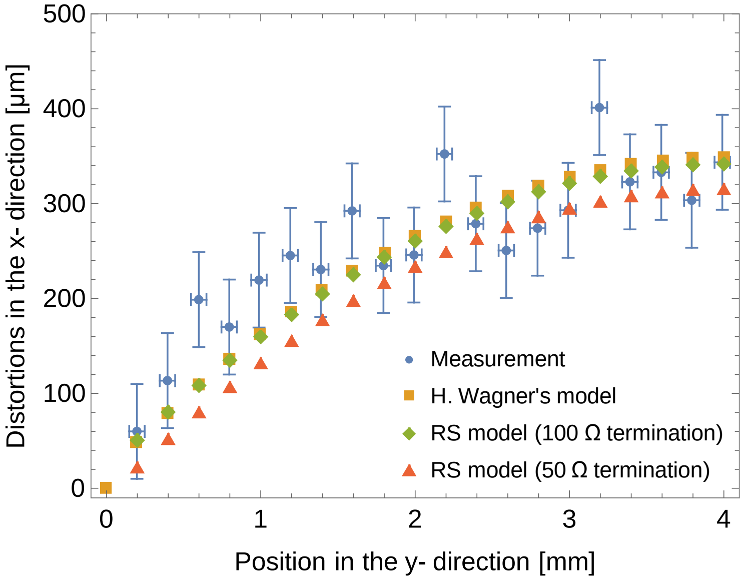
The MicroCAT's two-dimensional interpolating readout structure allows for a reduced number of electronic readout channels without loss of spatial resolution.

This resistive readout concept recently has enjoyed renewed interest within the development of a DC-Coupled LGAD device



Weighting potential map for one readout node





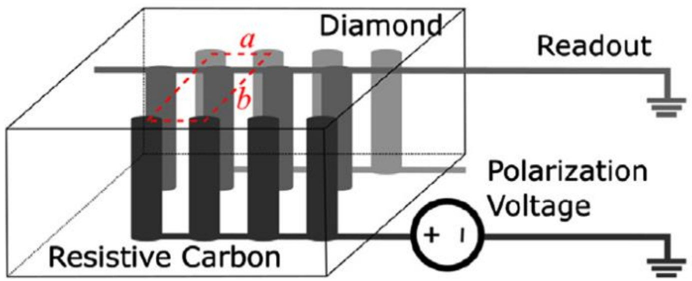
F. Bartol et al. J. Phys. III France, 6 (1996), p. 337
A. Sarvestani et al., Nucl. Instrum. Meth. A 410 (1998) 238–258
H. Wagner et al. Nucl. Instrum. Meth. A 482 (2002) 334–346

DC-coupled LGAD: N. Cartiglia, The 39th RD50 Workshop (Valencia) (17-19 November 2021).

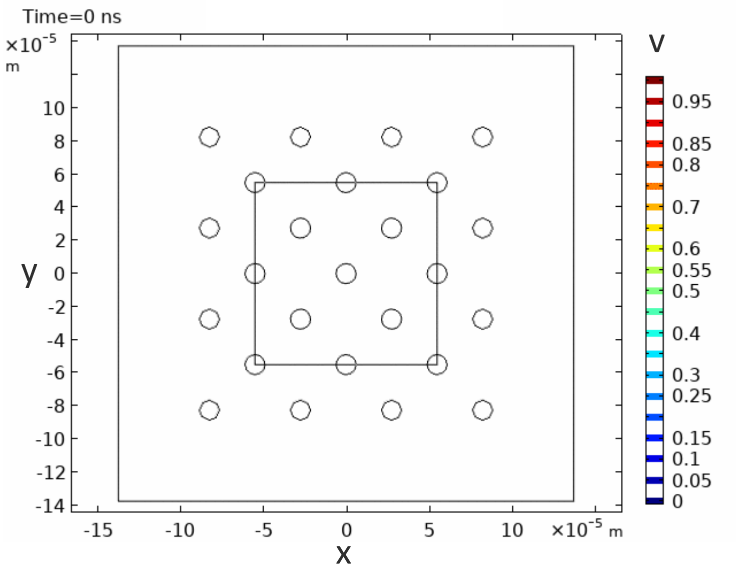
Diamond 3D Pixel Detector

A 3D geometry with thin columnar resistive electrodes orthogonal to the diamond surface, is expected to provide significantly better time resolution with respect to the extensively studied planar diamond sensors.

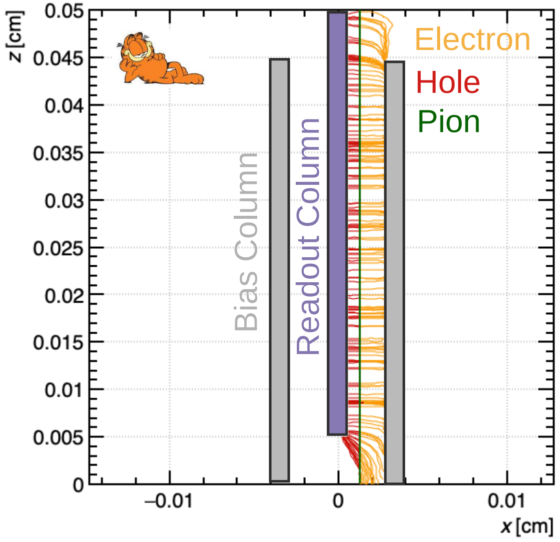
With the team of the INFN TimeSpot project, we are exploring the modelling of signal induction on the readout columns.

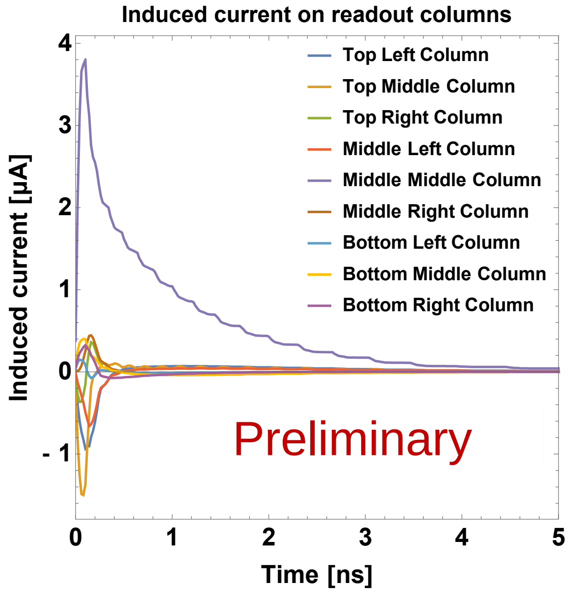


Weighting potential of a readout column at z = 250 μm.



Drift lines as modelled by Garfield++





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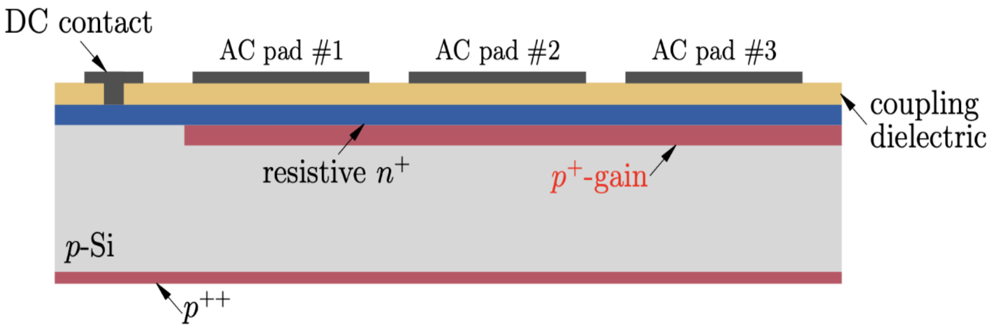
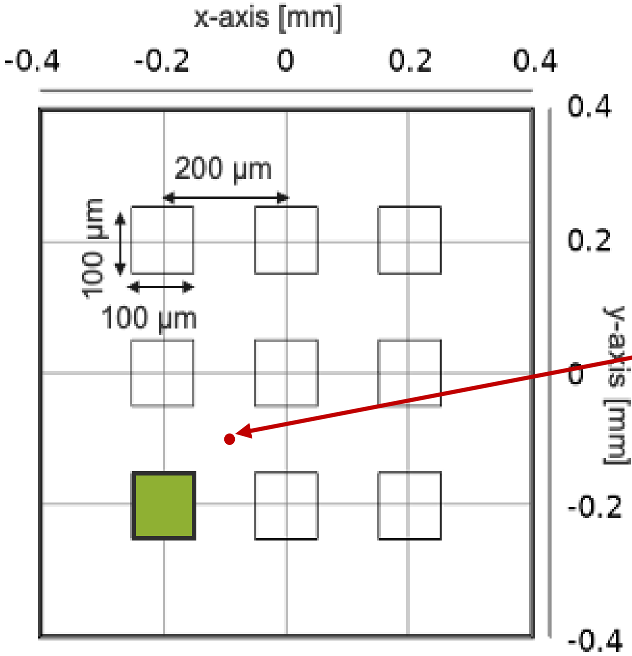
Anderlini L. et al., Frontiers in Physics 8 (2020)
For timing measurements and first modelling results see talk by M. Veltri: "A 4D diamond detector for HL-LHC and beyond".

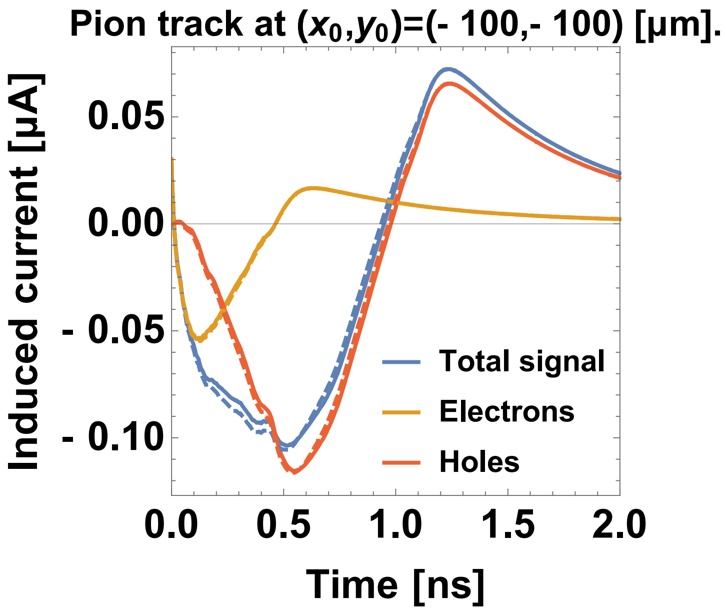
Signal formation in AC-Coupled LGAD

In collaboration with INFN Torino group of N. Cartiglia, we are currently looking at simulating the currents induced in the AC-Coupled Low Gain Avalanche Diode (LGAD) geometry.

When successfully benchmarked, it can be used to understand and explore novel readout designs.







Some of the detectors containing resistive elements

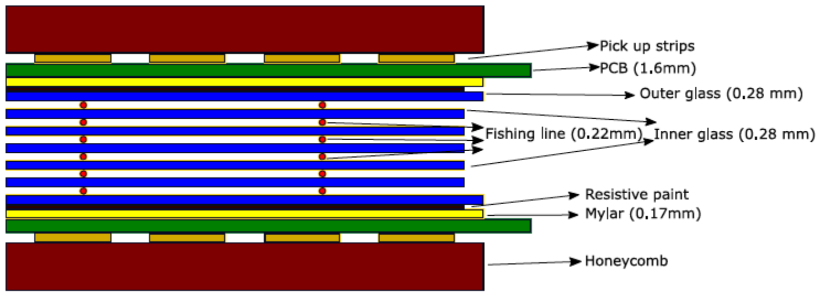
We are working on extending the list of detectors geometries that contain resistive elements.

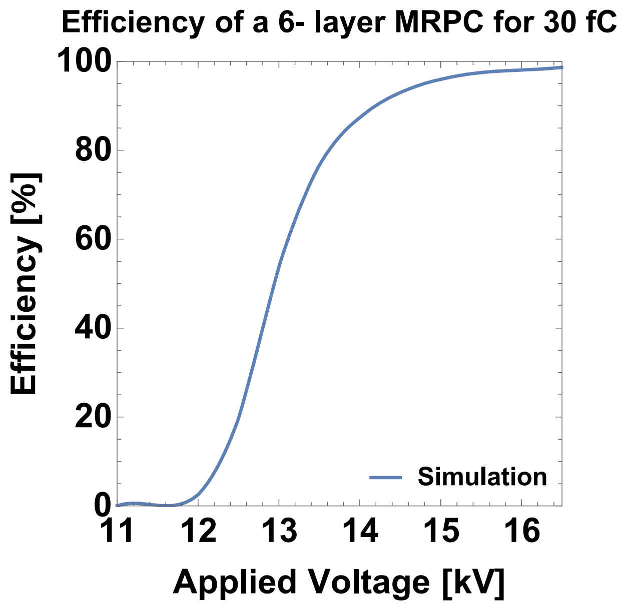
<u>Spatial resolution study:</u>

- MicroCAT's two-dimensional interpolating readout
- μ-Resistive-WELL
- Small-pad resistive Micromegas
- Resistive-strip bulk Micromegas
- AC-Coupled LGAD

<u>Timing resolution study:</u>

- Multigap Resistive Plate Chambers (MRPC)
- Resistive Picosec Micromegas Detector
- Diamond3D sensor
- AC-Coupled LGAD





M. Iodice et al., Nucl. Instrum. JINST **15** C09043 (2020).

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Summary

We want to use Garfield++ and COMSOL to model the signal formation in detectors with resistive elements by applying an extended form of the Ramo-Shockley theorem.

- The extension of the Ramo-Shockley theorem for conductive media allows for an efficient way to calculate the signals induced in resistive detectors.
- A numerical method for obtaining the time dependent weighting potentials is used to increase the range of applicability of the framework to a larger set of geometries (COMSOL and TCAD).
- Various induced signals were calculated for a variety of readout structures.

Outlook:

- Use a general-purpose circuit simulation program to describe the front-end electronics, e.g., Spice®.
- Measurements and simulation for resistive-bulk strip Micromegas, resistive plane Micromegas, Picosec Micromegas and μRWELL.
- Including Johnson thermal noise into the simulations.