XVII Conference on Resistive Plate Chambers and Related Detectors

Simulating MRPCs with Garfield++ and time-dependent weighting potentials

Djunes Janssens

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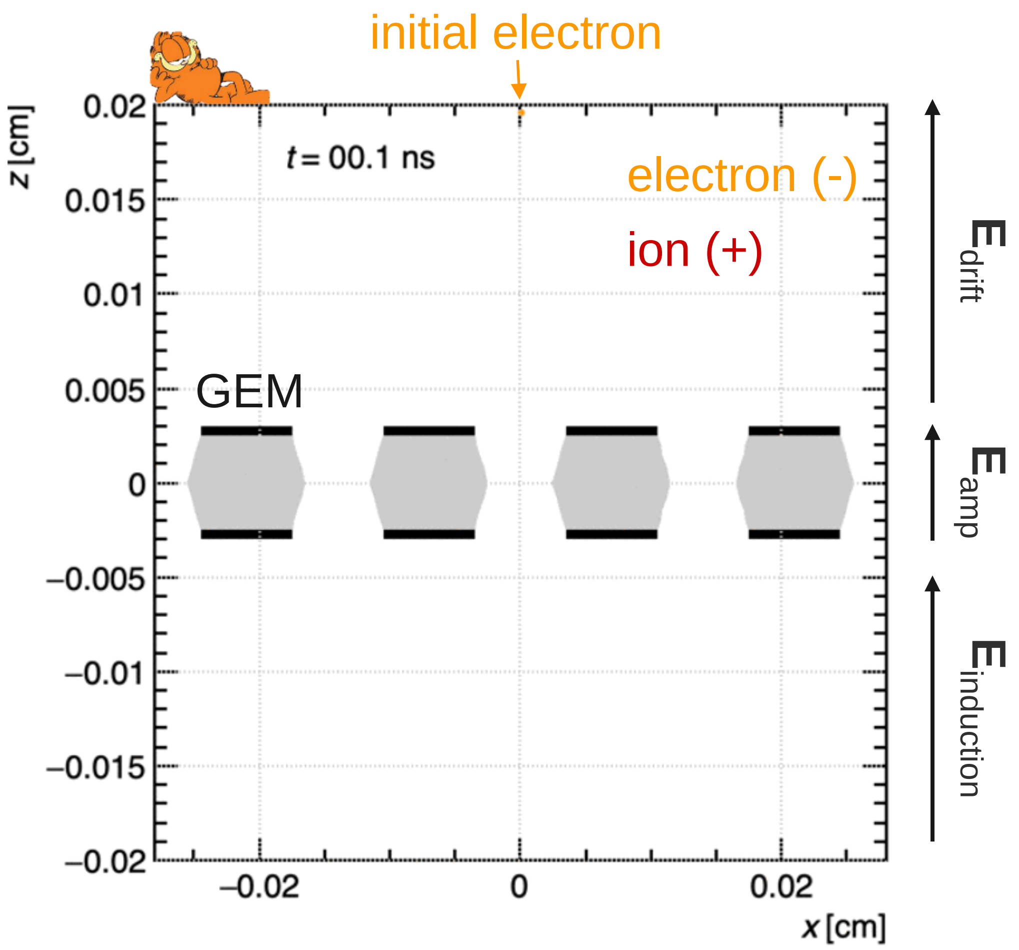
September 12th, 2024

Introduction

<u>Outline:</u>

- **Garfield++ MRPC simulation**
  - Grid-based avalanche method
  - Mixed method approach
- **Signal formation**
  - Ramo-Shockley theorem
  - Ramo-Shockley theorem extension for conductive media
  - Weighting potentials and signals in (M)RPCs
  - Signals in the presence of a thin resistive layer
- **Conclusion**



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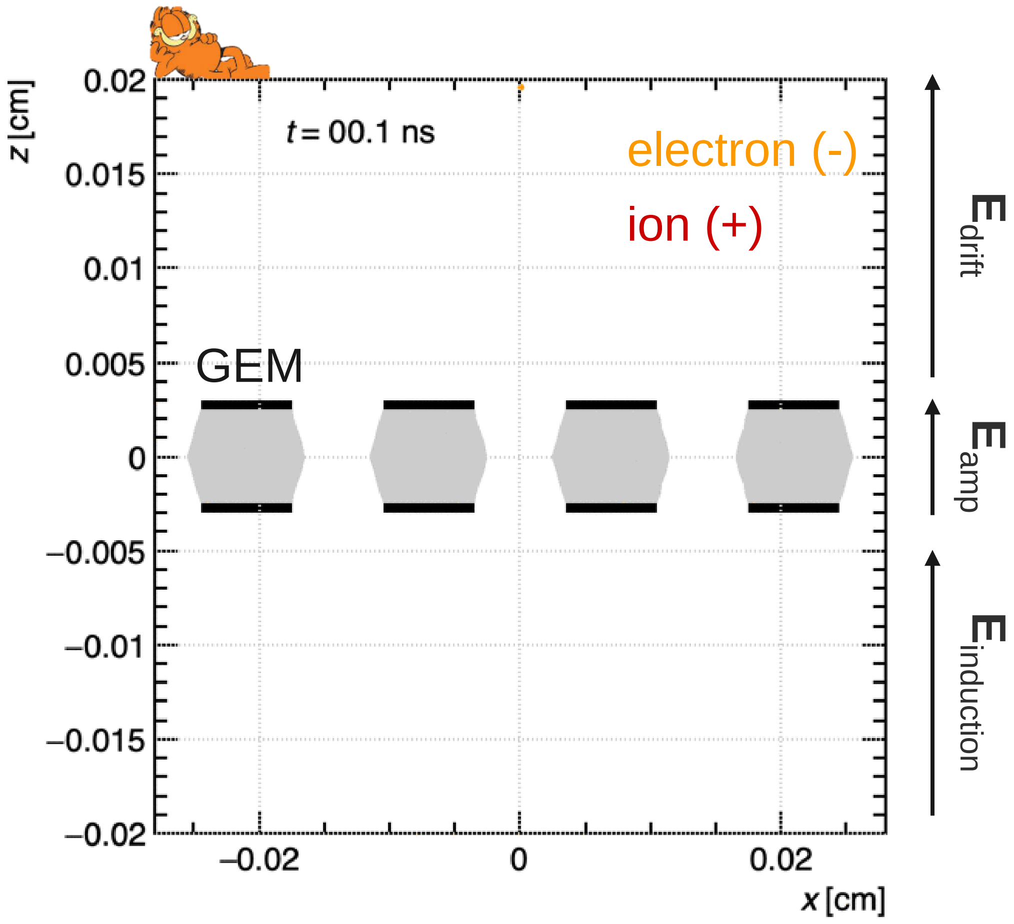
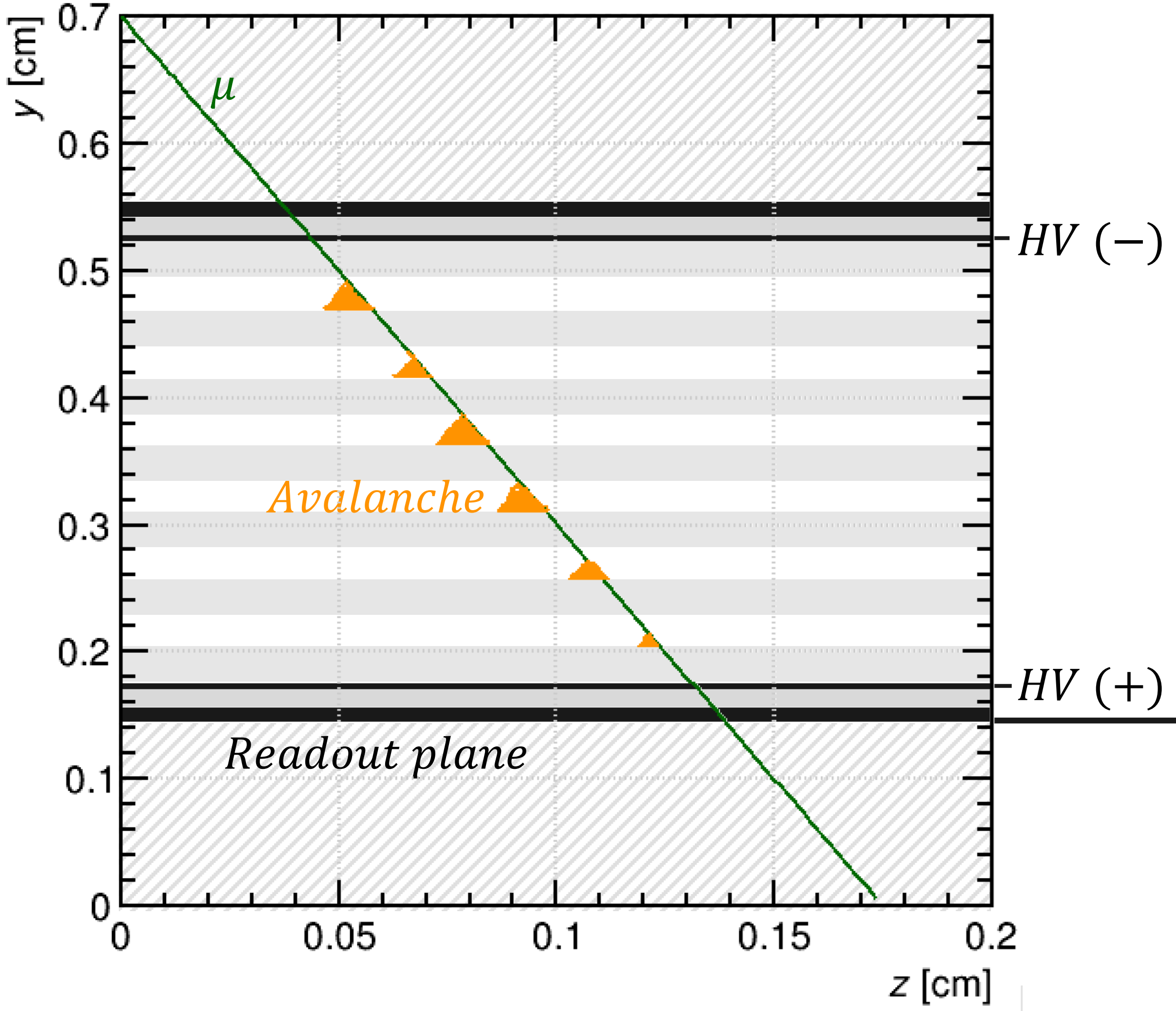


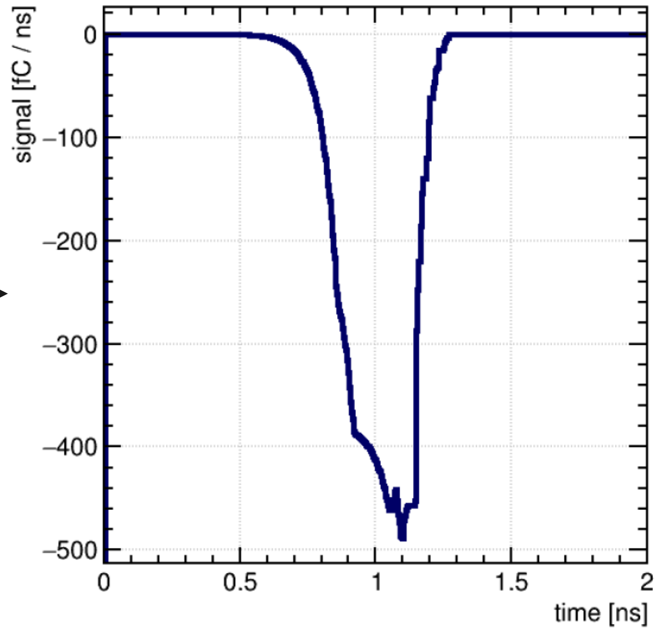
Garfield++: https://garfieldpp.web.cern.ch/garfieldpp/

Introduction



Using Garfield++, electron avalanches can be simulated microscopically on a collision-by-collision basis, where we consider the proportional regime of amplification.

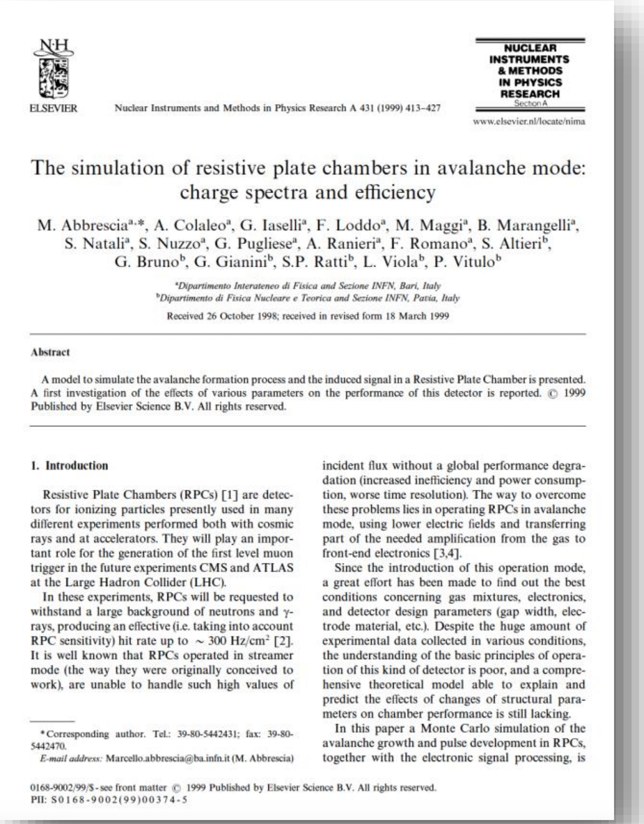
Our goal is to “efficiently” calculate the signal response, including the contribution from resistive materials.



Grid-based avalanche calculation

Grid-based avalanche calculation

The simulation approach for MRPCs relies heavily on a developed method that provide a one-dimensional description of avalanche dynamics using a grid-based approach.



Nuclear Instruments and Methods in Physics Research A 431 (1999) 413–427

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

The simulation of resistive plate chambers in avalanche mode: charge spectra and efficiency

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Abstract

A model to simulate the avalanche formation process and the induced signal in a Resistive Plate Chamber is presented. A first investigation of the effects of various parameters on the performance of this detector is reported. © 1999 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

Resistive Plate Chambers (RPCs) [1] are detectors for ionizing particles presently used in many different experiments performed both with cosmic rays and at accelerators. They will play an important role for the generation of the first level muon trigger in the future experiments CMS and ATLAS at the Large Hadron Collider (LHC).

In these experiments, RPCs will be requested to withstand a large background of neutrons and γ-rays, producing an effective (i.e. taking into account RPC sensitivity) hit rate up to ~ 300 Hz/cm^2 [2]. It is well known that RPCs operated in streamer mode (the way they were originally conceived to work), are unable to handle such high values of incident flux without a global performance degradation (increased inefficiency and power consumption, worse time resolution). The way to overcome these problems lies in operating RPCs in avalanche mode, using lower electric fields and transferring part of the needed amplification from the gas to front-end electronics [3,4].

Since the introduction of this operation mode, a great effort has been made to find out the best conditions concerning gas mixtures, electronics, and detector design parameters (gap width, electrode material, etc.). Despite the huge amount of experimental data collected in various conditions, the understanding of the basic principles of operation of this kind of detector is poor, and a comprehensive theoretical model able to explain and predict the effects of changes of structural parameters on chamber performance is still lacking.

In this paper a Monte Carlo simulation of the avalanche growth and pulse development in RPCs, together with the electronic signal processing, is

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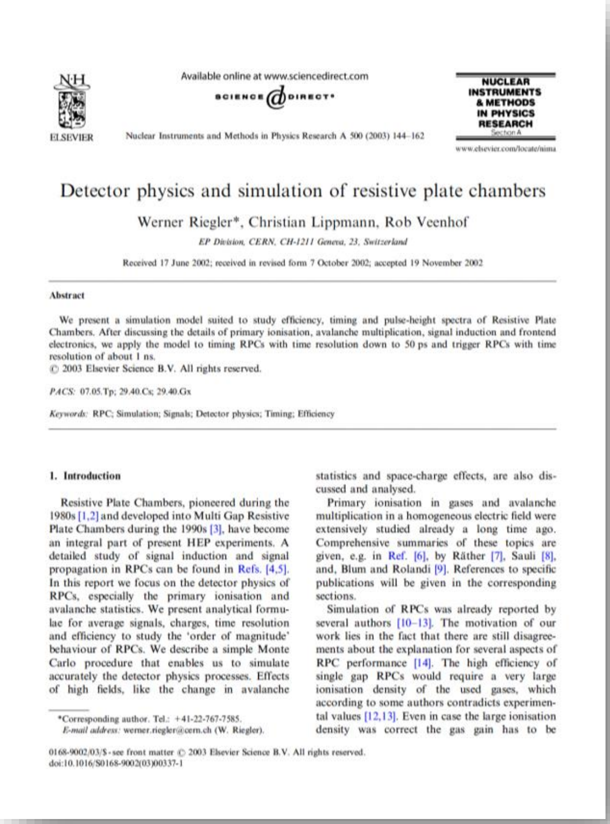

Available online at www.sciencedirect.com

Nuclear Instruments and Methods in Physics Research A 500 (2003) 144–162

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Detector physics and simulation of resistive plate chambers

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EP Division, CERN, CH-1211 Geneva, 23, Switzerland

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Abstract

We present a simulation model suited to study efficiency, timing and pulse-height spectra of Resistive Plate Chambers. After discussing the details of primary ionisation, avalanche multiplication, signal induction and frontend electronics, we apply the model to timing RPCs with time resolution down to 50 ps and trigger RPCs with time resolution of about 1 ns.
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PACS: 07.05.Tp; 29.40.Cs; 29.40.Gx

Keywords: RPC; Simulation; Signals; Detector physics; Timing; Efficiency

1. Introduction

Resistive Plate Chambers, pioneered during the 1980s [1,2] and developed into Multi Gap Resistive Plate Chambers during the 1990s [3], have become an integral part of present HEP experiments. A detailed study of signal induction and signal propagation in RPCs can be found in Refs. [4,5]. In this report we focus on the detector physics of RPCs, especially the primary ionisation and avalanche statistics. We present analytical formulae for average signals, charges, time resolution and efficiency to study the 'order of magnitude' behaviour of RPCs. We describe a simple Monte Carlo procedure that enables us to simulate accurately the detector physics processes. Effects of high fields, like the change in avalanche statistics and space-charge effects, are also discussed and analysed.

Primary ionisation in gases and avalanche multiplication in a homogeneous electric field were extensively studied already a long time ago. Comprehensive summaries of these topics are given, e.g. in Ref. [6], by Räther [7], Sauli [8], and, Blum and Rolandi [9]. References to specific publications will be given in the corresponding sections.

Simulation of RPCs was already reported by several authors [10–13]. The motivation of our work lies in the fact that there are still disagreements about the explanation for several aspects of RPC performance [14]. The high efficiency of single gap RPCs would require a very large ionisation density of the used gases, which according to some authors contradicts experimental values [12,13]. Even in case the large ionisation density was correct the gas gain has to be

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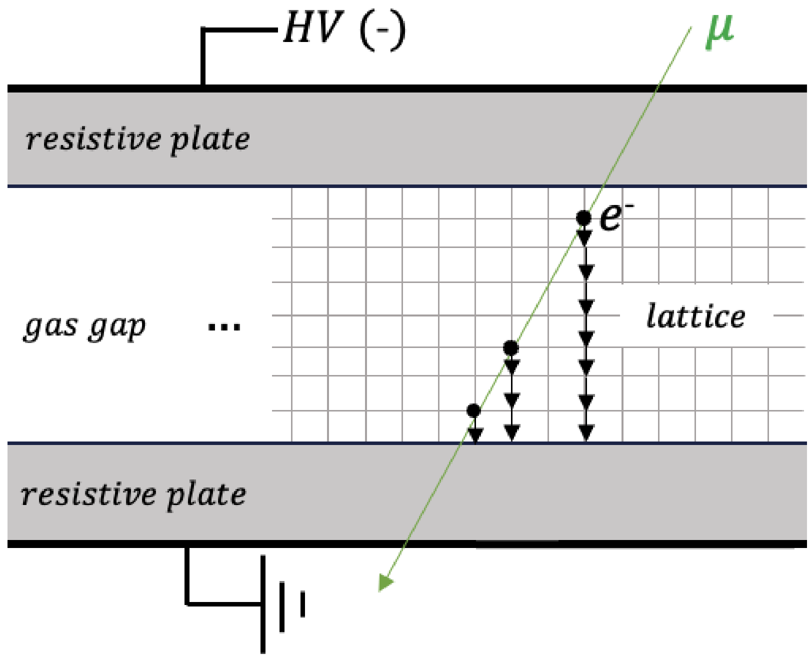
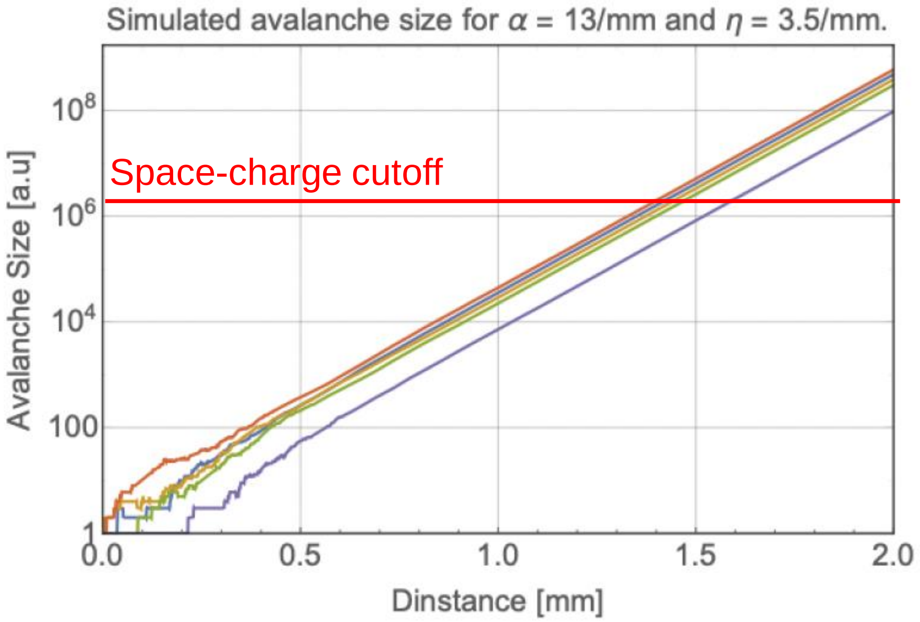
Garfield++ webpage example: https://garfieldpp.web.cern.ch/garfieldpp/examples/rpc/

Grid-based avalanche calculation

The gas volume is subdivided into a 3D grid, with electrons snapped to the nodes and propagated along the drift direction. The avalanche development is modeled using swarm parameters and the **Legler model**.

To approximate space-charge suppression, growth is capped at $1.6*10^7$ electrons.



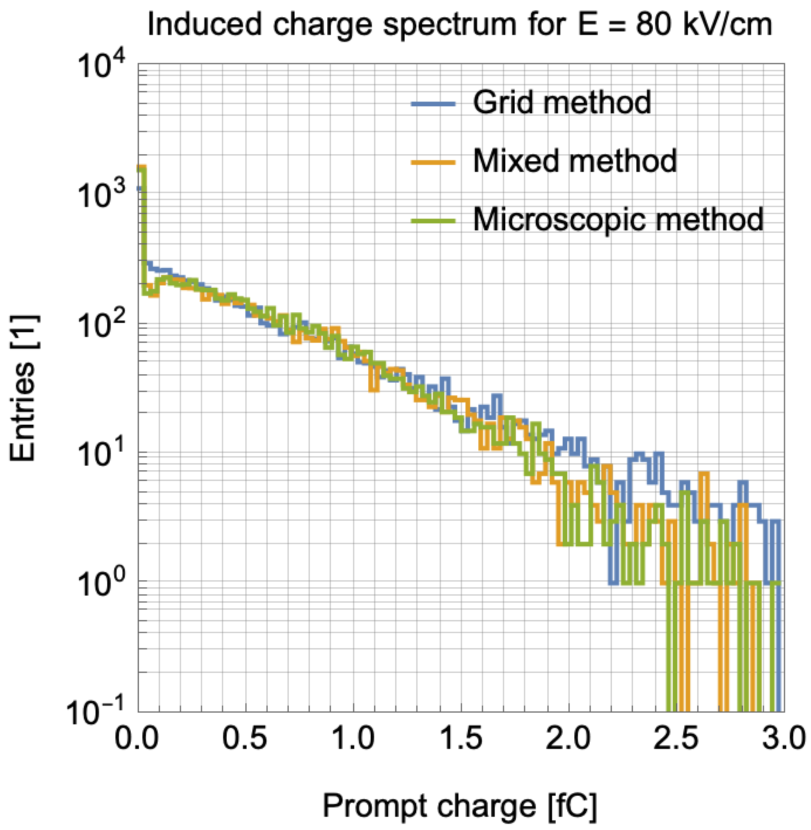


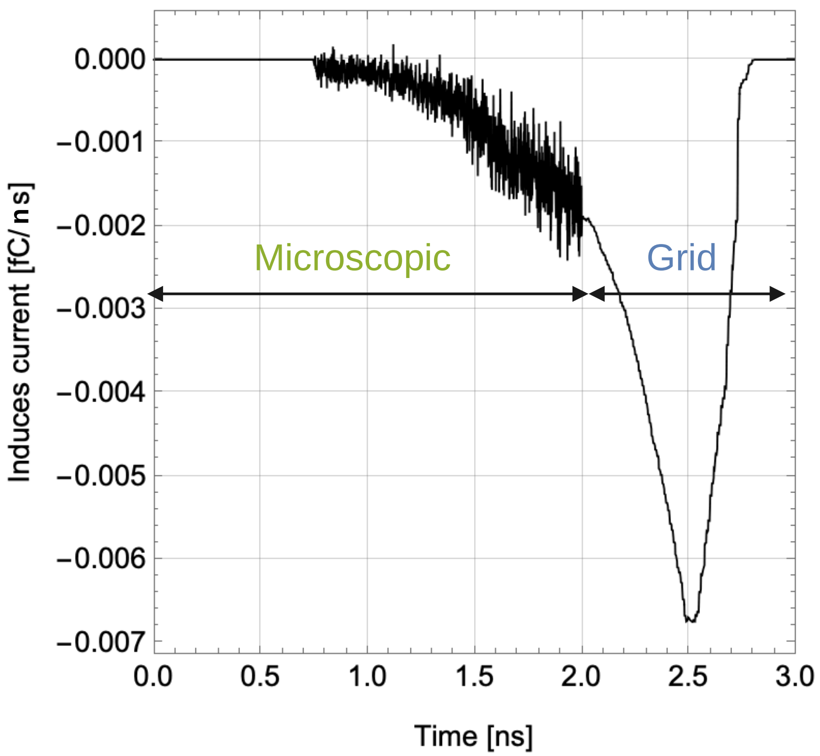
W. Legler, Z. Naturforschung. 16a (1961) 253.
C. Lippmann, W. Riegler, NIM-A 517 (2004) 54–76.
See presentation of Supratik Mukhopadhyay.

RD51–NOTE-2011-005, by Paulo Fonte.
RD-51 Open Lectures by Filippo Resnati.
See presentation of D. Bošnjaković.

Grid-based avalanche calculation

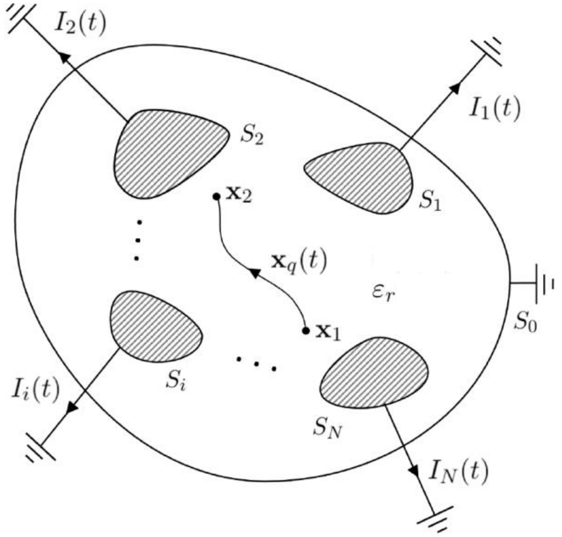
To accurately represent the early fluctuations' impact on the induced charge distribution, microscopic tracking in Garfield++ is used. After a set time (~ 50 - 100 electrons), the method switches to the grid model, forming a 'mixed method' approach.

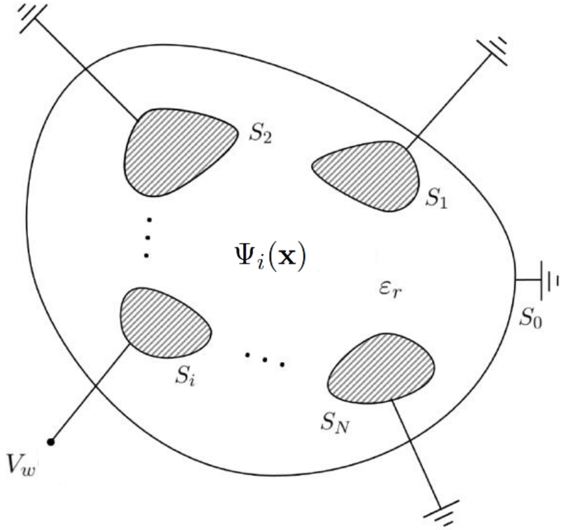




Ramo-Shockley theorem

Ramo-Shockley theorem





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

$$I_i(t) = -\frac{q}{V_w}\mathbf{E}_i(\mathbf{x}_q(t)) \cdot \dot{\mathbf{x}}_q(t)$$

$$\mathbf{E}_i(\mathbf{x}) = -\nabla\Psi_i(\mathbf{x})$$

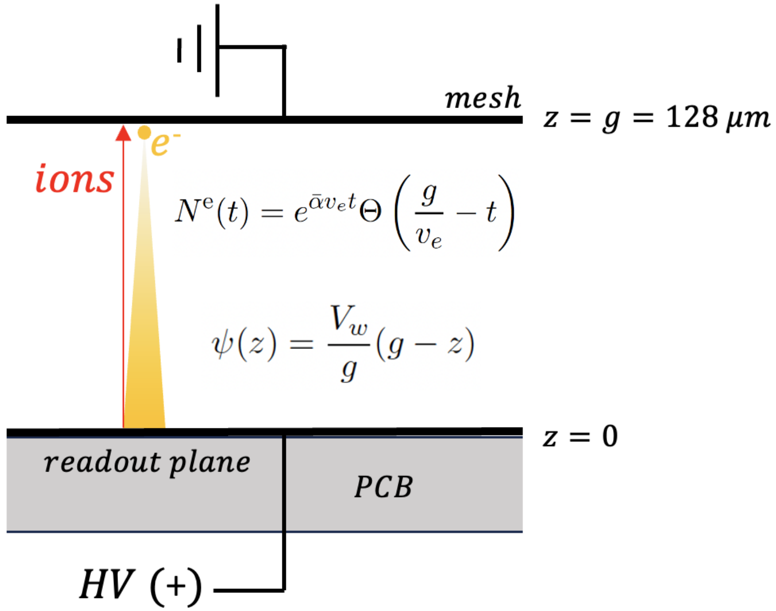
This static $\psi(\mathbf{x})$ can be calculated for a grounded electrode using the following step:

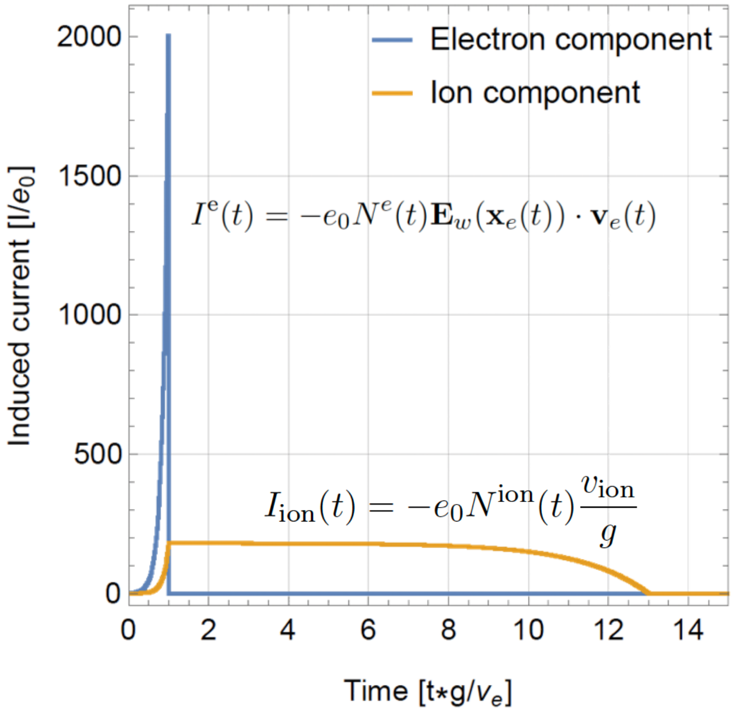
- Remove the drifting charges
- Put the electrode at potential V_w
- Grounding all other electrodes

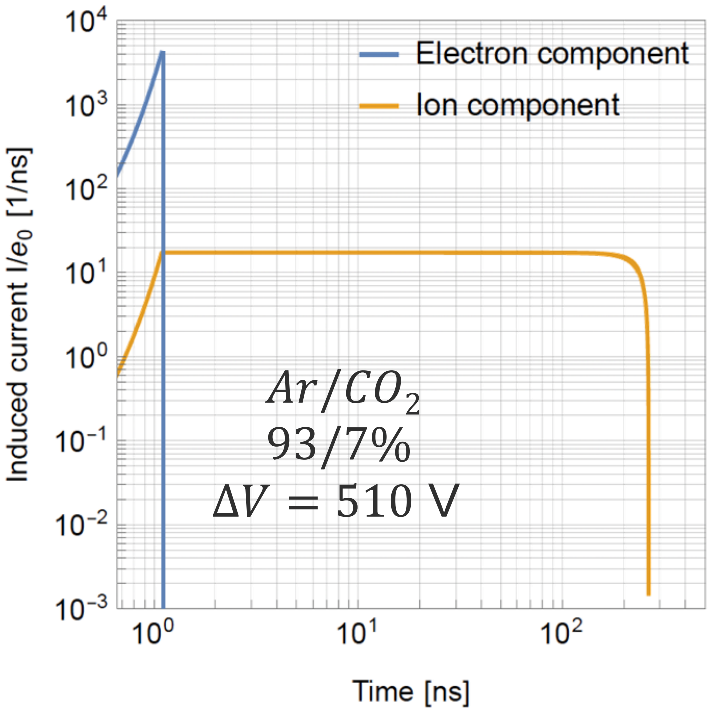
S. Ramo, PROC. IRE 27, 584 (1939).
W. Shockley, Journal of Applied Physics. 9 (10): 635 (1938).

Signal in a non-resistive Micromegas

Let us consider a Townsend avalanche inside the amplification gap of a parallel plate-type detector that induces a signal on the anode plane.

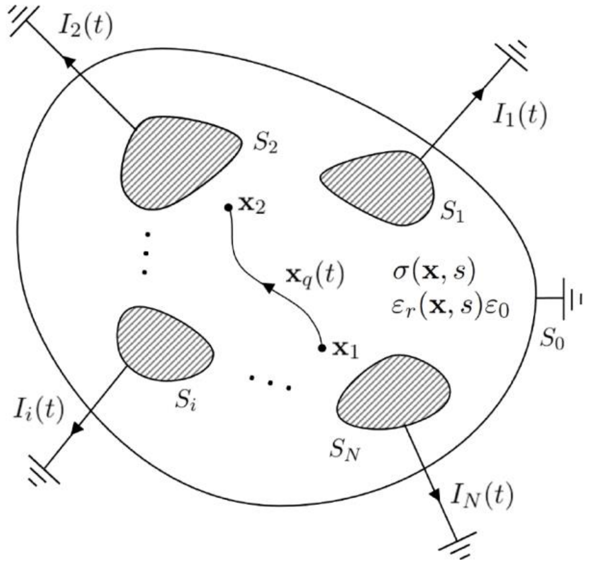


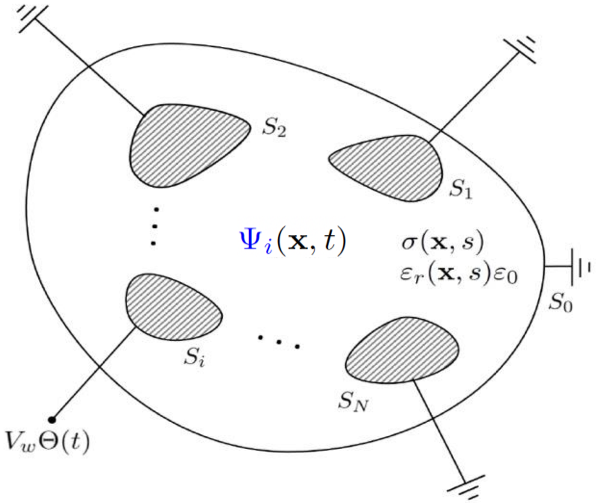




Ramo-Shockley theorem extension for conducting media

Ramo-Shockley theorem extension for conducting media





In detectors with resistive elements, signal timing 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 a dynamic delayed component:

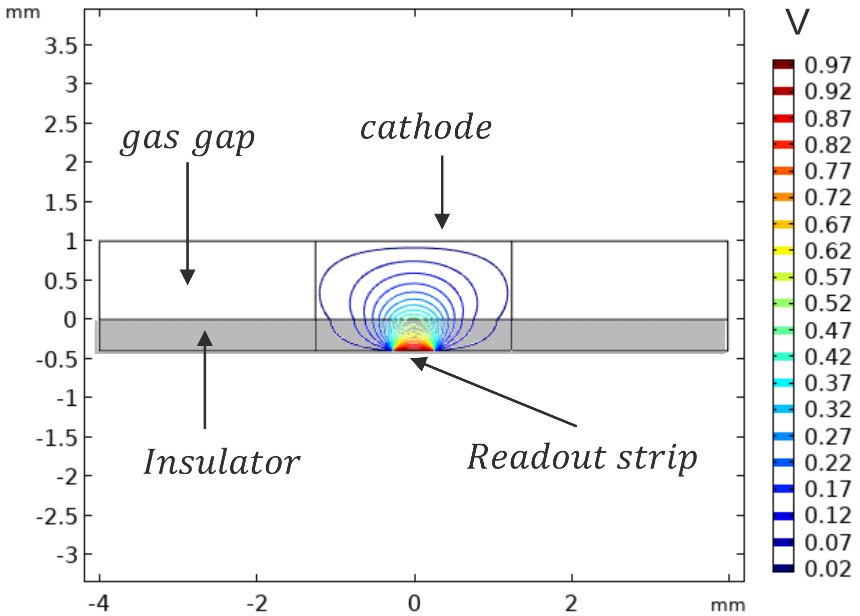
$$\psi_i(\mathbf{x},t) \doteq \psi_i^p(\mathbf{x}) + \psi_i^d(\mathbf{x},t) \quad \text{where} \quad \psi_i^d(\mathbf{x},0) = 0$$

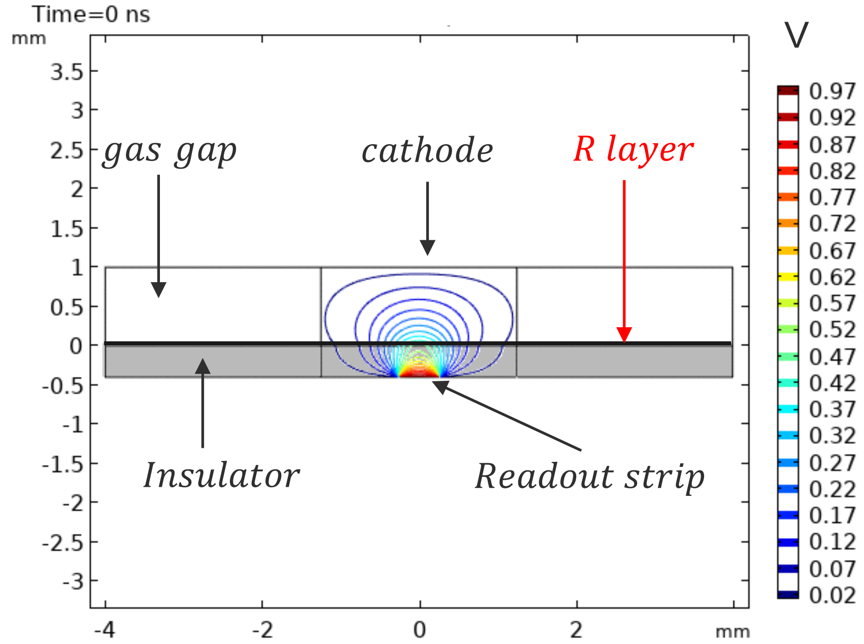
The current induced by a point charge q is given by:

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

Direct induction

Reaction from resistive material

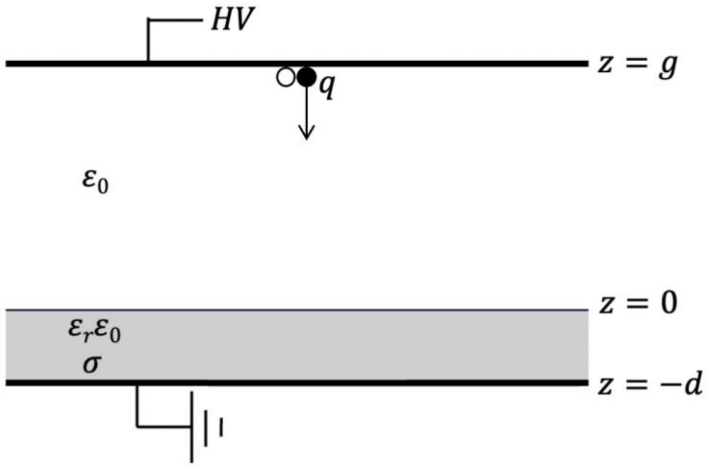




Weighting potentials of (M)RPCs

Delayed component of the signal

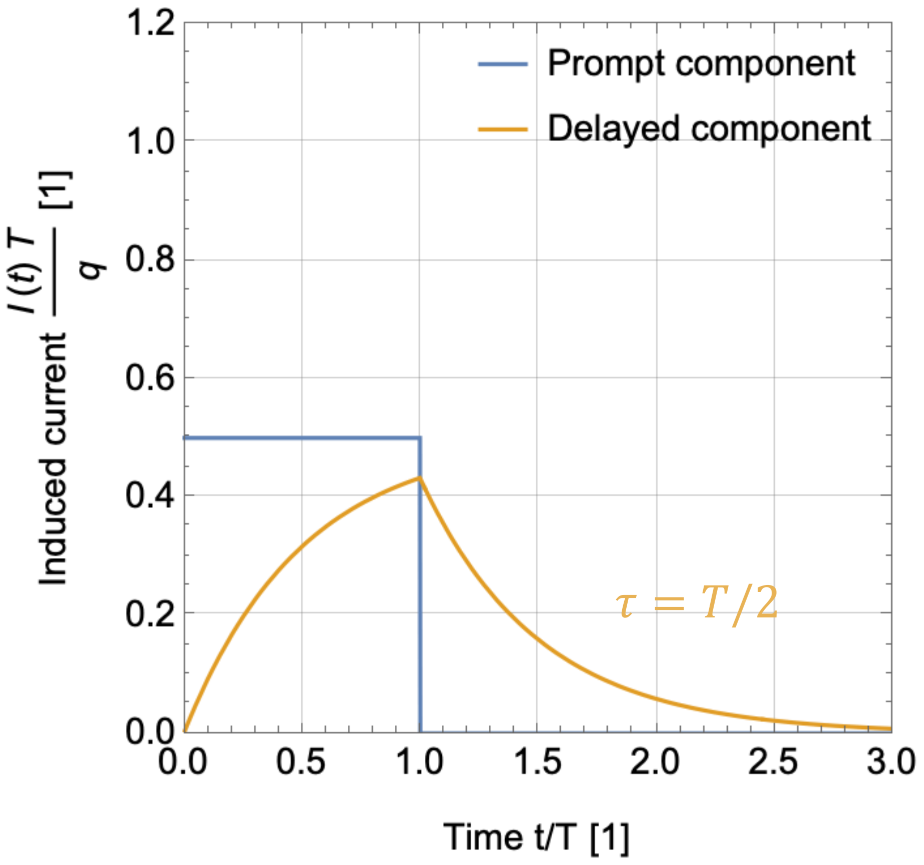
A charge q moves at a constant velocity through the gas gap before reaching the bulk resistive layer that separates it from the anode.



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

The dynamics is governed by the time constant:

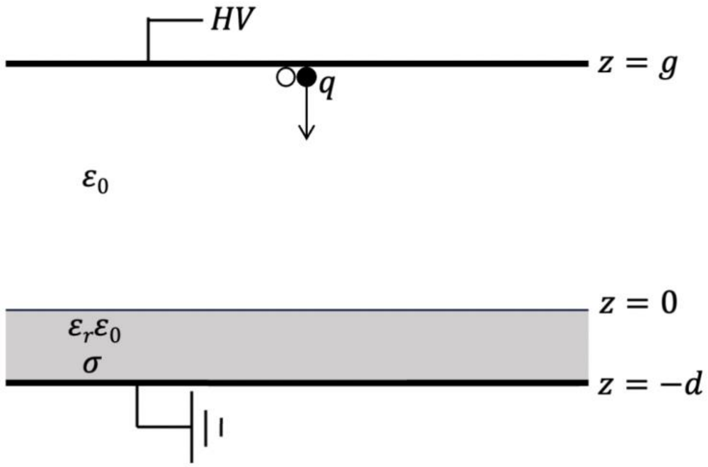
$$\tau := \frac{\varepsilon_0}{\sigma}\frac{d+\varepsilon_r g}{g}$$



W. Riegler, NIM-A 535 (2004) 287–293
Here we took $\epsilon_r = 1$.

Delayed component of the signal

Given the typically high volume resistivities of O(10⁹ - 10¹²) Ω·cm in RPCs, the delayed component is negligible.



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

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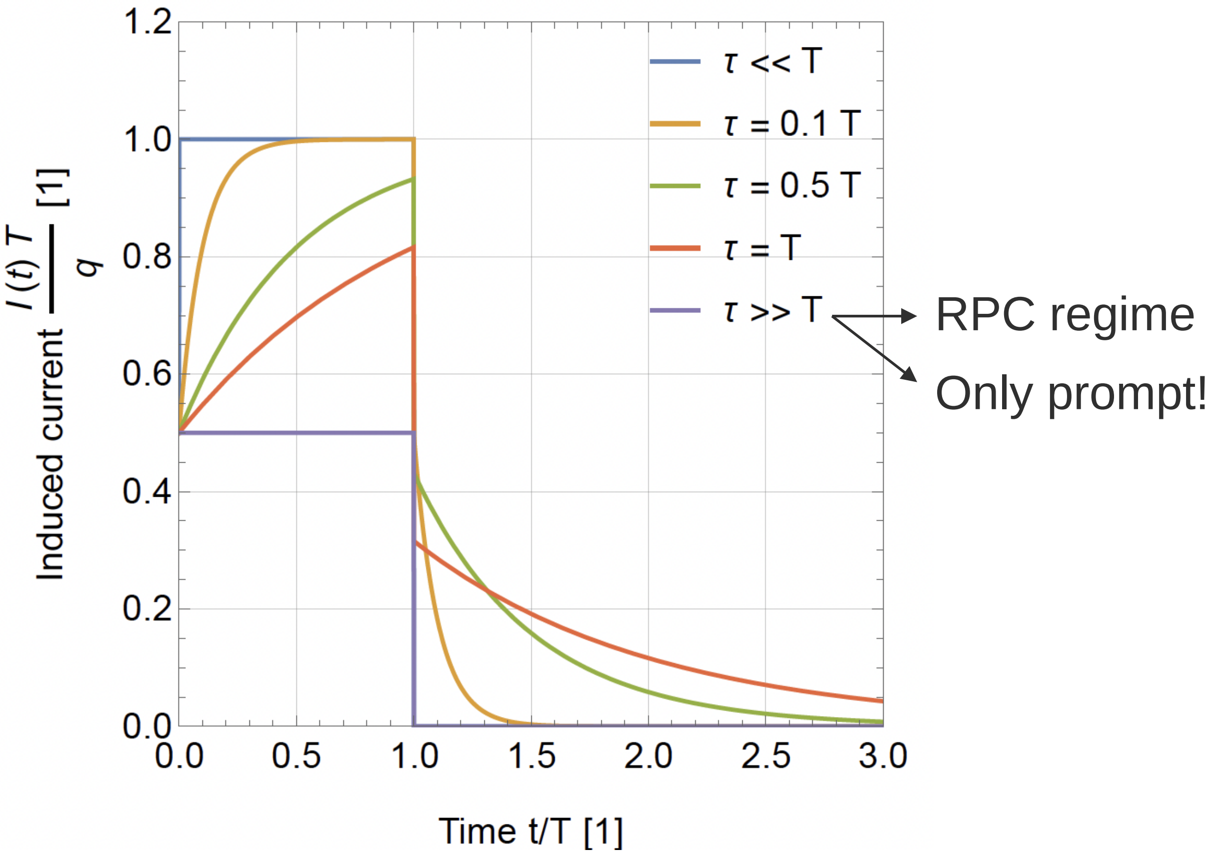
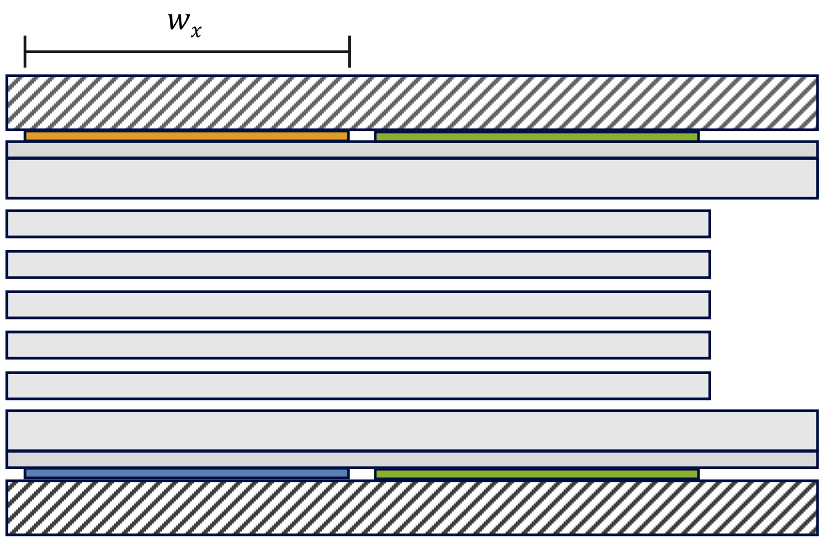


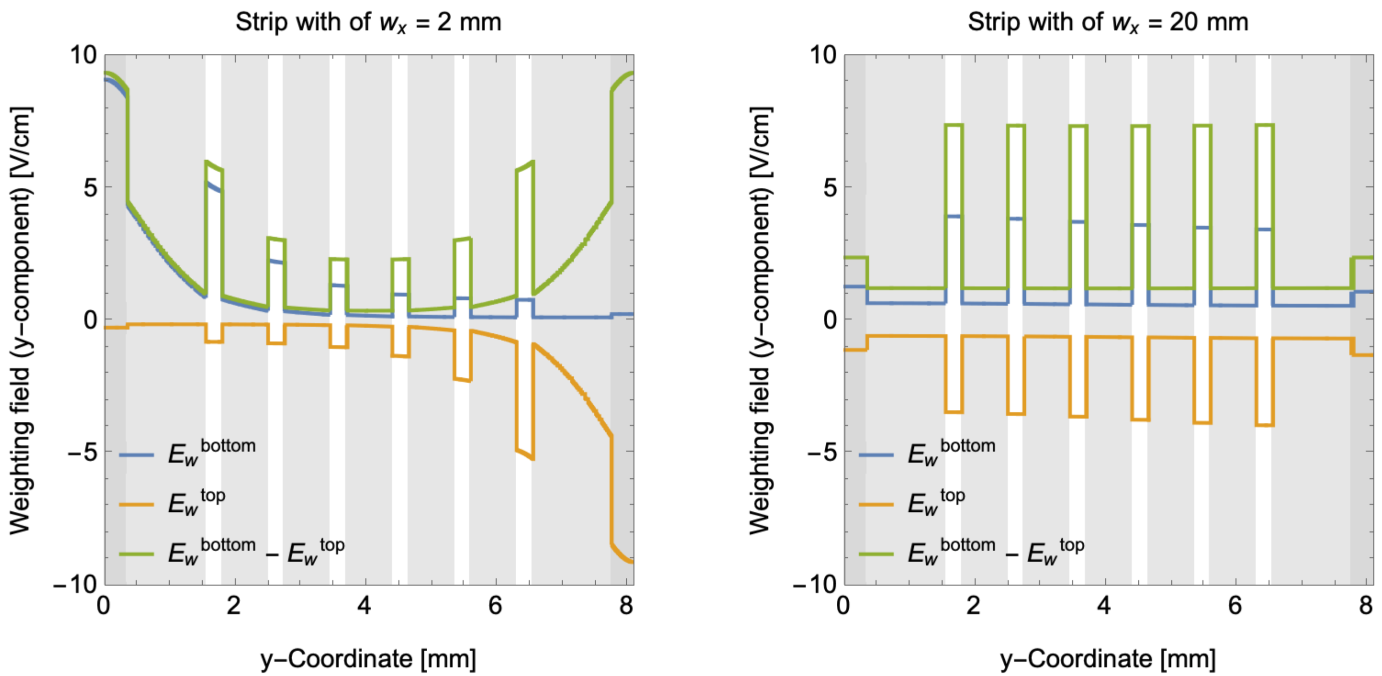
W. Riegler, NIM-A 535 (2004) 287–293
Here we took $\epsilon_r = 1$.

Weighting potentials of (M)RPCs

The analytical expression for the prompt weighting potential of rectangular electrodes within an N-layer geometry has been implemented in the new 'ComponentParallelPlate' class in Garfield++.

$$\psi^w(\tilde{x}', y_m) = \frac{2V_w}{\pi} \int_0^\infty \cos\left(k\left(\tilde{x} - \tilde{x}'\right)\right) \sin\left(\frac{k w_x}{2}\right) \frac{\varepsilon_1}{k^2} \left.\frac{\partial f_{m1}(k,y)}{\partial y}\right|_{(y=y_0)} dk$$



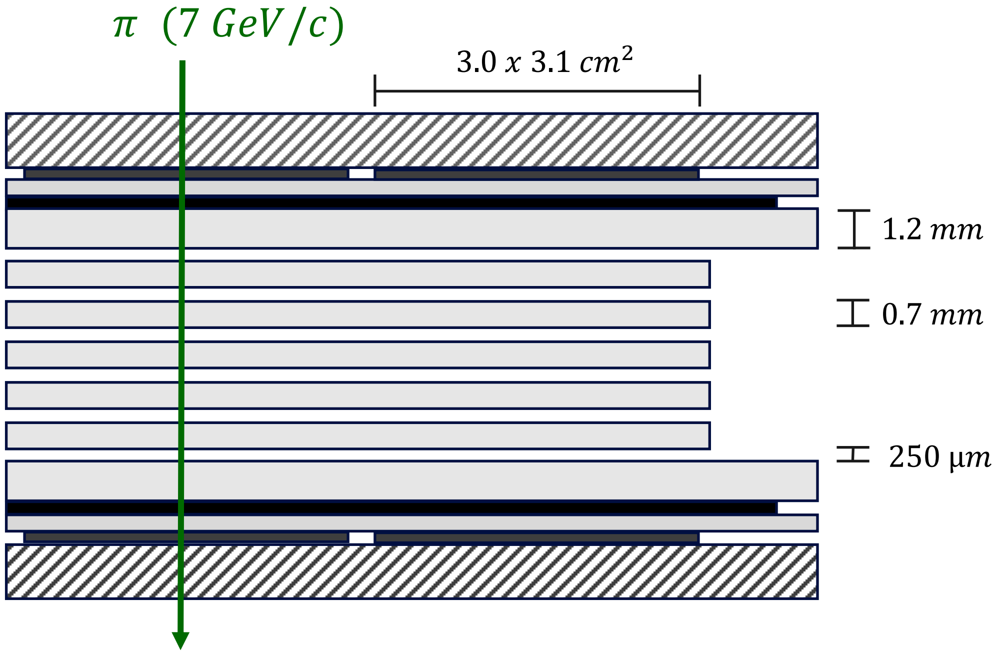


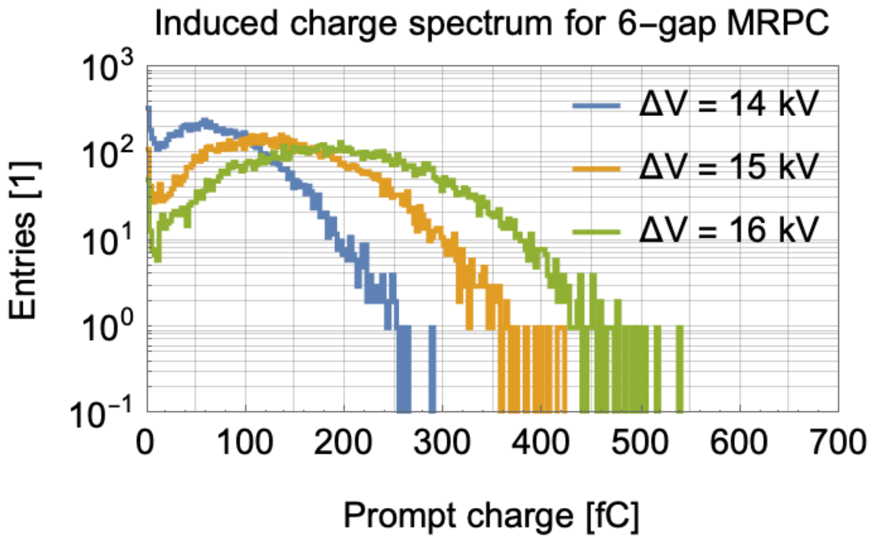
The function $f_{mn}(k,y)$ can be found in W. Riegler *JINST* 11 (2016) 11, P11002.

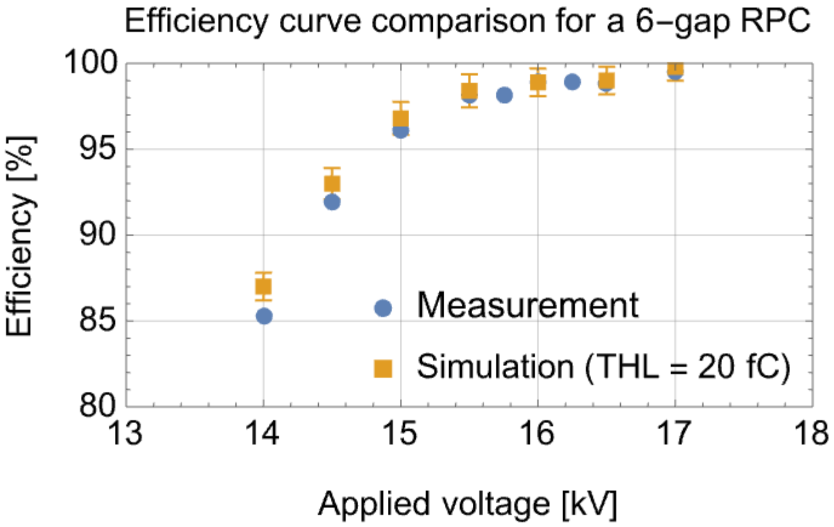
An example simulation of a 6-gap MRPC

Using the mixed-method approach, an event can be simulated in less then 0.3 s.

D. Stocco is extending this approach to the 2D model of C Lippmann. https://indi.to/c9hfk



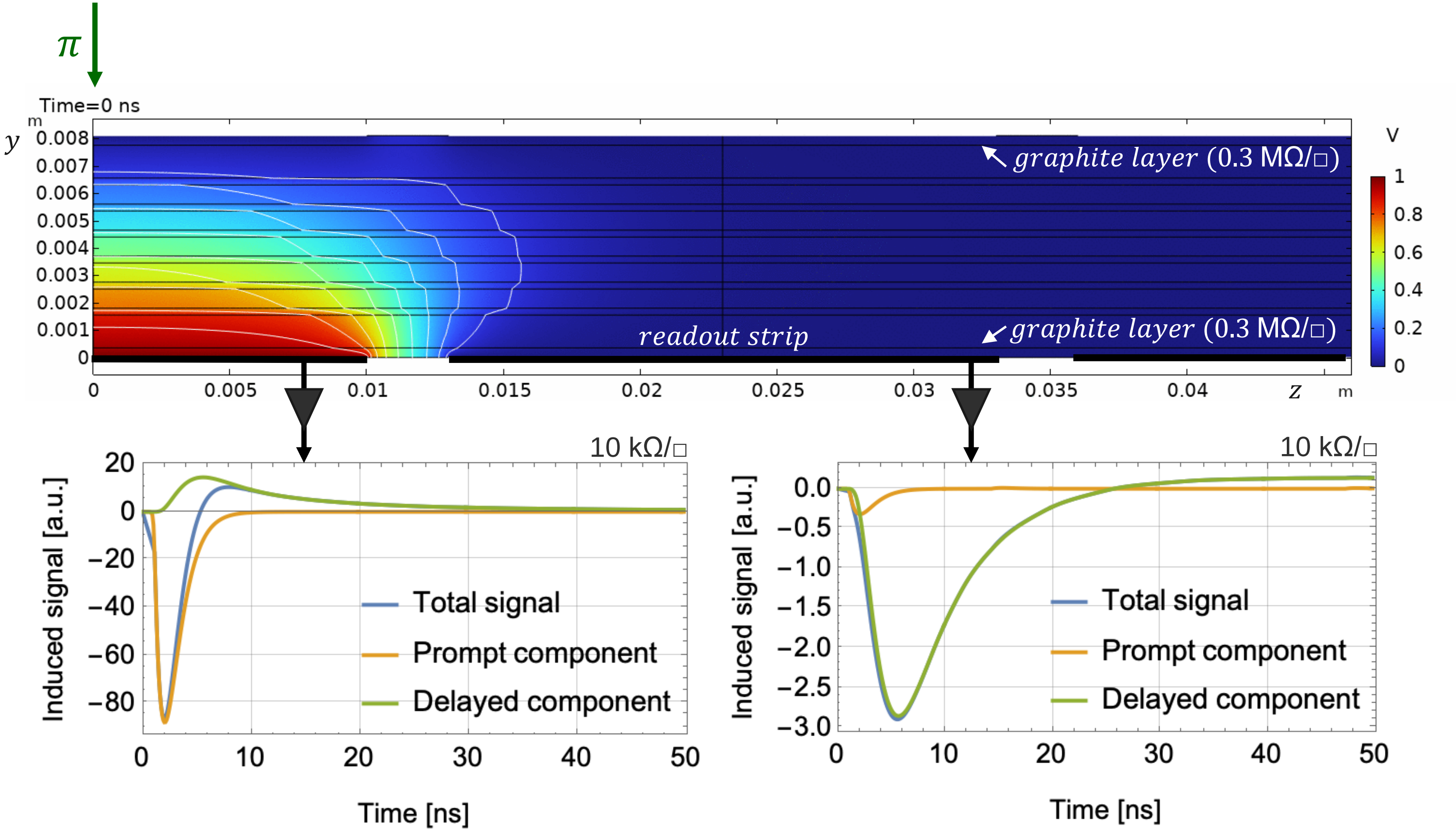


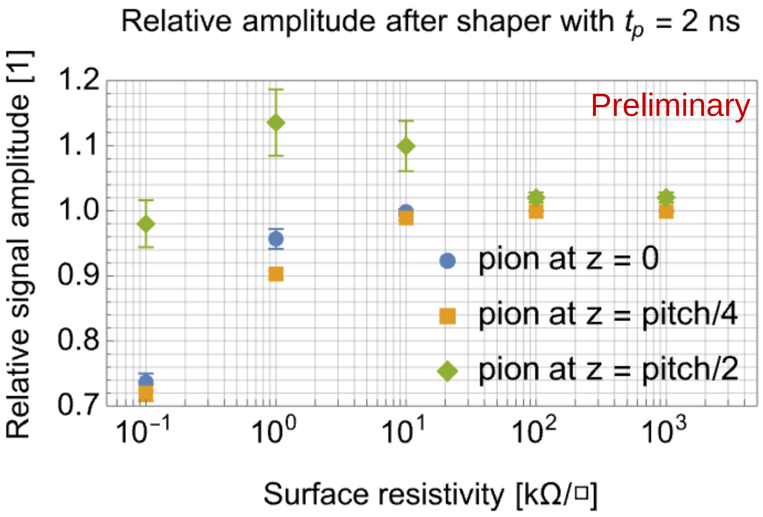


Measurements taken from M. Shao et al., NIM-A 492 (2002) 344–350.
Simulation performed for $iC_4H_{10}/SF_6/C_2H_2F_4$ (5/5/90%).

What about the resistive HV electrode?

The dynamic weighting potential was calculated using COMSOL and then applied in Garfield++ for induced signal calculations. For graphite layers with O(100 kΩ/□), the signal induced by electrons remains unaffected.





COMSOL Multiphysics: https://www.comsol.ch
Consistent with G. Battistoni et al., NIM in Physics Research 202 (1982) 459.

Garfield++ simulations of resistive particle detectors

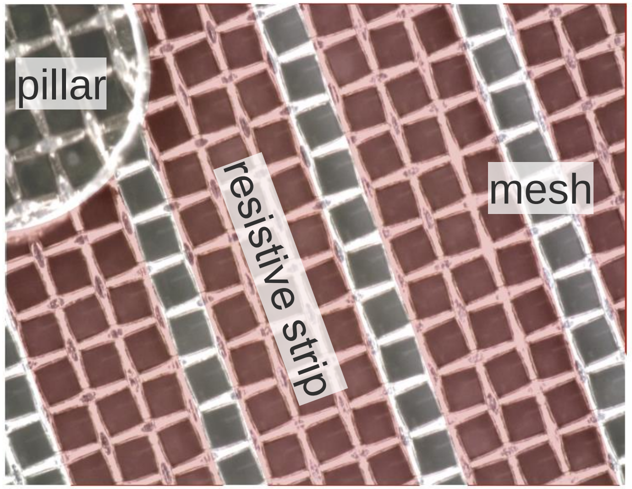
Using the finite element method, dynamic weighting potentials can be numerically obtained for a wide range of resistive detectors.

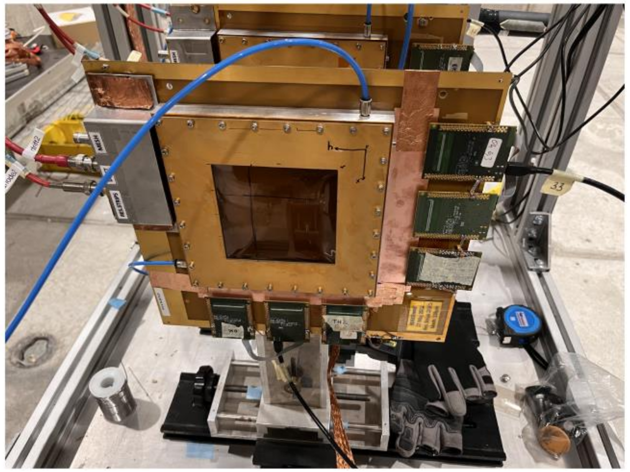
An (incomplete) list of resistive detectors:

- Multi-gap Resistive Plate Chambers (MRPC)
- Surface Resistive Plate Counter (sRPC)
- MicroCAT's two-dimensional interpolating readout
- μ-Resistive WELL
- μ-Resistive plate WELL
- Small-pad resistive Micromegas
- Resistive-strip bulk Micromegas
- Resistive PICOSEC Micromegas
- Un-depleted-silicon Sensors
- Resistive Silicon Detectors (RSD)
- 4D Diamond Sensor

RPC: MRPC, sRPC
MPGD: MicroCAT through Resistive PICOSEC Micromegas
Solid-state: Un-depleted-silicon Sensors, RSD, 4D Diamond Sensor

Resistive-strip bulk Micromegas





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

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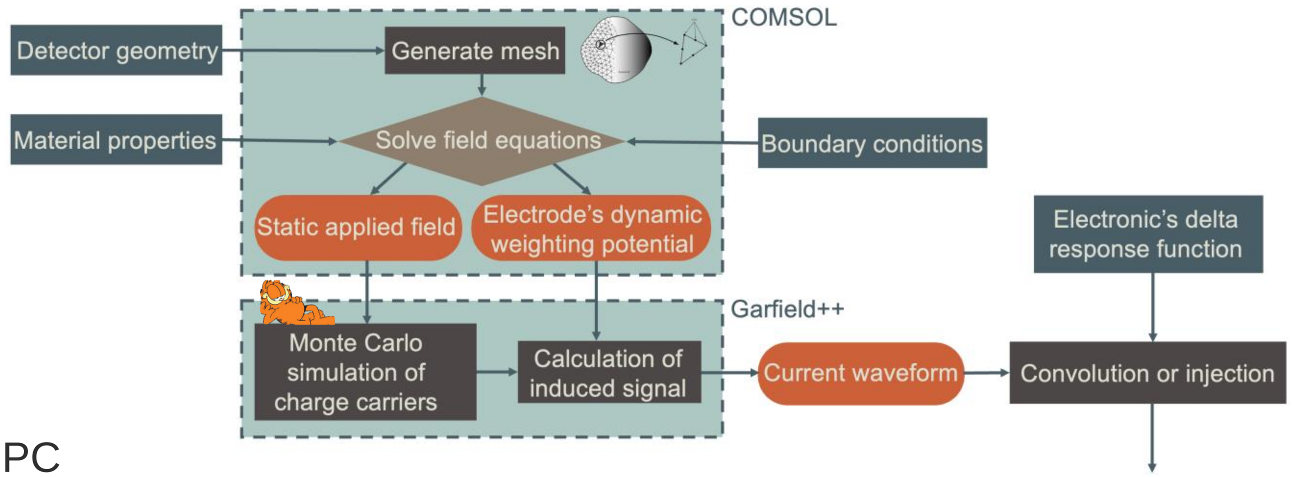

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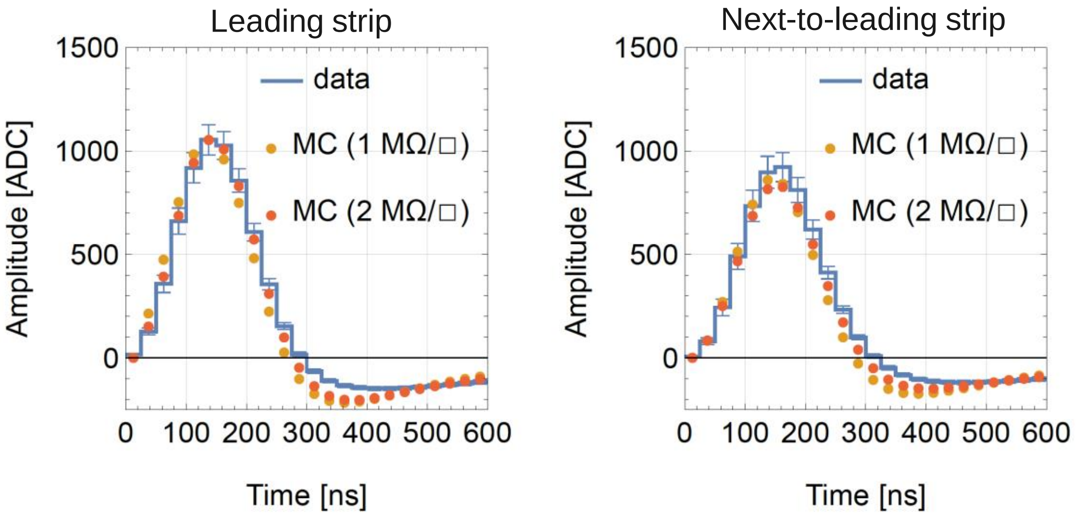
RPC: MRPC, sRPC
MPGD: MicroCAT's two-dimensional interpolating readout through Resistive PICOSEC Micromegas
Solid-state: Un-depleted-silicon Sensors, RSD, 4D Diamond Sensor



D. Janssens, Ph.D. thesis (2024), https://cds.cern.ch/record/2890572.

Conclusion

Using Garfield++, the MRPC response can be calculated from avalanche development to signal formation.

- For more efficient large-scale avalanche calculations, a mixed method is used: starting with microscopic electron tracking, followed by the Legler model.
- Garfield++ and COMSOL are used to model signal formation in detectors with resistive elements, applying an extended Ramo-Shockley theorem. A scan of different graphite layer surface resistivities showed results consistent with literature, confirming the prompt component's dominance.
- This approach applies to complex detector layouts in resistive gaseous detectors (RPCs, resistive MPGDs) and solid-state detectors.

Outlook:

- The grid-based method can be adapted for avalanche descriptions in SiPMs.
- A combined method will be implemented, using "super charges" that can be tracked microscopically.

Thank you for your attention!