DRD3 collaboration meeting

Simulating solid state detectors with Garfield++

Djunes Janssens and Heinrich Schindler

On behalf of all Garfield++ developers

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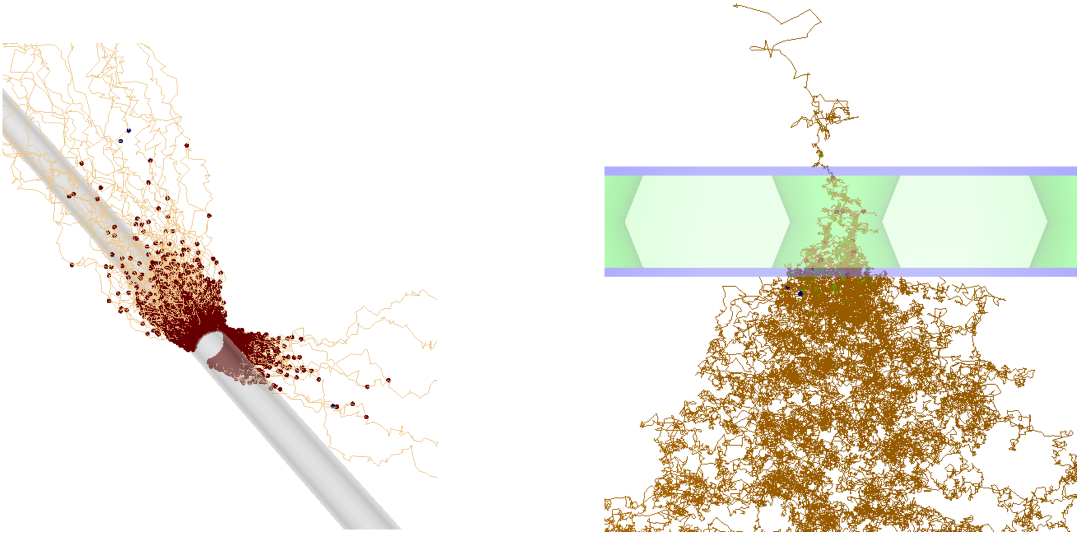
June 20th, 2024

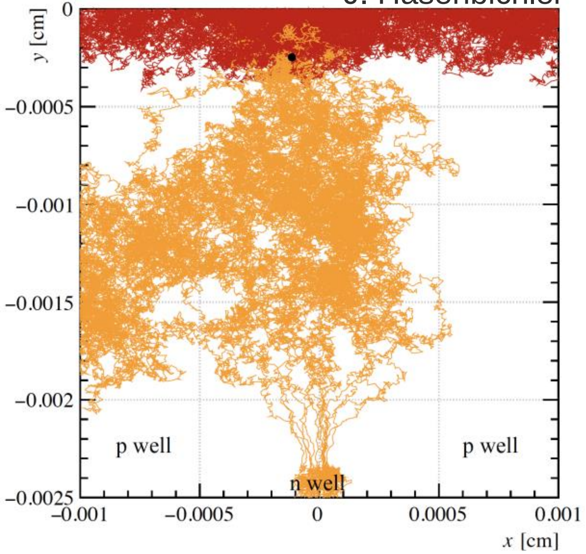
Introduction

Garfield++ is an open-source Monte Carlo toolkit developed for detailed simulations of particle detectors, utilizing ionization measurements in both gases and semiconductors.

It builds upon the foundation of the widely-used Fortran program Garfield (R. Veenhof), which has been extensively used for simulating gas-based detectors.



Microscopic simulation of electron avalanches in a GEM (left) and around a wire (right).



J. Hasenbichler

Drift lines from a Monolithic silicon sensors.

J. Hasenbichler, PhD thesis (2021): https://doi.org/10.34726/hss.2021.63185

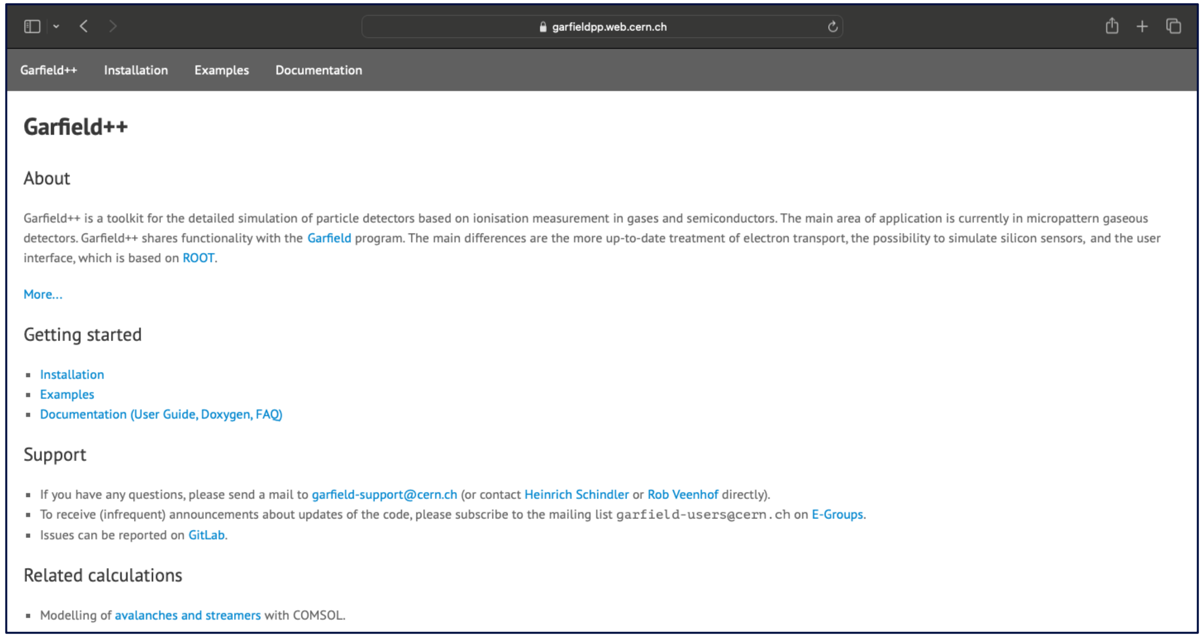
Introduction

The further development of Garfield++ is a community-driven undertaking, with new contributions to the main branch being reviewed by a small group of “maintainers”.

We will provide a brief overview of the simulation capabilities of this toolkit by covering some key examples.

<u>Outline:</u>

- Primary ionization
- Charge transport
- Signal induction
- Charge amplification (LGAD and SPAD)
- Time-dependent weighting potentials
- Summary



Garfield++

About

Garfield++ is a toolkit for the detailed simulation of particle detectors based on ionisation measurement in gases and semiconductors. The main area of application is currently in micropattern gaseous detectors. Garfield++ shares functionality with the Garfield program. The main differences are the more up-to-date treatment of electron transport, the possibility to simulate silicon sensors, and the user interface, which is based on ROOT.

More...

Getting started

- Installation
- Examples
- Documentation (User Guide, Doxygen, FAQ)

Support

- If you have any questions, please send a mail to garfield-support@cern.ch (or contact Heinrich Schindler or Rob Veenhof directly).
- To receive (infrequent) announcements about updates of the code, please subscribe to the mailing list `garfield-users@cern.ch` on E-Groups.
- Issues can be reported on GitLab.

Related calculations

- Modelling of avalanches and streamers with COMSOL.

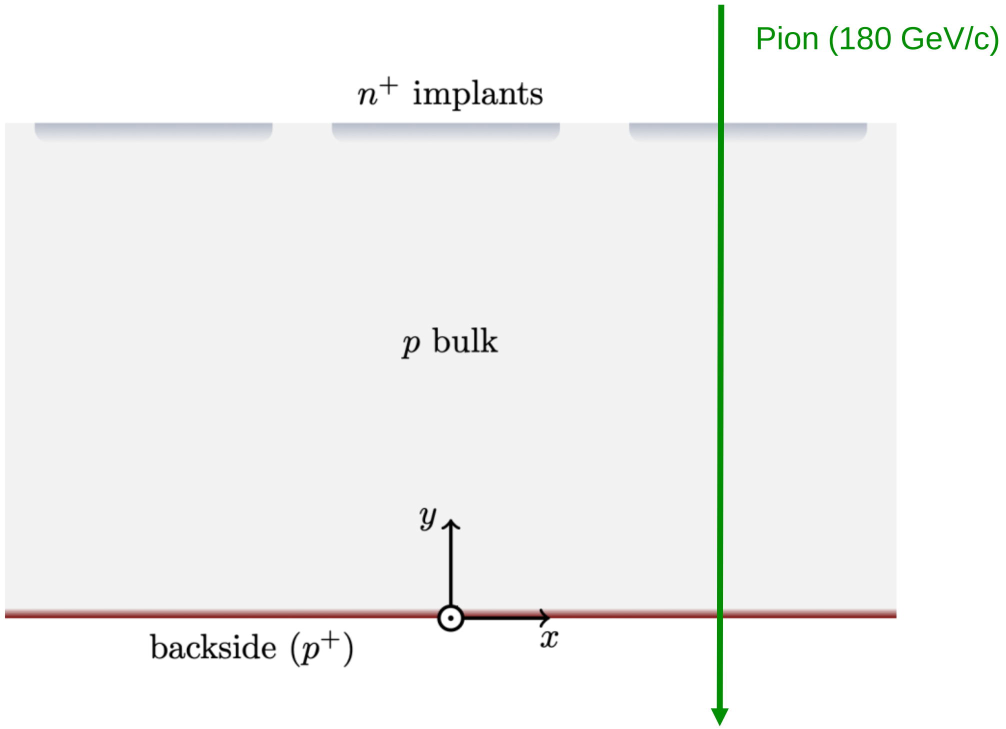
Garfield++ webpage: https://garfieldpp.web.cern.ch/garfieldpp/

GitLab: https://gitlab.cern.ch/garfield/garfieldpp
User guide: https://garfieldpp.web.cern.ch/documentation/UserGuide.pdf

Primary ionization

The primary ionization pattern resulting from the energy transfer from the incident particle to the sensitive medium can be simulated using Garfield++ for:

- **Charged relativistic** particle using the interface with Heed, based on an extended version of the PAI model.



I. Smirnov, Heed-C++: http://ismirnov.web.cern.ch/ismirnov/heed.

Primary ionization

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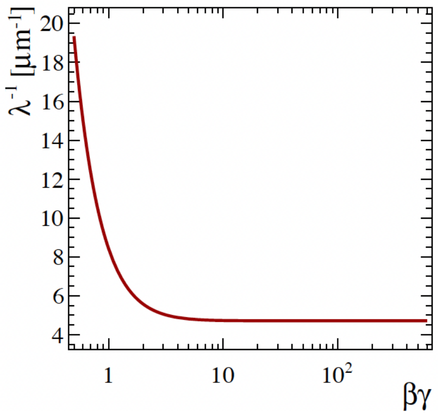
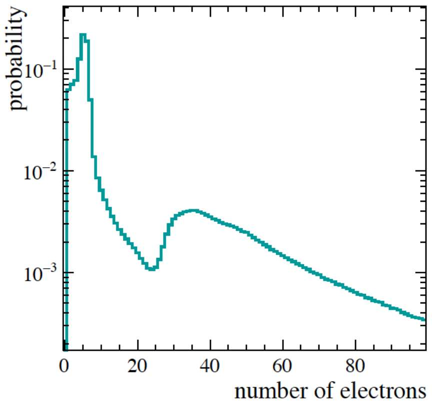
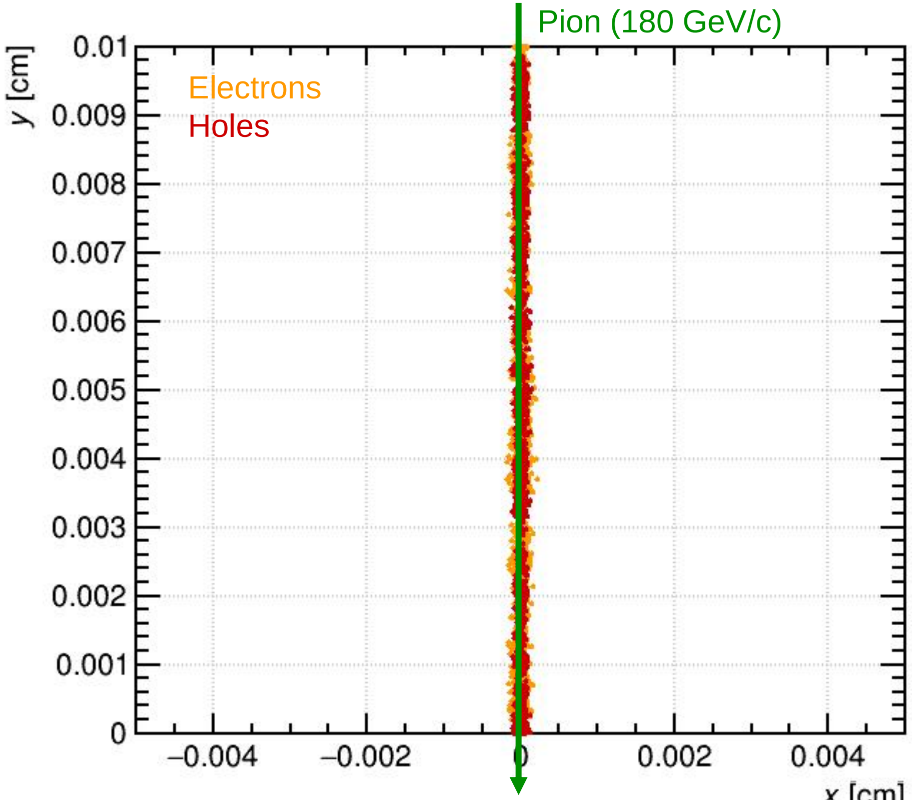
- **Charged relativistic** particle using the interface with Heed, based on an extended version of the PAI model.
- **X-Ray** photoabsorption using the interface with Heed.
- **Ion track** using simulation imported results from Srim or Trim.
- **Other** from a possible interface with GEANT4

Inverse mean free path



Simulated charge deposition spectrum



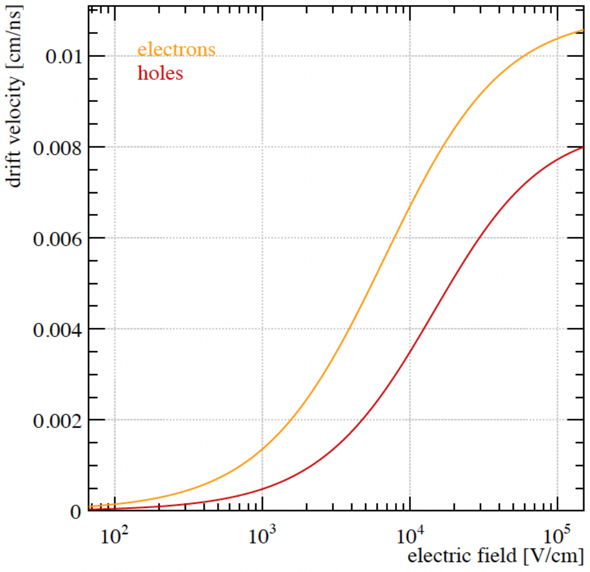


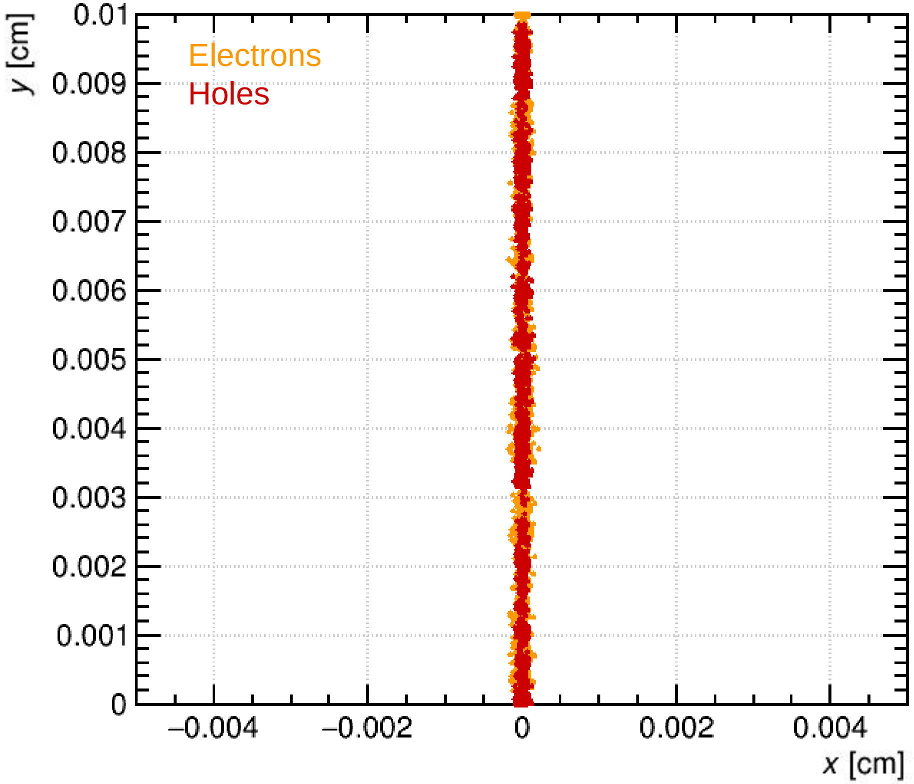
I. Smirnov, Heed-C++: http://ismirnov.web.cern.ch/ismirnov/heed.
W W M Allison and J H Cobb Ann. Rev. Nucl. Part. Sci. 30: 253-95 (1980).
D. Pfeiffer et al, NIM A 935 (2019), 121.

Charge transport

A typical approach for silicon is to simulate the drift lines of individual electrons and holes using a Monte Carlo technique based on macroscopic transport parameters.

- Canali high-field mobility model (drift velocity silicon)
- Other models and materials other than silicon are also available
- (Synopsys Sentaurus) TCAD transport data can be imported





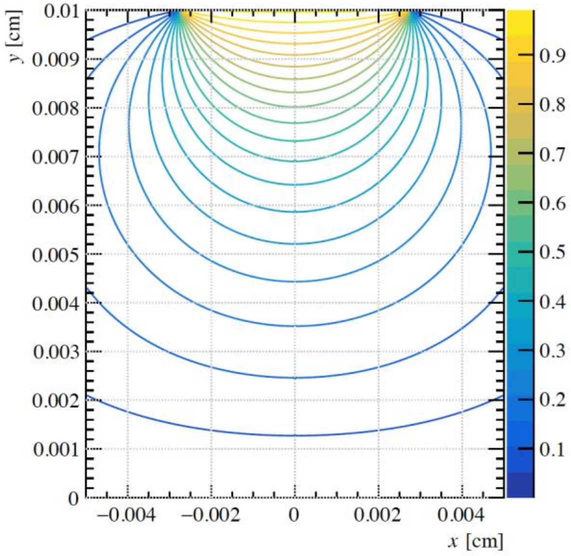
Importing TCAD field maps: https://garfieldpp.web.cern.ch/garfieldpp/examples/tcad/

Signal induction

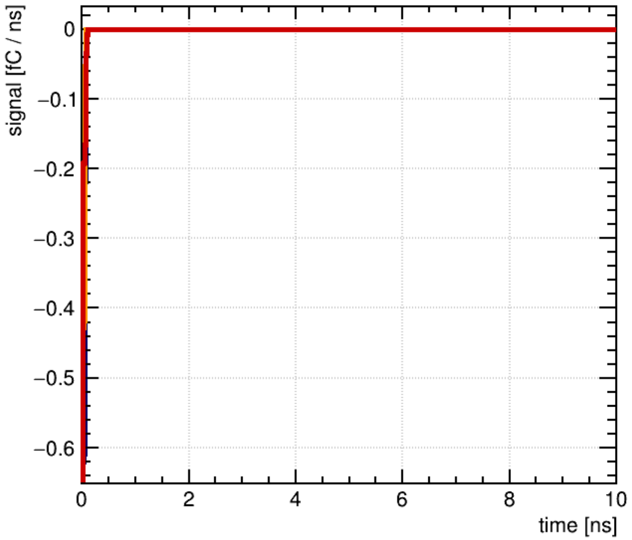
The Ramo-Shockley theorem is used to induce signals on readout electrodes by charge movement. Weighting potentials are calculated using built-in analytical solutions or numerically via FEM solvers.

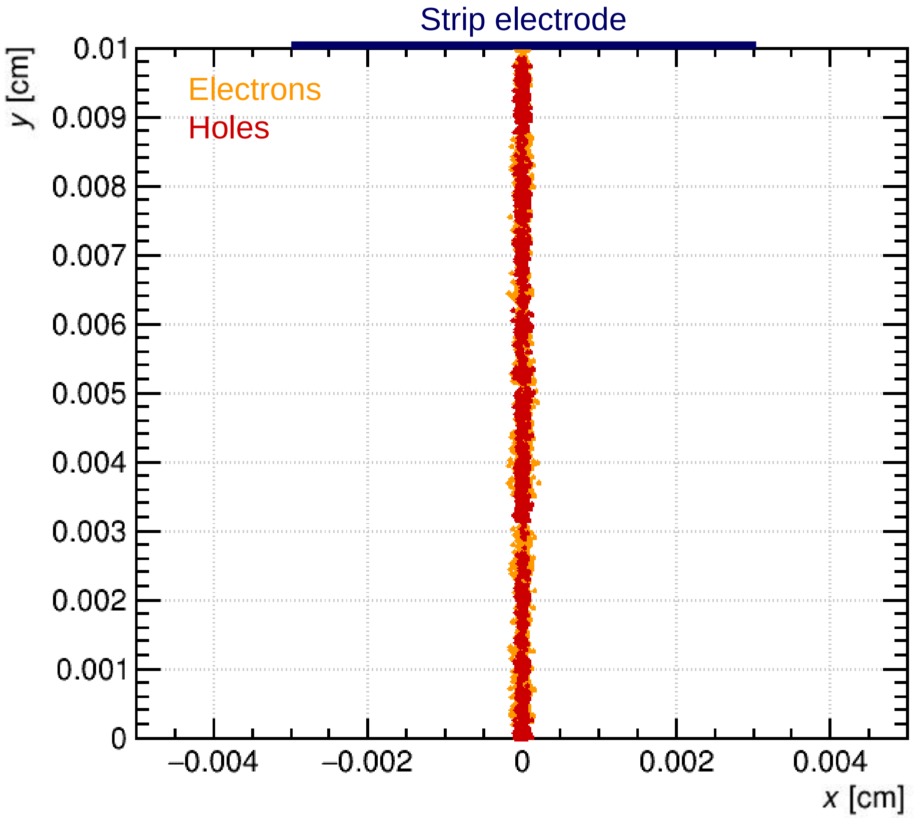
$$I_i(t) = -\frac{q}{V_w}\mathbf{E}_i(\mathbf{x}_q(t)) \cdot \dot{\mathbf{x}}_q(t), \qquad \mathbf{E}_i(\mathbf{x}) = -\nabla\Psi_i(\mathbf{x})$$

Weighting potential $\psi_i(\boldsymbol{x})$ of strip electrode



Signal $I_i(t)$ induced on strip electrode





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

Garfield++ example: https://gitlab.cern.ch/garfield/garfieldpp/-/tree/master/Examples/Silicon?ref_type=heads.

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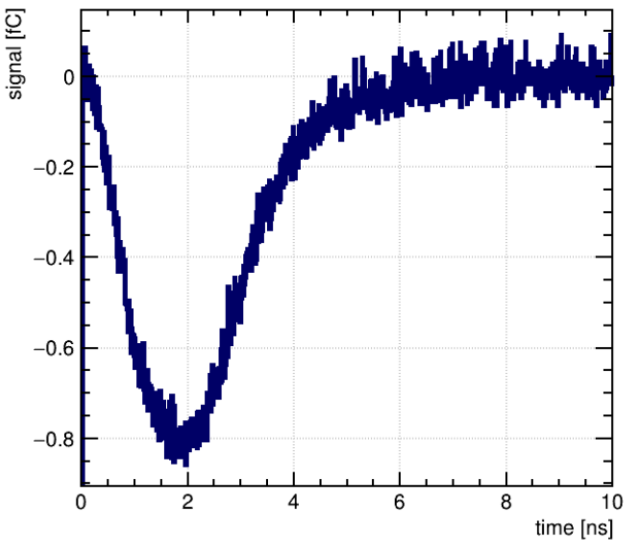
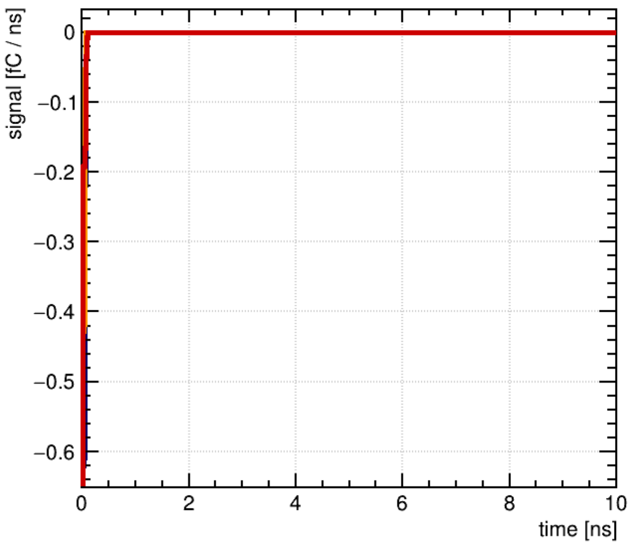
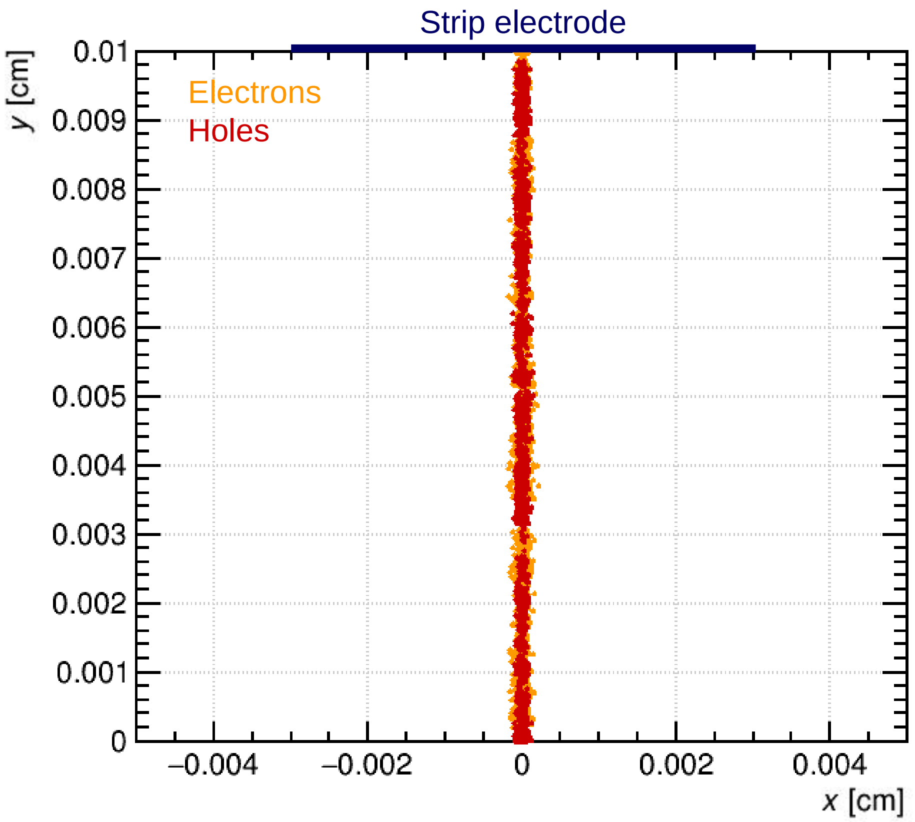
Noisy signal after front-end



Signal $I_i(t)$ induced on strip electrode





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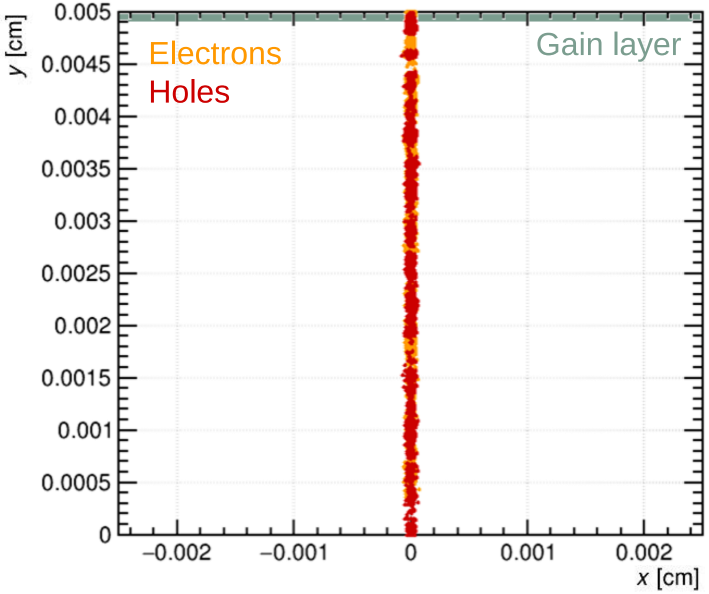
Garfield++ example: https://gitlab.cern.ch/garfield/garfieldpp/-/tree/master/Examples/Silicon?ref_type=heads.

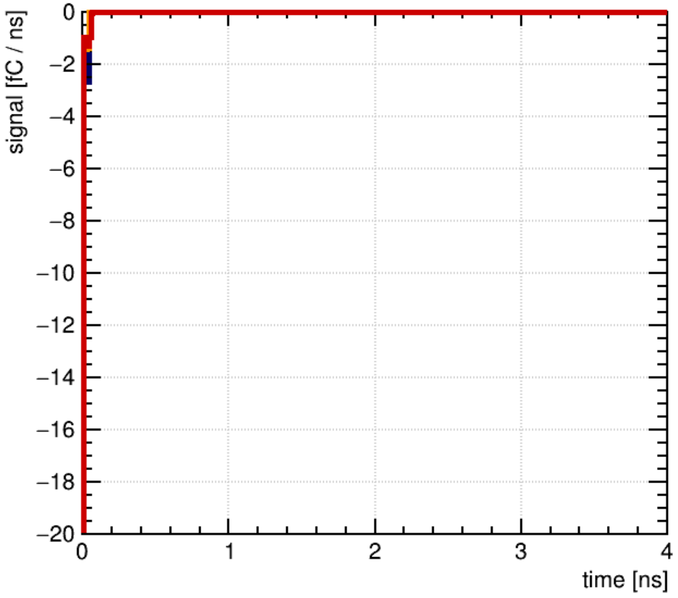
Charge amplification (LGAD)

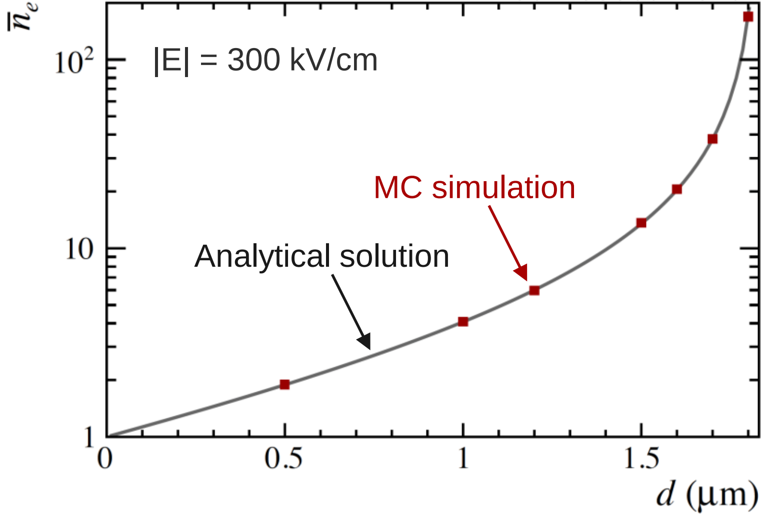
To simulate the development of an avalanche in high-field regions inside the sensor, such as a highly doped p+-type layer in an LGAD, one can:

- Use the Van Overstraeten - de Man model (for impact ionisation coefficient silicon)
- import a map of transport data from TCAD

180 GeV/c pion event







F. Carnesecchi et al.

R. J. McIntyre, IEEE Transactions on Electron Devices ED-13 (1) (1966) 164-168.

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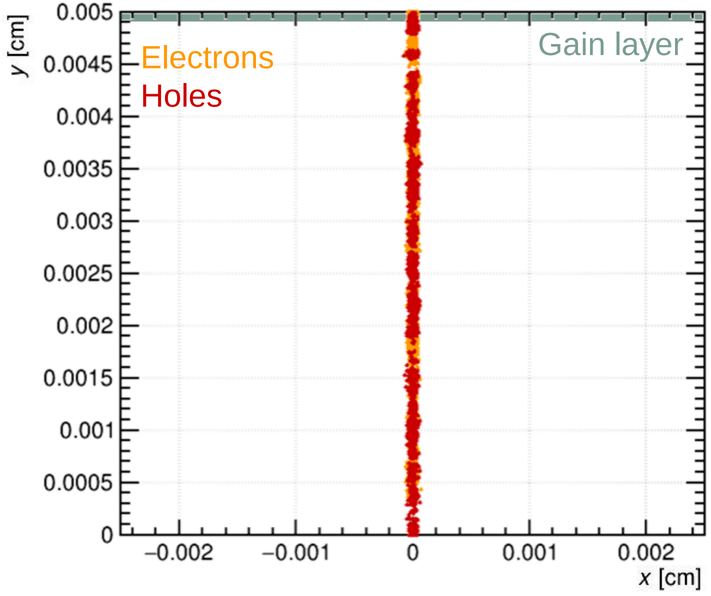
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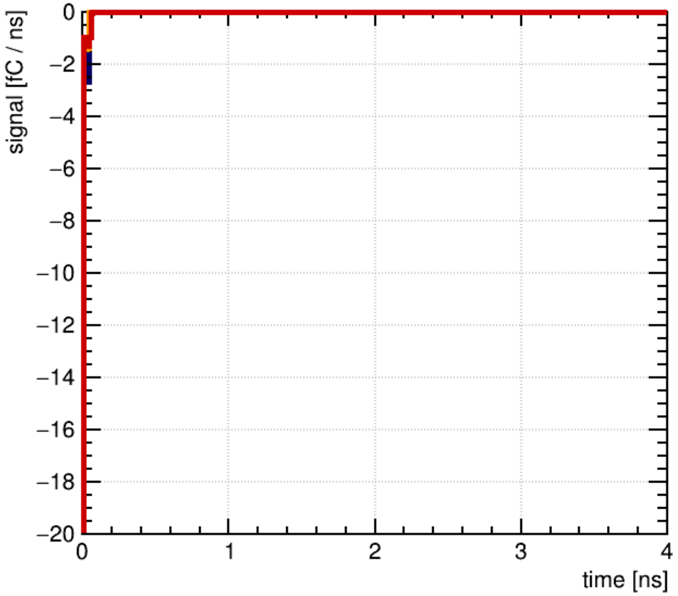
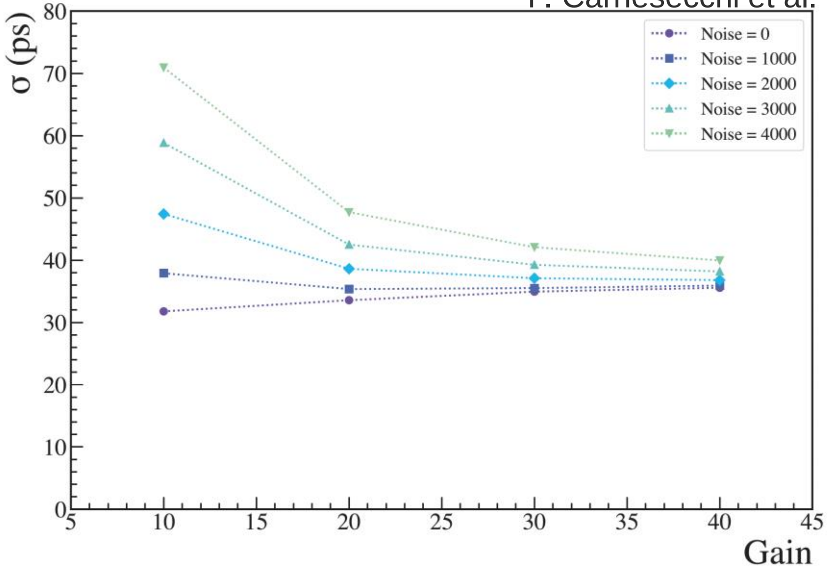

Induced signal on pad

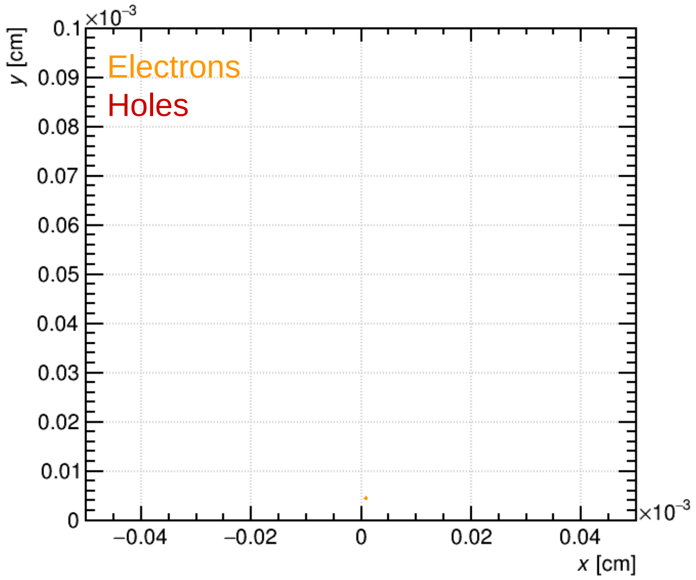

F. Carnesecchi et al.

Charge amplification (SPAD)

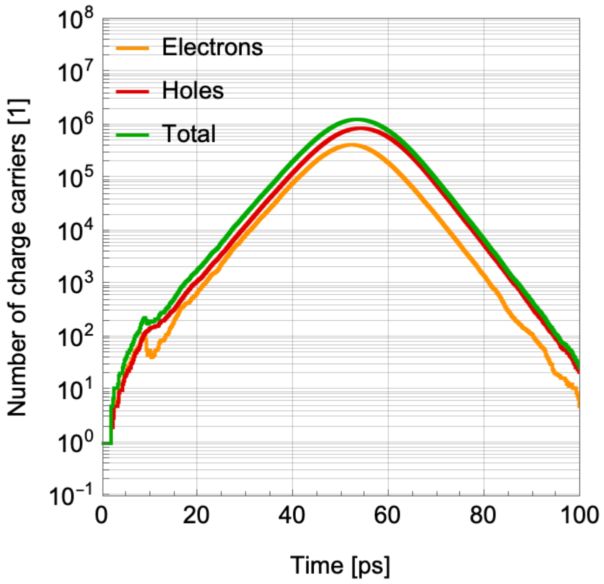
For SPADs Garfield++ can accurately capture the initial growth of the avalanche. However, there are two key mechanism to describe the later-time dynamics:

- **Field reduction:** Due to bias voltage drop from the quenching resistor. Work in progress!
- **Space-Charge effects:** Due to electrons and holes causing time-dependent field modifications. Ongoing efforts in DRD1 WG4 for MPGDs and (M)RPCs.

Simulated avalanche without quenching



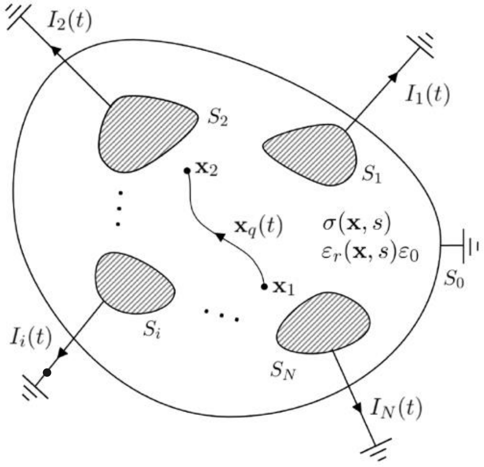
Simulated avalanche with quenching

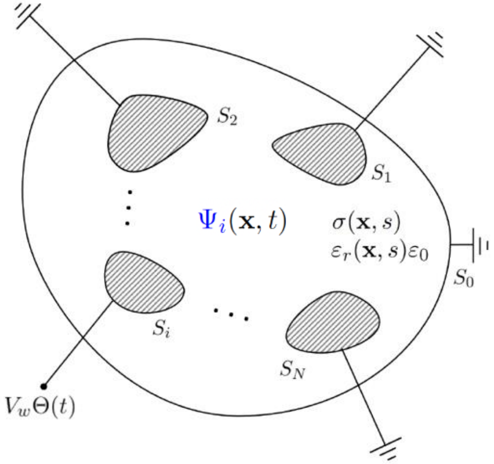


DRD1 WG4 topical meeting on large avalanches: https://indi.to/9TWnL

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:

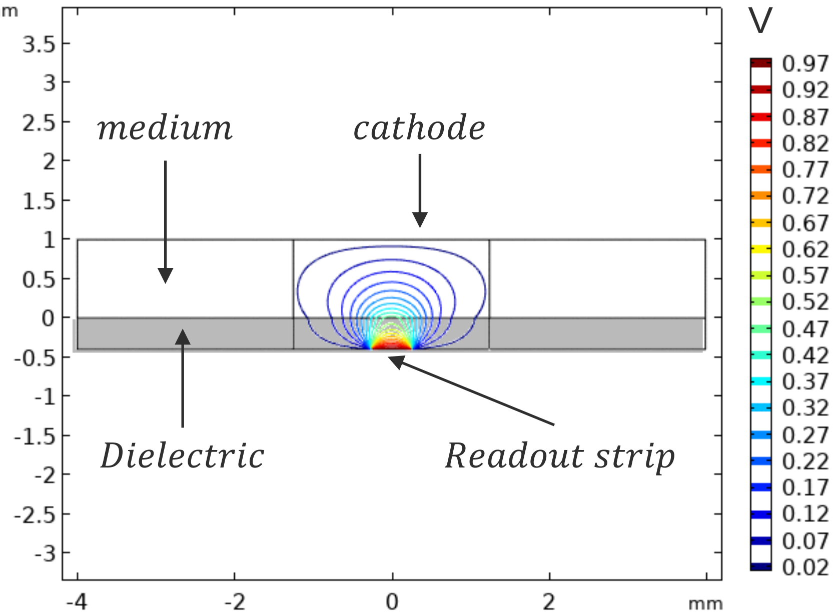
1. Remove the all the drifting charges.
2. Apply the biasing voltage V_b to obtain $\psi_b(\mathbf{x})$.
3. Apply an additional voltage pulls $V_w\Theta(t)$ to the electrode at time $t = 0$, where $V_w \ll V_b$. The resulting potential is given by $\psi(\mathbf{x}, t) = \psi_i(\mathbf{x}, t) + \psi_b(\mathbf{x})$.
4. Obtaining the weighting potential is thus: $\psi_i(\mathbf{x}, t) = \psi(\mathbf{x}, t) - \psi_b(\mathbf{x})$.

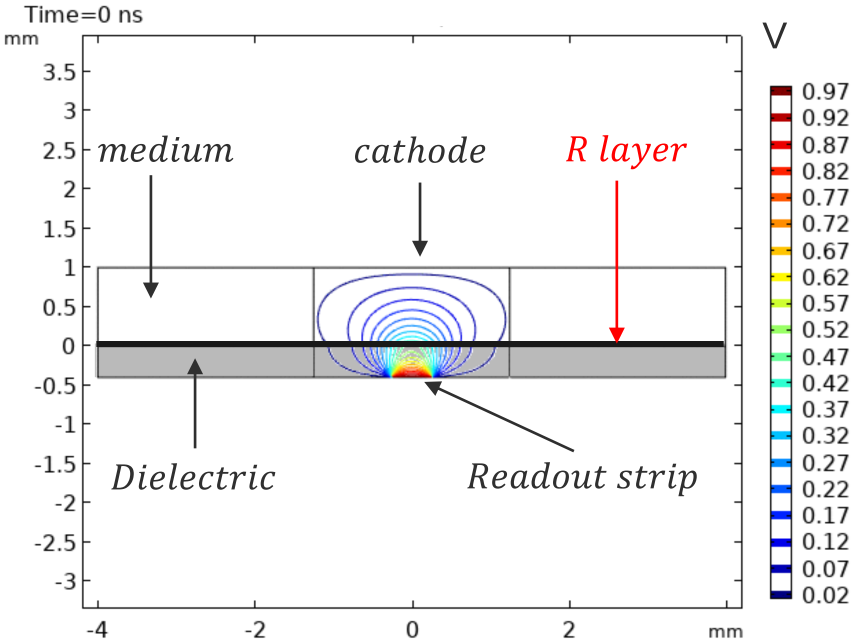
E. Gatti et al., Nucl. Instrum. Meth. in Physics Research 193 (1982) 651.
W. Riegler, Nucl. Instrum. Meth. A 535 (2004), 287-293.
W. Riegler, Nucl. Instrum. Meth. A 940 (2019) 453-461.

Ramo-Shockley theorem extension for conducting media

The time-dependent weighting potential captures signal dynamics from resistive elements. This can be obtained analytically for limited geometries; hence, a numerical approach was developed using FEM solvers:

- **COMSOL:** Implemented and verified against experimental data.
- **TCAD**: Implemented, but this still needs to be tested in more detail.

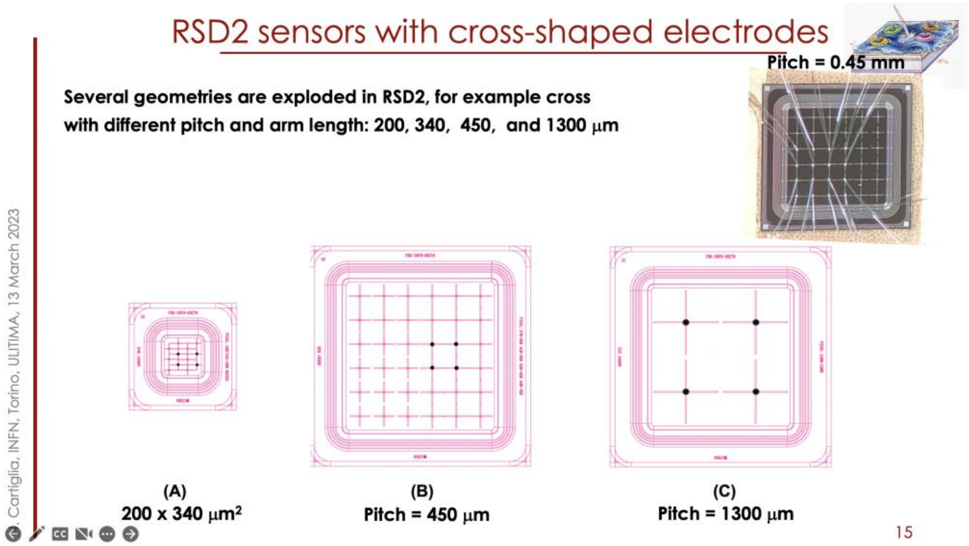




D. Janssens, Ph.D. thesis (2024), https://cds.cern.ch/record/2890572.
Garfield++ TCAD example: https://gitlab.cern.ch/garfield/garfieldpp/-/tree/master/Examples/TcadDelayed?ref_type=heads.

AC-LGAD or Resistive Silicon Detector

Using COMSOL, the weighting potential of cross-shaped electrodes in a Resistive Silicon Detector (RSD) was calculated. This is passed to Garfield++ for the Monte Carlo simulation.



RSD2 sensors with cross-shaped electrodes

Pitch = 0.45 mm

Several geometries are exploded in RSD2, for example cross with different pitch and arm length: 200, 340, 450, and 1300 μm

(A) **200 x 340 μm^2**

(B) **Pitch = 450 μm**

(C) **Pitch = 1300 μm**

Cartiglia, INFN, Torino, ULITIMA, 13 March 2023

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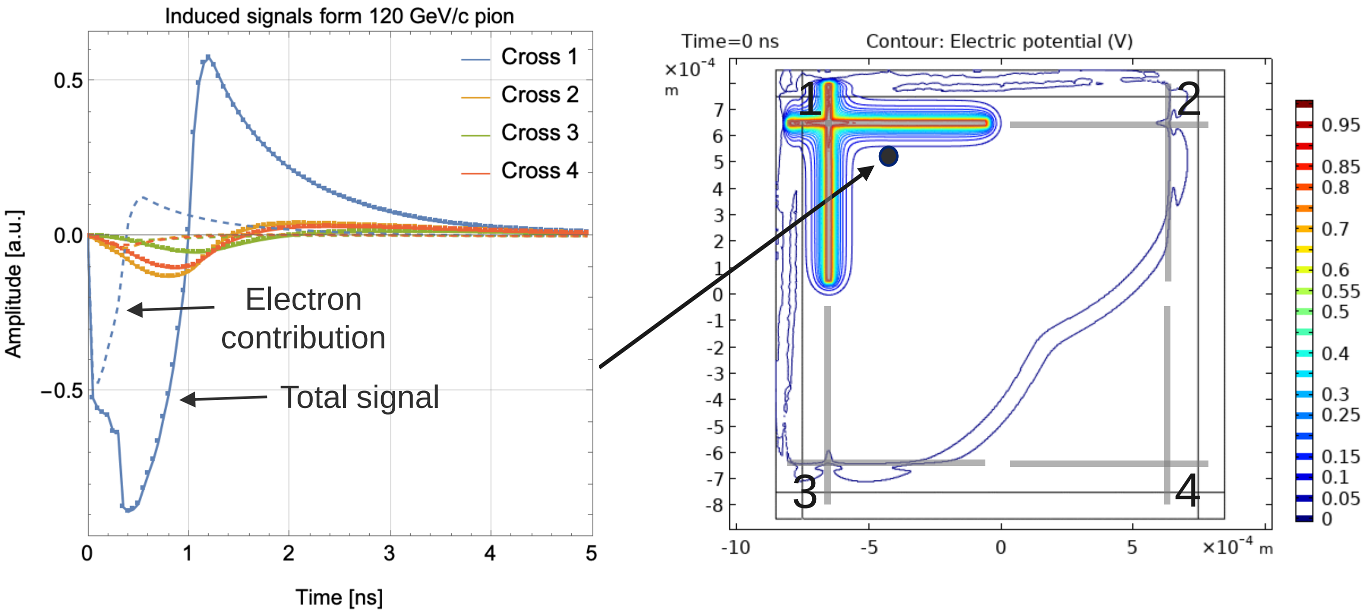
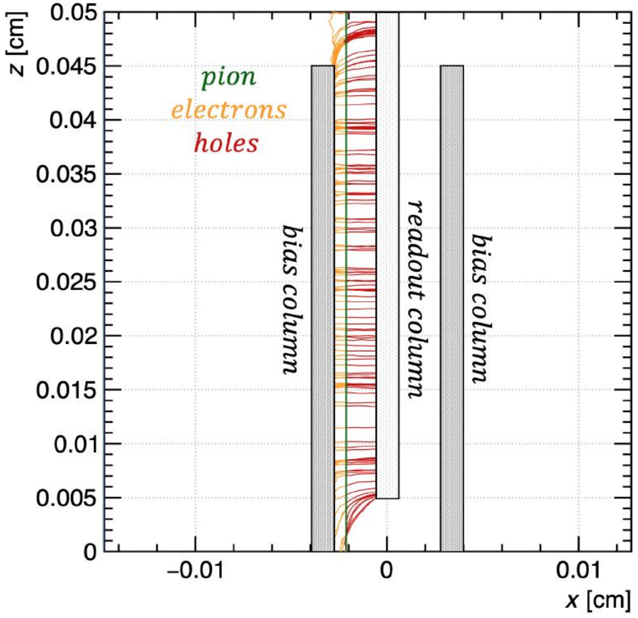
Slide borrowed form N. Cartiglia: ULITIMA 2023.

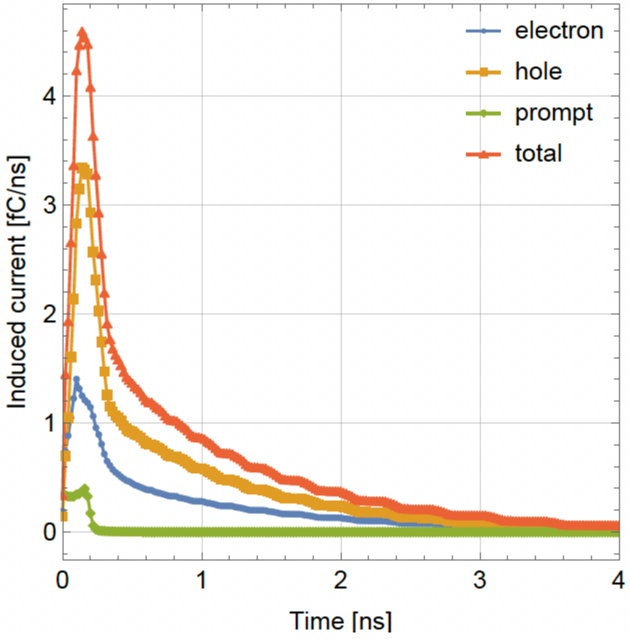
Preliminary simulated response

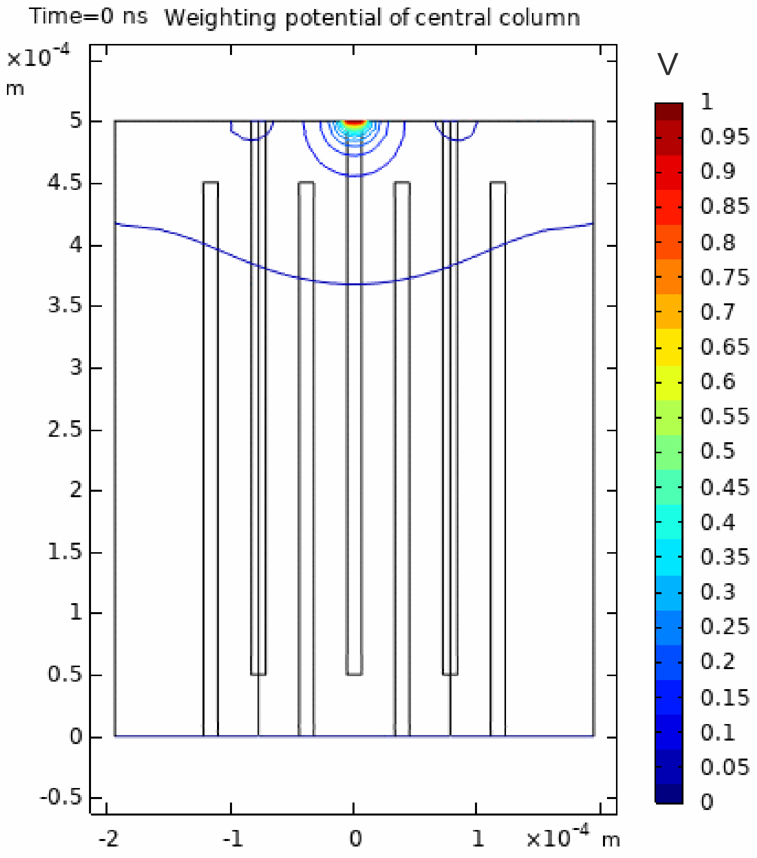


3D Diamond sensor

In contrast to its silicon counterpart, the 3D electrode structure is achieved by inducing a local phase transition in the diamond, resulting in graphitic pillar electrodes that have a finite conductivity.







Thanks to the fruitful discussions with the TIMESPOT collaboration.

Summary

Garfield++ is an object-oriented toolkit designed for detailed simulations of particle detectors, using ionization measurements in gases and semiconductors.

- **Primary interaction:** Interfaces with Heed to generate initial coordinates for electron-hole pairs from charged particles crossing the sensor.
- **Electric field setup:** Electric fields can be set using built-in functions or imported from FEM solvers, such as TCAD.
- **Drift and ionization simulation:** Includes built-in models for simulating drift lines and impact ionization for electrons and holes. Alternatively, relevant parameters can be sourced from TCAD.
- **Signal induction:** For sensors with regions of finite conductivity (e.g., AC-LGADs), the time-dependent weighting potential can be used for an accurate description of the signal induction process.

Thank you for your attention!