Garfield Simulation of Multiwire Proportional and Drift Chambers for the μCAP Experiment

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Abstract: The goal of this project is to simulate the multi-wire proportional chamber (MWPC) of μPC2 and drift chamber of the time projection chamber (TPC) for the μCAP experiment using Garfield simulation software. The proposed simulation optimizes the drift region of the TPC by adding wires in order to produce a more homogeneous electric field. The simulation also allows investigation into specific regions of the MWPC of the TPC and μPC2. Approximately six to ten wires were added to the corners of the TPC in various simulations to improve the drift field and prevent charge collection on the HV cathode frames. Addition of wires to the TPC expanded the effective drift volume without significantly disturbing the homogeneity of the MWPCs, or increasing charge build up on the insulators.

Table of Contents

1 Introduction

The purpose of this project is to simulate electric field lines and particle trajectories inside the muon detector chamber using Garfield software. This simulation serves the purpose of optimizing the time projection chamber (TPC) by adding wires for a more homogeneous electric field in the drift region. The simulation also allows investigating specific regions of the multi-wire proportional chambers (MWPC) in the internal beam chamber (μPC2) and TPC. The knowledge acquired from this simulation can help design a more efficient detector chamber by understanding the field line configurations.

1.1 Goal

The goal is to study the following features of μPC2 and TPC using Garfield simulation program:
- Homogeneity of the TPC drift region and MWPC
- Critical field gradients
- Charge build-up on insulators
- Delayed charge collection in MWPC

1.2 Method

The following methods are employed to ensure that the goals are met.
- Homogeneity of the TPC drift region and MWPC are analyzed through the plots of electric field and potential contours.
- Critical field gradients are determined from the electric field tables and plots along selected tracks.
- Charge build-up on insulators is explored via drift line plots of electrons for selected wires.
- Delayed charge collection in MWPC is examined via electron drift plots.

2 Description of Test Chambers

The two test chambers, μPC2 and TPC, are located inside a pressurized horizontal grounded cylinder. The side view of the cylindrical chamber is represented as two ground planes, one located on the top and the other on the bottom of the μPC2 and TPC. Fig. 1 shows the perspective backside view of the cylindrical chamber with the two test chambers embedded inside. Fig. 5 demonstrates the orientation of the wires for both chambers as well as the location of these two ground planes. The red and blue colors are chosen to show the wires' orientation; the red color represent wires running in the y and z directions whereas the blue symbolizes wires running in the x direction.

2.1 Time Projection Chamber (TPC)

The time projection chamber, TPC, detects the ionization tracks for charged particles in three-dimensions. This is accomplished by using a vertical homogenous electrical field of about 2.3 kV/cm inside the TPC and MWPC, which is located at the bottom of the TPC. High voltage TPC wires, which are located on the top of the TPC frame, are at potential –35 kV; they are equally spaced in the x-z plane and run in the z direction. Seven potential TPC wires form a field cage and wrap around the frame of the chamber running along the x and y direction, which are equally spaced between the high voltages TPC plane of wires and the MWPC. The placement and potential of these seven wires establishes a vertical nearly homogeneous electrical field. The MWPC consists of a plane of cathode, anode, and cathode strip wires, all lying in the x-z plane. The equally spaced anode wires of MWPC point in the x-direction unveiling the z coordinate of the ionization track; the equally spaced cathode and cathode strip wires stretch in the z-direction delivering the x coordinate of the ionization track. The drift time of the electrons determines the y coordinate, which is the height of the TPC.
Table 1 shows the model parameters used in the simulation as well as the design parameters for the TPC. The model parameters include the extended length of wires, caused by the solder pads on the frame of the TPC onto which the ends of the wires are joined.

2.2 2nd Muon Beam Chamber (μPC2)

The internal beam chamber, μPC2 is located in front of the TPC volume at approximately 7 cm. The MWPC of μPC2 provides precise tracking of the entering muons towards the TPC. The x positions of the muons are obtained from the MWPC equally spaced anode wires running in the y-direction and the y values of the muons are acquired from the equally spaced cathode wires running in the x-direction. The μPC2 is shielded from the high voltages of the TPC by a plane of grounded wires running in the x-direction; lying in the x-y plane.

Table 1: MuCap design and model parameters for TPC and μPC2 chambers

Parameter	μPC2		TPC	
	Design	**Model**	**Design**	**Model**
Cathode frame size (mm)	170 x 178 x 5	170 x 178 x 5	230 x 388 x 5	230 x 388 x 5
Anode frame size (mm)	170 x 170 x 2.5	170 x 170 x 2.5	246 x 380 x 2.5	246 x 380 x 2.5
Frames inner apertures	110 x 110	110 x 110	150 x 300	150 x 300
Anode/cathode distant (mm)	3.5	3.5	3.5	3.5
Cathode/strip cathode wires				
Diameter (μm)	50	50	50	50
Wire direction; spacing	X; 1 mm	X; 1 mm	Z; 1mm	X; 1 mm
Potential (kV)	-6	-6	-6.5	-6.5
Number of wires	110	112	150	150
Solder pads for strip cathode wires				
Diameter (μm)	-	0.49	-	0.49
Wire direction; spacing	-	X; 1 mm	-	X; 1 mm
Potential (kV)	-	-6	-	-6.5
Number of wires	-	-	-	39 (left); 45 (right)
Solder pads for cathode wires				
Diameter (μm)	-	0.49	-	0.49
Wire direction; spacing	-	X; 1 mm	-	X; 1 mm
Potential (kV)	-	-6	-	-6.0
Number of wires	-	-	-	9 (both ends)
Anode wires				
Diameter (μm)	25	25	25	25
Wire direction, spacing	Y; 4 mm	X; 4 mm	X; 4 mm	X; 4 mm
Potential (kV)	Ground	Ground	Ground	Ground
Number of wires	27	30	75	76
Solder pads for anode wires				
Diameter (μm)	-	0.49		0.49
Wire direction; spacing	-	X; 1 mm		X; 1 mm
Potential (kV)	-	Ground		Ground
Number of wires	-	23 (both ends)		9 (both ends)
TPC drift section				
Total drift length (mm)	-	-	120	120
Diameter of potential wires (mm)	-	-	0.5	0.5
Number of potential wires, spacing	-	-	7; 15 mm	7; 15 mm
Potential wires voltage grid (kV)	-	-	-(6.5 +1.2)	-(6.5 +1.2)
Diameter of HV wires (mm)	-	-	0.1	0.1
HV wire direction, spacing	-	-	Z; 1mm	X; 1mm
HV wire potential (kV)	-	-	-35	-35
Solder pads for HV wires				
Diameter (μm)	-	-	-	0.49
Wire direction; spacing	-	-	-	X; 1 mm
Potential (kV)	-	-	-	-35
Number of wires	-	-	-	7 (both ends)

Figs. 5 and 6 provide a detailed side view of the wire placement for μPC2 and Table 1 provides the model parameters used in the simulation as well as the design parameters for the μPC2. Similarly, the model parameters include the extended length of wires due to the solder pads on the frame of the μPC2 onto which the ends of the wires are soldered.

3 Description of Garfield Software and Simulation

3.1 Software Summary

The simulation software used for this project is Garfield version 7.05. Garfield calculates field maps, drift time, arrival time distributions and induced signals for two-dimensional chambers. In addition, it can interface with the Magboltz program, which computes the electron transport properties, and the Heed program that computes the cluster distribution for any gas. The Garfield help web page is available on the World Wide Web at http://consult.cern.ch/writeup/garfield/help/.

3.2 Simulation Procedures

3.2.1 Accessing Garfield

The following steps describe the procedures to enter Garfield, run a simulation, halt a simulation and exit Garfield. To access Garfield from an xterm window at a UNIX workstation at UIUC do the following:

a. Login into an npl account.
b. Be sure Garfield-7 exists in directory: `/usr/local/bin.`
c. Type `csh` at the command prompt.
d. Type `garfield-7` at the UNIX prompt and press enter.
e. Specify the workstation type (This enables plots to be displayed on the screen as the program is running. e.g. entering a number from 1-10 brings up the Higz window of different size).
f. When the command prompt `Main:` is displayed, Garfield is now active. Either enter Garfield commands such as `&cell` or run a simulation by typing `<filename`. For example `Main:<tpcs.in` will run the program file `tpcs.in` that is written in Garfield codes and is created with any text editing software.
g. While a simulation is running, hitting `Ctrl-C` exits Garfield completely and returns to Unix prompt.
h. While a simulation is not running, typing `&Stop` exits Garfield completely and returns the user back to the Unix prompt.

3.2.2 File Formats and Naming Conventions

The method used in naming the files is meant to differentiate the prototype program from the modified versions as well as file formats. The following are the description of the file formats used for the simulation:

a. Files ending with *`.in`* are the main simulation program files that contain `CELL`, `FIELD`, `GAS`, and `DRIFT` sections as described by Garfield. These files when compiled require cell and gas data files to be inputted to complete a simulation run. They also generate output files that contain plots. Refer to Attachment 1 for a sample of `.in` file.
b. Files ending with `.cel` are simulation program files but contain just the `CELL` section. These files, which contain cell description, when compiled output cell data and cell plot. See Fig. 5 for an example of a cell plot and Attachment 2 for a cell file. The cell data file generated is used by the `.in` file to acquire cell description. These files must be compiled first because the output cell data is needed by the `.in` files. The advantage of creating `.cel` files is to greatly reduce the run time of the main simulation program because Garfield does

not need to calculate the cell data again; it just gets the data directly from data file. In addition, these files need to be compiled only once if the cell parameters remain the same.

c. Files ending with `.gas` are also simulation program files, however they only contain just the `GAS` section. Only one file is created for use by the main simulation program files because the gas description is independent of the cell description. See Fig. 2 for the gas plots and Attachment 3 for a gas file.
d. Files ending with `.out` are outputted data files. These data files are generated by programs in `.cel` and *`.gas`* files, and are read by the programs when called upon by `.in` files.
e. Files ending with `.dat` are also outputted data files and generated by program files, however they are not read by the programs. The data saved, in these files, are usually in some sort of table format; hence, it is easier to read and is user friendly.
f. Files ending with `.ps` are plots outputted in a postscript format. These graphics files are outputted by the `.cel`, `.gas` and `.in` files to save certain plots in a postscript format
g. Finally, files ending with *`.eps`* are plots saved in encapsulated postscript format, they are outputted by the `.cel` and `.in` program files.

The following are the descriptions of the file naming conventions that are used to designate files corresponding to different cell types and scaling of cathode, high voltage, and solder pad wires. All the filenames contain the word `tpcs`, which signifies side view of TPC.

a. All files that begin with the same number belong to a group that fits a description of cell parameters regardless of their format (for example: 3 in the filename ***3***`tpcs11f4.eps`). Exception is made only for the prototype group (file names that begin `tpcs`) that fits the non-modified model cell parameters. The prototype program files `tpcs.in` and `tpcs.cel` are the basic model upon which all the other modified versions are built on. Table 2 lists the description of the cell for each numbers used.

Table 2: Filenames that begin with a number corresponds to a particular type of cell number or alternatively characters refer to specific model.

Cell number	Character	Modification made to the model cell (side view)	See Fig.
	A	Model Cell; prototype	A-1
1	B	10 wires added: 3 on left of high voltage plane, 3 on right of high voltage plane, 2 on the left of MWPC of TPC, and 2 on right of MWPC of TPC.	B-1
2	C	As A, but 2 ground planes moved closer to the chambers.	C-1
3	D	As B, but 2 ground planes moved closer to the chambers.	D-1
4	E	Plane of wires added on the left and right of the high voltage plane. 6 wires added: 1 on left of high voltage plane, 1 on right of high voltage plane, 2 on the left of MWPC of TPC, and 2 on right of MWPC of TPC.	E-1
5	F	As E, but 2 ground planes moved closer to the chambers.	F-1

b. Two numbers following `tpcs` in a filename correspond to the scaling of the number of selected wires present in a cell (for example: 11 in the filename `3tpcs`***11***`f4.eps`). The first number controls the density of cathode and high voltage wires; the second number controls the wires that represent solder pads. As the number increases, the total number of wires decrease in the cell and therefore shortens the amount of time it takes for the program files `.in` and `.cel` to run. This method is helpful especially when there are large numbers of wires in a cell and when trying to debug a program. However, the higher the number the lower the simulated cell accuracy. These two numbers show up only on the `.out`, `.eps`, and `.ps` file formats. The scaling numbers are controlled by the `scl1` and `scl2` global variables defined in the `.in` and `.cel` files within the `CELL` section.
c. A letter trailing the two numbers in a filename implies the type of data a file contains (for example: f in the filename `3tpcs11`***f***`4.eps`). Letters and their meaning are defined as the following:

i. Letter `c` corresponds to the cell information.
ii. Letter `f` corresponds to the field information
iii. Letter `g` corresponds to the gas information.
iv. Letters `cl` corresponds to the cluster information.
v. Letter `d` corresponds to the positron and electron drift information.

d. Last of all, a number before the period in a filename (for example: 24 in the filename `3tpcs11f`***`24`***`.eps`) suggests that the n^{th} plot created from a simulation is stored in the n^{th} *`.eps`* file.

The Garfield code in Attachment 1 is the `tpcs.in` file, which serves as an illustration to explain the file formatting and naming convention in the following example. When `tpcs.cel` file is ran, with both `scl1` and `scl2` set to one, `tpcs11c.out` data file and `tpcs11c.eps` file, which contains the plot of the cell, are produced. Running `tpcs.gas` file creates a gas data file, `tpcsg.out`, and an encapsulated postscript file, `tpcsg.eps`. Both data files are then ready to be called by `tpcs.in` file that uses the cell and gas data to compute the field, cluster, and drift plots. Several postscript and encapsulated postscript files whose names begin with `tpcs11`, for example `tpcs11f1.eps`, `tpcs11cl.ps`, and `tpcs11d9.eps` are in turn produced by `tpcs.in` during the simulation.

3.3 Simulation Discussion

The simulation produces plots pertaining to the potential contours, electric fields, cluster histograms, and drift lines of electrons and positrons. Most of these plots show in detail the homogeneity of the TPC drift region and MWPC, critical field gradients of the chambers, charge build-up on the insulators, and delayed charge collection in the MWPC. The electric field and contour plots allow analysis of homogeneity of the TPC drift region and MWPC. Along selected tracks, the electric field plots determine critical field gradients. The charge build-up on the insulators is studied through drift plots for positive and negative charges (called positrons and electrons, respectively). These drift line plots for electrons also demonstrate the delayed charge collection on anode wires in both MWPCs. In an attempt to accurately portray the field and drift lines of the chambers, these plots need to be created at high resolution. In addition, the model cell parameters should resemble the design cell. As with any simulation program, it comes with restrictions when compared to practical applications.

3.3.1 Shortcomings and solutions

Some limitations come with using Garfield; however using certain approximations allow one to overcome the boundaries. Various techniques were employed while writing the code for this simulation, thus closely resembling the actual cell design. The most significant shortcomings and applied solutions are listed below.

SHORTCOMING: Garfield software is a two-dimensional simulation program.
SOLUTION: Of course, in reality this is a three-dimensional problem. Consequently, simulating the chambers in two different views, front and side view, is sufficient to obtain a more realistic picture of the designed TPC. Slicing method can be used to extract partial data, which later can be integrated to project the whole picture. Model, first modified and fourth modified cells show the cross section of the chambers and the vessel at the center. The second, third and fifth modified cells show the cross section of the chambers and the vessel at the edge of TPC.

SHORTCOMING: Garfield allows only two planes per cell. For instance, the MWPC of the TPC and the μPC2, contain various potential planes; this limitation makes it difficult to simulate.
SOLUTION: A continuous plane can be simulated by wires placed close to each other.

SHORTCOMING: Only infinite potential planes can be added to the cell.
SOLUTION: Simulating finite potential planes as a plane of wires resolves this problem. The grounded end flanges of the hydrogen vessel were ignored.

SHORTCOMING: A cell can contain approximately 100 sense wires.
SOLUTION: Start with designating a few wires as sense wires. Then the *Select* command can be used to select wires as sense wires when needed.

SHORTCOMING: High resolutions plots are extremely time consuming.
SOLUTION: The density of wires in the cell can be scaled down for trial runs resulting in lesser computation time. Moreover, creating independent data files eliminates repetitive calculations within the main program.

SHORTCOMING: Garfield has limiting capability of simulating dielectrics.
SOLUTION: Further studies could use finite elements program to generate a field map and to read it into Garfield is one method of overcoming this problem. The main material to be considered are the Borofloat glass frames with a dielectric constant of ~4.6.

4 Simulation Results

The figures and data are the results of simulation programs and are presented in Appendix 4. Plots of cell configurations, potential field contours, electric fields on desired tracks, drift lines from wires and tracks, gaseous properties, and clustering properties are provided along with a stereo view of the chambers placed inside the cylindrical pressure vessel. The charges, capacitances, surface fields, and surface potentials of selected wires in both MWPCs are listed in Table 3, where as Table 4 shows the surface potentials and fields of two ground planes for all different models gathered from the data outputted by the simulations.

The properties of hydrogen at a pressure and temperature of 10 atm and 300 K, respectively, are plotted in Fig. 2. Plots included are the drift velocity, longitudinal and transverse diffusion coefficient, and Townsend and attachment coefficient as a function of electric field for an electron in hydrogen gas using the Monte Carlo method. Electron scattering processes in elastic and inelastic collision with hydrogen molecules determine the drift properties. Hence, it depends on the reduced electric field (E/P), temperature, mean collision time, and electron energy [1]. As expected, the drift velocity of electrons in hydrogen increases with the electric field. The longitudinal diffusion coefficient is generally less than or equal to the transverse diffusion coefficient, which can be seen in the plot. The Townsend and attachment coefficient is negligible (less than 0.01 per cm) for an electric field less than 0.1 MeV and increases with electric field above 0.1 MeV. Since the Townsend coefficient represents the number of ion pairs produced per centimeter, the multiplication (avalanche) factor is greatest when the electric field is maximum, which is close to the surface of the anode wires [2]. The gas properties calculated by Magboltz are used in the drift section from which the drift line plots are generated.

In addition, the cluster histograms for 1 cm of track for muons at energy 50 MeV using the Heed program are provided in Fig. 3 and Fig. 4. Fig. 3 shows the cluster properties that exclude delta electrons while Fig. 4 include them. When Garfield excludes delta electrons in cluster configuration, then all electrons generated by an ionisationing interactions are at put at the position of the primary interaction, i.e. the delta electron tracks are not followed. Hence, the cluster size distribution is realistic and the distance between a track and clusters is incorrectly underestimated. On the contrary, when Garfield includes delta electrons in cluster configuration, each electron generated by Heed is considered a cluster, thus the distance between clusters and track distribution shows the range of delta electrons. The cluster information is used in the drift section from which the drift lines are plotted. Fig. 3 and 4 indicate

# clusters produced in 1 cm	120
average cluster energy	34 eV

total energy deposition in 1 cm   4 keV
mean distance track and delta electrons   1.7 mm

Described below are the naming conventions utilized to group the figures according to the models. Since simulation programs output the same amount of figures regardless of the type of cell used, the letter in the name of the figure represents the type of cell it belongs to and the number corresponds to the type of plot. Because of the significant amount of plots, we present the data in two different ways. A limited set of figures is directly included in the report. A systematic presentation of standard plots is contained in attachment 4. The lettering and the numbering of these figures are as follows:

a. Each group of plots that belong to a specific model cell is put together under figure names that start with letters. The following letters represent the corresponding model cell.
   - Model cell A. The cell configurations are given in table 1.
   - modification B. This modified model cell contains 10 extra wires added to the TPC to observe the changes in drift region especially at the corners of the TPC.
   - modification C. As A, but the two ground planes are moved closer to the chambers. Since Garfield simulates only in two-dimension, the effects of the TPC edges on the cylindrical pressure vessel wall along with the homogeneity of the TPC drift region can be studied when the ground planes are moved closer to the chambers.
   - modification D. As B, but the two ground planes moved closer to the chambers.
   - modification E. In addition to the model B modification, this model cell also includes two short planes of high voltage wires on the top corners of the TPC
   - modification F. As E, but the two ground planes moved closer to the chambers. This version is used to evaluate the charge build-up on the cylindrical pressure vessel wall that is close to the TPC edges as well the field inside the drift region.

b. The numbers (see Table 3) following the letters in the naming of the figures show different studies.

Table 3: Description of the numbers found in the Figure a, b, and c, along with the postscript file in which they can be found

Numbers	Description	Region	Postscript Filename
1	Layout of the cell		tpcsgcl1.ps
2	Potential contours plots	Whole cell	tpcs11ff.ps
3-6	Potential contours plots	Coarse zoom, see Figure a	tpcs11ff.ps
7-15	Potential contours plots, MWPC	Fine zoom, see Figure a	tpcs11ff.ps
16-21	Electric field plots, TPC	Coarse zoom, see Figure b	tpcs11ff.ps
22-27	Electric field plots, MWPC	Fine zoom, see Figure b	tpcs11ff.ps
28, 30, 32, 34, 36, 38, 40, 42, 44	Electron drift lines	See Figure c	tpcs11ff.ps (N-28), rest in tpcs11ddd.ps
29, 31, 33, 35, 37, 39, 41, 43, 45	Pseudo (positron drift lines)	To show field lines originating on anodes	tpcs11ddd.ps

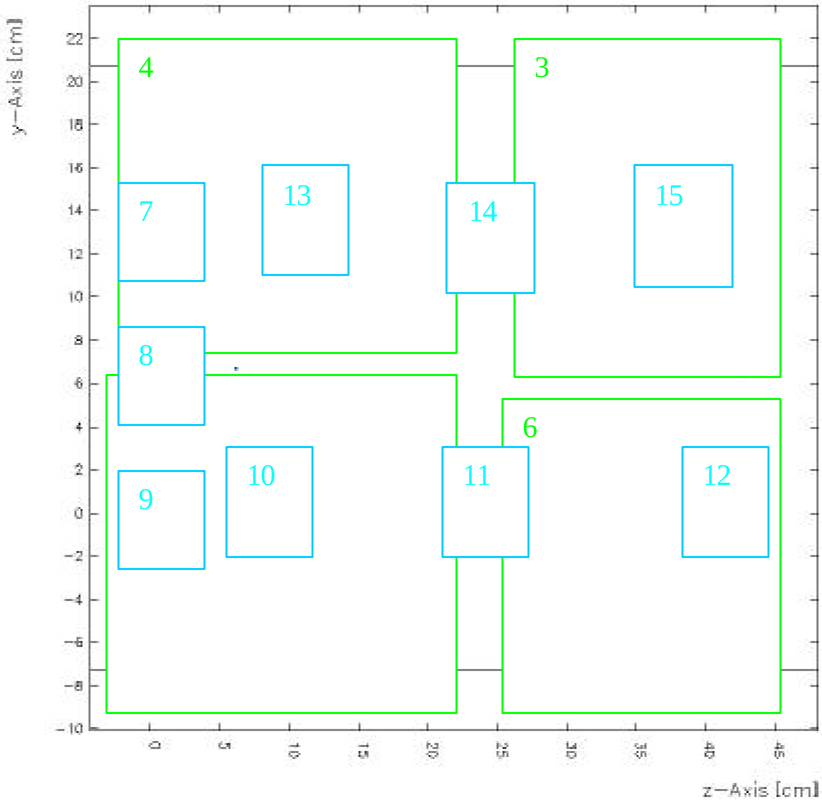

Figure a: Areas for number 2 to 15 as described in Table 3

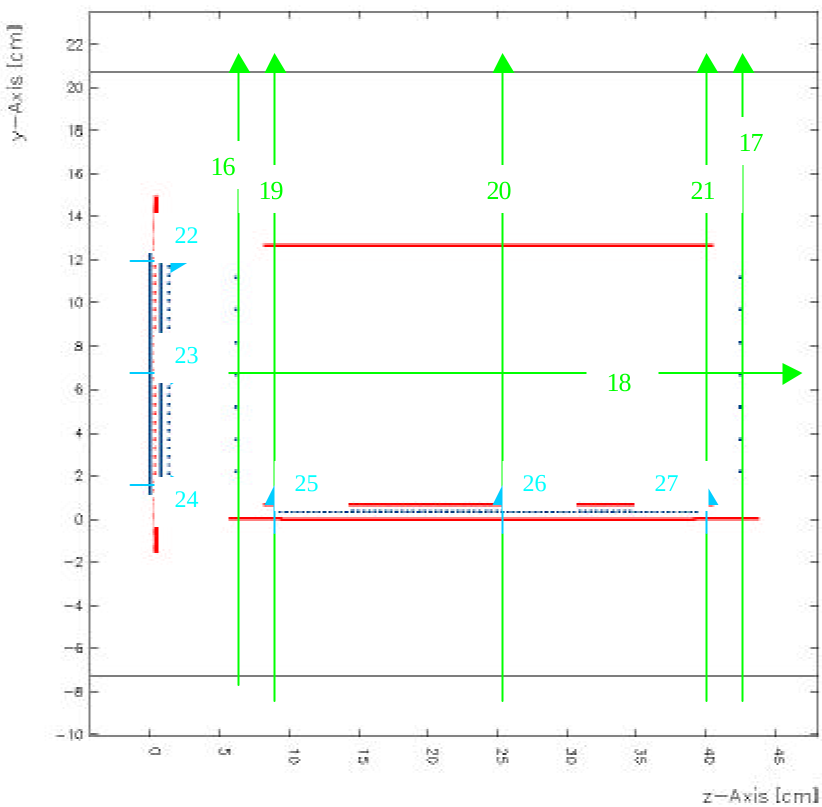

Figure b: Electric field path for number 16 to 27 as described in Table 3

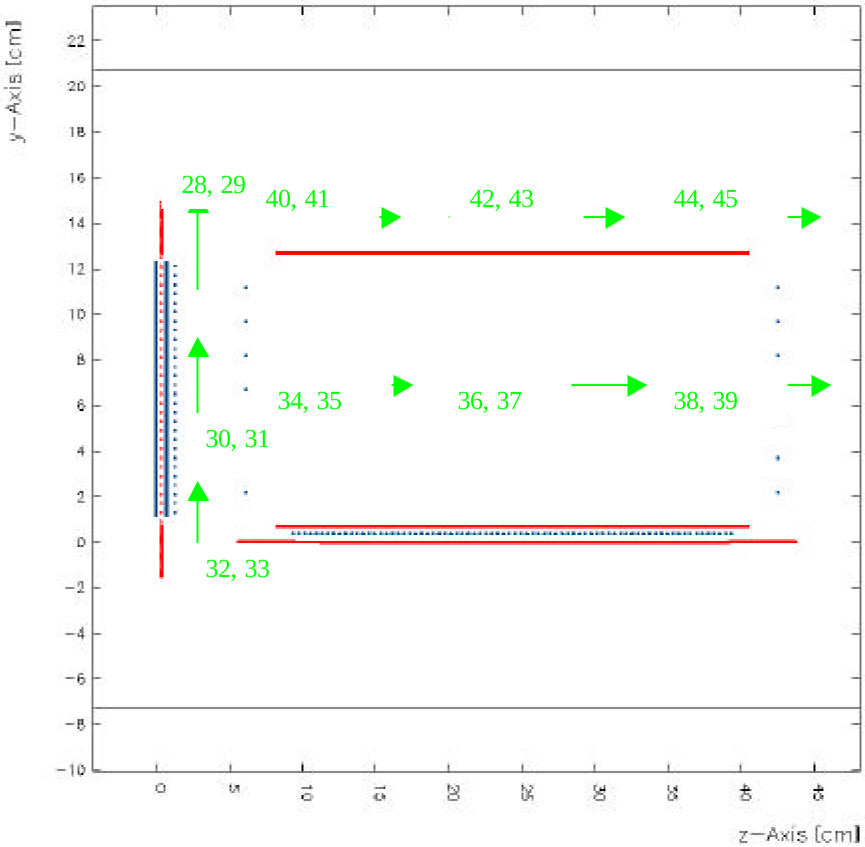

Figure c: Tracks for number 28 to 45 for the pseudo positron drift lines

All the figures in Attachment 4 are color coordinated for clarity. The colors are represented as the following:

a. Orange: Contours/isochrones that appear in potential and drift line plots.
b. Dark green and green: Electric field graphs, gas plots and cluster plots.
c. Light blue: Electron and positron drift lines from a wire or a track. (Though there are no drifting positrons, we use these plot to conveniently display field lines for ions. Electron drift lines starting at the HV cathode are also used to visualize the field lines in this region).
d. Brown: Tracks.
e. Purple: Delta-electrons.

Table 4 provides the charges, surface fields of selected wires and their capacitances for each model simulated. The values are uniform for the middle sections of both MWPCs for each model, however the values do vary for the wires that reside at the edges; three wires at the ends of both MWPCs are affected. Maximum surface fields are experienced by the wires that reside in the middle section of the TPC. Average surface electric field ranges from almost 200 kV/cm to about 800 kV/cm for all cells, while the difference is about 1 kV/cm for cells in which the two ground planes are moved closer to the chambers. Capacitance values agree with the estimated value, 8.325 pF/m, using Charpak geometry for all the wires excluding the ones close to the edges [3]. The change in capacity of the sense wires is noticed for model in which the two ground planes are brought closer to the chambers; the change is in the end wires only.

Table 5 provides the surface fields of the two ground planes, which represent the boundary of the cylindrical pressure vessel, as a function of z. The surface fields for the top ground plane ranges from about -530 V/cm to almost -5900 V/cm. For the bottom plane, the surface fields range from 270 V/cm to 1200 V/cm. It is apparent and expected for the fields to intensify as the two ground planes are moved closer to the two chambers. Hence, the charges build up on the plane surface as well as its capacitance. The same is true for cells in which only wires were added when comparing it to the prototype, however the intensity is not as much as when the planes are moved closer to the chambers.

Table 4: Capacitance and surface field of anode wires inside both MWPC for all types of cells

Wire No.	Z [cm]	Y [cm]	Charge [nC/cm]						Capacitance [pF/m]						Avg. Surface Field [MV/cm]					
			Model	1st	2nd	3rd	4th	5th	Model	1st	2nd	3rd	4th	5th	Model	1st	2nd	3rd	4th	5th
Top edge of ■PC2 MWPC																				
136	0.35	0.9	0.206	0.206	0.205	0.205	0.206	0.205	3.433	3.433	3.417	3.417	3.433	3.417	0.296	0.296	0.295	0.295	0.296	0.295
137	0.35	1.3	0.405	0.405	0.405	0.405	0.405	0.405	6.750	6.750	6.750	6.750	6.750	6.750	0.583	0.583	0.583	0.582	0.583	0.582
139	0.35	2.1	0.472	0.472	0.472	0.472	0.472	0.472	7.867	7.867	7.867	7.867	7.867	7.867	0.678	0.678	0.678	0.678	0.678	0.678
140	0.35	2.5	0.474	0.473	0.473	0.473	0.473	0.473	7.900	7.883	7.883	7.883	7.883	7.883	0.680	0.681	0.681	0.681	0.681	0.681
Middle section of ■PC2 MWPC																				
148	0.35	5.7	0.475	0.475	0.475	0.475	0.475	0.475	7.917	7.917	7.917	7.917	7.917	7.917	0.682	0.683	0.683	0.683	0.683	0.683
149	0.35	6.1	0.475	0.475	0.475	0.475	0.475	0.475	7.917	7.917	7.917	7.917	7.917	7.917	0.682	0.683	0.683	0.683	0.683	0.683
151	0.35	6.9	0.475	0.475	0.475	0.475	0.475	0.475	7.917	7.917	7.917	7.917	7.917	7.917	0.682	0.683	0.683	0.683	0.683	0.683
152	0.35	7.3	0.475	0.475	0.475	0.475	0.475	0.475	7.917	7.917	7.917	7.917	7.917	7.917	0.682	0.683	0.683	0.683	0.683	0.683
Bottom edge of ■PC2 MWPC																				
161	0.35	10.9	0.474	0.474	0.474	0.474	0.474	0.474	7.900	7.900	7.900	7.900	7.900	7.900	0.682	0.682	0.681	0.682	0.682	0.682
162	0.35	11.3	0.473	0.473	0.473	0.473	0.473	0.473	7.883	7.883	7.883	7.883	7.883	7.883	0.679	0.680	0.679	0.679	0.680	0.680
164	0.35	12.1	0.409	0.411	0.408	0.410	0.411	0.410	6.817	6.850	6.800	6.833	6.850	6.833	0.588	0.590	0.586	0.589	0.590	0.589
165	0.35	12.5	0.213	0.217	0.212	0.215	0.217	0.215	3.550	3.617	3.533	3.583	3.617	3.583	0.307	0.311	0.304	0.308	0.312	0.309
Left edge of TPC MWPC																				
653	9.35	0.35	0.578	0.578	0.578	0.578	0.578	0.578	8.892	8.892	8.892	8.892	8.892	8.892	0.831	0.831	0.831	0.831	0.831	0.831
654	9.75	0.35	0.534	0.534	0.534	0.534	0.534	0.534	8.215	8.215	8.215	8.215	8.215	8.215	0.768	0.767	0.767	0.767	0.767	0.767
656	10.55	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.755	0.754	0.754	0.754	0.754	0.754
657	10.95	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.754	0.754	0.754	0.754	0.754	0.754
Middle section of TPC MWPC																				
688	23.35	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.753	0.753	0.753	0.753	0.753	0.753
689	23.75	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.753	0.753	0.753	0.753	0.753	0.753
691	24.55	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.753	0.753	0.752	0.752	0.753	0.752
692	24.95	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.753	0.753	0.753	0.753	0.753	0.753
Right edge of TPC MWPC																				
724	37.75	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.745	0.745	0.744	0.744	0.745	0.744
725	38.15	0.35	0.525	0.525	0.525	0.525	0.525	0.525	8.077	8.077	8.077	8.077	8.077	8.077	0.745	0.744	0.744	0.744	0.744	0.744
727	38.95	0.35	0.534	0.534	0.534	0.534	0.534	0.534	8.215	8.215	8.215	8.215	8.215	8.215	0.757	0.756	0.756	0.756	0.756	0.756
728	39.35	0.35	0.578	0.578	0.578	0.578	0.578	0.578	8.892	8.892	8.892	8.892	8.892	8.892	0.830	0.829	0.829	0.829	0.829	0.829
Field Cage and HV Cathode																				
1150	12.00	12.7	-0.07	-0.06	-0.08	-0.07	-0.06	-0.07							0.024	0.022	0.028	0.027	0.022	0.026
1436	6.15	11.2	-1.23	-0.78	-1.29	-0.81	-0.69	-0.71							0.089	0.055	0.092	0.058	0.050	0.051
1450	6.15	13.2	n/a	-1.22	n/a	-1.27	-0.72	-0.78								0.087		0.095	0.052	0.056

Table 5: Surface potentials and field of two ground planes for all types of cells

z [cm]	Surface Field [V/cm]					
	Model	1st	2nd	3rd	4th	5th
Top ground plane						
0.0	-635.842	-777.496	-536.788	-672.990	-813.503	-704.607
4.4	-1879.83	-2293.45	-2370.56	-3095.81	-2417.14	-3307.16
8.8	-3359.04	-3723.67	-4694.32	-5287.12	-3858.57	-5533.11
13.1	-4113.99	-4229.39	-5649.20	-5754.16	-4274.88	-5799.09
17.5	-4311.70	-4335.48	-5791.12	-5802.68	-4344.92	-5807.60
21.9	-4349.74	-4354.70	-5806.29	-5807.57	-4356.67	-5808.12
26.3	-4352.22	-4356.25	-5806.84	-5807.81	-4357.84	-5808.23
30.6	-4328.07	-4345.82	-5797.03	-5805.19	-4352.82	-5808.68
35.0	-4197.24	-4285.35	-5703.29	-5778.62	-4319.91	-5810.94
39.4	-3677.10	-3985.45	-5030.85	-5508.13	-4099.76	-5709.41
43.8	-2607.83	-3059.55	-3245.08	-4042.82	-3193.13	-4282.86
Bottom ground plane						
0.0	275.870	273.871	280.488	278.158	273.931	278.207
4.4	567.275	563.118	803.020	795.494	563.176	795.600
8.8	796.571	794.757	1148.85	1147.01	794.779	1147.03
13.1	849.642	849.296	1179.66	1179.51	849.298	1179.51
17.5	856.452	856.401	1179.51	1179.50	856.404	1179.50
21.9	857.394	857.387	1179.46	1179.46	857.390	1179.46
26.3	857.623	857.624	1179.47	1179.47	857.628	1179.48
30.6	858.210	858.229	1179.70	1179.71	858.237	1179.71
35.0	861.256	861.391	1182.47	1182.50	861.456	1182.52
39.4	867.970	868.778	1194.91	1195.20	869.172	1195.42
43.8	847.605	851.835	1140.30	1143.05	853.544	1144.84

5 Discussion

In the course of studying the plots of the prototype model, non-homogeneous fields at the corners of the TPC drift region were found which led to creation of modified versions of the cell. These modified versions are attempts to optimize the TPC drift region as well as to study the edge effects of high voltage TPC wires on the two ground planes. Fig. 5 shows an overview of the main cell geometries; Fig. 7 focuses on typical MWPC potentials in the TPC. The change in homogeneity of the TPC drift region, homogeneity in MWPC, critical field gradient, delayed charge collection in MWPC and charge build-up on the insulators are inspected through the differences found in the simulation results of all cells.

- ***TPC field homogeneity.*** Influence of field-shaping wires on the potential contours and electric field lines are investigated using the corresponding plots of all model cells. Examining all the potential contours and the electric field plots suggests that the homogeneity in the corners of the TPC drift region is improved through addition of high voltage wires at the corners of the TPC (see Fig. 6 and 8). Shifting of the two ground planes closer (second, third, and fifth modified model cells) towards the chambers, the potential contours and electric field plots are unaltered when comparing to the prototype, first modified and fourth modified model cells, respectively. The drift plots of the second, third and fifth modified model cell are untouched even after moving the planes closer to the chambers. As the wires are added, the path of electrons are preserved for the μPC2 MWPC. Further studies should try to improve the homogeneity by non-linear voltage distribution of the TPC potential wires.
- ***Ground plane between TPC and mPC2.*** All electrons are collected by the plane of ground wires that exist between the μPC2 MWPC and the TPC; a few do escape in the direction of the anode solder pads. Probably they lead to some charge build-up on the intercepting glass frames, but won't be amplified to create a delayed signal. Electron drift lines for both MWPCs are displayed in Fig. 9.

- ***Other effects of different model geometries***. Capacitance of the sense wires is unaffected in both MWPCs when only the field shaping wires are added to the model cell. When the distant between the two ground planes and the chambers is decreased (second, third and fifth modified model), the capacitance of end anode wires in μPC2 MWPC falls about 0.05 pF/m while in TPC MWPC the capacitance stays the same. Since only the end anode wires of μPC2 MWPC are affected, field-shaping wires can be added to improve the drift region of TPC with little loss in tracking entering muons. The decrease in average surface electric field by a 1 kV/cm on the end anode wires of both MWPC in all model types are not enough to hinder the avalanche occurrences. When the field-shaping wires are added as in the first and fourth modified model cells, the fields on the top ground plane vary by 0.1 - 0.5 kV/cm. As the planes are moved closer (as in the second, third and fifth modified cell), the field on the top plane increases by 0.1 - 1.0 V/cm, respectively. On the bottom surface, the field varies by 0.3 V/cm - 4 kV/cm for all models. The study of the field on the two ground planes indicate that the capacitance of the planes is higher at locations where it is closer to the TPC edge
- ***Critical Field gradients.*** The locations of potentially large field gradients can be spotted from Fig. 5 and values given in Table 4 and 5. Typical values are given below (pretty stable for all models). The highest cathode fields appear at the upper corners of the cage wire box.

Table 6: Average surface field in MV/cm for both chambers

Chamber	Wire	Ave. surface field (MV/cm)
μPC2	Anode	0.68
	Cathode	0.050
TPC	Anode left	0.831
	Anode middle	0.753
	Anode right	0.831
	Cathode	0.034
	HV cathode	<0.028
	Highest cage	<0.092
	Additional top cage	<0.095

- ***Charge collection on glass frames.*** Field lines ending on the isolated glass frames lead to local charge build up due to the drift of electrons or ion, which were created by ionizing particles. Dangerous spots are
  - the top side of the frames for the HV plane. The pads and wires are mounted on the bottom side of the frame. Ions can be collected there.
  - the top side of the TPC upper cathode frame. Electrons can be attracted there by the anode field.
  - the outer sides of the μPC2 cathode frames, electrons can be attracted there by the anode field.
  - the outer hydrogen vessel if covered with an insulator. This possibility was discussed to stop diffusing μd atoms.

  We studied the charge collection on the HV cathode frames. The drift line plots (fig.10, 11) show that this problem is reduced with a single additional wire (model B) and practically eliminated with a conductor plane on the upper side of frame (model E).

6 Conclusions

The outcome of this project indicates Garfield software provides a thorough understanding of drift chambers and multi-wire proportional chambers functionality. The program enables visualization of potential and field gradients, particle trajectories and calculations of various properties for any cell geometry with few lines of code; a detail study of a cell can be performed as well. Optimization of the TPC drift chamber was possible even though a small number of hindrances were encountered. Nevertheless, Garfield software is user-friendly permitting diverse methods of simulation. The data and plots gathered in this report present the general properties of the μCap wire chamber system and suggest improvements concerning the drift field and prevention of charge buildup. The studies done in this report can be extended even further by examining the cells in three dimensions, including insulators and varying the field-shaping wires' location and potential.

Acknowledgements

The author would like to thank Professor P. Kammel from the Nuclear Physics Laboratory at the University of Illinois at Urbana-Champaign for motivation and guidance during the course of this project.

7 References

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[3] B.V. Dinesh, Calculation of capacitances, induced charges on cathodes, and gain variation in PHENIX cathode strip readout chambers, Bhabha Atomic Research Centre/Los Alomos National Laboratory, phenix-muon-96-5, 15 May 1996, http://www.phenix.bnl.gov/WWW/muon/notes/phenix-muon-96-5/csc.html.

8 List of Figures

9 Attachment 1: File `tpcs.in`

```
*----------------------------------------*
*                                        *
*SIMULATION FOR THE MODEL CELL PARAMETERS*
*                                        *
*----------------------------------------*
&CELL

options input

*MAIN PARAMETERS
global name=`tpcs`
global scl1=1
global scl2=1

* RESOLUTION OF THE PLOTS
global ngrid=50
global ncont=30

* MU ENERGY IN GeV FOR THE CLUSTER HISTOGRAMS & DRIFT PLOTS
global mu_e=0.05

* DEFINE CELL DIMENSIONS
global ll_z=-1.0
global ll_y=-8.0
global ur_z=45.0
global ur_y=22.0

* TURN ON METAFILE FLAGS
global eps_f=true
global eps_cls=false
global eps_d=false

* TURN OFF CREATING POSTSCRIPT FILES, OVERWRITES PS FLAGS
global nops=false

* NO POSTSCRIPT FILES
if nops then
  global eps_f=false
  global eps_g=false
  global eps_cls=false
  global eps_d=false
endif

* TURN OFF PLOTS, OVERWRITES PLOT FLAGS
global noplot=false

* STANDARD CONTROL VARIABLES
global cell_p=true
global field_p=true
global field_pe=false
global gas_p=false
global gasin=false
global drift_p=false

* NO PLOTS
if noplot then
  global cell_p=false
  global field_p=false
  global field_pe=false
  global out_g=false
  global gas_p=false
  global drift_p=false
endif

* DEFINE COLOURS
!
col blu red 0 green 0 blue 1
col brwn red 0.5 green 0.27 blue 0
col drkblu red 0 green 0.25 blue 0.5
col drkgrn red 0 green 0.25 blue 0
col grn red 0 green 1 blue 0
col lblu red 0.5 green 0.5 blue 1
col lgrn red 0.5 green 1 blue 0.5
col orng red 1 green 0.5 blue 0
col pnk red 1 green 0.5 blue 1
col rd red 1 green 0 blue 0
col prpl red 0.25 green 0 blue 0.25

* APPEARANCE OF THE PLOTS
rep s-wire marker-type circle
rep s-wire polymarker-colour rd
rep s-wire marker-size-scale-factor 0.3
rep c-wire marker-type -8
rep c-wire polymarker-colour drkblu
rep c-wire marker-size-scale-factor 0.3
rep p-wire marker-type -8
rep p-wire polymarker-colour rd
rep p-wire marker-size-scale-factor 0.3
rep other-wire marker-type -8
rep other-wire polymarker-colour drkblu
rep other-wire marker-size-scale-factor 0.3
rep contour-normal polyline-colour orng
rep contour-label character-height 0.0075
rep number character-height 0.01
rep labels character-height 0.015
rep isochrones linetype solid polyline-colour orng
rep isochrones polymarker-colour orng marker-type plus
rep comment character-height 0.015
rep title character-height 0.02
rep e-drift-line polyline-colour lblu
rep ion-drift-line polyline-colour lblu
rep auger-electron polyline-colour blu
rep auger-electron polymarker-colour blu marker-type cross
rep auger-electron marker-size-scale-factor 0.75
rep delta-electron polyline-colour prpl
rep delta-electron polymarker-colour prpl marker-type asterisk
rep delta-electron marker-size-scale-factor 0.75
rep function-1 polyline-colour drkgrn
rep function-1 polymarker-colour drkgrn
rep function-1 text-colour drkgrn
rep function-2 polyline-colour grn
rep function-2 polymarker-colour grn
rep function-2 text-colour grn
rep track polyline-colour brwn
rep track polymarker-colour brwn
layout x-label 0.025 y-label 0.025 title 0.025
exit

* GET ORIGINAL STORED CELL DATA
get "{name}{scl1}{scl2}c.out"

* PRINT & PLOT CELL INFO
if cell_p then
  opt wire-markers isometric layout
endif

& FIELD
```

```
*check wire plane charge keep-results

if field_p then
  if eps_f then
        !cont-par eps-gra 1e-4 eps-tra 1e-4
        !add metaf1 type EPS file-name "{name}{scl1}{scl2}f1.eps"
        !open metaf1
        !act metaf1
        !stamp "   PLOT OF THE WHOLE CELL"
        grid {ngrid}
        area {ll_z} {ll_y} {ur_z} {ur_y}
    !rep labels text-colour background
    plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
        !deact metaf1
        !close metaf1
        !delete metaf1

        * INCREASE SIZE OF WIRE-MARKERS
        !rep s-wire marker-size-scale-factor 0.4
        !rep c-wire marker-size-scale-factor 0.4
        !rep p-wire marker-size-scale-factor 0.4
        !rep other-wire marker-size-scale-factor 0.4

    !add metaf2 type EPS file-name "{name}{scl1}{scl2}f2.eps"
    !open metaf2
    !act metaf2
        !stamp "   PLOT OF 1ST QUADRANT"
        grid {ngrid}
        area 22.0 7.0 {ur_z} {ur_y}
    !rep labels text-colour background
    plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf2
    !close metaf2
    !delete metaf2

    !add metaf3 type EPS file-name "{name}{scl1}{scl2}f3.eps"
    !open metaf3
    !act metaf3
        !stamp "   PLOT OF 2ND QUADRANT"
        area {ll_z} 7.0 22.0 {ur_y}
    !rep labels text-colour background
    plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf3
    !close metaf3
    !delete metaf3

    !add metaf4 type EPS file-name "{name}{scl1}{scl2}f4.eps"
    !open metaf4
    !act metaf4
        !stamp "   PLOT OF 3RD QUADRANT"
        area {ll_z} {ll_y} 22.0 7.0
    !rep labels text-colour background
    plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf4
    !close metaf4
    !delete metaf4

    !add metaf5 type EPS file-name "{name}{scl1}{scl2}f5.eps"
    !open metaf5
    !act metaf5
        !stamp "   PLOT OF 4TH QUADRANT"
        area 22.0 {ll_y} {ur_z} 7.0
    !rep labels text-colour background
    plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf5
    !close metaf5
    !delete metaf5

        * INCREASE SIZE OF WIRE-MARKERS
        !rep s-wire marker-size-scale-factor 1.0
        !rep c-wire marker-size-scale-factor 1.0
        !rep p-wire marker-size-scale-factor 1.0
        !rep other-wire marker-size-scale-factor 1.0

    !add metaf6 type EPS file-name "{name}{scl1}{scl2}f6.eps"
    !open metaf6
    !act metaf6
        !stamp "   PC2 WIRES (TOP EDGE)"
        area -0.2 11.0 1.8 13.0
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf6
    !close metaf6
    !delete metaf6

    !add metaf7 type EPS file-name "{name}{scl1}{scl2}f7.eps"
    !open metaf7
    !act metaf7
        !stamp "   PC2 WIRE (MIDDLE)"
        area -0.2 5.7 1.8 7.7
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf7
    !close metaf7
    !delete metaf7

    !add metaf8 type EPS file-name "{name}{scl1}{scl2}f8.eps"
    !open metaf8
    !act metaf8
        !stamp "   PC2 WIRES (BOTTOM EDGE)"
```

```
        area -0.2 0.7 1.8 2.7
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf8
    !close metaf8
    !delete metaf8

    !add metaf9 type EPS file-name "{name}{scl1}{scl2}f9.eps"
    !open metaf9
    !act metaf9
        !stamp "   TPC MWPC (LEFT EDGE)"
        area 5.45 -0.2 10.15 0.9
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf9
    !close metaf9
    !delete metaf9

    !add metaf10 type EPS file-name "{name}{scl1}{scl2}f10.eps"
    !open metaf10
    !act metaf10
        !stamp "   TPC MWPC (MIDDLE)"
        area 23.35 -0.2 25.35 0.9
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf10
    !close metaf10
    !delete metaf10

    !add metaf11 type EPS file-name "{name}{scl1}{scl2}f11.eps"
    !open metaf11
    !act metaf11
        !stamp "   TPC MWPC (RIGHT EDGE)"
        area 38.5 -0.2 40.5 0.9
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf11
    !close metaf11
    !delete metaf11

    !add metaf12 type EPS file-name "{name}{scl1}{scl2}f12.eps"
    !open metaf12
    !act metaf12
        !stamp "   TPC HV WIRES (LEFT EDGE)"
        area 7.15 11.7 10.05 13.7
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf12
    !close metaf12
    !delete metaf12

    !add metaf13 type EPS file-name "{name}{scl1}{scl2}f13.eps"
    !open metaf13
    !act metaf13
        !stamp "   TPC HV WIRES (MIDDLE)"
        area 23.35 11.7 25.35 13.7
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf13
    !close metaf13
    !delete metaf13

    !add metaf14 type EPS file-name "{name}{scl1}{scl2}f14.eps"
    !open metaf14
    !act metaf14
        * DETAIL PLOT OF TPC HV WIRES, RIGHT EDGE
        !stamp "   TPC HV WIRES (RIGHT EDGE)"
        area 38.65 11.7 41.55 13.7
    !rep labels text-colour background
        plot cont n {ncont} nolabel
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metaf14
    !close metaf14
    !delete metaf14
  endif
endif

if field_pe then
  if eps_f then
        * HOMOGENIETY OF E INSIDE TPC
    !add metaf15 type EPS file-name "{name}{scl1}{scl2}f15.eps"
    !open metaf15
    !act metaf15
    !stamp "   TPC POTENTIAL WIRES (FRONT END)"
        track 6.15 {ll_y} 6.15 {ur_y}
        plot gra e
    !deact metaf15
    !close metaf15
    !delete metaf15

    !add metaf16 type EPS file-name "{name}{scl1}{scl2}f16.eps"
    !open metaf16
    !act metaf16
    !stamp "   TPC POTENTIAL WIRES (BACK END)"
        track 42.55 {ll_y} 42.55 {ur_y}
        plot gra e
    !deact metaf16
    !close metaf16
    !delete metaf16
```

```
      !add metaf17 type EPS file-name
"{name}{scl1}{scl2}f17.eps"
      !open metaf17
      !act metaf17
      !stamp "   CENTER OF THE CHAMBERS"
            track -0.5 6.7 45.0 6.7
      !rep labels text-colour background
            plot gra e
      !rep labels text-colour foreground
      call plot_x_label(`z-Axis [cm]`)
      call plot_y_label(`E*10^3`)
      call plot_end
      !deact metaf17
      !close metaf17
      !delete metaf17

      !add metaf18 type EPS file-name
"{name}{scl1}{scl2}f18.eps"
      !open metaf18
      !act metaf18
            !stamp "   FRONT END OF TPC"
            track 7.15 {ll_y} 7.15 {ur_y}
            plot gra e
      !deact metaf18
      !close metaf18
      !delete metaf18

      !add metaf19 type EPS file-name
"{name}{scl1}{scl2}f19.eps"
      !open metaf19
      !act metaf19
      !stamp "   CENTER OF TPC"
            track 24.35 {ll_y} 24.35 {ur_y}
            plot gra e
      !deact metaf19
      !close metaf19
      !delete metaf19

      !add metaf20 type EPS file-name
"{name}{scl1}{scl2}f20.eps"
      !open metaf20
      !act metaf20
            !stamp "   BACK END OF TPC"
            track 41.55 {ll_y} 41.55 {ur_y}
            plot gra e
      !deact metaf20
      !close metaf20
      !delete metaf20

      * HOMOGENEITY INSIDE PC2 MWPC
      !add metaf21 type EPS file-name
"{name}{scl1}{scl2}f21.eps"
      !open metaf21
      !act metaf21
      !stamp "   PC2 MWPC TOP EDGE"
            track -0.5 12.5 1.4 12.5
      !rep labels text-colour background
            plot gra e
      !rep labels text-colour foreground
      call plot_x_label(`z-Axis [cm]`)
      call plot_y_label(`E*10^3`)
      call plot_end
      !deact metaf21
      !close metaf21
      !delete metaf21

      !add metaf22 type EPS file-name
"{name}{scl1}{scl2}f22.eps"
      !open metaf22
      !act metaf22
      !stamp "   PC2 MWPC MIDDLE"
      track -0.5 6.7 1.4 6.7
      !rep labels text-colour background
      plot gra e
      !rep labels text-colour foreground
      call plot_x_label(`z-Axis [cm]`)
      call plot_y_label(`E*10^3`)
      call plot_end
      !deact metaf22
      !close metaf22
      !delete metaf22

      !add metaf23 type EPS file-name
"{name}{scl1}{scl2}f23.eps"
      !open metaf23
      !act metaf23
      !stamp "   PC2 MWPC BOTTOM EDGE"
      track -0.5 0.9 1.4 0.9
      !rep labels text-colour background
      plot gra e
      !rep labels text-colour foreground
      call plot_x_label(`z-Axis [cm]`)
      call plot_y_label(`E*10^3`)
      call plot_end
      !deact metaf23
      !close metaf23
      !delete metaf23

      * HOMOGENEITY INSIDE TPC MWPC

      !add metaf24 type EPS file-name
"{name}{scl1}{scl2}f24.eps"
      !open metaf24
      !act metaf24
      !stamp "   TPC MWPC LEFT EDGE"
      track 9.35 -0.1 9.35 0.8
      plot gra e
      !deact metaf24
      !close metaf24
      !delete metaf24

      !add metaf25 type EPS file-name
"{name}{scl1}{scl2}f25.eps"
      !open metaf25
      !act metaf25
      !stamp "   TPC MWPC MIDDLE"
      track 24.35 -0.1 24.35 0.8
      plot gra e
      !deact metaf25
      !close metaf25
      !delete metaf25

      !add metaf26 type EPS file-name
"{name}{scl1}{scl2}f26.eps"
      !open metaf26
      !act metaf26
      !stamp "   TPC MWPC RIGHT EDGE"
      track 39.35 -0.1 39.35 0.8
      plot gra e
      !deact metaf26
      !close metaf26
      !delete metaf26
  endif
endif

& GAS
```

```
if gasin then
  get "tpcsg.out"
  if gas_p then
     opt gas-plot
  endif
endif

& DRIFT

* CLUSTER HISTOGRAMS FOR 1 cm OF TRACK

if drift_p then
  track 9.35 0.35 9.35 1.35 mu+ energy {mu_e} GeV nodelta
  lines 50
  if eps_cls then
     clustering-histograms iter 500 bins 100 ...
        cluster-size-bins 100 cluster-count-range automatic ...
     cluster-count-bins 100 cluster-count-range automatic ...
     cluster-energy-bins 100 cluster-energy-range automatic ...
     delta-range-bins 100 delta-range-range automatic ...
     track-range-bins 100 track-range-range automatic ...
     energy-loss-bins 100 energy-loss-range automatic ...
     keep-histograms noplot-histograms
     !add metacl1 type EPS file-name "{name}{scl1}{scl2}cl7.eps"
     !open metacl1
     !act metacl1
     call plot_histogram(clusters,`Number of deposits`,`Number of clusters per track`)
     !deact metacl1
     !close metacl1
     !delete metacl1

        !add metacl2 type EPS file-name "{name}{scl1}{scl2}cl8.eps"
        !open metacl2
        !act metacl2
        call plot_histogram(size,`Number of electrons`,`Number of electrons per cluster`)
        !deact metacl2
        !close metacl2
        !delete metacl2

     !add metacl3 type EPS file-name "{name}{scl1}{scl2}cl9.eps"
     !open metacl3
     !act metacl3
     call plot_histogram(range,`Range[cm]`,`Range of the track`)
     !deact metacl3
     !close metacl3
     !delete metacl3

     !add metacl4 type EPS file-name "{name}{scl1}{scl2}cl10.eps"
     !open metacl4
     !act metacl4
     call plot_histogram(delta,`Distance[cm]`,`Distance between cluster and track`)
     !deact metacl4
     !close metacl4
     !delete metacl4

     !add metacl5 type EPS file-name "{name}{scl1}{scl2}cl11.eps"
     !open metacl5
     !act metacl5
     call plot_histogram(ecluster,`Energy[eV]`,`Energy per cluster`)
     !deact metacl5
     !close metacl5
     !delete metacl5

     !add metacl6 type EPS file-name "{name}{scl1}{scl2}cl12.eps"
     !open metacl6
     !act metacl6
     call plot_histogram(de,`Energy[MeV]`,`Total energy loss`)
     !deact metacl6
     !close metacl6
     !delete metacl6
  endif

  * INCREASE SIZE OF WIRE-MARKERS
  !rep s-wire marker-size-scale-factor 1.0
  !rep c-wire marker-size-scale-factor 1.0
  !rep p-wire marker-size-scale-factor 1.0
  !rep other-wire marker-size-scale-factor 1.0

  if eps_d then

       * ELECTRON DRIFT TRACK & DRIFT WIRE FOR PC2 MWPC

       !add metad1 type EPS file-name "{name}{scl1}{scl2}d1.eps"
       !open metad1
       !act metad1
       area -0.2 11.4 2.0 13.2
       int-par compute-if-interpolation-fails
       track 1.9 11.5 1.9 13.1 mu+ energy {mu_e} GeV delta-electrons heed
     !stamp "  PC2 MWPC TOP REGION"
     !rep labels text-colour background
     drift track notime-graph novelocity-graph noavalanche-graph solid ...
       noisochrone electron negative
     !rep labels text-colour foreground
     call plot_x_label(`z-Axis [cm]`)
     call plot_y_label(`y-Axis [cm]`)
     call plot_end
     !deact metad1
     !close metad1
     !delete metad1

     !add metad2 type EPS file-name "{name}{scl1}{scl2}d2.eps"
     !open metad2
     !act metad2
     area -0.2 11.6 0.9 13.0
       !stamp "     PC2 MWPC TOP REGION, Ekin={mu_e}GeV"
       int-par iso-connect 0.1
       !rep labels text-colour background
       drift wire lines 70 isochrone 0.015 electron negative
       !rep labels text-colour foreground
       call plot_x_label(`z-Axis [cm]`)
       call plot_y_label(`y-Axis [cm]`)
       call plot_end
       !deact metad2
       !close metad2
       !delete metad2
```

```
    !add metad3 type EPS file-name "{name}{scl1}{scl2}d3.eps"
    !open metad3
    !act metad3
    area -0.2 5.7 2.0 7.7
    int-par compute-if-interpolation-fails
    track 1.9 5.8 1.9 7.6 mu+ energy {mu_e} GeV delta-electrons heed
    !stamp "  PC2 MWPC MIDDLE REGION"
    !rep labels text-colour background
    drift track notime-graph novelocity-graph noavalanche-graph solid ...
      noisochrone electron negative
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metad3
    !close metad3
    !delete metad3

    !add metad4 type EPS file-name "{name}{scl1}{scl2}d4.eps"
    !open metad4
        !act metad4
        area -0.2 5.9 0.9 7.5
        int-par compute-if-interpolation-fails
        track -0.5 6.7 1.8 6.7 mu+ energy {mu_e} GeV delta-electrons heed
        !stamp "  PC2 MWPC (MIDDLE), Ekin={mu_e}GeV"
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.015 electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad4
    !close metad4
    !delete metad4

    !add metad5 type EPS file-name "{name}{scl1}{scl2}d5.eps"
    !open metad5
    !act metad5
    area -0.2 0.1 2.0 2.1
    int-par compute-if-interpolation-fails
    track 1.9 0.2 1.9 2.0 mu+ energy {mu_e} GeV delta-electrons heed
    !stamp "  PC2 MWPC BOTTOM REGION"
    !rep labels text-colour background
    drift track notime-graph novelocity-graph noavalanche-graph solid ...
      noisochrone electron negative
    !rep labels text-colour foreground
    call plot_x_label(`z-Axis [cm]`)
    call plot_y_label(`y-Axis [cm]`)
    call plot_end
    !deact metad5
    !close metad5
    !delete metad5

    !add metad6 type EPS file-name "{name}{scl1}{scl2}d6.eps"
    !open metad6
        !act metad6
        area -0.2 0.3 0.9 1.9
        int-par compute-if-interpolation-fails
        track -0.5 6.7 1.8 6.7 mu+ energy {mu_e} GeV delta-electrons heed
        !stamp "  PC2 MWPC (BOTTOM REGION), Ekin={mu_e}GeV"
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.015 electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad6
    !close metad6
    !delete metad6

        * ELECTRON DRIFT TRACK & DRIFT WIRE FOR TPC MWPC

    !add metad7 type EPS file-name "{name}{scl1}{scl2}d7.eps"
    !open metad7
        !act metad7
        sel 653 654
        !stamp "  TPC MWPC LEFT REGION"
        area 8.7 -1.0 10.3 7.8
        int-par compute-if-interpolation-fails
        track 8.95 6.7 9.95 6.7 mu+ energy {mu_e} GeV delta-electrons heed
        !rep labels text-colour background
        drift track notime-graph novelocity-graph noavalanche-graph solid ...
          noisochrone electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad7
    !close metad7
    !delete metad7

    !add metad8 type EPS file-name "{name}{scl1}{scl2}d8.eps"
    !open metad8
        !act metad8
        !stamp "  TPC MWPC (LEFT EDGE), Ekin={mu_e}GeV"
        area 8.5 -0.2 9.9 0.9
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.015 electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad8
    !close metad8
    !delete metad8

    !add metad9 type EPS file-name "{name}{scl1}{scl2}d9.eps"
    !open metad9
        !act metad9
        sel 690 691
        !stamp "  TPC MWPC MIDDLE REGION"
        area 23.55 -1.0 25.15 7.8
```

```
        track 23.75 6.7 24.95 6.7 mu+ energy {mu_e} GeV delta-electrons heed
        !rep labels text-colour background
        drift track notime-graph novelocity-graph noavalanche-graph solid ...
     noisochrone electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad9
    !close metad9
    !delete metad9

    !add metad10 type EPS file-name "{name}{scl1}{scl2}d10.eps"
    !open metad10
        !act metad10
        !stamp "    TPC MWPC (MIDDLE), Ekin={mu_e}GeV"
        area 23.8 -0.2 24.9 0.9
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.015 electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad10
    !close metad10
    !delete metad10

    !add metad11 type EPS file-name "{name}{scl1}{scl2}d11.eps"
    !open metad11
        !act metad11
        sel 727 728
        !stamp "   TPC MWPC RIGHT REGION"
        area 38.35 -1.0 39.85 7.9
        track 38.55 6.7 39.75 6.7 mu+ energy {mu_e} GeV delta-electrons heed
        !rep labels text-colour background
        drift track notime-graph novelocity-graph noavalanche-graph solid ...
     noisochrone electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad11
    !close metad11
    !delete metad11

    !add metad12 type EPS file-name "{name}{scl1}{scl2}d12.eps"
    !open metad12
        !act metad12
        !stamp "    TPC MWPC (RIGHT EDGE), Ekin={mu_e}GeV"
        area 38.65 -0.2 40.2 0.9
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.015 electron negative
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad12
    !close metad12
    !delete metad12

        * POSITRON DRIFT TRACK & DRIFT WIRE AT TPC HV WIRES

    !add metad13 type EPS file-name "{name}{scl1}{scl2}d13.eps"
    !open metad13
        !act metad13
        sel 1121 1122
        !stamp "   TPC HV WIRES (LEFT REGION)"
        area 8.6 12.6 9.7 13.6
        int-par compute-if-interpolation-fails
        track 8.7 13.5 9.6 13.5 mu+ energy {mu_e} GeV nodelta-electrons heed
        !rep labels text-colour background
        drift track notime-graph novelocity-graph noavalanche-graph solid ...
     noisochrone electron positive
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad13
    !close metad13
    !delete metad13

    !add metad14 type EPS file-name "{name}{scl1}{scl2}d14.eps"
    !open metad14
        !act metad14
        !stamp "    TPC HV WIRES (LEFT EDGE), Ekin={mu_e}GeV"
        area 9.05 12.6 9.3 12.8
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.005 electron positive
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad14
    !close metad14
    !delete metad14

    !add metad15 type EPS file-name "{name}{scl1}{scl2}d15.eps"
    !open metad15
        !act metad15
        sel 1273 1274
        !stamp "   TPC HV WIRES (MIDDLE REGION)"
        area 23.8 12.6 24.9 13.2
        track 23.9 13.1 24.8 13.1 mu+ energy {mu_e} GeV nodelta-electrons heed
        !rep labels text-colour background
        drift track notime-graph novelocity-graph noavalanche-graph solid ...
     noisochrone electron positive
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad15
    !close metad15
    !delete metad15
```

```
    !add metad16 type EPS file-name
"{name}{scl1}{scl2}d16.eps"
    !open metad16
        !act metad16
        !stamp "    TPC HV WIRES (MIDDLE),
Ekin={mu_e}GeV"
        area 24.2 12.6 24.5 12.8
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.005 electron positive
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad16
    !close metad16
    !delete metad16

    !add metad17 type EPS file-name
"{name}{scl1}{scl2}d17.eps"
    !open metad17
        !act metad17
        sel 1425 1426
        !stamp "   TPC HV WIRES (RIGHT REGION)"
        area 39.0 12.6 40.1 13.6
        track 39.1 13.5 40.0 13.5 mu+ energy {mu_e} GeV
nodelta-electrons heed
        !rep labels text-colour background
        drift track notime-graph novelocity-graph
noavalanche-graph solid ...
      noisochrone electron positive
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad17
    !close metad17
    !delete metad17

    !add metad18 type EPS file-name
"{name}{scl1}{scl2}d18.eps"
    !open metad18
        !act metad18
        !stamp "    TPC HV WIRES (RIGHT EDGE),
Ekin={mu_e}GeV"
        area 39.4 12.6 39.65 12.8
        int-par iso-connect 0.1
        !rep labels text-colour background
        drift wire lines 70 isochrone 0.005 electron positive
        !rep labels text-colour foreground
        call plot_x_label(`z-Axis [cm]`)
        call plot_y_label(`y-Axis [cm]`)
        call plot_end
        !deact metad18
    !close metad18
    !delete metad18

  endif
endif

& STOP
```

10 Attachment 2: File tpcs.cel

```
&CELL

options input

*MAIN PARAMETERS
global name: `tpcs`
global scl1=1
global scl2=1

* TURN ON METAFILE FLAGS
global ps_c=true

* STANDARD CONTROL VARIABLES
global cell_p=true
global out_c=false

* DIM OF SOLDER PADS
global spdia=0.049
global spptch=0.1*{scl2}

* PC2 ANODE
global a1ptch=0.4
global a1wrdia=0.0025
global a1v=0.00
global a1z=0.35
global a1ys=0.7
global a1l=12.0
global a1spz={a1z}-{a1wrdia}/2+{spdia}/2
global a1spl=2.3
global na1wr={a1l}/{a1ptch}
global na1swr=entier({a1spl}/{spptch})

* PC2 CATHODES
global c1ptch=0.1*{scl1}
global c1wrdia=0.005
global c1v=-6000
global c1az=0.0
global c1bz=0.7
global c1ys=1.1
global c1l=11.2
global nc1wr=entier({c1l}/{c1ptch})

* PC2 GROUND
global g1ptch=0.4
global g1wrdia=0.005
global g1v=0.0
global g1z=1.3
global g1ys=1.1
global g1l=11.2
global ng1wr={g1l}/{g1ptch}

* TPC ANODE
global a2ptch=0.4
global a2wrdia=0.0025
global a2v=0.00
global a2y=0.35
global a2zs=9.15
global a2l=30.4
global na2wr={a2l}/{a2ptch}

* TPC CATHODES
global c2ptch=0.1*{scl1}
global c2wrdia=0.005
global c2v=-6500.0
global c2ay=0.7
global c2al=30.6
global c2azs=9.05
global nc2awr=entier({c2al}/{c2ptch})
global c2asy={c2ay}+{c2wrdia}/2-{spdia}/2
global c2aspl=0.9
global nc2aswr=entier({c2aspl}/{spptch})
global c2by=0.0
global c2bzs=9.45
global c2bl=29.8
global nc2bwr=entier({c2bl}/{c2ptch})
global c2bsy={c2by}-{c2wrdia}/2+{spdia}/2
global c2blspl=3.9
global c2brspl=4.7
global nc2blswr=entier({c2blspl}/{spptch})
global nc2brswr=entier({c2brspl}/{spptch})

* TPC POTENTIAL WIRES
global tdl=12.0
global nc3wr=7.0
global c3wrdia=0.05
global c3ptch=tdl/({nc3wr}+1)
global c3az=6.15
global c3bz=42.55
global c3ty=13.225
global c3atz={c3az}-{c3wrdia}/2
global c3btz={c3bz}+{c3wrdia}/2

* TPC HIGH VOLTAGE WIRES
global c4ptch=0.1*{scl1}
global c4wrdia=0.01
global c4v=-35000.0
global c4y=12.7
global c4zs=9.05
global c4l=30.6
global c4spl=0.9
global c4sy={c4y}+{c4wrdia}/2-{spdia}/2
global nc4wr=entier({c4l}/{c4ptch})
global nc4swr=entier({c4spl}/{spptch})

* DEFINE COLOURS
!
col blu red 0 green 0 blue 1
col brwn red 0.5 green 0.27 blue 0
col drkblu red 0 green 0.25 blue 0.5
col drkgrn red 0 green 0.25 blue 0
col grn red 0 green 1 blue 0
col lblu red 0.5 green 0.5 blue 1
col lgrn red 0.5 green 1 blue 0.5
col orng red 1 green 0.5 blue 0
col pnk red 1 green 0.5 blue 1
col rd red 1 green 0 blue 0
col prpl red 0.25 green 0 blue 0.25

* APPEARANCE OF THE PLOTS
rep s-wire marker-type circle
rep s-wire polymarker-colour rd
rep s-wire marker-size-scale-factor 0.3
rep c-wire marker-type -8
rep c-wire polymarker-colour drkblu
rep c-wire marker-size-scale-factor 0.3
rep p-wire marker-type -8
rep p-wire polymarker-colour rd
rep p-wire marker-size-scale-factor 0.3
rep other-wire marker-type -8
rep other-wire polymarker-colour drkblu
```

```
rep other-wire marker-size-scale-factor 0.3
rep contour-normal polyline-colour orng
rep contour-label character-height 0.0075
rep number character-height 0.01
rep labels character-height 0.015
rep isochrones linetype solid polyline-colour orng
rep isochrones polymarker-colour orng marker-type plus
rep comment character-height 0.015
rep title character-height 0.02
rep e-drift-line polyline-colour lblu
rep ion-drift-line polyline-colour lblu
rep auger-electron polyline-colour blu
rep auger-electron polymarker-colour blu marker-type cross
rep auger-electron marker-size-scale-factor 0.75
rep delta-electron polyline-colour prpl
rep delta-electron polymarker-colour prpl marker-type asterisk
rep delta-electron marker-size-scale-factor 0.75
rep function-1 polyline-colour drkgrn
rep function-1 polymarker-colour drkgrn
rep function-1 text-colour drkgrn
rep function-2 polyline-colour grn
rep function-2 polymarker-colour grn
rep function-2 text-colour grn
rep track polyline-colour brwn
rep track polymarker-colour brwn
layout x-label 0.025 y-label 0.025 title 0.025
exit

cell-id "{name}{scl1}{scl2}"

* GRAVITY POINTING IN THE -Y DIRECTION
gravity 0 -1 0

* GROUND PLANES
plane y=20.7 v=0
plane y=-7.3 v=0

* WIRES
define awght 60.0
define cwght 140.0
define coffst {c1ptch}/2
define aoffst {a1ptch}/2
define goffst {g1ptch}/2
define c3dv ({c4v}-{c2v}+1200)/({nc3wr}+1)

rows
c_c1a {nc1wr} {c1wrdia} {c1az} {c1ys}+i*{c1ptch}+coffst
{c1v} cwght
p_a1b {na1swr} {spdia} {a1spz} {a1ys}-i*{spptch} {a1v}
p_a1 {na1wr} {a1wrdia} {a1z} {a1ys}+i*{a1ptch}+aoffst
{a1v} awght
p_a1t {na1swr} {spdia} {a1spz} {a1ys}+{a1l}+i*{spptch}
{a1v}
c_c1b {nc1wr} {c1wrdia} {c1bz} {c1ys}+i*{c1ptch}+coffst
{c1v} cwght
o_g1 {ng1wr} {g1wrdia} {g1z} {g1ys}+i*{g1ptch}+goffst
{g1v} awght
p_c2al {nc2aswr} {spdia} {c2azs}-i*{spptch} {c2asy} {c2v}
p_c2a {nc2awr} {c2wrdia} {c2azs}+i*{c2ptch}+coffst {c2ay}
{c2v} cwght
p_c2ar {nc2aswr} {spdia} {c2azs}+{c2al}+i*{spptch}
{c2asy} {c2v}
s_a2 {na2wr} {a2wrdia} {a2zs}+i*{a2ptch}+aoffst {a2y}
{a2v} awght
p_c2bl {nc2blswr} {spdia} {c2bzs}-i*{spptch} {c2bsy} {c2v}
p_c2b {nc2bwr} {c2wrdia} {c2bzs}+i*{c2ptch}+coffst {c2by}
{c2v} cwght
p_c2br {nc2brswr} {spdia} {c2bzs}+{c2bl}+i*{spptch}
{c2bsy} {c2v}
p_c4l {nc4swr} {spdia} {c4zs}-i*{spptch} {c4sy} {c4v}
p_c4 {nc4wr} {c4wrdia} {c4zs}+i*{c4ptch}+coffst {c4y}
{c4v}
p_c4r {nc4swr} {spdia} {c4zs}+{c4l}+i*{spptch} {c4sy}
{c4v}
c_c3a {nc3wr} {c3wrdia} {c3az} {c4y}-(i+1)*{c3ptch}
{c4v}-(i+1)*c3dv
c_c3b {nc3wr} {c3wrdia} {c3bz} {c4y}-(i+1)*{c3ptch}
{c4v}-(i+1)*c3dv

* PRINT & PLOT CELL INFO
if cell_p then
opt c-pr
  if ps_c then
  !add metac type EPS file-name "{name}{scl1}{scl2}c.eps"
  !open metac
  !act metac
  !rep labels text-colour background
  opt wire-markers layout
  endif
  if out_c then
  wr "{name}{scl1}{scl2}c.out"
  endif
endif

& MAIN
  !rep labels text-colour foreground
  call plot_x_label(`z-Axis [cm]`)
  call plot_y_label(`y-Axis [cm]`)
  call plot_end
  !deact metac
  !close metac
  !del metac


& STOP
```

11 Attachment 3: File tpcs.gas

```
& GAS

options input

*MAIN PARAMETERS
global name=`tpcs`
global n_e=50

* OUTPUT FILES, CHOOSE ONLY ONE TO BE TRUE AT A TIME
global gas_p=false
global ps_g=false

gas-id "Hydrogen"
pressure 7600
magboltz hydrogen=100 e-field-range 100 900000 n-e {n_e}
heed hydrogen=100

* DEFINE COLOURS
!
col drkgrn red 0 green 0.25 blue 0
col grn red 0 green 1 blue 0

* APPEARANCE OF THE PLOTS
rep function-1 polyline-colour drkgrn
rep function-1 polymarker-colour drkgrn
rep function-1 text-colour drkgrn
rep function-2 polyline-colour grn
rep function-2 polymarker-colour grn
rep function-2 text-colour grn
rep number character-height 0.01
rep labels character-height 0.015
rep comment character-height 0.015
rep title character-height 0.02
layout x-label 0.025 y-label 0.025 title 0.025
exit

if gas_p then
  opt gas-pr nogas-pl
  >tpcsg.dat
  & MAIN
  >
elseif ps_g then
  !add metag type eps file-name "{name} g.eps"
  !open metag
  !act metag
  opt gas-pl
  & MAIN
  !deact metag
  !close metag
  !del metag
else
  wr "{name} g.out"
endif

& STOP
```

12 Attachment 4: Figures Caption and Figures Model Cells

<u>Figures of model cell</u>

<u>Figures of first modified model cell</u>

Figures of second modified model cell

<u>Figures of third modified model cell</u>

Figures of fourth modified model cell

Figures of fifth modified model cell