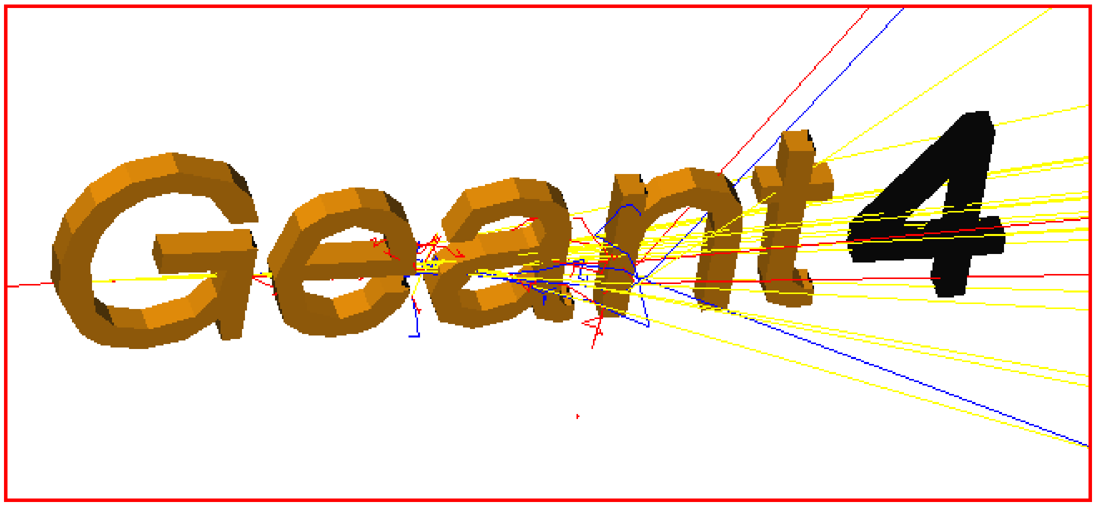
Parameterization of the Transport of Charged Particles through Gaseous Volumes in Geant4 Via an Interface with Garfield

Or How I Learned to Stop Worrying and Love Geant4

With a Spare Time Project



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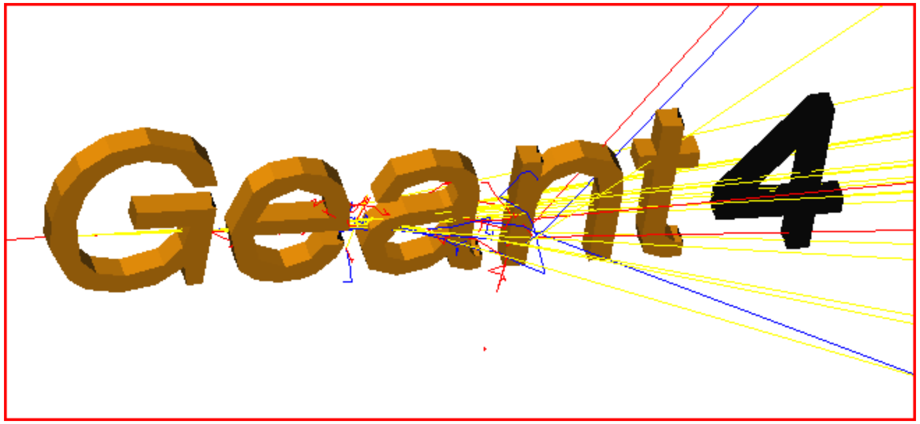
Outline

- What is Geant4?
- Gas Detector Basics
- Physics of Particle Transport in Gases
- Parameterization of Transport
- Magboltz
- What is Garfield?
- The Geant4 Parameterization Framework
- *GarfieldModel* the Geant4/Garfield interface
- Conclusion

What is Geant4?



"**Geant4** is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science." – *Geant4 website*

<u>Strengths:</u>

- Detector Construction/Geometry
- Visualization
- Accessibility
- Lots of built in features

<u>Weaknesses:</u>

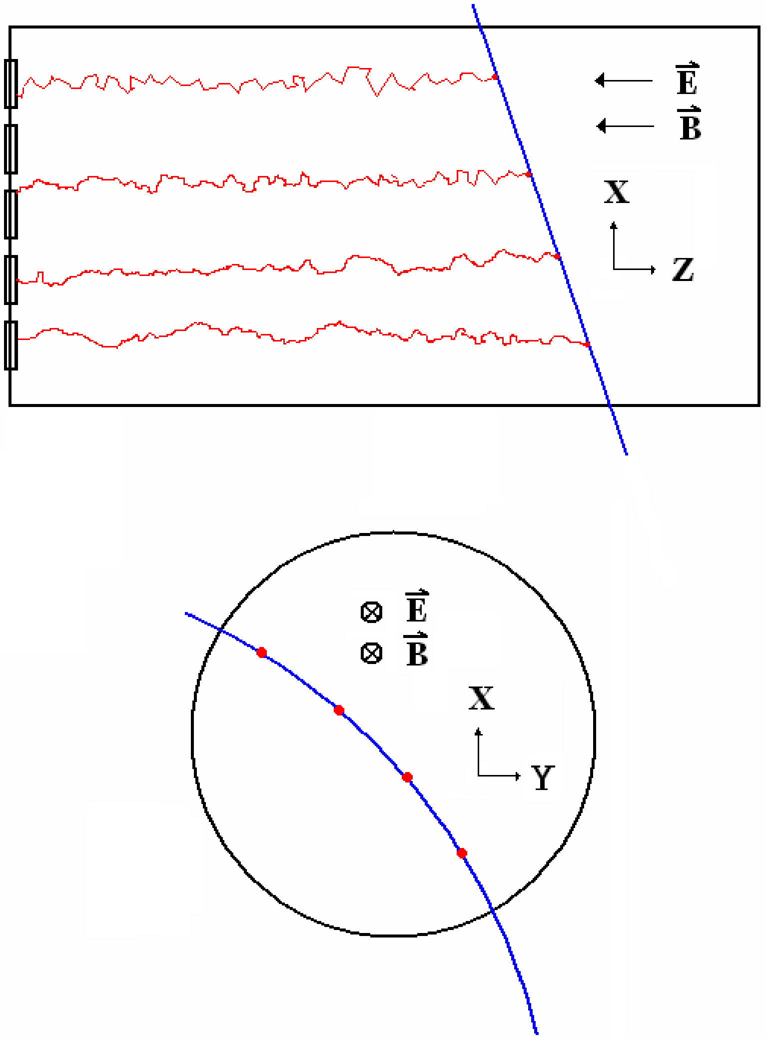
- Transport through Gases
  - Accuracy
  - Speed
- Limited support for EM fields
  - Only uniform fields or user entered field maps

Weaknesses severely limit simulations of gas detectors!

Gas Detector Basics

- Large gaseous volume with applied EM fields
- Used in particle physics experiments to detect and identify charged particles
  - Determines the position of the primary particles trajectory
  - Collects ionization

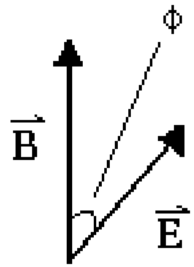
Example TPC:

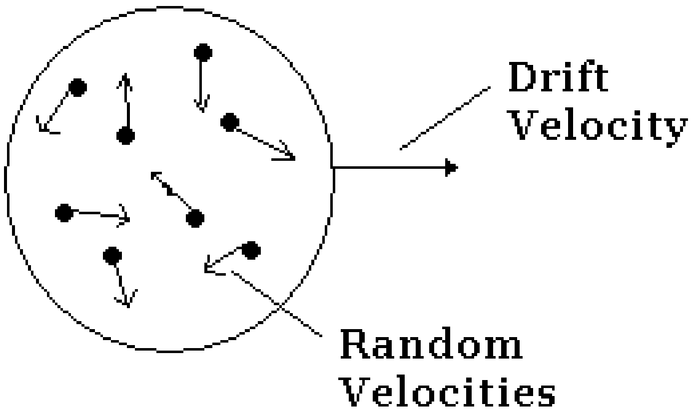


Charged Particle Transport in Gas – Drift Velocity

Assumptions of Model

1. Low pressure gas
2. Electron loses all kinetic energy upon interaction
3. Electron has randomly oriented velocity, $v_r \gg v_{drift}$
4. Cold Gas
5. Free flight time, τ, has Poisson distribution





$$v_{drift} = \begin{bmatrix} \frac{\varepsilon_x \tau}{1+\omega^2\tau^2} \\ \frac{-1+\omega\tau^2}{1+\omega^2\tau^2} \\ \varepsilon_z \tau \end{bmatrix}$$

$$v_{drift}^2 = \left(\frac{e}{m} E\tau\right)^2 \left(\frac{1+\omega^2\tau^2\cos^2(\phi)}{1+\omega^2\tau^2}\right)$$

$$\varepsilon_i = \frac{e}{m} E_i \qquad \omega = \frac{e}{m} B$$

- Electrons obey Lorentz force between interactions
- Averaging over free flight time gives **drift velocity**
- Angle between drift velocity and Electric field is called **Lorentz Angle**

Charged Particle Transport in Gas - Diffusion

Diffusion in a field free gas:

- D is the Diffusion coefficient

$$\frac{\delta n}{\delta t} = D \frac{\delta^2 n}{\delta r^2}$$

Solution for initial point density:

$$n(r,t) = \frac{N}{(4\pi Dt)^{3/2}} \exp\left(\frac{r^2}{4Dt}\right)$$

Comparison with general form of Gaussian:

$$D = \frac{\sigma^2}{2t}$$

Diffusion Coefficient, D, is proportional to RMS of Distribution

Charged Particle Transport in Gas - Diffusion

- Treat diffusion as Random Walk
- Use mean free flight time, τ,and random velocity v_r to find mean free flight length, l_o

$$P(l)dl = \frac{1}{l_o}\exp\left(\frac{-l}{l_o}\right)dl$$

- Calculate RMS displacement for a 3d random walk
- Isotropic stepping with variable length l = P(l)dl

$$\sigma^2 \equiv \langle l^2 \rangle = \int l^2 \cdot P(l)dl$$

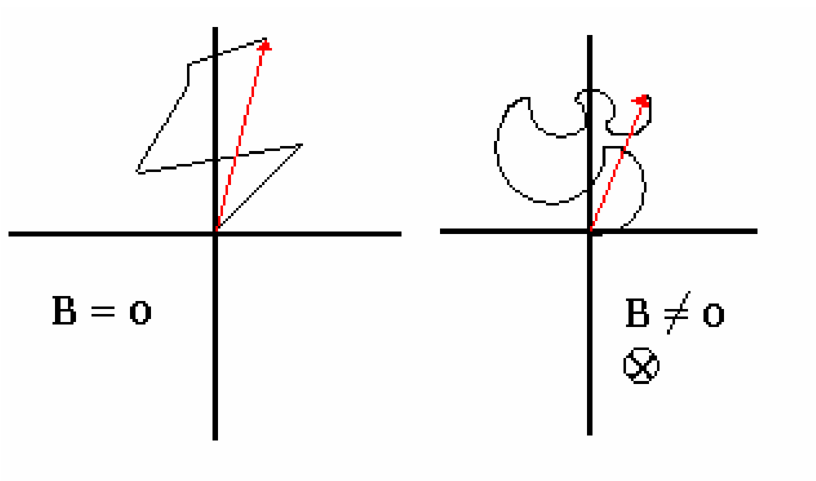
$$\sigma^2 = \frac{2}{3}\frac{l_o^2}{\tau}t \longrightarrow D = \frac{l_o^2}{3\tau}$$

Effect of Applied Field on Diffusion

Applied Magnetic Field:

- Decrease transverse diffusion

$$D_T = \frac{D}{1+\omega^2\tau^2}$$



Applied Electric Field:

- Add time dependence to mean
- Increase longitudinal diffusion

$$D_L = \frac{1+\gamma}{1+2\gamma} D_T$$

- The electric field introduces a preferred direction
- Elongation of electron in this direction distribution parameterized by, γ

Parameterization of Gas

Required Parameters from theory:

- Drift Velocity v_{drift}
- Lorentz Angle α
- Longitudinal Diffusion D_L
- Transverse Diffusion D_T

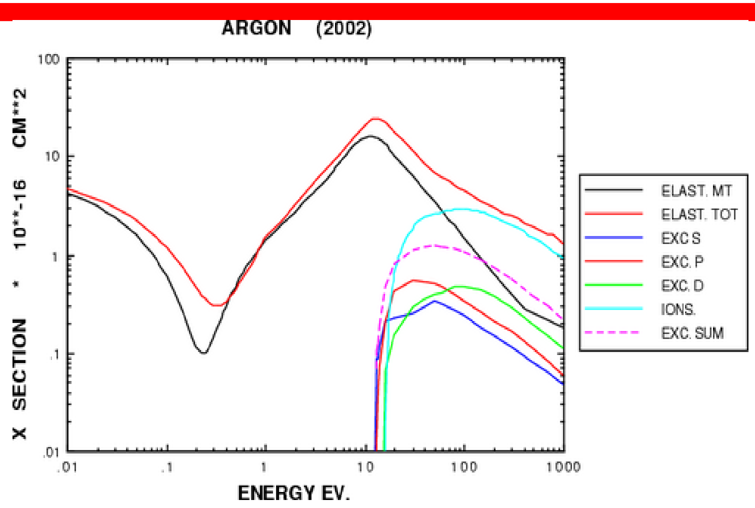
These 4 parameters are required to describe the *physics*

Additional Parameters:

- Townshend Coefficient (production of secondary ionization)
- Attachment Coefficient (electron capture by gas molecules)

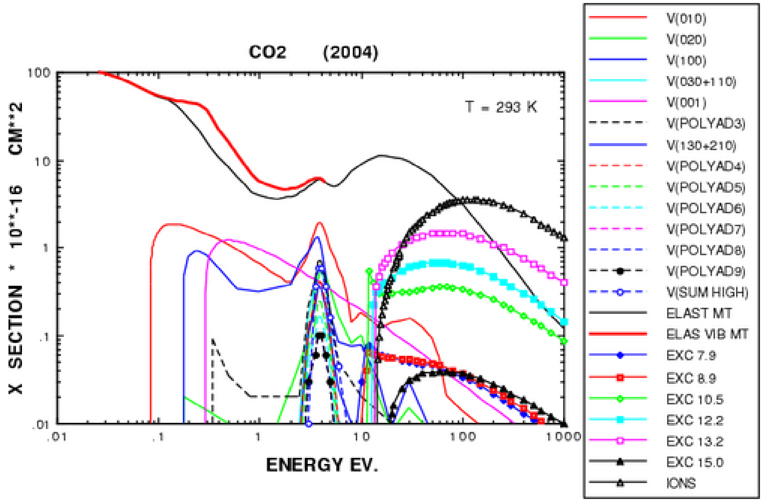
Magboltz – Parameterization of Gases

- Behaviour of a single electron over large number of collisions represents mean behaviour of electron swarm
  - ~10^5 collisions



<u>Required Inputs:</u>

- Cross Sections (from experiment)
  - Elastic
  - Inelastic
  - Attachment
  - Ionizing
  - Super elastic
- Field geometry (strength and angle)
- Gas mixture (percentages)



Example cross section inputs for Magboltz (*http://rjd.web.cern.ch/rjd/cgi-bin/cross?update*)

Magboltz – MC Calculation

- During free flight, δt, electron follow simple kinematics equations
- Only unknown is δt find using Null collision technique
  - HR. Skullerud, J. Phys. D 1 (1968)
- Angular distribution calculated by technique of Longo and Capitelli
  - S. Longo *et al.* Plasma Chem. Process 14 (1993)

$$P_{Forward} = \frac{1}{2} + \frac{\sigma_{totIn} - \sigma_{ptrans}}{\sigma_{totIn}}$$

$$x_1 = x_0 + v_{x0}\delta t + \frac{e}{2m} E_x \delta t$$

$$y_1 = y_0 + \frac{\sin\Omega}{W}\left(v_{y0} - \frac{E_z}{W}\right) + \frac{v_{z0}}{W}(1-\cos\Omega) + \frac{E_Z \delta t}{W}$$

$$z_1 = z_0 + \frac{v_{z0}\sin\Omega}{W} - \frac{1}{W}\left(v_{y0} - \frac{E_z}{W}\right)(1-\cos\Omega)$$

$$v_{x1} = v_{x0} + \frac{e}{m} E_x \delta t$$

$$v_{y1} = \left(v_{y0} - \frac{E_z}{W}\right)\cos\Omega + v_{z0}\sin\Omega + \frac{E_z}{W}$$

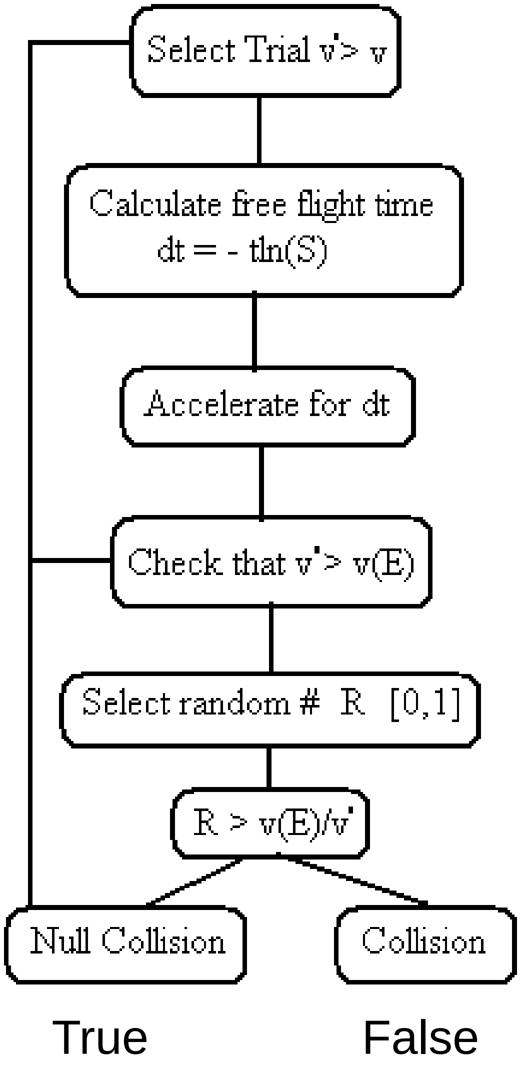
$$v_{z1} = v_{z0}\cos\Omega - \left(v_{y0} - \frac{E_z}{W}\right)\sin\Omega$$

Calculation of Parameters:

- Electrons energy, speed and position recorded after N collisions
- Drift velocity and Lorentz angle calculated from data using simple formulas
- Diffusion tensor calculated using

$$D_{ij} = \frac{1}{2N}\sum_{0}^{N}\frac{(x_i - v_i\delta t)(x_j - v_j\delta t)}{\delta t}$$

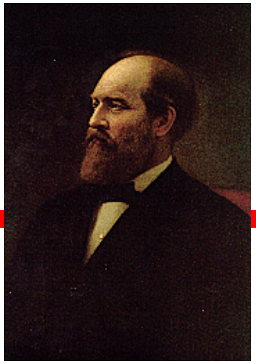
Magboltz – MC Calculation



- Collision frequency, υ, function of energy and since energy changes with time free flight time had to calculate

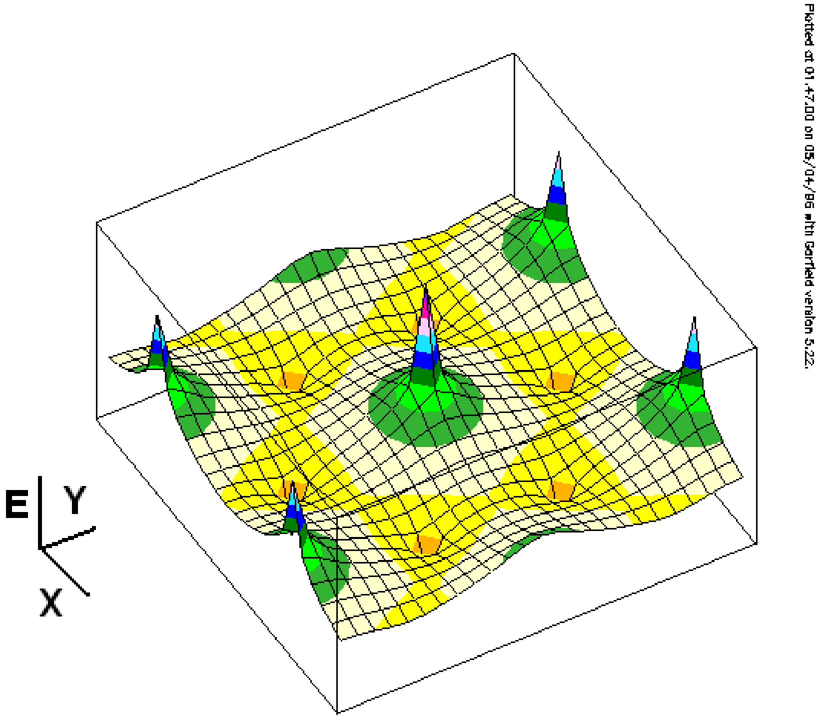
$$\tau = \frac{1}{\nu(E)}$$

What is Garfield?



"**Garfield** is a computer program for the detailed simulation of two- and three-dimensional drift chambers."

– *Garfield website*



- Example field map calculation done by Garfield for a "honeycomb" of wires.
(http://consult.cern.ch/writeup/garfield/examples/hex1.gif)

- FORTRAN based
- Wrapped for use in C++ by Rob Veenhof
- Amalgamation of Programs
  - Heed, Magboltz, Maxwell

<u>Reasons to Interface with Geant4:</u>

- Access to Magboltz!
  - Increase accuracy and speed for transport through Gases
- Easy Implementation of EM fields

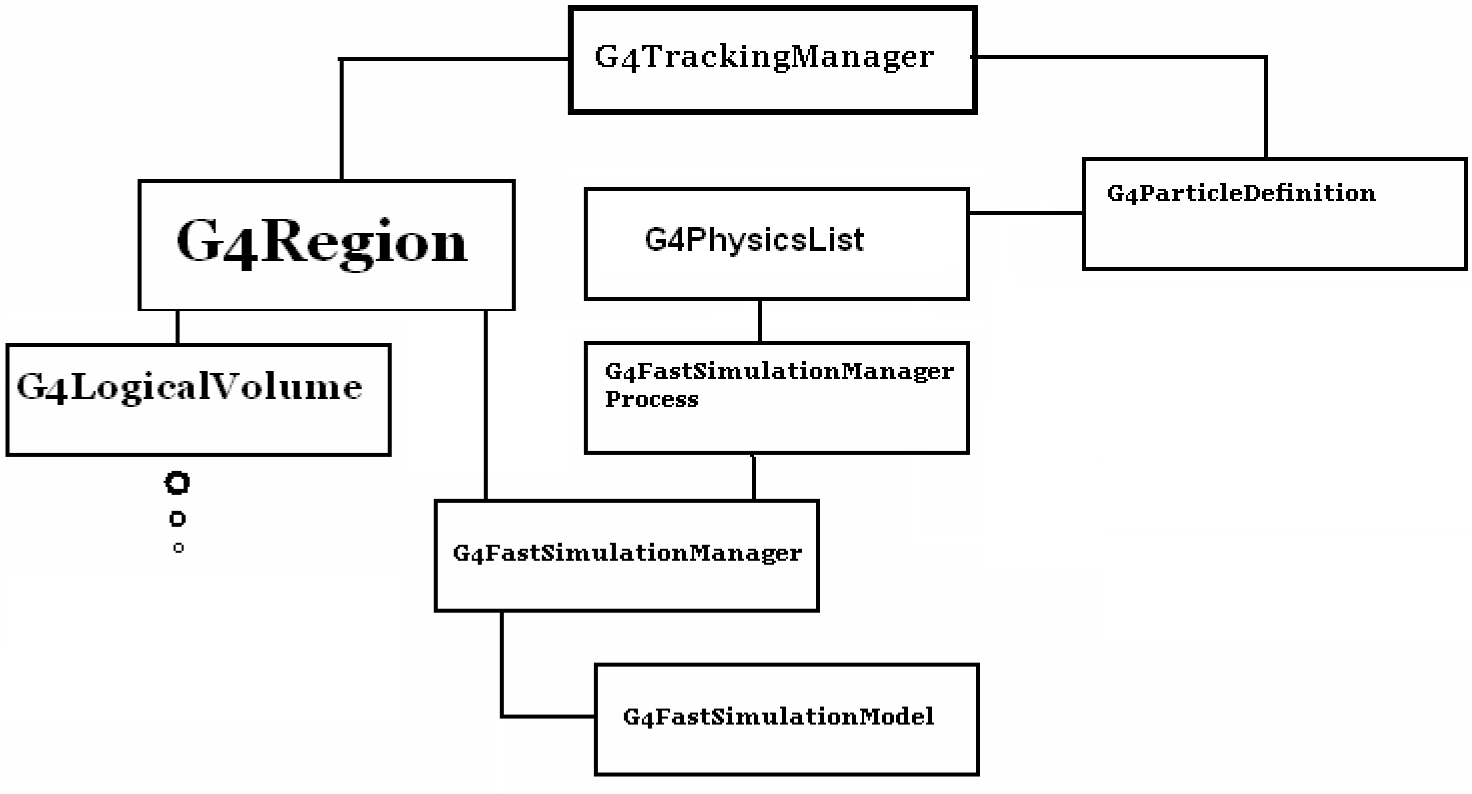
Components of a Garfield Simulation

- Detector described by 2 classes
  - Cell
  - Gas
- Simulation calculated by 3 classes
  - Track
  - DriftLine
  - Signal (not fully implemented)

How do we connect Garfield and Geant4?

Geant4 Parameterization Framework

"The Geant4 parameterization facilities allow you to shortcut the detailed tracking in a given volume and for given particle types in order for you to provide your own implementation of the physics and of the detector response." – *Geant4 Application Developers Guide*



Geant4 Parameterization Framework

- To implement parameterization need to define concrete instance of abstract class G4VFastSimulationModel:
- Define 3 pure virtual functions:
  - void DoIt(G4FastTrack&, G4FastStep&)
  - bool isApplicable(const G4ParticleDefinition&)
  - bool ModelTrigger(const G4FastTrack&)

Interfacing Geant4 and Garfield

- Primary Particle
- Detector geometry

- Primary Particle
- Ionized electron Paths

Need to create Garfield Simulation in Geant4:

- Cell
- Gas
- DriftLine
- Track

Want to do this using G4FastSimulationModel:

- Define constructors
- Define pure virtual functions
  - isApplicable
  - ModelTrigger
  - DoIt

G4FastSimulationModel: GarfieldModel

GarfieldModel Class Definition:

- Declares Members:
  - *Cell * cell*
  - *DriftLine * dl*
  - *Gas * gas*
  - *Track * track*
  - *G4PolyLine* electronPaths*

- Member Functions:
  - Constructors
  - *void BuildCell()*
  - Get methods
  - Virtual Functions
    - *bool isApplicable*
    - *bool ModelTrigger*
    - *void DoIt*

G4FastSimulationModel: GarfieldModel

Constructors:

- Defines Gas
- Initializes DriftLine and Track
- Specialized for drift techniques
- initializes Gas, DriftLine and Track
- does NOT define Cell

GarfieldModel*(G4String modelName, G4Region* envelope, G4String gasFile, G4String trackModel, G4String driftModel,G4String mcMethod, G4double maxE, G4double maxStepLength, G4double interval);*

GarfieldModel*(G4String modelName, G4Region* envelope, G4String gasFile, G4String trackModel, G4String driftModel, G4double accuracy, G4double maxE);*

GarfieldModel*(G4String modelName, G4Region* envelope, G4String gasFile, G4String trackModel, G4String driftModel, G4double maxE);*

G4FastSimulationModel: GarfieldModel

<u>Pure Virtual Functions</u>:

- ***isApplicable*** and ***ModelTrigger*** return true
- ***DoIt****(const G4FastTrack&, G4FastStep&)*

incoming

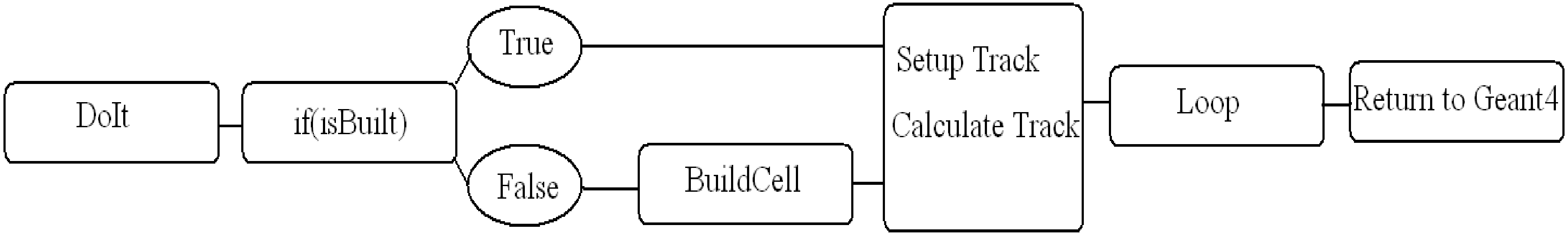
- Access
  - logical volume
  - Incident particle

outgoing

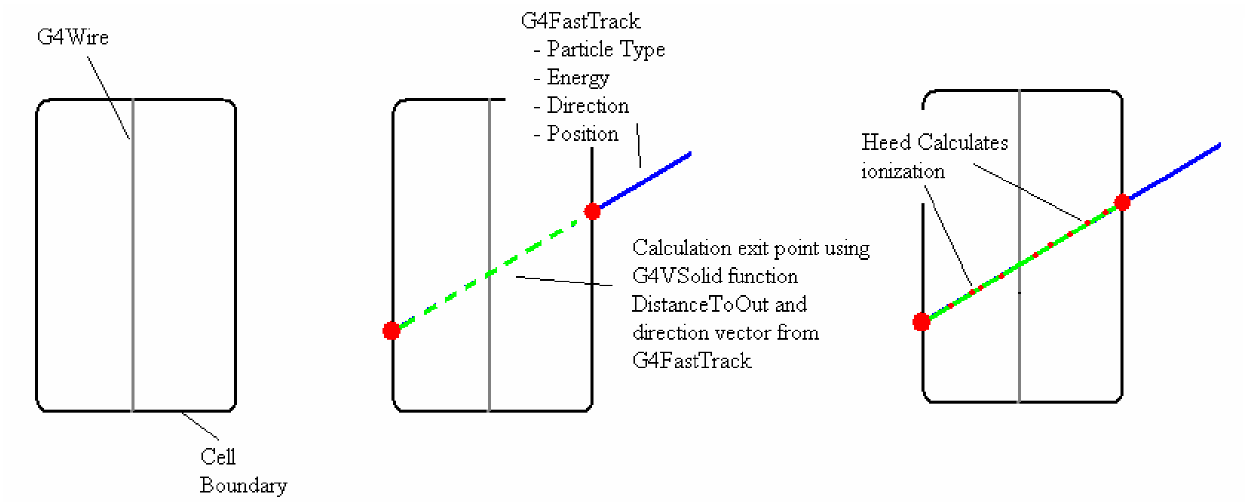
- Return particle to Geant4

G4FastSimulationModel: GarfieldModel

The DoIt Member Function Flow Chart:

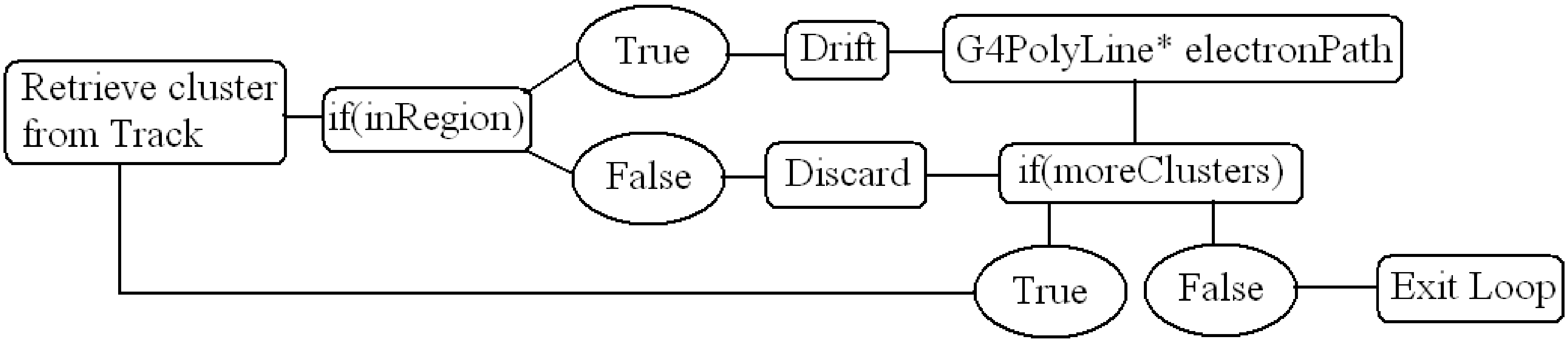


The DoIt Member Function Pictorial Representation:



G4FastSimulationModel: GarfieldModel

The DoIt Member Function Loop:



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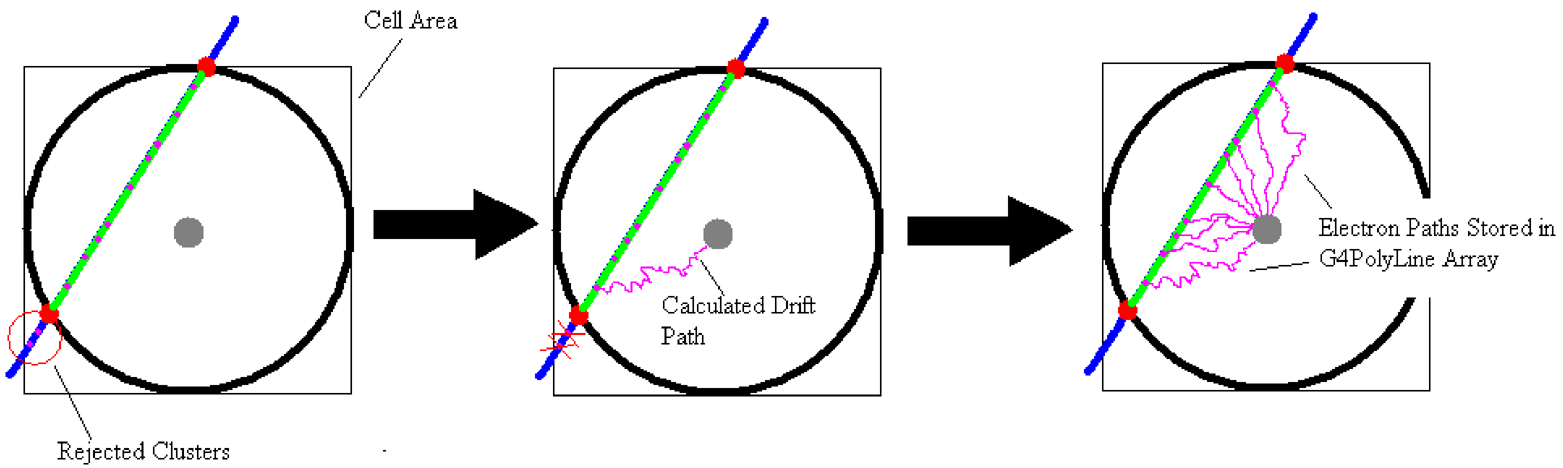

G4FastSimulationModel: GarfieldModel

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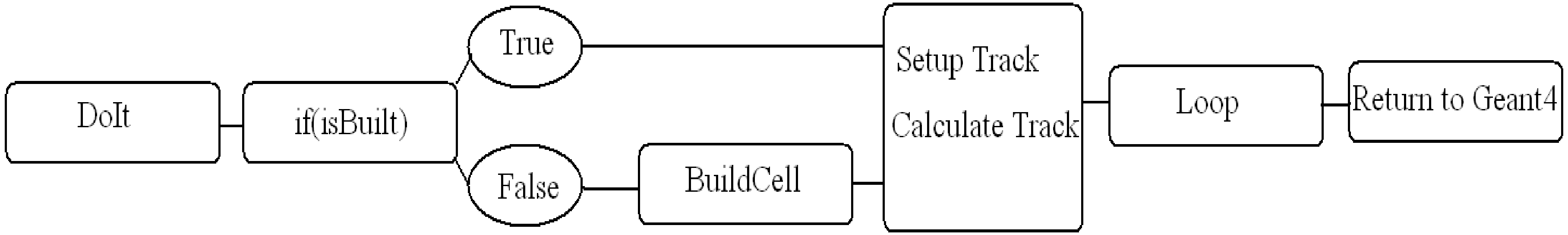

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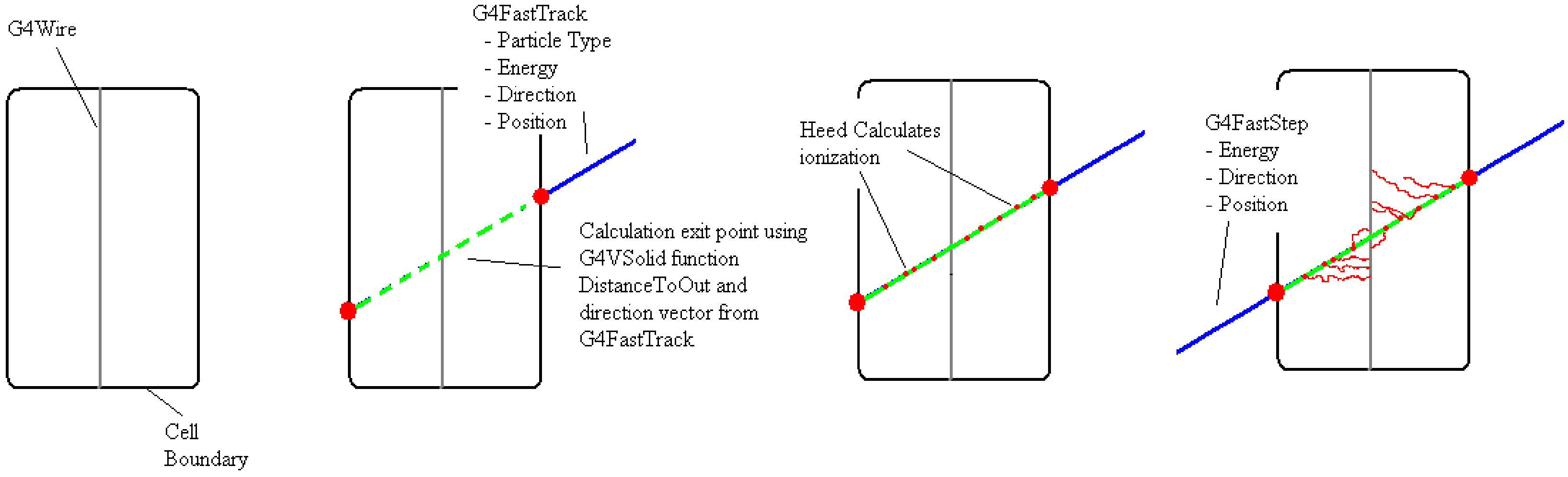
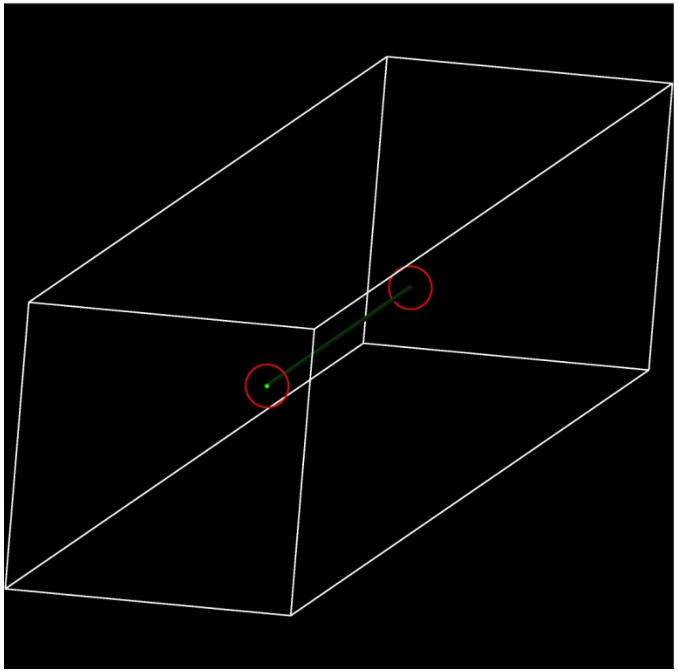


Example: Atlas Muon Tube

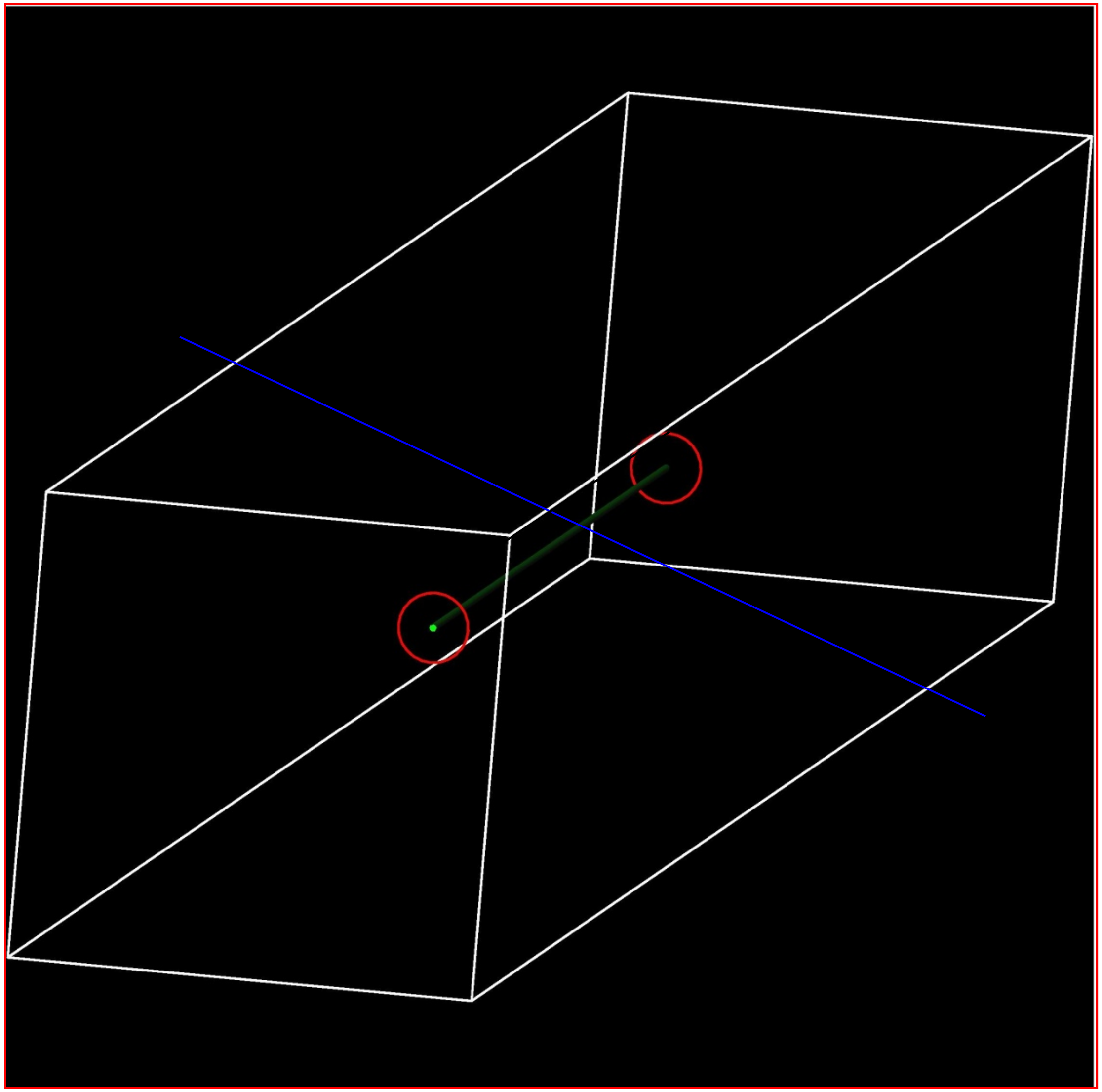
- Tube R = 1.5 cm
- Al wire R = 30 um
- Gas mixture 93% Argon and 7% CO_2
- T = 25^{o}C and P = 3 atm

} Geometry defined in Geant4



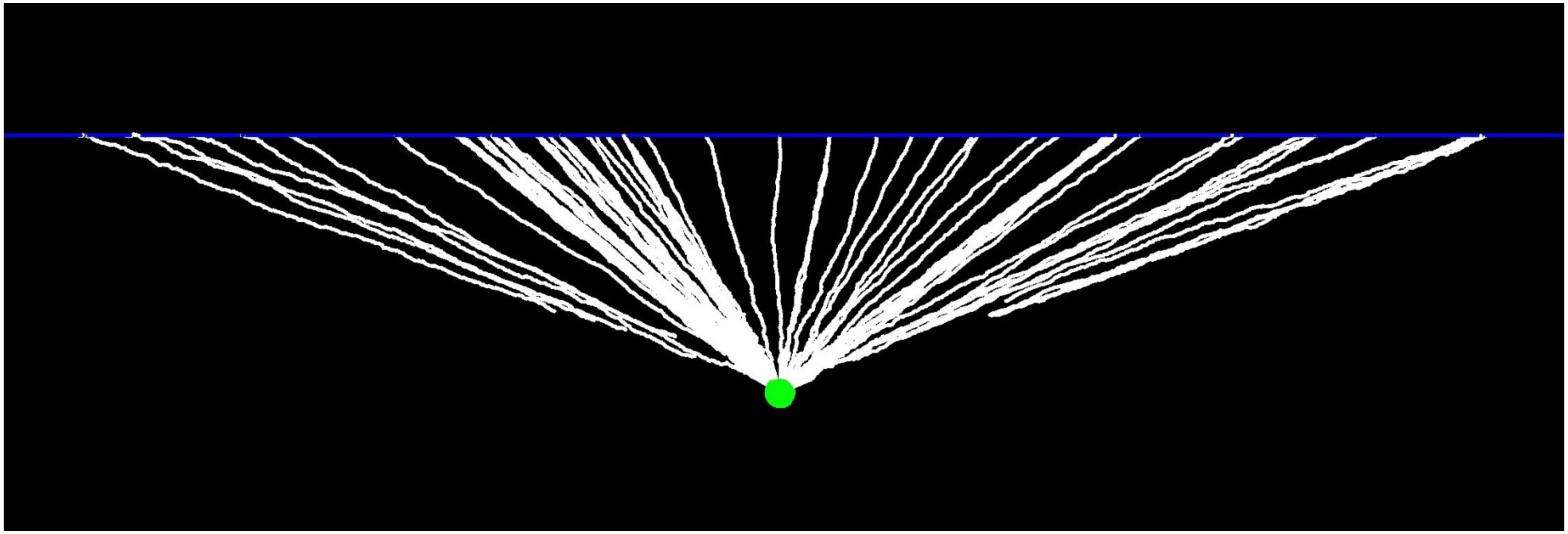
- Attach GarfieldModel to Tube Region
- Use both MC and RKF drift techniques

Example: Atlas Muon Tube



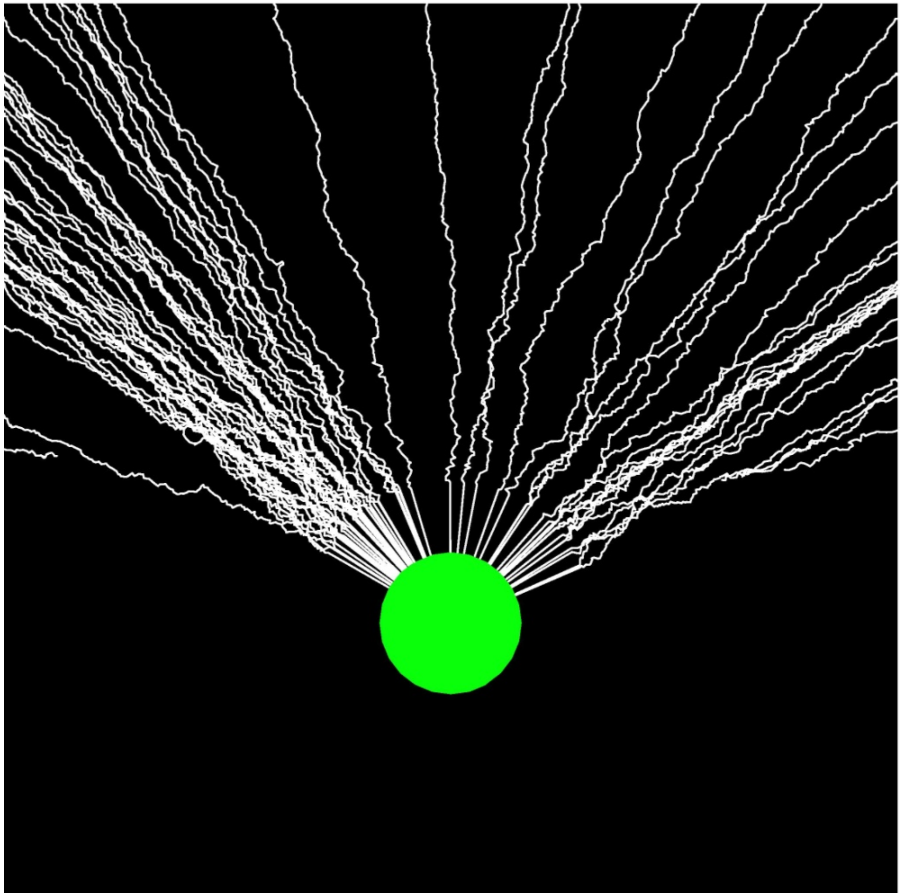
Example: Results

Visualization of Electron Paths in Geant4:



Example: Results

Visualization of Electron Paths in Geant4:



Conclusion and Future Work:

- Interface between Geant4 and Garfield Successful
  - Can run Garfield Simulation in Geant4 and exchange information
- Basic interface complete however Garfield has many more features
  - More ionization models
  - FEA field maps
  - Magnetic fields
  - Signal Calculations

Thanks for Listening

Questions?

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