Detector Simulation in Garfield++ with Open-Source Finite Element Electrostatics

Gaseous detector hands on session

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Requirements:

- **An active google account to access the Colab notebook used during the session.**
- **The activities will require some basic Python programming.**

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Introduction

Gaseous radiation detectors are used in a variety of fields ranging from nuclear and high-energy physics to dosimetry, medical instrumentation and cultural heritage studies. They rely on the interaction of incident radiation with gas, which is used as the active detection medium. Due to the low density of gas, the number of primary electron-ion pairs created in the initial interaction is low and often not sufficient for direct detection. Signal amplification by charge multiplication in the gas may be used to significantly increase the number of charges and thus permit the detection of incident radiation.

In the field of gaseous detectors and in particular of proportional counters (output signal proportional to the energy released by the radiation in the medium) a special role is played by Multi Wire Proportional Chambers (MWPC). They were invented by Georges Charpak in 1968, while at the European Organization for Nuclear Research (CERN). MWPC opened the possibility in High Energy Physics experiments to produce electronic signals, acquire, store and process them via computers, opening the roadmap to the current experiments. This invention resulted in Charpak winning the Nobel Prize for Physics in 1992.

At the end of the eighties and nineties, thanks to the development of printed circuit board (PCB) manufacturing techniques, the family of gaseous detectors was enriched by the introduction and development of Micro Pattern Gas Detectors (MPGDs). Starting with Micro Strip Gas Chambers (MSGCs), several developments followed: Gaseous Electron Multipliers (GEMs), Micro Mesh Gaseous Structures (Micromegas), micro-resistive well (μRWELL) detectors, to name but a few. Many of these technologies are already employed in fundamental research and other sectors of science. At CERN, major upgrade projects of the ATLAS, ALICE and CMS experiments are currently installing GEMs and Micromegas instrumenting large areas with these technologies.

These technologies are characterized by micrometric structures that can offer large amplification factors, good resolution in terms of energy, space and time, high rate capabilities, radiation hardness and reduced aging, and large area coverage.

Proper understanding of the physics behind these technologies has been achieved thanks to a continuous improvement of modelling and simulation tools. This laboratory session will give the possibility to work with one of the most commonly used frameworks: Garfield.

Detector physics, simulations and software tools

With the increase in complexity of novel instrumentation, fast and accurate detector-physics simulation activities have gained considerable importance. Among several developments, one of the most successful is Garfield. Developed by Rob Veenhof many years ago and continuously updated, Garfield represents a unique software package for microscopic modelling of detector response. Garfield, together with HEED, Degrad and Magboltz, represents the core of gaseous detectors and in particular of MPGDs simulation tools.

In most of the new MPGD R&D projects, the suggested concepts are corroborated by these simulation studies; they permit better understanding of the operation mechanisms and expected detector performances. Simulating MPGDs requires an integrated approach of field calculations

and charged particle transport, since the field changes substantially over the free path between collisions.

Significant efforts were also devoted towards modelling of MPGD performances for particular applications; e.g. studies of electron losses in MM with different mesh specifications for the ATLAS NSW, and GEM electron transparency, charging-up and ion-backflow processes for the ALICE TPC upgrades, and their comparison with experimental data.

Garfield

Rob Veenhof started developing Garfield in 1984 as a drift-chamber simulation program. Garfield is based on the following operating principles:

1. Charged particles or photons ionise molecules when they pass through the gas.
2. Electric field in the gas volume transports the ionisation electrons and ions.
3. Electrons multiply in high field areas.
4. Moving electrons and ions induce currents in electrodes.

Nowadays Garfield covers virtually all types of gaseous detectors (wire chambers, TPC, microgas detectors: GEM, MSGC) and interfaced with a number of other programs

The first version, written in Siemens FORTRAN 77, was ready for use with MVS. It contained the basic features of the present program but was far less elaborate. In its original development, Garfield tries to simulate the behaviour of drift-chambers: it calculates and plots the electrostatic field, the drift-lines of electrons and ions and the currents on the sense wires resulting from the passage of a charged particle through the chamber. The program can also assist you in finding optimal potential settings under certain constraints. For calibration purposes, Garfield can compute x(t)-relations and arrival time distributions.

At the following link, you can have one of the first Garfield user's guides:
http://lambda.phys.tohoku.ac.jp/~kobayash/seminar/files/cern/garfield.pdf

Guiding principle

From the start, the guiding principle has been to use the best approximations reasonably available, at the price of execution time, memory usage etc. Thus, the level of detail of the calculation differs substantially from what GEANT does. While in 1984 a calculation was considered precise when it was accurate to 200 µm, users in 2000 would typically expect 50 µm.

Input

Garfield needs two ingredients: Description of the chamber and composition of the gas. The chamber description is the basis for the electric field calculations: interpolation in a finite element field map, or analytic formulae for a chamber composed only of wires, planes and periodicities. The gas description serves to compute: transport coefficients and ionisation tables.

Products

The ingredients that can be plotted and printed: field vectors, contours, gas tables, ionisation statistics, etc. etc. Combining the ingredients yields drift paths for electrons and ions, which are used to calculate: calibration curves, resolution estimates, signals on electrodes, wire movements...

Electric field

The electric field can be computed using analytic formulae (accurate, fast, applicable to TPCs, tubes, drift chambers) or using finite element field maps from external programs (inaccurate for large devices with small structures, reasonably fast, deals with dielectrics and complex electrode shapes). Interface with an integral equations program does not suffer from the inherent flaws of finite elements: discontinuous fields, polynomial approximations of 1/r fields; though sadly, not widely available commercially.

Transport properties

Transport properties for nearly arbitrary mixtures can be computed using the Magboltz program (Steve Biagi). Full Monte Carlo simulation of electron transport Based on elastic, inelastic, ionisation and attachment cross sections for individual molecules.

Ionisation properties

The Heed program (Igor Smirnov) simulates ionisation processes: Charged particles exchange, virtual photon and produce, Auger electrons, delta electrons, photons all of which can re-interact. Contains detailed cross section tables for nearly all common ingredients.

Electron and Ion drift

Exists in several variants: analytic integration in a gas, linear drift equations, RungeKuttaFehlberg technique, automatically adjusted step size, optional integration of diffusion, Monte Carlo integration in a gas, linear equations, non-Gaussian in divergent and convergent fields, user-defined step size, drift in vacuum, nonlinear equations. The Monte Carlo needs corrections to correctly model microgas detectors such as GEMs.

Signals

Signal calculation forms the basis of nearly all resolution calculations. Garfield-produced signals are fed into Spice for full electronics processing. Technique pioneered in Atlas MDT where it has been extensively tested.

Garfield++

Garfield++ (https://garfieldpp.web.cern.ch/) is an object-oriented toolkit for the detailed simulation of particle detectors based on ionisation measurement in gases and semiconductors. The main area of application is currently in micro pattern 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.

For more details, please refer to https://garfieldpp.web.cern.ch/documentation/UserGuide.pdf

Laboratory Session

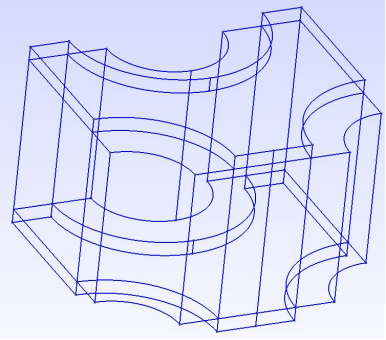
The laboratory session will start with a brief introduction by Rob Veenhof, followed by the hands-on part of Josh Renner. The session will close with a brief explanation of the exercises that will have to be completed. In this lab session, you will work with the microscopic simulation of a GEM element. A brief introduction to the Gas Electron Multiplier foil is reported at the end of this document.

Simulations in Garfield++ with open source finite element field computation

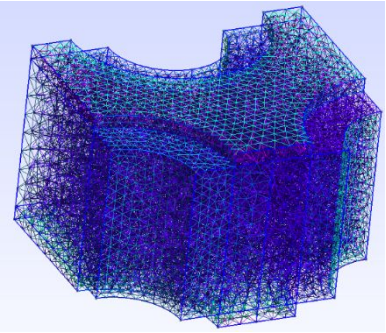
The hands on session will be done using the following notebook:
https://colab.research.google.com/github/jerenner/garfieldfem/blob/master/garfield_FEM_ESIPAP.ipynb

The finite element method can be used to compute a numerical solution for the electrical potential in a detector setup given the geometry and applied voltages. The main steps are:

1. Define the geometry



2. Mesh the geometry (discretize the space over which the geometry is defined)



3. Use a FEM solver to determine the solution over the entire mesh
4. Import the mesh and FEM solution into Garfield++

For further information
see: https://garfieldpp.web.cern.ch/garfieldpp/examples/elmer/garfield_elmer_doc.pdf

In the notebook two examples are present. The first one on a wire-based detector and the second one on a THGEM (or LEM). We will work through these examples together in the lab session, and they will serve as the basis of several exercises:

Exercises

1. **Gain curve:** compute a gain curve (gain vs. delta-V LEM) for the parameters used in the 3D LEM example.
2. **Gas properties:** repeat the gain curve calculation from exercise #1 for 2 different quencher ratios (CO_2%).
3. **Hole geometry:** repeat the gain curve calculation from exercise #1 with 2 different hole radii.

* Note: tune your parameters to keep gains in the range of several hundred electrons at the most (to keep running times reasonable)

Items to include in the report:

- produce several avalanche plots at different settings (voltages, gas compositions) for both the LEM and the wire examples and comment on the different features as discussed during the lecture
- the gain curve for the LEM parameters used in the example (exercise #1)
- a plot containing three gain curves for 3 different CO_2 concentrations (exercise #2)
- a plot containing three gain curves for 3 different LEM hole radii (exercise #3)

Gaseous Electron Multipliers

The laboratory session hands-on is focused on Gaseous Electron Multipliers (GEM) foils. They belong to the family of Micro Pattern Gas Detectors and have been introduced by Fabio Sauli at CERN at the end of the nineties [1]. They consist of an insulating layer separating two metal electrodes. Based on copper-polyimide-copper foil composites, they are structured with a high density of microscopic holes with photolithographic patterning and etching techniques. A schematic of a GEM foil displaying the hole pattern build-up is shown in Fig. 1. Standard GEM foils feature holes with a diameter of 70 µm arranged in a hexagonal pattern with a pitch of 140µm. The insulating layer is 50µm thick polyimide and 5µm thick Cu electrodes on both sides are used. THGEM[2] (Thick GEM) or LEM[3] (Large Electron Multipliers), characterized by larger sizes, one order of magnitude larger roughly, are as well commonly used. The example available in the hands-on lab session notebook refers to a THGEM (LEM).

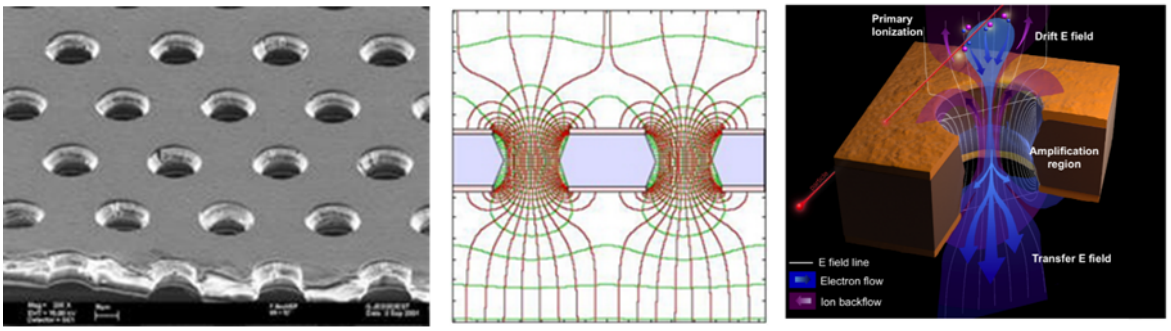


Figure 1: (Left) Microscopic image of GEM holes. (Center) Electric field lines in the cross section of GEM holes. (Right) Charge transfer and amplification in a GEM hole. Electrons and ions paths are shown. [4]

When a potential difference is applied across the two electrodes, high electric field regions are created inside the holes of the GEM foil as shown in Fig. 1. Electrons entering into these high electric field regions will be accelerated and can reach energies sufficient for subsequent ionization of gas atoms. Upon ionization, an additional free electron is created, which can in turn be accelerated and undergo further ionizations. This avalanche multiplication process increases the number of free electrons and is used for signal amplification in gaseous detectors. The produced charges (electrons and ions) will drift in the gas following field lines and diffusing. As shown in Fig.1 (right) part of them will be trapped in the closest electrode and part of them will move away from it. Because of these losses [5], a definition of 'visible gain' (today normally called 'effective gain') is used and it takes into account this loss of charges. Despite these losses, because a significant part of the produced electrons will drift away from the GEM foil, multiple layers of GEMs can be used in sequence to achieve higher factors of amplification with more stable conditions.

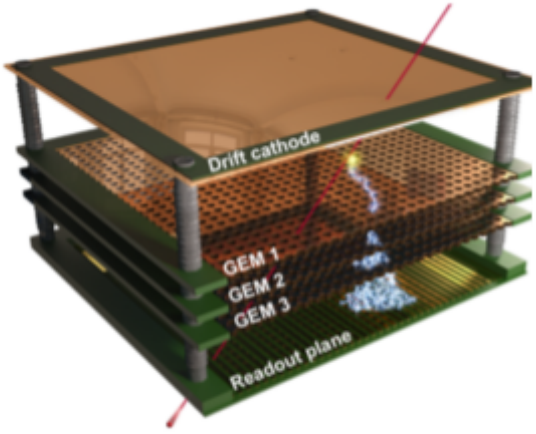


Figure 2: Pictorial sketch of a triple GEM detector [4].

A schematic of a detector based on three GEM foils is shown in Fig. 2 [4]. Above the GEM foils, a cathode is placed to define an electric drift field in the so-called conversion region. Below the foils, a readout anode or window (depending on readout modality) is placed to collect signals after the amplification. Radiation entering the detector through the radiation window can interact in the conversion region by ionizing gas atoms. The produced primary electrons move towards the GEMs under the influence of an electric field in the conversion region. In the GEMs, they undergo signal amplification and the resulting signals are collected on the readout anode. Alternatively, optical readout can be done by detecting the scintillation light produced by excitation during electron multiplication in the holes of a GEM and subsequent de-excitation of gas atoms and molecules.

For further information please refer to the reference section of:
https://garfieldpp.web.cern.ch/garfieldpp/examples/elmer/garfield_elmer_doc.pdf

[1] F. Sauli, *"GEM: A new concept for electron amplification in gas detectors"*, Nuclear Instruments and Methods A, 386 (1997), p. 531
[2] R. Chechik *et al*., "*Thick GEM-like hole multipliers: properties and possible applications"*, Nuclear Instruments and Methods A, 535 (2004), p. 303
[3] A. Badertscher *et al., "Operation of a double-phase pure argon Large Electron Multiplier Time Projection Chamber: Comparison of single and double phase operation"*, *Nuclear* Instruments and Methods A, 617 (2010), p. 188
[4] J. A. Merlin, PHD Thesis, https://cds.cern.ch/record/2155685/files/CERN-THESIS-2016-041.pdf
[5] R.Bellazzini et al., *"What is the real gas gain of a standard GEM?"*, Nuclear Instruments and Methods A, 419 (1998), p. 429