

# Interface Prototype of GEANT4 with Garfield with Applications to the Study of Drift Electrons Inside an ATLAS Muon Tube

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# 1 Introduction

This paper describes the work done to interface two simulation tools, Geant4 and Garfield, in part for the simulation of the ATLAS muon chambers. This interface was done in order to add measurements such as ionization and electron drift time to gas detectors. This was applied to a charged muon traversing through a muon tube to have a better understanding of how a signal is created inside the chamber.

Geant4 [1, 2] is a toolkit which is used to simulate particle interactions and passage through matter, with specific applications in high energy physics. Geant4 can be used to simulate muons traversing a muon tube in ATLAS, however it is unable to simulate the processes in the gas such as ionization and the resulting drift of electrons inside the tube.

Garfield [3] on the other hand is a FORTRAN program which is designed specifically for the simulation of drift chambers and gas detectors. This makes it a useful program to use with Geant4 to further the applications and simulation of physics inside a wide range of gas detectors.

It will be described how the first interface has been created between the two simulation toolkits and its application to the ATLAS muon tubes. The extent of the physics of Geant4 will be shown when it is used with the interface to Garfield. Finally, the measurements of the drifting electrons and their signal on the Aluminum tube is calculated and shown. The information is then sent back to Geant4 and the interface is complete.

This work has been done with the collaboration from the Institute of Particle Physics in Canada while at the European Organization for Nuclear Research (CERN).

## 2 Geant4 Simulations

Geant4 is a simulation toolkit used to simulate the passage of particles through matter. It has application in many different fields of industry and research, one of them being high energy physics. Geant4 is able to simulate particle interactions with matter and give relevant information about the trajectory of particles, the creation of secondary particles and the energy deposition.

Geant4 has been applied to most of the high energy physics experiments. Its other prime applications are found in the fields of space and radiation, medical technology and technology transfer.

Geant4 was developed to replace Geant3 in the middle of 2003, which was used to model the ATLAS detector for the TDR and technical proposals. Since then, it has been the primary simulation toolkit used for the ATLAS experiment. It can be run in the Athena framework and has been linked to ROOT libraries. [4].

Included in the simulation are:

- the geometry and materials of the detector,
- tracking trajectories of particles,

- physical processes and interactions,
- generation of data and storage of events.

A great advantage of the Geant4 toolkit is that it is designed for modern experiments and has a variety of controls, including the interface to other programs. It contains several components such as the event generator, detector simulation, event, and storage of data which can be tailored to the user's preferences.

For the creation and analysis of the muon tubes, Geant4 is used to:

- create the geometry and material of the detector and physical world volume, defining the boundary of the process,
- initiate the muon particle, its energy, momentum direction, and charge, to launch at the detector,
- create the different gases inside the detector and world volume,
- include all the physical processes such as ionization and multiple scattering inside the detector,
- to determine when a hit on the detector has occurred; thereby determining its position, particle identification, and momentum.

Using the information provided by Geant4, an interface with the Garfield simulation tools allows for a better modelling of the physical process inside the gas detector.

### 3 Garfield Simulations

Garfield is a program which is used to make detailed descriptions of gas detectors, especially drift chambers, time projection chambers (TPCs) and multiwire counters. It is able to create field maps, simulate the drift of electrons and the simulation of induced signals.

However, three dimensional solutions for fields are non-trivial, most of which are not solved analytically. Therefore Garfield uses other finite element programs such as Maxwell, tosca, QuickField and FEMLAB for its calculations. This is also due to the complexity of dielectric media and other electrode shapes, which are difficult to be treated with just analytic techniques.

This makes Garfield a very powerful program at treating gas detectors and fields inside gases. Its interface with Magboltz, a program which designs the gas and all the internal fields, allows for the computation of most electron transport properties. This can be done in most all arbitrary gas mixtures. This is used for the treatment of large gas detectors, and has special applications in the simulation of the ATLAS muon tubes. Therefore interfacing this program will allow Geant4 access to physical processes such as:

- field maps for fields as well as contour plots in two and three dimensions,
- compensation in fields and signals due to wire sag in detectors,
- calculation of drift parameters of electrons and ions, specifically drift time and drift plots,

- determination of a signal induced by the charged particles as they move through the detector, with the inclusion of factors such as “delta-electrons”, diffusion, and electron pulse.

## 4 Interfacing the Simulation Programs

To run Geant4 and Garfield simultaneously, the libraries between the two programs must be linked. This is the first attempt to interface Garfield with Geant4. The first important step is to manage the correct libraries from each program. The libraries required to run the interface are: Geant4, CLHEP, Garfield, and ROOT. Though ROOT libraries are not essential, they are needed for any visualization of the simulation.

Not all of the versions for these four programs are compatible. Geant4 requires the proper libraries from CLHEP in order to run any task. For ROOT to be added, version 5.10.00 is the one used in this example. The choice of CLHEP and Geant4 is not important as long as they are compatible with each other.

The next stage in interfacing the two programs comes from linking the shared libraries in the makefiles. This needs to be done with care for different versions, 64 or 32 bit computers. However this must stay consistent in both makefiles. This is the same for the compiler used. Garfield is a FORTRAN program and needs `g77` to compile properly.

The next step is to add the proper files. The simulation needs to have a class which links the two programs together. For this example this class is given the name `garftube`. The `garftube` class is called from inside Geant4 and uses other Garfield specific classes to make its analysis. The flow chart is found in Fig. 1. For the current example, the method `Process Hits` inside Geant4 calls `garftube`.

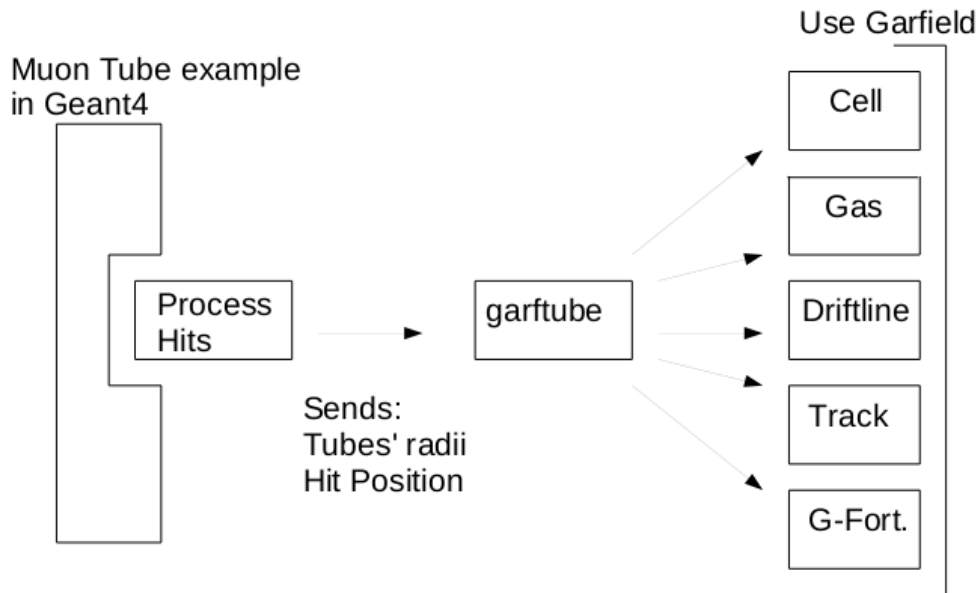


Figure 1: Flow chart for the first prototype interface, which calls Garfield properties in the Geant4 method `Process Hits` of our muon tube example.

Therefore all of the classes from Garfield, along with the ROOT libraries must be added to the regular Geant4 makefile. After compiling these garfield classes, their output is added to the makefile of the Geant4 example. This is done as follows.

In the GNUmakefile of the example in Geant4:

```
ifdef ROOTSYS
CPPFLAGS += $(shell $(ROOTSYS)/bin/root-config --cflags)

ROOTLIBS = Tube/garftube.o Tube/plotlib.o Tube/garfieldfortran.o
          Tube/garfielddalgebra.o Tube/garfieldfield.o
          Tube/GarfieldGraphics.o Tube/Cell.o Tube/Driftline.o
          Tube/Track.o Tube/Gas.o
          $(shell $(ROOTSYS)/bin/root-config --glibs) -lMinuit
          -lHtml $(shell cernlib kernlib, mathlib, packlib) -lg2c
ROOTLIBS := $(filter-out -lNew,$(ROOTLIBS))
ROOTLIBS := $(filter-out -lThread,$(ROOTLIBS))
ROOTLIBS := $(filter-out -lpthread,$(ROOTLIBS))
LDLIBS +=$(ROOTLIBS)
endif
```

This is the core of the linking procedure. This brings all of the libraries together in the Geant4 makefile. From here, Geant4 can run an example without separately using Garfield for analysis. Geant4 now adds all of the Garfield libraries it needs for gas detector analysis. Next, an example is constructed in Geant4 to show how this process works. This is the first prototype of its kind.

## 5 Muon Tube Set-up and Run Action in Geant4 using Physical Applications from Garfield

To begin the Run Action, the detector construction is written in Geant4. The Run Action is the physical process which uses a particle gun to simulate a single particle directed towards the detector. The energy of the incoming particle is controlled, along with its initial direction from Geant4 before the run begins.

The particle simulated for the analysis is a positively charged muon with an incoming energy of 10 GeV, about what should be expected from muons produced at the LHC. They begin at the world volume boundary, shooting through the detector. Geant4 is able to track the particle through the designated physical boundary and into the detector.

The detector is rotated 90 degrees so that the particle will hit the tube perpendicular to the long end. From this point of entry, the class garftube is called which uses Garfield physical applications. The return of information is sent back to the Geant4 example and the muon is tracked by Geant4 until it reaches the boundary of the world volume.

## 5.1 Detector Construction

For the analysis of the muons, the detector constructed is that of the ATLAS muon tube. The first object which is created is the world volume. This is the area in Geant4 at which our physical process will occur. It defines the physical boundary at which all of the physics will be recorded.

The creation of the objects, in this case the muon tube detector, is done in two phases. The first is the establishment of the logical volume. The second is the creation of the physical volume, which creates the physical attributes of the logical volume. The world volume is filled with normal room condition air.

The detector itself is made of a gas of 93 % Argon and 7 % CO<sub>2</sub> just as in the ATLAS muon spectrometer. It is held at 25 °C and at a pressure of 3 atm. The detector is constructed with an outer radius of 1.5 cm. In the centre of the Tube runs an Al wire with an outer radius of 30 μm. This information is all created in Geant4 and can be visualized from Geant4 control as in Fig. 2.

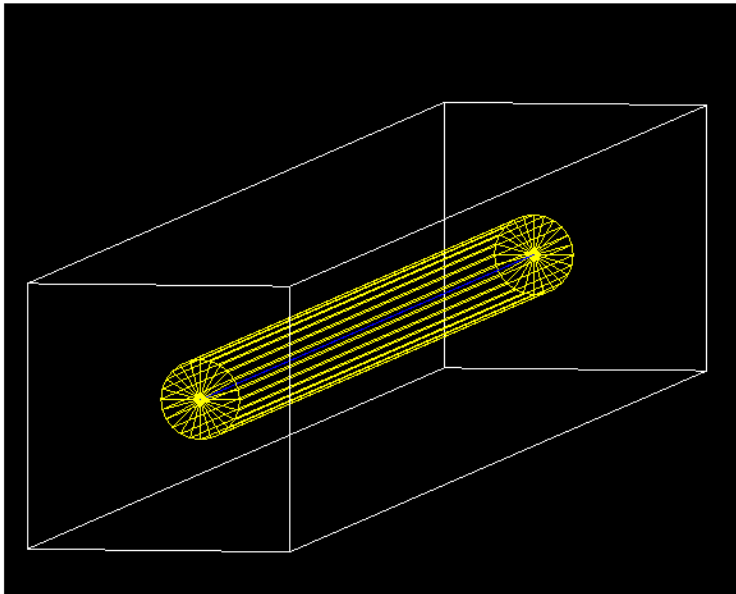


Figure 2: ATLAS muon tube constructed in Geant4 and visualized by OPENGL.

Now that our detector is constructed in Geant4, it must also be properly created in garftube from Garfield. Since all the hit parameters will be passed during the simulation, the gas must be created beforehand for ionization purposes. It is created by Magboltz, seeding the gas and HEED model for ionizations which will be described in detail later.

## 5.2 Gas in Detector

The gas in the detector is constructed in Geant4, however it does not have the capabilities to analyse the ionization in the muon tube. Therefore, for the analysis, Garfield is used to create the gas inside the tube. This is done using Magboltz 7.1 [5] which creates a gas mixture of 93 % Argon and 7 % CO<sub>2</sub>.

This process must be done separately in a gas file. This gas file is created ahead of time by the interface with Magboltz which creates all the parameters of the gas given the structure and size of the detector. Using this information, it produces all of the properties of the fields numerically and stores them to a file. This procedure takes several hours and is needed to be completed ahead of the simulation.

### 5.3 Run Action

The Run Action is started by creating the detector from all the set parameters. Geant4 sets and describes the detector and the surrounding world volume by its list of properties and physical processes. Once the detector has been constructed, Geant4 then begins by shooting the muon at the detector.

The muon traverses through the Geant4 world volume until it reaches the muon tube, which is defined as the sensitive detector. This sensitive detector is the region in which Geant4 records hits. When a particle hits the sensitive detector, it is stored in memory. As the hit is being processed by Geant4, the physics of Garfield is used. This is done by calling the `garftube` class which uses the physics of Garfield.

Once the call to this class has been completed, with each step in the sensitive detector, the muon continues traversing, into the world volume after the sensitive detector until it reaches the boundary of the world volume. This boundary stops the run action and collects all the information from the event. An event which has been created for the muon tube is shown in Fig. 3. The trajectory of the muon traversing through the world volume and into the sensitive detector can be seen by the red line.

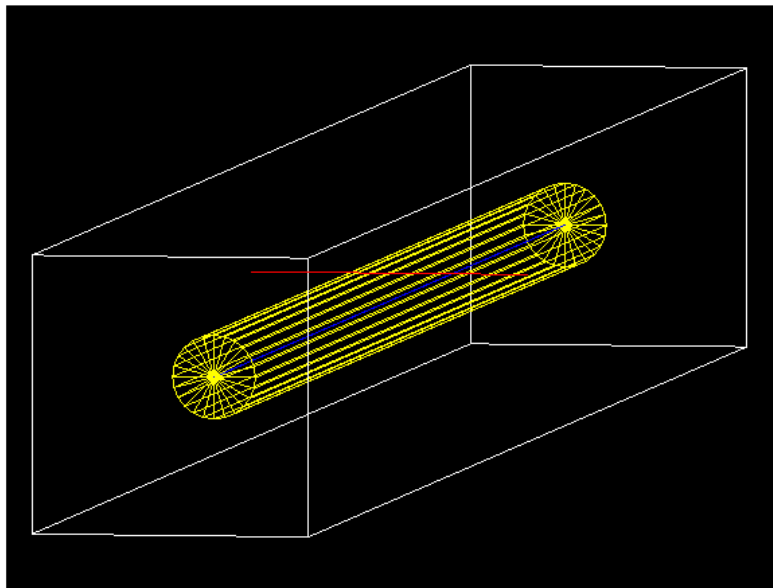


Figure 3: The world volume containing the event of a 10 GeV muon traversing through the muon tube. The call is made to `garftube` when the muon is inside the sensitive detector, defined by our muon tube in yellow.

The call for the `garftube` class is made upon hitting the sensitive detector in the `ProcessHits` method as follows:

```
#include <vector>
#include "/afs/cern.ch/user/g/guindon/GEANT4/Tube/garftube.h"

G4bool ExN02TrackerSD::ProcessHits(G4Step* aStep,G4TouchableHistory*)
{
    ...

    G4ThreeVector v1;
    G4ThreeVector v2;
    v1 = aStep->GetPreStepPoint()->GetPosition();
    v2 = aStep->GetPostStepPoint()->GetPosition();
    G4double x1tem = v1.getX();
    G4double y1tem = v1.getY();
    G4double z1tem = v1.getZ();
    G4double x2tem = v2.getX();
    G4double y2tem = v2.getY();
    G4double z2tem = v2.getZ();

    double drifttime = garftube(fRadius,fRadius2,x1tem,y1tem,z1tem,x2tem,y2tem,z2tem);
    printf("The 10th electron arrives at %g.\n", drifttime);
    return true;
}
```

In this procedure, firstly the pre and post step positions are determined by Geant4. These points are the initial and final position of the muon in the sensitive region. Each position is recorded according to our world position and it is passed through the argument of the call to `garftube`.

The other two variables passed in the argument are `fRadius` and `fRadius2`. These are the radii of our muon tube and Al tube respectively. These variables are passed to allow an arbitrary volume to be created in Geant4. Therefore any detector can be passed along with any entrance and exit point. All of these parameters are used by our class `garftube` for physics inside the muon tube, such as drift time and velocities which would otherwise be impossible using only Geant4 physical properties.

The class `garftube` also returns a double term, denoted here as `drifttime`. This `drifttime` is the signal on the trigger which can be further used in Geant4 for other applications. How this is done in the class `garftube` will be described in the next section.



## 6 Muon Tube Studies

This analysis uses the transport properties of the gas inside the tube and calculates the electron transport due to ionizations from the muon. The drifting electrons are tracked and collected in the signal process. These physical descriptions are all possible with the first interface between Geant4 and Garfield.

### 6.1 Physics using Garfield Capabilities

As the muon passes through the muon tube, it causes ionization of the gas, resulting in electrons being produced. For this simulation, the HEED model for ionizations is used. The HEED model produces ionizations randomly. They are randomly spaced with random energy. The garftube class records the ionizations created by the muon and traces them based on the electric field inside the tube.

An electric field is created inside the tube by Garfield. The electric field as a function of radius in the muon tube is shown in Fig. 4.

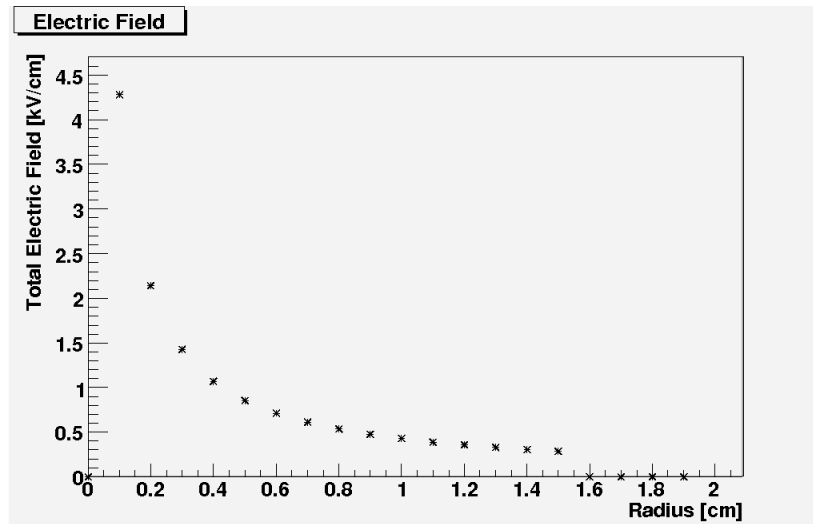


Figure 4: Electric field inside the muon tube as a function of the radius. It can clearly be seen that the electric field ends at the boundary of the tube with a radius of 1.5 cm.

The electric field inside the tube is strongest at the centre of the tube, along the Al wire. As it is further from the centre, the electric field diminishes and this property has an effect on the drift of the electrons. This is calculated after the ionizations of the electrons.

### 6.2 Simulating the Ionizations

The ionizations in the muon tube are created by the HEED method. This traces the track of the muon and places ionized electrons along the path with various energies. The ionized electrons begin to drift from their position according to the electric field. This can be seen in Fig. 5.

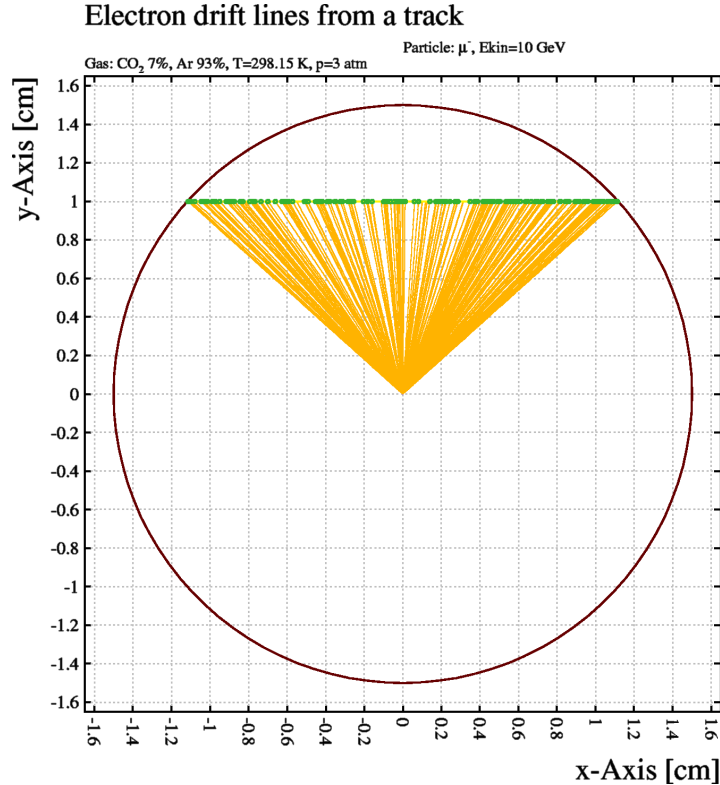


Figure 5: Ionized electrons are created along the path of the muon. This is the horizontal line across the top of the tube. They drift according to the electric field, leaving a path of lines in yellow.

Due to the electric field created in the tube, the electrons drift to the centre of the tube, the Al wire. Due to the drifting electrons, a signal is created at the wire. The signal allows the determination of the distance from the wire to the muon.

From the diagram it can easily be seen where the muon entered and exited, however this is not possible in the ATLAS muon tube. What must be done is a calculation of the time on the signal. From this, one is able to tell how far away from the wire the muon passed through the tube. With the hit of 20 muon tubes on average per muon, the exact position can be triangulated. This makes it important to study the drift parameters and to understand how the electron is drifting inside the tube.

### 6.3 Calculating Drift Velocities

It is possible to study the drift velocities of the electrons inside the gas using Garfield. Once the electrons have all arrived at the wire, the time it took them to drift towards the electrode can be calculated. This is done for different segments of the detector. The transport properties of the gas can be calculated due to the known electron mobility.

From measurements of the electron mobility, the velocity of the electrons can be seen for different magnitudes of electric field. For a gas of 93 % Ar and 7 % CO<sub>2</sub>, the drift velocity of the electrons can be plotted against the electric field. This is shown in Fig. 6.

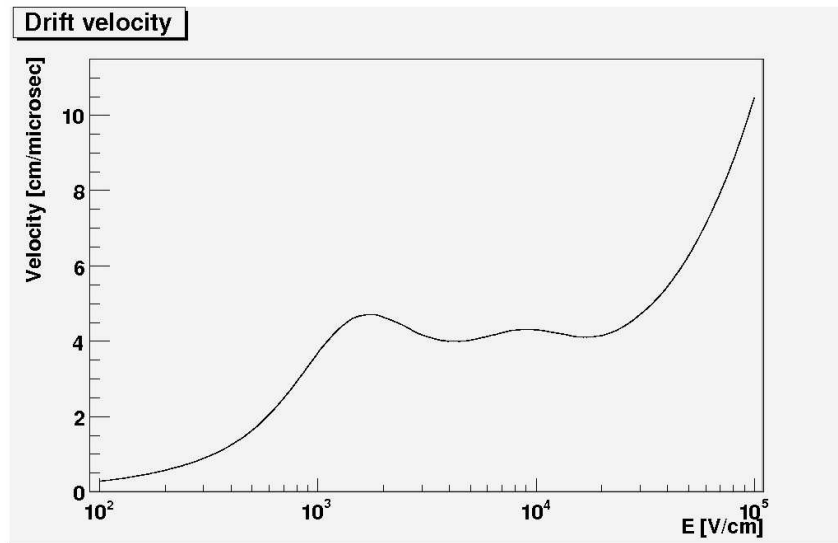


Figure 6: Drift Velocity of the electrons inside the gas of the ATLAS muon tube. It is interesting to note the plot does not show a linear relationship, yet is dependent on quantum effects from the gas.

The first thing to note from the graph is that it is not linear. The electric field can be represented in terms of electron energy. At an electric field between  $10^3$  and  $10^4$  V/cm, there is a dip in the velocity of the electrons. It corresponds to a decrease in the velocity for a given increase in the electric field. This does not seem obvious. However, if the electric field could be translated into the electron energy it would coincide with about 0.2 or 0.3 eV.

Looking at the properties of Argon, the cross-section for Argon as a function of energy in eV is given in Fig. 7. It can be seen that at the energy of 0.2 and 0.3 eV there is a large decrease in the cross section. This coincides exactly with the decrease in drift velocity of the electrons at certain places in the strength of the electric field.

The reason for such a dip in the cross section is due to the phase shift in the wavefunction of the electron [6]. This minimum is known as the Ramsauer minimum. As the electron approaches, it undergoes an S-wave phase shift of  $\pi$  due to a strong attractive force with the argon nucleus. At this point, the cross section is smaller and thus, the electrons at this electric field will drift slower. The same effect can be seen in  $\text{CO}_2$ , however the effect is much slower. This is also seen in Fig. 5.8.

The Ramsauer effect was first discovered in 1921 and was one of the first quantum effects to be observed and published [7]. It was later published by J.S. Townsend and V.A. Bailer [8] and therefore it is also known as the Ramsauer-Townsend effect.

This effect is not only limited to Argon, but the heavier Noble gases all have a similar effect at progressively higher energies. In the heavier noble gases such as Krypton and Xenon it occurs at 0.5 eV and 0.65 eV, respectively.

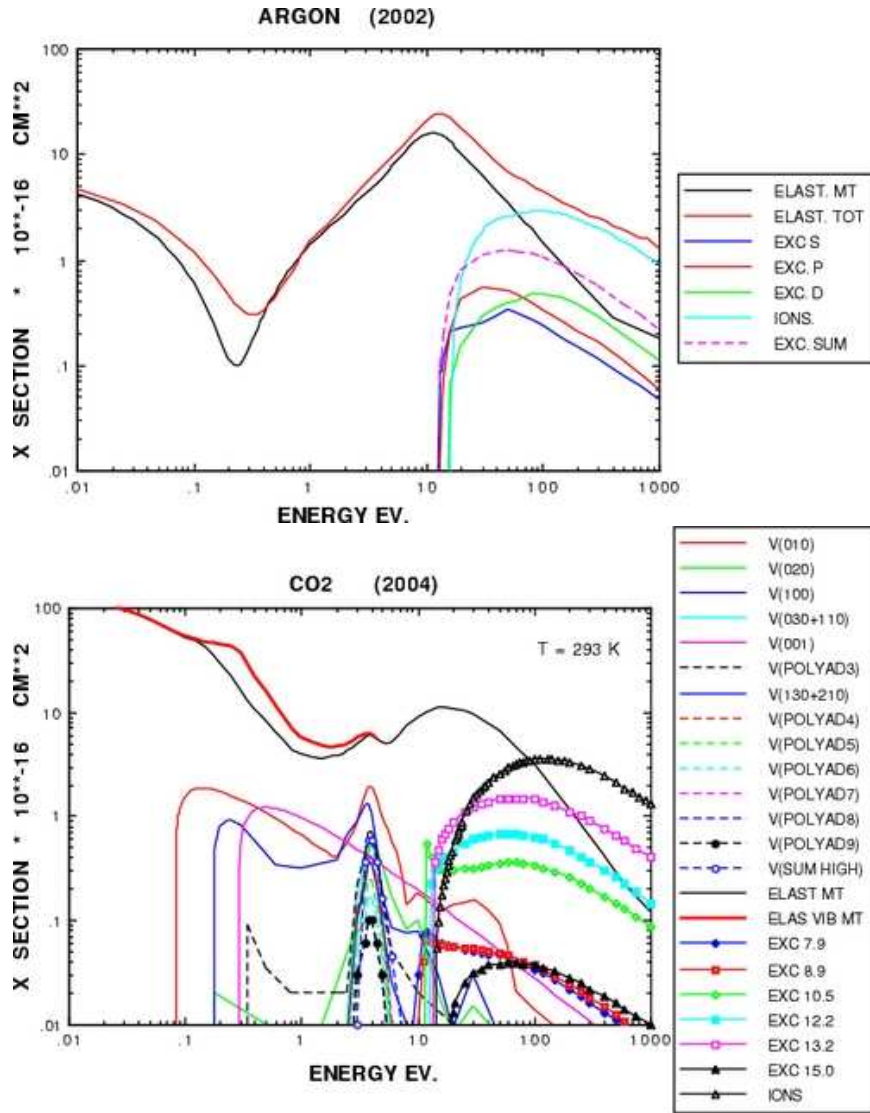


Figure 7: Cross Section of argon and carbon dioxide as a function of energy. These graphs are taken from the Magboltz 7.1 database for gas properties.

## 6.4 Calculating Drift Time

For the measurement in gas detectors the drift time is an important measurement for signal analysis. The location of the traversing muon can thus be determined. The drifting is used to understand how the electrons propagate in the gas and to see from where the resulting signal originates from.

The drifting electrons are due to ionization of the gas which creates the primary and secondary electrons. These electrons then drift according to the electric field and diffusion properties. In the ATLAS muon tube, they drift towards the Al wire where the signal arrives with a certain time delay from the muon entering the tube.

During the drift of the electron, there are also processes which affect the time. One of these processes is diffusion. Due to diffusion, some electrons arrive quicker and some slower. This is simulated by Garfield and taken into account in the present muon tube example. Fig. 8 shows the different drift times of the electrons according to their location along the distance from where the muon entered the tube.

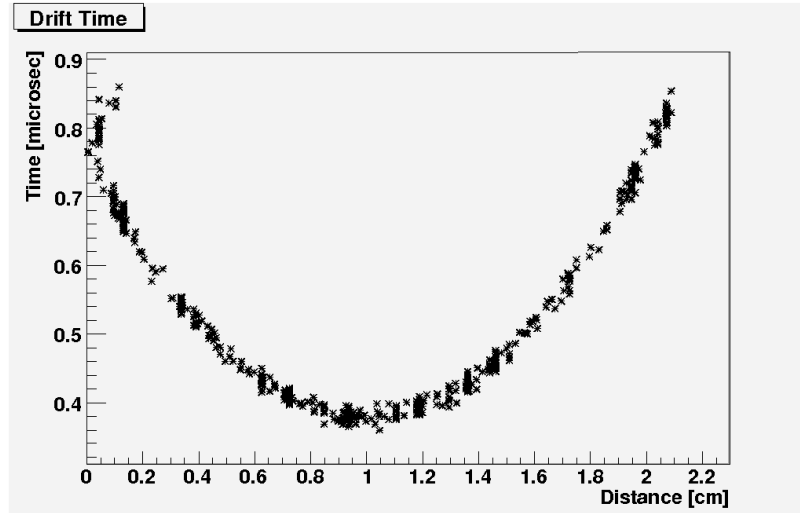


Figure 8: Drift time of the electrons from across the track of the muon. The distance along the bottom represents the distance of the muon in the tube. Therefore, 0 cm corresponds to the entrance and 2 cm corresponds to the exit. The quickest electrons to arrive are the ones created closest to the Al wire, the centre of the track inside the tube. The calculation also takes into account diffusion.

## 6.5 Trigger Time back to Geant4

The simulation of the signal which the Al tube registers is done in `garftube`. This is done to allow users access to the trigger time for further applications in Geant4. To do this simulation, all of the drift times are calculated using Garfield. Instead of storing all of them in memory due to huge file sizes and long calculation times a vector is used to calculate the signal.

To do this, a vector calculates the tenth electron to reach the Al wire by checking all of the values of the drift time. The time of the tenth electron is the time deemed for the signal to trigger. This is due to electronic noise and other delays in the electronics. This is a very realistic simulation of the time for the signal from the drifting electrons due to the delay in the electronics.

This time for the triggering of the signal in the tube is then recorded in the class `garftube` and is returned to `ProcessHits`, the method inside Geant4. From here this number can be used in Geant4 for purposes of the user. This completes the interface and demonstration for the ATLAS muon tube.

## 6.6 Muon Measurements per Bunch Crossing and Timing of Interface

The outer most part of the ATLAS detector is made up of the muon detectors. Since the muon is a minimum ionizing particle, it is able to escape the inner detector and calorimeter. Therefore, the muon spectrometer is put on the outside of the detector to identify the muons created in ATLAS.

The muon detector is composed of 400 000 tubes as stated earlier. To study the simulations of events in ATLAS, the amount of muons produced per event needs to be understood to make proper accounts for timing of the simulation.

In one bunch crossing at ATLAS, an average of 25 protons are collided head-on with another 25 protons. Per bunch crossing, on average, about 20 events will occur [9]. From these 20 events, about 1 muon will be created on average. Most likely it will not reach the muon tubes due to insufficient energy. This leaves the number of muons reaching the tubes to be very low, much lower than 1 per bunch crossing.

If however, a muon does reach the tubes, it will hit about 20 tubes as it traverses outwards from the interaction point. For simulation purposes, this means that the simulation time must be able to handle between 20 and 100 tubes being hit out of 400 000 per 25 ns to be sure the timing is sufficiently fast.

## 7 Conclusion and Outlook

The first prototype design for interfacing Geant4 with Garfield has shown to be very useful for simulating large gas detectors. The interface adds physical properties of events inside gas detectors. This would otherwise not be possible with only Geant4. It allows Geant4 to make calculations of gas detectors without using a secondary simulation.

The applications of Garfield go further beyond just the muon tube example. So far, drift properties of the electrons have been calculated. But also the properties of the gas of the detector can be clearly shown using Garfield.

The next application being sought after is the generalization of this first prototype to other models. One example already being pursued by TRIUMF in Vancouver, Canada, is the application of this prototype to time projection chambers. This has applications in particle simulations of ALICE, and the ILC development.

One field which is of particular interest to many is the avalanche effect. This occurs in the muon tubes, and other gas detectors, as the electrons approach the Al wire. The number of electrons increases with the increase of the electric field. Garfield can take this into account and this can be added to the simulation for an even more advanced description of the drifting of the electrons. This can be done with the addition of a method in `garftube`.

Other additions to the first prototype are also being looked at by members of the Geant4 Collaboration at CERN. Further additions to the calculation of the signal in the Al wire can be done. Another attempt is to add many muon tubes in one simulation. Another area which could be looked into is to call `garftube` at every step in the sensitive detector. This code only gives the entrance and exit coordinates of the sensitive

detector. This will allow a step by step calculation of drift times as the muon makes trajectory steps across the detector. It will also make better trajectories with respect to external magnetic fields.

This prototype is also a test of CPU time for such a process. As mentioned previously, the number of muons, which hit the muon spectrometer per bunch crossing is much less than one. However, if it is to be assumed that one muon reaches the muon spectrometer which is created per bunch crossing, it would hit about 20 tubes. If the computer is to call the garftube class each step in approximately 20 sensitive detectors out of 400 000, this calculation would be sufficient. This shows not only the ability of Garfield to calculate field maps and drift parameters with impeccable accuracy, but with also an irrelevant amount of time.

All of these additions will help improve simulation of gas detectors with Geant4. This interface will vastly increase the usefulness of an already very widely used toolkit. It will allow for a whole new branch of physical simulations via Geant4 and will help in the design and study of the future International Linear Collider (ILC).

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