Simulation and Reconstruction of Charged Particle Trajectories in an Atypic Time Projection Chamber

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1 Introduction

Time Projection Chamber (TPC) is a type of gaseous detector that detects charged particle trajectories by measuring the position and drift time of ions created in the gas (details are given in section 2). The energy of such particles can be determined thanks to the curvature of their trajectory in the magnetic field.

The goal of this thesis is to develop an algorithm for reconstruction of charged particle trajectory and energy in an atypic TPC (with orthogonal electric and magnetic fields, i.e. Orthogonal Fields TPC, abbreviation OFTPC) used in the X17 project in Institute of Experimental and Applied Physics, Czech Technical University in Prague (IEAP CTU). Furthermore, we present the results of testing this algorithm with different samples of simulated data. In the future, we also wish to test this algorithm by measuring real particles with known energy distribution. In order to achieve this, we use the Garfield++ toolkit [1] in combination with the ROOT framework [2]. We run some of our more demanding simulations on MetaCentrum.

The X17 project in IEAP CTU aims to reproduce measurements of anomalous behavior in the distribution of angular correlation of pairs produced by the Internal Pair Formation (IPF) mechanism during the decay of certain excited nuclei (^{8}Be, ^{12}C and ^{4}He) observed by the ATOMKI group in Hungary.

Add citations MetaCentrum, X17 project, VdG, ATOMKI papers. Maybe also TPC, IPF, ...

1.1 ATOMKI Measurements

Short summary of results of measurements in ATOMKI.

1.2 X17 IEAP CTU

Short description of our detector. Why we use atypic TPC. Magnetic field simulations in Maxwell. Description of the coordinate system used in this thesis (+ figure).

2 Time Projection Chamber

Description of TPC, working principle, standard vs our field layout.

3 Track Simulation

In order to develop and test the reconstruction algorithm, electron and positron tracks are simulated inside our detector with different initial parameters. Three approaches are used to simulate tracks for different purposes.

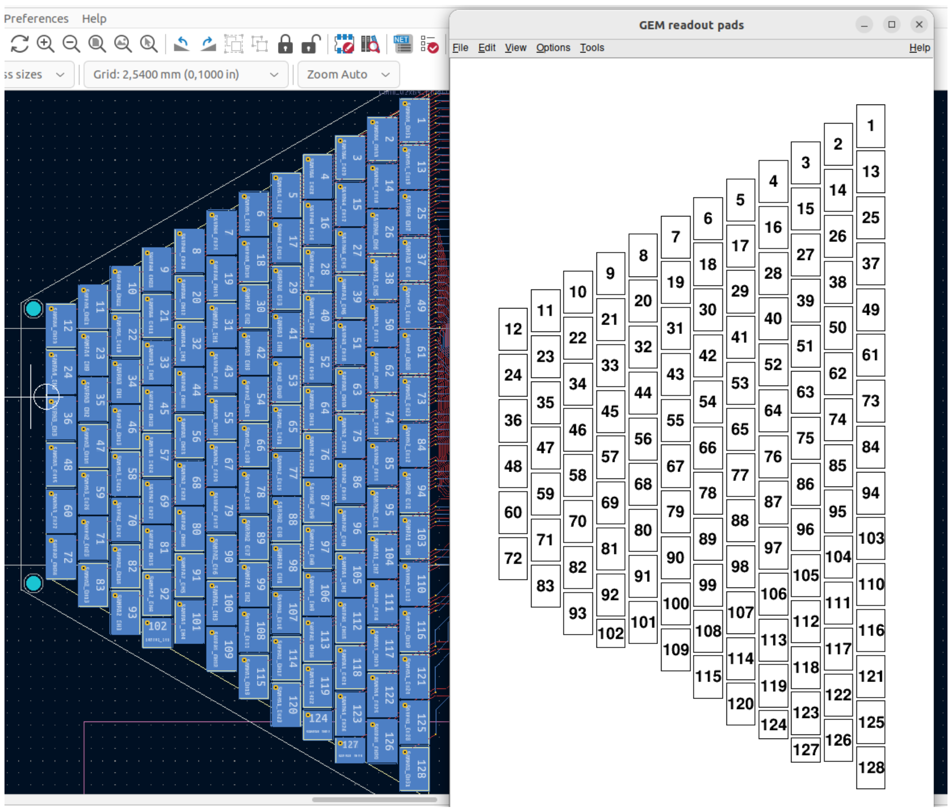

Figure 1: Pad layout of the TPC. Swap for better image.

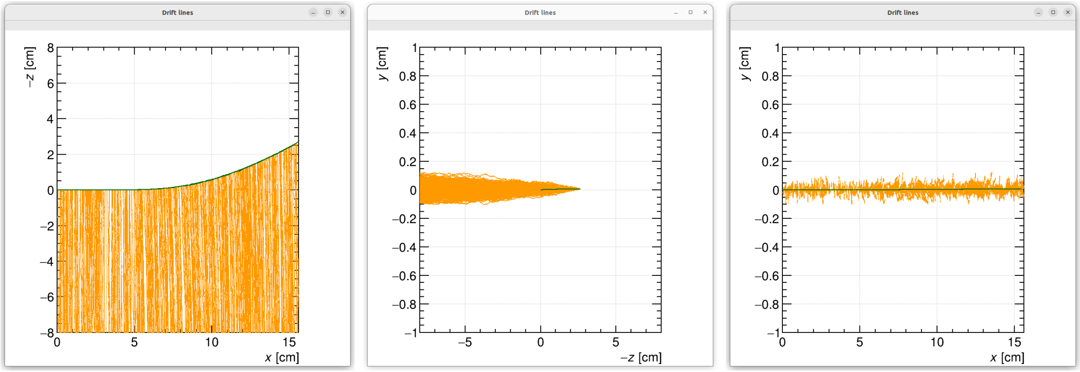

Figure 2: Example of a simulated electron track in 70 % argon and 30 % CO_2 atmosphere (on the left). Swap for better images, better zoom. Explain drift lines, primary particle.

The **Microscopic Simulation** uses the Garfield++ toolkit [1]. Within this toolkit, the program HEED (High Energy Electro-Dynamics) [3] is used to simulate the primary particle and class *AvalancheMicroscopic* to simulate the drift of secondary electrons created by ionization in the gas. This is the most precise and time-consuming simulation used, our current goal is to be able to successfully reconstruct its results and determine our best-case energy resolution.

The **Runge-Kutta Simulation** uses the 4th order Runge-Kutta numerical integration (add citation for Runge-Kutta) to simulate the trajectory of the primary particle in the electromagnetic field inside the detector. It is relatively fast since it does not simulate the secondary particles. It is used as a part of our reconstruction algorithm as well as for testing of some parts of the reconstruction.

The **Fast Simulation with Ionization Electron Map** is planned for the future, it will use the HEED program [3] to simulate the primary particle and the Ionization Electron Map (see section 4.2) to simulate the drift of secondary electrons. It should be significantly faster than the Microscopic Simulation but offer comparable precision since it will rely on an already simulated drift map.

All of these simulations require the knowledge of the electromagnetic field inside the detector. Uniform electric field 400 V$\cdot$cm^{-1} is assumed. The magnetic field was simulated in Maxwell (add citation? details? own subsection with figures? more details in section 1.2?).

Single track in positive x direction or initial parameters randomization. Importance of gas composition, used gas compositions.

3.1 Microscopic Simulation

Primary track simulated in HEED. Ionization electron drift simulated with AvalancheMicroscopic in Garfield.

3.2 Runge-Kutta Simulation

Trajectory simulation with 4th order Runge-Kutta. Relativistic equation that is numerically integrated by the algorithm.

3.3 Future?: Fast Simulation with the Ionization Electron Map

Primary track simulated in HEED. Readout parameters by interpolating the map. Diffusion from the map for randomization.

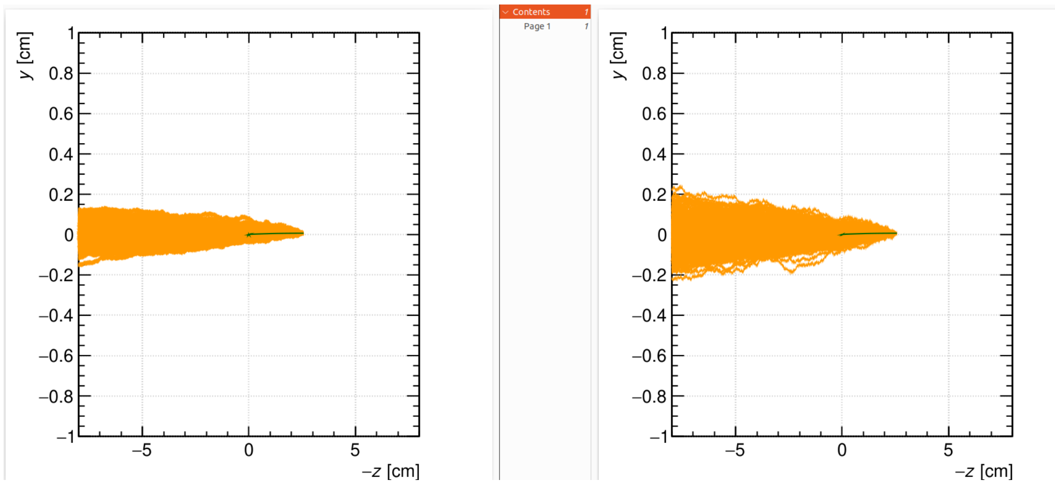

Figure 3: Comparison of diffusion in a simulated electron track in 70 % argon, 30 % CO_2 atmosphere and in 90 % argon, 10 % CO_2 atmosphere (on the right). Swap for better image, better zoom. Or put same pictures for both comparisons in one subfigure, etc. Describe better.

4 Track Reconstruction

The first stage of our reconstruction algorithm is the reconstruction of the track of the primary particle (electron or positron). The results of this step are then used to determine the energy of the particle (see section 5).

First Attempts at a track reconstruction were made using the standard approach. Here we assume we know the readout coordinates (x', y', t) exactly (i.e. we neglect the pads and time bins). In standard TPC (with parallel fields) we only need to reconstruct the z coordinate from drift time using the known drift velocity.

Reconstruction with the **Ionization Electron Map** (from now on referred to as *the map*) uses simulation of the drift of the secondary (ionization) electrons in the volume of the detector. This simulation can then be used to interpolate the initial position of the secondary electrons. First attempts neglect the pads.

The **Discrete Reconstruction** is made using the map, instead of reconstructing the exact position of each electron we reconstruct the middle point of each hit pad with time corresponding to the middle of the time bin. The number of electrons in each TPC bin (consisting of the pad and the time bin) is counted and used as a charge in the energy reconstruction.

Reconstruction of one track simulated with microscopic tracking in Garfield++.

4.1 First Attempts

Using the same method as in standard TPC (calculating z from the drift time). Gas composition 90/10.

4.2 Ionization Electron Map

Explanation of the map. Simulated on MetaCentrum, workload distribution between multiple jobs. More electrons at one location to get statistics. Two methods of reconstruction using this map. Comparison of 90/10 and 70/30 maps.

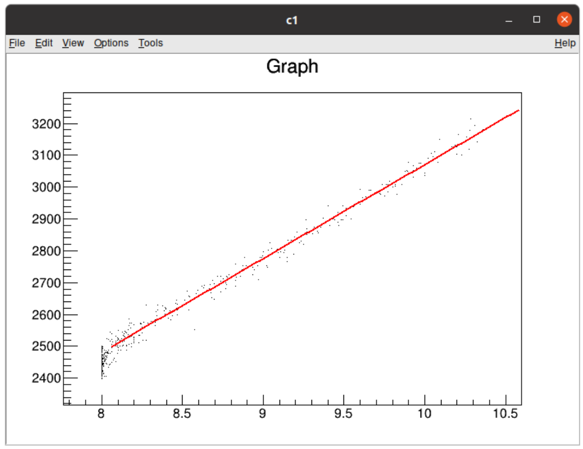

Figure 4: Dependence of the drift time on the z coordinate in 90 % argon and 10 % CO_2 atmosphere, fitted with a linear function. The fitted function gives us the average drift velocity in the gas and can be used for rough reconstruction in our TPC. Swap for better image with axis labels, etc. Maybe write the fitted equation.

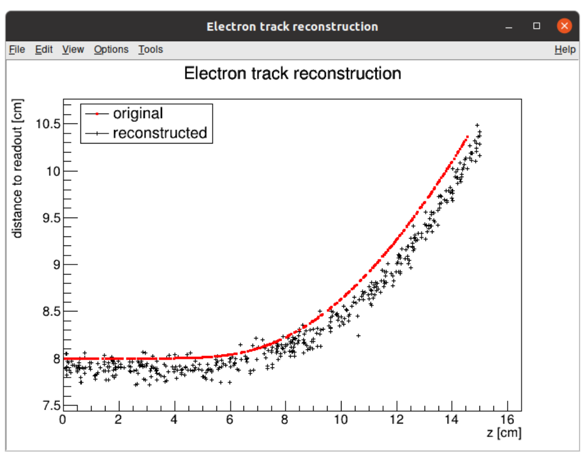

Figure 5: First attempt at a track reconstruction using only the drift velocity. This approach works well in a standard TPC (ideally cite some source?). 90 % argon and 10 % CO_2 atmosphere. Swap for better image, correct coordinates.

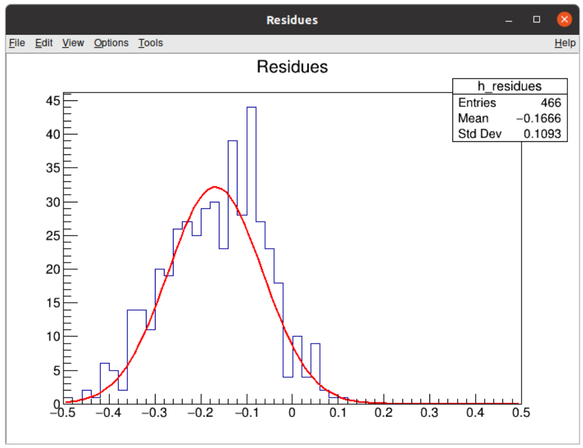

Figure 6: First attempt at a track reconstruction using only the drift velocity, residues. Swap for better image, correct coordinates. What's causing the shift? Explain details.

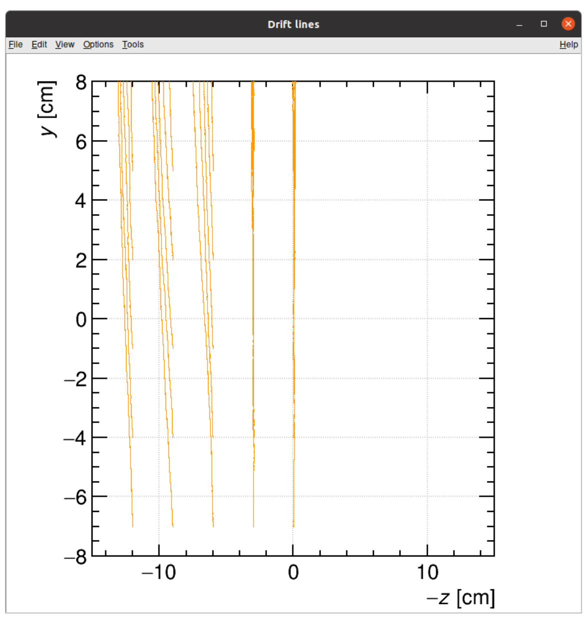

Figure 7: Example of map generation. Swap for better image, correct coordinates.

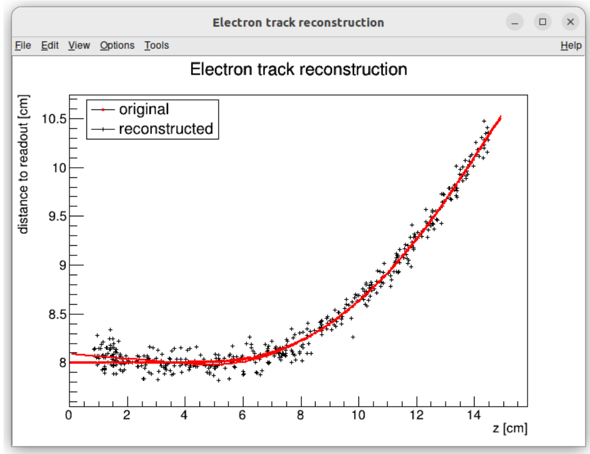

Figure 8: Example reconstruction with the map. Swap for better image, correct coordinates.

4.2.1 Gradient Descent Search

Gradient descent search of a point in the original space that gets mapped to the given point of the readout space (trilinear interpolation).

4.2.1.1 Trilinear Interpolation

Explanation of trilinear interpolation.

4.2.2 Interpolating in the Inverse Grid

Interpolating between known points in the readout space. Gaussian elimination, multivariate polynomial.

4.3 Discrete Reconstruction

Reconstruction with pads and time bins. Maybe testing different pads.

5 Energy Reconstruction

The second stage of our reconstruction algorithm is the reconstruction of the particle's energy using its reconstructed track (see section 4). We can achieve this by fitting the track and extracting the needed parameters of the trajectory. We have tested three ways of reconstructing the energy. Fitting is done using the MINUIT algorithm implemented in ROOT [2]. Maybe cite some CERN article directly on MINUIT?

The **Cubic Spline Fit** is a rejected attempt at the reconstruction of energy. It uses smoothly connected piecewise cubic polynomials between uniformly spaced nodes. Energy can then be computed using from the fit parameters by computing the radius of curvature in different points of the fitted curve using the known magnitude of the magnetic field perpendicular to the trajectory. This approach was rejected because tuning the fit to have a reasonably stable radius of curvature is unpractical.

The **Circle and Lines Fit** was chosen as an alternative since this corresponds to the shape of a trajectory of a charged particle moving through a finite volume with a homogeneous magnetic field. The energy of the particle can be estimated using the fitted radius and the magnitude of the perpendicular magnetic field in the middle of the TPC.

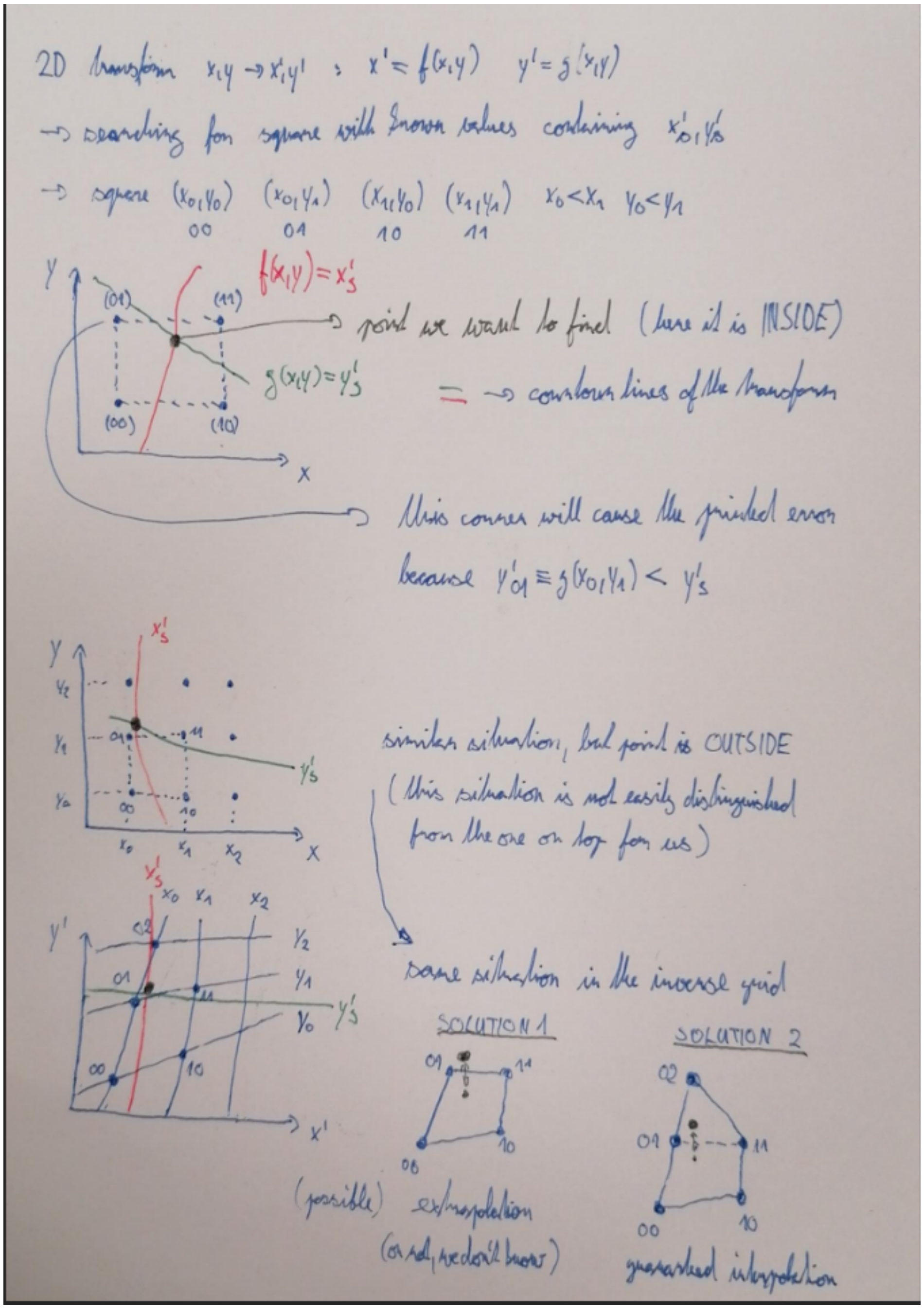

Figure 9: Selection of the points for interpolation. Create better images, use the explanation interpolation vs extrapolation strange property. Solution 2 probably does not make much sense.

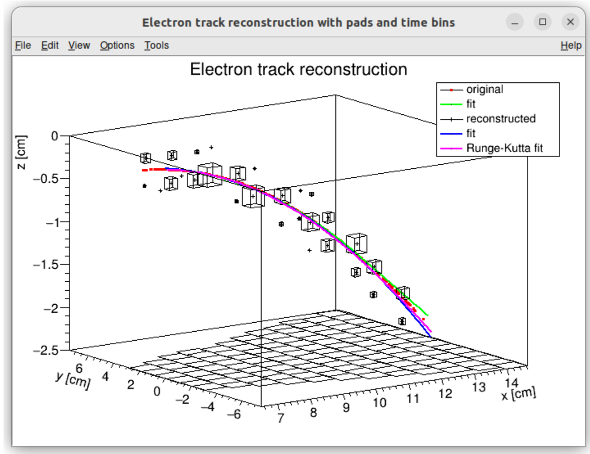

Figure 10: Example of a fitted reconstructed track. Swap for better image.

The **Runge-Kutta Fit** uses the 4th order Runge-Kutta numerical integration described in section 3.2. Initial parameters of the track (including the particle's energy) are optimized so that the integrated trajectory fits to the reconstructed one. This fit can also be performed as a single parameter (energy) fit if we can get the initial position and orientation of the particle on the entrance to the TPC from previous detectors (Tpx3 and MWPC, see section 1.2).

5.1 Cubic Spline Fit

Bad attempt at energy reconstruction using cubic splines.

5.2 Circle and Lines Fit

Energy reconstruction with circle and lines fit. Trilinear interpolation of the magnetic field. Tested on Runge-Kutta sample, future testing with microscopic simulations and map simulation. Preliminary 2D version and complete 3D version. Geometry of the fit with its derivation.

5.3 Runge-Kutta Fit

Single parameter fit with 4th order Runge-Kutta simulated track. Future testing with microscopic simulations and map simulation. Derivation of the geometry (least squares).

6 Conclusion

Here or at the end of each section.

References

[1] Garfield++. `https://garfieldpp.web.cern.ch/garfieldpp/`. Accessed: 2023-05-18.

[2] Rene Brun and Fons Rademakers. Root — an object oriented data analysis framework. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 389(1–2):81–86, Apr 1997. Proceedings AIHENP'96 Workshop, Lausanne, Sep. 1996, See also https://root.cern/, Paper published in the Linux Journal, Issue 51, July 1998.

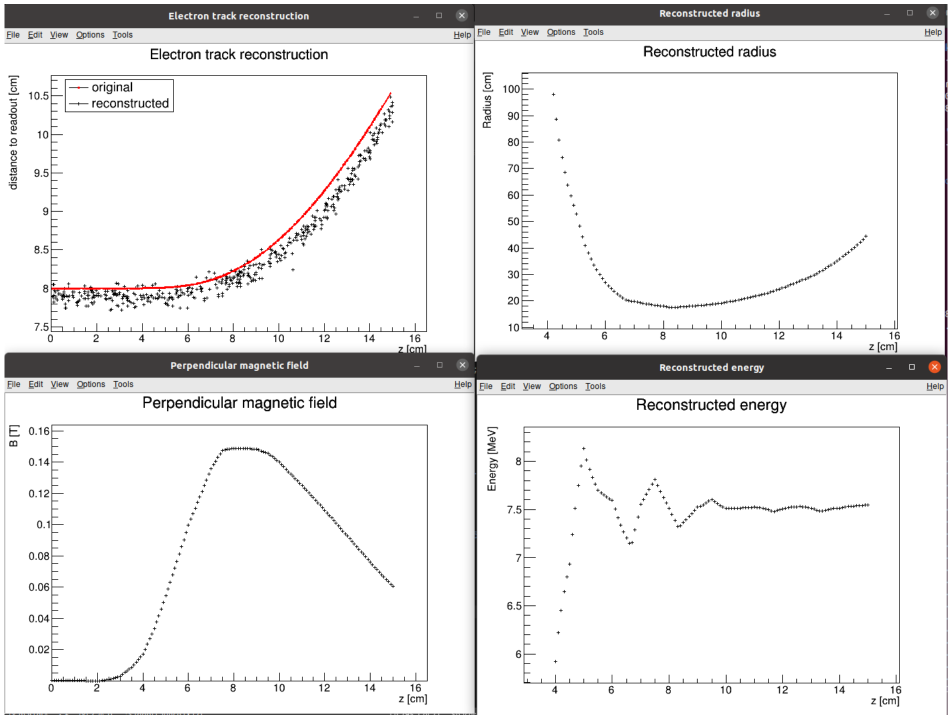

Figure 11: First attempt at a track reconstruction using only the drift velocity. Spline energy reconstruction attempt. Swap for better image(s) – subfigure enviroment., correct coordinates.

[3] I.B. Smirnov. Modeling of ionization produced by fast charged particles in gases. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 554(1):474–493, 2005.

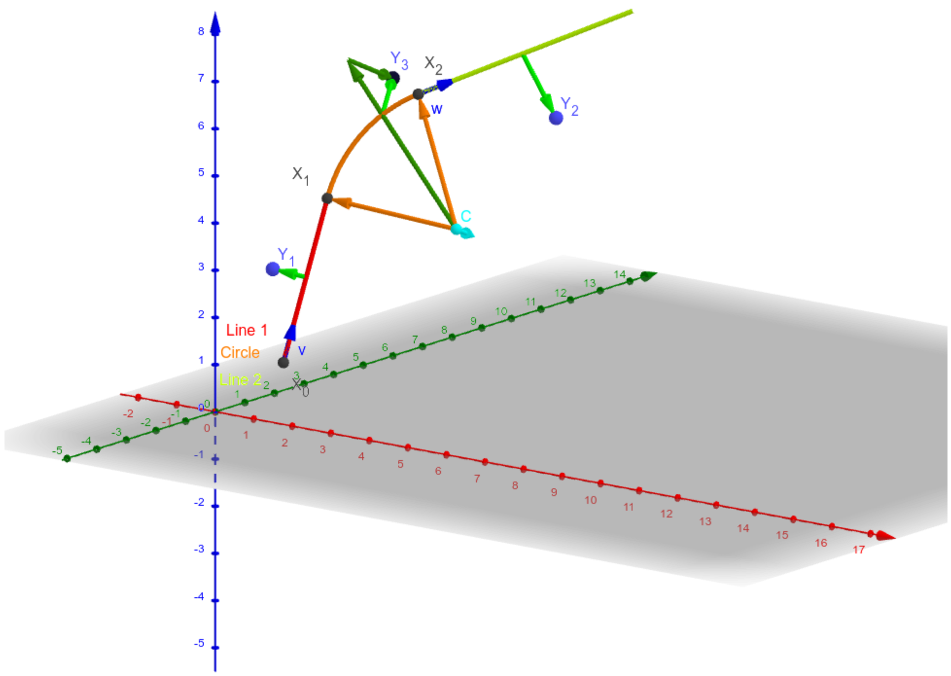

Figure 12: Circle and Lines Fit 3D geometry. Swap for better image.

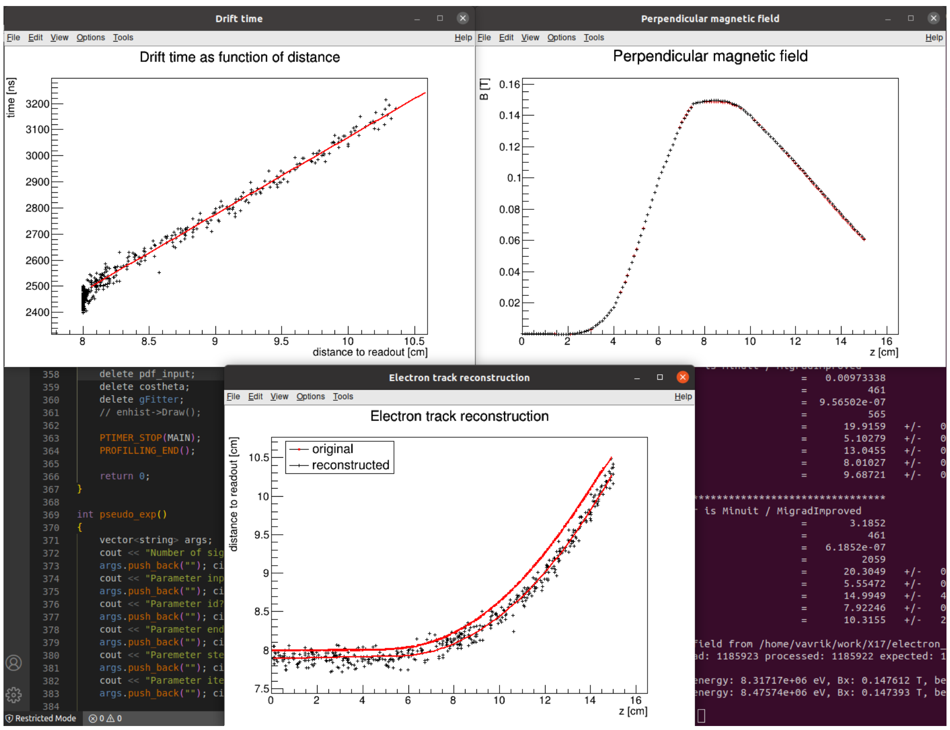

Figure 13: First attempt at a track reconstruction using only the drift velocity. Circle and Lines Fit in 2D. Swap for better image, correct coordinates.