THE 16TH VIENNA CONFERENCE ON INSTRUMENTATION

Induced signals in particle detectors with resistive elements: modelling novel structures

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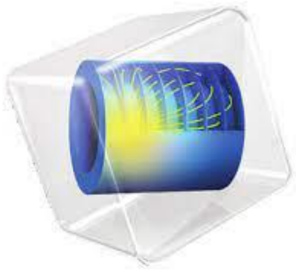
Introduction

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



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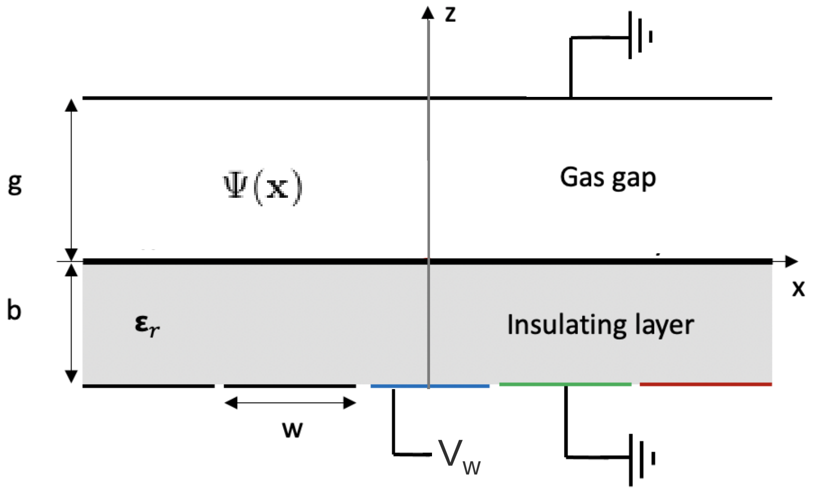
Garfield++: https://garfieldpp.web.cern.ch/garfieldpp/
COMSOL Multiphysics: https://www.comsol.ch

Ramo-Shockley theorem

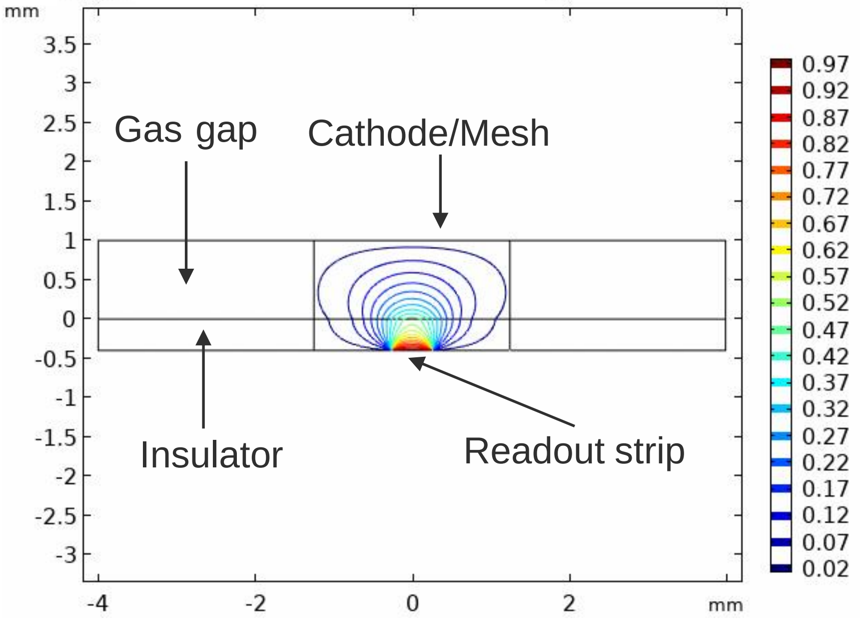
The Ramo-Shockley theorem allows the current induced by an externally impressed charge density on any electrode to be calculated by the usage of a so-called weighting potential $\psi(\mathbf{x})$.

This static $\psi(\mathbf{x})$ can be calculated for a grounded electrode 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).

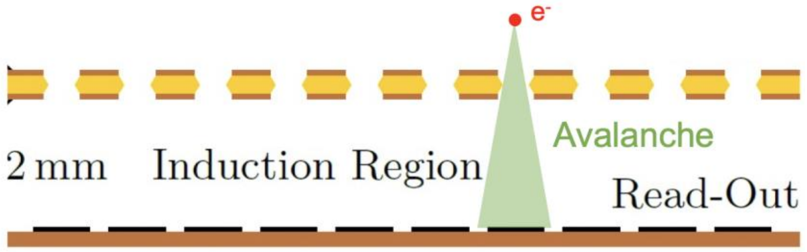
Ramo-Shockley theorem

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.

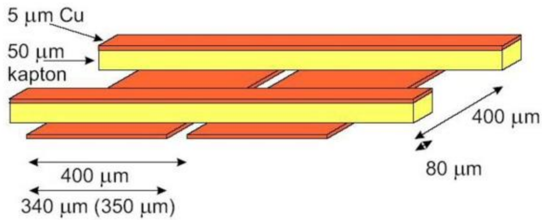
$$I^{ind}(t) = -\frac{dQ^{ind}(t)}{dt} = \frac{q}{V_w}\nabla\psi[\mathbf{x}(t)]\dot{\mathbf{x}}(t)$$

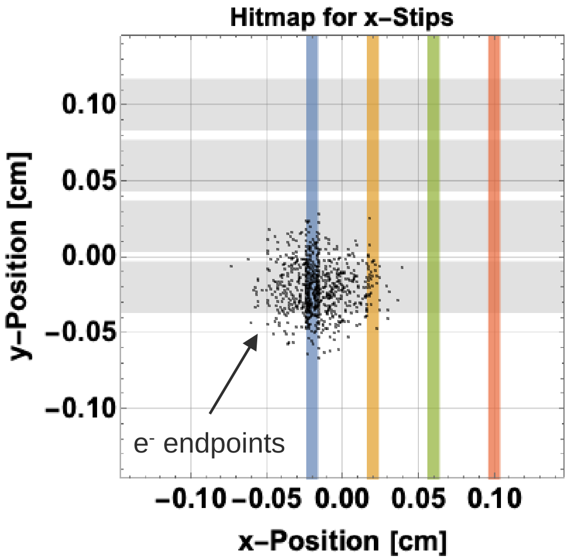
This can be repeated for every charge in the avalanche created in the detector:

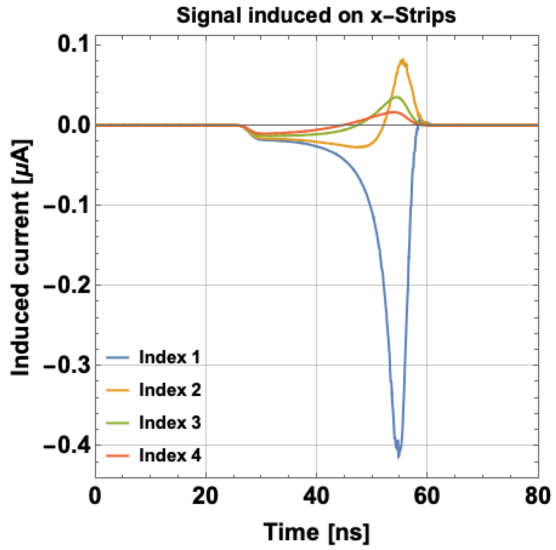
GEM



XY strip readout





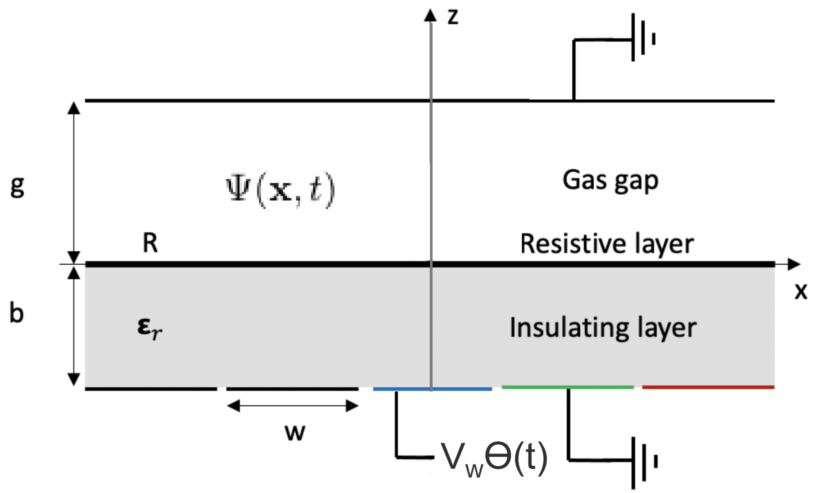


Ramo-Shockley theorem extension for conducting media

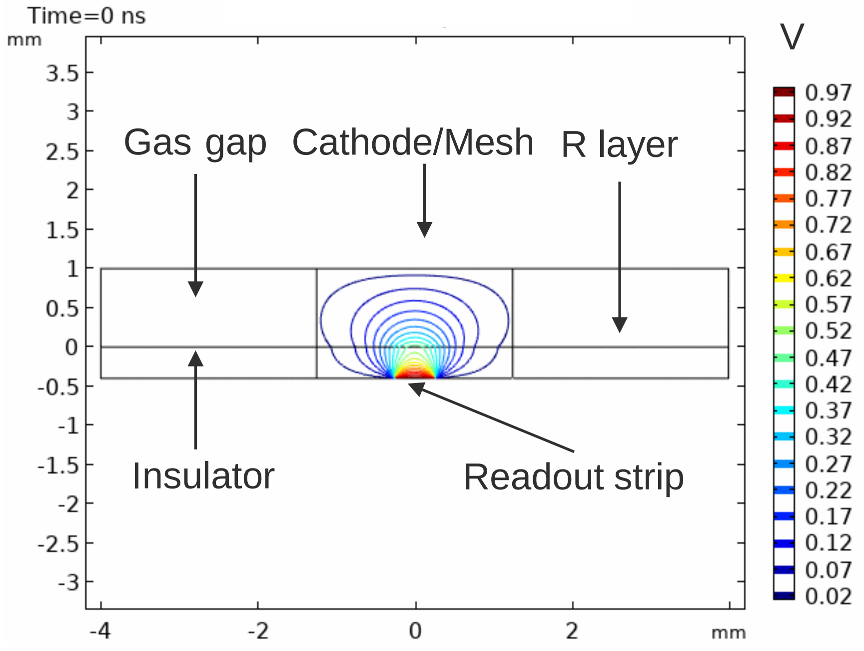
For detectors with resistive elements, the time dependence of the signals is not fully given by the movement of the charges in the drift medium but also by the time-dependent reaction of the resistive materials.

This dynamic $\psi(\mathbf{x}, t)$ can be calculated for a grounded electrode by:

- Remove the drifting charges
- 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.



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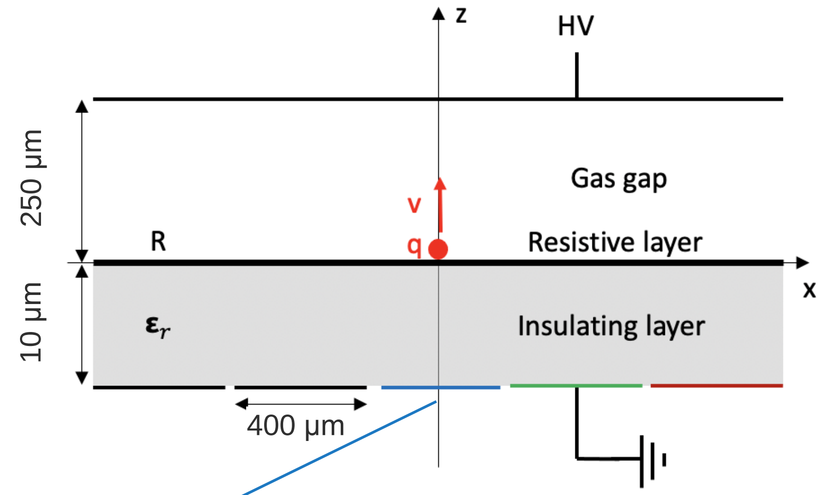
W. Riegler, Nucl. Instrum. Meth. A 535 (2004), 287-293.
W. Riegler, Signals in Particle Detectors, CERN’s Academic Training Lecture Regular Programme (2019): https://indico.cern.ch/event/843083/

Ramo-Shockley theorem extension for conducting media

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



The current induced by a point particle Q is given by:

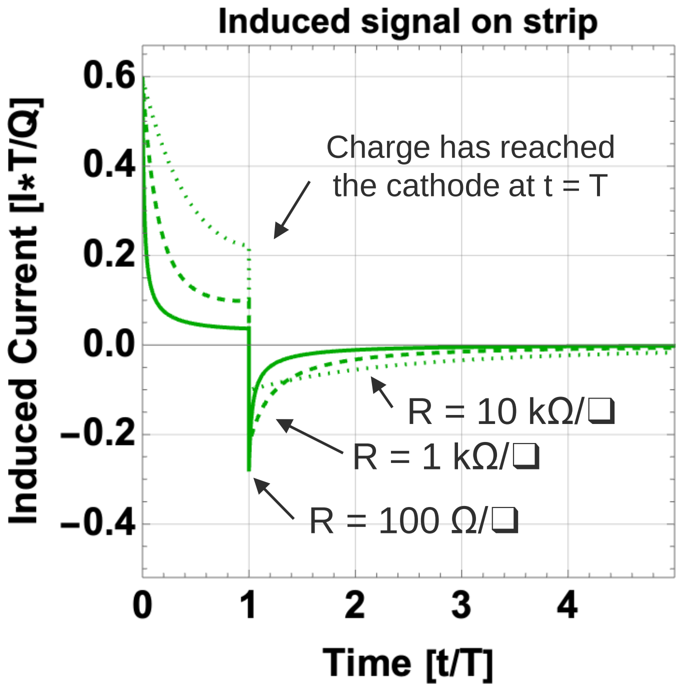
$$I(t) = -\frac{Q}{V_w}\int_0^t \mathbf{H}\left[\mathbf{x}(t'), t-t'\right]\dot{\mathbf{x}}(t')\,dt'$$

$$\mathbf{H}(\mathbf{x},t) = -\nabla\frac{\partial\Psi(\mathbf{x},t)}{\partial t}$$

$$= \boxed{-\nabla\psi^0(\mathbf{x})\delta(t)}\boxed{-\nabla\frac{\partial\psi(\mathbf{x},t)}{\partial t}\Theta(t)}$$

Direct induction

Reaction from resistive material



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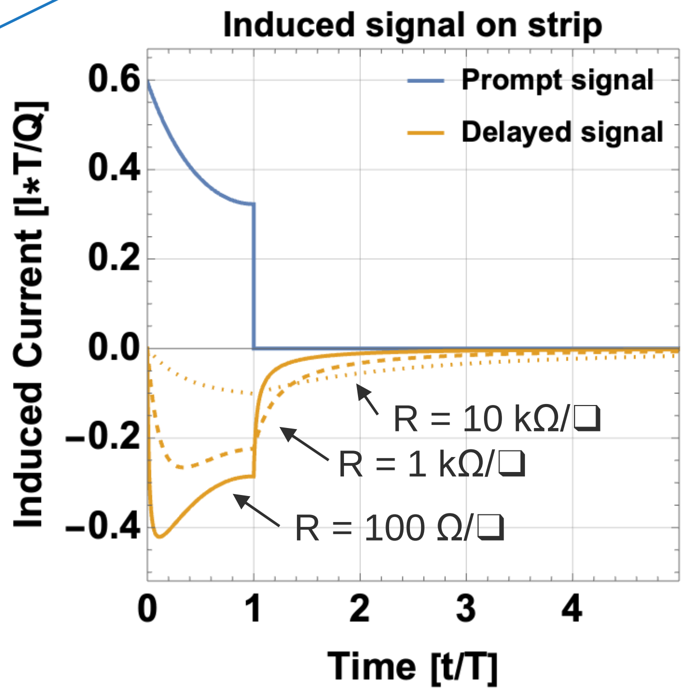
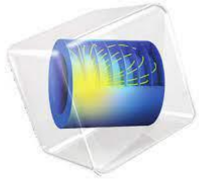


Overview of the numerical methodology

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.



COMSOL® :

- Numerically obtain the dynamic weighting potential.

Garfield++:

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

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.

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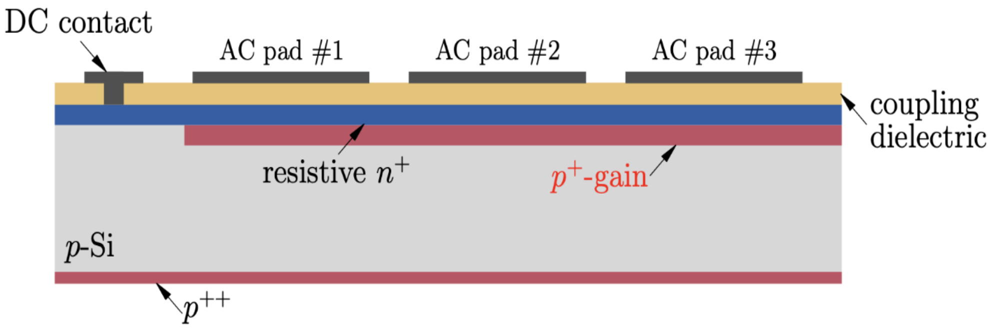
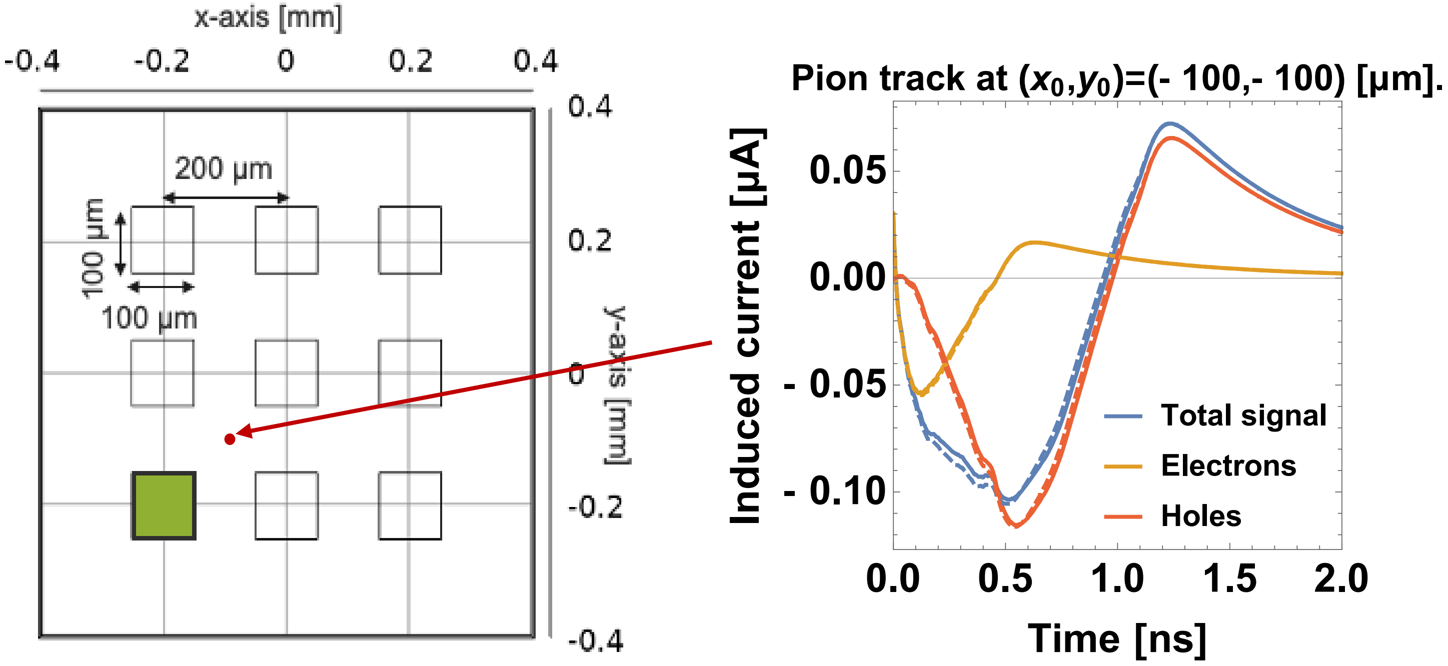
Garfield++: https://garfieldpp.web.cern.ch/garfieldpp/
See H. Schindler's VCI 2022 presentation: "Garfield++: status and plans".
COMSOL Multiphysics: https://www.comsol.ch /

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.





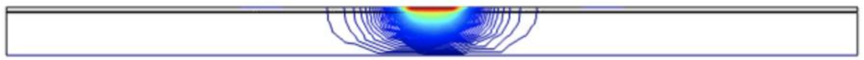
M. Tornago, R. Arcidiacono, N. Cartiglia et al., Nucl. Instrum. Meth. A **1003** (2021).
See N. Cartiglia's Friday VCI talk: "4d-tracking, LGADs, and fast timing detectors".

Signal formation in AC-Coupled LGAD

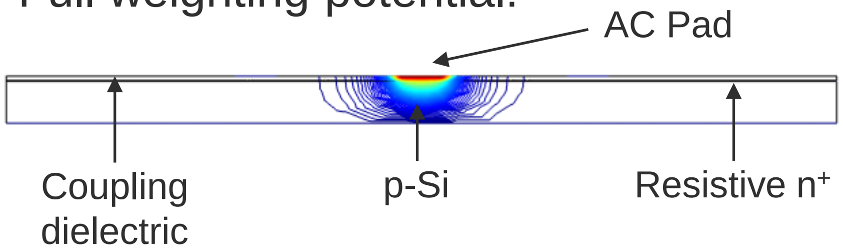
Drifting a single hole at velocity v = g/T, where g is the thickness of the p layer, we can characterise the induced signal.

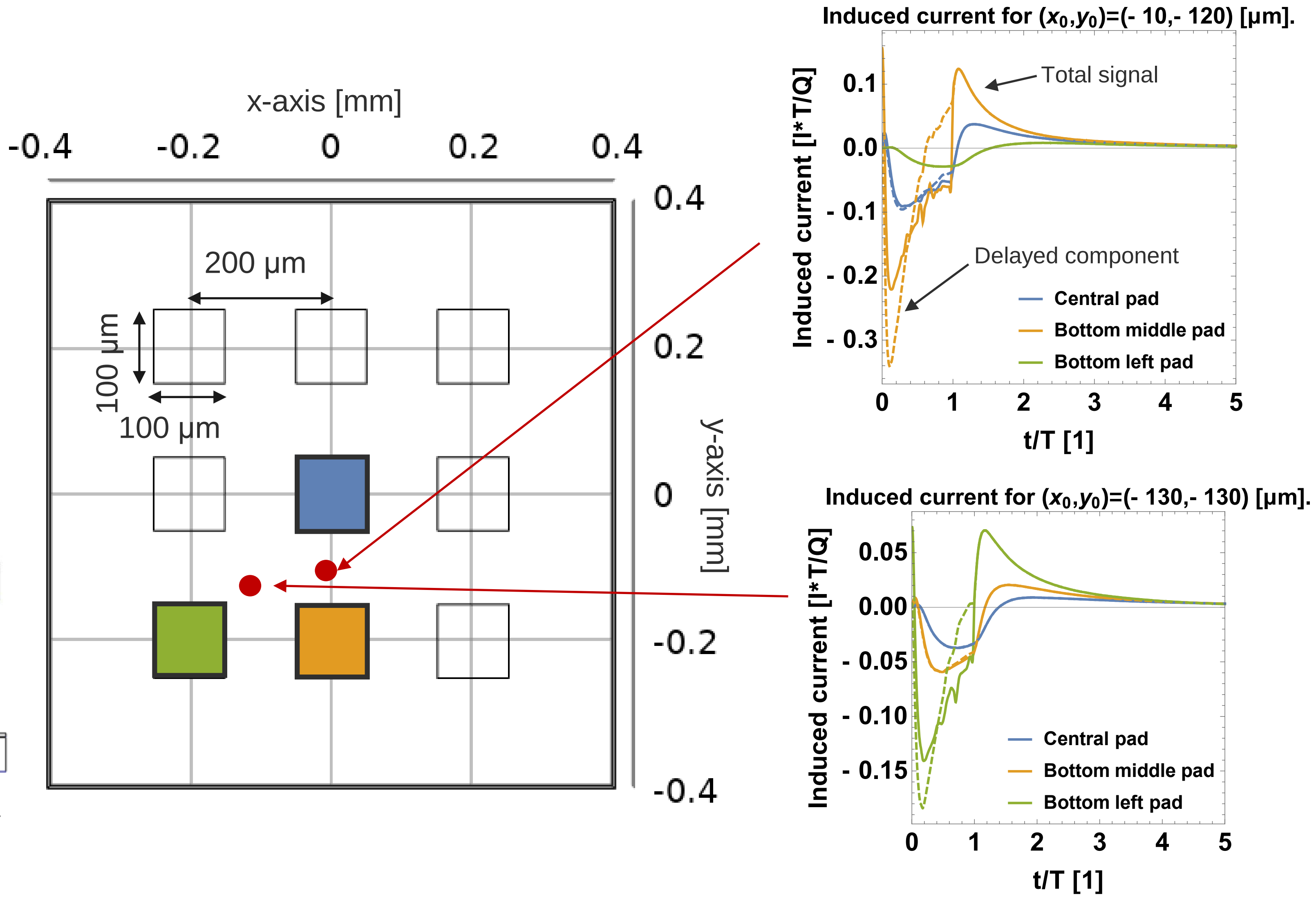
The role that the prompt component plays can be understood by looking at the central pad on the bottom row.

Prompt weighting potential:



Full weighting potential:



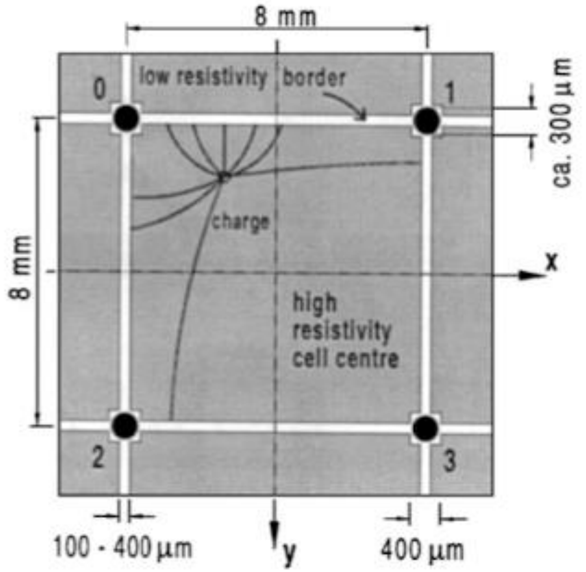


Signal formation in a MicroCAT detector

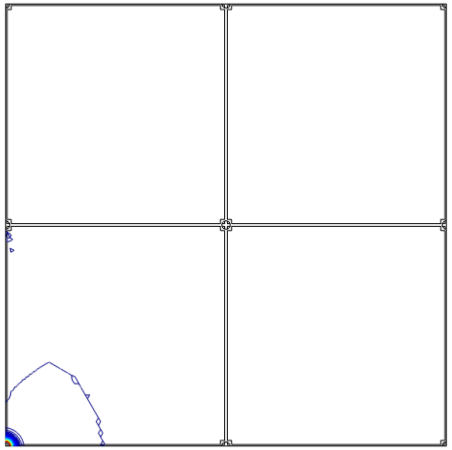
The MicroCAT's two-dimensional interpolating readout structure allows for a reduced number of electronic readout channels without loss of spatial resolution.

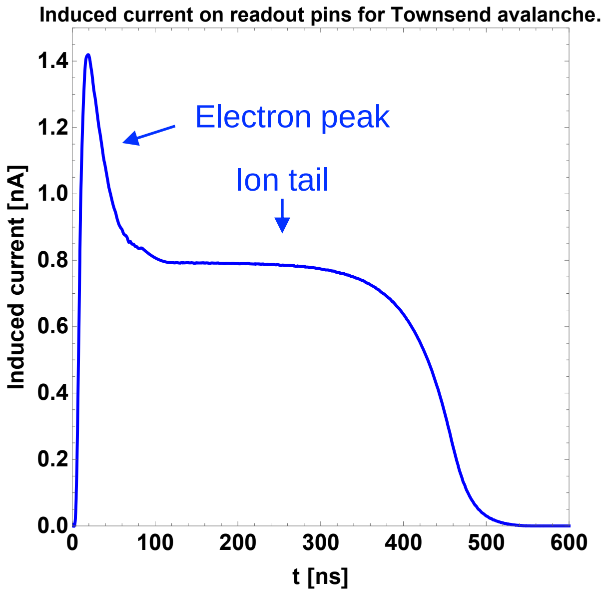
This is an exemplar readout anode where the signal is dominantly comprised of the effect of the resistive material, i.e., the delayed component.

H. Wagner et al. Nucl. Instrum. Meth. A 482 (2002) 334–346



Weighting potential map for one readout node

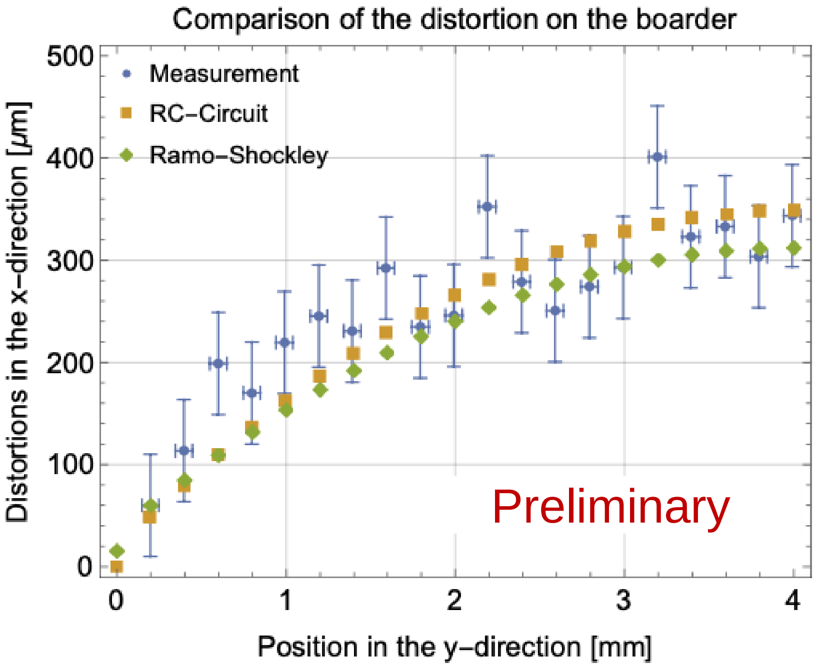


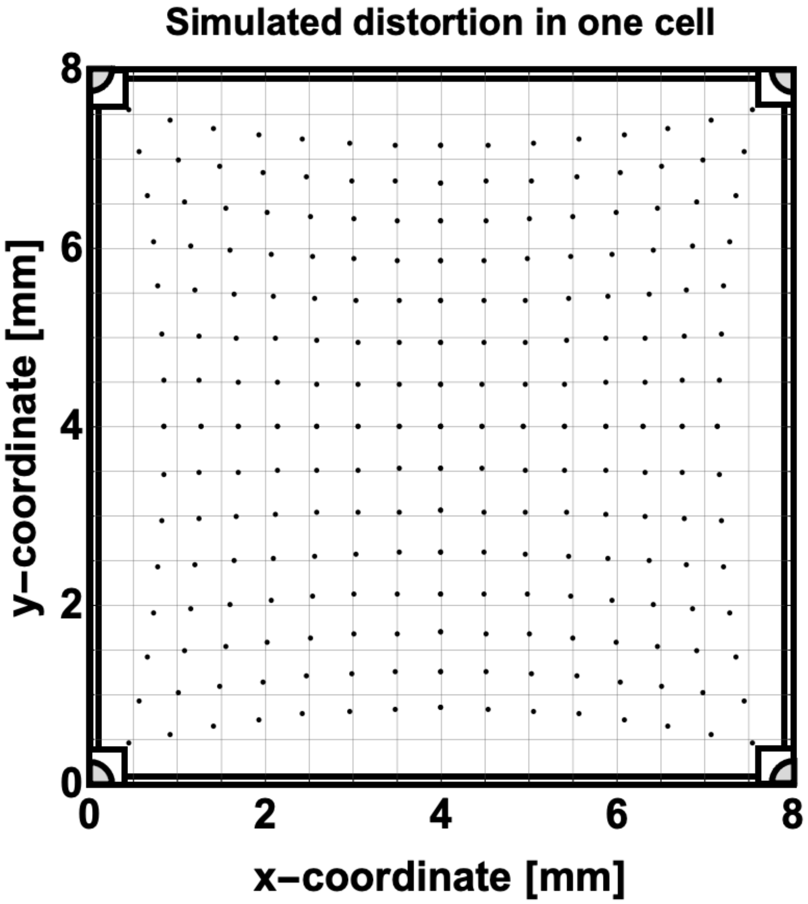


F. Bartol et al. J. Phys. III France, 6 (1996), p. 337
A. Sarvestani et al., Nucl. Instrum. Meth. A 410 (1998) 238–258
A. Sarvestani et al., Nucl. Instrum. Meth. A, 419 (1998) 444

Signal formation in a MicroCAT detector

Using a linear interpolation algorithm, the calculation captures the increase in distortion as the charges are deposited further away from the readout node on the low resistivity border.

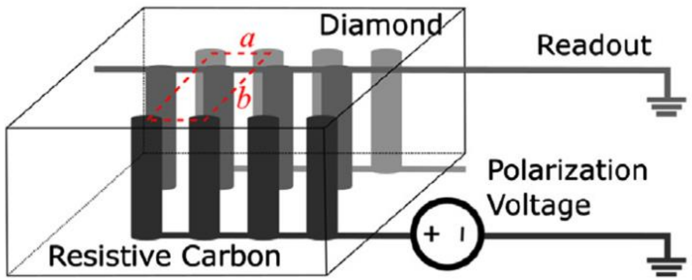




Measured and RC-Circuit simulated data are taken from H. Wagner et al. Nucl. Instrum. Meth. A 482 (2002) 334–346.

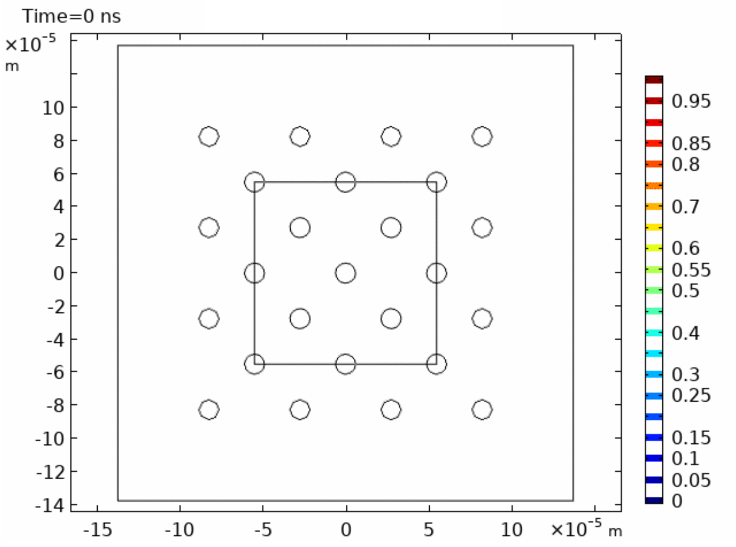
Diamond 3D Pixel Detector

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.

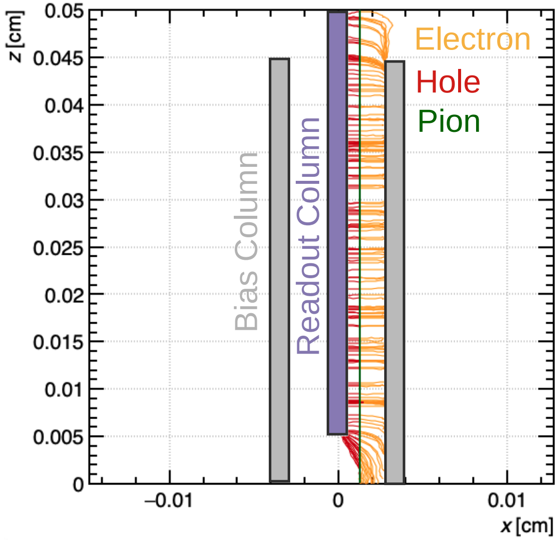


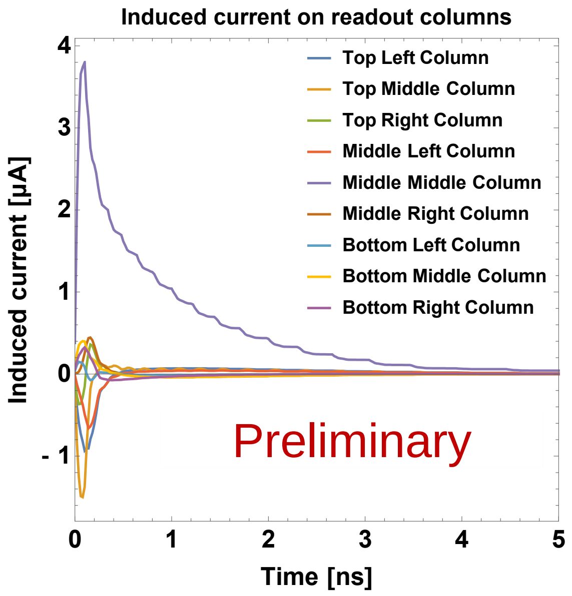
With the team of the INFN TimeSpot project, we are exploring the modelling of signal induction on the readout columns using Garfield++ and COMSOL.

Weighting potential of a readout column.



Drift lines as modelled by Garfield++





For timing measurements and first modelling results see talk by M. Veltri on Friday: "A 4D diamond detector for HL-LHC and beyond".

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.
- Various induced signals were calculated for a variety of readout structures.

<u>Outlook:</u>

- 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.