DRD1 working group 4 meeting

Tutorial on numerically calculating the induced signal in resistive detectors

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Introduction

Using Garfield++ in conjunction with COMSOL, the induced signal on electrodes in resistive detectors can be calculated numerically. We will go through the steps to build up such a simulation.

Outline:

- Ramo-Shockley theorem extension for conductive media
- Numerical approach
- Toy model example of an RPC in COMSOL
- Signals in the presence of a thin resistive layer in COMSOL
- Exporting the data
- Resistive strip MicroMegas in Garfield++
- TCAD and other extensions
- Summary


VUB VRIJE UNIVERSITEIT BRUSSEL

Thesis submitted in fulfilment of the requirements for the award of the degree of Doctor of Sciences

RESISTIVE ELECTRODES AND PARTICLE DETECTORS

Modeling and Measurements of Novel Detector Structures

Djunes Janssens

February 2024

Promotor: Prof. Dr. J. D'Hondt
Co-promotors: Dr. H. Schindler

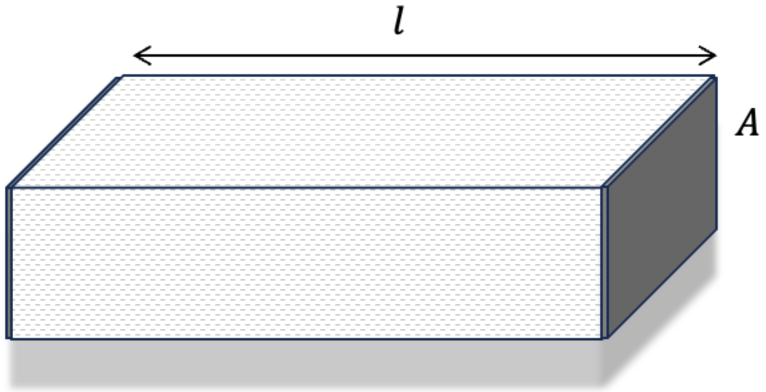
Sciences and Bio-Engineering Sciences
Physics department

Garfield++: https://garfieldpp.web.cern.ch/garfieldpp/
Ph.D. thesis: https://cds.cern.ch/record/2890572

Ramo-Shockley theorem extension for conductive media

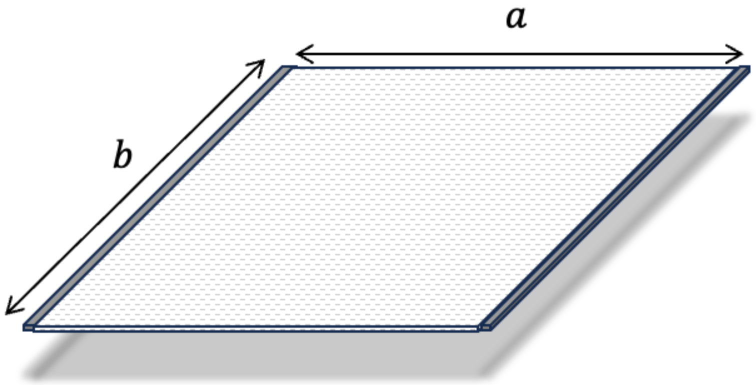
Resistive materials

The materials inside the detector can have a finite conductivity σ, e.g,. in Resistive Plate Chambers, un-depleted silicon sensors, and resistive strip bulk Micromegas.



volume resistivity

$$\rho = \frac{1}{\sigma} = R_1 \frac{A}{l} \; [\Omega\, cm]$$



surface resistivity

$$R = R_1 \frac{b}{a} \; [\Omega/\square]$$

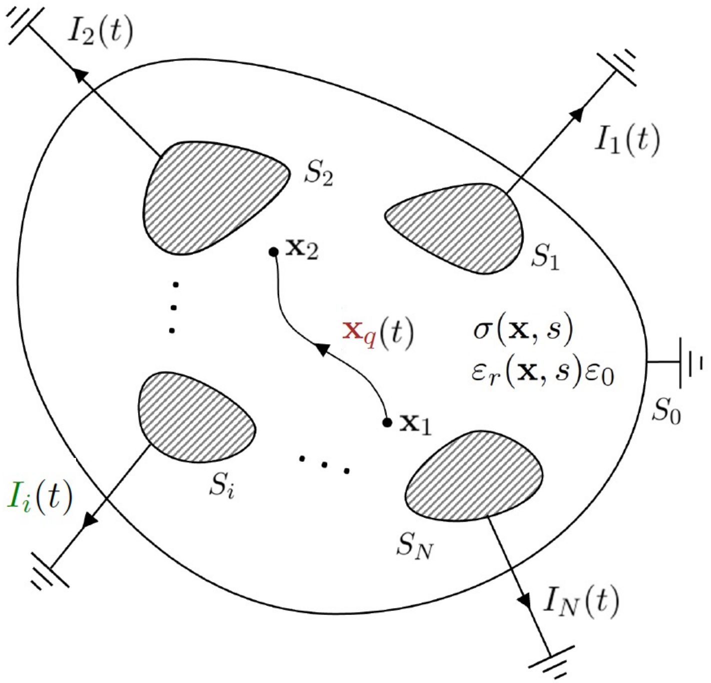
The (nonuniform) conductivity, reciprocal with the volume resistivity, establishes the connection between the local electric field and the local current density.

$$\mathbf{j}(\mathbf{x}) = \sigma(\mathbf{x})\mathbf{E}(\mathbf{x})$$

Ramo-Shockley theorem extension for conducting media

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

Solving Maxwell's equations:

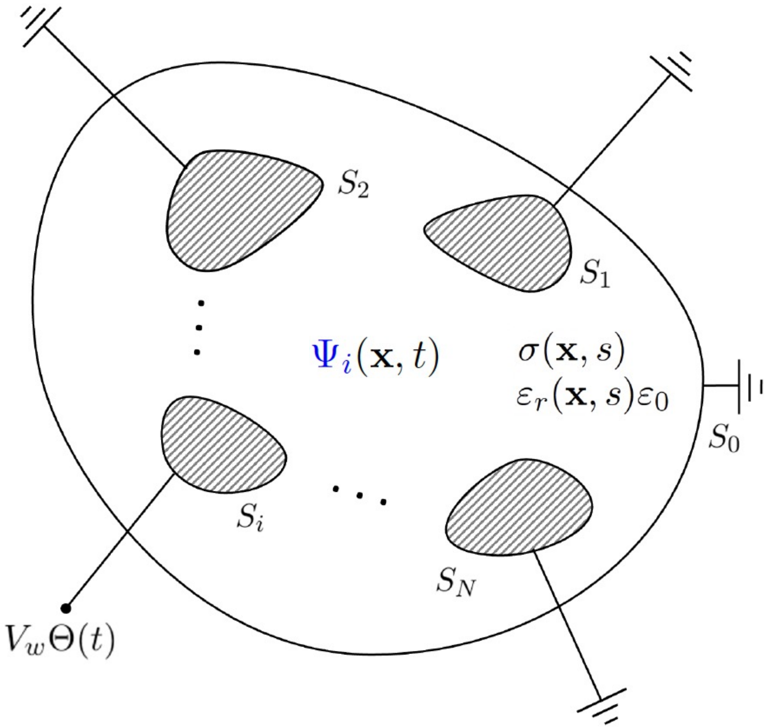


$$I_i(t) = -\frac{q}{V_w}\int_0^t \mathbf{H}_i\left[\mathbf{x}_q(t'), t-t'\right]\cdot \dot{\mathbf{x}}_q(t')\, dt'$$

$$\longleftrightarrow$$

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

Simplify calculations using dynamic $\psi_i(\mathbf{x}, t)$:



E. Gatti, G. Padovini and V. Radeka, Nuclear Instruments and Methods in Physics Research 193 (1982) 651.
W. Riegler, Nucl. Instrum. Meth. A 535 (2004), 287-293.
W. Riegler, Signals in Particle Detectors, CERN's Academic Training Lecture (2019)

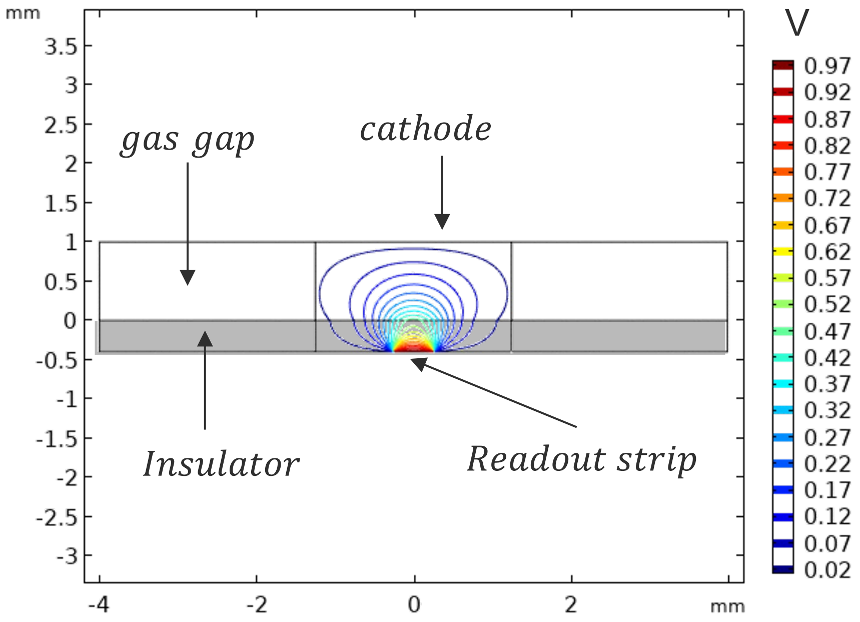
Ramo-Shockley theorem extension for conducting media

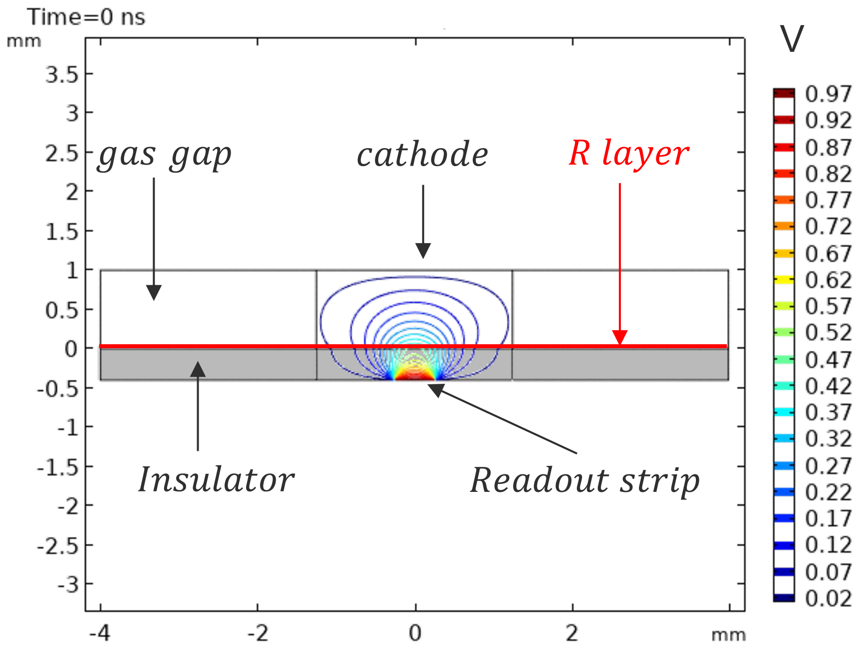
The time-dependent weighting potential is comprised of a static prompt and a dynamic delayed component:

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

The current induced by a point charge q is given by:

$$I_i(t) = \underbrace{-\frac{q}{V_w}\mathbf{E}_i^p(\mathbf{x}_q(t))\cdot\dot{\mathbf{x}}_p(t)}_{\text{Direct induction}} \underbrace{- \frac{q}{V_w}\int_0^t dt'\,\mathbf{H}_i^d\left[\mathbf{x}_q\left(t'\right),t-t'\right]\cdot\dot{\mathbf{x}}_q\left(t'\right)}_{\text{Reaction from resistive material}}$$

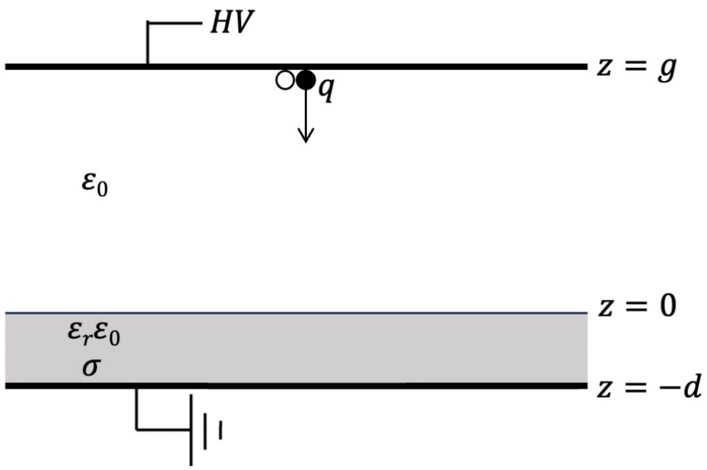




Resistive Plate Chamber

Delayed component of the signal

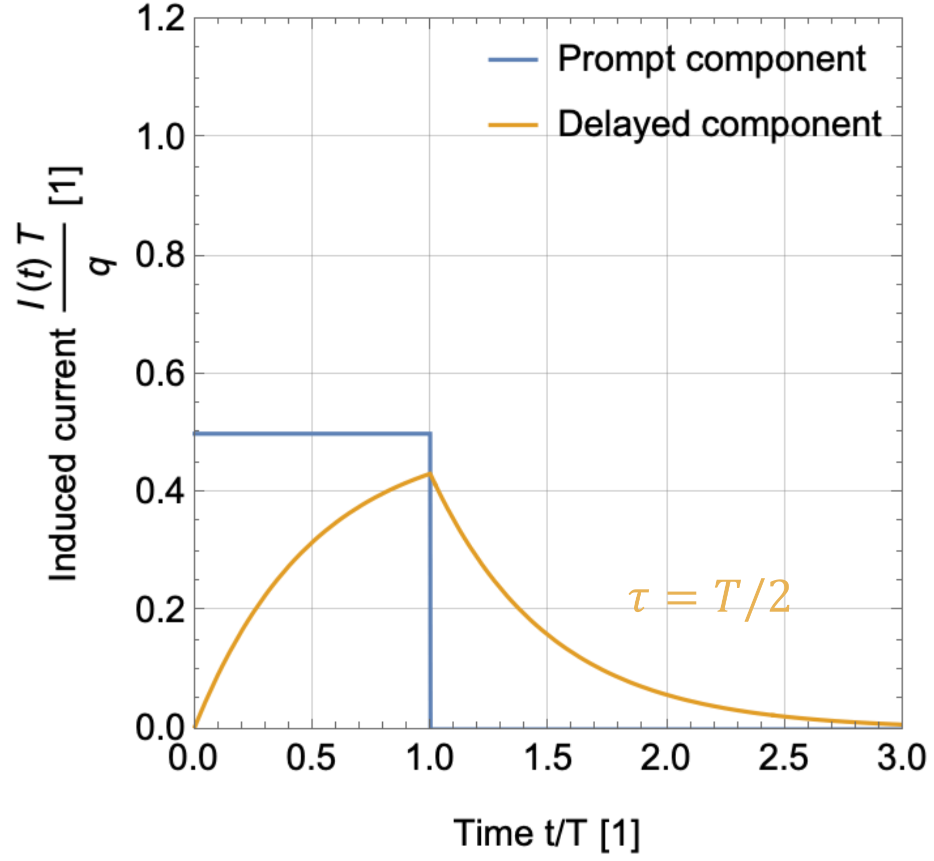
A charge q moves at a constant velocity through the gas gap before reaching the bulk resistive layer that separates it from the anode.



$$\mathbf{H}(z,t) = \hat{\mathbf{z}}\frac{V_w\varepsilon_r}{d+\varepsilon_r g}\delta(t) + \hat{\mathbf{z}}\frac{V_w}{g\tau}\frac{d}{d+\varepsilon_r g}e^{-t/\tau}\Theta(t)$$

The dynamics is governed by the time constant:

$$\tau := \left(1+\frac{d}{g}\right)\frac{\varepsilon_0}{\sigma}.$$



Here we took $\epsilon_r = 1$.

Delayed component of the signal

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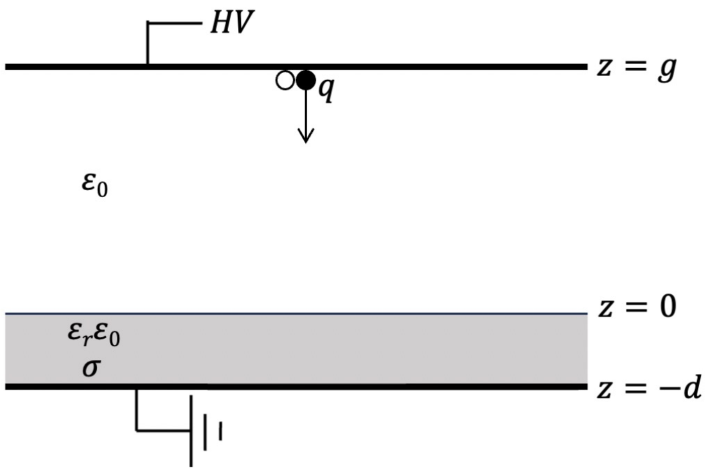

$$\mathbf{H}(z,t) = \hat{\mathbf{z}}\frac{V_w\varepsilon_r}{d+\varepsilon_r g}\delta(t) + \hat{\mathbf{z}}\frac{V_w}{g\tau}\frac{d}{d+\varepsilon_r g}e^{-t/\tau}\Theta(t)$$

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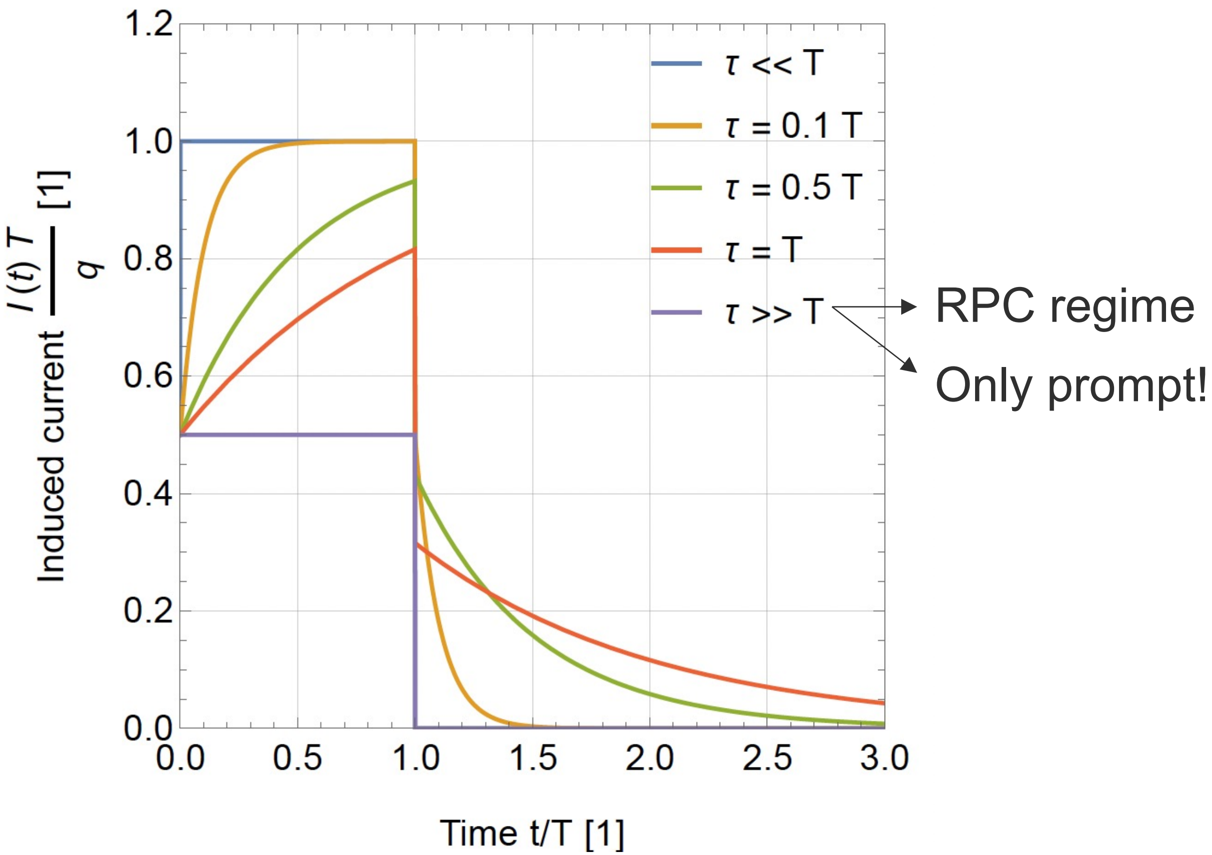
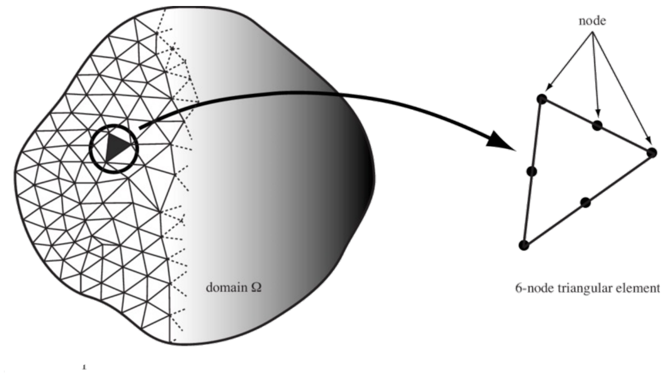


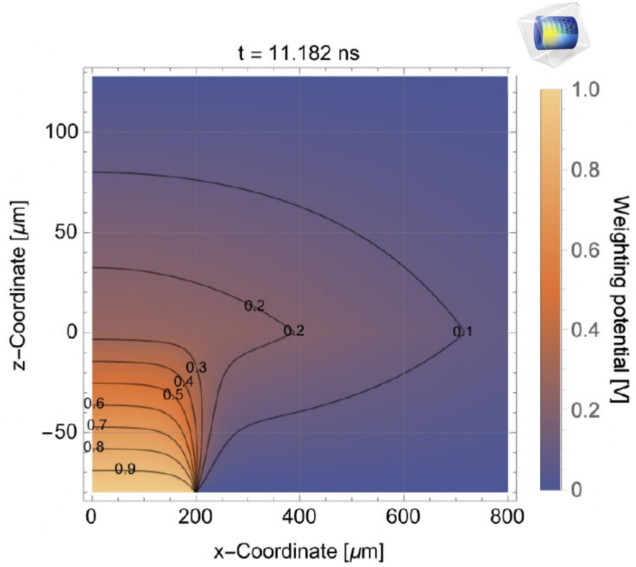
Here we took $\epsilon_r = 1$.

Numerical approach

Using a finite element method approach, the weighting potential $\psi_i(\mathbf{x}, t)$ is calculated numerically.

- **Accurately represent the boundary conditions** by coordinate mapping of the model to the full active area.
- **The contribution of external impedance elements** is included by incorporating it on the level of the weighting potential.





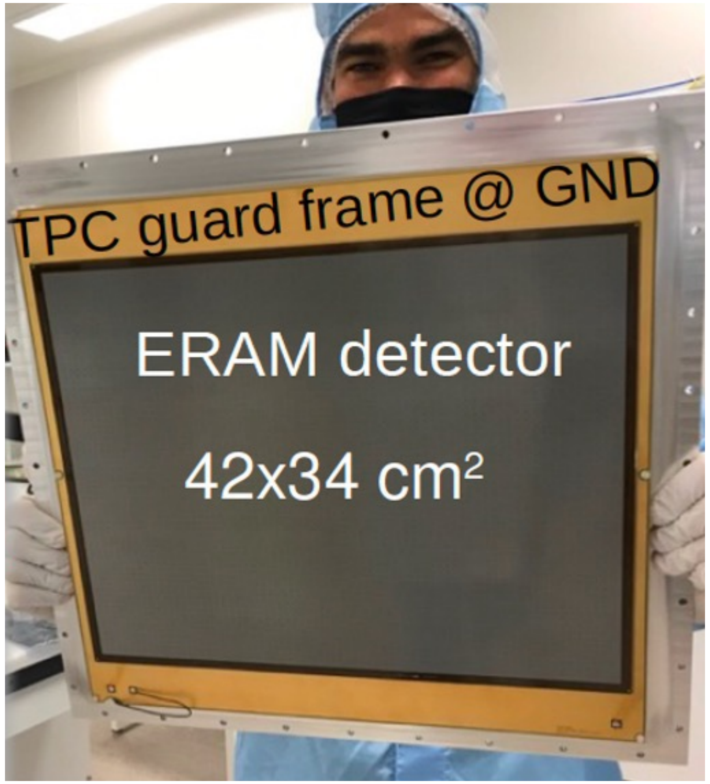


Image taken from S. Hassani RD51 Mini-Week slides.
D. Janssens et al., Nucl. Instrum. Meth. A 1040 (2022)
D. Janssens et al, JINST 18 (2023) 08, C08010

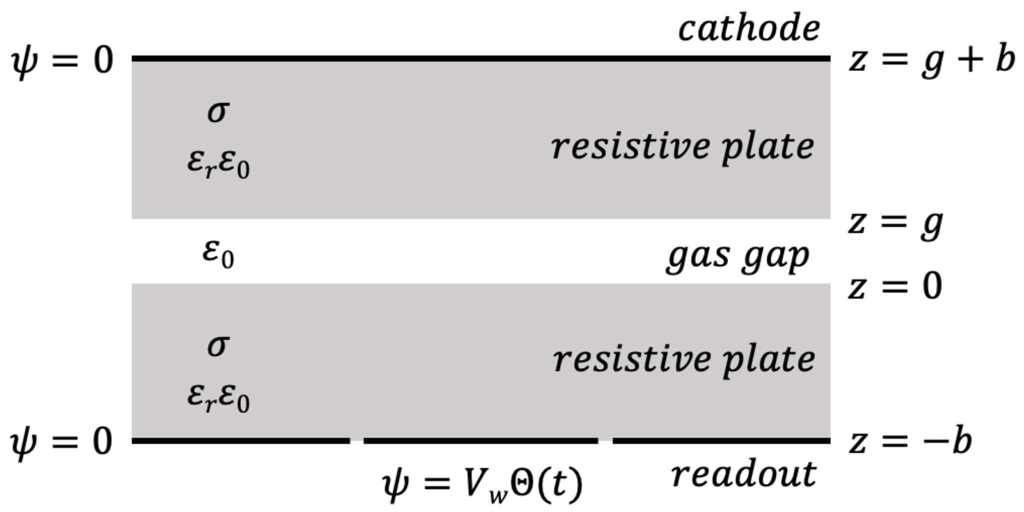
COMSOL Multiphysics: https://www.comsol.ch

COMSOL tutorial

We will numerically calculate the weighting potential of a plane and pad electrode located within a resistive plate chamber geometry for a low-resistivity material.

Main steps:

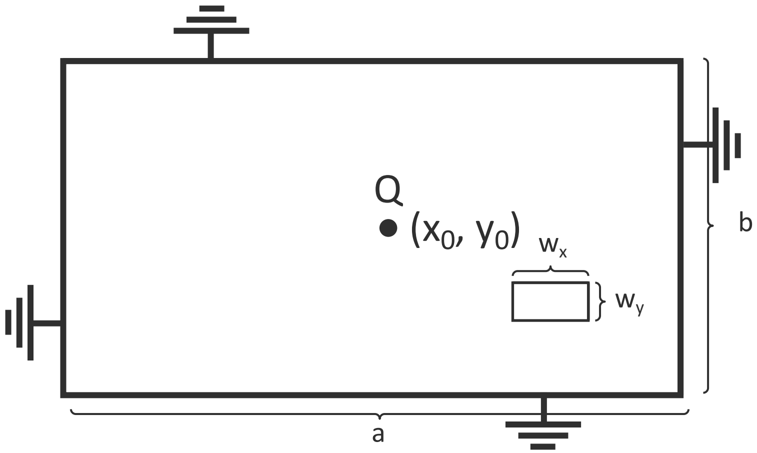
- Making the three-layered geometry using elementary shapes
- Assigning the material properties to the different domains
- Define bounder conditions
    - Apply a voltage ramp to the electrode under study
    - Perfectly ground all other electrodes
- Solve the system for exponential-spaced time points

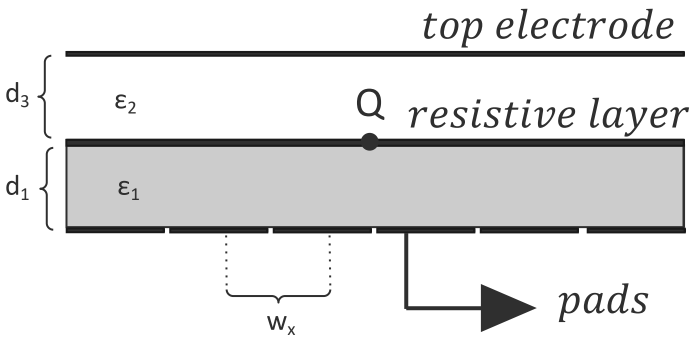


Resistive plane MicroMegas

Charge diffusion in a thin resistive layer

Given a parallel-plate type geometry with a grounded resistive layer separated from the pad electrodes by an insulating layer.





The induced charge on each pad can be analytically calculated to study the effect of the size of the resistive layer:

$$Q^{\mathrm{ind}}\left(x_0, y_0, t\right) = Q \sum_{\alpha,\beta=1}^{\infty} A_{\alpha\beta}\left(x_0, y_0\right) e^{-t/\tau_{\alpha\beta}}$$

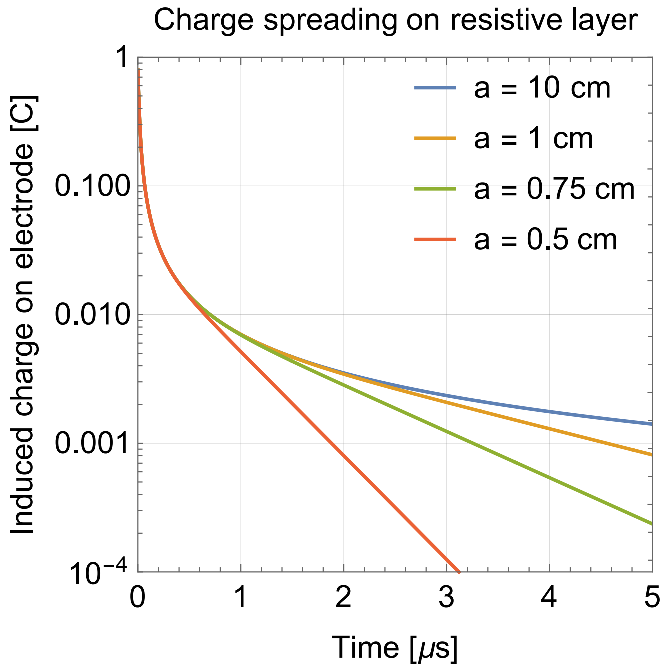
Time-dependent part

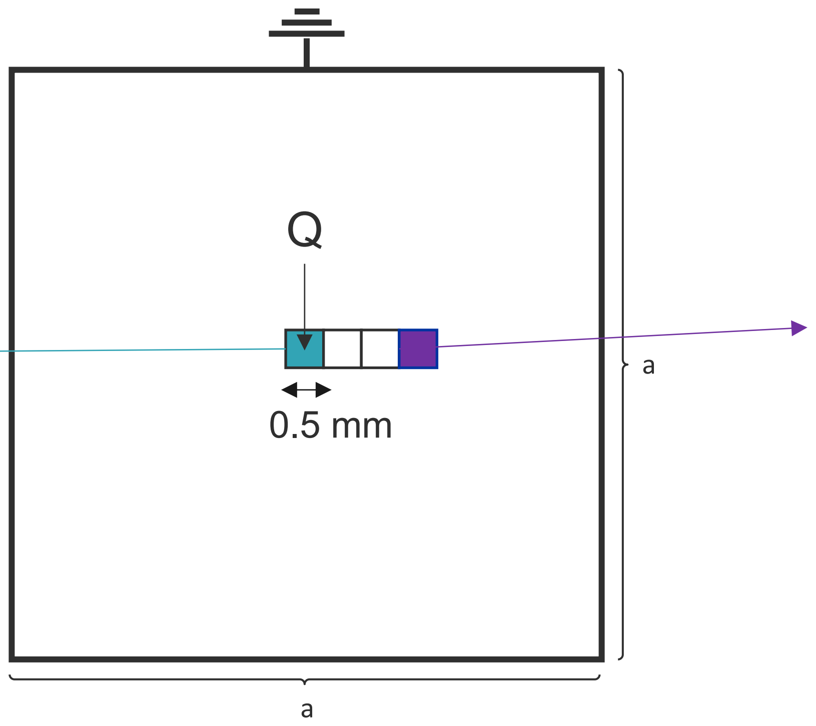
with the infinite number of time constants given by

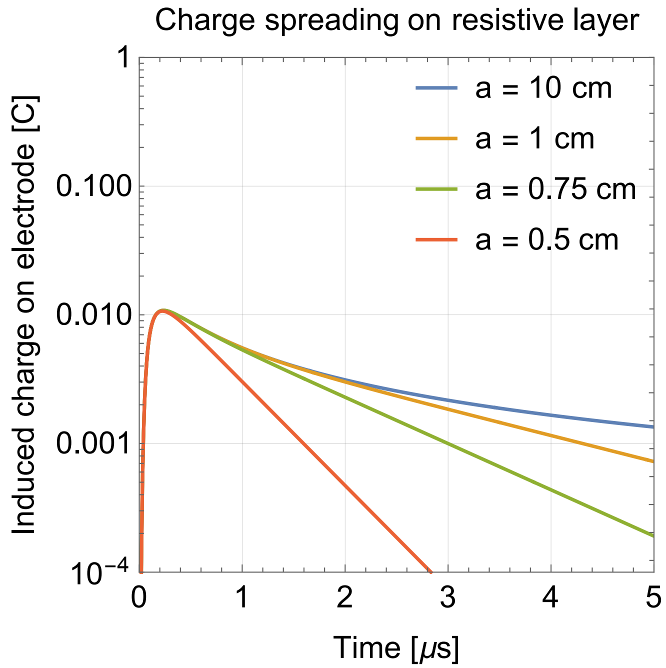
$$\tau_{\alpha\beta} = \frac{R}{\pi\sqrt{\frac{\alpha^2}{a^2}+\frac{\beta^2}{b^2}}}\left[\varepsilon_1 \coth\left(\pi\sqrt{\frac{\alpha^2}{a^2}+\frac{\beta^2}{b^2}}d_1\right)+\varepsilon_3 \coth\left(\pi\sqrt{\frac{\alpha^2}{a^2}+\frac{\beta^2}{b^2}}d_3\right)\right]$$

Charge diffusion in a thin resistive layer

The size of the resistive layer does play a role in the evolution of the signal. For the initial part of the induced current for a large-area resistive detector can be approximated by a smaller counterpart.







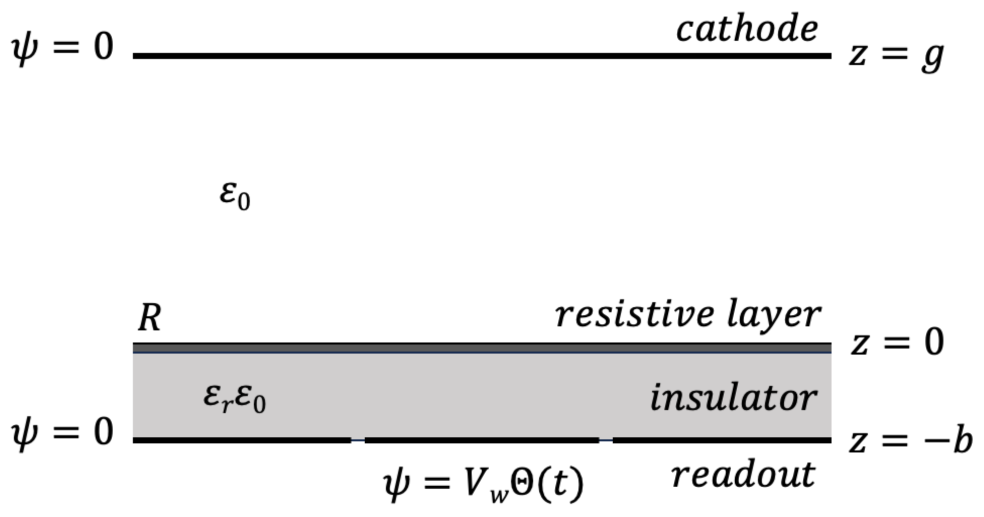
Here we took R = 1 MΩ/□.

COMSOL tutorial

We will numerically calculate the weighting potential of a pad electrode embedded in the readout structure of a resistive plate MicroMegas.

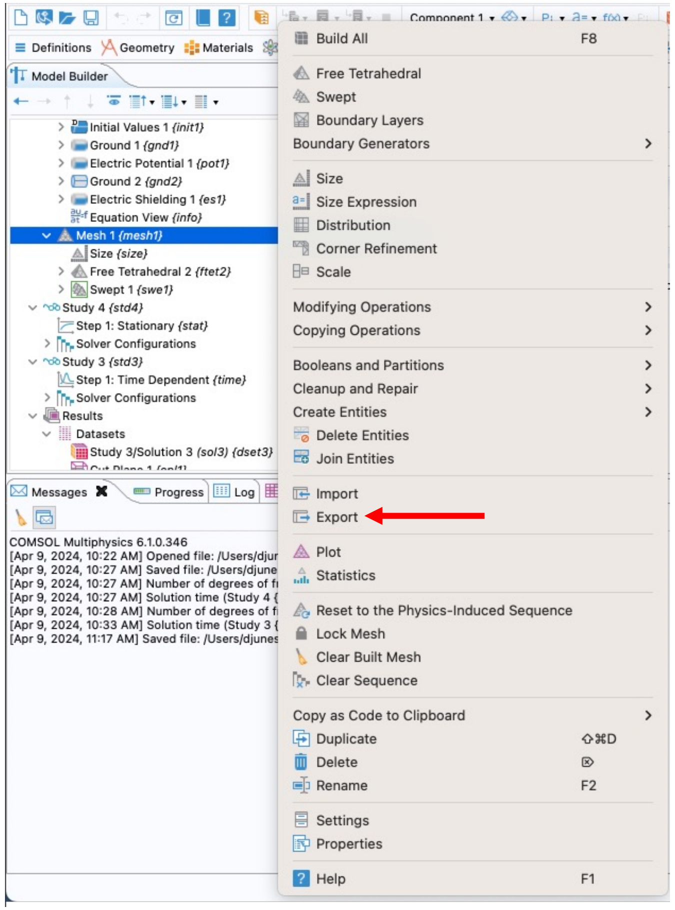
<u>Main steps:</u>

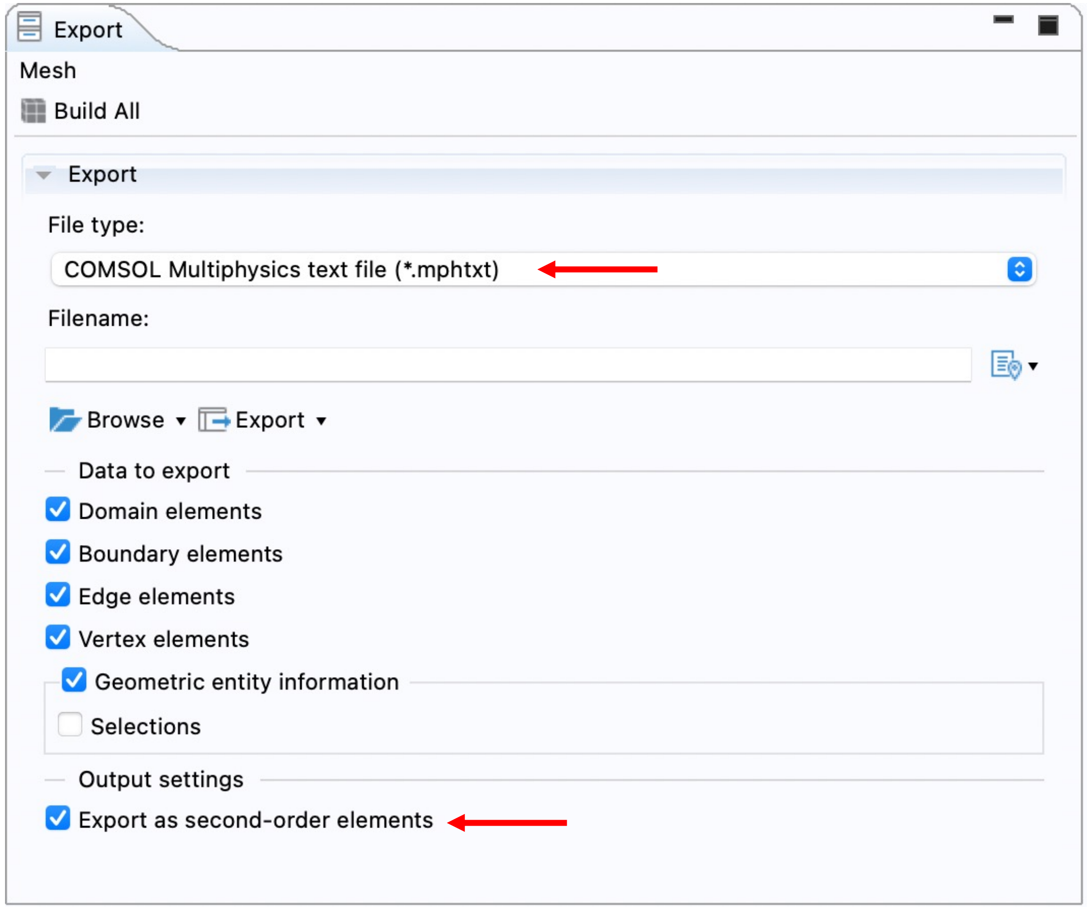
- The thin resistive layer can be represented as a 2D structure using the *Electric Shielding* condition
- To accurately represent the boundary, conditions describing the grounding of the resistive layer coordinate mapping was used to ‘stretch’ the geometry
- The region that is stretched is meshed using pentahedral elements; everywhere else, tetrahedral elements are used



Exporting mesh from COMSOL

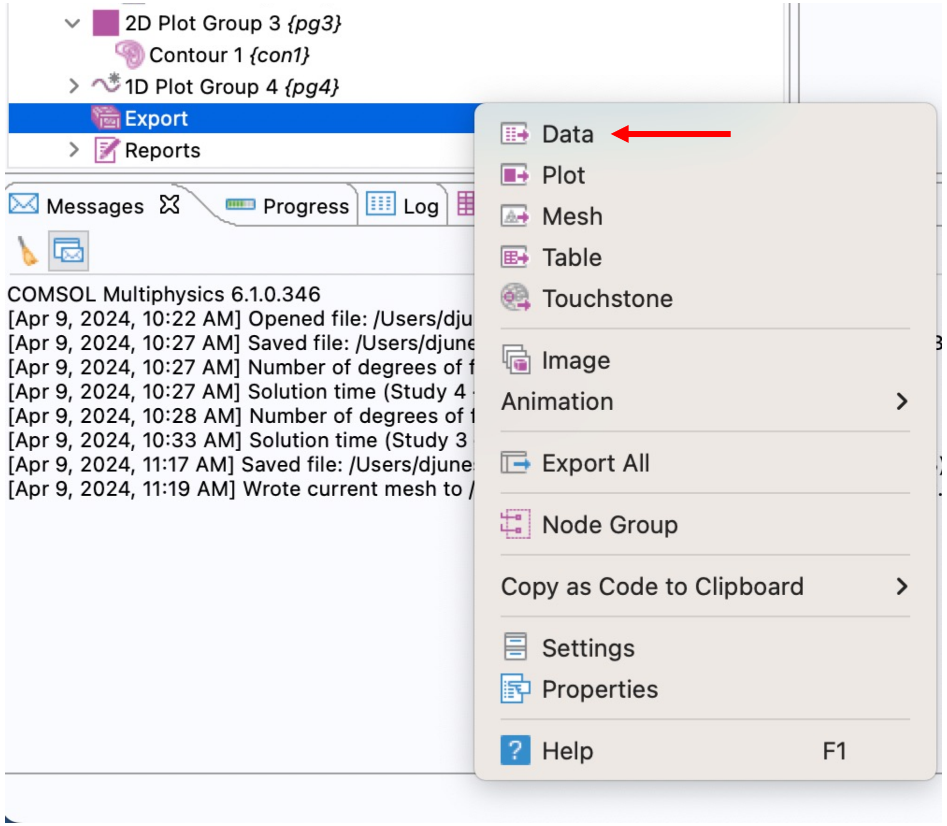
This file contains information on the types of mesh elements being used, in which domain they are located, and in what position their nodes are placed.

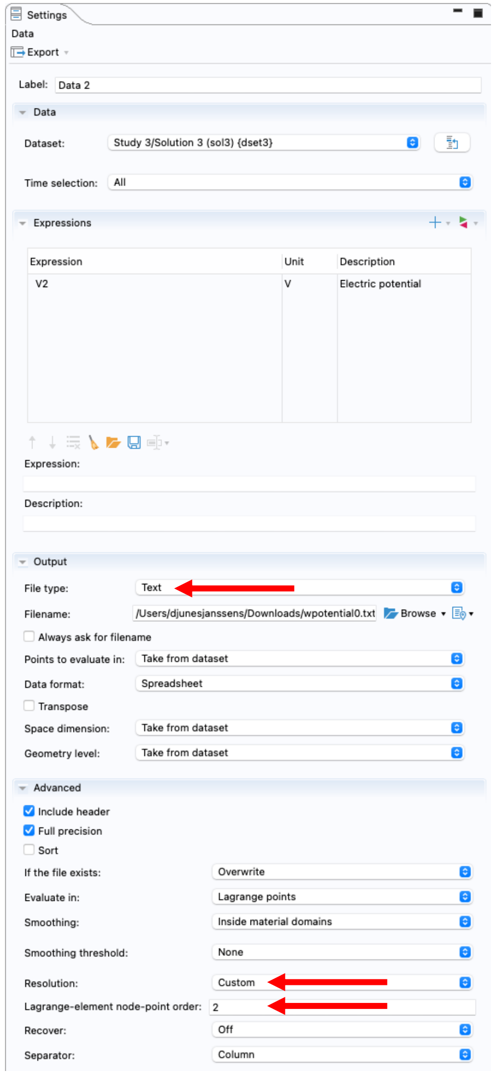




Exporting weighting potential maps from COMSOL

This file contains a list of weighting potential values on the nodes of the elements for all time slices.





EP R&D

Making the dielectric.dat file

The final file needs to be created manually, as it contains information on the relative permittivity of the material of each domain.

- *The first line indicates the number of relative permittivities are used.*
- *The second line list the values of these relative permittivities.*
- *The third line indicates the total number of domains in the geometry.*
- *This is followed by the list of domains, represented by their respective numbers, and which relative permittivity it has, indicated by the index (starting at zero) of the entries of the list defined in line two.*

```
2
1 4
18
1 1
2 0
3 1
4 0
5 1
6 0
7 1
8 0
9 1
10 0
11 1
12 0
13 1
14 0
15 1
16 0
17 1
18 0
```

Importing the data to Garfield++

To import the set of time-sliced weighting potential maps $\psi_i(x, t_n)$, $n \in \{0, 1, . . . ,N\}$, from the FEM calculation, the exported files are needed. Using the *ComponentCOMSOL* class, we can import them into our simulation.

```
// Import COMSOL's potential, mesh and dielectric constant map
ComponentCOMSOL fm;
fm.Initialise("mesh.mphtxt", "dielectrics.dat", "Potential.txt", "m");
fm.EnableMirrorPeriodicityX();
fm.EnableMirrorPeriodicityY();
fm.PrintRange();

// Import weighting potential maps of two neighboring electrodes
const std::string label[2] = {"electrode1","electrode2"};
fm.SetDynamicWeightingPotential("WPotential.txt",label[0]);
```

When the readout structure exhibits a symmetry such that the weighting potential of a second electrode can be mapped through rotation or translation of the solution of a first electrode, we can duplicate the weighting potential of the initial electrode.

```
const double pitch = 0.1; // Pitch between electrodes [cm]
fm.CopyWeightingPotential(label[1], label[0], pitch, 0, 0, 0, 0, 0);
```

Importing the data to Garfield++

To determine which domain(s) constitute the drift-able medium, we should designate a gas medium to the domain characterized by a unit relative permittivity:

```
// Setup of the gas
MediumMagboltz gas;
gas.SetComposition("ar", 70., "co2", 30.); // [%]
gas.SetTemperature(293.15); // [K]
gas.Initialise(true);

// Assign relative permittivity to geometry domains
const unsigned int nMaterials = fm.GetNumberOfMaterials();
for (unsigned int i = 0; i < nMaterials; ++i){
    const double eps = fm.GetPermittivity(i);
    if(eps==1) fm.SetMedium(i, &gas);
}

// Print all materials
fm.PrintMaterials();
```

Calculating the induced signal in Garfield++

We can assign which potential map will be used to propagate the charges, and for which electrodes the signal needs to be calculated:

```
// Setup of the sensor
Sensor sensor;
sensor.AddComponent(&fm); // Assign potential map
sensor.AddElectrode(&fm, label[0]); // Assign weighting potential map
sensor.AddElectrode(&fm, label[1]);
sensor.EnableDelayedSignal();  // Enable delayed signal calculation
```

The bounds of the time window in which the signal needs to be computed, and how finely it is resolved, can be set:

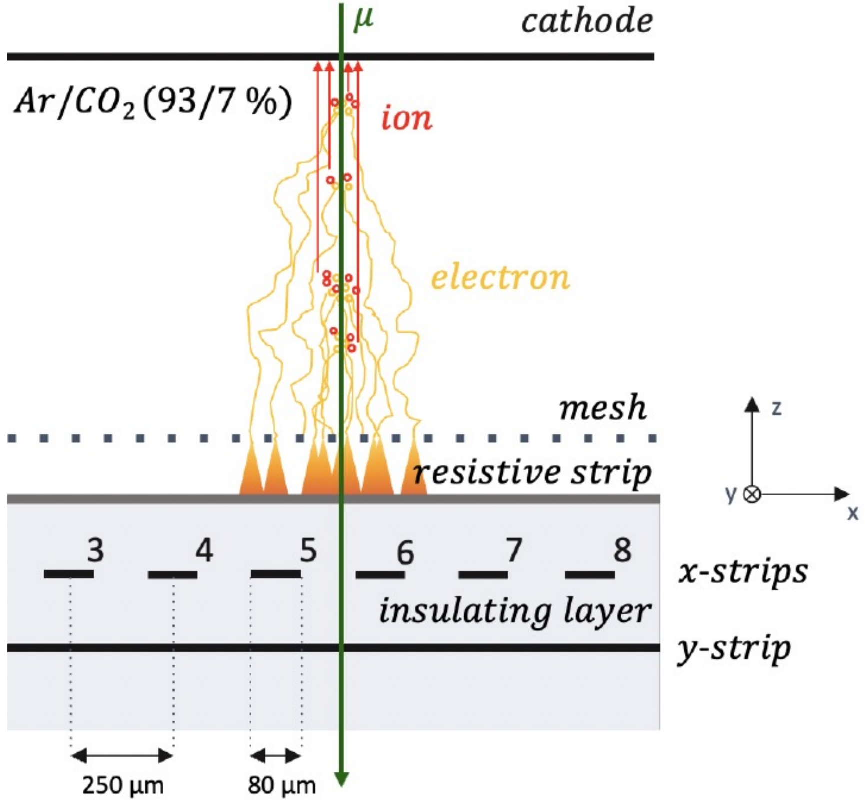
```
// Set time interval
const double tmin =  0.; // [ns]
const double tmax = 1e3.; // [ns]
const int nTimeBins = 100;
const double tstep = (tmax - tmin) / nTimeBins;
sensor.SetTimeWindow(tmin, tstep, nTimeBins);
```

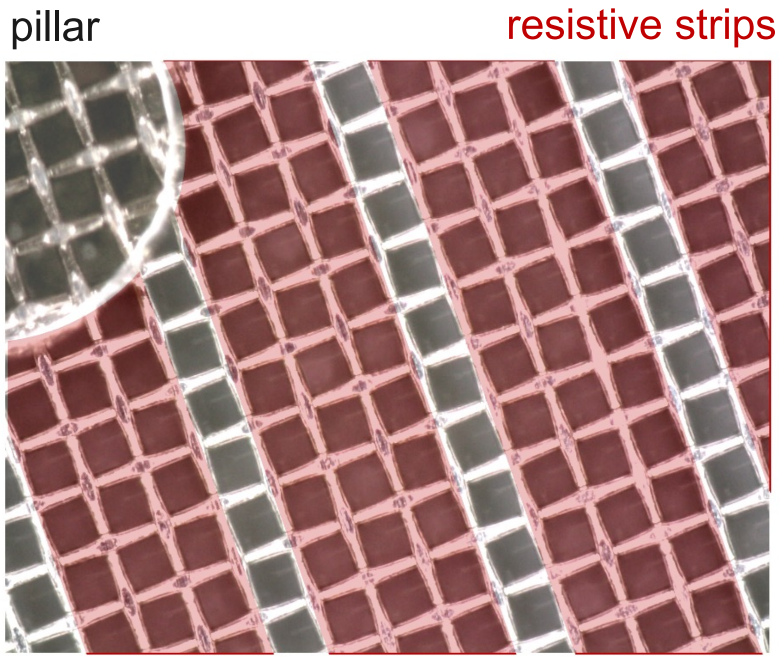
The time convolution of the velocity vector with the weighting vector needs to be evaluated over the set time range at several predetermined time points.

```
// Time points at where the delayed signal is calculated
std::vector<double> times;
for(int i=0;i<nTimeBins;i++) times.push_back(tmin+tstep/2+i*tstep); // [ns]
sensor.SetDelayedSignalTimes(times);
```

Resistive strip MicroMegas

The resistive strips in the geometry of this MicroMegas facilitate the sharing of the signal over many neighboring readout strips strips running orthogonal to them.

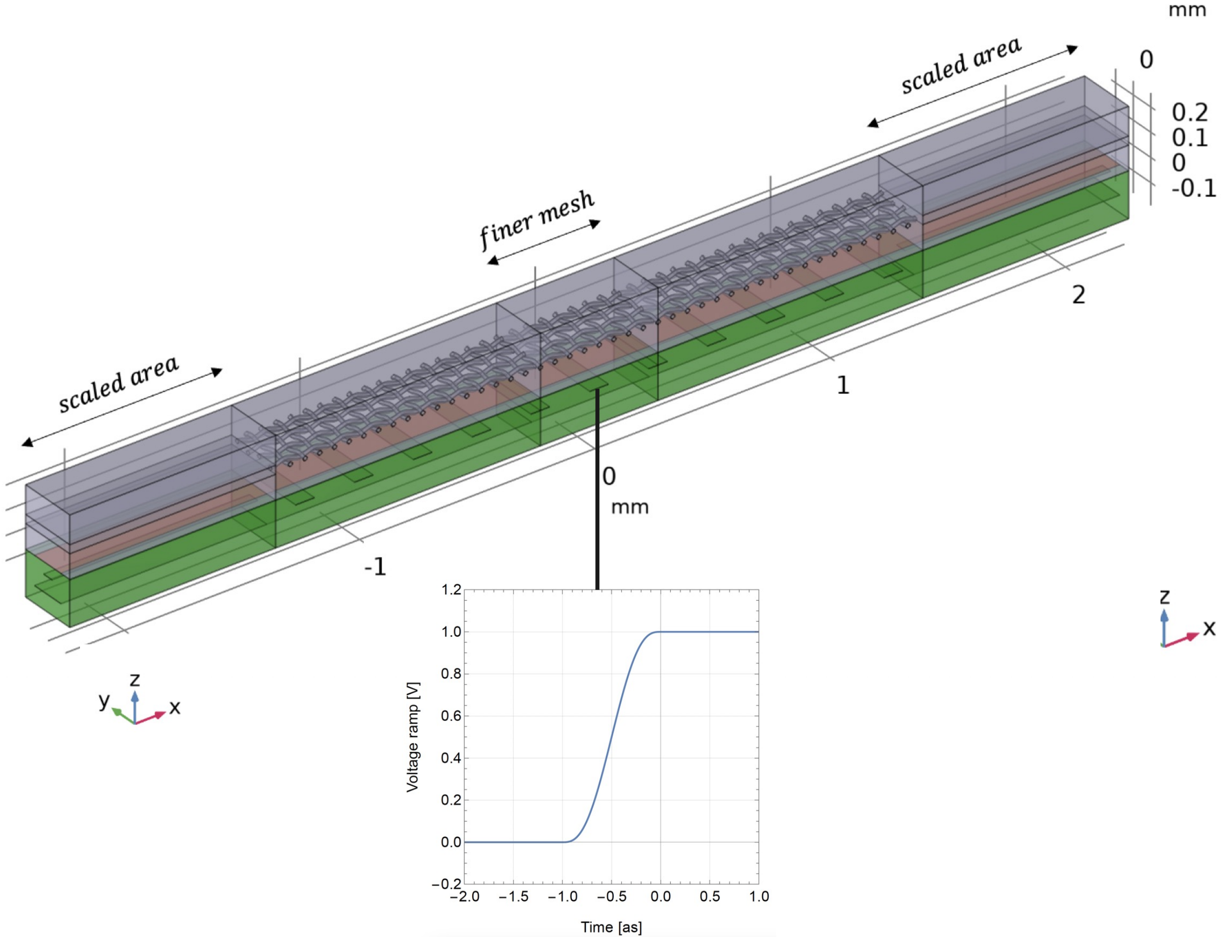




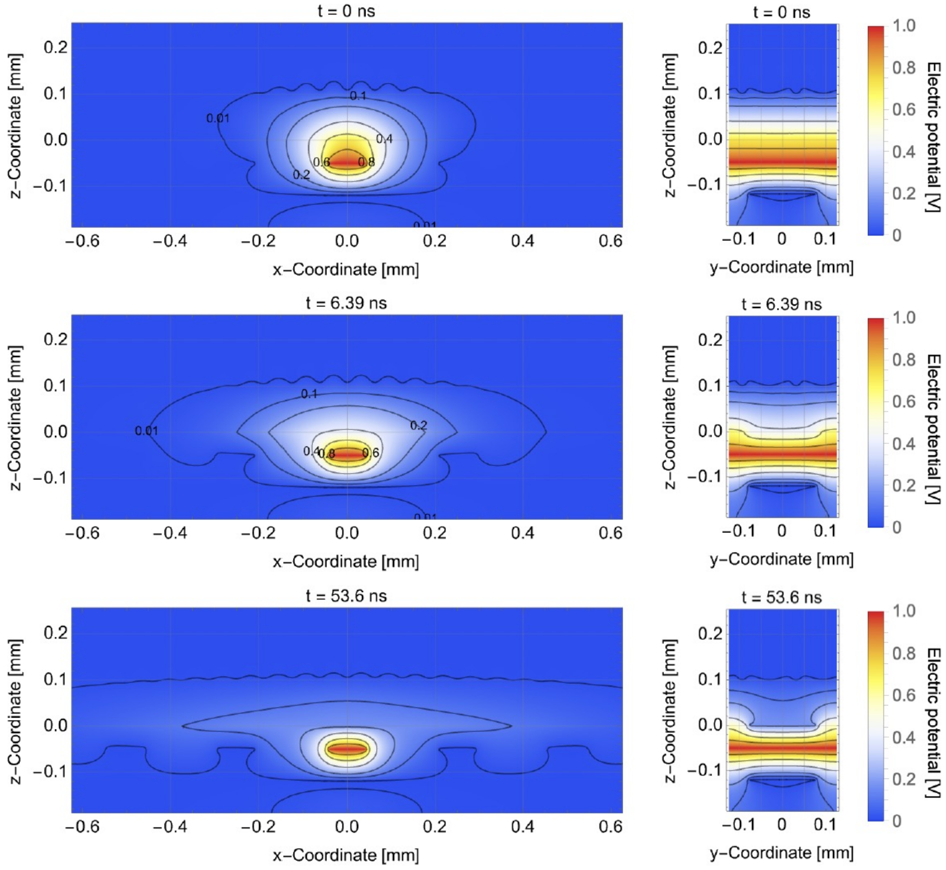
T. Alexopoulos, et al., Nucl. Instrum. Meth. A 640 (2011) 110.
M. Byszewski and J. Wotschack, JINST 7 C02060 (2011).

Resistive strip MicroMegas

To calculate the dynamic weighting potential, a voltage ramp is placed on the readout strip under investigation.

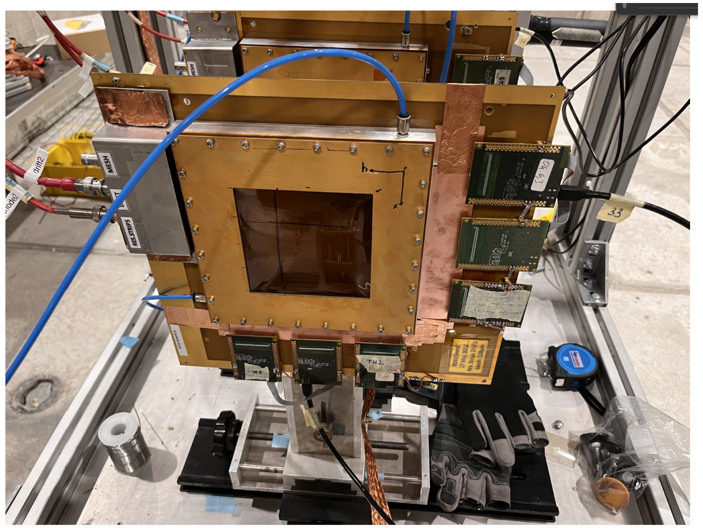


Calculated dynamic weighting potential



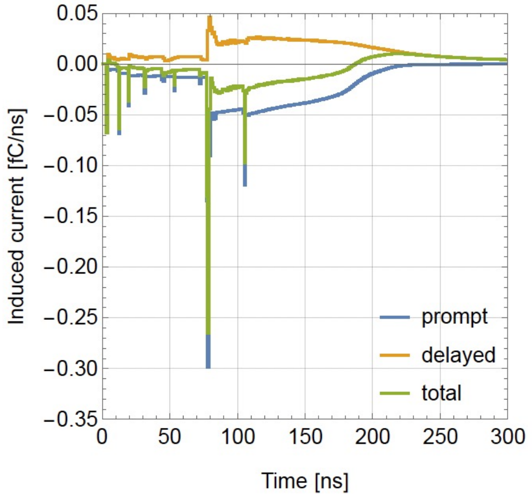
Resistive strip MicroMegas

After having calculated the signals induced on the strip electrodes, the electronics with which the detector is read out needs to be considered.

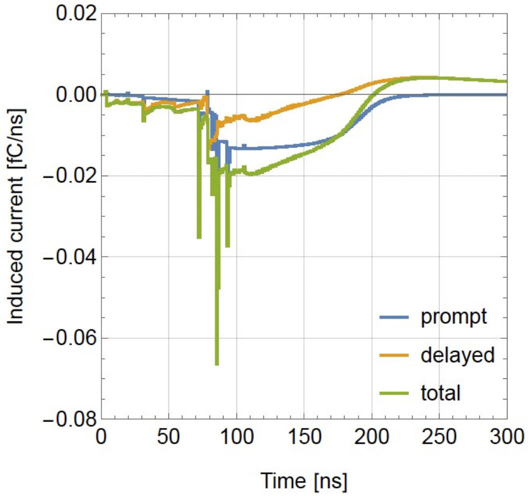


$\psi_i(\mathbf{x}, t) \rightarrow$

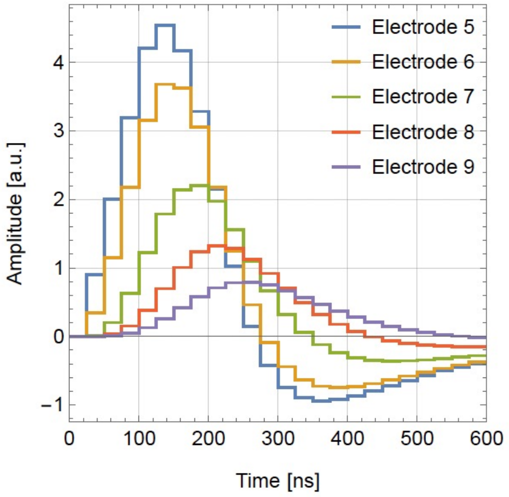
Leading strip (5)



Next-to-leading strip (6)



APV25

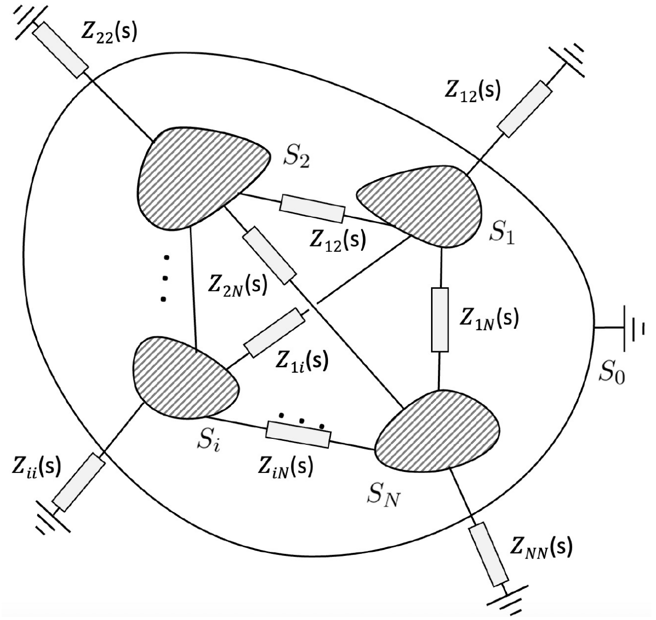


For a result on the ion tail length: D. Janssens,"Ion mobility in a MicroMegas detector: a puzzle between measurement and simulation", RD51 Collaboration Meeting.

Extensions to the numerical approach

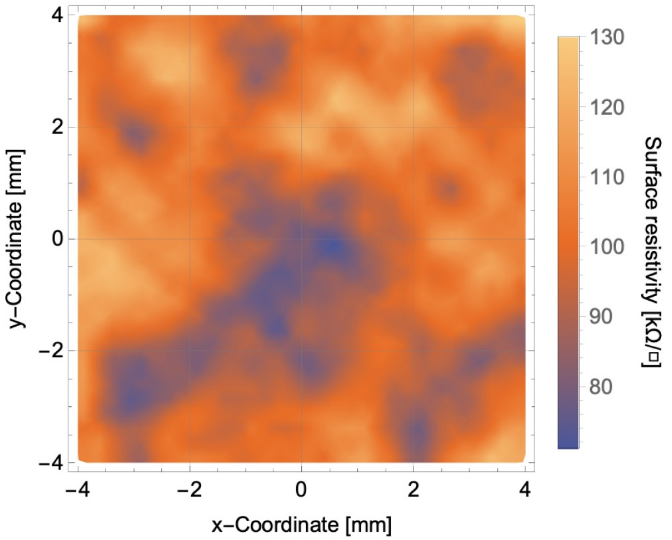
The discussed method can be extended for the cases where the detector is connected to external impedance elements or non-uniform conductive properties of a resistive element.

External impedance elements

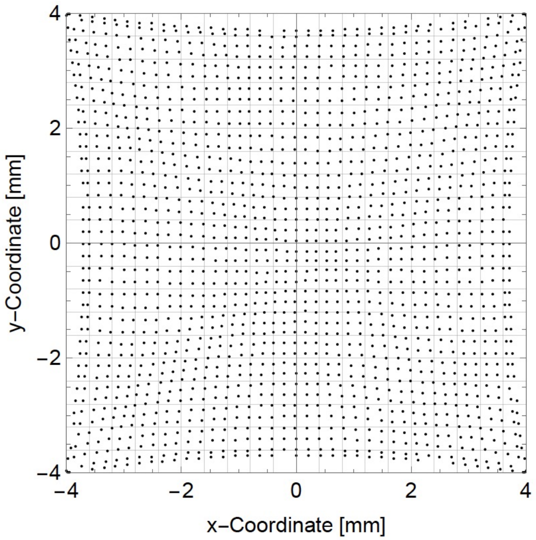


MicroCAT resistive interpolating readout

Map of non-uniform resistivity

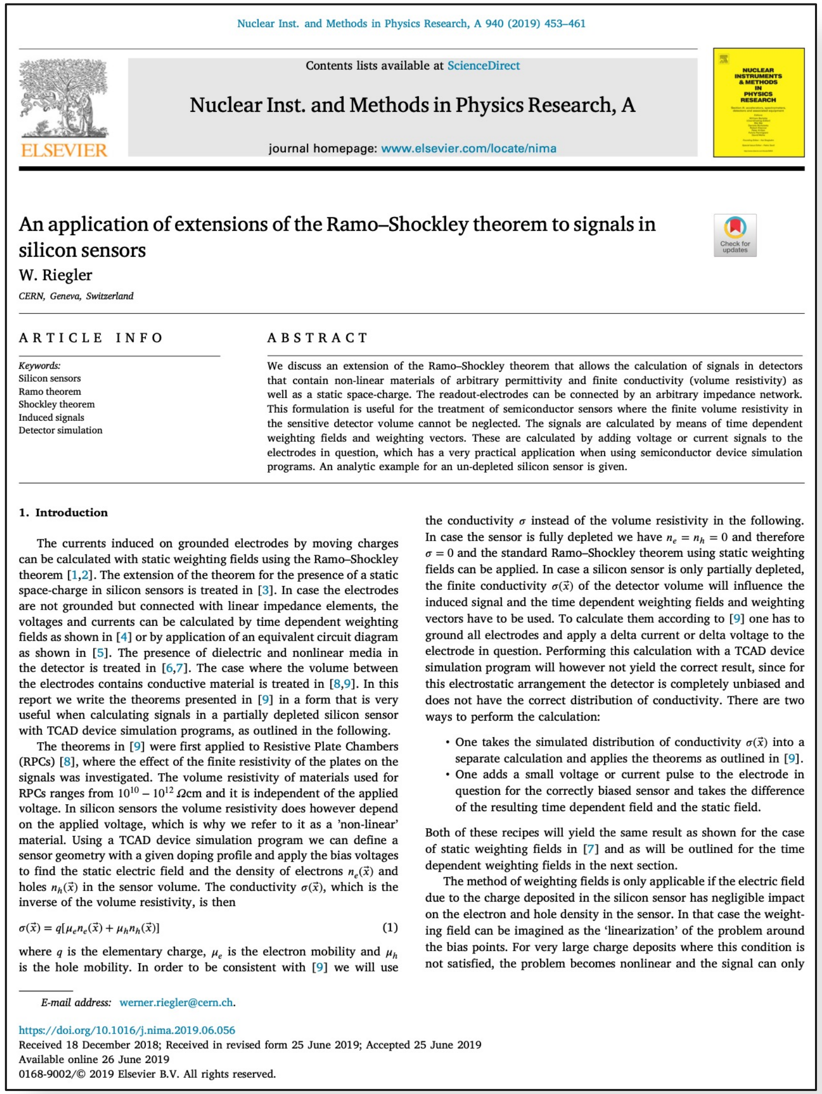


Correction map



For more information: https://cds.cern.ch/record/2890572

TCAD



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An application of extensions of the Ramo–Shockley theorem to signals in silicon sensors

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Ramo theorem
Shockley theorem
Induced signals
Detector simulation

ABSTRACT

We discuss an extension of the Ramo–Shockley theorem that allows the calculation of signals in detectors that contain non-linear materials of arbitrary permittivity and finite conductivity (volume resistivity) as well as a static space-charge. The readout-electrodes can be connected by an arbitrary impedance network. This formulation is useful for the treatment of semiconductor sensors where the finite volume resistivity in the sensitive detector volume cannot be neglected. The signals are calculated by means of time dependent weighting fields and weighting vectors. These are calculated by adding voltage or current signals to the electrodes in question, which has a very practical application when using semiconductor device simulation programs. An analytic example for an un-depleted silicon sensor is given.

1. Introduction

The currents induced on grounded electrodes by moving charges can be calculated with static weighting fields using the Ramo–Shockley theorem [1,2]. The extension of the theorem for the presence of a static space-charge in silicon sensors is treated in [3]. In case the electrodes are not grounded but connected with linear impedance elements, the voltages and currents can be calculated by time dependent weighting fields as shown in [4] or by application of an equivalent circuit diagram as shown in [5]. The presence of dielectric and nonlinear media in the detector is treated in [6,7]. The case where the volume between the electrodes contains conductive material is treated in [8,9]. In this report we write the theorems presented in [9] in a form that is very useful when calculating signals in a partially depleted silicon sensor with TCAD device simulation programs, as outlined in the following.

The theorems in [9] were first applied to Resistive Plate Chambers (RPCs) [8], where the effect of the finite resistivity of the plates on the signals was investigated. The volume resistivity of materials used for RPCs ranges from $10^{10}-10^{12}$ Ωcm and it is independent of the applied voltage. In silicon sensors the volume resistivity does however depend on the applied voltage, which is why we refer to it as a 'non-linear' material. Using a TCAD device simulation program we can define a sensor geometry with a given doping profile and apply the bias voltages to find the static electric field and the density of electrons $n_e(\vec{x})$ and holes $n_h(\vec{x})$ in the sensor volume. The conductivity $\sigma(\vec{x})$, which is the inverse of the volume resistivity, is then

$$\sigma(\vec{x}) = q[\mu_e n_e(\vec{x}) + \mu_h n_h(\vec{x})] \quad (1)$$

where q is the elementary charge, μ_e is the electron mobility and μ_h is the hole mobility. In order to be consistent with [9] we will use the conductivity σ instead of the volume resistivity in the following. In case the sensor is fully depleted we have $n_e = n_h = 0$ and therefore $\sigma = 0$ and the standard Ramo–Shockley theorem using static weighting fields can be applied. In case a silicon sensor is only partially depleted, the finite conductivity $\sigma(\vec{x})$ of the detector volume will influence the induced signal and the time dependent weighting fields and weighting vectors have to be used. To calculate them according to [9] one has to ground all electrodes and apply a delta current or delta voltage to the electrode in question. Performing this calculation with a TCAD device simulation program will however not yield the correct result, since for this electrostatic arrangement the detector is completely unbiased and does not have the correct distribution of conductivity. There are two ways to perform the calculation:

- One takes the simulated distribution of conductivity $\sigma(\vec{x})$ into a separate calculation and applies the theorems as outlined in [9].
- One adds a small voltage or current pulse to the electrode in question for the correctly biased sensor and takes the difference of the resulting time dependent field and the static field.

Both of these recipes will yield the same result as shown for the case of static weighting fields in [7] and as will be outlined for the time dependent weighting fields in the next section.

The method of weighting fields is only applicable if the electric field due to the charge deposited in the silicon sensor has negligible impact on the electron and hole density in the sensor. In that case the weighting field can be imagined as the 'linearization' of the problem around the bias points. For very large charge deposits where this condition is not satisfied, the problem becomes nonlinear and the signal can only

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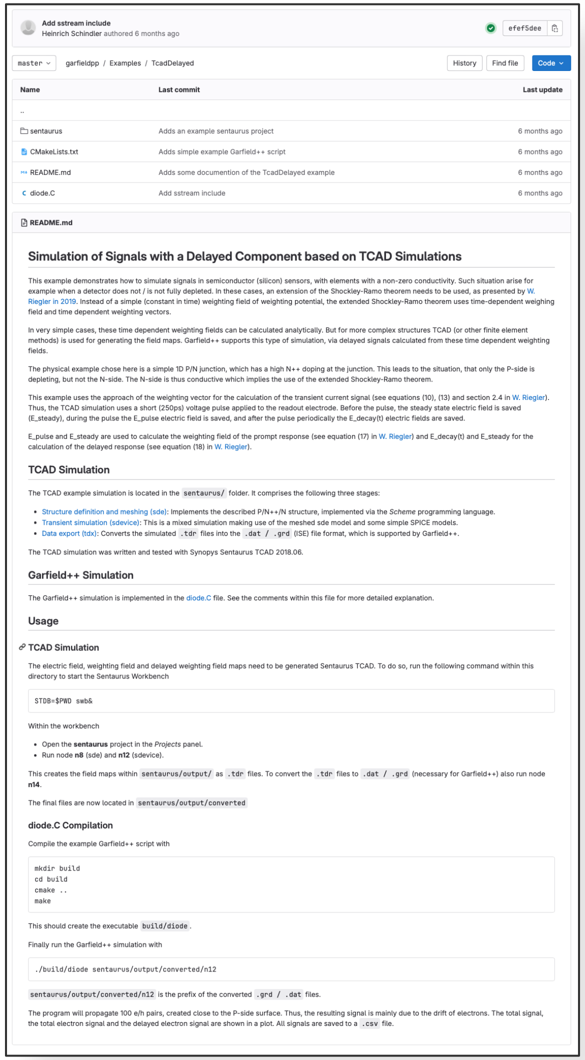

Add sstream include
Heinrich Schindler authored 6 months ago
efef5dee

master garfieldpp / Examples / TcadDelayed   History Find file Code

Name	Last commit	Last update
..		
sentaurus	Adds an example sentaurus project	6 months ago
CMakeLists.txt	Adds simple example Garfield++ script	6 months ago
README.md	Adds some documention of the TcadDelayed example	6 months ago
diode.C	Add sstream include	6 months ago

README.md

Simulation of Signals with a Delayed Component based on TCAD Simulations

This example demonstrates how to simulate signals in semiconductor (silicon) sensors, with elements with a non-zero conductivity. Such situation arise for example when a detector does not / is not fully depleted. In these cases, an extension of the Shockley-Ramo theorem needs to be used, as presented by W. Riegler in 2019. Instead of a simple (constant in time) weighting field of weighting potential, the extended Shockley-Ramo theorem uses time-dependent weighing field and time dependent weighting vectors.

In very simple cases, these time dependent weighting fields can be calculated analytically. But for more complex structures TCAD (or other finite element methods) is used for generating the field maps. Garfield++ supports this type of simulation, via delayed signals calculated from these time dependent weighting fields.

The physical example chose here is a simple 1D P/N junction, which has a high N++ doping at the junction. This leads to the situation, that only the P-side is depleting, but not the N-side. The N-side is thus conductive which implies the use of the extended Shockley-Ramo theorem.

This example uses the approach of the weighting vector for the calculation of the transient current signal (see equations (10), (13) and section 2.4 in W. Riegler). Thus, the TCAD simulation uses a short (250ps) voltage pulse applied to the readout electrode. Before the pulse, the steady state electric field is saved (E_steady), during the pulse the E_pulse electric field is saved, and after the pulse periodically the E_decay(t) electric fields are saved.

E_pulse and E_steady are used to calculate the weighting field of the prompt response (see equation (17) in W. Riegler) and E_decay(t) and E_steady for the calculation of the delayed response (see equation (18) in W. Riegler).

TCAD Simulation

The TCAD example simulation is located in the `sentaurus/` folder. It comprises the following three stages:

- Structure definition and meshing (sde): Implements the described P/N++/N structure, implemented via the *Scheme* programming language.
- Transient simulation (sdevice): This is a mixed simulation making use of the meshed sde model and some simple SPICE models.
- Data export (tdx): Converts the simulated `.tdr` files into the `.dat / .grd` (ISE) file format, which is supported by Garfield++.

The TCAD simulation was written and tested with Synopys Sentaurus TCAD 2018.06.

Garfield++ Simulation

The Garfield++ simulation is implemented in the diode.C file. See the comments within this file for more detailed explanation.

Usage

TCAD Simulation

The electric field, weighting field and delayed weighting field maps need to be generated Sentaurus TCAD. To do so, run the following command within this directory to start the Sentaurus Workbench

```
STDB=$PWD swb&
```

Within the workbench

- Open the **sentaurus** project in the *Projects* panel.
- Run node **n8** (sde) and **n12** (sdevice).

This creates the field maps within `sentaurus/output/` as `.tdr` files. To convert the `.tdr` files to `.dat / .grd` (necessary for Garfield++) also run node **n14**.

The final files are now located in `sentaurus/output/converted`

diode.C Compilation

Compile the example Garfield++ script with

```
mkdir build
cd build
cmake ..
make
```

This should create the executable `build/diode`.

Finally run the Garfield++ simulation with

```
./build/diode sentaurus/output/converted/n12
```

`sentaurus/output/converted/n12` is the prefix of the converted `.grd / .dat` files.

The program will propagate 100 e/h pairs, created close to the P-side surface. Thus, the resulting signal is mainly due to the drift of electrons. The total signal, the total electron signal and the delayed electron signal are shown in a plot. All signals are saved to a `.csv` file.

W. Riegler, NIM-A A 940 (2019) 453–461
TCAD example: https://gitlab.cern.ch/garfield/garfieldpp/-/tree/master/Examples/TcadDelayed?ref_type=heads

Summary

With resistive materials becoming increasingly more common in particle detector designs, it was therefore prudent to keep the capabilities of Garfield++ aligned with this technological advancement.

- We discussed the numerical approach used for applying the extended form of the Ramo-Shockley theorem to the calculation of induced signals in resistive particle detectors.
- Using COMSEL the dynamic weighting potential was calculated for two toy model examples: RPC and resistive plane MicroMegas.
- To import this data in Garfield++ the export files of COMSOL need to have a specific format.
- A minimally working example for signal induction calculations in Garfield++ was discussed.
- This methodology can be applied to a wide range of resistive (large active area) detector structures within the families of gas detectors, MPGDs, and solid-state sensors.

Thank you for your attention!